Proposal: Study of ion beam generation from interaction of 10 $\mu$m laser with near critical density plasmas

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Laser-accelerated protons: Properties and applications

- High laminarity, ultralow emittance
- Short duration: \( \sim 1 \) ps
- High energy: up to 60 MeV at present
- High brightness: \( 10^{11} - 10^{13} \) ions per shot
- High current: kA range
- Broad spectrum

Laser beam characteristics
- Energies > 100 J per shot
- Wavelength \( \sim 1 \) µm
- Pulse Lengths \( \lesssim 1 \) ps
- Power > 100 TW
- Intensities > \( 10^{19} \) Wcm\(^{-2}\)
- Shot rate \( \approx 1 \) per / hour

CHALLENGES!
- Energy increase
- Monochromatic beams
- Beam transport (divergence control)
- High repetition

Radiography, deflectometry
Fusion Energy (Fast Ignition)
Cancer therapy
Isochoric heating of matter
Industrial applications
Time-resolved (<10\(^{-12}\) s) ion-matter interaction studies

Credits to M. Borghesi, Queen’s Univ. of Belfast
Scaling of ion acceleration with \( \text{CO}_2 \) lasers

- \( \text{CO}_2 \) laser at \( 10^{16} \) Wcm\(^{-2} \) is equivalent to \( 10^{18} \) Wcm\(^{-2} \) glass laser.

- At the same power and energy, \( \text{CO}_2 \) laser will provide the same ponderomotive action within \( \sim \lambda^2 \) (100 times) bigger area or \( \sim \lambda^3 \) (1000 times) bigger volume. Accordingly, we expect that the number of accelerated ions would grow with \( \lambda \).

- 5-ps \( \text{CO}_2 \) laser similar to 500-fs glass laser in number of cycles (but acceleration time is longer).
Gas jet as an ion beam source

- Pure (compared to solid targets which become quickly covered in impurities)
- Can employ H, He and other species difficult to make in other targets
- Allows changing target material quickly
- Can run at high repetition rate
- Can be collimated by magnetic fields
Supersonic gas jet available at Imperial College

- Targets in excess of $5 \times 10^{20} \text{ cm}^{-3}$ (plasma density equivalent) can be made in H, He, Ne, Ar.
- Sizes can be made down to 125 µm, with sharp gradient.
 Ion beams produced from gas jets

Maximum ion energy at critical density plasma


Near-critical and over-critical regimes

• Basic primary process: Laser energy is absorbed by plasma electrons and then transported into the target.
• This process is still not well understood. This is mainly because for optical laser irradiation, the targets typically used to create overdense interaction have been of solid density, which are impossible to probe optically, and extremely difficult to investigate by other methods.

• Using IR laser allows over-critical interaction with optically transparent plasma.
Summary of added benefits from combining gas jet with a CO$_2$ laser

- Due to $\lambda = 10 \, \mu m$, $n_{cr} = \varepsilon_0 m \omega_0^2/e^2$ is also 100 times less ($\approx 10^{19} \, cm^{-3}$) than for a glass laser. Gas jets easier to make at this density.
- Allows easy switching between under-critical and over-critical regimes by changing backing pressure.
- Allows to operate a hydrogen jet (proton source) in the most efficient, near-critical regime.
- Plasmas critical for CO$_2$ are optically transparent, allowing for the first time interferometric diagnostic of interaction in over-critical regime.
Gas jet to be installed into existing interaction chamber
Second harmonic YAG is available for interferometry to diagnose:

- a light pressure driven plasma shock at the front of the target
- path of the hot electrons through the target
- the critical surface motion at the rear of the target due to the space charge field generated by hot electrons escaping out into the vacuum
The study of the emission of energetic ions from both rear and front surfaces of the plasma is the prime objective from two viewpoints:

- characterising these ion beams for possible applications
- the energy and structure of the ion beam gives information about the hot electron generation

Thomson parabola TR1 is installed already.

Additionally radiochromic film (RCF) and CR39 stacks would be used on some individual shots to characterise a beam divergence.
Laser focus produced with $f_{#}=2$ parabola

Gaussian approximation

\[ I(r, z) = I_0 \left( \frac{w_0}{w(z)} \right)^2 \exp \left( -\frac{2r^2}{w^2(z)} \right) \]

$w_0=65 \, \mu m$ - best fit

- $1.5 \times 10^{16} \, W/cm^2$ @ 1 TW
- $a_0=1$ @ $\lambda=10 \, \mu m$

- just sufficient to look for MeV protons and ions
Available resources:

• Two postgraduate students from Imperial College, C. Palmer and N. Dover, experienced in ion acceleration experiments will assist local members of the ion acceleration consortium.

• Funds for visits available from the Libra Consortium (a UK based Consortium into laser driven ion acceleration)

• Simulation support - Dr J. Schreiber – Max Planck Institute for Quantum Optics, Garching.

• A gas jet and an additional Thomson parabola will be brought from the UK.