Modification of Gas Jet Density Profile with Hydrodynamic Shocks for CO2 Laser Ion Acceleration* in ATF Experiment AE35

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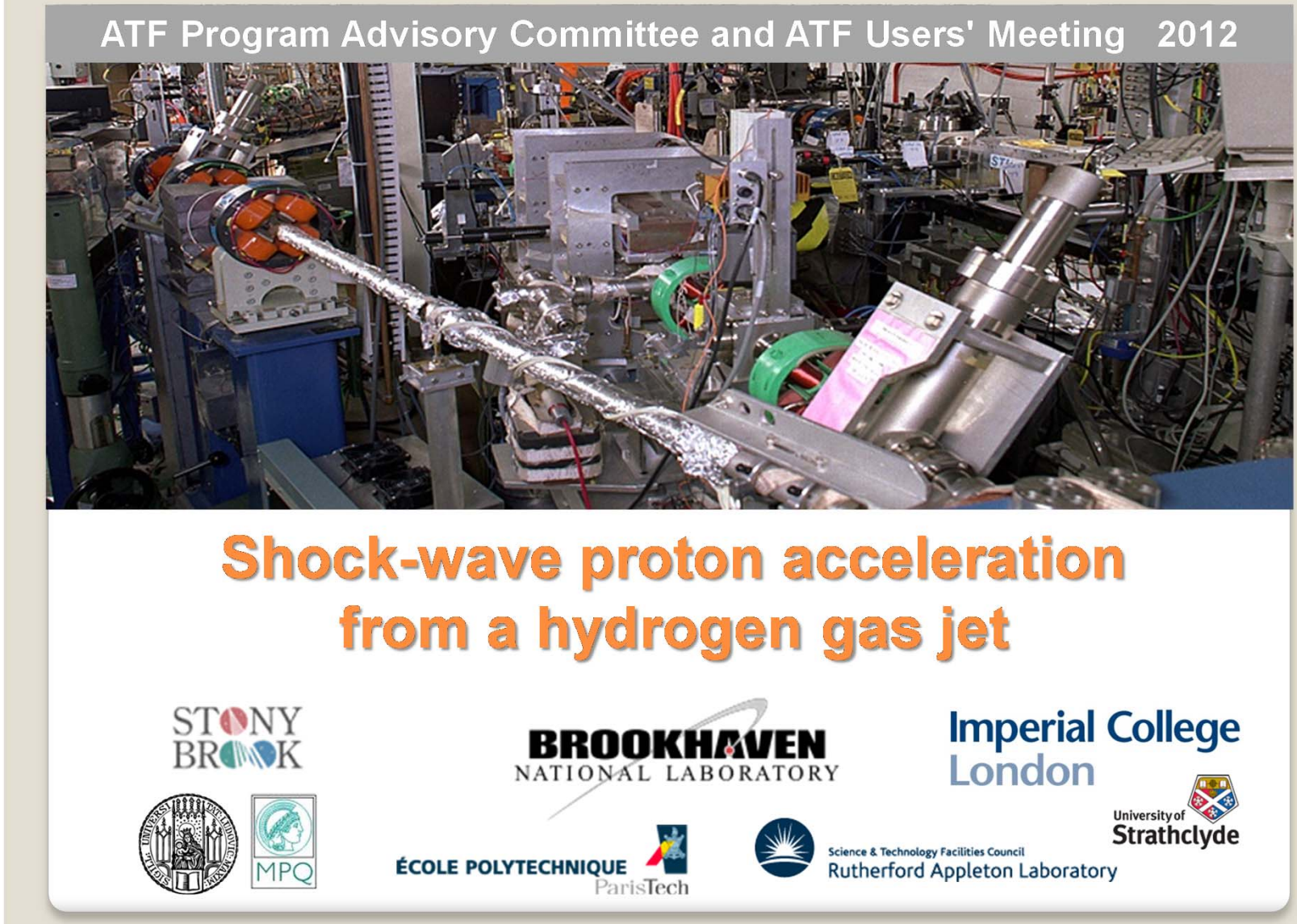
ATF Experiment AE35



Outline

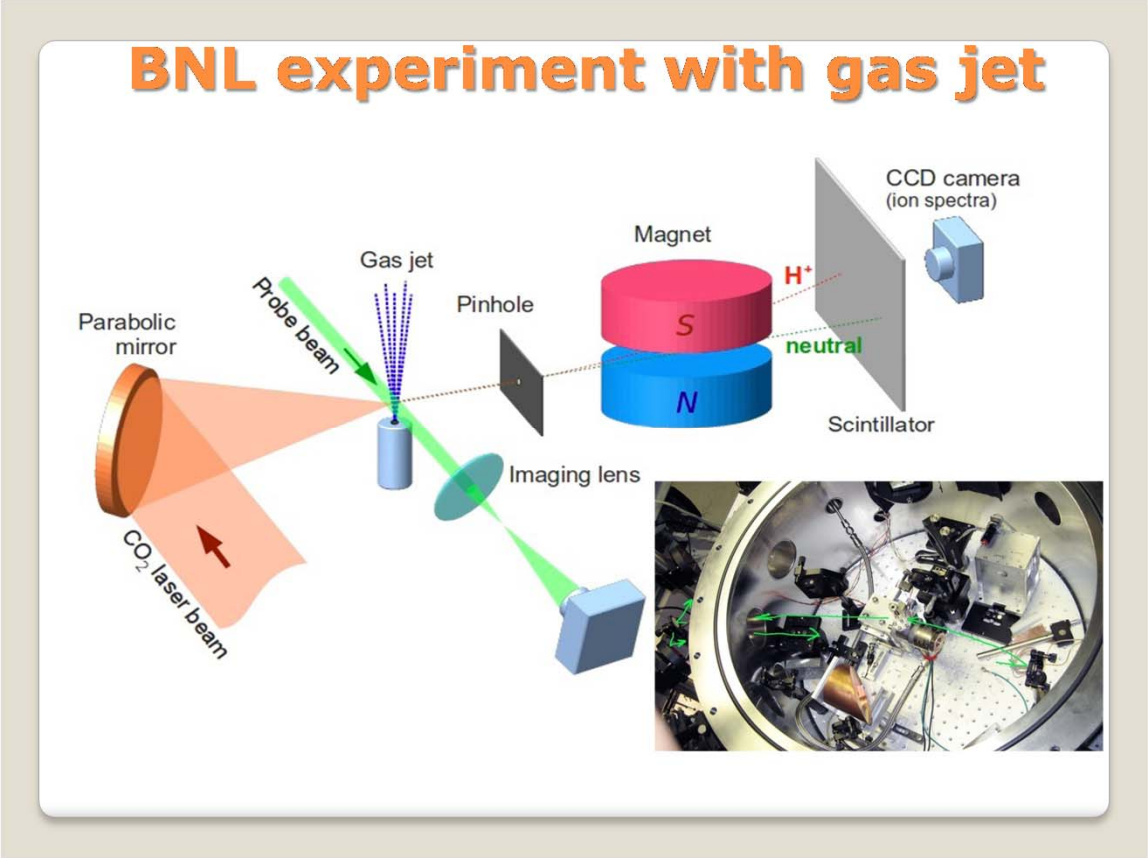
- Objectives
- Introduction
- Approach
- Tasks
- Beam/Laser time request
- Conclusions

Objectives

- To modify the plasma density profile and examine the effects of sharp density gradients on the acceleration of ion from gaseous targets as part of the CO2 laser ion acceleration experiment (AE35).

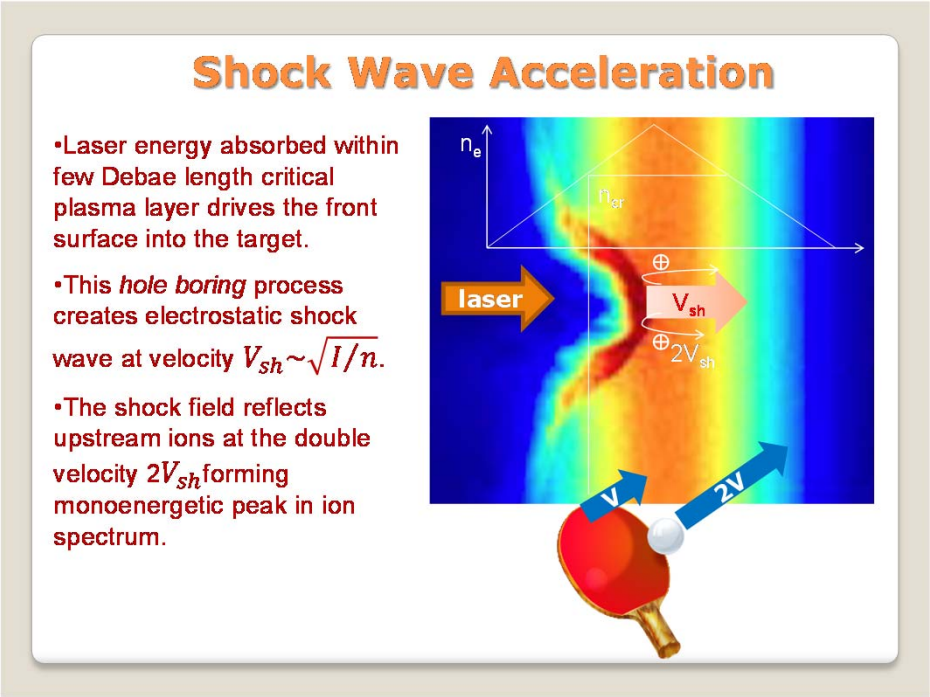
Introduction

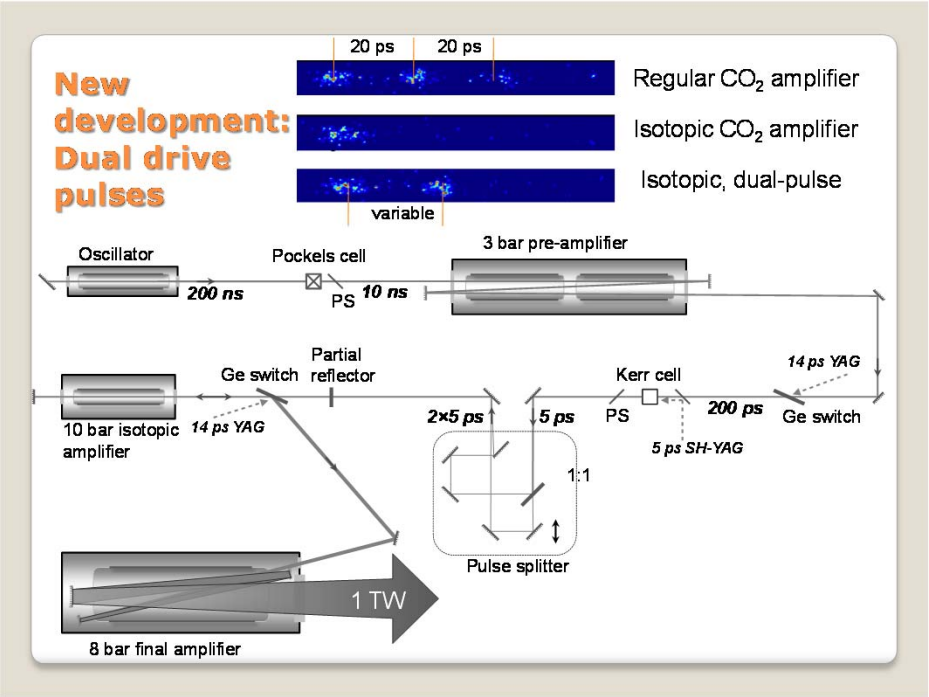
- Most laser ion acceleration schemes require critical density plasma and use solid targets that are single shot and hard to make
- Gas jet provides infinite supply of targets but plasma density can be too low
- CO2 laser can reach critical plasma densities in gas jets.



Shock Wave Ion Acceleration

- Ions can be accelerated by shock wave generated by CO2 laser in plasma
- Double CO2 laser pulses are used, one to form shock, the other to accelerate shock
- Not an efficient way of using the CO2 laser energy



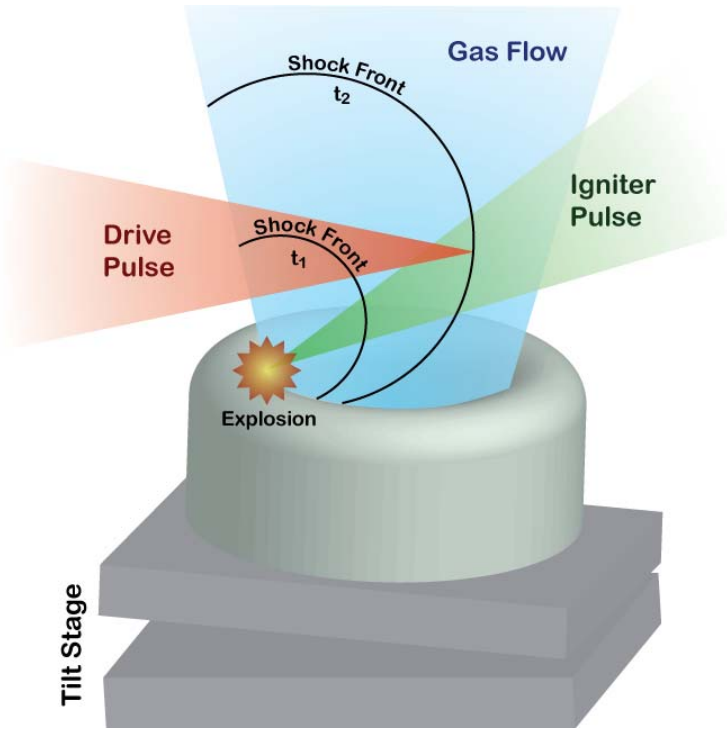


Benefits of a Preformed Plasma Density Profile

- Sharp front gradient reduce ionization defocusing generating smaller laser spot size
- Better laser plasma coupling as sharp gradient simulates solid target conditions
- Sharp rear gradient generates well defined charge separation in TNSA type situations
- Sub-critical or above-critical plasma densities can be generated for various ion accelerating laser wavelengths
- Various plasma density profiles can be generated by adjusting timing of the hydrodynamic shock and the gas jet geometry

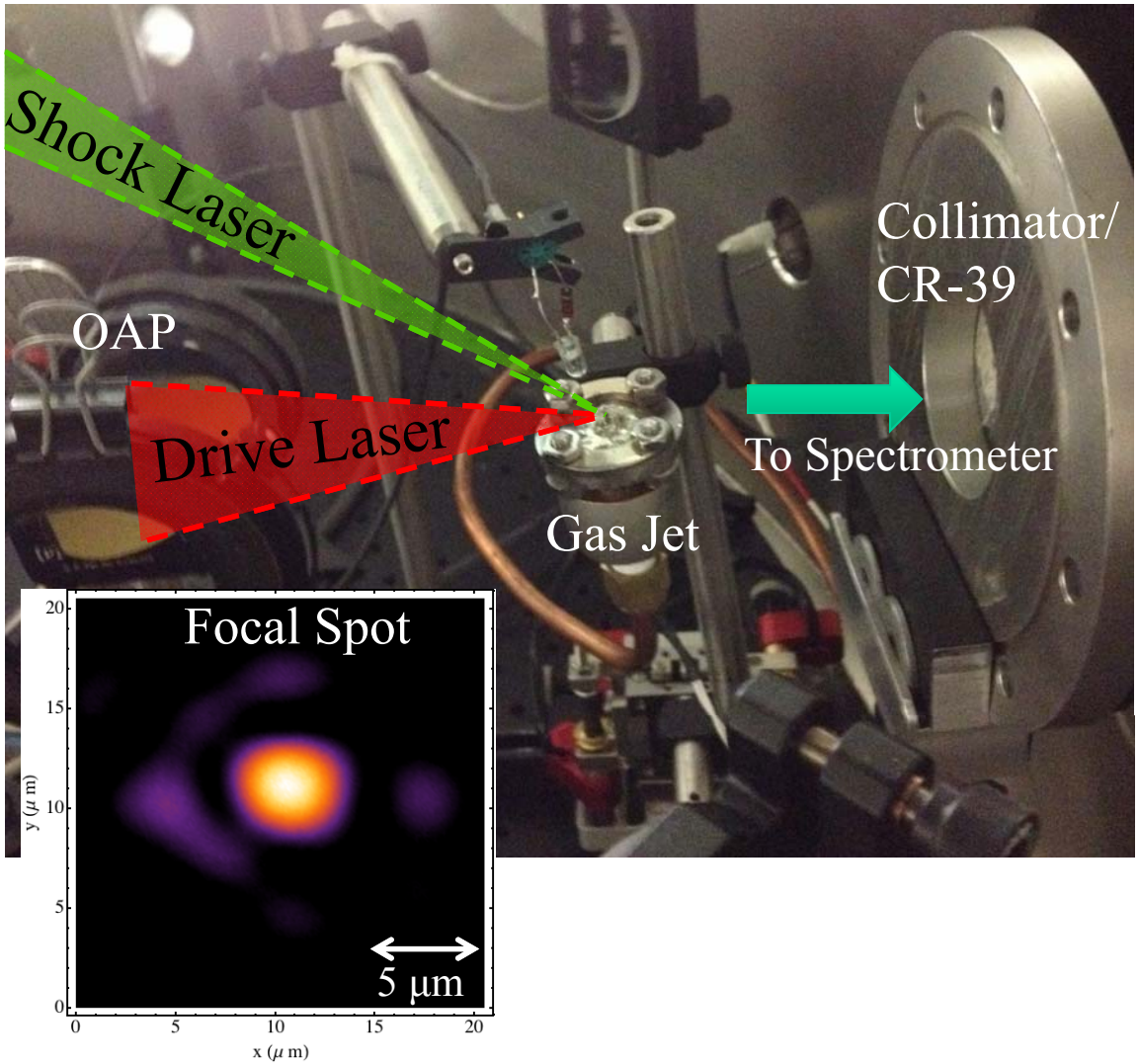
Near Critical Plasma from Gas Jets

- Start with supersonic gas jet
- Ignition pulse drives hydrodynamic shock
- Shock wave produces large density gradients (~50 μm)
- Local density enhancement of $\gamma+1 / \gamma-1$ times ambient



D. Kaganovich, M. H. Helle, D. F. Gordon, and A. Ting, "Measurements of colliding shock wave and supersonic gas flow," Appl. Phys. Lett. **97**, 191501 (2010)

Hydrodynamic Shock Generation and Experiment at NRL



Experimental Parameters

Drive Laser :
λ = 800 nm
E = 500 mJ
τ = 50 fs
f# = 2 (OAP)
r_0 = 2.6 um
I = $1.0*10^{20}$ W/cm^2 ($a_0 \sim 6$)

Gas Jet:
Diameter = 1 mm
Pressure = 100-1200 PSI

Plasma Diagnostics:
Schlieren Shadowgraphy
Interferometry

Measurement of Hydrodynamic Shock Density

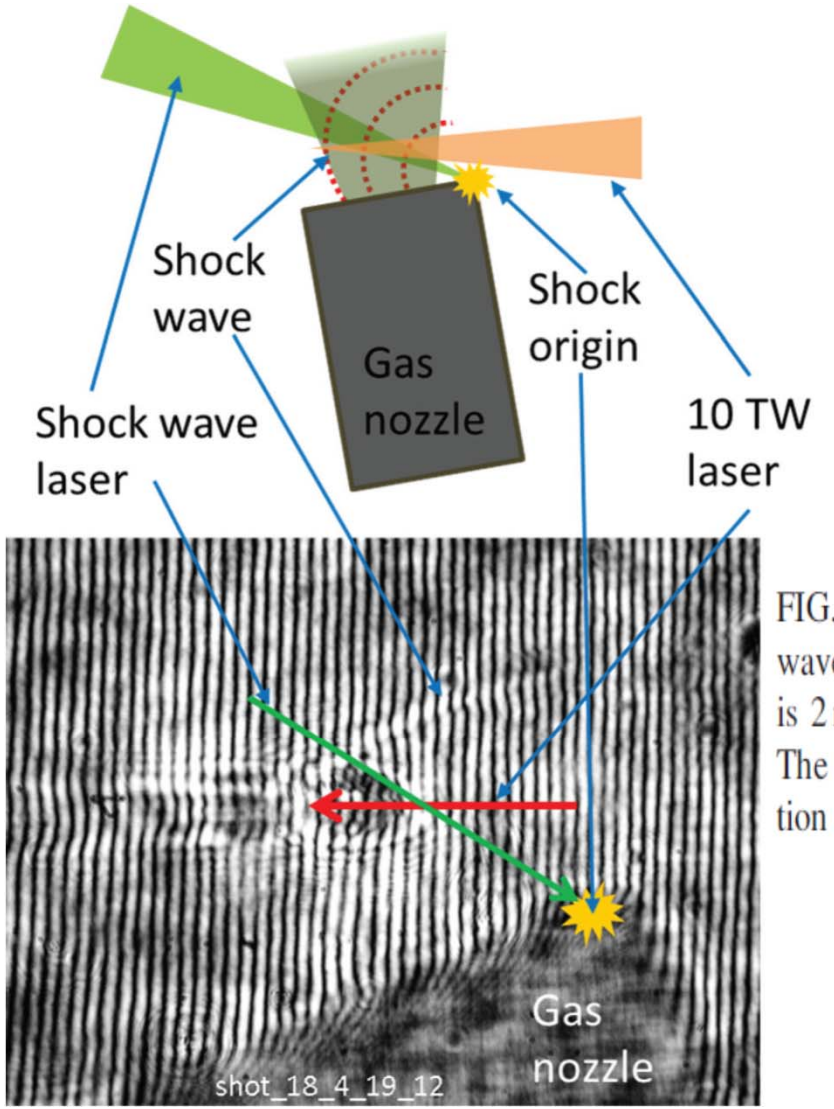
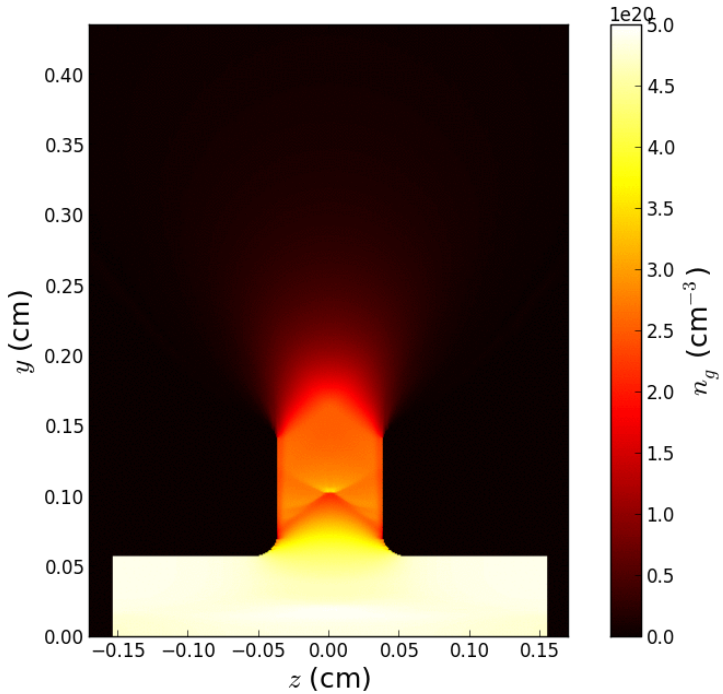


FIG. 1. Experimental setup and typical interferometry image of the shock wave and laser generated plasma. The total width of the interference image is 2 mm. The estimated energy deposited into the shock wave was 1.5 mJ. The fringe shifts along the 10 TW laser path are formed by the laser ionization of the gas molecules.

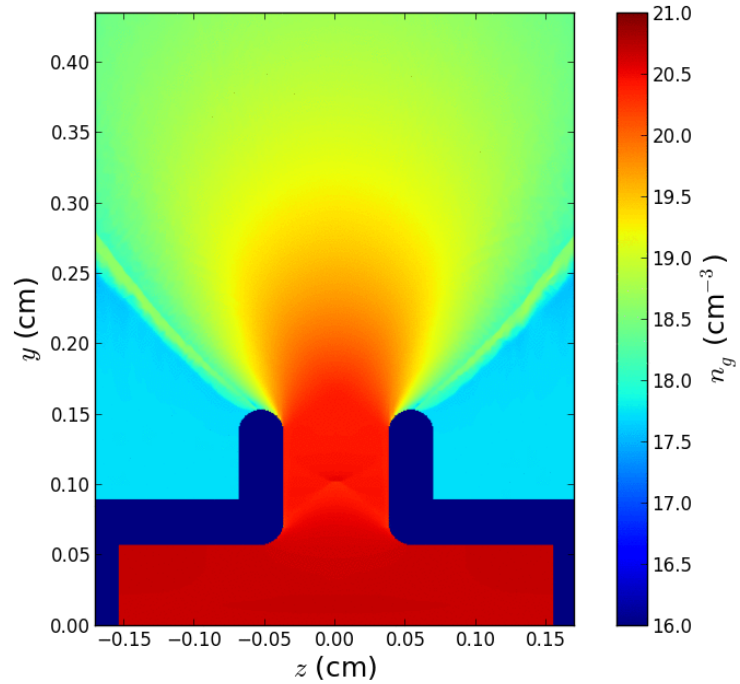
D. Kaganovich, D.F. Gordon, M.H. Helle, and A. Ting, "Shaping gas jet plasma density profile by laser generated shock waves", J. Appl. Phys. 116, 013304(2014)

3D SPARC Simulations of Shock Wave in Gas Jet

Linear scale



Logarithmic scale



SPARC (Streamer Propagation and ARCing) code

- Fully nonlinear gas dynamics, including viscosity and heat conduction
- Arbitrarily shaped walls around/within flow region
- Multi-temperature chemical kinetics

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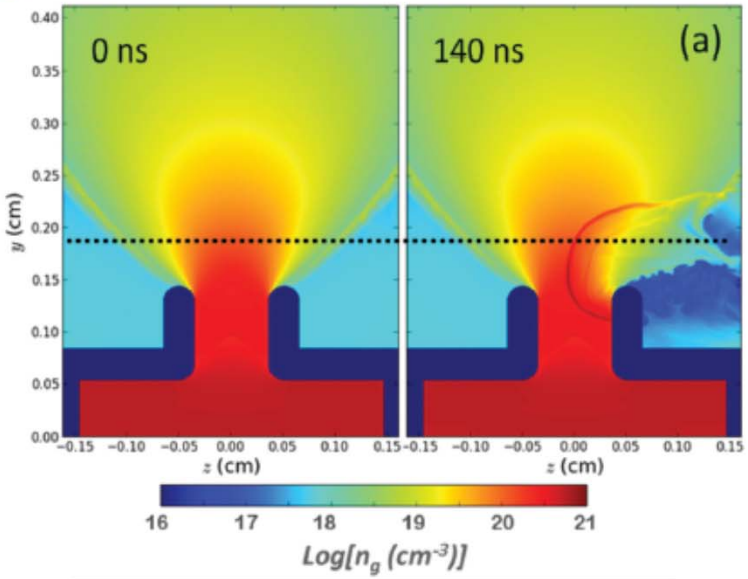
3D SPARC Simulations of Shock Wave in Gas Jet



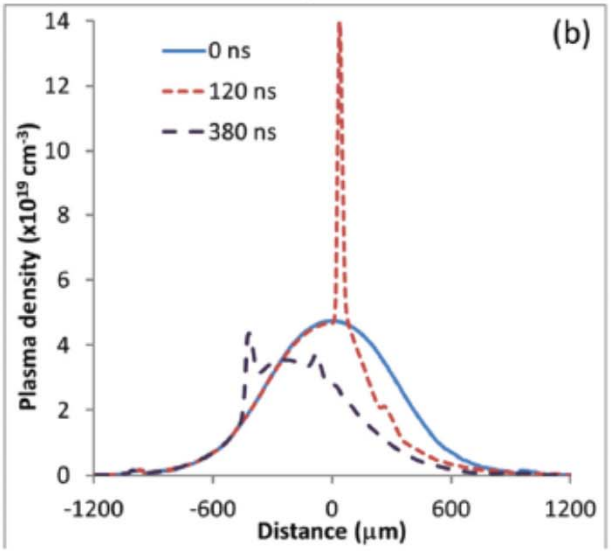


FIG. 3. SPARC simulation of shock propagation in gas jet flow, showing (a) false-color images of gas density in a plane that bisects the nozzle and the shock wave initiation point, and (b) lineouts of the gas density along the dotted line in (a) at different times. Lineouts for the different tilt angles presented in Figures 4–6 were acquired by tilting the dotted line to the corresponding angle. The energy deposited into the simulated shock wave was 2.6 mJ. Note that the flow creates a weak shock of its own, roughly in the form of a Mach cone emanating from the nozzle. This explains the small bump in the simulated density curves at −1600 μm in Figure 4.

D. Kaganovich, D.F. Gordon, M.H. Helle, and A. Ting, "Shaping gas jet plasma density profile by laser generated shock waves", J. Appl. Phys. 116, 013304(2014)

Comparison of Simulation and Experiment

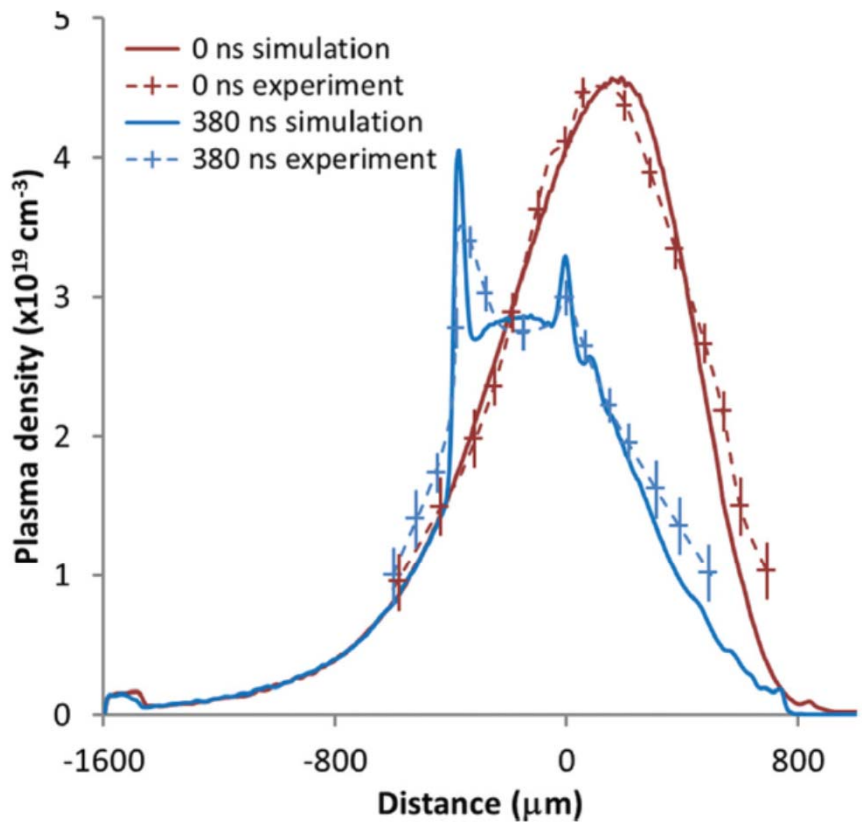


FIG. 4. SPARC simulations and experimental measurements of gas density profiles. The nozzle was tilted 20° in both experiment and simulation, the gas density was measured 0.5 mm above the nozzle. The shock wave originated at the 400 μm position and propagated left. The energy deposited into both experimental and simulated shock waves was 2.6 mJ. Error bar of the experimental points corresponds to the measurement and data retrieval uncertainties.

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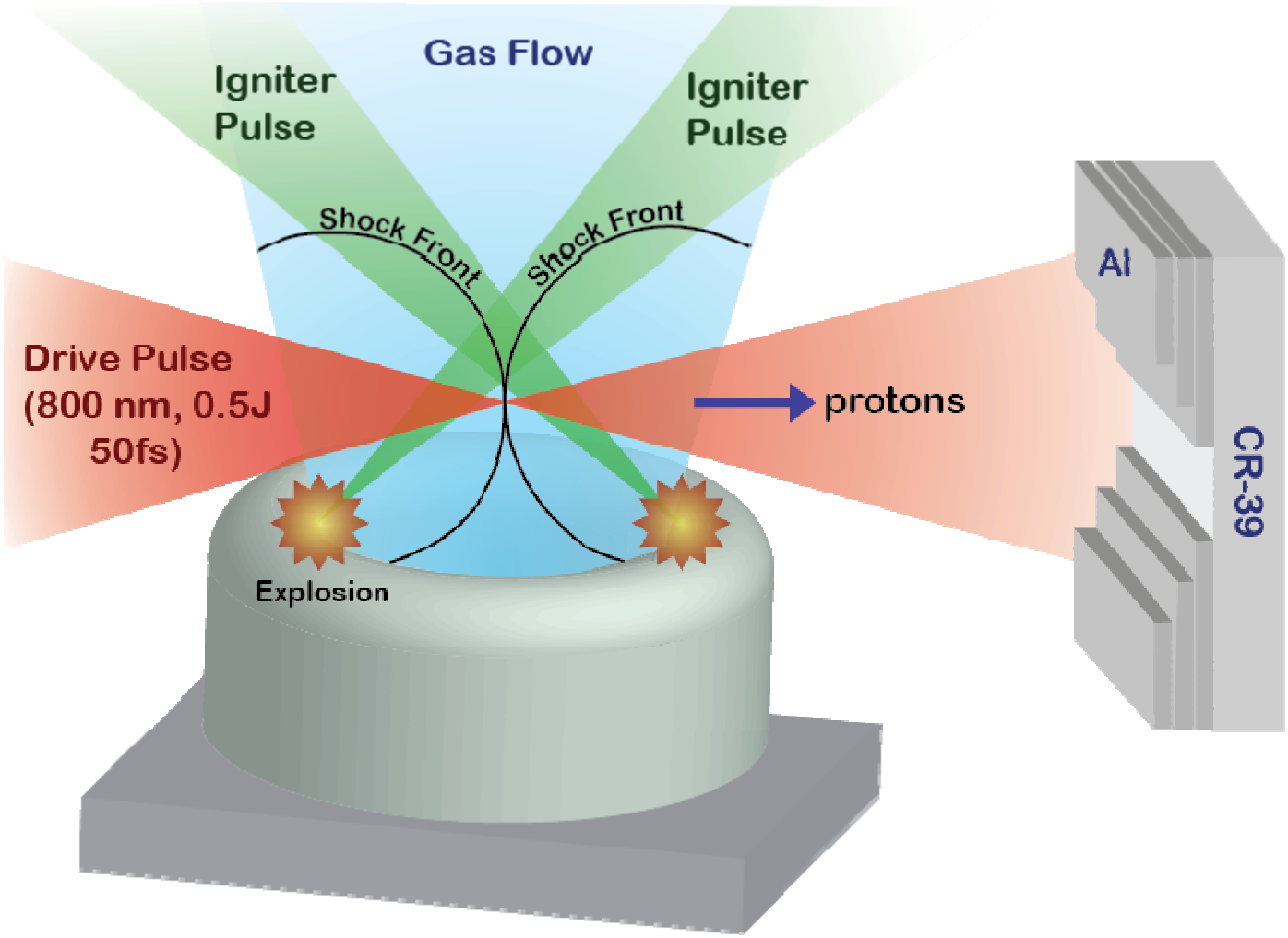
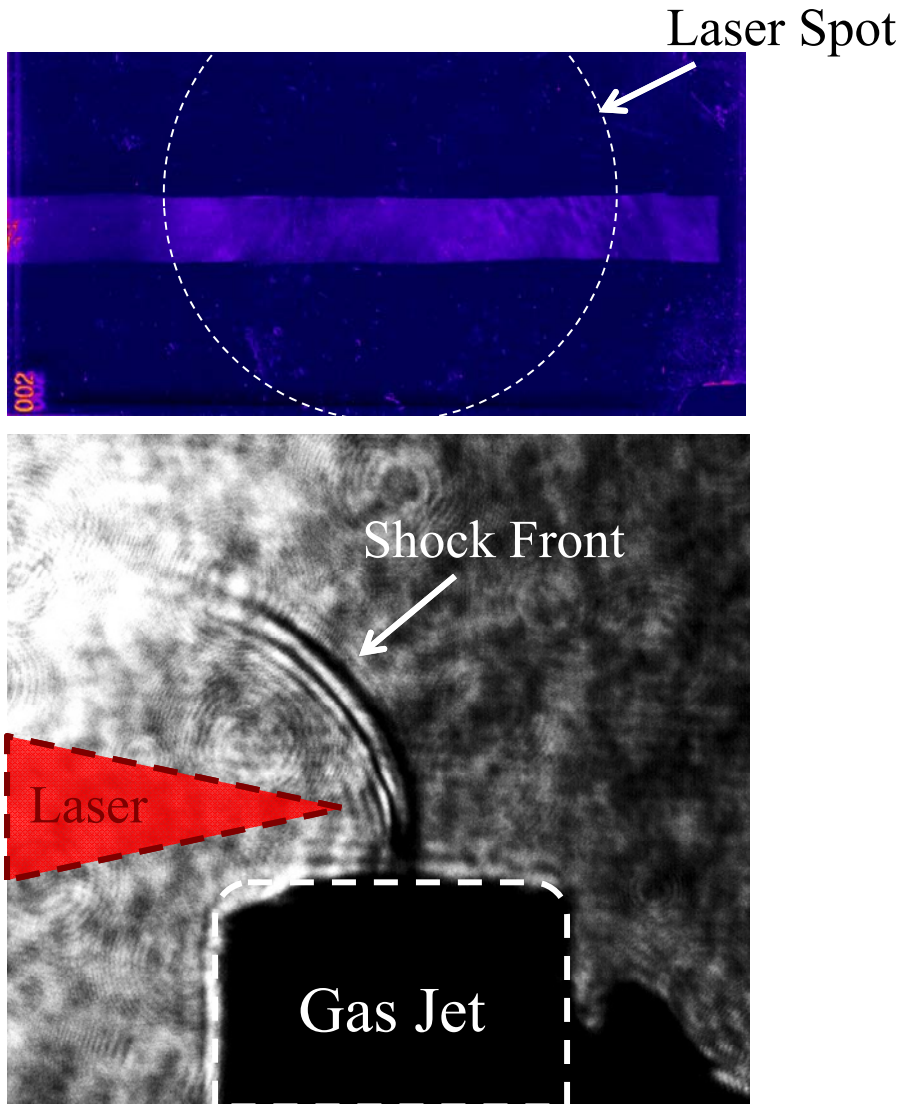
NRL Experiment of Laser Accelerated Protons

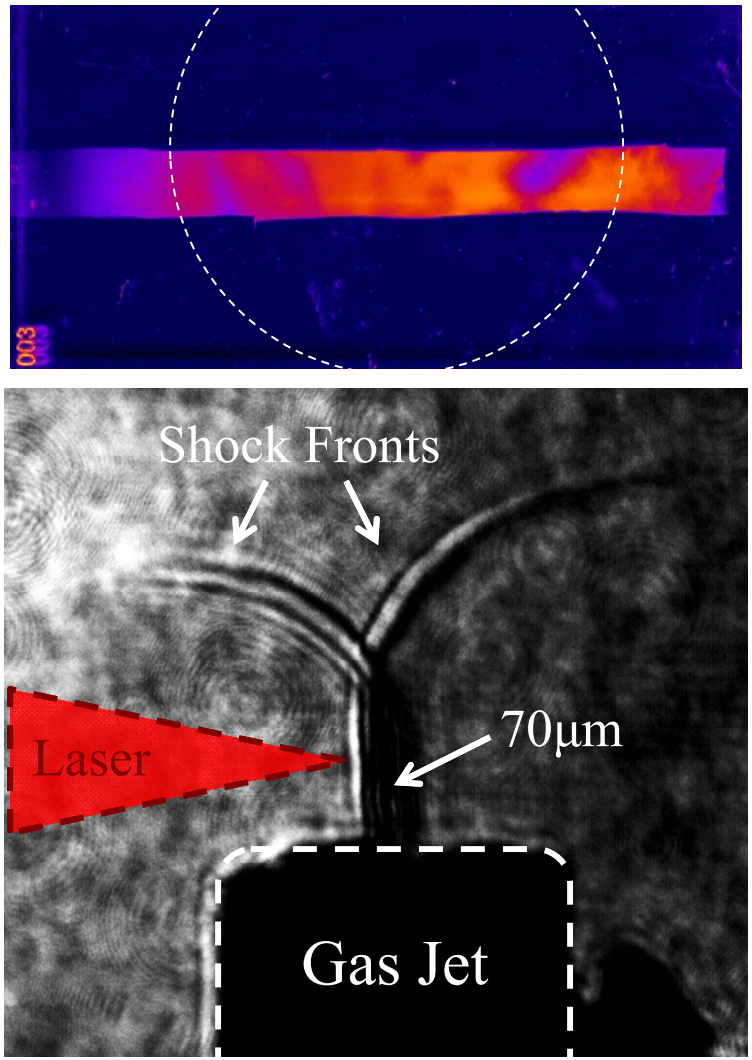


M.H. Helle, DD.F. Gordon, . Kaganovich, A. Zingale and A. Ting, "Accelerated Protons from Near Critical Density Gaseous Targets", submitted to 2014 AAC Workshop Proceedings (2014)

Hydrodynamic Shocks for Ion Acceleration



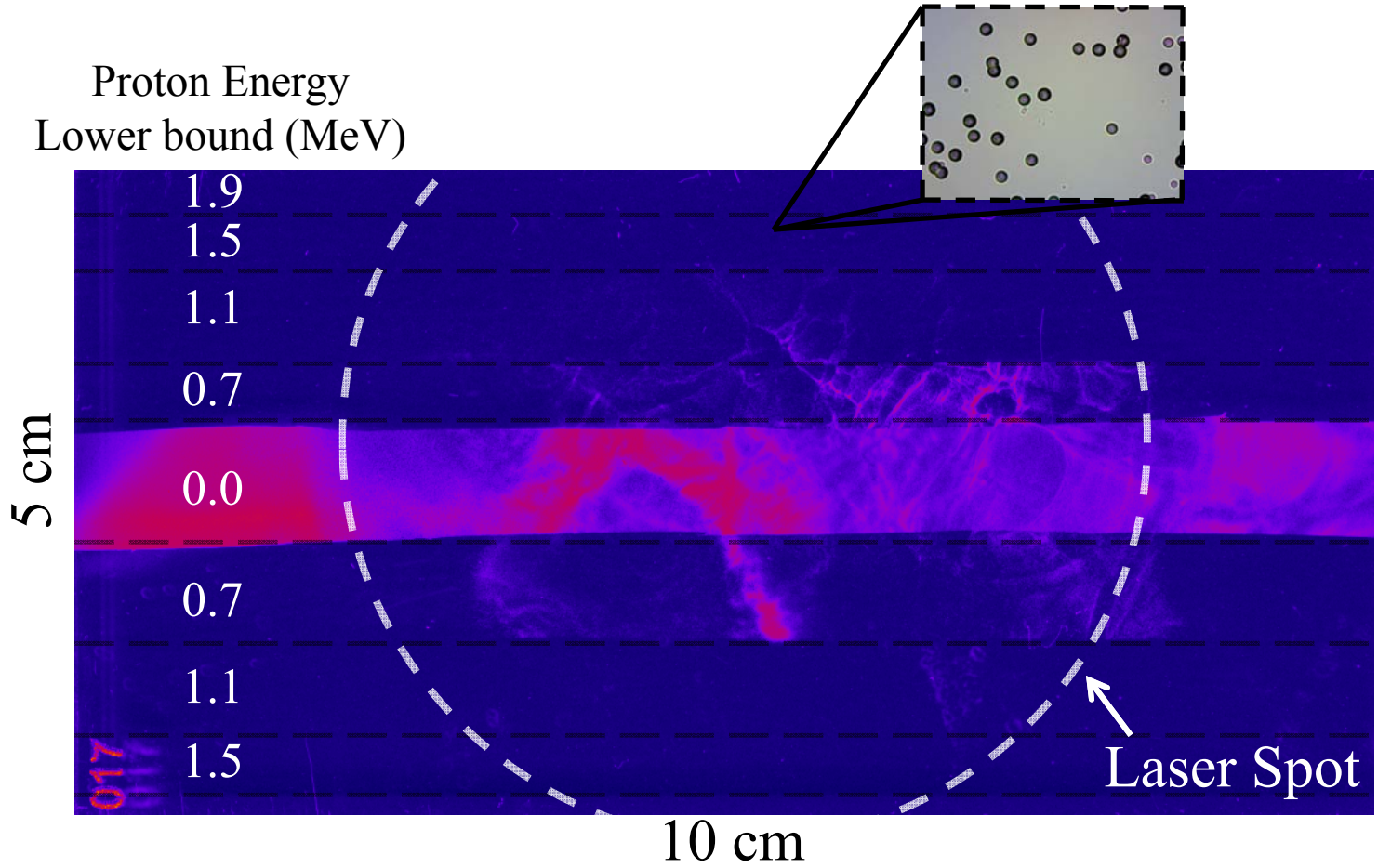
Single Shock



Colliding Shocks

A. Ting, Nov. 9, 2011

Accelerated Protons



- Low energy protons extending beyond laser spot
- Energetic protons between 1.5-1.9 MeV contained within laser cone
- Pit counting underway to extract beam characteristics
- Scanning parameter space for efficient acceleration

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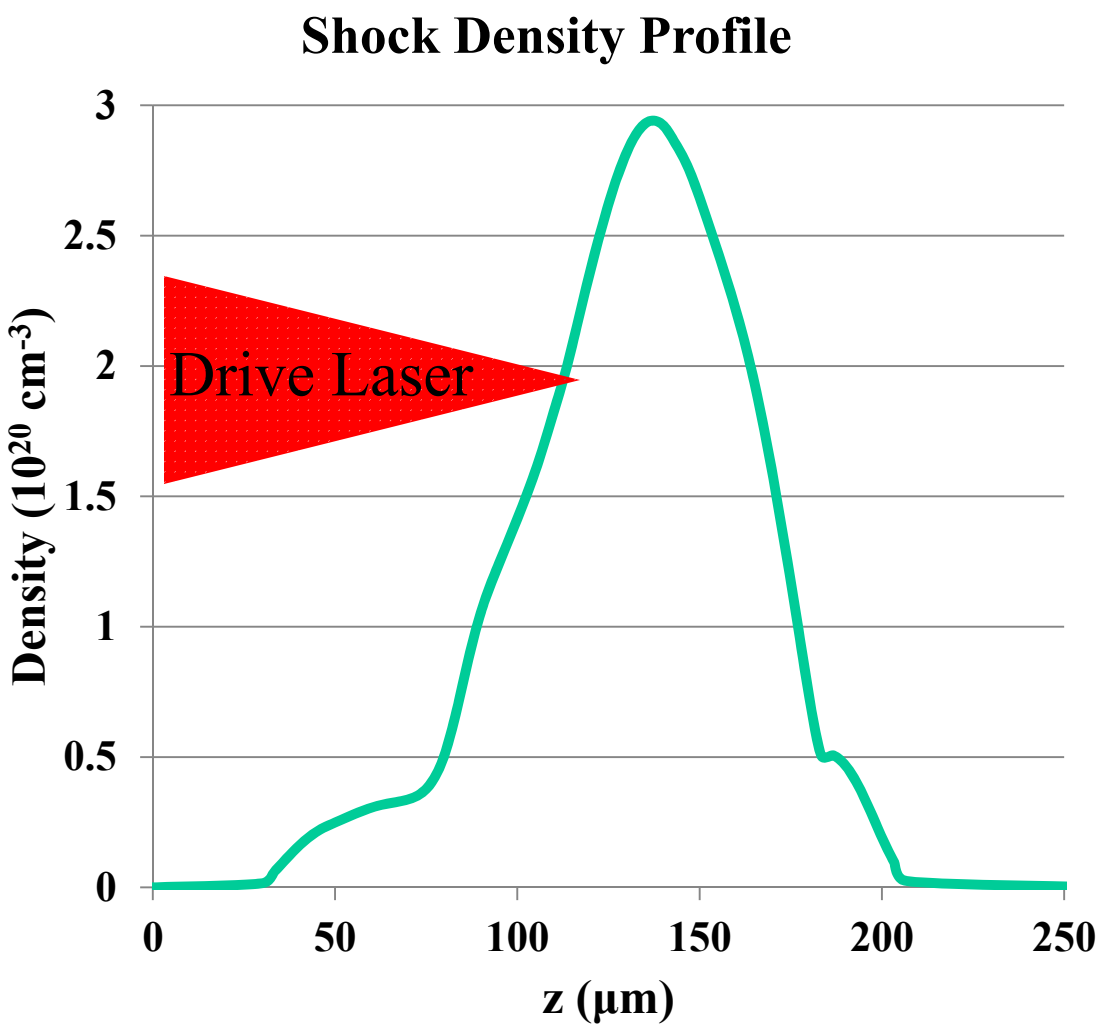
Simulated Interaction



Experimental density profile (peak at 0.34 n_c) used as input in TurboWAVE PIC Code

Drive Pulse Parameters:

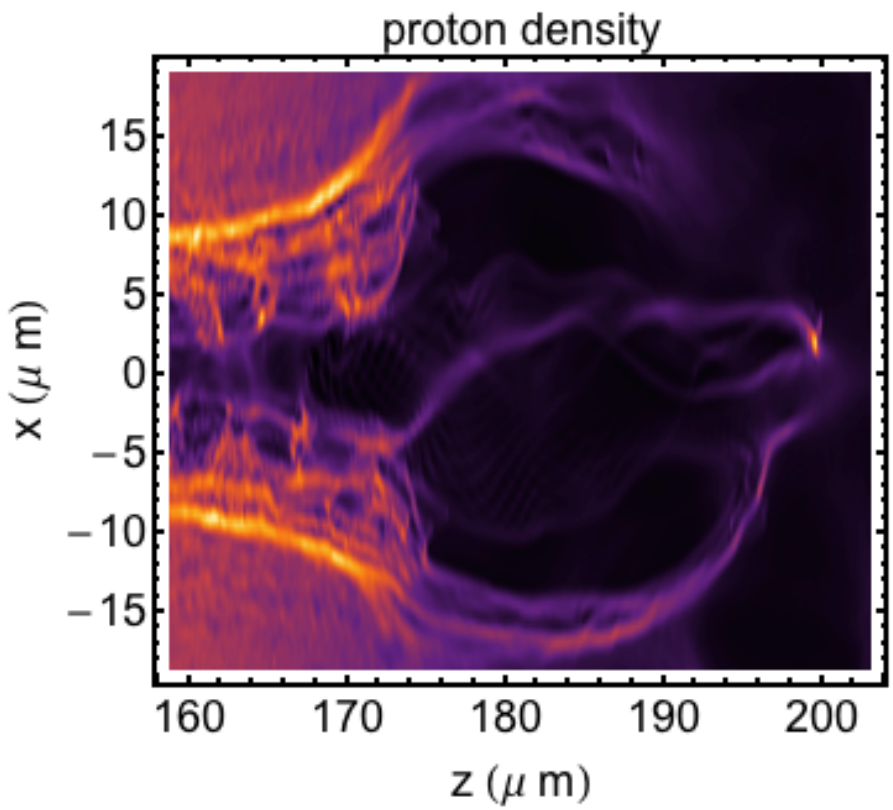
λ = 800 nm

τ = 50 fs

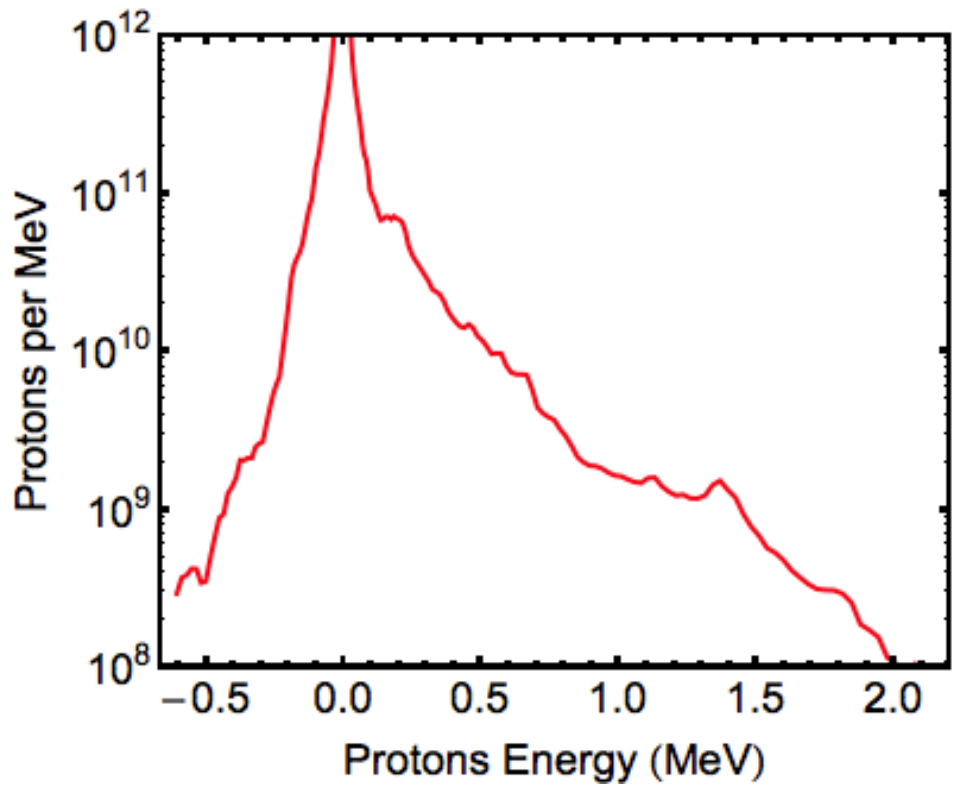
r_0 = 3 um

a_0 = 4

Simulated Accelerated Protons



Proton Density
(Exit end of plasma region)

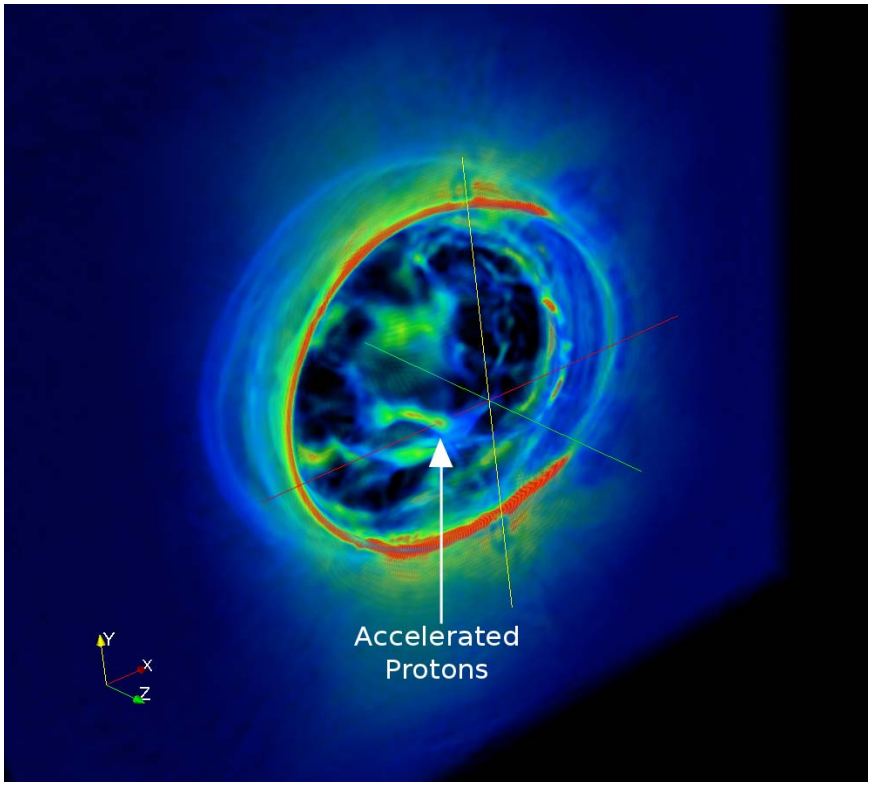


Proton energy peaked at 2 MeV

M.H. Helle, DD.F. Gordon, . Kaganovich, A. Zingale and A. Ting, "Accelerated Protons from Near Critical Density Gaseous Targets", submitted to 2014 AAC Workshop Proceedings (2014)

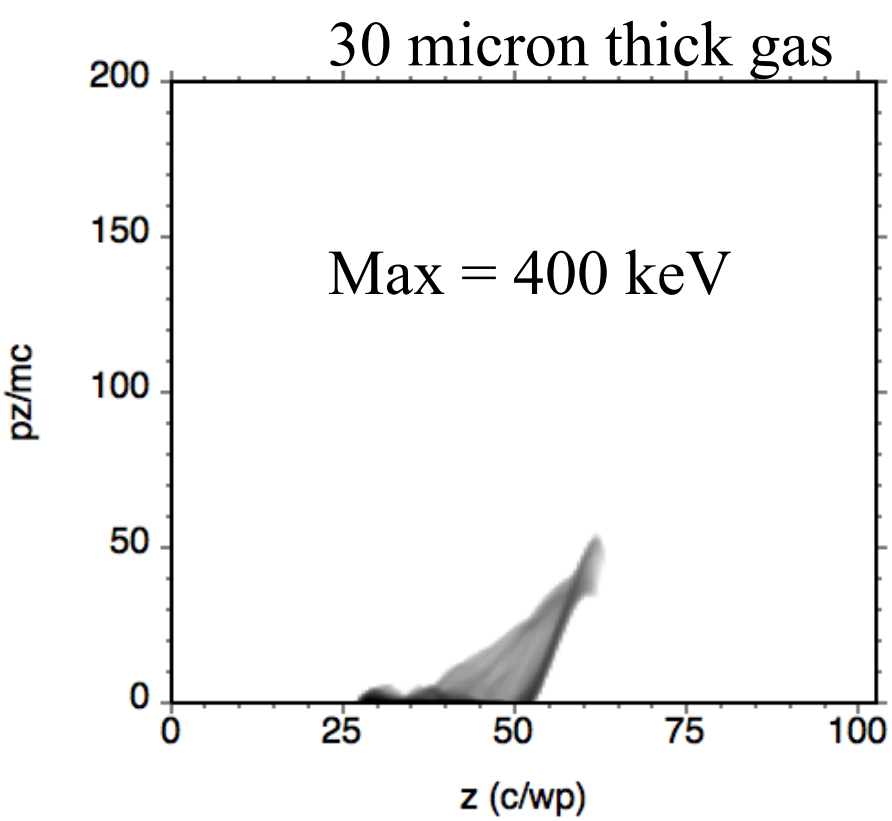
CO2 Laser Ion Acceleration Simulation

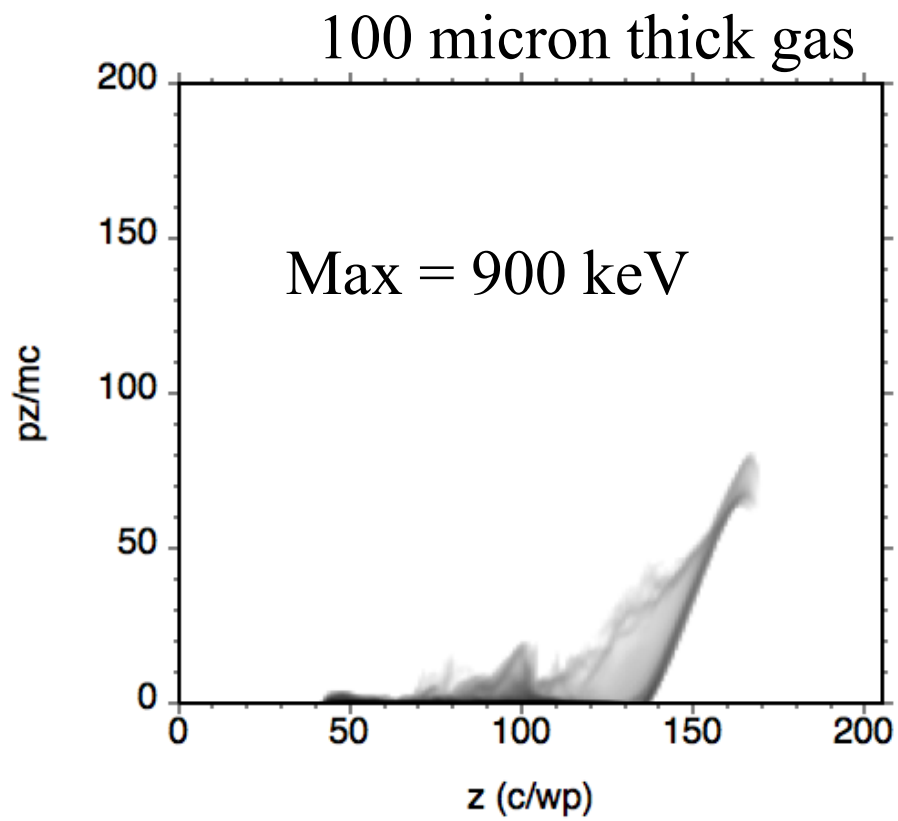
3D View in 30 Micron Thick Case



Laser Energy= 1 Joule
Laser Pulse Width = 100 fs
Laser Power = 10 TW
Laser Spot = 30 microns
Gas Thickness = 30 microns/100 microns
Plasma Density = half-critical

Comparison of Acceleration





A. Ting, Nov. 9, 2011

Scaling with Wavelength for Ion Acceleration

- CO2 laser wavelength ~10 time longer than Ti:Sapphire laser
- The plasma density should be 100 times lower
- Same energy protons should be obtained using a system where all the dimensions are 10 times larger, and the time scales are 10 times longer.
- 500 micron plasma region and 500 fsec laser pulse needed
- The charge obtained can be 10 times greater, but the laser energy required is also 10 times larger (a_0 stays fixed)
- 5 J, 1/2-psec CO2 laser pulse in a 1/2-mm sub-critical gas region
- Thicker plasma region already available from the gas jet
- Only need one hydrodynamic shock to sharpen front gradient

Approach

- Generate hydrodynamic shock using a nsec laser as ignition laser
- Initial shock configuration is to sharpen front density gradient
- Adjust ignition laser delay time from CO2 drive laser while monitoring plasma density profile (over critical density) and shock front location
- Adjust CO2 laser pulse characteristics to optimize ion acceleration.
- Generate sub-critical peak plasma density to access different ion acceleration mechanisms
- Vary hydrodynamic shock configuration to have a sharp rear density gradient to study effect on ion acceleration
- Compare experiment to simulations
- Continue experiments when ATF II upgrade CO2 laser is available

Hydrodynamic Shock Generating Laser

New Wave Laser:
$\lambda = 532$ nm
E = 45 mJ
$\tau = 5$ nsec

Tasks

1) Installation of nsec laser at the ion acceleration experimental set up. Laser is provided by NRL.
2) Alignment of nsec laser into chamber.
3) Set up of shadowgraphy/interferometry to image hydrodynamic shock for timing adjustment with respect to CO2 laser pulse and to measure the gas density profile.
4) Measure ion acceleration characteristics as a function of different density profiles, such as sharp front gradient or sharp rear gradient.
5) Analyze ion acceleration data and compare with simulations.
6) Prepare manuscript to document results for publication.

Beam/Laser Time Request

- Concurrent with allocated beam time for AE35
- First two weeks of November, 2014
- Set up time is projected to be one week, tentatively scheduled for the week of October 27, 2014

Conclusions

- NRL proposes to incorporate a hydrodynamic shock generation capability in the existing AE35 experiment of ion acceleration in a gas jet using the ATF CO2 laser
- The purpose of the hydrodynamic shock is to modify the plasma density profile and examine the effects of sharp density gradients on the acceleration of ion from gaseous targets
- The hydrodynamic shock generation mechanism has been well studied at NRL.
- Ion acceleration using a Ti:Sapphire laser in a hydrodynamic shock has been observed at NRL.
- Using a hydrodynamic shock can be beneficial to ion acceleration using CO2 laser, such as better laser plasma coupling for ion acceleration.
- NRL will provide the ignition laser for generating the hydrodynamic shock.
- Requested beam time is concurrent with AE35.