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TOPICAL PROBLEMS OF NONLINEAR WAVE PHYSICS (NWP-2025)

Nonlinear Dynamics
and Machine Learning
(NWP-1)

High-Power Lasers and Applications
(NWP-2)

Nonlinear Phenomena
in the Atmosphere and Ocean
(NWP-3)

ABSTRACTS

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Nonlinear Dynamics and Machine Learning (NWP-1)

RESERVOIR COMPUTING AS AN EFFECTIVE TOOL FOR PREDICTING THE BEHAVIOR OF STOCHASTIC SYSTEMS

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In the era of data-driven science, machine learning has emerged as a transformative approach for analyzing complex systems, particularly in forecasting stochastic dynamics where noise plays a defining role [1]. Among modern techniques, reservoir computing (RC) stands out due to its ability to model the behavior of dynamical systems exhibiting chaotic regimes, spatial complexity, and other intricate characteristics [2].

A fundamental challenge in this field involves predicting stochastic systems the dynamics of which is significantly influenced by noise [3]. A canonical example of this challenge is the phenomenon of stochastic and coherent resonances, observed in nonlinear systems subjected to noise. These effects are widespread in the nature, occurring in neural networks, sensory systems, lasers, and climate models, often playing a vital role in biological processes such as weak signal amplification and neural synchronization.

We present an RC-based framework designed to predict noise-influenced dynamics with two distinct operational modes: (i) strong prediction – high-accuracy reconstruction of system trajectories under fixed noise conditions; and (ii) weak prediction – statistical characterization of system behavior when precise forecasting becomes unstable.

The transition between these regimes follows an on-off intermittency pattern, closely resembling noise-induced synchronization observed in nonlinear systems. Our approach demonstrates how carefully tuned reservoir computers can capture noise-dependent dynamics, offering new possibilities for applications in biomedical engineering, adaptive control, and brain-computer interfaces.

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REPRESENTATION AND CLASSIFICATION OF fMRI DATA USING RESERVOIR COMPUTING AND SPATIAL PATTERNS

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Accurate representation and classification of brain activity patterns from fMRI data remain central challenges in computational neuroimaging [1]. Traditional approaches often fall short in capturing the intricate temporal dynamics and spatial organization inherent in multivariate BOLD signals. In this study, we present a novel approach that integrates reservoir computing (RC) [2] and common spatial patterns (CSP) [3] to jointly model both temporal and spatial structure in fMRI data. The reservoir component enables nonlinear encoding of temporal dependences in the signal, while CSP serves as a powerful tool for extracting discriminative spatial features.

We explore two RC-based architectures. The first applies anatomically structured input to the reservoir, followed by CSP-based spatial filtering of its dynamic states. The second, more comprehensive approach includes an initial CSP transformation of the raw fMRI data to emphasize spatial patterns before feeding it into the reservoir, with a secondary CSP applied to the reservoir outputs. Both approaches are evaluated on a clinical dataset including 70 patients with major depressive disorder (MDD) and 94 healthy controls.

The results obtained demonstrate that the combined CSP–RC–CSP pipeline achieves superior classification accuracy (up to 86%), outperforming simpler models and conventional CSP-based methods. Moreover, the proposed method preserves anatomical specificity and highlights key brain regions implicated in MDD. This work underscores the utility of combining spatial filtering and temporal modeling for robust, interpretable analysis of fMRI data in clinical and research applications.

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SYMMETRY-BREAKING DYNAMICS OF COUPLED OSCILLATORS IN QUANTUM REGIME

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Exploring cooperative dynamics in open quantum systems has recently been a vibrant topic of research. The well-known dynamical manifestations of emergent dynamics, such as synchronizations and symmetry breaking are well understood in the classical domain; however, their behavior in the quantum domain is still elusive. Studies on this problem require formalism from open quantum system that rely on the construction and solution of quantum master equations, which are nontrivial and thus challenging. In this talk I will explore the concept of quantum limit cycle in dissipative quantum systems and discuss some intriguing emergent dynamics such as symmetry-breaking transitions [1, 2] and quantum aging transition [3] in a network of coupled quantum oscillators.

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A HYBRID FRAMEWORK FOR OPTIMIZED AND DIVERSIFIED STOCK PORTFOLIO CONSTRUCTION USING CLUSTERING, CAUSAL INFERENCING AND RESERVOIR COMPUTING: EVIDENCE FROM NIFTY 50

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We present a meticulous, data-intensive multistep framework for stock selection, and portfolio optimization in the context of the Indian equity market (Nifty 50) with a focus on integrating quantitative finance, machine learning, and causal inferencing. To ensure no multicollinearity amongst the features, correlational filtering, Variance Inflation Factor (VIF) and the method of matrix rank retention are used. Causal inference is introduced through the Granger causality statistic test. Reservoir Computing (RC) is used to predict the log return for the next 90 days, which is further verified with RMSE and visual trend matching for various NIFTY50 constituents. Growth and value indicators are summed up through a composite weighted scoring method, which is then weighted by the crisis-resilience measure (market regime identification based on historical 10 years' data) to produce a probabilistic score. A sector and cluster-sensitive portfolio sampling method is applied for diversification, and then numerical optimization (SLSQP) to maximize the return-to-risk ratio is used considering exposure and allocation constraints. Back-testing also ensures that the optimized portfolio outperforms the NIFTY50 benchmark both in cumulative returns and risk-adjusted returns. Further, a pivot-based monthly breakout trading strategy with strict risk control is introduced to enhance risk-controlled short-term trading performance.

APPLICATION OF THE METHOD FOR ANALYZING THE COUPLING BETWEEN OSCILLATORS BY MODELING THEIR PHASE DYNAMICS, RELYING ON THE SPECTRAL PROPERTIES OF THE EEG

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In recent decades, thanks to the analysis of cardio signals using methods of nonlinear dynamics, new insights into the characteristics of the interaction of low-frequency rhythms (at a frequency of about 0.1 Hz) of the circulatory system have been obtained. It has been shown that in healthy individuals 0.1 Hz rhythms of signals of cardiointervalogram and photoplethysmogram are synchronized with each other. In case of pathologies (e.g., heart failure, myocardial infarction, etc.), the degree of synchronicity of these processes decreases [1]. Several recent studies have been dedicated to the investigation of low-frequency EEG rhythms both in healthy subjects and in various pathologies [2]. In this paper we consider the task of selecting a technique for analyzing directional coupling of low-frequency (at frequencies <0.5 Hz) EEG rhythms in healthy subjects. To analyze the strength and direction of coupling, we used a method based on the phase dynamics modeling [3]. The method allows calculating indices of the presence and direction of coupling based on estimates of model coefficients. The method is sensitive to weak couplings, which makes it promising for signal processing in many practical applications. However, this method has a few limitations; in this paper we investigate the possibility of its application to analyze the signals of test systems that reproduce the properties of real EEG signals.

It is shown that the reliability of conclusions about the direction of coupling can be influenced by the filtering method used to extract the low-frequency component from the EEG signal. The parameters of signal filtering were selected at which the method demonstrates a low level of errors ($p < 0.05$). A quantitative criterion for the level of erroneous conclusions about the direction of coupling is proposed.

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CHIMERA TRAVEL CAUSED BY KINKS IN A SYSTEM OF PARTICLES WITH AN INTERNAL DEGREE OF FREEDOM

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The study of active particles is a current research topic at the intersection of physics, chemistry, biology and engineering. From a physical point of view, active particles and the structures they form represent a new complex object of research, located at the intersection of statistical, chemical and biological physics, in which many nonequilibrium and nonlinear effects are observed. Active particles can also have their own dynamics. The state of each particle can be described, for example, by a phase. In this case, particles can exhibit different variants of phase dynamics, for example chimera states.

Chimera states are one of the key spatiotemporal structures that are realized in systems of nonlocally coupled identical oscillators with attractive interaction. Moreover, they coexist with a completely synchronous state, characteristic of systems with spatial symmetry. However, particle motion can destroy the fully synchronous state, leading to the dominance of the chimera regime. Here we show that the emergence of a group of kink pairs in a chain of particles described by a phase leads to a directed travel of chimera states. Moreover, the speed of the chimera motion is proportional to the number of kink pairs.

We consider a chain of particles located in a periodic potential under the action of a constant force, with an additional degree of freedom given by the phase. The coordinates of the particle are described by the driven dissipative Frenkel-Kontorova model. In this model, the coexistence of kinks – topological solitons – is possible. The phase dynamics of particles is given by the Kuramoto-Battogtokh model of non-locally coupled phase oscillators. We show that localized perturbations of particle coordinates relative to potential wells can lead to the emergence of coexisting pairs of kinks. The motion of kinks leads to the emergence of a constant drift of particles along the medium. The drift of particles leads to the destruction of fully synchronous phase dynamics and the emergence of a chimera state. The travel speed of the chimera depends linearly on the number of kink pairs.

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METHODS FOR MONITORING MENTAL FATIGUE BASED ON BIOSIGNAL ANALYSIS

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During prolonged mental tasks, a person goes through several stages, including adaptation, effective work, and mental fatigue, leading to decreased productivity [1]. Objective assessment of mental performance is important for various patients, especially regarding cognitive function decline during anesthesia and viral diseases like Covid-19. Monitoring mental fatigue is necessary for calibrating neurointerfaces and enhancing educational effectiveness through personalized learning trajectories. Currently, no tools exist for objective monitoring of mental fatigue. Existing studies rely on psychological methods, such as questionnaires, which are subjective and difficult to formalize. Research utilizing biosignal analysis has been criticized for low accuracy, associated with a limited toolkit focused on event-related potentials and time-frequency analysis [2].

In this work, quantitative indices for monitoring mental fatigue have been developed based on various biosignal analysis methods. Specifically, statistical and dynamic methods for analyzing the non-stationarity of electroencephalogram (EEG) signals and heart rate variability (HRV) have been employed. Nonlinear dynamic characteristics of HRV and the architecture of connections between brain structures and autonomic regulation of circulation have also been investigated. A protocol for experimental research on visual attention has been developed, including monitoring indicators of mental fatigue and performance, as well as recording biosignals. During the experiment, cognitive stimuli and measurement methods were selected, allowing for data accumulation for further analysis. A comparison of the proposed methods with known indices based on time-frequency characteristics of EEG and self-report results has been conducted, enabling the determination of optimal parameters and applicability limits of the developed methods. These studies have significantly improved the understanding of mental fatigue and contributed to developing effective monitoring tools.

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EFFECT OF INTERLAYER COMMUNICATION DELAY IN THE FITZHUGH – NAGUMO NETWORK ON ITS LEARNING PERFORMANCE

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One of the simplest oscillatory models of a neuron is the FitzHugh – Nagumo model [1, 2], which is characterized by the presence of type II excitability [3]. The use of the FitzHugh – Nagumo neuron for modeling spiking biologically relevant neural networks is complicated by the fact that, unlike classical neurons of artificial neural networks, it quickly returns to the equilibrium state with negative membrane potential. However, there is a signal accumulation effect that allows the FitzHugh – Nagumo neuron to be considered as a node of a spiking neural network [4]. In real biological networks, links between neurons are characterized by significant delays [5, 6].

In this study, we consider a two-layer network of FitzHugh – Nagumo neurons with unidirectional coupling from the input to the output layer. Each layer consists of 25 neurons and can be represented as a two-dimensional lattice with a side of 5. The input layer of the network is fed with graphic signals in the form of vertical and horizontal lines transformed into a Poisson process with a frequency corresponding to the brightness of the related pixel. We study in detail the influence of the delay parameter distribution in the coupling of the output layer with the input layer on the possibility of training the network of FitzHugh – Nagumo neurons using the space-time-dependent-plasticity learning method.

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MULTI-ALGORITHMIC SOFTWARE FOR VISUAL-TO-AUDITORY SENSORY SUBSTITUTION

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Visual-to-auditory sensory substitution (VASS) refers to a process in which visually impaired individuals use image sonification algorithms to compensate the impaired visual sensory system [1–3]. Both sighted and visually impaired individuals productively master various developed sonification algorithms in laboratory environment [2, 3]. However, outside of laboratories, where the complexity of the environment imposes higher requirements on the sonification algorithms, they are criticized for low ergonomics and mobility and sensory-cognitive overload arising under their use [4].

This work aimed at developing a mobile multi-algorithmic software subsystem for VASS with extensible complex of sonification algorithms, that provide different visual information representations depending on the environment and/or user preferences (Fig. 1).

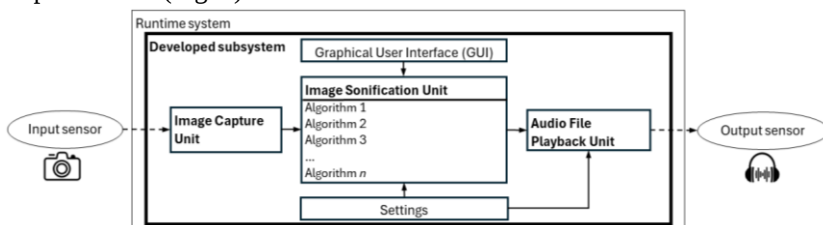


Fig. 1. Developed multi-algorithmic software subsystem for VASS

The developed subsystem operated on an Android mobile device with three embedded algorithms: The vOICe [1], stereo algorithm, the author’s modification of The vOICe [2], and the authors’ “curtains” algorithm [5].

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DYNAMICS OF A MULTI-MACHINE POWER GRID WITH A COMMON LOAD AND ITS STABILITY TO CONNECTION AND DISCONNECTION OF GENERATORS

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A power grid is a complex network consisting of many generators, consumers, intra- and inter-system connections (transmission lines) [1]. Stable operation of the grid is necessary for reliable supply of consumers. It is constantly exposed to various disturbances, which can lead to both single and short-term power supply failures affecting relatively small parts of the system, as well as cascading failures with serious and large-scale power outages [2]. Therefore, studying the dynamics of power grids is an important task from both fundamental and applied points of view.

The dynamics of a power grid consisting of an arbitrary number of generators operating on a common passive linear load is studied. The presence of homogeneous and inhomogeneous synchronous modes, quasi-synchronous and asynchronous modes is shown. The homogeneous mode is characterized by the same powers and currents flowing through all load supply paths except the first one. The inhomogeneous mode is characterized by equal powers, but different currents flowing through different (along with the first) supply paths. The partition of parameter space into regions corresponding to various dynamical modes of the grid is obtained. It is shown that the presence of active resistances in transmission lines or a load can lead to a significant increase in the total power that can be safely obtained, compared to the case of purely inductive resistances.

The stability of the power grid to disconnection and connection of generators is studied. The analytic conditions on parameters are found, ensuring safe disconnection of generators, including, if any, “inhomogeneous” generator. The regions of parameters corresponding to safe disconnection and connection of generators in power grids of various sizes are found numerically.

Acknowledgements

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MULTISCALE OF LIFE AND INTELLIGENCE

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The possibility of the existence of life, including non-biological life, on stellar and galactic scales, as well as on the scale of the Universe as a whole is explored. The analysis is based on three ideas: 1) rejection of the idea of a person and the environment limited in spatial scales surrounding him as the center of the Universe; 2) prevalence of information and intellectual processes in living matter; 3) multiscale structuring of life as a state of matter.

Our place on the scale of the Universe. The size of an electron (or proton) is 10^{-15} m. The largest known size of the Universe according to modern data is estimated to be 10^{27} m. The characteristic size of a human being is ~ 1 m. But a person boldly builds a model of the picture of the entire universe based on his very limited spatial and temporal experience. It can be quite far from reality.

So what is life? The concept formulated from the point of view of physics by E. Schrödinger more than 80 years ago did not include a biological substrate as an obligatory basis for life and claimed that “Life is an ordered and lawful behavior of a state of matter, based not only on one tendency to pass from order to disorder, but also partly on the existence of order, which is maintained all the time.” Today there is an understanding that life, as a concept, should be associated with the exchange of information between the environment and a living object and the processing of this information in the object (A.N. Kolmogorov 1964, G.R. Ivanitsky 2010, P. Nurse 2020, F. Capra 2014, H. Maturana and F. Varela 1984).

Thus, there are grounds for abstracting from a specific substrate when constructing hypotheses about the possibility of the existence of life and its structural organization on different spatial scales. At the same time, we have information about the large-scale structuring of biological life on the size range from a virus to the biosphere. These are: molecular level, subcellular level, cellular level, tissue level, organ level, organism level, population level, species level, biocenotic level, biosphere level.

A total of 10 levels – approximately 15 orders of magnitude of spatial scale in decimal notation, on the average the scale changes 30 times per level or 15 dB. Thus, life in the entire more or less range of sizes available for human study is multiscale and exists in the entire range of sizes.

The spatial range of significantly larger sizes: from the sizes of individual stars (for example, the Sun), to the sizes of the Universe has up to 17 orders of magnitude of spatial scale and, at least, such structural levels as individual stars, planetary star systems, constellations, galaxies, the Universe as a whole. It is here that opportunities open up for searching for signs of life in a broad sense.

APPLICATION OF ULTRA-WIDEBAND CHAOTIC SIGNALS FOR INDOOR WIRELESS DISTANCE MEASUREMENT AND POSITIONING

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One of the promising applications of chaotic signals is indoor wireless distance measurement and positioning. This is an area of active research and rapid technological development. Global positioning systems are not applicable indoors, and the requirements for measurement accuracy are quite high. Today a set of the radio technologies such as Wi-Fi, Bluetooth, ZigBee, and UWB are used for positioning. But among them, only ultra-wideband (UWB) technologies based on ultrashort pulses can achieve positioning accuracy of less than 50 cm indoors.

Chaotic signals also belong to ultra-wideband signals and have the potential to be used in high-precision positioning. The reasons for the interest in using this class of signals are the noise-like nature of chaotic signals, ease of generation, and their immunity to multipath fading.

In this work we consider two approaches to wireless distance measurement using chaotic radio pulses: based on measuring the power of the received signal and based on measuring the propagation time of the signal. Experimental layouts of the transmitter and receiver and the principles of their operation are described. The results of experimental verification of the proposed approaches in various propagation conditions in several outdoor and indoor environments in the mode of measuring the coordinates of an object on a straight line and on a plane are described.

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A NOVEL RESERVOIR COMPUTING MODEL: SELF-ORGANIZED CRITICALITY, ADAPTIVITY AND HIGHER-ORDER INTERACTIONS

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The construction of new highly efficient, fast acting and computationally lightweight neural networks is an important challenge in machine learning. A promising direction for solving this issue is the paradigm of reservoir neural networks, which, unlike classical recurrent neural networks, are dynamic systems and have inherent memory. The structure of the main part of such networks – the reservoir – does not change during the learning process, and only the output weights of the neural network are adjusted. There is an intriguing point of view that the brain works on the principle of reservoir neural network, thus, the reservoir computing framework is positioned at the intersection of machine learning, nonlinear dynamics and neuroscience. Here, we introduce a novel biologically inspired reservoir neural network model and demonstrate its computational capabilities.

The reservoir computing model consists of coupled Kuramoto oscillators and takes into account such key properties of brain neural ensembles as self-organized criticality [1], adaptivity [2] and higher-order interactions among units [3]. The network's performance has been tested on benchmark machine learning tasks, including reproducing multidimensional periodic patterns and predicting the dynamics of the chaotic Lorenz attractor. We have found that the main contribution to the formation of the target output of the neural network is made by the adaptive couplings. Furthermore, we have demonstrated that during the task execution, self-organized criticality is preserved for the couplings, while for the phases it may disappear.

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MACROSCOPIC SELF-ORGANIZATION OF RECURRENT SYNAPTIC NETWORKS BEYOND THE DIFFUSION APPROXIMATION

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Shot-noise naturally emerges in microscopic devices due to discrete nature of electrical charges and photons, in neural network due to discrete synaptic pulses, in social, economic and other decision-driven systems due to the discreteness of the decision events. One encounters shot-noise both in time and in space (an example of the latter is the discrete impurity atoms in a semiconductor). Given the reference temporal/spatial interval between these discrete events/objects is small against the background of the macroscopic scale of the system, one can adopt the so-called diffusion approximation, where the shot-noise is represented by the sum of the mean-drive and an effective “continuous” white Gaussian noise (derivative of a Wiener process). Many classical problems with shot-noise in condensed matter, synergetics, and mathematical neurosciences were studied and solved within the framework of the diffusion approximation (DA).

For a sparse network of neurons, the sparseness of the net of recurrent synaptic links generates an effective endogenous shot-noise [1] related to the irregularity of arrival of postsynaptic potentials. For sparse networks with balanced individual excitation and synaptic inhibition this irregularity and the consequent effective noise are present also in the case of identical (homogeneous) neurons. We consider the network of quadratic integrate-and-fire neurons. On the basis of the continuity equation for the probability density for the case of shot-noise, we construct a complete mean field theory [1]. DA is delivered by the first two terms of the Taylor series of the noise term in the continuity equation. The true macroscopic dynamics pertained to the shot-noise is much more diverse and sophisticated than the ones given by DA. Moreover, the most nontrivial and physiologically interesting regimes of global oscillations are observed where DA fails.

Acknowledgements

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DYNAMICS OF TRAINING A SIMPLIFIED NETWORK MODEL CoLaNET ON A SIMPLE CLASSIFICATION TASK

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Spiking neural networks (SNNs) are important for both understanding functioning of the brain and development of next-generation artificial intelligence systems. When deployed on special neuromorphic hardware, SNNs can consume much less energy and operate faster than traditional artificial neural networks [1]. However, to ensure their efficiency it is necessary to use special architectures and learning rules. Recently, one of the authors developed a novel SNN architecture, the so-called CoLaNET (Columnar Layered Network) designed to solve classification problems [2]. Since the circuitry and dynamics of this architecture is quite complicated, a simplified digital model was suggested [3]. The latter simplified model mimics a single column of CoLaNET.

The present paper is devoted to the learning dynamics of CoLaNET in a simple classification problem which is to split real numbers into two classes. The input signals were encoded by the Gaussian receptive field method. A theory was developed that describes the learning dynamics of the simplified model allowing one to estimate the learning time and the number of trained neurons (microcolumns). Theoretical results are in a good agreement with the numerical experiments with a simplified model. However, the learning of the full CoLaNET model can be much slower, which is due to the discrete nature of the pulse signals in the latter.

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ON SOME PROPERTIES OF OUTPUT MATRICES IN RESERVOIR COMPUTINGS

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We study the peculiarities of the training process in the task of trajectory prediction (strong prediction) using reservoir computing. We investigate the hypothesis that with the increase in the number of trajectories in the training set, trained output weight matrices become closer. To do this, we conducted numerical experiments with the Li – Sprott [1] and the Rössler [2] systems. The dynamics of the reservoir was simulated using a 4th-order Runge – Kutta scheme, where the input to the reservoir remained unchanged for a given step number. The obtained reservoirs differed from each other only in weights of the trained output matrices.

It was shown that for a single trajectory in training the predicted trajectory can fade (for the Rössler system) or shift (for the Li – Sprott system). With the addition of more trajectories to the training set, such fades and shifts become rarer and the distance between the output matrices decreases both on mean and variance. We also observed a decrease in the MSE metric for the time series and for its spectra.

It can be assumed that the matrices converge to a single projection from the states of the reservoir to the states of the system and this is critical for ensuring robust generalization in reservoir computing, particularly for chaotic systems where small perturbations can drastically alter the dynamics. This result highlights the importance of training reservoirs on multiple trajectories.

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AI AND NETWORK THEORY APPROACHES FOR STUDYING AND DIAGNOSING BRAIN DISORDERS

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Recent advances in artificial intelligence (AI) and network theory have revolutionized the study and diagnosis of brain disorders, offering novel insights into their underlying neural mechanisms. This paper synthesizes findings from multiple studies that leverage fMRI- and EEG-based functional brain networks, combined with machine learning and graph theory, to improve diagnostic accuracy and uncover disorder-specific patterns.

In major depressive disorder (MDD), disruptions in functional segregation mechanisms are evident, with reduced node strength and clustering coefficients compared to healthy controls. Consensus network analysis reveals distinct topological differences, where MDD patients exhibit stronger associations with the default mode network, while healthy controls show dominance of the central executive and salience networks. Graph neural networks trained on these topological features achieve high classification accuracy (93%), with the shortest path length emerging as a critical determinant of model performance [1].

For autism spectrum disorder (ASD), contrastive variational autoencoders uncover latent neural signatures, particularly weak frontal lobe connectivity in the alpha band, enabling highly accurate classification (F1-score: 95%) [2]. Similarly, in early mild cognitive impairment (EMCI), a novel high-order functional connectivity network combined with structural constraints improves diagnostic precision (accuracy: 91.42%), outperforming traditional methods [3].

These studies highlight the power of AI-driven network analysis in overcoming intersubject variability and enhancing biomarker discovery. By integrating multiscale network features—from macroscale topology to mesoscale connectivity—researchers can develop robust, interpretable diagnostic tools. Future work should focus on refining model generalizability and translating these computational approaches into clinical practice for early and precise detection of brain disorders.

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USING NEURAL NETWORKS TO DETECT COUPLING BETWEEN VAN DER POL OSCILLATORS FROM NOISY AND SHORT TIME SERIES

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Coupling detection is important both for practical application and fundamental studies in various fields, including physics [1] and medical diagnostics [2]. We trained a fully connected neural network, a convolution neural network, and a recurrent neural network to detect a unidirectional coupling between two van der Pol oscillators from short time series. The networks were trained to solve a problem of binary classification on the basis of the presence/absence of coupling. We tested the network in the presence of intense Gaussian zero-mean measurement noise.

A fully connected neural network demonstrated the best noise resistance among the considered networks. It maintained the accuracy of classification above 95% in the presence of noise, the standard deviation of which reached the standard deviation of the time series, calculated before the addition of noise. However, the accuracy of the classification dropped to 60–80% for the coupling coefficients below 0.1. The convolution neural network showed less resistance to noise compared to the fully connected network, and maintained the accuracy above 95% in the presence of noise with standard deviation up to 20% of the standard deviation of the noiseless time series. It also maintained similar accuracy for a coupling coefficient below 0.1; however, noise resistance was even lower in that case. The considered recurrent network was found inadequate for the task of coupling detection.

Many questions, such as cases of synchronization, bidirectional coupling, and nonlinearity, are beyond the scope of the study and require deep investigation; however, our first results are positive, and show that the neural networks can detect unidirectional coupling from very short time series and in the presence of intense noise.

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AI FOR DRUG DISCOVERY

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Artificial Intelligence (AI) is rapidly transforming the landscape of drug discovery, accelerating processes that traditionally took years into timelines of months or even weeks. AI-driven approaches—particularly Deep Learning, generative models, and reinforcement learning—are being used to identify novel drug candidates, optimize molecular properties, and predict biological activity with unprecedented speed and accuracy. This talk focuses on how AI models—especially machine learning potentials, graph neural networks, and quantum-inspired architectures—are enhancing our ability to predict electronic structures, reaction pathways, and molecular interactions with high accuracy and lower computational cost. By bridging quantum chemical simulations with data-driven inference, AI enables faster exploration of chemical space, aiding in the design of novel drug-like molecules and understanding their behavior in biological environments. We will discuss recent breakthroughs, current limitations, and the emerging synergy between AI and quantum chemistry as a foundation for next-generation pharmaceutical innovation.

HAMILTONIAN DYNAMICS OF RING DARK SOLITONS

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The dynamics of dark solitons considered as Landau quasiparticles is quite complicated even in one-dimensional geometry due to the contribution of the background flow into the canonical momentum of such a quasiparticle. We have developed the method, which allows us to find the Hamiltonian and canonical momentum of a dark soliton for a wide class of nonlinear wave equations. In particular, they include situations when a soliton propagates along a non-uniform and time-dependent background. Supposing that the width of a ring-like dip in a soliton is much smaller than the radius of the ring, we have obtained the equations of Hamiltonian dynamics of ring dark solitons. The theory is applied to the dynamics of ring solitons in expanding clouds of Bose-Einstein condensates. The analytical theory is confirmed by the results of numerical simulations.

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HYPERCHAOTIC DYNAMICS IN ECONOMIC MODEL OF OLIGOPOLY MARKET

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A duopoly represents a specific case of an oligopolistic market characterized by a high degree of interdependence among economic agents. The Kopel model, introduced by Michael Kopel [1], serves as a fundamental framework for analyzing both duopolistic and oligopolistic competition. This model can be extended to accommodate any number of market participants by increasing the number of equations in the system, as described in [2].

This study focuses on the investigation of hyperchaotic behavior in dynamic systems with symmetry that model the interactions in Kopel-type oligopolistic markets. Special attention is given to strange attractors exhibiting more than one positive Lyapunov exponent—a key challenge in the field of high-dimensional chaos theory. The first such attractors, termed hyperchaotic attractors, were introduced in [3]. A typical trajectory of a hyperchaotic system possesses at least two directions of exponential instability, as indicated by the presence of more than one positive Lyapunov exponents in numerical simulations.

According to the scenarios proposed in [4], we derive conditions for the onset of chaotic and hyperchaotic regimes in these systems and explore the potential for the emergence of pseudohyperbolic attractors, which represent a robust chaotic dynamics.

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USING THE MODELS OF PHOTOPLETHYSMOGRAM AND ELECTROCARDIOGRAM SIGNALS TO ADJUST THE METHOD FOR DETECTING SYNCHRONIZATION BETWEEN BIOLOGICAL SYSTEMS

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The autonomic control of circulation, mediated by the sympathetic and parasympathetic nervous systems, is crucial for maintaining cardiovascular homeostasis. Dysfunctions in this control are linked to diseases such as myocardial infarction and arterial hypertension. This study focuses on detecting phase synchronization between low-frequency (LF) oscillations in heart rate variability (HRV) and photoplethysmogram (PPG) signals, which reflect the autonomic regulation of heart rate and arterial pressure, respectively.

We developed mathematical models for ECG and PPG signals with preset phases of LF oscillations [1], enabling controlled simulation of synchronization patterns. The phase difference between LF oscillations in HRV and PPG was modeled as alternating horizontal (synchronous) and sloped (asynchronous) segments, effectively reproducing the characteristics of experimental data. Colored noise, derived from experimental spectra, was added to enhance realism. The models accurately replicated the statistical and spectral properties of real signals, including power distributions in the VLF, LF, and HF bands.

Using these models, we refined a synchronization detection algorithm based on phase difference slope analysis [2]. Testing on 100 synthetic datasets (20 minutes each) revealed optimal parameters for sensitivity (0.69) and specificity (0.60), improving upon the original method (sensitivity: 0.64, specificity: 0.63). The refined algorithm demonstrated an AUC of 0.75, highlighting its enhanced accuracy.

Our findings underscore the utility of synthetic signals for method validation and parameter optimization in physiological signal analysis.

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HIERARCHICAL FORMATION OF SYNCHRONIZATION PATTERNS IN ADAPTIVE NETWORK WITH HIGH-ORDER INTERACTION

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In this work, we study the influence of high-order interactions and coupling adaptivity on the dynamics of coupled oscillators. It was found that the introduction of second-order adaptive couplings leads to the emergence of a new type of synchronous behavior in the form of double antipodal clusters, which was not observed in the case of pairwise interactions [1].

We discovered various scenarios for the emergence of synchronization patterns, including multicluster and chimera states. Like in the case of adaptive networks with pairwise interactions [2], the process of forming such states is hierarchical in nature, but has a number of important distinctive features. In this case, the process of sequential formation of synchronous groups includes two stages with characteristic properties. The first stage is associated with the emergence in part of the network of a pair of high-frequency and low-frequency synchronous groups, the sizes of which are ordered in a hierarchical way. The emergence of such pairs is accompanied by the suppression of the impact from the rest of the network oscillators and the presence of strong interaction within each pair. During the second stage, the synchronization process of the remaining incoherent part of the network occurs. The features of this process are determined by the presence of a complex structure of interactions between the oscillators of the formed groups and the rest of the network via second-order couplings. In this case, the interaction of oscillators with different frequencies within the corresponding simplex does not lead to suppression of the effect on the oscillators of the resulting new synchronous groups. As a result, their structure is not always stationary and can change to the point of complete destruction during the further evolution of the network. We have established the dependence of the scenario implemented in the network on the type of the adaptation function.

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DYNAMICS OF CHAINS OF COUPLED SYSTEMS WITH A LARGE NUMBER OF ELEMENTS

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A wide class of chains of coupled nonlinear systems is considered. Among the most frequently encountered ones, chains with one-sided, two-sided, diffusion-type connections and fully connected chains are investigated. The main assumption that opens the way to the application of asymptotic methods is that the number of elements in the chain is sufficiently large. This assumption allows us to move from a model with a discrete nature of connections to a spatially distributed system of integro-differential equations or partial differential equations containing a small parameter that is equal to the value inverse to the number of elements. Critical cases in the problem of the stability of the equilibrium state are identified. It is shown that all of them have infinite dimension, i. e. infinitely many roots of the characteristic equation tend to the imaginary axis as the small parameter tends to zero. A special method for constructing quasi-normal forms is proposed – partial differential equations that do not contain a small parameter, the non-local dynamics of which determine the local dynamics of the original system.

New dynamic effects arise in cases where the chains under consideration are not closed, i. e. are not periodic in the discrete argument.

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ROBUST CHAOS IN THE GENERALIZED KURAMOTO MODEL

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One of the most fundamental problems in multidimensional chaos theory is the study of strange attractors which are robustly chaotic (i.e. they remain chaotic after small perturbations of the system). It was hypothesized in [1] that the robustness of chaoticity is equivalent to the pseudohyperbolicity of the attractor. Pseudohyperbolicity is a generalization of hyperbolicity. The main characteristic property of a pseudohyperbolic attractor is that each of its orbits has a positive maximal Lyapunov exponent. In addition, this property must be preserved under small perturbations. The foundations of the theory of pseudohyperbolic attractors were laid by Turaev and Shilnikov, who showed that the class of pseudohyperbolic attractors, besides the classical Lorenz and hyperbolic attractors, also includes wild attractors which contain orbits with a homoclinic tangency.

In this talk, using the pseudohyperbolicity notion, we will explain how to check whether the attractor is robustly chaotic or not. We will describe the corresponding numerical methods and apply them for the study of a totally symmetric network of four phase oscillators.

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NEUROTECHNOLOGIES IN EDUCATION: PERSONALIZATION OF LEARNING THROUGH A RECOMMENDATION SERVICE

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Modern education increasingly requires personalized approaches to address individual cognitive and psychological differences among students. We present a neuroeducational recommendation service that combines neuroscientific data and artificial intelligence to optimize learning trajectories. The system employs EEG-based neuroimaging and behavioral testing to assess four key cognitive functions: visual search, working memory, mental arithmetic, and their combined operation. By analyzing both neurophysiological indicators (attention stability and fatigue levels from EEG data) and behavioral metrics (error rates and response times), the service creates detailed cognitive profiles for each student [1, 2].

The recommendation engine matches profiles with validated activities from a database of 35 methodologies, such as abacus training for memory enhancement. Incorporating student preferences and school resources, AI algorithms refine suggestions quarterly using supervised learning and correlation analysis [3].

School trials demonstrated effectiveness: 78% of 60 participants showed cognitive improvement within six months, with significant working memory gains ($p < 0.05$) in a follow-up study. 92% of teachers reported better understanding of students' needs, confirming the system's practical value for personalized education. These results confirm that the integration of neurotechnologies and AI can effectively personalize education while remaining feasible for standard classroom implementation.

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NUMERIAL MODEL OF SPIKING NEURAL NETWORK CoLaNET LEARNING PROCESS

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In the present work, we study a spiking neural network (SNN) architecture CoLaNET which can be used in a wide range of supervised learning classification tasks. CoLaNET strictly adheres to the learning process locality principle – all participating signals (classified object description, correct class label and SNN decision) have spiking nature, and synaptic weight modification rules include only variables available locally with respect to learning neuron (components of its state and activity of its immediate neighbors). The distinctive feature of this architecture is a combination of prototypical network structures corresponding to different classes and significantly distinctive instances of one class (=columns) and functionally differing populations of neurons inside columns (=layers). The other distinctive feature is a novel combination of anti-Hebbian and dopamine-modulated plasticity. High performance of CoLaNET has been demonstrated on various classification tasks. However, to reach this result, adjustment of several CoLaNET hyperparameters is needed. A direct way to avoid expensive optimization procedures would be selection of optimum hyperparameter values from a theoretical model of the CoLaNET learning process. However, the SNNs behavior is a hard subject to study because of their discrete and stochastic natures. To overcome this difficulty, a smoother numerical model of CoLaNET learning was created. We demonstrate that this model reproduces the main features of CoLaNET and can be used as a convenient tool for CoLaNET exploration and tuning. Besides that, it can be considered as a novel machine learning method.

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DYNAMIC CONVOLUTION FOR IMAGE MATCHING

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Convolution neural networks (CNNs) are omnipresent in modern computer vision models and also widely used in other tasks such as voice recognition, time series analysis, machine translation, etc. In the present paper, we introduce a novel architecture of CNNs using dynamic convolutions in which the kernels are generated based on the input data. We apply this architecture to the image matching problem and develop a two-branch network in which one branch generates kernels used in convolutional layers of the other branch. We test our model on a canonical MNIST benchmark and demonstrate that it shows faster learning and better performance than the baseline model with standard convolutions. Potential applications of our architecture include numerous problems in image analysis, time series forecasting, physical-informed machine learning, etc.

HOW POPULATION CODING SHAPES RECURRENT NEURAL NETWORK DYNAMICS IN CONTINUOUS SIGNAL PROCESSING

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Recurrent neural networks leverage their inherent dynamics to process temporal information, transforming time-varying inputs into meaningful computations through evolving network states. This computation-through-dynamics paradigm is particularly powerful for continuous signal processing, where stability, adaptability, and temporal integration are critical. In this work, we examine how population coding shapes these dynamics in the context of a navigation task—a canonical example of continuous sensorimotor processing that demands real-time integration of noisy inputs.

A number of biological experiments related to navigation in confined spaces have demonstrated the emergence of place cells in the brains of animals [1]. Several studies have also suggested the existence of the so-called bump attractors [2].

We trained an artificial neural network to solve a ring navigation task using population coding for inputs and outputs. We investigated the dynamic mechanism underlying task performance and its formation during machine learning [3].

Population coding forces the network to represent the ring in the structure of connections between neurons. The emerging structure is conceptually similar to bump attractors. The explicit form of ring representations allows focusing on their interaction mechanisms without being distracted by structure recognition.

We trained the network with multiple different population codes and studied how their representations coexist within a single network. Such an approach provides a framework for investigating remapping in frames of artificial networks [4].

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APPLICATION OF MACHINE LEARNING AND LONG-RANGE TEMPORAL CORRELATIONS IN EEG FOR THE DIAGNOSIS OF FOCAL EPILEPSY

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Epilepsy diagnosis often relies on detecting abnormal neural responses to intermittent photic stimulation (IPS), yet traditional spectral analysis methods like continuous wavelet transform (CWT) show limited sensitivity in nonphotosensitive cases [1]. This study explores whether long-range temporal correlations (LRTC), measured via detrended fluctuation analysis (DFA) [2], serve as better biomarkers. EEG data from 54 patients with focal epilepsy and 54 healthy controls were analyzed during IPS across 9 frequencies (1–30 Hz). Event-related spectral perturbations (ERSP) from CWT [3] and scaling exponents (μ) from DFA were computed for 5 frequency bands (δ , θ , α , β , and IPS-specific ranges). Cluster permutation tests [4] identified significant spatial-frequency group differences. Support vector machine classifiers, trained on principal component analysis-reduced [5] and cluster selection-features, demonstrated that DFA-based models outperformed CWT-based models, achieving higher F1-scores (0.83 vs 0.75), accuracy (0.82 vs 0.7), and precision (0.78 vs 0.65).

Feature importance analysis [6] revealed distinct spatial patterns: DFA highlighted occipital and parietal β -band LRTC reductions, whereas CWT emphasized frontal and temporal ERSP changes. Notably, DFA captured alterations in cortical excitability dynamics that were not visible through spectral features, reflecting critical state disruptions in epileptic networks. These findings demonstrate that DFA reveals novel aspects of brain organization in nonphotosensitive epilepsy and suggest that integrating DFA into routine IPS protocols could enhance diagnostic sensitivity. Overall, the results underscore the value of analyzing scale-free neural dynamics and advocate for multimodal biomarkers in clinical neurotechnology.

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INTERMITTENCY IN FORECASTING STOCHASTIC SYSTEM BEHAVIOR USING RESERVOIR COMPUTING

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Intermittency is one of the most widespread effects in nonlinear dynamic systems [1]. This phenomenon was initially identified in relation to the transition to chaotic behavior in dynamic systems [2].

One of potent tools for prediction of chaotic dynamic systems is reservoir computing (RC) [3]. We can expect an on-off intermittency effect near the regime where accurate RC prediction of the system's behavior is achieved [4].

We have demonstrated that when the control parameters of both the predicted stochastic FitzHugh – Nagumo (FHN) system and the RC model are tuned, intermittent behavior emerges. Specifically, near the threshold parameter value, the RC model achieves accurate prediction most of the time, but there are intervals during which accurate prediction is absent.

When we tune the FHN system, such behavior demonstrates on-off intermittency with exponent of approximately -1 . However, when the tuned system is RC model instead, the behavior of prediction does not correspond to on-off intermittency as its exponent of approximately -1.2 is below the expected value of -1 . We propose the concept of effective noise, internal noise of the reservoir, to address this discrepancy and develop a method of its estimation. When we account for effective noise when tuning the RC model, the prediction intermittency exponent becomes close to -1 instead of former -1.2 , adhering to on-off intermittency. Thus, we have successfully proved that the prediction quality of RC follows on-off intermittency.

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ANALYSIS OF SIMPLICIAL COMPLEXES AS AN EFFECTIVE APPROACH FOR DETECTING HIGHER-ORDER INTERACTIONS IN COMPLEX NETWORKS: APPLICATION EXAMPLES

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Functional network analysis provides powerful insights into the organizational principles of the human brain, both in health and disease. Psychiatric disorders, such as major depressive disorder (MDD), are often associated with subtle yet critical deviations in functional connectivity across multiple network scales. Traditional network analysis, which focuses solely on pairwise interactions, fails to capture the higher-order interactions that underlie complex brain dynamics. To address this limitation, we employ Q-analysis—a method for detecting strongly connected simplicial complexes across different topological levels—to uncover higher-order interactions in both synthetic and real-world functional brain networks.

Using model networks with diverse topologies (scale-free, configurational, random, and small-world), we demonstrate how Q-analysis metrics vary with network structure. Our simulations reveal distinct topological signatures: scale-free networks exhibit concentrated connectivity in lower-dimensional simplices, whereas configurational networks display a more uniform distribution. Random networks show a nonlinear dependence of topological entropy on edge probability, while small-world networks highlight the impact of nearest-neighbor connectivity and rewiring probability on higher-order organization.

Applying this framework to resting-state fMRI data, we identify significant disruptions in higher-order brain network architecture in MDD. Patients exhibit reduced topological diversity and complexity, with fewer and less interconnected cliques. Key alterations include hyper-engagement of limbic structures alongside diminished involvement of the cerebellum, occipital, and temporal lobes. These findings underscore the utility of simplicial complex analysis in detecting higher-order network abnormalities associated with neuropsychiatric disorders.

The Q-analysis metrics, such as structure vectors and topological entropy, provide a concise representation of network structure. They capture topological features that allow for analysis and comparison across different networks.

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SYMMETRY APPROACH TO THE PROBLEM OF THE GAS EXPANSION INTO A VACUUM

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We present the results on the expansion of quantum and classical gases into a vacuum based on the use of symmetries. For quantum gases in the Gross-Pitaevsky (GP) approximation, additional symmetries arise for gases with a chemical potential μ that depends on the density n powerfully with exponent $\nu = 2/D$, where D is the space dimension. For gas condensates of Bose atoms at temperatures $T \rightarrow 0$, this symmetry arises for two-dimensional systems. For $D = 3$ and, accordingly, $\nu = 2/3$, this situation is realized for an interacting Fermi gas at low temperatures in the so-called unitary limit. The same symmetry for classical gases in three-dimensional geometry arises for gases with the adiabatic exponent $\gamma = 5/3$. Both of these facts were discovered in 1970 independently by V.I. Talanov for a two-dimensional nonlinear Schroedinger (NLS equation, which coincides with the Gross-Pitaevskii equation), describing stationary self-focusing of light in media with Kerr nonlinearity, and for classical gases, by S.I. Anisimov and Yu.I. Lysikov. In the quasiclassical limit, the GP equations coincide with the equations of the hydrodynamics of an ideal gas with the adiabatic exponent $\gamma = 1 + 2/D$. Self-similar solutions in this approximation describe the angular deformations of the gas cloud against the background of an expanding gas by means of Ermakov-type equations. Such changes in the shape of an expanding cloud are observed in numerous experiments both during the expansion of gas after exposure to powerful laser radiation, for example, on metal, and during the expansion of quantum gases into the vacuum.

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UNVEILING THE LEARNING PROCESS: DYNAMIC REPRESENTATIONS IN RL-DRIVEN RECURRENT NEURAL NETWORKS

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Recurrent neural networks (RNNs) trained via reinforcement learning (RL) have emerged as powerful models for studying the evolution of neural computation in dynamic cognitive tasks. While traditional analyses focus on the final mechanisms in fully trained networks, the emergence and transformation of these mechanisms during learning remain largely unexplored. Here, we investigate how dynamic representations and selective neuronal populations evolve in RNNs trained on a context-dependent decision-making task – a paradigm inspired by neuroscience experiments. By analyzing ensembles of RNNs at multiple training stages, we reveal the formation and transformation of phase-space structures, such as fixed points and quasiperiodic attractors, that underpin task performance. Using tools from nonlinear dynamics, information theory, and autoencoder-based dimensionality reduction, we demonstrate that RL leads to distinct internal representations, including oscillatory dynamics not observed in supervised learning. Our results highlight the interplay between the training method, the task complexity, and the diversity of emergent neural populations, providing new insights into the dynamic processes that shape computation in artificial and biological networks.

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BIOLOGICALLY INSPIRED NEURAL NETWORKS BASED ON ADAPTIVE KURAMOTO MODEL WITH HIGHER-ORDER INTERACTIONS

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The talk accumulates the results of studying the dynamics of small ensembles and networks of Kuramoto oscillators with adaptive couplings and higher-order interactions among units. We demonstrate how these models reproduce the key properties of the real neural ensembles and present a study of its dynamical regimes. A range of possibilities for using these networks in applied problems, such as reservoir computing and information coding, is shown.

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INTERPRETING BRAIN ACTIVITY WITH NONLINEAR AND NEURAL NETWORK BASED MODELS

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Existing deep neural networks for decoding brain activity prioritize performance over interpretability, failing to link the decision rule to cortical sources and the dynamic properties of their electrical activity. Conversely, traditional neuroimaging identifies neural substrates behind behavior-specific brain states but relies on oversimplified models unable to capture the complexity of brain activity variations. Our approach integrates interpretable neural networks with source-level cortical dynamics, bridging these gaps to reveal physiologically meaningful patterns that differentiate complex brain states, enabling us to build compact yet powerful decoders and mine potentially novel neurophysiological knowledge.

MACHINE LEARNING MODEL ABILITY TO RECONSTRUCT COMPLEX ATTRACTORS

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In [1] it was demonstrated that a neuromap obtained with machine learning for flow dynamical system can reproduce its dynamics. In [2] it was experimentally confirmed that a neuromap can identify fixed points absent in training trajectories. In the present study we focus on investigating the ability of neural mappings to detect and reproduce nontrivial attractors not present in training data, using a multistable Chua system. The parameters ($\alpha=8.4$, $\beta=12$, $\gamma=0.05$, $m_1=-0.23$) were fixed, while m_0 was varied to construct a bifurcation diagram. The dataset was generated via the Runge-Kutta method, with initial conditions sampled from diverse phase space regions, totaling 100,000 points per attractor. The neural mapping architecture featured a single nonlinear layer (128 neurons, tanh activation), trained using SGD and MSE loss.

The experiments revealed that the model could detect hidden attractors excluded from training data. For example, omitting a limit cycle led to its reconstruction with slight distortions. Increasing data volume improved accuracy, enabling distinction between chaotic attractors and fixed points. When two attractors were excluded, the model identified hidden regimes but introduced artifacts (e.g., a fixed point became a small cycle). Small datasets resulted in incorrect recovery. The model accurately reproduced dynamics in data-covered regions but performed poorly outside them, highlighting the dependence on training data representativeness.

The results underscore neural mappings' potential for analyzing multistability and detecting hidden attractors. While requiring sufficient data and class balance, the method shows promise for system reconstruction from experimental data. Future work should optimize network architectures and explore applicability in more complex systems.

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TOWARD A DATA-DRIVEN NEUROSCIENCE: PREMISES AND TOOLS OF THE COMPUTATIONAL TURN

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In recent years, the search for reliable psychiatric biomarkers has intensified. Functional MRI (fMRI) has been central to this effort, revealing brain changes linked to major depressive disorder (MDD), schizophrenia, and bipolar disorder. Yet, findings remain inconsistent due to the heterogeneity of mental illnesses.

Multivariate analytical techniques offer a solution by examining multiple domains—neuroimaging, behavior, symptoms, demographics—simultaneously. This study applies methods like Principal Component Analysis (PCA), Multivariate Linear Models (MLM), and Canonical Variate Analysis (CVA), supported by Singular Value Decomposition (SVD), to analyze high-dimensional fMRI data. When combined with machine learning, these techniques enable the classification of psychiatric subgroups and identification of neural signatures relevant to diagnosis and treatment.

Empirical work involved fMRI data from patients with MDD, schizophrenia, and healthy controls. MLM applied to emotional tasks revealed brain patterns distinguishing groups with 67–98% accuracy [1]. Multimodal analyses integrating morphometry, resting-state, and task-based fMRI further improved diagnostic differentiation and identified key brain regions.

These findings underscore the promise of multivariate neuroimaging and machine learning in precision psychiatry. By enabling personalized neural profiling, they can refine diagnostics, predict treatment outcomes, and support tailored interventions. Future clinical integration will require interdisciplinary collaboration and ongoing methodological innovation.

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IMAGE RECOGNITION USING A SMALL SPIKING NEURAL NETWORK

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To solve the problem of image recognition, networks consisting of a large number of neurons are usually used [1–3]. We have investigated the possibility of using a small neural network to recognize simple black and white images with added noise. The network under study consists of simple neurons, like LIF neurons [4] or FitzHugh-Nagumo neurons [5], which are capable of generating spikes in response to external forcing. An unsupervised learning of our spiking neural network is based on the spike-timing dependent plasticity (STDP) method.

We studied the result of image recognition depending on the number of neurons in the network, synaptic weights, STDP method parameters, and noise intensity in the images. Depending on the parameters of STDP learning, two different variants of the output layer dynamics are observed. In the first case, only one neuron in the output layer exhibits spiking activity, and different images cause spikes in different output neurons. In the second case, when an image is fed into the network, spikes are generated in a group of neurons in the output layer, and the combination of such firing neurons is unique for different images.

Then, we have demonstrated the possibility of using a spiking neural network consisting of a small number of neurons for image recognition.

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FEATURES OF SYNCHRONIZATION OF THE ENSEMBLE OF FITZHUGH – NAGUMO NEURONS WITH LÉVY NOISE

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This study is devoted to the investigation of the synchronization of an ensemble of FitzHugh – Nagumo neurons with noise impact. Synchronization plays a huge role in the dynamics of neuronal networks, as various pathologies of brain dynamics, such as tremor, epilepsy and Parkinson's disease, are associated with the appearance of synchronization. Excitation of spike activity in the ensemble is produced by additive inhomogeneous Lévy noise, which best describes jump-noise processes observed in real neural networks.

In order to synchronize the ensemble, we developed an algorithm for fitting the coupling strengths, which works on the analysis of differences in the spike times of the coupled neurons and allows us to determine the minimum sum of coupling strengths necessary for synchronization. We use the coefficient of variation of interspike intervals to characterize the synchrony of the coupled elements. The Lévy noise source is characterized by a noise scale parameter, a stability parameter and a skewness parameter. The optimal value of the Lévy noise scale parameter was determined and the influence of the coupling radius and Lévy noise parameters on synchronization was studied. The results obtained allow determining the noise parameters and the link radius at which, synchronization occurs at the smallest sum of link forces.

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THE IMPACT OF INTERNAL NOISE ON DEEP AND SPIKING NEURAL NETWORKS

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In this work, we study the impact of noise on deep and convolutional trained neural networks. The types of noise studied originate from a real optical implementation of a neural network, but we generalize these types to enhance the applicability of our findings on a broader scale. The noise types considered include additive and multiplicative noise, which relate to how noise affects individual neurons, as well as correlated and uncorrelated noise, which pertains to the influence of noise across one layers. We demonstrate that the propagation of uncorrelated noise primarily depends on the statistical properties of the connection matrices. Specifically, the mean value of the connection matrix following the layer impacted by noise governs the propagation of correlated additive noise, while the mean of its square contributes to the accumulation of uncorrelated noise. Additionally, we propose an analytical assessment of the noise level in the network's output signal, which shows a strong correlation with the results of numerical simulations. For a convolutional network, it is shown that additive noise significantly worsens the network performance in the presence of a convolutional layer, but its negative impact can be reduced by the presence of a pooling layer immediately after the convolution layer. For multiplicative noise, the conclusions are not so clear. In most cases, its impact is the same regardless of the presence of convolution and pooling layers. However, using MaxPooling in the pooling layer makes the network less robust to multiplicative uncorrelated noise.

For deep networks, the layer in which the noise is introduced plays a major role. For example, introducing noise in the first and last layers leads to the greatest deterioration in the accuracy of the work, and in other cases, the network itself often suppresses internal noise.

As for spiking networks, we have considered trained networks consisting of FitzHugh-Nagumo neuron models in oscillatory mode. It has been shown that additive and multiplicative noise effects in the case of oscillatory mode cause absolutely no effects, and additive noise is not so important for such networks.

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CONTROL OF DETERMINISTIC AND STOCHASTIC WAVEFRONT PROPAGATION FOR NETWORKS OF BISTABLE OSCILLATORS

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The effect of wavefront propagation is an interdisciplinary phenomenon observed in a broad spectrum of dynamic systems, including the bistable ones. A wide range of bistable systems exhibiting wavefront propagation determines the significance of the development of universal schemes for controlling the propagation velocity and direction. For this purpose, one can vary parameters to increase or to reduce system's asymmetry [1]. In addition, stochastic control of the wavefront propagation can be applied [2]. In networks of coupled oscillators, one can modify the coupling topology or tune the coupling strength to control the wavefront propagation.

The present work addresses the wavefront propagation control based both on the stochastic impact (Gaussian and Lévy noises are distinguished, as well as additive and multiplicative noise sources) and the intrinsic peculiarities of the coupling of different topologies. A list of considered networks includes single-layer rings of locally and nonlocally coupled bistable oscillators [3], as well as multilayer multiplex networks [4]. It is demonstrated that varying the coupling strength and radius provides controlling the propagation velocity and save fronts and spatial domains destroyed in the presence of local coupling due to the action of high intensity noise. In addition, Lévy noise is shown to be a useful tool for the stochastic wavefront propagation control when tuning the noise parameters (especially, the skewness parameter of Lévy noise).

All the effects mentioned above are discussed on an example of networks of identical bistable oscillators generally written in the form:

$$\dot{x}_i = -x_i(x_i - a)(x_i + b) + f_i(\vec{x}) + \xi_i(t), \quad (1)$$

where f_i and $\xi_i(t)$ are the coupling and additive noise terms, correspondingly. The multiplicative noise is introduced through the stochastic modulation of parameters a and b .

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APPLICATION OF MACHINE LEARNING AND EVALUATION OF MODEL PERFORMANCE IN ENVIRONMENTAL FORECASTING TASKS

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Forecasting the dynamics of the state of the environment is one of the problems underlying decision-making in the field of environmental policy. Solving this problem involves building models and evaluating their performance. Modern intensive development of computing technologies, especially in the field of machine learning, provides researchers with a powerful tool for building hybrid models. This paper proposes approaches to constructing input variables for predictive models based on subject representations, such as land use [1]. Approaches to constructing non-random training sets are considered [2]. Along with the traditional Taylor diagram [3], a permutation method to assessing model performance [4] is proposed. Finally, we propose a counter-prediction approach that can be used in problems of estimating missing data [5].

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A NEW TYPE OF CHIMERA STATE IN AN ENSEMBLE OF ACTIVE PARTICLES

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We consider a system of nonlocally coupled Kuramoto-Battogtokh phase oscillators located on a ring. The oscillators in the medium behave as follows: one part of the oscillators does not change its position, the position of the oscillators from the second part obeys a harmonic law with the same frequency and different amplitude. All moving oscillators are localized in a small area in the center of the ring. Some random and deterministic amplitude distributions are considered for them. A new dynamic chimera state has been obtained in which three clusters of different oscillator behavior exist in the medium: a coherent cluster in which the oscillators are synchronized in both frequency and phase, an incoherent cluster, and a coherent cluster in which the oscillators are synchronized in frequency with an almost constant phase shift. The effect of compensating for fluctuations in a coherent cluster with a linear shift of the distribution with a fixed sample is demonstrated. The influence of the nonlinearity of the coupling on the formation of higher harmonics during oscillations with large amplitudes is demonstrated.

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DYNAMICS OF LARGE OSCILLATOR ENSEMBLES WITH RANDOM INTERACTIONS

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The dynamics of large populations of oscillators with random interactions is a topic crucial for understanding the collective behavior of systems in physics, engineering, and life sciences, where disorder in coupling is prevalent. While collective synchronization in regular setups is well-understood, the impact of disorder in coupling remains an active research area, particularly relevant in neuroscience. This study explores large ensembles of oscillators with random interactions, described by phase dynamics incorporating natural frequencies, individual Gaussian white noise and interaction terms. The complexity of these interactions, especially under the influence of randomness, presents significant challenges for both theoretical and numerical analyses. We examine the Kuramoto-Daido model and the Winfree model, both of which were adapted to include random coupling terms. We consider situations, where pairwise coupling terms are random functions. In particular, we investigate how randomness in coupling strengths and phase shifts affects the collective synchronization of oscillators. By representing random interactions through complex Fourier coefficients, we establish a framework to approximate the behavior of large oscillator populations under random influences. This framework allows for deriving effective deterministic coupling terms by averaging over the random interactions.

A key finding of the study is that, despite the random nature of interactions, it is possible to reduce the dynamics of the system to an effective deterministic ensemble. This simplification is achieved by averaging the random coupling functions, leading to effective coupling functions that maintain the essential behavior of the system. In particular, our main theoretical result demonstrates that the randomness of coupling strengths in a large oscillator population renormalizes total coupling strength in an effective ensemble without disorder, whereas randomness in phase shifts alters the form of the coupling function. Numerical simulations confirm these predictions, showing that the effective coupling function becomes a convolution of the original function with the phase shift distribution. This work provides a framework for understanding synchronization in complex systems with disordered interactions, with implications for modeling neuronal activity and other applications.

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TOPOLOGICAL SIGNATURES OF FUNCTIONAL BRAIN NETWORKS IN MAJOR DEPRESSIVE DISORDER USING PERSISTENT HOMOLOGY

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Background: Major Depressive Disorder (MDD) is a prevalent and debilitating mental illness. While functional magnetic resonance imaging (fMRI) studies have extensively investigated alterations in functional brain networks in MDD, often using traditional graph-theoretical measures based on correlation matrices, these approaches are often limited by arbitrary thresholding choices and sensitivity to noise.

Objective: This study aims to apply methods from Topological Data Analysis (TDA), specifically Persistent Homology (PH), to characterize the topological structure of fMRI-derived functional correlation networks in individuals with MDD compared to healthy controls (HC). We hypothesize that TDA, by capturing multiscale structure independent of arbitrary thresholds, can reveal robust quantitative topological differences potentially missed by standard graph metrics, offering novel insights into the large-scale network pathology of MDD.

Methods: Resting-state fMRI data were acquired from cohorts of MDD patients and HC participants. Functional connectivity matrices were computed based on interregional BOLD signal correlations. Persistent homology was then applied using a filtration based on correlation strength to track the evolution of topological features (connected components, Betti-0; loops, Betti-1) across the range of connectivity strengths. Statistical comparisons of quantitative measures derived from persistence diagrams will be performed between the MDD and HC groups.

Potential Significance: By quantifying multiscale topological features inherent in functional brain networks, this TDA approach offers a principled way to analyze network organization without relying on arbitrary thresholds and hyperparameters. Identifying distinct topological signatures in MDD could enhance our understanding of its systems-level pathophysiology and potentially contribute to the development of more robust neuroimaging biomarkers.

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POSE ESTIMATION APPROACH IN VERTEBRAE RECOGNITION

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Automated segmentation of spinal X-ray images is a highly relevant task that can assist neurosurgeons in diagnosis and surgical planning by reducing routine workload and enabling greater focus on complex medical decision-making. From the perspective of computer vision, this task involves detecting anatomical landmarks such as vertebral corners and endplates. Given the anatomical consistency of vertebrae within each spinal region, the problem shares conceptual similarity with human pose estimation. Based on this analogy, we propose adapting the state-of-the-art pose estimation techniques to develop a model capable of estimating the “pose” of the spine in radiographic images.

This work presents an automatic labeling approach for spinal radiographs based on RTMPose, a modern framework originally designed for human pose estimation [1]. The model was trained on a composite dataset combining CSXA [2], BUU-LSPINE [3], and our own dataset of full-length spine X-rays annotated with vertebral landmarks. We describe key model features and training strategies, present preliminary results, and benchmark model performance against expert-annotated ground truth data.

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MACHINE LEARNING IN THE ASSESSMENT OF THE NOMOLOGICAL ORGANIZATION OF TRAITS

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This paper explores trait theory within translational neuroscience, highlighting how unsupervised machine learning applied to hybrid data (psychometric and neuroimaging) enhances the precision in mapping personality structure. Traits are interpreted as elements within a nomological network, expressing stable patterns of brain–behavior relationships.

Personality traits, in contrast to psychological traits, reflect behavioral variability influenced by environmental factors. Translational neuroscience integrates psychometric and neuroimaging data, requiring both multidisciplinary and transdisciplinary approaches to address the nonlinear complexity of brain–personality systems. Hybrid data were analyzed using principal component analysis and agglomerative clustering. Functional resting-state data and A. Lowen’s typology were employed to examine traits as stable components reflected in resting-state networks (RSNs), particularly within fMRI measures. Our previous study validated Lowen’s personality typology, linking traits to neural features in the FPN, DMN, and DAN, measured via node strength (NS) and clustering coefficient (CC). Three principal components explained 76% of variance, with one driven by rigid and schizoid traits. Co-clustering revealed up to 94% precision and 62% specificity, evidencing mutual dependence between personality and neural systems.

Monodisciplinary approaches fail to grasp the nonlinear nature of brain–trait relationships. Our findings, aligned with Cloninger’s theories, support the existence of a nomological organization of traits reflected in brain networks and measurable via integrative machine learning methods.

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MACHINE LEARNING FOR SOLUTIONS OF THE MIND-BRAIN PROBLEM IN PSYCHIATRY

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This paper presents a scoping overview of a series of task-related functional MRI (fMRI) studies in psychiatry, where tasks were adapted from clinically validated diagnostic scales and analyzed using machine learning. The goal was to address the mind-brain problem within a framework of non-reductive physicalism by capturing the non-linear dynamics of mental and brain systems.

The research applied Group Independent Component Analysis (Group ICA), Statistical Parametric Mapping, and Multivariate Linear Methods to three datasets comparing patients with depression, schizophrenia, and healthy controls. The adapted tasks were related to differential brain activations and modulated specific neural circuits, revealing diagnostic specificity in brain network responses.

Findings indicate that these brain responses are not localized anatomically but are instead distributed across large scale networks. These patterns support a computational neuroscience interpretation of psychiatric disorders, in line with non-reductive physicalism, highlighting the complexity and state-dependence of brain functions.

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BENEFICIAL ROLE OF NOISE IN THE DYNAMICS OF COMPLEX NETWORKS: CHIMERA RESONANCE

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Random perturbations are inevitable and sometimes permanently present in many real-world systems and thus can significantly affect their functioning and characteristics. Despite the generally accepted interpretation of noise as a source of destruction, noise impacts can sometimes play a counter-intuitive beneficial role in the system behavior by enhancing the degree of order or improving its characteristics. Since real-world systems consist of interacting nodes with different individual dynamics and coupling topology and can demonstrate various complex nonlinear patterns, studying the robustness of spatiotemporal structures, such as, e.g., chimera and solitary states [1, 2], toward noise influences has become one of the prominent research directions in different scientific fields.

We present numerical results on the systematic studies of the impact the impact of additive Gaussian noise on the dynamics and chimera observation in networks of nonlocally coupled discrete-time systems. As individual elements, we use the logistic map, the Henon map, and the Ricker map. We construct 2D diagrams of typical dynamical regimes that are observed in noise-free networks depending on the local dynamics parameters and the coupling strength. After introducing additive noise, we calculate the probability of observing chimera states in the three networks when the noise intensity and the coupling strength are varied. The numerical results are summarized in the 2D distributions of the probability drawn for several selected values of the local dynamics parameters. It is shown that the chimera existence demonstrates a resonance-like dependence on the noise intensity and the coupling strength. Moreover, there is an optimum noise level at which the interval of the coupling strength within which chimeras are observed with a high or even maximum probability is the widest. Thus, this fact constitutes the constructive role of noise in analogy with stochastic and coherence resonance and may be referred to as chimera resonance [3].

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ALTERED CONNECTIVITY OF THE SALIENCE, SENSORIMOTOR, VISUO-OCCIPITAL AND CEREBELLAR NETWORKS MAY DELINEATE VALUABLE INSIGHTS IN THE PATHOPHYSIOLOGY OF THE DEPRESSIVE SYNDROME

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Depression is not only one of the most common and debilitating psychiatric conditions, but it can also be a manifestation of multiple psychiatric illnesses such as Major Depressive Disorder (MDD) and Bipolar Disorder (BD). It often occurs in the context of somatic diseases as well. Yet, the exact pathophysiological mechanisms underlying this syndrome are still unknown, which is reflected in the insufficient efficacy of current preventative and therapeutic strategies. A step towards remedying this issue was made with the concept for mental illness as a continuum instead of a categorical entity. This research is another attempt to contribute to elucidating the pathophysiological mechanisms of the depressive continuum by exploring the ROI-to-ROI whole brain resting-state functional connectivity (rs-FC) in patients with depressive syndrome in the context of MDD and BD and healthy individuals (HC).

For this study 104 HC and 119 patients with a depressive syndrome in the context of MDD or BD underwent resting-state functional Magnetic Resonance Imaging. The data analysis was performed via the CONN Toolbox running on MATLAB.

The ROI-to-ROI analysis yielded a statistically significant increase of the rs-FC between a cluster comprised of the postcentral gyrus bilaterally and the right precentral gyrus and a cluster comprised of the insular cortex bilaterally in patients with depression as opposed to HC. Furthermore, reduced rsFC between a cluster formed by the cerebellum VI and the anterior cerebellum and a cluster comprised of the bilateral occipital fusiform gyrus and the bilateral opercular gyrus was observed in the patient group in comparison with HC.

This research adds to the growing evidence of the cerebellar involvement in the pathophysiology of the depressive syndrome. The altered rsFC between the cerebellar and visuo-occipital networks may be associated with symptoms such as cognitive dysfunction, insomnia, melancholy, etc. In addition, the aberrant connectivity between the salience and sensorimotor networks may be related to impaired affective and interoceptive integration in depression.

ALTERED CONNECTIVITY BETWEEN THE RIGHT LINGUAL GYRUS AND RIGHT ANTERIOR INSULA MAY DIFFERENTIATE UNIPOLAR FROM BIPOLAR DEPRESSION

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Bipolar disorder (BPD) and major depressive disorder (MDD) are two of the leading causes of mental health-related disabilities, however a significant number of individuals with these conditions remain undiagnosed, face misdiagnosed, or receive insufficient treatment. According to latest studies both illnesses exhibit distinct patterns of dysconnectivity both between and within large-scale networks and among regions associated with sensory input processing. This study seeks to build upon existing knowledge by analyzing the effective connectivity strengths among eight predefined regions: anterior cingulate cortex (ACC), anterior insula (AI), precuneus (PCu), lingual gyrus (LiG), superior temporal gyrus (STG), inferior temporal gyrus (ITG), fusiform gyrus (FFG), and cerebellum externum (CerE) chosen based on our previous research.

For this study 109 HC, 83 patients with UD, and 47 patients with BD underwent resting-state functional Magnetic Resonance Imaging. The data were processed using spm12 running on MATLAB and IBM SPSS Version 28.0 .

The analysis yielded statistically significant differences in three connections, namely LiG → AI (excitatory), ACC → STG (inhibitory), and PCu → STG (excitatory). The post-hoc analysis demonstrated that the value of the LiG → AI connection was different between the UD and BD groups whereas the ACC → STG and PreCu → STG values showed differences between the BD and HC groups. Furthermore, for LiG → AI the coupling values significantly differed from zero only in the UD group, for ACC → STG only in the BD group and for PCu → STG only in the HC group.

Our study is concordant with current evidence on the involvement of the salience and default mode networks in the pathophysiology of depression. In addition, we observed that in BD the excitatory connection from the right LiG to the right AI is missing as compared to UD. This can be interpreted as a disintegration of the sensory input processing leading to an alteration of the perception of the self and the environment in both illnesses and may provide explanation for the divergent clinical presentation and course of MDD and BPD.

EFFICIENT PRECONDITIONING FOR ITERATIVE METHODS WITH GRAPH NEURAL NETWORKS

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Recent research has shown that convolutional neural networks (CNNs) [1, 2] and graph neural networks (GNNs) [3, 4] can be trained to provide an approach for constructing preconditioners for the iterative methods of solving linear systems arising from the discretization of partial differential equations (PDEs). These methods use trained neural networks to construct a preconditioner in the form of incomplete factorizations, which are further used during iterations of conjugate gradient method (CG). The use of GNNs can be advantageous because of the duality between sparse matrices and graphs, which allows the use of a message-passing framework with GNNs with a small number of parameters.

Training the neural network for preconditioner construction can be unstable and lead to suboptimal solutions. To mitigate these problems, we propose the PreCorrector method, which is trained to predict the correction to well-known classical preconditioners. The PreCorrector starts learning with incomplete factorization, which allows it to construct preconditioners that reduce the condition number of the initial system more significantly than classical preconditioners and achieve more stable training.

We also investigate how the chosen objective can change the resulting preconditioners. In our experiments, we observe that training with a certain loss function results in preconditioners that have a more desirable effect on the spectrum of matrices from the discretization of PDEs.

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EFFECTS OF COUPLING AND NOISE IN NETWORKS OF EXCITABLE FITZHUGH – NAGUMO NEURONS

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Noise plays an important role in the behavior of excitable systems, such as neuron networks. Together with topology and parameters of coupling, noise can be considered as a factor that controls processes in networks [1–3].

The spiking activity induced by independent noise sources of different characteristics in a network of excitable FitzHugh – Nagumo neurons with nonlocal coupling was considered. The influence of white α -stable noise and colored Gaussian noise on the behavior of a neural network was investigated both in the case of noise affecting fast variables and slow variables of neurons. A small ensemble of 10 neurons was chosen, which made it possible to construct detailed maps of average spike frequency of neurons on the plane of various control parameters. The influence of the coupling strength on the average firing rate and on the effect of coherent resonance was studied.

For all considered types of noise a general regularity was established in the evolution of the neuron spike activity with the strengthening of the coupling between them. Weak coupling leads to an increase in the average firing frequency of neurons, while strong connection suppresses spike activity and, in some cases, can reduce it to zero. With various types of noise impact, it was observed that neurons exhibit the effect of coherence resonance. Furthermore, if the coupling strength is insufficient to suppress the effect of noise, the interaction of the neurons may actually enhance the effect of coherence resonance. At the same time, the external signal applied to all neurons in the network, or to a group of neurons, causes neurons to fire in the presence of both weak and strong coupling between them. So, the coupling parameters can provide effective control of the spiking activity of the network neurons. By introducing a sufficiently strong coupling, it is possible to suppress the influence of noise sources and thus ensure optimal propagation of the useful signal.

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AI TECHNOLOGIES FOR MODELLING COMPLEX PHYSICAL PROCESSES. CASE OF SELF-SUPERVISED COMPUTATIONAL GRAPH COARSENING

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Physics systems are often chaotic, computationally expensive to simulate and may contain the so-called parametrizations (approximations). AI can be used to improve different parts of the simulation workflow or even replace it. We show-case several AI technologies for constructing a digital twin of a complex physical system.

Physics simulations are often performed by solving PDEs on fine unstructured grids with the help of finite elements methods (FEM). We discuss the possibility to accelerate such simulations by the AI-powered compression of their computational graph. We propose a learnable framework to coarsen these grids via global points positions optimization while preserving essential dynamics, thus achieving substantial speed-up [1]. Also, we present a graph neural network (GNN) based approach to perform differentiable coarsening in a self-supervised manner. We demonstrate the universality of our approach by integrating both explicit and implicit finite volume solvers into the training loop and testing the approach on both parabolic and hyperbolic types of PDEs. The inclusion of a stability term into loss function helps to avoid divergence in explicit schemes, while switching to an implicit solver naturally addresses stability concerns. Results on two-dimensional PDEs describing subsurface flow dynamics show that the coarsened meshes can greatly reduce node count without significant loss of accuracy. Future directions include extending to 3D domains and exploring advanced PDE systems (e.g., multiphase flows or wave equation with nonlinear terms).

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THE PSEUDO-ANALYTICAL PROBABILITY SOLUTION TO PARAMETRIZED FOKKER-PLANCK EQUATIONS VIA DEEP LEARNING

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Efficiently solving the Fokker-Planck equation (FPE) is crucial for understanding the probabilistic evolution of stochastic particles in dynamical systems. However, analytical solutions or density functions are only attainable in specific cases. To speed up the solving process of parametrized FPEs with several system parameters, we introduce a deep learning-based method to obtain the pseudo-analytical density (PAD). Unlike previous numerical methodologies that necessitate solving the FPE separately for each set of system parameters, the PAD simultaneously addresses all the FPEs within a predefined continuous range of system parameters during a single training phase. The approach utilizes a Gaussian mixture distribution (GMD) to represent the stationary probability density, the solution to the FPE. By leveraging a deep residual network, each system parameter configuration is mapped to the parameters of the GMD, ensuring that the weights, means, and variances of the Gaussian components adaptively align with the corresponding true density functions. A grid-free algorithm is further developed to effectively train the residual network, resulting in a feasible PAD obeying necessary normalization and boundary conditions. Extensive numerical studies validate the accuracy and efficiency of our method, promising significant acceleration in the response analysis of multi-parameter, multi-dimensional stochastic nonlinear systems.

INCREASED CONNECTIVITY OF DEFAULT MODE AND SALIENCE NETWORK HUBS IN AUDITORY VERBAL HALLUCINATIONS

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Auditory verbal hallucinations (AVH) occur in 40–80% of the patients with schizophrenia [1]. Functional MRI (fMRI) studies have revealed abnormal functional connectivity (FC) in schizophrenia, particularly within the salience and default mode networks (DMN) [2]. However, the findings remain inconsistent. Thus, the aim of the present study was to examine the differences in FC in patients with schizophrenia having persistent AVH as compared to healthy controls (HC). Resting state fMRI data were collected from 42 AVH patients and 63 matched healthy controls. Patients met DSM-IV criteria for schizophrenia, P3>3 on PANSS. MRI data were analyzed using the CONN toolbox (SPM12, MATLAB R2024a), generating whole-brain ROI-to-ROI connectivity maps. ROI-to-ROI analysis showed increased rsFC in three clusters in the AVH group: (1) between bilateral superior frontal gyrus (SFG), supplementary motor area (SMA), and anterior cingulate cortex (ACC); (2) between bilateral putamen and DMN regions including the posterior cingulate cortex (PCC) and precuneus; and (3) between bilateral putamen and medial prefrontal cortex (MPFC) and paracingulate gyrus. The results from the current study support the growing evidence of DMN and SN dysconnectivity in schizophrenia. This study is part of the project DPD-03/2024, Medical University – Plovdiv, "Brain lateralization in schizophrenia and healthy individuals – data from functional neuroimaging".

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PHASE DYNAMICS OF NOISE-INDUCED COHERENT OSCILLATORS

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Noise can induce coherent oscillations in excitable systems. How these noise-induced oscillators interact with each other remains elusive. Here, we focused on a special noise-induced coherence phenomenon, namely, self-induced stochastic resonance (SISR). Through the proposed distance matching condition or the first passage time distribution, we identified the most probable escape positions on the slow manifolds. Then, the hybrid approximation can be applied to establish the stochastic periodic orbit, via which the phase reduction approach was constructed. The reduced phase equation can be employed to reveal the entrainment of a single system to the periodic force and the mutual synchronization of two coupled SISR oscillators. This approach was further extended to the global coupling case, where five different synchronization stages were observed. In particular, the SISR breathing chimera was discovered, which was shown to be robust to parameter variations. These results provide an insight into the collective behaviors of noise-induced coherent oscillators in fast-slow dynamic systems, e.g., biological systems.

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High-Power Lasers and Applications (NWP-2)

POSITRON GENERATION IN LASER PLASMA AND INTENSITY DETERMINATION

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Quantum processes in extremely strong electromagnetic fields currently attract a great interest because of the rapid advancement of laser technologies. Laser intensity of the order of 10^{23} W/cm² was already achieved several years ago [1], which has stimulated further theoretical and experimental efforts concerning strong-field quantum electrodynamics (QED). There are a number of ambitious projects which aim at reaching even higher intensities and observing diverse QED phenomena.

In the reported study, we investigate the process of electron-positron pair production initiated by neutral xenon atoms in the presence of intense laser pulses of linear or circular polarization. According to QED, charged particles in strong external fields can emit high-energy photons which may then decay producing electron-positron pairs via the nonlinear Breit-Wheeler mechanism. In one of our previous investigations [2], we proposed a diagnostic scheme allowing one to determine the intensity of laser pulses by measuring the number of positrons produced. This kind of laser diagnostics can be quite accurate due to the threshold behavior of the pair production process with respect to the field amplitude. In our next paper [3], we generalized our computational procedures and addressed the effects of QED cascade processes that can be launched in super-intense laser fields. Our new findings concern the effects of external magnetic fields on the above mechanism.

It was demonstrated that the pair-production threshold with respect to the laser intensity is quite sensitive to the magnetic-field configuration. In particular, it is shown that the magnetic field substantially modifies the dynamics of charged particles and can significantly enhance the generation of positrons. These effects can be of great importance in the context of measuring laser intensity according to the proposed diagnostic scheme.

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EFFICIENT SOURCES OF ULTRA-RELATIVISTIC PARTICLES AND HARD RADIATION BASED ON DIRECT LASER ACCELERATION OF ELECTRONS IN FOAM TARGETS

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Low-density polymer foam converted into plasma using a well-controlled nanosecond pulse is an excellent plasma target for effective direct laser acceleration (DLA) of electrons using relativistic laser pulses.

Over the past five years, a highly efficient and robust DLA process by irradiating such plasma targets with the PHELIX laser pulse (700 fs, 10^{19} W/cm², $f/5$, $a_0 = 3.5\text{--}4$) was demonstrated. This resulted in the generation of well-collimated, high-current beams of superponderomotive electrons with energies above 100 MeV and effective temperatures of 10–20 MeV [1, 2].

PW-class laser systems capable of generating subpicosecond and femtosecond pulses focused to ultrarelativistic intensity, are good candidates for creating high-current beams of ultrarelativistic electrons in extended plasma with a density close to critical in the DLA process [2–4]. These electron beams can be used to produce bright betatron radiation, MeV bremsstrahlung, isotopes, and neutrons with record-breaking conversion efficiencies, and to demonstrate the FLASH effect with a dose rate of 50 Gy/ps in water [5–8].

3D PIC simulations show that the charge of the DLA electron beam grows almost linearly with laser energy. This paves the way for the application of low-density foams in kJ-PW-class laser facilities used in HED and ICF-relevant research such as ARC (NIF) and PETAL (LMJ), where the beam-times in 2026 and 2027–28 were granted.

Application of such advanced plasma targets to generate GeV electrons and MeV betatron radiation [9] at ELI Prague is also under discussion.

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LOW-FREQUENCY RADIATION OF LASER ACCELERATED ELECTRONS LEAVING METAL/PLASMA TARGETS

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Description of low-frequency emission from the targets irradiated with a short light pulse requires a complete understanding of all possible radiation mechanisms of laser-accelerated relativistic electrons in the targets, including the self-consistent fields. Here we discuss the radiation of the trapped electrons accelerating and decelerating in the Debye sheath, the transition radiation and synchrotron-type radiation during the reversal of electrons in the double layer sheath field [1]. We also have studied the transition radiation of fast electrons emitted from the target and compared it with their radiation due to the deceleration of the electron bunch in the charge separation field. The advantage of a relativistic self-trapping regime of electron acceleration for the generation of terahertz pulses is also demonstrated [2].

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RECENT PROGRESS IN DEVELOPMENT OF A LOW-POWER MULTI-BEAM COHERENT COMBINING SYSTEM PROTOTYPE FOR THE XCELS PROJECT

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The ambitious XCELS (eXawatt Center for Extreme Light Research) [1] project, which is being actively discussed, is aimed at creating in Russia a major scientific infrastructure based on a laser radiation source with a total peak power of more than 0.5 exawatts. The prototype of the project is the petawatt laser PEARL [2] operating at the Institute of Applied Physics. The XCELS project involves the simultaneous delivery of ultrashort optical beams to the vacuum target chamber via twelve channels, combining these beams using F/1 off-axis parabolic mirrors in the main focus. The topology of the optical field structure formed in the main focus is an experimental approximation of a dipole wave inverted in time.

This work presents the recent progress in the experimental development of a low-power small-aperture four-beam prototype of a coherent combining system in a topology relevant to the twelve-beam XCELS project setup [3]. Four pairwise counter-propagating optical beams converge in the main focus using F/2 off-axis parabolic mirrors. For this geometry, the ratio of the electric field to the dipole limit is approximately 0.1, while for the XCELS the corresponding ratio has a value of about 0.81.

Within the framework of this research, a pointing stability system at the input of the beam combining system as well as a relative phase stability system have been developed. A method for measuring stable distribution of the optical field in the main focus using a scanning subwavelength probe has been developed and tested.

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SOLITONS IN HIGH-FIELD RELATIVISTIC OPTICS AND PARTICLE ACCELERATION: APPLICATIONS

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Current issues in the laser-plasma high-energy physics relevant to the self-trapping of laser light pulses in a relativistic plasma in the form of solitons which can exist in the regimes of “laser bullets” and “bubbles” are discussed. Such specific realizations of relativistic self-focusing are comparatively considered in detail. Electron acceleration in soliton regimes by relativistically intense laser pulses up to multi-hundred-MeV energies with a multi-nanocoulomb charge carried by the accelerated electron bunches for quite affordable lasers of only a few Joules is analysed. Possible applications of the generated electrons may concern the radiation-nuclear applications. The discussion includes the generation of synchrotron-type secondary radiation from laser-irradiated transparent targets or converter targets in the range from hard X-rays to gamma-rays; the generation of terahertz pulses, including unique half-cycle unipolar pulses; the generation of neutrons and positrons; possible deep radiography of strongly shielded objects based on laser-induced super-bright gamma-ray bursts; an all-optical inverse Compton source for high spatial resolution radiography; and electron FLASH-radiotherapy.

STUDY OF LASER-DRIVEN PROTON ACCELERATION IN SULF FACILITY

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High-intensity laser interaction with plasma is creating an appealing pathway for compact proton accelerators, providing a significant value on advancing both fundamental and applied research applications in science and industrial fields, including probing high-energy density states, radiation therapy, fast ignition fusion, nuclear physics, and radiation protection of spacecraft. How to comprehensively improve the quality of laser proton source is an important issue in future applications. This paper will introduce the experimental research we have performed in the Shanghai Superintense Ultrafast Laser Facility (SULF) in recent years. By irradiating planar targets and novel micro/nano structure targets with multi-PW intense lasers we conduct systematic research on proton cutoff energy, energy conversion efficiency, proton source size, and beam collimation. Several targeted optimization schemes will be discussed.

ORBITAL ANGULAR MOMENTUM GAIN BY CHARGED PARTICLES IN A SPATIALLY STRUCTURED INTENSE LINEARLY POLARIZED LASER BEAM

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Alongside with energy and linear momentum, electromagnetic waves may carry angular momentum. Angular momentum is usually divided into a spin angular momentum, related to the wave polarization, and an orbital angular momentum, related to the spatial amplitude distribution. The presence of the angular momentum in light waves may strongly influence the process of interaction with matter, broadening the observed physical effects. The angular momentum transfer from laser waves to matter finds different applications, such as compact information storage, optical tweezers, particle acceleration and quasi-static magnetic field generation in plasma. The interaction of charged particles with such waves requires, in general, consideration of collective plasma effects. However, in a rarefied plasma, single particle dynamics may serve as a first step towards understanding the collective plasma response.

Quasi-static magnetic field generation in a rarefied plasma, irradiated by a radially polarized laser wave, was theoretically demonstrated in the paper [1]. The angular momentum transfer was shown to occur as a single-particle effect. However, the analytical description of the process was insufficient to describe the angular momentum transfer for interactions with other field configurations, such as in the case of a linearly polarized laser beam, carrying the orbital angular momentum considered in [2].

This work is devoted to the analytical description of the process of angular momentum transfer in the case of plasma interaction with a linearly polarized structured laser wave. Corrections to the lowest orders of paraxial and slowly varying envelope approximations are required to describe the process of angular momentum gain. Following [3], the critical properties of the wave structure, which define the efficiency of the angular momentum transfer, are analyzed by solving the equations of motion of a charged particle in an external field.

Acknowledgements

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WAKEFIELD ACCELERATION WITH THE XCELS LASER DRIVER IN PLASMA WITH A LONGITUDINAL DENSITY GRADIENT

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Wakefield acceleration of charged particles in plasma is a promising method allowing a significant increase in the acceleration rate compared to traditional accelerating structures, such as radio-frequency resonators. This method utilizes the strong electric fields in a plasma wave generated by a high-energy laser pulse or a charged particle beam. Due to fields with strengths of 10–100 GV/m, it enables a substantial reduction in the length of accelerating elements compared to classical methods.

The aim of this work is to study the acceleration of an electron beam in plasma using a powerful laser pulse from the Center for Extreme Light Studies (XCELS) as the driver. A positive longitudinal plasma density gradient is used for effective acceleration, which shortens the plasma wavelength. This allows the beam to stay longer in the accelerating phase of the wave, promoting the gain of higher energy.

The main parameters of the laser pulse are the following: energy $W=715$ J, wavelength $\lambda=910$ nm. During a multi-parameter optimization performed using the Bayesian method on a discrete grid, the optimal values of the plasma density, its longitudinal gradient, the laser pulse radius, and the focal position inside the plasma section were determined to achieve the maximum energy of the accelerated electrons.

The optimal regime corresponds to the transitional region between the blow-out and linear modes, where electrons are accelerated to energies exceeding 25 GeV in a plasma section approximately 1 meter long. Further acceleration is limited by the depletion of the laser pulse.

Numerical calculations were performed using the two-dimensional axially symmetric quasistatic code LCODE, with the laser pulse described through its envelope.

POPULATION LENSING IN A DISK MULTIPASS AMPLIFIER WITH A-CUT Yb:KGW ACTIVE ELEMENT

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Broadband amplifiers with Yb:KGW active elements are used in the front ends of terawatt [1, 2], and even petawatt [3] laser systems, as well as for amplification of high-resolution time-profiled chirped pulses. In the context of the work on the photoinjector laser with three-dimensional pulse profiling option, a population lensing in an a-cut Yb:KGW active element was investigated.

The time dynamics of the quadratic component of the induced spatial phase distortion was measured at a probe wavelength of 633 nm in the saturating amplification mode. Numerical modeling of pump absorption in a quasi-four-level active medium and calculation of the theoretical electron lensing time dependence on the obtained population inversion distribution allowed determining the change in the polarizability of a-cut Yb:KGW at the $^2F_{7/2} \rightarrow ^2F_{5/2}$ transition $\Delta p(633 \text{ nm}) \approx 1 \cdot 10^{-25} \text{ cm}^3$.

Next, the contribution to the polarizability change Δp of the resonant absorption of Yb:KGW near 1 μm was evaluated, yielding $\Delta p(1030 \text{ nm}) \approx 0.9 \times 10^{-25} \text{ cm}^3$ for the wavelength of interest. Based on this value, the dynamics of the electron lens in the working beam at a wavelength of 1030 nm was predicted. The experimentally observed electron lensing fits within the calculated curve. An important conclusion in terms of applications is the absence of a critical growth of Δp when the test radiation wavelength of 633 nm is changed to the working wavelength of 1030 nm in spite of the proximity of resonance absorption to the latter.

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AMPLIFICATION OF CEP-STABILIZED FEW CYCLE PULSES IN THE 2 μm SPECTRAL RANGE

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Femtosecond light pulses consisting of only a few wave cycles became common place in the early 21st century. Since then, controlling the field evolution within a single oscillatory cycle of few-cycle light has paved the way for a fundamentally new approach to studying and controlling processes in the microcosm [1]. Waveform control of such pulses has enabled the generation of isolated attosecond pulses [2].

For research on high-harmonic generation of laser radiation with a high-density gas jet, an intense 2 μm spectral range pulse source was developed. The experiment implemented an approach combining methods of nonlinear temporal compression, passive carrier-envelope phase (CEP) stabilization, and other nonlinear transformations of ytterbium laser radiation. This combination of technologies not only enhances temporal resolution but also improves laser radiation contrast and ensures CEP control.

We succeeded in obtaining pulses with energies exceeding 100 μJ at a repetition rate of 2 kHz in the spectral range of 1850–2400 nm (Fig.1a). These pulses were compressed using a silicon wafer, achieving a duration of 22 fs (Fig.1b), close to the transform limit. To evaluate the CEP stability, the f-2f interferometry method was employed. Experimentally, CEP stabilization of the output pulses was demonstrated, with a RMS phase deviation of 350 mrad.

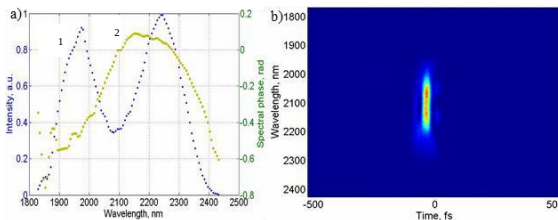


Fig. 1. a) Retrieved spectrum (curve 1) and spectral phase (curve 2); b) Experimental FROG trace of the pulse

The initial studies of high-harmonic generation made it possible to obtain harmonics in a continuous argon gas jet up to the 11th order. In the future, the goal is to increase the energy to the mJ level and optimize spectral measurements using a flat-field spectrometer based on an UV diffraction grating combined with a back-illuminated CCD camera.

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SURFACE RELIEF GRATINGS USED IN HIGH POWER LASER SYSTEMS: PERFORMANCE ENHANCEMENT AND APPLICATION FRONTIERS

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High-power lasers represent a pivotal strategic frontier in international scientific competition. While Chirped Pulse Amplification (CPA) technology, recognized by the 2018 Nobel Prize, has propelled the peak power of ultra-short lasers to the petawatt (10^{15} W) level and beyond [1], scaling power output further necessitates increasing pulse energy and compressing pulse duration. Crucially, the performance of compressor gratings—specifically their aperture size and laser-induced damage threshold (LIDT)—imposes fundamental constraints on power scaling through either route [1]. To overcome these limitations and reach the 100PW regime, multi-beam coherent combination techniques have been developed.

Focusing on enhancing grating performance, our research targets critical parameters: damage threshold, aperture, and spectral bandwidth. We report significant progress in two key areas: the development of metal pulse compression gratings tailored for high-intensity femtosecond laser applications [2, 3], and all-dielectric pulse compression gratings optimized for picosecond/sub-picosecond lasers [4, 5]. Building upon these advances, meaningful strides have also been made in the development of gratings for spectral beam combining and chirped volume Bragg gratings.

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IMPACT OF SMALL-SCALE OBSCURATION, SURFACE ROUGHNESS AND REFLECTIVITY FLUCTUATIONS OF DIFFRACTION GRATING ON THE TEMPORAL CONTRAST OF A FEMTOSECOND PULSE

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The impact of compressor gratings and transport optics imperfections on the power contrast ratio (*PCR*) is considered analytically taking into account diffraction and all dispersion orders. All types of imperfections, including surface roughness, reflectivity fluctuations, surface dirt/damage/obscuration as well as the roughness and obscuration on the optics used to write holographic gratings are allowed for. With the same roughness and the same obscuration, the contribution to the *PCR* of the optics used to write holographic gratings is significantly greater than the contribution of the gratings themselves. This is due to the fact that shorter-wave radiation is used for writing, and the phase distortions are proportional to λ^{-1} . For finding *PCR* it is sufficient to know the power spectral density (*PSD*) of the field reflected from an imperfect optical element.

For the second and third gratings, *PCR*(*t*) is proportional to the one-dimensional *PSD1*(k_x) of the reflected field with the arguments of these functions being related linearly as $t = \tau_x k_x / k_0$. The magnitude of τ_x determined by compressor geometry is typically in the range of a few nanoseconds. The radiation scattered by the second and third gratings arrives at the target at the time $t = -t_c$, illuminating a vertical stripe at the distance $x = Ft_c / \tau_x$. Then this stripe bifurcates and its replicas move in opposite directions at a speed F / τ_x . One of them, at the time of the main pulse arrival ($t = 0$), reaches the beam axis and continues to move in the same direction at the same speed.

For the first and fourth gratings, as well as for transport mirrors, the *PCR* is nonzero only at $t > 0$. This radiation reaches the target at $t = 0$ exactly on the beam axis and further moves away from the axis like a circle on water from a thrown stone. *PCR*(*t*) is proportional to the two-dimensional *PSD2*($k_\perp$) of the reflected field, with the arguments of these functions being related quadratically: $t = t_d k_\perp^2 / k_0^2$. The t_d value is determined by compressor geometry and is typically in the range of a few tens of nanoseconds. It is the scattering on the first and fourth gratings as well as on transport mirrors that explains the contrast asymmetry observed in the experiment when the sign of the time is changed.

Comparison of the *PCR* caused by obscuration and by roughness showed that at short times the latter prevails, whereas at long times the obscuration is dominant.

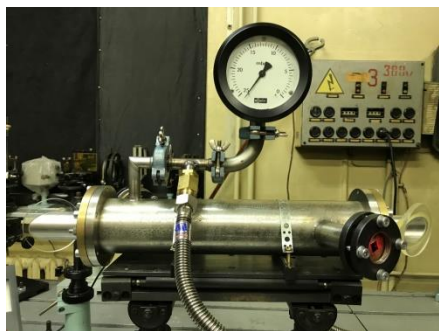
THz NH₃ LASER EMISSION AT PUMPING BY CO₂ LASER

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The development of terahertz (THz) laser radiation sources is required to solve a number of problems, for example, in spectroscopy, plasma diagnostics [1], for detecting explosives behind barrier [2], etc. A promising source of THz radiation is a well-studied NH₃ laser with optical pumping by a pulsed CO₂ laser, which allows obtaining a large number of lines with high efficiency.

In our previous work [3], the generation of a terahertz NH₃ laser with optical pumping by “long” (~100 μs) pulses of an electron-beam-controlled discharge CO₂ laser (pulse energy up to 1 J, peak power up to 100 kW) was implemented, and both the NH₃ laser radiation pulses and the CO₂ laser pump pulses were measured simultaneously with nanosecond resolution. When pumped by the 9R(30) CO₂ laser line, the NH₃ laser wavelengths were 67.2, 83.8 and 88.9 μm. When pumped by the 9R(16) CO₂ laser line, only the 90.4 μm line was detected from the possible NH₃ generation lines.



In this work, an optical cell was created (see the figure) providing for the longitudinal use of CO₂ laser radiation with Brewster windows for a given frequency and a transverse zig-zag resonator for terahertz radiation. In this case, it was possible to measure the absorption of CO₂ pump radiation. Calibrated Ophir 3A meters were used to measure the radiation energy of both the NH₃ laser and the

CO₂ laser. The maximum energy of terahertz radiation reached 0.2 mJ, which corresponds to a conversion efficiency of 0.02% of the CO₂ laser energy (line 9R(16)) and 0.2% of the energy absorbed in the cell.

Acknowledgements

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PHOTON STATISTICS AND RADIATIVE LOSSES OF RELATIVISTIC ELECTRONS IN STRONG EM FIELDS

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Recent breakthroughs in laser technology, particularly the generation of ultra-high-power pulses (10 PW) and extreme intensities (10^{23} W/cm²), have revitalized interest in the interaction of charged particles with intense electromagnetic fields. When an electron encounters such strong fields, it emits photons, but fundamental aspects—such as the precise analytical determination of the number of emitted photons—remain incompletely understood, especially for high-energy electrons. In the quantum regime, this interaction exhibits unique phenomena, including radiation reaction, stochastic broadening, and beam heating, which affect the number of emitted photons as well as the characteristics of the electron beam after interaction with the field.

Knowledge of photon statistics is very important for calculating the radiation losses of an electron beam moving in a strong electromagnetic field [1]. We have developed the analytical model of photon emission by relativistic electrons and verified it by Monte Carlo simulations and by the Focker-Planck approach. As expected, for the classical regime, the theoretical solution is in a very good agreement with numerical simulations. In the strong-field QED regime $\chi > 1$, the model predictions and the numerical results coincide only in order of magnitude. We discuss the condition of validity for the developed model taking into account the stochastic nature of photon emission, the quantum recoil effect and multiphoton correlations.

Acknowledgments

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ELECTRODYNAMIC COUPLING OF RELATIVISTIC ELECTRONS AND GUIDED THz RADIATION IN ULTRAFAST LASER-PLASMA INTERACTIONS

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The interaction of laser radiation with solids represents a promising avenue for the generation of high-power terahertz radiation [1]. The employment of wire targets facilitates the direction of surface electromagnetic pulses of terahertz radiation and the guidance of electron motion [2]. A number of studies have utilised this approach [3]. The variety of processes occurring in the laser-plasma interaction results in the generation of an electromagnetic pulse moving along the surface [4–6]. The absence of diagnostic tools, however, complicates the unambiguous identification of this pulse.

In this study, we have used a combination of PIC simulations and the genetic algorithm to circumvent the constraints imposed by conventional diagnostic techniques employed in high-intensity laser experiments. Our objective has been to reconstruct the field generated in a specific region of laser-target interaction. The task was solved on the basis of the information from image plates located at considerable distances from an interaction point, as well as theoretical surface electromagnetic pulses resulting from various laser-plasma processes [4–6]. In the initial phase, the movements of charged particles following the impact of laser radiation on the target were estimated by means of PIC simulations. Subsequently, by solving the equation of motion for the electrons in conjunction with a genetic algorithm, it was possible to reconstruct possible initial distribution of the fields moving along the wire.

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HIGH-POWER MULTICHANNEL Yb:YAG LASER WITH COHERENT BEAM COMBINING

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Today Yb:YAG lasers are a leading laser technology providing both, high peak and high average power radiation. With their advance, power increase becomes increasingly more problematic, approaching its limit [1]. A promising option for the further power scaling is switching to a multichannel laser scheme with coherent beam combining. The key problem here is the creation of identical channels, which is aggravated by the strong influence of thermal effects. We propose a new architecture of a multichannel laser amplifier that simplifies this task significantly. The idea is to amplify several beams in one rod active element (AE), when the beams are located along its cooled side surface. This provides effective cooling of the AE through the side surface and symmetric gain and thermal conditions for all beams. Based on the presented geometry, a MOPA laser system with a 4-channel Yb:YAG amplifier and coherent beam combining has been implemented (Fig. 1). Coherent combination has been realized with a "tiled aperture" scheme using the digital controller based on the "hill climbing" algorithm. To date, such a system has achieved full pulse energy >17 mJ at an average power of ~20 W, with 57% power in the central lobe of the beam and ~1% RMS of residual intensity fluctuations.

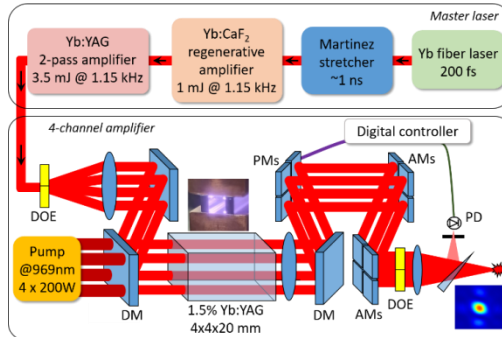


Fig. 1. Optical scheme of laser system. DOE – diffraction optical element, DM – dichroic mirror, AMs – adjustment mirrors, PMs – mirrors on piezo actuator, PD – photodiode

This work was supported by the Russian Science Foundation No. 23-12-00199, <https://rscf.ru/en/project/23-12-00199>.

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HIGH-POWER, HIGH-ENERGY 2- μ m Ho:YLF COMPOSITE THIN DISK LASER

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The advancement of the solid-state laser has been historically marked by various types of gain medium. Thanks to the efforts of generations of laser researchers, several representative gain media dominate specific scientific and industrial areas. Driven by the high demands of pioneering optical parametric chirped-pulse amplifiers (OPCPA), cutting-edge table-top soft x-ray source, and high harmonic generation (HHG), high-power high-energy 2- μ m ultrafast laser sources are highly demanded. We report on multiple 2- μ m laser sources based on the Ho:YLF composite thin disk architecture, delivering > 500 W average power and >200 mJ single pulse energy, which demonstrate the great capacity of the Ho:YLF composite thin disk laser to achieve high efficiency, high power, and excellent beam quality in the 2- μ m regime.

ATTOSECOND COHERENT SYNCHROTRON EMISSION BROADENING IN PLASMA TARGET

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To probe the dynamics of inner-atomic electrons, access to their natural attosecond timescale is essential [1]. A promising approach for generating intense attosecond pulses in the UV and X-ray regimes is Attosecond Coherent Synchrotron Emission (ACSE) from short electron bunches produced on a plasma surface irradiated by a few-cycle relativistic laser pulse [2]. A key advantage of ACSE is its inherent high-pass filter mechanism: the overdense plasma suppresses frequencies below the plasma frequency, naturally generating attosecond pulses. But the dispersion of plasma target degrades the temporal resolution needed for probing electron dynamics, making its quantification critical.

In this study, through analytical modeling and particle-in-cell (PIC) [3] simulations we demonstrate that the generated attosecond pulses undergo temporal broadening and chirping due to frequency dispersion within the plasma target. The PIC simulations reveal significant broadening of the pulse temporal profile as the attosecond pulse propagates through the dispersive plasma layer, with the extent of broadening strongly dependent on plasma density and layer thickness. To quantify temporal broadening, we use a wave propagation method, solving the 1D Helmholtz equation in the spectral domain to reconstruct pulse evolution dynamics. The observed pulse stretching is also consistent with the theoretical model accounting for group velocity dispersion (GVD) and third-order dispersion (TOD).

Thus, this study provides constraints on optimal plasma target thickness and density parameters to minimize dispersion effects for applications requiring sub-100-as resolution.

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APPLICATION OF ARTIFICIAL INTELLIGENCE IN OPTICAL TESTING

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With the increasing demand for high-precision and high-efficiency quality control in modern manufacturing, optical test technology plays a crucial role in the positioning, shape recognition, and dimensional measurement of precision components. The rapid development of artificial intelligence (AI) technology has provided new opportunities for breakthroughs and upgrades in optical inspection technology. This paper focuses on the application research of AI in the fields of spectral measurement, interferometry, and surface shape measurement, aiming to enhance detection accuracy, stability, and automation levels. In spectral measurement, traditional methods are time-consuming, labor-intensive, and prone to damaging samples, while existing deep learning detection methods, as black-box models, exhibit poor physical consistency. This study proposes a non-contact, non-destructive, and high-precision grating parameter measurement algorithm based on a physical model and an improved Tandem model. This enables the inversion of microstructural parameters such as groove depth, duty cycle, and period from the surface scattering signals of grating samples. In the field of interferometry, AI demonstrates strong potential. For vibration-resistant measurement technology, this study proposes an improved AntiVNet model that combines UNet with interferometric knowledge. From the perspective of phase recovery, the surface shape restored by the network is smoother than the results obtained from traditional four-step phase-shifting and three-step iterative algorithms. In surface shape measurement, this study employs a UNet model for fringe pattern analysis under vibration conditions, using synthetic data generated through Zernike polynomials. The difference between the training data and vibration-free labeled fringes is minimized to achieve precise fringe reconstruction. This accelerates the automation of surface shape measurement, reduces Homo sapiens intervention, and improves detection speed and stability. AI technology has injected new vitality into optical test, significantly enhancing detection performance across spectral analysis, interferometry, and surface shape measurement.

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INTERFEROGRAM-FREE ADAPTIVE WAVEFRONT INTERFEROMETRY: FOURIER SPOT ANALYSIS

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This study presents an interferogram-free adaptive wavefront interferometry (IF-AWI) method that overcomes the limitations of conventional approaches reliant on incomplete interferogram analysis. By directly optimizing the Fourier spot (FS) without requiring initial interference fringe observation, IF-AWI enables efficient directional optimization for freeform surfaces with significant deviations ($PV > 100\lambda$). The method eliminates wavefront sensors and phase-shifting procedures, simplifying the measurement workflow while maintaining sub-wavelength accuracy. Numerical simulations demonstrate successful compensation of a 109.08λ PV & 13.49λ RMS wavefront within dozens of iterations. Experimental validation on a 104.07λ PV & 24.89λ RMS test surface achieved residual errors of 0.89λ PV and 0.17λ RMS in 60 adaptive iterations, proving IF-AWI's capability for high-precision metrology of highly aberrant optics without interferogram constraints.

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THOMSON SCATTERING SPECTRUM IN INTERACTING LASER AND ELECTRON BEAMS

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When an intense laser pulse interacts with a relativistic electron beam, high-energy photons can be generated with frequencies significantly exceeding the fundamental frequency of the laser. In classical electrodynamics, this process is known as Thomson scattering. Of particular interest is the calculation of the scattered radiation with allowance for the realistic structure of both the electron and laser beams, which enables meaningful comparison with experimental data.

The primary objective of this study is to investigate the spectral and angular characteristics of nonlinear Thomson scattering in a head-on collision between a relativistic electron beam and a focused laser pulse of finite duration. The spectral-angular distribution for an arbitrary pulse envelope across all angles can only be obtained numerically. To address this, a computational code has been developed based on the phase interpolation method [1, 2] for evaluating spectral integrals.

Using this code, we have computed the spectral-angular, spectral, and angular distributions for a range of laser pulse and electron beam parameters relevant to the Intensive Inverse Compton source developed at the National Center of Physics and Mathematics [3].

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FILTERING SPATIAL NOISE IN A DIFFRACTION GRATING COMPRESSOR TO SUPPRESS SMALL-SCALE SELF-FOCUSING AT POST-COMPRESSION STAGE

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The laser pulse power can be increased either by increasing the pulse energy or reducing pulse duration. Currently, the main approach to reducing the duration of laser radiation after an optical compressor is the method of nonlinear post-compression [1]. It is based on the use of thin (~ 1 mm) dielectric plates and dispersion mirrors. As a powerful (TW or even PW) laser pulse propagates through the plate, it experiences self-action, which leads to frequency chirp and spectral broadening. The self-action is caused by the cubic polarization of the plate medium. Dispersive mirrors allow correcting the frequency chirp and compressing the pulse in time. At the same time, cubic nonlinearity can affect the spatial profile of the laser beam due to the manifestation of small-scale self-focusing. The modulation can destroy the pass-through and reflective optics.

The problem of amplification of spatial harmonics in a medium with cubic nonlinearity in the presence and absence of spatial filtering of harmonic disturbance is addressed. Filtering using optical compressors with symmetric and asymmetric diffraction grating configurations is considered. It is shown that when using a compressor, a significant decrease in the amplitude of fluence modulation in the near field is observed. Using a compressor with an asymmetric configuration of diffraction gratings leads to the formation of a structure consisting of two symmetric rings in the angular spectrum of fluence fluctuations. As the asymmetry of the compressor increases, the diameter of the rings in the angular spectrum increases too. It is shown that the best spatial harmonic filtering is achieved using a compressor with a symmetric configuration of diffraction gratings. This behavior is explained by two factors: some of the angular components are closer in time (or even synchronous) to the central frequency harmonic from which the energy for amplification is taken, compared to the case of using a compressor with a symmetric grating configuration. The presence of asymmetry leads to insufficient filtering of the harmonics in the instability band and to their amplification.

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HIGH APERTURE ACTIVE MIRROR DISK LASER HEAD FOR 10 J AND 10 Hz LASER AMPLIFIER

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Increasing the electro-optical efficiency of high-energy lasers and their frequency mode operation are two of the most important scientific tasks. The solutions of these problems are associated with the use of wide-aperture active elements (AE), optimization of their cooling methods, and diode pumping. The first results of the development of a multi-joule disk laser are presented and the possibility of its scaling in more than 100 J energy range is considered.

The AEs of the developed laser head are made of ytterbium-doped yttrium aluminum garnet (Yb:YAG) single crystals in the active mirror geometry, which ensures their most efficient cooling [1]. The active mirror disk laser head with AE clear aperture of 28 mm, pumped by a 70 J (10 Hz) diode pump laser has been manufactured and tested (Fig. 1a). The small signal gain in the AE reached 1.77, which corresponds to 13.4 J of stored energy (Fig. 1b). The final amplifier will include 2 disk laser heads, which will allow extracting more than 10 J of pulse energy.

The use of large-aperture ceramic AEs in lasers has been considered to be promising for their scaling for two last decades, but laser ceramics is still significantly inferior to single-crystal materials in both optical quality and quantum efficiency. Research aimed at growing high-quality wide-aperture (up to 100 mm) Yb:YAG crystals (Fig. 1c) is being performed jointly with foreign colleagues. This will scale the active mirror disk amplifier technology to the 100 J energy range.

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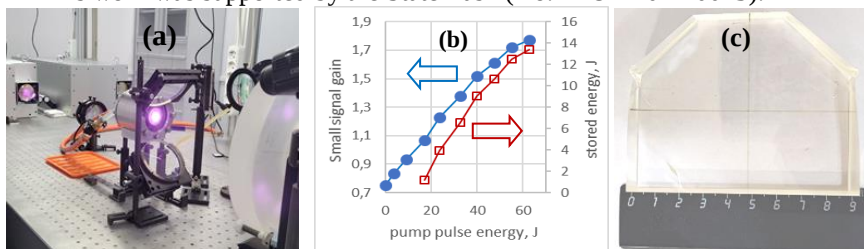


Fig. 1. Photo (a) and small signal gain (b) in 10 J disk laser head; blank Yb:YAG single crystal for disk active mirror AE with 75 mm aperture (c)

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APPLICATION OF NANO- AND FEMTOSECOND LASERS FOR VISUALIZATION OF SURFACES OF SOLID MATERIALS AND BIOLOGICAL TISSUES

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An overview of the current state of development of the methods of mass spectrometric visualization of biological tissues and solid materials using laser desorption-ionization (LDI) and matrix-assisted laser desorption-ionization (MALDI) will be presented. Particular attention will be paid to the influence of wavelength and pulse duration on ionization processes.

REFOCUSING HIGH-POWER FS PULSES USING CONE-SHAPED CURVED CHANNELS

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Methods for increasing the peak intensity of laser pulses are currently being actively developed, and the pulses themselves are used in the study of various laser-plasma effects. There is a problem of transporting high-power laser pulses and focusing them on the target, which also implies matching the target and the focal spot parameters.

The solution to this problem can be based on the effects occurring when laser pulses propagate in hollow channels, either with smooth or curved parallel walls. The interaction of laser pulses with cone-shaped channels is investigated in many studies, where the effects of refocusing laser beams, the generation of electron bunches, and other phenomena are observed.

The effect of refocusing a laser beam in a channel with curved walls shaped as solid-state cylinders and the field increased by a factor of 2 or more is shown using 2D PIC modeling. It is demonstrated that by adding a thin wall at the channel output it is possible to accelerate protons with energy significantly higher than in the case without refocusing.

Acknowledgements

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2D calculations were supported by the Russian Ministry of Science and Higher Education, project FSWR-2020-0035.

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HOW CAN NONLINEARITY HELP FUTURE COMPTON GAMMA SOURCES?

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The nonlinear aspects of the Compton effect in the development of narrow-band gamma radiation sources based on the interaction of electron beams with laser pulses are considered. The study focuses on parameters relevant to a project being implemented at the National Center for Physics and Mathematics (NCPM) [1]. Estimates of photon yield and relative spectral width are presented, along with the influence of laser and electron beam parameters on these characteristics. Particular attention is paid to the weakly nonlinear regime of the Compton effect, where radiation pressure on electrons is significant but not dominant, and quantum effects are negligible. Both analytical calculations and numerical simulations are used to describe the gamma radiation generation processes and optimize system parameters. Methods for a significant increase of photon yield due to the interaction nonlinearity are proposed [2], and their experimental feasibility within the project framework is discussed. The possibility of studying the strongly nonlinear regime within this project is also addressed. The obtained results will be applied to the development of highly efficient narrowband gamma sources.

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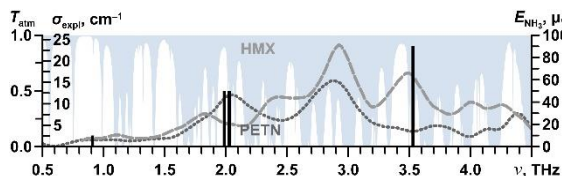
POSSIBILITY OF EXPLOSIVE DETECTION BY TERAHERTZ NH₃ LASER

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There is great interest in using terahertz (THz) waves to detect hidden weapons, explosives, and other threats. Many explosive materials have characteristic signatures in the terahertz band, enabling THz spectroscopy to be used as a tool to identify them [1]. One source of THz radiation is an NH₃ laser. Due to optical pumping by different lines of a CO₂ laser, the NH₃ laser can generate dozens of THz lines with small enough linewidth (~ 100 MHz), which is important for atmospheric sensing. The differential optical absorption spectroscopy (DOAS) is a powerful method to study the atmosphere and detect explosives in particular. The method requires two wavelengths, which are chosen so that (while their difference is as small as possible) one wavelength is at the center of an absorption line of the studied matter, the other besides the line.

In this paper, we consider the possibility of using the NH₃ laser for detection of the following explosives with known absorption cross-sections in the terahertz band by DOAS: RDX, PETN, TNT, HMX [2]; TAGAZ, GUAZ, TEX, HNIW, AAZ, SAZ [3]. For each explosive, we selected suitable for its detection NH₃ laser lines with optical pumping by CO₂ laser lines. The NH₃ laser lines were taken from [4]. Several of the suitable for detecting HMX and PETN lines (bars



NH₃ laser lines suitable for detection
of HMX and PETN

in the figure) have already been obtained experimentally in our work [5]. In the future, we plan to obtain experimentally the generation of other NH₃ laser lines.

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PRODUCTION OF ELECTRON-POSITRON PLASMA AND STRONG MAGNETIC FIELDS IN THE INTERACTION OF EXTREMELY INTENSE LASER RADIATION WITH A STRUCTURED SOLID TARGET

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Several configurations featuring extremely intense laser radiation incident on the surface of a solid target at a grazing angle are investigated via full scale 3D QED-PIC simulations [1, 2]. Such an interaction results in the electrons being extracted and accelerated along the surface of the target to GeV energies [3]. Collision of these accelerated electron bunches with a counter-propagating laser pulse, originating either from reflection or radiation from a different laser channel, leads to the development of a QED cascade [4, 5] and production of electron-positron pairs with a peak density exceeding 10^{24} cm^{-3} . Besides initiating a QED cascade, the electrons produce strong surface current resulting in generation of GGs level quasi-static magnetic field. It is shown that for a target with a conical cavity this magnetic field can be strong enough to trap the produced electron-positron plasma for hundreds of femtoseconds, i.e. well beyond the characteristic laser timescale. The proposed all-optical scheme simultaneously addresses three key challenges of producing laboratory pair plasma: production of high-energy seed particles, conversion of the seed particles into dense pair plasmas, and, finally, confinement of the produced plasma for sufficiently long time. The latter one in particular poses a significant advantage over the previous schemes as plasmas in e.g. astrophysical environments are commonly strongly magnetized.

Acknowledgements

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SECONDARY SOURCES WITH HIGH REPRATE LASER ACCELERATED ELECTRON SOURCES

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Laser plasma accelerators are capable of producing electron bunches with energies up to 10 GeV, exponential or quasi-monoenergetic spectrum, low divergence and high charge. The record parameters were obtained using PW lasers having a very low repetition rate. By contrast, tabletop femtosecond lasers can accelerate electrons up to 100 MeV at high repetition rates ranging from 10 to 10000 Hz. Hence, such lasers are very attractive for numerous applications. This paper presents our recent experimental studies of various secondary sources using a few TW laser for electron acceleration: X-ray and gamma sources, neutron sources, and THz sources. All the data is supported by numerical simulations using PIC and other codes.

This work was partially supported by the Scientific Program of the National Center for Physics and Mathematics (project “Physics of High Energy Density” 2023-2025).

PHYSICS AT THE FRONTIER OF TIME: FROM SOLAR CLOCKS TO ATOMIC PULSES

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How was time measured in ancient times, in the Middle Ages, and how is it measured today? What do we need precise time measurements for and what are the boundaries of this accuracy? How did the advent of lasers and the mastery of nonlinear optics tools allow orders-of-magnitude improvements in measurement accuracy and provide a glimpse inside molecules, atoms, and nuclei?

Answers to these questions are at the forefront of modern science. The shortest pulse ever generated and used by physicists is about 40 attoseconds, or $4 \cdot 10^{-17}$ s, which is several times shorter than the orbital period of an electron in the first Bohr's orbit. The most accurate clock today is atomic optical clock, where the laser radiation frequency is “locked” to the frequency of electronic transitions in atoms or ions, which enables an accuracy of $1:10^{18}$. In 2024, a nuclear optical clock based on the nuclear transition in thorium-229 was demonstrated for the first time. This opens the door to even more precise timekeeping at the level of $1:10^{20}$, which corresponds to a “drift” of only 10 ms over the lifetime of the Universe and makes it possible to study the stability of fundamental constants and detect light particles of dark matter.

RESEARCH PROGRESS AND FUTURE PROSPECT OF AI+LASER AT SIOM

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Artificial intelligence (AI), revolutionizing optics by enabling unprecedented capabilities from surpassing diffraction limits to intelligent adaptive systems, has attracted much attention owing to its power to transform both scientific discovery and industrial applications. This talk shows how Shanghai Institute of Optics and Fine Mechanics (SIOM) is merging artificial intelligence with laser technology. We highlight the progress of recent AI+Laser at SIOM, including advanced laser components design, AI-enabled laser components manufacturing, and AI-empowered computational backend, etc. Looking ahead, the future opportunities and challenges about further research on AI+Laser at SIOM are also addressed. SIOM is expanding the combination of AI and the field of high-power lasers, and seeking new breakthrough points and opportunities for the development of high-intensity laser science and technology.

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3 PW OPCPA PEARL FACILITY

A.A. Shaykin, V.N. Ginzburg, I.V. Yakovlev, A.A. Kuzmin, A.A. Kochetkov, S.Yu. Mironov, I.B. Mukhin, A.A. Soloviev, I.A. Shaikin, S.E. Stukachev, A.I. Pavlikov, and E.A. Khazanov

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The laser is based on optical parametric chirped pulse amplification in a DKDP crystal at a wavelength of 910 nm with 0.8 ns.chirped pulse duration.

As compared to the previous experiments [1], the energy of the pump laser pulse was increased. Also, the efficiency of conversion to the second harmonic and the efficiency of parametric amplification were increased due to shaping a quasi-rectangular pump pulse. All this enabled enhancing the signal energy at the parametric amplifier output from 20 to 40 J. The pulse duration was ~ 30 fs.

To implement CafCA, a 3-mm thick quartz plate was used as a nonlinear medium. The total dispersion of the chirped mirrors was 200 fs^{-2} .

Controlling the second and third dispersions of the initial pulse enabled generation a short femtosecond pulse. The shape and phase of the output pulse are plotted in Fig. 1, and the pulse shape and phase before compression in Fig. 2. The minimum duration of the compressed pulse was 10 fs.

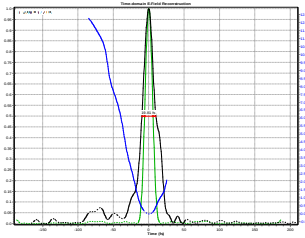


Fig. 1. Optical pulse after CafCA

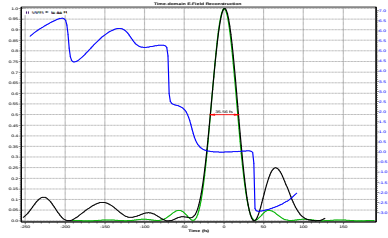


Fig. 2. Optical pulse before CafCA

The high efficiency of CafCA (97%) and of the diffraction grating compressor (78%) enabled the generation of an optical pulse with a power of 3 PW.

Acknowledgements

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PROBLEMS OF HIGH-PRECISION MEASUREMENTS OF WIDE-APERTURE ASPHERICAL OPTICS

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The creation of high-precision wide-aperture aspherical optics is currently in high demand. Such optics is used, for example, in extremely high-power laser facilities, including those for inertial confinement fusion. Such facilities use precision aspherical elements with apertures reaching almost 1 meter. In addition, wide-aperture aspherical optical elements with nanometer-level accuracy are vital for creating high-resolution photolithography. Modern lithographs from ASML use optical elements with an aperture of up to 500 mm and a manufacturing accuracy of the order of a nanometer. As is known, precise manufacturing of the surface shape is impossible without metrology; therefore appropriate metrological support is required to measure the surface shape of wide-aperture aspheric elements with a nanometer-level accuracy.

Two approaches are currently most often used to measure aspherics: point-by-point scanning of the surface shape with an optical sensor and the use of compensators. The first type of devices includes, for example, the LUPHOScan line of devices that allow measuring optical elements with an aperture of up to 850 mm. The second approach is based on transforming a flat or spherical wavefront into a wavefront conjugate to the measured aspherical surface using a specially calculated and created compensator. The compensator is either an aspherical optical element or a synthesized diffraction element. The report examines the problems and limitations of these methods, their accuracy characteristics. It also examines a device currently being developed by IAP RAS for measuring aspherical optical surfaces with an aperture of up to 850 mm. This device is based on scanning the measured surface with a Fizeau interferometer with a small aperture (50 mm) with subsequent stitching of the measurement results. The advantages of this method are high measurement speed with simultaneously high transverse resolution (in the created device it is up to 10 μm), as well as low sensitivity to vibrations. The main characteristics of the device being created, as well as the experimental results obtained during its testing are considered.

DIPOLE FOCUSING OF EXAWATT LASER RADIATION: AN EXPERIMENTAL WAY TO THE THEORETICAL LIMIT

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A key benchmark for contemporary laser system projects is the direct experimental demonstration of vacuum nonlinearity, one aspect of which is the Schwinger effect—the generation of electron-positron pairs from the physical vacuum when subjected to an electric field of extreme strength. However, the current capabilities of existing laser systems and those under development are insufficient to reach the required Schwinger fields. Meanwhile, in the presence of seed particles, quantum electrodynamics (QED) processes that lead to the production of particle cascades, such as the Breit-Wheeler process, can occur even at lower field strengths and may be realized with relatively moderate laser powers that are currently achievable in modern laboratories. In this scenario, both the electric field amplitude and the focusing geometry become critical factors.

Methods for experimentally demonstrating QED effects in the laboratory using existing technologies are explored in the presentation. Specifically, it covers achieving the maximum optical energy density through the optimization of focusing and nonlinear pulse shortening via the CafCA method [1], the coherent combination of multiple pulses in a multibeam dipole focusing configuration [2], and the potential for attaining peak values with two counter-propagating beams [3]. Experiments were performed at the PEARL laser-plasma facility [4].

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SECOND HARMONIC GENERATION FROM PLASMA CHANNEL SHEATH FOR LASER-PLASMA ELECTRON ACCELERATION DIAGNOSTICS

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One of the popular laser plasma electron acceleration mechanisms is Direct Laser Acceleration (DLA [1]). Efficient electron energy gain by DLA is observed under resonance condition, which is determined by the phase velocity of a laser pulse in a plasma channel [2]. The proposed method of plasma channel diagnostics by second harmonic generation from plasma channel sheath is based on the same matching condition as DLA, which makes it most suitable for characterizing the DLA efficiency. We demonstrated the experimental implementation of the DLA diagnostics. The PIC-simulations we have performed show that this method allows obtaining information about phase velocity with a very good accuracy of $\sim 0.05\%$ (Figure 1).

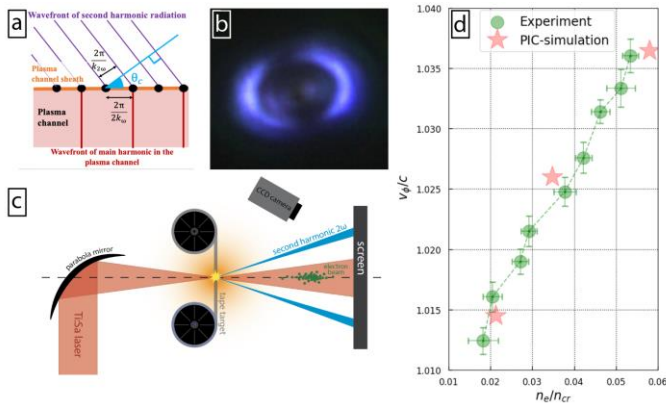


Fig. 1. Phase-matching conditions for second harmonic generation from plasma channel sheath (a). Second harmonic radiation recorded by a CCD camera (b). Experimental setup (c). Dependence of phase velocity on electron density outside the channel: green – experiment, red – PIC-simulation (d)

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XCELS-100 PROJECT

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Multipetawatt lasers are an important tool for conducting unique experiments in various fields of physics, such as ultrarelativistic and high-energy physics, plasma physics and astrophysics, nuclear physics, materials science, and others. Laser peak power is constantly growing. Several projects aimed to create 100 PW class laser systems are currently under way: SEL-100PW [1] (China), OPAL [2] (USA), and XCELS (eXawatt Center for Extreme Light Studies, Russia). The XCELS project, proposed back in 2011 [3] was significantly updated in 2023 [4]. Its goal is to create the world's largest Center for Extreme Light Field Research. It will have a unique 12-channel light source with a total power of 600 PW based on optical parametric amplification of chirped pulses in a DKDP crystal.

The XCELS project will be implemented in two stages. At the first stage, called XCELS-100, it is planned to create a two-channel laser with a radiation power of up to 50 PW in each channel to be located on the basis of the operating new-generation laser facility in Sarov. At the second stage, the laser system will be relocated to a specially constructed building and upgraded to the planned 12 channels, which will increase the peak power level to 600 PW (0.6 exawatt). The result of the first stage of project implementation will already be a unique two-beam laser system with a total power of 100 PW, which will enable not only debugging and testing all the main laser technologies and training specialists, but also conducting a number of unique experiments. A brief overview of the XCELS-100 project will be presented in the talk.

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RECENT RESEARCH PROGRESS ON THE ULTRA-BROADBAND AND HIGH-EFFICIENCY OPCPA TECHNOLOGY FOR HIGH-ENERGY FEW-CYCLE LASER

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The amplification technology in the ultra-broadband spectrum ranging from the near-infrared (NIR) to the mid-infrared (MIR) is particularly demanded and extensively explored for the laser pulse generation of few-cycle duration. The optical parametric chirped pulse amplification (OPCPA) technology is now the most effective method to support the amplification of such a broad band needed for few-cycle pulses. However, the existing OPCPA schemes used in a few-cycle laser system plagued by issues such as moderate conversion efficiency and complexity of the system.

In this paper we will specifically introduce an OPCPA technology based on hybrid crystal amplification, which can support spectral gain across hundreds of nanometers of bandwidth, providing spectral and technical support for generating high-energy periodic laser pulses in the future. We conducted experimental research on hybrid crystal amplification OPCPA using the OPCPA front-end of the SG-II 5 PW laser facility. Based on the alternating amplification of a hybrid cascade crystal composed of LBO and YCOB crystals, the problem of insufficient pump pulse utilization was effectively solved through a single-wavelength pumped, segmented amplification OPCPA system structure. The final experiment verified that this scheme can achieve an ultra-wide gain bandwidth output of nearly 400 nm with an amplified energy of 20 mJ and a total gain of 10^8 .

EFFICIENT GENERATION OF SYNCHROTRON RADIATION IN THE RELATIVISTIC SELF-TRAPPING REGIME

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Synchrotron radiation sources based on the interaction of short laser pulses with low-density plasma have unique properties such as small size ($\sim \mu\text{m}$), narrow directivity (~ 10 mrad), and ultra-short duration of generated radiation (~ 10 fs), as well as high brightness [1]. They can be used not only for diagnostics and control of the laser-plasma experiment, but also have real practical applications in the fields of security, medicine, microelectronics, as well as for research into extremely fast physical processes.

The properties of this secondary radiation are affected by both the laser pulse parameters and the plasma target density. Here, our studies are devoted to the relativistic self-trapping regime of the laser propagation in the form of the laser bullet and self-modulation regime, when hard x-ray photons of synchrotron radiation are generated [2].

We consider 1 J laser pulses with different durations, namely 40 and 10 fs. Such transformations can be performed in experiments using CafCA (TFC) [3, 4]. In our recent works [5, 6], we have already shown that decreasing the pulse duration leads to an increase in the conversion of laser energy to the total energy of fast electrons by up to 50%. Therefore, a corresponding improvement in synchrotron radiation characteristics is expected.

Acknowledgements

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NONLINEAR RESPONSE OF DILUTED GASES TO AN ULTRAVIOLET FEMTOSECOND PULSE: QUANTUM MECHANICAL DESCRIPTION

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Experiments on UV filamentation reveal a long-wavelength shift of the spectrum as a whole to the long-wavelength range by several nanometers [1]. However, simulations [1] demonstrated the symmetrical spectral broadening. In this work we study experimentally and theoretically the long-wavelength spectral shift under UV filamentation.

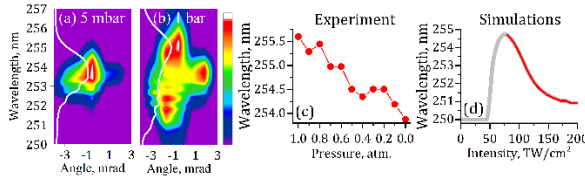


Fig. 1. Measured angle-wavelength spectra of femtosecond UV pulse focused into air-filled cuvette at a pressure of 0.005 atm (a) and 1 atm (b). Spectral shift obtained numerically (d) and experimentally (c)

We carried out an experiment in which the pulses centered at ~ 250 nm with a duration of ~ 100 fs and energy up to 0.2 mJ were focused into the cuvette filled with argon of various pressures. We have measured angle-wavelength distribution for different pressures of gas in cuvette. The increase in pressure results in the monotonic shift of the UV pulse spectrum mass center towards the long wavelengths (Fig. 1(a, b)).

In order to reveal the physical explanation for the long-wavelength shift of the spectrum of ultraviolet filament we numerically solve time-dependent Schrödinger equation with one-dimensional potential well with 3 bound states corresponding to lowest energy levels of argon and laser pulses at duration of 10–80 fs, a central wavelength of 250 nm. In our simulations for the intensities lower than ~ 80 TW/cm² the spectrum shifts towards the long wavelengths as whole. Nonlinear polarization obtained from our simulations delays on the intraperiod timescale relative to the cube of the pump electric field and induces the long-wavelength spectral shift. The increase in pressure leads to the decrease in the pulse intensity in our experimental conditions. The increase in the shift of the central wavelength with increasing pressure obtained in the experiment is shown in Fig. 1(c).

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RESEARCH ON BROADBAND HIGH DAMAGE THRESHOLD ULTRAFAST LASER COATINGS

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Addressing critical challenges in ultra-intense laser development, dispersion mirrors (DMs) demand revolutionary advancements in simultaneously achieving broad dispersion bandwidth and high laser-induced damage threshold (LIDT). This research pioneers a new class of high-damage-threshold ultrafast coatings – including low-dispersion mirrors and chirped mirrors – through innovative material-structure co-design. We establish a unified design framework enabling exceptional broadband performance with high reflectivity and robust LIDT synergy. Fundamentally, we decode femtosecond laser damage mechanisms via electric field analysis, transforming understanding of thin-film component reliability. These breakthroughs provide foundational optical solutions for the post-compression technology, significantly advancing high-power ultrafast laser capabilities toward petawatt-level systems and enabling unprecedented applications in attosecond science and extreme light infrastructure.

LASER-BASED MANUFACTURING TECHNOLOGY FOR FABRICATING HIGH UV-LASER DAMAGE-THRESHOLD FUSED SILICA OPTICS

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Fused silica optics is commonly used in high-energy laser systems due to the high intrinsic damage threshold. However, laser-induced damage in fused silica optics has seriously limited the development of high-energy laser systems. The fundamental reason is that the processing defects introduced by the current contact grinding and polishing process are difficult to be completely removed, which greatly reduces the damage resistance of the optics. Here, we proposed a whole-light processing chain (including laser ablation, laser cleaning, laser polishing, and laser beam figuring) to fabricate high damage threshold and ultra-precision fused silica optics based on the principle of step-by-step removal of defects and step-by-step convergence of accuracy. Through this chain, the laser-induced damage threshold of the sample fabricated is 41% (0% probability) and 65.7% (100% probability) higher than those of the samples fabricated by the conventional processing chain. At the same time, full-spatial-frequency error convergence with nanoscale surfaces is achieved at negligible stress. This innovative whole-light processing chain provides a new direction for the fabrication of highly damage-resistant and ultra-precision fused silica optics for high-energy laser applications.

ULTRAHIGH PEAK POWER FEMTOSECOND LASER PULSE COMPRESSION METHODS

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Here, some dispersion control methods for the pulse compression of ultrahigh peak power femtosecond lasers are reported.

1. The dispersion control in PW level OPCPA systems by the use of double-grating Öffner stretcher is demonstrated [1]. In a proof-of-principle experiment, amplified pulses with 210 nm spectral bandwidth and 3 ns chirped pulse duration are directly compressed to near FTL pulse duration of ~ 15 fs, just by cooperating a double-grating Öffner stretcher with a Treacy compressor.

2. A novel double chirped pulse amplification laser system implementing the combination of negatively and positively chirped pulse amplification (NPCPA) is proposed for the first time [2]. This scheme can make it possible to cancel out the GVD, TOD and FOD simultaneously, without using any additional dispersion compensation components. And near FTL pulses with ~ 20 fs can be achieved in high peak power femtosecond laser systems up to multi-PW level.

3. The dispersion management for a 100 PW level laser by using mismatched-grating compressor is reported [3]. And near FTL compressed pulses with 12.8 fs can be expected in the mismatched-grating compressor based SEL-100 PW laser. Moreover, the tolerances of a mismatched-grating compressor to the misalignment of a stretcher, the error of desired grating groove density, the variation of material dispersion are comprehensively analyzed and verified, which is crucially important for its practical application.

Furthermore, to obtain single-channel 100 PW lasers, the full-aperture grating compressor (FAGC) is proposed and proved [4, 5]. FAGC can realize noticeable laser energy improvement within the damage threshold of compression gratings, and thus achieve higher laser peak power. Meanwhile, there is no significant influence of FAGC on the spatiotemporal characteristics of output compressed pulses. Hence, FAGC should be a promising solution for realizing single-channel 100 PW lasers, and it is also suitable for the peak power upgradation of existing high peak power lasers.

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RECENT RESEARCH PROGRESS ON THE ULTRA-BROADBAND AND HIGH EFFICIENCY OPCPA TECHNOLOGY FOR HIGH ENERGY FEW-CYCLE LASER

**Xiao Liang, Meizhi Sun, Xinglong Xie, Ping Zhu, Lijuan Qiu,
and Jianqiang Zhu**

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The amplification technology in the ultra-broadband spectrum ranging from the near-infrared (NIR) to the mid-infrared (MIR) is particularly demanded and extensively explored for the laser pulse generation of few-cycle duration. The optical parametric chirped pulse amplification (OPCPA) technology is now the most effective method to support the amplification of such a broad band needed for few-cycle pulses. However, the existing OPCPA schemes used in few-cycle laser system plagued by issues such as moderate conversion efficiency and complexity of the system.

The paper will specifically introduce an OPCPA technology based on hybrid crystal amplification, which can support spectral gain across hundreds of nanometers of bandwidth, providing spectral and technical support for generating high-energy periodic laser pulses in the future. We conducted experimental research on hybrid crystal amplification OPCPA using the OPCPA front-end of the SG-II 5 PW laser facility. Based on the alternating amplification of a hybrid cascade crystal composed of LBO and YCOB crystals, the problem of insufficient pump pulse utilization was effectively solved through a single-wavelength pumped, segmented amplification OPCPA system structure. The final experiment verified that this scheme can achieve an ultra-wide gain bandwidth output of nearly 400 nm with an amplified energy of 20 mJ and a total gain of 10^8 .

LUMINESCENCE BEHAVIOR AND STRUCTURAL RELATIONSHIP OF BISMUTH DOPED SILICA GLASSES AND FIBERS

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Serving as advanced gain media exhibiting broadband near-infrared (NIR) emission and amplification, bismuth-doped silica fibers hold significant potential for extending communication bandwidth. However, the fundamental mechanism underlying Bi-related NIR luminescence remains controversial, particularly there are few reports on the properties of Bi-doped silica glass. This presentation reports recent progress in Bi-doped silica glasses and fibers developed at SIOM from three aspects. First, systematic investigation of the effect of glass structures on the spectral properties reveals critical structure-property relationships in Bi-doped silica glass. Second, through bismuth coordination engineering, a novel bismuth near-infrared luminescence center was created, achieving broadband luminescence at 1400 nm–1700 nm. Finally, the self-developed Bi-doped silica fibers exhibit broadband amplification from O-band to U-band and laser output performance in the O-E band.

Acknowledgements

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ULTRASHORT-PULSE STRETCHER FOR XCELS LASER COMPLEX PROTOTYPE

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An XCELS prototype with a beam diameter of 200 mm without final parametric amplification stage but with spectral-temporal characteristics close to final is under construction.

The new scheme has a wider radiation spectrum of ~ 120 nm and a larger stretching factor of the signal pulse compared to the radiation parameters in the operating laser system PEARL [1]. The duration of the signal pulse stretched to 2.8 ns will enable transferring to it more energy at parametric amplification stages, and a wide spectrum will provide record small duration of the amplified pulse after compression.

A four-grating compressor scheme with an incidence angle of signal radiation on the grating close to the Littrow angle was developed for the prototype. A vacuum chamber of the compressor with a length of 7 m and a diameter of 1.3 m was created. Diffraction gratings with a size of 69 cm in the direction across the grooves were manufactured at SIOM (China). The gratings are holographic, gold-coated, with a density of 1200 lines/mm and reflection efficiency to the first diffraction order of more than 90% at a central wavelength of 910 nm.

Based on the results of the analysis of possible stretcher schemes, including traditional Martinez and Offner and original ones, a stretcher scheme for the XCELS prototype was developed. The stretcher with dispersion characteristics matching the compressor will be a four-pass one (the beam will be incident on the gratings 8 times). It will have holographic gold-coated diffraction gratings with a density of 1200 lines/mm, as well as large-aperture spherical mirrors, in particular, a concave mirror with a curvature radius of 2.5 m and a size of 45 cm.

The focus is system stability at high pulse energies. Much attention is paid to the homogeneity of the energy density distribution in the transverse structure of radiation in the laser beam. In particular, it is intended to develop new ideas for smoothing the fluence. Elimination of “hot spots” will increase the total energy of the output radiation pulse.

Acknowledgements

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DESIGN, FABRICATION AND PERFORMANCE STUDY OF THE ALL-SOLID ANTI-RESONANT FIBER

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A novel all-solid anti-resonant fiber (AS-ARF) is proposed, featuring large-mode-area single-mode transmission combined with intrinsic spectral filtering, effectively mitigating detrimental effects under high-power operation. Utilizing a drilling, rod-in-tube, and high-temperature drawing process, both passive and active AS-ARFs were fabricated for 1 μm transmission suppression, as shown in Fig. 1 (a)–(c). The passive AS-ARF exhibits a core diameter of 43 μm , a numerical aperture (NA) of 0.023, and a strong attenuation of ~ 12.3 dB at 1030 nm relative to 1550 nm over a 12 cm fiber length. Electron probe microanalysis (EPMA) reveals significant elemental diffusion during the fiber drawing process, as shown in Fig. 1 (d), which can be further enhanced via thermal annealing to tune the resonant band toward longer wavelengths. These results demonstrate the great potential of AS-ARFs in high-power fiber lasers and amplifiers based on various rare-earth dopant systems.

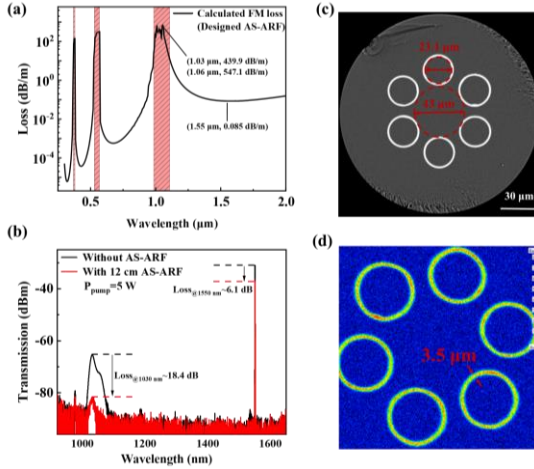


Fig. 1. The calculated FM loss of the AS-ARF in the wavelength range of 0.35 μm to 2 μm . Structural parameters: $D=40$ μm , $t=1.37$ μm , $d/D=0.68$ (a); The evolution spectra of the signal and Yb ASE before and after fusion splicing of 12 cm-long AS-ARF (b); the complete cross section of fabricated AS-ARF under the SEM (c); the distribution of Ba elements scanned by the EPMA (d)

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INSTABILITIES AND MAGNETIC STRUCTURING OF PLASMA JETS INDUCED BY INTENSE PEARL LASER

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Experiments involving high-velocity laser plasma flows provide critical insights into fundamental questions in plasma physics and enhance our understanding of astrophysical phenomena, such as the formation of collisionless shock waves, deceleration of accretion flows, and the evolution of solar and stellar flares. At the PEARL laser facility [1] high-speed plasma flows were generated by irradiating solid targets with femtosecond laser pulses at an intensity of approximately 2×10^{18} W/cm². We observed the formation of current filaments with diameters of several tens of micrometers and lengths reaching a few millimeters by corresponding megagauss magnetic fields. These filaments were oriented normally to the target surface and were accompanied by plasma density modulations that persisted for up to 20 ns post-irradiation. Theoretical estimates and modeling of plasma filamentation using Particle-In-Cell (PIC) and hybrid codes indicated that the observed structures arise from Weibel instability, linked to the anisotropic distribution of charged particles ejected from the target and propagated in the background plasma. Notably, we demonstrated that the formation of these structures is unaffected by external magnetic fields up to 18 T, aligned parallel to the target surface.

Additionally, we present the first direct experimental observations of stagnation and redirection in counterstreaming jets of laser plasma induced by intense laser pulses. Hybrid modeling (PIC-fluid), which incorporates kinetic effects from ion motion and the evolution of the electron pressure tensor, reveals compression of counter-directed toroidal self-generated magnetic fields embedded within these counterstreaming plasma flows.

Acknowledgements

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ADVANCED DIRECT DRIVE PROGRAM IN NATIONAL LABORATORY ON HIGH POWER LASER AND PHYSICS

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The perspective for future laser fusion energy is now coming to the actuality with great achievements in recent years. The National Laboratory on High Power Laser and Physics dedicated in the laser confined fusion research for over 60 years, has launched an advanced direct drive program aimed at the laser fusion energy, including upgrading the present laser facility, performing related experimental campaign, and building new larger laser facilities. We have developed a series of advanced laser and diagnostic technologies for direct drive and fast ignitions, and conducted physical experiments utilizing various spatiotemporal manipulation techniques of laser fields to meet the practical requirements for efficient laser absorption in direct drive, which enhanced our understanding of the roles of irradiation uniformity, coherence, and other optical parameters in laser-plasma interactions. These advancements provide a robust technical foundation for future in-depth research on direct drive physics.

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SUBWAVELENGTH FIBER PROBES FOR SCANNING THE STABLE ELECTRIC FIELD STRUCTURE IN COUNTERPROPAGATING LASER BEAMS

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Simultaneous delivery and subsequent focusing of twelve ultra-powerful laser pulses to one point is one of the topical problems to solve within the XCELS project [1]. The topology of the optical field in the system main focus will allow observing phenomena associated with the physical vacuum nonlinearity. This naturally raises the problem of studying the resulting field structure, which can be solved by a method using a subwavelength fiber probe (SFP) employed in scanning near-field optical microscopy (SNOM) [2]. Unlike SNOM, the optical field itself is probed, rather than its scattering on any surface. Within the framework of this research, a method for diagnosing this type of SFP for the features of its radiation energy transfer with different spatial characteristics was developed. The experimental setup allowing laser radiation to be input into the SFP from different directions and with variable polarization was created. A 1W Ti:Sa femtosecond master oscillator was used as a laser source. The studied SFPs showed sensitivity to direction and polarization of the probed radiation. The obtained results may have practical significance for problems of coherent combining of a large number of counter-propagating laser beams.

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Nonlinear Phenomena in the Atmosphere and Ocean (NWP-3)

ANISOTROPIC WEAKLY TURBULENT SPECTRA OF OCEAN SWELL: ANALYTICAL RESULTS AND SIMULATIONS

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The physical setup of ocean swell is used as a testbed for the results of the weak turbulence theory [1, 2]. The issue of spectra anisotropy is detailed with the novel Geogjaev – Zakharov numerical approach [3] to the solution to the kinetic equation (KE) for deep water waves [4]. The high-frequency asymptotics of wave spectra is shown to be close to the approximate Kats-Kontorovich (KK) solutions to KE [4]. The spectra sidelobes at oblique directions in the range of about 2–3 spectral peak frequencies are related to the recently developed extension of KK solutions [5].

Acknowledgements

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CHALLENGE AND MYSTERY OF THE OCEANIC SYNOPTIC EDDIES

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Until the late 1960s, oceanographers thought of the ocean circulation as consisting of nearly laminar (i.e. smooth and steady) currents: slowly moving interior gyres, fast moving western boundary currents, and mighty Antarctic circumpolar current. However, over the years strong evidence emerged that the ocean circulation also contains ubiquitous and vigorous mesoscale (synoptic) eddies characterized by spatial scales from a few kilometers to hundreds of kilometers, evolving over time scales from weeks to years. Physical oceanographers observe these eddies from the surface-drifter and deep-float trajectories, from satellite images of sea surface height, temperature, and ocean color, from underwater acoustic and current measurements. On the larger scales these eddies are thought of as giant planetary waves, and on the smaller scales they are blended with internal gravity waves, giving rise to various submesoscale phenomena. The eddies populate all parts of the ocean, including the Arctic and Antarctic regions, and they tend to be larger near the equator and smaller towards the poles. The eddies constitute “oceanic weather”, because they are dynamically analogous to atmospheric cyclones and anticyclones in common weather maps. They are viewed as specific turbulence that exists in stratified fluids on surfaces of rotating planets. The eddies are characterised by pressure anomalies associated with spatial changes in water density. The corresponding pressure gradients are nearly exactly balanced by the Coriolis force arising due to the Earth rotation — this is the geostrophic balance, which results in solenoidal flow motions. The eddies are controlled by large-scale background currents, by bottom topography and continental boundaries, by interactions with the atmosphere, and by variety of physical processes on smaller scales. They are forced by complex instabilities of large-scale currents, which are in turn driven by the atmospheric momentum, heat, and fresh water fluxes. The main reason to care about the eddies has to do with their roles in global climate, because the eddies play crucial role in shaping up oceanic general circulation, which is the most important part of the climate system, along with the atmosphere. The oceanic general circulation plays important role in the present climate by redistributing heat, which is a key player in climate change and sea level rise, and by recycling carbon. The main eddy roles in ocean circulation and climate are: (1) maintaining large-scale currents through nonlinear turbulent stresses; (2) converting large-scale available potential energy into kinetic energy of nearly horizontal vortical motions; (3) cascading spectral energy to the larger and smaller scales; (4) Lagrangian dispersion of material properties and eddy induction of mean transport; (5) control over stratification and restratification in the upper-ocean mixed layer; (6) ventilation of the interior ocean; (7) eddy-induced frontogenesis; (8) eddy pumping and quenching of nutrients to the euphotic zone; (9) eddy-induced climate variability; and (10) ocean-atmosphere interactions and coupling. Fundamental properties of the eddies are studied within the framework of geophysical fluid dynamics, and practical applications of the outcome are immense. This talk aims at broader audience and will discuss some most important aspects of the eddies and their dynamics.

NONLINEAR PHENOMENA IN THE IONOSPHERIC F-REGION INDUCED BY HF PUMPING UNDER HIGH EFFECTIVE RADIATED POWER

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The results of experiments on ionosphere modification of the F2 layer by powerful ordinary (O-mode) polarized HF radio waves at frequencies $f_H < foF2$, carried out in recent years at the HAARP and EISCAT/Heating facilities, have shown that at high effective radiation powers ($ERP > 250$ MW) the generation of phenomena impossible at the $ERP \leq 150\text{--}200$ MW is observed. These include: the creation of additional layers in the ionosphere [1], and the reappearance of excitation of Langmuir and ion-acoustic plasma waves coexisting with the small-scale artificial field-aligned irregularities (AFAI) [2].

The aim of this presentation is to study the features of the phenomena in the high-latitude upper (F-region) ionosphere that occur at high effective powers under conditions when the O-mode pump wave is not reflected from the ionosphere. We have analyzed the results of experiments, using the multi-instrument diagnostics, carried out at the EISCAT/Heating facility at Tromsø, Norway (69.6° N, 19.2° E) under quiet magnetic conditions in early evening hours. In the course of experiments the O-mode HF pump waves radiated towards the magnetic zenith at frequencies $f_H = 6.2$; 6.77 and 7.953 MHz which significantly exceeded the critical frequency of the F2 layer ($f_H - foF2 = 1.0\text{--}2.0$ MHz). Effective radiated power was $ERP = 360\text{--}840$ MW.

We found the creation of ducts with the enhanced electron density N_e , the excitation of artificial field-aligned irregularities (AFAI), and narrowband stimulated electromagnetic emission within ± 1 kHz of the heater frequency (NSEE), recorded at a large distance (1200 km) from the Heating facility. A comparison was made of The features of small-scale artificial field-aligned ionospheric irregularities and spectral structure of the narrowband stimulated electromagnetic emission for alternative O-/X-mode HF heating at frequencies significantly exceeding the critical frequency of the F2 layer. The plausible generation mechanisms of non-resonance phenomena observed are discussed.

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WAVE-VORTEX INTERACTIONS IN GEOPHYSICAL FLOWS

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A review of the current state of the problem of wave-vortex interactions in problems of geophysical hydrodynamics of atmospheric and oceanic motions is presented. A special accent is given to the analytical results obtained recently, in particular, at the Institute of Atmospheric Physics. Modern and historical experimental results are discussed.

This work was supported by the Russian Science Foundation (project No. 23-17-00273).

EXPERIMENTAL INSTALLATION FOR THE CREATION AND MAINTENANCE OF HYPOMAGNETIC CONDITIONS

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Studying the influence of hypomagnetic conditions on fundamental biological processes is an important task, which requires the creation of a laboratory facility to provide hypomagnetic conditions with good uniformity and sufficient area for growing plants. To ensure the experiment, a system of three pairs of mutually perpendicular Helmholtz coils was selected. Based on the simulation results, the square shape of the coils was chosen [1]. This choice was determined by several factors. Firstly, the working area of square coils is larger compared to a system of round rings. Secondly, using square coils, it is easier to ensure the correct geometry of the structure and, therefore, to guarantee the magnetic field created in them and the area of its uniformity.

The level lines were calculated with a pitch deviation of 0.1% from the field in the center of the coils. When the rings are located at a distance of 90 cm (half of the side of the square coil), the area of uniformity is approximately 0.03 m^2 . As the distance between the rings increases, the area of uniformity increases and reaches its maximum at a distance between the rings of 98.7 cm. To create a useful area of 0.1 m^2 , the linear size of a square coil should be 180 cm. Based on the geometric parameters of the installation ($R=0.9 \text{ m}$), technical capabilities ($I_{\text{max}}=3\text{A}$) and the typical value of the Earth's magnetic field ($B \approx 50 \text{ mT}$), the number of turns and the wire cross section for winding coils were calculated, a wire with a diameter of 0.8 mm was selected, 50 turns were wound on each coil. To maintain hypomagnetic conditions, we used a three-channel programmable power supply Rigol DP832A, a fluxgate magnetometer WitMotion HWT3100 PNI, Raspberry Pi, as well as a "Magnetic field compensation control program for modeling hypomagnetic conditions".

It is important to note that, despite the large estimated area of uniformity of the installation, the actual usable working area is smaller. First of all, this is due to the impossibility of strictly observing the geometric dimensions of the installation, and the second most important factor is the presence of inhomogeneous magnetic fields of anthropogenic origin, which cannot be compensated. Despite the problems described above, the manufactured installation allows for experiments with reduced magnetic fields. During the experiment, the magnetic field fluctuates around an average value of 216 nT, with a standard deviation of 80 nT. Thus, with the help of this system, it was possible to reduce the Earth's field by two orders of magnitude.

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ANALYSIS OF GLOBAL SPRITE DISTRIBUTION BASED ON WWLLN DATA

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Sprites are one of the largest discharges in the Earth's atmosphere and a clear manifestation of the electromagnetic interaction of the lower and middle atmosphere [1]. Conditions for sprite initiation are created after particularly powerful cloud-to-ground tropospheric discharges, when, at the stage of continuous current, an electric charge of tens and sometimes hundreds of Coulombs is transferred from the cloud, and the dipole moment of the uncompensated charge in the cloud is several hundred C·km [2]. Field observations of high-altitude discharges, together with laboratory and numerical modeling, allow us to conclude that there are significant local disturbances in atmospheric parameters accompanying the development of sprites [3, 4]. Particularly powerful mesoscale convective systems can create conditions for the initiation of a series of high-altitude discharges and thus lead to long-lived, accumulating conductivity disturbances.

One of the main questions for understanding the degree of the influence of high-altitude discharges in general and sprites in particular on physical and chemical processes in the mesosphere is the question of their prevalence and initiation frequency. Based on the previously proposed parametrization [5], calculations were made on the global distribution of sprite activity according to WWLLN data for the period from 2015 to 2021. It is shown that the number of sprites per year varies significantly: from 420 thousand sprites in 2015, to 108.5 thousand sprites in 2019. On the average, 24.5 thousand discharges are initiated in March, and in October their number is half that.

Acknowledgements

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THE ROLE OF NONLINEAR PROCESSES IN OBSERVED CLIMATE EVOLUTION

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The presentation will concern the following issues.

1. What are climate systems? An example of the Earth's global climate system (GCS).
2. Why is it important to know whether the nonlinearity of the system affects its dynamics?
3. How to identify manifestations of nonlinearity in observational data? Model example.
4. Empirical reconstruction. Selecting the functional form of the empirical model, the need to correctly account for the known features of the model.
5. Forecasting capabilities of empirical models. Bayesian approach to forming an ensemble of models with assessment of the degree of their compliance with the studied system (statistical significance of different models).
6. An example of studying the mechanisms of evolution of the Earth's climate system: causes of climate change in the Pleistocene. Nonlinear-dynamic mechanisms responsible for changes in the climate evolution regime in the Middle Pleistocene.
7. An example of studying the effect of changes in the state of climate systems on their resilience to “large” disturbances: changes in the stability of the GCS over the past 2.5 million years.
8. Practical significance of empirical models and existing problems.

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ON ANISOTROPIC KOLMOGOROV SPECTRA FOR DEEP WATER SURFACE WAVES

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Self-similar spectra for deep water surface waves are the object of both theoretical interest and practical value. Well-known is the Zakharov – Filonenko spectrum [1]. The Katz – Kontorovich spectrum [2] adds anisotropy to this spectrum providing an adequate approximation to the experimental spectra.

We perform a general study of anisotropic additions to the Zakharov – Filonenko spectrum with different angular harmonics. We find some new anisotropic-powerlike approximate solutions. We calculate the next approximation order for the Katz – Kontorovich spectrum and show that it transits to bimodality at lower frequencies. We calculate numerically the Kolmogorov constant for the Katz – Kontorovich spectrum.

Special attention is paid to the long-short wave interactions. These interactions may result in divergence of the interaction integral and limit the validity span for the powerlike solutions.

Acknowledgements

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NUMERICAL SIMULATION OF TURBULENCE IN URBAN ENVIRONMENT WITH IDEALIZED AND REALISTIC SURFACE MORPHOLOGIES

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We present numerical models of urban turbulence developed at INM RAS and RCC MSU. We show the results of simulations performed using these models both for idealized urban-like geometries and for a realistic representation of the urban environment. The effects of thermal stratification and tree vegetation on urban turbulence dynamics are considered. We show and discuss the results of statistical analysis of LES data in terms of developing and refining the simplified one-column RANS models of urban canopy layer. The perspectives and trends in large eddy simulation as applied to urban meteorology problems are discussed.

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INSTABILITY, CHAOTIC BEHAVIOR AND RESPONSE PROPERTIES OF ATMOSPHERIC MODELS

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In this presentation we examine a number of issues related to the application of dynamic systems theory to the analysis and description of the behavior of chaotic atmospheric dynamics models (its trajectories as well as the corresponding invariant attracting sets) subject to external forcing. The possibility of using unstable periodic orbits to approximate the trajectories of the models under consideration and their statistical characteristics are discussed. The possibility of constructing relationships between the response of such systems to external influences and their unperturbed statistical characteristics are analyzed. Our results reinforce the idea of the possibility of using basic methods of nonequilibrium statistical mechanics and high-dimensional chaotic dynamic systems to approach the problem of understanding climate dynamics.

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GENERATION OF ULTRA-WIDE-BAND ELECTROMAGNETIC PULSES BY LONG SPARK DISCHARGES: NEW EFFECTS IN LIGHTNING PHYSICS

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Although electromagnetic radiation of lightning in the gigahertz frequency range has been known for a long time, the possibilities of localizing such radiation and experimentally studying its specific waveforms have appeared only in recent years in connection with the development of pulse measurement technology and broadband oscillography. Since the study of fast (nano- and picosecond) processes in real lightning is hardly possible, model laboratory experiments with long spark discharges, carried out on special high-voltage devices, acquire particular value. The paper describes a series of such laboratory experiments that led to the observation of an interesting physical effect – the generation of ultra-wideband (UWB) subnanosecond electromagnetic pulses (EMPs) in long spark discharges. Similar results were obtained on several high-voltage setups, including a charged water droplet cloud generator, as well as two pulse voltage generators – GIN-1MV and GIN-6MV. It has been established that a spark in the range of 1 to 10 m can emit large-amplitude (at the level of 100 V/m at a distance of about 100 m) EMPs with a duration of about 500 ps and a rise time of about 200 ps. Pulsed radiation occurs as a result of the interaction of a spark with a grounded electrode of a long gap (or “object struck by lightning”) during the start of the ascending leader. The reception of EMPs by several spatially spaced pulse probes with synchronous high-speed photography makes it possible to localize the radiation source near the grounded electrode, i.e. the discharge cathode. The results of these experiments, as well as a series of other works carried out in recent years, allow us to assert that the generation of subnanosecond UWB EMPs is a universal phenomenon that develops in the near-electrode region of long spark discharges and is presumably caused by the formation of subnanosecond electron avalanches.

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THE UNDERSTANDING OF THE ARCTIC OCEAN HYDRO- AND SEA ICE DYNAMICS: MULTISCALE PHYSICS AND NUMERICAL MODELING

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The Arctic Ocean (AO) is one of the least explored regions in the World due to its geographic location. The observational net is still sparse, especially in the deep ocean. The climate change leads to the structural reorganization of the polar climate system. That's why the sophisticated numerical models built on the basis of the first physical principles are of great importance for the AO processes diagnosis, monitoring and forecast.

The experience of the international activity on the AO modeling shows that many of the problems formulated more than 20 years ago are still on the agenda, despite the impressive refinement of the modern ocean models spatial resolution and improvements in physical parameterizations. This may be attributed to the complex nonlinear physics of the polar ocean, sea ice and under-ice boundary layer.

The main linear and nonlinear features of the Arctic Ocean hydrothermodynamics, sea ice dynamics and heterogeneous under-ice boundary layer, and their input to the large-scale state formation, will be discussed. There are continent slope jets, deep and shallow convection, cascading, differential and double diffusion, sea ice ridging, external and internal tides, ice-ocean drag and under-ice turbulence.

Special attention will be paid to the problem of the correct projection of the physics of ocean and ice on the numerical methods and model parameters, the problem will be illustrated by the examples of the INM RAS climate model INMCM development.

LARGE-SCALE PARAMETERIZATION OF GLOBAL LIGHTNING ACTIVITY

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In recent years, the primary approach in atmospheric electricity studies has been to analyze electrical processes within the unified framework of the global electric circuit (GEC). Lightning discharges serve as sources in the alternating current (AC) GEC. However, parameterizing lightning activity from first principles presents significant challenges, including the selection of appropriate spatial and temporal scales and the need to account for diverse physical mechanisms. A proper understanding of the relationship between lightning activity and fundamental atmospheric parameters is essential, as it is critical for advancing research in lightning climatology—a key area in both fundamental and applied atmospheric science.

A major obstacle in global-scale lightning parameterization is the land-ocean contrast. While the convective available potential energy (CAPE) in oceanic clouds is typically much higher, lightning frequency over land is, on the average, four times greater than over the ocean.

This study presents a machine learning-based approach to parameterizing AC GEC sources (lightning flashes) using experimental lightning distribution data. We identify three key atmospheric parameters that enable global lightning parameterization without artificially separating land and ocean regions:

1. Rainfall over the past hour (RAIN).
2. Convective available potential energy (CAPE).
3. Moisture above the zero isotherm (PWHI).

We trained and optimized a classifier for lightning activity, deriving an analytical expression for binary classification that estimates hourly lightning occurrence.

This work was supported by the IAP RAS state assignment (Project No. FFUF-2025-0009).

TOROIDAL VORTICES: THEIR EFFECTS ON DYNAMICS AND MICROPHYSICS OF CUMULUS CLOUDS

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We summarize findings from recent studies, focusing on the connection between Cu dynamic properties, such as velocity field, entrainment/detrainment, and cloud microphysical properties, such as cloud dilution rate and droplet size distribution parameters. We focus on numerical and analytical derivations from the results of 10-m-resolution Large Eddy Simulations (LES) with spectral bin microphysics and statistical analysis of the motion of passive tracers. We used wavelet filtration to separate the clouds' dynamic and microphysical fields into turbulent and convective ones. The main parameters of cloud turbulence and convective motions were evaluated. Turbulence was shown to form an interface zone of a few tens of meters between the cloud and the surrounding air. Convection-scale motions are responsible for dynamic and microphysical properties' formation in the cloud interior. The dominating role of the vortex ring (toroidal vortex, TV) arising in the upper part of developing clouds is stressed. This TV is responsible for dynamic and microphysical cloud structure formation. It determines the cloud size, internal dynamics, and ascent velocity of the cloud top. The TV determines the width of the cloud core and disappears as soon as the core becomes diluted. Knowledge of the TV effects on cloud microphysics and dynamics allows one to propose parameterization of the main dynamic and microphysical properties of small Cu using sounding data and aerosol concentrations.

Acknowledgements

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ADVANCING PREDICTIVE UNDERSTANDING OF SUMMER ARCTIC SEA ICE

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Understanding how to predict changes in the Arctic environment, especially sea ice variations, is crucial because of their significant impacts on economies and societies, both locally and globally. Of particular interest is predicting summertime Arctic sea ice on subseasonal time scales, i.e., from early summer into fall, when sea ice coverage in the Arctic reaches its minimum. The extent of summer sea ice in the Arctic is influenced by many factors, ranging from daily weather changes to long-term shifts in global wind patterns, which are affected by slowly changing ocean temperatures worldwide. The Sea Ice Outlook assessment of the multi-model predictive skill for September Arctic sea ice [1] demonstrated that our understanding of how these factors interact remains limited due to the short duration of reliable satellite data and the complexity of sea ice-ocean-atmosphere interactions, which pose challenges for climate and statistical models.

The preconditioning of sea ice before the summer months has long been recognized as a vital predictor of September sea ice extent. Improving prediction accuracy involves examining the impacts of external climate components and their interactions with persistent local conditions before the season. We develop models of regional Arctic sea ice based on a diverse array of observational data on a global scale, integrated using an advanced machine learning method called data-adaptive harmonic decomposition (DAHD) modeling [2, 3, 4]. This method explicitly incorporates nonlinear, memory, and synoptic (stochastic-like) weather effects within a universal parametric family of nonlinear stochastic models—frequency-ranked coupled Stuart-Landau oscillators. DAHD is theoretically guided by the Mori-Zwanzig formalism of statistical mechanics and Koopman theory, aimed at optimally modeling partially observed, complex, and nonlinear dynamical systems [5, 6]. This approach seeks to capture the complex, nonlinear variations in both local and remote influences across various timescales in a global context. The results of meticulously designed reforecast experiments are presented to isolate and quantify the influence of various physical drivers on summertime regional Arctic sea ice.

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EVALUATION OF REGIONAL CLIMATE SIMULATIONS OVER THE NORTHERN EURASIA USING A NEW LAND SURFACE MODEL

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This study aims at validation of regional climate simulation using the Voeikov Main Geophysical Observatory atmospheric regional climate model (RCM) coupled to a new land surface model (MGOLSM v1.1). The MGOLSM is developed within the framework of the Key Innovative Project of National Importance “Unified National System for Monitoring of Climate-Active Substances” (Government order of the Russian Federation No. 3240-r dated October 29, 2022).

The MGOLSM is a state-of-the-art land surface model with detailed representations of the snowpack and soil, dynamic evolution of snow density and albedo, phase transitions of soil moisture, and the ability of snow to retain liquid water [1].

Here the model output is compared with observational data from 1990–2012 across 18 catchments in the Northern Eurasia. The results indicate that the use of MGOLSM allows for reasonable agreement of the simulated seasonal cycle of snow water equivalent, precipitation, and surface temperature with that derived from observations.

A river discharge is simulated using the CaMa-Flood hydrodynamic model [2], driven by runoff output from the RCM with incorporated MGOLSM. Comparison with the observational data from 44 hydrological gauges shows that the RCM with the new land surface model simulate river discharge at the gauges closer than observed.

An advanced version of MGOLSM (v2) featuring an enhanced representation of heat and moisture transfer in frozen ground is presented. MGOLSM v2 simulations show better agreement with the observations of active layer thickness and soil moisture as compared with that of MGOLSM v1.1 at 23 locations across Northern Eurasia.

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EMULATION AND S2S PROBABILISTIC PREDICTION OF 2-M TEMPERATURE AND PRECIPITATION OVER THE GLOBAL DOMAIN USING LINEAR INVERSE MODELING

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We developed a data-driven system for joint prediction of daily precipitation (Pr) and near-surface temperature (T2m) over the global domain by utilizing NASA's satellite observations and the associated reanalysis products, with the focus on S2S hydrologic forecasting. Our approach is based on a well-established methodology of linear inverse modeling modified and adapted by our research team for high-resolution modeling of precipitation. The key element of this new methodology is the usage of the so-called pseudo-precipitation (PP) variable, equal to the actual Pr where precipitation occurs and, otherwise, equal to the (negative) air-column integrated water-vapor saturation deficit — the amount of water vapor to be added to the air column to achieve saturation at each vertical level. The model's jointly obtained Pr and T2m forecasts are then validated against the observed fields as usual.

The above model is shown to be an efficient tool for emulating daily sequences of global coupled T2m and Pr fields with spatiotemporal characteristics strikingly similar to the observed characteristics. We used a large (100-member) ensemble of our statistical model's hindcasts of precipitation over a global domain to predict probabilities of weekly and biweekly precipitation amounts in one of the three categories (below normal, normal, and above normal) and compared these hindcasts with those based on the NASA GEOS2S v2p1 model (4-member ensemble), calibrated using extended logistic regression. While the statistical model's 2S precipitation forecast skill is somewhat lower than that of the reference NASA state-of-the-art system, it exhibits similar geographical and seasonal distributions, which warrants further research. We are currently looking into incorporating automated ML/AI feature identification techniques into our existing set up (with a linear activation function), to fine-tune the model learning and improve its predictive potential.

IMPROVING PREDICTABILITY OF CLIMATIC DYNAMICS OF CHARACTERISTICS OF THE TROPICAL BASIN OF THE PACIFIC AND INDIAN OCEANS USING JOINT EMPIRICAL MODELS

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Forecasting the climate dynamics of the World Ocean is the most important task in terms of long-term forecasting of the Earth's climate. Within the framework of this problem, forecasting the dynamics of the tropical basin of the Pacific and Indian Oceans is one of the main problems, since it is here that such important climatic phenomena as the El-Nino Southern Oscillation and the Indian Dipole occur. In this work we discuss a method for constructing an empirical model of part of the World Ocean basin – the equatorial basin of the Pacific and Indian Oceans, which makes it possible to improve the quality of forecasting the characteristics of the Oceanic climate dynamics.

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CONVECTIVE AND ELECTROSTATIC STRUCTURES IN DUST AEROSOL EMISSION

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During wind-sand transport, particles moving in the flow are electrified as a result of mutual impacts. This affects the value of the electric field [1, 2]. The main factor determining the dust aerosol ($\sim 0.1\text{--}5\text{ }\mu\text{m}$) transfer from arid territories and changes in the value of the electric field is wind [3, 4]. When the threshold wind velocity is exceeded, jump-like movements of large particles ($\sim 70\text{--}150\text{ }\mu\text{m}$) near the surface (saltations) occur. In summertime, under conditions of considerable surface heating, convective motions have a significant influence [5].

Measurements of temperature and wind velocities (1000 Hz), electric field strength (100 Hz), and dust aerosol concentration (10 Hz) in arid conditions (2022–2024) allow us to reveal permanently emerging coherent structures [5]. Synchronization of fluctuations in aerosol concentration, temperature and electric intensity are observed. The correlations for their averaged values should also be noted.

For the spectra of temperature, velocity, concentration, and electric field strength, in addition to the known slope $-5/3$, other slopes -1 , -3 , and $-1/3$ associated with convective processes and structures are observed.

The following characteristic scales were determined at the points of changing the slope of the power spectra taking into account the values of wind velocities at the height of measurements: for velocity fluctuations $\sim 0.2\text{ m}$ (time scale 0.03 s), for dust aerosol concentration $\sim 0.7\text{ m}$ (time scale 0.1 s), for temperature $\sim 2.7\text{ m}$ (time scale 0.46 s), for electric field strength $\sim 5.3\text{ m}$ (time scale 0.9 s).

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LIGHTNING RETURN STROKE: MODELING PROBLEMS

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The return stroke is the most dangerous phenomenon, connected to lightning. The lightning return stroke is the process of discharging to the ground an extended charged system created by the lightning leader. This system is a plasma channel (the leader channel) surrounded by a partial charge (the leader's sheath). The lightning return stroke begins at the moment when the streamer zone of the descending leader closes with the ground or with the streamer zone of the upward connecting leader starting from the surface of the earth, forming a common streamer zone of two counter-propagating leaders. Knowledge and correct modeling of the physical processes occurring during lightning return stroke is one of the fundamental problems in lightning discharge physics.

This study presents still unsolved problems of the return stroke physics related to its laboratory and theoretical modeling, in particular:

1. Optical registration of streamers in the streamer zone of the leader discharge.
2. Measurements of the spatio-temporal dynamics of a positive leader discharge with synchronous recording of the discharge current and voltage using a streak camera, high-speed cameras, an autonomous current meter on a high-voltage electrode, and a voltage divider.
3. Numerical modeling of the return stroke and comparison of their results with the results of laboratory measurements and data on natural lightning.

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DATA-DRIVEN METHODS FOR STUDYING NONLINEAR CLIMATE PHENOMENA

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Climate variability is governed by a complex multicomponent dynamical system that includes nonlinear interactions across time and space scales. Data-driven approaches to forecasting climate dynamics and investigating underlying laws have become widely used due to the availability of high-resolution climate monitoring data and the limited ability of current Earth system models to simulate observed processes. Such approaches are aimed at derivation from data of statistically optimal dynamical models capturing key properties of the system that manifest themselves in the observations. Here we present some methods for constructing data-driven models elaborated at IAP RAS, as well as some examples of their applications to analyze climate phenomena. The methods are based on representing the system's evolution operator in the form of nonlinear random maps accounting for unresolved components via state-dependent stochasticity. Different parametrizations of the model evolution operator are compared and discussed, e.g., feedforward and recurrent neural networks and hidden Markov models. The focus of this presentation is on the possibility to reveal from data nonlinear evolution laws which are crucial for explanation of the observed dynamic properties such as critical transitions and nontrivial system response to external forcing. In particular, we demonstrate how the obtained models reveal the nonlinear properties and mechanisms of Pleistocene climate which led to the emergence of long-period and high-amplitude glacial cycles 1 million years ago, the nonlinear evolution law of El-Nino Southern Oscillation manifested as non-symmetry of its cold and warm phases, and metastable persistent states of mid-latitude atmospheric circulation known as weather regimes.

Acknowledgements

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DEVELOPMENT OF FLUTE INSTABILITIES DURING THE EXPANSION OF PLASMA FLOWS IN A MAGNETIC FIELD IN SPACE PLASMA SIMULATION EXPERIMENTS AT KROT PLASMA DEVICE

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The expansion of dense high-speed plasma in an external magnetic field in a vacuum or in a less dense background magnetized plasma is observed both in near-Earth plasma during active experiments, and in deep space (the formation of astrophysical jets, the accretion of matter in young stars, supernova explosions, etc.) Scaled laboratory modeling of these processes is an opportunity to study these phenomena in controlled conditions. The main problems include the large-scale dynamics and deceleration mechanisms of plasma flows, the structure and generation processes of external magnetic field disturbances, the role of plasma instabilities in flow dynamics, and the excitation of wave disturbances and discontinuities. Flute instability can significantly affect the maximum size and rate of plasma expansion, which, in turn, determines the nature of magnetic diffusion, and the maximum size and dynamics of the diamagnetic cavity [1, 2].

This work presents a laboratory study of flute instability in model experiments studying the expansion of a plasma flow injected along a magnetic field. The experiments were conducted on the large-scale Krot plasma device, which features an exceptionally large size of magnetized plasma across the uniform magnetic field (1.5 m). A miniature coaxial erosion plasma gun served as the source of high-speed (up to 100 km/s), dense ($\sim 10^{14} \text{ cm}^{-3}$) plasma flows. The cases of expansion of a plasma jet into vacuum, background plasma (He, Ar) and into neutral gas in both sub- and super-Alfven expansion regimes were studied. Multipoint magnetic probe measurements combined with high-speed ICCD imaging enabled not only studying the formation dynamics and subsequent evolution of flute structures with estimation of instability growth rates, but also correlation of plasma glow characteristics with diamagnetic cavity dynamics. The study demonstrates multiple regimes of flute instability development, which vary depending on the background medium properties.

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FULLY NONLINEAR INTERNAL WAVES AND THE SHEAR FLOWS INDUCED BY THEM IN THE SEA OF OKHOTSK

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The natural features of the Sea of Okhotsk (non-uniform bottom bathymetry, pronounced stratification of sea water density, fairly strong barotropic tides with complex structure and seasonal variability) favor the complicated and nonlinear nature of the internal wave dynamics. Although there are few full-scale field observations in this region, there are many satellite images, in particular, internal wave trains, confirming the richness of internal wave dynamics and their important role in the region under study. Numerical modeling of transformation scenarios of fully nonlinear long internal waves can serve as a powerful auxiliary tool, partly compensating for the scarcity of available in-situ measurements. The instrument of this study is CFD package for numerical solution of Euler equations in a quasi-2D stratified fluid with the use of the Boussinesq approximation, which has been successfully applied to similar problems. In some cases, modeling was performed in SUNTANS (Stanford unstructured-grid, nonhydrostatic, parallel coastal ocean model).

To study the features of baroclinic currents, several vertical cross-sections were selected in the north-eastern part of the shelf zone of the Sakhalin Island. It is shown that the baroclinic component makes a significant contribution to the current field and has a complex multimode highly nonlinear structure. Several regimes of long-wave transformation are identified; the estimates of amplitudes of both baroclinic tide waves (diurnal and semidiurnal) and short-period internal waves generated at their fronts are obtained. It is shown that the studied shear flows are nonlinear and are characterized by significant asymmetry in the distribution both in direction (from the coast / to the coast) and in depth. The main local maxima of the velocity field are located from Cape Elizabeth (Sakhalin) to Piltun Bay, and another one is from Cape Bellingshausen to Cape Terpeniya. Lagrangian particle trajectories were analyzed in the simulated cases. Maps of horizontal and vertical displacement distances were constructed, the "patchiness" of which does not directly correlate with the bathymetry, and can be interpreted again as a result of the nonlinear dynamics of internal waves in this region.

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NONLINEAR RESPONSE OF THE ATMOSPHERIC TRANSPORT MODEL TO METEOROLOGICAL FORECAST UNCERTAINTIES

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One of the possible applications of numerical models for forecasting meteorological parameters is the simulation of the dispersion of emissions of potentially harmful substances into the atmosphere. In such tasks, uncertainties play a significant role: meteorological forecast, estimation of the emission source, advection-diffusion model in a stratified atmosphere, and description of the underlying surface properties. Under different conditions, these uncertainties have varying impacts on the modeling results, which are generally quite difficult to assess. In this work, a model is proposed to evaluate the nonlinear response of the atmospheric transport model to uncertainties in the meteorological forecast.

In the model, we will use tracer experiment data for the predicted levels of pollutant concentration in the environment, meteorological monitoring data to control the uncertainty of the meteorological forecast, and atmospheric transport model validation results to determine the threshold sensitivity of the modeling results to perturbations. The validation results of the atmospheric transport model in this work will be considered the limit of the achievable accuracy of the atmospheric transport model, the improvement of which is difficult within the framework of the statistical theory of atmospheric diffusion used in the model.

In this case, by transforming the uncertainty of the meteorological forecast through the atmospheric transport model, it is possible to construct a distribution function of the deviations between calculated and measured concentrations and, having limiting values, estimate the permissible levels of meteorological forecast uncertainty. As an example, we present the results of the model work based on an experiment conducted at the “Kinkaïd” power plant site. Figure 1 shows the distribution function of the deviation of the concentration forecast according to the NMSE metric, as well as the threshold levels of the quality criteria for atmospheric transport modeling. It can be seen that the resulting distribution exhibits a nonlinear error distribution in concentration modeling relative to changes in meteorological quality.

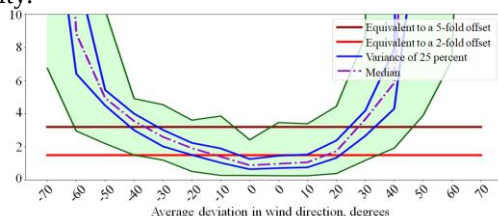


Fig. 1. NMSE metric distribution function

APPLICATION OF RECURRENT NEURAL NETWORKS TO THE ANALYSIS OF MID-LATITUDE ATMOSPHERIC DYNAMICS REGIMES

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Atmospheric circulation in mid-latitude and polar regions spans a hierarchy of interacting scales and can repeatedly lock into *metastable regimes*—quasi-stationary patterns that persist for several weeks and dominate sub-seasonal anomalies. Predicting and analyzing these regimes is challenging, because their onset and decay depend on nonlinear cross-scale interactions and strongly reflect the memory of previous states.

In this work we present a stochastic recurrent neural-network (RNN) approach that links two complementary coordinate sets: a low-dimensional projection of geopotential-height fields obtained with linear principal-component analysis (PCA) and a kernel-PCA representation that sharpens the separation of the target regimes. Networks of this type can capture long-range dependences, while requiring only a modest number of parameters, thereby limiting overfitting on relatively short records—an important benefit when working with atmospheric data spanning many time scales. The network predicts the step-wise evolution of the PCA coordinates, while simultaneously mapping them into kernel space. These trajectories are then examined with a hidden Markov model, which isolates metastable regimes and allows their persistence and transitions to be compared between simulations and observations [1].

The method is evaluated for Northern Hemisphere winters using 100-hPa geopotential heights from NCEP/NCAR reanalysis together with simulations from the INMCM and MPI climate models. Preliminary results obtained from synthetic and real datasets indicate the potential of this approach in forecasting enduring weather structures.

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IDENTIFICATION OF SEASONALLY DEPENDENT ATMOSPHERIC CIRCULATION REGIMES WITH NON-HOMOGENEOUS HIDDEN MARKOV MODEL

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Weather regimes are usually defined as repetitive and quasi-stable structures of atmospheric circulation on sub-seasonal several-weeks time scales. The inter-regime dynamics makes a major contribution to the low-frequency variability of the atmosphere. It has time scales beyond synoptic predictability and is known as poorly understood and least predictable component of the atmospheric dynamics. These structures strongly modulate synoptic-scale activity and thus have a significant impact on regional weather patterns. That's why reliable identification of such regimes is essential for understanding climate dynamics and improving sub-seasonal to seasonal forecasts. While hidden Markov models (HMM) have been successfully applied to winter data under the assumption of stationarity and lack of seasonal influence [1, 2], year-round analysis requires explicit accounting of seasonal variability. In this study, we present a non-homogeneous HMM framework developed to identify atmospheric regimes continuously across all seasons. We also adapted a graph-based community detection algorithm from a quasi-stationary winter case [1, 2] to identify metastable regimes during full years making decomposition of time-varying transition matrices of the NHMM. This methodology is applied to reanalysis data and realizations of state-of-the-art Earth system models such as INMCM and MPI. The ability of the algorithm to identify physically meaningful regimes is demonstrated. Also, a comparative evaluation of model skills in reproducing observed regime statistics and transitions is presented. This approach may help to better understand the physical basis underlying the regime dynamics and to improve the predictability of atmospheric variability.

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REVEALING EVOLUTION OF ENSO IN A CHANGING CLIMATE: DATA-DRIVEN DYNAMIC SYSTEMS APPROACH

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El Niño–Southern Oscillation (ENSO) is the most prominent mode of inter-annual climate variability with far-reaching socioeconomic consequences. Many studies were dedicated to understanding how ENSO responds to climate change. Some of them [1, 2] indicate significant changing of the key ENSO features under future greenhouse warming. In this study we identify the evolution of ENSO in a changing climate via the analysis of the upper ocean heat content variability in the tropical Pacific from both high-resolution reanalysis dataset and ensemble simulations, produced by six state-of-the-art Earth system models (ESM) participating in the Coupled Model Intercomparison Project. The approach we propose seeks to analyze the dynamics of low-dimensional, nonlinear, stochastic models of interannual ENSO variability obtained directly from data. We compare and analyze the corresponding stochastic models derived from historical ESM simulations as well as from ESM simulations of the future climate under different SSP scenarios (Shared Socioeconomic Pathways). The possibility of purely data-driven (without involving ESM) projections of the future ENSO changes is also introduced and discussed.

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MODELING SCHUMANN RESONANCES EXCITED BY REAL SOURCES AND COMPARISON WITH OBSERVATIONAL RESULTS

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The study of the natural electromagnetic environment of the Earth is currently gaining great importance in the context of its potential connection with climate change and biological processes. One of the key elements of this environment are Schumann resonances – eigenmodes of the Earth-ionosphere resonator excited by global lightning activity [1]. Understanding the relationships between Schumann resonances and large-scale atmospheric processes can provide additional information on climate change and serve as an auxiliary tool for climate monitoring [2]. To achieve these goals, it is necessary to develop not only theoretical models, but also systems for continuous monitoring of Schumann resonance characteristics.

The paper presents the results of numerical modeling of the Schumann resonance characteristics and comparison with observational results obtained in the Upper Volga region. We use a numerical model based on solving the two-dimensional telegraph equation describing the propagation of electromagnetic waves excited by a single lightning discharge in the “Earth-ionosphere” cavity. The model presented in [3] is implemented in the form of the open-source schupy software package written in Python. The obtained results are compared with the data of long-term measurements of Schumann resonances carried out near Nizhny Novgorod since the end of 2023. A correspondence between the observed and modeled daily variations in the amplitude of one of the components of the first harmonic is established.

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EXPERIMENTAL FACILITIES FOR LABORATORY MODELING OF ELECTROMAGNETIC RADIATION GENERATION IN PLANETARY MAGNETOSPHERES AT IAP RAS

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Cyclotron interaction of waves and charged particles largely determines the dynamics of the Earth's radiation belts and the overall energy balance in the magnetosphere. The emissions generated during such interactions are among the most intense signals in cosmic plasma. The patterns of formation of these emissions and the parameters of their impact on energetic charged particles are the subject of active research, as the nonlinear nature of these processes introduces a range of yet-unsolved problems. Among these are the studies of the processes responsible for the formation of fine structures in the spectra of cyclotron radiation in both laboratory and space plasmas. These processes share much in common and can be explained within the framework of a unified theory.

In recent years, significant advances in understanding the mechanisms of generation of certain types of magnetospheric waves have been achieved due to new findings from satellite missions. However, in some cases, there are objective technical limitations in satellite experiments, which can be partially addressed through laboratory investigations. At the Institute of Applied Physics of the Russian Academy of Sciences (IAP RAS), studies of kinetic instabilities in non-equilibrium plasma under electron-cyclotron resonance (ECR) discharge have been successfully conducted for over fifteen years using a laboratory open magnetic trap sustained by high-power gyrotron radiation at the experimental setups SMIS-37 [1, 2] and GISMO [3]. Through the use of modern techniques for diagnosing electromagnetic radiation in laboratory experiments, unique data on the radiation spectra of plasma generated as a result of instability development have been obtained.

This talk will provide an overview of the experimental facilities at IAP RAS designed for laboratory modeling of kinetic instabilities and a summary of the main results obtained with their use in recent years.

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ON THE UNIVERSALITY OF SQUALL STATISTICS: SELF-SIMILARITY AND TURBULENT FEATURES

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The relevance of diagnostics of the squalls' main characteristics —extreme weather events of a local, sudden nature in the atmospheric boundary layer — remains extremely high. An approximate assessment of the damage caused by squall is still insufficiently studied. This is particularly important in the context of improving the accuracy of operational forecasting and identifying the causes of squall formation and development. Using a large data set of wind velocity and direction from a high-altitude meteorological tower (Meteo Tower) of the Institute of Experimental Meteorology NPO Typhoon for 2014–2024, we have obtained the results on the statistical distributions of the main diagnostic characteristics with sufficient reliability: velocity, and wind energy and power — indicators of destructive force. For different and in no way related events of wind strengthening dependences of maximum and average velocity, energy, power on scale, as well as energy and power on average velocity, are described by universal power correlations with a probability of approximately 95–98%. We assume a connection with the causes of squall formation as well as the accompanying turbulent and coherent structures such as streaks. Such dependences and the obtained energy spectrum with the slope of -3 and $-5/3$ indicate self-similarity of squalls.

We have assessed the scale and energy of destruction using Kolmogorov's theory of 1934 [1]: the estimation of the transverse scale of a squall is, on average, 3–4 times greater than its longitudinal scale. To draw a more accurate relationship, one can use the results of numerical modeling, for example, WRF findings. Based on the squall sizes, we made an evaluation of the destruction energy through the squall characteristic times and forcings.

Another key result we should mention is related to the strong anticorrelation between the horizontal velocity components. It is noteworthy that a sharp surge in that anticorrelation discovered slightly ahead of each squall under our consideration begins. This fact is presumably due to validity of continuity equations for each velocity components.

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ANALYSIS OF THE GLOBAL TEMPORAL DISTRIBUTION OF SPRITES

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A sprite is a large-scale, short-term electric discharge that develops in the mesosphere at altitudes of 50–90 km [1]. It is triggered by an intense positive cloud-to-ground (CG) lightning discharge. The quasi-static electric field produced by the uncompensated charge in the parent thundercloud penetrates into the mesosphere and creates the conditions required for initiating a high-altitude discharge. Such conditions are met primarily at night, when mesospheric ionization and electrical conductivity decreases. In daytime the high conductivity of the middle atmosphere screens the electric field, modifying the threshold conditions for sprite initiation and, according to model calculations [2], shifting the initiation region downward.

The present study uses the global sprite-distribution model proposed in [3]. Calculations are performed with World Wide Lightning Location Network (WWLLN) data for the period 2015–2021 and are restricted to night conditions, defined here as times when the Sun is below the horizon at an altitude of 90 km.

We examine how sprite occurrence frequency varies throughout the night as a function of local time. The diurnal behavior differs significantly over land and ocean: over land the highest activity occurs immediately after sunset and then decays monotonically, whereas over the ocean sprite activity increases gradually, reaching a pronounced maximum roughly 7–9 h after sunset. We also analyze sprite initiation frequency in Coordinated Universal Time (UTC), which clearly reveals the seasonal modulation associated with the principal regions of lightning—and therefore sprite—activity.

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COMPOSITE STRUCTURE OF JUPITER'S GREAT RED SPOT

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According to measurements obtained in interplanetary missions and on the Hubble Space Telescope, the main outer part of the vortex of the Great Red Spot of Jupiter (JGRS) is anticyclonic, while its inner region is in cyclonic rotation. This allows us to consider the JGRS as a quasi-geostrophic formation composed of two vortices embedded into each other. Such a vortex structure with “embedding” can be called a composite vortex.

Two variants of vortex formation are considered.

1. A stationary composite vortex composed of two ellipsoidal confocal vortices in a horizontal zonal barotropic flow with a constant shear. An exact solution of this nonlinear problem is obtained within the framework of a rotating stratified atmosphere in the approximation of a quasi-geostrophic f-plane. An important condition here is the stationarity of the shape of both vortices. In such an approach, for a given geometry of the vortices and shear of the background flow, the potential vorticities of both vortices are determined uniquely. The main vortex has the same sign of potential vorticity as the background flow. The embedded vortex has the opposite vorticity. The energy of the composite vortex exceeds the energy of a homogeneous stationary vortex without embedding.

2. A combination of a stationary external vortex and a non-stationary embedded vortex, provided that it weakly affects the behavior of the main vortex boundary. Both vortices have an ellipsoidal core shape and are affected by the same external flow as in the first case. The potential vorticity of the main vortex is calculated exactly, and the vorticity of the embedded vortex can be arbitrary. The internal vortex moves as a whole along elliptical orbits inside the main vortex. In this case, the deformations of its core change periodically with limited oscillation of the horizontal semi-axes. When the centers of the vortices coincide, the internal vortex, remaining in place, can rotate with limited deformation of its boundary. If the embedded vortex has a vorticity opposite to the main vortex, then the energy of the composite vortex is less than the energy of the homogeneous vortex without embedded vortex. The latter property indicates the energetic preference for the existence of composite eddies with non-stationary embedding that weakly affects the boundary of the main vortex.

BEHAVIOR MODES OF A QUASI-GEOSTROPHIC ELLIPSOIDAL VORTEX IN A HORIZONTAL FLOW WITH VERTICAL SHEAR

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The talk addresses the problem of the behavior modes of baroclinic geostrophic vortices with ellipsoidal-shaped cores in horizontal flows with a constant vertical shear. In such flows, the vortex core is confined between two stationary horizontal planes, which the vortex touches at its upper and lower points. Under the influence of the background flow, the lengths of all the axes of the ellipsoid can change, and the angles of orientation of the vortex in space also change. The authors identify three modes of vortex behavior. The first mode is the survival mode of the vortex in a shear flow, where the vortex undergoes finite oscillations of the semi-axes for an indefinite period of time and may exhibit complex behavior in terms of its orientation angles. This mode corresponds to strong vortices. In the second mode, the vortex is stretched along the flow from the very beginning, remaining with finite horizontal dimensions perpendicular to the flow and compressed vertically. This is the destruction mode of the vortex by the flow, where the final result is the formation of a thin vertical structure of the ocean from the vortex. Weak vortices undergo this type of evolution. This mode is referred to as the “unlimited stretching mode.” Finally, there is a third mode, called the “finite lifetime mode,” in which, for a finite period of time, the vortex behaves similarly to the survival mode (its shape is finitely deformed, and the vortex rotates or oscillates in space), but eventually, the vortex stretches indefinitely in a manner similar to the destruction mode. The authors have delineated the regions of existence for each mode on a dimensionless parameter plane of the problem and determined the boundaries separating the above-mentioned modes of vortex behavior.

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