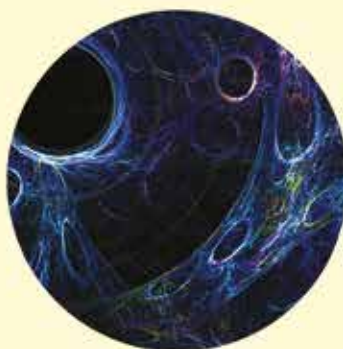
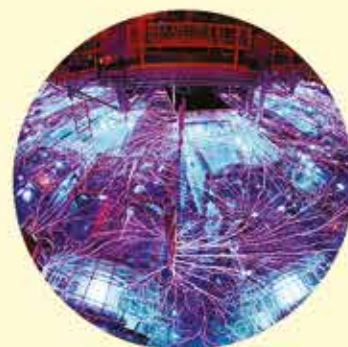
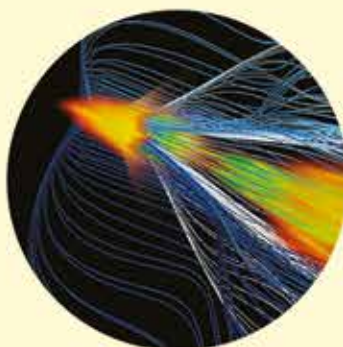
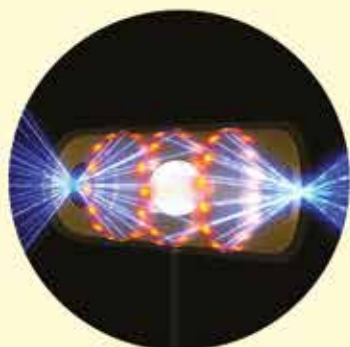
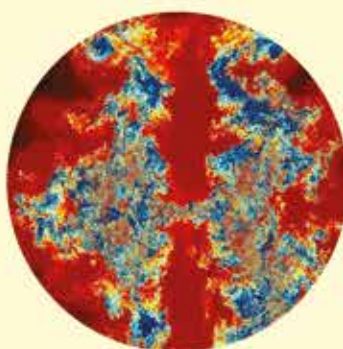
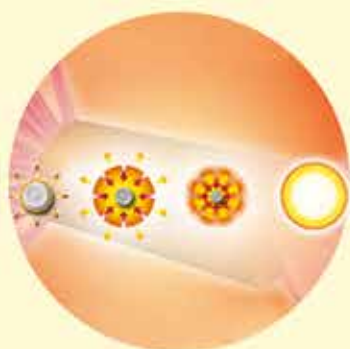




21st International Symposium on
HEAVY ION FUSION
Astana, Kazakhstan • July 18-22, 2016

Book of Abstracts



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J 69

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21st International Symposium on Heavy Ion Inertial Fusion was held in Astana on July 18-22, 2016. The purpose of the symposium was to review the status of heavy ion fusion (HIF) research, and to stimulate further progress in understanding inertial fusion energy production and the science and technology needed for its implementation. Controlled fusion has the potential of becoming an important energy source because the fuel is widely available and because the reaction is relatively clean. Heavy ion accelerators are promising candidate drivers for energy production due to their high repetition rate and high efficiency. A current state of the worldwide HIF facilities and ongoing heavy ion accelerator projects will be also addressed.

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Autonomous Organization of Education
“Nazarbayev University”, 2016

Dear colleagues,

HIF 2016 symposium continues the series of symposia that began in Berkeley in 1976. The most recent symposia occurred in Lanzhou, China (2014), Berkeley, USA (2012), Darmstadt, Germany (2010), Tokyo, Japan (2008), and Saint-Malo, France (2006). The purpose of the symposia is to review the status of heavy ion fusion research, and to stimulate further progress in understanding inertial fusion energy production and the science and technology needed for its implementation. Heavy-ion accelerators are promising candidate drivers for energy production due to their high repetition rate and high efficiency. We also expect to critically assess the PW-laser applications in ICF (Inertial Confinement Fusion). A positive emphasis is given to the ongoing heavy ion accelerator projects at large institutions located in Europe, Russia, China, Japan, USA and other countries. The highlighted topics of HIF2016 cover:

- Heavy-Ion Inertial Fusion and other ICF programs;
- Properties of Warm Dense Matter: Theory, experiments, and advanced diagnostic techniques;
- Ion sources and high power accelerators, Pulsed Power (pulsed energy);
- Fusion target physics, Hydrodynamic instabilities;
- Beam-plasma interactions, Atomic processes in plasma, laser plasma interactions;
- Applications of ICF;
- TOKAMAK, Nuclear Science (related to the Kazakhstan activities);
- Dark Energy and Dark Matter research;
- Heavy ion stopping.

Nazarbayev University is hosting HIF2016 on July 18-22, 2016. The conference brought together over 90 professionals from United States, Switzerland, South Korea, Germany, France, Russia, Kazakhstan, China and Japan.

We welcome all participants and are looking forward to a successful meeting!



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INVITED TALKS

Kazakhstani material testing Tokamak KTM. project status

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Creation of cost-efficient and safe fusion reactor will require the development of special structural materials for first wall, blanket, reactor components, which will be operated under conditions of the high heat fluxes, superconducting magnets, plasma heating systems and other elements. The existing tokamaks and other fusion facilities do not currently allow for conduction of specialized researches of plasma-facing structural materials. Kazakhstani Material Testing Tokamak (hereinafter - KTM) provides for a unique opportunity to conduct materials research and testing of separate units and components of fusion reactors.

Tokamak KTM is being constructed in Kurchatov, East Kazakhstan region, at the National Nuclear Center of the Republic of Kazakhstan in accordance with the decision of the Government of the Republic of Kazakhstan in support of the ITER program, as well as for the development of modern science and technology, and training of scientific engineering and highly qualified personnel in the country. The main distinctive feature of the tokamak KTM in comparison with similar facilities is the presence of the movable divertor and transport-sluice device, which allows for prompt replacement of the investigated samples without loss of vacuum in the vacuum chamber. KTM facility is meant for research and testing of the materials, technologies and separate units of future fusion reactors, as well as for working out the operation scenarios of the fusion neutron sources for hybrid reactors. Putting of tokamak KTM into operation long before completion of construction and full-scale experimental researches at ITER reactor will be a basis for wide international cooperation in the field of fusion material science, including the studies of both new materials, and technological solutions and designs. Moreover, tokamak KTM is the only mega-ampere facility in the world, which allows for replenishment of the databases on physics of the processes of plasma confinement in the border area between the spherical

tokamaks and classical ones, and will be a prototype for future compact energy fusion reactor.

Parameters of energy loads, wide range of used methods and diagnostics allow for high level studies and tests in divertor volume, which is highly important for studies of plasma facing materials in ITER and DEMO programs and for other experimental and power fusion reactors. Trial start-up of Tokamak KTM was done on September, 5, 2010. Now the number of the experiments has been carried out on the tokamak KTM with the use of capacitor battery as the power source. KTM project design documentation was re-developed according new requirements and has passed the State Expertise. At the moment, the Government of Kazakhstan allocated funding to complete the construction of the complex KTM. The physical start-up of KTM tokamak is expected in 2017, commissioning – in 2018. The joint work program with the participation of Russian specialists is implemented to prepare for the KTM physical start-up.

Tokamak KTM will be the object of EXPO-2017, which will be held in Astana.

Readiness of HIF Using the Single Pass RF Driver

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Readiness for a concerted push to power production was the underlying theme from the inaugural HIF Workshop in 1976 through the review of ICF programs by DOE's Energy Research and Advisory Board in 1979. Using John Lawson's 1987 paper "Whither Heavy Ion Fusion?" [1] as a foil, this paper discusses the continuing vitality of the argument for HIF's readiness against the backdrop that this vision is not in evidence today, having been occluded by political policies causing diversion of the HIF community into peripheral science that, although excellent, is in fact not required to complete the development of a HIF energy source.

Instead of pressing ahead to power production, HIF in the US diverged onto a path that occluded its strength at high beam parameters for ignition and power production and forced HIF into inappropriate competition with laser systems for low level experiments. Then the readiness of HIF based on a half (now whole) century of steady development was stood on its head in the US by concentrating instead on developing essentially from scratch the manifestly unready technology of the linear induction accelerator.

The present paper emphasizes major advances with pellet ignition approaches and the Single Pass RF Driver (SPRFD) that represent the development anticipated at HIF's outset. Writing in 1987, Lawson was reflecting the significant loss of momentum already suffered by HIF, but went further to express pessimism that major advances like the foregoing would happen.

Lawson's main concerns about the RF driver focus on the use of storage rings, particularly the "black cloud" problem, are attacked directly by the reconceptualization of the RF driver without storage rings. SPRFD makes this entire section of Lawson's piece null and void. The combination of the SPRFD and matching cylindrical targets using fast ignition represents "new ideas or inventions" that Lawson admitted could

"transform the prospects." Lawson pessimistically averred that such advances were not likely to come along because "our understanding of the basic limitations of accelerators, targets and reactors is now (viz., in 1987) too great."

Diverging from the overall cautionary tone of his article, Lawson misplaced credence in 1987 calculations of pellet performance: "present expectations are reliable." We now know they were not. On the other hand, the performance of HIF pellets, always advantaged by heavy ion beams' classical energy deposition, leaped further toward readiness. SPRFD's exploitation of the increased total useable volume of phase space with many different isotopes provides a path to the small spots needed for fast ignition in cylindrical pellets as simulated by leading scientists [2]. These again "transformed the prospects" for HIF. But, also again, recognition of HIF's readiness on this score is held back by the owners of the most accredited US simulation codes claiming that these cylindrical pellets are classified despite the fact that such claims are not supported by the US classification guide.

The major advances redouble the importance of the basic readiness of accelerator technology that caused much of the excitement at HIF's debut in 1976: predictability of accelerators to work as designed, repetition rate, efficiency, reliability, durability, and project cost-ability. In the four decades since 1976, accelerator technologies, which include computers, electronics generally, control systems, and large project management, as well as RF structures, RF power, and magnets, have continued their monotonous advance, as have beam theory and simulation capabilities.

The future age in which Lawson saw HIF as fitting has arrived: The world stands in need of the large outputs of carbon-neutral synthetic fuels, additional electricity, hydrogen, and potable water that FPC's HIF plants can produce.

¹ J. Lawson, *NIMA* **A278** (1989) 22-4

² R. Ramis and J. Meyer-ter-Vehn, *Laser and Particle Beams* (2014), 32, 41-47 and references therein

² R. Ramis and J. Meyer-ter-Vehn, *Laser and Particle Beams* (2014), 32, 41-47 and references therein

Laboratory Astrophysics Using Intense Ion and Photon Beams Generated by Large-Scale Accelerator Facilities in Korea

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Several large-scale accelerator facilities are operational or under construction in Korea, such as the Korea Multi-purpose Accelerator Complex (KOMAC), the Pohang Accelerator Laboratory X-ray Free Electron Laser (PAL-XFEL), and the Rare Isotope Science Project (RISP). These accelerator projects open up new opportunities in basic science researches in Korea, and provide excellent platforms particularly for laboratory astrophysics.

The KOMAC project [1] started in 2002 and completed the linac commissioning in 2013. The KOMAC linac consists of a 50-keV proton injector, a 3-MeV four-vane RFQ, and a 100-MeV drift tube linac (DTL). The RF frequency is 350 MHz and the maximum beam pulse current is 20 mA. So far, two beamlines are available for users. One is located at the end of the 20 MeV DTL and the other at the end of the 100 MeV DTL.

The PAL-XFEL project [2] started in 2011 and is currently under commissioning. The PAL-XFEL will have a dog-leg branch line at 3-GeV point of the linac for two soft X-ray undulator lines, and three hard X-ray undulator lines at the end of 10-GeV linac. A 1.6-cell type photocathode RF gun is used to inject 0.2 nC of electron beam pulse with 120 Hz repetition rate. The main accelerating structure is an S-band normal conducting linac.

The RISP project [3] will be composed of a 70 kW proton cyclotron as a low-power ISOL driver, an 18 MeV/u linac for ISOL post-accelerator and a 200 MeV/u main linac for high-power ISOL and IFF driver. The main driver linac named RAON will accelerate all elements up to Uranium with beam power up to 400 kW. To maximize the average currents of the primary beam on target, continuous wave (CW) operation is preferred, and therefore superconducting RF (SCRF) technology has been adopted for the linac design.

The laboratory astrophysics is a new emerging field of basic sciences, and has tremendous discovery potentials. The laboratory astrophysics investigates the basic physical phenomena in

the astrophysical objects in controlled and reproducible manners, which has become possible only recently due to the newly-established intense ion and photon beam facilities worldwide. In Korea, however, no concrete laboratory astrophysics program has yet been established within the scope of the accelerator projects introduced above.

In this work, we present several promising ideas for laboratory astrophysics programs that might be readily incorporated in the accelerator projects in Korea. For example, spectroscopy experiments using Electron Beam Ion Trap (EBIT) and intense X-ray photons from the PAL-XFEL can be performed to explore the fundamental processes in high energy X-ray phenomena. Measurements of nuclear reaction rates relevant to rare isotopes by utilizing the RISP facility will enable us to investigate the effect of reaction rates on explosive phenomena around the astrophysical compact objects.

In many violent astrophysical events, the energy density of matter becomes so high that the traditional plasma physics description becomes inapplicable. Generation of such high-energy density states can be achieved by using the intense photon beams available from the PAL-XFEL. Understanding the interactions between the intense photons and over-dense plasmas (such as those produced in solid targets or foils) will be useful not only for the astrophysics, but also for the study of laser acceleration of protons and ions.

On the other hand, while not directly connected with the astrophysics, we also note that the low-flux proton beams available from the KOMAC facility can be used to provide space radiation environment, which is essential to test the performance of detectors for observation satellites.

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PW-laser produced MeV proton beams stopped in WDM plasmas (H, He, Ar, N, Xe)

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Physical processes involved in the interaction of ion beams in Warm Dense Matter (WDM) (i.e. 1-100 eV, 0.01-100 g/cc) is fundamental to the understanding of condensed matter, solid-state physics, fusion sciences, and astrophysical phenomena. In particular, in the WDM regime the charge equilibrium and stopping power of ions differs significantly from that of both cold matter and ideal plasma due to free electron contributions, plasma correlation effects and electron degeneracy. Furthermore, experimental data is extremely scarce in this regime; the reason being that the creation a WDM state with a temporal duration consistent with the particles used to probe it has been extremely difficult to achieve experimentally. For the past couple of years, we have been developing an experi-

mental platform using short pulse lasers that can produced relatively short bunches of protons (picosecond time scale) to study plasmas in the WDM regime. Earlier this year, using the Titan Laser at JLF, we used the CPA laser to create two identical proton beams in a gas jet. One was used as a reference, and the other beam was used to perform the stopping power measurement in a first evaluation of semi-empirical formulas that are being used to predict the stopping power of ions in numerical codes that are often used in ICF and astrophysics. The development of this short-pulse laser platform thus shows great promise to push further the investigation of ion interactions in the experimentally challenging conditions of WDM.

Creating, Diagnosing, and Controlling High Energy Density Matter with the National Ignition Facility

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Progress in understanding ignition physics for laser-driven inertial confinement fusion at the National Ignition Facility (NIF) will be over-viewed. New diagnostics permit more detailed measurements of implosion experiments. In addition to continuing fusion research, a portion of NIF beam time is open for innovative Discovery Science experiments, which can be proposed by members of the high energy-density community. This program will be described.

High energy density physics with intense ion and laser beams

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We will present the status and perspectives of High Energy Density Physics (HEDP) with intense heavy ion beams as a tool to induce extreme states of matter. This report will emphasize the recent progress at FAIR/GSI. The development of this field connects intimately to the advances of accelerator physics and technology and aims to investigate the properties of intense heavy ion beams as a driver for inertial fusion energy. We will cover the generation of intense heavy ion beams starting from the ion source and follow the acceleration process and transport to the target. Intensity limitations and potential solutions to overcome these limitations are discussed. This is exemplified by citing examples from existing machines at the Gesellschaft für Schwerionenforschung (GSI-Darmstadt), the Institute of Theoretical and Experimental Physics

in Moscow (ITEP-Moscow), and the Institute of Modern Physics (IMP-Lanzhou). Facilities under construction like the FAIR facility in Darmstadt and the High Intensity Accelerator Facility (HIAF), proposed for China will be included. Developments elsewhere are covered where it seems appropriate along with a report of recent results and achievements.

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Photons as signature for dark matter and dark energy: The Cast experiment at CERN

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The CAST experiment is designed to search for solar axions which are produced in the dense plasma the interior of the sun via the Primakoff effect. Detection of axions and their energy spectrum will immediately reveal the temperature of the core plasma. The central part of the experiment, the helioscope is an LHC prototype magnet that has attached different types of sensitive detectors for x-rays in the regime of 1-10 keV. The experiment has been taking data since 2003 and provided the most restrictive limits on the axion-photon coupling in a broad mass range. Beyond 0,02eV/c**2 the mass the sensitivity is degraded due to coherence loss. In order to restore coherence, the magnet was filled with a buffer gas providing an effective mass to the photon. By changing the pressure of the buffer gas in steps, CAST did scan the range of axion mass values

from 0.02eV to 1.18eV. CAST has set the strongest limit yet on Axion-photon coupling across a wide range of Axion masses (i.e., any rest mass below 1.18eV), surpassing astrophysical limits for the first time. An overview of the total data set and data analysis will be presented.

The significant upgrades of CAST in 2014 allows first experiments to shed some light into the dark energy sector by searching for axions with its better performance due to a 2nd XRT, while continuing the search for solar chameleons in the sub-keV range. Gravitational lensing may enhance the sensitivity by many orders of magnitude. At this point the equation of state of Jupiter and other planets play a significant role. Proposals for the future include an International Axion Observatory (IAXO) as a 4th generation Axion Helioscope. This proposal is currently under review/approval by CERN SPS committee.

Near-term experiments and long-term goals at INURA pulsed ion accelerator in Nazarbayev University

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Nazarbayev University works on establishing a research program on inertial confinement fusion, high energy physics and critical states of matter. Long term plans include building a new multi-MV, ~10 to several hundred GW/cm² ion accelerator facility which will be used in studies of material properties at extreme conditions. Two design options are being considered. The first option is a 1.2 MV induction linac similar to the NDCX-II at LBNL, but with modifications, capable of heating a 1 mm spot size thin targets to a few eV temperature. The second option is a 2 - 3 MV, ~200 kA, single-gap-diode proton accelerator powered by an inductive voltage adder, to obtain power densities of several hundred GW/cm² at ~1 cm spot size. In both cases to achieve high beam intensity on target we plan to use plasma neutralization to focus the beam both spatially and temporarily.

Our first beam-physics experiments will be started on currently constructed ion accelerator test-stand (INURA), to be commissioned on December 2016. INURA ion accelerator will have an accelerating voltage of 400 kV, pulse duration of 80 ns, and total beam current of 10 kA. Initially the diode system of the INURA will be based on Br-applied focusing ion diode with an active anode plasma source. Plasma on the anode surface will be generated by an additional high-voltage pulse followed by the primary one. The composition of an ion beam will range from light ions (H⁺) to heavy ions (W⁺) as determined by the material of the potential electrode. Near-term experiments on INURA ion accelerator will include studies on formation of ablation plasma on the surface of materials, material modification by high intensity pulsed ion beams, ion beam neutralized transport and longitudinal and transverse compression, and research on suitable ion diode concepts.

Update on beam-plasma interaction research at PPPL

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We have performed experimental and theoretical studies of beam neutralization by background plasma. Near-complete space-charge neutralization is required for the transverse compression of high-perveance ion beams for ion-beam-driven warm dense matter experiments and heavy ion fusion. One approach to beam neutralization is to fill the region immediately before the target with sufficiently dense plasma. The plasma provides a charge-neutralizing medium for beam propagation and makes it possible to achieve a high degree of compression beyond the space-charge limit.

Experiments were performed on the Princeton Advanced Test Stand to investigate the degree of charge neutralization for different methods of neutralization [1]. A high-perveance 38 keV Ar⁺ beam was propagated in a plasma produced in a Ferroelectric Plasma Source (FEPS) discharge. By comparing the measured beam radius with the envelope model for space-charge expansion, it was determined that a charge neutralization fraction of 98% is attainable with sufficiently dense FEPS plasma and 83% with neutralization by plasma produced from a background gas. The transverse electrostatic potential of the ion beam is reduced from 15 V before neutralization to 0.3 V, implying that the energy of the neutralizing electrons is below 0.3 eV. Measurements of the time-evolution of beam radius show that near-complete charge neutralization is established 5 μ s after the driving pulse is applied to the FEPS and can last for 35 μ s.

Numerical simulations of effects of the two-stream instability on the propagation of ion beam in background plasma were performed. Development of the two-stream instability between the beam ions and plasma electrons may lead to beam breakup, a slowing down of the beam particles, acceleration of the plasma particles, and transfer of the beam energy to the plasma particles and wave excitations. Making use of the particle-in-cell code LSP, a one-dimensional Vlasov code, the effects of the two-stream instability on beam propagation over a wide range of beam and plasma parameters were simu-

lated. Because of the two-stream instability, the plasma electrons can be accelerated to velocities twice as high as the beam velocity. The resulting return current of the accelerated electrons may completely change the structure of the beam self-magnetic field, thereby changing its effect on the beam from focusing to defocusing. Therefore, previous theories of beam self-electromagnetic fields that did not take into account the effects of the two-stream instability must be significantly modified [2,3]. As a result of the two-stream instability, an ion beam pulse can generate an electron beam propagating ahead of the ion beam pulse and perturb plasma ahead of the ion beam pulse [4]. One simple method to avoid two-stream instability is to use tenuous plasma that can well neutralize ion beam space charge provided enough electrons can be supplied to the beam pulse from the plasma volume or chamber sides [5]. The associated change in plasma parameters affects the two-stream instability and causes its decay. This effect can be observed on the National Drift Compression Experiment-II (NDCX-II) facility by measuring the spot size of the extracted beamlet propagating through several meters of plasma.

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Researches in Japan on heavy ion inertial fusion

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Recent research activities in Japan are presented in this paper in heavy ion inertial fusion (HIF) [1]: shown are particle accelerator developments, beam dynamics researches, interaction between heavy ions and target materials, ion source developments, and illumination schemes of heavy ion beams (HIBs) in HIF.

The HIB has remarkable preferable features to release the fusion energy in inertial fusion and also for studies on the warm dense matter (WDM) physics [2]: in particle accelerators HIBs are generated with a high driver efficiency of $\sim 30\text{--}40\%$, and the HIB ions deposit their energy inside of materials. Therefore, a requirement for the fusion target energy gain is relatively low, that would be $\sim 50\text{--}70$ to operate a HIF fusion reactor with the standard energy output of $\sim 1\text{GW}$ of the electricity. The HIF reactor operation frequency would be $\sim 10\text{--}15$ Hz. Several-MJ HIBs illuminate a fusion fuel target, and the fuel target is imploded to about a thousand times of the solid density. Then the DT fuel is ignited and burned. The HIB ion deposition range is defined by the HIB ions stopping length, which would be $500\text{ }\mu\text{m}\sim 1\text{ mm}$ or so depending on the material and on the ion particle energy. Therefore, a relatively large density-scale length appears in the fuel target material. One of the critical issues in inertial fusion would be a spherically uniform target compression, which would be degraded by a non-uniform implosion. The implosion non-uniformity would be introduced by the Rayleigh-Taylor (R-T) instability, and the large density-gradient-scale length helps to reduce the R-T growth rate.

The HIB accelerator has a high controllability to define the ion energy, the HIB pulse shape, the HIB pulse length and the HIB number density or current as well as the beam axis. The HIB wobbling axis motion may give another tool to smooth the HIB illumination non-uniformity [2].

In the paper the KEK digital accelerator is first presented based on an induction acceleration technique for the all-ion accelerator [1]. Then the activities in Japan are shown for the beam dynamics researches in Nagaoka, the HIB interaction with target materials in Nagaoka and Utsunomiya, the ion source developments in KEK, Tokyo Tech., BNL, and AIST, the illumination scheme of heavy ion beams in Utsunomiya and Osaka, and other issues in HIF

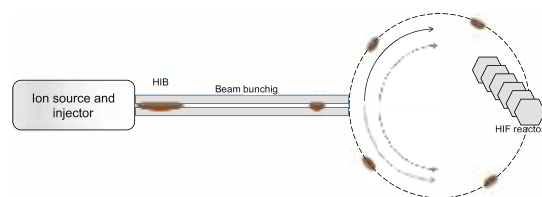


Fig. 1 A concept of a HIF reactor system.

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Recent activity on beam dynamics study during longitudinal bunch compression by using compact beam simulators for heavy ion inertial fusion

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In heavy ion inertial fusion scenario, heavy ion beams with extreme high current are most important assignment [1]. Predictions of beam behavior are basic necessity to design the accelerator complex. Especially, a bunch compression manipulation in the final stage of accelerator complex is required to generate the beam with high current and suitable short pulse duration [2].

Recent research activities in beam dynamics during bunch compression with strong space charge effect using compact beam simulators [3-11] are introduced in this study.

In Tokyo Institute of Technology, a compact simulator of electron beam was constructed [3-5]. The compact simulator consists of an electron gun, an energy modulation gap, an induction modulator, a drift line with a solenoidal electromagnet, and a Faraday cup. Electrons emitted from the electron gun with 2.8 keV of kinetic energy come in the modulation gap. The induction modulator gives the deceleration voltage into the gap. The synthesized voltage waveform applies the kinetic energy modulation to the electron bunch with head-to-tail velocity tilt. The electron bunch is compressed during the drift transport of 2 m length. The electrons are transversely confined due to the magnetic field of several tens mT produced by the solenoid coil. Finally, the electron bunch achieves to the Faraday cup placed in the transport line. The beam current increases up to 25 times from the initial one due to the pulse compression. It is estimated that the electron bunch is changed to space-charge-dominated states.

In Kanazawa University, a compact simulator based on the Malmberg-Penning trap was demonstrated for the investigation of space-charge-dominated beam [6]. In the device, the electron cloud is transversely confined with 0.1 T of axial magnetic field generated by the solenoidal electromagnet, and is axially confined with the saddle shaped axisymmetric potential of negative barriers at both ends. After the confinement, the electron cloud is extracted from

the trap region, and a phosphor screen and a CCD camera detect the density profile. By controlling the potential barriers, the energy distribution of the electrons is also measured. The axial compression is carried out by applying voltage to ring electrodes. The diameter of electron cloud is 1 mm. The length is shortened from 170 mm to 80 mm due to the axial compression. The number density of electron plasma is achieved up to $4.3 \times 10^{13} \text{ m}^{-3}$.

In Nagaoka University of Technology, we study the beam dynamics in the compact electron beam simulators, theoretically and numerically [7-11]. Using the longitudinal envelope equation, the ratio between the repulsion forces due to the space charge and the emittance was estimated. The numerical simulations were carried out in the parameters of compact device. These approaches suggested that the compact simulator is able to simulate the beam dynamics around the stagnation point. A numerical code based on molecular dynamics is developed to calculate the beam dynamics in three-dimensional space. In the multi-particle simulation result, a longitudinal-transverse coupling motion is studied in the compact simulator.

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Recent progress of coherent beam combining Kumgang Laser (0.4J@10kHz/10ns)

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A coherent beam combining is the most promising technique to achieve a high output energy and a high repetition rate laser system with a good beam quality [1]. It has been demonstrated experimentally that the coherent beam combination using self-phase-controlled stimulated Brillouin scattering phase conjugate mirror (SC-SBS-PCM) is the simplest coherent beam combination method [2-3].

For an average output power of a kW range, the experimental verification of coherent beam combination is now underway by the Kumgang laser [4-5].

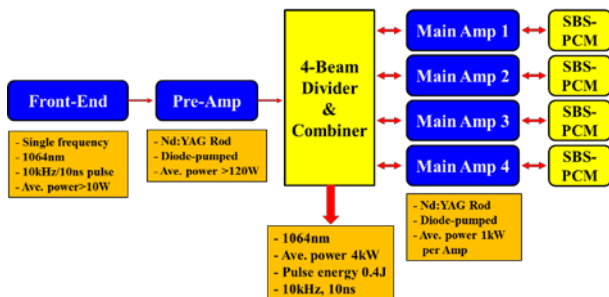


Figure 1. A schematic diagram of the Kumgang laser system

Figure 1 shows the schematic diagram of the Kumgang laser system. The front end (FE) produces a single-frequency seed beam of 1064 nm at a repetition rate 10 kHz. The average output power of the FE is 11 W (1.1mJ@10kHz/8.5ns), and the M2 of the out-put beam of the FE is 1.31.

The seed laser beam from the FE is amplified by the pre-amplifier (PA) from 11 W (1.1mJ@10kHz/8.5ns) to 128 W (12.8mJ @10kHz/8.5ns), and the M2 of the output beam of the PA is 1.8.

After the amplification process, the laser beam is divided into 4 sub-beams by the coherent beam divider/combiner. The wave-front distortion of the each sub-beam is compensated by SBS-PCMs.

The main amplifier stage is composed of a diode-pumped Nd:YAG rod amplifier chain and an SBS-PCM.

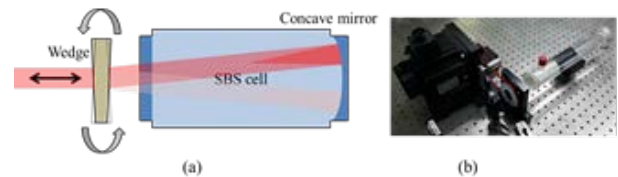


Figure 2. rotating wedge self-phase-controlled SBS-PCM (RW-SC-SBS-PCM); (a) a schematic diagram, (b) A picture of the RW-SPL-SBS-PCM.

For high average power operation of the SBS-PCM, thermal effect at a focus point should be released to keep high reflectivity. In Kumgang laser, the rotating wedge is used to reduce the thermal effect at its focal point. Figure 2 shows the schematic diagram of the rotating wedge self-phase-controlled SBS-PCM (RW-SC-SBS-PCM). The input laser beam is refracted by the rotating wedge, and reflected by the self-phase-controlled SBS-PCM.

After the reflection at the SBS-PCM and after passing through the main amplifier module (MA) again, the sub-beams will be combined by the coherent beam divider/combiner. The MA module can amplifies the laser beam from 128 W (12.8mJ@10kHz/8.5ns) to 640 W (64mJ @10 kHz/8.5ns) for single-pass amplification. In this case, the M2 of the output beam is 1.9. The reflectivity of the SBS-PCM is 56.9% at the input power of 500 W (50 mJ@10kHz/8.5ns).

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Plasma lensing of a laser wakefield accelerated electron bunch

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We report on the first all-optical demonstration of plasma lensing using laser wakefield accelerated electrons in a two-stage setup. The LWFA electron bunch was focused by a second plasma stage without any external fields applied.

Plasma wakefields can provide electrical fields in the order of hundreds of GV/m and thus allow to build compact particle accelerators. However, transportation, shaping and focusing of accelerated particle beams still requires conventional structures which will be much larger than the accelerator itself. As a plasma is used for the acceleration process, it has been shown, that a plasma can be used for focusing the particle bunch as well due to transversal fields inside the plasma wave [1, 2].

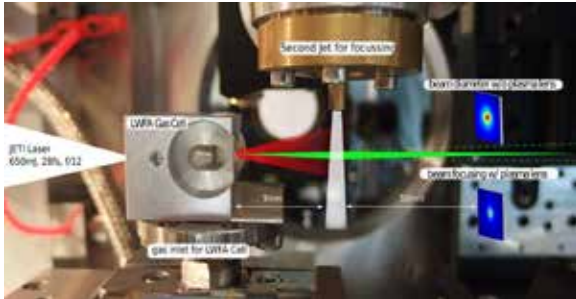


Figure 1: Illustrated photo of experimental setup: the laser pulse, incident from the left, drives an LWFA stage in a mixed-species gas cell, and the generated electron beam expands in vacuum according to its obtained divergence. If the second gas jet is turned on, the remnant and diverged laser pulse preionizes the H₂ gas and the trailing electron beam experiences plasma lensing, which reduces the divergence substantially as observed on a Lanex (Fig 2).

The experiment presented here was conducted at the 40 TW "JETI" Ti:sapphire laser system at the University of Jena, delivering $\tau = 28$ fs pulses at a central wavelength $\lambda_0 = 800$ nm with $E = 650$ mJ on target. The laser pulses were focused by an $f/12$ off-axis parabolic mirror to a spot size $w_0^2 = 120$ μm^2 (FWHM), resulting in a vacuum peak normalized amplitude of $a_0 = 2.2$. The laser focus was aligned to the entrance aperture of a $z_c = 2.5$ mm long gas cell (acceleration stage) as seen in figure 1. The gas in the gas cell was composed of a 95% He, 5% N₂

mixture in order to make use of higher-level laser ionization injection [3, 4]. The LWFA stage produced electron bunches up to $E_{\text{max}} = 130$ MeV with a large energy spread and a total charge of up to 10 pC.

As soon as the focusing stage is turned on, the solid angle covered by the electron beam on the Lanex scintillator screen reduces from 16 mrad² to 6 mrad² (figure 2) while the total charge of the bunch decreases to 75% of its initial value only (not shown). Thus not only a decrease of the electron divergence but also an increase in electron intensity on the Lanex (a net focusing effect) was measured.

The measured focusing matches the results from particle-in-cell simulations with the EPOCH Code (not shown here).

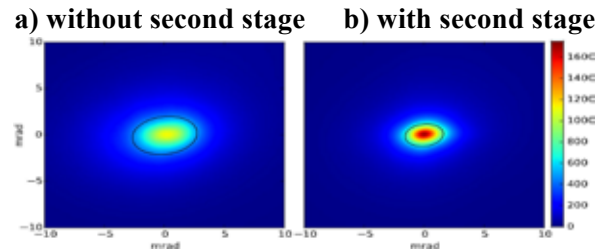


Figure 2: Averaged and center aligned (pointing corrected) beam profile as seen on the Lanex: a) 227 reference shots with the acceleration stage only. b) 175 shots with the second lensing stage. In both pictures the ellipse encloses the standard deviation of a best fit 2D gaussian function to the beam profile. The ellipse reduces its area from 16 mrad² (left) to 6 mrad² (right) when the focusing stage is turned on.

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Multi-Beam Type LINAC for HIF Injector

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The very high intense heavy-ion beam is a high attraction for heavy ion researches and heavy-ion applications, but it is limited by heavy-ion production of existing ion source and space-charge-effect in acceleration. There is one way, accelerating several heavy-ion beams in one cavity at same time and funneling them, which could achieve the acceleration of very high intense heavy-ion beam with existing ion source and accelerating technology.

1. The study of Multi-beam type cavity started in 1990s, and the first multi-beam type cavity, a 2-beam type RFQ which was designed and fabricated by Tokyo Institute of technology, accelerated 108mA C²⁺ beams (54mA / channel) from 5 keV/u up to 60 keV/u [1]. This is a

real breakthrough for accelerating high intensity heavy ion beam. And a prototype 4-beam RFQ was calculated and simulated for the HIF driver. In our proposed multi-beam-type-linac-based HIF injector, there are four laser ion sources which will be connected to a 4-beam RFQ type injector, and a funneling system will be used to funnel the accelerated the four beams to two beams at the outside of the RFQ, then, the two beams will be injected to a 2-beam type drift tube linacs (DTL), after that, the two beams from DTL will be funneled to one beam, and finally, the funneled one beam will be delivered to the post-facilities by using the superconducting type linacs. The image of the multi-beam-cavity-based HIF injector is shown in figure 1.

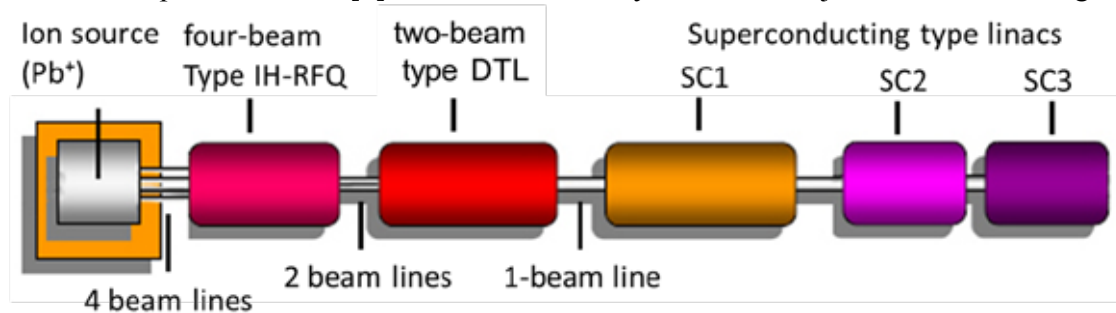


Figure 1. The image of the multi-beam-cavity-based HIF driver.

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High Energy Density Experiments at FAIR

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The Facility for Antiproton and Ion Research (FAIR) will offer unique research opportunities in the field of plasma physics. This research will focus on the study of high energy density matter generated with heavy ion beams.

The equation of state of high energy density matter is important for many scientific fields, ranging from studying the interior structure of giant gas planets and the metallization of hydrogen to the dynamics of laser-driven capsules for inertial confinement fusion. To better understand the relevant processes, knowledge of the equation of state and of the transport coefficients of states with high energy density (eV temperatures and near solid density) is essential. The experiments at FAIR will focus on these measurements.

At FAIR, the SIS-100 heavy ion synchrotron will provide heavy ion beams with up to $5 \cdot 10^{11}$ U^{28+} ions with 2 AGeV in a 50 ns bunch for plasma physics experiments. These ion beams can be used to isochorically heat macroscopic (mm-sized) samples and turn them into warm dense matter with eV temperatures (e.g. in the HIHEX experiment [1,2]). Alternatively, the heavy ion beams can be used to indirectly compress cryogenic samples. By using an annular beam profile to heat a payload, it is possible to quasi-isentropically compress hydrogen to Mbar pressures at sub-eV temperatures, as planned in the LAPLAS experiment [2].

SIS-100 will not only provide heavy-ion beams, but also high-energy protons (up to 10 GeV with up to $2.5 \cdot 10^{13}$ protons per bunch). These proton beams will be used to diagnose dense samples using a proton microscope with a resolution of 10 μm (PRIOR [2,3]). The proton microscope can be used to either study high-

energy density matter generated with secondary drivers (e.g. a laser or a gas gun) or for other applications such as imaging biological samples [4].

Experiments using the SIS-100 heavy ion synchrotron are scheduled to start in 2022. Before that (2018-2021) it is planned to carry out first experiments using the upgraded UNILAC and SIS-18 accelerators at GSI ("Phase 0"). The interim science program ("Phase 0") at GSI (using PHELIX, UNILAC and SIS-18) and at other facilities is essential for further R&D work, and to keep up with technological and scientific progress until the start of FAIR. Activities in this phase will include the further development of PRIOR and work on diagnostics, such as laser particle acceleration, as well as other experiments that do not require the beam intensity of SIS-100. With the start of SIS-100, the experiments of the Modularized Start Version will begin, initially with reduced beam intensity ("Phase 1") and later on with the full beam intensity ("Phase 2").

In my presentation I will give an overview of the experimental facilities and of the planned experiments at FAIR.

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Future energy must be abundant, reliable, clean, safe, and cheap. The problem has to be considered in complex, and not only no of the listed above requirements can be cancelled but on the contrary, many additional requirements should be added. The requirements, in general, contradict each other and cannot be met independently. Mathematically we have a multi-objective optimization problem, where the importance of each factor must be evaluated on the basis of techno-economic analysis.

The global future energy problem is reduced finally to that of energy sources, systems for power generation, transmission distribution, power systems stability and control. Approaching the global problem is an extremely complex task that needs a profound research in fundamental and applied sciences: mathematics, physics, new materials, advanced sensors, big data etc., and original engineering solutions.

Renewables – solar and wind are considered today to be the main sources of future energy. The common feature of them – intermittency,

that leads to the necessity of inclusion into future energy systems energy storage. Intermittency will also result in instabilities of energy systems that in turn leads to the necessity of development of new control and automation systems, new sensors, new control methods - like big data. Taking these novelties in future energy system into account, the evaluations of costs of wind and solar energy become more sophisticated. According to some studies of EROI (energy return on invested energy), solar panels are unprofitable. Other studies result in opposite conclusions. The only we may conclude, that many fundamental questions concerning our knowledge of future energy remain unanswered. Wind and solar will not cover the growing energy demand. New physical solutions are necessary to provide the world population by energy in the future.

In the presentation an overview of main future energy challenges is given.

Operating experience with the laser ion source relevant the HIF application

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Since March 2014, a laser ion source (LIS) has been used to provide high brightness low charge state heavy ion beams for regular routine operation of the hadron accelerator complex in Brookhaven National Laboratory (BNL)[1]. The peak current and pulse width of the typical beams from the LIS are several hundreds of microampere and about 200 microseconds, respectively. Of course, these specifications cannot be directly applied to the HIF. However, only by reducing the plasma drift distance to one tenth, the beam current and pulse width will become 1000 times and 1/10 respectively and these values are not far from the HIF's requirements. Therefore, it would be useful to discuss some operational difficulties and to investigate what should be improved in the existing LIS in BNL toward the HIF application.

The LIS, nicknamed as "LION," was designed to provide multiple ion species to the electron beam ion source (EBIS) where the charge state of the injected ions are multiplied to meet the acceptance of successive linear accelerator chain ($q/m > 6$)[2]. The front-end radio frequency quadrupole (RFQ) accelerates the beams up to 300 keV/u and the following interdigital π mode linear accelerator (IH-LINAC) increases the energy to 2.0 MeV/u. Then, by passing a 275 degree bending section, the undesired charge state beams are scraped and the only purified beams are injected to the booster synchrotron which accelerates the beams around 1 GeV/u. The accelerated beams are guided to two destinations, NASA space radiation laboratory (NSRL) and relativistic heavy ion collider (RHIC). The NSRL requires various species to simulate the cosmic rays and operates in day time. The RHIC accelerate gold beam provided through alternating gradient synchrotron (AGS). The RHIC runs 24 hours for 6 months a year for gold ions from the LIS and protons from the optically pumped polarized ion source (OPPIS). Therefore, the LIS is intensively used to provide heavy ions to two user facilities simultaneously.

Through the long time none stop operation of the LIS, we have experienced some troubles including mechanical failures of the motorized target scanner, built up debris on the vacuum window for the laser beams, suspected accretion on the beam extraction electrodes and energy degradation of the laser systems. Those occurrences were investigated and the structure of the LIS was updated.

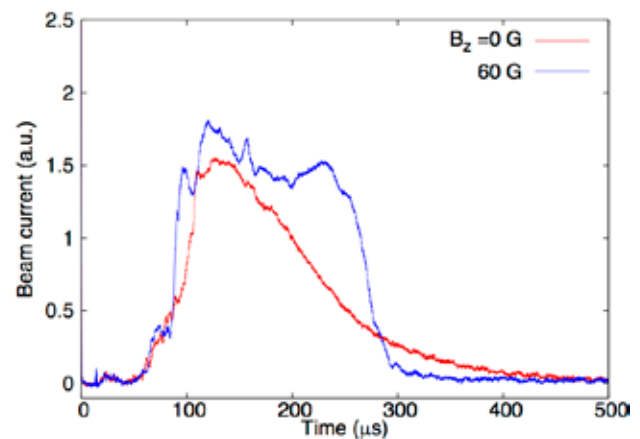


Figure 1. Beam current profile of Fe^{1+} from the LION. The red curve shows the original shape due to thermal distribution in the ablation plasma and the blue curve indicates the modified profile by the pulsed coil.

In addition, recently we have tested a pulsed solenoid in the LIS. This is the new device to tailor the beam current profile. As shown in Figure 1, we could obtain a flat top beam by applying pulsed magnetic field. It is very important to achieve constant current with the minimized variation of the beam emittance.

In the conference, we will explain the details of the difficulties and discuss how we approach to the ideal laser ion source for the HIF application.

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Microscopic and Dynamical Properties of ICF/WDM Plasmas

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Investigation of physical properties of dense plasmas is one of the important topics in the physics of inertial confinement fusion, warm dense matter and high-power lasers physics. Due to the big difference between the mass of ions and electrons the considered plasma is dense and non-isothermal. It is known that the interaction potentials between particles are also of importance for correctly calculation of plasma properties taking into account peculiarities and parameters of investigated plasma [1]. In the case of ICF plasma effective potentials should take into account both quantum and collective (screening) effects for dense, nonideal, nonisothermal plasma. In order to describe the interactions between particles several effective potentials are used. These potentials take into account quantum mechanical, screening and polarizations effects in dense plasmas [2]. The effective potentials between particles in dense nonisothermal plasmas are derived on the basis of the method of dielectric response functions and multipole expansion. The effective dynamically screened potential of a classical ion in a stationary flowing quantum plasma at finite temperature is investigated [3]. The Coulomb logarithm for dense semiclassical fully and partially ionized plasmas has been derived. Stopping power and dynamical processes of dense ICF plasma have been studied by the Coulomb logarithm [4]. Thermodynamic and transport properties of dense plasma have been studied on the basis of proposed effective potentials [5,6]. Calculations of ions energy losses in dense ICF plasma for different values of the temperature and plasma density were carried out. The comparison with data of other theoretical and experimental works has been done.

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Generation and Application of High Intensity Pulsed Ion Beams Using Active Plasma Sources

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The report highlights the researches relating to generation and application of high intensity pulsed ion beams formed by the direct ion acceleration in diode systems or the collective ion acceleration using pulsed electron beams. The dense plasma formed by additional plasma sources served as an ion source. These techniques allow us to form the ion beams of various masses, 10^{-8} to 10^{-6} pulse durations, and 10^5 to 10^7 eV energies for direct ion acceleration. In the case of collective acceleration of heavy ions, the energy can reach 10^8 eV and more.

The explosion of research activities in the field of beam generation dates back within the 60th – 90th of the last century. Last 20 years, we have been observing a certain recession in ex-

perimental and theoretical researches on beam generation. However, the researches on practical application of high intensity ion beams for material science were ongoing.

The application of such beams to study material behavior under energy flows exceeding 10^9 W/cm² or to form ablation plasma ranging within 10^8 – 10^9 W/cm² seem to be very promising. The researches on practical applications of high intensity ion beam sources with energy flows exceeding 10^6 to 10^7 W/cm², which have been developing in Tomsk Polytechnic University, are reviewed. Most important goals of these researches, which would allow us to extend the application potential of high intensity ion beams of nanosecond duration, are considered.

Compressed, Short-Pulse Ion Beams at the Neutralized Drift Compression Experiment

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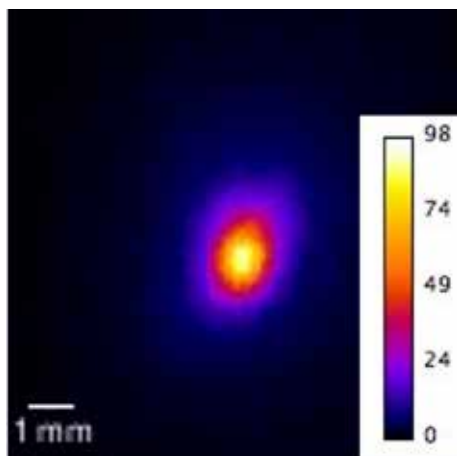
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We will summarize the recent experiments with intense short pulses of ion beams on the Neutralized Drift Compression Experiment (NDCX-II) at Lawrence Berkeley National Laboratory [1], where we have achieved 1-mm beam spot radius within 2.5 ns full-width at half maximum. The ion kinetic energy is 1.2 MeV. To enable the short pulse duration and mm-scale focal spot radius, the beam is neutralized in a 1.5-meter-long drift compression section following the last accelerator cell. A short-focal-length solenoid focuses the beam in the presence of the volumetric plasma that is near the target. In the accelerator, the line-charge density increases due to the velocity ramp imparted on the beam bunch [2]. The scientific topics to be explored are warm dense matter [3], the dynamics of radiation damage in materials [4], and intense beam and beam-plasma physics [5] including select topics of relevance to the development of heavy-ion drivers for inertial fusion energy [6].



The transverse (x, y) distribution of the He⁺ beam at the target plane is shown with a color calibration bar indicating the relative intensity.

Below the transition to melting, the short beam pulses offer an opportunity to study the multi-scale dynamics of radiation-induced damage in

materials with pump-probe experiments [7,8], and to stabilize novel metastable phases of materials when short-pulse heating is followed by rapid quenching [9]. First experiments used a lithium ion source; a new plasma-based helium ion source shows much greater charge delivered to the target [10].

Acknowledgments

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Study of the intense pulsed electron beam energy spectrum from BIPPAB-450

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Intense pulsed particle beams have been widely used and studied as an effective method for material surface modification in the past several decades. Beihang Intense Pulsed Particle Beams 450 accelerator (BIPPAB-450) can produce Intense Pulsed Ion Beams (IPIB) and Electron Beams (IPEB) in two modes with different Magnetically Insulated Diodes (MID). For IPEB, the pulse duration, accelerating voltage, total beam current are 100ns, up to 450keV and 3kA, respectively. In order to get a clear view of IPEB, and further broaden its application, the energy spectrum of IPEB was studied in this work with two approaches. With Child-Langmuir Law, the accelerating voltage of IPEB can be transformed into electron current density. After accumulating the current over the pulse time for separate voltages, an energy

spectrum of IPEB before passing through the Titanium foil cathode can be obtained. Monte-Carlo simulation with Fluka and EGSnrc was applied to calculate the final IPEB energy spectrum after Titanium cathode. To verify the accuracy of the above algorithm, a magnetic spectrometer with an Imaging Plate (IP) was designed to test the IPEB energy spectrum. The IP was placed perpendicular to the electrons' incident direction to record the intensity of electrons with specific radius of curvature in a constant magnetic field. Afterwards, the locations on the IP can be transformed into corresponding electron energies with the theory of relativity. According to the comparison of the above energy spectra, the energy distribution of the IPEB can be basically determined.

A Quantum Beam Driver for the Future Inertial Fusion

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Several heavy ion drivers for the inertial fusion have been proposed in Europe and US based on the existing the RF technology and the linear induction linac technology, though their concepts don't still achieve the reality in a gigantic large scale. Developing accelerator technology may allow a compact and relatively cheap quantum beam driver for the future inertial fusion as an alternative scheme. Through the last decade the induction synchrotron has been developed [1, 2], which can take away a limitation of RF frequency band-width inherent for all RF accelerators and remarkably increase a freedom of beam handling by the functional separation of beam acceleration and confinement in the moving direction. Especially the feasibility study of induction microtrons [2], in which heavy ions such as Pb²⁺ or C-6010⁺ with a large mass to charge ratio can be accelerated from their extremely low energy, tells us that it may be available as a kind of injector for the downstream main driver. At the conference, a novel driver system will be proposed, which consists of a multiple and two-way induction synchrotron, a permanent magnet stacking ring, and induction microtrons as an injector. The paper is accompanied with related papers describing the cluster ion source and the high power 3.3 kV SiC-MOSFET switching device that are crucial to realize the novel quantum beam driver of concern.

KEK 12GeV PS and Tevatron of Fermilab have been already shutdown. Other high energy accelerators being operated in the world will cease their roles until 2030. SuperKEKB, RHIC of BNL, and HERA of DESY may be among them. Their infrastructures such as accelerator tunnels with the perfect radiation shield capability are quite valuable. Their recycle uses for the future fundamental energy science should be supported by tax payers, though there may be some friction with the existing stakeholders. The authors wish to create a kind of international consortium to consider our present task with the same vector.

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High Energy Density Research at the future project HIAF in China

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A large scale scientific research platform, named the High Intensity heavy-ion Accelerator Facility (HIAF), was proposed in light of the trend and development in nuclear physics and the associated high energy heavy ion research fields. HIAF is one of the 16 approved national projects for basic sciences and technologies as the 12th five-year-plan in China; it will be a laboratory open to the outside world, similar to CSR which was built as the 9th five-year-plan in China [1]. The HIAF complex, as shown in Fig. 1, includes a SECR (Superconductive Electronic Cyclotron Resonance) ion source, an ion linear accelerator (i-Linac), a Booster Ring (BRing), a Spectrometer Ring (SRing), a Compression Ring (CRing) and about 8 experimental terminals.



Figure 1. Layout of the HIAF complex and the two terminals for HEDP research

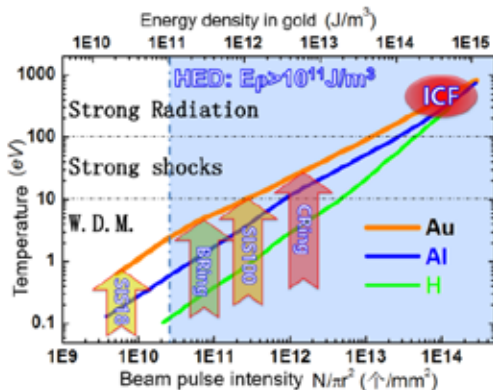


Figure 2. Temperature and energy density achievable by different accelerators

Since both BRing and CRing can produce high-energy and high-intensity ion beams (see Fig. 2), two terminals for HEDP (High energy density physics) research were proposed at HIAF, one for crossing (T1) and the other for colliding (T2) of the beams from BRing and CRing at the target area. However, mainly due to the budget limitation

and

technical challenges, CRing will **NOT** be included in the first stage of the HIAF project.

The key parameters related to HEDP research at HIAF and other advance heavy ion drivers is listed in Table 1, where E_0 , N , E_{total} , S_f , t and E_p are the particle energy, the beam intensity (unit, ppp), the total beam energy per pulse, FWHM of the beam spot, the pulse duration and energy density in a lead target (J/m^3), respectively.

	SIS-18	FAIR(Ph-I)	HIAF (Ph-I) ^a
E_0	0.4 GeV/u	1 GeV/u	1.1 GeV/u
N	4×10^9	4×10^{11}	$1-3 \times 10^{11}$
E_{total}	0.06 kJ	15 kJ	4-12 kJ
S_f	~ 1 mm	~ 1 mm	1 mm
t	130 ns	50 ns	130-400 ns
E_p	2×10^{10}	2.4×10^{12}	$6-18 \times 10^{11}$

Table 1. Key parameters related to HEDP research at HIAF and other heavy ion drivers (for uranium beam).

^a The upper limit may rely on the budgets of HIAF, and Ph-I means that we take the beam parameters of BRing.

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Energy Deposition and Excitation of Wakefield in Case of 100keV/u Ion Beam Passing through a Plasma Target

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Recently our team investigated the energy deposition and excitation of wakefield in case of hundreds keV proton/helium ion beams passing a gas-discharged plasma target. The plasma target was produced by igniting an electric discharge of hydrogen gas in two-collinear quartz tubes, each of 5mm in diameter and 78mm in length, the electrical current even up to kA will flow in two opposite directions in either of the two quartz tubes. This device could produce the hydrogen plasma with the line-integrated free electron density of up to 10^{17-18} /cm², and with the temperature of around 2eV when the discharge current was reaching the maximum, as shown in figure1.

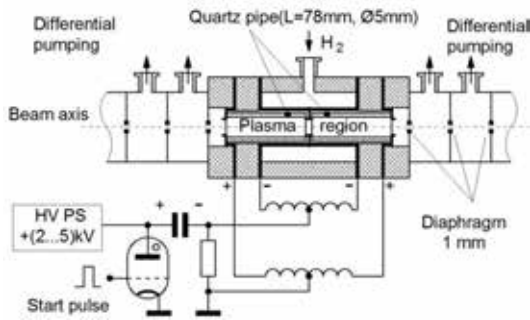


Figure 1 the scheme of the plasma target

The experiments were performed at the HV-ECR platform at IMP (see details in ref [1, 2]). As an example, figure 2 shows the measured beam after 100keV proton beam penetrating the hydrogen plasma target (with initial gas pressure of 3mbar, and discharging High-Voltage of 3kV) in terms of time after discharging. Enhanced energy loss comparing to that for neutral gases has been observed. Moreover, we found that the proton beam was strongly focused while energy of the focused beams is uniform. We carried out some PIC simulations, which suggests that the wake-field could form a self-modulated, periodic(pulsed), focusing, collision-less tunnel. More details will be reported later [3,4].

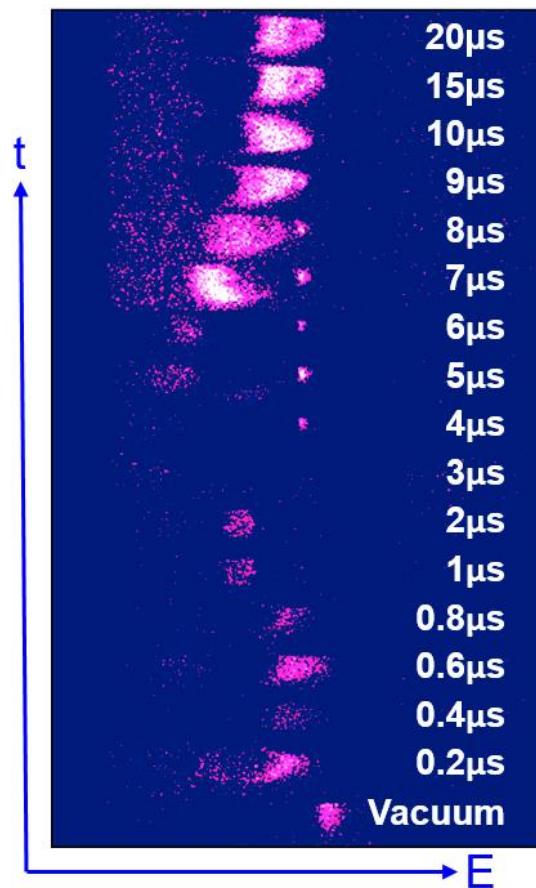


Figure 2 the measured beam after 100keV proton beam penetrating the hydrogen plasma target.

The work is supported by NSFC (11275241, 11375034 and U1532263).

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ORAL TALKS

Stopping of relativistic ions in multicomponent plasmas

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Investigation of the processes of stopping of charged particles moving in different media is of significant interest for many realms of Physics, such that Nuclear Physics, Condensed Matter Physics, Plasma Physics, etc.

The problem of evaluation of energy losses of relativistic protons has acquired special importance recently [1] and, due to the experimental conditions, it is necessary to estimate relativistic corrections to the asymptotic form of energy losses in non-ideal multicomponent plasmas.

Thus, we have studied corrections to the modified asymptotic Bethe-Larkin expression for the stopping power taking into account those related to the target ions, described in [2], and different components of ions in the nonrelativistic target plasma.

The polarizational formalism, which becomes more precise for faster projectiles, has been used in the present work to calculate the energy losses of a fast particle penetrating the Coulomb system. In 1959 Lindhard obtained an expression relating the plasma polarizational stopping power to the system dielectric function, which can be generalized using the Fermi golden rule [3]:

$$-\frac{dE}{dx} = \frac{2(Ze)^2}{\pi v^2} \int_0^\infty \frac{dk}{k} \int_{\alpha_-(k)}^{\alpha_+(k)} \omega n_B(\omega) (-Im\epsilon^{-1}(k, \omega)) d\omega,$$

$\alpha_\pm(k) = \pm kv + \hbar k^2 / 2M$, Ze , v , M are the projectile charge, speed, and mass, while $n_B(\omega) = (1 - \exp(-\beta\hbar\omega))^{-1}$, where β^{-1} is the system temperature in energy units.

The dielectric formalism we employ is based on the method of moments [4], which permits to determine the dielectric function in terms of the first known converging sum rules:

$$\epsilon^{-1}(k, z) = 1 + \frac{\omega_p^2(z+q)}{z(z^2 - \omega_2^2) + q(z^2 - \omega_1^2)},$$

where

$\omega_1^2 = \omega_1^2(k) = C_2 / C_0$, $\omega_2^2 = \omega_2^2(k) = C_4 / C_2$, for any $q = q(k, z)$, analytic in the upper half-plane $Imz > 0$, where its imaginary part is positive, and such that $\lim_{z \rightarrow \infty} q(z)/z = 0$ there.

Under the sum rules we understand the power-frequency moments of the plasma loss function, defined as:

$$\mathcal{L}(k, \omega) = -\omega^{-1} Im\epsilon^{-1}(k, \omega) \quad \text{and}$$

$$C_\nu(k) = \pi^{-1} \int_{-\infty}^{\infty} \omega^\nu \mathcal{L}(k, \omega) d\omega, \nu = 0, 1, \dots$$

Relativistic corrections to the Linhard formula were studied in [5]. Using the dielectric formalism of the method of moments, we can write the estimating formula for the energy losses of relativistic particles as:

$$\begin{aligned} \left. \frac{-dE}{dx} \right|_{v \rightarrow c} &\simeq \left(\frac{Ze\omega_p}{v} \right)^2 \ln \frac{2mv^2}{\hbar\omega_p \sqrt{1+H}} + \\ &+ \left(\frac{Ze\omega_p}{c^2} \right)^2 \int_{\frac{\omega_p \sqrt{1+H}}{v}}^{\frac{2mv}{\hbar}} \frac{dk}{k^3} \frac{\omega_2^2(k) \left(1 - \frac{\omega_2^2(k)}{k^2 v^2} \right) (\omega_2^2(k) - \omega_1^2(k))^2}{\Omega^4(k) + \left(\frac{\omega_p^2 \omega_2(k) Imq(k, \omega_2(k))}{|q(k, \omega_2(k))|^2} \right)^2}, \end{aligned}$$

where

$$\begin{aligned} \Omega^2(k) &= \omega_p^2 + (\omega_2^2(k) - \omega_1^2(k)) \left(1 - \frac{\omega_2^2(k)}{k^2 c^2} \right) + \\ &+ \frac{\omega_p^2 \omega_2(k) Req(k, \omega_2(k))}{|q(k, \omega_2(k))|^2}. \end{aligned}$$

In the multicomponent plasmas, we can calculate the power moments with taking into account all types of ions, as was done in [4], but for the model of "averaged" hydrogen-like atom [5].

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Subsystem Tabulation of the Single Pass RF Driver

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This paper presents a subsystem-by-subsystem description of the Single Pass RF Driver (SPRFD). The purposes are to show SPRFD's relationships to RF driver features assessed from 1976, to isolate the differences that affect prior conclusions about workability of RF drivers including confidence in pellet ignition, and to highlight the key associated technical issues to help prompt experts in the various areas to appreciate the specific challenges and perhaps become interested in their assessment. For important context and to show the excellent prospects for the complete HIF power plant, the pellet and chamber subsystems are likewise described and assessed.

The SPRFD has been described in various ways, at HIF2010, AHIF in 2011, and HIF2012. The most useful attention was by the working group for RF drivers at AHIF, which reported out a set of recommendations with the first being: "A more detailed examination of the Single-Pass HIF Driver concept may be a good starting point" pursuant to the objective that: "Now is the time for developing detailed conceptual designs for economical energy production that take advantage of decades of progress in accelerator physics and RF accelerator technology." [1] Examination of detailed conceptual designs was the essence of the format

of the first several HIF Workshops, and the features of the SPRFD, the matching pellet design, and the chamber with a "hat trick" of advances needs that kind of focus and intensity.

This paper continues the effort to disseminate information about the SPRFD to facilitate the progress on its design recommended at AHIF. To that end, the paper is organized as a set of tables presenting descriptions and assessments of its subsystems: front ends comprising multiple HVDC, initial RF stages each accelerating

16 different isotopes for a total of 1024 separate ion sources, and alignment of the 16 isotopes into single beamlines for a total of 64 parallel beams; main RF linac with zippers that reduce the number of beams to four; the linac section that outputs isotopes at equal magnetic rigidity to telescope at the pellet; delay lines that rearrange the macropulses and then remove the preponderance of empty space between them; drift

lines that maintain the phase spaces of individual microbunches while the distances between the isotopic macropulses decrease in a prelude to telescoping; chirping the individual microbunches in each isotopic macropulse to drive a final compaction of each macropulse; spiral wobbling the different isotopic pulses by different amounts according to their role in driving pellet implosion and ignition; and focusing the equal stiffness beams to build the power profile for the sequence of pre-pulse, compression, and ignition. The pellet subsystem table covers the results of the most recent simulations of implosion and fuel burn for cylindrical targets with fast ignition [2]. Description of the chamber subsystem focuses on the multiple ways lithium is deployed to combat the fusion neutrons, deliver very high temperature Li to the primary heat exchangers, and keep structural materials at temperatures like an automobile engine.

In setting forth this description of the SPRFD in accessible pieces, we hope to prompt appropriate action according to AHIF's clear recommendation, and restore HIF dedication to push this highly recommended, "best bet" for fusion power to the energy market.

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Investigations on the interaction between the low energy heavy ion beams and hydrogen plasma

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The investigations on the interaction between ion beam and matter is one of the most important topics in atomic physics and nuclear physics. It is indeed a requirement for a deeper understanding of the interaction processes. Especially the energy deposition by an intense heavy ion beam with the low energy impinging into a degenerate matter, which is related to the topics of warm dense matter, fast ignition process and helium ions self-heating in the fusion process.

The study on the energy loss of the low energy protons and helium ions in a hydrogen plasma target which is produced by an electrical discharge in hydrogen gas at Institute of Modern Physics is carried out [1-3]. With the independent laser interferometry measurement, the linear electron density of the plasma column is obtained. The energy loss for the ions in the low energy regime with linear electron density of 10^{17}cm^{-2} is compared. It is found that the enhanced energy losses in plasma than that in cold gas for both of proton and helium ions. In the proton case, the results can be well described by the Bethe, Standard Stopping Model (SSM), Li-Petrasso and Vlasov models, respectively. The energy loss in plasma is enhanced by a factor of 2.8 to that in

cold gas; the Bethe-Bloch Coulomb logarithm term of the stopping equation is larger by a factor of 4 for free electrons as compared to the situation where bound electrons prevail. In helium ions case, not only the enhancement of energy loss is found, but also the effective charge states of helium ions in plasma and in cold gas are compared.

More experimental details and the discussions will be presented in the conferences.

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Creation of nanoporous SiO₂/Si with precipitated Zn using track technology

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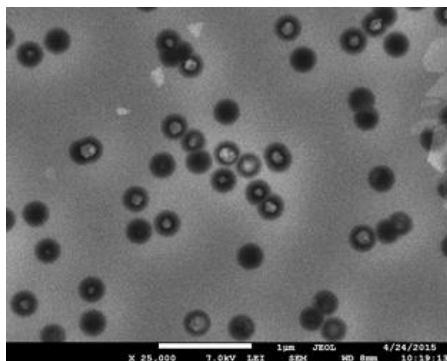
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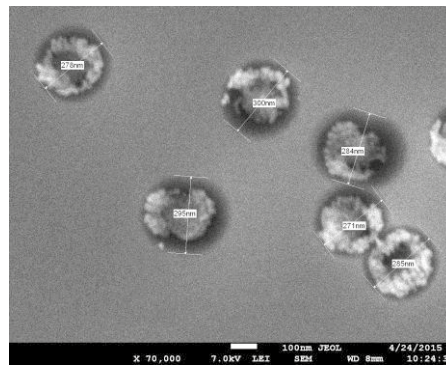
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SiO₂/Si structures, produced by thermal oxidizing of silicon substrate. According to ellipsometric data, thickness of oxide layer is 600 nm. Samples were irradiated on accelerator DC-60 (Astana, Kazakhstan) with Xe ions with energy 133 MeV fluence $1 \times 10^9 \text{ cm}^{-2}$.

After etching of ion tracks in 4% water solution of hydrofluoric acid (HF), a precipitation of Zn was performed by chemical and electrochemical methods, at room temperature. Morphology of SiO₂/Si surface before and after precipitation was examined on scanning electronic microscope (SEM) JSM-7500F.



The surface of Si/SiO₂/Zn, (SiO₂/Si irradiated with Xe 133 MeV, $1 \times 10^9 \text{ cm}^{-2}$), after chemical deposition during 1 min.



The surface of Si/SiO₂/Zn, (SiO₂/Si irradiated with Xe 200 MeV, $1 \times 10^9 \text{ cm}^{-2}$), after electrochemical deposition during 7 min.

Photoluminescence spectrum of SiO₂/Si(Zn) has a weak peak at 376 nm and sharp peak at 492 nm. For ZnO, the former is related to emissive **exciton** annihilation, and the latter is related to oxygen vacancy. Thus, it is safe to argue that ZnO forms in nanopores during the Zn precipitation process. Luminescence intensity of electrochemically precipitated sample is higher than that of chemically precipitated sample. Annealing in argon atmosphere and in air leads to sudden weakening of glowing of the electrochemically precipitated sample, while the chemically precipitated sample displays little change. Luminescence curve's form in both cases undergoes significant changes after annealing

Two-body and three-body mesonic bound states in ultradense plasmas of fusion catalysis concern

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Atomic and molecular recombination of negatively charged mesons in warm dense matter (WDM) and fast ignition (FIS) ultradense plasmas, on low lying bound states is demonstrated, as well as a former conjecture about the negligibility of meson sticking on fusion produced α particles.

Mesonic catalysis of DT fusion reactions is then shown possible in short lived FIS and WDM plasma targets.

Collisional and optical properties of the dense semiclassical plasma

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Elastic and non elastic scattering of the electrons are the elementary processes that continuously attract the attention of the researchers. For developing of the applications, where plasma is a working medium, one needs adequate data on physical properties of the system. Electron scattering strongly influences the transport, optical and other properties of plasmas. A large number of various theoretical and experimental studies is devoted to the scattering of the electrons on the noble gas atoms. Various theoretical methods are used for studying of the elementary processes and plasma properties.

In this work we consider the dense partially ionized plasma of the noble gases consisting of the electrons, ions and atoms. Particle densities are in the range of $n = 10^{20} \div 10^{23} \text{ cm}^{-3}$ and the temperature range is from $2.5 \times 10^4 \text{ K}$ up to $5 \times 10^4 \text{ K}$.

In work [1] the effective potential of electron-atom interaction, taking into account both quantum-mechanical effect of diffraction and screening effects, is presented. The way to take into account the dynamic screening was proposed in work [2], where the statical Debye radius was replaced by the dynamic one:

$$r_o = r_D \left(1 + \frac{v^2}{v_{Th}^2}\right)^{1/2}, \quad (1)$$

here v is the relative velocity of the colliding particles, v_{Th} is the thermal velocity of the particles in the system. Then the effective potential of electron-atom interaction with dynamic screening can be rewritten as [3]:

$$\Phi_{ea}(r) = -\frac{e^2 \alpha}{2r^4 (1 - 4\tilde{\lambda}_{ea}^2 / r_o^2)} \left(e^{-Br} (1 + Br) - e^{-Ar} (1 + Ar) \right)^2, \quad (2)$$

where

$$A^2 = \frac{1}{2\tilde{\lambda}_{ea}^2} \left(1 + \sqrt{1 - 4\tilde{\lambda}_{ea}^2 / r_o^2} \right),$$

$$B^2 = \frac{1}{2\tilde{\lambda}_{ea}^2} \left(1 - \sqrt{1 - 4\tilde{\lambda}_{ea}^2 / r_o^2} \right).$$

In the framework of this pseudopotential model for the particle interactions, the scattering phase

shifts δ_l were calculated on the basis of the Calogero equation:

$$\frac{d\delta_l(k, r)}{dr} = -\frac{1}{k} U(r) \times \left[\cos \delta_l(k, r) \cdot J_l(kr) - \sin \delta_l(k, r) \cdot n_l(kr) \right]^2, \quad (3)$$

$$\delta_l(k, 0) = 0.$$

Here k is the magnitude of the wave vector of the incident particle, $U(r) = \frac{2m}{\hbar^2} \Phi_{ea}(r)$, $j_l(kr)$ and

$n_l(kr)$ are the Ricatti - Bessel functions.

Phase shifts enable us to calculate the transport scattering cross section $Q_{ea}^T(k)$. The collision frequency of the electrons with atoms ν_{ea} can be obtained by the following expression:

$$\nu_{ea} = 4 \sqrt{\frac{2}{\pi}} n_a \sqrt{\frac{k_B T}{\mu_{ea}}} \int_0^\infty Q_{ea}^T(g) g^3 \text{Exp}(-g^2) dg, \quad (4)$$

here $\mu_{ea} = m_e m_a / (m_e + m_a)$ is the reduced mass of the electron-atom pair, g is the reduced velocity.

Dielectric function due to the electron - atom interactions was calculated using the generalized Drude-Lorentz equation:

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 - i\nu_{ea}\omega}. \quad (5)$$

From the dielectric function the reflectivity of the semiclassical electron plasma is calculated, using the Fresnel formula, and is compared with experimental results [4].

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Thermodynamic properties of non-isothermal plasma of ICF

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In this work dense non-ideal, non-isothermal plasma of ICF (inertial confinement fusion) was considered. Correct calculation of plasma properties requires taking into account parameters of plasma. For this purpose interaction potentials of particles were used. The electron-ion temperature in [1] was used in the form $T_{\alpha\beta} = \sqrt{T_\alpha T_\beta}$.

Effective screened interaction potentials taking into account the quantum-mechanical effect of diffraction were used [2-3]:

$$\Phi_{\alpha\beta}(r) = \frac{Z_\alpha Z_\beta e^2}{r} \frac{1}{\gamma^2 \sqrt{1 - (2k_D / \lambda_{ee} \gamma^2)^2}} \times \\ \times \left(\left(\frac{1/\lambda_{ee}^2 - B^2}{1 - B^2 \lambda_{\alpha\beta}^2} \right) \exp(-Br) - \left(\frac{1/\lambda_{ee}^2 - A^2}{1 - A^2 \lambda_{\alpha\beta}^2} \right) \exp(-Ar) \right) - \\ - \frac{Z_\alpha Z_\beta e^2 (1 - \delta_{\alpha\beta})}{r} \frac{1}{1 + C_{\alpha\beta}} \exp(-r / \lambda_{\alpha\beta}), \quad (1)$$

where $k_D^2 = k_e^2 + k_i^2$ is the screening parameter taking into account the contribution of electrons and ions, $\gamma^2 = k_i^2 + 1 / \lambda_{ee}^2$,

$$A^2 = \frac{\gamma^2}{2} \left(1 + \sqrt{1 - \left(\frac{2k_D}{\lambda_{ee} \gamma^2} \right)^2} \right), B^2 = \frac{\gamma^2}{2} \left(1 - \sqrt{1 - \left(\frac{2k_D}{\lambda_{ee} \gamma^2} \right)^2} \right), \\ C_{\alpha\beta} = \frac{k_D^2 \lambda_{\alpha\beta}^2 - k_i^2 \lambda_{ee}^2}{\lambda_{ee}^2 / \lambda_{\alpha\beta}^2 - 1}.$$

Pair correlation functions were obtained in the exponential approximation:

$$g_{\alpha\beta}(r) = \exp\left(-\frac{\Phi_{\alpha\beta}(r)}{k_B T}\right), \quad (2)$$

Composition of plasma was studied using the system of Saha equations:

$$\frac{n_0}{n_e n_i} = \frac{g_0}{g_e g_i} \exp\left(\frac{I - \Delta I}{k_B T}\right), \quad (3)$$

where g_k is statistical weight, ΔI is the lowering of the ionization potential.

Thermodynamic properties were calculated on the basis of effective potentials (1): internal energy $U = \sum_\alpha 3/2 N_\alpha k_B T_\alpha + U_N$, where the correlation energy of interaction is:

$$U_N = 2\pi V \int_0^\infty \sum_{\alpha, \beta} n_\alpha n_\beta \Phi_{\alpha\beta}(r) g_{\alpha\beta}(r) r^2 dr, \quad (4)$$

and the equation of state:

$$P = P_{id} - \frac{2\pi}{3} \int_0^\infty \sum_{\alpha, \beta} n_\alpha n_\beta \frac{\partial \Phi_{\alpha\beta}(r)}{\partial r} g_{\alpha\beta}(r) r^3 dr, \quad (5)$$

where $P_{id} = n_e k_B T_e + n_i k_B T_i$ is the pressure of ideal plasma, N is the number of particles in the system.

The obtained thermodynamic properties were used for solving the Hugoniot equation [4].

The Hugoniot equation describes the connection between density and pressure of the gas in front of and behind the shock front. Parameters of gas change very rapidly and in a very narrow field with the passage through the shock wave.

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Electron-ion energy partition for alpha particle moving in fusion DT Plasmas mixed with hot Au

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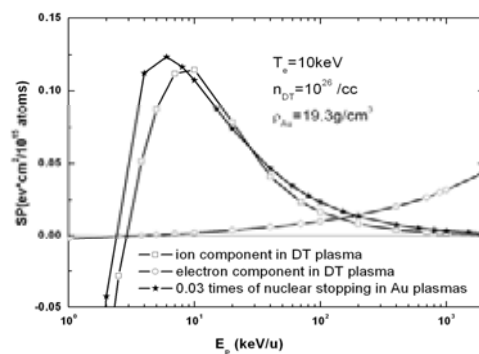
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The heating of DT ion by alpha particle is crucial to the realization of the nuclear fusion and it has been studied for many years. Besides DT material, some other materials such as Be and Au are often used in the design of fusion targets [1] or fusion device of fast ignition driven by ions. During the implosion process these materials would mix with DT fuel inevitably. How the mixed material influence the heating of DT ion is still unknown to us, which is the motivation of the present work, where the case for Au mixture is considered.

For this problem the electron-ion energy partition for alpha particle in DT Plasmas should be studied first. The related investigation has been made with the mechanism for the excitation of the ionic acoustic wave to discuss the problem in ICF dense plasma [2]. In recent time this problem was discussed in BPS model [3] in a complex form when both the coulomb binary collision and the ionic acoustic wave excitation were considered. In the first part of the present work the mechanism of the field fluctuation [4] is introduced to discuss the problem in DT plasmas. It is naturally found that the heating of the plasma is stopped when the projectile energy is slowed down to the plasma temperature T_e , which is more reasonable than the models mentioned above. Based on this the electron-ion energy partition in DT plasmas is obtained, which is compared with different models with their differences explained.

Au ion is almost in fully ionized state for $T_e \geq 5\text{keV}$ according to the average atom model [5]. Near the end of alpha particle range the energy exchange between alpha particle and the Au ion becomes important, which will influence the heating of DT ion in the mixed plasmas due to the highly charged state of Au ion. Reasonable result of the problem is obtained by us according to the binary collision mechanism with the Au ion potential obtained from the average atom model. It is found that the well-known binary collision model with constant Coulomb logarithm [6] as well as the revised model by Ferrariis and Arista [7] is not suitable in this case although they work well in DT plasmas. The reason for this is found and how to improve this in Coulomb potential is obtained, which is useful for rapid and reliable calculation.

Basing on the above work electron-ion energy partition for alpha particle in the mixed DT+Au plasmas is studied in the case of solid Au density with a huge range of plasma temperature and DT density for different percentage of Au. The preliminary results show that the heating of DT ion will be strongly affected by the mixed highly charged Au ion for the temperature beyond 10keV and the percentage of Au beyond 5%. The following figure presents the related components of stopping power for DT, electron and Au ion in a specific case. The relevant results will be presented in detail in the conference.



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The Economics of an HIF SPRFD Fusion System in a Desert Region

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The economics of the FPC SPRFD fusion power system have been discussed previously by Helsley and Burke (2014) in a general model that was based on marketing of electricity and the production of synthetic fuel from the excess generating capacity. The SPRFD system can produce electricity at a price between US\$0.04 to US\$0.06 per kWh and synthetic fuel at about US\$3 per US Gallon. Desert regions not only need electricity and fuel for their development but they also need water. Since electric generators and synfuel production both produce low temperature waste heat, we examine the value of producing water from the waste heat using multieffect distillation(MED) processes. We will focus on the energy and water needs of Iran as a site specific model.

Iran's population has grown 8-fold in the past 100 years and continues to grow at more than 1 percent per year. Water shortages are common and per capita consumption is between 180 liters and 250 liters per day depending on location. Expanding industrial and agricultural needs are also present. Thus water becomes a limiting resource for economic development.

A typical SPRFD system produces 100 GigaJoules of heat. Unless direct electrical conversion process are implemented, approximately 50 percent of this heat is captured during the conversion to electricity and the production of synfuels. The other 50 percent is either lost to the environment by radiation from hot surfaces or is discharged via cooling towers or cooling water. Using the analysis provided by SIDEM, a major multi-effect distillation (MED) system supplier, we find that the maximum heat desired is 75 degrees C. and that the waste heat from a 2.7 GW combined cycle gas turbine plant, assumed to be about 60 percent efficient, can deliver 800,000 m3 per day (SIDEM Video on Marfaïq Jubail facility - <http://www.sidemdesalination.com/medias/multimedia/?playId=42491>) simply by use of the spent steam to heat seawater for low pressure evaporation.

A fully developed SPRFD facility can produce about 20 times as much electricity as the Jubail facility and thus it should be able to produce 20 times as much fresh water. Cost information

supplied by SIDEM indicate that the water making portion of the facility with an output of 15 Million m3 per day would cost about US\$16 Billion. Burke and Helsley (2014) estimated that the SPRFD system including a modest synfuel making facility would cost US\$80 Billion. Thus for a combined cost of US\$100 Billion one could get 50 GigaWatts of electricity (continuous capacity), 15 million m3 of distilled water per day, and the ability to produce at least 100,000 barrels of carbon-neutral synthetic liquid fuel per day.

Most of the populated areas of Iran are above 1000 meters but less than 2000 meters. There are major land areas that could be irrigated at less than 500 meters in essentially undeveloped areas. Pumping costs can be estimated to be 6kWh per m3 for a lift of 1800 meters and the fully amortized horizontal transport of water can be as low as US\$0.09 cents per hundred kilometers (UN Publication E/ESCWA/SDPD/2009/4). But the challenge in Iran will be the high mountains between the Persian Gulf and interior use areas. If a SPRFD system were built near Bandar Abbas, a delivery route exists at elevations less than 2000 meters that could deliver water to central areas such as Rafsanjan and continue on to the vicinity of Tehran – a total distance of about 1500 km.

Water produced by MED systems has a fully amortized cost of about US\$0.50 per m3 produced. Pumping cost to the high elevations of central Iran would add an additional US\$0.24 per m3 and long distance transportation in pipe and canals would add an additional US\$0.09 per hundred kilometers of transport. Thus for a cost of approximately US\$1.00 to \$2.00 per cubic meter water could be delivered anywhere in central Iran at elevations less than 1800 meters.

The combined income from electricity, synfuel and water from a SPRFD system may be a viable option for industrial and economic growth of Iran. A system could be 'in place' in a decades time.

Development of an advanced water filtering system based on graphene irradiated by gas cluster and highly charged ions

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Effects of a heavy low energy ion bombardment of various materials are explored for the purposes of creating new materials that have advanced properties. In this study, features of the defects' formation in the samples of graphene, graphene oxide and silicon by Ar cluster ions irradiation are given. Irradiation was performed by Ar cluster ions with acceleration energy 30 kV and total fluence of Ar cluster ions ranged from $1 \times 10^9 \text{ cm}^{-2}$ to $1 \times 10^{13} \text{ cm}^{-2}$. Samples of multi-layer graphene oxide, mono- (SLG), few-layer (FLW) of graphene and polished Si are used for irradiation experiments. Characterization of the irradiated samples was conducted by the methods of Raman spectroscopy, atomic force microscopy and NEXAFS. Irradiation of graphene, graphene oxide and silicon resulted in crater/defect formation over the surface. Small pores on the surface of the graphene oxide samples were formed under such parameters, with the mean pore size of 10-20 nm and depth of 2-4 nm. AFM results proved the presence of nanopores on graphene oxide structure. AFM images of irradiated silicon shows formation of craters on surface of silicon with crater dimension of 20 nm in diameter and 1 nm deep. The distribution of craters was concordant with the Gaussian distribution of the mass-to-charge ratio for individual clusters measured using TOF and the size distribution with an average size of about 1000 atoms per cluster. Additionally to AFM irradiated samples of graphene, graphene oxide and silicon was characterized by Raman spectroscopy. Characteristics of the defects formation in the samples of graphene oxide produced by cluster ions were compared to those by highly charged $^{131}\text{Xe}^{+22}$ ions, with fluences of 10^{12} - $10^{15} \text{ ions/cm}^2$ and with

kinetic energy 1.75 MeV were presented. The analysis of irradiated samples was conducted by using Raman spectroscopy and the near edge X-ray absorption fine structure (NEXAFS). Computer simulations of defects were studied by multiscale method. Ab-initio DFT was applied to study mono- and divacancies in monolayer and multilayer graphene. Individual gas cluster ion impacts on suspended graphene sheet and a graphene on various substrates were carried out using Sandia Labs LAMMPS package and the results were passed to a finite element COMSOL multiphysics package for the development of a porous media filtering system.

Effect of tapered magnetic field on expanding laser produced plasma for heavy ion inertial fusion

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The ion source performance required for heavy ion inertial fusion (HIF) is beyond that used for current operating particle accelerator facilities. Ion sources are required to provide several tens to hundreds mA of low charge state heavy ions ($q/A \sim 100\text{--}200$), such as Bi^{1+} to minimize the difficulty of a final focusing system caused by space charge repulsion force.[1] A laser ion source (LIS) is one of a promising candidate of such ion sources. We already demonstrated more than 60 mA of the accelerated highly charged carbon and aluminum beam by a RFQ accelerator by extracting ion beam inside of the RFQ. [2] This method is called direct plasma injection scheme (DPIS).

Laser produced plasma containing heavy ions are produced from a solid state target irradiated by a high power pulsed laser. The laser power density of below 10^9 W/cm^2 is typically required for the production of singly charged ions [3]. The plasma expands toward the normal direction to the target surface before ions are extracted by extraction potential. The plasma pulse width is proportional to the plasma drift distance. However, in case of free expansion, the ion beam current rapidly decreases as expanding and follows, $j \sim L^{-3}$, where j is current density and L is a drift distance, respectively. To avoid a blowup of a beam caused by space charge effect, it is essential to manipulate the shape of the plasma before an intense ion beam is extracted.

The behavior of the expanding laser produced plasma in a magnetic field has been extensively investigated at BNL. So far, we demonstrated that a static solenoid magnetic field confines the plasma in transverse direction. We observed the enhancement of the Cu^{1+} beam current by ~ 60 times with the solenoid field of 160 Gauss.[4] We also demonstrated that a

pulsed solenoid magnet can be used to control the temporal profile of the plasma from the shifted Maxwellian distribution. [5]

In this paper, we will discuss the effect of a tapered magnetic field on the expanding laser produced plasma. The previous studies showed that the plasma follows magnetic field lines to some extent and could be treated as a virtual particle. [6] The solenoid magnetic field of the interest has a wider opening on the target side. This configuration is to collect more area of the plasma to the ion extraction aperture, which could be about 10 mm in diameter slightly smaller than the aperture of a RFQ accelerator. This is highly preferable when a large laser is used. For example, the laser spot radius could be about 40 mm in diameter assuming a 100 J/10 ns laser for the production of singly charged ions. Other advantage is that the option to use multiple small lasers to irradiate different spots on a target for a single ion beam pulse. In this case, we can tolerate multiple failures of the lasers without disturbing the operation of a power plant.

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Target implosion uniformity in heavy ion fusion

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It is well known that heavy ion beams (HIBs) have a high controllability, a high driver energy conversion efficiency and a high repetition rate. Wobbling HIBs are easily available as the energy driver in inertial fusion.

Previous studies have shown that spiral wobbling HIBs mitigate the illumination non-uniformity [1]. Figure 1 shows a schematic diagram for the spiral wobbling beam. For the spiral wobbling beam the beam radius changes from 3.1mm to 3.0mm at $t = 1.3\tau_{wb}$. Here τ_{wb} is the time for one rotation of the wobbling beam axis. The beam rotation radius becomes 2.0mm at $t = 2.0\tau_{wb}$. After that, the beam rotation radius is 2.0mm.

If we actively impose the perturbation phase by the driving energy source wobbling or oscillation, and so if we know or define the phase of the perturbations imposed actively, the perturbation growth can be controlled in a similar way as the feedback control mechanism. The wobbling HIBs define the perturbation phase. This means that the perturbation phase is known, and so the perturbations successively imposed are superposed in the plasma. The HIBs accelerate the fusion target fuel with a large acceleration in inertial fusion. The wobbling HIBs would provide a small oscillating acceleration perturbation in the target implosion. So the Rayleigh-Taylor instability growth would be reduced by the phase-controlled superposition of the HIBs perturbations in heavy ion inertial fusion [2].

The purpose of this study is to evaluate the mitigation of the non-uniform implosion by the spiral wobbling HIBs.

Figure 2 shows a non-uniformity history of the target ion temperature. The non-uniformity is evaluated by the total relative root-mean-square (RMS). In Fig. 2, the target is a spherical aluminum shell having a thickness of 1 mm, and the intensity of the beam is constant at 100TW. The beam irradiation time duration is 40 ns. The Pb beam particle energy is 8 GeV. The total beam number is 32.

In conclusion, Fig. 2 demonstrates that the non-uniformity is reduced well by the spiral wobbling HIBs. By the HIBs wobbling motion, the non-uniform illumination is mitigated, and

the Rayleigh-Taylor instability growth is mitigated by the oscillating acceleration perturbation induced [2].

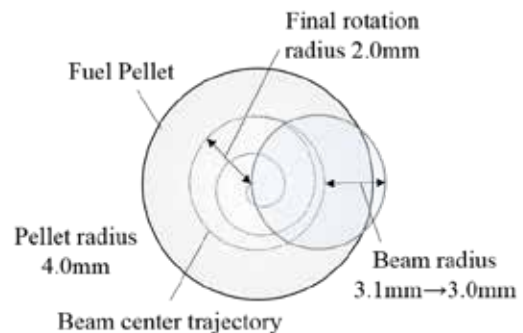


Fig. 1 Schematic diagram for the spiral wobbler.

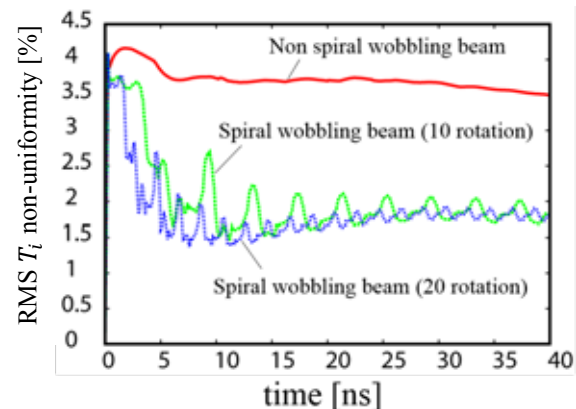


Fig. 2 Non-uniformity of ion temperature.

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Effects of irradiation of stainless steel and TiMoN coatings on stainless with low-energy Alpha-particles, Krypton and Xenon ions

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One of the directions for development of new structural materials for nuclear installations is deposition of protective coatings with high stability of physical and mechanical properties to ionizing irradiation on the existing structural materials. In particular, this applies to the nuclear reactors of generation IV, among which are considered as promising reactors with liquid metal and gas coolant. Materials in such reactors in addition to the neutron flux will undergo to high temperatures and corrosive environments. Ternary transition metal nitrides (TiZrN, TiCrN and others) have high strength, corrosion resistance and can be regarded as promising. However, the properties stability of these materials under irradiation not investigated. In this paper we study the effect of irradiation with low-energy alpha particles, krypton and xenon ions, on the stability of the physical and mechanical properties of coatings TiMoN. Alpha particles simulate accumulation transmutant helium, krypton and xenon ions simulate nuclear fuel fission fragments.

TiMoN coating formed by deposition a substance from the plasma phase under ion bombardment. The coatings were deposited in an atmosphere of N₂ gas at a pressure of 1.10 Pa in the chamber, the substrate potential is 120 V and currents of the cathodes of the arcs of molybdenum and titanium is 100 and 180 A.

Irradiation with low-energy ions He, Kr, and Xe was carried out on the low-energy channel of heavy-ion accelerator DC-60 in the Astana branch of the INP. The ion energy was 20 keV/ charge. Selected irradiation fluences ranged from $5 \cdot 10^{16}$ to $5 \cdot 10^{17}$ ions/cm², the area of the irradiated surface – 1 cm², irradiation temperature does not exceed 150 °C.

Study of the structure and properties of Cr18Ni10Ti steel and TiMoN coating before irradiation and after were conducted by X-ray diffractometry, atomic force and scanning electron microscopy, nanohardness measurements and corrosion resistance measurements.

1. Studies have shown that the physical and mechanical properties of the non-irradiated coating greatly exceed the properties of steel Cr18Ni10Ti, see **Table 1**.

Table 1. Nanohardness and the corrosion rate of the unirradiated coating TiMoN and steel

Material	nanohardness, GPa	Vcorr, mm/year
TiMoN	35	$6 \cdot 10^{-6}$
steel	3,3	$9 \cdot 10^{-3}$

2. Irradiation by alpha particles, starting from fluence $1 \cdot 10^{17}$ cm⁻², results in the surface blistering and flaking. For TiMoN coating blistering's not fixed, even at the maximum fluence $5 \cdot 10^{17}$ cm⁻².

3. Irradiation by Kr ions with energy 280 keV and by Xe ions with energy 360 keV leads to strong surface sputtering both steel and TiMoN coating. The surfaces of coating remain sufficiently smooth with no obvious signs of ion etching. The surface of the steel has obvious traces of ion etching.

4. Physical and mechanical properties of both steel and coating TiMoN degraded under ion irradiation, see Table 2, where presented data of physical and mechanical properties for coating irradiate by He, Kr and Xe ions up to fluence $5 \cdot 10^{16}$ cm⁻².

Table 1. Nanohardness and the corrosion rate of the irradiated coating TiMoN by He, Kr and Xe ions

Fluence, $5 \cdot 10^{16}$ cm ⁻²	nanohardness, GPa	Vcorr, mm/year
TiMoN, irr. He	5	$3 \cdot 10^{-3}$
TiMoN, irr. Kr	25	$17 \cdot 10^{-6}$
TiMoN, irr. Xe	32	$534 \cdot 10^{-6}$

In spite of degradation, the mechanical properties of the coatings significantly exceeds the mechanical properties even unirradiated steel Cr18Ni10Ti.

Development and fabrication of electro-magnetic shock tube with high resolution spectrometer for stopping power measurement in atomic hydrogen gas

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Stopping power measurement in matter is very important for heavy-ion fusion and heavy-ion-driven high-energy density physics [1]. The database of the stopping power has been developed for many elements and compounds under a normal temperature and pressure [2, 3]. However, the stopping cross section can change due to a change of electronic state in the target such as excitation and ionization [4, 5]. Especially, there is few experimental results for the energy loss of charged particles in a dissociated target. Hydrogen is a suitable element to investigate the dissociation effect because it has only one valence electron.

An electro-magnetic shock tube [6, 7] was chosen as a driver to generate well-defined dissociated hydrogen. The electromagnetic force pushes the discharge current sheet and the filled hydrogen gas to the top end of the shock tube, and the shock front is formed in front of the compressed gas region, which can become the dissociated hydrogen. In this process, the uniformity of the discharge current sheet was important for the well-defined dissociated hydrogen target with a high shock velocity to dissociate the hydrogen gas completely [8].

In the previous experiments [7], a semiconductor detector was used for the energy loss measurement of the heavy ion beam. The energy resolution of the semiconductor detector was $\Delta E/E \sim 10\%$, which was not enough to measure the dissociation effect precisely. Therefore, we develop a high resolution spectrometer with $\Delta E/E \sim 1\%$. The high resolution spectrometer consists of a 90 degree bending magnet (Max. B: 1.13 T, Bending radius: 1 m) and position sensitive detectors.

In this presentation, we report the development and fabrication of the electro-magnetic shock tube with the high resolution spectrome-

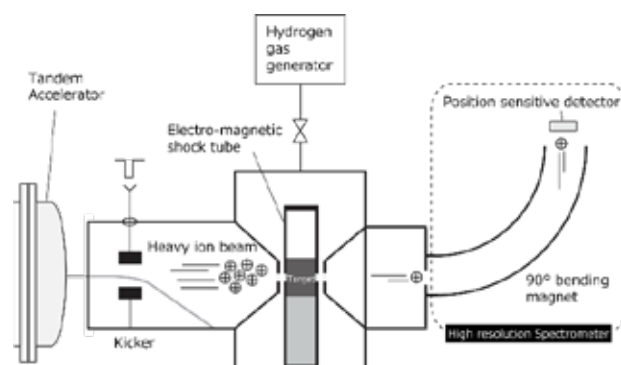


Figure 1. Schema of stopping power measurement in atomic hydrogen gas using the electro-magnetic shock tube with the high resolution spectrometer.

ter for stopping power measurement in the atomic hydrogen gas.

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Study of fluctuations in secondary particles distributions in interactions of nuclei of different energies and asymmetry degree

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According to the present-day conceptions, the hadron substance transits within the interactions of the nuclei, at the high energies, into a state of the quark-gluon plasma (QGP), in which the quarks and gluons stay in a quasi-free state; that is, the process of deconfinement is observed [1].

Experimentally, a deconfinement process (a process of transition of the hadronic matter into a state of the quark-gluon plasma) may be registered by analysis of the essential fluctuations within the distributions of the secondary particles.

In this work a classification of typical fluctuations in distributions of secondary particles and fragments in interactions of various nuclei (*S*, *Au*, *Pb*) with photoemulsion nuclei (*Em*) in dependence of energy and asymmetry degree of interaction nuclei, is carried out.

Experimental data of EMU01-collaboration [2], including interactions of *S+Em* 200 AGeV, *S+Em* 3.7 AGeV, *Pb+Em* 158, *Au+Em* 10.7 AGeV, were used.

For *S+Em* 200 AGeV interactions the essential number of events with large values of the nucleons, which are participants of the interaction, of a projectile nuclei, n_g , is discovered. This peculiarity is absent in events of *S+Em* 3.7 AGeV. Thus, appearance of events with a large n_g essentially depends on energy of projectile nucleus.

For comparison the n_g distributions for interactions of *Au* nuclei at 10.7 AGeV and *Pb*

nuclei at 158 AGeV with photoemulsion nuclei, are presented.

The growth of number of events with great values of n_g , is not found as for *Au+Em* interactions at 10.7 AGeV and for *Pb+Em* 158 AGeV. Thus, appearance of events with a large n_g depends not only on energy of projectile nucleus, but also, probably, on type of nuclear interaction.

To estimate of probability of appearance of events with great values of n_g in various types of nuclear interactions, events with various number of fragments of a target nuclei, N_h , are analysed.

It is revealed, that the n_g distribution in interactions of *S+Em* 200 AGeV has essential peak at great values of n_g only in interactions with heavy nuclei of a photoemulsion ($N_h > 8$). The behavior of n_g distribution in events with $N_h < 8$, is not discovered.

Thus, appearance of events with a large number of nucleons of projectile nucleus, which are participants of the interaction, essentially depends both on energy and on asymmetry degree of interaction nuclei.

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Dynamical screening of charge potential in classical, quantum and ultrarelativistic plasmas

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Dense plasmas have recently gained growing interest due to their relevance for the interior of giant planets as well as for laser interaction with matter and inertial confinement fusion scenarios. Examples of recent experimental studies include the ultrafast thermalization of laser plasmas or free electron laser excited plasmas, inertial confinement fusion experiments at the National Ignition Facility, and magnetized Z-pinch experiments at Sandia. Questions of fundamental theoretical importance are the conductivity and heat conduction, the free energy loss of energetic particles (stopping power) in such a plasma, or the temperature equilibration of the electronic and ionic components.

In the mentioned experiments the generated plasma is nonequilibrium. Therefore for adequate description of processes in plasmas the dynamical screened interaction potential has to be used instead of static screened potential [1].

On another hand, in recent years, wake effects have been extensively studied in nonequilibrium plasmas appearing in classical complex plasma experiments [2]. Therefore, it is very appealing to compare the features of plasma wakes observed in warm dense matter with those in classical plasmas, where the experimental investigation does not require sophisticated devices and is straightforward. Analogies, but also identified differences may be of

direct importance for various fields, where a deviation from the static Yukawa potential due to streaming effects can be expected.

The first purpose of this work is to present dynamical screened potential for situations relevant to warm dense matter and obtain results that are quantitatively reliable allowing for predictions that can be tested in experiments. To this end we will use a dielectric function of quantum degenerate electrons streaming with a constant velocity relative to the ions that fully includes the effects of finite temperature T and collisions (correlations).

The second purpose of this work is outline the topological structure and characteristics of the dynamically screened potential for three representative systems in completely different physical regimes: (i) a classical complex plasma, (ii) a degenerate electron-ion plasma at high densities, and (iii) an ultrarelativistic quark-gluon plasma [3].

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Experimental investigation of the interaction of plasma flow with the wall of fusion reactor

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One of the problems of controlled fusion physics related to the control of the plasma flow is minimization of erosion of intrachamber components, in particular, the first wall of the reactor, which leads to formation of dust (micron-sized particles) and nanostructured products.

Accumulation of dust in the reactor volume mainly plays a negative role. Firstly, it leads to instability of the high-temperature plasma burning and the emergence of disruptions, secondly, it leads to the capture and accumulation of tritium, which worsens safety of the reactor and its efficiency, etc. [1-5].

Nowadays, carbon or its composites are adopted as materials contacted with plasma used as a facing in the separatrix area of the diverter. Candidate materials are the materials that could characterize the processes occurring with materials from which the reactor is made and to find the best composite, which could replace the material of the reactor.

This work is devoted to the study of the formation of dust at interaction of accelerated pulsed plasma flow with graphite plates. To imitate and investigate this process a plasma accelerator of the coaxial type has been used. The accelerators of such type are universal setup for generation of plasma flow and to investigate its interaction with candidate materials of first wall of the reactors (TOKAMAK). In the experiments, as the plasma-forming gas, hydrogen and argon were used, the charging voltage of the capacitor battery of the accelerator varied from 3 to 14 kV. To determine the energy characteristics of the plasma the Faraday cup and cone calorimeter were used. Pre-treated graphite plates in the interaction with the plasma confirmed formation of a film and particles with highly developed surfaces like "cauliflower" and fractal structures similar to the results of fusion devices (Figure 1). By the results of preliminary investigations it is assumed that the

growth of such structures is probably associated with the processes of deposition and diffusion of adatoms.

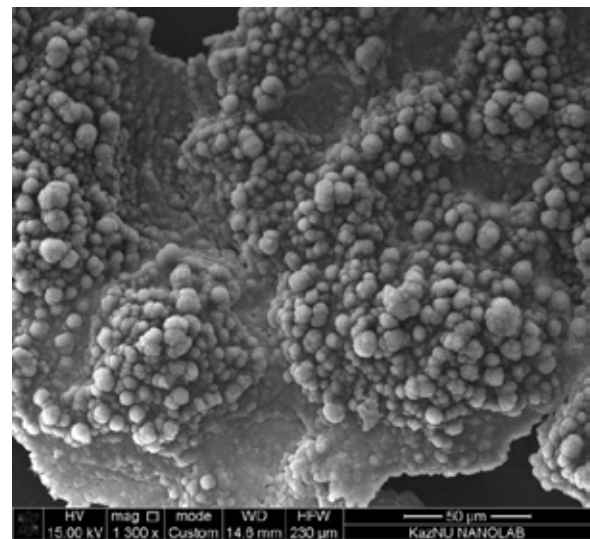


Figure 1. Fractal structure of graphite surface.

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Creation of intense heavy ion beams with short pulse duration in BRing at HIAF

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HIAF- the High Intensity heavy-ion Accelerator Facility will provide intense heavy ion beams to expand nuclear and related researches into presently unreachable region. Compared to the present HIRFL(Heavy Ion Research Facility in Lanzhou) project, the primary heavy ion beams will increase by a factor of 1000 which will open a new path for the HED physics research in laboratory.

HED physics study requires high quality, well focused, strongly bunched intense particle beams to satisfy the very high energy deposition to achieve high target power density, so,

how to generate such kind of beams will be the issue of this report.

Based on the beam parameters of 238 34' proposed by the BRing at HIAF, the two critical issues are studied. One of them is efficiency of adiabatic capture which can be a necessary prerequisite to improve the beam intensity, and the other one is the method of producing short pulse duration bunch.

POSTER PRESENTATIONS

Impact of pulsed plasma beam on the thermal erosion and the surface structure of graphite

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Among materials prospective as plasma-face materials for first wall of fusion reactor a priority is given to the materials with low atomic number, high threshold for physical sputtering, high thermal conductivity, low chemical activity to hydrogen, high thermal resistance and melting point. According to modern point of view, preferred plasma-face materials for tokamaks and future Generation IV reactors should be based on the carbon, beryllium and tungsten. Tungsten is one of the most promising materials for protection of tokamaks diverter plates.

The effect of plasma beam impact on the surface structure changes and thermal erosion of ARW graphite are experimentally studied in present work. For experiments was prepared graphite specimens with dimensions $1 \times 1 \times 0.5$ mm³ from the plate of ARW graphite, which usually used in nuclear reactors. Crystalline structure, surface morphology and weight of specimens were studied before plasma treatment by the X-ray diffractometry, atomic force microscopy (AFM), scanning electron microscopy (SEM) and by weighing for determination of weight and hydrostatic density. Examples of AFM images of specimen surface before and after plasma treatment are shown in **Figure 1 a,b**.

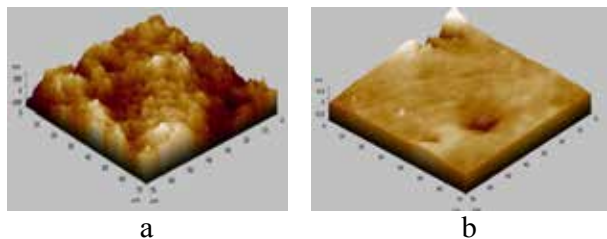


Figure 1. Surface morphology of graphite specimen before (a) and after (b) plasma treatment

From **Figure 1,a** can be seen high degree of surface roughness. As follow from X-ray diffractometry specimen is polycrystalline graphite with hexagonal structure. Weight of specimens before and after plasma impact is given in **Table 1**.

Table 1. Weight of graphite specimens before and after plasma treatment

#	Weight before treatment m_1 , g	Weight after treatment m_2 , g	Δm , G
1	0.772	0.768	0.004
2	0.811	0.810	0.001

Exposure of specimens by pulsed plasma beam was carried out on plasma accelerator of Kazakh National University. Each specimen was undergo by 13 impulses, duration of impulse was 2.5 microseconds, period between impulses was 10 min, energy release in each impulse was $Q = 10 \text{ J/cm}^2$.

Investigations of the structure and weight loss by the same methods as before plasma treatment shows:

1. Crystalline structure of treated samples does not change significantly.

2. Surface of specimens become much smoother, compare **Figures 1a** and **1b**. That indicates that thermal erosion of the surface under irradiating by plasma beam takes place. Probably, there has been a melting of the surface under laser beam treatment. Results of the weightings of the specimens before and after treatment (see **Table 1**) is confirms thermal erosion at laser beam treatment.

So, main effects of the laser beam exposure on the surface structure are thermal erosion and surface smoothing.

We also have undertaken theoretical calculation of the mass lost of graphite under laser beam treatment. The calculation was performed in the framework of a model based on the solution of heat conduction equation under pulse release of heat on the surface and determination the depth temperature distribution, taking into account only the sublimation of graphite and the heat radiation from the irradiated surface. Under this model were calculated distribution of temperature fields and the rate of evaporation of graphite depending on the time. According to estimated calculations the mass loss of graphite sample constitute $5 \cdot 10^{-3} \text{ g}$, which is consistent with experimental results.

Effective potential of interactions between ions in dense quantum plasmas

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In this paper we consider the effective potential of interaction between ions in quantum plasmas. Effective interaction potential, taking into account the wave nature of ion at small interparticle distances can be obtained by the method of the dielectric response function in combination with so called quantum potential approach. AS the quantum potential for description of the semiclassical ions the Deutsch potential, which has a finite value at $r = 0$, was used [1]. Considered plasma density is $n > 10^{24} \text{ cm}^{-3}$. In this case, electrons are quantum, ie should be described by Fermi-Dirac statistics. Next, we consider the case $\theta_i \geq 0.5$, where θ_i is the ration of the thermal energy to the Fermi energy of protons. The degeneracy parameter of ions and electrons related as $\theta_e = \theta_i \times m_e / m_i \ll 1$, thus in the considered case the electronic subsystem is completely degenerate. As a result, the chemical potential of

the electrons can be taken equal to the Fermi energy of the electrons. In the considered range of plasma parameters the effective coupling parameter $\Gamma_{ii}^* \leq 1$, here $\Gamma_{ii}^* = Q_i^2 / ak_B T \exp(-ak_Y)$ is defined as the ratio of the energy of interaction of two ions at an average interparticle distances to their thermal energy. This means that the ionic subsystem is weakly coupled and can be described by random phase approximation [2].

On the basis of the obtained effective interaction potential between ions, the thermodynamic properties of a dense plasma (warm dense matter) were investigated.

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The stopping power and straggling of strongly coupled electron fluids revisited

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Measuring energy losses of beams of charged particles is an important diagnostic tool in both modern condensed matter and plasma physics. If single-particle effects can be neglected, the general expression for polarization losses [1] simplifies as

$$\left(\frac{dE}{dx}\right)^{pol} = \frac{2}{\pi} \left(\frac{Z_p e}{v}\right)^2 \int_0^\infty \frac{dk}{k} \int_0^{kv} \omega^2 L(k, \omega) d\omega.$$

Here $Z_p e$ and v are the projectile charge and velocity, while $L(k, \omega) = -\text{Im}\varepsilon^{-1}(k, \omega)/\omega$ is the target plasma loss function, $\varepsilon(k, \omega)$ being the system dielectric function (DF). Another important characteristic of energy loss by the beam of projectiles is the straggling:

$$\Omega^2 = \frac{2\hbar}{\pi} \left(\frac{Z_p e}{v}\right)^2 \int_0^\infty \frac{dk}{k} \int_0^{kv} \frac{\omega^3 L(k, \omega) d\omega}{\tanh(\beta\hbar\omega/2)}.$$

Usually the polarizational stopping power and its straggling are calculated presuming the target plasma to be an electronic fluid and the DF of the latter has been evaluated within the random-phase approximation (RPA), the T-matrix approach, the method of effective potentials, or using the Mermin or more sophisticated DF models, see [2] for the references. It has been shown recently in [2] that all these perturbative DF models, except for the local-field corrected RPA do not satisfy the interaction-related sum rules and thus cannot be applied for the calculation of the stopping power and its straggling under the conditions of strong coupling. The approach we suggest here is based on the method of moments. It is not perturbative and the only limitation is that the electron fluid is presumed to be in the liquid phase. The moments are effectively the power frequency of the loss function,

$$C_\nu(k) = \frac{1}{\pi} \int_{-\infty}^\infty \omega^\nu L(k, \omega) d\omega, \quad \nu = 0, 2, 4$$

and are the sum rules. The approach permits to apply the Nevanlinna formula of the classical method of moments and to model the system DF via the Nevanlinna parameter function (NPF) $q(k, z)$ [3]:

$$\varepsilon(k, \omega) = 1 + \frac{\omega_p^2(\omega + q)}{\omega(\omega^2 - \omega_2^2 + \omega_p^2) + q(\omega^2 - \omega_1^2 + \omega_p^2)},$$

where $\omega_1^2(k) = C_2/C_0$ and $\omega_2^2(k) = C_4/C_2$ and ω_p is the plasma frequency. We model the NPF here as $q(k, \omega) = q(k, 0) = i\omega_2^2(k)/\sqrt{2}\omega_1(k)$, which is justified by the specific behavior of the one-component plasma (OCP) dynamic structure factor near the zero frequency [4]. Thus the calculation of the OCP plasma stopping power and straggling is reduced to the knowledge of the system static structure factor. The latter can be either calculated within a modified or local-field corrected RPA, or computed using the MD method with an adequate effective potential [5].

The results of our calculations are to be compared to the available experimental or simulation data.

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Structural defect creation by swift heavy ions in CaF₂ single crystals

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Calcium fluoride single crystals belong to the most popular optical materials due to their transparency in a wide spectral region. Pure and doped with different cation impurities (Me³⁺, Me²⁺, Me⁺) CaF₂ can be used for many applications, for instance as lenses and windows in ultraviolet laser lithography, laser media, radiation detectors and dosimeters, elements for navigation and orientation, etc. (see, e.g., [1] and references therein). High-dense irradiation (e.g., by swift heavy ions - SHIs) creates in CaF₂ different structural radiation damages including F-type aggregate centres and metal colloids. The presence of extrinsic defects (impurities) and the rise of a number of structural intrinsic defects (point defects and their aggregates) during a prolonged irradiation strongly affect the properties of CaF₂ useful for different applications. More than 95% of the energy of SHI with $E > 1$ MeV/u is spent on ionization losses providing an extremely high density of electronic excitations within cylindrical ion tracks (see [2]).

Oxygen-free single crystals of CaF₂ irradiated at room temperature by SHIs in Darmstadt (²⁰⁹Bi, energy per nucleon 11.4 MeV/u, 3×10^{11} - 10^{12} ions/cm², ion range $R \sim 90$ μm) or at DC-60 cyclotron in Astana (¹³²Xe, 1.75 MeV/u, 5×10^{12} - 10^{14} ions/cm², $R \sim 18$ μm) have been the main investigation objects. The radiation-induced optical absorption (RIOA) measured from 1.5 to 10.5 eV after preheating of the ion-irradiated samples to different temperatures (up to ~ 1200 K) has been analyzed in order to separate different types of F-aggregates, calcium colloids as well as the defects responsible for the absorption in UV-VUV spectral region (4.5-10.5 eV). In addition, the curves of thermally stimulated luminescence were measured during linear heating ($\beta = 2$ K/s) of preliminary irradiated samples. Activation energies and frequency factors have been determined for separated peaks in ion-irradiated pure and thulium-doped CaF₂ samples.

SHI-irradiation of CaF₂ causes the appearance of a complex wide RIOA band in visible range tentatively associated with F-aggregate centres

and calcium colloids [1]. The annealing of different F-type bands mainly occurs at 400–600 K. There are several RIOA bands in UV-VUV spectral region as well. It is worth noting that just high-dense ion-irradiation is responsible for such radiation damage, because some of these bands (especially RIOA band peaked at ~ 9.7 eV) cannot be induced by 100-keV protons or X-rays (50 keV, 20 mA, W). Similar to the case of model alkali halides (see, e.g. [3]), these RIOA bands at 5–10 eV can be tentatively ascribed to trihalide quasi-molecules or electronic excitations localized near complex radiation damages (i.e. Greek bands in alkali halides), while a detailed study of their origin still lies ahead.

The joint action of impact (causing shock waves) and nonimpact (decay and recombination of radiation-induced electronic excitations) mechanisms is considered to be responsible for the creation of novel structural defects with complex structure (including 3D defects involving many host ions) under Xe¹³² or Bi²⁰⁹ irradiation. These 3D defects serve as stoppers for dislocations thus impeding their movement to the surface and facilitating the cracking and brittle destruction of the irradiated single crystals.

Thus, the irradiation with SHIs affects the mechanical properties and causes the efficient cracking and fracturing of CaF₂ single crystals into pieces with (111) faces. These mechanical effects are especially efficient in the samples irradiated with ²⁰⁹Bi ions with an extremely high nuclear spin of 9/2, while ¹³²Xe ions have zero nuclear spin (see also [4]). A specific contribution of ion magnetic properties to radiation damage needs further analysis.

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Getting free heat energy based on cavitation and nuclear fusion according Revinov's pilot plants

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In the report describes and compares two innovative process for producing thermal energy: based on cavitation and nuclear fusion reactions in the indoor environment. Experiments conducted in the laboratory Intensive Heating System – "IHS" of FE "Revinov N.M." indicates that the process of lasso-vortex cavitation, which generates by means of an electric arc obtained HV-EI, gas-liquid plasma state in the electro-hydraulic heater with cavitation thermal camera (EHH-CTC) is not inferior and sometimes even superior in heat transfer nuclear fusion reactions in ambient conditions (NF-AC).

Introduction. Since 2006, our initiative group of experts has been developing rapidly intensive heating systems (IHS) of different modifications: Lasso-based vortex cavitation Ranke-Hilsch pipe, called us briefly LVC-RHP; created in different years were called modifications - vortex cavitation heater (VCH), the hydrodynamic cavitation heater (HCH), sometimes referred to as HCR - hydrodynamic cavitation reactor; the current state of development is called the mini-thermal power plants based on the LVC-RHP to create IHS. As well as the development of individually-intensive heating systems (IIHS) on the basis of the electro-cavitation heater thermal camera, called us briefly EHH-CTC, the current state of development is called a mini-boiler-based EHH-CTC to create IIHS. These developments gradually escalated into nuclear fusion reaction at room conditions (NF-RC). All this seems to us a natural, natural.

1. Natural phenomena - the mother of all the above processes

The LVC-RHP process lasso-vortex cavitation in the Ranke-Hilsch pipe has as its progenitor - a tornado, indeed, everything that happens inside RHP have repeated in miniature of what takes place in the natural tornado: at one end of the fire spurts, the other end of hail pours. Similarly, during steady state operation TPX inside the tube formed two parts, separated by a thin partition, on one side of which the water is more and more heated to a vapor state, and on the other side of the water is still sensitive and sensitive cooled. However, it confirms the scientific assumption J. Maxwell, Lord Kelvin sarcastically called "Maxwell's Demon": In a single vessel, all slowest molecules can assemble at one end, while at the same time, the fastest molecules rush to the other end. This

is - a fantasy, but - a fact! Due to this phenomenon, LVC-RHP unit can be used as the heating and cooling apparatus as. What has been realized by Soviet specialists Laboratory ONIL-9 in the Kuibyshev Aviation Institute for aviation and space technology. The thermo-camera EHH-CTC process Arch-vortex cavitation in the gas-liquid plasma environment is generated by an electric arc obtained HV-EI has as its progenitor - lightning in miniature, really, if lightning generates plasmids in the gas-drop environment cloud the electric arc facilitates the formation of the gas-liquid plasma states in the electro-cavitation heater thermal camera.

In both cases, the installation produce more energy than they consume as food pump - in the case of the LVC-RHP, as a make-up HV-EI - in the case of EHH-CTC.

To describe this state of affairs experts began to use as an indicator of the ETC - energy transformation coefficient. Additional energy is also taken due to cavitation, i.e., the formation and collapse of count-less air bubbles and their collapse because of high pressure in the caverns. By definition, the American experts, the temperature of the micro-explosions of bubbles varies 5 C ... 25000 C range. Although these microbursts last a few milliseconds, they manage to give impetus to their thermal environment, i.e., in this case - the water (in both cases, the working material is plain water at room temperature).

In fact, we are dealing with a supplement to the statement V.I. Vernadsky that in nature a source of additional energy is radiation, it appears more cavitation has the same status, i.e., It is also a source of additional energy.

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Elastic and inelastic longitudinal electron scattering from ${}^9\text{Be}$ in the first excited state

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The $1/2^+$ first excited state of ${}^9\text{Be}$, which lies at energy of 1.68 MeV and only about 20 keV above the neutron-emission threshold, is of especial interest. It is found that this state can be considered as a halo (the root mean-square radius is $\langle R^* \rangle = (3.42 \pm 0.2) \text{ fm}$) [1].

Electron scattering is one of the most effective methods of studying the properties of the energy levels of atomic nuclei [2]; so it is extremely productive and powerful tool to research nuclear structure.

Elastic and inelastic longitudinal electron scattering has been researched in the framework of three-particle ($2\alpha+n$)-model with the $\alpha\alpha$ Ali-Bodmer potential [3]. Our calculations show that ${}^9\text{Be}$ in the first excited state has a halo-structure (the rms charge radius is about $\langle R_{\text{ch}} \rangle = 2.84 \text{ fm}$).

In this paper we calculated the transitions to the $J^\pi = 1/2^+$, $3/2^+$ states of ${}^9\text{Be}$. According to the results, the probability of the transition to the $(3/2^+, 1/2)$ state is extremely low.

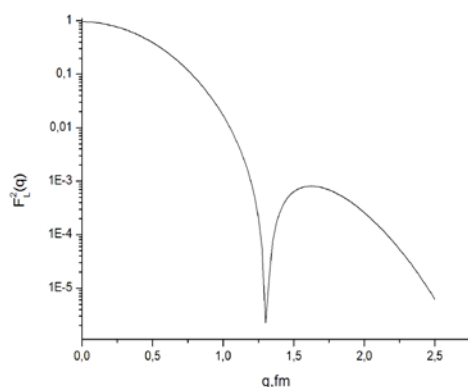


Figure 1. Elastic Coulomb form factor for the transition to the $(1/2^+, 1/2)$ state in ${}^9\text{Be}$

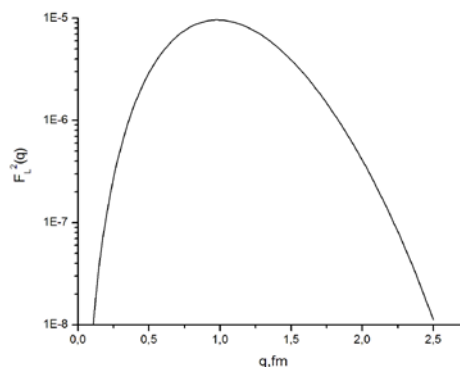


Figure 2. Inelastic Coulomb form factor for the transition to the $(3/2^+, 1/2)$ state in ${}^9\text{Be}$

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Investigation of correlation of generated nuclearactive particles in the proton-antiproton annihilation at momenta 22.4 and 32 GeV / c

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Separation of the individual events corresponding to antiproton-proton annihilation gives the possibility to carry out the analysis of multiparticle correlations for generated particles and to compare them with corresponding data for inelastic pp and non-annihilation $\bar{p}p$ interactions.

The correlation function [1]

$$R_k(G) = \frac{F_k(G)}{F_k^\emptyset(G)} - 1,$$

where $G = \eta_{i+k} - \eta_i$ - the gap of quasirapidities; η_i and η_{i+k} - quasirapidities of boundary particles of the interval with $(k - 1)$ charged particles inside it; $F_k(G)$ - measured differential distribution; $F_k^\emptyset(G)$ - expected differential distribution in the absence of correlations (background distribution).

The graphs of R_k on G dependence have been received for the reaction of antiproton – proton annihilation and for non-annihilation $\bar{p}p$ - interactions at momenta of primary antiprotons 22.4 and 32 GeV/c, and also for inelastic pp -interactions at momentum 69 GeV/c.

In interactions of antiproton – proton annihilation the observed correlation of charged particles is more weak, than in non-annihilation interactions.

In proton – proton and non-annihilation antiproton – proton collisions similarity of correlation functions is observed.

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Patenting the HIF Power System Using the SPRFD

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This paper discusses the rationale for patenting inventions that enable the HIF power plant and the status of the prosecution of these patents. Our rationale for starting a business to pursue HIF power was its “suspended animation” despite being held since its 1976 debut to face “no showstoppers” and considered to be “the conservative approach to power production.” In turn, the rationale for patenting the unique features in our HIF approach is that intellectual property (IP) is essential to attract investors to a business endeavor that could readily be taken over by large competitors. In contrast to other fusion startup companies using such claims as compactness or a-neutronic reactions to attract investors, FPC uses the technology given the highest expectations worldwide for success: ICF driven by beams of high-energy heavy ions. Fully conscious that our present HIF concept will undergo substantial evolution during the project to bring fusion to the market, not unlike how Project Apollo involved much evolution of rocketry and other essential technologies, FPC’s vision combines leadership from industry and finance (a major departure from Apollo’s approach) to overcome lethargy in the various communities—governments, industry and finance, environmental, peace and security — and even in the science and technical communities whose expectations have sunk low resulting from NIF’s failure to ignite a pellet and ITER’s failure of promise.

The impetus for founding Fusion Power Corporation in 2009 was completion of the concept for an RF accelerator driver (Single Pass RF Driver or SPRFD) that avoided the uncertainties of systems involving storage rings. Besides avoiding the “black cloud” problem of storage rings, omission of storage rings opened a path to the small spots needed for fast ignition by eliminating the large increase in transverse beam emittance accompanying multi-turn injection. Two main principles drove the SPRFD: 1) seeking a more straightforward way than explored 1994-96 by HIDIF to exploit the major and basic advantages of multiple heavy ion species, and 2) “give HIF its head” by stressing workability and basic energy economics (independent variables) rather than being deterred by the dependent variables of large size and capital requirements.

Indeed, our system is large and will take much capital—as do the fossil fuel complexes that the world needs to obsolete.

The patenting process has mirrored the present condition of fusion development worldwide. The US Patent and Trademark Office (USPTO) first rejected the application on the grounds that decades of work by highly skilled researchers using many \$billions from many governments worldwide had concluded that fusion was far in the future, and quoted a report from the US HIF program at LBNL that had concluded that HIF might never work. Resubmittal included “utilities” for a neutron source as well as for power, and adroit persistence by our patent counsel, finally resulted in a US patent covering the driver aspects [1]. We expect the prosecution for the pellet and chamber innovations to continue for up to another two years in the US.

Russia granted a patent in 2013 on the accelerator parts of the patent application. Russia also insisted, like the US and Europe, that the accelerator and fusion chamber parts of the application are separate inventions. The last round of questions from Europe was completed in March 2016, and a patent on the chamber aspects could be granted this year. Prosecution in China stalled on objections such as whether “microbunch” is an acceptable term of the art, and we abandoned the effort after 6 years. After 7 years, India finally questioned whether the application conflicts with the Atomic Energy Act, and we dropped that effort.

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- [1] Patent number US 20120328066 A1

Joint Comprehensive Plan of Action Opportunity for HIF in Iran

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Cooperation in fusion energy research and high-energy accelerators has been a “bridge over troubled waters” for most of a century. Physics research has traditionally been an international endeavor, involving the earliest accelerator developments, and hitting a hiatus only during World War II. Fusion energy research using magnetic confinement was internationalized by the Geneva meeting in 1958. Iran is and has been a participant in fusion research, even during the troubles of the past couple decades. And, although “laser fusion” was public and acknowledged by the US in 1972, that year Iran hosted “The Future of Lasers” at Esfahan [1].

Unequivocal statements in the 2015 nuclear agreement, the Joint Comprehensive Plan of Action, known in Iran as the barjam, increase the opportunities for collaborative projects to develop fusion as an economic energy source. The clear opportunity for heavy ion fusion is to be forthright about the historic and ongoing conclusion that HIF is the most promising path to fusion energy—especially fusion energy that actually delivers on its promise to be the deep-clean and safe, affordable, abundant energy source that the world desperately needs.

A caveat for Iran about investing too much money or political capital in fusion cooperation is that the world’s mainstream fusion energy programs are failing to the extent that no contribution from fusion is anticipated for another several decades, and much of the political classes show serious doubts that it ever will be an important energy source. In this regard, the HIF community shares culpability for having retreated from the vision of 1976. This has been a political failure not a technical one. HIF never was going to be simple or easy [2], but the laser-driven ICF community, viz. the military interests, strenuously opposed HIF [3], the entrenched tokamak community was impervious to the message that there was a better way, and the accelerator community felt no compunction to continue its advocacy until a secure home for HIF had been established [3].

Reflecting the condition of worldwide fusion energy research, the JCPOA specifies “facilitating contribution of Iran to ... (ITER)” but continues with “and/or similar projects.” JCPOA is silent on

ICF, unsurprising given ICF’s strong connections to the on-going, and arguably more dire, worldwide problem of the existence of nuclear weapons. This is good for HIF in Iran.

HIF has since its inception always been only about production of energy from fusion, in contrast to “laser-fusion” development being primarily for weapons research, funded almost entirely in the US for national security [4]. JCPOA also specifies cooperative accelerator projects, highlighting the fact that there is no security concern for the HIF driver. We argue there are no security concerns either for HIF’s fusion aspects: pellets or potential use of fusion neutrons to breed fissile fuel. First, HIF’s best performing, fast-ignited cylindrical pellets as simulated by experts such as Avorin, Meyerter-Vehn, and Basko [5] are *not* classified according to the US classification guide. Second, we expect the world to choose to solve the energy-environment problem by finding a way to handle sensitive EOS and similar information. Third, strong international oversight is obvious, and zero presence of any fission materials can be assured because their radiation signatures would stand out like a sore thumb in the low radiation environment of lithium-protected chambers.

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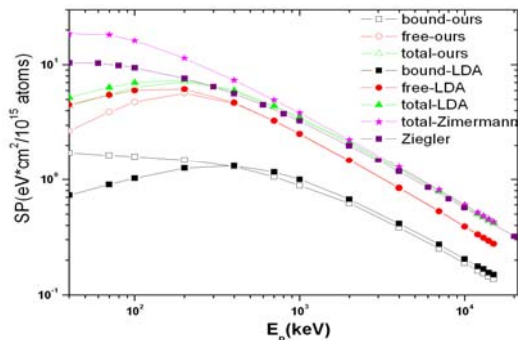
Stopping power and energy loss for protons in Be plasmas

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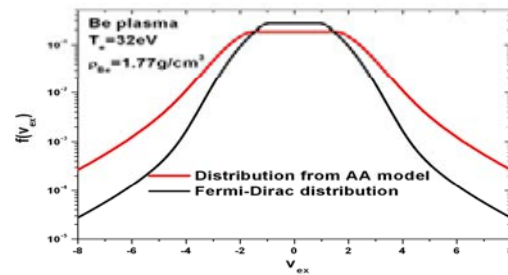
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Stopping power (SP) for ions in plasmas is a basic and old problem, which data is important for heavy ion driven inertial fusion and heavy ion transport in hot matters. So far there are some relevant experiments and many theoretical researches. Last year [1] the energy loss of proton at projectile energy $E_p = 15\text{MeV}$ was measured in cold and partially ionized Be materials at solid density with temperature $T_e = 32\text{eV}$ and length $L = 532\text{ }\mu\text{m}$. Energy loss was found a little higher than that in cold targets.

Ab initio calculation of SP is necessary for partially ionized plasmas. At 1998 Wang *et al* [2] made the first such work in Au plasmas by the local density approximation (LDA) based on average atom model (AA model) [3]. In the model the stopping power can be divided into two part the inelastic and plasma wave stopping although the inelastic part is not obtained by the calculation of inelastic processes. Sometimes at high E_p Bethe equation is used to get the inelastic contribution, where the average ionization energy $\langle I \rangle$ obtained by some phenomenal methods [4], as well as the plasma wave stopping, where $\langle I \rangle$ replaced by electron plasma frequency [5]. In recent year some improvements are made by us [6] for *ab initio* calculation of SP in plasmas where the inelastic processes are calculated in detail and velocity distribution for free electrons in plasmas is revised. In the present work our results are compared with the experimental data together with the other models. The above figure gives the SP as a function of E_p for proton in Be plasmas, where the words bound, free and total mean the contribution from inelastic and electron plasma wave and their total result, respectively.



Difference between ours and LDA for plasma wave contribution at lower E_p is found mainly come from different velocity distribution of free electron at plasmas, which is shown in the following figure.



The following table presents the energy loss from experiment and different models. New experiments are suggested to test which one is better for LDA and our model.

Table 1 Energy loss ΔE (MeV) for $E_p=15\text{MeV}$, 1.77g/cc and $L=532\text{ }\mu\text{m}$

T_e	Expt	Simulation				
		Our model	LDA		Zimmermann	
			Ref.[1]	Ours	Ref.[1]	Ours
Cold	2.71 ~ 2.72	2.71	2.80	2.81		
32eV	2.85 ~ 2.98	2.87	2.85	2.89	2.90	2.94

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Control of fuel target implosion non-uniformity in heavy ion inertial fusion

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Reducing the non-uniformity of fuel implosion is one of issues to achieve ignition in inertial fusion targets, and has been studied by various mitigation mechanisms [1, 2]. The non-uniformity is caused by several factors. The Rayleigh-Taylor instability (RTI) is one of them.

One way to reduce the non-uniformity is the RTI growth mitigation proposed in [1], in which a controlled vibration of the implosion acceleration perturbation δg reduces the RTI growth significantly. We propose to realize the mitigation mechanism by vibrating foot and main pulses of the heavy ion beams (HIBs) (see Fig.1). Each HIB has its vibration phase depending on the HIB axis position (see Fig. 2) in order to produce the controlled δg to mitigate the implosion non-uniformity.

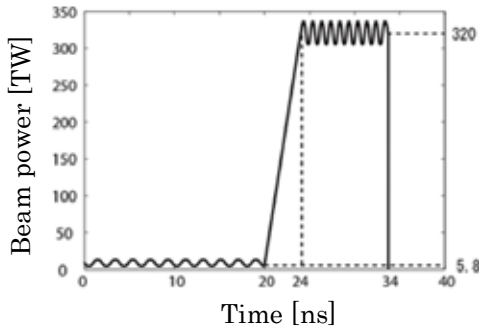


Fig. 1 Beam power vibration

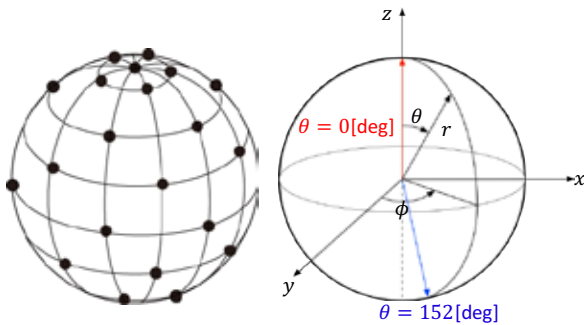


Fig. 2 HIBs illumination scheme

The target shell is accelerated by the 32 HIBs with the controlled δg , which induces a small controlled implosion acceleration vibration (see Fig.3). The vibrating acceleration reduces the implosion non-uniformity (see Fig.4). Figure 5 represents the mode of the ion temperature at the DT layer. It is shown that vibration HIBs reduce especially the largest mode of the “Mode 2”.

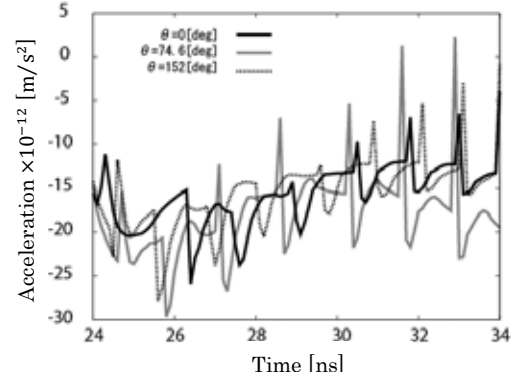


Fig. 3 Acceleration of each θ position

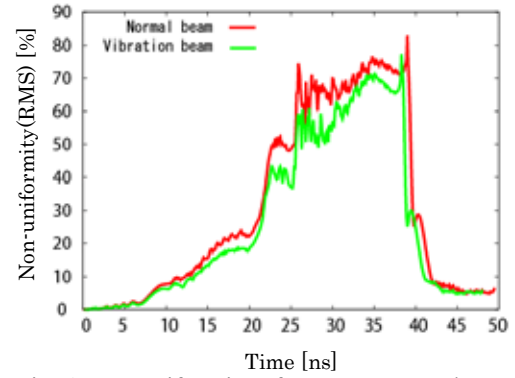


Fig. 4 Non-uniformity of pressure at DT layer

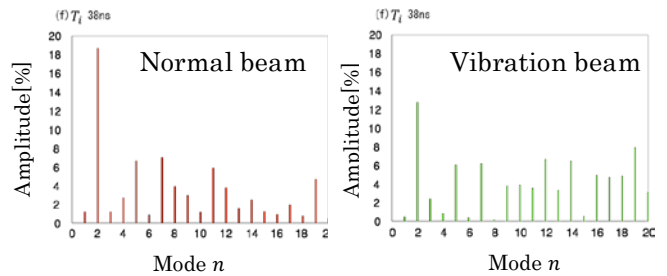


Fig. 5 Mode of ion temperature at DT layer

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Decay $B \rightarrow \phi l^+ l^-$ in covariant quark model

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The work is devoted to the study of the rare $B_s \rightarrow \phi l^+ l^-$ decay where $l = \mu, \tau$. We use the Wilson coefficients obtained at the next-to-leading logarithmic (NLL) order in our calculation of the observables in the full kinematical region of the momentum transfer squared in the framework of the covariant quark model with infrared confinement. The calculated form factors are used to evaluate branching fractions and polarization observables in the cascade decay $B_s \rightarrow \phi(\rightarrow K^+ K^-) l^+ l^-$.

One can conclude that the results provided by the covariant confined quark model do not allow to claim a significant deviation from the SM and they demonstrate the non-negligible effect of the two-loop corrections for the Wilson coefficients which bring the theoretical predictions closer to the data. We compare the obtained results with available experimental data and the results from other theoretical approaches.

Calculation of ion structure factors in warm dense matter

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Recently, the interest in the study of various properties of warm dense matter, i.e. matter with kinetic energies of more than 0.2 eV and particle densities of more than 10^{25} m^{-3} , strongly increased. Under such conditions, the transport coefficients of plasmas are strongly influenced by the ion distribution, i.e. by the ion-ion structure factor. The larger the ratio of the ion-ion potential energy to the ion kinetic energy Γ , the stronger the effect. On the other hand, it is believed that hypernetted chain (HNC) approximations and the mean spherical (MS) approximation are applicable for systems with large Γ . Thus, in the present work, electrical and heat conductivities of warm dense matter are calculated within Born approximation neglecting the ion-ion structure factor and considering it. For the ion-ion structure factor values are taken into account, which were observed in experiments or are calculated using HNC or MS approximations. It is found that the values of the electrical and heat

conductivities in plasmas at solid state density, calculated considering the ion-ion structure factor, are about 20 times larger than the values obtained neglecting the structure factor.

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Improved the properties of laser-produced plasma ions using multichannel laser beams

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At present, there are number of works devoted to the study of laser-produced plasma as a source of ions for ICF together with heavy ion accelerators and the systems on the base of powerful impulse of electrical charge, i.e. Z-pinches. Laser ion source (LIS) has been recently designed to load the Heidelberg electron beam ion trap with a pulsed beam of charged ions from solid elements. Due to many characteristics of laser-produced plasmas, LIS takes advantages over e.g. a common metal vapor vacuum arc method as a source of ions. The system generates beams of large amount of highly charged atoms and nucleus of elements, including rare and radioactive isotopes to inject into the electro-physical equipments. Therefore, the investigation of interaction of laser radiation and plasma beams with different kinds of targets gives additional information to improve the characteristics of laser drivers for ICF. The main objective of the current work is to improve the charge state and intensity of ions using multichannel laser beams.

In these experiments, the initial laser beam creates a plasma on the surface of solid targets. The following laser beam(s) will interact with already

created plasma, thus increasing the charge state and energy of the ions. It was found that the increase of the focusing condition (distance) from $L=0$ to $L=1.0$ mm leads to the increase of intensity of ions with $Z>1$ and to the disappearance of low energy part of the plasma ions spectra, while the maximal charge of ions is not changed.

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Dynamic estimation of emittance growth with tune depression and nonlinear field energy factor during longitudinal bunch compression for heavy ion inertial fusion driver

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In general, the radial matched beam is according to an equilibrium condition, and depends on the radial (transverse) confinement force and the ratio of repulsion forces between the space charge potential and the thermal pressure [1-3]. During longitudinal bunch compression, parameters of charged particle beams are changed, and the beam current is also increased due to the increase of the charge density. Not only thermal equilibrium distribution but also the linear-Courant-Snyder invariant distributions such as Kapchinskij-Vladimirskij (KV), waterbag (WB), Gaussian (GA), parabolic (PA), and semi-Gaussian (SG) distributions, the radial density profile is changed with increase of the beam current during the longitudinal pulse compression [4]. Finite nonlinear field energy factor produces the emittance growth, because the space charge potential can be thermalized.

The possible emittance growth was written as a function of the nonlinear field energy factor which depends on the radial density distribution and the tune depression [5,6]. The equilibrium radial density profile is redistributed according to the balance between the space charge and thermal potentials. The possible emittance growth was estimated with the thermal equilibrium distribution [7], and has the maximum value in a low tune depression regime [8], as a static analysis. However, the beam current increase due to the longitudinal bunch compression causes dynamically the unbalanced state.

For this reason, one of factors for emittance growth is resulted with the redistribution of density profile caused by the longitudinal pulse compression. Wangler *et al* showed the differential equation of emittance growth with change of the nonlinear field energy factor [2,3]. As a result, if the change of the nonlinear field energy factor is clear, the emittance growth can be evaluated. In this study, the emittance growth based on Wangler's differential equation is evaluated with the nonlinear field energy factor. Also, multi-particle simulation shows the emittance growth, and is compared to the above estimation.

The dynamic emittance growth during the beam transport was estimated theoretically as a function of the tune depression and the nonlinear field energy factor with various initial particle distributions. The tune depression was given by the initial beam parameters and the beam current including the bunch compression. The nonlinear field energy factor was obtained by the numerical simulation examples. In comparison with the analytical and numerical simulation results, the analytically estimated emittances were larger than the numerical result. In the initial distribution with the space-charge-induced instability, the integrated possible emittance growth was not applicable. However, the overestimation is 14 % as the highest case, and the beam for the distribution with the space-charge-induced instability is an especial case, such as KV distribution. Consequently, it is expected that the dynamic estimation of possible emittance growth as a function of the tune depression and the nonlinear field energy factor with the bunch compression model is useful to design the particle accelerator complex such as the heavy ion inertial fusion driver.

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Dynamical properties of inertial confinement fusion plasmas

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Study of the interaction processes of ion beams with dense plasmas is one of the important problems in the physics of inertial confinement fusion (ICF), warm dense matter and high-power lasers physics. Nowadays, a state of matter under extremely high pressure is an object of high interest. Investigation of dense matter has crucial importance for application [1] as well as for understanding of universe evolution. Particularly, many expectations associated with an ICF, where dense plasma is a working substance. The goal of ICF implosions is to achieve sufficiently high temperature and compression within deuterium-tritium (DT) fuel to sustain a thermonuclear burn [2].

One of the important values that describes the energy loss of the ions in plasma is the Coulomb logarithm. The Coulomb logarithm is obtained on the basis of effective potentials [3]. These interaction potentials take into consideration long-range many particle screening effects as well as short-range quantum-mechanical effects [4-7]. We investigate the energy loss of heavy particles in DT plasma and other energetic characteristics of

fuel. Calculations of ions energy losses in the plasma for different values of the temperature and plasma density were carried out. Also, a comparison of the calculated data of ion stopping power with experimental and theoretical results of other authors was done.

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Researches on reactor core in Heavy ion inertial fusion.

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In Heavy ion inertial fusion (HIF), the issues include the generation and transport of heavy ion beam (HIB), the optimum pellet structure, the realistic nuclear fusion reactor design, etc. In this research, we have studied a conceptual design of a nuclear fusion reactor system in HIF (see Fig. 1).

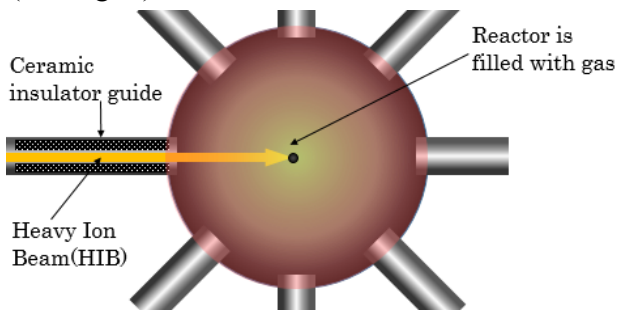


Fig.1 A conceptual diagram of a HIF

The HIB should be focused and transported in a fusion reactor against the beam space charge onto a fuel pellet at the reactor center. The target radius is the order of mm. One of the promising transport schemes is the neutralized ballistic transport, in which preformed-plasma electrons or wall-emitted electrons neutralize the HIB space charge. On the other hand, the HIB ion number density increases from $n_{b0} \sim 10^{11} - 10^{12} \text{ cm}^{-3}$ at a HIB port entrance to $100 \sim 200 \times n_{b0}$ at the fuel pellet position. As a practical HIB neutralization method in an HIF reactor, an insulator annular tube guide was proposed at the final transport part, through which a HIB is transported (see Fig. 1) [1]. A local electric field created by the intense HIB induces local discharges, and a plasma is produced at the annular insulator inner surface. The electrons are extracted from the plasma by the HIB net charge. The electrons neutralize the HIB charge, and move together with the HIB in the reactor chamber [2].

In addition, the chamber background electron density should be always larger than or equal to the HIB number density: $n_{ce} > Z_b n_b$. Here, n_{ce} is background electrons density, Z_b is degree of ionization and n_b is HIB density. In our design, the fusion reactor is filled with helium gas, and its density is $\sim 10^{16} \sim 10^{17} [1/\text{cm}^3]$.

In this case, the HIB space charge is always neutralized in the reactor well. The instability analyses were also performed including the two-stream instability and the filamentation instability; it was found that the HIB is rather stable in the reactor chamber gas [3].

However, a part of the exhaust gas and debris coming up may have influences to the HIB accelerator. The vacuum of the accelerator part should be kept to the low pressure to avoid the HIB ions scattering and the halo formation. In the HIF reactor system we may have the ceramics HIB transport annular guide as shown above, whose inner surfaces would absorb the upcoming exhaust chamber gas to the accelerator final section. At the final part of each accelerator near the chamber wall, each accelerator final part may several mechanical shutters, and two pairs of the mechanical shutters would confine the exhaust gas and absorb it at the ceramics guide inner surface, as shown in Fig.2.

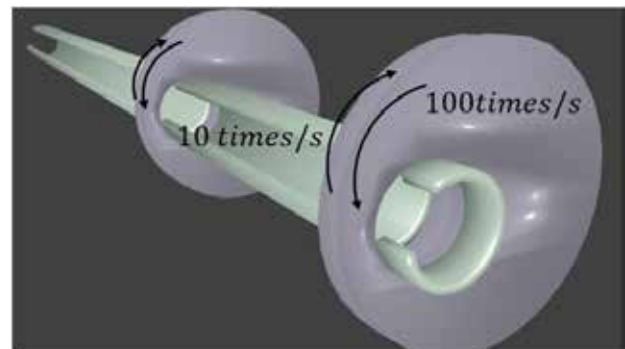


Fig.2 Mechanical shutter

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Thermal stability of color centers in LiF crystals: dependence on radiation type and dose

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Accumulation of radiation defects at irradiation is the complex result of consecutive and mutually independent events: formation of primary pair, spatial separation of its components and their transformation into stable ones under experimental conditions [1]. In ion crystals - at least, in those of alkali halide and alkali earth metal fluorides - high efficiency in formation of initial defects is observed. If the temperature is high enough, the initial genetically linked pairs are spatially separated through thermally activated movement of movable component of primary pair and this process is also highly efficient [2].

The present work is devoted to the research of thermal stability of color centers formed in LiF crystals exposed to irradiation of different doses and types. On the one hand, LiF is a typical AHC crystal; on the other hand, formation of molecular fluorine ions is possible in the crystal, which might affect stability of radiation-induced color centers.

Crystals were irradiated by beams of electrons and oxygen ions at room temperature. There were following parameters of electron irradiation produced by pulse accelerator: pulse duration - 10 nsec, average electron energy - 250 keV, energy density of initiating pulse - 15 mJ/cm². Electron range was 0.2 mm. The absorbed single pulse energy in LiF crystal was 8 10² Gy. For the procedure of irradiation by oxygen ions DC-60 accelerator (Astana) was used with 15 μm oxygen ion range; irradiation by uranium ions was performed at GSI accelerator (Darmstadt) with 94 μm uranium ion range [11]. Absorption spectra were measured by SF-256 UV spectrophotometer.

Presented results (see **Ошибка! Источник ссылки не найден.**) of stability tests of irradiation-induced color centers in pure and activated LiF crystals allow drawing the following key findings:

1. Thermal stability of color centers accumulated in LiF crystals at their exposure to electron irradiation depends on irradiation dose and rises with the increase of dose of pre-irradiation exposure.

2. Irradiation by ions of oxygen and uranium with doses up to 2.0x10⁸ Gy results in creation of color centers within LiF crystals; thermal stability of these centers is higher than that within crystals pre-irradiated with electron beams with doses up to 2.0x10³ Gy.

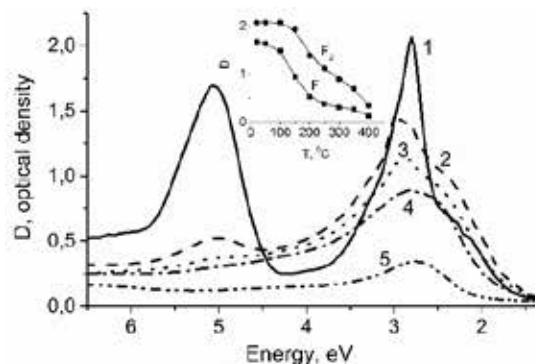


Figure 1. Absorption spectra of LiF crystal exposed to ¹⁶O ion irradiation at E=28 MeV up to reaching fluence of 10¹⁴ ion/cm² and heated up to: 1 – prior to heating, 2 – 200 °C, 3 – 250 °C, 4 – 350 °C, 5 – 400 °C. The insert shows the dependence of optical density level at maxima of F and F₂ bands on the annealing temperature.

With the growth of irradiation dose, stable neutral fluorine molecules are probably formed in interstitial spaces as a result of interaction of several H-type hole centers. Fluorine molecule in the interstitial space is an equivalent of two H-centers which is a stable defect poorly interacting with other defects. Destruction of fluorine molecule in the interstitial space results in formation of instable H-centers annihilating with F-centers and complex electron color centers.

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Contribution of electronic excitation and nuclear mechanisms in ion induced hardening of LiF crystals

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A study of radiation damage in LiF crystals under irradiation with MeV energy ions, from ^{12}C to ^{132}Xe , at 300K temperatures, depending on the ion energy, energy loss is presented. For light ions (^{12}C , ^{14}N) at low fluences, it is mainly color centers that are created. Increasing the fluence leads to the overlapping of tracks and the formation of more complex color centers, defect aggregates and dislocations. For ions with an energy loss above a threshold value ($dE/dx = 10$ keV/nm) the tracks exhibit a core damage region, surrounded by a halo which mainly contains single color centers. In this case, ion-induced nanostructuring is observed.

Formation of dislocations is acknowledged by an increase of hardness of LiF crystals. The depth profiles of indentation hardness have been studied. The results show a joint contribution of electronic excitation and nuclear (impact) mechanisms in ion-induced hardening. The damage via electronic excitations is responsible for hardening in the major part of the ion range whereas the impact mechanism plays a dominant role in a narrow zone at the end of the ion range where nuclear energy loss displays a maximum. The relative contribution of impact mechanism becomes important at low energies of ions (52 MeV, Fig.1) and high fluence irradiations (10^{13} - 10^{14} ion/cm²). The variation of hardness along the ion trajectory is consistent with changes of the dislocation structure, revealed by chemical etching.

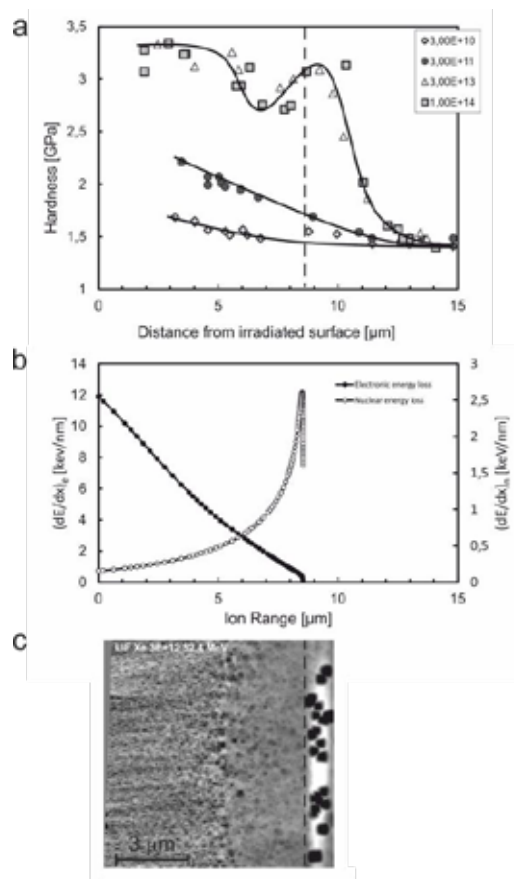


Figure 1. (a) Depth profile of hardness of LiF irradiated with 52 MeV Xe ions at different fluences; (b) Energy loss of 52 MeV Xe ions in LiF; (c) Structure of LiF irradiated with 3×10^{12} Xe/cm². AFM image from cleaved cross-section (profile). Size 5x5 μm.

Pressure of Partially Ionized Non-degenerate Hydrogen Plasmas

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Physical parameters of plasma – ionization degree, pressure, an average distance between particles, etc. – are connected with its thermodynamic functions (chemical potential, free energy, etc.) [1, 2]. Dense plasmas and moderate density plasmas thermodynamic, transport et al. properties depend on collective effects, especially pair interactions of charged particles [1, 2]. In classical plasmas an interaction between charged particles obeys Coulomb's law at large distances. The Coulomb potential diverges at small distances between charged particles. At small distances the interaction between particles should be considered by taking into account quantum effects. That is at classical consideration of plasma one should suggest short-range repulsive forces influence. By including short-range repulsive forces at small distances between charged particles plasma medium is considered as quasiclassical system of particles. This allows one to avoid the difficulty with the Coulomb potential's divergence.

Quantum effects of diffraction cause weakening of charged particles interactions and decrease of plasmas ionization degree [3]. In practice of importance is to define pressure of quasiclassical plasmas. So the purpose of the article is a definition of pressure of partially ionized non-degenerate hydrogen plasma at thermal equilibrium by its ionization degree. The method of investigation is applying modified equation of the ionization equilibrium for non-ideal plasmas, obtained on the basis of Saha equations and F. Baimbetov approximation [4].

Modified equation of the ionization equilibrium for non-ideal plasmas is given by [4]

$$\frac{1-\alpha}{\alpha^2} = n\lambda_{Br}^3 \sigma(T) \exp\left(-\frac{e^2 \kappa_0 \sqrt{\alpha}}{k_B T} G(\kappa_0 \lambda_{ie} \sqrt{\alpha})\right).$$

In F. Baimbetov approximation excess pressure is given by [4]

$$\beta \cdot P_{ex} = n(1 + \alpha) - \frac{1}{24\pi} (\kappa_0 \sqrt{\alpha})^3 \Phi(z),$$

variable “z” and its function $\Phi(z)$ are defined as follows

$$z = \sqrt{\pi \alpha \kappa_0} \lambda_{ie} / 4,$$

$$\Phi(z) = \frac{3}{5\sqrt{1+2z}} - 4 \left(\frac{1+z-0.5z^2-\sqrt{1+2z}}{5z^3\sqrt{1+2z}} \right).$$

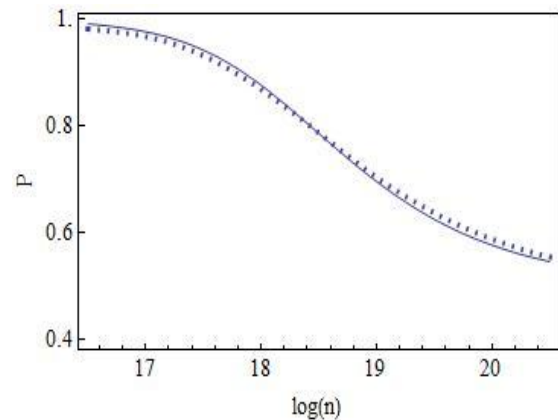


Figure 1. Relative pressure in F. Baimbetov approximation versus concentration, $T=20000K$: solid line – this work, dotted line– [2].

Pressure of quasiclassical hydrogen plasmas at different concentrations and $T=20000K$ is shown on Figure 1. Also for comparison on Figure 1 the same dependence accomplished by other authors [4] is shown.

Non-degenerate hydrogen plasma model proposed is based on the Saha approach and includes non-ideality effects: quantum effects as well as the screening of charged particles. Ionization degree and pressure as functions of parameters of plasma are defined.

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Correlation Functions of One-Component Plasmas

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The one-component plasma (OCP) is a model of plasma, in which it is considered as a system of point-like charges, immersed in a uniformly distributed neutralizing background of opposite sign charge. OCP is an object of constant interest in physics of non-ideal plasmas [1, 2].

At investigation of non-ideal plasmas it is necessary to take into account collective effects, especially the screening effect: the Coulomb interaction of chosen two particles is reduced by impact of neighbor charged particles, i.e. plasma medium. The screening radius is the Debye radius, which defined by

$$r_D = \sqrt{\frac{k_B T}{4\pi e^2 n}}. \text{ Here } T \text{ is the plasma}$$

temperature; k_B is the Boltzmann constant, e is a charge of electron, n stands for particles concentration. So the interaction potential as a function of distance r may be written as follows

$$\varphi_{ee}(r) = \frac{e^2}{r} \ell^{-r/r_D}.$$

This expression represents a pseudopotential. The pseudopotentials (i.e. macropotentials) or effective potentials are particles interaction potentials, depending on medium characteristics (temperature, concentration), i. e. $\Phi = \Phi(\vec{r}, T, n)$. For multicomponent plasmas pseudopotentials could be obtained by solving the Boltzmann-Poisson equations system [3].

The correlation function $g(r)$ determines particle distribution in the system. The correlation functions, i.e. radial distribution functions, are applied for evaluation of plasmas thermodynamic characteristics such as pressure, free energy etc [3]. To estimate them a method of pseudopotentials, hypernetted chain approximation, the Monte-Carlo method etc. are used. By the pseudopotential method two-component plasma (TCP) and partially ionized plasmas (PIP) are explored [3]. By hypernetted chain approach one-component

plasma (OCP), TCP and PIP have been examined. The advantage of this approach is concluded in its applicability both to non-degenerate and degenerate systems [4].

In the pseudopotential theory the binary correlation function can be defined by pseudopotential [3]

$$g_{ab}(r) = 1 - \frac{\Phi_{ab}(r)}{k_B T}$$

Indexes 'a' and 'b' correspond to interacting particles. Pseudopotentials $\Phi_{ee}(r)$ can be found by direct Furje transform of the Boltzmann-Poisson equation for OCP and then by reverse Furje transform of the equation's solution:

$$\Phi_{ab}(r) = \int \tilde{\Phi}_{ab}(k) \exp(ikr) dk.$$

Here $\tilde{\Phi}_{ab}(k)$ is the solution of the Boltzmann-Poisson equation for OCP in Furje-space.

In hypernetted chain approach correlation function $g(r)$ is found by a procedure, which in detail is considered in [2].

A purpose of the article is to get the correlation functions of OCP by method of pseudopotentials and by hyper-netted chain approach and to compare results.

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Effect of swift heavy ions irradiation on SiN_x matrix with Si nanodefects

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Fast ions irradiation is one of the key processes for the modification of thin layers and embedded nanostructures. The promising field of swift heavy ions application is a possibility for controlling the shape and size of nanoclusters embedded in dielectric matrix via heavy ion irradiation. A new wave of interest in studying the swift heavy ions (SHI) - SiO₂ interaction is due to a possible use of SHI for creation of Si light-emitting nanostructures by SiO₂ disproportionation in the ion tracks. While most of the previous studies have concentrated on SHI induced modifications of SiO_x thin films, the effect of ion irradiation on the Si-nanostructures embedded in α -SiN_x matrix has not been studied. A wafer of Si-rich amorphous SiN_x film on Si substrate was formed by low pressure chemical vapor deposition at 800 °C. The SiN_x thickness was 325 nm, the initial film stoichiometric parameter “x” was 1.0, and excessive Si concentration in nitride was 7 %. The 1×1 cm² samples were cut out of SiN_{1.0}/Si wafer and irradiated with 200 MeV Xe ions in fluence range of (10⁹ – 10¹⁴) cm⁻². The irradiated and initial samples have been characterized by means of Raman spectroscopy and room-temperature photoluminescence (PL).

The Raman spectrum of virgin SiN_{1.0}/Si (Fig.1) contains a broad band at 480 cm⁻¹ attributed to amorphous silicon phase (amorphous silicon nanoclusters). SHI irradiation results in band inten-

sity decreasing, and a signal from Si amorphous nanoclusters disappears completely after the irradiation to fluence of 10¹⁴ cm⁻². We can suggest the effect of Si nanoclusters dissolution into nitride matrix during 200 MeV Xe ions passage through. The visible PL with maximum at 450 nm was detected for virgin SiN_{1.0}/Si samples after annealing at 1100 °C for 60 min. SHI irradiation results in PL intensity decrease, too. A nature of silicon nitride matrix modifications under SHI irradiation is discussed.

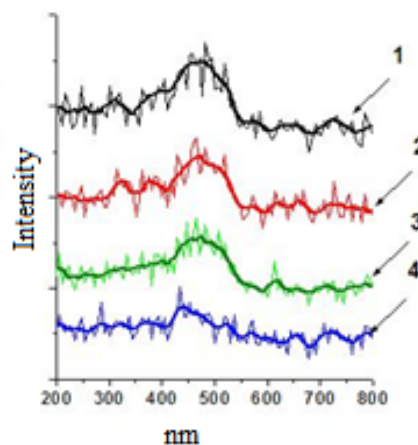


Figure 1. Raman spectrum of SiN_{1.0}/Si irradiated with 200 MeV Xe ions: 1-virgin, 2 - F=10⁹ cm⁻²; 3 - F= 10¹² cm⁻²; 4 = F=10¹⁴ cm⁻²

Control of laser-driven ion acceleration

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In laser-driven ion acceleration, there are issues, including repetitive ion source, ion beam quality, energy efficiency from laser to ion beam, the total number of ions accelerated, laser efficiency, particle energy, etc. [1]

We have worked on a multi-stage laser ion acceleration as shown in Fig. 1 in order to control the ion beam quality and to fulfill the requirements toward laser-ion cancer therapy.

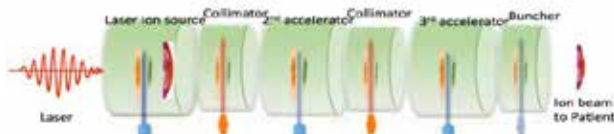


Fig.1 A concept for a future laser ion accelerator for cancer therapy

Figure 1 shows the concept of the future ion acceleration system. An ion beam is generated by an intense laser, and each stage / component has one function to control the ion beam quality by the beam bunching and the collimation. The ions are generated by the interaction of the intense laser with a thin film target. The laser-produced ions tend to have a divergence angle as shown in Fig. 2a) by the laser-produced transverse electric field. However, when the target has the hole in Fig. 2b) the focusing transverse electric field is created at the hole wall and a collimated ion beam is successfully generated.

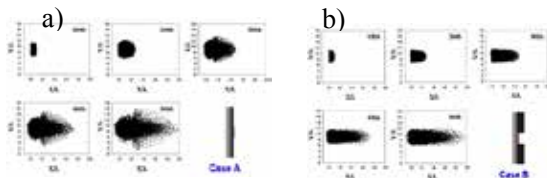


Fig.2 A hole target generates a collimated ion beam.

Figure 3 shows an example of a simulation model of the ion-beam collimation. The ion beam transverse divergence is suppressed by the walls behind the target. At the walls behind the

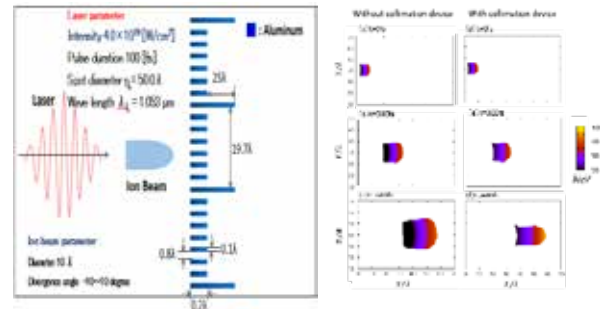


Fig. 3 The ion beam collimation is realized by the structured target shown here. The transverse electric field at the walls behind the thin foil target reduces the pre-accelerated ion beam transverse divergence.

target, the transverse electric field is also created to collimate the pre-accelerated ion beam. In Fig. 3 the Al thin foil substrate has another fine structure to absorb the laser energy efficiently.

Figure 4 shows an example simulation for the beam bunching of the pre-accelerated ion beam. The longitudinal electric fields generated at the target surfaces are designed to reduce the velocity tilt as shown in Fig. 4.

In this paper, we will present the latest research related to the control of laser-driven ion acceleration.

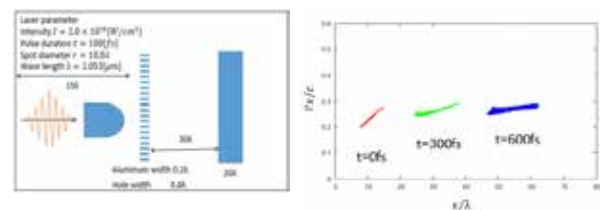


Fig. 4 The bunching of the pre-accelerated ion beam is realized by the multi-foil target.

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Alpha cluster resonance structure of light nuclei close to coulomb barrier

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The aim of this experimental study is to investigate the structure of the ^{19}F nuclei at energies representing astrophysical interest. Here we study the resonant interaction $^{15}\text{N}+^4\text{He}$ in the cyclotron DC-60 in Astana.

Important astrophysical processes which are taking place during the formation of new stars can be analyzed studying γ -radiation of the stars [1]. While the main source of γ -radiation within the first few hours of life of a novae is the annihilation of positrons following the $\beta +$ decay of ^{18}F [2], it turns out that the data on the synthesis and decay of ^{18}F is crucial for the understanding of this emission. However, the study of ^{19}Ne is experimentally difficult to implement [3], and therefore instead of a direct study of the structure ^{19}Ne it is suggested to investigate it through the mirror nucleus ^{19}F .

Structure of ^{19}F we studied utilizing the method of thick target inverse kinematics [4,5]. Following this approach the ion beam (^{15}N , $q=+3e$) with an energy of 26.25 MeV enters the scattering chamber through the titanium film (Ti 2 μm) losing in it 3.64 MeV. Scattering chamber is filled with a gas target (^4He) with pressure of 276 Torr chosen so that the beam is stopped before the detectors (10x10 mm Si, 375 μm), located along the far wall of the chamber at a distance of 445 mm from the input window, at 0° in the lab frame. The advantage of this method is that we exclude the impurities in the target and in the beam. The energy resolution of the detector is 15-20 keV measured for the α -source (^{226}Ra) with energy 4.8-7.7 MeV.

Here we present our early experimental results. Figure 1 shows the 180° excitation function in comparison with the data of [6]. Figure 1 shows that our data support the

absolute cross section measurements of [6]. Our data (blue curve) has the advantage of the better energy peaks positioning and widths for narrow states. However, the quality of the results is quite comparable at cm energies above 3 MeV. Also it is important to note that our experimental methodology allows measuring larger energy interval at much shorter time.

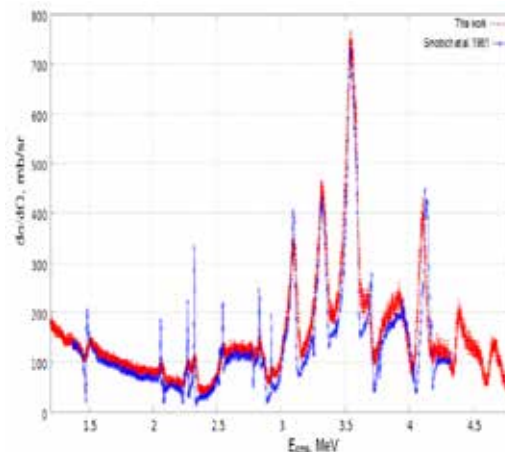


Figure 1. Excitation functions for elastic scattering of α particles on ^{15}N in c. m. frame at angle 180° vs the previous data at angle 169° [6]

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Numerical modeling of magnetic field dynamics in tokamak taking into account the induced eddy currents

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Modeling of magnetic configurations in the vacuum chamber of the tokamak, including a null-field, taking into account eddy currents is actual for planning the initial phase of plasma production at tokamak – initiation of the plasma discharge. Since analytical calculations of magnetic field are impossible for dynamic currents in multi-element structure of tokamak, special computer code have to be used. The numerical code for modeling of magnetic field dynamics in tokamak calculates magnetic field inside the vacuum chamber of tokamak using known functions of current $I_j(t)$ for every active magnetic field source j . Eddy currents in passive elements are

calculated by solving circuit equations for every time step.

The code implemented in C++ using QT and QWT libraries for GUI. GUI of the code based on the code TokScen [1]. Numerical algorithms of matrix inversion and bicubic spline interpolation from ALGLIB library are used.

The code verification is being done on experimental data from series of diagnostics of KTM tokamak.

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Laser-induced-fluorescence measurement of thermal conductivity in warm dense matter generated by pulsed-power discharge

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Thermal conductivity in warm dense matter is one of the interests for thermonuclear fusion scenarios. Alternative inertial confinement fusion, which is a fast ignition with applied magnetic field [1], has been considered to improve the coupling efficiency. The target behavior of the fast ignition with applied magnetic field depends on the anisotropic thermal conductivity. The magnetic confinement fusion (MCF) [2] Up to now, the heat load on the divertor in previous MCF systems has been unreached parameter. Thus, to predict properties of the divertor under these heat loads, several experiments have been performed using several methods[3-6]. To predict the performance of the divertor in MCF, we should analyze not only metallurgical properties but also thermophysical properties of ablated tungsten.

To clarify these topics, we should understand the physical properties of warm dense matter (WDM). WDM physics is applied when the density ranges from $10^{-3} \rho_s$ (ρ_s is the solid density of matter) to $10 \rho_s$ and the temperature ranges from 0.1 eV to 10 eV. WDM offers the possibility for scientific exploration of the properties of plasma at high densities and moderate temperatures. In this study, we experimentally demonstrated a laser-induced-fluorescence measurement of thermal conductivity in WDM generated by pulsed-power discharge.

Figure 1 shows the typical image of the laser-induced-fluorescence measurement of thermal conductivity in WDM generated by pulsed-power discharge [7-8]. The ruby capillary as a tamper can be sustained the high pressure up to 3 GPa, which is enough to conserve the dense plasma without hydrodynamic behavior. The capillary is also phosphor to measure the pressure and its temperature. The physical properties of ruby are well-known.

To evaluate the specific heat of dense plasma, the pulsed-power discharge technique is compatible due to the correctly evaluation of the input energy and the temperature for dense plasma. From the time-resolved spectroscopic measurements of both the sample and the ruby

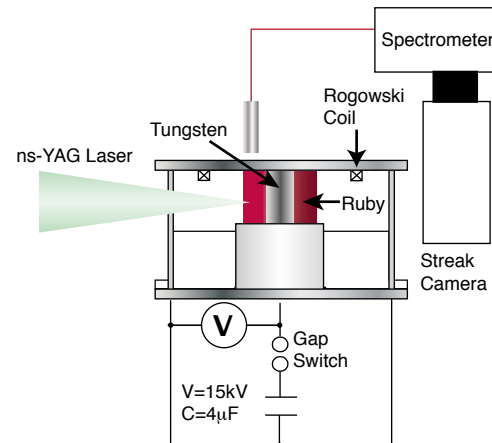


Fig. 1 Typical image of the laser-induced-fluorescence measurement of thermal conductivity in WDM generated by pulsed-power discharge

fluorescence driven by ns-YAG laser, we can determine the temperature of dense plasma and that of ruby capillary. The time-evolution of input power for the dense tungsten plasma is directly estimated by the input voltage and the current. Therefore, the specific heat of the dense tungsten plasma as a function of that temperature can decide the time-evolution of input power. The time-evolutions of ruby and plasma temperatures were observed. From these temperatures, we can determine the thermal conductivity of warm dense matter by using laser-induced-fluorescence measurement.

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Energy yield of thermonuclear fuel

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Use of the D³He-fuel as the efficient fuel in thermonuclear process is considered. It is shown that this type is preferable due to some aspects rather than traditional DT-plasma [1]. The ignition temperature value for the D³He fuel is greater than for traditional DD or DT fuels. The extreme conditions should be kept for reaching the ignition and achieving self-supporting thermonuclear process stage. We assume, for such conditions, temperature value about ~40-50 keV and total densities of D³He fuel as ~10²³ cm⁻³. Realization of the process is possible only by bringing fuel to mentioned conditions for a very short time as ~10⁻⁸-10⁻⁷ s.

The energy yield of the burning of the fuel implies the detection and use of product particles (charged, neutral) that leave the local burning area. However those high-energy product particles while passing the burning volume transfer heat to the fuel mainly by Coulomb scattering. The deposited in such way energy rise the temperature of fuel. This affects the reaction rate as it increases with temperature, and, therefore, the production of high-energetic particles also increases. The temperature equalization occurs in ~10⁻¹²-10⁻¹¹ s. after the energy transfer. Because of fact, that this value is relatively small in comparison with whole thermonuclear process time, the bulk fuel particles are always considered to be described by Maxwell distribution.

1. The high energetic reaction products, mainly 14,68-MeV protons, 14,07-MeV neutrons and 3,67-MeV α -particles determine the energy deposition and yield of the thermonuclear process. For these energetic particles the average relative energy transfer $\langle \frac{\Delta E}{E} \rangle$ calculated over the range of impact parameters. This directly implies the averaging over the all scat-

tered angles of projectiles. The $\langle \frac{\Delta E}{E} \rangle$ value depends on the mass ratio of interacting particles.

The average distance between fuel particles with considered fuel conditions allows mentioning only quasi-elastic scattering in distant flight approach $n^{-\frac{1}{3}} \gg b$. Where b -impact parameter of projectile, n -fuel particle concentration.

Here we estimate average energy deposition of high-energetic particle in quasi-elastic scattering, and the energy yield of the fuel. The burning process is simulated over the time. The results are compared with those for traditional DT, DD fuels.

2. The diagnostics of the energetic particles emphasizes determination of the particle population outgoing of burning volume, energy of particles, temperature of burning volume. By using the wall elements with amounts of ⁶Li, ⁹Be, ¹²C due to reactions ⁶Li(t,p γ)⁸Li, ⁶Li(d,p γ)⁷Li ⁹Be(α ,n γ)¹²C, ¹²C(d,p γ)¹³C the diagnostics of protons, alpha-particles and deuterons is possible [2,3]. Also the D³He fuel can be used as thermal neutron $\rightarrow$ fast neutron converter [4].

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Reflectivity of the dense xenon plasma

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The investigation of optical properties of the dense xenon plasma is important for the realization of different technological applications [1-2].

In this work we consider the dense partially ionized xenon plasma consisting of the electrons, ions and atoms. Particle densities are in the range of $n = 10^{20} \div 10^{23} \text{ cm}^{-3}$ and the temperature range is from $2.5 \times 10^4 \text{ K}$ up to $5 \times 10^4 \text{ K}$.

In work [3] the effective potential of electron-atom interaction, taking into account both quantum-mechanical effect of diffraction and screening effects, is presented. The way to take into account the dynamic screening was proposed in work [4], where the statical Debye radius was replaced by the dynamic one:

$$r_o = r_D \left(1 + \frac{v^2}{v_{Th}^2}\right)^{1/2}, \quad (1)$$

here v is the relative velocity of the colliding particles, v_{Th} is the thermal velocity of the particles in the system. Then the effective potential of electron-atom interaction with dynamic screening can be rewritten as [5]:

$$\Phi_{ea}^{dyn}(r) = -\frac{e^2 \alpha}{2r^4 (1 - 4\tilde{\lambda}_{ea}^2 / r_o^2)} \left(e^{-Br} (1 + Br) - e^{-Ar} (1 + Ar) \right)^2, \quad (2)$$

where $A^2 = \frac{1}{2\tilde{\lambda}_{ea}^2} \left(1 + \sqrt{1 - 4\tilde{\lambda}_{ea}^2 / r_o^2} \right),$

$$B^2 = \frac{1}{2\tilde{\lambda}_{ea}^2} \left(1 - \sqrt{1 - 4\tilde{\lambda}_{ea}^2 / r_o^2} \right).$$

In the framework of these pseudopotential models for the particle interactions, the scattering phase shifts were calculated on the basis of the Calogero equation [6].

Phase shifts enable us to calculate the transport scattering cross section $Q_{ea}^T(k)$. The collision frequency of electrons with atoms ν_{ea} can be obtained by the following expression:

$$\nu_{ea} = 4 \sqrt{\frac{2}{\pi}} n_a \sqrt{\frac{k_B T}{\mu_{ea}}} \int_0^\infty Q_{ea}^T(g) g^3 \text{Exp}(-g^2) dg, \quad (3)$$

here $\mu_{ea} = m_e m_a / (m_e + m_a)$ is the reduced mass of the electron-atom pair, g is dimensionless reduced velocity. The results will be compared with earlier results which were based on experiments for the transport cross section [7].

After that the dielectric function due to the electron atom interactions was calculated using the generalized Drude-Lorentz [8] equation:

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 - i\nu_{ea}\omega}. \quad (4)$$

However, for the total electronic dielectric functions contributions due to electron-ion and electron-electron interactions will also be considered [8,9]. From the dielectric function the reflectivity of the semiclassical electron plasma is calculated, using the Fresnel formula, and is compared with experimental results [10].

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Ion current density profile of laser ablation plasma transported in multicusp magnetic field

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Laser ion sources are capable of supplying ion beams with high current because a laser produced plasma has initially high number density same as that of solid. [1]. By transporting ablation plasmas for several 10 cm ~ 1 m, the beam pulse width of 20 us which is required for heavy ion inertial fusion (HIF) at the ion source can be obtained [2]. Therefore, the laser ion source is considered to be one of the candidate for the ion source for the HIF.

Because a pulsed laser is used for generation of plasmas, the laser ion sources supply pulsed ion beams, which have the ion current waveform of the shifted-Maxwellian distribution. To obtain current waveform with less variation in the pulse, modulations or extending the transport distance of the plasma is required. In addition, uniform plasma profile with large area is also required to realize multi-beamlet extraction [3].

We have been proposed that applying multicusp magnetic field to ablation plasmas to get high current with long pulse beams by confining the plasma in the lateral direction [4]. In this study, to obtain uniform plasmas in the lateral direction, we investigated the relation between plasma density distribution and magnetic structure by measuring ion currents in the lateral direction during transport through the multicusp magnetic field.

The second harmonic wavelength 532 nm of a Nd:YAG laser with 16-18 ns pulse width and 0.4 J pulse energy was used to generate ablation plasmas. The incident angle of the laser was 60 deg from the line perpendicular to the target surface. The laser was focused with a lens and the estimated intensity is order of 10^8 W/cm² on the target.

To generate the magnetic field, neodymium magnets whose magnetic flux density on the surface is about 0.2 T were located around a drift tube. Plasma ion currents were measured with biased Faraday cups.

We evaluated the ion current of the plasma as a function of the distance between the target surface and the Faraday cups with different configurations of the multicusp magnetic field. The relation between plasma density distribution and magnetic structure will be discussed.

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Design of velocity measurement system to generate warm dense matter of insulator by flyer impact

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A table-top pulsed power generator with isochoric heating using sapphire hollow capillary was proposed and used to generate the extreme state of matter such as warm dense matter (WDM) [1]. However, to generate WDM of insulated materials is difficult by the Joule heating.

In fast ignition of inertial confinement fusion (ICF), the guiding cone is used to increase the energy conversion efficiency from laser. Diamond-Like-Carbon (DLC) is one of candidates as the material of guiding cone for the improvement of conversion efficiency. The guiding cone becomes WDM by irradiation of the heating laser [2].

However, physical properties of insulator (DLC and Silicate [3] and so on.) of WDM condition is unclear. We designed to generate WDM of insulator by flyer impact method due to intense electron beam using by intense pulsed power supply ETIGO-II [4][5].

A solid target irradiated by intense laser or charged particle beam, irradiated surface becomes ablation plasma. It expands and accelerates the remnant of solid target. The flyer accelerated by a light ion beam was studied by using intense pulsed power generator ETIGO-II [6].

In this study, we designed to measure the flyer velocity by TOF using backlight pulsed laser.

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Study of Peeling of Single Crystal Silicon by Intense Pulsed Ion Beam

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The surface peeling process induced by intense pulsed ion beam (IPIB) irradiation was studied. Single crystal silicon specimens were treated by IPIB with accelerating voltage of 350 kV current density of 130 A/cm². It is observed that under smaller numbers of IPIB shots, the surface may undergo obvious melting and evaporation. As the number of shots increased, surface peeling may occur. Numerical thermal and me-

chanical analysis was carried out and it is deduced that under IPIB irradiation, cracks may be induced by the thermal-stress. Cracks on the surface may be smoothened by the surface melting under IPIB irradiation while in deeper region of the target, cracks may be preserved and keep growing under series of IPIB, finally lead to surface peeling from deeper region under the surface.

Accelerator complex based on DC-60 cyclotron

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DC-60 heavy ion accelerator [1], put into operation in 2006, according to its specifications - spectrum, charge and energy of accelerated ions, has the high scientific, technological and educational potential. The highest possible universality both by spectrum of accelerated ions and acceleration energy and regimes was built in DC-60 heavy ion accelerator designing. The new interdisciplinary research complex based on cyclotron DC-60 makes it possible to create a highly-developed scientific-technological and educational environment in the new capital of Kazakhstan.

DC-60 accelerator is a dual cyclotron, which is capable of charged particles acceleration up to kinetic energies in MeV/nucleon, expressed in the following relation: $E = 60(z_i/A)^2$, where z_i - accelerated ion charge, A - atomic weight of ion. Relation (z_i/A) in formula must be within the following limits: $(z_i/A) = (1/6 \div 1/12)$, that impose constraints on charge of accelerated ions.

Prototypes ECR heavy-ion source are sources DECRIS-2 and DECRIS-3 which is used in the accelerator DC-60. On the "ECR - surface" is used magnetic field configuration «minimum B» for the plasma confinement and electronic heating. This configuration is obtained as a result of the superposition of an axial field of magnetic mirror and a radial field of a sextupole magnet. Two single coils with an iron yoke form an axial magnetic field and the radial magnetic field is created by an NdFeB permanent sextupole of a magnet.

The operating frequency of UHF the ECR generator is 14 GHz. The flash chamber of source is insulation meant for a voltage up to 25 kV. The extraction of ions is performed two elements Plasma electrode and the mobile extraction electrode.

For the beam transport from the ECR ion source to the cyclotron created an powerful system of axial injection of beam, which is consisting of:

- focusing element;
- energy-analysing magnet;
- detecting of elements;
- bunchers;
- vacuum pumps;
- electrostatic inflectors.

The entrapment of phase to accelerate in the center of the cyclotron is $30^\circ \div 35^\circ$. This means

that no more than 10% of ion of the desired charge will be involved in the acceleration process. To increase efficiency the entrapment of the beam by axial injection systems is installed the buncher with a sine wave, which includes the beam particles in the desired range of phases and increases the capture coefficient to 30 | 50 %. Turn of the beam from the vertical axial injection channel in the median plane of the cyclotron using the electrostatic spiral of inflector.

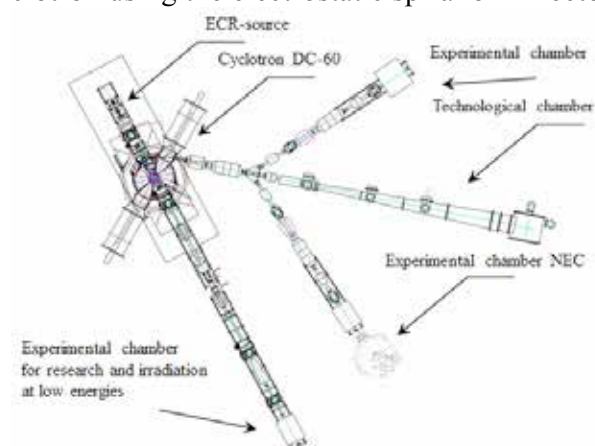


Figure 1. The scheme of the accelerator complex

The upper energy of the accelerated ions is 1.75 MeV/nucleon. The variation of the energy of ions in the range from 0.35 to 1.75 MeV/nucleon is provided by changes in the charge of the accelerated particles and magnetic field of the cyclotron.

High frequency system has a variation of the frequency in the band 12 - 18 MHz and provides the acceleration of ions on harmonics 4 and 6.

The electrostatic deflector with the electric field strength of 75 kV/cm is used for the beam extraction from the cyclotron which located in the cavity of the magnet. The beam transport channels from the cyclotron to the target chamber include the standard system focusing and rotation of the accelerated ions. Thus, range of ions accelerated on DC-60 cyclotron is ${}^6\text{Li}$ to ${}^{132}\text{Xe}$, variation of ion energy is over the range 0.35 to 1.75 MeV/nucleon.

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Study on Ablation Products of Zinc by Intense Pulsed Ion Beam Irradiation

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As a kind of flash heat source, intense pulse ion beam can be used for material surface modification. The ablation effect has important influence on interaction between IPIB and material. Therefore, the understanding of ablation mechanism is of great significance to IPIB application. In this work, pure zinc targets were irradiated and ablated by IPIB. In the ablation process under the different ion beam energy density and number of

pulses, the ablation products were collected by monocrystalline silicon substrate. By analyzing the ablation products with scanning electron microscope and atomic force microscope, the surface morphology of the substrate and the spatial distribution of ablation product quantity were obtained. The results are useful for clearing the ablation process and the influence of beam parameter on the ablation effect.

X-ray emission for 424 MeV/u C ions impacting on selected targets

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In inertial Confinement Fusion (ICF), X-ray radiation drives the implosion requiring not only sufficient conversion efficiency of the drive energy to the X-ray but also the highly spatial symmetry. Consequently, it is important to investigate the X-ray radiation in the interaction of high energy heavy ions beam with solid target. In this work, we would like to investigate the X-ray emission induced by high energy heavy ions.

The K-shell X-ray emissions of the selected elements (Ti ~ Zn) are investigated for high energy (424MeV/u) carbon ions impact. The X-ray production cross sections are calculated and compared with various theoretical estimations. It is indicated that, in such high energy collisions, the L-shell electrons of the target atoms are multiply ionized, this lead to a blue shift the K X-ray and an enlargement of the ratio of $K\beta$ to $K\alpha$ X-ray. The inner-shell ionization induced by high energy heavy ions can be simulated by the BEA model, but the effect of the multiple-ionization should be taken into account when determining the X-ray cross section, which is linearly decrease with the increasing target atomic binding energy in the present work (figure 1).

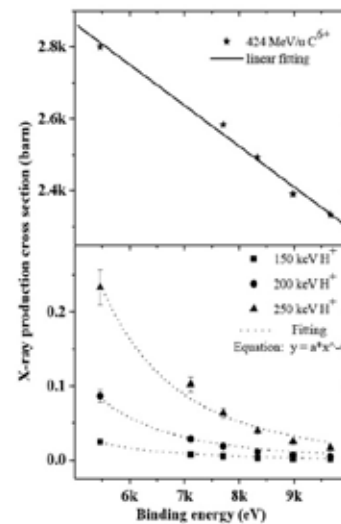


Figure 1. X-ray production cross section as a function of the target atomic binding energy induced by high energy C⁶⁺ ions and low energy protons.

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THE CALCULATION OF PARAMETERS AND DESIGN OF «PLASMA FOCUS» FACILITY

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In this paper, the plasma focus type devices are seen as an alternative to traditional magnetic systems and laser fusion. The authors present the research results of plasma formation on the "CPA-30" plasma accelerator and plasma installation "Focus fusion".

Today, the efforts of scientists to address the fusion problems are mainly associated with magnetic systems, especially with tokamak's (ITER project), as well as some other methods, for example by laser inertial fusion, traps and others. All of these methods are studied decades, published thousands of scientific papers, but operating reactor is not built. First of all, this is due to technical difficulties, but there are reasons of principle.

So, the direct calculation of all coordinates of plasma particles is not possible to individually [1], even at very low concentrations of plasma real objects. In such a situation, an alternative approach is the consideration of collective phenomena in plasma and study of its self-organization. Problems of plasma self-organization in various plasma devices are just beginning to be studied. For the first time structuring of the plasma in the form of striations observed in experiments on Z-pinch in the last century [2], a number of works registered in the structuring of the plasma accelerators [3,4]. In the high-dense plasma formed the objects of geometric structures, filaments and other peculiarities [5]. It is obvious that the presence of such objects points to a fundamental property of a dense and hot plasma structured. In this case, they will play a decisive role in the work of fusion devices.

Another approach to create fusion devices is a method based on plasma generation in devices such as plasma focus. Based on the study of dynamic structures in various PF devices the authors raise the question of creating a new type of reactor, based on the focus of plasma beams in a small area with a high density.

The estimation of the value of the discharge current and the dynamics of discharge circuit on the basis of the electrodynamic model was calculated for "plasma focus" installation. On the data obtained calculated the geometry of the electrode system. The description of the vacuum chamber and installation of electrical parts presented.

Finally, we discuss general problems common to all types of plasma focusing devices from a single viewpoint. In our opinion, a simple increase of the focus energy by increasing the current path is not acceptable. Much more important to develop the geometry of the electrodes so that the interaction between the current and the magnetic field is maximized. At the same time, an important indicator is not the plasma density and the path of the particles to provide a large number of collisions.

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Investigation of Diffusion Processes at Metal Target Irradiation by Pulsed Plasma Flow

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Pulsed irradiation of metals and alloys by plasma flows and ion beams follows by an emergence of significant temperature gradients and thermo mechanical stresses in near-surface region of a target [1-3]. Processes of heat and mass transfer are intensified. Diffusion is stimulated by temperature growth. Diffusion coefficients are increased on 5-8 orders of magnitude in compare with their stable values, corresponding to the irradiation in continuous regime. A depth of impurity particles penetration doesn't exceed the value of projectile path length in metals. At deceleration of the impurity particles their collisions with atoms nuclei cause atoms displacement of crystal lattice sites. Because of medium continuity a dominant mechanism of structural damages creation could be atom-atomic collisions cascades, which involve large area, several times exceeding a volume of near-surface region of the target. It is obvious, that the large part of diffusion flow is transferred within displacement cascades [1].

At high temperature plasmas impact on the target hot ions reach the surface practically with no energy loss. Since electrons are more mobile to neutralize ion charge a cold electron flow from the edge plasma emerges. Because of interaction of hot electrons with the cold ones the energy of electrons, hitting upon the surface, is less on order than the energy of falling ions. Corresponding estimates for plasmas interaction with diverter plane, the first edge of thermonuclear reactor, are proposed in [4]. So the predominant factor is the interaction of ions with solid.

A purpose of the article is to estimate magnitudes of concentrations of implanted ions, vacancies and interstitial atoms at impact of pulsed nitric plasma

flow on a sample of stainless standard prepared austenitic steel.

Non-uniform heating of the target has been determined by the heat transfer equation [1-3]. Diffusion equations system for nitrogen ions, vacancies and interstitial atoms of the target, initial and border conditions are written. A simulation is accomplished for the next parameters of the plasma flow: the surface density of absorbed energy flow, $q_0=50 \text{ J/cm}^2$; the pulse duration, $\tau=10 \text{ } \mu\text{s}$.

At first approach the impurity ions (nitrogen) penetration process is supposed to be isothermal, besides subsurface layers of the target is close to the melting temperature. Of interest is the process flowing during time interval of an order of the pulse duration, with the embedded impurity diffusion in subsurface layers being thermal-stimulated.

Temperature space profiles at different time moments and concentration space profiles of the embedded ions, vacancies and interstitial atoms have been obtained. The space profiles of temperature and embedded ions concentration space profiles have been compared with experimental data. The profiles agree with them.

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