SLAC-WP-123

Ion Acceleration by Laser Plasma Interaction from Cryogenic Micro Jets

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Office of Science, Science Undergraduate Laboratory Internship (SULI) Program

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SLAC NATIONAL ACCELERATOR LABORATORY

Abstract

Processes that occur in extreme conditions, such as in the center of stars and large planets, can be simulated in the laboratory using facilities such as SLAC National Accelerator Laboratory and the Jupiter Laser Facility (JLF) at Lawrence Livermore National Laboratory (LLNL). These facilities allow scientists to investigate the properties of matter by observing their interactions with high power lasers. Ion acceleration from laser plasma interaction is gaining greater attention today due to its widespread potential applications, including proton beam cancer therapy and fast ignition for energy production. Typically, ion acceleration is achieved by focusing a high power laser on thin foil targets through a mechanism called Target Normal Sheath Acceleration. Based on research and recent experiments, we hypothesized that a pure liquid cryogenic jet would be an ideal target for this type of interaction, capable of producing the highest proton energies possible with today's laser technologies. Furthermore, it would provide a continuous, pure target, unlike metal foils which are consumed in the interaction and easily contaminated. In an effort to test this hypothesis and investigate new, potentially more efficient mechanisms of ion acceleration, we used the 527 nm split beam, frequency-doubled TITAN laser at JLF. Data from the cryogenic jets was limited due to the flow of current up the jet into the nozzle during the interaction, heating the jet and damaging the orifice. However, we acheived a pure proton beam with an indiciation of a monoenergetic feature. Furthermore, data from gold and carbon wires showed surprising and interesting results. Preliminary analysis of data from two ion emission diagnostics, Thomson parabola spectrometers (TPs) and radio chromic films (RCFs), suggests that shockwave acceleration occurred rather than target normal sheath acceleration, the standard mechanism of ion acceleration. Upon completion of the experiment at TITAN, I researched the possibility of transforming our liquid cryogenic jets into droplet streams. This type of target should solve our problems with the jet as it will prevent the flow of exocurrent into the nozzle. It is also highly effective as it is even more mass-limited than standard cryogenic jets. Furthermore, jets break up spontaneously anyway. If we can control the breakup, we can synchronize the droplet emission with the laser pulses. In order to assist the team prepare for an experiment later this year, I familiarized myself with the physics and theory of droplet formation, calculated values for the required parameters, and ordered the required materials for modification of the jet. Future experiments will test these droplet streams and continue towards the goal of ion acceleration using cryogenic targets.

Ion acceleration

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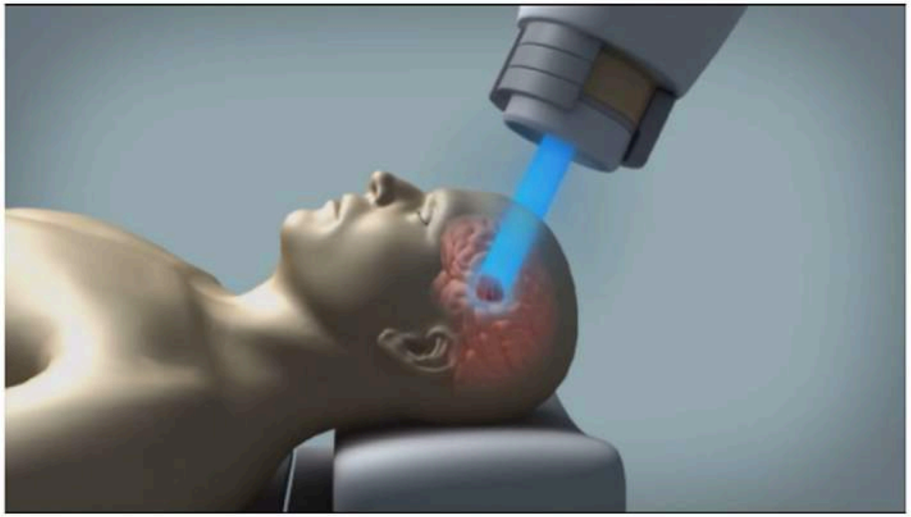
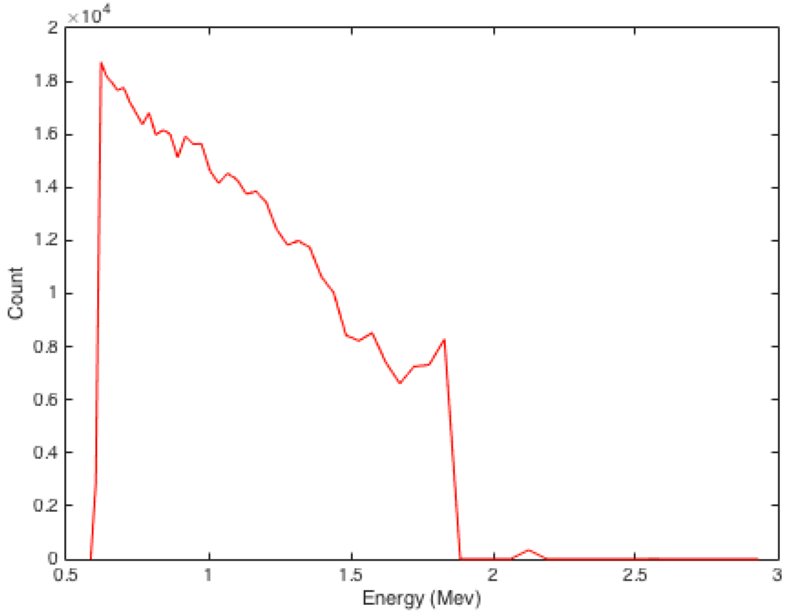
- High power laser-driven ion acceleration is a hot topic in high energy density science
- Exciting potential applications
  - **Cancer therapy** – requires quasi-monoenergetic beam of about 300 MeV
    - Already developed, but impractical & expensive
  - **Clean energy** through fast ignition, fusion – requires dense proton beams
  - **Compact laser-based accelerators**



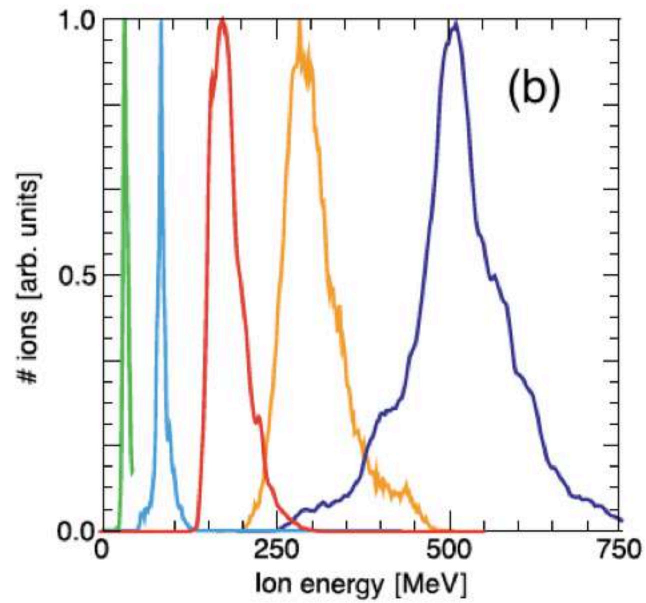
Not all mechanisms of ion acceleration are equal

Target Normal Sheath Acceleration



Problems:
- Not high enough energy
- Other ion contaminants
- Not monoenergetic

Collisionless Shockwave Acceleration

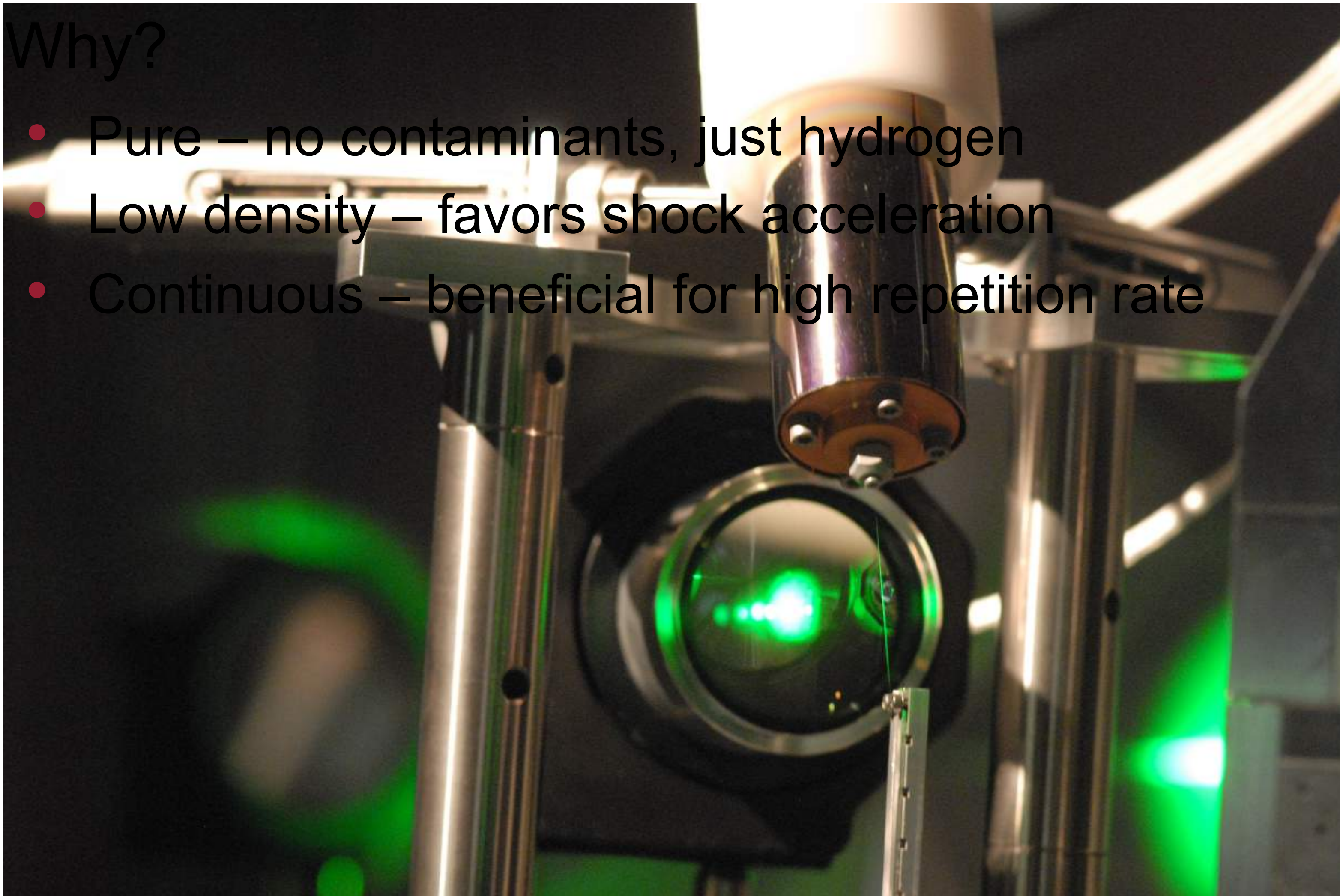


Benefits:
- High energy
- Monoenergetic

Images courtesy of K. Markey & F. Fiuza/APS

A cryogenic hydrogen jet is an ideal target

- Why?
  - Pure – no contaminants, just hydrogen
  - Low density – favors shock acceleration
  - Continuous – beneficial for high repetition rate



Experiment at Titan

Laser:

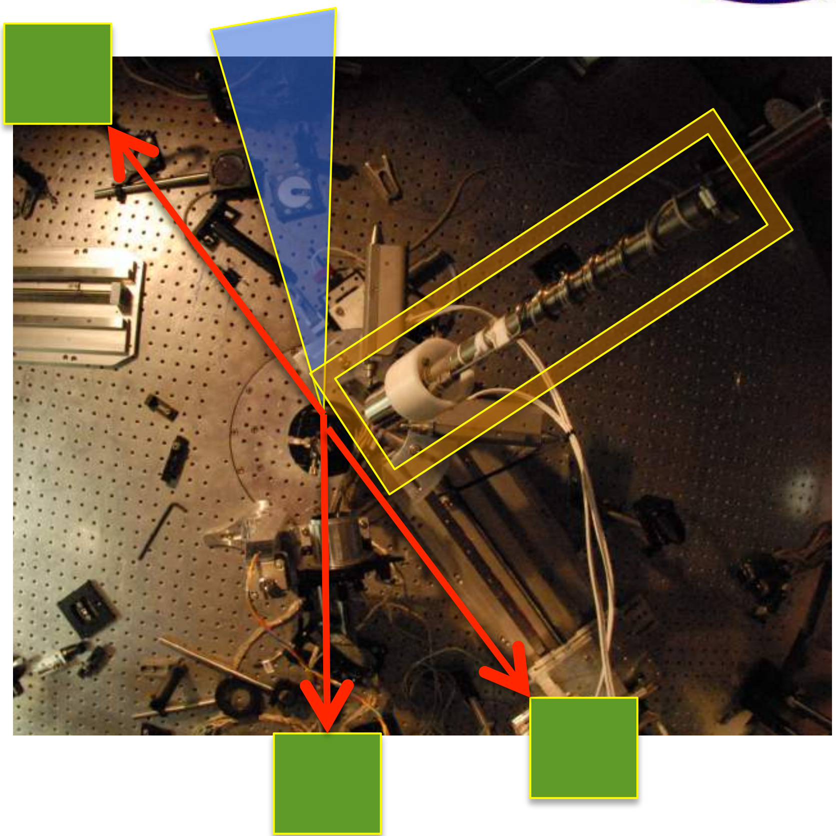
- Duration of pulse: ~ 1 ps
- Peak Intensity: ~ 5e19 W/cm^2
  - (Power: > 40 TW)

Target:

- Cryogenic hydrogen jet + others

Diagnostics:

- Ion energy spectrometer + others
- Located in 3 positions

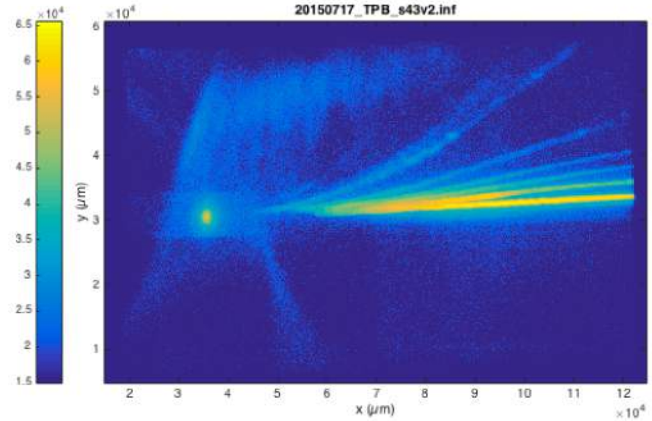


Top-down view of target chamber

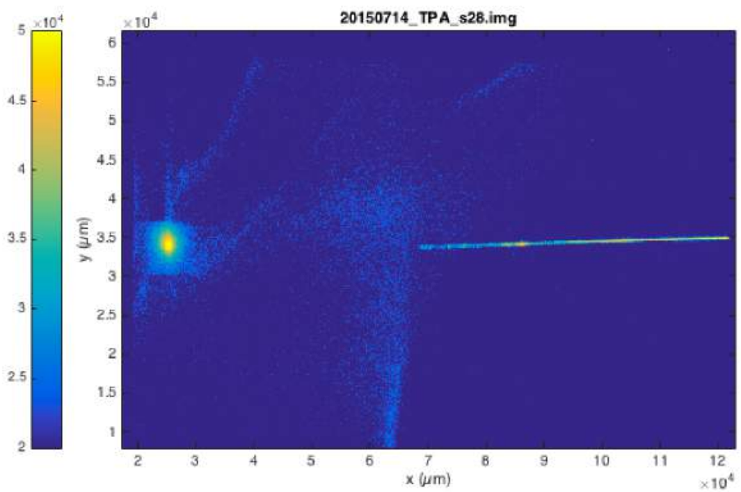
Results from shots with hydrogen jet

Goals:

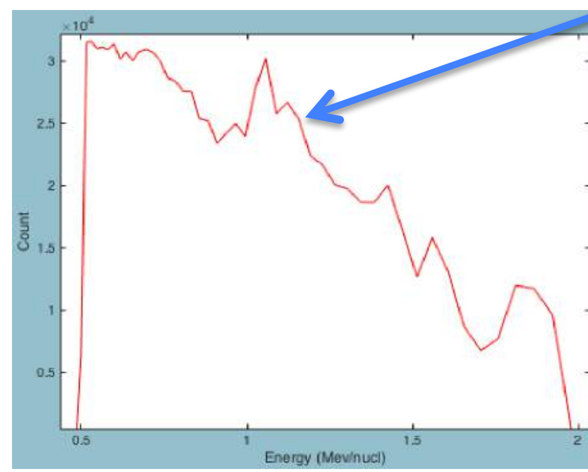
- Pure proton beam ✓
- Monoenergetic ○
- Energy increase ✗



TNSA
Impure



Not TNSA



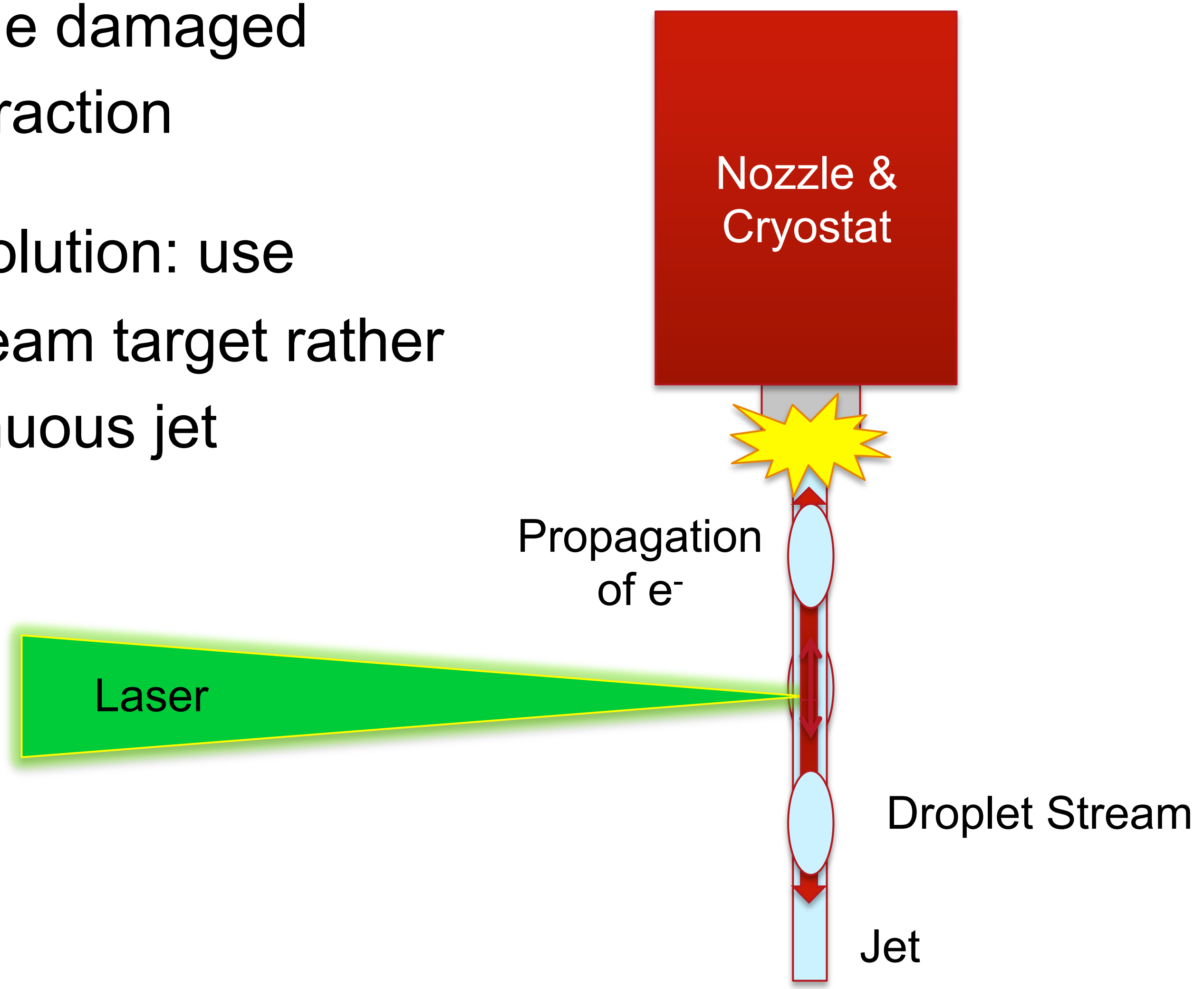
Increasing ion energy

Increasing ion energy

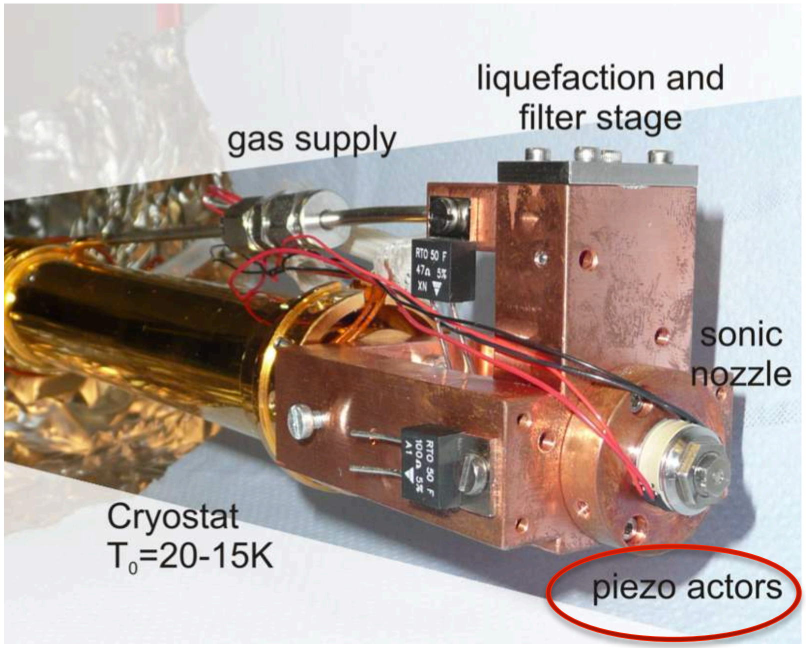
Spectrometer data from shot with jet

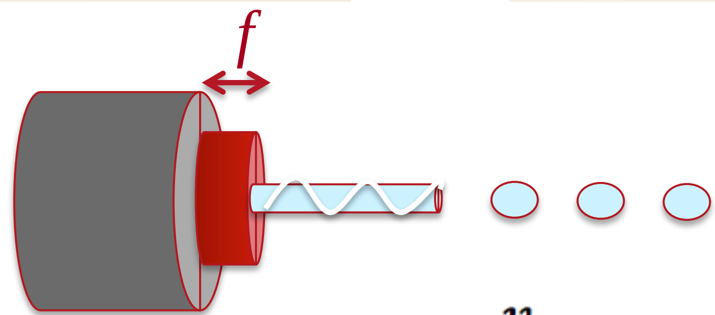
Problems encountered & solutions

- Jet & nozzle damaged during interaction
- Possible solution: use droplet stream target rather than continuous jet

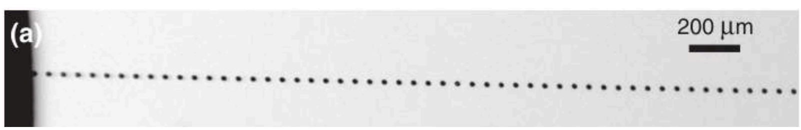


Driving the breakup of the jet





$$\lambda = \frac{v}{f}$$



- Attach piezo components to nozzle, drive with frequency determined from calculations
- Vibrations in nozzle result in droplet breakup

Images courtesy of S. Goede & Costa Fraga et al.

Parameters governing droplet breakup

Reduced Wavenumber

$$x = \frac{\pi d_{jet}}{\lambda}$$

Reynolds Number

$$Re = \frac{\rho v_{jet} d_{noz}}{\mu}$$

Weber Number

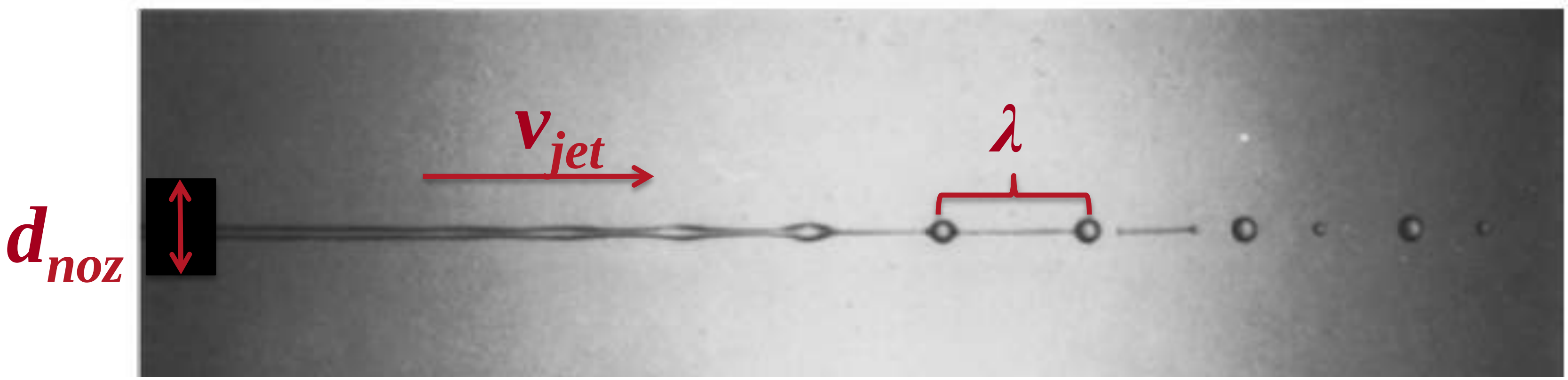
$$We = \frac{\rho_l d_{jet} v_{jet}^2}{2\gamma}$$

Want:

$x \approx 0.7$ *gives optimum wavelength*

$Re < 2000$ *ensures laminar flow*

$0.2 < We < 4$ *ensures jetting*



μ = *dynamic viscosity*, γ = *surface tension*, ρ = *density*

Image courtesy of J Eggers & E Villermaux

Conclusions

- Titan experiment provided interesting & exciting results
  - Achieved pure proton beam with cryogenic hydrogen jet target
  - Progress towards monoenergetic beam
  - Still analyzing results
- Piezo-driven droplet stream could serve as solution to jet problems experienced at Titan
  - Initial development has started
  - Will be tested in upcoming experiments this year

Acknowledgements

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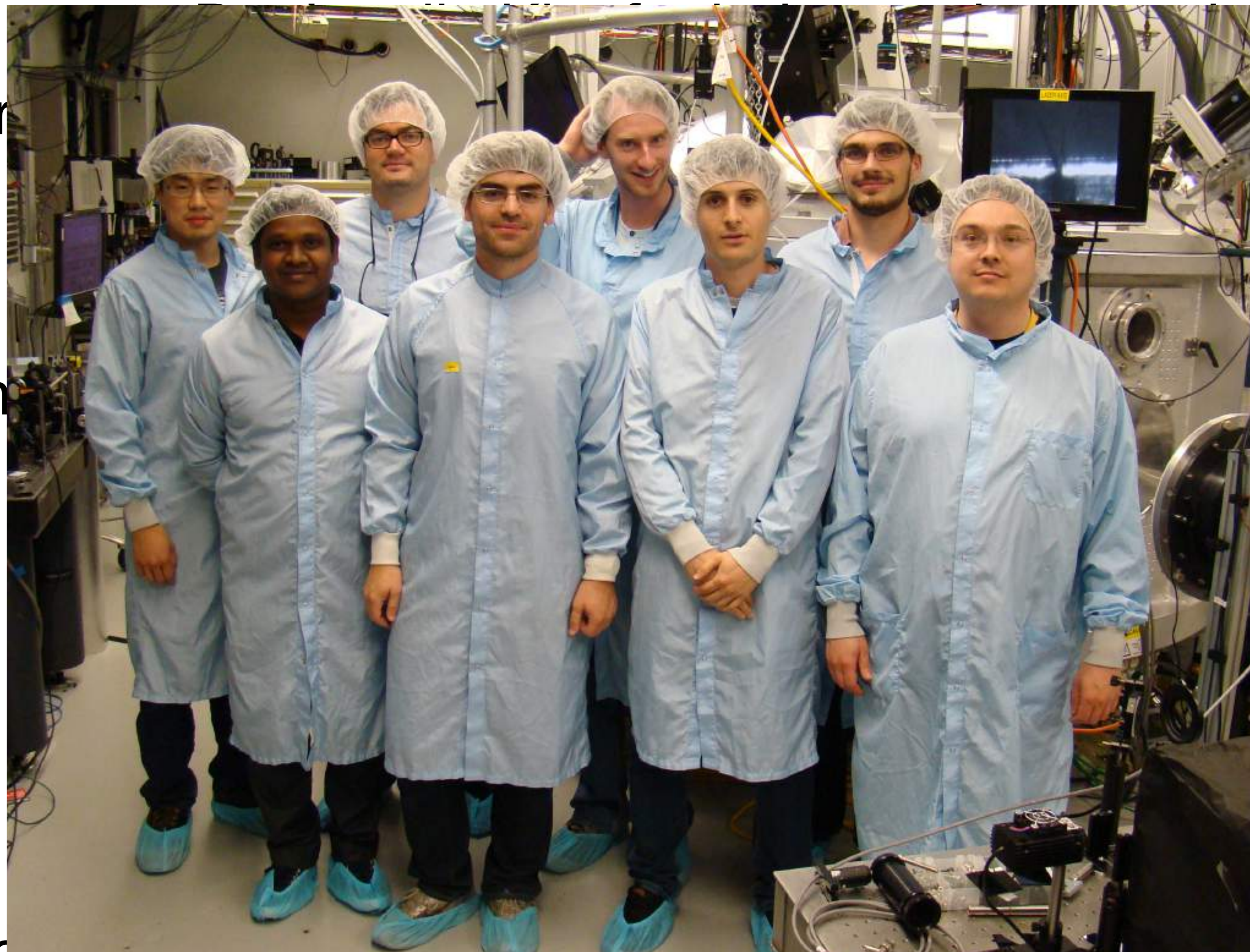
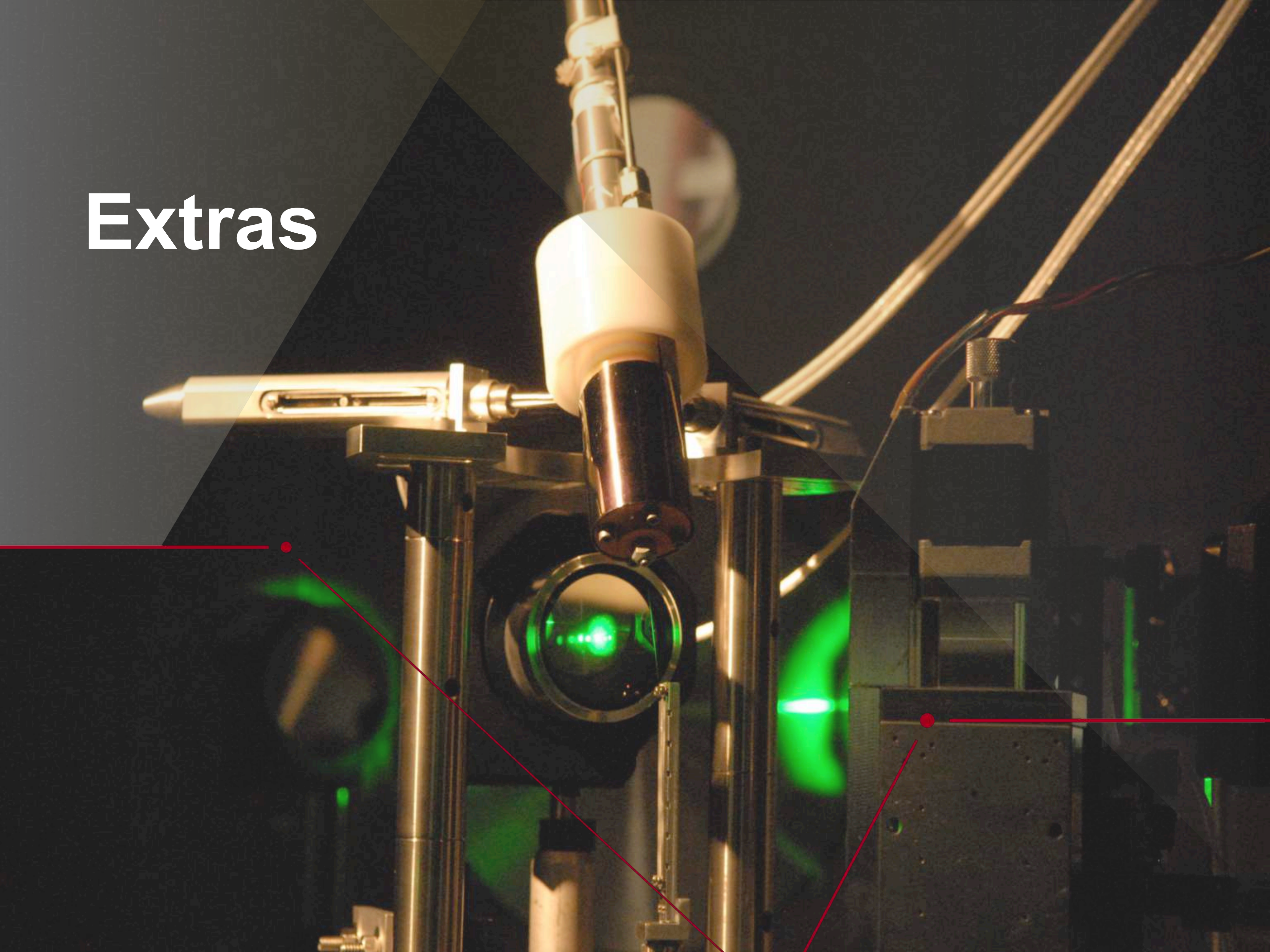


Extras



Spontaneous breakup v. Piezo-driven breakup

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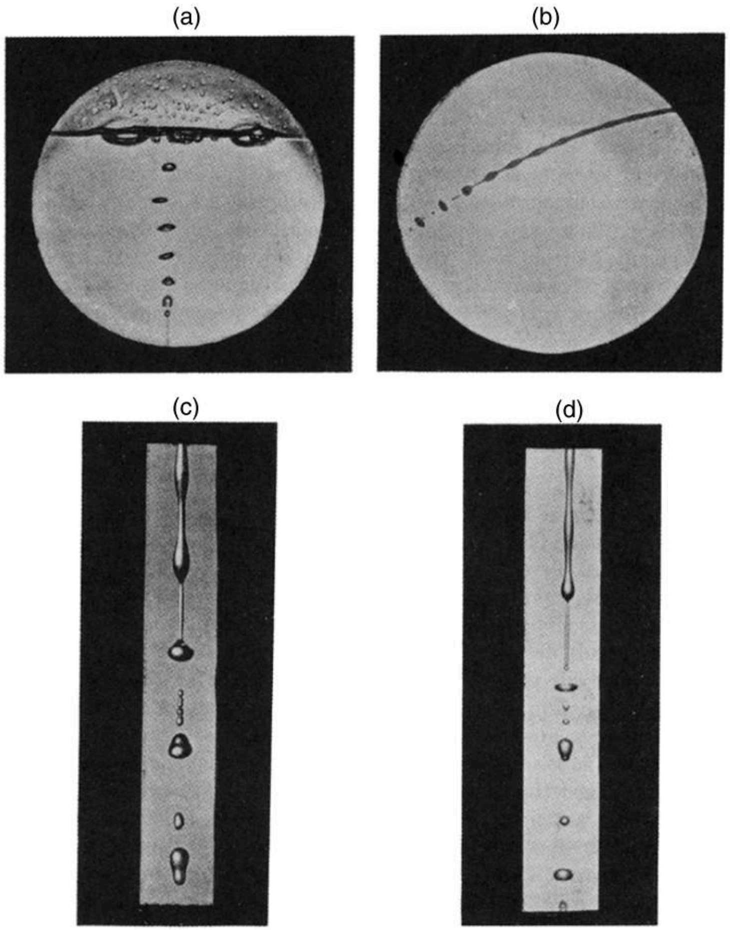
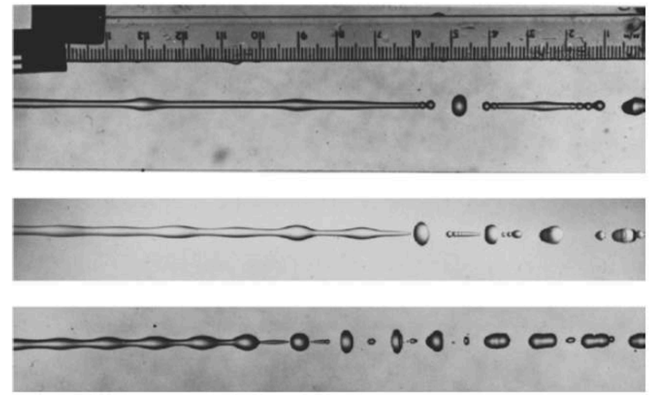
Spontaneous



J Eggers and E Villermaux

Driven



J Eggers and E Villermaux

025102-3 Costa Fraga *et al.*

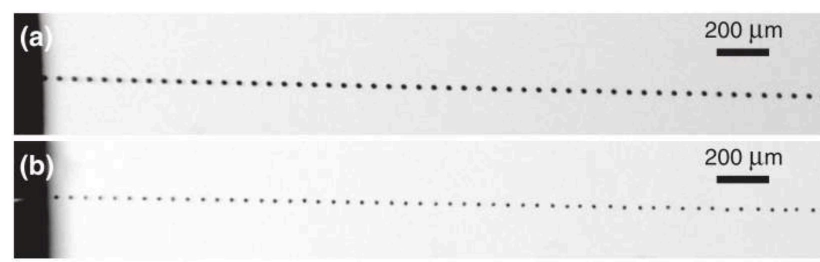


FIG. 2. Stroboscopic images of periodic (a) argon and (b) hydrogen droplet beams propagating in vacuum. The argon beam is produced from a 10

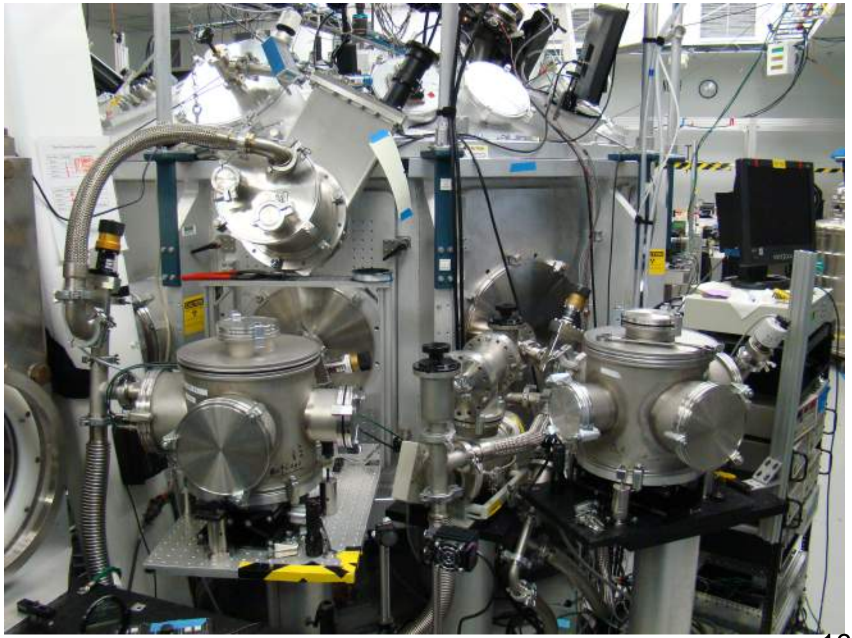
Plan & Expectations - Hydrogen

- Want laminar flow
  - Reynolds' number should be < 2000
  - Gives upper bounds for velocity depending on nozzle diameter
    - v < 66 m/s for 10 micron
    - v < 330 m/s for 2 micron
  - Optimal wavelength: $\lambda = 4.5\ D_{jet}$ **or** $\lambda_{opt} = 2\sqrt{2}\ \pi\ r$
    - $D_{jet} = (\sqrt{3} / 2)\ D_{noz}$
    - Gives optimal wavelength of 9 < λ < 45 microns
    - Also found by setting *x* = 0.7 → Rayleigh number for fastest sinusoidal perturbation growth
- Based on $v = \lambda f$, frequency should be between 1 MHz & 36 MHz
  - Want to avoid coalescence effect
  - Use piezo that operates up to 2.5 MHz

Experiment at TITAN

Goal: accelerate protons in high intensity laser plasma interaction from liquid hydrogen & deuterium targets

- Characterize the acceleration mechanism



Before & After

Images from experiment preparation documents & https://jlf.llnl.gov

Experiment at TITAN

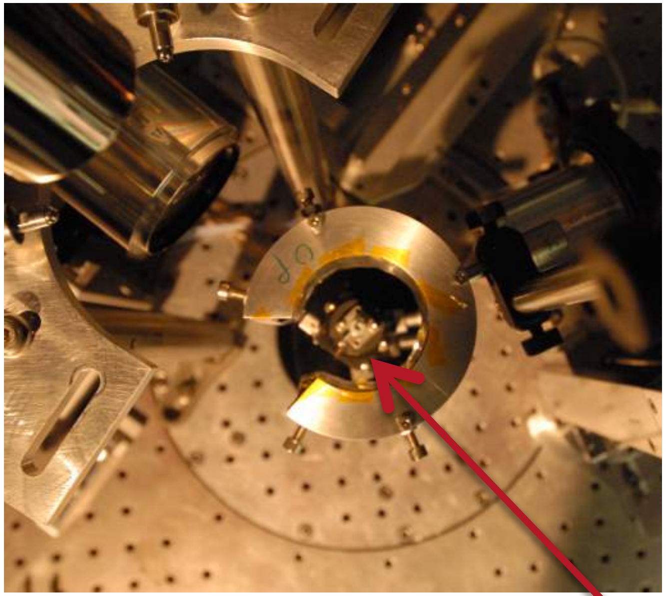
TITAN Laser parameters:

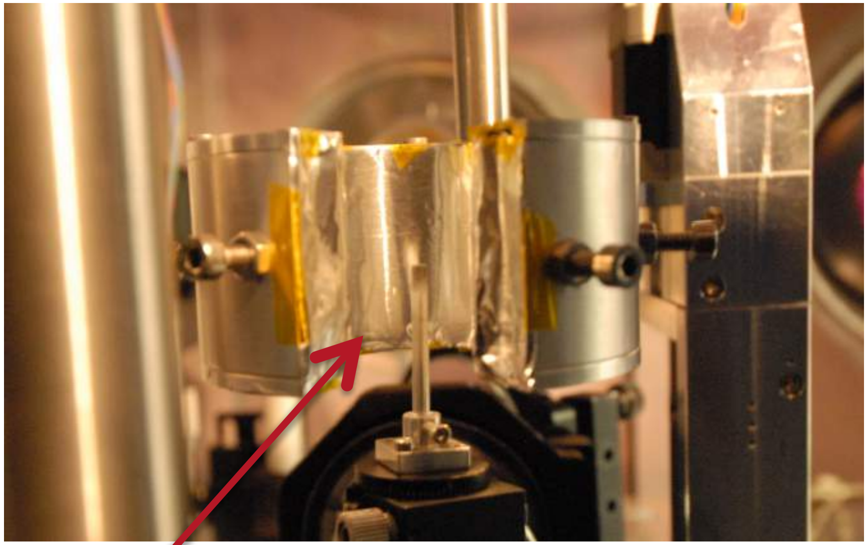
- Duration of pulse: ~ 1 ps
- Diameter of beam at best focus: 10-15 μm (shot-to-shot fluctuations)
- Energy on target: 40 to 65 J (shot-to-shot fluctuations)
- Peak Intensity: ~ 5e19 W/cm^2
- Power: >40 TW
- Wavelength: 2w, (527nm)
- Contrast: below 1e-9 intensity (below the diagnostic detection limit)

Images from experiment preparation documents & https://jlf.llnl.gov

The Reference Target – Metal Wires

- Originally intended as a reference due to cylindrical shape
- Gold & carbon, 10 shots total
- Provided unexpectedly interesting results



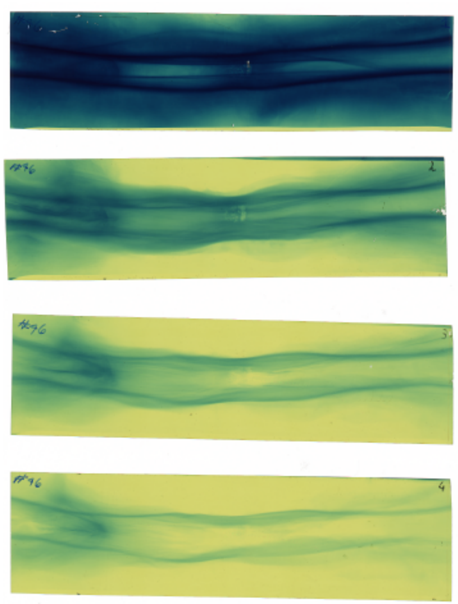


Solid wire target

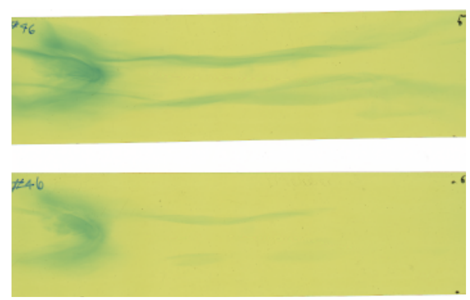
Results

- Based on preliminary analysis, not just TNSA (Target Normal Sheath Acceleration – the standard mechanism of ion acceleration)
  - Potentially shockwave acceleration

Increasing proton energy

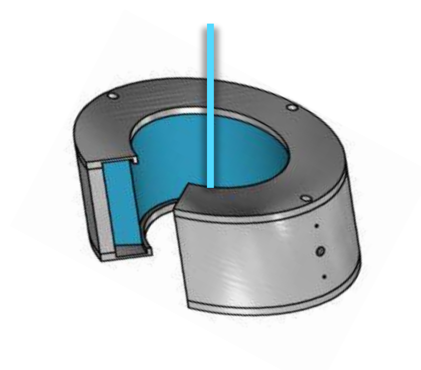


Layers 1 - 4



Layers 5-7

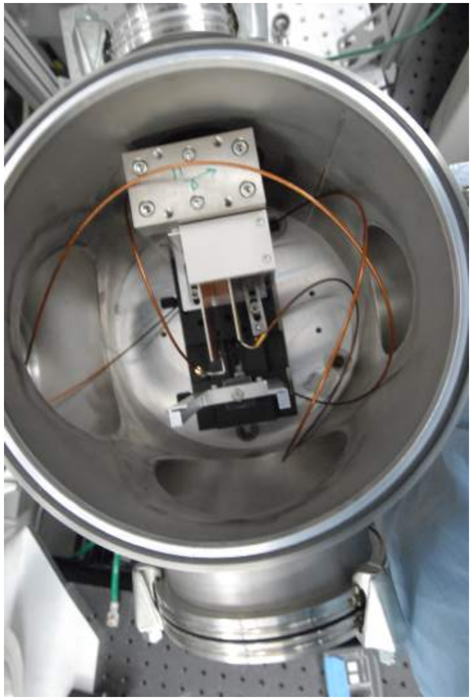
*Interesting features:
- Banding
- Modulations
- Feature on side



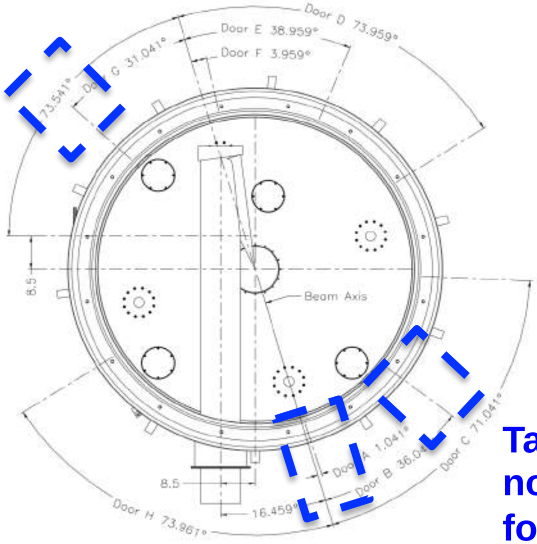
Shot 46 – 10 um gold

Diagnostics

- Thomson Parabolas
- RCFs

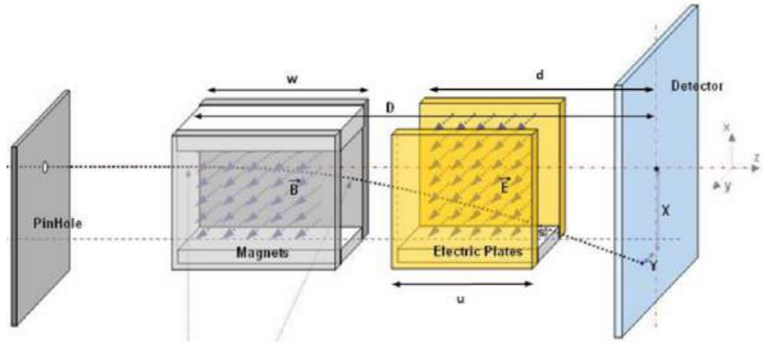


Target normal backward TP: 6 way cross



Laser axis TP: Pot chamber

Target normal forward TP: Pot chamber



Images from experiment & preparation documents