Temporal and Spatial Evolution of Poloidal Magnetic Field in Damavand Tokamak for Different Plasma Currents

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The spatial and temporal poloidal magnetic signals in the Damavand tokamak have been studied. Array of Mirnov coils inside the tokamak vessel are used to determine the magnetic perturbation as discharge progresses. Magnetic probes show different oscillations for shots in which maximum plasma currents varies from 17 KA to 32 KA. Mirnov magnetic signals from normal shots are compared to the signals from shots where disruptions have been taken place. Comparison of plasma currents and poloidal magnetic fields for different shots show that as plasma current increases the poloidal magnetic field also increases which is expected but magnetic signals by varies magnetic probes in different locations differ from each other which is indication of asymmetrical magnetic topology.

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Design and Fabrication of Langmuir Probe Circuit for Measurement of Plasma Edge Electron Temperature and Density in IR-T1 Tokamak

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To achieve the edge plasma properties, 2 electronic circuit have been fabricated and a set of 4 single Langmuir probes installed in Iran –Tokamak1 (IR-T1). The Floating Potential has been measured without applying any voltage, Ion Saturation Current by a negative DC power supply and then by applying a sweep voltage to tips, I-V curve and so electron temperature is obtained. Then we compare these results to investigate of some properties of edge plasma.

Regarding to the first results without position control of plasma column, we can compare properties of edge plasma such as floating potential, electron density and temperature in 4 points near to limiter. As the results show, the floating potential, Ion density and electron temperature for deeper pins are more than closers.

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A Fast Integral Tokamak Deposition Model in the Single Null Configuration

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Energy deposition on the tokamak plasma facing materials is one of the main hurdles along the road to commercial fusion on the grounds of both material deterioration and impurity management. Modelling deposition, due to it considerable complexity, generally demands purely numerical simulation of non integrable behaviour by way of heavy processing on not very wieldy codes. Furthermore, these models are necessarily applied to the edge locality, as more inclusive systems soon become prohibitive. On the basis of the Hamiltonian nature of the tokamak equilibrium field, an integral model of the popular poloidal divertor single null configuration is presented which is physically self consistent, highly descriptive and extremely light on processing as it does not rely on numerical storage. The model, based on the formalism of Legendre transformation homeomorphisms, is specifically designed thanks to the inclusion of non ideal MHD perturbations via the Rayleigh function of the system. The resulting canonical mapping is applied to real deposition conditions yielding revealing images of the target field topology which contribute to a better understanding of experimental observations.

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Particle and Power Balance in Fusion Plasma with Different Fueling Scenarios and Helium Ash Removal

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Achieving the fusion power in tokamak JET in the operation with the deuterium and tritium mixture plasma and the possible next step in the controlled fusion device ITER stimulate the further study of the fusion plasma in a toroidal magnetic trap of the reactor scale. Among many problems there is an unsolved question about the role of cold alpha-particles in power and particle balance of fusion plasma. Here we consider the effect of the removal of the cold alpha-particles on the achieving of the steady state and plasma parameters in steady state. We model the removal of cold alpha-particles inducing the rule of the cold alpha-particle confinement time evolution during the plasma discharge. We suppose that τ_α is not constant but is the harmonic function of the time.

We obtain dependence of plasma ignition boundary from plasma parameters: density, temperature, fraction of alpha-particles, and operation pass for different ignition regimes.

The careful control of the plasma density by fuelling S_{DT} is necessary. Real time measurements of plasma density and ion temperature during the heating phase are needed to get the desirable operating point on the n-T plane (POPCON). The thermally stable ignition regime can be reached by control of alpha particles fraction and plasma ion temperature.

When the alpha ash confinement time changes, the alpha ash density and plasma density changes together. Without diagnostics which plasma parameters, like alpha ash fraction or energy confinement time, are changed during ignition and ignited operation it's easier to operate plasma ignition pass by the feedback control of heating power and fuelling of deuterium and tritium by monitoring fusion power. Plasma parameters evolution and operation paths (plasma density versus plasma temperature) on the background of the POPCON shows us the consequence of the stages of the plasma heating and density increase due to fuel coming and heating.

For investigation of time evolution with time dependent law for alpha-ash removal we use next expression

$$\tau_\alpha = 7.5 + \frac{4}{\pi}\sum_{j=2n}^{\infty}\frac{j}{j^2-1}\sin(j\omega t)\text{, where } \omega\text{=0.27sec}^{-1}.$$

The effect of the removal of cold alpha-particles on the plasma parameters is demonstrated here. We get some reduction of the bremsstrahlung losses and that in the steady state the plasma parameters are more stable in time under the removal of the cold alpha-particles. The fusion power is more "flat". Another important fact is found here. This is the effect of the change of the fuel source S_{DT} dynamics in time on the plasma parameters in the steady state. We should notice that in the case of the smaller fuel rate the steady state is established on the level of the lower value of the helium ash. The fusion power is some smaller in the case of the smaller fuel rate in comparison with the power in the previous case. Plasma operation paths can distinguish noticeably under the different scenarios of fueling.

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Simulations of Single Charged Particle Motion in External Magnetic and Electric Fields

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In this paper we present a software package for computational simulation of a single particle motion in the presence of static and dynamic external magnetic and electric fields and show the applications of our package to some relevant general cases and to laboratory and fusion plasmas. In addition we further elaborate the capabilities of new concept named "Larmor Center Trajectory" that we introduced in our previous work (2007) as a generalization of well known Guiding Center Approximation, and show the ranges of applicability of this concept, especially in strongly inhomogeneous fields when adiabatic approximations break.

Since it is very difficult to predict a charged particle trajectory for an arbitrary combination of field parameters, except in simplified cases, the only way to follow the particle path in a general case is to perform a particle motion simulation in space and time. For this purpose we developed our package which, however, in previous versions was suited for dealing with only analytically defined electric and magnetic fields. Even with such a limitation these veins of software still are a powerful user-friendly tool for various scientific and engineering purpose. However there is a limited number of analytic options to choose from *analytically* predefined fields (e.g. magnetic mirror, magnetic cusp, homogeneous fields, etc.) where a user can set certain number of typical parameters of those fields, to formula defined field, in which all Matlab expressions can be implemented. In realistic cases, one can not define magnetic and electric fields with simple analytical formulas but rather with highly complex ones, if at all possible for arbitrary problem of interest. In order to expand the use of the package also to a pragmatic level, new features were necessary to be implemented. Namely, field data set is usually given by external numerical method obtained either in special additional modules of our package or from other programs developed elsewhere when our modulus turns out to be insufficient for particular problem. Such special programs are suited for generating magnetic and electric fields from physical conductors and and/or other physical field sources. Besides such data sets there is frequently a need to use field data from experimental measurements. For such purposes an option for importing external fields independent of their origin is developed and applied in our work.

This kind of data is usually stored in text files as numbers in several lines and columns. A parser for text file data with some predefined file structure requirements is made in order to unify the imported data. As field data is given in only discrete points, an interpolation function deals with the rest of the space between points. It is not necessary for data distribution to be uniform through space for our code, as so there can be large space with some more detailed small regions investigated.

With these new features, our software might be of great interest for investigating complicated analytically unpredictable charged particle motion at a very basic engineering purposes, as well as in the fields of gaseous electronics and laboratory, fusion and space plasmas. Finally it can be especially useful in understanding and resolving adiabatic from non-adiabatic motion for which purpose our new concept of “Larmor Center Trajectory” seems to be very promising.

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Non-Circular Cross Section Geometry Effects on Perturbed Radial Magnetic Field in Damavand Tokamak

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In this work, linear perturbation of MHD equation in flux coordinate system has been derived for non-circular cross section of tokamak plasma. The coefficients of derived equation are function of cross section geometrical parameters such as elongation, triangularity, and etc... We have solved this equation numerically for non-circular cross section of Damavand tokamak plasma and from which the perturbed radial magnetic field have been obtained.

We also have shown the effects of non-circular cross section parameters on our results and have compared the results to the results from common MHD equation in cylindrical coordinate system by consideration of circular cross section and large aspect ratio approximations.

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Simulations of Anomalous Diffusion of Particles in Experimentally Measured Turbulent Potential

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This paper presents 2D numerical simulations of particle diffusion in edge plasma of CASTOR tokamak. Particle motion in our simulations is governed by a perpendicular magnetic field and a potential experimentally measured by 2D array of 8x8 Langmuir probes. The potential was measured in an area of 4.5 x 6 mm and for a purpose of the simulation it was periodically extended in poloidal as well as in radial direction using interpolation with discrete Fourier basis. It means that the potential in both directions represents 8 lowest harmonics of a real potential.

The simulation mainly traces diffusion of ions of heavy impurities for which test particle approach that we used is valid. Running diffusion coefficient was computed for different particle species and it was evaluated for radial and poloidal direction separately.

We found that the diffusion in radial direction is Gaussian, i.e. diffusion coefficient is constant in time (~ 1,5 m^2/s for C^+ ions). Poloidal diffusion coefficient grows in time (~16,8 m^2/s after 30 μs for C^+) and the diffusion can therefore be denoted as Lévy kinetics.

It was also confirmed that magnitude of diffusion for different particle species depends on ratio of their mass and charge $R=m/q$. The diffusion coefficient in poloidal direction drops down with growing R whereas radial diffusion coefficient grows.

Obtained results where confronted with other works addressing particle diffusion in edge tokamak plasma.

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Upgrade of the Minimum Fisher Regularisation Tomography to Final Width of Viewing Chords

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Minimum Fisher Information principle proved to provide robust analyses of sparse data in plasma diagnostics. In recent past, the inversion methods based on Minimum Fisher Regularisation (MFR) were successfully validated both in spatial analyses of plasma neutron emissivities (MFR tomography) and in spectral analyses of neutrons measured by the NE213 compact spectrometer (MFR unfolding) at JET. Spatial analyses of neutron emissivity need to be further developed in preparation of the ITER operation, in order to establish the degree and origin of poloidal assymetries in the neutron emissivity of tokamaks. Moreover the MFR algorithm is a candidate for inverse analyses of data from other systems, including the planned SXR tomography on the COMPASS tokamak.

At present, the MFR tomography implements chi-square smoothing optimisation, rapid reconstruction (inverting several time frames in a single run), abelisation (assuming constant emissivity on flux surfaces) and unisotropic smoothing (providing strong smoothing along flux surfaces). On the input side, set-up of the detection system – i.e. the JET neutron profile monitor with 19 projection chords – was until recently approximated by assuming straight lines-of-sight. In this contribution a simple technique allowing for implementation of finite width of the chords is described. While the full analytic description would be numerically demanding, the proposed solution is rapid and allows for arbitrary precision. Performance of the MFR upgrade is studied in comparison to the previous straight lines-of-sight assumption both on phantom functions and on experimental data. Systematic errors due to the neglected final width of viewing chords are estimated and the impact on statistical errors is studied via Monte Carlo noise modelling. It is demonstrated that the new MFR upgrade provides an efficient tool enhancing tomography performance by implementing realistic width of the viewing chords.

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Design of New Optical System for Visible Plasma Radiation Measurements at COMPASS Tokamak

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The COMPASS tokamak, a divertor device with a clear H-mode and ITER- relevant geometry (R=0.56 m, a=0.23 x 0.38 m, I_p=200-400 kA, B_T=1.2-2.1 T and pulse length up to 1 s), is being re-installed to IPP Prague from Culham in U.K. New diagnostic tools will be built to address aims of the COMPASS scientific program focused on H-mode physics and pedestal investigations. Among spectroscopic diagnostics, an optical system for visible plasma radiation measurements will be designed and used to obtain information on hydrogen and impurity emission and its evolution during discharges.

Monitoring of integral plasma radiation in the visible range (400-800 nm) is planned for the first stage of the COMPASS operation. Complementary, this system can be used for measurement of specific spectral lines, like hydrogen or the most intensive impurity lines. Consequently, information on neutral atoms density, impurity inflow, recycling processes and rough estimation of particle confinement time can be derived. Also an MHD activity can be studied using such observations. Effective ionic charge Z_{eff} will be evaluated from the line free region slightly above 520 nm comparing to pure hydrogen plasma bremsstrahlung using known plasma density and temperature.

In the next step, a spatial resolution at centimetre scale will be introduced using collimating optics. The light emission of each spatial point will be collected by the optical fibre and led to the detector. In case of at least two independent observation points, the tomography technique of local emissivity reconstruction will be applied giving spatial distribution of plasma radiation at observed poloidal cross-section.

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Nonlinear Interaction of Localized LHW with Plasma Electrons

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Usually, interaction of lower hybrid waves with plasma electrons is described via quasilinear approximation. In our foregoing papers we have shown that in some regimes the quasilinear description can be inadequate. These nonlinear interaction regimes can appear when basic assumptions of the quasilinear description cannot be fulfilled, namely, when the interaction region is narrowly localized in space and therefore averaging the result of the interaction over the whole magnetic surface is not possible. This may occur due to the fact that area of a grill launching LHW into tokamak plasma is small compared to area of the magnetic surface and LHW propagates into the plasma in a well defined space structure, cone.

We found that in this case the interaction does not depend only on a basic resonance but there may exist a whole series of further possible resonances. Due to this fact, the velocity resonance region is broader than region of phase velocities given by range of wave numbers of injected wave spectrum. This effect was proposed as a candidate mechanism to 'bridge' spectral gap between velocity of the tail electrons and the lowest phase velocity in the spectrum during LHW heating. In our foregoing papers we estimated the difference between quasilinear and nonlinear regime numerically. Nevertheless our model did not take into account relativistic effects that appear by the interaction.

The present paper therefore brings more accurate results obtained using relativistic equations of motion, which enforce the necessary relativistic limits on velocities of accelerated electrons. The relativistic approach makes possible to compute particle velocity distribution function given by LHW-particle interaction. The effect of the nonlinear interaction was computed for different spatial profiles of the localized LHW. Integrals of motion were found for the case of monochromatic wave with rectangular envelope. It enables, for this case, very accurate evaluation of the effects under investigation. Properties of the other profiles were evaluated using numerical integration.

Moreover we extended our model to take into account collisions with thermal electrons resulting in the more appropriate particle velocity distribution function. Incorporating collisions helps us examine relevance of the collisionless limit previously used.

We discuss the acceleration of electrons also in the region just in front of the grill in a vacuum. We use the method of direct integration of equations of motion for particles in the grill region. The results are compared with literature.

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Transport Simulations for the COMPASS Tokamak with NBI and LH Heating and Current Drive Systems

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The re-installation of the COMPASS tokamak in Prague will have as additional heating and current drive systems the original lower hybrid (LH) system and a new neutral beam injection (NBI) system, which was not originally included in the installation at Culham. With the novel NBI system, predictive simulations for the tokamak heat confinement performance are highly desirable. Plasma heat transport modeling was performed using the ASTRA transport code. The LH power deposition and current density profiles were calculated using the ACCOME and the LUKE suite of ray-tracing and Fokker-Planck solvers. The NB power deposition and current density profiles were calculated using the ASTRA, ACCOME, and FAFNER codes. We concentrate here mainly on understanding the effect of NB injection and its synergy with LH heating and current drive (CD) via NB-driven electron heating. One of the principal features of NB operation in the COMPASS configuration is relatively large ion orbit losses. At typical operating conditions - peak electron density 3×10^{17} m^{-3}, the charge exchange losses are likewise quite high - about 15%. For NB counter-injection the ion orbit plus charge exchange losses make up to 53% of injected power loss. For NB co-injection these losses are lower, between 10-25%. The NB co-injection is therefore the preferred mode of operation. Up to 10% of the injected NB power is deposited on the electrons, facilitating the electron Landau damping of the injected LH slow waves. The ACCOME and ASTRA simulations are performed for few basic COMPASS operation scenarios: at low- and high-triangularity and at $B = 1.2$ T, $I = 170$ kA, and $B = 2.1$ T, $I = 250$ kA. At the higher magnetic field and current operation conditions, the total non-inductively driven current (bootstrap+LH+NB) is about 200 kA, substantially supporting the 250 kA feedback-controlled plasma current.

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Test of Potential Interturn Faults of COMPASS-D Toroidal Field Coils

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Toroidal field (TF) coils are one of the most electrically and mechanically loaded parts of the tokamak devices. During a long term operation different kinds of faults can be developed. This contribution describes search for potential interturn faults of TF coils of tokamak COMPASS-D. Especially, it brings a comparison of these coils before and after transport of the device from Culham Laboratory, UKAEA to IPP Prague.

Tokamak COMPASS has been completed in 1988 and operated in Culham several years with circular and since 1991 with D-shaped vacuum vessel. Since 2001, as a result of start of tokamak MAST (Mega Amper Spherical Tokamak), the COMPASS has been not more active. Because not all envisaged studies were fulfilled on the COMPASS, it was decided in 2006 to transport this device to IPP Prague, where the studies would continue. During assessment of this possibility by an international group of experts a necessity to check carefully the insulation between turns inside every COMPASS TF coil has been pointed out. This requirement emerged from an event on tokamak JET, where after six years of operation the interturn faults were found in 1989. The faults lead eventually to unavoidable change of 3 from total 32 pieces of the JET TF coils. In the case of COMPASS, the confining toroidal magnetic field is generated by 16 TF coils. Every TF coil, having resistance about 130μΩ (and inductance L about 26μH), consists of 4 flat mutually insulated Cu turns. And just insulation between every adjacent Cu turns should be regularly checked.

It is hardly possible to find any degradation of the TF coils interturn insulation by a direct measurement of the every coil resistance. Even a decrease of the insulation, let's say to 100Ω (i.e. to the value many orders greater comparing the turns mutual resistance), represents already dangerous and therefore not allowed value. Contrary to a comparative method of several fixed frequencies used in the case of JET, another sensitive method of interturn faults, based on a resonant LC circuit (here L is inductance of the tested coil), will be described in this contribution. Using a changeable probing frequency, the resonant frequency and impedance of this LC circuit tuned to the resonance is measured. The method has been first tested on a power mockup coil (diameter 0.35m, length 0.73m, 70 turs in total, resistance 100mΩ and inductance 700μH), separated into 4 equal sections (simulating 4 turns). During the test one of these sections has been loaded by gradually decreasing resistance up to zero value (short-circuiting, i.e. excluding of this section from the coil). The circuit has been also numerically modeled. The tests have shown that while for a measurable increase of the circuit resonant frequency the ratio of simulated "interturn fault" to the turn resistance must drop from infinity to the value about 10^4-10^3, a drop of this ratio to the value 10^5 is already sufficient if we detect the circuit impedance (i.e. a measurable decrease of the voltage on the circuit can be observed). These conclusions have been found in a full concordance with the numerical modeling of the scheme used.

The method has been eventually used for the test of COMPASS TF coils before and after the transport to IPP Prague (using an identical measuring scheme). The coils exhibit no serious departure each other after the transport, contrary to the measurement in Culham, where resonant frequency of the coil No 9 has been demonstrably (repeatable) increased. These results will be shown and discussed in the contribution too.

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Plasma Instabilities in Magnetic Field

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The work deals with a generalization of the classical two-stream plasma instability on the case with a nonzero magnetic field and thermal processes where the unbounded plasma is assumed. We are interested in a dispersion relation.

For solving the two-stream instability in the magnetic field we use a two-fluid model. In this model we assume that a solution can be expanded into a perturbation series. Next, the equations of the two-fluid model are linearized, and then is applied Fourier transformation. We get a system of linear algebraic equations. From the condition for the nontrivial solution is found the dispersion relation.

The results can be used particularly in astrophysics (e.g. jets from stars and galactic nuclei) where the assumption of the unbounded plasma is acceptable. Note that the magnetic field plays an important role in astrophysical applications. We would also like to apply the results to z-pinch phenomena. However, the condition of the unbounded of the plasma is contentious in the z-pinch. Therefore we have to be very careful in using these results on the z-pinch phenomena.

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Determination of Mass- and Energy-Spectra of Ions on the Basis of Thomson Parabolas Recorded in Plasma Experiments

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The paper concerns measurements of mass– and energy–distributions of various ions, which are emitted from plasma discharges performed under different experimental conditions. The most convenient method to determine such distributions is based on the application of a Thomson–type analyzer. Such analyzers have been used in many plasma experiments, including those which produce intense plasma-ion streams, as Plasma-Focus (PF) facilities and Rod Plasma Injectors (RPI). Depending on gas conditions and parameters of the produced plasma streams, an input diaphragm should have an appropriate shape (forming a so–called skimmer system), which must enable the investigated ions to be separated from plasma streams without considerable changes of ion velocity (energy) distributions. An amount of the investigated ions, which might penetrate the input system, as well as intensities of the recorded Thomson parabolas depend on a diameter of the input diaphragm, but this opening determines also a gas inflow. If a plasma experiment is carried out at a relatively high pressure, e.g. several hPa (as it often occurs in PF–type facilities), in order to eliminate electrical breakdowns between the analyzing electrodes, the Thomson analyzer should be equipped with an additional pumping system, which must evacuate the analyzer volume effectively. On the other hand, a diameter of the analyzed ion beam and sharpness of the recorded Thomson parabolas depend also on the input diaphragms. Hence, the dimensions of the input diaphragms and the pumping efficiency determine accuracy of the determination of the mass– and energy–spectra.

The main aim of this paper was to discuss all factors influencing this accuracy and to present examples of the ion analysis in different plasma experiments. The paper considers the basic principles of measurements performed by means of Thomson analyzers and it presents important formulas determining the accuracy of the ion analysis. Some examples of Thomson parabolas, which were recorded by the authors in different plasma experiments, are presented and analyzed. The presented results are of importance for any experiment to be carried out with the use of a Thomson–type analyzer and/or ion pinhole cameras.

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The Characterization of the Ion Beam from a Sn-based DPP with Respect to the Ignition Parameters

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Extreme-UV (EUV) radiation produced by a Sn-based discharge-produced-plasma (DPP) makes this type of plasma a potential candidate for the EUV source of the next generation lithography exposure tools. The DPP not only generates the desired 13.5 nm radiation, but also produces debris that damages the collector optic in the lithographic system.

This research reported on in this paper focuses on the characterization of the fast ionic debris produced by DPP. The ion beam emitted from the DPP is analyzed using different time-of-flight techniques while the discharge was monitored by a current probe and gated MCP imaging. By varying the ignition parameters the maximum kinetic energy of the emitted fast ions could be reduced with a factor of 10.

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Progress in a Single-pulse Nanosecond Interrogation Technique for Detection of Hidden Illicit Materials (e.g. Explosives)

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Recent progress in a single-pulse technique of interrogation of hidden objects is presented. The method uses very bright neutron pulse having a duration of the order 10 ns, which is generated by Dense Plasma Focus (DPF) devices PF-10 (Institute of Theoretical and Experimental Physics, RF) or PF-6 (Institute of Plasma Physics and Laser Microfusion, Poland). This powerful and short neutron pulse is irradiated by the PF source in the form of a shell propagating into a space almost spherically and having a thickness of about 20 cm. Such a small size occupied by the neutron flash, its intensity and mono-chromaticity ensure an opportunity to use a time-of-flight (TOF) technique with flying bases of about a few meters. During previous research we used a DPF chamber counted on the DPF bank energy of about 7 kJ and generating neutron yield on the level of 10^9 neutrons per pulse with pulse duration of 15 ns. TOF base in those tests was 18.5 meters. In the experiments presented in this paper we have experienced an opportunity to use much lower bank energy (~2-3 kJ), smaller DPF chamber, decreased neutron yield (~10^8 n/shot), and TOF base as well (7 meters). In this case it appeared that the neutron pulse duration became 7-8 ns and the above-mentioned new TOF base is long enough to distinguish different elements composing the substance (H_3PO_4) under interrogation by means of measuring of the elastically scattered neutrons. The wavelet technique was engaged to “clean” the experimental data.

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Monte Carlo Method for Neutron Spectrum Recovery - a New Approach Based on the Accelerated Ions Distribution

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Plasma-Focus devices are known to be very efficient, pulsed sources of neutrons. At present the biggest device of such type is the PF-1000 operating at the Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland. For future application of the device as a neuron source knowledge on energetic spectrum of the neutron bursts is of primary importance. An experimental basis for this kind of investigations has been already prepared. Nine scintillator -photomultiplier probes, suitable for registration of the time-of-flight signals have been already built, calibrated and tested during experimental sessions performed on the device. To recover a neutron spectrum from signals registered by the above mentioned systems a development of a special computer code is necessary. Such codes, used up to now, were capable to perform de-convolution of signals giving spectrum (E, t) of neutrons emitted in one direction while it is well known that the spectrum depends on angle of registration. New method of neutron spectrum recovery described in the paper involves accelerated deuterons (that produce neutrons in DD reaction) and allows getting neutron spectrum in any direction

from computed time-velocity (t, $\boldsymbol{V}$) characteristics of deuterons. Time of flight signals registered in various distances and directions are used, that makes information involved in the recovery process (Monte-Carlo simulation) more complete than in a one-directional case. In the paper recent results of several standard tests of the proposed method are presented demonstrating its capability to recover neutron spectrum from time-of-flight signals.

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Nuclear Reaction Caused by the Neutrons Emitted From the d-d Reaction Occurred by the Repetitive Plasma Focus Device PF-6

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The paper describes investigations of nuclear reactions produced by small plasma focus device PF-6 operating in the Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland. Main part of investigation has been conducted by spectrometric system based upon pre-calibrated HPGe detector and software for the geometry compose as well as the setup of specially selected ensemble of activation detectors. For the activation purpose have been chosen elements as follow: In, Cd, Hf, Au, Y, Se. Dozens of nuclear reaction caused by neutrons from d,d reaction occurring inside the PF-6 device and after that activating the above metals were identified. Those reactions were classified based upon gamma lines library established especially for the above methodology. Finally, experimental measurements shows that nuclear reaction inducted by plasma focus devices can be useful for quantitative and qualitative analyze of neutron spectrum.

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Deuterium Gas-Puff Z-Pinch on S-300 Pulsed Power Generator

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The primary objective of our experiments at the S-300 generator is to get deeper insight into the process of generating fast ions in Z-pinch plasmas. For that purpose we measured the production of fusion neutrons during the implosion of a deuterium gas-puff Z-pinch. These experiments were performed on the S-300 Z-pinch generator (Kurchatov Institute in Moscow) at a peak current of about 2 MA with a rise time of 100 ns.

In order to observe Z-pinch dynamics, various diagnostics were used: e.g. an optical streak camera, an optical frame camera and a differentially filtered X-ray pinhole camera. High-voltage and dI/dt probes provided information about electrical characteristics and the power input into the discharge. The neutron emission was measured with an indium activation counter (for neutron yield measurements) and 12 scintillators-photomultipliers (for time of flight analysis). The reconstruction of neutron energy distribution function was used to obtain information about acceleration of fast deuterons.

The fusion neutrons were generated at about 150 ns after the current onset, i.e. during the stagnation and at the beginning of the expansion of a plasma column.. The emission lasted on average 25 ns. The peak neutron yield approached 10^{10} on the current level of 2 MA. The side-on neutron energy spectra peaked at 2.44±0.05 MeV with about 400 keV FWHM. In the downstream direction, the peak neutron energy and the width of a neutron spectrum were 2.52±0.08 MeV and 300 keV, respectively. The average kinetic energy of fast deuterons which produced fusion neutrons was about 100 keV.

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Spatial-Time Characteristics of Z-pinch from Deuterated Polyethylene

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On the S-300 installation at currents up to 2MA with the rise time of 100 nanoseconds, the investigation of the formation process of high-temperature plasma in fast Z-pinch was carried out. The central part of the loads was made from agar-agar and represented a deuterated polyethylene cylinder with small density of 50 and 75 mgr/sm^3 and 1-2 mm diameter. On the ICT images, obtained in optical and soft x-ray range of a spectrum with 3-5 nanoseconds exposition a cord is formed on the axis of the polyethylene cylinder at the current rise time and it is separated into bright formations. They were observed on a background of a luminous area which occupied the initial neck volume. In the time-integrated pinhole pictures obtained in SXR range (E > 1-4 keV), hot points with minimal size of 50 microns were registered. From the chronograms results, obtained by means of the optical high –speed-streak camera mount along the neck axis with time resolution < 1ns, it follows that luminous formations arise sequentially during the different time moments (in 10-30 ns). Occurrence of luminous formations was accompanied by x-ray radiation occurrence with energy E > 1 keV with short duration of 2-4 nanoseconds. Simultaneously with x-ray radiation, neutrons with the maximal yield of 4.5×10^9 were registered. The average energy measured in 4 directions under angles with an axis of: 0^0 (above the anode), 90^0, 180^0 (under the cathode) and 270^0, were accordingly: 2.4±0.2, 2.5±0.1, 2.5±0.1, 2.5±0.1 MeV.

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High Reprate Vacuum Spark with Two Liquid Metal Jet Electrodes as VUV Source

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New type of vacuum spark with two liquid metallic alloy jets serving as electrodes was proposed as powerful source of VUV and specifically EUV radiation. Vacuum spark was ignited using laser ablation of one of jets (cathode). Ga:Sn eutectic alloy which is liquid at room temperature is circulating in a closed loop and creates fast moving jets.

Two jet electrode system was tested at up to 4 kHz reprate with discharge energy as 1 - 4 J. Burst of EUV radiation (10 – 20 nm) was observed at a moment of pinch convergence on the axis and development of neck-type instability (micropinch).

High velocity of the jets (~30m/s) is able to provide a renewed electrode surface for every next short for reprate frequency up to 30-50 kHz which allows to solve a problem of electrode erosion. High heat capacity of liquid metal flow provides effective heat transportation from discharge zone. It is expected that the proposed scheme is able to dissipate up to 200 kW of electrical power.

* * *

Tearing Instability in Nonzero Rezistivity Gradient

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Thermonuclear fusion seems to be one of the most promising energy sources of the future. In all the attempts, tokamak, z-pinch, inertial fusion and others, the main problem consists in various plasma instabilities. Their number is enormous, from MHD instabilities to resistive and micro-instabilities. Some of these instabilities are harmful for the success of the fusion process; others are in some cases helpful, e.g. thermalization process during the two-stream instability.

One of the most interesting instabilities is the tearing instability linked with the reconnection of the magnetic field lines. This type of instability belongs to the resistive ones. It is supposed, that in tokamaks this instability is responsible for the saw-tooth oscillations and the Mirnov oscillations. In plasma devices this instability evolves in regions with finite resistivity near the so called resonance surface $\mathbf{k}\cdot\mathbf{B}_0 = 0$ (in tokamaks it concerns so called *mn* surfaces). On different sides of this resonant surface the magnetic field has opposite direction.

Some aspects of this instability were intensively studied by various research groups. The plasma behavior depends on a great number of parameters and conditions. The driven forms of this instability ought to be of the special interest. One of the additional "forces" can originate in the presence of the resistivity gradient.

The driving force is calculated for resistivity, which is dependent on the distance from the resonant surface. The set of ordinary differential equations for the displacement vector and the induced magnetic field had been put together and solved by standard Runge-Kutta methods. Program code was written in FORTRAN 95. FORTRAN compiler and linker were used from Compaq Visual Fortran 6.1C embedded in the Microsoft Development studio GUI.

All the components of the perturbed magnetic fields are calculated and discussed. The results are presented in comprehensible charts. The influence of the resistivity on the instability onset, the stabilization effect of the non-zero resistivity gradient, the influence of the former field course and the other related phenomena are discussed in the paper.

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Dependance of the Energy Distribution of the Fusion Neutrons and Fast Deuterons on the Neutron Yield in PF Discharge

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The plasma focus PF-1000 device in IPPLM Warsaw with the maximal current 2 MA is convenient for the study of fusion deuterium-deuterium reaction with the total neutron yield $10^{10} – 10^{11}$ per one shot. For investigation of the plasma parameters the set-up of x-ray and neutron diagnostics is used. 9 scintillation detectors in axial direction and one in side-on direction were used for determination of energy distribution of neutrons.

The neutron signals were filtered via wavelet transform, using of discrete wavelet transformation, the Mallat multiresolution algorithm and discrete Meyer wavelet function. For modification of the detail coefficients the multiple with the hard threshold function is used. The neutron energy distribution was calculated using modified time-of-flight methods. From the energy distribution of neutrons the energy distribution of the fast deuterons producing neutrons was calculated.

In this contribution 7 shots were processed. Energy distribution of neutrons in axial and side-on directions was compared for shots with different neutron yield. We determined dependence of the neutron energy maximum and dependence of the ratio of the downstream and upstream deuterons on the neutron yield. We also estimated the energy distribution of the absolute value of fast deuterons producing neutrons on the neutron yield.

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Comparison of Spectra of Accelerated Ions Produced by LPP and DPP

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Discharge-produced and laser produced plasmas (DPP and LPP) are often used as a source of short-wave radiation. However both plasmas also emit strong fluxes of ions which are able to damage source optics. This circumstance makes important quantitative characterizations of ion fluxes from both plasmas together with understanding of mechanisms of ion production and acceleration. Comparison of ion fluxes was made for plasmas with similar or close electron temperature and ionic charge distribution.

Discharge of z-pinch type (vacuum spark) with a stored electrical energy 1 – 5 J between axially symmetric electrodes was initiated by laser (YAG:Nd 1.06 μm) ablation of tin cathode.

Pulsed CO_2 (10.6 μm) laser was used to produce LPP by focusing laser radiation on plane tin target. Measurements of energy and spatial distribution of ionic fluxes were carried out with the help of Faraday cup. Energy distribution functions were measured at different angles against discharge's axis and at different angles against the direction of CO_2 laser beam.

Investigations have shown sufficient difference in ionic spectra between considered cases of DPP and LPP. Presence of fast ions with energies of about several tens keV distinguishes DPP from LPP where largest energies are limited to 10keV. In both cases there are preferable directions of ionic fluxes.

Also we discuss mechanisms of ions' acceleration.

* * *

Plasma-Focus Sheath Dynamics, Pinch Formation as well as Neutron Generation from the Point of View of the MHD Similarity Laws

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Scaling law for the plasma sheath dynamics, shape and plasma parameters are derived from similarity considerations of the MHD model. It is shown that for properly working PF device some of the plasma parameters like density and temperature are independent of the size of the device (energy in the condenser bank), while others, like: dimensions (radius, length) scales as the total current.

Consequences of such scaling for thermal neutron yield are derived showing that it depends only on the current to the fourth power, while previous considerations (involving Bennet equilibrium) lead to a formula containing few other parameters with unknown scaling. Scaling of the PF electrodes dimensions are presented as well, demonstrating that the electrodes geometry, for high energy devices, will be closer to the Filipow's rather than Mather's one.

Some consequences of the derived scaling law for neutron generation via beam-target mechanism are also demonstrated.

Observations of Extreme Ultraviolet Emission from Plasma Produced by Capillary Discharges

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This paper reports our results of the recent experimental studies concerning extreme-ultra-violet (EUV) measurements which were carried out during gas discharges in capillary. The main aim of these EUV spectra studies was to provide information about the radiative processes in the plasma. We studied plasma inside the gas filled capillary channel as an active media generating extreme ultraviolet radiation mainly in 10–50 nm regions.

Discharge setup consists of brass anode, brass cathode and alumina capillary of 2 mm inner diameter and 8 mm length. The capillary was evacuated below 10^{-5} mbar using a turbo-molecular pump and then the working gas was introduced continuously inside the capillary under the controlled pressure. Processes were conducted under different experimental conditions such as various kind of filing gas (pure Xe mainly, sometimes admixture of Xe with Ar, or air), different gas pressure (25–140 Pa) and discharge voltage (3–10 kV).

Spectroscopic studies were carried out by means of EUV spectrometer which was upgraded for special lithography purposes. Rectangular grating of 4200 grooves/mm, designed for measurements in range from 10 to 50 nm, and X-ray film were placed on a cylindrical surface on the Rowland circle. Zirconium or aluminium filters were used to protect the film from visible light, the material of filter depended on the radiation range to be registered.

The recorded EUV spectra demonstrated different lines corresponding to highly-ionized species, in particular to xenon lines, originating from the working gas, as well as brass lines, originating from the material released from the electrodes.

In order to study the time evolution of different broad bands and line emission of plasma we have tried to catch the spectrum at different time by giving selected time delays gating pulse to the Multichannel Plate (MCP) detector. These measurements will provide important information about EUV radiation processes. Examinations of the plasma with the MCP detector have been carried out currently.

Results of our investigations deliver information on properties of plasma generated in capillary discharges and could be of particular interest for EUV lithography.

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Development of Diagnostic Equipment for Large PF-1000 Experiment

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The PF-1000 installation is the largest plasma focus device operating with deuterium at this moment in the world. It is used in fundamental magnetized plasma experiments. Using the extensive diagnostics capabilities of the facility the main objectives of the recent experiments were as follows:

- To determine the neutron emission characteristics of the PF-1000 facility within the whole operational range.
- To determine the detailed characteristics of the fusion-produced neutron pulses (their temporal evolution, emission anisotropy, spectral properties, and relative contribution of different mechanisms to the total neutron yield).
- To investigate the relation between the neutron yield and plasma sheath dynamics, with particular attention paid to structures occurring within the pinch column and to their relationship with the neutron yield.
- To find correlation between neutron generation and other types of ionizing radiation produced at the DPF discharge (fast electrons and ions, soft and hard X-rays etc.).

To win the objectives different kinds of diagnostics systems are developed.

The absolute neutron yield was measured by means of several silver-activation counters and bubble detectors. Both the Ag-counters and the bubble detectors were placed around the PF-1000 experimental chamber, at different distances and under various angles with respect to the electrode axis.

Time-resolved X-ray signals were measured by means of PIN diodes covered with different filters, and they were compared with other signals (voltage waveforms, *dI/dt* signals, and neutron-induced pulses) in order to determine their correlations.

In order to investigate the role of the structure and dynamics of current sheet and plasma column in the neutron generation, and to define the role of plasma density evolution in the neutron yield, the 16^{th} frame Mach-Zehnder interferometer is under construction on the PF-1000 device. Project and studies of the interferometer are presented in this paper.

The above diagnostic systems will be applied to determine operational regimes of the PF-1000 facility, in which the maximum neutron emission occurs, and to define characteristic features of the last phase of plasma evolution.

* * *

Characterization of Dense Xe and He-Xe Plasma Streams Generated by Magnetoplasma Compressor

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Dense plasma streams of heavy noble gases are widely used in different technological applications: EUV lithography, plasma thrusters, surface processing etc. This paper presents the investigations of plasma streams generated by magnetoplasma compressor (MPC) of compact geometry with conical-shaped electrodes. The stored energy in the discharge is 28 kJ for applied voltage of 25 kV.

The experiments were performed in two operation modes of the plasma source: pulsed gas supply of Xe directly to the discharge area, which provides generation of pure Xe plasma stream and pulsed injection of Xe to the plasma focus region during the MPC operation with He.

Spectroscopy measurements of plasma density and electron temperature in compression region of MPC have been performed on the base of Stark broadening of spectral lines and intensities ratio in visible wave-range. The influence of self absorption of XeII and XeIII spectral lines on results of plasma density measurements was analyzed. Radial distributions of the plasma density were estimated using Abel inversion procedure. It was found that maximum value of plasma density in compression region achieved 10^{18} cm^{-3}.

Dynamics of the discharge and time behavior of plasma focus were analyzed for both Xe and He-Xe plasma streams as well as for varied discharge voltage and time delays between the discharge and gas supply pulses. AXUV photodiodes with different filters have been applied for the measurements of Xe plasma radiation in the wave ranges of 5-11 nm, 12.2 – 15.8 nm, and 17-80 nm. It is shown that the total radiated energy and peak power strongly depend on operational regime, and in particular, considerably depend on time delay between the gas supply start and the discharge ignition. The regimes which characterized by maximal intensity of EUV radiation from the focus region were chosen. It is shown that the maximum radiation corresponds to the spectral range of 12.2-15.8 nm. First measurements of radiation spectrum with EUV spectrometer are presented also. The spectrometer was calibrated in visible, UV and EUV regions. The obtained results are compared with AXUV measurements.

Plasma source efficiency was analyzed from electrotechnical discharge characteristics, namely discharge current, total resistance and inductance in the case of pure xenon discharge and the mixtures of xenon and helium in different proportions.

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Capillary Discharge EUV Radiation Focused by the Ellipsoidal X-Ray Optic

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The paper describes an experiment in which extreme ultraviolet (EUV) radiation from a capillary discharge was focused by the ellipsoidal mirror. The system was modified for the second period of measuring to improve better optics positioning device, better protection from the unwanted radiation, better statistics of the measurements, and to achieve better measurement repeatability. The capillary discharge source was designed and built at the Czech Technical University. Focused high intensity EUV radiation will be used in studies directed towards EUV scientific and industrial applications (e.g. biocompatibility of materials modified by EUV radiation, EUV lithography, EUV lasers etc.). The experiment demonstrated significant gain of radiation intensity in 200μm focus. EUV/Soft X-Ray radiation generated by capillary discharge was detected by the X-ray CCD camera. Theoretical model and comparison with experimental results are presented.

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Current Sheath Studies in Plasma Focus PF-400 by Magnetic Field Probes

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In the report the preliminary results of the time resolved studies of current sheath formation in plasma focus discharge are presented. The experiments were done on Filippov type Plasma Focus with energy stored in capacitors 60 kJ and maximum current 0.9 MA (The installation "Tyulpan" – PF-400). For plasma diagnostics two magnetic probes placed at radii 15 cm and 20 cm were used. Also in the experiments Rogovsky belt was used for total current measurements.

It was found that in the discharges with low neutron yield ($< 10^8$ n/pulse) the several repetitive current sheathes during 1-st, 2-nd and even 3-th half-period of discharge are formed. As it was shown in the Plasma Physics Reports, (V. Ya. Nikulin, S. N. Polukhin, and A.A. Tikhomirov Vol. 31, No. 7, 2005, pp. 591–595) such phenomenon can be explained by low efficiency of snowploughing of the working gas by current sheath. The formation of single current sheath was observed in the discharges with high neutron emission ($>10^9$ n/pulse).

The absolute current measurements show that during radial implosion of current sheath the whole discharge current goes throw paraxial area r < 15 cm. At the same time the current at the peculiarity instant does not exceed half of this value. The value of the current through the pinch is under the question. Apparently, the significant part of the total current is shunted by the secondary plasma sheathes. This value depends on the transparency of the first current sheath.

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Reconstruction of the Time-Resolved Neutron Energy Spectra in D-D Z-Pinch Experiments

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This work describes the neutron diagnostics of hot dense z-pinch plasma where the neutrons are produced (for example deuterium gas in z-pinch discharges). The time-resolved neutron energy spectrum with the height energy resolution (with only a few dozens keV) can be reconstructed by this diagnostic method. Further, other plasma parameters such as temperature of the reacting ions can be determined from the neutron energy spectrum.

The reconstruction method that is used in this work is based on time-of-flight (TOF) method where the energies of particles are determined from its velocities. We apply the extended TOF method where several time-resolved neutron detectors are placed at the different distances from the neutron source. This reconstruction method can be improvement if we include the detectors from the opposite direction. If we want to employ both directions of neutron detection, we must know the relation between the neutrons which are emitted in one direction and in the opposite direction. The relation consists of (i) the anisotropy in neutron energies and (ii) the anisotropy in neutron yields. This relation was calculated on the basis of the kinematics of the binary fusion system for D-D reaction.

There are several theoretical approaches for the development of algorithms for reconstruction of time-resolved energy spectra using extended TOF method. We have used Analog Monte Carlo Reconstruction Technique (AMCRT). The advantages of the usage of the AMCRT with neutron signals from detectors placed on two opposite direction were demonstrated by many numerical tests. The main advantages are: (i) better reconstruction of neutron energy spectra and (ii) smaller influence of scattered neutrons. We apply this reconstruction primary to data processing from PF 1000 experiments (Institute of Plasma Physics and Laser Microfusion, Warsaw) and secondary with small modification to data processing from S-300 experiments (Kurchatov Institute, Moscow).

This contribution presents (i) the description of the reconstruction technique including the improvement which simultaneously uses neutron detectors placed on two directions, (ii) the numerical tests with scattered neutrons, and (iii) the application of this technique to data processing from D-D z-pinch experiments.

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Generation of Short-Soft X-Ray Pulses

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Nowadays X-ray sources ranging in the soft region can be produced by laser-produced plasma utilising metal targets. It is known that laser induced plasma is a very efficient generator of soft X-ray of energy range for applications in lithograph, sequencing of DNA and living cell studies. The plasma was generated by a pulsed KrF excimer operating at 248 nm, 23 ns. The laser beam was focused by a convergent lens of 15 cm focal length reaching a spot diameter of about 1 mm. The emitted X-ray energy was studied at 40, 80 and 120 mJ laser energy. The corresponding incident laser intensities on the target surface were 1.7, 3.5 and 5.2×10^{8} $\mathrm{Wcm^{-2}}$.

The metal target utilised to study the X-ray generation were made of Ta, Cu and Si. The pulsed X-ray analyses were performed by means of a very sensitive fast polarized Faraday cup (FC). At the maximum laser energy a plasma temperature of about 1 MK (87 eV) was measured. Measurements of the X-ray energy were done by means of a filter of 0.2 μm thin deposited on 1 μm C_3H_6. It was placed on the collimator in order to filter part of X-ray and to measure the transmittivity values. Comparing the X-ray percentage reduction with the attenuation coefficient of the filter we calculated the X-ray energy.

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Influence of Current Filamentation on Angular Distribution of Fusion-Produced Protons in PF-Type Experiments

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The paper concerns a role of current filaments, which can appear in high-current pulsed discharges of the Plasma-Focus (PF) and in Z-pinch type. In fact the distinct current filaments were observed in different PF experiments, and in particular they were recorded in a current-sheath layer during its axial motion as well as the final radial-collapse. Images of the current filaments were obtained by means of high-speed cameras operated in the visible radiation, and the first observations of the distinct current filaments in the PF pinch column were performed with an X-ray pinhole camera many years ago. Some researchers neglected a role played by such current filaments, particularly in the fusion-neutron production, but a deeper analysis of these phenomena showed that such opinion is not well grounded. Strong local magnetic fields, which surround individual current filaments, can influence motions of charged particles, e.g. primary deuterons (responsible for the fusion reactions) as well as charged products of those reactions (particularly fast protons).

The computational modeling of different filamentary structures of PF pinch columns was initiated several years ago, but that theoretical analysis concerned mainly the accelerated primary deuterons. The main aim of this paper was the modeling of motions of fusion-produced protons of energy close to 3.05 MeV, which have recently been measured in several PF experiments. Assuming different numbers and dimensions of the current filaments inside the considered PF pinch column, there were computed the corresponding magnetic fields, and subsequently trajectories of the fast protons. The computations were carried out under the assumption that the 3.05-MeV protons are emitted from local sources in the all the radial directions.

The most important result of the described analysis was the confirmation of the hypothesis that the influence of the current filaments on the angular distribution of the fusion-protons might be very strong, particularly when the discharge current is high enough, and the number of such filaments is not too high. It was found that if the total discharge current in the pinch column is above 350 kA almost all fusion protons rotate in the proximity of the pinch column and they cannot be detected at larger radial distances, except for those which are scattered by collisions. It was also demonstrated that if there are formed only several filaments the azimuthal distribution of the fusion protons shows some periodical structure. If the number of the current filaments is larger the azimuthal distribution of the fusion protons becomes more diffused. The presented analysis is of importance not only for the interpretation of experimental results, but also for the understanding of the internal structure of high-current pinch columns.

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Soft X-ray Spectroscopy of Pinching Discharge in Capillaries of Various Material

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The high voltage pinching discharge in the capillary filled by nitrogen gas is a prospective medium for soft X-ray laser pumping. We present spectroscopic measurements done at FNSPE CTU Prague that investigate the influence of the material of the capillary on the properties of the plasma. The ablation of the material from the wall contaminates the plasma created in the filled gas altering the dynamics of the plasma and its spectral emission. The materials of the capillaries used in the experiment are alumina, sapphire and boron nitride ceramics. The capillaries are filled by nitrogen and argon at various pressures. The time integrated spectra of range 2-30 nm are presented and compared with computer simulation. A possibility to achieve soft X-ray lasing at boron ions is discussed.

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Monte Carlo Simulations of Scattering and Detection of Pulsed Neutrons from a Plasma-focus Source for Detection of Hidden Illicit Materials

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A new-generation plasma-focus device is proposed to be used in a new inspection system for detection of hidden explosives and other illicit materials. Fast neutrons are produced in the D-D reaction (2.45 MeV) and are emitted during very short (~ 10 ns) and intense pulses (up to 10^9 neutrons per pulse). The neutrons scattered by the investigated object are detected. Nuclide-specific information is present in the scattered neutron field and a deconvolution of these registered energy spectra allows the identification of the type of unknown material. This type system allows using the time of flight method for the spectrometric analysis of the neutrons on a short flight path (1 or 2 m).

Preliminary results of modelling the proposed system with use of the Monte Carlo method are presented. The standard MCNP code (version 5) has been used to simulate scattering of neutrons from considered objects (spheres). In the first stage, single elements characteristic for explosives (H, C, N, O) have been used as the filling material. Then mixtures of these elements like: RDX (explosive), amfetamine (drug) or melamine (everyday use materials) have been tested. The 2.45 MeV incident neutron energy (corresponding to the D-D reaction) has been used. Neutron scattering has been observed in five directions in respect to the incident beam: 30°, 45° (forward), 90°, 120°, 150° (backward). As the result of the MCNP simulations, the scattered neutron flux $\Phi/\Delta E$ (fluency) is obtained. The 1 m distance between sample and detectors has been used. The angle-energy spectra of the scattered neutrons have been obtained in the detection points. They are sufficiently different for different materials and it seems to be promising to apply the proposed method. The spectra have been re-calculated for the time of flight on the used base. Independently, they have also been obtained from the direct MCNP simulations of the time-dependent process.

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Generation of Fast Ions in Vacuum Sparks

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Vacuum spark with current of about 10 – 20 kA triggered by material ablation from a tin containing electrode (mostly cathode) by laser pulse – is a commonly recognized technical solution for a prototype EUV source for the next generation of a projection lithography. EUV, namely radiation around 13,5 nm, is excited at the moment of plasma compression with the development of micropinches - neck type instabilities of a discharge plasma column. Fast ions generated during the time of discharge can seriously damage EUV collecting optics. We present results of detailed studies of energetic spectra of ions together with measurement of ion charge distribution. Energetic spectra were measured using Faraday Cup and “time of flight” technique, the charge distribution – with the help of ion spectrometer based on cylindrical type capacitor. Ion flux characteristics are given at different discharge and laser pulse parameters.

In addition to discussing the studies of the energetic spectra of ions, methods of mitigation of ion production are discussed.

* * *

Influence Effect of "Shielding" on the Formation of Multiply Charged Ions Spectra of Be, Al, Co Laser Plasma

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Results of study influence effect "shielding" on the formation ionization composition of Be, Al, Co laser plasma are given in the present work. In our experiments, we used neodymium laser with power density of laser radiation $q = 10^7 \div 10^{12}$ W/cm^2, and angle of incidence on surface ~ 18^0, and also laser mass spectrometer which is described in journals (Prib. Tekh. Eksp., 1996, № 6, p. 139, and Fizika Plazmy, 2002, vol. 28, № 12, pp.1110-1114). As targets, we used Be, Al, Co pellets 10 mm in diameter and 3 mm thick.

Analysis of the obtained mass-charge, and energy spectra of multiply charged ions depending on power density of laser radiation at angle $\alpha = 18^0$, and element composition of targets have allowed to install the role of effect "shielding" on formation of spectra, and escape multiply charged laser plasma ions, which are concluded in typical change: threshold of formation ions (plasmas); formation of mass-charge, and energy spectra multiply charged ions; nonlinear dependency ionization composition of the plasma from power density laser radiation, and others.

It was found experimentally that, with increase target atomic mass increase threshold power of the appearance ions, nonlinearly ionization composition of plasma, and intensity ions, and increase energy spectra multiply charged ions. Effect "shielding" in laser plasma reveals itself with $q \geq 10^8 \div 10^9$ W/cm^2 depending on element composition of targets. We note that, in targets Be, Al by laser ray is completely ionized and formed multiply charged ions, and nucleus Be^{+4}, Al^{+13}. High degree to ionizing in plasma is reached in target Co (Co^{+18}). We note that, picture of formation, and escape flow multiply charged ions with Z_{max} and nucleus depending on element composition of targets corresponds to different maximum values power density (q) of laser. At effect "shielding" increase charge number of plasma ions observing with increase q laser for all investigation targets has a nonlinear dependency in different degree that particularly reveals itself as from $q \geq 10^{11}$ W/cm^2. With increase charges number of ions width of the energy spectra is decrease, and maximums of the distribution move aside greater energy, but at intensity their decreases. Also got results of the study are discussed.

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Al_2O_3 Plasma Production during Pulsed Laser Deposition

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A Nd:Yag laser operating in second harmonic (532 nm), 3 ns pulse duration, 150 mJ pulse energy, and 10 Hz repetition rate, is employed to irradiate Al_2O_3 target placed in high vacuum. The produced plasma is investigated by an ion collector used in time-of-flight configuration and by a mass quadrupole spectrometer, in order to determine the equivalent plasma temperature and the atomic and molecular composition.

Pulsed laser deposition technique has been used to produce thin films on different substrates placed close to the target. Different surface analyses, such as XPS, SEM, EDX and surface profilometry, are employed to characterize the produced films. Measurements of ablation yield, plasma density, surface growth rate, stoichiometric composition and grain distribution are presented and discussed.

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Langmuir Probe Characterization of Laser-Generated Plasmas

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The interaction between the 9 ns Nd:YAG laser and metallic bulk targets (Ta, Ag, Fe, Ti) produces non-equilibrium plasmas expanding in vacuum at supersonic velocities. The plasma plume is emitted mainly along the normal to the irradiated target surface and the plasma temperature and density are strongly dependent on the expansion time and distance from the target surface. Plasma characterization measurements were performed “in situ” with a millimetric Langmuir Probe. The probe tip current vs. the polarization voltage is measured as a function of the expansion time. 3D plots of the probe I-V curve with respect to the time are reconstructed in order to describe the plasma plume dynamics. Investigations on the plume structure, electron density, electron temperature and ion saturation currents are reported.

Obtained results indicate that high temperature and density gradients are present and that strong ion accelerations occur. The temperatures and densities measured by means of the Langmuir probe have been compared with those obtained by other analysis techniques such as those referred to ion and photon energy distributions and to fast CCD camera imaging.

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Femtosecond Laser-Target Interaction Experiments at FNSPE CTU

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Laboratory of femtosecond Ti:Sapphire laser has been opened at the Department of physical Electronics of FNSPE CTU. Laser delivers 70 fs pulse of energy up to 12 mJ with repetition rate 10 Hz. Laser is focused into cylindrical vacuum chamber of diameter 50 cm and height 40 cm. In the preliminary experiments ablation of various materials by femtosecond pulses in air and in vacuum has been tested. In particular, quality of PMMA surface exposed by single femtosecond laser pulses was studied for comparison with the impact of short wavelength SASE FEL laser pulses of similar duration. XUV emission from nitrogen gas cell has been also measured.

We report here measurement of XUV emission form bulk brass targets irradiated by femtosecond laser pulses. Lens of 10 cm focal length focused laser on the target at the incidence angle 45°. The focal spot diameter of about 15 μm was measured by filtered CCD camera. The estimated peak laser intensity was approximately 2×10^{16} W/cm^2. The laser contrast with respect to a prepulse 12.5 ns ahead of the main pulse was approximately 5000. XUV radiation was detected in the target normal direction by the grazing incidence spectrograph LSP-VUV1-3S based on a Rowland circle detection scheme. Time-integrated spectra were registered on the photographic film UV-4. The grating with 1200 grooves per mm provided a useful spectral range of 2-25 nm. In this region, spectral lines of K-like copper ions were dominant. L-shell spectrum of Cu and Zn ions was analyzed by means of non-LTE atomic physics code PrismSpect. The electron temperature of 50 eV was estimated from the XUV spectrum.

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Characterisation of Laser-Produced Tungsten Plasma Using Optical Spectroscopy Method

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Tungsten is one of very few possible materials for in-vessel components in future thermonuclear reactors. Therefore, any investigation of its properties and behaviour is very important, in particular characterisation of its evaporation processes from the inner wall of tokamak chamber is needed.

This paper describes results of spectroscopic investigation of laser-produced tungsten plasma. Pure tungsten target was irradiated by intense laser-pulses (1.06 μm, 0.5 J, 3 ns) at different experimental conditions. Series of laser shots consisted of various number of pulses and were performed for different lens distances from the tungsten target.

The spectra emitted from plasma plumes, formed in vacuum conditions in front of the tungsten target due to interaction with Nd-YAG laser pulses, were characterised by means of an optical spectrometer with main parameters: wavelength range 300-1100 nm, spectral resolution $\lambda/\Delta\lambda$ = 900. The spectra were recorded automatically with the use of CCD detector with exposition time from 100 ns to 50 ms. In observed range the optical spectra were dominated by WI and WII lines and made it possible to estimate electron density and electron temperature of tungsten plasma. The correlation between the intensity of spectral lines and lens-target distance was also estimated.

The spectroscopic observations have been confirmed by results of ion diagnostics, namely an electrostatic ion energy analyser and ion collectors (Faraday cups). The spectra collected by the ion energy analyser showed that the plasma includes tungsten ions up to 6+ ion charge. Optical microscope and SEM investigation suggested that laser irradiation caused structural changes on the surface of the target.

The study characterises optical and ion properties of tungsten evaporation caused by intense laser irradiation and may be useful for a comparison with results of measurements of plasma-wall interactions inside various tokamak devices.

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Fe and Fe+2%Si Targets as Ion Sources via UV Laser Ablation Plasma

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In the last years the ion component of a laser-produced plasma has been considered and studied as an object of the development to provide high-density ion sources, which can be applied in many fields such as the laser-induced implantation. In this work a KrF laser beam of 10^8 W/cm^2 irradiance was focused onto single-crystalline Fe and single-crystalline Fe with 2% of Si targets in order to compare the characteristics of free expanding laser-produced plasmas. The time-of-flight (TOF) method was applied to determine the velocity distribution and the ion angular spread of emitted ion species. The analyses of TOF spectra, which were measured with a Faraday cup at various laser fluences, showed a synergetic effect of the silicon admixture in target material on the Fe ions production. Besides, this admixture is also responsible for the increasing of the kinetic energy of the particles as well as for the more collimated ion distribution.

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Study of Plasma Produced from Titanium Targets Irradiated by Intense Laser Pulses

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The paper reports on experimental studies of plasma generated by the irradiation of titanium (Ti) targets with intense laser beams delivered from a Nd:YAG laser. Two variants o the irradiation were investigated: at 1063 nm (0.5 J) and at 355 nm (0.1 J). In both cases the FWHM of each laser pulse was about 3 ns and the laser power density on the target amounted to (0.4–2) x 10^{10} W/cm^2, depending on focusing conditions.

Titanium is the well known constructional material and a component of many alloys, which are often used in different parts of experimental facilities designed for high-temperature plasma research. Titanium is also a good getter of hydrogen or deuterium. Hence, in different plasma experiments performed with the use of those gases, one should pay attention to a release of hydrogen or deuterium, which might be previously absorbed in titanium components.

The main motivation of the described studies was to investigate efficiency of the erosion of titanium parts and the release of the absorbed gases under influence of heating by laser- or particle-beams. Such data were not available up to the date, and they were needed for design of different diagnostic equipment as well as fusion-oriented facilities.

In the experiment to be described pure Ti and deuterium-saturated ($Ti+D_2$) targets were subsequently placed in the center of a vacuum chamber, and irradiated with laser beams at an angle of 55^0 to the target surface. Spectroscopic measurements of a plasma plume were performed by means of a Mechelle®900 spectrometer in the wavelength range of 300–1100 nm and with the exposition time varied from 100 ns to 50 ms. The spectrometer was coupled with a PC unit equipped with a software, which enabled the fast identification of spectral lines. The recorded spectra showed numerous lines originating from Ti– and D–ions (from $Ti+D_2$ target). The emission of different ion-species (ranging from Ti^+ to Ti^{+14}) and D^+ was confirmed by means of ion time-of-flight (ToF) measurements performed with the use of an electrostatic ion-analyzer and Faraday-type ion collectors. Efficiency of the D^+ release was estimated as a function of laser pulses parameters, i.e. their wavelength, intensity and duration. Changes in the target surface structure (laser craters produced by the irradiation) were investigated outside the experimental chamber by means of an optical microscope. The erosion of the titanium surface was estimated as a function of laser power density on the target surface.

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Spectroscopic Measurements in Different Plasmas Produced by Pulsed Laser Ablation

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A pulsed Nd:Yag laser, at intensities of the order of 10^{10} W/cm^2, is employed to irradiate different thick metallic targets (Ti, Fe, Ag, and W) placed in vacuum. The obtained non-equilibrium plasmas are investigated with various analytical techniques.

An electrostatic ion energy analyzer and different ion collectors are employed to monitor in-situ the ejected ions from the plasma and to determine the core plasma temperature, the ion energy distributions and the ion angular emission.

An optical spectrometer is employed to analyze the coronal plasma emitted light vs. wavelength and to identify the characteristic emitted lines. The optical spectroscopy permitted to evaluate the electron temperatures and densities.

Results show that strong temperature and density gradients occur in the laser-generated plasma plume.

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SBS PCM Technique Applied for Aiming at IFE Pellets: First Tests with Amplifiers and Harmonic Conversion

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One of important challenges in the IFE integrated approach deals with successful irradiation of thermonuclear targets (pellets) by powerful laser beams inside of the reactor chamber. Careful tracking of pellets' trajectories after injection is necessary for reliable prediction of the place most suitable for achievement of the required compression. Taking into consideration potential obstacles (e.g. collisions with debris from a previous shot) bringing targets into an acceptable vicinity of the optimal position is not an easy task. However, even if succeeding in such delivery, some adjustment of final optics for every shot and every laser beam will always be necessary. Due to the required level of symmetry of pellet irradiation, the number of the laser beams needed for effective thermonuclear fuel compression might be rather high (many dozens) with time available for any such adjustment very short (in particular if mechanical movements of some components would be involved). This makes achieving the whole task of proper pellet irradiation complicated.

As an alternative to the classical approach described above, the usage of the SBS PCM technique has been considered and theoretically studied. It was demonstrated that such approach could take care of automatic self-aiming of every individual laser beam with no need for any steering optics to allow for final beam position adjustment. Even if for every shot the injected pellets will inevitably reach random positions within the required area, their subsequent displacement from the position in which they will be illuminated by the short seeding pulse (glint) into the position in which they will be irradiated by the amplified, SBS PCM reflected, and once again amplified glint (laser pulse) will always be the same. This displacement will be determined by the trajectory travelled by the pellet during the time period needed for the glint amplification to take place (typically ~ 100 μm). Due to the non-linear feature of the third harmonic conversion (required for the final IFE pellet irradiation) the appropriate optical element (crystal) can be placed directly into the beam line.

In this paper the very first results obtained in experiments performed at KAIST and especially designed for verification of basic ideas proposed above including amplification and higher harmonic conversion will be presented and discussed.

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Theoretical Study of Excitation of Low–Energy Nuclear Transition in Laser–Produced Plasma

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The possibility to excite low–energy nuclear states using laser induced plasma on the Prague Asterix Laser System PALS is evaluated on the basis of the theoretical estimates and numerical modeling. The laser system PALS yields interaction intensities at the level of 10^{16} – 10^{17} W/cm^2 thus producing subrelativistic plasmas with electron temperature of the order of 1 – 10 keV. Based on a previous survey of suitable nuclei candidates, ^{181}Ta has been selected and the search for its 6.238 keV excitation and decay is a subject of this study. Theoretical estimates on the observation probability of this low-energy nuclear transition are based on one–dimensional hydrodynamic modeling of the laser–matter interaction. Laser–produced radiation field and spectra are evaluated in space and time by solving the radiation transport equations. These detailed simulations provide a possibility to explain many experimental observations and theoretical results obtained, including controversial reports on excitation and decay of the 6.238 keV transition in ^{181}Ta. The simulations confirm preliminary estimates based on simple theoretical models, i.e., very low nuclear excitation yields under current experimental conditions. Analysis of potential experimental approaches resulting in measurable yields represents a challenge for the future research.

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Plasma Generated during Laser Ablation of Hydroxyapatite

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Plasma plume generated during laser ablation of a hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$) target was studied during expansion into a vacuum or water vapour at a pressure of 20 Pa. Hydroxyapatite is a biocompatible ceramic. It is deposited onto orthopaedic implants in order to increase the bone-implant contact. The process of deposition significantly depends on the mechanism of plasma plume formation and the conditions of its expansion. In this experiment ArF laser operated at the wavelength of 193 nm with the pulse energy of 300÷350 mJ and 20 ns pulse duration. The laser intensity was 0.35 $GW \cdot cm^{-2}$. The emission spectra of the plasma plume were registered with the use of a spectrograph/monochromator and an Andor iStar ICCD camera. The camera was gated by a digital delay generator (DDG) triggered by the signal from the laser. The spectra were registered at various distances from the target (from 0 to 30 mm). The emission spectra consisted mainly of calcium lines. The lines of other elements were weaker and overshadowed by calcium lines. Before the spectral lines were registered with the use of ICCD camera the spectrograph was set as a monochromator and the temporal evolution of the intensity of specific spectral lines was measured with a photomultiplier and oscilloscope at various distances from the target. These measurements allowed us to determine the expansion velocity of the plasma plume using the time of flight method and establish delay times and gate widths for ICCD camera digital delay generator. The dynamics of the plasma plume was also imaged by means of fast photography. The ICCD images of the plume were recorded at different delay times with respect to the laser pulse using short 18 ns gate pulse. The radiation of ionic and atomic lines was separated with the use of interference filters.

It has been found that in the case of the expansion into a vacuum the plasma front moves with a constant velocity of 1.75×10^4 $m \cdot s^{-1}$. In the ambient water vapour the velocity decreases with a distance from the target - up to $\sim 2 \times 10^3$ $m \cdot s^{-1}$ 25 mm from the target. The electron density reaches $\sim 1.2 \times 10^{24}$ m^{-3} near the target and drops to $\sim 4.5 \times 10^{21}$ m^{-3} at a distance of ~18 mm from the target. The electron temperature is 11500 K close to the target and decreases to 4500 K at a distance of 25 mm from the target. The results allow estimation of thermal and kinetic energies of ablated particles. During the expansion into a vacuum the kinetic energy of Ca and O atoms is 63.5 eV and 25.4 eV, respectively assuming the same velocity of both particles. During the expansion into the water vapour these energies drop to 0.47 eV and 0.19 eV, respectively at a distance of 30 mm from the target and are comparable to the energy of thermal motion. The decrease of kinetic energies is not compensated by the heating in the shock wave region because the temperature jump in the shock wave results in loss of energy due to radiation and dissociation of the water vapour. At a distance of 30 mm from the target the temperature rise in the shock wave is already small. It is therefore clear that in the case of deposition in ambient water vapour particles arriving to the substrate have very low energy and additional energy necessary to achieve crystalline structure must be delivered by heating the substrate.

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Laser and Mass Quadrupole Spectrometry Analyses Applied to Cultural Heritage

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Laser Ablation coupled to Mass Quadrupole Spectrometry (LAMQS), Energy Dispersive X-ray fluorescence (EDX), Scanning Electron Microscopy (SEM) and Surface Profilometry Analysis (SPA) are applied to the investigation on the composition and morphology of ancient coins.

A Nd:Yag defocused laser beam, in repetition rate, hits a metallic surface, placed in high vacuum, removing the most superficial atomic layers. During the ablation a mass quadrupole spectrometer detects the molecular, atomic and isotopic emission from the target permitting to characterize its surface.

Quantitative relative analysis of elements, chemical compounds and isotopic ratios have been investigated analyzing the surface patina of the coins.

Obtained results are presented and discussed overall from the point of view of the physical non-destructive techniques useful to establish the differences between apparently true and false coins.

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2-D PIC Simulation of the Termalization Process in Plasma Pinch

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In this paper the numerical PIC simulation of high density plasma fiber is presented. The aim of this work is the study of the conditions under them the transformation of the microscopic kinetic energy to the thermal energy occur. The model is characterized by following conditions: 2-D geometry (cylindrical coordinates, symmetric in azimuthal angle), two species (electrons and ions), interaction of particles with both electric and magnetic fields and pair collisions calculated by Monte Carlo method. The boundary conditions are determined by the total electric current of plasma fiber and by parameters of the external circuit. On the opposite plans perpendicullar to the z-axis thus arise the floating electric potential. The periodic boundary conditions for the flow of particles through mentioned planes are used, so that the quantity of particles remains constant, except them which fly away perpendicular to the plasma fiber. All of the variables are defined as dimensionless. As initial conditions wass tested two components of ions with differend velocities and the dissipation of their energy was observed.

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The Calculation of Electronic Transport Coefficients of Alkali Metals in the Region of Plasma-Liquid Transition

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At present time the main problem in description of the electronic transport coefficients of metals is the region of the plasma-liquid transition. (These transport coefficients are the conductivity, the thermoconductivity and the thermopower). Near the critical point the values of these coefficients increases from gaseous to metallic values. This phenomenon is also observed for a number of gases (under other conditions). It is referred to as the pressure ionisation or the metal–non-metal transition. There are several approaches to the problem in hand, i. e. the phenomenological models, the generalized chemical models and so-called *ab initio* calculations. The substance in the generalized chemical models is considered as the mixture of positive ions, atoms and electrons. But they have limitation with the increase of densities due to the degeneracy of the electrons as consequence of the ionization. The *ab initio* calculations basing on the density functional theory are formally exact. They successfully describe the region of liquid and dense fluid but fail to reproduce correct ionisation degree at lower densities. There are many measurements of the thermophysical properties of alkali metals under high temperatures. In this work the results obtained by means of the approaches above and the results of the measurements were compared. The comparison showed that only the combination of two types of models (for low and high densities) could correctly describe the experimental data in the region of the plasma-liquid transition.

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Net Emission Coefficients of Radiation in Various Arc Plasmas

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Net emission coefficients of radiation were calculated for various arc plasmas as a function of the plasma temperature (1 000 – 30 000 K), arc radius (0.01 to 10 cm) and the arc plasma pressures from 0.05 to 2 MPa. The following plasmas and their various mixtures have been taken into consideration: SF_6, PTFE, Ar, N_2, air, CO_2, H_2O, SF_6+PTFE, SF_6+PTFE+Cu, Ar+H_2O, air+Cu, air+Fe, air+Ag. Temperature dependence of the net emission coefficients of radiation for various radii are presented in the form of viewgraphs.

Both line and continuum radiations were considered in the calculations of the absorption coefficients which are related to the net emission coefficients of radiation. Photorecombination and bremsstrahlung radiation contribute to the continuous spectrum. The absorption coefficients of each spectral line depend on the line shape, where Doppler, Stark and resonance effects were respectively considered. More than 25 000 spectral lines altogether have been analysed and taken as an input to the computations. The fine multiplet structure and overlapping have also been taken into account. Particular attention was given to the contribution of molecular species which have quite significant effect in low temperature regions. For the corresponding particular plasmas, we have accounted the following molecular species: SF_6, N_2, N_2+, O_2, NO, NO+, H_2O, H_2, C_2, CN, CO, CO+, FeO, CuO, AgO.

An important quantity in predictions of the thermal plasmas properties is the fraction of the plasma radiation that is in various region of the spectrum. An ultraviolet radiation is of central importance. It is usually emitted from the central parts of the plasma and re-absorbed in narrow layer at the edge. We have performed a comparison of net emission of radiation inherent to various spectral intervals.

Definition of the net emission coefficients assumes isothermal plasma. Consequently, approximation of the radiation losses by using the net emission coefficients is valid only for a flat temperature distribution. In the outer and cooler parts of the plasma, prediction of energy balance using the net emission coefficients of radiation will not be accurate. In this case, method of partial characteristics is more appropriate.

We have prepared extensive database of both net emission coefficients and partial characteristics of above mentioned kinds of thermal plasmas.

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Continuous Synthesis of Carbon-Encapsulated Magnetic Nanoparticles by RF Thermal Plasma

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Magnetic nanoparticles exhibit unique properties (e.g., higher coercive force and retencivity than bulk materials) but their practical applications are strongly limited. Magnetic nanoparticles are very sensitive to oxidation and agglomeration because of their large specific surface areas and high chemical reactivity. Under ambient conditions, rapid oxidation of the nanoparticles surfaces occurs, leading to the creation of thin oxide layers that dramatically changes the particle properties. Natural agglomeration of nanoparticles into larger clusters is another problem that renders the processing of such materials difficult. In order to preserve their specific magnetic properties, and to protect nanoparticles from both oxidation and agglomeration, the encapsulation procedure was proposed. Encapsulation in carbon seems to be one of the most promising ways, since the carbon coating exhibits high thermal and mechanical stability. Moreover, the ability to functionalize the carbon coating extends the prospective applications of carbon-encapsulated magnetic nanoparticles (CEMNPs). CEMNPs may find many prospective applications, e.g., in magnetic data storage, catalysis, xerography, magnetic resonance imaging, and in biomedical applications.

Herein, we report on the continuous fabrication of Fe nanoparticles encapsulated in protective carbon cages. CEMNPs were produced during Radio Frequency (RF, 30 kW) thermal plasma processing of mixtures containing fine Fe powder and a carbon source. We studied the influence of the carbon precursors (aliphatic and aromatic hydrocarbons, and aliphatic alcohols) on the yield, structure and magnetic properties of the as-formed CEMNPs. Moreover, we also investigated the influence of the addition of oxygen to the plasma gas. It was found that each carbon feedstock yielded CEMNPs with the diameter between 20 and 50 nm. Nanoparticles exhibit ferromagnetic behavior with maximum coercive force and saturation magnetization of 240 Gs and 100 emu/g, respectively. Oxygen (in an internal or external source) significantly reduced the amounts of amorphous carbon, what resulted in an increase of the saturation magnetization.

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Properties of Arc Discharge with Hybrid Stabilization for Different Radiation Models

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This paper deals with numerical investigation of properties and processes in arc with hybrid type of stabilization based on combination of principles of Gerdien arc (vortex-stabilized) and a common gas stabilized arc. Such kind of arc has been elaborated and studied at the Institute for several years. Two arcs in series are used: The first one is a short gas stabilized argon arc with low gas flow rate. This arc creates a cathode for the second arc stabilized by water vortex. Parameters of the generated thermal plasma jet and plasma composition can be controlled by a change of parameters of both arcs and by conditions of their interaction.

A two-dimensional axisymmetric numerical model describes the region between the inlet and outlet nozzles in the arc discharge chamber. It is assumed that plasma flow is steady, laminar, compressible, in the state of local thermodynamic equilibrium, and water and argon plasmas create a homogeneous mixture. The governing continuum, momentum and energy equations with temperature-dependent transport and thermodynamic properties are solved numerically by the Finite Volume Method.

The aim of this paper is to study the influence of different radiation models on the radial energy transfer from the hybrid arc and overall arc performance for different currents and molar ratios argon-water. We employ two radiation models in our calculation, namely, the net emission coefficient and the partial characteristics method for plasmas containing atmospheric pressure water and the argon-water mixture with different molar fractions of argon and water. In the partial characteristics method we include contributions due to continuum radiation and several hundreds of oxygen lines and nearly 4 000 argon lines. In addition, band spectra of H_2, O_2, O_2^+, OH and photodissociation of O_2 and OH molecules have been included in the partial characteristics. Broadening of spectral lines due to Doppler, Stark and pressure effects has been considered. Dissociation of molecules and radiation from hydrogen lines have been neglected so far.

Results carried out for 150-600 A and for argon mass flow rates of 7.5-27.5 slm proved that hybrid stabilized electric arc exhibits higher outlet velocities under the practically unchanged plasma enthalpy compared to Gerdien arc. Reabsorption of radiation employed in the partial characteristics method implies higher outlet temperatures and velocities regarding the case of zero reabsorption (net emission coefficient). The total amount of reabsorbed radiation range between 16 – 11 % for currents 150-600 A. Radial distance from the arc axis with zero divergence of radiation flux (emission equals absorption) exhibits increasing tendency with current and ranges from 2.2 to 2.8 mm. Comparison between present calculation and experiments carried out at the Institute exhibits good agreement.

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Wide-Range Equations of State for Metals at High Temperatures and Pressures

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A description of the thermodynamic properties of matter at high energy densities is of both fundamental and practical interests. Equations of state for metals over the range from normal conditions to extremely high temperatures and pressures are required for analysis and numerical simulations of hydrodynamic processes in plasmas under pulsed power influences. In this report, a new semiempirical equation-of-state model, which takes into account the melting, evaporation and ionisation effects, is presented. Wide-range equations of state for some metals (aluminium, gold and tungsten) are constructed on the basis of model developed. Calculation results are compared with available experimental data on shock compression as well as isentropic and isobaric expansion at high temperatures and pressures. The equations of state obtained can be used efficiently in numerical simulations of different processes at high energy densities.

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Boundary Instability of Plasma Jet Generated by Plasma Torch with Modulated Arc Current

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Oscillations of plasma jet generated by hybrid water-argon stabilized plasma torch WSP-H500 were studied for two frequencies of current ripple. We used classical thyristor power supply with the frequency of current ripple 300 Hz and the rectifier with high frequency converter which generated the current with ripple 30 kHz. Pulsations of plasma jet were recorded as oscillations of plasma radiation using linear array of high frequency photodiodes. This array was positioned parallel or perpendicular to the axial axis of the jet image.

Changes of spectra of oscillations along the jet were evaluated from signals of photodiodes in parallel position. For classical thyristor power supply the characteristic frequency of the boundary layer instability of the plasma jet was 20 – 150 kHz for the arc currents 300 – 500 A. Consequently, in this case the current modulation (300 Hz) do not influence the high frequency jet boundary oscillations. However, when the power supply with current ripple frequency of 30 kHz was used, we observed the boundary instability with dominant frequency 30 kHz at the arc current 300 A, and for arc currents 400 A and 500 A we detected strong excitation of oscillations with frequency 60 kHz. An interaction of the boundary instability with the arc current modulation thus took place.

The signals from the array of photodiodes positioned perpendiculary to the jet axis were processed to get maps of the same photodiodes currents. These maps, with coordinates corresponding to transversal position in the jet and to time, represent the spatial structure of oscillations during their passage along the photodiode arrray. It can be seen that the oscillations with frequencies 30 kHz and 60 kHz respectively, in case of current ripple with frequency 30 kHz, are mostly excited at the periphery of plasma jet. They can be interpreted as the boundary layer instability.

Statistical analysis of the records of photodiodes signals positioned parallel to the jet axis was performed and mean amplitudes and phase velocities of oscillations in various spectral windows for several arc currents were evaluated. The total mean amplitudes of oscillations were substantially higher for low frequency modulation of arc current. The phase velocity of oscilations with the frequency of current ripple depends strongly on position with respect to the anode attachment.

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Volt-Ampere Characteristic of the Stabilised Arc

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This paper deals with the conductance calculation of the stabilised arc. For the design of the arc model it is supposed that the whole system is in the local thermodynamic equilibrium and the electrical arc is along the whole channel axial symmetrical. The aim of this paper is to propose the method of the conductance calculation of the stabilised arc and to apply the program for the electrical conductivity calculation created by the author. By using of the measured values of the arc current it can be calculated the arc voltage. The measuring was realized on the experimental arc heater for atmospheric pressure and the working gas was argon. The calculated conductance of the arc was compared with the conductance calculated from the measured values of the voltage and the current. Then the V-A characteristic of the arc was plotted and compared with the experimental V-A characteristic.

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Cluster Model of Aluminum Dense Vapor Plasma

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Thermodynamic model of dense ionized vapor of aluminum that take into account metallic clusters both neutral and ionized is suggested. Maximum quantity of atoms in cluster in this model is equal to 6. Available in literature data of *ab initio* calculations of their energy and force coefficients have been used for calculation of cluster internal partition function. Vibration-rotation dissociation effects are taken into account for calculation of partition function. Thermal and caloric equation of state and metal vapor composition are calculated in vicinity of critical point using designed model. Calculated composition has been used for estimation of conductivity of aluminum vapor plasma. Comparison with existing experiments is made for theoretical model verification. In above mentioned experiments isochoric pressure and conductivity dependence on internal energy are measured at the same time in wide range of densities and temperatures. Executed calculations and comparison with experimental data allowed to establish role of metallic clusters in vicinity of vapor metal critical point and their role in interphase boundary formation of vapor-liquid metal transition.

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A Study of Z-Pinch in Capillary Filled by Boron Vapors

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Pinching discharge in both non-ablative and ablative capillaries filled by boron vapors is studied. The aim is to find out conditions for lasing at Balmer alpha transition of hydrogen - like boron ions B^{4+}. The primary pumping process under consideration is a three-body collisional recombination, taking place in non-stationary under-cooled plasma created during the pinch expansion stage.

Simulations of every shot consist of three steps: (1) Radial and time dependences of mass plasma density, plasma electron temperature, plasma ion temperature and plasma electron density are evaluated by means of the MHD code NPINCH. (2) Time dependences of ionization fractions and energy level populations for lithium-, helium- and hydrogen-like ions are estimated by means of the kinetic code FLY. (3) Time dependences of gain factor on the capillary axis are assessed.

The results of computer modeling for capillary radius R_0 = 2.5 mm presuming damped sinus profile for the current with peak value I_{max} = 90 kA and two different quarter periods $T_{1/4}$ ~ 80 ns and ~ 50 ns are reported here. The maximum peak value of evaluated gain for $T_{1/4}$ ~ 80 ns is G ~ 1.6 cm^{-1} is found for initial boron vapor density $N_0 = 3.9\ 10^{17}$ cm^{-3} in non-ablative capillary, whereas the gain is very small if the wall ablation is taken into account.

The reason for that is the plasma cooling effect caused by the incoming ablated material from capillary wall. If the shorter current pulse ($T_{1/4}$ ~ 50 ns) is taken into account, influence of the cold ablative material on the achievable gain is less pronounced.

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Equilibrium Composition and Thermodynamic Functions of Non-Ideal Plasma

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A general method for calculating the composition and thermodynamic functions of non-ideal closed gaseous system in thermodynamic equilibrium is proposed. The method is based on the minimization of the Gibbs energy of a system in terms of successive approximations. The Gibbs energy of the system is expressed by means of chemical potentials of individual substances comprised in the system, whereas no limitation on the functional form of the non-ideal part in the chemical potential is imposed. The method described is applied to the calculation of the composition and thermodynamic properties of the system containing both neutral and charged particles composed of Sulphur and Fluorine atoms.

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Radiation of Electrical Arc Burning in Argon

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The electrical arc burning in argon has been investigated both experimentally, and theoretically. Experiments have been carried out on an arc heater with the electrical arc stabilised by flowing argon of atmospheric pressure. Typical operating conditions are characterised by the arc current between 80 and 220 amperes, the arc voltage about 100 volts, and argon flow-rate approximately 20 grams per second. The arc has been burning in a channel 80 millimetres in length and 8 millimetres in radius. A set of integral quantities including energy loss in individual segments of the arc heater has been measured during each experiment. The measured data have then served as input data of the designed mathematical model of the arc. The model is based on energy and mass conservation equations and Ohm

law and uses the known transport and thermodynamic properties of the gas medium. After some simplifications it makes it possible to compute axial and/or radial dependencies of some quantities of interest (temperature, velocity, electric field intensity, arc radius, etc.) and subsequently judge energy exchange between the arc and its surroundings.

Special attention has been paid to radial energy transport from the arc to the channel wall. The analysis of the computed and measured data has proved that the hot gas has reached the cooled channel wall in none of the studied cases. Thus, the mechanism of energy transfer from the arc to the wall is supposed to be radiation. Using the measured and computed data and accepting some simplifying presumptions, we have tried to estimate temperature dependency of the radiation coefficient of argon plasma in the limited extent of temperatures and arc cross-sections. The obtained results are given in figures. An interesting question is comparing these values computed from experimental data with the results of theoretical computations published by Aubrecht and Bartlova in Czechoslovak Journal of Physics D 52 (2002). Considering the applied simplification in the computation and the differences between the real situation and the theoretical model, the correspondence of the data is satisfactory.

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Computational Study of Impulsively Generated Waves in a Solar Coronal Loop

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In our contribution we numerically investigate standing waves that are impulsively excited in a solar coronal loop by pressure and density perturbation. This problem is considered as one-dimensional in space. The corresponding computer model is described by the ideal magnetohydrodynamic equations that are solved numerically by means of so-called flux limiters methods on uniformly structured mesh.

The obtained numerical results show, i.e. velocity, mass density, energy and perturbed mass density time evolution. The next presented results are the spatial profiles of velocity for various positions in the work area and for various points of the initial perturbations in the plasma equilibrium. In our work we discuss the fundamental mode and the first harmonic mode which are generated in dependence on position of initial perturbation.

Our presented work is aimed at the explanation of coronal oscillations and its attenuation. These calculations are very important for the explanation of problem of coronal heating and mechanisms of solar coronal oscillations.

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Finite Larmor Radius Corrections on Self-Gravitating Anisotropic Heat-Conducting Plasma

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In this paper the effect of finite Larmor radius (FLR) corrections on self-gravitational instability of anisotropic heat-conducting plasma is investigated. The present work is the extended one [Prajapati et al. *Phys. Plasmas* **15**, 012107 (2008)] in the field of anisotropic pressure plasma taking into account of heat flux vector. The usual Chew-Goldberger-Low (CGL) set of equations is used to discuss the instability as well as stability of the system. The medium is supposed to be rotating with uniform angular velocity. The general dispersion relation is obtained using normal mode analysis by constructing the linearized set of equations, which is discussed for propagation both longitudinal and transverse to the direction of the magnetic field for each cases of rotation. The effect of FLR correction together with rotation is seen on the growth rate of the system. It is found that rotation plays the stabilizing role on the growth rate of Jeans instability. It is also demonstrated that the Alfven wave and the associated "firehose" instability are not affected by the presence of heat

flux corrections, FLR corrections and rotation also. The numerical analysis is performed to show the effect of FLR corrections, rotation, pressure anisotropy and heat flux parameter on the condition of instability in the spiral arms of galaxy in space plasma. The Jeans condition of gravitational instability is obtained for both the cases of propagation which is found to be unaffected by the presence of FLR corrections and heat flux vector.

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