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HAL Id: jpa-00223321
https://hal.archives-ouvertes.fr/jpa-00223321
Submitted on 1 Jan 1983

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HEAVY ION PARTICLE BEAM INTERACTION WITH A HOT IONIZED TARGET

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RESUME

On décrit dans cet article le dispositif expérimental en cours de réalisation destiné à l'étude des mécanismes d'interaction d'un faisceau d'ions lourds traversant un plasma créé par laser. On analyse en particulier certains aspects tels que le couplage du laser et du tandem, les performances nécessaires du faisceau et les contraintes à satisfaire sur les paramètres du plasma et les diagnostics à utiliser.

ABSTRACT

The present status of the experimental facility consisting of a heavy ion beam travelling through a laser created plasma target is described. Some aspects such as laser-tandem coupling, beam performances, constraints on the plasma parameter ranges, plasma and beam diagnostics are analysed.

I - INTRODUCTION

Atomic Physics is intimately involved in the physics of inertial and magnetic confinement fusion particularly when highly stripped heavy ions are concerned. Recently heavy ion beams have been considered as promising drivers for inertial fusion [1] and multi megajoule heavy ion beams may also play a role for additional heating in large tokamaks [2,3].

There are many areas where heavy ions atomic processes are important in magnetically confined plasmas, namely [4]:

- radiation losses through line radiation and charge exchange [5],
- plasma heating and diagnostic,
- impurity concentration effect on ignition parameters and impurity extraction [6] and so on.

In inertially confined plasmas, the knowledge of highly stripped ion atomic processes is even more important since:

- equations of state, opacities and heat capacity of the pellet material depend directly on the effective charge of the ions,
- on the other hand slowing down processes (ranges, energy deposition profiles, coulomb scattering) are very sensitive to the ionization states of heavy ion particles and these processes are of prime importance not only in the heavy ion fusion concept but also in some other fields like slowing down of fission products in nuclear induced plasmas and nuclear pumped lasers or slowing down of runaway ions produced for example in laser created plasmas.

In this paper we want to specify the main goals of our experiment, then to analyse the needed beam and plasma performances and finally to describe some experimental aspects and the diagnostic methods we intend to use to characterize the plasma.

II - MAIN AIMS OF THE EXPERIMENT

The beam probe technic is a powerful method which was applied in different field and Figure 1 gives the principle of our experiment. A CO$_2$ TEA laser focused on a target will create a plasma characterized by different conditions depending on the target material and laser parameters. The three density regions (0,1,2) [7] are characterized by different values of the ion coupling parameter \( \Gamma = \left( \frac{Z_p e}{R_0} \right)^2 \); \( R_0 \) being the ion sphere radius and \( Z_p \) the plasma ionization state.

![Figure 1 - Principle of the heavy ion beam interaction with a laser created plasma.](image_url)

The different regions (0,1,2) depend on the ion coupling parameter (R.M. MORE [7])
A bunched beam probe delivered by a 7 MV tandem accelerator will travel through the plasma; in a first phase we want to explore the corona region where the characteristic length \((\frac{\eta m}{n})^{-1}\) is of the order of a few mm and where induced electric and magnetic fields are negligible. By measuring the beam charge distribution, the energy loss and the beam divergence (which will be enlarged by Coulomb scattering) one should be able to obtain experimental data in the following three areas:

- stripping and charge transfer processes in an ionized target,
- energy losses and charge evolution during the particle slowing down
- and ionization model of the plasma itself since the beam output parameters will contain informations on the plasma ionization states.

II-1-Stripping and charge transfer processes

Many experimental data exist on the charge state equilibrium distribution in the case of a heavy ion beam travelling through a solid or a gaseous target. A semi-emperical formula gives the charge state of the projectile as a function of his atomic charge and of his particle velocity \(\beta\):

\[
\frac{Z_b}{Z_{at}} = 1 - 1.034 \exp (- \frac{137}{\beta} Z_{at}^{0.69})
\]  
(1)

For an ionized target MEHLHORM [8] takes the relative velocity between plasma electrons and projectile ions to calculate the \(\beta\) value; in fact, it is more difficult for the projectile to capture a free electron than a bound electron and the equilibrium charge state of the projectile in a partly or a fully ionized target may differ significantly from the formula (1). Figures 2 a,b (taken from [9]) give for example the projectile effective charge calculated with different hypothesis. In our experiment, one should be able to put some experimental data on these calculated curves.

As the energy loss has a \(Z_b^2\) dependance, the ranges and the beam energy deposition profiles will have a completely different behaviour depending on the \(Z_b\) variation during the slowing down process and it is well known that a precise knowledge of these parameters is very important to optimize a complete scenario of pellet implosions in the heavy ion fusion concept [10].

II-2-Heavy ion slowing down in an ionized target

To delineate the ranges of experimental interest we have studied the slowing down of heavy ions in an ionized target by adapting a Monte Carlo code [11] used extensively in fast neutral heated tokamak plasmas [12].
In this simplified model [13], the energy loss is given by

\[
\frac{dE}{dx} = -\frac{1}{E} (\alpha + \beta + \gamma)
\]

where \(\alpha\) is the loss on ions, \(\beta\) on free electrons and \(\gamma\) on bound electrons.

\[
\begin{align*}
\alpha &= 1.310^{-13} A_b Z_b^2 n_p Z_p^2 A_p \ln \Lambda_i \\
\beta &= 2.3910^{-10} Z_b^2 Z_p n_p A_b F(\zeta) \ln \Lambda_e \\
\gamma &= 2.3910^{-10} Z_b^2 (Z_t - Z_p) n_p A_b \ln \frac{2.1710^{-4} E}{Z_t A_e}
\end{align*}
\]

FIG. 2 - Charge state evolution of an Al and C beam during the slowing down in C and Li targets for different hypothesis (see ref.[9]).
We have assumed that the excitation energy is simply given by

\[ I_0 Z_t; Z_p, n_p, T_e \]

are assumed to be known and are introduced with their profile as entry parameters.

\[ F(\xi) = \text{erf}(\xi) - \frac{2}{\sqrt{\pi}} \xi e^{-\xi^2} \quad \text{with} \quad \xi = \frac{v_b}{v_{\text{the}}} \]  

(4)

The Coulomb scattering time is derived from \[ [14] \]

\[ \tau_{sc} = \frac{\langle \Delta v \rangle^2}{v^2} \]  

and

\[ \theta_{sc} (\text{deg}) = \frac{410^7 Z_b Z_p}{v_b A_b} \sqrt{\frac{n P \log \Lambda_i (\phi - G)}{2}} \]  

(5)

where

\[ \phi - G = 2 \xi^2 F(\xi) \quad [14]. \]

The suffix b indicates the beam and p the plasma.

We have checked that we can restore many of the published data (experimental or calculated) within a 10% error bar with this simplified model PEP [13]. As an example, Figure 3 compares our results to the LANL [15] values.

Figure 4 shows the different regions of interest in magnetically confined plasma (MF region) and in the inertial fusion case (IF region). Many experimental data have been collected in the MF case in connection with the fast neutral heating methods and the conclusions of these studies were that slowing down processes and pitch angle scattering were found to be classical. In the IF case there is no direct measurement and many other mechanisms have to be taken into account [16] to describe the physics of the slowing down in a hot and dense plasma.

In our experiment we will explore an intermediate region (HI-CO\textsubscript{2} region) where there is no more direct measurement at our knowledge. Depending on target material, the plasma will be described by different ionization models (corona, LTE or mixed model). In laser plasmas, the study of a particles or runaway particles created in the implosion process itself and slowed down by the pR line density of external shells needs a very good knowledge of the source term and of the induced electric and magnetic field distributions to restore the physics of the slowing down process in a hot and dense plasma.
FIG. 3 - Range of a Xe beam versus energy in two cases: a cold target and an ionized target (Te = 200 ev). LANL values see ref. [15].

FIG. 4 - Regions of interest in MF (magnetic confinement), IF (inertial confinement) and HI - CO₂ (our proposal: heavy ion interaction with a CO₂ laser created plasma).
In comparison with the cold material case, where many experimental data exist, other effects have to be taken into account in ionized targets; the energy losses on free-electrons will contribute significantly to the total energy losses and Figure 5 [13] shows an example of the range shortening due to the free electron contribution. Figure 6a [13] shows that the exit energy of a 50 MeV Xe beam travelling through a laser created plasma is strongly dependant, in some parameter ranges, on the electron temperature. On the other hand this exit energy is also sensitive to the hypothesis made on the behaviour of the beam charge state equilibrium evolution during the slowing down (see figure 6b [13]). Indeed, in an ionized plasma, the recombination time:

$$\tau_R = \frac{1}{n_e \alpha_n} (Te)$$

$$(\alpha_n^{n+1}$$ being the recombination rate) may be longer than the slowing down time.

\[\text{FIG.5} \quad \text{Range shortening of a 1 GeV Xe beam in an Au target as a function of the electron temperature.}\]
Fig. 6a - Exit energy of a 50 MeV Xe beam travelling through a laser created plasma as a function of the electron temperature for two ionization models.

Fig. 6b - Exit energy of 50 MeV Xe beam travelling through a gold target as a function of the electron temperature. The corona model is assumed and two hypothesis have been done on the beam charge state evolution: with and without recombination.
This slowing down time is calculated on the free electron part only, in the case where \( \zeta = \frac{v_b}{v_{th}} < 1; E_c \) is the critical energy for which the energy transferred to the electrons equals the energy transferred to the ions. Taking into account the bound electron contribution, the actual slowing down time is even smaller. Therefore, if \( \tau_R > \tau_{sl} \) the empirical formula (1) giving the mean equilibrium charge state of the beam is no longer valuable and this will significantly changes the beam energy deposition profile which play an important role on the overall pellet calculations.

Figures 7 (from [9]) and 8 (from [13]) give examples of the effect of the plasma temperature on the beam energy deposition profiles. In a hot target, the Bragg peak becomes apparent.

FIG. 7 – From Ref. [9]. Energy deposition profiles in cold and hot targets.
II-3-The plasma ionization model

A lot of works are concerned with the plasma ionization models in MF and IF (see for example [7]); if the beam charge state evolution and the slowing down processes were well understood, one should be able to bring some experimental data on the plasma charge state since the beam exit parameters (energy, scattering angle) are $Z_p$ dependent. By using different target materials, one can explore different plasma conditions as it is shown on Figure 9 (from reference [7]) where we have indicated the accessible region in our case.
FIG. 9 — (from Ref. [7]). Density regions defined by the ion coupling parameter \( \Gamma \) for different target materials. The accessible region with our experiment is indicated.

III - BEAM AND PLASMA CHARACTERISTICS

The main difficulty of this experiment comes from the fact that the plasma is pulsed and, to obtain good measurements, we need to extract the beam and plasma data in one pulse. As we want to measure the charge distribution and the energy loss simultaneously, the beam emittance has to be small; typically the bunched beam should have a pulse duration of 5-10 nsec with a number of particles in the bunch in the range of \( 2 - 5 \times 10^3 \). The beam diameter should be of the order of 1 mm and the beam divergence should not exceed 1.5 mrad. Tests have been done on our tandem facility with a C-beam and we have obtained bunched beams of \( 4 \times 10^3 \) particles with the right emittance.

During the beam pulse duration, the plasma should be quasi-homogeneous and quasi-stationary; on the other hand, the line density \( n_e \) and the electron temperature have to be such that energy loss on free electrons should be measurable and at least of the same order as the energy loss on bound electrons (see formula 3). The line density should not be too large to limit the Coulomb scattering at a maximum value of the order of the beam divergence (see formula 5). Therefore the plasma temperature should be in the 100 - 300 eV range and the line density in the \( 1 - 5 \times 10^{18} \) cm\(^{-2}\) range. Table I gives the energy loss on the free electron part only, for different projectiles, assuming a line density of \( 2.5 \times 10^{18} \) cm\(^{-2}\) and a beam kinetic energy of 30 MeV.
This shows clearly the interest of using heavy ions; by reducing the kinetic energy, for intermediate mass ions, the energy loss will be significantly increased since \( \Delta E \propto \frac{1}{E} \).

These plasma characteristics are obtainable by using a CO\(_2\) laser. The plasma energy \( \frac{3}{2} n kT x \omega \) is of the order of 10 J, then the laser energy has to be in the 100 - 200 J range to create the needed plasma. To minimize the runaway particle production, we will work at a low power level (a few 10\(^{10}\) W/cm\(^2\)). Figures 10,11 give some examples of plasma characteristics calculated by using a 1 D - Lagrangian hydrodynamical code [17]. If the beam travels through the plasma at a chord of 7 - 10 mm, the plasma will have the needed characteristics.

### IV - EXPERIMENTAL SET UP AND DIAGNOSTICS

Figures 12,13 give schematic views of the experimental set up and of the interaction chamber. The heavy ion beam produced by an HICONEX source is accelerated by a 7 MV tandem accelerator; the beam will be bunched and focused on the plasma target.

To produce the plasma target we will reuse an old CO\(_2\) TEA laser [18] which will be adapted to our purpose. The pilot has to be optimized in another way than it was done before in the M1 - M3 configurations [18]; indeed, due to the large jitter of the laser pulse (of the order of 100 ns) we will start with a long pulse duration (>> 100 ns) of the oscillator pilot by modifying the gas mixture conditions (He, CO\(_2\), N\(_2\)).

After amplification, the pilot pulse is truncated by using two A\(_S\) G\(_A\) cells fired by the particle beam itself through a pick up system delivering a timing signal at the right time. The 50 ns (FWHM) laser pulse is then amplified by 3 \( \varnothing 45 \) mm amplifiers and 2 \( \times 2 \varnothing 70 \) mm amplifiers.

To maximize the output energy we will use a mirror in the pilot instead of a grating to use all the wavelengths and we will arrange the amplifiers in two arms (Figure 14), in such a way one should obtain of the order of 100 J per beam. In the M1 configuration [18], without the \( \varnothing 70 \) mm amplifiers,
50 J was obtained in 50 ns and Figure 15 shows typical evolutions of the plasma interferograms.

Figures 16, 17 show views of the interaction chamber and of the particle spectrometer which will be built to analyse the energy and the charge state distribution of the beam. We will use a Thomson parabola spectrometer and Fig. 18 shows traces of an actual beam for different charge states and 4 energies 50, 45, 40 and 35 MeV.

**FIG. 10** - Density and temperature profiles calculated by a 1 D. Lagrangian code. Al target; CO₂ laser: 10¹⁰ W cm⁻².
target AL

FIG. 11 - Line density of a CO$_2$ laser created plasma. Al target. 50 J, $10^{10}$ W/cm$^2$ and 200 J, $2.10^{10}$ W/cm$^2$.

FIG. 12 - Schematic arrangement of the experimental set up.
FIG. 13 - Schematic view of the interaction chamber.

FIG. 14 - The CO$_2$ laser configuration.
FIG. 15 - Interferograms obtained with a 33 J, 50 ns CO₂ laser.
FIG. 16 - Elevation view of the interaction chamber and of the X-ray and particle spectrometers
FIG. 17 - Plan view of the interaction chamber and of the X-ray and particle spectrometers.
In the detection plane, one should observe an energy decrease, a beam scattering and a charge state distribution. We want to develop a detection imaging system consisting of microchannel plates coupled to a scintillator, an optical lens and a multidiode camera.

A JOHANN X-ray crystal spectrometer shown on Figures 16, 17 is under development; for the detector we will use a 1024 diode array. The intensity ratios of heliumoid and hydrogenoid lines will give the electron temperature[19]. The electron temperature will also be measured through the X-ray flux emission by using the absorption method.

The time density evolution and isodensity curves will be analyzed by using a JAMIN interferometer at 1.06 and 0.53 μm as shown on Figure 19.

V - CONCLUSIONS

As a conclusion we just want to specify the planning of the experiment. We have started with the reassembling of the laser and the beam line is under construction. We hope to active the laser during the summer and to test the overall set up at the end of this year.
FIG. 19 - Interferometry and shadowgraphy by using a 1.06 and 0.53 μm laser.

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M. Cukier, C. Deutsch, M. Pouey, Laboratoire de Physique des gaz et des Plasmas, Bât 212 - 91405 ORSAY.