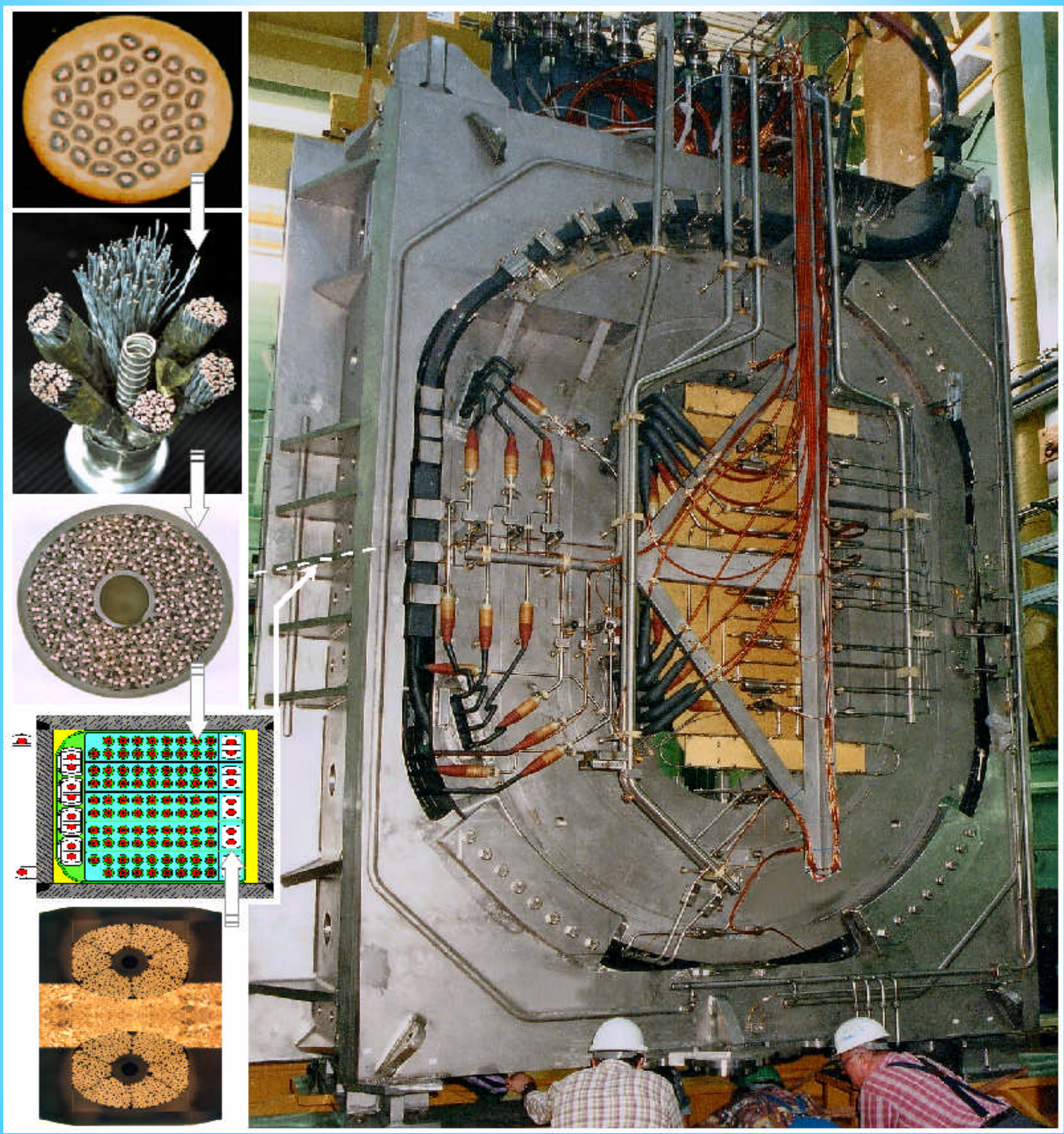
FUSION TECHNOLOGY

Annual Report of the Association EURATOM/CEA 2001

Compiled by : Ph. MAGAUD and F. Le VAGUERES



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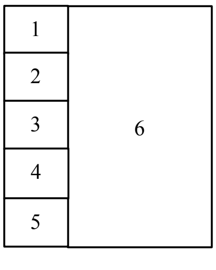

Cover : Toroidal Field Model Coil (TFMC) installation and test
1 – Superconducting strand (courtesy of ENEA)
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Fuel cycle

Safety and Environment

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ICF01

Task Title : INTENSE LASER AND PARTICLE BEAMS DYNAMICS FOR I.C.F. APPLICATIONS

INTRODUCTION

Our work was devoted (i) to the transport of high current heavy ion beams through plasma, in relation to the Heavy Ion Inertial Fusion (HIIF), and (ii) to the modeling of intense laser and electron beams interacting with plasmas in connection with the fast ignitor concept [1] within the framework of the Inertial Confinement Fusion (ICF) with either laser beams or heavy ion beams drivers. We focus on theory, experiment and modelling on the following items:

A) CORRELATED STOPPING OF RELATIVISTIC ELECTRON BEAMS IN SUPER COMPRESSED DT FUEL

The transport of intense high energy electron beams in super dense matter is a key point in the Fast Ignitor Scenario (FIS) [1]. Here the numerical simulations are not yet able to take full account of the various scales in length and in time of all the important interaction processes. In particular, the dimension of the grid in the Particle In Cell (PIC) simulation induced a cut-off in the interaction at small scale lengths. We are thus developing theoretical modelling of the interaction process at these small scales, that can be included, through an effective collision frequency, inside the PIC simulation [P3-P4].

B) THE PROPAGATION OF A VERY HIGH INTENSITY LASER PULSE USING A CAPILLARY TUBE AS A GUIDING STRUCTURE

Due to instabilities, an intense electron beam cannot propagate over a large distance in a dense plasma. Therefore, in the FIS, it is necessary to create the beam as close as possible of the most ultra-dense inner-part of the ICF target. This can be accomplished by propagating, through the outer part of the target, the beam in channelling conditions. Experiments using capillary tubes offer an unique opportunity to study the propagation in channelled conditions of a very high intensity laser pulse. Previous results (see report 2001 and [P1], [P2]) have demonstrated the effectiveness of this propagation scheme on distances of several Rayleigh lengths. Theoretical modeling of ultra-high intense laser beam under channeling condition are being developed and the results are compared to the experimental results [P2].

C) TRANSPORT OF HIGH CURRENT HEAVY ION BEAMS THROUGH PLASMA IN HIIF

Our objective here is to determine (i) the modification in the target properties induced by the ion beam and (ii) what is the influence of this modification on the transport of the beam.

In case of dense plasma targets there is only a static correlation between (i) and (ii), this point is related to the interaction of the beam with the HIIF target and our work here is devoted to a precise determination of the charge dependent stopping and charge transfer cross sections that are necessary to get accurate prediction of the energy deposition profile and for diagnostics purposes in beam-target experiments [P7] [P9]. For low density targets, as in the reactor chamber for HIIF, there are dynamical correlations between (i) and (ii). Ionization of the target and beam ions/atoms created electrons that can quickly react under the strong E.M. created by the beam. Numerical simulations [P5], [P6] have shown that the focussing of the beam is greatly affected by these electrons.

2001 ACTIVITIES

As our three activities pertain to rather different physical phenomena we will presented details on only one of our activities. In the 2001 report we have detail our results on point B, here we concentrate on recent results for point C and give a brief summary on the other two points.

A) CORRELATED STOPPING OF RELATIVISTIC ELECTRON BEAMS IN SUPER COMPRESSED DT FUEL [P3] [P4]

The purpose of our study was to examine the influence, through the exchange of energy, of the pair-correlation within the beam particles, on the propagation of high current electron beams in dense plasmas, for applications to the fast ignitor scenario.

If pair correlation is neglected we have retrieved the now common result of simulations and theoretical calculations, that the Weibel instability prevents the propagation of the beam over several micro-meters in an uniform plasma at solid density.

We then showed that pair-correlation, while increasing the energy deposition rate in the end and denser part of the interaction process, has rather an indirect rather than a direct influence on the propagation.

In particular the energy deposited by the beam inside the target at density lower or comparable with the solid density remains small in a rectilinear propagation scheme.

We thus propose to incorporate the indirect influence of the pair correlation through an effective collision rate, which appears to be larger than the standard “Spitzer” like collision rate.

This effective collision rate, can in fact be larger than the growth rate of the Weibel instability, it is thus expected to play a non-negligible influence in the dynamic evolution of the beam-plasma interaction process. This will be the subject of our future investigation.

B) PROPAGATION OF A VERY HIGH INTENSITY LASER PULSE USING A CAPILLARY TUBE AS A GUIDING STRUCTURE [P1] [P2]

A numerical code (CAPITOOL) has been developed in order to describe the propagation of a high-intensity laser pulse inside a capillary tube in a multi-mode regime, both in void and in gas by introducing the mode coupling by the ionization of the gas filling the tube. The decomposition of the electric field into leaky modes introduced in our model has proved to be a powerful idea to describe and quantify physical effects such as dispersion, plasma defocusing and absorption, self-focusing, and self-steepening, while preserving the numerical efficiency. Simulations and experimental results are in agreement concerning the energy transmission and the blueshift in presence of gas. The simulations show that the transmission is very sensitive to the coupling of the incident beam to the capillary tube. This coupling was not perfectly controlled in the experiment due to the pointing fluctuations of the laser beam.

The coupling could be improved by using a tapered capillary tube. For applications such as x-ray lasers, which require the creation of a high-density plasma, the laser beam must be focused in vacuum in order to avoid beam refraction before the entrance of the capillary tube. This can be achieved experimentally by putting the capillary tube inside a gas cell.

The simulations also show that a long (4 cm), homogeneous, plasma column with electron density of the order of 2.5 10^{17} cm^{-3} for a filling He pressure of 10 mbar, is generated inside a capillary tube with the laser parameters used.

For the resonant laser wakefield scheme, it is also crucial that the guided beam retains its spatio-temporal shape along the propagation length so that the resonance condition linking the pulse duration and plasma density is fulfilled. The simulation results indicate that a low-density plasma (pressure < 10 mbar for He gas) is appropriate for this scheme, corresponding to pulse durations larger than 100 fs.

The theoretical model, within which the CAPITOOL code is contructed, has to be modified to describe the propagation of beam intensity above 10^{16} $W.cm^{-2}$. It concerns mainly the relativistic effects, the hydrodynamic motion of the gas and a dynamic evolution of the properties of the walls of the capillary tube. Works in that direction are in progress using fluid and PIC codes.

C) TRANSPORT OF HIGH CURRENT HEAVY ION BEAMS THROUGH PLASMA IN HIIF [P7] [P9]

We describe here our new results on the interaction of a swift heavy ion beam with a dense target.

That is, as said in the introduction, when there is only a static correlation between the beam-plasma interaction and the macroscopic evolution of the target.

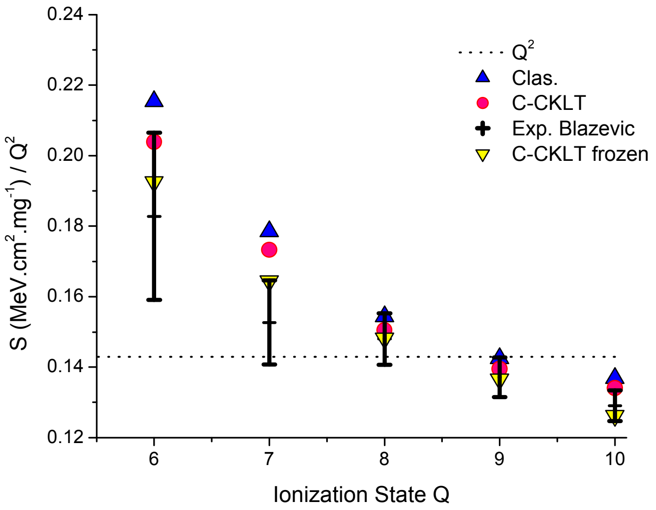
At the GSI-Darmstadt and ITEP-Moscou accelerator facilities an important upgrading of the machines is planned for the years 2000-2010. This upgrading it will be possible to produce directly by the beam-target interaction of a hot and dense plasma of up to 300 eV in temperature, that is corresponding to the actual parameter range of beam-plasma interaction processes in HIIF [2]. Plasma target created by swift heavy ion beams are more dense and homogenous than laser created plasmas. So beside application to ICF, the high current ion beam appear quite promising to investigate the fundamental physical properties of hot and dense plasmas, with applications to ICF and astrophysics. It appear that the beam that created the plasma can also be use to diagnose the target. One of our objective is to improve such diagnostic by a better description of the beam-plasma interaction process.

Previous experimental works in beam–plasma interaction performed in Europe and in Japan (see ref. in [2]) were devoted to check theoretical evaluations. The latest theoretical developments together with precise comparisons with experimental results now lead to a level of accuracy in a plasma target that is better than available through experiments, the accuracy of which being limited by the diagnostics. Then it becomes now possible to invert the procedure, in using the analysis of the charge and energy distribution of the ion-beam after interaction as a powerful diagnostic of the statistical and dynamical properties of the plasma target.

Compared with photon and light particles (electrons and light ions) analysis of heavy ion beams provide more information coming from the charge state distributions and its correlation with the energy loss mechanism. The central quantity of this analysis are the charge state distributions P(Q) and the mean energy lost for each charge state $\Delta E(Q)$. P(Q) gives information mainly on the target density and on the electrons bound to target ions while $\Delta E(Q)$ is more sensitive to the interaction with the free electrons. In the experiments of beam-plasma interaction using a thin carbon foil irradiated by a laser, or a current discharge in hydrogen, as done at GSI and at Orsay [2] the integrated linear density is not very high ($\approx 10^{18}$ cm^{-2}), then the variation $|\Delta E(Q)-\Delta E(Q +/- 1)|$ is large enough compared with $\Delta E(Q)$ to allow an accurate determination of the stopping cross section of the charge changing processes and of the stopping. This cross sections can then be compared to theoretical calculations to deduce physical properties of the plasma target.

At Orsay we are developing new theoretical models to improve the accuracy of the calculations of these cross sections. They are derived through a semi-classical model well adapted to heavy ion, making use of the Wigner quasi-distribution function (see [P7] [P9]). These calculations have been compared successfully with accurate measurement in hydrogen discharge plasma [P8] and thin carbon foils. Below we give an example of our result in the last case.

A. Blazevic et al. [3] have measured the energy loss of neon ions at 2 MeV/u in thin carbon foil at frozen charge state. That is, looking at the energy distribution function for each charge state, they were able to select those ions that do not make any charge transfer. From these results they determined the stopping cross section for a frozen charge of the projectile. The comparison with our calculations is reported in the figure below.



In this figure, crosses with error-bars are the experimental results, dotted-line are the usual Q^2 scaling law often used in stopping calculation, the up-triangles are the results of a classical calculation, for the circles we have introduced quantum corrections and for the down-triangle we have exclude to the energy loss those events that lead to a charge transfer process.

We see on the figure strong deviations from the Q^2 law. At high charge the stopping is lower due to non-linearities in the interaction process while at low charge we have a clear signature of an imperfect screening of the projectile nucleus by its bound electrons. As a consequence the variation of the stopping cross section with the charge of the projectile is much smaller than predicted by the Q^2 scaling law. Note that the figure demonstrate a good agreement between the experiments and our calculation, all of the calculated points being inside the error bars.

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ICF02

Task Title : CRYOGENIC TARGETS PRODUCTION USING MAGNETIC LEVITATION

INTRODUCTION

Production of electrical energy with a reactor based on Inertial Fusion Energy (IFE) will be a real challenge.

To obtain a useful power of 1000MWe, it has been shown that it will be necessary to develop specific devices able to produce and inject cryogenic targets in the vacuum chamber of the reactor at a rate of about 5 Hertz [1], [2].

Targets are hollow spheres of about 5mm in diameter made of polystyrene or beryllium. Their internal wall is covered with a D_2 or DT solid layer [3]. The solid layer must be homogenous in thickness to a few percent.

We previously showed [4] that magnetic levitation could be a way to obtain a uniform thickness of liquid hydrogen in a sphere before freezing it. To freeze the liquid layer, in magnetic levitation, the required time is about 30 seconds [5].

That means that if we use simple solenoid to produce the targets, we need 150 solenoids.

To avoid the use of so many coils, it could be possible to use long multipole coils as so used for particle accelerator (Large Hadron Collider at CERN for example). Those multipoles could be used to simultaneously freeze many targets during their levitation.

We report here a summary of a study of a 600 mm in length multipole in which 30 targets move at the rate of 20 mm per second.

Each target levitates during 30 seconds (time for solidification) and each second a target is ready to be shot.

2001 ACTIVITIES

SPECIFICATIONS

Targets design

Targets are indirect drive targets whose dimensions are reported on the figure 1. The thickness of the micro balloon is 400µm and the thickness of the D_2 layer is 250 µm.

The targets need a sabot to withstand the acceleration during the shot. During the free fly, the sabot is separated in two halves parts which are stopped before the entrance in the vacuum chamber.

Coil design

The multipole must provide a product of the magnetic field by the field gradient of $1000T^2/m$ to levitate deuterium. The uniformity of the product of the field by the field gradient must be 1 % in a cylinder of 5 mm in diameter and 600 mm in length.

The targets will be introduced into the multipole at a temperature of 19 K. At this temperature deuterium is liquid (the triple point of deuterium is 18.7 K). The targets will go out of the multipole at a temperature lower than 18 K (figure 2).

The tube in which they will move will be 12 mm in diameter and so will be submit to a longitudinal thermal gradient.

Targets will be cooled by helium gas at low pressure (100 mbars) contained in the tube where the targets move. The moving speed of the targets in the tube is 20 mm/s.

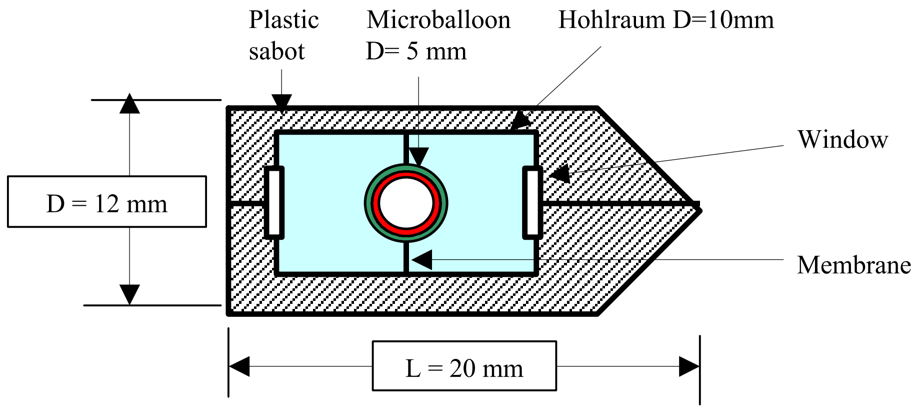

Figure 1 : A scheme of the targets

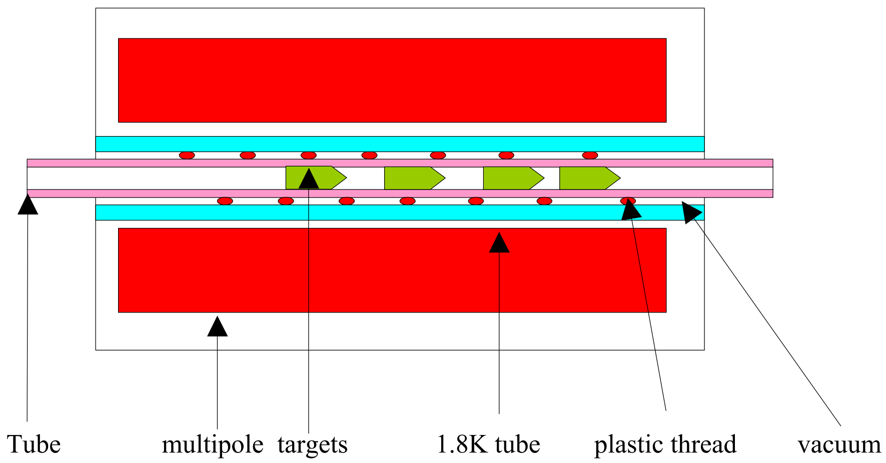

Figure 2 : A scheme of the coil showing the targets

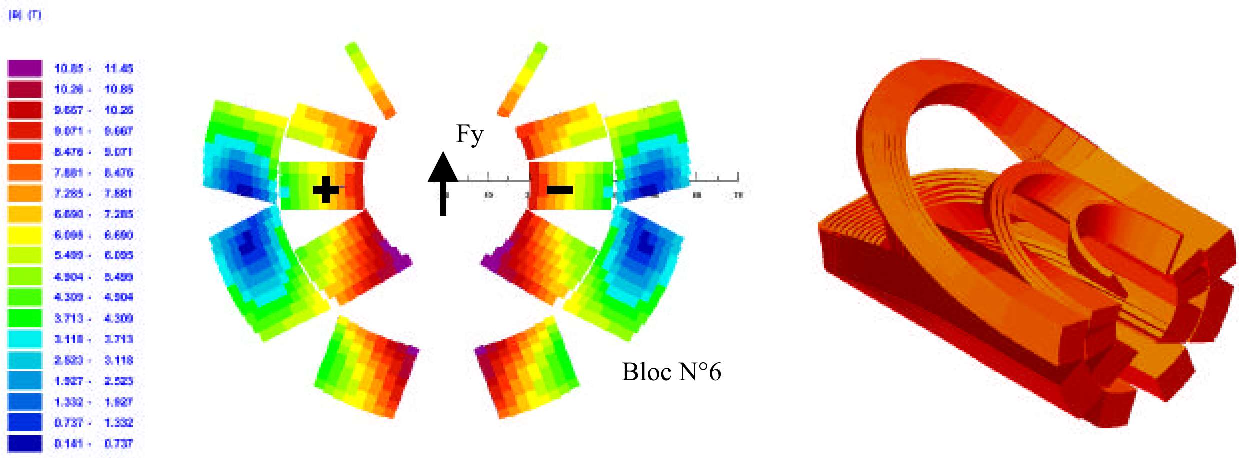

Figure 3 : A view of the structure with the magnetic field map and one extremity

MAGNET STUDY

For calculating the magnet, we used a method based on inverse magnetic field calculation.

This method, well described in ref. [6], consists in calculating the current surface density to distribute on the cylinder in which we want levitate to reproduce the magnetic field distribution corresponding to the following complex potential:

$$W(z)=-\lambda z^{3/2} \qquad \text{where } z = x + iy$$

The current surface density obtained is one of a multipole series, which fits with an association of several superconducting magnets as particle accelerator magnets.

The multipolar structure is then discretized, this time the currents are modeled by volumic densities, using a formalism giving a real structure for the magnet [7].

This structure is then optimized with the ROXIE software [8] to minimize the residual magnetic forces on the x and y axis.

RESULTS

A magnetic structure giving a homogeneous compensation of gravity better than 1 % in D_2 into the specified volume has been found but the magnetic field and current required were not compatible with the superconducting material known today.

So calculations have been redone with a superconducting cable found in ref [9] (2600 A/mm² à 13.8T at 1.8K).

With a current of 25000 A in a conductor of 17.8×2.38 mm² we have obtained the design shown on the figure 3.

With this structure, the gravity compensation is homogeneous at 1 % on the vertical axis but on the horizontal axis it is only 7 %.

The peak field is 11.45Tesla (on the block N°6) that give a minimal quench margin of 17.8 %.

The magnetic forces in the magnets have also been performed with the ROXIE software. The maximum is 1.37 10^6N/m also for the block N°6.

CONCLUSION

A multipole allowing the gravity compensation in deuterium in a cylinder of 5 mm in diameter and 600 mm in length has been designed with a realist superconducting cable. The compensation of gravity is homogeneous at 1 % on the vertical axis but on the horizontal axis it is only 7 %. It will be necessary to control if this residual horizontal force is acceptable for IFE targets. If the horizontal force distorts too much the shape of deuterium liquid/gas interface, it will be necessary to study an other design of multipole and use superconducting cable more efficient.

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THIS WORK HAS BEEN SHARED WITH

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- The "Service des Accélérateurs et de Cryo Magnétisme" (SACM) - CEA-Saclay. 91191 Gif-Sur-Yvette. France.

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Task Title : LASER-MATTER INTERACTION AT RELATIVISTIC INTENSITIES AND FAST IGNITER STUDIES

INTRODUCTION

We have investigated the generation of intense proton and ion beams from laser irradiation of thin foils. We have studied the dependence of the ion energy with emission angle and determined the quality of the beam. We have also tried to produce intense ion beams of specific charge states, and to study the focusing and defocusing of the ion beam with appropriate target shaping. We have then studied the feasibility of using laser-accelerated ions (protons) to interact with secondary targets, which could be diagnosed by means of an auxiliary laser probe beam. Finally, we have attempted to explore the underlying physics with a set of dedicated experiments at a higher degree of accuracy to benchmark computer simulations. On a more theoretical side, we have exploited a new type of particle-in-cell code which is particularly suited for studying fast electron transport in overdense plasmas.

2001 ACTIVITIES

We have demonstrated the acceleration of fluorine ions by short pulse lasers up to 100 MeV which corresponds to more than 5 MeV per nucleon. This is the highest observed energy for laser accelerated, beamed heavy ions up to date and opens new possibilities for laser driven accelerators.

A high energetic beam of light ions and protons is observed when irradiating thin foil targets with laser intensities up to 5 x 10^{19} W/cm^2.

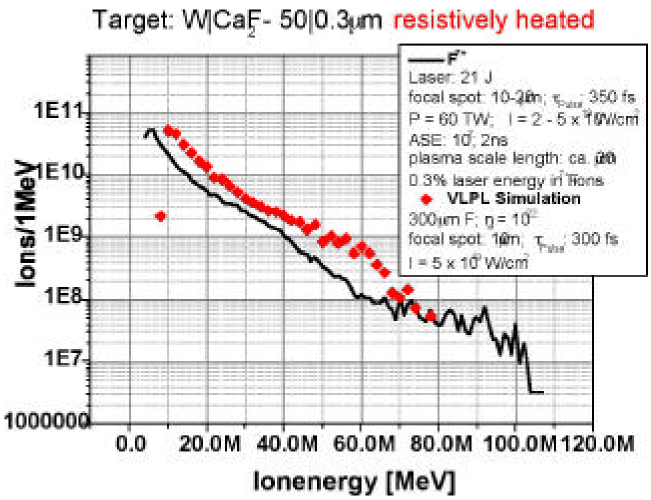

Figure 1 : Fluorine VIII ion distribution measured at LULI laser conditions compared to VLPL particle-in-cell simulations. Theresistively-heated target is made of 50 mm tungsten coated with 0.3 mm CaF$_2$

Experiments with teflon coated targets show that the ions originate from the back surface of the target, where they are ionised and accelerated by a quasistatic electric field set up by hot electrons penetrating the target. Figure 1 shows the energy distribution of F^{7+} ions obtained under the abovementioned irradiation conditions.

We have found that the acceleration of light ions can be enhanced by orders of magnitude by heating the targets before the interaction, suppressing normally dominant proton acceleration. By this means C^{4+}-ions could be accelerated up to 12 MeV. The ion spectra for different charge states were measured and used for modelling the acceleration dynamics at the back surface of the target. Figure 2 shows the experimental results obtained for the nominal laser conditions at LULI.

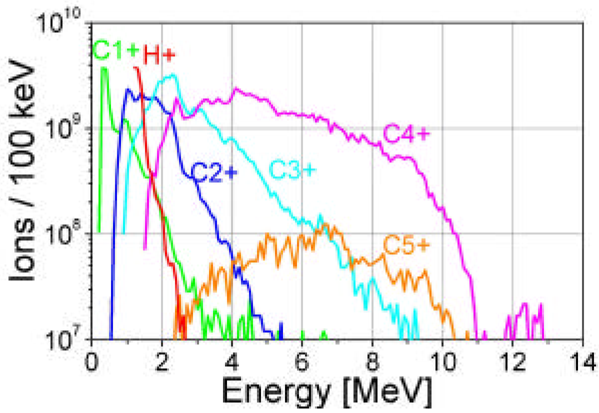

Figure 2 : Carbon ion distribution of different charge states measured at LULI laser conditions. The fact that little CV ions exist at low energies is an indirect proof that field ionisation is the dominant process for highly-charged ion production

An important question to be addressed for any future application of laser-accelerated protons and ions is the possibility of tailoring the proton beam, either collimating or focusing it, by changing the geometry of the target surface.

We first attempted to defocus the beam in one dimension, by using a convex target. Using a 60 µm diameter Au wire as a target basically constituted such a one-dimensional de-focusing lens, and we observed a line image. Tilting the wire also changed the orientation of the line image, which results from the radial, fan-shaped expansion of the protons normal to the surface of the wire. We then attempted to focus the protons by modifying the curvature (concave) of the target foil. The curvature of the target used for this purpose was changed from a flat target to concave shaped targets with radii of curvature between 10 and 2.5 mm.

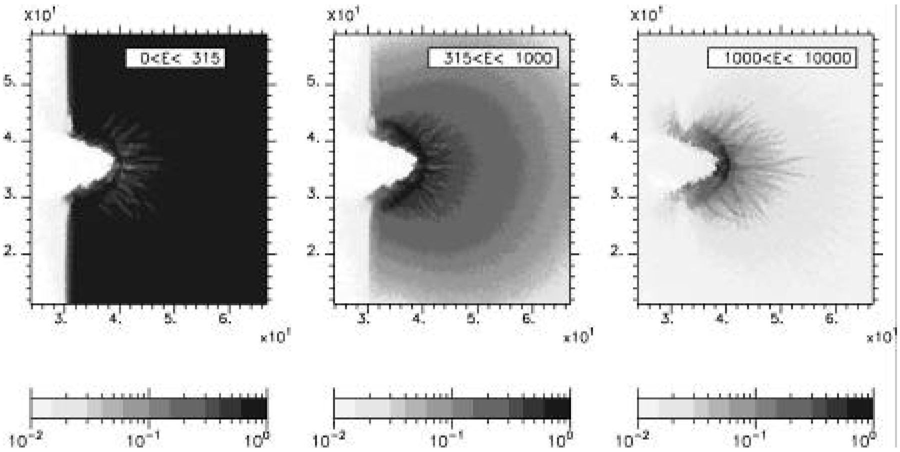

Figure 3 : Density spectrum for 3 energy ranges as a function of space. Laser (see text) is coming from the left

In this particular simulation, most of the particles with E < 300 keV contribute to the return current. The results indicate a strong reduction in the divergence of the central core of the beam representing ballistic collimating of laser produced proton beams.

The interaction of ultra-intense laser pulses for irradiances ranging from 10^{19} W/cm^2 to 10^{21} W/cm^2 with strongly overdense collisionless plasmas (100 n_c) has been investigated by using the newly developed particle-in-cell code.

This code uses a novel method to calculate the currents which is more conservative, relaxing the constraints on the boundary conditions. Accordingly, electrically isolated targets surrounded by "vacuum" can now be studied.

We have found that the emission of energetic particles occurs in a quasi-isotropic way within an angle of ± 40°. We have also shown that particles with energies up to 100 keV contribute to the return current, and this for the higher irradiances we have used. Figure 3 shows the density spectrum (scaled to the initial density) for a density of 80 n_c and an irradiance of 10^{21} W/cm^2.

CONCLUSION

We have shown that by heating the target it is possible to completely remove the contaminating hydrocarbon layers thereby strongly enhancing the acceleration of heavy ions.

We have measured high resolution energy spectra for different charge states of laser accelerated MeV-ion jets in the forward direction.

We showed that field ionization is the dominant mechanism while electron-induced processes (recombination, collisional ionization) are by far less effective. Since the coating was only at the back surface of the target and we successfully removed contaminations we can rule out front side acceleration within the parameters of our experiment. We have developed a new type of particle-in-cell code which allows to better treat the transport of fast electrons in complicated geometries (e.g. isolated targets).

REPORTS AND PUBLICATIONS

Spectroscopy of MeV Ion Jets from Ultraintense Laser-Plasma Interaction with thin Foils - M. Hegelich, S. Karsch, M. Allen, P. Audebert, A. Blasevicz, T. Cowan, J. Fuchs, J.C. Gauthier, W. Guenther, M. Geissel, D. Habs, W. Heinrich, J. Meyer-ter-Vehn, G. Pretzler, A. Pukhov, T. Schlegel, K. Witte and M. Roth, to be submitted to PRL.

The dependence of intense laser-accelerated ion beams on target properties - M. Roth, T.E. Cowan, J. C. Gauthier, M. Allen, P. Audebert, A. Blazevic, J. Fuchs, M. Geissel, M. Hegelich, S. Karsch, J. Meyer-ter Vehn, A. Pukhov, T. Schlegel, submitted to PRE.

Acceleration of laser driven MeV-Ion jets from thin foil targets- M. Hegelich, S. Karsch, M. Allen, P. Audebert, A. Blasevicz, T. Cowan, J. Fuchs, J.C. Gauthier, W. Guenther, M. Geissel, D. Habs, W. Heinrich, J. Meyer-ter-Vehn, G. Pretzler, A. Pukhov, T. Schlegel, K. Witte and M. Roth, Invited talk at the 2nd International Conference on Inertial Fusion Sciences and Applications, Kyoto, Sept. 9-14, 2001.

Intense Ion Beams Accelerated by Relativistic Laser Plasmas - J. C. Gauthier, M. Roth, T.E. Cowan, M. Allen, P. Audebert, A. Blazevic, J. Fuchs, M. Geissel, M. Hegelich, S. Karsch, J. Meyer-ter Vehn, A. Pukhov, - Invited talk at SPIE Conference, San Diego (August 2001, to be published).

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Task Title : EUROPEAN COLLABORATIVE EXPERIMENT ON THE FAST IGNITER CONCEPT

INTRODUCTION

In order to encourage collaboration on Inertial Fusion for Energy (IFE) in the EURATOM countries, the LULI laboratory has made a call for experimental proposals corresponding to collaborative experiments on the Fast Igniter (FI) concept. Two weeks of laser time have been dedicated to a single "French/EURATOM collaborative experiment". The LULI European programme committee has chosen the experimental proposal by Markus Roth, from GSI, Darmstadt, entitled "Basic Research on the Fast Igniter concept using intense ion beams accelerated by ultra-intense lasers". This experiment has taken place in August 2001. Preliminary status of the experimental results is presented below.

2001 ACTIVITIES

The main objectives of the experimental campaign were to test the energy and yield of protons with respect to varying target thickness, to increase the heavy ion energy by using thinner, heated targets, to investigate the duration of ion acceleration, and, finally, to test the spatial beam modulation using micro-structured targets. Most of the scientific goals could be achieved in this experimental run. During the run in August the main problem was the damage on the final compressor gratings (causing a reduced maximum beam energy) and fluctuations in the output energy of the laser system.

The laser spot on target changed during the experimental run and had to be re-adjusted between the experiments. The influence of the target thickness was verified. We reduced the target thickness and maintained the ion maximum energy while we simultaneously reduced the laser energy. Similar results were found for the heavy ion production. Using the Thomson parabolas, we could clearly identify high energetic fluorine ion beams.

Due to the limitation in the laser energy we were not able to produce heavy ions at higher energies than in the experiments in May, but to achieve comparable ion energies at reduced laser energy. We tested the pulse duration by using a second short pulse beam to disrupt the ion acceleration and used variable time delays. We observed an effect on the ion acceleration, however due to the fluctuations of the laser, the results are not yet conclusive (see Fig.1).

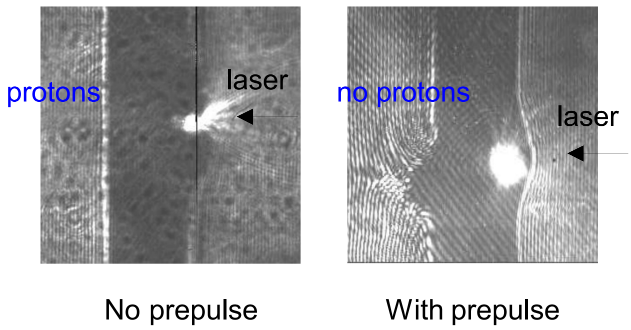


Figure 1 : Side-on ombroscopy images showing the effect of the pre-pulses on the steepness of the backside of the target, and, as a result, the occurrence or lack of accelerated protons

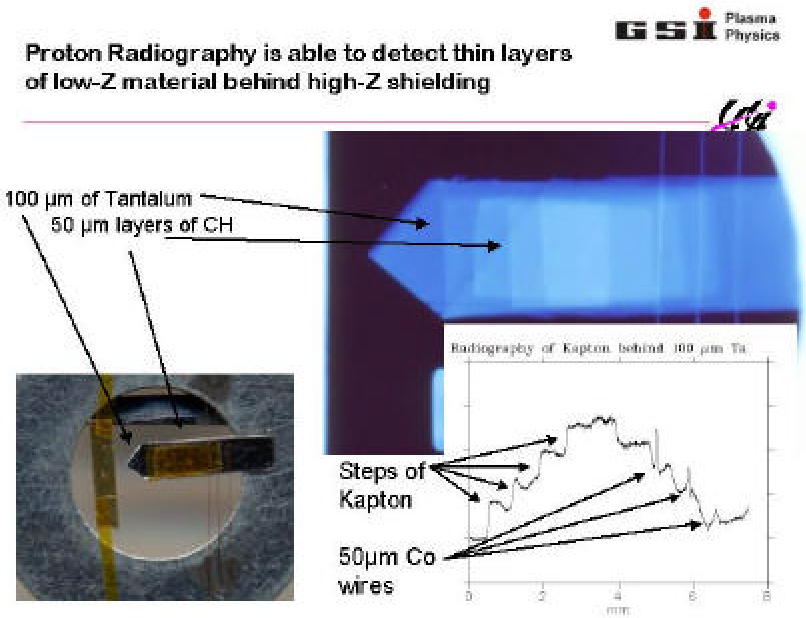
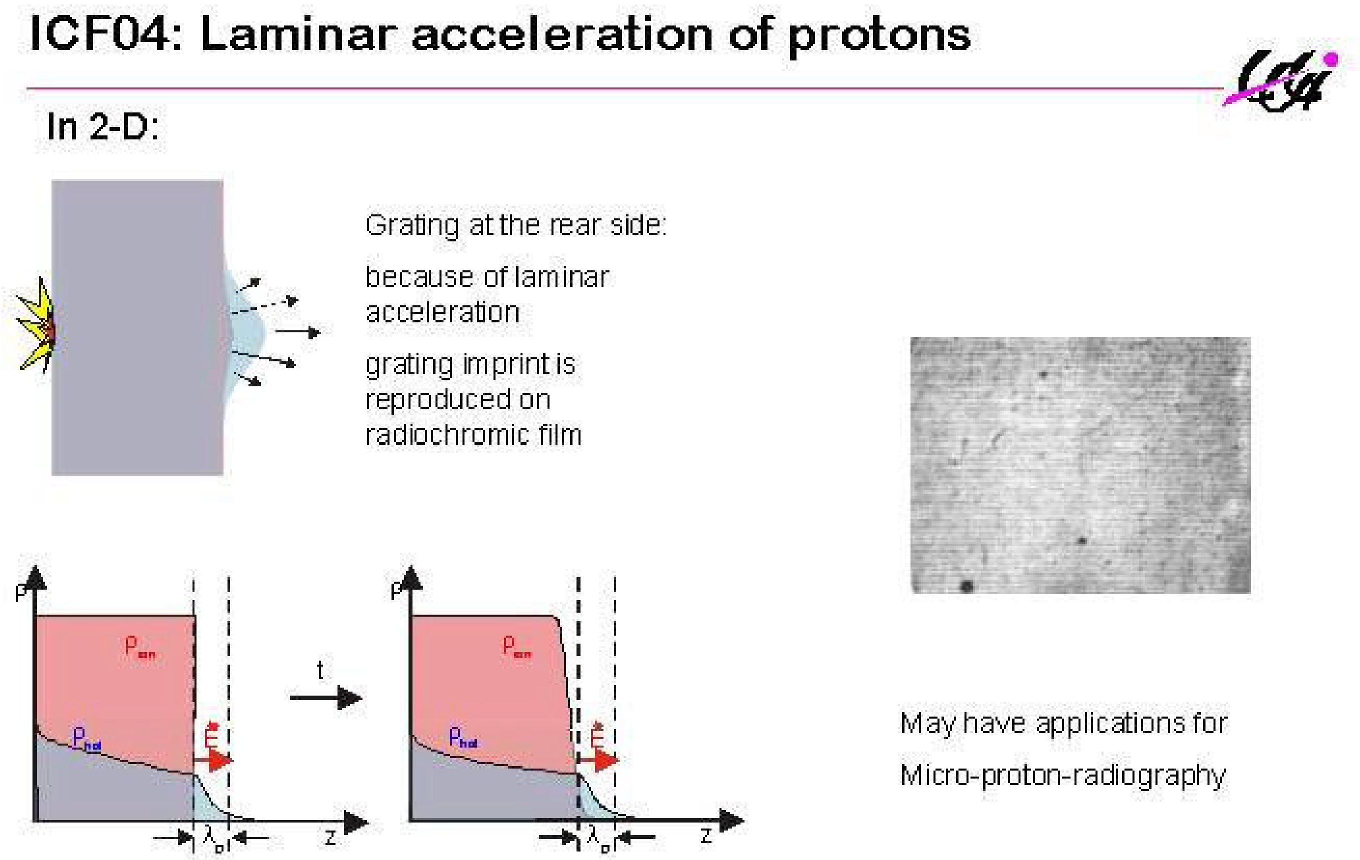


Figure 2 (above) shows that thin layers of plastic (CH) can be seen behind a 100 µm foil of tantalum. Copper wires could also be seen in the proton-imaged target



Other experiments to show the usefulness of proton imaging have been made by imaging special targets made of a combination of low-Z and high-Z materials.

We could demonstrate that we can control the spatial beam profile using specially designed targets.

By engraving a grating at the rear of a target, we have shown (see Fig. above) that the proton beam follow closely the surface corrugation, pointing again to the fact that the proton acceleration is laminar.

CONCLUSION

The EURATOM campaign was largely a success. In particular, the experiments using the micro-structured targets were very successful. We could demonstrate that we can control the spatial beam profile using specially designed targets. Moreover, based on these results we could identify the mechanism for the beam filamentation.

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ICF-KiT-PRC

Task Title : OVERVIEW ON POWER REACTOR CONCEPTS

INTRODUCTION

The IFE-KiT task aims at establishing an overview of the existing tendencies and technical orientations related to IFE power reactor concepts design.

From the early beginning, ICF leading research has been conducted within defense objectives.

This range of Fusion Power (100-1000 MJ) is the same as required in a IFE power reactor. That has led some scientists and engineers to propose common research facilities for defense and energy purposes [1].

The US DOE has already commissioned two large, multi-institutional IFE power plant design studies: Prometheus [2] and OSIRIS/SOMBRERO [3]. That has stimulated the fusion energy promoters and given birth to some design variants such as SIRIUS-P [4].

However, these first attempts of inertial fusion reactor conceptual design lacked maturity and their feasibility need be demonstrated. As far as EU is concerned, a European Heavy-Ion ICF-reactor study (HIBALL) was performed by Gesellschaft für Schwerionenforschung, Darmstadt (GSI), Kernforschungszentrum – karlsruhe, and the University of Wisconsin, [5].

The activities carried out during the FY-2000 [6] and FY2001 [P1] based on a large survey of some 120 publications and report lead to the conclusion that the most critical issues in the IFE power reactor concept are those related to: 1/ the target chamber and the internals, 2/ the target injection & tracking, and 3/ the energy drivers.

Adding to these three critical issues a specific forth critical issue which is the "Interface & Integration" of these 3 systems.

In this technical note, we identify the most critical scientific/technical issues and the most promising R&D orientations to find out adequate technical solutions. The details of these investigations are given in [P1].

This work is covered by the Inertial Confinement Fusion – Keep-in-Touch.

2001 ACTIVITIES

During 2001, a large survey of some 120 publications and report has lead to the conclusion that the most critical issues in the IFE power reactor concept are those related to: 1/ the target chamber and the internals, 2/ the target injection & tracking, and 3/ the energy drivers.

TARGET CHAMBER

The IFE Target Chamber (TC) provides the interface between the target, the driver, the blanket and balance of plant. According to calculated estimations, the TC represents a small share in the plant total capital cost (9-12%). The TC influences the unit power production-cost through the driver-target coupling, driver energy control, plant availability performance and plant safety level. The TC concept design and options selection will thus have major leverage on the attractiveness of an IFE power plant. It should allow to: 1/ Recover to the initial conditions in the TC at high repetition rates (5-10 Hz), 2/ Protect the TC structure and beyond for many years (ideally plant lifetime, 20-30 years), 3/ Extract fusion energy (1000-3000 MWth), 4/ Confine tritium bred inside, and 5/ Reduce the inventory of radioactive materials and control their release. An IFE TC conceptual design should then cover the following 4 technical topics: 1/ chamber dynamics, 2/ structure materials, 3/ liquid hydraulics, and 4/ radioactive inventory and safety.

If unprotected, the TC walls receives ~ 0.5-5 J/cm2 X-ray fluence (depending on the diameter of the chamber, R ~ 5 m) per shot (~ 5-8 ns). Studies estimate X-ray would ablate ~ 0.1 to 1 µm per shot (depending on the materials) off the solid wall at a nominal 5 m radius. For the IEF, ablation must be limited to << 1 nm/shot. In all cases dry surface option (unprotected walls) does not seem today acceptable for the protection of the TC walls, especially, if one adds the neutron-gamma shielding issues and efficient fusion energy removal. Options use thin liquid shield (Promethius conceptual design) or thick liquid shield (HYLIFE II, HIBALL) are studied and offer very promising shielding options.

Liquid metals (Pb, LiPb, LiSn) and molten salts (FliBe) are currently the most studied candidates for liquid-walls option. However, it results in new scientific and technical challenges concerning: 1/ the formation of the liquid film/shield, its dynamic behaviour, its integrity under X-ray ablation and neutron-gamma transport, 2/ the partial vaporization of the liquid film/shield, its condensation and related dynamic behaviour, 3/ the TC cleaning between the shots (1/5 – 1/10 s). The use of the renewable liquid surfaces seems widely accepted in the IFE community. It provides promising solutions for tritium breeding (TBR ~ 1.2 – 1.7), heat removal and reasonable shielding capability for the TC wall and the final-optics/focus-magnet of the energy driver.

Several small-scale experiments on the characteristics of liquid jets are being conducted at UC Berkeley, UCLA, and Georgia Institute of Technology. Two basic types of jet flow are investigated: 1) oscillating jets to form the thick liquid pockets around the target at every shot, and 2) steady-flow jets that are arranged to form any array of ports for beam entry.

The primary goals of these experiments are to 1) demonstrate that the liquid jet configurations required for a power reactor of HYLIFE-2 can be established, 2) to improve the quality (low surface ripple) of the steady flow jets, and 3) demonstrate that the jet configuration can be re-established between the shots.

Chamber-Driver Interface (CDI) are another critical issue in the TC design. It presents several challenges, particularly with current driver designs that have 100 beams or more. The integration of the driver requires meeting many constraints: 1/ liquid wall configurations, 2/ filling gas pressure and transparency, 3/ neutron heating, activation and damage of the driver structure (final focus magnet for the Ion-Drivers, final optics for Laser drivers). The choices of the CDI influences directly the life-time of the drivers.

TARGET IGNITION & TRACKING

To achieve an inertial fusion explosion, a target has to be compressed and heated to fusion conditions by the incident driver energy beams. For direct drive, the target is of a spherical capsule that contains DT fuel.

For indirect drive, the capsule is inside a cylindrical or spherical metal container or "hohlraum" which converts the incident driver energy into x-rays to drive the capsule. Preliminary design studies of target injection for both direct drive and indirect drive IFE power plants were done as part of the SOMBRERO and OSIRIS studies completed in early 1992.

The direct drive SOMBRERO design proposed a light gas gun to accelerate the cryogenic target capsules enclosed in a protective sabot. After separation of the sabot by centrifugal force, the capsule would be tracked using cross-axis light sources and detectors, and the laser beams were steered by movable mirrors to hit the target when it reached chamber center. Target steering after injection was not proposed. The indirect drive OSIRIS design proposed a similar gas gun system without a sabot for injection and crossed dipole steering magnets to direct the beams.

Besides, a gas gun indirect drive target injection experiment was done at LBNL. The results showed that relatively simple gas gun technology could inject a non-cryogenic simulated indirect drive target to within about 5 mm of the driver focus point, easily within the range of laser or beam steering mechanisms to hit, but not sufficient to avoid the need for beam steering.

Recent results of DT ice layer tolerance of temperature changes indicate that much higher injection speed will be needed for direct drive targets. The LBNL experiments showed, also, that for low speed (~100 m/s) indirect drive target injection photodiode detector technology was adequate to detect the target position with sufficient accuracy that the driver beams should be able to achieve the ~ ±200 µm accuracy needed. The case of higher speed direct-drive targets is to be considered. High shooting-rate guns (5-10 Hz) at high reliability looks today as one of the serious technological trade-offs that requires to be investigated and appeals for innovative ideas.

At an annual delivery rate of 1-2 10^8 targets, a success probability of injection of the order of 99.999% would mean some 1-2 10^3 targets lost per year, (a complete target costs today about $2000). That would mean also 1-2 10^3 false LASER shoots/year. Higher reliability delivery procedures would certainly be required. That is beyond our to-day technological performances. However, relying on SOMBRERO/OSIRIS preliminary designs, tracking systems and related electronics do not seem as difficult to be achieved as the injection guns.

ENERGY DRIVERS

The three serious candidates are presented in table 2 in [P1] : the Krypton-Flouride (KrF) laser, the Diode Pump Solid-State Laser (DPSSL) and the Heavy-Ions Driver (HID). The Krypton-Flouride (KrF) laser uses electron-beam pumping of a gas mixture to produce a UV laser beam (248 nm). The DPSSL uses a diode arrays to pump a solid-state medium to produce an IR laser beam whose frequency-tripled into the UV (350 nm). The heavy-ions driver (HID) is an induction linear accelerator that creates a high current (~ 10's-100's of kA) beam of some-GeV heavy ions.

For fusion reactors using direct-drive, the two lasers currently under investigation are the KrF laser and the DPSSL. A KrF driver for a power reactor would have a core module slightly larger than the 5-6 kJ achieved with the Nike laser at NRL. The existing pulsed power technology would be replaced by efficient and reliable non-linear magnetic switches similar to the Repetitive High Energy Pulsed Power device (RHEPP), or the recently developed Semiconductor Opening Switch (SOS).

The real concern about the KrF is its durability. The two major durability problems with the Nike laser are currently identified as the lifetime of the thin foils that separate the laser gas cell from the electron beam source, and the lifetime of the anti-reflection coating on the windows of the laser cell. However, KrF drivers are believed to be very promising for fusion energy direct drive approach as being expressed by the National Research Laboratory (John Sethian) in a recent publication, based on their operating experience feedback from Nike laser at NRL. NRL is involved in an Integrated Research Experiment (IRE) to develop a KrF laser for the Fusion Energy reactor applications. Although, the gap separating between the present performances and the objective ones is indeed large as shown in the following, table 2 in [P1].

The Mercury laser system is another high power solid-state laser. Its design is based on a scalable architecture for inertial fusion with goals of 10 % electrical efficiency and 10 Hertz operation for 100 J / 5 nsec pulses. Three component technologies had to be developed for high power solid-state laser fusion drivers: large-scale high performance diode laser arrays, high-speed gas-cooling of the gain media, and Yb:Sr(PO)F (Yb:S-FAP) crystal amplifiers. High speed gas cooling allows operation at 10 Hz while maintaining wave-front quality for a 5X diffraction limited beam as shown in recent experiments using surrogate Nd:glass slabs which indicate less than 1/16 wave-front distortion induced by the gas flow.

Large-scale diode laser array fabrication has begun with the completion of 72 diode laser tiles, each consisting of 23 bars operating at over 115 Watts/bar. These tiles will complete 1 of 4 diode arrays; each producing more than 160 kW of 900 nm light at a wall plug efficiency of 45%. Recent breakthroughs have been made in the growth of Yb:S-FAP crystals with large areas free of defects allowing half scale slabs to be diffusion bonded together to achieve full-scale amplifier slabs.

Employing these technologies, the Mercury Laser design averts damage while offering a scalable architecture. Extensive ghost, amplified spontaneous emission, and pencil beam analysis were performed, validating the current architecture and setting constraints on optical quality, surface reflectivity, wedge angles, and the extinction required of an average power Pockels cell currently being tested for the reverser. The near-term goals include demonstration of the half Mercury system (i.e. one amplifier) including: architecture, diodes, gas cooling, and seven full aperture S-FAP amplifier slabs.

As for Heavy ion drivers (HID), they are considered based on the capability of accelerators to generate high average beam power (of the order of 100 MW) with high repetition rate, and at an efficiency in the range of 15-20%. As was shown in the European HIDIF study the main challenge is to reconcile high peak power with low beam loss in the accelerator.

A valuable reference base for this issue is the technology of high power proton, which has been advanced in recent years with the design/construction of proton drivers for spallation neutrons, for neutrino factories/muon colliders, and for nuclear waste transmutation. Currently work is pursued in two directions: as driver for dense plasma physics using high-intensity facilities which are designed or are under construction for nuclear physics/radioactive beam factories; or dedicated technology development on a more direct (down-scaled) path towards a fusion driver.

CONCLUSIONS

The FY-2001 survey concludes that the major critical issues in an IFE power reactor are: 1/the target chamber, 2/ the target ignition & tracking, and 3/enrgy driver.

In the TC, the use of the renewable liquid walls (thin/thick jets) presents a very promising option to protect the TC walls, to breed tritium and transfer heat. However, many technical challenges related to the formation and the integration of the liquid walls at the required frequencies (5-10 Hz) should be managed before making use of this option. This issues covers many interacting topics such as TC cleaning, interfaces with the drivers and with the target injectors, and the TC dynamic.

As for targets ignition & tracking, indirect ignition seems providing the option with less technical risks and it suites more gas-gun injection options.

However, topics related to the optimum injection speed in order to allow high precision target tracking, and ignition contains many technical challenges as well.

Lastly, among the many options proposed for the energy drivers, the Heavy Ions drivers seems very promising with les technical risks.

Its main attractiveness come from its high energy efficiency, high repetition rate capability and its higher lifetime figures.

However, technical problems related to the TC interfaces and radiation protection of the focus-magnet presents serious technical challenges.

Most of the IFE community seems positive regarding the feasibility of the IFE power reactors taking into account the corresponding time scale.

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