Ion acceleration with optically shaped gas jets using the ATF CO_2 laser - AE66

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Ion acceleration experiments - AE66

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BROOKHAVEN NATIONAL LABORATORY
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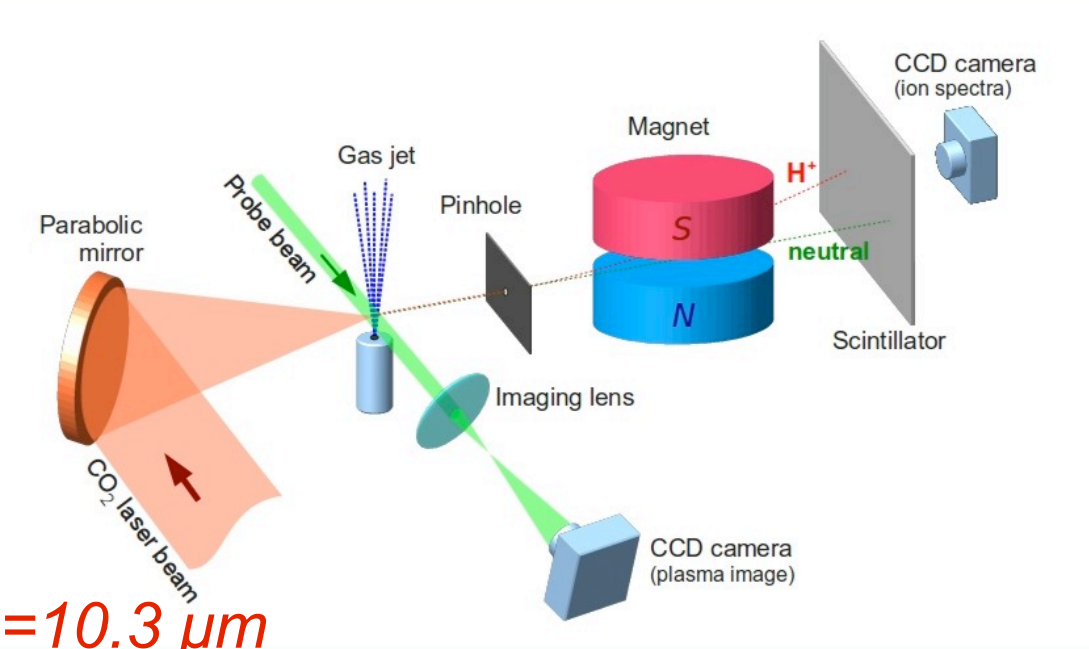
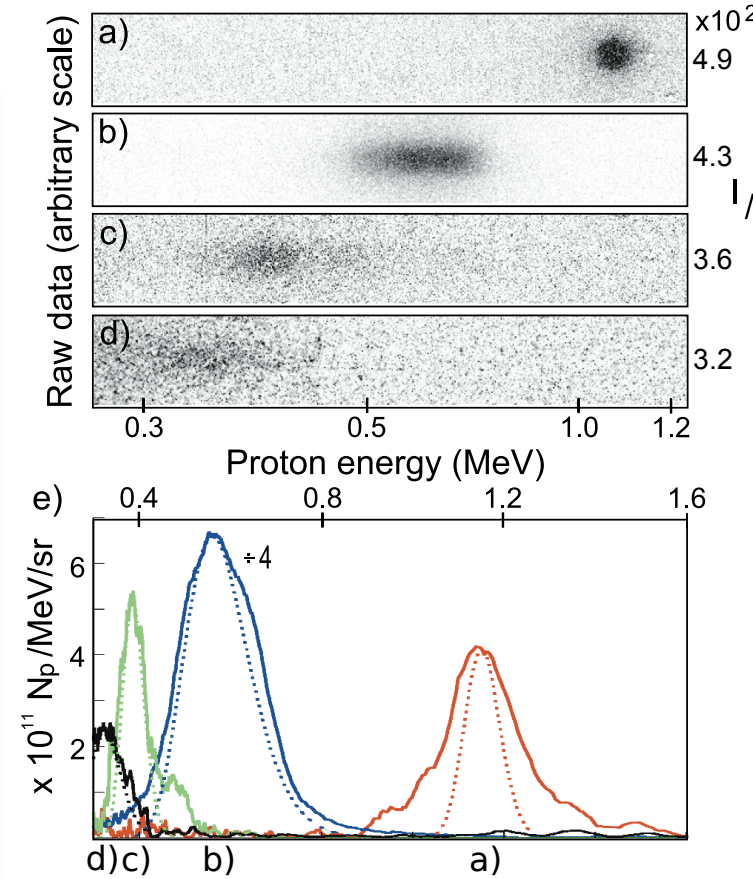
N. Cook, C. Maharjan, P. Shkolnikov

NAVAL RESEARCH LABORATORY WASHINGTON, DC

Y-H. Chen, D. Gordon, M. Helle, A. Ting

First experiments

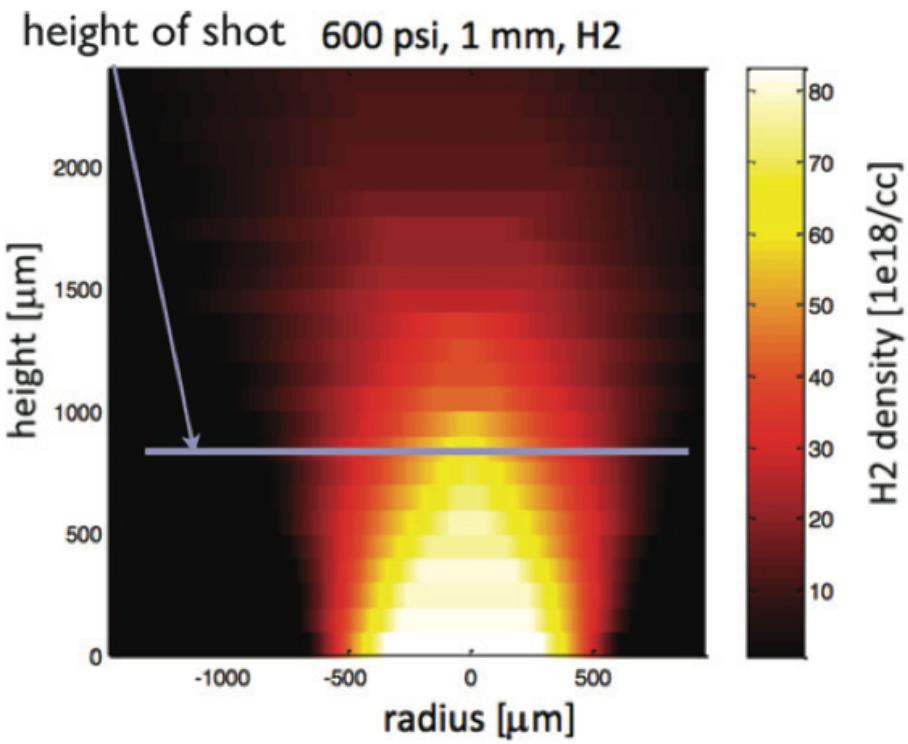


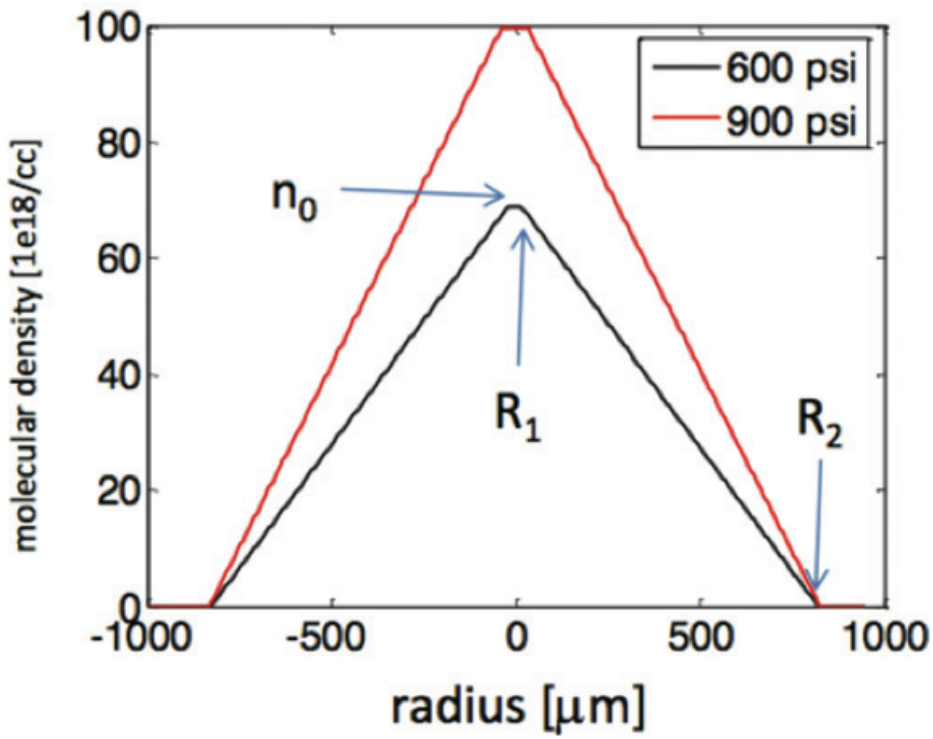


λ=10.3 μm
Pulse length=6 ps
Spot size = 70 μm
Intensity ~ 10^{16} W/cm^2

*See: Palmer, Dover, Pogorelsky et al., PRL, **106,** 014801(2011)*

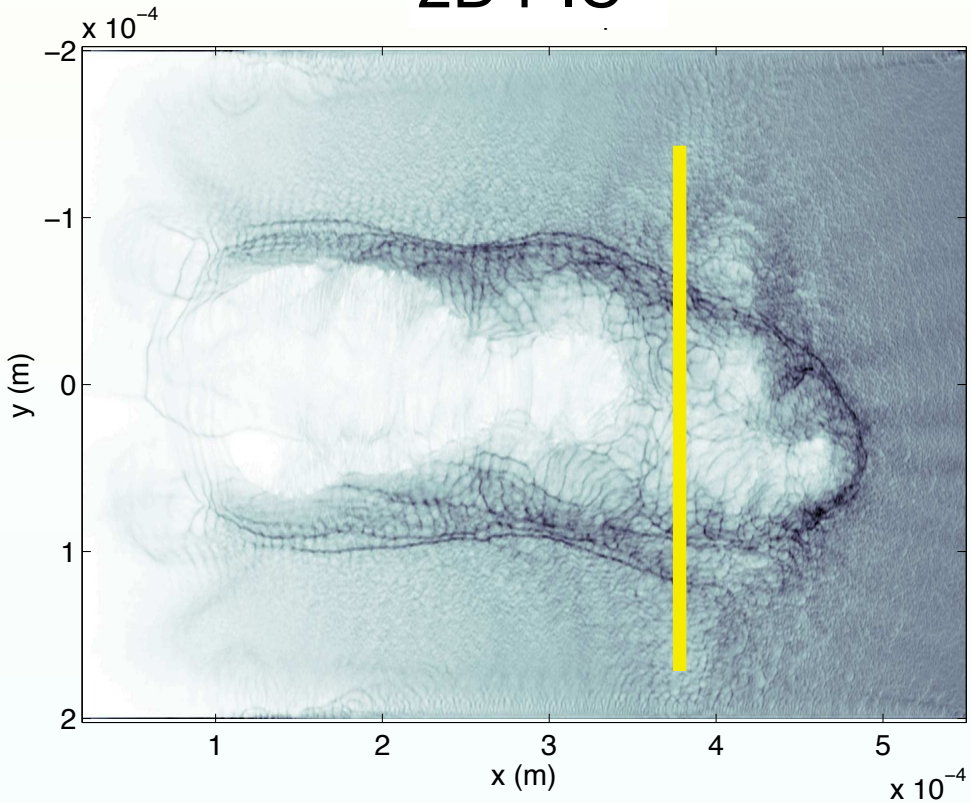
Typical Gas profile



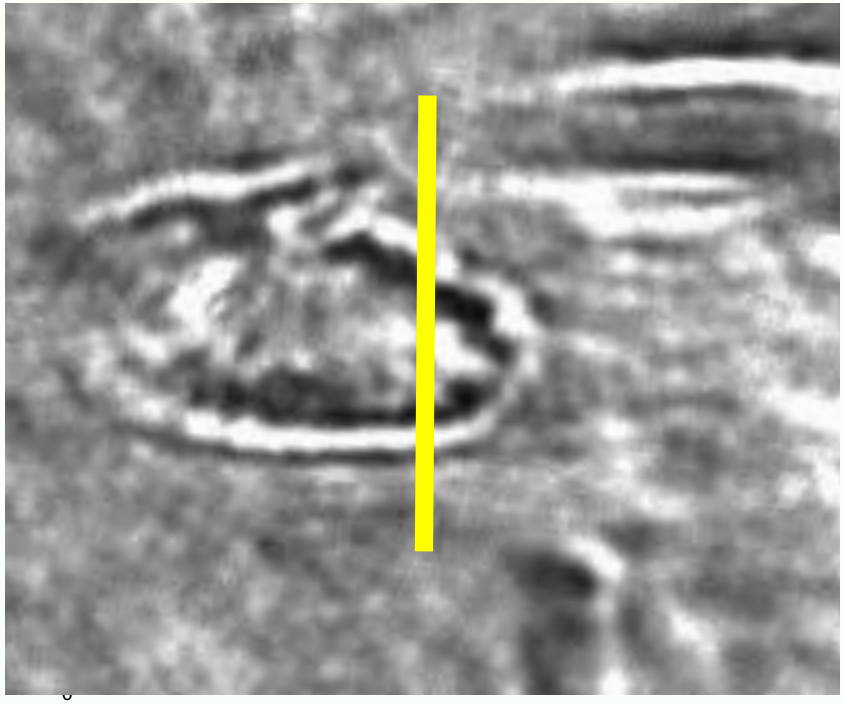


2D PIC no prepulse

2D PIC

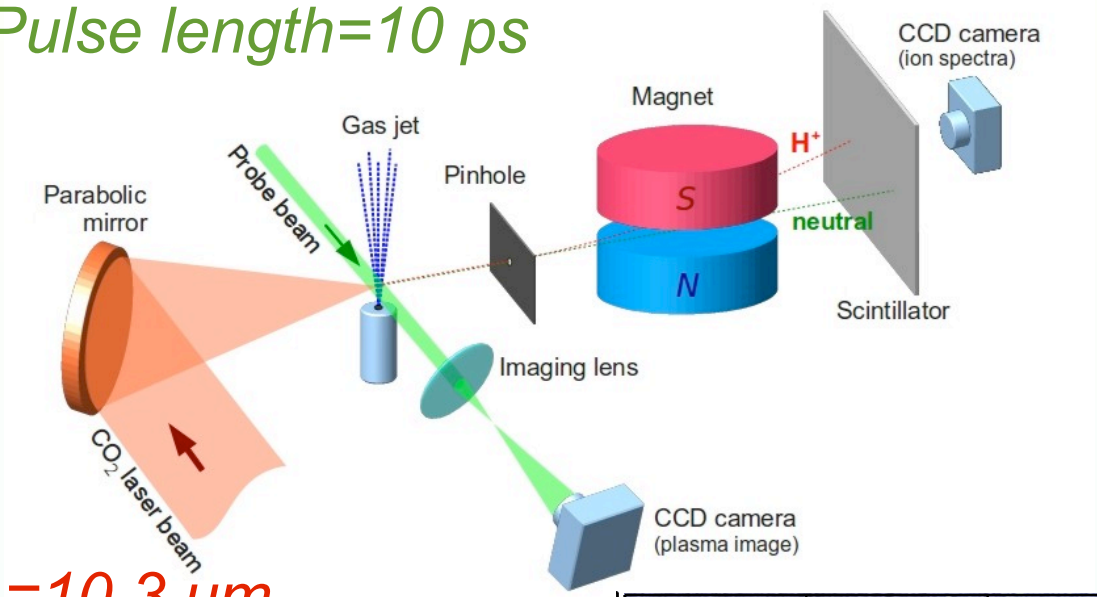


Experiment



Placeholder

λ=527 nm
Pulse length=10 ps



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Spot size = 70 μm
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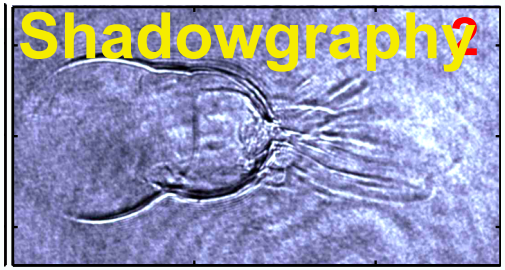
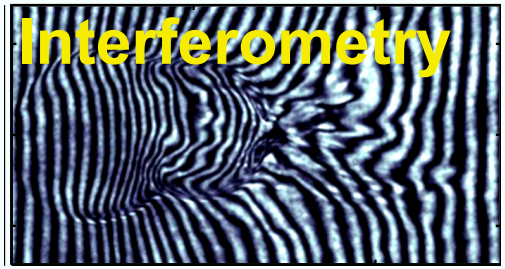
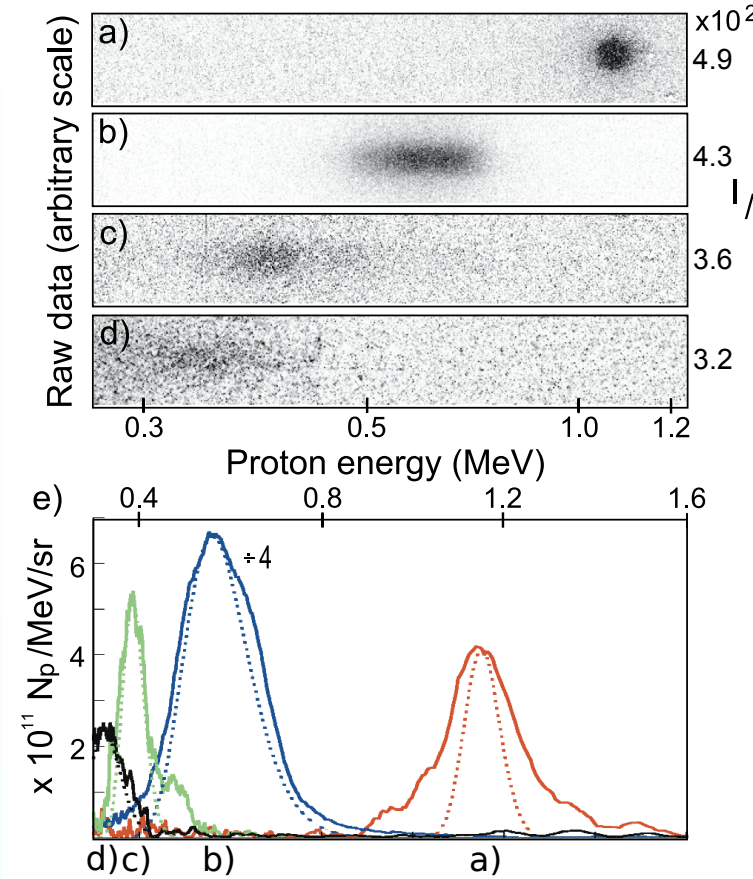






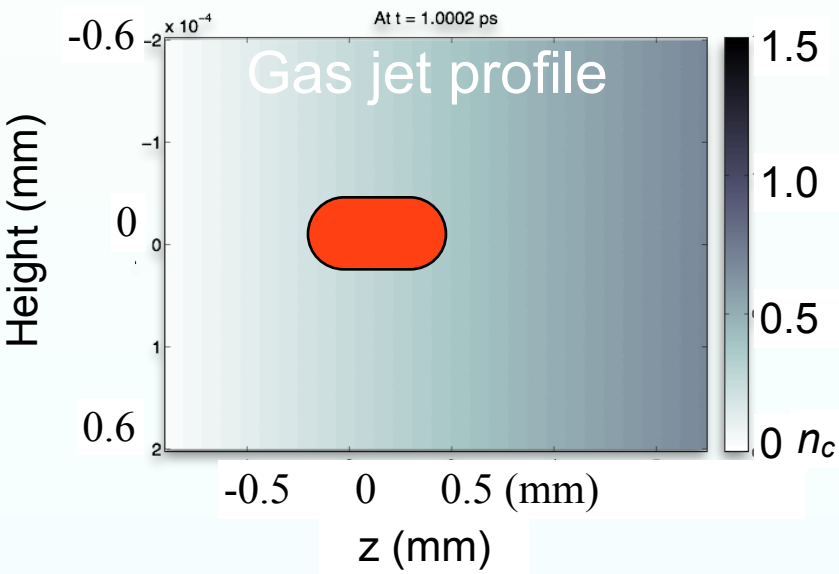
Probe at 2 times*
on single shot

*See: Palmer, Dover, Pogorelsky et al., PRL, **106** 014801(2011)*

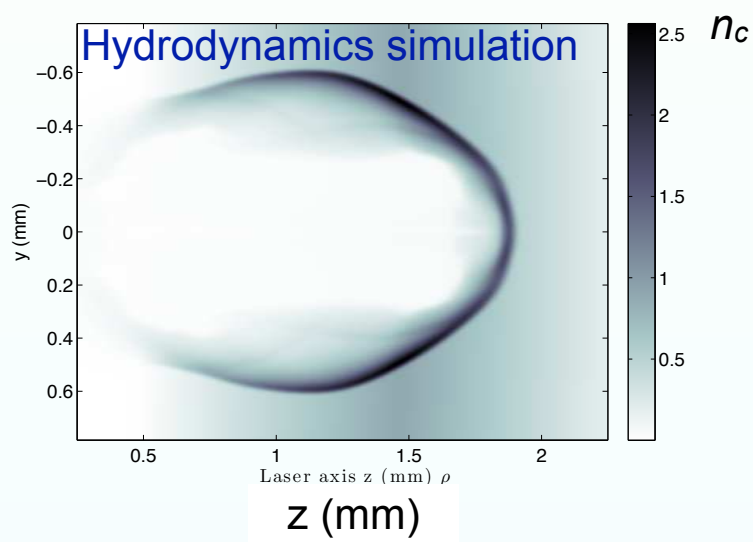
New technique: blast wave shaping

- *Single intense pulse* to drive acceleration controllably
- Prepulse 25 ns before main pulse to optically tailor density
- Helium gas to generate helium beams with shock acceleration

Prepulse deposits energy, gas expands and forms blast wave

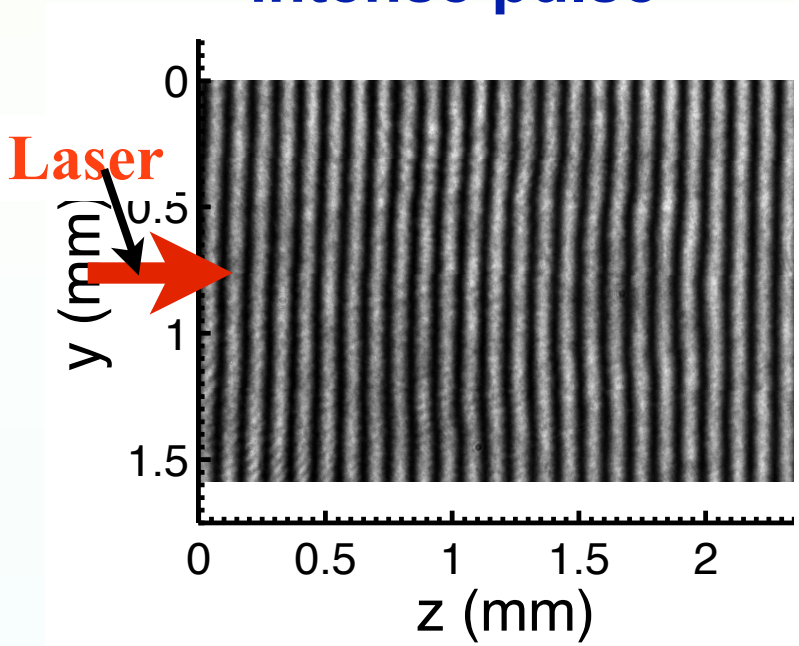


Main pulse interacts with steepened profile

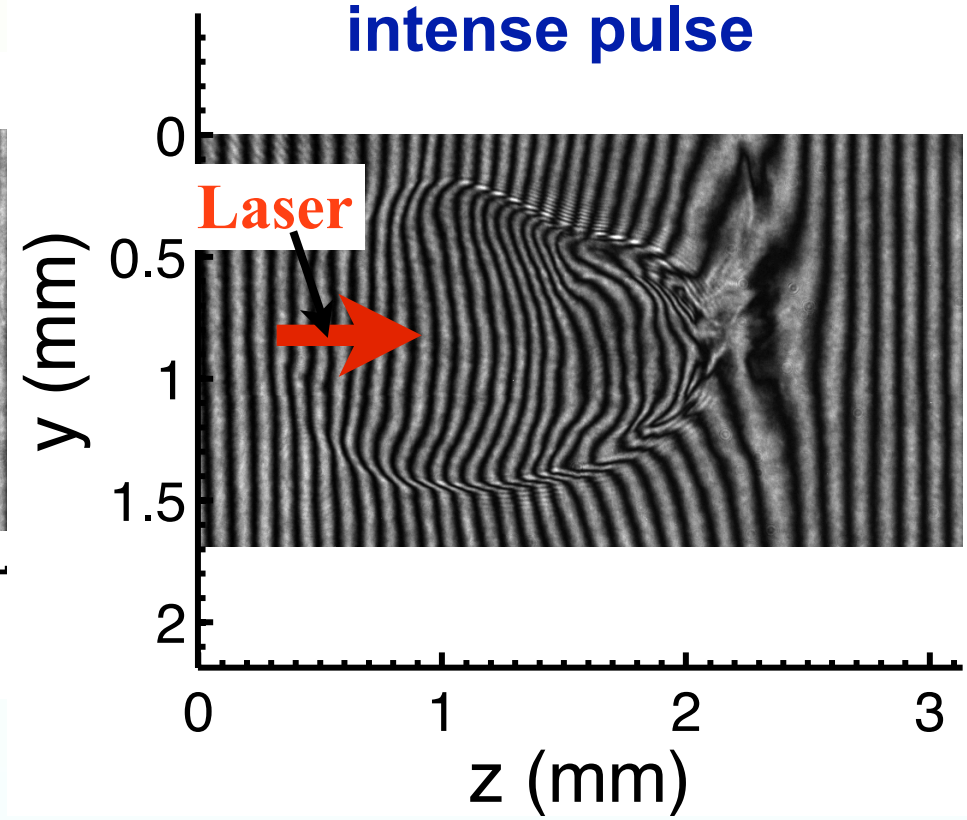


Varying prepulse changes initial conditions

400 ps <u>before</u> intense pulse

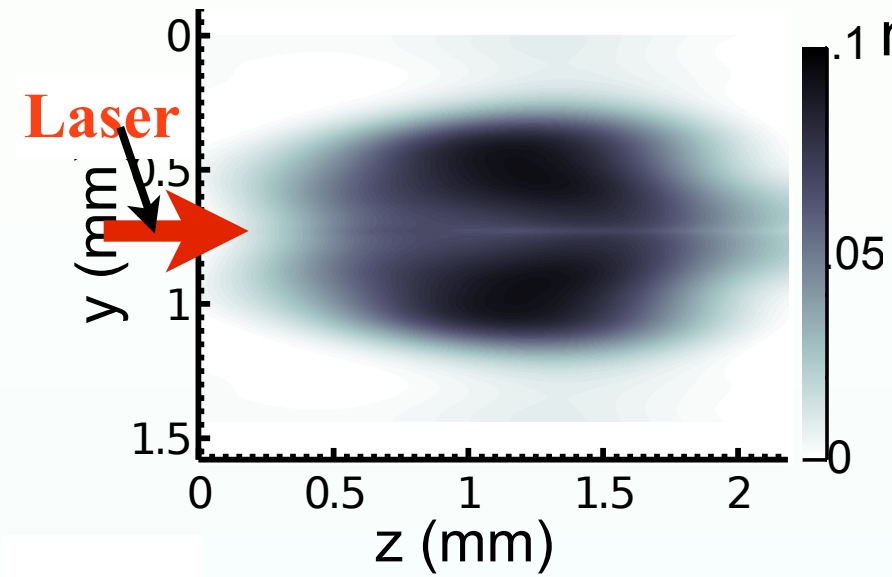


100 ps <u>after</u> intense pulse

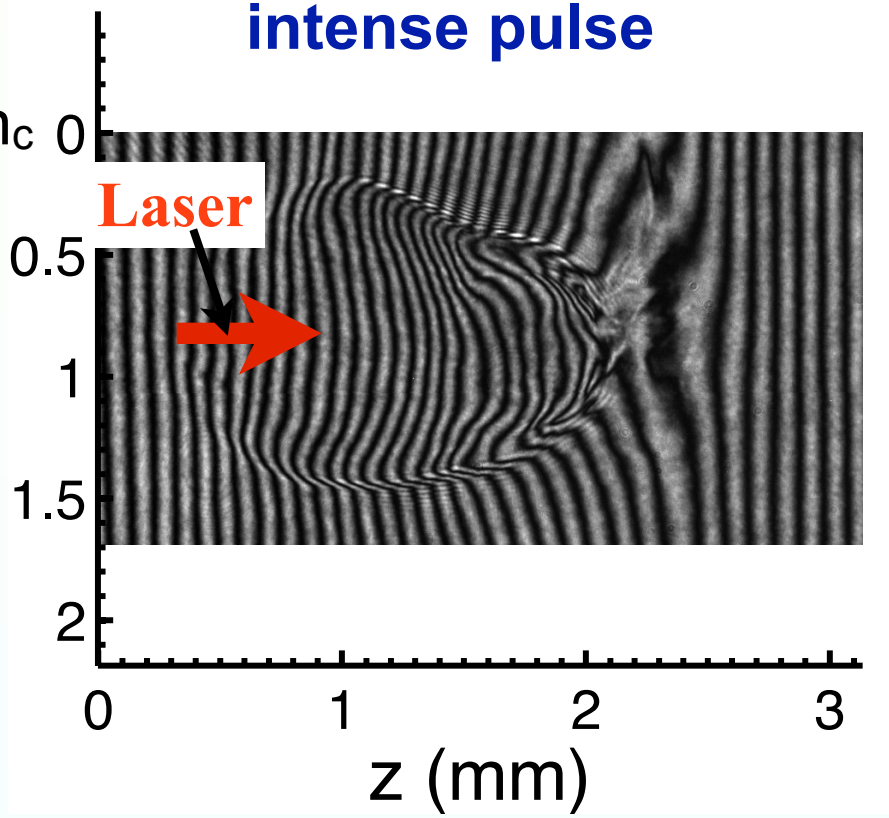


Varying prepulse changes initial conditions

400 ps <u>before</u> intense pulse

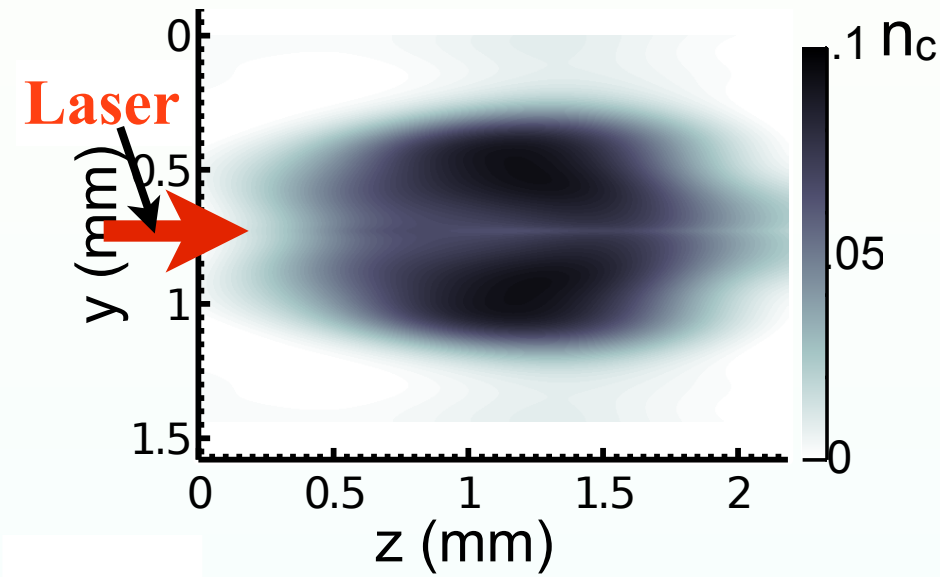


100 ps <u>after</u> intense pulse

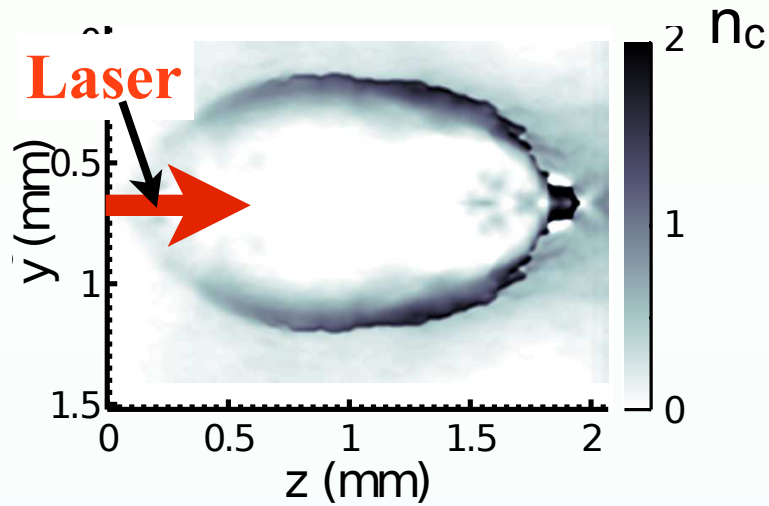


Varying prepulse changes initial conditions

400 ps <u>before</u> intense pulse

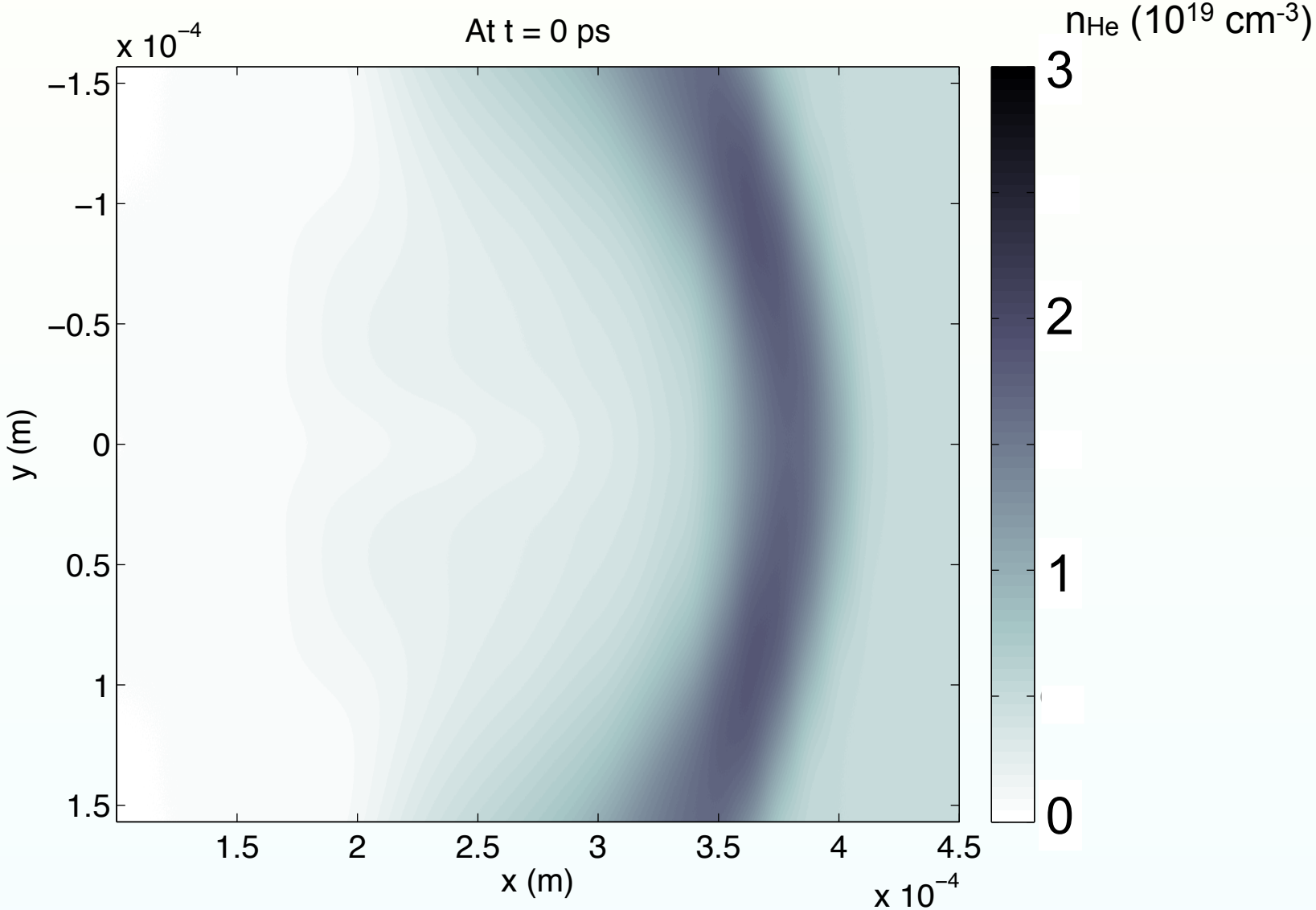


100 ps <u>after</u> intense pulse

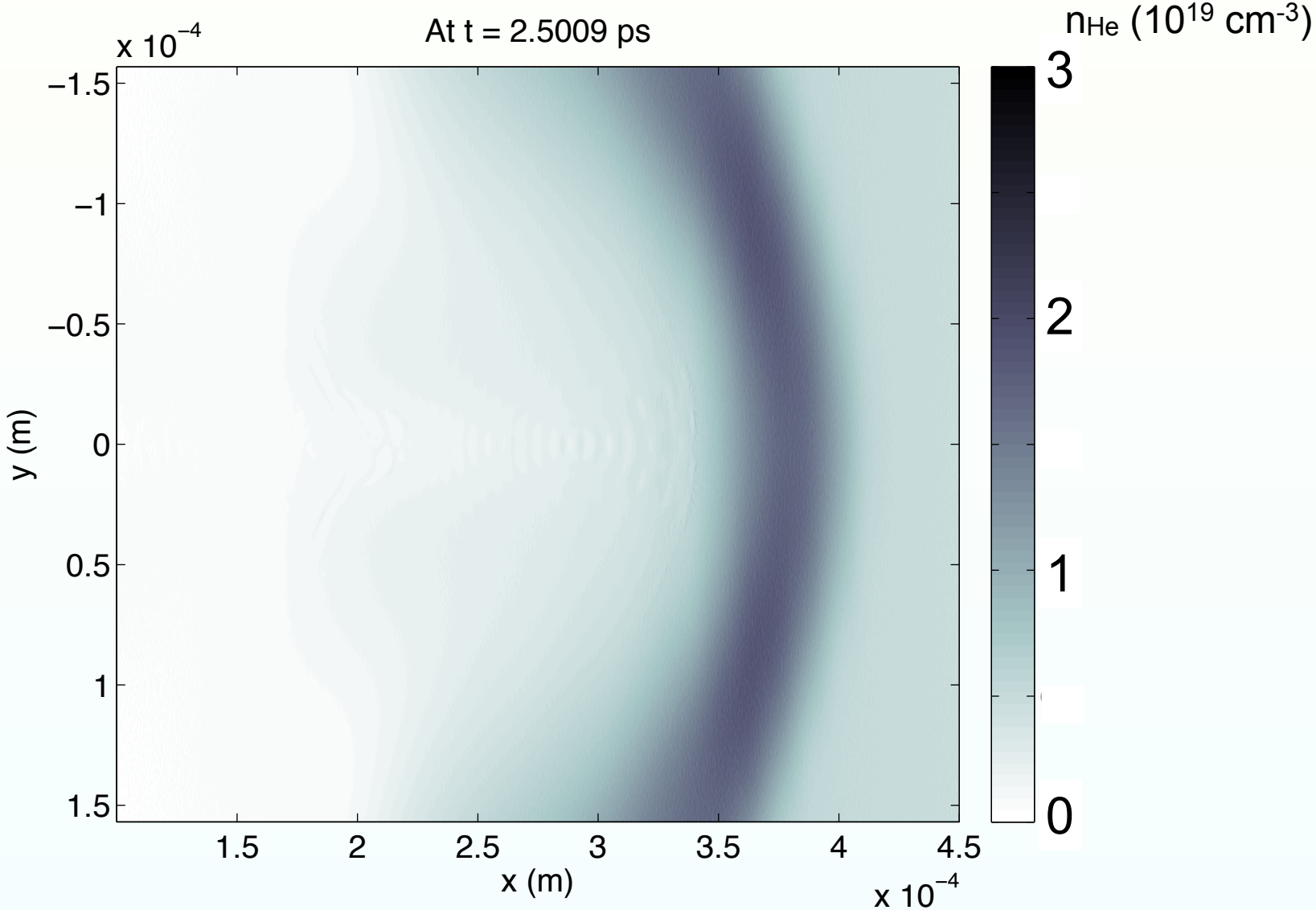


- "100 mJ" prepulse: significant preionisation prior to the interaction, indicative of optical tailoring of gas jet
  - **<u>First observation of energetic helium ions from shockwave acceleration in overdense gas-jets</u>**

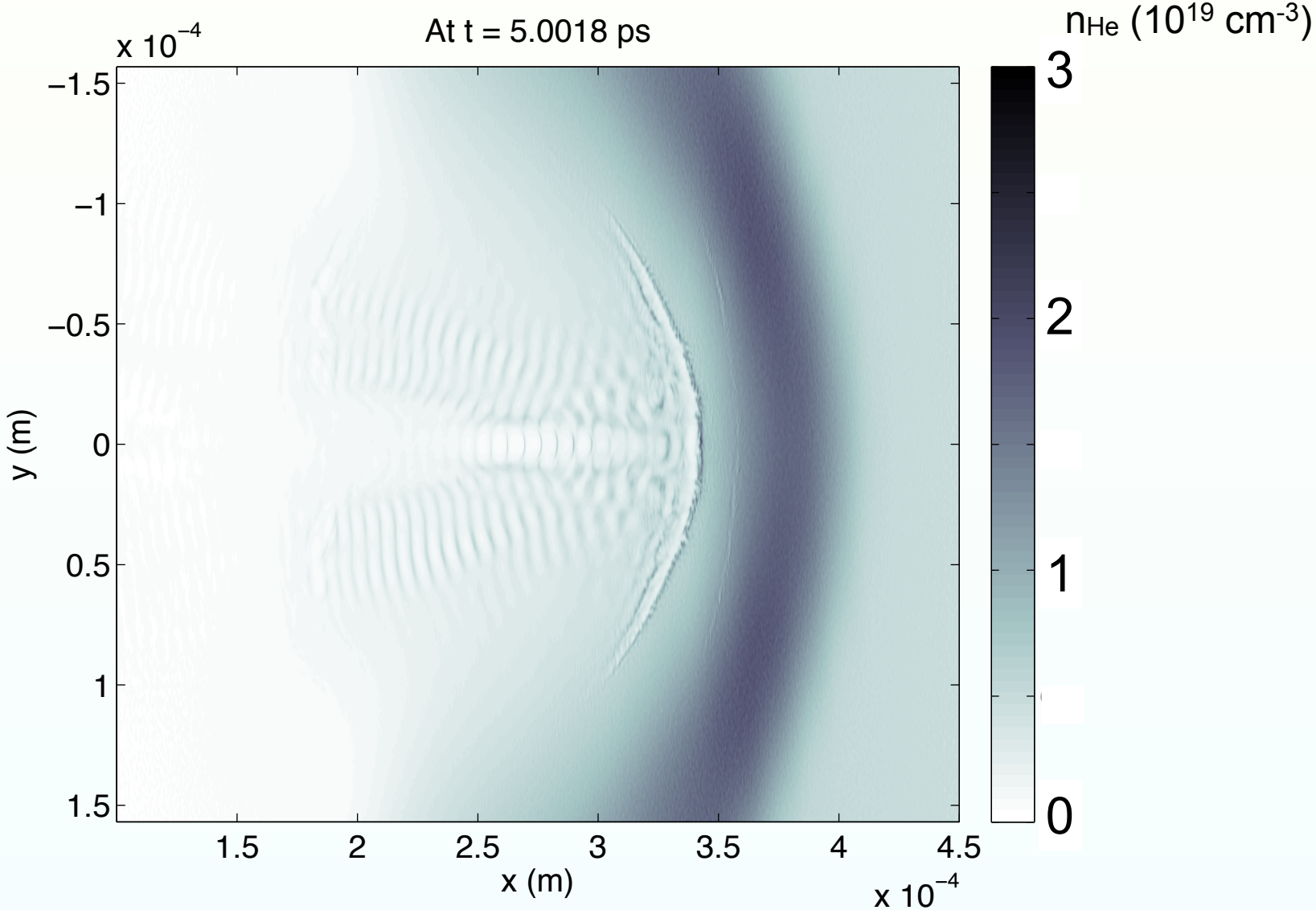
2D PIC with prepulse



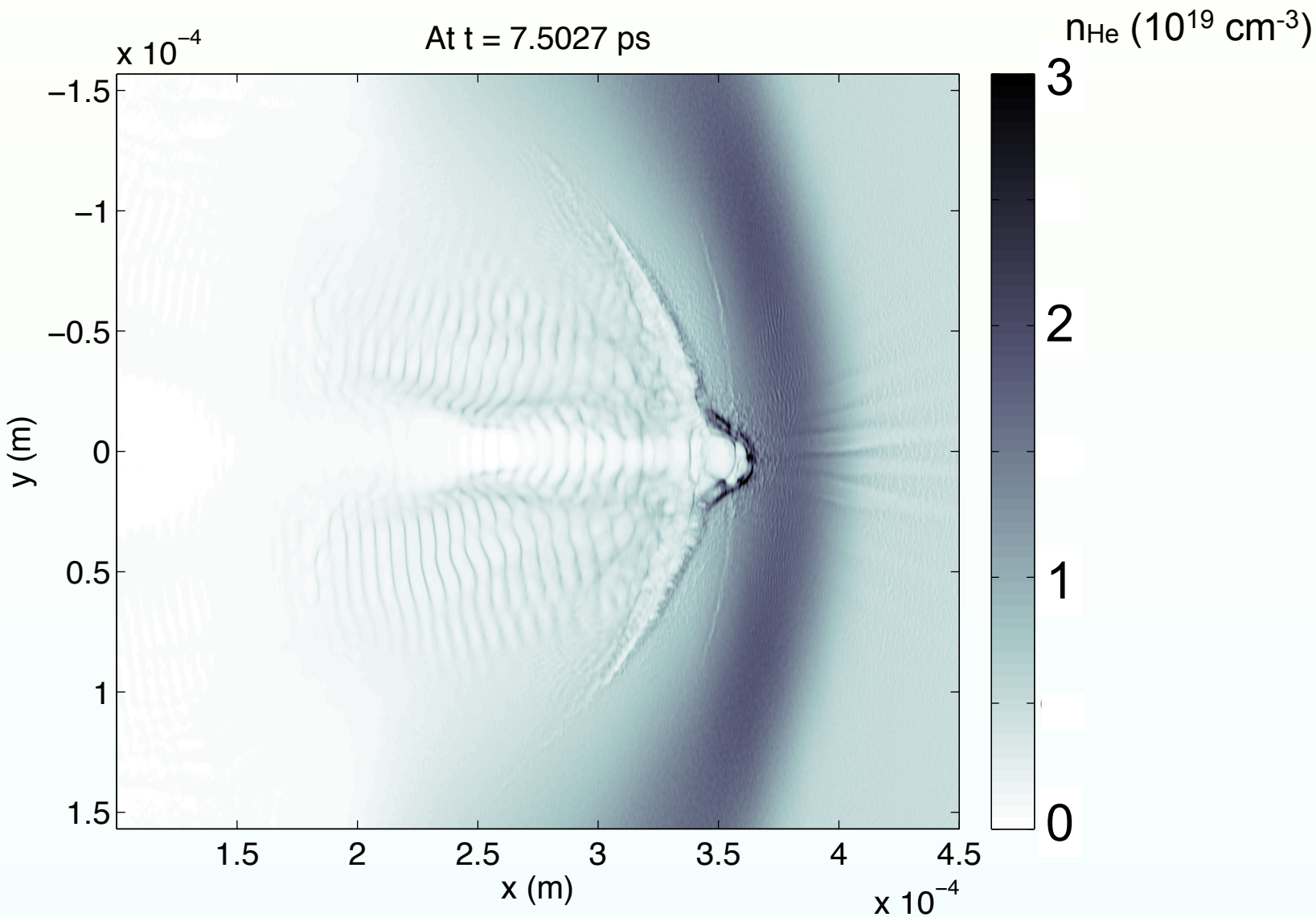
2D PIC with prepulse



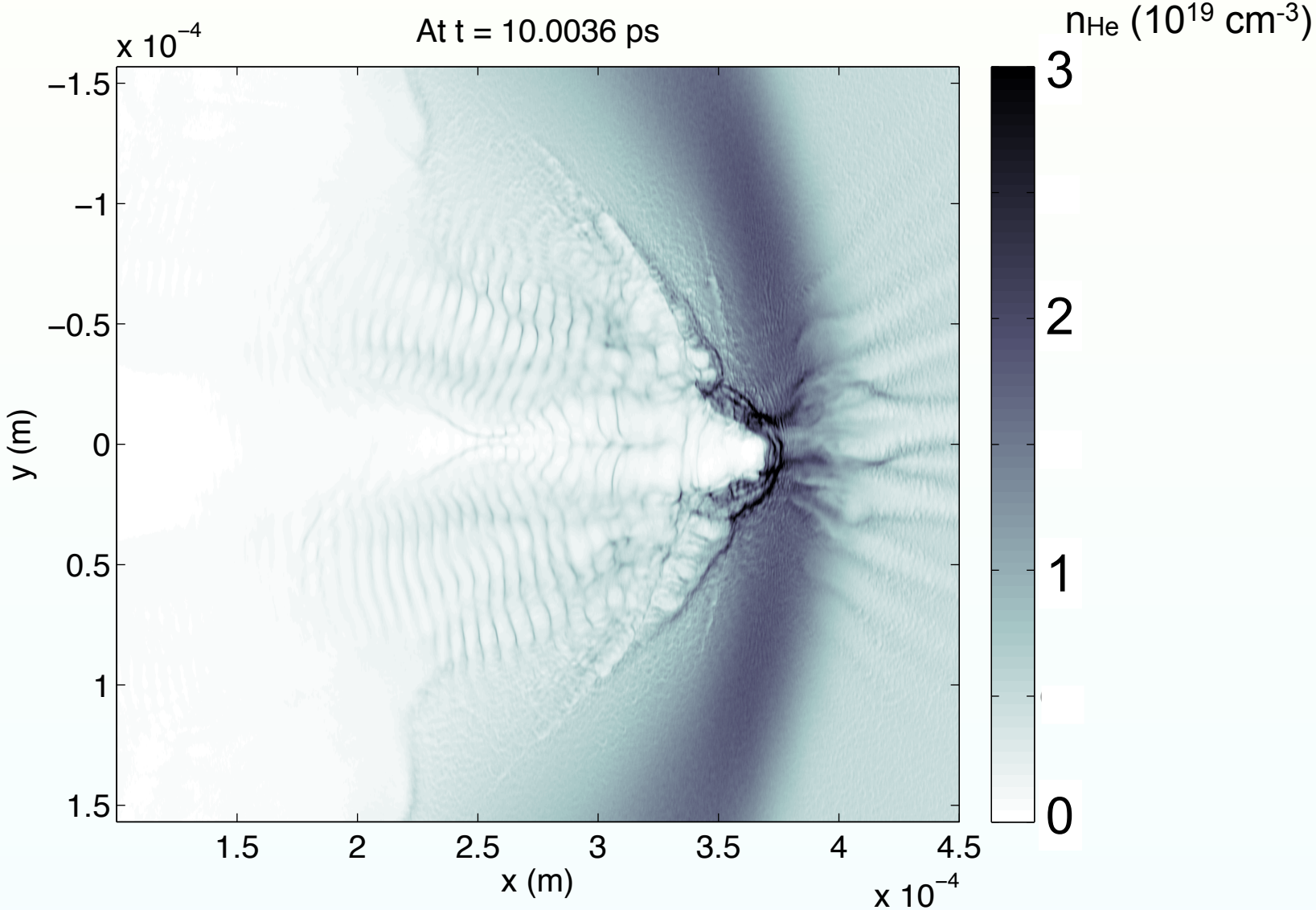
2D PIC with prepulse



2D PIC with prepulse



2D PIC with prepulse



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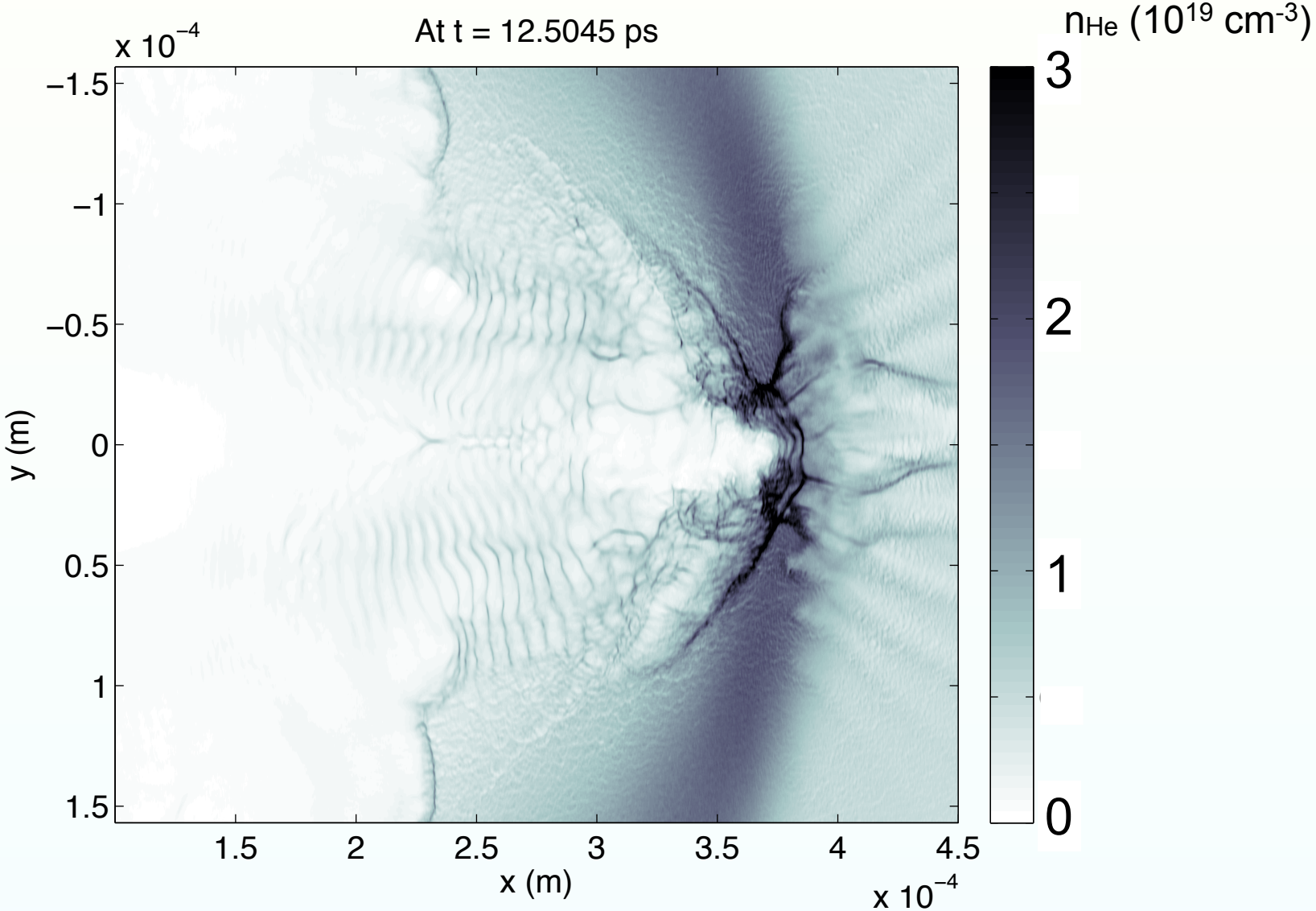
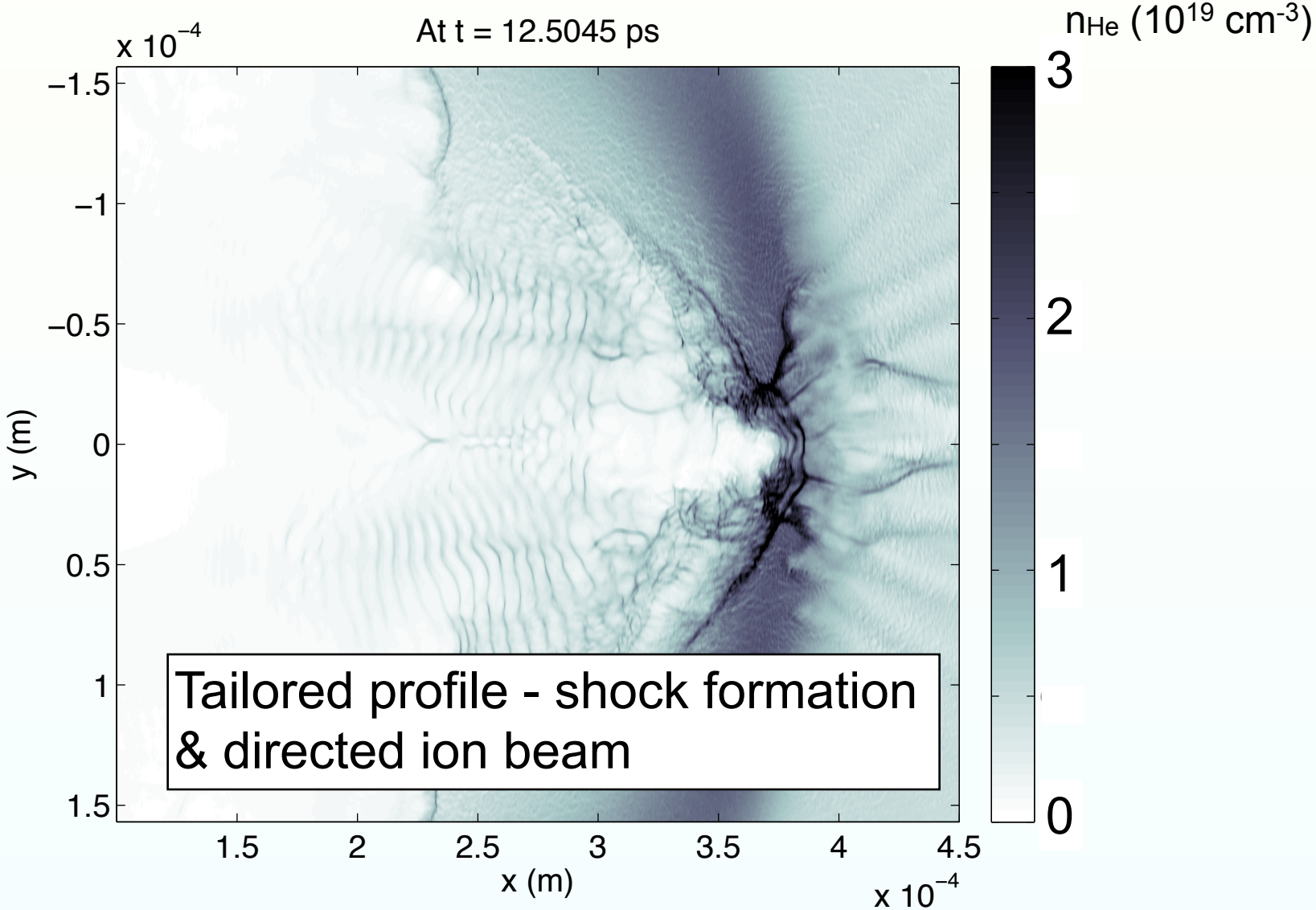


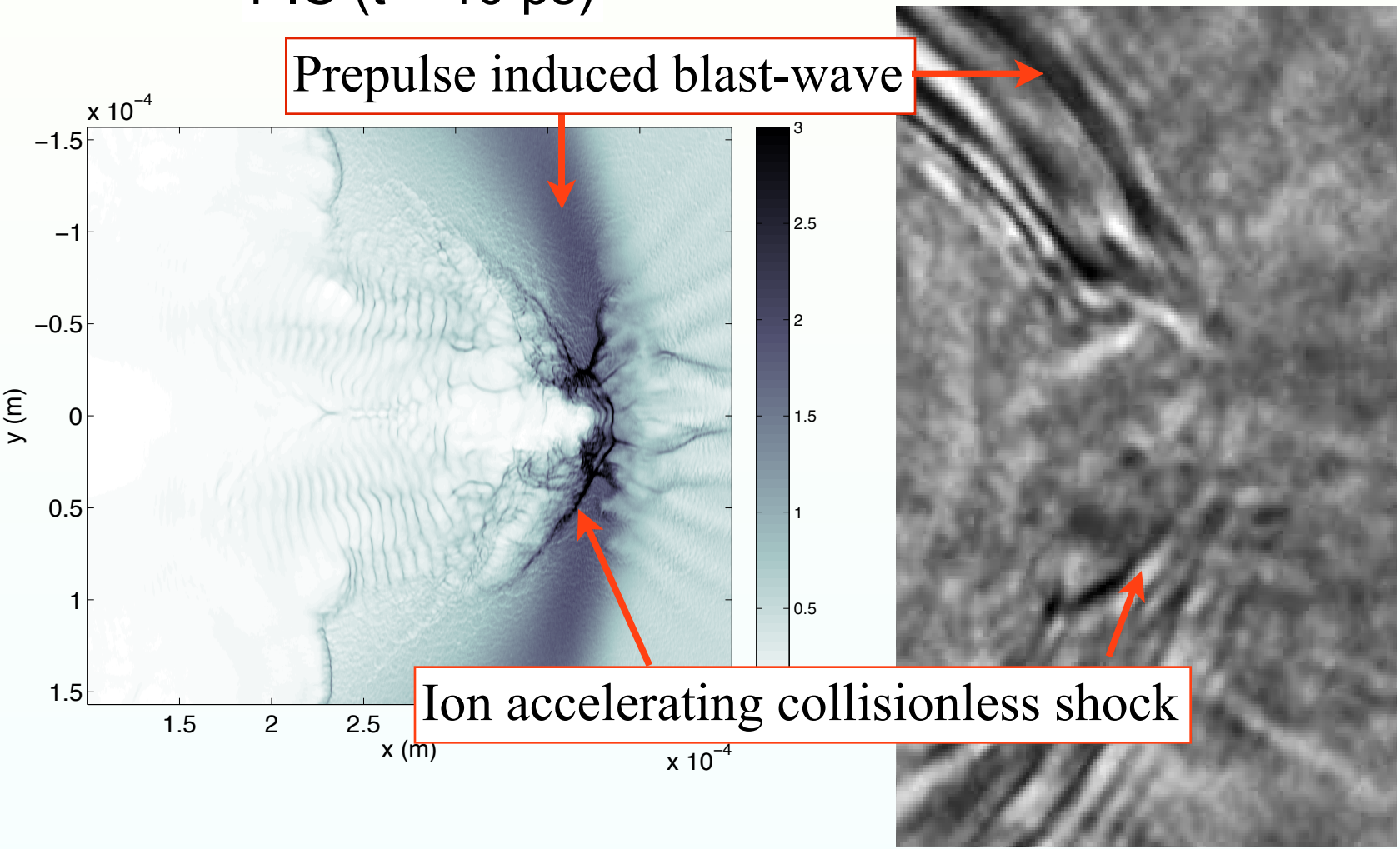
2D PIC with prepulse



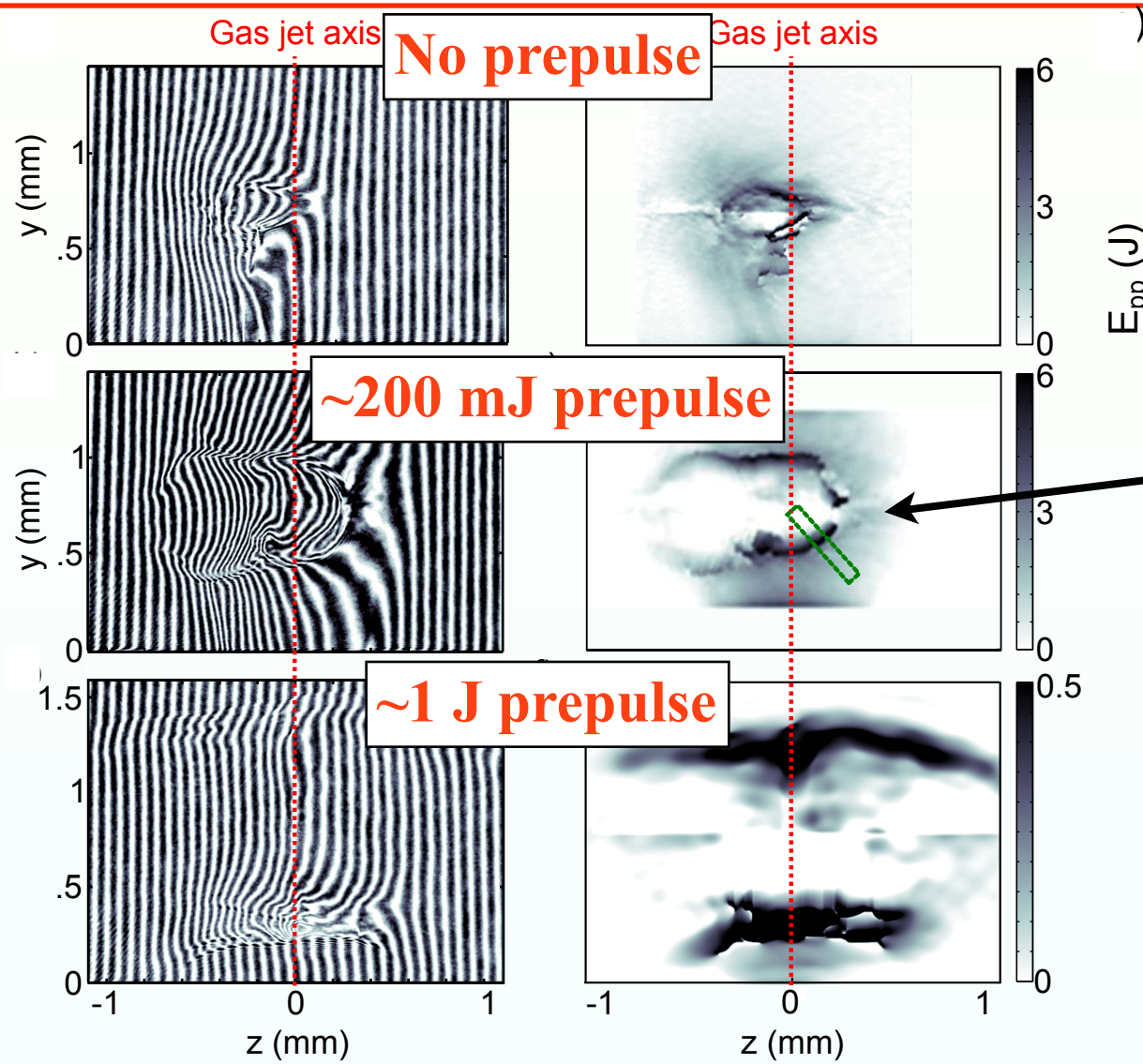
PIC shows agrees with experiment

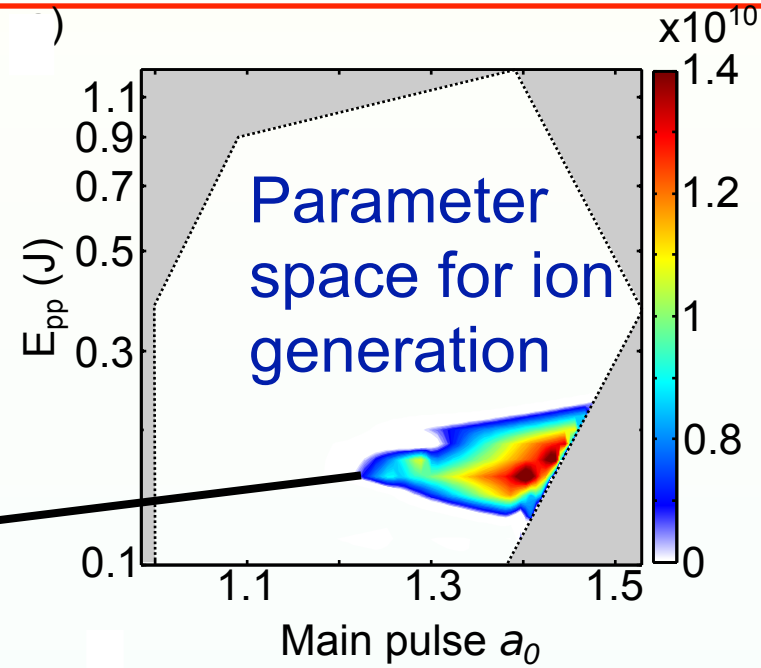
PIC (t ~ 10 ps)

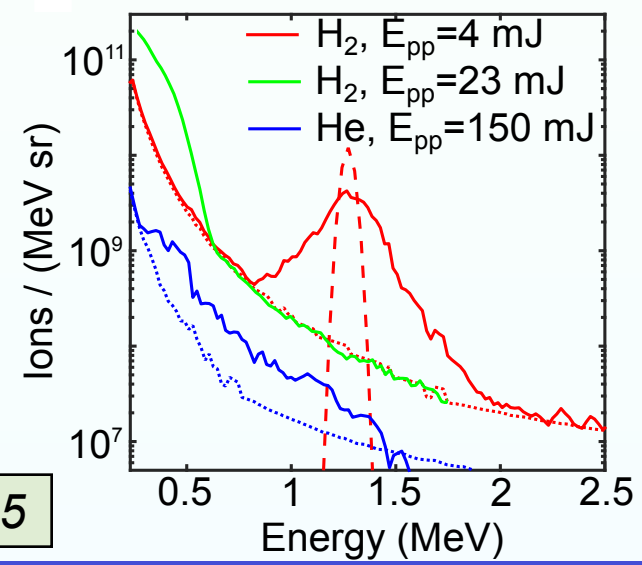
Experiment (t ~ 100 ps)



Varying prepulse changes ion beam properties

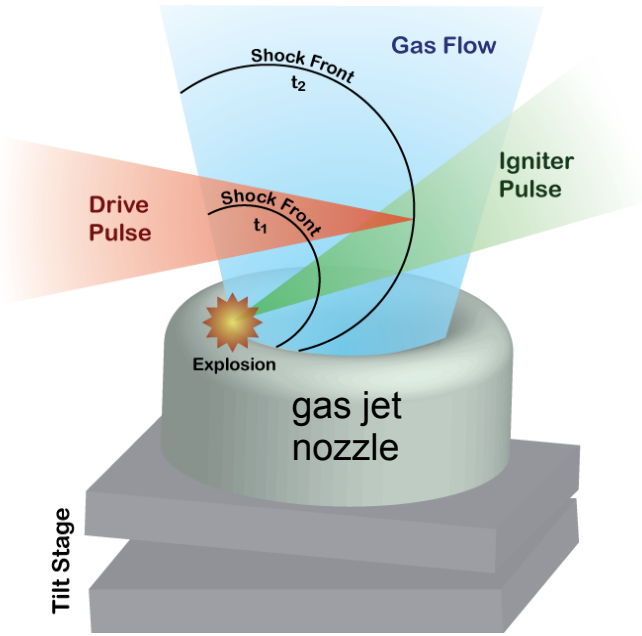






*See: Tresca, Dover, Cook et al., PRL **115,** 094802, 2015*

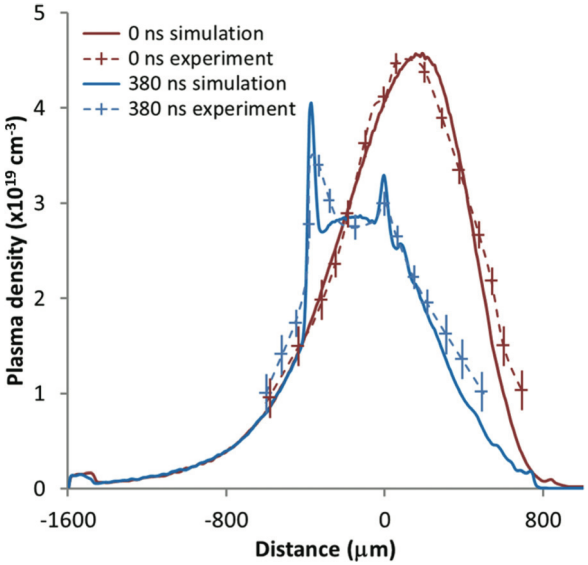
Density Shaping with Independent Blast Wave Driver



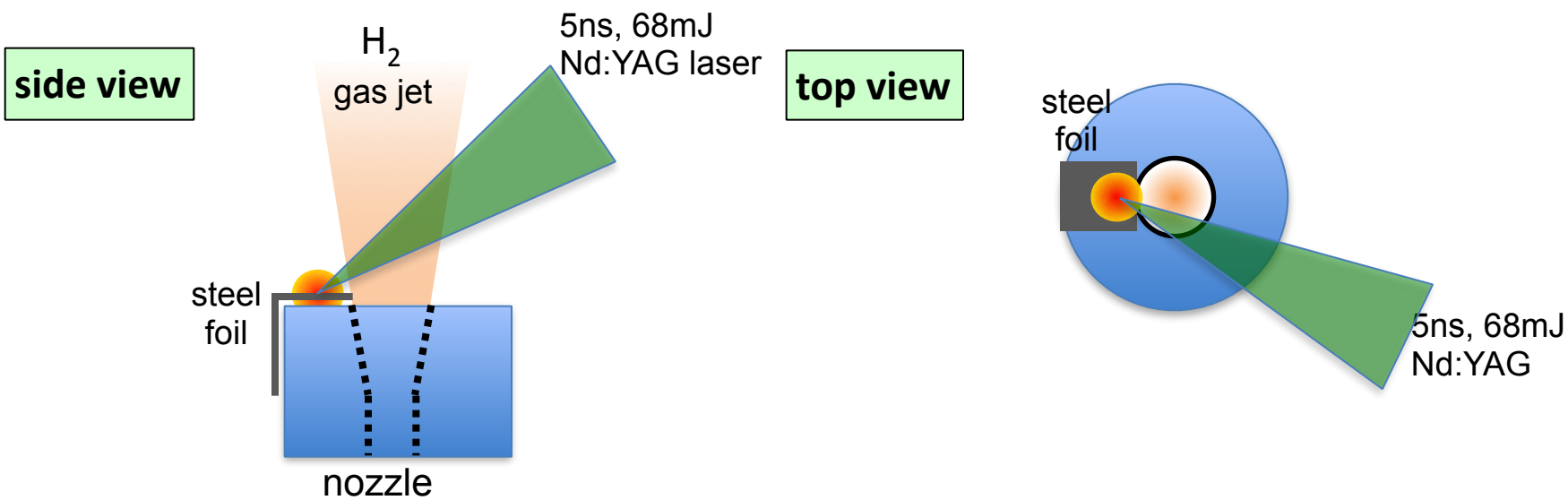
Drive Pulse: 4 J, 10 um
Igniter Pulse: 0.1 J, 1 um

- Typical gas density from a supersonic gas jet nozzle ~ 10^{19} cm^{-3}
- Laser-ablated material (initially at solid density) launches a hydrodynamic shock into the gas column, producing large density gradients within ~ 50 μm
- Timing adjustment allows for a variety of density profiles.

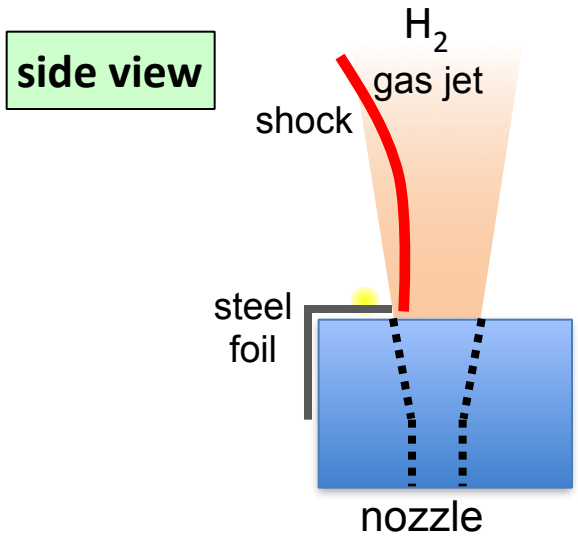
Comparison of gas profiles before and 380 ns after blastwave [D. Kaganovich et al., J. Appl. Phys. **116**, 013304 (2014)]

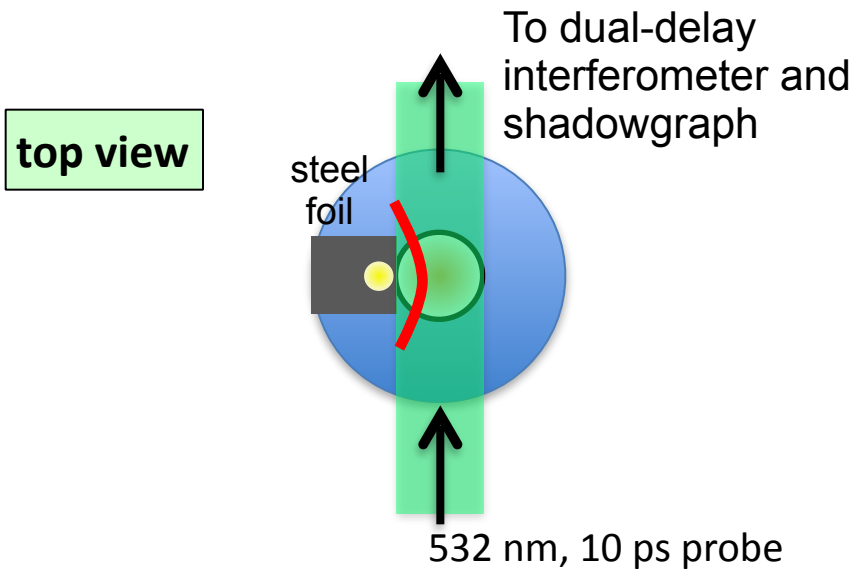


Density Shaping Configuration at BNL-ATF

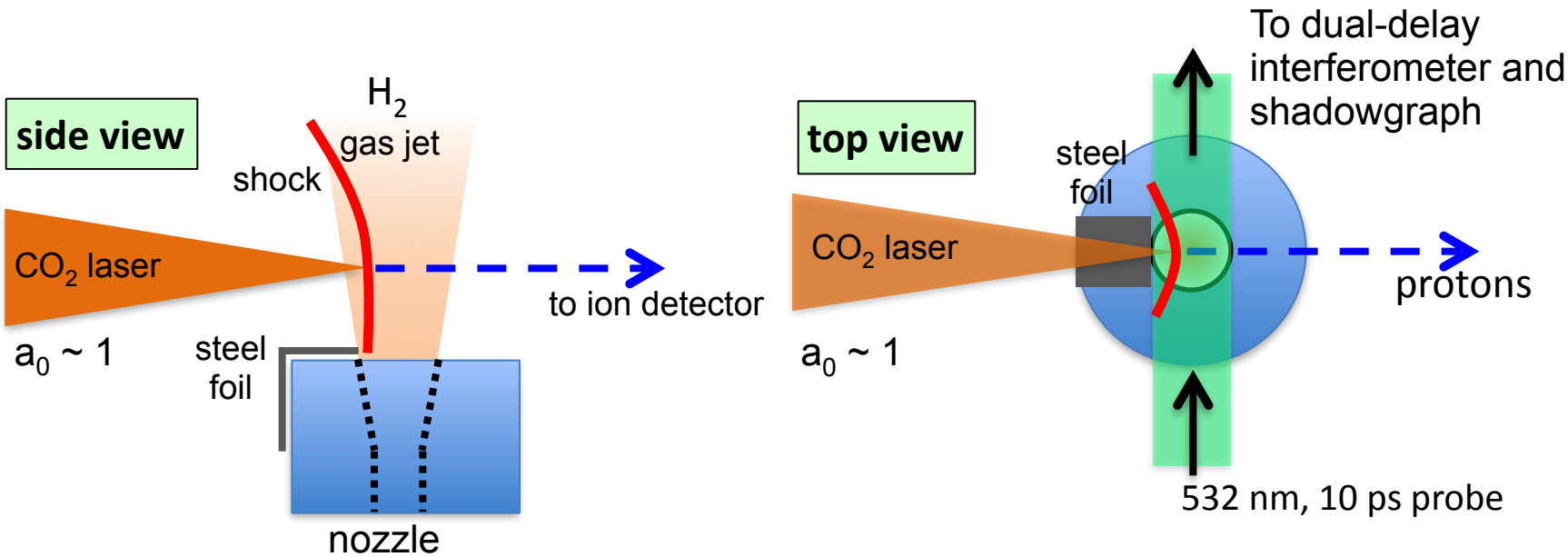


Density Shaping Configuration at BNL-ATF

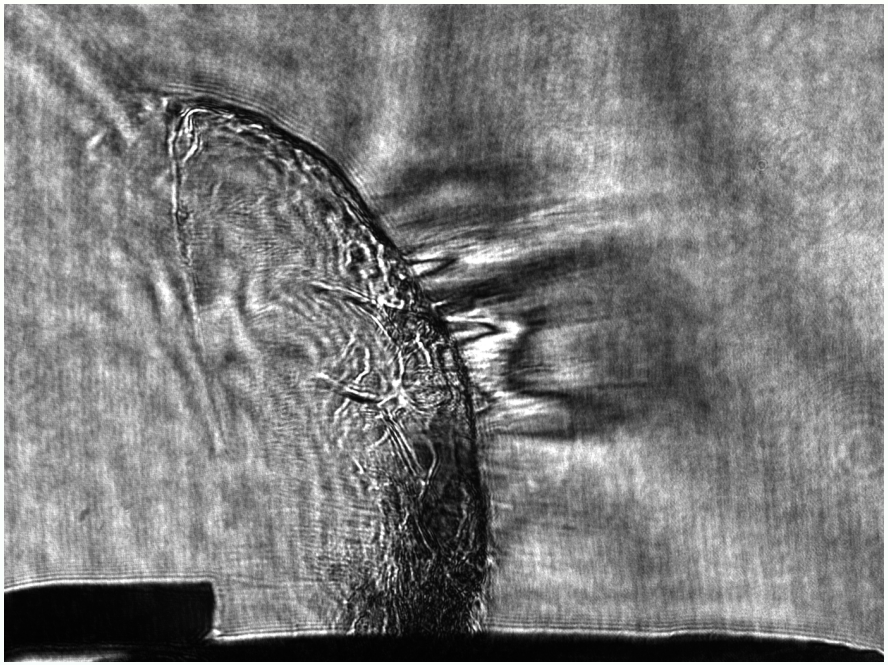


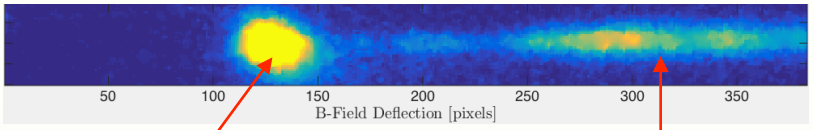


Density Shaping Configuration at BNL-ATF



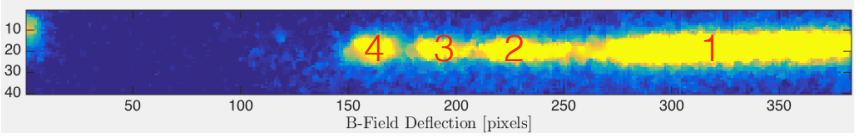
YAG Driven Blast Waves

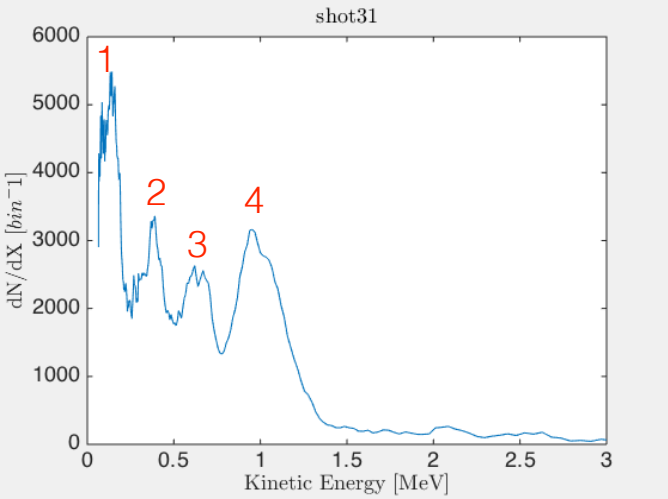




High Energy Bunch Low Energy Thermal Tail

Multiple 'bunches' observed on some shots





Shock loses energy through reflection of upstream ions, which is then replenished by the laser and the cycle repeats

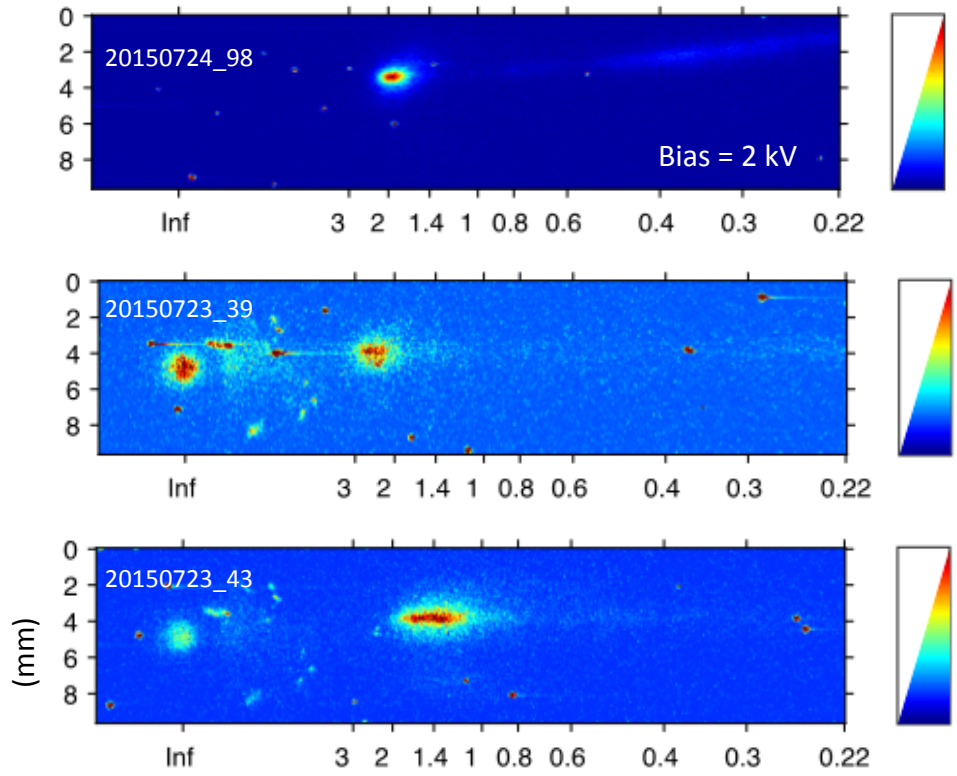
Monoenergetic proton beams

Backing pressure = 4 bar

CO2 = 3.42 J

3.44 J

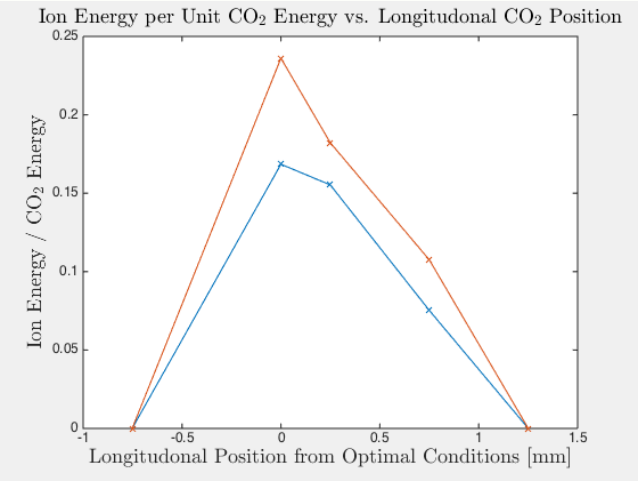
3.03 J

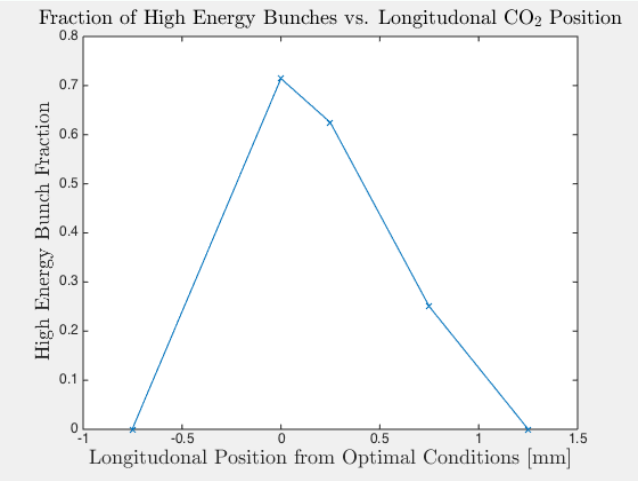


Proton Energy

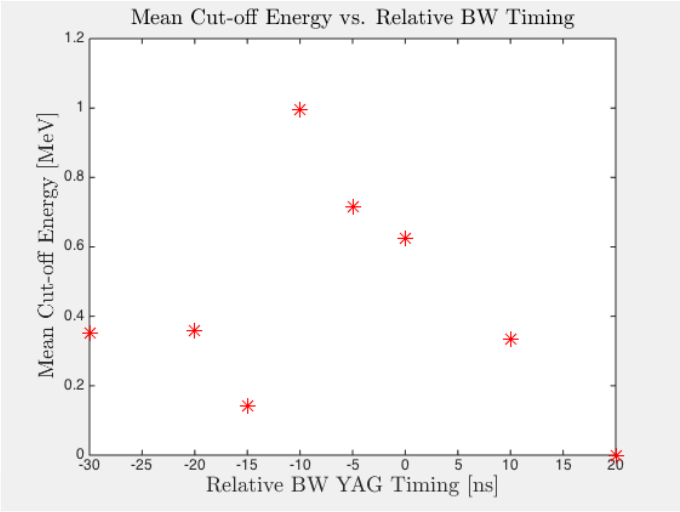
YAG Driven Blast Waves

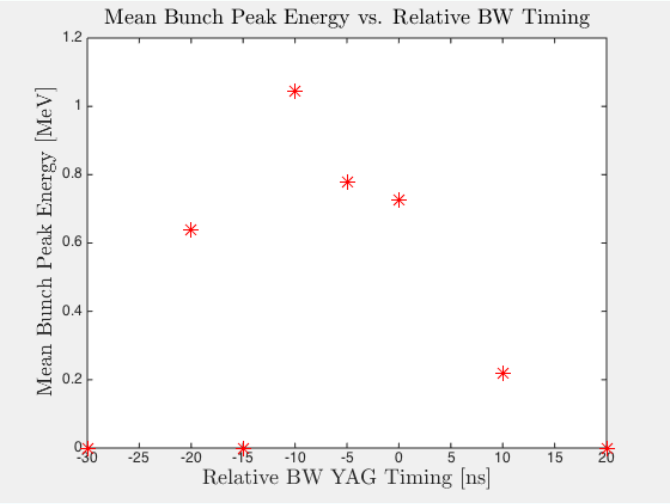
Asymmetry in effect of longitudinal focussing





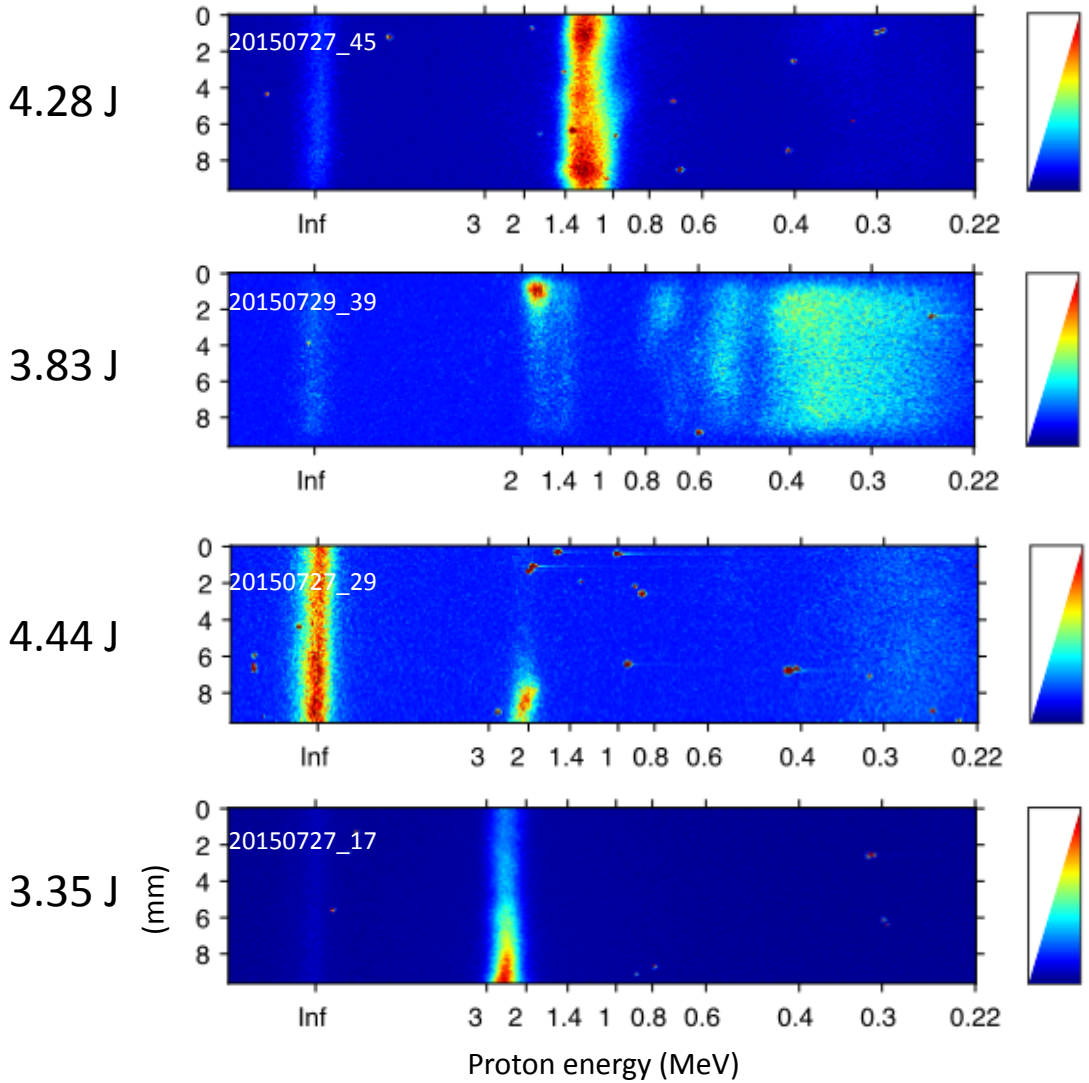
Strong dependance on timing to produce the highest energies





Monoenergetic proton beams with 1-D profiles

Backing pressure = 4 bar



The monoenergetic component has narrow angular spread with erratic pointing.

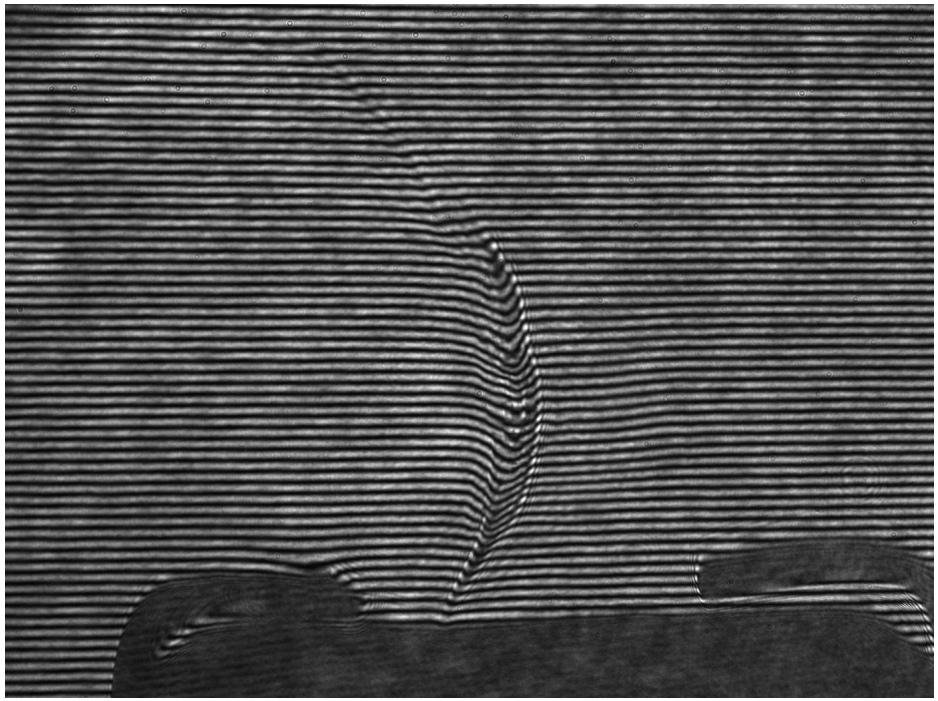
The proton energy is much higher than predicted by the hole-boring model (0.6 – 0.9 MeV).

Single vs. double shocks

Backing pressure = 2 bar

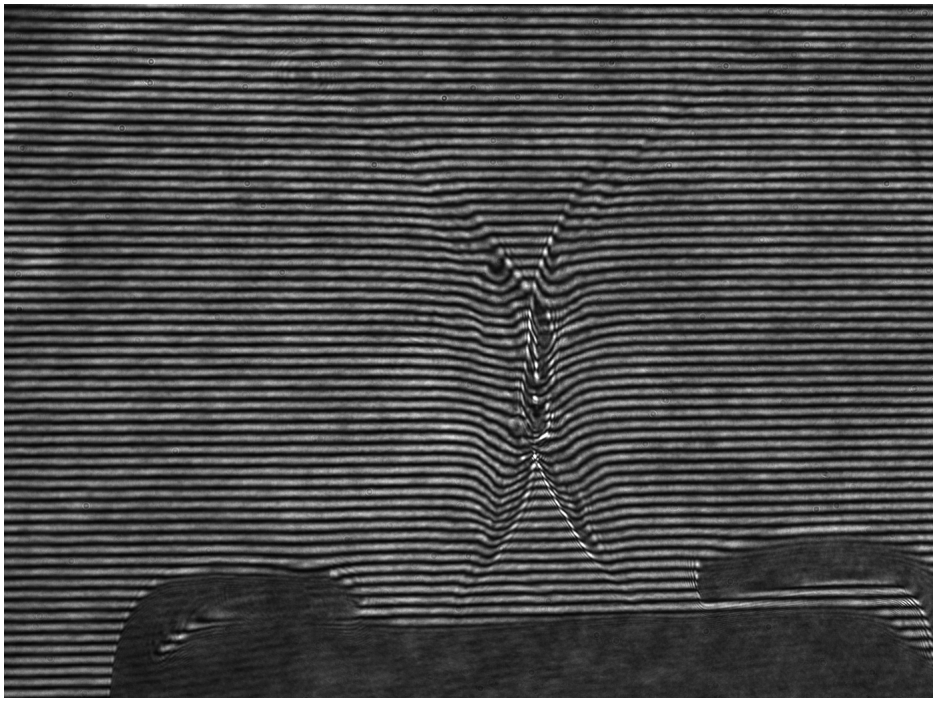
Single shock
CO_2 = 4.01J

20150729_21



Double shocks
CO_2 = 4.25J

20150729_18

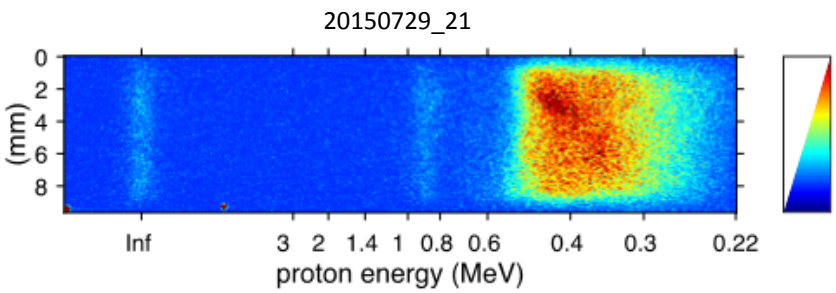


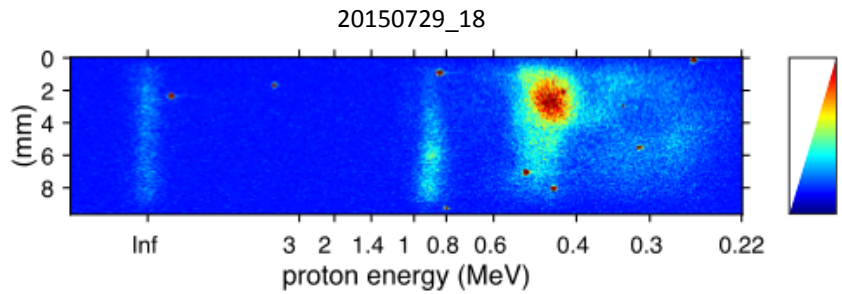
Single vs. double shocks

Backing pressure = 2 bar

Single shock
CO2 = 4.01J

Double shocks
CO2 = 4.25J



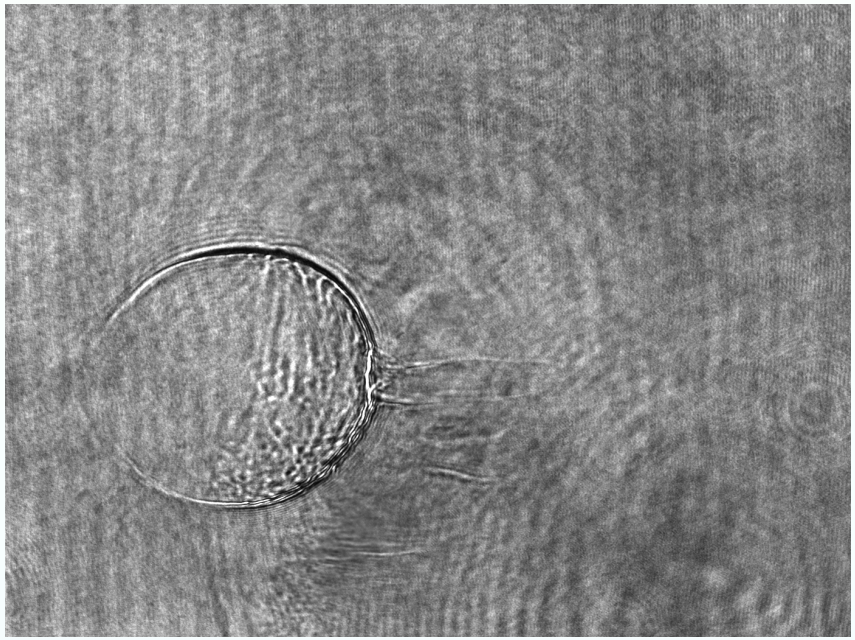


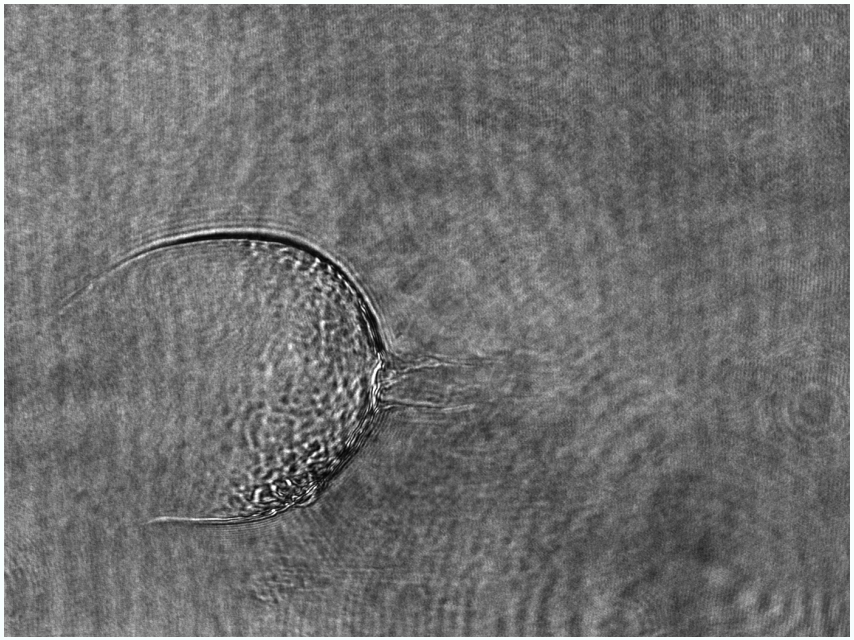
The additional hydrodynamic shock appears to have no significant effect on proton energy spectrum but degrade the uniformity of the beam profile.
Probe timing is several hundred ps later than the CO2 pulse.

Pre-pulse Driven Blast Waves

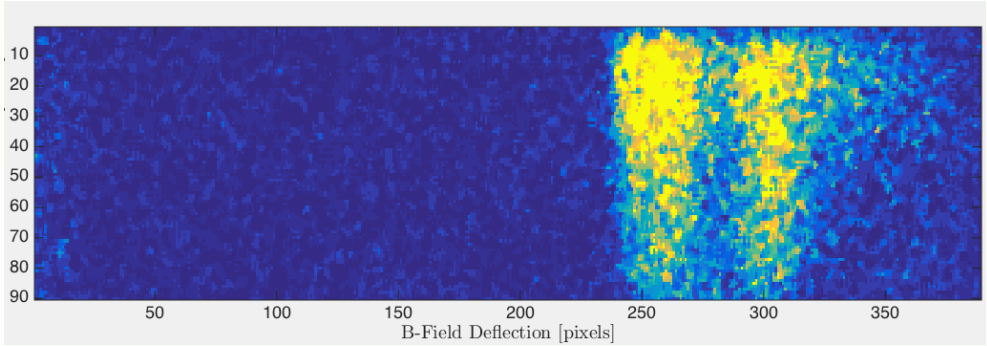
Optically driven blast waves also attempted, as on previous experiments - new method for producing pre-pulse

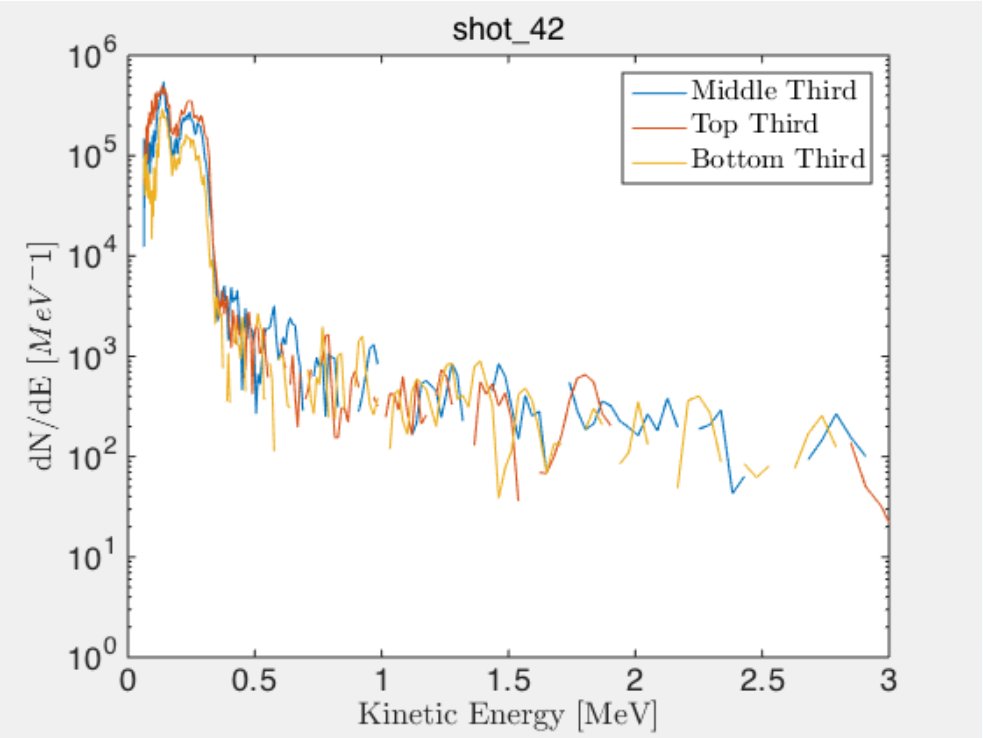
Shorter energy deposition should give reduced density scale lengths at interaction surface





Pre-pulse Driven Blast Waves





Low energy ion beams produced on some shots, but not most

Pre-pulse parameters fixed at ~2% Energy and separation ~5ns

Energy and separation not sufficient to allow ideal cavitation and shock formation - new method needed for future runs

Experiment Overview

Background

- Two experimental runs during 2015; May and July
  - May experiment hampered by 'technical problems'
  - July experiment much more successful - 593 shots over the two weeks including set-up time.

Statistics

- Stable ion acceleration achieved in certain regimes - 91% proton success rate over 120 shots during one day!

Results

Proton energies exceeding 2 MeV

YAG driven blastwave improves reproducibility compared to shaping with **fixed** time CO_2 prepulse

Transverse structure observed in proton beam - explains fluctuations in protons collected in a small solid angle

Wish list

- Controllable 10μm prepulse to be implemented - compare to ablated shocks
- Extend intensity scaling (faster focussing)
- Investigate higher Z gases - and potentially double species targets.
- Measure shock speed (Doppler)
- More exhaustive density / timing scan
- Linear vs. circular polarisation