*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-1.029 (2006)*

Kinetic Simulations of Proton Acceleration from Ultra-thin Foils

A.P.L.Robinson[1],P.Gibbon[2], M.Sherlock[1],P.Norreys[1],D.Neely[1]

[1] *Central Laser Facility, CCLRC Rutherford-Appleton Laboratory, UK*

[2] *John von Neumann Institute of Computing, ZAM, Forschungzentrum Julich, Germany*

Introduction:

The generation of multi-MeV proton beams via irradiation of solid targets by ultraintense lasers is a subject of great interest in the short pulse laser-plasma community. Pure scientific interest aside, this could find applications ranging from oncology to Fast Ignition ICF.

Although these laser accelerated proton beams have some properties that are superior to conventional accelerators, e.g. tiny transverse emittance, and shorter acceleration time, the energy spectra of beams are typically broad and Maxwellian. Nearly all applications require *control* of the energy spectrum, and many require an essentially monoenergetic spectrum.

In the past few years there has been a considerable amount of theoretical work on this problem. Furthermore this year has seen a number of reports on experiments showing the generation of ion beams with narrow-band features in the energy spectra, e.g. [6]. This has been extremely encouraging, especially since each experiment seemed to employ a different approach. However there are still a number of issues to resolve, particularly as regards the understanding and interpretation of these experiments.

In the body of work that we report here, we have focussed on microdot targets and their potential for generating quasimonoenergetic proton beams from ultra-thin targets. By ultra-thin we mean targets that are less than 1μm thick. The generation of enhanced proton beams from such foils has recently been demonstrated by Neely et al. [7] who used plasma mirrors to achieve a contrast ratio in excess of 10^{10}. The main purpose of this investigation is to determine the properties of the microdot which most strongly affect the features in the energy spectrum. In this paper we report on 3D kinetic simulations of microdot targets in which we have varied the ion composition of the microdot.

Theory:

Previous theoretical work [2, 1, 3] has shown that when protons are a minority species, i.e. their density is reduced below $n_{e,0}$ and replaced by heavier ions, that peaks should be formed in the energy spectrum. In qualititative terms this can be seen by noting that an electrostatic shock must form at the heavy ion front where the heavy ion density rapidly vanishes. When moving through this shock the protons, which, being a minority species, are a negligible electrostatic source term, experience a relatively slowly changing electric field structure. Any electric field structure that is relatively static will produce an accumulation in phase space, and thus mono-energetic spectral features. Beyond this ion front the proton can undergo a further expansion process, however. One can also show that the maximum energy that the protons can achieve must be reduced in the low proton density limit using simple analytical model.

Numerical investigations based on these analytical insights have essentially confirmed all of these predictions in 1D isothermal scenarios with Maxwellian electron reservoirs. The outstanding questions are therefore: (i)What are the effects of the fast electron population being non-Maxwellian, which may be important in the case of very thin targets? (ii)What about multi-dimensional effects,i.e. does this work as well in 2D and 3D? (iii)Are the spectral peaks produced by density reduction stronger, in general, than the value of $dn/d\varepsilon$ produced by a high proton density expansion?

In contrast to the above theory, a recent experiment on microdot targets has been interpretated as showing that a proton rich microdot should produce a narrow-band proton spectra [6]. The argument being that since the protons are spatially localised, that the protons should all move through the same potential structure and thus reach approximately the same energy. An explicit prediction of 1D expansion theory is that the proton energy is not equal to the electrostatic potential, as the electric field is not stationary. Fundamentally the reason why self-similar expansion theory is physically relevant is because of the proton space charge, and the 'microdot argument' neglects this. One can estimate the effect of space charge in 1D by integrating Gauss's law across a thin proton layer that has been moved away from the target surface. Let the proton layer have density n_p and thickness L, and we also assume that the fast electron density is constant across the layer and equal to n_f. The variation in the electric field across the layer is then given by $\Delta E_x = eL(n_p - n_f)/\varepsilon_0$. For a 10nm layer at $10^{29}\mathrm{m}^{-3}$ and fast electrons at a density close to the critical density, $10^{27}\mathrm{m}^{-3}$, one calculates that $\Delta E_x \approx 10^{13}\mathrm{Vm}^{-1}$. This is comparable to maximum value of the sheath field at intensities below $10^{23}\mathrm{Wcm}^{-2}$, so one generally expects high proton density targets to undergo expansion and produce broad energy spectra.

Clearly one cannot be absolutely certain about these theoretical arguments, and this motivated us to carry out a set of 3D kinetic simulations.

Simulations:

The numerical simulations were carried out using the PEPC code [5]. PEPC is a mesh-free particle code that directly solves for the Coulomb force between quasiparticles. This is feasible by using multipole expansions to reduce the computation time to $O(N \log N)$. The code is purely electrostatic with laser absorption incorporated via a ponderomotive model.

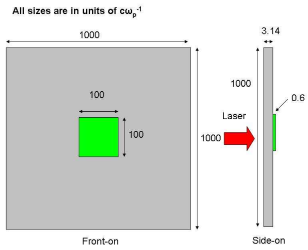

Figure 1: Target configuration in PEPC simulations.

The target was set up as shown in fig.1. In the standard run A, the microdot is actually set inside the target and the relative proton density is 4.7%. In runs B and C, the microdot is affixed to the outside of the target and the relative densities are 100% and 50% respectively. The foil density is $16n_{crit}$, and the laser model simulates a s-polarised beam at normal incidence with $a_0 = 2.7$, $\lambda = 800$nm, a 35fs duration and a FWHM spot radius of $150c\omega_p^{-1}$. The simulations were carried out up to $1000\omega_p^{-1}$.

We shall now summarise the key results of these simulations:

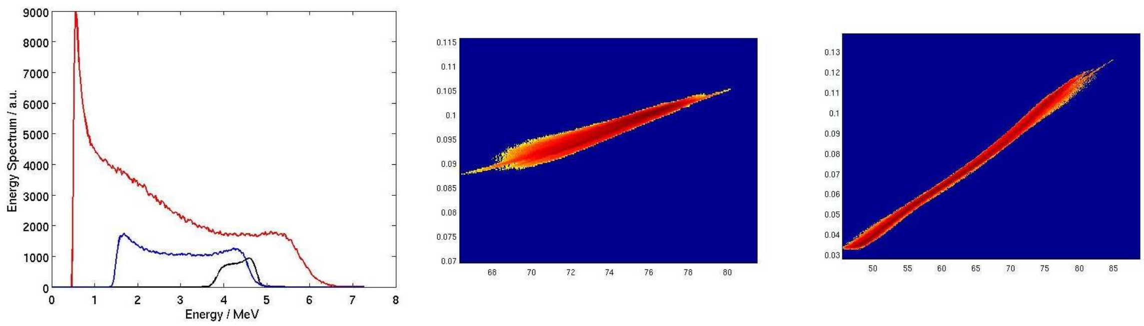

Figure 2: (Left)Proton energy spectrum of runs A(black),B(red), and C(blue) at $1000\omega_p^{-1}$. (Middle)Proton phase space in run A at $1000\omega_p^{-1}$. (Right) Proton phase space in run B at $1000\omega_p^{-1}$.

1. The width of the energy spectrum gets narrower as the relative proton density decreases. A pure proton microdot does not produce a narrow energy spectrum. See fig.2.
2. The maximum proton energy decreases with relative proton density, but the energy of any peak increases with decreasing relative proton density. See fig.2
3. Inspection of phase space shows a transition from expansion to test-particle like motion with decreasing relative proton density. See fig.2.
4. In all cases the two species become spatially separated so motion across the ion front is not important.

Conclusions:

We have found that an ideal proton microdot does not produce a monoenergetic spectrum at intensities $O(10^{19}\text{Wcm}^{-2})$. However on reducing the proton density the spectrum does get narrower, until a quasi-monoenergetic beam is produced. These simulations do not yet fully explain recent experimental results, but the small size of the microdot may explain this, since the species rapidly become separated in the case of such a small microdot. Nonetheless, these simulations do indicate that the 'microdot interpretation' is inadequate, and that microdot composition must be considered when understanding these experiments. Furthermore there is a suggestion that making progressively smaller microdots may not be the optimal strategy for improving beam quality.

References

[1] V.Yu.Bychenkov et al., Phys.Plasmas **11**, 3242 (2004)

[2] V.T.Tikhonchuk et al., Plasma.Phys.Control.Fusion **47**, B869 (2005)

[3] A.P.L.Robinson et al., Phys.Rev.Lett. **96**, 035005 (2006)

[4] P.Mora, Phys.Rev.Lett. **90**, 185002 (2003)

[5] P.Gibbon et al., Phys.Plasmas **11**, 4032 (2004)

[6] H.Schwoerer et al., Nature **439**, 441 (2006)

[7] D.Neely et al., Appl.Phys.Lett., in press (2006)