Radiation pressure acceleration with circularly polarized laser pulses

A. P. L. Robinson
Central Laser Facility, STFC, Rutherford Appleton Laboratory, Didcot, Chilton, OX11 0QX, UK

M. Zepf and S. Kar
Dept. of Physics and Astronomy, Queen's University Belfast, BT7 1NN, UK

R. G. Evans* and C. Bellei
Plasma Physics Group, Blackett Laboratory, Imperial College London, SW7 2BZ, UK

* RGE is also affiliated to the CLF.

Main contact email address **M.Zepf@qub.ac.uk**

Introduction

It has been known for many decades that if an object is accelerated by the radiation pressure of a laser beam then it is possible to reach extreme energies with very high conversion efficiency. In fact, in decades past, this has been the basis of proposals for instellar space flight[1]. Simple models show that one requires a laser system that delivers 10^7-10^8Jcm^{-2} in order to accelerate thin foils (<1μm) to MeV energies. Since the entire foil is accelerated this yields an intrinsically monoenergetic spectrum. However, it has been found experimentally that such foils are ablatively destroyed by "long pulse" lasers, and that TNSA dominates in the case of high intensity (>10^{18}Wcm^{-2}) lasers. Computational studies suggest that this regime can be accessed at intensities in excess of 10^{23}Wcm^{-2} [2], however this is currently not an accessible intensity range. Therefore, in order to access this regime that yields high energies, monoenergetic spectra, and high conversion efficiency, the challenge is to find those conditions in which Radiation Pressure Acceleration (RPA) is dominant for realistic laser-target configurations. Recent computational studies that we have carried out suggest that using circular polarization rather than linear polarization results in RPA dominating in the case of sub-micron foils in the intensity range of 10^{20}-10^{21}Wcm^{-2}.

Theory

To understand why RPA is such an attractive acceleration paradigm, one can consider a simple analytical model. Consider the one-dimensional (1D) problem of a foil being moved by the radiation pressure of normally incident light. One quickly arrives at the following equation of motion,

$$\frac{dp}{dt} = \frac{2I}{c}\frac{\sqrt{p^2+\sigma^2c^2}-p}{\sqrt{p^2+\sigma^2c^2}+p} \qquad (1)$$

This can be solved analytically, yielding,

$$p = \sigma c\left(\sinh\psi - \frac{1}{4\sinh\psi}\right) \qquad (2)$$

where,

$$\psi = \frac{1}{3}\sinh^{-1}\left(\frac{6It}{\sigma lc^2}+2\right) \qquad (3)$$

Note that for a laser pulse of finite duration, the actual illumination time is greater than the pulse duration. This formula will therefore underestimate the acceleration by setting t equal to the pulse duration. Nonetheless this model makes the potential of RPA very clear. Figure 1 plots eqn.s 2 and 3 for the case of an intensity of 2×10^{21}Wcm^{-2}, a foil thickness of 150nm, and a foil density of 2000kgm^{-3} as a function of illumination time, t.

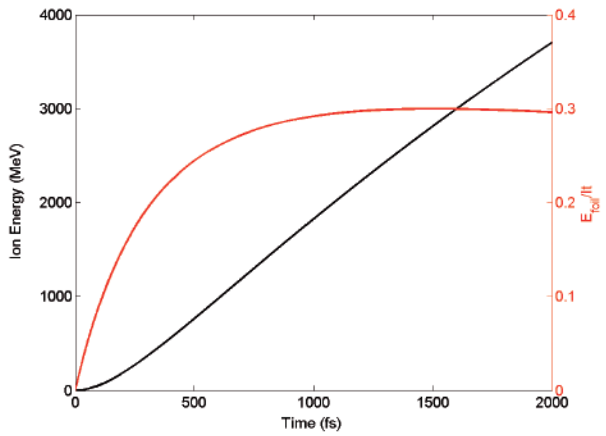

Figure 1. Predictions of analytic model (eqn.s 2 and 3; see text).

Figure 1 shows that for conditions that are increasingly realistic one should, in principle, be able to accelerate ions to energies several hundred MeV or a few GeV with a conversion efficiecies of up to 30%. In this model the ions are also intrinsically monenergetic. The challenge is to access this regime, and from a theoretical viewpoint this requires detailed numerical simulation.

1D Simulation

The interaction between a 64fs laser pulse reaching a peak intensity of 2×10^{21}Wcm^{-2}, and a 150nm foil was investigated using a 1D electromagnetic particle-in-cell code. This code is the same as that used in [3]. The foil consists of protons at a density of $80n_{crit}$, and the initial electron temperature is 10keV. The standard run used a circularly polarized laser pulse with a $\sin^4$ profile. The laser wavelength was 1μm. The calculation was performed up to 400fs.

In figure 2, the energy spectrum for the standard run (black line) and a run that is identical apart from the laser pulse being linearly polarized (magenta line). This clearly shows that changing polarization switches between two radically different regimes. Linear polarization results in Target Normal Sheath Acceleration (TNSA) being dominant. In the case of circular polarization, RPA is dominant. This can be shown to be the case by noting three aspects of the simulations. Firstly the ion energy of the standard run can be accurately predicted by a semi-analytic model that numerically integrates eqn. 1, and an expression that specifies the laser pulse. This is shown in figure 3.

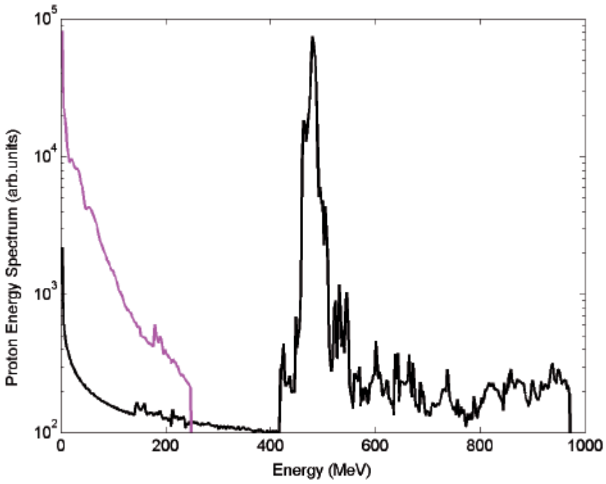

Figure 2. Proton energy spectra at 300fs of standard run (black) and standard run with linear polarization (magenta).

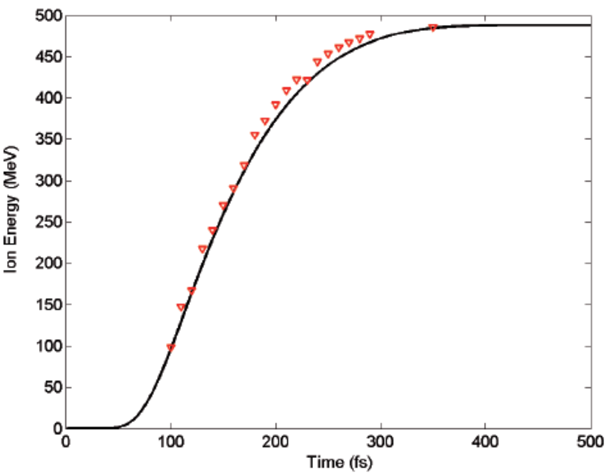

Figure 3. Ion energy in standard run against time (red triangles), compared to the semi-analytic model (black line).

The agreement is excellent. Secondly, in RPA the only relevant material property is the density-thickness product, σl. The ion charge, Z, has no bearing. Indeed when Z was varied, but σl kept constant, the changes to the simulation results were less than 10%. Thirdly, in RPA the wavelength of the incident radiation has no bearing either. The obvious caveat to this is that the foil reflects the radiation. On trying shorter and longer wavelengths the change to the simulation results was again less than 10%. These three aspects together show that in the case of the standard run, RPA is the dominant acceleration mechanism. The laser-proton conversion efficiency in the standard run reached 60%, although it needs to be stressed that this is a function of the final ion velocity. At $v \ll c$, the conversion efficiency is extremely low, but at $v \sim c$ the conversion efficiency is very high [1].

In summary, the 1D simulations clearly demonstrated that using circular polarization allowed the RPA regime to be accessed even at intensities of 10^{20}-10^{21}Wcm^{-2}.

2D OSIRIS simulations

In order to study 2D effects a number of calculations were carried out using the 2D3P OSIRIS Particle in Cell code. In these simulations a 100nm foil consisting only of protons and electrons with an initial density of $100n_{crit}$ was irradiated by a pulse with a peak $a_0 = 31$ and a pulse duration of 31fs. In the transverse direction the beam had a supergaussian profile with a 1/e width of 13μm.

It was found that the central portion of the foil did undergo RPA. By 75fs the foil had been accelerated to 240MeV, whereas the 1D model would predict 260MeV. The divergence angle of these protons was less than 4 degrees.

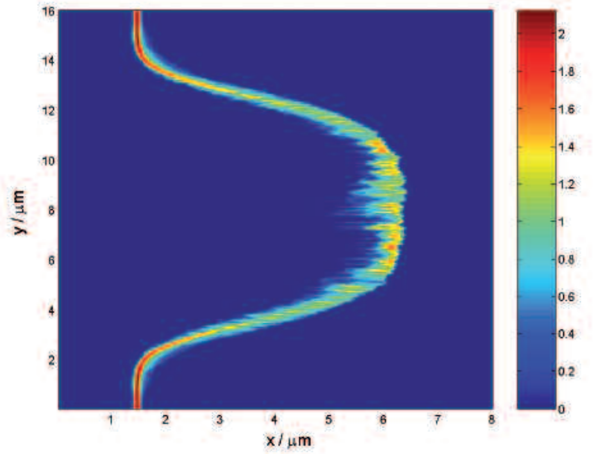

Figure 4. Proton density in 2D simulation ($\log_{10}(n_p/n_{crit})$) at 64fs.

In figure 4, the proton density at 64fs is shown. As can be seen there is some sort of transverse instability which may be like a Rayleigh-Taylor instability. However it was found that, as the initial number of particles per cell was increased, the effect of this instability decreased considerably. In this calculation there is initially 400 particles per cell, and this represents the current limits of our computational capacity. The effect of the instability is to degrade the energy spectrum of ions i.e. gradually broaden it away from a highly monoenergetic spectrum.

Summary

In this work we have shown that it is indeed possible to produce highly energetic ion beams via Radiation Pressure Acceleration at intensities that are currently accessible. This is achieved primarily by using circular polarization at normal incidence, although one must also tailor the foil, which means using foils of around 100nm to reach high energies. Clearly this demands a very good contrast ratio (our studies indicate that 10^8 at least is required), but this is not impossible. Since RPA is capable of scaling to high energies, produces highly monoenergetic spectra, and can be highly efficient, it is undoubtably a route that should pursued in the field of ion acceleration.

Acknowledgments

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