DETERMINATION OF PROTON STOPPING POWER IN HOT PLASMA AT KALIF

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Résumé - Les premières expériences de ralentissement de faisceaux de protons issus d'une diode réflex à pincement (facilités KALIK au KFK, Karlsruhe) ont été effectuées et comparées aux prévisions théoriques. L'énergie maximum des protons vaut 1,5 MeV. La densité crête de puissance sur la cible est située entre 0,15 et 0,3 TW/cm ^{2} . On observe une augmentation d'un facteur 2,6 pour le ralentissement des protons dans le plasma produit, ramené à son équivalent en cible froide. Ces résultats sont analysés à l'aide du code cible KATACO. On observe un bon accord entre les mesures et les prévisions théoriques. La température du plasma produit dans la cible est estimée à 25 eV.

Abstract - First stopping power experiments with proton beam from a pinch reflex diode at the Karlsruhe Light Ion Facility - KALIF - have been performed and compared with the results of theoretical predictions. The maximum proton energy in these experiments is 1.5 MeV. The peak power density on the target is between 0.15 to 0.3 TW/sq.cm. An enhancement of proton stopping power up to a factor of 2.6 is observed. These results are analysed with the target code KATACO. There is a good agreement between theoretical prediction and experimental results. The analysis shows that plasma temperatures of about 25 eV are achieved at KALIF.

1. INTRODUCTION

The feasibility of the ion beam driven inertial fusion as an alternative to the magnetically confined or laser driven fusion [1-3] has initiated research in different aspects of generation, propagation and coupling of ion beam energy to the target. The coupling of ion beam i.e its stopping power in the cold target is a long standing field of research. However during irradiation with intense ion beams the target gets heated and becomes partially or even fully ionised. Change in temperature density and degree of ionisation of the target plasma can drastically modify its stopping power and the range of beam particles. The range of the ion has to be known accurately to guarantee an efficient working of the target design. In fact not only the range but also the stopping power profiles during different phases of beam irradiation need to be known. In recent years a number of theoretical and experimental work is underway to study ion beam stopping phenomena in plasma. Charged particles, light ions[4,5] as well as heavy ions[6,7], have recently been used to measure the enhancement of stopping power in plasma. In both cases the particle energy is about 1.5 MeV/amu. In the case of heavy ions, since, till date no intense beam is available, the plasma has to be created by an external source. Light ion beams, such as at KALIF, are intense enough to create their own plasma starting from the cold solid target. Thus if the stopping power can be measured throughout the whole length of the pulse situations typical of the ablation plasma in an ICF target can be simulated. In an earlier publication [8], we have analysed at what plasma conditions a dE/dX experiment can be performed at the Karlsruhe Light Ion Facility KALIF. It was concluded that plasma temperatures around 20 eV can be achieved with the presently available proton beam using pinch reflex diodes. The temperature profiles are expected to be fairly uniform. Density profiles in a thin target are of gaussian type.

In previous experiments to investigate the stopping power for light ions i.e. proton or deuterons intense ion beams similar to that of KALIF have been used. The very first experiment was performed at NRL [4]. In this experiment the Gamble I I generator with pinch-reflex diode was used. The target was sandwiched between two deuterated plastic foils. The energy of deuteron beam entering and leaving the target was inferred from the peak energy of neutrons from the d(d,n)p reactions. The neutron energy was measured using a neutron time-of-flight spectrometer. In each experiment only one data point could be measured. In the published data there is no indication of plasma parameters. However this experiment provided a first indication of enhanced energy loss in plasma. The second and more elaborate experiment [5] was performed with PROTO-I using a barrel shaped applied B diode. The experimental setup allowed the determination of the beam energy loss in the target only in the latter part of the beam pulse. In the present experiment the measurement could be extended throughout the whole duration of the pulse. An enhancement of stopping power for protons in aluminum plasma by a factor

of 2.6 is observed. The layout of the remaining portion of this contribution is as follows; In the next section the basic theory of the energy deposition of charged particles in plasma is briefly underlined. This follows with a sketch of the experiment. In section 4 the data is analysed and discussed. The paper closes with some concluding remarks in section 5.

2. THEORY OF ENERGY DEPOSITION OF CHARGED PARTICLES IN PLASMA

The energy loss of fast charged particles in cold matter is a vastly studied subject. There is a series of compilation of experimental data and theoretical fits to them. The latest compilation of the stopping and ranges of ions in solid is published by Ziegler, Biersack and Littmark [9]. The slowing down of fast ions in cold matter predominantly occurs by the way of ionisation and excitation of atomic electrons. This is given by the well known Bethe's formula:

$$\frac{dE}{dX} = \frac{4\pi Z_{eff}^2 e^4}{m_e v^2} \; NZ \left[\ln \frac{2m_e v^2}{I} \; - \beta^2 - \sum_i \frac{C_i}{Z} - \frac{\delta}{2} \right] \qquad [1]$$

Z_{eff} is the effective charge of the fast particle, v is its velocity, $\beta = v/c$; Z and N are the charge number and the number density of the field particles. C_i and δ are the correction terms due to shell effect and polarisation. Note that instead of particle charge its effective charge is used as during the passage through the matter it may capture or loose electron [10-12]. The other important parameter in the above formula is the effective mean ionisation energy I.

In plasma in addition to the excitation and ionisation mechanisms there is always a number of free electrons. These electron contribute to the slowing down of fast particles by the way of two body collisions or collective polarisation effects. There is a fair amount of theoretical work for energy deposition of fast ions in plasma [8,13-23]. The common feature of these studies is that both bound and free electrons are treated separately. They differ however in the way I is calculated and the way free electrons are treated. There is also some loss of energy due to plasma ions. But at medium and high energies this contribution is negligibly small. In its general form stopping power of fast ions in a plasma can be written as:

$$\left[\frac{dE}{dX} \right]_{plasma} = \left[\frac{dE}{dX} \right]_{bound} + \left[\frac{dE}{dX} \right]_{free} + \left[\frac{dE}{dX} \right]_{ion} \qquad [2]$$

For the present work we confine ourselves to the calculation of the contribution due to the first two terms. To calculate contributions of bound and free electrons separately the degree of ionisation Z* has to be calculated. This is done by the hydrodynamics code using the Thomas-Fermi theory. To calculate the contribution of bound electron Eq.(1) is used with the difference that now Z has to be replaced by Z - Z* i.e. the number of bound electrons and that Bethe's I has to be calculated for the appropriate ion instead of the neutral atom.

2a. Bethe's I

At KfK the code GORGON[24] has been used to calculate energy loss of fast ions in plasma. This code is based on the work of Nardy & Zinamon [13]. To calculate I Bohr's model in conjunction with Thoms-Fermi statistics is used. For each frequency the integration is stopped at a radius at which the equivalent energy will correspond to a free electron. Orbits with velocities larger than the beam particle velocity are excluded from the integral. I values thus obtained are temperature dependent and give fairly good results at high temperatures. McGuire et al.[25] have calculated I values for aluminum isolated atom for different degrees of ionisation and have compared their results with available ionisation cross sections. Garbet et al.[18] have used variational approach to calculate I values and have given an analytical formula.

2b: Calculation of contribution due to free electrons

The contribution of the free electrons to ion slowing down can either be calculated by using plasma dielectric theory [26] or treating it as collisions between charge particles[27]. In the region of interest both theories give similar results[8]. The first method is used in the code GORGON. We use, because of its simplicity the second approach. In this approach the contribution of the free electrons in the plasma is given by:

$$\left[\frac{dE}{dX} \right]_{free} = \frac{Z_{eff}^2 e^4}{v^2} \, \omega_p^2 G\left(\frac{v_\theta}{v} \right) \ln\left(\frac{0.764v}{\omega_p b_{min}} \right) \qquad [3]$$

with

$$G(x) = erf(x) - x erf'(x)$$

here ω_p is the plasma frequency, v_θ is the mean thermal velocity of electrons. A Maxwellian velocity distribution is assumed. The factor $G(v_\theta/v)$ is a consequence of the averaging over Maxwell distribution. b_{min} is the minimum impact parameter. This lower limit can be calculated either by quantum mechanical or the classical consideration. Usually the larger of the two values is taken. Basko[16] suggests a use of mean square root of the two values.

3.Experimental setup

The experiment was performed at the Karlsruhe Light Ion Facility - KALIF using a tent shaped pinch reflex diode[28]. The beam parameters are given in Table I. For a complete measurement of the energy loss in plasma one must know the particle energy while it enters and leave the target. Since the particle beam is intense and generates plasma from a target of known thickness one needs to know the temperature and density of the plasma as a function of time. These quantities depend on the incident beam power. The experimental setup is shown in Figure 1.
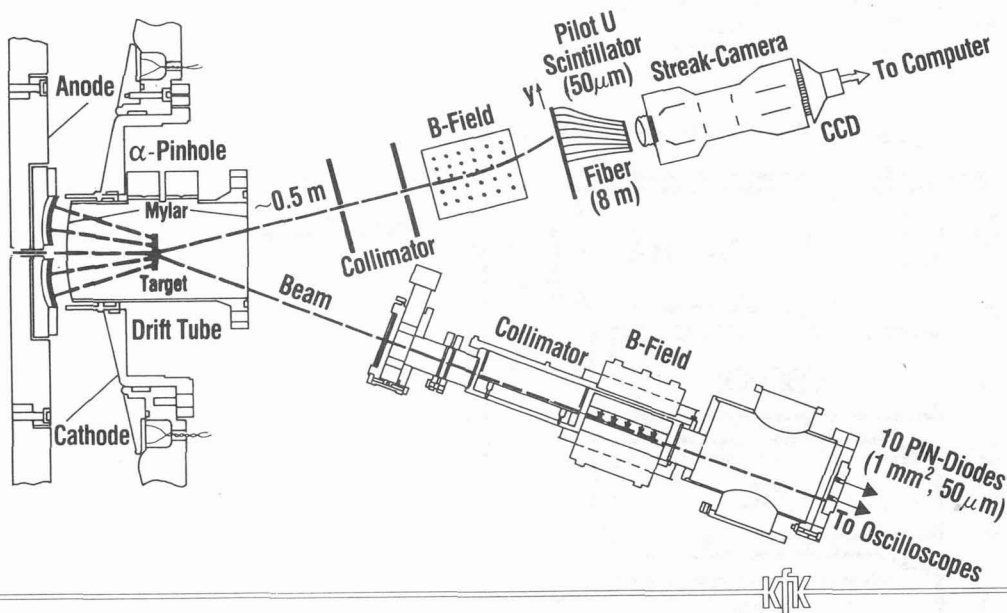

Figure 1.   Experimental setup.

It is seen that the space for the diagnostic is limited; not all the quantities can be measured simultaneously. The initial particle energy was correlated to the measured diode voltage in repeated experiments [29]. The particle energy determined with magnetic spectrometer without the target matched well with the derived diode voltage (Figure 2). The energy of the particles leaving the target was determined with magnetic spectrometer using pin-diodes or a NE 102A scintillator with a streak camera. The beam power fluctuated from one shot to another, however, some bounds to this quantity could be inferred from other measured signals of the machine. The temperature and density of the plasma was then inffered form the hydrodynamic analysis of the data keeping the beam power within the limits given by the neighbouring experiments.

Beam Composition	80% protons 20% carbon
Maximum proton energy	1.5 MeV
Peak power	0.3 TW/cm^2 = > 37.5 TW/g in Al
Pulse duration	50 ns
Focal length	4 - 5 cm
Angular spread	30°

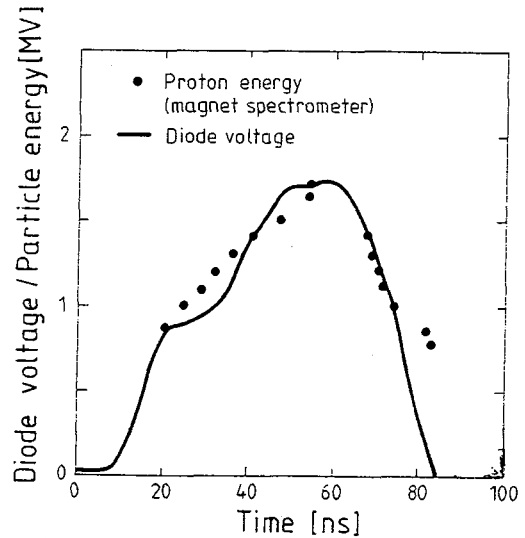Table 1.   Beam parameters at KALIF with PRD-diodes

Figure 2.   Verification of diode voltage as a measure of particle energy.

4. Analysis and results

The computer code used to make the hydrodynamics analysis of the experimental data is the KArlsruhe TArget COde KATACO. The hydrodynamics and numerical setup of the code is based on the code MEDUSA-KA [29,30,8]. It has been augumented with physics modules shown in Figure 3.
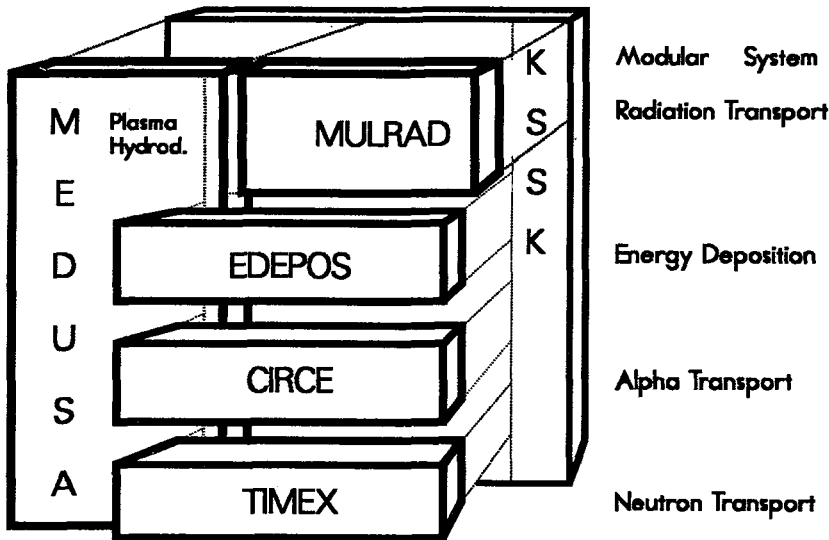

Figure 3.   The KArlsruhe TArget COde KATACO

Different transport and reaction coefficients in the hydrodynamics parts have also been updated. The details of the code will not be described here. For the calculation of beam ion coupling the formalism given in Sec. 2 is used. This formalism is very close to that used by Mehlhorn [15]. To calculate the contribution of the bound electron the effective mean ionisation energies given by McGuire et al.[25] for isolated ions are used. These are practically the same as calculated by Garbe and Deutsch [18]. The latter authors have also shown that below plasma temperatures of about 25 eV temperature and density effect on the value of I are small. The contribution of bound electrons is calculated using the Eq. (3). Figure 4. a comparison of the experimental results and cal-

culated data is shown. With an assumed beam power of 0.16 TW/sq. cm. The agreement between theory and experiment is pretty good.
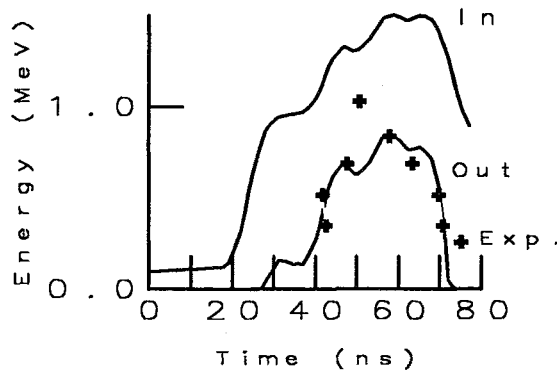
Figure 4. **Comparison of theoretical and experimental results.:** The experiment was performed at a 12.5 μm thick aluminum foil. The calculations are for a beam power density of 0.16 TW/sq.cm.

In Figure 5. the evolution of the midplane temperature and density of the target as calculated with the code KATACO are plotted. The beam characteristics used for these calculations, which are the same as used in the calculation for the Figure 4, are shown in Figure 6.
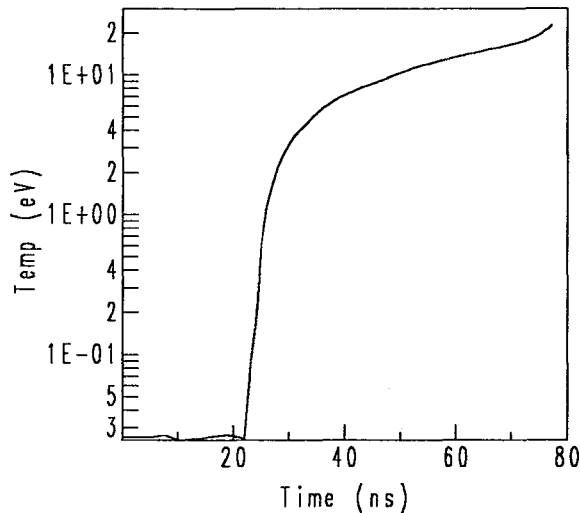
Figure 5. **Evolution of temperature at target midplane.**

It is seen that temperatures of almost 20 eV are achieved in this experiment. The dE/dX measurement in the experiment, however, terminates prior to reaching this temperature. The maximum temperature dE/dX can be measured is 15 eV as the particle energy has gone down to values whose range is below the thickness of the plasma. This is evident from the Figure 7.
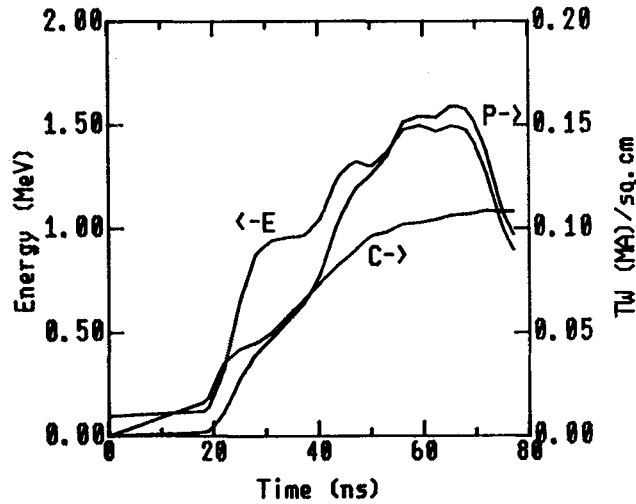
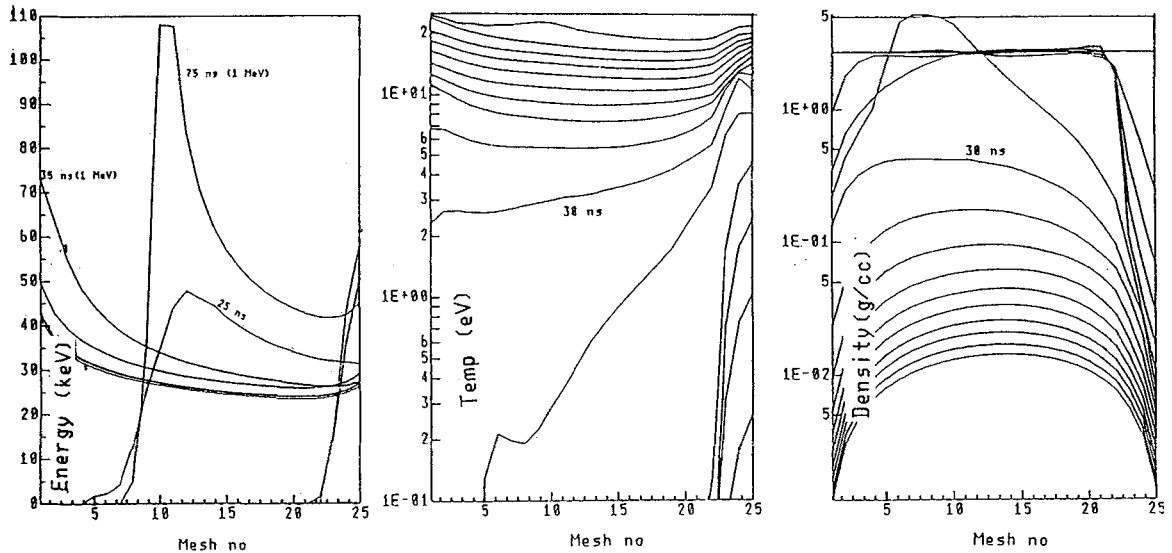**Figure 6.   Characteristics of proton beam as a function of time.**

Figure 7.   Behaviour of target during irradiation.:   Shown are (a) energy loss per proton per mesh of the target, (b) temperature and (c) denstity along the target at differnet times. Curve are drawn at 5 ns intervals starting with 5 ns.

At the start of the pulse the beam particle energy increases and the beam penetrates deeper in the target. At 30 ns the proton energy has reached a value of 1 MeV and its range is slightly above the target thickness. At 75 ns the proton energy has again fallen back to 1 MeV but at this time due to the enhancement of stopping power in the plasma the range shortening has taken place and the protons do not emerge out of the target to be detected in the magnetic spectrometer. Increasing penetration of the beam in the target in the beginning also causes a shock wave generation. This is the cause of the increase in the density at the starting phase of the pulse as seen in the density plot. The temperature profiles of the target in the region in which measurement is conducted are fairly flat. The density of course shows a gaussian profile. Another experiment with a thinner aluminum foil has

also been analysed. Theoretical and experimental results are given in Figure 8. Again we find a reasonably good agreement in experiment and theory. In this figure we also show the change in proton energy due to the plastic foils bounding the drift tube. Temperatures reached in this experiment are in the range of 25 eV.
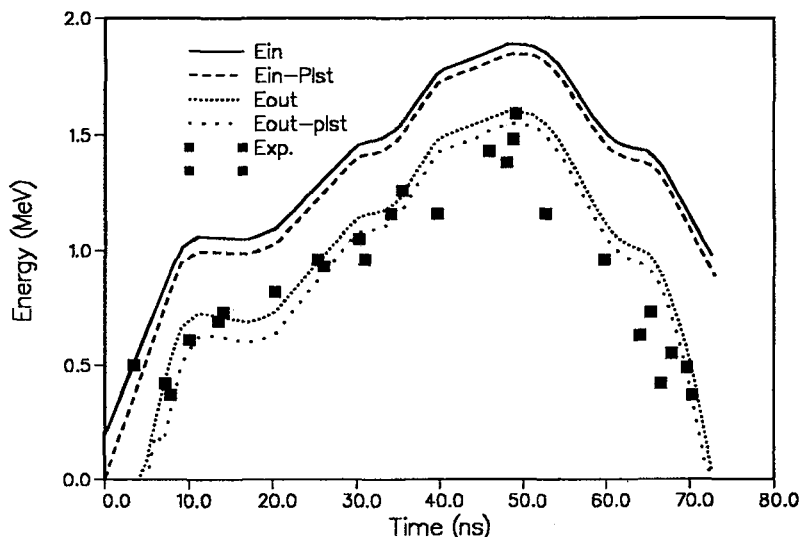
Figure 8. **Comparison of theoretical and experimental results.:** The experiment was performed at a 6.2 μm thick aluminum foil. The calculations are for a beam power density of 0.2 TW/sq.cm. Also shown is change in beam energy due to the plastic foils bounding the drift tube.

The range lengthening at moderate densities and low temperatures as predicted recently by Long and Tahir[20] and Basko [16] is not seen. Long's predictions are based on the results of the code GORGON. It is known that degeneracy treatment is not complete and the range lengthening at solid density has resulted due to the wrong treatment of partial degeneracy region. In case of Basko may be the interpolation scheme in this region is not adequate.

5. Concluding remarks

In summary we remark that the present experiments at KALIF have shown the feasibility of measuring the stopping power of light ions in plasma situation typical of ICF target i.e. starting with the cold target the measurement continues in the heated and ablated plasma. The plasma temperatures reached in these experiments are of the order of 20 eV. It is recognised that we have yet to improve the diagnostics of the experiment to the effect that it is possible to do more simultaneous diagnostic. On the theoretical side, we have just analysed experiments on one material i.e. aluminum for which good values for effective mean ionisation potential are available. Goeing to other materials may improve the insight to the involved processes. Nevertheless these experiments have shown one important result. Namely the range lengthening at moderate densities and low temperatures is not seen.

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