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Paving the way for a revolution in high repetition rate laser-driven ion acceleration

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Exceptionally strong TV m^{-1} fields generated during the interaction of high intensity lasers with plasma targets are capable of accelerating ions to MeV energies over micron-scale distances. This offers exciting possibilities for the development of compact accelerators. It has been demonstrated that the maximum achievable ion energy scales with the laser intensity and consequently much of the work in this field has utilised lasers at the cutting edge of development with multi-J energies and short (<ps) duration. The peak fluxes of laser-plasma generated ion beams are extremely high, but owing to the low repetition rate ($\ll$1 Hz) of most high power laser systems, the average flux is very low. A significant increase in the average particle flux is required for many applications of these beams, including hadrontherapy. The challenge in producing these sources lies not only in the development of stable, high energy, high repetition rate laser systems but also of suitable targetry and diagnostics. In the paper of Morrison *et al* (2018), the authors demonstrate a novel planar target compatible with kHz production of MeV proton beams and kHz-compatible beam diagnostics, which represent important steps in the development of laser-driven ion sources for applications.

While energetic ions were measured during laser-plasma interactions in the mid-1980s, the development of chirped pulse amplification, allowing amplification of short laser pulses to higher energy, lead to a dramatic enhancement in acceleration to tens MeV energies. When the high intensity ($I_L > 10^{18}$ W cm^{-2}) laser pulse is incident on a target, typically a few microns in thickness, a dense plasma is formed and the newly freed electrons are rapidly accelerated to relativistic energies in the laser fields. These 'hot' electrons escape the target, from the front and rear surface, which is left with a net positive charge leading to TV m^{-1} 'charge-separation' fields that can accelerate ions. Ion beams produced in this way are typically directed along the surface normal, have exceptionally low emittance, divergences of tens of degrees and a broad energy spread with the maximum energy depending on multiple factors including the laser intensity.

While the low repetition rate of high energy laser facilities has limited development of these ion sources, several multi-Joule, multi-Hz laser systems will become available over the next 5 years. However, exploiting these presents many technical challenges. The high laser intensities required for maximal electron heating lead to destruction of the targets that must then be replaced with micron level precision in position and ablation of solid target material rapidly coats surrounding optics with debris.

Over the last decade, many groups have been exploring potential high repetition rate targetry and diagnostics using low energy laser systems. Tape-drive targets with thicknesses of 10s μm have produced few-Hz, MeV-level proton beams (McKenna *et al* 2002, Noaman-ul-Haq *et al* 2017), although as target thickness is reduced to increase maximum proton energy, thin tapes suffer from tearing as they are held under tension to provide a smooth interaction surface. Similar repetition rates and energies have been achieved using liquid droplet targets (Karsch *et al* 2003, Ter-Avetisyan *et al* 2006). These have the advantage of being on the scale of the laser focus and electrically isolated from their surroundings. This has been demonstrated to improve the conversion efficiency of laser energy to energetic ions. Experiments at kHz-level have also been performed using mJ laser system (similar to that of Morrison *et al* 2018) and solid-targets in the form of thick spinning disks (Hou *et al* 2009, 2011) that are carefully engineered to maintain target position with sub-micron precision as the disk spins. For these thick targets, ion acceleration only occurs at the front surface, where the elongated plasma density gradient of the heated surface plasma hinders efficient ion acceleration. Alternatively, kHz-compatible, micron-scale, liquid jets have been explored (Thoss *et al* 2003, Hah *et al* 2016). Ion energies of hundreds keV were observed by Thoss *et al* (2003) originating from the non-irradiated surface of the jet with divergence angles of 40°. These thin liquid targets, offer the exciting opportunity to 'scale-up' to higher energy lasers and produce MeV-level ion beams.

Here, Morrison *et al* have utilised a few mJ laser, strongly focused to intensities $>10^{18}$ W cm^{-2}, to produce proton beams with energies up to 2 MeV. The experiment introduces a thin, planar liquid target whose continuous flow operation means that the target is rapidly refreshed between kHz pulses, and planar geometry favours the production of lower divergence proton beams. A key challenge associated with liquid targets is maintenance of the target in a sufficiently high vacuum to ensure that acceleration of ions from the target surface is not impeded. Here, the vacuum pressure is reduced through careful choice of liquid (ethylene glycol), the use of a catcher to capture the liquid following the interaction and arrangement of the catcher in such a way as to minimise vaporisation. Additionally, in contrast to most of the experiments described above that employ single-use detector plates, Morrison *et al* have utilised a scintillator-coupled CCD for diagnosis of the ion beam, enabling them to capture the energy spectrum on each shot at high repetition rate. (*Development of 'online' beam profile diagnostics to replace film and detector plates is currently another vibrant area of study* (Dover *et al* 2017)).

Shots taken while translating the target through the laser focus, highlight the potential of high repetition rate experiments by demonstrating that while electron temperature and the proton energy increase with laser intensity as expected, at the highest intensities the proton energy dramatically drops. Probing of the target during the interaction revealed that this is due to disruption of the target by plasma formation and heating before the arrival of the peak intensity. Experiments utilising moderately higher energy laser pulses, combined with contrast enhancement (reducing the energy arriving before the peak of the laser pulse) to prevent early ionisation of the target, should be able to push the achievable energy of these beams to the 10s and 100s of MeV needed for applications such as hadrontherapy.

This kHz-compatible target and diagnostic setup represents an important development for laser-driven ion acceleration, permitting exploitation of the new multi-Hz high energy systems to explore laser-driven ion acceleration with great depth to provide compact accelerators for research and industry.

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