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E308: Underdense Plasma Lens
status and future plans

FACET-II Users Meeting

Oct. 17, 2023

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Contents

The Importance of Strong Focusing

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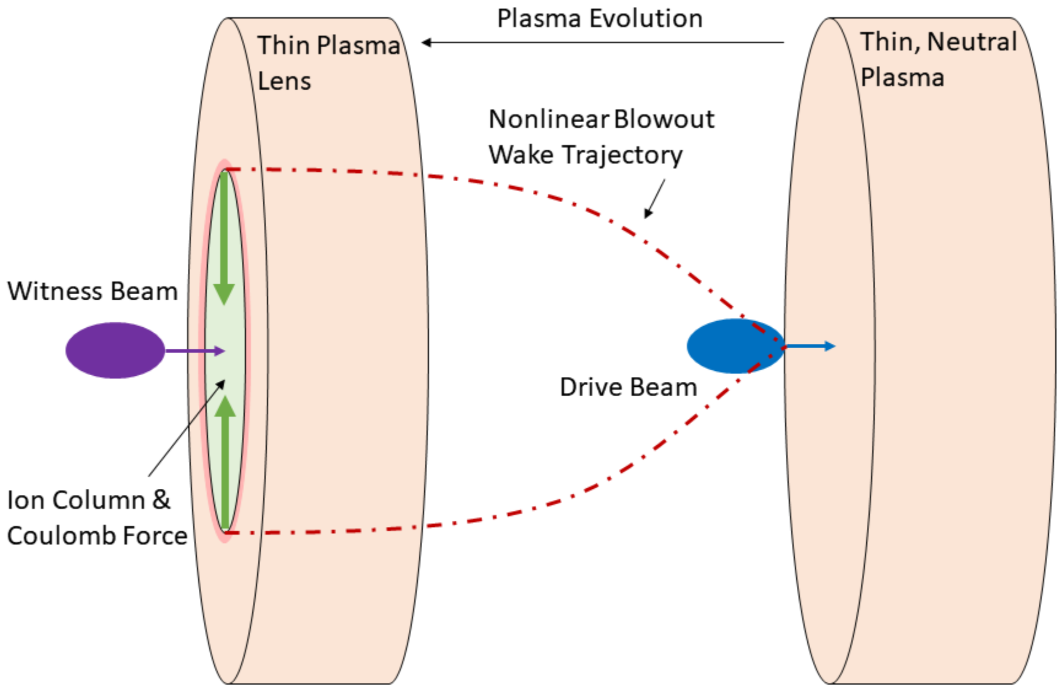
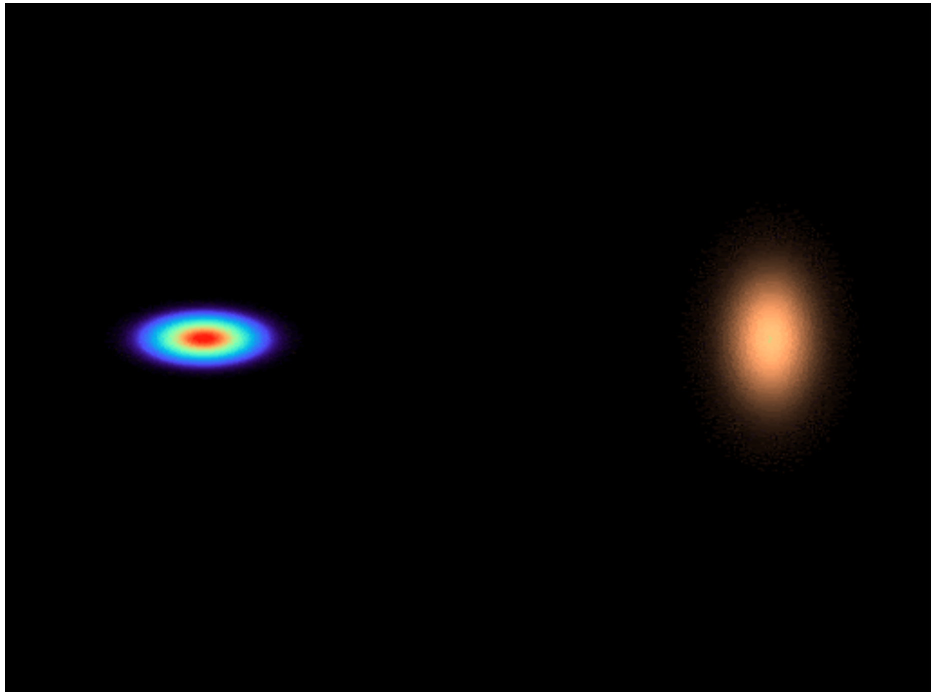
- Matching into plasma stages
  - Necessary to prevent chromatic emittance growth
  - Quadrupole magnets not strong enough
- Divergence control coming out of plasma stages
  - Prevent chromatic emittance growth in vacuum from high divergence
  - Match injected beams exiting plasma to magnets / undulators
- Collider final focus
  - Axisymmetric – can reduce length
  - Ultra compact and strong – can provide tightest focus
  - Serve as proxy for collider FF in strong focusing studies (Oide effect)
- Other
  - SFQED – increase χ: nonlinear quantum param.
  - ICS – increase brightness by reducing source size
  - HEDP – increase energy density on target

Thin, Underdense, Passive Plasma Lens (TUPPL)

- Thin – PWFA much shorter than one betatron period
- Underdense – Nonlinear blowout regime
- Passive – No reliance on externally driven current
- Plasma Lens – Transverse focusing impulse with negligible energy change





Attractive Features of TUPPL

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- **Extremely strong focusing**
  - Orders of magnitude beyond electromagnets and PMQs
- **Axisymmetric focusing**
  - Single lens can achieve symmetric focus in x & y
- **Ultra-compact**
  - Plasma lens itself: ~100 μm
  - Gas jet & laser hardware: ~1 cm footprint along beam line
- **Rapidly and easily tunable**
  - Strength scales with density → gas pressure
  - Strength scales with length → laser energy / focus
- **Self-aligning**
  - Central axis of blowout determined by electron beam

Thin Lens Focusing

Focal length depends on beam energy and plasma lens density & length:

$$f \equiv \frac{1}{KL} = \frac{1}{2\pi r_e} \frac{\gamma_b}{n_p L}$$

(cgs)

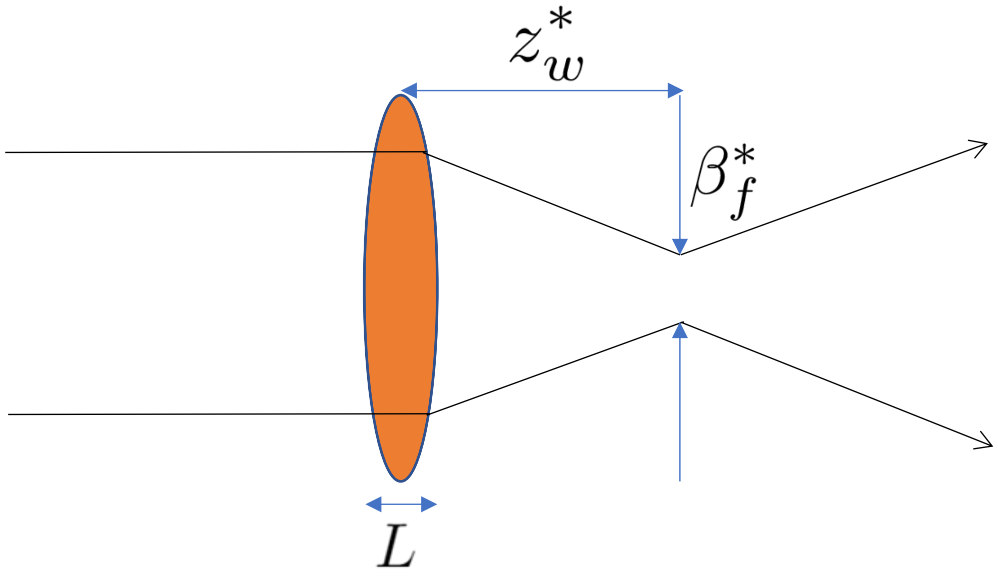
- Beam Energy
- Plasma Density
- Plasma Length

Can easily determine waist location and waist CS parameters as a function of initial CS parameters:

$$\beta_f^* = \frac{1}{K^2L^2\beta_0 + 2KL\alpha_0 + \gamma_0}$$

$$z_w^* = \frac{KL\beta_0 + \alpha_0 - L\gamma_0}{K^2L^2\beta_0 + 2KL\alpha_0 + \gamma_0}$$

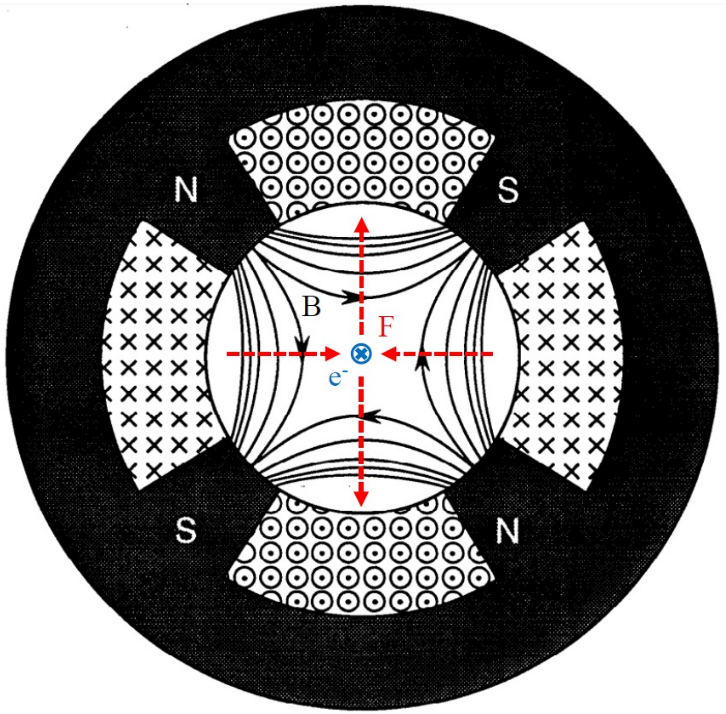
Doss et.al., Phys. Rev. Accel. Beams, **22**(11)111001 (2019)



Comparison to Magnetic Quadrupoles

TUPPL focusing strength is orders of magnitude stronger than magnets of equivalent phase advance (normalized length).

Quadruple Magnet



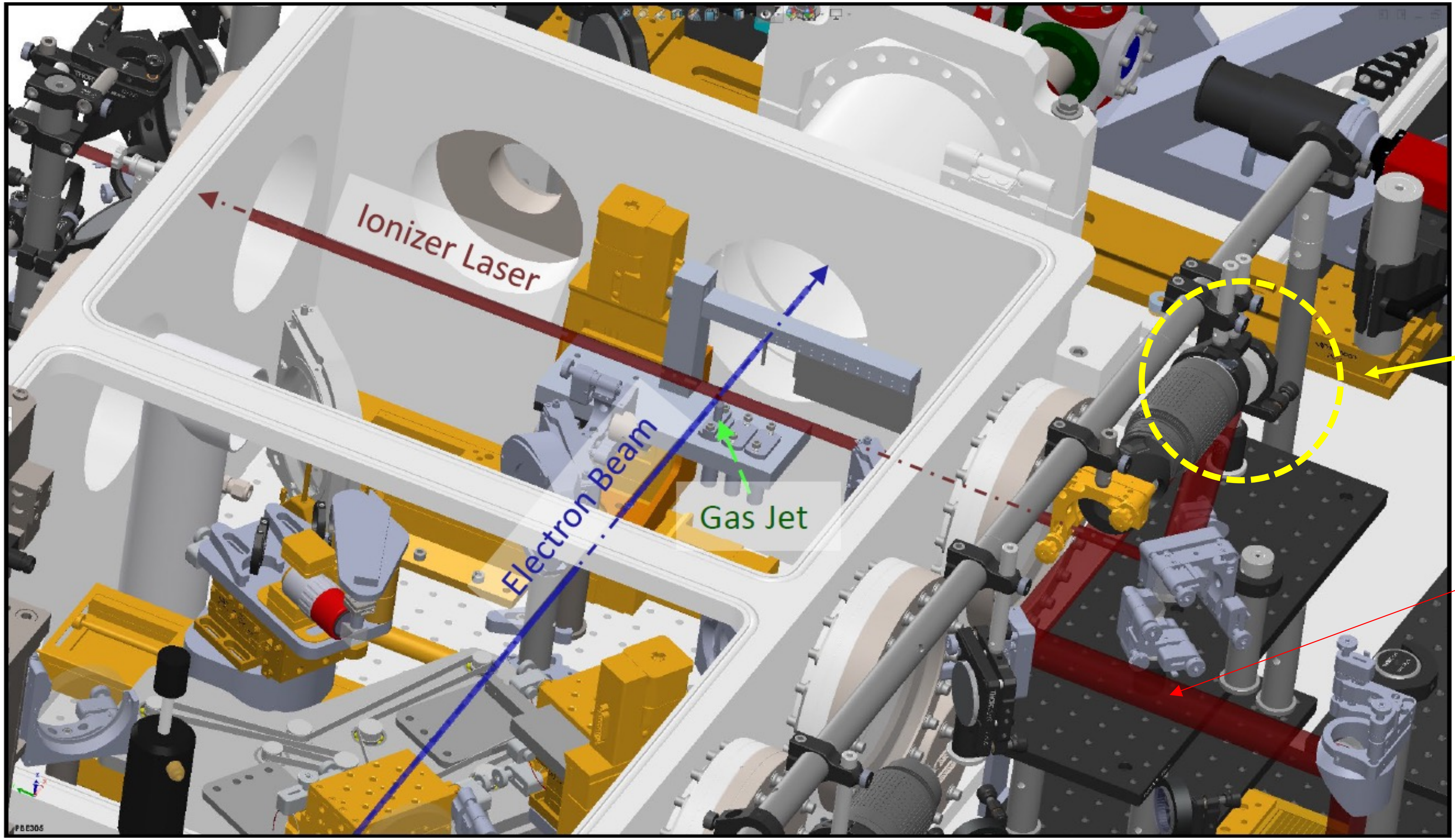
Adapted from Taylor, SLAC-PUB-5621 (1991)

Phase advance (normalized length): $\Delta\psi = \sqrt{K}L = 0.1$

Type	K [m^{-2}]	L [mm]	f [cm]
Quadrupole Electro-magnet	**0.3**	**180**	**1000**
Permanent Magnetic Quadrupole	**150**	**8.2**	**81**
Underdense Plasma Lens at $n_p = 10^{17}$ cm^{-3}	**88400**	**0.34**	**3.3**

Not only are plasma lenses **stronger**, but they are **axisymmetric**, unlike quadrupole magnets.

FACET-II: Nominal Experimental Design



646 mm OAP

Low energy laser: <10mJ

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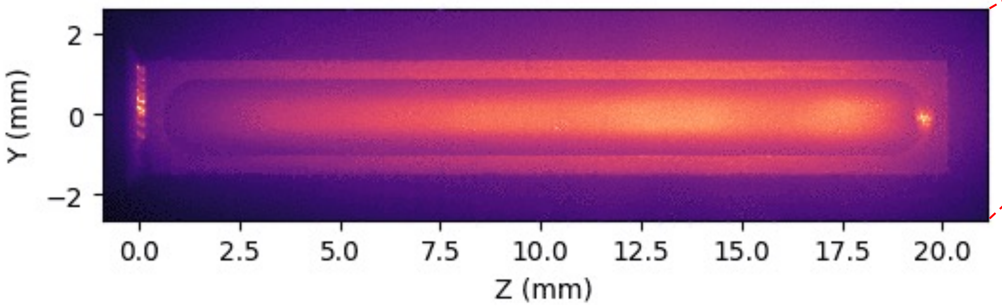
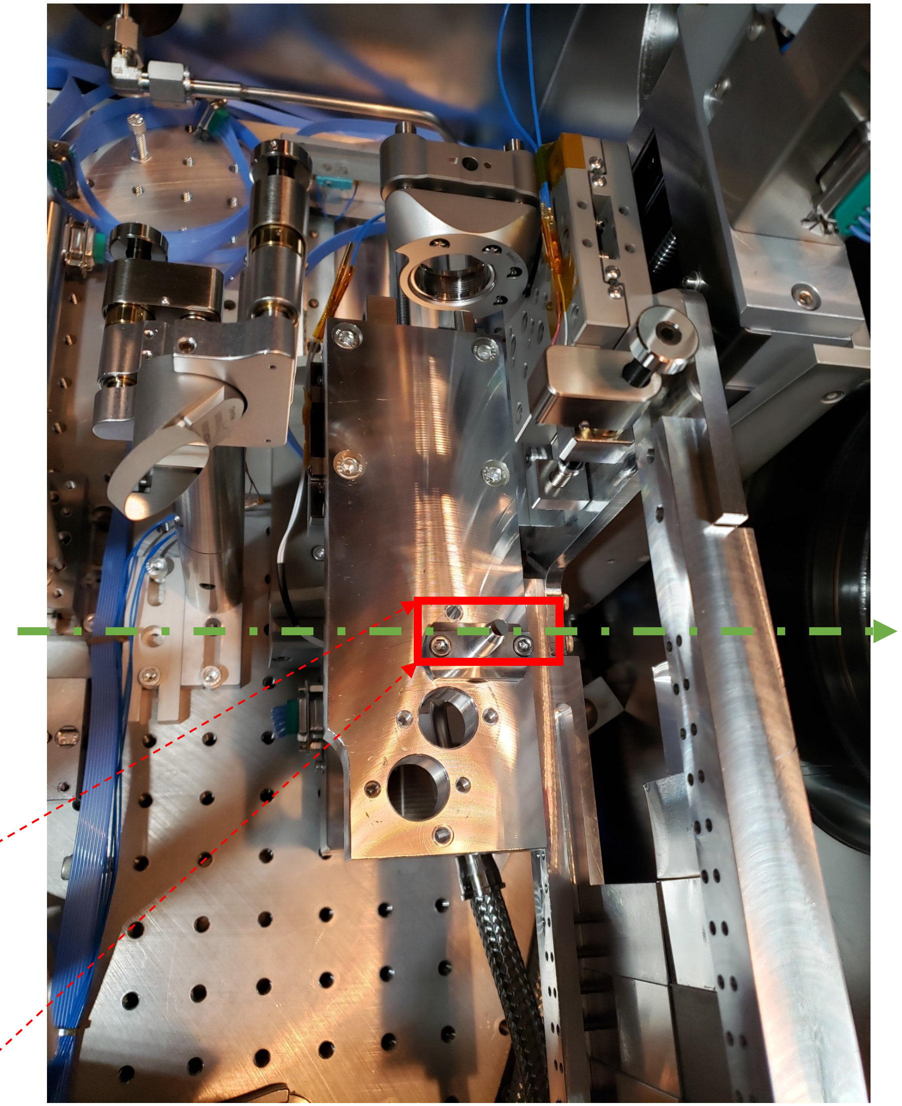
FACET-II: Commissioning Setup

- Experimental chamber with moveable gas jet below the beamline; e-beam travels left to right
- 2 cm elongated nozzle
- Gas outflow is laser-ionized at focus of an axilens; laser propagating left to right





<u>Not ideal conditions</u>, but allowed us to commission basic equipment, diagnostics, experimental procedures, and analysis techniques.

FACET-II: Commissioning Datasets

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- Used what was available at the time
- Didn't know until later what regimes we are operating in
- One dataset had potential (but unclear)

Experimental Conditions

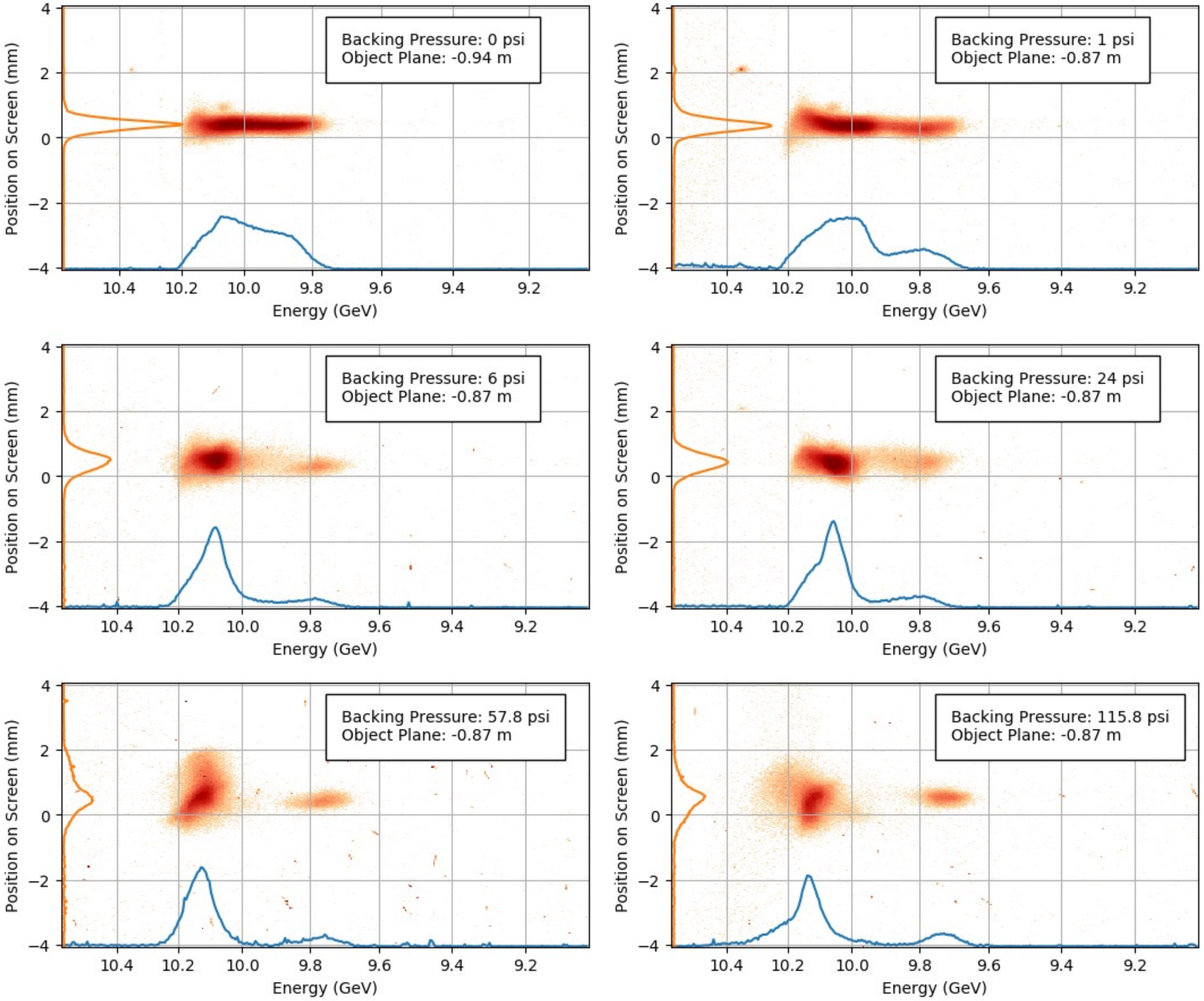
Parameter	Available	Desired
Gas Jet Backing Pressure	~ 1-100 psi	~ 0.1-10 psi
Nozzle Shape	2 cm Slit	~5mm Round
Laser Direction	Longitudinal	Transverse
Number of e^- Bunches	1	2
Transverse Size of e^- Beam	> 30 µm	< 5 µm
e^- Drive Beam Density	1.7×10^{16} cm^{-3}	5×10^{17} cm^{-3}

Datasets

Backing Pressure	0 psi	1 psi	6 psi	24 psi	57.8 psi	115.8 psi
Approximate Density (cm^{-3})	0	0.27×10^{16}	1.6×10^{16}	6.5×10^{16}	15×10^{16}	32×10^{16}
Underdense Regime?		Yes(?)	No(?)	No	Nope	No Way
Plasma Lens Thickness?		Thick Lens	Very Thick Lenses – Short PWFA Stages			

FACET-II: Commissioning Raw Data

- Imaging spectrometer set to image plane 1m downstream of TUPPL for these images.
- Expect large divergence for strongly focused beam.
- Expect no energy change for true TUPPL.
- Evidence of divergence, but also energy modulation, even at TUPPL candidate density.



FACET-II: Commissioning Data Analysis

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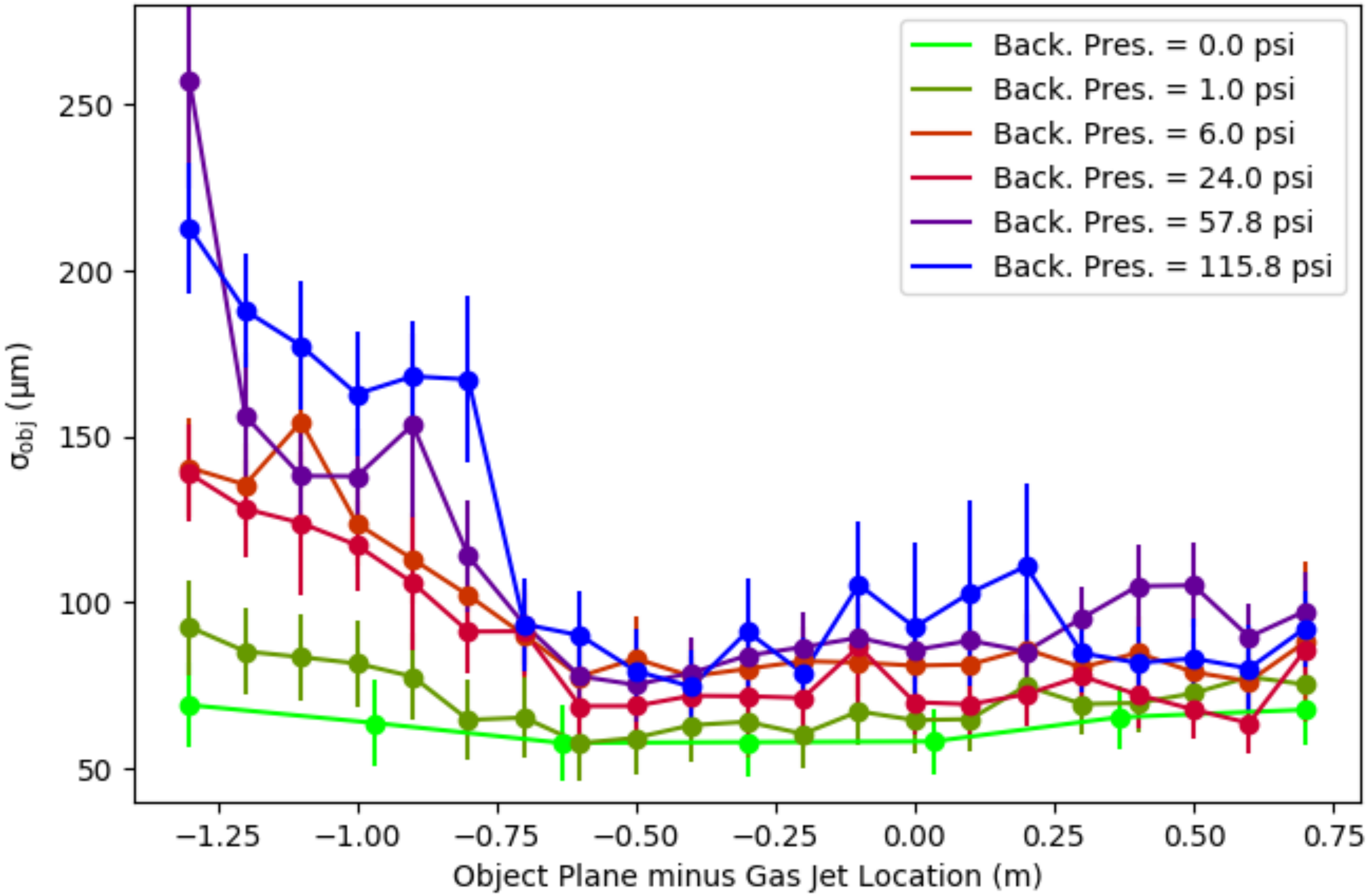
- Horizontal beam sizes vs object plane relative to gas jet.
- Beam size is rms from Gaussian fit to projected beam.
- Difficult to interpret, except to say that we likely weren't in the TUPPL regime for any dataset.
- Lessons learned; analysis road tested; better prepared for next attempt.



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1) Overview of E308

2) Commissioning Progress

3) Future Plans

Plans for 2024 FACET-II Runs

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- Phase 1: ionize with main laser
  - Prefer 2 mm round gas jet nozzle
  - Could use rotated slit nozzle (possible configuration?)
  - Use axilens with main laser
  - Start with measurement of divergence (alá E332)
  - Follow-up with measurement of waist
- Phase 2: ionize with probe beam
  - Prefer 2 mm round gas jet nozzle
  - Could use back-filled Picnic Basket (must avoid beam ionization)
  - Need ~10 mJ on target, compressed, good wavefront
  - Use telescope + spherical lens
    - Configuration already laid out; may benefit from tweaking
    - Compensate GDD with chirp; must be confirmed during access
    - Install reflective telescope to reduce B-integral

Long-Term Plans (2025 and beyond)

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- Ultra-strong focusing (stronger than FF quads)
- Two-bunch TUPPL
- Matching into PWFA
- Divergence control of plasma injected beams
- Transverse gradient TUPPL studies
- Observe and study Oide effect

Collaborators and Credits

Dr. Chris Doss
now at LBNL
...future collaborator?

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