INTERNATIONAL ATOMIC ENERGY AGENCY

Report of the 8TH IAEA Technical Meeting on

Physics and Technology of Inertial Fusion Energy Chambers and Targets

8–9 March 2018, Tashkent, Uzbekistan

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Contents

A. Background

In the field of fusion energy, projects oriented towards the development of the technology basis for the provision of energy from inertial confinement fusion, have started in several countries. The demonstration of an integrated reactor system including repeated target injection, tracking and firing is the nearest milestone towards Inertial Fusion Energy (IFE) realization. The success of integrated systems will increase the reliability of IFE and open new applications.

In this context, an additional problem towards the design and building of large fusion facilities – based on plasma confinement principles – is the damage of plasma facing components due to steady state, transient thermal loads and interaction with plasma particles. Although at the present day there is no devices that can obtained exactly the same values predicted for next step fusion devices (i.e. the parameters that characterize the interaction between the plasma and the materials), progress in understanding the interaction between materials and power plasma fluxes has been made. Further research is needed and must be pursued by using different plasma facilities that are capable of generating high temperature plasma with the same heat flux factors.

The IAEA plays an active role in providing the framework for catalysing innovation and enhancing worldwide commitment to fusion energy achievement. The purpose of this technical meeting is to serve as a forum where key issues relating to the physics and technology of chambers and targets of IFE devices are discussed.

B. Objectives and Expected Outputs

The meeting primarily aimed at identifying technical solutions for closing both physics and technology gaps to an IFE power plant.

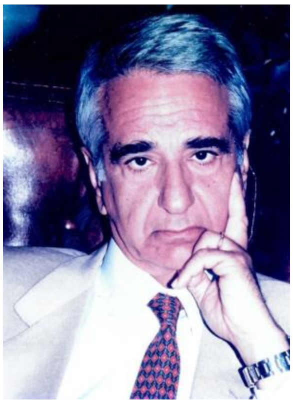
The meeting covered the following topics:

- Physics Related to Inertial Fusion Energy Reactors and Reactor Design (PRD);
- IFE Reactor Technology and Systems Integration (RTI);
- Target Fabrication with Emphasis on Mass Production (FMP);
- Target Injection and Tracking (TIT);
- Assessment of Safety, Environment and Economy Aspects of IFE (SEE).

More detailed information about the meeting can be found on the Technical Meeting IAEA Fusion Portal Webpage, https://nucleus.iaea.org/sites/fusionportal/Pages/IFE/2018/Main.aspx.

C. Work done

The meeting was attended by 20 participants from 10 Member States (see List of Participants) and it opened with a Memorial Lecture in honour of Prof. G. Velarde (photo) and his pioneering work in IFE. Mr. Velarde actively contributed to the declassification of information related to Inertial Confinement Fusion (ICF) in the 1980s, allowing the progress of civil applications in this field.



Prof. G. Velarde

The 2 days of the meeting were dedicated to the individual presentations by the participants, discussions and setting up the conclusions. Enough time was also allocated for questions-answers and discussions following each presented paper. Brief summaries of individual presentations are given at the end of this report (see Book of Abstracts).

Below text briefly resumes individual presentations and highlights major findings presented:

- The study of the influence of grain boundaries on the radiation-induced damage and light species behaviour in nanostructured W contributes to the understanding of basis phenomena needed for the development of new materials, with improved radiation resistant to be located at the first wall of an inertial fusion reactor.
  - Grain boundaries favour hydrogen out-diffusion, however, the thermal stability of nanostructured tungsten needs to be improved.

- In order to achieve the IFE, a module of the laser fusion driver should have the output energy more than 2.5 kJ and the repetition rate more than 10 Hz. One of the most promising techniques to achieve both high repetition rate and high output energy is a coherent beam combining using Self-Phase-Controlled Stimulated Brillouin Scattering Phase Conjugate Mirrors (SPC-SBS-PCMs). The coherent beam combing using SPC-SBS-PCMs is successfully demonstrated at the low average power of W class with the repetition rate of 10 Hz. However, the SBS-PCM suffers a thermal problem at the high average input power. The absorbed laser beam is accumulated in the SBS media. This causes the optical haze in the liquid medium. So, it is necessary to develop an SPC-SBS-PCM that overcomes this issue and useful for the high average input power to construct the high average power coherent beam combination laser using SPC-SBS-PCMs.
  - To develop an SBS-PCM for high power laser input, the HT-110 liquid is selected for the SBS medium and purified carefully. A kW class high power laser, called Kumgang laser, is used to measure SBS reflectivity, reflected beam patterns, and pulse temporal shapes. With the purified HT-110, the SBS reflectivity was 69% at the input power of 99 W (99 mJ at 1 kHz) without any additional equipment. However, the reflected pulse shape has steep rising edge, which can break the optical elements and the laser gain medium. The pre-pulse technique is applied to preserve the temporal pulse shape. With this pre-pulse technique, the double-pass amplified power of 95 W (95 mJ at 1 kHz) was obtained at the input power of 3.1 W (3.1 mJ at 1 kHz). Coherent 2 beams combination using purified SBS-PCM with Kumgang laser was demonstrated, and the relative phase stability was measured to be less than $\lambda/20.0$.

- Some low-activation steels are considered as constructional materials for inertial fusion devices due to their high swelling resistance and low irradiation creep-rates. Influence of powerful plasma impacts in a wide range of plasma parameters on RAFM steel surface, coatings of various materials etc. has been discussed in presentation. Analyses and comparisons of experimental results of research on materials behaviour under their irradiation with steady-state and high-power pulsed plasma-streams, which can be generated in different plasma devices with various specific heat loads and different particle fluxes, are necessary in inertial fusion science.

  - Experimental research on surface modifications of different stainless-steel (SS) grades was performed. The samples of the Eurofer (Cr-9.7%, Mn-%0.4, Fe-89.6%) ferritic/martensitic-steels covered by tungsten coatings were treated within the QSPA Kh-50 quasi-stationary plasma accelerator and the MPC magneto-plasma compressor. Possibility of the alloying of SS-surfaces with tungsten coatings was demonstrated. The maximum tungsten content of about 85 wt% was observed in the surface layers of the Eurofer samples modified by plasma streams generated by QSPA.
  - The reduction of the coating thickness together with an increase in the number of plasma treatment cycles might create conditions for the better penetration of an alloying element into the treated substrate.

- Study of the operational windows of the final lenses for the three foreseen HiPER scenarios under realistic operation conditions.
  - For a proper work of the final lenses their temperature has to be constant and uniform during start up and operation. The working temperature has to be $800\ K < T < 1223\ K$.
  - An engineering system has been developed, which allows fulfilling the previous mentioned conditions.

- Application of destructive and non-destructive analysis method for analysis of thermomechanical properties of high-temperature plasma irradiated tungsten-based materials.
  - Double forging of tungsten has led to improvement of the materials properties, namely strengthening of binding between grains. The decrease of generated droplets on double forged samples, as estimated by SEM images, is noteworthy. Doping of tungsten with lanthanum-oxide may lead to a decrease in defects with sharp edges (craters, cracks), which would otherwise lead to a detachment of bigger drops of material from the surface. The microhardness analysis show, that in general the first layer has greater hardness, which is connected with fast melting and subsequent crystallization of the first layer (a similar effect is noticed in the case of stainless steels in the flux of hydrogen and nitrogen plasmas). Comparison of results of conductivity measurements and analysis of cross-sections of irradiated tungsten samples allows to conclude that the decrease of conductivity is related to thermal and mechanical damages in the bulk of material.

- The power production with the use of the p–^{11}B reaction would be very clean from the viewpoint of ecology. However, the use of this reaction for power production may be impossible due to its small cross-sections. Recently, it was assumed that effective ignition and, eventually, the practical use of the p–^{11}B reaction could be provided by avalanche reactions of several kinds. It was also assumed that such reactions were already observed in the experiments at Prague Asterix Laser System.
  - It has been shown that the aforementioned assumptions on the possibility of avalanche p–^{11}B fusion reactions are mistaken, since deceleration of alpha-particles is not taken into account. Therefore, at least in the near-term future the fusion power plants will be able to utilize only the D–T, D–D and D–^{3}He fusion reactions. The most effective

scenarios of the use of advanced fuels will be based on compression of such fuels by or with the use of thermal radiation from D-T microexplosion(s).

- Shock waves play a major role in ICF as a process to control the target implosion and fuel heating.
  - Under the shock ignition conditions, the hot electrons play a double role: they may enhance the shock pressure or could preheat a cold fuel and inhibit the compression.

- Darkening of optical windows under different kind of ionizing radiation from exploding targets in the reactor chamber and e-beam scattering or bremsstrahlung X rays in KrF drivers plays a crucial role in the UV laser beam delivery and stable laser operation.
  - A comprehensive research has been undertaken to solve this problem and various UV optical materials has been irradiated, i.e. fused silica glasses, CaF2, MgF2 and Al2O3 crystals commonly used as KrF laser windows or coatings of multilayer mirrors. Overall, windows darkening under e-beam irradiation appear to be stronger for deeper UV radiation of a KrF laser.

- IFE targets mass manufacturing and rep-rate delivery.
  - Expert analysis has shown that the FST layering method allows fabricating cryogenic layer inside moving free-standing targets. That will allow one to economically fabricate large quantities of IFE targets and to continuously inject them at the laser focus. Our theoretical research and proof-of-principle experiments have shown that it is possible to create the FST transmission line based on the FST layering method and on the noncontact delivery system using quantum levitation effect of high temperature superconductors.

D. Conclusions and Recommendations

The meeting participants formulated the following final conclusions on:

- **<u>OPTICS</u>**
  - <u>Engineering solutions to temperature control in final lenses</u>. For different operational stages are designed, by using a fluid system of cooling/heating uniformly the lenses during initial and steady operation. Modelling allows assessing successful operation of this solution.
  - <u>Swift heavy ions irradiation of Silica studied by computation and experiments</u>. An experimental campaign using Br ions of 5–50 MeV has been carried out measuring the refractive index; we observe the refractive index decreasing when fluence is increasing. The effect of the strain field on the density could explain the decrease in the refractive index as concluding with our methodology coupling MD and FEM.
  - <u>Transmission of laser radiation through pre-irradiated lenses of SiO_2</u>. Transmission of Nd:YAG laser pulses (0.7–7 mJ, 28 ps, 266 nm) through KV-type silica glass preliminary irradiated with ^{60}Co-gamma quanta to 10^9 R and neutron fluences to 10^{20} cm^{-2} has been experimentally studied by means of SEM, FTIR and UV3600. The following features were found on the glass surface the following features: <3 mkm structured ripples in the laser focus, radial shock waves 10 mkm propagating to 100 mkm, weakening of Si-O stretching vibration bands due to radiation induced oxygen vacancies absorbing at 260 nm. Part of the observed microdefects is annealed due to the glass network relaxation within 2 weeks.

- Research of irradiation of various UV optical materials (i.e. fused silica glasses, CaF_2, MgF_2 and Al_2O_3 crystals commonly used as KrF laser windows or coatings of multilayer mirrors). A compact 25 kW linear electron accelerator with electron energy 1 MeV and beam current up to 25 mA was adjusted to irradiate optical samples in successive runs with a total e-beam energy fluence up to 6.5 $kJ \cdot cm^{-2}$ (absorbed doses in samples up to 23 MGy). Induced optical density (OD) for all tested materials revealed saturation with increasing the dose. At 248 nm wavelength, the lowest saturated OD ~ 0.1 (it corresponds to transmittance fall by 9.5 %) was observed in a "dry glass" KS-4V, which contains the minimal hydroxyl impurity responsible for the formation of E' centers and non-bridging oxygen hole centers with absorption bands around 215–260 nm. At 353 nm wavelength the lowest OD ~ 0.016 (1.4 %) was in a "wet glass" Corning 7980, which has the lowest impurity content except for a hydroxyl. Overall, windows darkening under e-beam irradiation appear to be stronger for deeper UV radiation of a KrF laser.

- **TUNGSTEN (W)**
  - Light species behaviour depending on grain boundaries. Important differences are observed in the density of vacancies between nanostructured and coarse-grained samples as well as the preferential places for H accumulation concluding with the influence of temperature.
  - Nanostructured W and pulsed H and thermal irradiation. In collaboration with the Plasma group at the Comisión Chilena de Energía Nuclear lead by L. Soto, we have irradiated samples under different conditions (H factor and number of pulses) by D and He. Then, we have studied the morphology of the irradiated samples by optical and scanning electron microscopy (SEM). We have also investigated their microstructure by X ray diffraction and their elemental composition by using Energy Dispersive X ray spectroscopy (EDX). We have checked the thermal stability of nanostructures by studying the morphology of annealed samples (SEM) and their microstructure (XRD).
  - First Wall (FW) thermo-mechanical analysis. Considering ions deposition, fatigue and crack analysis, conclusion – among other results – is that the necessary thickness for avoiding undesired effects is at least 200 µm. Detailed calculations of energy loads dependent on time and space from target emissions give a source of credible information for these thermo-mechanical ulterior studies.
  - Plasma Focus (PF) diagnosis/analysis using destructive and non-destructive methods of W and W alloys. The interplay of the very strong (high power flux density) plasma and ion pulses, and weak plasma pulses with the armour materials is study, by using different tungsten grades. Different sequential irradiations of strong and weak pulses were used. Surface damages studied by SEM images showed that the damage on surface did not differ from each other on different samples. Bulk damages, studied by measurements of conductivity and microhardness of cross-sections, showed that the sample firstly irradiated with strong pulses was damaged the most in comparison with the samples irradiated firstly with weak pulses. This indicates that choosing proper plasma shield materials, the damages in the bulk as well as interplay of plasma pulses with different damage factors should be investigated more thoroughly.
  - PF reliability analysis of its plasma, ions, neutrons source term. Consequences in the interpretation of final results.
  - Creation/modification of material surfaces for FW applications, such as that of W-RAFM from 4 to 20/50 µm. Characterization of different steel types with respect to their response to intense plasma pulses, damage features and erosion products under repetitive high flux plasma loads have been performed. The large sputtering rate under high-energy particles is the main disadvantage of steel as armor material for fusion

devices. One of the potential ways of improving stainless steel properties is by alloying theirs surface layer with heavy elements such as tungsten. As a result, the delamination of the coatings upon the stainless-steel surfaces was not observed during their irradiation by plasma streams within the QSPA facility.

TARGET DESIGN

- Shock ignition. Role of hot electrons in shock ignition targets is being identified, and shock ignition campaigns in OMEGA are actively being developed with the goal of using hot electrons for strengthening the shock and optimizing the ignition. The control of the energy transport in target design codes with flux limiter is shown to be insufficient with no physical meaning. A new fast inline kinetic model accounting for 3D laser energy deposition is under development and testing in experiments. Its implementation will allow new more robust design of high gain targets.

- **TARGET MANUFACTURING**
  - IFE targets mass-manufacturing and repetition rate delivery. The application of the FST layering method for fabricating cryogenic layer inside moving free-standing IFE targets has been mathematically and experimentally analysed. The conception of the FST transmission line is developing based on the FST layering method and noncontact delivery system using a quantum levitation effect of the high temperature superconductors. That will allow one to economically fabricate large target quantities and to continuously inject them at the laser focus.

- **DRIVER: LASER**
  - SPC-SBS-PCM. This is a promising tool for bulk laser coherent beam combination, which is expected to contribute to build a real laser fusion driver. It is now almost developed to be applied to high average power laser amplifier system. Now the thermally induced optical haze in the SBS cell is the main issue to be resolved. It is necessary to have a new SBS cell design and/or to find a new SBS material having lower optical haze.

- **p+B target**
  - It is shown that recent assumptions according to which the effective ignition and practical use of the p–^{11}B reaction could be provided by avalanche reactions of several kinds are mistaken. The yield corresponding to the physically important p–B^{11} reaction would be unacceptably high. The current IFE studies should be concentrated on the problems related to the effective ignition and use of D–T microexplosions. The possible use of such microexplosions includes the effective ignition of microexplosions with the physically important D–D and D–^{3}He fusion reactions.

- **NEUTRON SOURCES**
  - IFE materials programme, similar to magnetic approach, need as soon as possible an experimental machine for neutron irradiation.
  - Design of IFMIF-DONES is the closer solution to get enough fluences in adequate dose rate.
  - The appetite in neutrons by the high brilliance compact neutron sources for neutron scattering research open a potential opportunity to colonize with a small effort those facilities for our interest in material irradiation.

I. Draft Meeting Agenda

Thursday, 8 March, 2018

9:00-9:30	**Registration**
9:30-9:45	**Welcome and Opening Address** *S. Gonzalez- De-Vicente, J.M. Perlado*
Session 1 **Chair: Tikhonchuk V.**	
9:45-10:30	Professor Verlade memorial *by Perlado J.M.*
10:30-10:50	**O-1:** Tikhonchuk V. *Recent progress in the target design and experiments on the shock ignition scheme of the inertial fusion reactor*
10:50-11:20	**Coffee Break**
Session 2 **Chair: Khaydarov R.T.**	
11:20-11:40	**O-2:** Khaydarov R.T. *Combined effects of gamma and UV-laser radiations on the microstructure of silicate glass*
11:40-12:00	**O-3:** Soto L. on behalf of Panizo M. *Behavior of nanostructured and coarse-grained tungsten under pulsed irradiation: hydrogen and thermal loads*
12:00-12:30	**O-4:** Perlado J.M. *Feasibility of potential Projects of Neutron Sources for Materials Irradiation, Thermo-mechanical study of W First Wall in non-protective chamber in IFE*
12:30-12:50	**O-5:** Shirokova V. *Application of destructive and non-destructive analysis method for analysis of thermomechanical properties of high-temperature plasma irradiated tungsten-based materials*
12:50-14:20	**Lunch Break**

Session 3 **Chair: Gonzalez-Arrabal R.**	
14:20-14:40	**O-6:** Soto L. *Table top plasma focus as tunable pulsed irradiator to study materials for inertial fusion energy chambers: Statistical study and reliability analysis*
14:40-15:00	**O-7:** Gonzalez-Arrabal R. on behalf of Rivera A. *Conceptual design of final lens systems for laser fusion power plants based on direct-drive targets*
15:00-15:20	**O-8:** Gonzalez-Arrabal R. *Influence of the grain boundaries on the radiation-induced damage and on the hydrogen behavior in tungsten*
15:20-15:40	**O-9:** Marchenko A. *Materials surface damage and modification under high power plasma exposures in relevant inertial fusion reactor conditions*
15:40-16:10	**Coffee Break**
Session 4 **Chair: Zvorykin V.D.**	
16:10-16:30	**O-10:** Zvorykin V.D. *Degradation of UV optical materials tested in a continuous irradiation at 1-MeV linear electron accelerator*
16:30-16:50	**O-11:** Zvorykin V.D. on behalf of Koresheva E.R. *FST transmission line for mass-manufacturing of IFE targets*
16:50-17:10	**O-12:** Kong H.J. *Development of the self-phase-controlled stimulated Brillouin scattering phase conjugate mirror (SPC-SBS-PCM) toward a high average power coherent beam combination laser*
17:10-17:30	**O-13:** Shmatov M.L. *Analysis of some assumptions about the possibility of avalanche proton-boron11 fusion reactions*
17:30-18:00	**Discussion**

II. List of Participants

Perlado Martín, J.M. (chair)	Spain
Khaydarov, R. (local host)	Uzbekistan
Gonzalez Arrabal, R.	Spain
Gonzalez de Vicente, S.M.	IAEA
Ibragimova, E.M.	Uzbekistan
Kong, H.J.	Republic of Korea
Laas, K.	Estonia
Laas, T.	Estonia
Marchenko. H.	Ukraine
Shirokova, V.	Estonia
Shmatov, M.	Russian Federation
Soto, L.	Spain
Tikhonchuk, V.	France
Zvorykin, V.	Russian Federation

O-1: Combined effects of gamma and UV-laser radiations on the microstructure of silicate glass

R. T. Khaydarov[1,2], E. M. Ibragimova[3,1], V. V. Kim[1], V. Sh. Yalishev[1], N. E. Iskandarov[1] and F.M. Tojinazarov[2]

[1]*Center of High Technologies*
[2]*National University of Uzbekistan, 100174, Tashkent, Uzbekistan*
[3]*Institute of Nuclear Physics, 100214, Ulugbek, Uzbekistan*

E-mail of Corresponding Author: rtkhaydarov@yahoo.com.ph

Fused silicon dioxide is extensively used as an optical material in ultraviolet (UV) pulse laser systems, e.g., in inertial confinement fusion (ICF) programs, due to its excellent UV transparency, optical homogeneity, and radiation hardness. In practice, the critical issue is the defect formation under intensive high energy photon, electron and ion irradiations and shock compressions [1,2]. The effect of neutron and gamma radiation on optical materials is crucial for constructing highly specialized window materials for transmission lines in plasma heating and diagnostic systems in nuclear fusion reactors [3-5]. Recently we have shown [6], that prior irradiation of Al targets by neutron fluencies 10^{15} –10^{20} neutron/cm^2 effects considerably on the following interaction with pulse laser beam, namely, not only on the efficiency of the material evaporation and emission of plasma beam, but also on the efficiency of ionization and recombination processes in the plasma beam on the stage of formation and expansion [7]. Lately much attention is paid on coherent excitations: a) when incident electrons locally polarize the target, which can radiate directly or couple to other electromagnetic modes that are available such as surface plasmon polaritons; b) when an electron travels faster than the phase velocity of light, a coherent shockwave can be formed known as Cherenkov radiation [8].

In this work, we experimentally study the effect of intense laser radiation (YAG:Nd, pulse 28 ps, energy 12 mJ at 266 nm) focused on the surface of silica glass (pure KV type and doped with alkali metals), which had been irradiated by ~ 1 MeV ^{60}Co gamma rays with doses ranging from 10^6 R to 5 × 10^9 R and reactor irradiation to fluencies 10^{16}–10^{20} cm^{-2} accompanied with gamma-rays. Surface damage (morphology and element composition) due to irradiation was studied at SEM-EDS and FTIR spectrometer. It was shown that the gamma irradiation to 5 × 10^7 R causes only 1 mass% loss of oxygen in the surface layer, while neutron-gamma irradiation to 10^{19} cm^{-2} resulted in 5 mass% oxygen loss with generation of oxygen vacancies. The following UV laser pulses at 10% power ablated microdroplets around the microhole, and 25% power resulted in radial shockwaves around the hole. Since glass structure is viscose, these surface micro-damages relaxed within two weeks. Conclusion: different static and dynamic defects in the pre-irradiated silica glass target affect the efficiency of the target destruction and consequently change the parameters of the plasma.

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O-2: Influence of the grain boundaries on the radiation-induced damage and on the hydrogen behavior in tungsten

R. Gonzalez-Arrabal[1], M. Panizo[1], A. Rivera[1], P. Diaz[1], C. Gonzalez[1], G. Valles[1], R. Iglesias[2], E. M. Bringa[3], F. Munnik[4], and J. M. Perlado[1]

[1] *Instituto de Fusión Nuclear, ETSI de Industriales, Universidad Politécnica de Madrid, Spain*
[2] *Departamento de Física, Universidad de Oviedo, E-33007 Oviedo, Spain*
[3] *Facultad de Ciencias Exactas y Naturales, Universidad Nacional de Cuyo, Mendoza 5500, Argentina*
[4] *Helmholtz-Zentrum Dresden-Rossendorf, PO Box 10119, D-01314 Dresden, Germany*

E-mail of Corresponding Author: raquel.gonzalez.arrabal@upm.es

Nowadays, tungsten is considered one of the most promising candidates as plasma-facing material (PFM) in future fusion reactors, both in magnetic (MCF) and in inertial confinement (ICF) approaches. However, light species such as hydrogen and helium tend to nucleate in defects resulting in detrimental effects, which turn out to be unacceptable for a PFM. In this context, the development of new materials with better compliance is needed.

In the last years, we focused our attention on the study of the capabilities and limitations of nanostructured materials as PFM. For this purpose, we carried out different experiments and multiscale computer simulations (DFT, MD, OKMC) to find out the role of grain boundaries on the behavior of light species (H and He). All these data show that ordered GBs favour hydrogen release [1-6], whereas disordered GBs favor hydrogen trapping [7]. Recently, we went a step further correlating radiation-induced damage and hydrogen behavior on nanostructured samples. We will discuss the observed differences in the density of vacancies between nanostructured and coarse-grained samples as well as, the preferential places for hydrogen accumulation. We will also show the influence of temperature on the previous studies.

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O-3: Behavior of nanostructured and coarse grained tungsten under pulsed irradiation: hydrogen and thermal loads

M. Panizo[1], R. Gonzalez-Arrabal[1], A. Rivera[1], G. Balabanian[1,2], M.J. Inestrosa-Izurieta[3,4], J. Moreno[3,4], G. Avaria[3,4], B. Bora[3,4], S. Davis[3,4], J. Jain[3,4], C. Pavez[3,4], L. Soto[3,4], and J. M. Perlado[1]

[1]*Instituto de Fusión Nuclear, ETSI de Industriales, Universidad Politécnica de Madrid, Madrid, Spain*
[2]*Carl Zeiss Microscopy GmbH, Oberkochen, Germany*
[3]*Comisión Chilena de Energía Nuclear, Santiago, Chile*
[4]*Center for Research and Applications in Plasma Physics and Pulsed Power, Santiago, Chile*

E-mail of Corresponding Author: raquel.gonzalez.arrabal@upm.es

Plasma facing materials in both inertial (IC) and magnetic (MC) confinement nuclear fusion power plants will be subject to intense transient thermal loads (ion and X ray pulses) and radiation-induced damage. The irradiation parameters (pulse duration, deposited energies and peak powers) in IC and in MC conditions differ, however, the heat flux parameters (H) for PFM in ITER divertor and in the first wall in a typical direct drive target of 154 MJ reach values as high as $H \geq 70$ (MWm^{-2} s$^{1/2}$) [1]. Even when similar H values induce similar thermomechanical effects, ion-matter interactions resulting in defect production, i.e. ion implantation, play also an important role in the determination of the materials damage threshold. Therefore, to establish operational windows, it is necessary to study the behavior of materials under pulsed irradiation in which they are simultaneously subjected to ion irradiation and intense thermal loads. In this context, plasma focus devices are unique tools for these studies with the added advantage that they have table-top dimensions [2].

In this work we study the microstructural and light species behavior for nanostructured and coarse-grained W samples irradiated under different conditions (heat flux parameter and number of pulses) in a hundred joules table top plasma focus device (PF-400J) located at the Comisión Chilena de Energía Nuclear (CCHEN). In the PF-400J is possible tune the H value in the range 10 - 10^3 (MWm^{-2} s$^{1/2}$). We show that hydrogen accumulation in nanostructured coatings is lower than in coarse grained samples (further details about the role of grain boundaries on the hydrogen behavior are shown by Gonzalez-Arrabal *et al.*) However, the H value threshold for thermomechanical damage is significantly lower in nanostructured coatings than in coarse grained samples. The possible sources for such differences in the H value threshold for damage are discussed.

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O-4: Feasibility of potential Projects of Neutron Sources for Materials Irradiation

J M Perlado[1], A Rivera[1], F. Sordo[1,2]

[1]Instituto de Fusión Nuclear, ETSII, Universidad Politécnica de Madrid, Spain
[2]European Spallation Source-Bilbao

E-mail of Corresponding Author: josemanuel.perlado@upm.es

A positive licensing of components under realistic neutron irradiation needs to be demonstrated. Important efforts in different laboratories are oriented to computationally model the conditions and to get representative results to be confirmed by experiments with appropriate irradiation sources. Currently, ions beams are being used to mimic realistic irradiation conditions. However, the community is urgently requesting facilities with as realistic as possible neutron fluxes and fluences. IFMIF-DONES [1] is one of the proposals with expectations to be finally approved and will be here considered. However, the present real build-up of neutron sources mostly dedicated to neutron scattering, such as ESS in Lund (Sweden) and others [2,3], need to be considered to potentially obtain useful neutrons for the same objective but in a shorter time scale. In this work a critical review of the different options will presented.

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Thermo-mechanical study of W First Wall in non-protective chamber in IFE

J M Perlado[1], D Garoz[1,2], A. R. Páramo[1], A Rivera[1], R González-Arrabal[1]

[1]*Instituto de Fusión Nuclear, ETSII, Universidad Politécnica de Madrid, Spain*
[2] *Mechanics of Material and Structures, Ghent University*

E-mail of Corresponding Author: josemanuel.perlado@upm.es

One of the bottlenecks for fusion to become a reality is the lack of materials able to withstand the harsh conditions occurring in a reactor environment. In particular, plasma facing materials (PFM) have to resist large radiation fluxes and thermal loads. Different IFE FW protections lead to diverse irradiation conditions and macroscopic effects; the European project HiPER advanced some years ago the possibility of non-protective FWs considering W and nano-W. In this context, we have studied the role of grain boundaries on the radiation-induced damage and light species behavior. This work is presented in this Technical Meeting [1] with references therein. The other main concern is related to the capability of PFM to withstand large thermal loads. The behavior of a tungsten first wall is studied under the irradiation conditions predicted for the different operational scenarios of the European laser fusion project HiPER [2] by using advanced engineering modeling tools. First, we calculate the radiation fluxes assuming the proposed geometrical configurations. Then, we estimate the irradiation-induced evolution of first wall temperature as well as, the thermomechanical response of the material. Finally, we carry out crack propagation calculations. Results allow us to define operational windows and to identify the main limitations for operation.

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O-5: Application of destructive and non-destructive analysis method for analysis of thermomechanical properties of high-temperature plasma irradiated tungsten-based materials

Veroonika Shirokova[1], Tõnu Laas[2], Katrin Laas[2], Jana Paju[2], Berit Väli[2], Jaanis Priimets[2], Merike Martsepp[2]

[1]Tallinn University of Technology, Virumaa College, Kohtla-Järve, Estonia
[2]Tallinn University, Tallinn, Estonia

The different pure tungsten and tungsten alloy samples were irradiated on plasma-focus devices and using deuterium as a working gas with very short (50-200 ns) and powerful plasma pulses accompanied with ion generated shock-waves. For modelling interplay of different events with different heat flux densities all the investigated samples were irradiated with two series of repetitive plasma pulses on the different regimes.

The defects generated on irradiates samples were analysed using non-destructive methods as analysis of damages using SEM-images and 3D-profilometry. A novel method, measurements of electrical conductivity, is compared with measurements of microhardness of cross-sections. It has been showed that the change of mechanical properties in the bulk of irradiated materials is due to mechanical shock-waves generated due to flux of fast ions characteristic for all the plasma devices with short plasma pulses.

As a novel method to estimate the thermomechanical properties and withstand to powerful plasma fluxes of materials, multifractal analysis of SEM images of irradiates samples is proposed. It is hoped that multifractal function allows to estimate the stability range of materials to the fatigue-thermal loads and to relate the fractal parameters to the strength properties of materials. This will hopefully enable to relate the damages in bulk of material with surface damages without using any invasive research methods in the future.

O-6: Table top plasma focus as tunable pulsed irradiator to study materials for inertial fusion energy chambers: Statistical study and reliability analysis

L. Soto, D. Zanelli, S. Davis, G. Avaria, B. Bora, J. Jain, J. Moreno, and C. Pavez

Comisión Chilena de Energía Nuclear, Santiago, Chile
Center for Research and Applications in Plasma Physics and Pulsed Power, Santiago, Chile

E-mail of Corresponding Author: leopoldo.soto@cchen.cl

One of the pressing problems in the design and construction of nuclear fusion reactors is the selection of candidate materials for its plasma-facing components. The essential constraint is that such a material has to be able to withstand extreme heat fluxes, together with high fluxes of neutrons, ions beams, and He and H isotopes such as deuterium.

The time of interaction, peak power and deposited energies on materials in inertial and magnetic confinement differ. However, the parameter defined as $Q\sqrt{\tau}$ (with Q the power flux and τ the time of interaction with the material), known as damage factor F or heat flux parameter H, reach values as high as ≥ 70 (MWm^{-2} $s^{1/2}$) for both, ELM´s in ITER divertor and in the first wall in a typical direct drive target [1]. For similar F values, similar thermomechanical effects are produced. These thermomechanical effects, are the results of heat, ion-matter interactions resulting in defect production. Thus, the determination of the materials damage threshold is an important issue to study different materials for plasma-facing components of nuclear fusion reactors.

Plasma focus devices are unique tool for these studies with the added advantage that the damage factor F varies smoothly with the energy of the device E, as $F \alpha E^{1/6}$. In addition, F has a strong dependence with the distance to the target. Therefore, by changing the distance to the target it is possible tune the value of damage factor. Thus, in a table top plasma focus device of low energy (few joules to hundred joules) the same damage factor than the obtained in mega joules plasma foci can be obtained. In the hundred joules plasma focus (PF-400J), at the Chilean Nuclear Energy Commission, is possible tune the F value in the range 10 - 10^3 (MWm^{-2} $s^{1/2}$) [2]. In addition, table top plasma focus device operating at low energy are possible to be operated at repetition rate of Hz or greater, allowing integrate pulses of radiation on the samples. Moreover, for inertial confinement, the table top plasma focus produces a time interaction with the target in the same order than the expected in this case, tens to hundred nanoseconds.

However, a feature of plasma focus is that the emitted radiation varies shot to shot, therefore a characterization of its statistical reproducibility and a reliability analysis is indispensable for any application, in particular for the application considered here. In this work a statistical study and reliability analysis program for table top plasma focus devices is presented. The program considers statistical inference using both Bayesian and machine learning techniques.

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O-7: Conceptual design of final lens systems for laser fusion power plants based on direct-drive targets

A Rivera[1], D Garoz[1,2], A. R. Páramo[1], J M Perlado[1], R González-Arrabal[1], F. Sordo[1,3]

[1]*Instituto de Fusión Nuclear, ETSI Industriales, Universidad Politécnica de Madrid, Spain*
[2]*Mechanics of Material and Structures, Ghent University*
[3]*European Spallation Source-Bilbao*

E-mail of Corresponding Author: antonio.rivera@upm.es

The final focusing elements of laser fusion power plants are critical for appropriate plant operation, because target compression and ignition entirely depend on them. The design of these elements requires taking into account not only optical considerations but the hostile irradiation conditions present in the fusion chamber during operation. In the case of direct-drive targets, the lenses will be exposed to intense ion pulses in addition to the neutron pulses generated with every target explosion. Ion pulses must be necessarily somehow mitigated to prevent fatal damage. On the other hand, neutrons will unavoidably reach the focusing elements.

We have carried out a detailed study [1] to design a full conceptual final focusing system based on silica transmission lenses for dry wall chambers. According to calculations, neutron irradiation will produce a non-uniform steady state temperature profile along the final lenses, which will lead to aberrations with fatal consequences for the laser spots. We describe a possible solution to overcome this problem. It consists of a temperature control system based on a heat transfer fluid that will keep the temperature profile smooth enough to prevent aberrations. In addition, it will make possible to keep the temperature constant during all the operation phases (start up, normal operation condition and special operation conditions). This way, the problem of reaching steady operation from cold conditions will be overcome.

In our design, the final lenses are enclosed by two silica windows. The fluid flows in the space between the lens and the windows. The final focusing system is located 16 m away from the target and receives an average neutron power density of 510 kW/m^3. Details on the design, figures of merit, operation scenarios, suggestions for ion mitigation strategies and other aspects such as resistance or lifetime of the optical system will be discussed.

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O-8: Recent progress in the target design and experiments on the shock ignition scheme of the inertial fusion reactor

Vladimir Tikhonchuk and Dimitri Batani

Centre Lasers Intenses et Applications, University of Bordeaux – CNRS – CEA, 351, Cours de la Libération, Talence, France

E-mail of Corresponding Author: tikhonchuk@u-bordeaux.fr

The paper presents a short resume of the work conducted in France in the context of this CRP on the following problems:

(i) theoretical analysis of nonlinear processes of laser plasma interaction and energy transport in the shock ignition scheme and implementation of a numerical package in the radiation hydrodynamic code;

(ii) design and conduction of new experimental campaigns at large scale laser facilities in the Europe and USA;

(iii) theoretical analysis of the performance of existing shock and fast ignition targets and design of a more robust and efficient target;

(iv) re-organization and structuring of the international coordination on the direct drive IFE research in Europe.

In particular, I will present the experimental results on the successful laser imprint mitigation, which is one if the major problems of all direct drive approaches, by using low density plastic foams [1]. The experiment was performed on the OMEGA laser facility in direct-drive for plastic foils coated with underdense foams. Numerical simulations of the laser beam smoothing in the foam and of the Rayleigh-Tailor instability growth were performed with a suite of paraxial electromagnetic and radiation hydrodynamic codes. The smoothing effect is explained by the parametric instabilities developing in the foam plasma.

Another problem of crucial importance for the shock ignition approach is generation of a strong ignitor shock and the role of hot electrons in the fuel preheat. An integrated experiment on the OMEGA laser facility is successfully interpreted with the French radiation hydrodynamic code demonstrating the important role of hot electrons in boosting the shock amplitude but at the same time reducing the shock strength [2]. We also investigate the robustness of the existent shock ignition target design, a control of hot electron production and stopping range by choosing an appropriate ablator material. Further experiment addressing the critical issues of the shock ignition approach will be tested in upcoming experiments in March 2018 on the OMEGA laser facility and in October 2018 on the LMJ-PETAL facility in France.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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O-9: Materials surface damage and modification under high power plasma exposures in relevant inertial fusion reactor conditions

A. Marchenko[1], O. Byrka[1], I. Garkusha[1], V. Makhlaj[1], V. Taran[1], S. Herashchenko[1], S. Malykhin[2], K. Nowakowska-Langier[3], M J Sadowski[3], E Skladnik-Sadowska[3]

[1]*National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine*
[2]*National Technical University "Kharkiv Polytechnical Institute", Kharkov, Ukraine*
[3]*National Centre for Nuclear Research (NCBJ), 05-400 Otwock, Poland*

E-mail of Corresponding Author: marchenkoak@kipt.kharkov.ua

Simultaneous impacts of high energy and particle loads to the material surface are typical for material performance in various extreme conditions: fusion devices (both magnetic and inertial), space apparatus in upper atmosphere, operation of turbines, nuclear engineering etc.

Influence of powerful plasma impacts on number of the energy system materials, i.e. different tungsten grades and RAFM steels, coatings of various materials etc. has been discussed. Material exposures with hydrogen and helium plasma streams have been performed in several high current pulsed and quasi-stationary plasma accelerators providing variation of power loads to the surface as well as the particle flux in wide range: energy density 1-25 MJ/m^2, particle flux up to 10^{26}-10^{29} ion/m^2s, plasma stream velocity ~ 500 km/s, pulse duration 1-250 µs. Highest energy loads were applied for material characterization in extreme conditions while moderate short pulsed loads were used for surface modification studies.

Material response to extreme plasma loads relevant to transient events in fusion reactor is briefly discussed. However, it is demonstrated that broad combination of mechanisms of powerful plasma influence on material properties includes not only the surface damage due to different erosion mechanisms, but it may also result, under certain conditions, in significant improvement of material properties in near-surface layer of 20-50 µm, its structure and substructure due to high-speed quenching, shock wave formation and material alloying with plasma and coating species. Creation of unique surface structures (including ordered nanostrucrures) and considerable improvement of physical and mechanical properties of different materials are achieved by pulsed plasma alloying, i.e. pre-deposited coating modification and mixing by impacting plasma streams.

The possibility of alloying of RAFM steels surfaces with tungsten is being discussed. The increasing of tungsten concentration is shown. Tungsten phase is recognized together with lines of Fe phase on treatment surfaces. The concentration of tungsten has been achieved several wt% in surface layer up to 4 µm. Maximum value of tungsten (about 85 wt%) was registered in surface layer of Eurofer steel modified by QSPA plasma streams.

This work has been performed in partially supported by IAEA CRP F13016 "Pathway to Energy from Inertial Fusion: Materials beyond Ignition".

O-10: Degradation of UV optical materials tested in a continuous irradiation at 1-MeV linear electron accelerator

V.D. Zvorykin[1,2], S.V. Arlantsev[1], V.I. Shvedunov[3], and D.S. Yurov[3]

[1]*Lebedev Physical Institute of RAS, Leninskiy Pr. 53, Moscow, 119991 Russia*
[2]*National Research Nuclear University* ***"MEPhI",*** *Kashirskoe Sh. 31, Moscow, 115409 Russia*
[3]*Skobel'tsyn Institute of Nuclear Physics, Moscow State University, Vorob'evy Gory 1, Moscow, 119992*

Requirements for the economically attractive laser-driven Inertial Fusion Energy engine, i.e. a target gain over 100 at laser pulse energy ∼1 MJ, rep-rate 5-10 Hz, and overall efficiency ∼7 % nowadays could be implemented only with 3ω DPSSL and e-beam pumped KrF laser (T.C. Sangster, *et al*., 2007, *Nucl. Fusion* **47**, S686), both operating in the UV range at 353 nm and 248 nm wavelengths favorable for a thermonuclear target compression. Darkening of optical windows under different kind of ionizing radiation from exploding targets in the reactor chamber and e-beam scattering or bremsstrahlung X rays in KrF drivers plays a crucial role in the UV laser beam delivery and stable laser operation. During 2-year duty cycle, the expected absorbed dose in the windows of IFE-scale laser driver might be around 1 MGy. Electrons are absorbed in a small depth of a few millimeters nearby the surface; while X rays penetrate through windows, which thickness are a few centimeters. Both types of radiation break interatomic bonds in optical material and produce electrons and holes, which are further trapped by lattice imperfections or impurity inclusions. The resulted color centers change optics transmittance in specific absorption bands mostly lying in the UV spectral range (V.D. Zvorykin, *et al.*, *Plasma Fusion Res*. 8, 2405000 (2013)).

In the present research, we have irradiated various UV optical materials, i.e. fused silica glasses, CaF_2, MgF_2 and Al_2O_3 crystals commonly used as KrF laser windows or coatings of multilayer mirrors. A homemade compact 25-kW linear electron accelerator with electron energy 1 MeV and beam current up to 25 mA (D.S. Yurov, et al., *Phys. Rev. Accel. Beams* 20, 044702 (2017)) was adjusted to irradiate optical samples of 15–30 mm in diameter and 3–9 mm thickness. A uniform irradiation field over the entire area of 5×35 cm^2 was provided by e-beam scanning system at the linac exit. The total absorbed dose up to 100 kGy measured with Risø B3 radiochromic dosimeter film was compared with a total electron charge collected on the Faraday cup; then in subsequent runs with increased doses up to 10 MGy it monitored samples irradiation. A newly developed Monte Carlo code simulated distributions of electron and bremsstrahlung radiation dose in the samples. Their transmittance spectra in the range 200–750 nm was measured with a spectrophotometer, and optical density (OD) of e-beam induced absorption was defined as a natural logarithm of a ratio of initial to acquired tramsmittance after irradiation. In dependence on the total e-beam energy fluence, induced OD for all tested materials revealed a saturation. At 248-nm wavelength, the lowest saturated OD ~ 0.1 (it corresponds to transmittance fall by 9.5 %) was observed in a "dry glass" KS-4V, which contains the minimal hydroxyl impurity responsible for the formation of oxygen-deficient centers and non-bridging oxygen hole centers with absorption bands around 250 and 260 nm. At 353-nm wavelength the lowest OD ~ 0.016 (1.4 %) was in a "wet glass" Corning 7980, which has the lowest impurity content except for a hydroxyl. Overall, windows darkening under e-beam irradiation appears to be stronger for deeper UV radiation of a KrF laser.

This research was undertaken under IAEA Contract No. 19273 in the frame of the CRP "Pathways to Energy from Inertial Fusion: Materials beyond Ignition".

O-11: FST transmission line for mass-manufacturing of IFE targets

I.V.Aleksandrova, E.R.Koresheva, E.L.Koshelev, A.I.Nikitenko

P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia

E-mail of Corresponding Author: elena.koresheva@gmail.com

In the scope of IAEA Research Contract #20344 the following activity was realized:

I. *Expert analysis of the basic requirements relevant to the key science and technology issues* has shown that depending on the formation method (more specifically, on the cooling rate) and the experimental conditions (using of additives to the fuel content or influence of vibrations during fuel freezing), the solid fuel layer can be in the state with a different micro-structural length or grain size: isotropic ultra-fine layers or anisotropic molecular macro crystals (like real single crystals, e.g., as a result of the beta-layering). Determination of an optimal fuel micro-structure (permissible grain size and anisotropy level of the solid fuel) is of critical importance because it allows making provision for the operating efficiency of IFE power plant. It concerns both the possibility of forming the high-quality, high-strength and heat-resistant fuel layers, and the possibility of regular propagation of the shock wave, the front of which has to be extremely smooth. For all these reasons the FST layering method (developed at the P.N. Lebedev Physical Institute) is a promising candidate for creation of the FST-transmission line at a high rep-rate capability intended for mass manufacturing of IFE cryogenic targets.

II. *The existed mathematical model optimization has been done* relevant to the shell container (SC) depressurization and IFE target fabrication. Modeling the target rolling (pure rolling without sliding) inside a single-spiral layering channels (LC) has been performed to calculate the time of the target residence in the LC. The project IFE targets are the shells of ~ 4 mm in diameter with a shell wall of different designs from compact and porous polymers. The layer thickness is ~ 200 μm for pure solid fuel and ~ 300 μm for in-porous solid fuel.

III. *Experimental modeling has been carried out on testing and benchmarking the operational conditions of key elements of the FST transmission line*. The following activity was performed: (a) measurements of the polymer shells strength with the goal to optimize the SC depressurization stage, (b) experimental modeling of the free-standing shells moving in different LC mockups made from different materials, (c) updating of the mockup`s geometry according to the results of the mathematical and experimental modeling, (d) experimental modeling of the conditions of target positioning and transport between the elements of the FST transmission line using type-II superconductors.

The main obtained results are as follows:

1. The FST-layering time does not exceed 30 s, which is a necessary condition for mass target manufacturing, and which is of important for a tritium inventory minimization as well.

2. The targets can be uniformly fabricated in n-fold-spiral LC at n = 2, 3.

3. A three-fold spiral LC was manufactured and tested. The target residence time in the LC is about 35 s, which allows developing the FST-LM of repeatable operation using a target batch rolling along the LC.

In this report the obtained results are discussed.

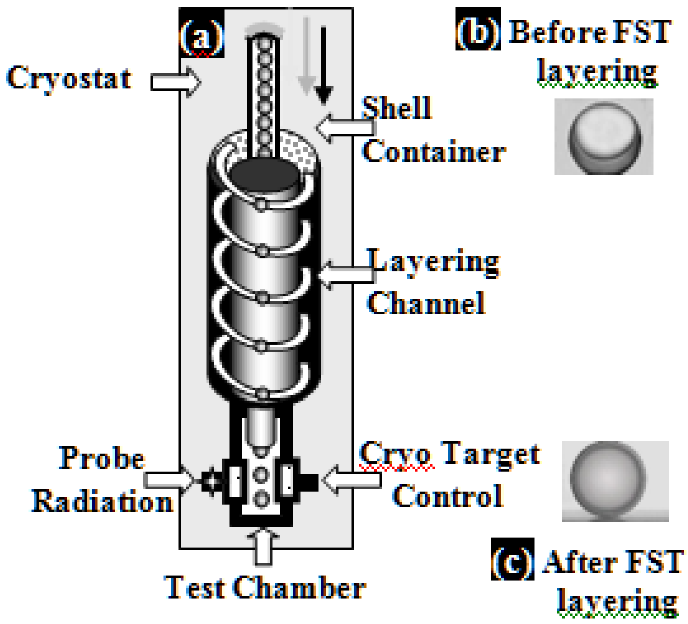

Fig. 1. FST Layering Method Provides Rapid Symmetrization and Formation of Solid Ultra-fine Fuel Layers

Fig. 3. Sequential frames of the HTSC-sabot motion over the PMG under the action of the driving electromagnetic pulse generated by the field coil; the HTSC-sabot velocity v = 1m/s

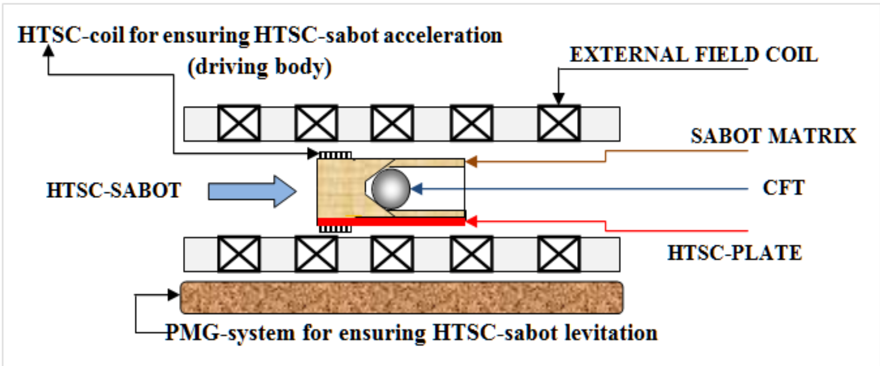

Fig. 2. Schematics of the noncontact delivery system, developing in the Lebedev Physical Institute. The system keeps a friction-free motion for providing an efficient magnetic acceleration of the levitating HTSC-sabot

O-12: Development of the self-phase-controlled stimulated Brillouin scattering phase conjugate mirror (SPC-SBS-PCM) toward a high average power coherent beam combination laser

Hong Jin Kong and Seongwoo Cha

Department of physics, KAIST, Republic of Korea

E-mail of Corresponding Author: hjkong@kaist.ac.kr

To achieve the inertial fusion energy, a module of the laser fusion driver should have the output energy more than 2.5 kJ and the repetition rate more than 10 Hz [1]. One of the most promising techniques to achieve both high repetition rate and high output energy is a coherent beam combining using self-phase-controlled stimulated Brillouin scattering phase conjugate mirrors (SPC-SBS-PCMs) [2]. The coherent beam combining utilizes small gain media to amplify the beams and combines the amplified beams coherently to produce a high average output power beam [3]. The small media are easy to cool down. By the phase conjugation property of the SBS-PCM, the output beam shows good beam quality. The coherent beam combing using SPC-SBS-PCMs is successfully demonstrated at the low average power of W class with the repetition rate of 10 Hz [1].

However, the SBS-PCM suffers a thermal problem at the high average input power. The absorbed input beam is accumulated in the SBS media. This causes the optical haze due to the convection of the liquid SBS media and the defocusing of the laser beam near the focal spot [4]. So, it is necessary to develop an SPC-SBS-PCM useful for the high average input power to construct the high average power coherent beam combination laser using SPC-SBS-PCMs.

This presentation will report the recent progress of the development of the SPC-SBS-PCM for high average input power. To develop an SPC-SBS-PCM for high average input power, the authors select HT-110 as an SBS medium and purify the HT-110. A kW class high average power laser, called Kumgang laser [5], is used to measure the SBS reflectivity, the SBS reflected beam patterns and the pulse temporal shapes for high average input power. With the purified HT-110, the SBS reflectivity was 69% at the input power of 99 W (99 mJ @ 1 kHz). The pre-pulse technique is applied to preserve the temporal pulse shape. With pre-pulse technique, the double-pass amplification with Kumgang laser using SPC-SBS-PCM is measured. The detailed experimental result will be presented in the technical meeting.

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O-13: Analysis of some assumptions about the possibility of avalanche proton-boron11 fusion reactions

Mikhail L. Shmatov

Ioffe Institute, St. Petersburg, Russia

E-mail of Corresponding Author: M.Shmatov@mail.ioffe.ru

The possibility of using the p-^{11}B fusion reaction for power production is discussed for many years [1-6]. The interest to this reaction is initiated by the fact that it generates only alpha-particles. Although the p-^{11}B reaction would be accompanied by the $^{11}B(\alpha,n)^{14}N$ reaction generating neutron and several other nuclear reactions and some of the hydrides of boron are toxic [7], the power production with the use of p-^{11}B fuel would be very clean from the viewpoint of ecology [1-6]. However, the cross sections for the reaction under consideration are rather small even when the energy of the collision of proton and ^{11}B in their centre-of-mass system is high. Therefore, the effective use of this reaction for power production may be impossible [1, 2].

Recently, several authors assumed that effective ignition and, eventually, the practical use of the p-^{11}B reaction could be provided by avalanche reactions of several kinds [3-6]. It was also assumed that such reactions were already observed in the experiments at PALS (Prague Asterix Laser System) [6]. It has been shown that these assumptions are mistaken [8, 9]. For example, in estimates presented in Refs. [3, 4] deceleration of alpha-particles is not taken into account (note that this effect was mentioned in Ref. [3]). Details will be presented.

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O-14: CETAL-PW laser facility for ultra-intense laser interaction

M. Zamfirescu[1], B. Calin[1], F. Jipa[1], O. Budriga[1], M. Serbanescu[1], G. Cojocaru[1], R. Ungureanu[1], A. Achim[1], R. Gavrila[2], A. Dinescu[2]

[1]*CETAL Department, National Institute for Laser, Plasma and Radiation Physics, Atomistilor 409, 077125 Magurele, Romania*
[2]*National Institute for Microtechnology, 126A Erou Iancu Nicolae Street, Bucharest, 077190*

E-mail of Corresponding Author: marian.zamfirescu@inflpr.ro

The laser-driven particle acceleration opened the path to the compact "table-top" accelerators with many applications, such as fast ignition [1], tumour therapy [2] and radiation hardening for space industry. The energy of the accelerated particles depends on the laser intensity on target surface. Theoretical studies, have demonstrated that the engineered 3D laser targets increase the absorption of the ultra-intense electromagnetic field, producing for the same laser intensity, particles with higher energy and better directionality [3].

We propose the 3D laser lithography as method for fabrication of 3D shaped targets. In this work, micro-cone targets are fabricated by Two-Photon Photopolymerisation (TPP) in photopolymers with submicrometer resolution. The targets has the height of 100 µm, the input diameter of 100 µm and the bottom diameter of 10 µm (Fig 1.b). Arrays of 3D targets are fabricated on silicon wafers and combined with thin film metallic membranes placed on the apex of the cone. The 3D targets are fabricated at the laser processing facility of the Center of Advanced Laser Technology (CETAL).

Particle in Cell (PIC) numerical simulations were used for designing of the cone targets (Fig.1c). Proton energies up to 30 ÷ 40 MeV are estimated from simulation [4]. The design is optimized for the laser parameters of our CETAL-PW laser facility. The CETAL-PW is a Ti:Sapphire laser system delivering femtosecond pulses at 25 fs, and maximum energy after optical compressor at 25 J [5].

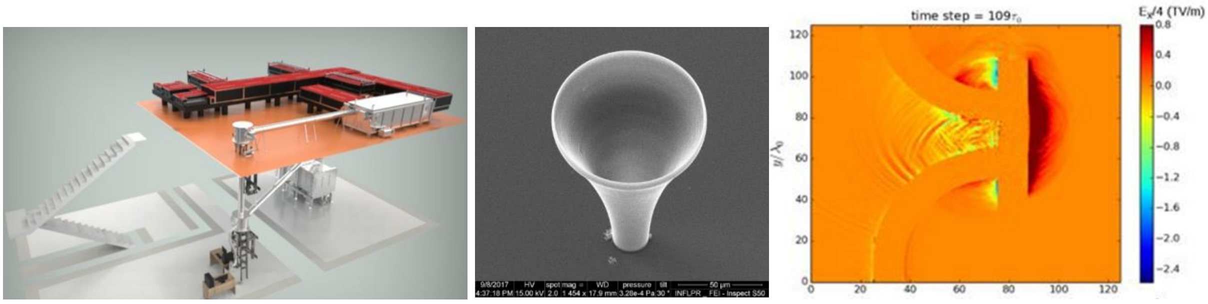

Fig.1 a) The shetch of teh CETAL-PW laser system incuding the 1PW laser (first floor), the vaccum beam transportm and the interaction chamber (underground bunker); b) Cone-shaped target fabricated by 3D laser lythography; c) PIC numerical simulation of the laser interaction with cone target.

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