INHIBITION IN THE PROPAGATION OF FAST ELECTRONS IN PLASTIC FOAMS BY RESISTIVE ELECTRIC FIELDS

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Introduction

Electric effects may cause a reduction of the range of fast electrons as compared to what is predicted taking into account collisional effects only. These arise from the electric field $E$ generated by charge separation and by inductive effects, as the fast electrons propagate into the target. These electrons carry a current density $J_{\text{hot}}$ of magnitude which can be as large as $10^{12}$ A/cm². The electric field $E$ depends on the conductivity $\sigma$ of the target material, $EJ_{\text{hot}}/\sigma$, because a return current balancing the current of fast electron must be set up to maintain quasi-neutrality (i.e. $J_{\text{hot}}J_{\text{return}}$) and allow propagation [1]. A significant inhibition is thus expected, and was evidenced, first of all in targets with low electrical conductivity [2,3]. An even larger inhibition is however expected in low density materials (foams).

An important aspect is that, as resistivity and inhibition increases, at the same time collisional effects, described for example in terms of stopping power [4], are in first approximation only sensitive to the total areal density of the material crossed by the fast electrons. This means that the collisional penetration range of fast electrons, $l_{\text{col}}$, scales as $l_{\text{col}} \sim \rho l_o/\rho_o$, where $\rho_o$, $\rho$ and $l_o$ are respectively the standard density of the material, the density of the material in foam state and the collisional penetration range in the material at standard density.

As a result of the different dependence of the two effects (electric and collisional), when the density is decreased the collisional range will become much larger than the electric range which in first approximation can be determined using Bell's formula [1]

$$l_{\text{el}} \ (\mu\text{m}) \sim 3 \times 10^{-3} \sigma_{\text{foam}} (T_{\text{hot}})^2 / \eta \ I_L$$

(1)

where $T_{\text{hot}}$ (keV), $\eta$ and $I_L$ are the fast electron temperature, conversion efficiency in fast electrons, laser intensity and conductivity (in units of $10^{17}$ W/cm² and $10^6$ (Ω cm)$^{-1}$).

Experimental set-up
We carried out the experiment using the LULI TW laser chain delivering pulses with $\lambda = 534$ nm, duration 350 fs and an on-target irradiance of the order of $2 \times 10^{19}$ W/cm$^2$.

We used multilayered targets and K-\(\alpha\) emission spectroscopy as the main diagnostic for the propagation of electrons. The laser beam interacts with a first layer of 1.5 \(\mu\)m Al, where the fast electrons are generated and accelerated. It is essential in our experiment because it allows the effects of propagation to be separated by those of fast electron production (i.e. the electron source is the same irrespective of the foam density). Also it allows to use the experimental values of $T_{\text{hot}}$ and $\eta$ obtained in [3] for Al targets.

After this first layer there is the foam where fast electrons penetrate before reaching two fluors layers (20 \(\mu\)m of Mo and 20 \(\mu\)m of Pd) where they cause impact ionisation followed by K-\(\alpha\) X-ray photon emission. Finally there is a layer of 50 \(\mu\)m of polyethylene to shield the Pd layer and avoid any spurious emission due to the electrons reaching the Pd layer after crossing the target rear side (and pulled back by electric fields) or due to the electrons going around the target. To detect the K-\(\alpha\) X-rays, we used a $1024 \times 256$ pixels CCD camera.

The foam layers were realised at Dundee University [5]. The monomer was TMPTA ($C_{15}H_{20}O_6$). We have chosen two different foam densities (0.025 and 0.1 g/cm$^3$) and the corresponding thickness ($d = 0.2$ and 0.05 cm) so to have the same areal density: 0.005 g/cm$^3$, which is also the areal density chosen for the layer of solid plastic (which has a density $\rho_o = 0.96$ g/cm$^3$ and a thickness $d = 50$ \(\mu\)m). This is important because, as said before, collisional effects are proportional to areal density of the target. Hence, differences between various target densities will be due to different field effects only.

**Results and discussion**

Fig. 1 shows the experimental K-\(\alpha\) yield obtained in typical shots vs. foam density

![Graph](image1.png)

Fig. 1: K-\(\alpha\) yield from Mo (black circles) and Pd (white circles) vs. target density in mg/cm$^3$.

Since the areal density is the same for all targets, the reduction of K-\(\alpha\) yield gives the experimental evidence of inhibition of fast electron penetration, with respect to collisional penetration, and obviously points out that we are in a regime of electric dominated transport.
Ref. [3] shows that the K-α yield from 500 keV electrons in plastic, obtained in exactly the same conditions of the present experiment, follows an exponential law, i.e. \( K(d) = K_0 \exp(-d/R_0) \), where \( d \) is the propagation layer thickness, \( R_0 \) is the penetration range and \( K(d) \) is the experimental yield. We also estimated that \( R_0 = 180 \pm 30 \) µm in plastic. Since in our case the constant \( K_0 \) is the same for all targets thanks to the presence of the Al layer, we can write that the K-α yield from a target with density \( \rho \) and thickness \( d \) is

\[
K(d, \rho) = K_0 \exp\left(-\frac{d}{R(\rho)}\right) = K_0 \exp\left[-\frac{m}{\rho R(\rho)}\right]
\]

Here \( R(\rho) \) is the penetration range in a foam target. By comparing the K-α yield from plastic and foam targets, and since the penetration range \( R_0 \) in normal density plastic is known, we can obtain the penetration \( R(\rho) \) in a foam target. The values we get from our experimental results are shown in Fig. 2 and scale approximately as \( \rho^{-0.5} \).

![Fig. 2: Calculated penetration range \( R(\rho) \) in \( \mu \text{m} \) vs. target density in g/cm\(^3\).](image)

A said before, we can neglect the collisional contribution and therefore tentatively identify the experimental values in Fig. 2 with the electric penetration range \( l_{el} \) given by Bell.

In our case, the changes in \( R(\rho) \) are only due to changes in conductivity \( \sigma \). The data in Fig. 1 and Fig. 2 shows that electric inhibition becomes stronger at lower densities as can be seen by observing that the ratio \( l_{col}/l_{el} \) scales as \( \rho^{1.5} \). Nevertheless \( l_{el} \), and hence conductivity, is bigger for lower density foams, which may appear in contradiction with the expectation that at lower densities there are less electrons in the material available for the return current. In reality the situation is more complicated than this: in order to calculate \( \sigma \) we must calculate the temperature \( T \) (and ionisation degree \( Z^* \)) in the background material. This will scale as

\[
T \propto A E_{\text{hot}} / (p r^2 \rho R(\rho) Z^* N_A)
\]

where \( A \) and \( N_A \) are the average atomic weight and Avogadro's number, \( E_{\text{hot}} \) is the energy in the fast electron beam (= \( \eta E_L \)), and \( r \) the actual electron spot radius (of the order of the laser focal spot radius). In practice the volume where the fast electron energy is deposited is \( (p r^2 R(\rho)) \), and the quantity \( (p r^2 \rho R(\rho) Z^* N_A / A) \) is the number of free electrons in such a volume. The assumption of a cylindrical volume is not unrealistic due to the beaming
effects induced by strong self-generated magnetic fields which are predicted to play a major role in fast electron propagation [6]. By using the typical parameters of our experiment, we can evaluate temperatures between 200 eV, in the case of normal density plastic, and 1500 eV in the case of more tenuous foams. The increase in temperature when $\rho$ is decreased is not only a consequence of eq. (2) but is already implied by our experimental results the reduction of K-\(\alpha\) yield, reduction of penetration range, when target density is decreased.

The important point is now that at such high temperatures, the conductivity of all materials is expected to follow a Spitzer-like behaviour, according to which [7]

$$\sigma (\Omega \text{ cm})^{-1} = \frac{97.09 T^{3/2}}{(Z* \ln \Lambda)}$$  \hspace{1cm} (3)

where $T$ is in eV and $(\ln \Lambda)$ is the Coulomb logarithm. Moreover we can expect the ionisation to be almost complete. Hence the conductivity becomes independent (explicitly) on the density $\rho$, and is dependent on temperature $T$ only (which however depends on density). By coupling eqs. (1), (2) and (3), and recalling that we have identified $l_{el}$ and $R(\rho)$, we derive

$$l_{el} \propto \sigma_{foam} \left( \frac{97.09 T^{3/2}}{(Z* \ln \Lambda)} \right) \propto [ (\rho R(\rho))^{-1}]^{3/2}$$

which finally implies a scaling $R(\rho) \propto \rho^{-3/5} = \rho^{-0.6}$. The fact that experimentally we have found $R(\rho) \propto \rho^{-0.5}$ must certainly be considered a result in very good agreement, seen all the approximations used in our simple heuristic model. Let's notice that not only the scaling is approximately correct, but also the absolute numbers, i.e. if we use the values of temperature and conductivity calculated from eq. (2) and (3) and we insert them in Bell's formula, we get a penetration which is close to the experimental result. Moreover, completely different scaling laws are obtained if we assume a semi-classical behaviour of resistivity ($\sigma \propto \rho^{2/3} T^{-1/2}$) or a semi-spherical propagation of fast electrons (as appropriate to a strongly collisional case).

In conclusion we have shown how the use of low density foams is a suitable experimental technique to maximise the inhibition of fast electron penetration in matter and we have developed a simple model and derived a theoretical scaling for the penetration range vs. target density (which is valid in the Spitzer limit).

References