Proposal: Study of ion beam generation from interaction of 10 μm laser with near critical density plasmas

Igor Pogorelsky

on behalf of Dr. Zulfikar Najmudin

Imperial College London

Laser-accelerated protons: Properties and applications

- High laminarity, ultralow emittance
- Short duration : ~ 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

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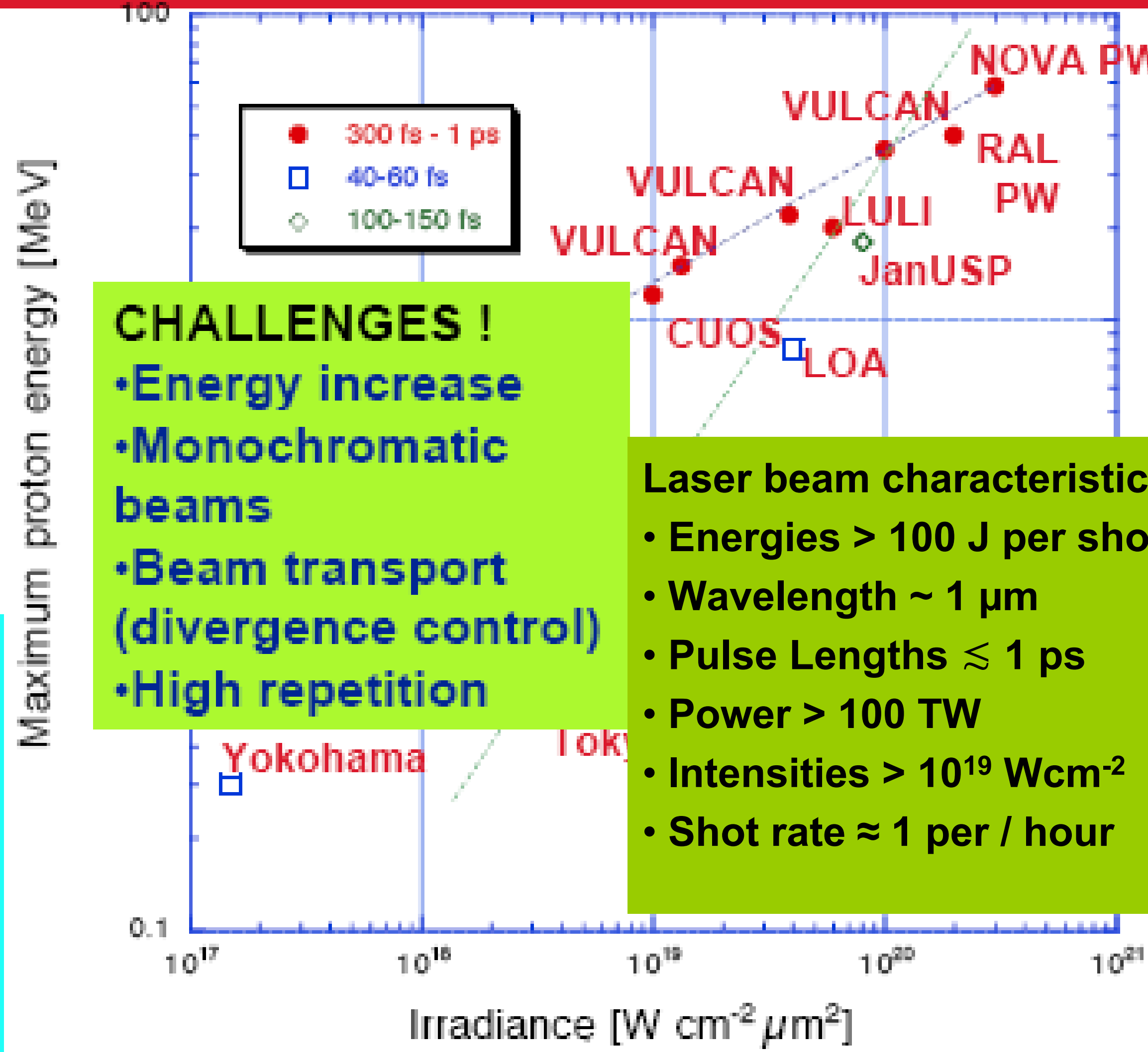
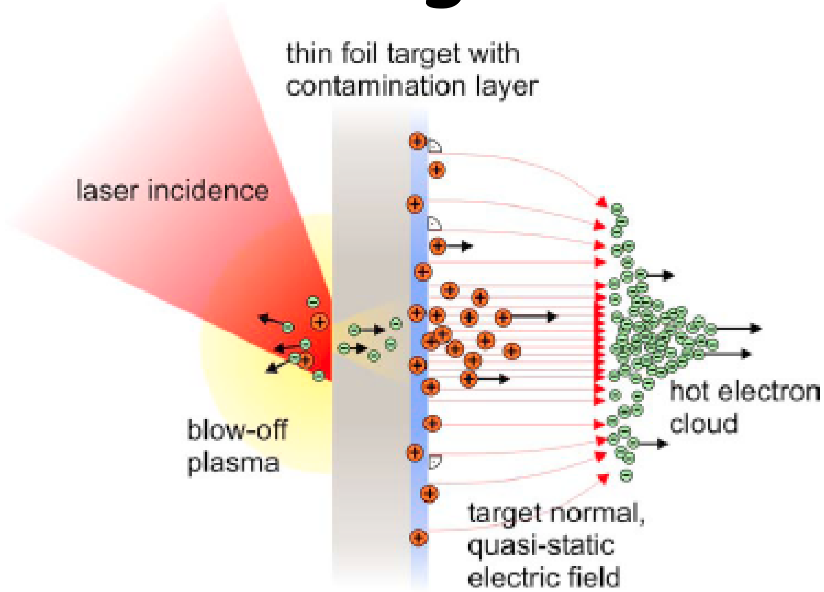


CHALLENGES !
•Energy increase
•Monochromatic beams
•Beam transport (divergence control)
•High repetition

Laser beam characteristics
- Energies > 100 J per shot
- Wavelength ~ 1 μm
- Pulse Lengths ≲ 1 ps
- Power > 100 TW
- Intensities > 10^{19} Wcm^{-2}
- Shot rate ≈ 1 per / hour

Credits to M. Borghesi, Queen's Univ. of Belfast

Scaling of ion acceleration with CO_2 lasers



$$m \frac{d\mathbf{U}}{dt} = -e \nabla \Phi_{\text{pond}},$$

$$\Phi_{\text{pond}} = \frac{1}{4} \frac{e}{m\,\omega^2} |\mathbf{E}_0|^2 .$$

- CO_2 laser at 10^{16} Wcm^{-2} is equivalent to 10^{18} Wcm^{-2} glass laser.

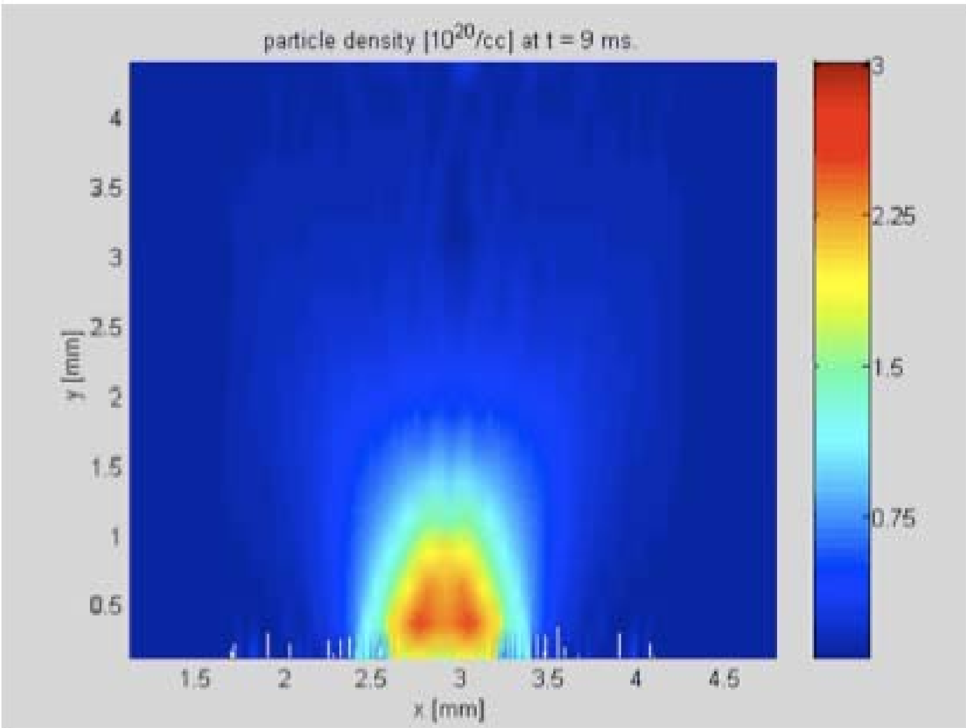
- At the same power and energy, CO_2 laser will provide the same ponderomotive action within $\sim\lambda^2$ (100 times) bigger area or $\sim\lambda^3$ (1000 times) bigger volume. Accordingly, we expect that the number of accelerated ions would grow with λ.

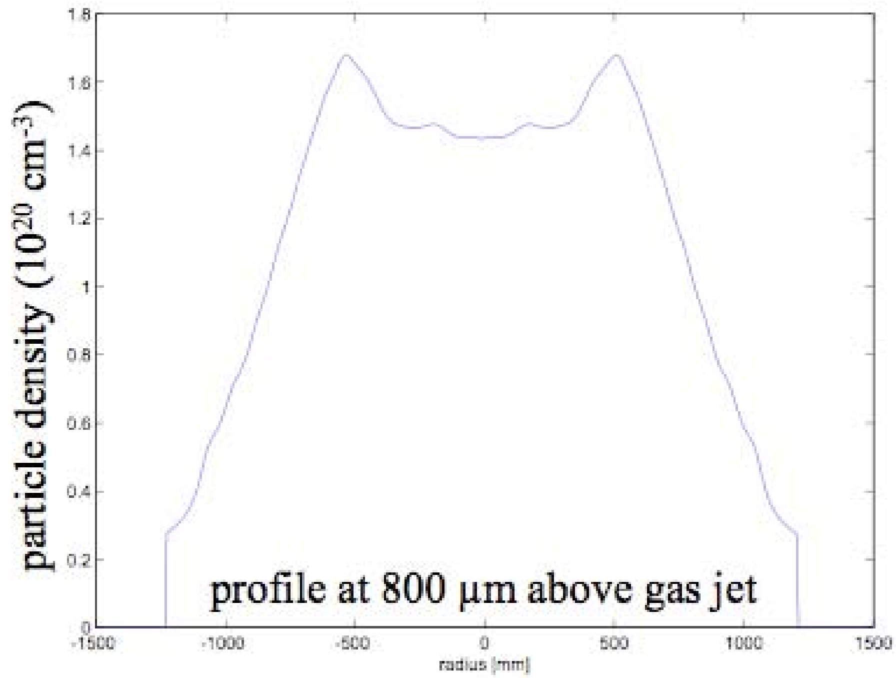
- 5-ps CO_2 laser similar to 500-fs glass laser in number of cycles (but acceleration time is longer).

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

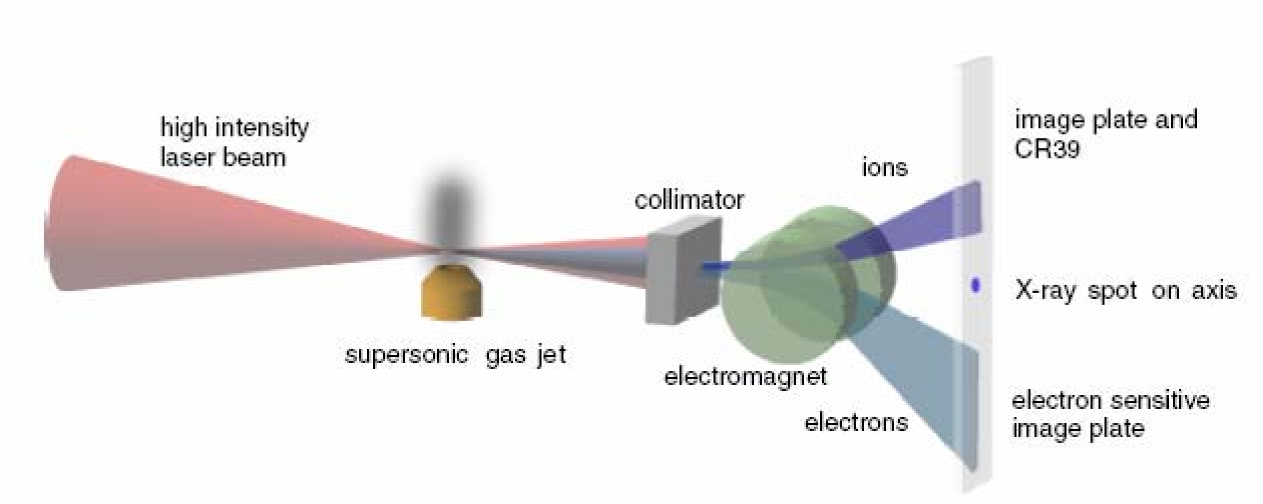
Supersonic gas jet available at Imperial College

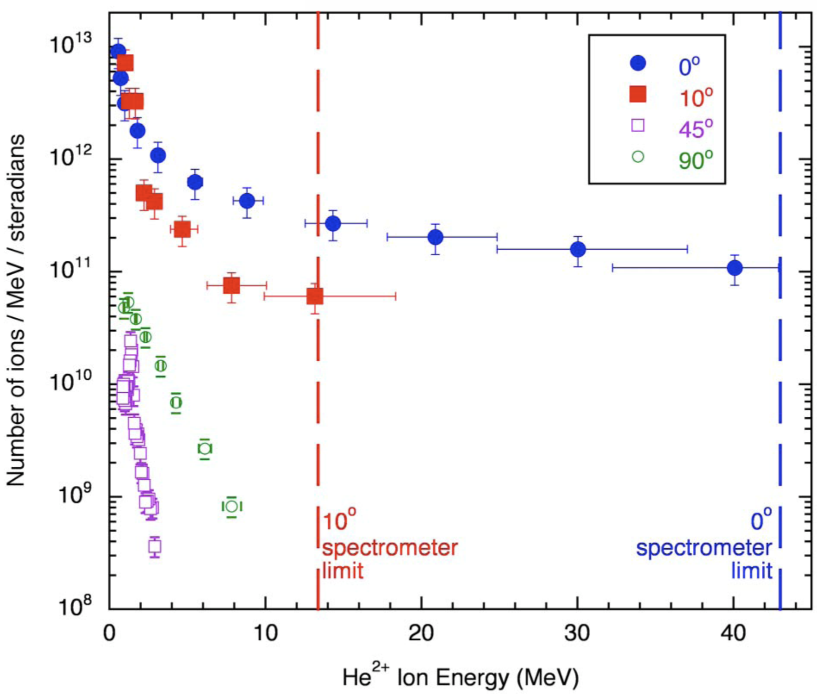


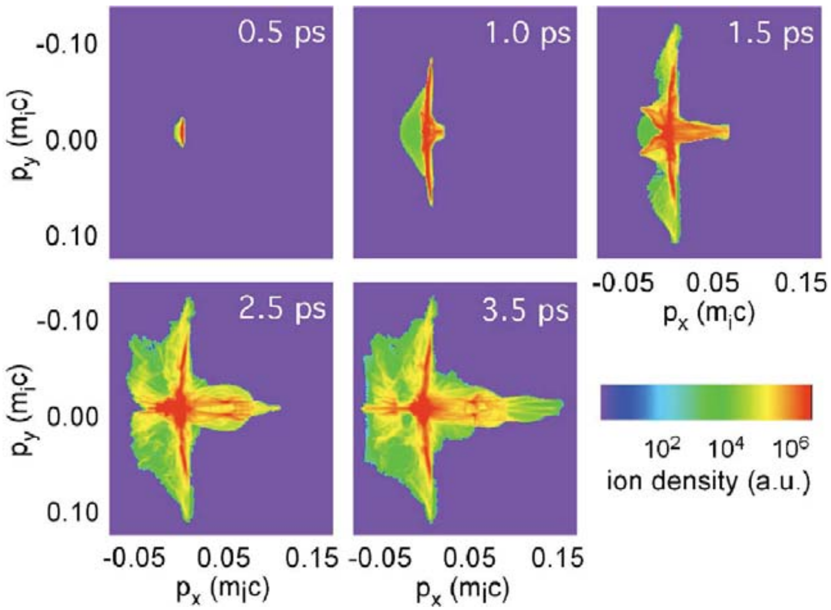


- Targets in excess of 5 ×10^{20} cm^{-3} (plasma density equivalent) can be made in H, He, Ne, Ar.
- Sizes can be made down to 125 μm, with sharp gradient.

Ion beams produced from gas jets







Willingale, L., et al., *Collimated multi-MeV ion beams from high-intensity laser interactions with underdense plasma.* Physical Review Letters, 2006. **96**(24).

Maximum ion energy at critical density plasma

simulation

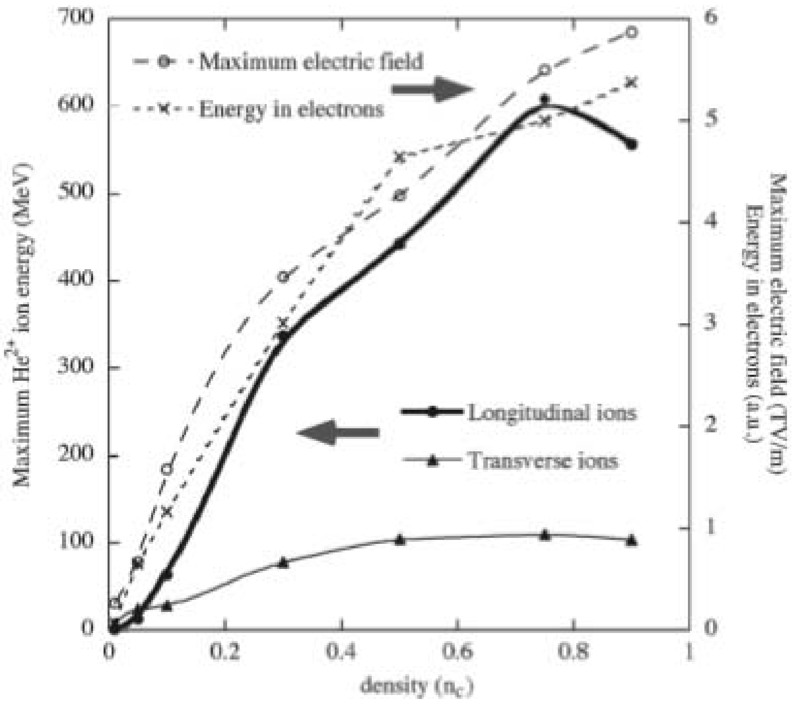
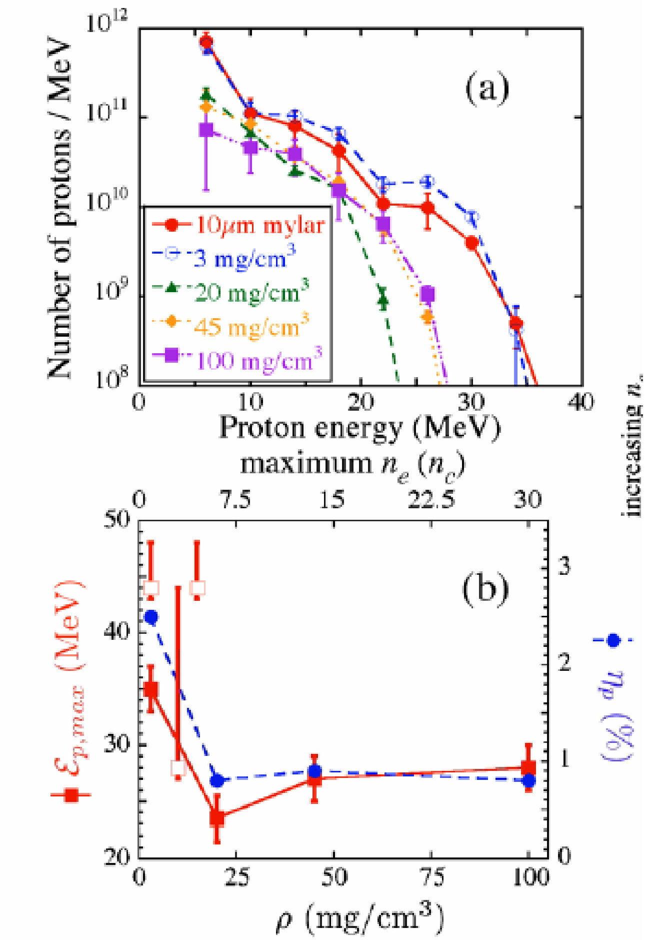


Fig. 4. Maximum He^{2+} ion energies in both the longitudinal and transverse directions at 1.9 ps into the simulations, the maximum electric field (not at the same times in the simulations), and the total longitudinal energy in the electrons (>10 MeV) for each of the densities. The lines are a visual guide only.

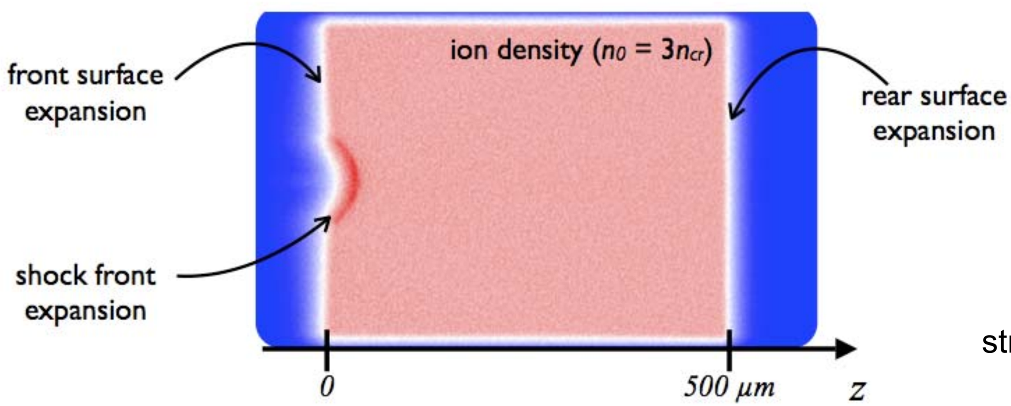
experiment with foam targets

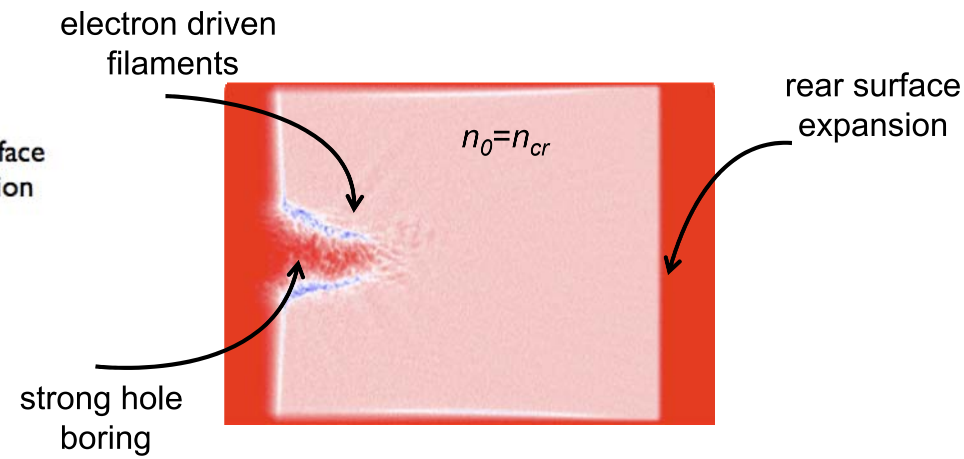


Willingale, L., et al., *Longitudinal ion acceleration from high-intensity laser interactions with underdense plasma.* IEEE Transactions on Plasma Science, 2008. **36**(4): p. 1825-1832.

Willingale, L., et al., *Characterization of High-Intensity Laser Propagation in the Relativistic Transparent Regime through Measurements of Energetic Proton Beams.* Physical Review Letters, 2009. **102**: p. 125002

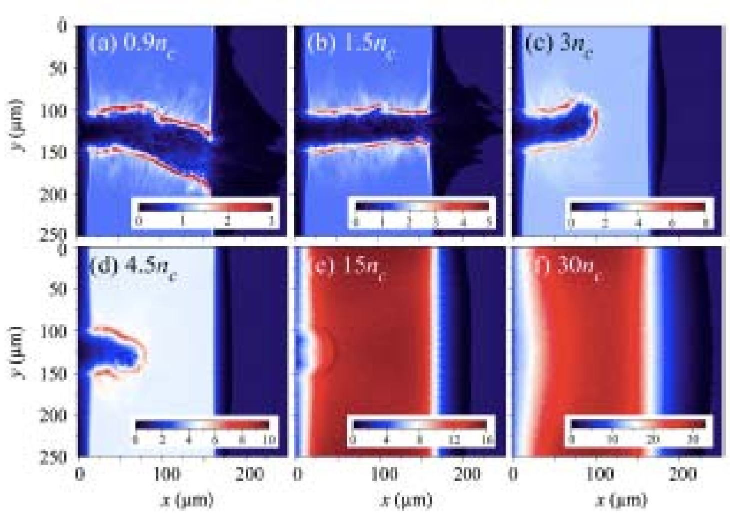
Near-critical and over-critical regimes



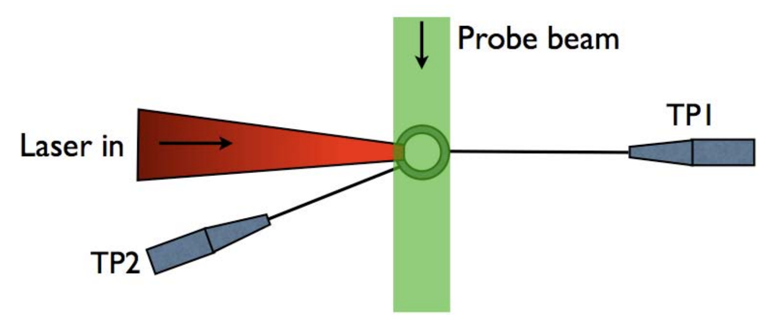


•Basic primary process: Laser energy is absorbed by plasma electrons and then transported into the target.

•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.



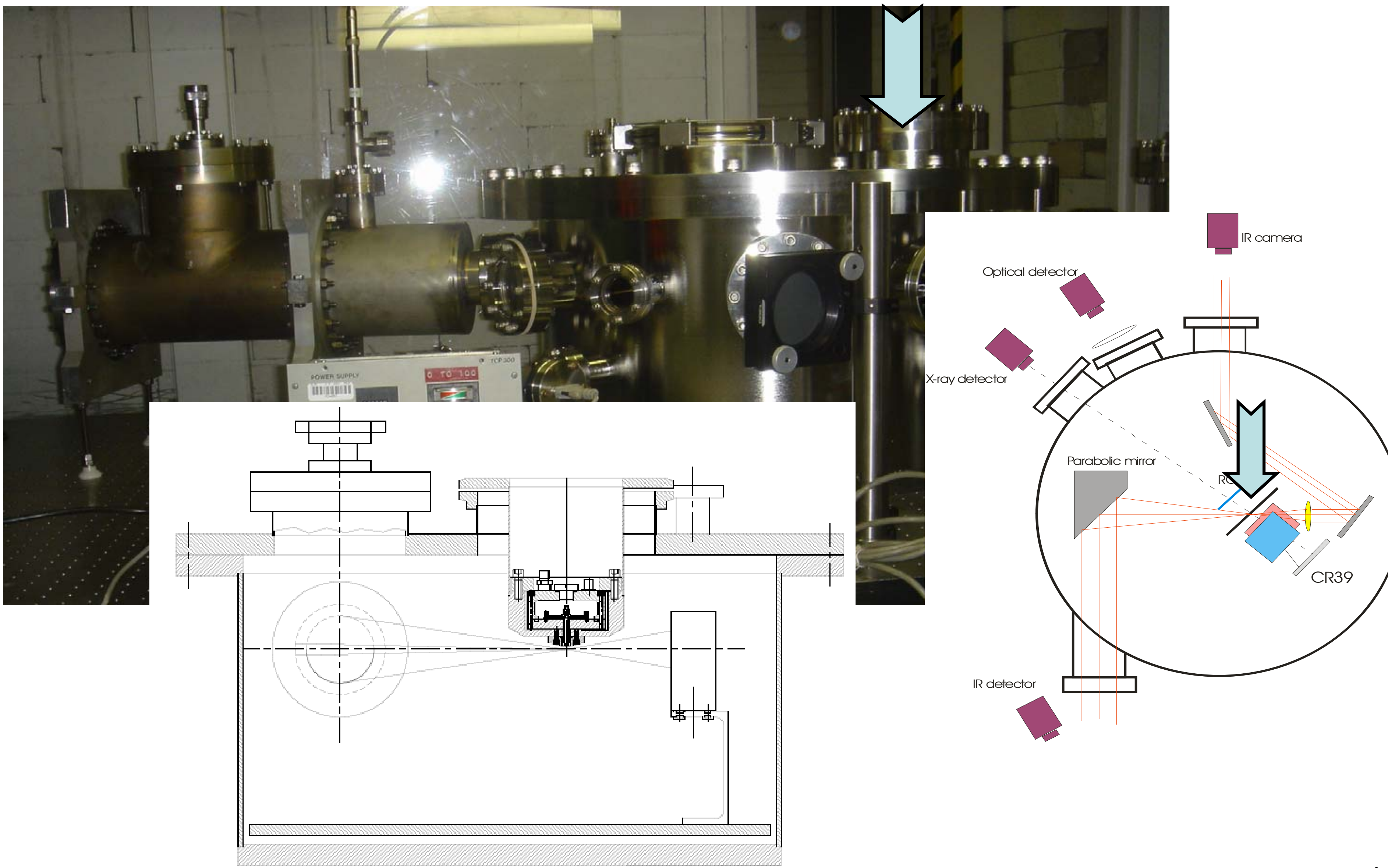
• Using IR laser allows over-critical interaction with optically transparent plasma.



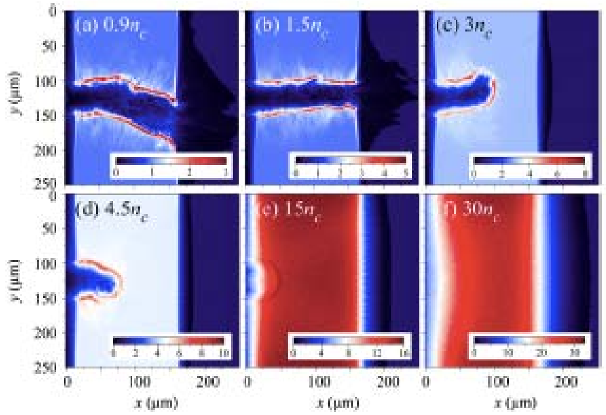
Summary of added benefits from combining gas jet with a CO_2 laser

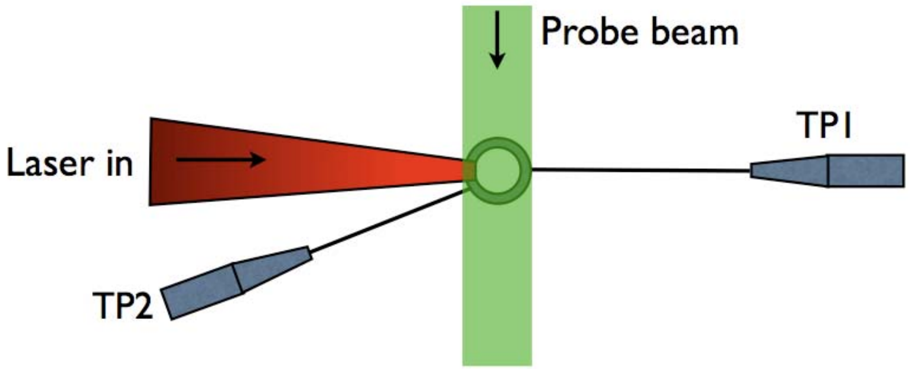
- Due to λ =10 μm, $n_{cr} = \varepsilon_0 m \omega_0^2/e^2$ is also 100 times less (≈ 10^{19} cm^{-3}) than for a glass laser. Gas jets easier to make at this density.
- Allows easy switching between under-critical and over-critical regimes by changing backing pressure.
- Allows to operate a hydrogen 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.

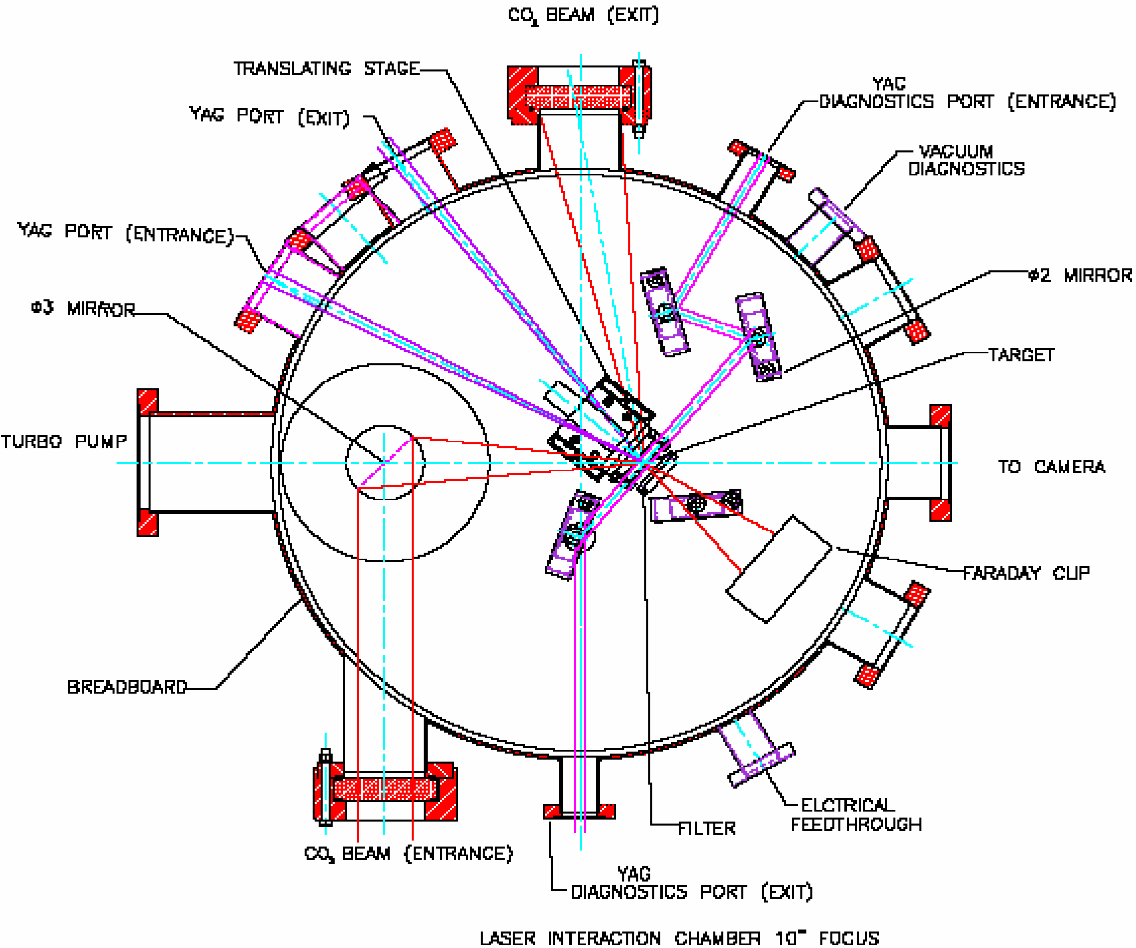
Gas jet to be installed into existing interaction chamber



Diagnostic 1



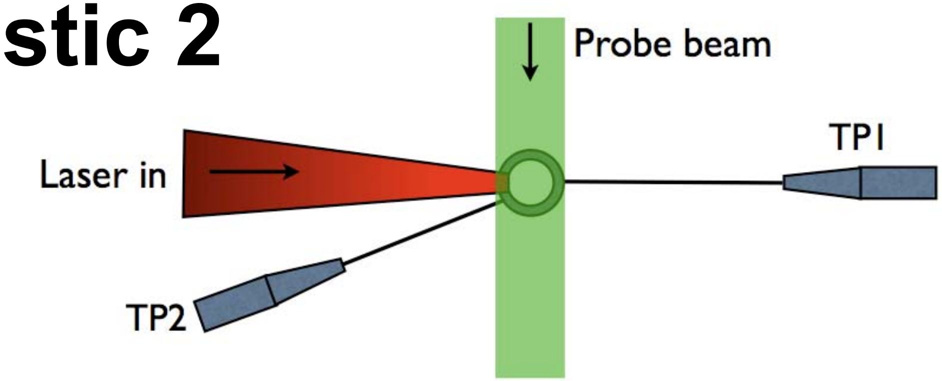




Second harmonic YAG is available for interferometry to diagnose:

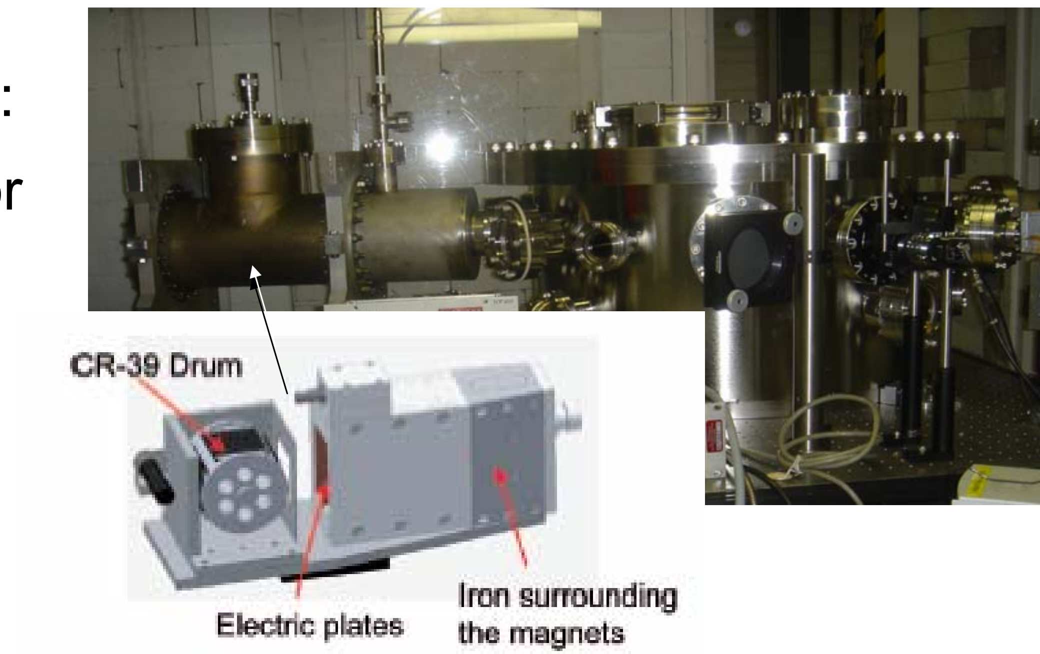
- a light pressure driven plasma shock at the front of the target
- path of the hot electrons through the target
- the critical surface motion at the rear of the target due to the space charge field generated by hot electrons escaping out into the vacuum

Diagnostic 2



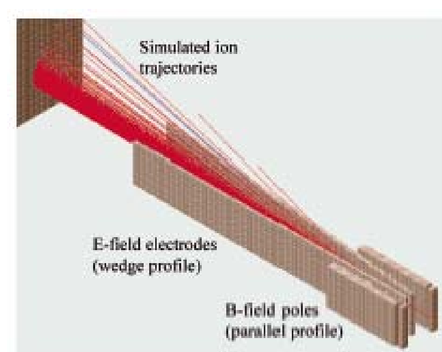
The study of the emission of energetic ions from both rear and front surfaces of the plasma is the prime objective from two viewpoints:

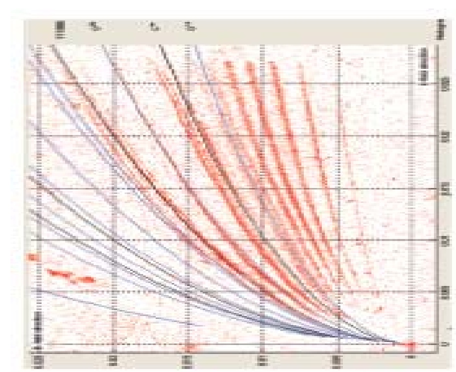
- characterising these ion beams for possible applications
- the energy and structure of the ion beam gives information about the hot electron generation



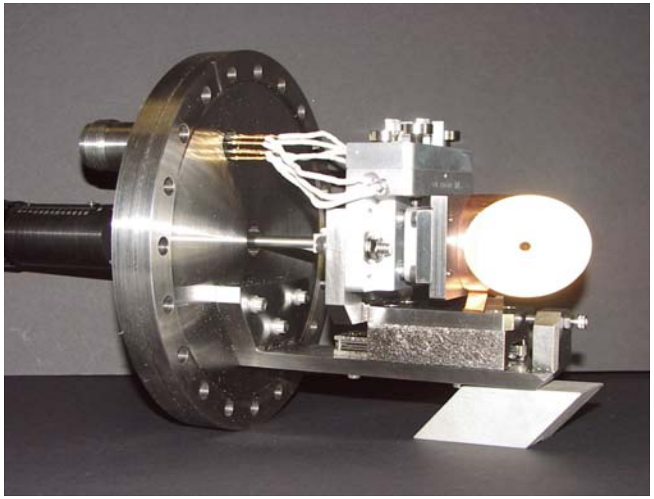
Thomson parabola TR1 Is installed already.

Additionally radiochromic film (RCF) and CR39 stacks would be used on some individual shots to characterise a beam divergence.

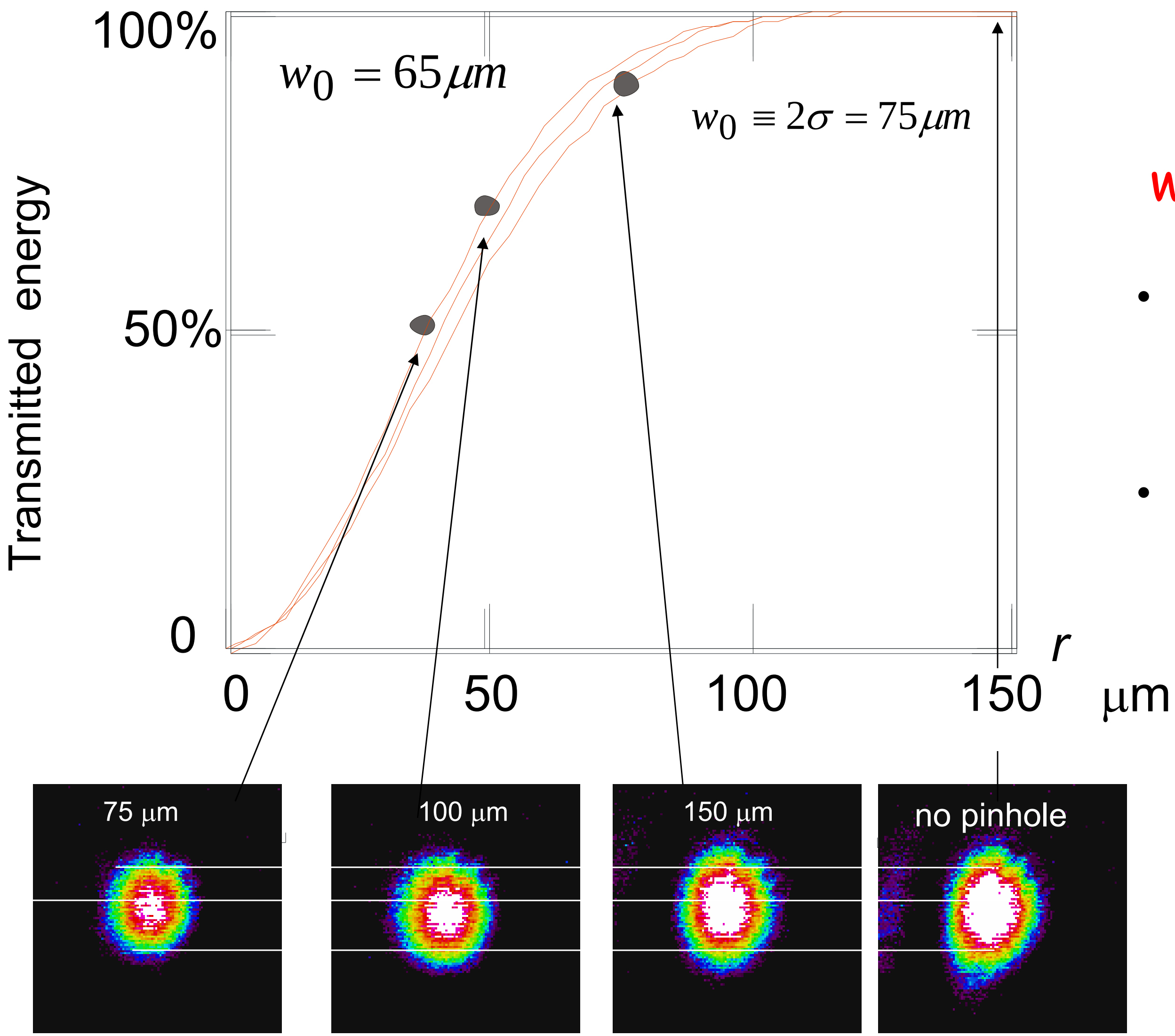




Laser focus produced with $f_{\#}=2$ parabola



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 μm – best fit

- 1.5×10^{16} W/cm^2 @ 1 TW
- a_0=1 @ λ=10 μm
  - 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.