Effects of target Z in ultra-high intensity laser solid interactions

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Introduction

Ultra-high intensity laser pulses ($I\lambda^2 > 10^{18}$Wcm$^{-2}\mu^2$) incident on solid targets generate enormous currents of relativistic electrons. The transport of these laser generated relativistic electrons in solid density plasmas is important in Fast Ignition for ICF and in determining the details of proton and ion emission from solid targets which have a potentially valuable application in medicine.

Low current beams of relativistic electrons, where the beam electrons essentially behave as isolated particles, lose energy due to interaction with bound and free electrons in the solid and also scatter in angle, predominantly due to screened Coulomb collisions with the nuclear charge Ze. High current beams behave very differently [1] because their self generated electric and magnetic fields can dominate the transport and energy loss. Since the electric field E is determined largely by the Ohm's Law $E = \eta j$ the target atomic number Z influences the beam transport through the Z dependence of resistivity.

These high current beams hugely exceed the Alfvén current and must be very largely compensated by a return current in the background 'thermal' plasma. The combination of forward and return currents is unstable to a variety of plasma modes, often loosely referred to as 'Weibel instabilities'. Gremillet *et al.* [2], Silva *et al.* [3] and others have analysed the full dispersion relation for these modes including the electro-static and electro-magnetic contributions and Short and Myatt [4] have shown the connection of the collisionless and collisional modes through a generalised impedance (inductive for the collisionless electromagnetic branch and resistive for the collisional branch).

PIC simulations of the transport of a high current beam through a background plasma (Honda and Meyer-ter-Vehn [5]) show a vigorous instability accompanied by an extremely large, 10^3 - 10^4 enhancement of the classical collisional stopping of the electron beam. All of these beam instabilities are driven by the free energy of the electron beam and have characteristic growth rates on the order of the plasma frequency of the beam species.

Observed Z dependence of electron beam transport

Measurement of the bulk heating produced by the intense laser pulse on time scales of 10^{-12} sec is difficult and often relies on spectroscopic measurement of temperature from the line emission spectrum of mid-Z materials with a low-Z tamper layer, frequently CH, to hinder the target expansion while allowing the escape of the X-rays from the tracer layer.

In the context of Fast Ignition or High Energy Density plasma physics the interest is in creating material in the temperature range 100eV - 10keV whereas many experiments on K-α spectroscopy measure 'dilute' electron transport far from the source where the beam density has fallen by orders of magnitude compared with its value near the focal spot of the laser. Attempts to produce hot high density material [6,7] have shown that transport of the high density electron beam through low Z material (CH plastic) is very much less efficient than through similar amounts of mid Z material such as Al. Chen, Gregori *et al.* [7] showed conclusively that a front coating of 2µ of CH suppressed the Ti He-α emission from the bulk target whereas 1µ of Al gave bright He-α emission when all other conditions including laser pre-pulse were identical. Attempts to model these experiments [6,8] with sophisticated implicit PIC methods that include the Z dependence of resistivity and specific heat conclude that there is an additional inhibition in the CH targets.

Suppression of Weibel instability in higher Z targets

The PIC simulations of 'Weibel' instability and most of the analytic calculations do not include the effect of angular scattering of the beam electrons from the background plasma. At solid densities this scattering rate can be appreciable and increases strongly with nuclear charge Z. Davies *et al.* [9] in their consideration of the transport of high current relativistic electron beams use the result derived from the relativistic Fokker Planck equation:

$$\left\langle \Delta\theta^2 \right\rangle = \left(\frac{Z^2 n e^4}{2\pi\varepsilon_0^2} \frac{\gamma m}{p^3} \ln\Lambda \right) t = \nu_\perp t$$

This shows that an electron beam initially with no transverse velocity spread will acquire a transverse temperature that in moderate Z plasmas increases approximately linearly with time since the angular scattering is faster than the slowing down of the beam. If the initial beam is relativistic and $\beta_\perp$ is the transverse velocity normalised to the speed of light then Silva *et al.* [3] have shown that the transverse filamentation instability observed in the simulations of Honda and Meyer-ter-Vehn [5] is stabilised by a relatively small transverse temperature in the electron beam. They show that for a beam with a longitudinal velocity $\beta_{//}$ and a transverse velocity $\beta_\perp$ the instability threshold is $\alpha > \gamma \frac{\beta_\perp^2}{\beta_{//}^2}$ where γ is the Lorentz factor for the beam electrons and α is the ratio of the density of beam electrons to the density of background electrons. The density of the beam electrons at their source is given by $f_{abs}\, a_0 n_c$ (Evans HEDP 2006) [8] where f_{abs} is the absorption fraction, a_0 is the normalised vector potential of the laser and n_c is the usual value for the critical density. For a laser irradiance around 10^{19}Wcm^{-2} the beam density is around 10^{21}cm^{-3}.

The importance of the angular scattering is that in moderate Z materials it is large enough that within one growth time for the filamentation instability the electron beam can acquire through collisions a transverse temperature that is large enough to stabilise the filamentation. From the above equations the condition for stabilisation can be written $\frac{\gamma \nu_{\perp} \tau}{\alpha \beta_{//}^2} > 1$

where τ is the instability growth time $\tau \sim \omega_{pb}^{-1}$

If we evaluate this for the case of CH (Z~3, $n_i=10^{23}$ cm^{-3}) and Aluminium (Z=13, n_i =6 10^{22} cm^{-3}), taking a beam of 1 MeV electrons and assuming the logarithmic term in the scattering function is of order 3 for a high density plasma then we find

Stabilisation Factor	CH	Al
$\frac{\gamma \nu_{\perp} \tau}{\alpha \beta_{//}^2}$	7.2 10^{-2}	1.9

In CH targets the filamentation instability can grow as in the PIC simulations whereas in Aluminium and higher Z targets the growth in transverse beam temperature due to scattering stabilises the filamentation and the stopping is dependent only on the classical collisions and the electric field. At the low density of the PIC simulations the enhanced stopping due to instability growth is large (times 10^3 - 10^4). At solid density a smaller relative increase is expected since the collisional stopping is much larger and an increase by a factor less than 10 would easily explain the experimental results of Chen [7].

Conclusion

Experiments show an anomalously low penetration of relativistic electron beams through thin layers of low Z materials such as CH. Since Fast Ignition specifically requires propagation of the heating beam in a plasma with Z = 1 and observation of X-rays from High Energy Density plasmas requires surface layers of low Z for low X-ray opacity it is clearly important to understand this effect and under what conditions the low penetration comes into play. Further experiments using a range of materials and pairs of insulating / conducting material with similar Z such as Al and SiO_2 or doped CH and Be would be of great benefit. Modelling of the Weibel instabilities including the effects of collisions would also be a valuable contribution.

References

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