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# APPLICATION POSSIBILITIES OF PLASMAS GENERATED BY HIGH POWER LASER ABLATION

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ABSTRACT. High-power pulsed lasers emitting IR and visible radiation with intensities ranging between $10^8$ and $10^{16}$ W/cm$^2$, pulse duration from 0.4 to 9 ns and energy from 100 mJ up to 600 J, operating in single mode or in repetition rate, can be employed to produce non-equilibrium plasma in vacuum by irradiating solid targets. Such a laser-produced plasma generates highly charged and high-energy ions of various elements, as well as soft and hard X-ray radiations. Heavy ions with charge state up to 58+ and kinetic energy up to 10 MeV are detected. The plasma emits ion current densities of the order of tens of mA/cm$^2$. Interesting application possibilities of the generated plasmas concerning the ion implantation technique, the laser ion sources, the high intensity and resolution X-ray sources, the laser propulsion technique and the nuclear reaction of light elements are presented and discussed.

## 1. Introduction

Medium energy pulsed power lasers operating at intensities of about $10^{10}$ W/cm$^2$ and high energy pulsed lasers operating at about $10^{16}$ W/cm$^2$ can be employed to produce in vacuum hot and super dense plasmas. The non equilibrium processes involved by laser pulses of 400 ps to 10 ns duration in solid targets produce high ablation rate with crater formation, the emission of matter of the order of mg/pulse and g/pulse, respectively, the generation of an highly ionised vapour reaching more than 90% of fractional ionisation and charge state up to about 50+ for heavy elements, as a result of the laser-vapour interaction. The result of the laser-solid interaction is the generation of a non-equilibrium plasma with duration of the order of 1-10 $\mu$s, expanding at super-sonic velocity along the normal to the target surface, whose temperature and density decrease exponentially with the time. Thermal, gas-expansive and Coulomb processes are involved, as described by the Coulomb-Boltzmann shifted energy distributions followed by ions, electrons and neutrals emitted from the plasma [1, 2]. Time of flight (TOF) measurements on particles emitted from the plasma indicate that the ion energy increases regularly with the charge state and it reaches about 5 keV for medium power lasers and about 5 MeV for high power lasers, as a result of the electric field acceleration occurring inside the plasma [3]. The high ion flux and energy found interesting applications, such as multi-energetic ion implantation techniques, laser ion sources, X-ray generation, laser propulsion of microsatellites and nuclear reactions induced by the ablated particles. Measurements of equivalent temperature of the produced plasma core indicate values of the order of 400 eV for medium power lasers and 80 keV for high power lasers [4]. In these conditions, for times lower than $1\mu$s, the plasma becomes a highly intense light source emitting IR, visible, UV and X-ray radiation. Ultra short soft and hard X-ray pulses can be obtained by the pulsed laser ablation processes, as a result of the Bremsstrahlung of the hot electrons interacting with the solid target. The hot electrons can be generated by several possible mechanisms such as resonant absorption, vacuum heating, ponderomotive-force heating, and anomalous skin effects [1]. The very high intensity and very small dimension of the X-ray source found interesting applications, such as astrophysical simulations, high-resolution X-ray imaging and matter structure investigations.

## 2. Experimental set up

A Nd:Yag laser with 1064 nm fundamental wavelength, 9 ns pulse width, 900 mJ maximum pulse energy, operating at INFN-LNS (Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali del Sud) of Catania in single mode, or at 30 Hz repetition rate, is employed to ablate metals in vacuum at a pulse intensity ranging from $10^7$ up to $10^{11}$ W/cm$^2$ [5]. A Iodine mixture laser with 1315 nm fundamental wavelength, 400 ps pulse width, 600 J maximum pulse energy, operating at PALS (Prague Asterix Laser System) laboratory of Prague in single mode, is employed to ablate different kinds of solids in vacuum at a pulse intensity ranging from $10^{10}$ up to $10^{16}$ W/cm$^2$ [6]. Fig. 1 shows a photo of the laser set-ups, with a first plain devoted to the vacuum chambers of interaction, at INFN-LNS (a) and at PALS (b), respectively.

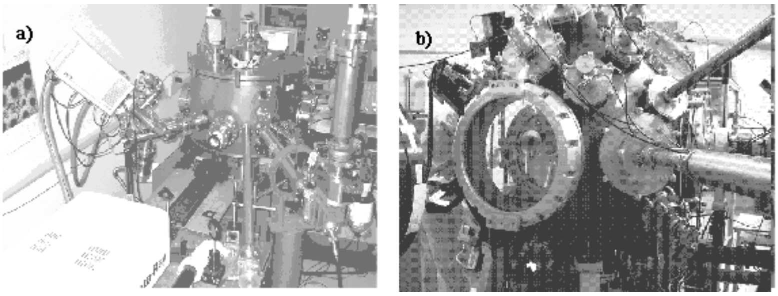

FIGURE 1. Experimental apparatus at INFN-LNS (a) and at PALS (b).

In the two laboratories, the pulse energy is monitored during the laser irradiation and the main ”on line” facilities include: TOF measurements of ions and electrons with Faraday cups; energy-to-charge ratio measurements with an electrostatic ion deflector IEA (Ion Energy Analyzer); mass-to-charge measurements with mass quadrupole spectrometry; CCD camera with a minimum exposition times of $1\mu$s detecting the visible emission; Si detectors for soft and hard X-ray emission; optical spectroscopy in visible and UV region. Fig. 2 shows a typical example of TOF measurements by IEA deflector evidencing up to 50 charge states of Au ions produced at PALS by ablating at $10^{15}$ W/cm$^2$ (a) and several of the corresponding ion energy distributions, for the Au charge states from $1^+$ up to $6^+$. The recorded experimental data (points) are fitted with the ”Coulomb-Boltzmann shifted” function (line) (b), as described in the literature [2].

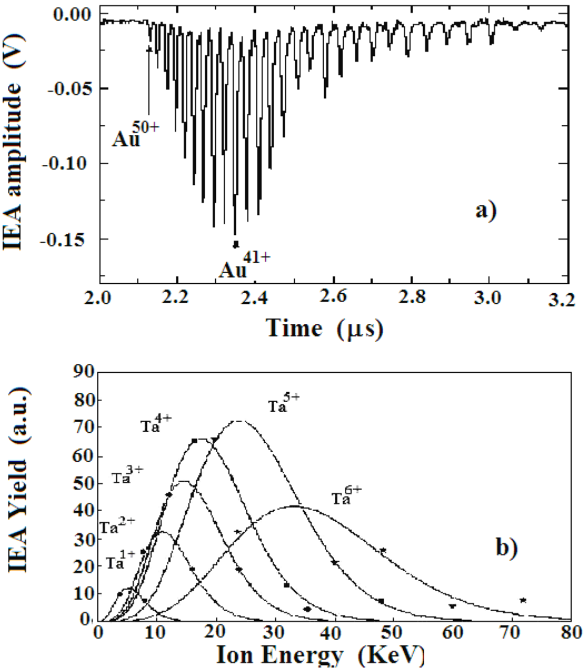

FIGURE 2. Typical IEA spectrum obtained ablating Au (a) and comparison of the ion energy distributions for the first six charge states (b).

Different ”off line” measurements are performed on the ablated targets and on the photo-deposited thin films or on the photo-implanted surfaces of different substrates exposed in vacuum to the plasma action. A surface profiler can be employed to analyse the crater depth and to calculate the amount of atoms ejected from the crater; a SEM microscope can be employed to investigate about the laser-irradiated target and about the morphology of photo-deposited thin films. 2.0 MeV helium beam is employed to analyse, with the RBS (Rutherford Backscattering Spectrometry) technique, the implanted dose and the implanted depth profile of the exposed surfaces. A very controlled chemical etching can be employed to observe by means of the optical microscope the ion tracks produced in polymeric substrates (PM 355) exposed to the plasma. As an example, Fig. 3 shows a typical SEM photo of the Ta crater produced at PALS by a single pulse of 230 J at $10^{15}$ W/cm$^2$ (a) and a typical thin film detector employed to record the micrometric tracks due to protons ($\sim$2 $\mu$m size) and to tantalum ($\sim$ 11.5 $\mu$m size) ions produced by the plasma (b) [7].

## 3. Results

In the following a synthesis of the main results about five possible applications of plasmas generated by high power laser ablation will be presented. Applications in the fields of ion implantation, laser ion sources, X-ray generation, laser propulsion and nuclear fusion are considered.

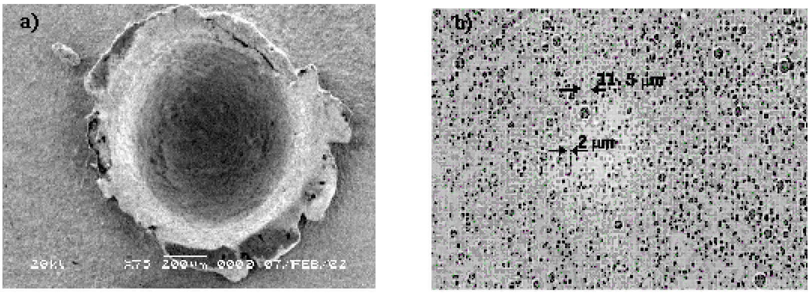

FIGURE 3. Ta crater produced by a single shot laser at PALS (a) and polymeric detector showing the tracks due to protons and to tantalum ions emitted from the plasma(b).

**3.1. Ion implantation.** The energetic ions emitted from the laser-generated plasma found interesting applications in the field of ion implantation because a multi energetic ion stream can be employed to irradiate different surfaces and to induce a significant modification of their physical and chemical properties. The depth profile of the ion implant can be controlled by the laser pulse intensity, which accelerates ions from some keV up to some MeV. Raising this intensity increases the plasma temperature, the average ion energy and, consequently, the ion range in the substrate. The number of laser shots controls the ion dose of the implant by changing their concentration in the implanted layers. Fig. 4 shows a typical RBS spectrum of Ge ions implanted in a silicon substrate at PALS laboratory. The ions are produced by 10 laser shots at 438 nm wavelength and 40 J pulse energy. The substrate is $SiO_2$ (200 nm)/Si-bulk placed 16 cm away from the target and at a deposition angle of 25° with respect to the target surface normal. The shape of the Ge spectrum is relative to an implanted dose of $3.5\text{x}10^{15}$ Ge atoms/cm$^2$. The Ge RBS peak corresponds to a total depth of 810 nm of implanted layers, i.e. to a maximum Ge ion energy of 1.1 MeV. Results are in agreement with IEA measurements and they show that the main ion emission occurs along the normal to the target surface independently of the incidence angle of the laser beam; consequently in this direction there is the maximum implanted dose. A similar ion implantation effect, with multi-energetic ions, can be obtained with lower laser fluences, by using the LNS laser and a post ion acceleration and ion focalisation with suitable electrodes placed near to the target and biased to a potential of about 50 KV [8].

**3.2. Ion sources.** In order to increase the ion charge states, the current and the emissivity of traditional ion sources (evaporation, sputtering, electron beam), a hybrid ion source can be obtained by using a laser to produce a plasma and by injecting the emitted ions in the ion source chamber. The laser ion source (LIS) system, applied to the ECR (Electron Cyclotron Resonance) of the INFN-LNS of Catania, shows good emittance, stability and energy spread. In order to maximize the ion extraction from ECR, the laser-ECR coupling needs a low laser fluence ($\sim 10^8$ W/cm$^2$), a negative biased target ($\sim$3 kV) and a low frequency repetition rate ($\sim$1 Hz). In such conditions the ion emission from the laser ablation interacts with the ECR equilibrium plasma (oxygen or argon ions) produced by microwaves (18 GHz, 2 kW). The interaction time is sufficient to produce a near-thermalization of the ablated species with a consequent increase of the average ion charge state and extractable

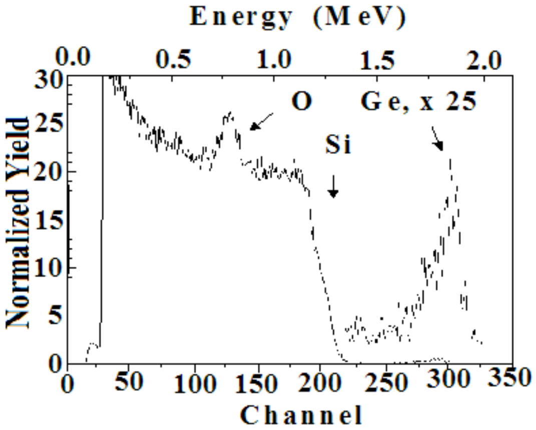

FIGURE 4. Typical RBS spectrum of Ge ions implanted in Silicon oxide substrate due to 10 laser shots at PALS.

currents. Finally, ions can be extracted and selected by electric and magnetic filters. A very interesting feature of the LIS system is the possibility to obtain heavy ions of elements with high boiling points (Ta, W, Re), high ion charge states ($\sim 40^+$) and high ion currents

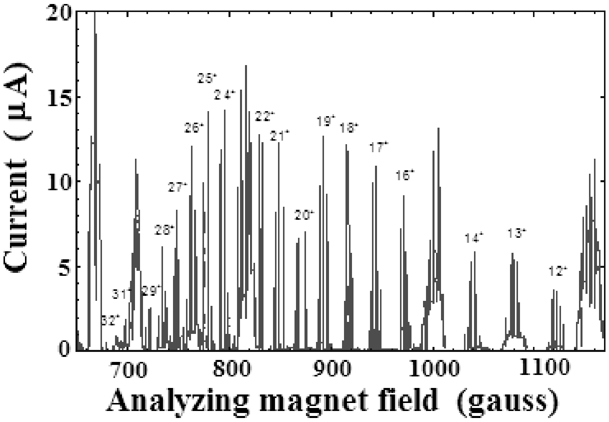

FIGURE 5. Typical example of Ta ions, vs. charge state and deflecting magnet field produced by LIS at LNS.

($\sim$50 $\mu$A). Potentially, it is also possible to obtain radioactive ions and ion beams. Fig. 5 shows an example of extracted ion currents from the SERSE (Supeconducting Electron Resonance SourcE) source of LNS vs. analysing magnet field and charge state for Ta ablation at $10^8$ W/cm$^2$ and 1 Hz repetition rate [9].

**3.3. X-rays generation.** The laser-produced plasma reaches temperatures of hundreds eV and densities of about $10^{16}$/cm$^3$ for pulse intensity of the order of $10^{10}$ W/cm$^2$. These

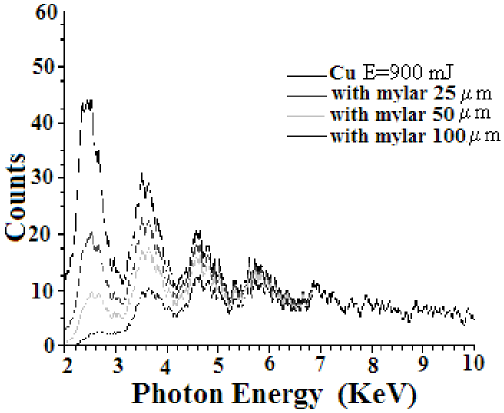

FIGURE 6. Typical X-ray spectrum obtained at LNS ablating Cu vs. absorber thickness.

parameters reach tens keV and about $10^{19}$/cm$^3$ for pulse intensity of the order of $10^{15}$ W/cm$^2$.

Under such conditions the plasma represents a special X-ray source, characterised by very high intensity and very low size, due to Bremsstrahlung and electron-ion recombination processes. The X-rays are emitted into the 4 $\pi$ solid angle with a peak along the normal to the target surface. The photon emission is very wide in wavelength, ranging from the IR to the region of X-rays. Intensities higher than more than $10^{10}$ W/cm$^3$·sr and photon energies higher than 5 keV can be obtained with laser pulse intensity starting from about $10^{10}$ W/cm$^2$. Values even two-orders of magnitude higher can be obtained for laser intensities higher than $10^{15}$ W/cm$^2$. The X-ray source can be employed as a diagnostic tool for the same produced plasma, as a laboratory simulator of photon emission for astrophysical studies and as a powerful method for lithography and imaging applications. Fig. 6 shows a typical X-ray spectrum obtained at LNS ablating a Cu target with 900 mJ pulse energy, $10^{10}$ W/cm$^2$ intensity and 30 Hz repetition rate as a function of the thickness of a mylar absorber placed in front of the Si(Li) detector [10].

**3.4. Laser propulsion.** Typically, about 30:1 fuel/payload ratio is needed for launching a near-earth satellite. Thus, most of the launch cost is for fuel to propel fuel and for the large expensive non-reusable launch vehicle required to contain the enormous fuel volume.

Since propulsive force is given by F = V$_E$ (dm/dt), if the exhaust velocity V$_E$ could be increased by a factor of 10 the rate of propellant used, (dm/dt), could be reduced by the same factor. Lasers can heat gases to much higher temperatures than combustion, tens of millions of K rather than thousands, making possible increase in propellant velocities by a factor of ten or more. The Ablation Laser Propulsion (ALP) is based on the specific impulse, Is, imparted to the target by a single laser pulse:

$$I_s = \frac{1}{W}\int_0^{\tau} F(t)dt \qquad (1)$$

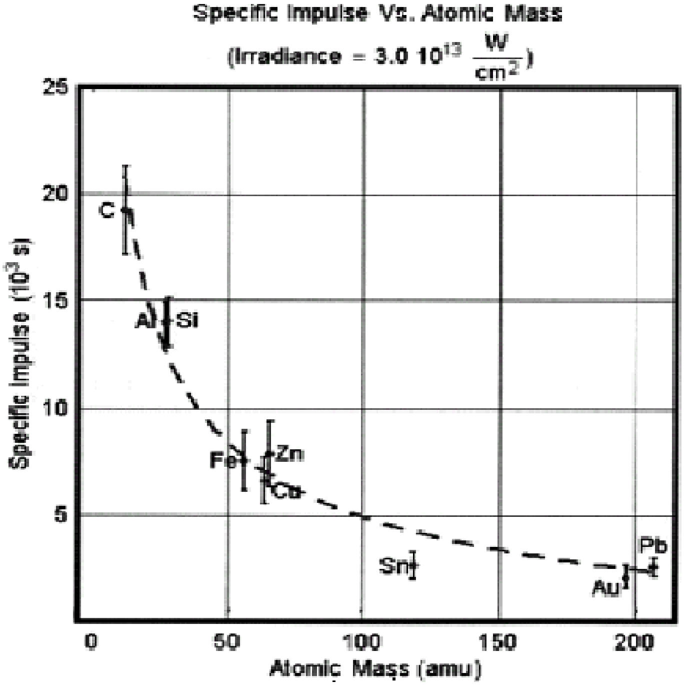

FIGURE 7. Specific impulse vs. atomic mass of propellant as derived from ion velocity and force measurements.

where W is the weight of the propellant ablated per pulse and F is the force acting for a time $\tau$. An ALP-based space vehicle would be driven by high energy, short duration ($10^{-10}$s or less) laser pulses, focused on a solid propellant. In such a condition plasma and laser pulses are temporally separated and the direct ablation dominates over other possible momentum transfer mechanisms. ALP is the optimum laser propulsion technique in terms of energy efficiency, providing specific impulses and mass-power ratios higher than other techniques based on longer laser pulses, or continuous wave irradiation. The high impulse and low mass-removal rates are obtained for low-Z targets, while high-Z targets provide higher momentum transfer. $I_s$ reaches 2x$10^4$s with carbon. All studied characteristics indicate that high $I_s$ ALP must be based on solid low-Z propellants, such as carbon, silicon, or aluminum. High power lasers permit to accelerate microsatellites of 5 Kg mass, used for telephony, TV, metrology, and imaging, at values of tens of g. Fig. 7 shows the specific impulse vs. atomic mass of propellant as derived from ion velocity and force measurements [11].

**3.5. Nuclear fusion.** The high temperature reached by the laser-generated plasma, of the order of 80 keV for pulse intensities of about $10^{16}$ W/cm$^2$, energizes the particles of the plasma gas and increases their interaction probability giving high possibility (cross-section) to generate nuclear fusion. The interest of the nuclear fusion is devoted to light nucleuses, like deuterium, lithium and boron, which show a low Coulomb barrier. In particular for the controlled thermonuclear fusion the main reactions of interest are:

$$D_1^2 + D_1^2 \xrightarrow{50\%} T_1^3(1.01MeV) + H_1^1(3.02MeV)$$
$$D_1^2 + D_1^2 \xrightarrow{50\%} He_2^3(0.82MeV) + n_0^1(2.45MeV)$$
$$D_1^2 + T_1^3 \longrightarrow He_2^4(3.52MeV) + n_0^1(14.06MeV)$$
$$D_1^2 + He_2^3 \longrightarrow He_2^4(3.67MeV) + H_1^1(14.67MeV)$$

The high plasma temperature, the confinement time, the high plasma density and the magnetic confinement space increase significantly the probability of nuclear fusion with production of energetic products of the reactions. For such applications high energetic lasers can be employed with success (Terawatt and Petawatt lasers). Compressed DT pellets act as a solid fuel, which is ignited by the impact collision of energetic particles ejected from the plasma. Special geometries of the laser irradiation and of the chamber of plasma production are investigated in order to have a better control of the nuclear fusion process. High magnetic fields are employed to define the plasma volume and to increase particle interactions. Fig. 8 shows the calculated $\langle \sigma v \rangle$ reaction parameter (cross sections by ion velocity) for the previously reported reactions as a function of the plasma temperature in the range of power interest for the lasers operating at LNS (T $\sim$ 400 eV) and PALS (T $\sim$ 80 keV) [12].

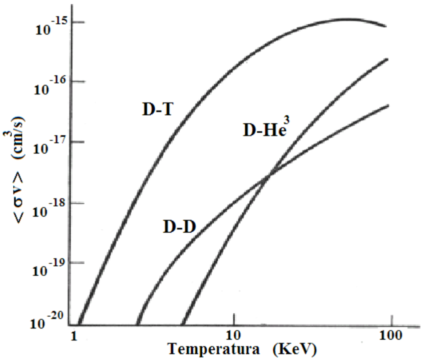

FIGURE 8. Cross sections vs. plasma temperature for the D-T, D-He$^3$ and D-D nuclear reactions.

## 4. Discussion and conclusions

The laser ablation of solids produces very hot and dense plasma with non-equilibrium conditions, very useful for different new possible applications. The ion implantation of the energetic species ablated is one of the possible applications which interest the field of the matter structure and which permits to modify the chemical and physical properties of many materials, such as hardness, wetting, roughness, wear and chemical reactivity. Also the traditional pulsed laser deposition of thin films can be improved thank to the good adhesion obtainable at the film-substrate interface due to the energetic ions implantation effects. The laser ion sources are giving the possibility to build a new generation of ion sources without limitation of the ion species and improving the ion current and the ion charge state limitations. Some special projects in this field are dedicated to the possibility to build a new kind of ion accelerator laser-ablation based, using electrical and magnetic ion focalisation and post-ion acceleration. The high intensity of the X-rays generated by the plasma-laser is reaching a good number of applications in different fields. The X-ray detection permits to characterize the produced plasma; microelectronics is using it for photolithographic processes with high spatial resolution; biology and medicine are interested to the high resolution of X-ray images obtainable on small samples; matter structure can use it for X-ray diffraction in nanocrystals. The laser propulsion chapter represents an interesting application of the laser-generated plasma for the spatial propulsion of rockets in the next future. It will reduce the actual cost of the launch of small satellites around the earth. Moreover, it can be potentially applied to supply the fuel of rockets designed for long space travels for which it is necessary to prolong the duration. Finally, the high temperature of the plasma-laser can be employed to energize the atomic species and to ignite the thermonuclear fusion of light nucleuses, such as deuterium and lithium. These reactions represent the main energy in the universe, but on the earth they are only artificially generated. The good control of this process allows to improve the energy conversion without producing dangerous radioactive cinders giving to the humanity a better hope to solve the world energy related problems.

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## References

[1] D. Giulietti and L.A. Gizzi, *Rivista Il Nuovo Cimento* **21**, (10), 1 (1998).

[2] L. Torrisi, L. Andò, S. Gammino, and L. Laska, *J. Appl. Phys.* **91**, (5), 18 (2002).

[3] L. Laska, K. Jungwirth, J. Krasa, M. Pfeifer, K. Rohlena, J. Ullschmied, J. Badziak, P. Parys, J. Wolowski, F.P. Boody, S. Gammino, and L. Torrisi, *Czech. J. of Physics* **54**, C370 (2004).

[4] L. Torrisi, S. Gammino, A. Picciotto, L. Andò, L. Laska, J. Krasa, K. Rohlena, and J. Wolowskii, *Proceedings of the* $32^{\mathrm{nd}}$ *EPS Plasma Physics Conference* **29C**, P-1.144 (2005).

[5] L. Torrisi, G. Ciavola, S. Gammino, L. Andò, A. Barnà, L. Laska, and J. Krasa, *Rev. Sci. Instr.* **71**, 4330 (2000).

[6] K. Jungwirth, A. Cejnarova, L. Juha, B. Kralikova, J. Krasa, E. Krousky, P. Krupickova, L. Laska, K. Masek, T. Mocek, M. Pfeifer, A. Prag, O. Renner, K. Rohlena, B. Rus, J. Skala, P. Straka, and J. Ullschmied, *Phys. Plasmas* **5**, 2495 (2001).

[7] A. Szydlowski, J. Badziak, P. Parys, J. Wolowski, E. Woryna, K. Jungwirth, B. Kralikova, J. Krasa, L. Laska, M. Pfeifer, K. Rohlena, J. Skala, J. Ullschmied, F.D. Boody, S. Gammino, and L. Torrisi, *Plasma Phys. Control. Fusion* **45**, 1417 (2003).

[8] J. Wolowski, J. Badziak, A. Czarnecka, F. P. Boody, S. Gammino, J. Krasa, L. Laska, A. Mezzasalma, P. Parys, M. Rosinski, K. Rohlena, L. Torrisi, and J. Ullschmied, *Rad. Eff. and Def. in Solids* (2005), *in press*.

[9] S. Gammino, L. Torrisi, G. Ciavola, L. Andò, L. Celona, S. Manciagli, J. Krasa, L. Laska, M. Pfeifer, K. Rohlena, A. M. Mezzasalma, C. Gentile, A. Picciotto, J. Wolowski, E. Woryna, J. Badziak, P. Parys, D. Hotz, and G. D. Shirkov, *J. Appl. Phys.* **96**, 2961 (2004).
[10] L. Torrisi, E. Amato, S. Gammino, D. Margarone, G. Bonanno, and S. Scuderi, *Report INFN-LNS 2003* 178, (2004).
[11] F. P. Boody, J. Badziak, H.A. Eckel, S. Gammino, J. Krasa, L. Laska, A. Mezzasalma, A. J. Pakhomov, P. Parys, M. Pfeifer, K. Rohlena, W. Schall, L. Torrisi, and J. Wolowski, *Rad. Eff. and Def. in Solids* (2005), *in press*.
[12] P. Caldirola, R. Pozzoli, and E. Sindoni, *Il fuoco della fusione termonucleare controllata* (Edizioni Sci. e Tecniche Mondadori, Milano, 1984).

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