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Antonio Trifirò, Carmen Altana, Davide Bortot, Pablo Cirrone, Fabrizio Consoli, Saverio De Luca, Roberto De Angelis, Salvatore Cavallaro, Caterina Ciampi, Gaetano Lanzalone, Luciana Malferrari, Davide Mazzucconi, Fabrizio Odorici, Libero Palladino, Gabriele Pasquali, Antonino Picciotto, Angelo Maria Raso, Raffaella Testoni, Marina Trimarchi, Salvatore Tudisco, Matteo Valt, Claudio Verona, Antonio Zurzolo, Simona Privitera, Massimiliano Scisciò, Antonio Domenico Russo

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Measurement of ion stopping power in the framework of nuclear reactions in plasmas

A. Trifirò[1,*], C. Altana[2], S. De Luca[2], R. De Angelis[3], S. Cavallaro[2], C. Ciampi[4], G. Lanzalone[2,5], G. Lo Presti[3], L. Malferrari[6], F. Odorici[6], L. Palladino[7], G. Pasquali[8], S. Privitera[1], A. Russo[2], M. Trimarchi[1], D. Bortot[9], G.A.P. Cirrone[2,10], F. Consoli[11], D. Mazzucconi[9], A. Picciotto[12], A. Raso[13], M. Scisciò[11], R. Testoni[14], M. Valt[12], C. Verona[13], A. Zurzolo[14], S. Tudisco[2]

[1]Dip. MIFT, Università di Messina, Messina, Italy & INFN, Sez. di Catania, Catania, Italy
[2]INFN, Laboratori Nazionali del Sud, Catania, Italy
[3]Dip. di Fisica e Astronomia, Università di Catania, Catania, Italy
[4]GANIL, Caen, France
[5]Dip. Di Ingegneria ed Architettura, UNIKORE, Enna, Italy
[6]INFN, Sez. di Bologna, Bologna, Italy
[7]INFN, Sez. dell'Aquila, L'Aquila, Italy
[8]Dip. Di Fisica, Università di Firenze & INFN sez. di Firenze, Firenze, Italy
[9]Politecnico di Milano & INFN, Sez. di Milano, Milano, Italy
[10]Centro Siciliano di Fisica Nucleare e Struttura della Materia, Catania, Italy
[11]ENEA – Nuclear Department, C.R. Frascati, Frascati, Italy & INFN – Sez. Tor Vergata, Roma, Italy
[12]Sensors and Devices Centre - Fondazione Bruno Kessler, Trento, Italy
[13]Dipartimento Ingegneria Industriale, Università di Roma Tor Vergata, INFN Sez. Roma2, Roma, Italy
[14]Dipartimento Energia, Politecnico di Torino & INFN, Sez. di Torino, Torino, Italy

Abstract The study of nuclear reactions and interactions in plasmas has recently assumed great importance because of its connection with processes such as laser-driven ion acceleration and nuclear fusion for massive energy production. In fact, the extremely high electron densities established in the plasma bring to different behavior of charged particles with respect to that observed when a stable beam impinges on a solid target.

Ion stopping power in cold matter is relatively well known and has been characterized with the help of a large set of experimental data and theoretical studies; on the contrary a lot of open questions remain when it comes to ions stopping in a plasma, especially in the energy domain where the projectile ion velocity approaches that of free plasma electrons. The main aim of this work is a systematic and careful measurement of stopping power for several ions versus plasma parameters, especially in the region of thermal velocities, where the energy deposition should depend strongly on plasma temperature, density and ionization fraction.

The plasma will be generated under vacuum, by interaction of a laser beam with a solid target. Plasma plume will be characterized in temperature and density by optical and X-ray diagnostics; simultaneously the energy loss will be measured for an ion microbeam crossing the plume.

This contribution provides an overview of the experimental technique, and the results obtained during first tests for the characterization of experimental apparatus.

Keywords Stopping power, ion, plasma, laser

INTRODUCTION

This work is developing in the framework of the Fusion experiment, a project that has been financed by the Italian institutions INFN and ENEA. The experiment is devoted to the study of fusion reaction between protons and ^{11}B, a process already observed almost 100 years ago that yields 3 alpha particles with energy between 0.9 and 3.9 MeV. One of the most important applications of this reaction is the fusion for energy production and in this framework the most studied channel is the D-T one, due to its high cross section. This process, however, has two drawbacks: the first is the production and

* Corresponding author: Antonio.trifiro@unime.it

management of radioactive fuel, which imply remarkable supply costs and risk of environmental pollution (Tritium in fact emits beta radiations with a half-life of 12 years); the second drawback is the production of high energy neutrons, that activate surrounding material producing compound nuclei that emits prompt gammas of very high energy, or beta and gamma emitters. For instance, the interaction of this neutrons with oxygen of air or water produces ^{16}N, a nuclide that emits gammas and electrons of several MeV:

$$n + {}^{16}O \rightarrow p + {}^{16}N \rightarrow p + \gamma\,(5 - 7\,MeV) + e^{-}(0 - 10.4\,MeV) + {}^{16}O. \tag{1}$$

Reactions between p and ^{11}B instead produce only alpha particles, without involving any radioactive nucleus; on the other hand, the cross section at low energy is very small compared to the D-T one, but it has been observed a resonance around 150 keV [1] that could be exploited to increase the fusion yield.

This observation dates back to almost 40 years ago, so a first goal of the experiment is a more accurate measurement of the cross section in this low energy region. Moreover, the energy of this first peak is 3 times that of the D-T one, and the possibility of increasing the energy of the plasma is linked to the self-heating of the system, that in turns depends on the energy loss of the ions involved. For this reason, a second goal of the experiment is a systematic and careful measurement of stopping power for several ions in plasmas, especially in the low energy region, where the ion speed approaches the thermal velocity of plasma electrons. In this range in fact there is a strong difference between the cold matter and plasma [2]. Theoretical and semiempirical simulations are thus essential to ensure appropriate experimental designs and interpretation of results. However, in the aforementioned energy domain there is a lack of experimental constraints, needed to tune-up the simulations; in particular, data reported in literature are few and in poor agreement with prediction of existing models.

EXPERIMENTAL TECHNIQUE AND RESULTS

In the framework of nuclear reactions in plasmas a careful measurement of stopping power for several ions is fundamental, also because during the last years a strong development of target and production techniques has been observed, then important changes in temperature, density and ionization fraction of plasmas produced are expected.

The experimental apparatus developed for the measurement of stopping power is sketched in Fig.1.

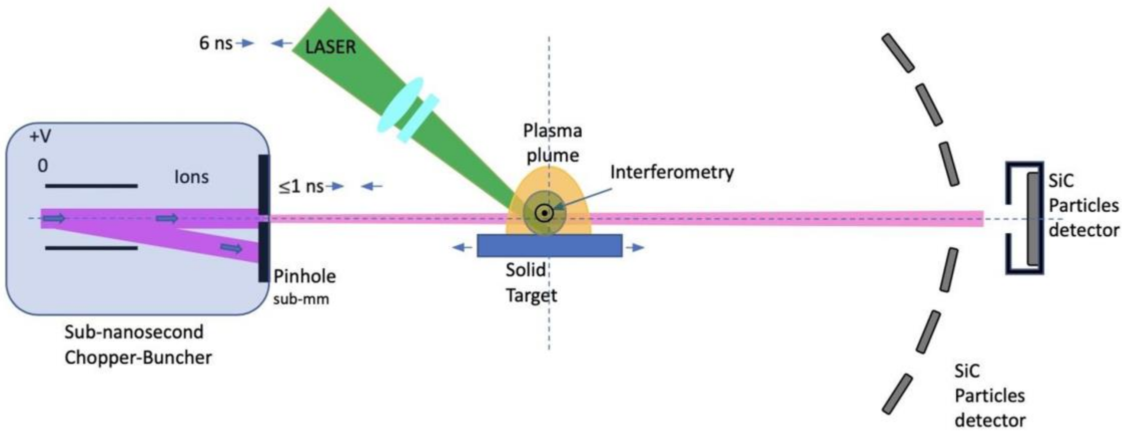
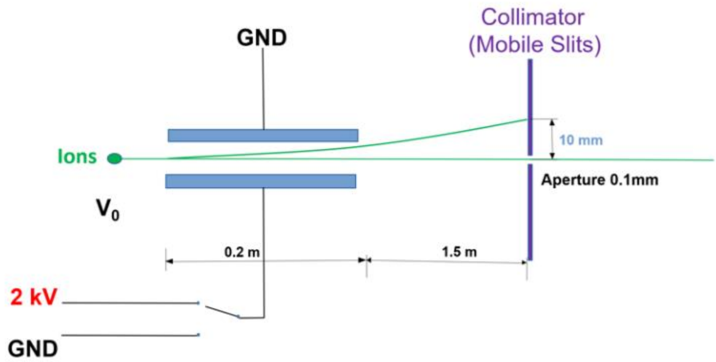


Figure 1. *Experimental apparatus designed for systematic measurement of stopping power of light ions in laser produced plasmas at different conditions of temperature and density.*

For this study the Laser light will be focused on a target in order to reach power densities of the order of 10^{13} W/cm^2; the plasma plume produced will be crossed by a bunched ion beam that after energy loss will be detected by means of solid-state detectors based on SiC [3,4], that is a material particularly resistant to radiation damage [5] (expected from the ion beam itself and from charged particles emitted by the plasma plume) and insensitive to visible light. With this apparatus a systematic measurement of stopping power will be performed for several light ions such as p, α and C in various laser produced plasmas at different conditions of temperature and density.

The Plasma plume is characterized using several high (time and spatially) resolved diagnostic tools, such as *Second-Harmonic Dispersion Interferometry* for plasma density, *Optical Emission Spectroscopy* for temperature, *Intensified Time-resolved Imaging* for plume geometry and *Pin-hole Camera* coupled to a *x-ray-CCD* for density and temperature of the hotter electrons; the energy loss of ions instead is measured with the time-of-flight technique applied by using a start time stamp provided by the beam buncher and a stop stamp produced by the SiC detector (Fig. 1).



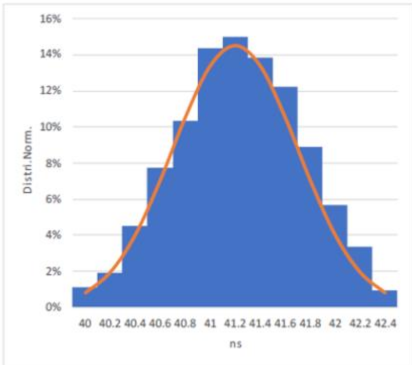


Figure 2. *Diagram of the chopper-buncher system (a). The deflection of 10 mm and the bunch temporal distribution (b) is obtained with "Opera Simulation Software" for 1 MeV proton beam assuming an electrodes gap of 20 mm.*

The most peculiar component of the apparatus is the chopper-buncher system, because in this low energy range all ion accelerators produce continuous beams while this technique requires bunches of few particles concentrated in few ns; for this reason, a modular chopper has been developed that can be easily installed along a classic beam line.

The chopper-buncher is based on fast electrostatic deflection of the beam across a system of mobile slits adjusted to select the number of ions per bunch and is schematized in Fig. 2.

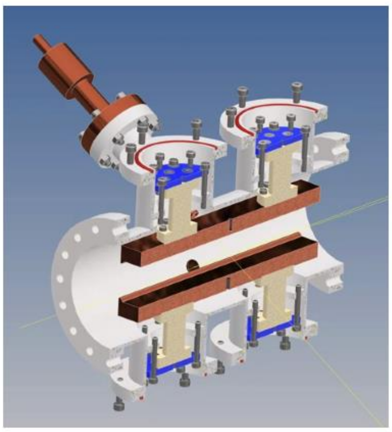


Figure 3. *Design (left) and implementation (right) of the chopper-buncher system.*

By using two electrodes with a length of 200 mm and a distance of 20 mm, an electric field of 100 kV/m is obtained, providing an electric rigidity of 2 MV for 1 MeV proton beams; moreover, driving the electrode high voltage through particular high-speed switches already installed, simulations of the beam dynamics performed with *Opera* software predict a bunch length of the order of 1 ns (Fig. 2b) and reducing the gap opening to below 1 mm few particles per bunch are expected, even just one.

The chopper-buncher system has been designed down to the smallest detail and has already been built, as shown in Fig. 3. Several tests carried out have confirmed that the system complies with all the design characteristics. For instance, the 10%-90% rise and fall times of the step voltage, measured directly on the deflection plates, are of the order of 8 ns, as shown in Fig. 4.

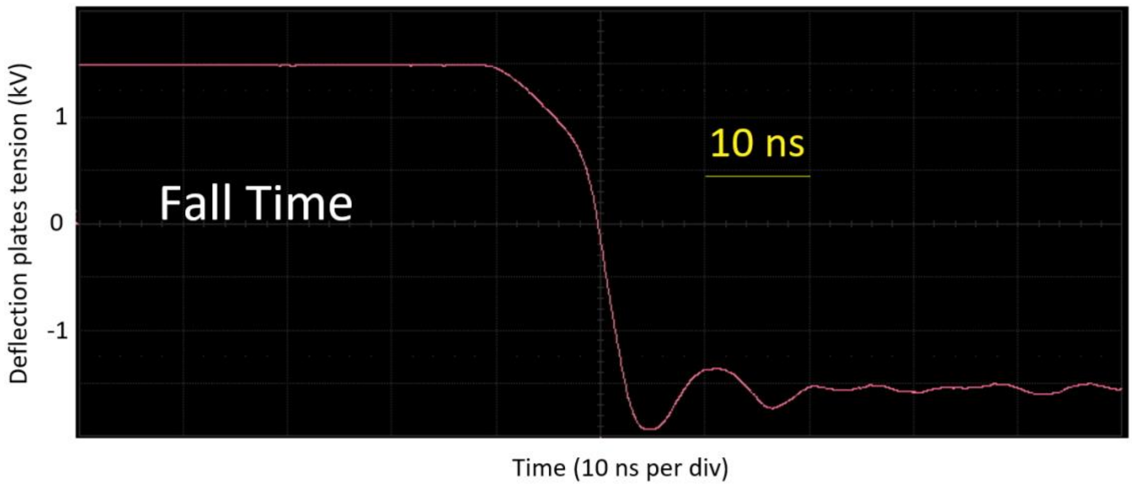


Figure 4. *Fall time of the step voltage applied to deflect the beam across the system of mobile slits, measured on the deflection plates.*

The system is then ready to be interfaced with the diagnostic systems for next phase of the experiment, i.e. the measurement of ion energy loss in plasma.

CONCLUSIONS

Reaction between protons and ^{11}B represents an interesting method to produce energy and energetic alpha particles avoiding remarkable supply costs and physical agents harmful to humans and the environment. A key aspect for the exploitation of this process is the energy loss of ions in plasma, especially in the low energy interval where the projectile ion velocity approaches the velocity of free plasma electrons and there is a lack of experimental constraints, needed to tune-up the simulations. For this reason an apparatus for systematic and careful measurement of stopping power for several ions in plasmas has been developed; the most critical component of the apparatus is the chopper-buncher system, necessary to provide bunches of few ions with a time spread of the order of 1 ns; this system has been already designed and manufactured, so a campaign is planned in the coming months for measurement of stopping power of light ions, such as protons, α and C, in various laser produced plasmas at different conditions of temperature and density.

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