Laser-ion acceleration – towards table top accelerators

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When any material is heated to a sufficient degree, its constituent atoms separate into negative electrons and positive ions. This state of matter is called plasma and has unique properties that make it an attractive medium for particle acceleration.

Conventional accelerator cavities can only sustain accelerating field gradients of the order of 10^6 V/m, as they are limited by the electric breakdown of the accelerator materials. Plasmas are already broken down and so the accelerating fields are not limited by this effect. Plasmas exhibit quasineutrality, i.e. the negative charge density of the electrons is equal to the positive charge density of the ions. Any significant separation of positive and negative charge is accompanied by strong electrostatic restoring fields. These transient fields are of interest as compact ultrahigh-gradient accelerating structures.

Cutting edge laser technology is capable of producing pulses of light focusable to intensities of 10^{21}-10^{22} W/cm^2. At these intensities the laser's electric field rips electrons from their atomic orbitals and accelerates them to highly relativistic energies, $E_{kin} >> mc^2$. These extremely energetic electrons propagate through the surrounding material, causing further plasma formation. Recent studies have indicated that ions can be efficiently accelerated during such interactions via several mechanisms [1-6].

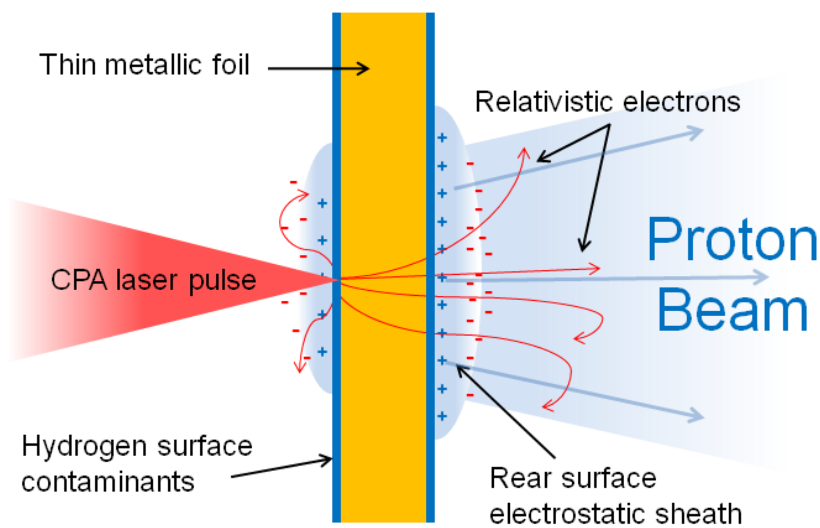

Figure 1 – Schematic of the proton acceleration from thin foils via target normal sheath acceleration (TNSA). Hydrogen surface contaminants on the foil surface are most readily accelerated in the sheath field set up at the plasma vacuum boundaries. As the boundary is sharpest at the rear unirradiated side, protons from this region achieve the highest energies and exhibit unrivaled laminarity.

The most studied acceleration mechanism is known as Target Normal Sheath Acceleration [7]. This occurs readily when thin foils, several microns thick are irradiated with ultraintense laser pulses such as those produced by the Vulcan Petawatt [8] or Astra Gemini lasers. On reaching a plasma vacuum interface the electrons stream out into the vacuum, while the plasma ions are relatively immobile due to their higher mass. Due to the negative charge escape into the vacuum a large positive charge is induced at the plasma vacuum interface. The positive potential electrostatically traps most of the relativistic electrons, drawing them back to the interface. As long as there is a source of fast electrons, i.e. over the laser pulse duration, a capacitor plate like charge separation is formed with electric fields of the order of 10^{12} V/m generated at the interface. Light ions at the plasma vacuum surface are most readily accelerated in the field, reaching energies of tens of megavolts over an acceleration length of a few tens of microns, over picoseconds timescales. As the ions gain energy the sheath field drops and the fast ions and electrons propagate ballistically as a quasineutral beam.

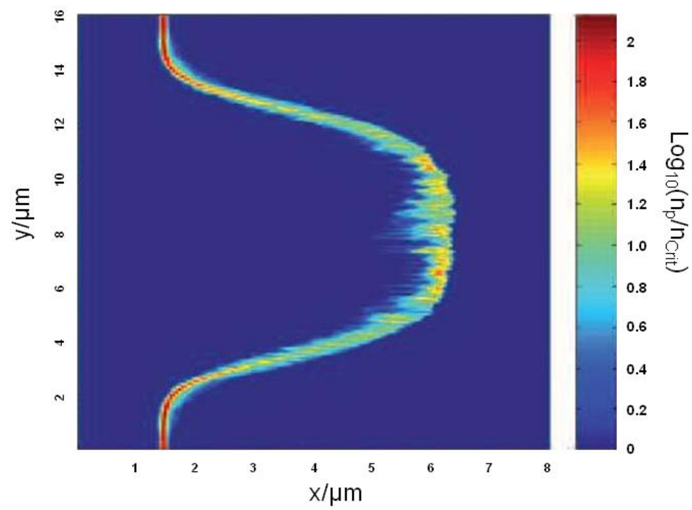

Figure 2 – Computer simulation of an ultrathin foil irradiated by a circularly polarized laser pulse [9]. The whole foil is accelerated in the x direction (the laser propagation axis) by the incident laser radiation pressure. The use of circular polarization inhibits hot electron generation, effectively switching the regime from TNSA to RPA.

Another regime of ion acceleration from intense laser plasma interaction is radiation pressure acceleration, sometimes referred to as the laser piston regime [5, 6]. Here the light pressure of a laser pulse incident on an ultrathin foil, less than 100 nm thick, accelerates the whole foil as a plasma slab. Simulations predict that the RPA regime can be extremely efficient and can provide higher ion energies than TNSA with the accelerated ions exhibiting quasi-monoenergetic spectra (see figure 2). This regime has so far been difficult to access as maintaining the integrity of such ultrathin targets during the interaction requires extremely high laser performance in terms of contrast (pulses rise time) and intensity while avoiding considerable hot electron generation. Hot electrons generated in the foil drive TNSA which expands and destroys the ultrathin plasma slab. Hot electron generation is known to be inhibited by changing the laser polarisation from linear to circular. The polarisation state does not affect the laser intensity, or light pressure, so circular polarisation offers easier access to the RPA regime than linear polarisation.

Future laser technology currently in development will operate at much higher repetition rates than current systems and will drive laser ion sources towards average currents comparable to conventional RF accelerators. These developments, coupled with the reduction in laser system cost and size may make laser based sources an attractive alternative to cyclotron or synchrotron systems in applications such as isotope production (e.g. for positron emission tomography) [10,11], nuclear physics, deep ion implantation in semiconductor substrates, radiobiological studies and particle beam therapy. Additionally, the short acceleration length, ultralow emittance and picosecond-scale bunch duration achievable with laser accelerated ion sources contrasts sharply with the parameter space occupied by existing RF accelerator technology, where typically nanosecond bunches are accelerated over many metres. The unique properties of laser ion sources have encouraged investigation into several novel and exotic applications, which cannot be pursued with conventional sources.

- TNSA protons have already been used extensively as a particle probe in laser plasma interaction studies [12, 13]. Such beams can be used to image, with micron resolution, electric and magnetic fields which evolve on shorter timescales than the hydrodynamic motion of the irradiated material (e.g. figure 3).

- The high peak current and ultrashort duration allows such beams to be used to heat target materials to extremely high temperatures extremely quickly. This isochoric (constant density) heating of solid materials can be used to create and study warm dense matter (WDM) states [14]. This state of matter is under intense theoretical and experimental investigation and is thought to be present in large planetary cores and during the heating stage in Inertial Confinement Fusion

- Achieving controlled thermonuclear fusion for energy production has been a long term goal of plasma physics. The fast ignition scheme of inertial confinement fusion involves the laser based compression of a thermonuclear fuel to a hundred times solid density (over a few nanoseconds) followed by the isochoric heating of a small region of the fuel (over a few picoseconds) to initiate a thermonuclear burn wave which ignites the rest of the fuel. One variation of fast ignition proposes the use of an intense laser accelerated proton beam as the ignitor [15]. The transport and energy deposition properties of protons may be superior to the electron beam FI scheme.

- The full realisation of the radiation pressure regime at extreme intensities achievable with future technology, currently at the conceptual stage, may allow the generation of high density plasma slabs, propagating relativistically (at GeV energies). Two counter-propagating heavy ion slabs would constitute a compact linear collider of exceptional peak luminosity [16]. Such a system could be of interest in fundamental particle physics.

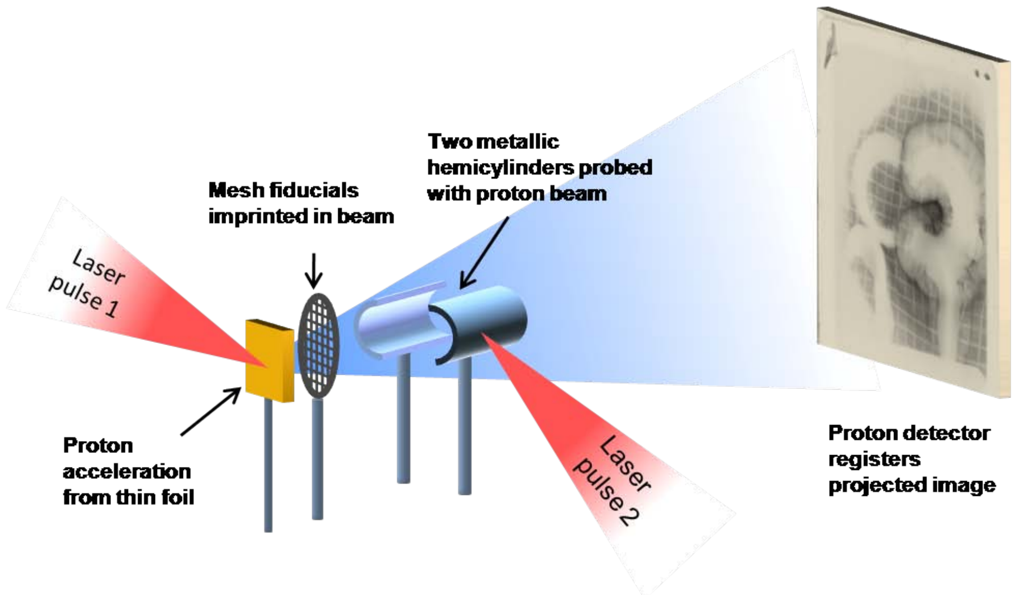

Figure 3 – Proton imaging of the picosecond dynamics of laser plasma interaction: the hemicylinder on the right is irradiated with an intense laser beam, heating electrons and generating strong electrostatic fields at the target-vacuum interface, which deflect the probe particles. This causes the halo effect around the target in the detector image. These fields decay over a few tens of picoseconds. Figure adapted from [13].

References

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