Experimental Progress of Passive Plasma Lens at FACET-II

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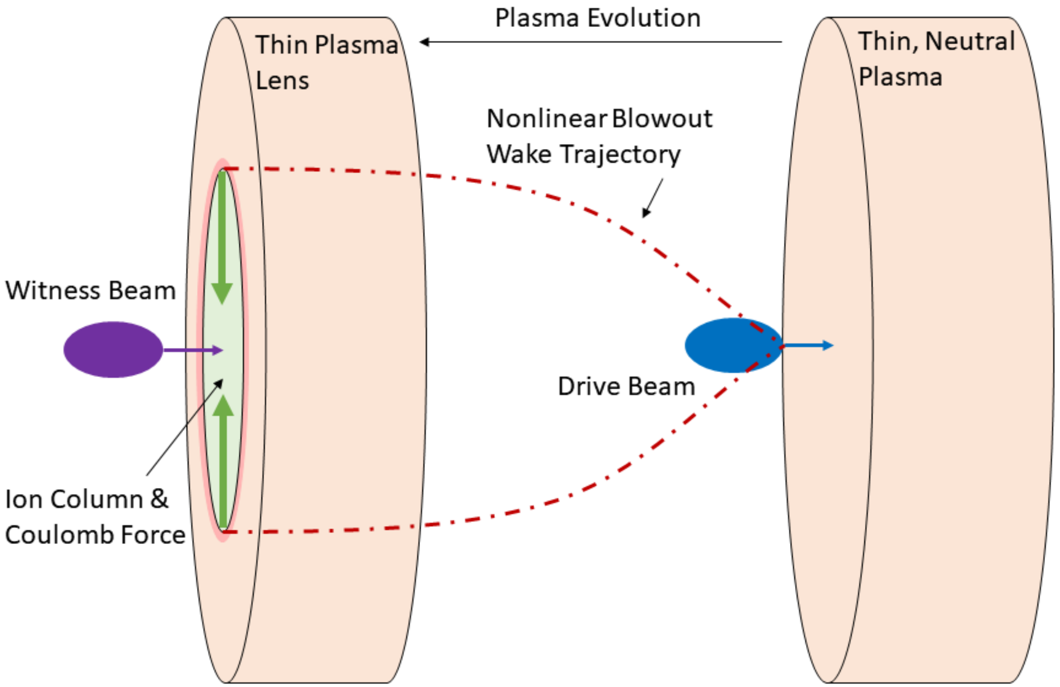
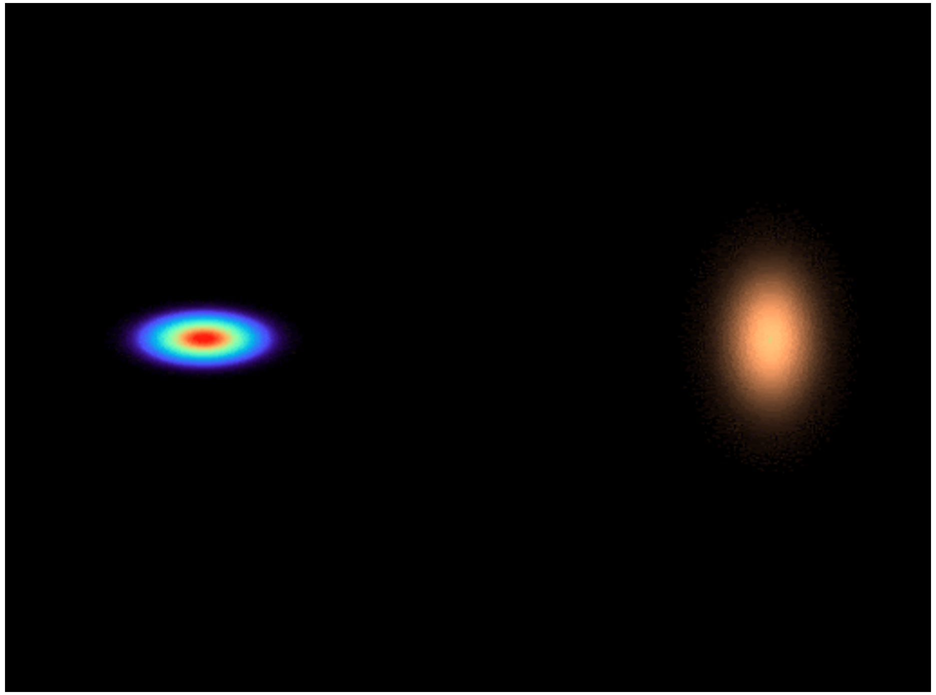
The Importance of Strong Focusing

- 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 chi: 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





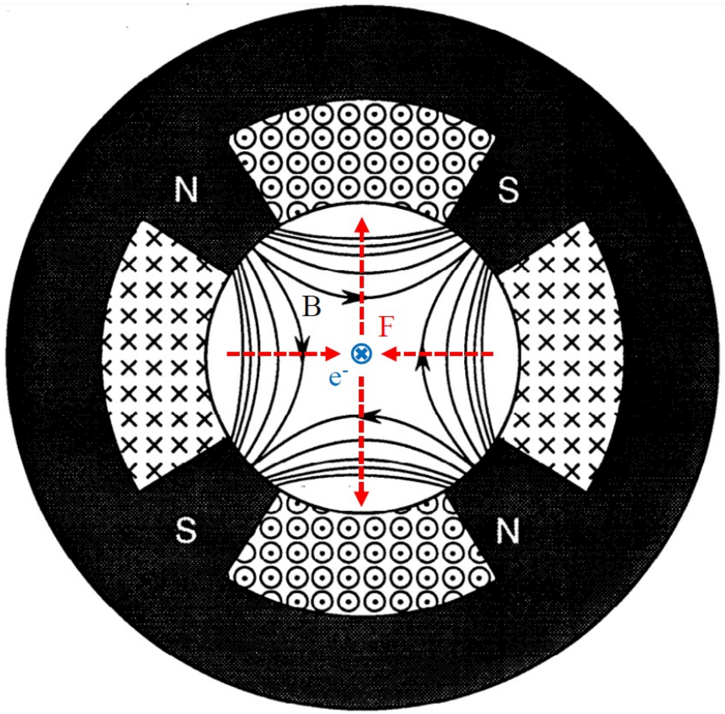
Attractive Features of TUPPL

- **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

Comparison to Magnetic Quadrupoles

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

Quadruple Magnet



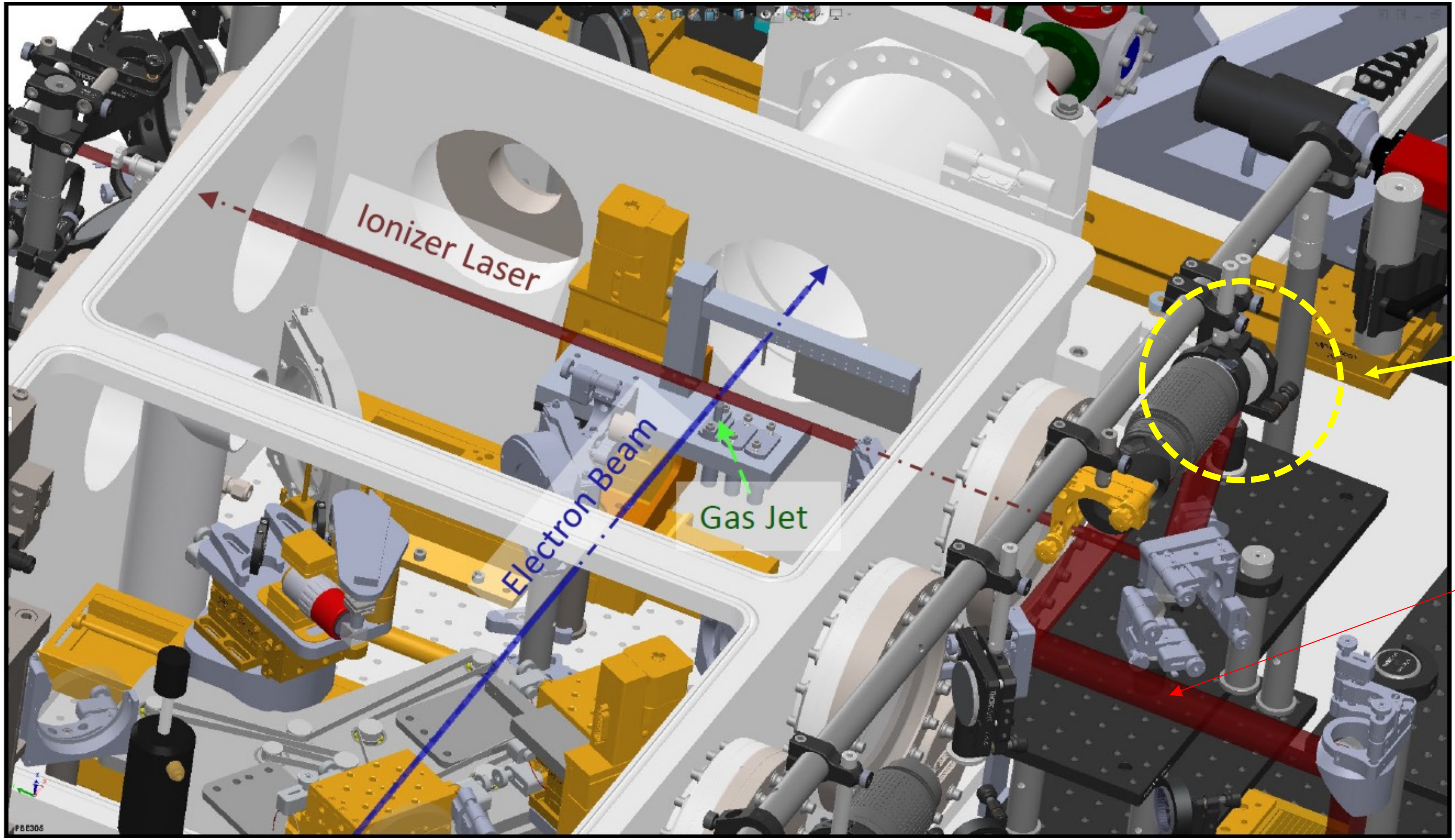
Adapted from Taylor, SLAC-PUB-5621 (1991)

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

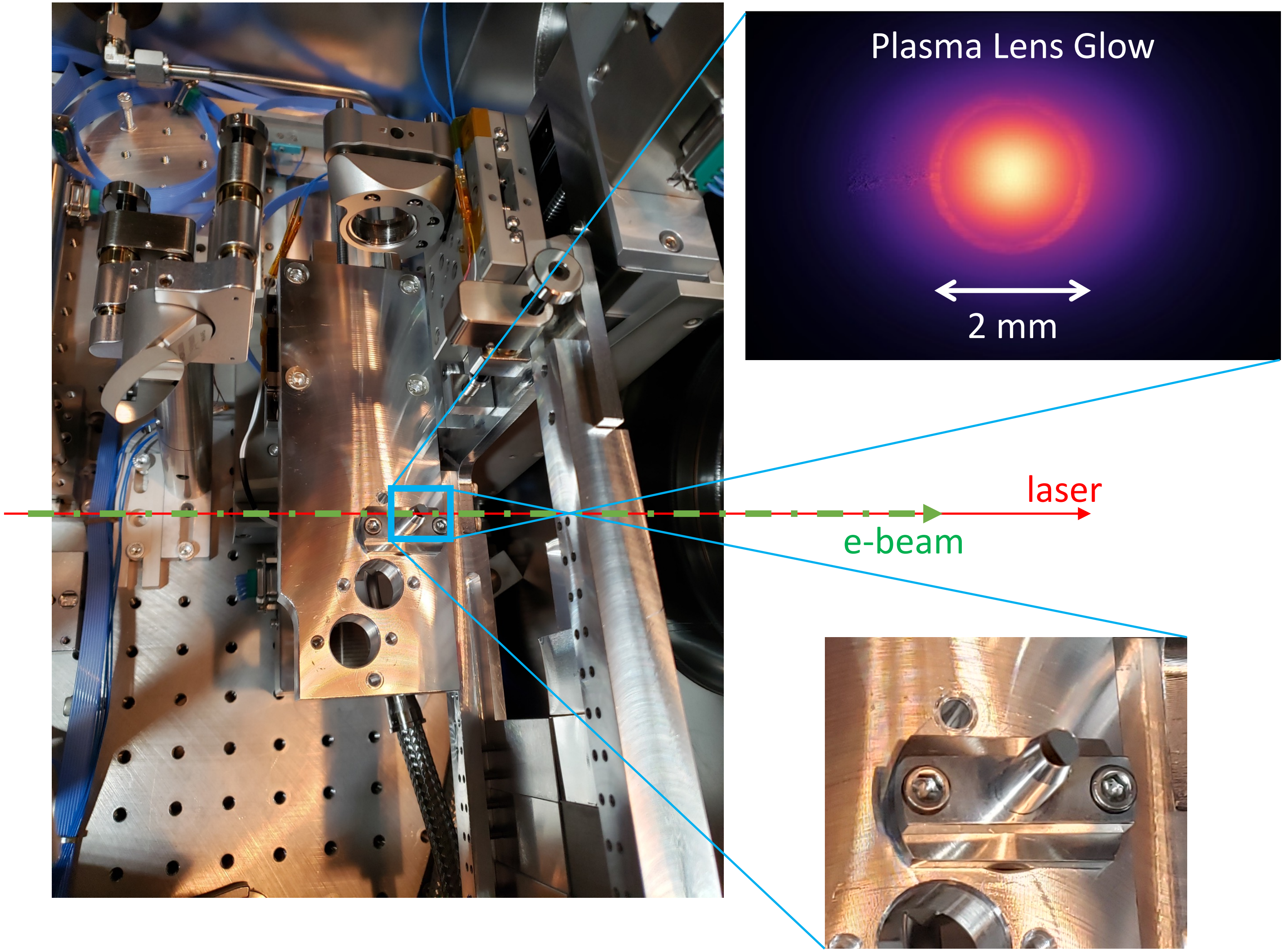


646 mm OAP

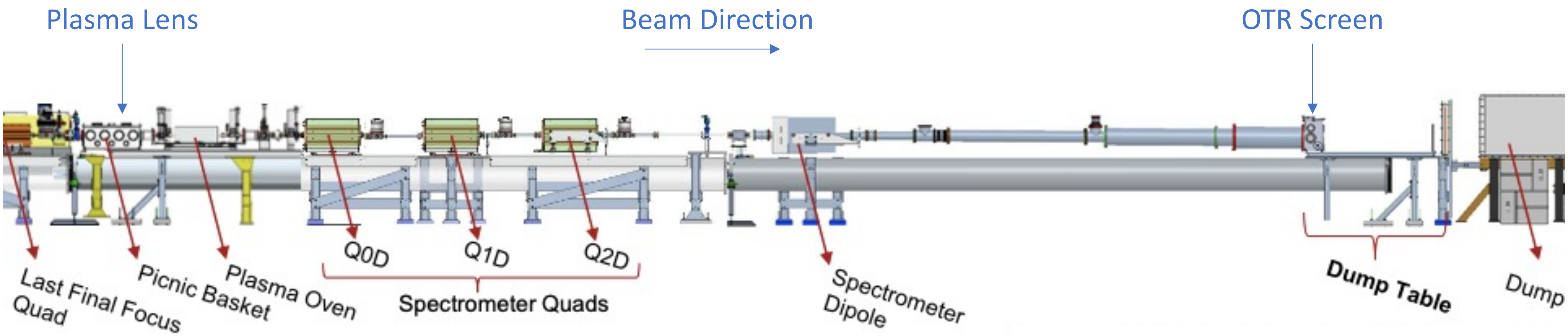
Low energy laser: <10mJ

FACET-II: E-308 Experimental Setup

- Vacuum chamber with moveable gas jet
- 2 mm round nozzle, 2 mm below e-beam
- Gas ionized by laser
- Laser focused by axilens along e-beam direction
- Limitations:
  - Not well characterized at low pressure
  - Axial focusing means jet defines plasma profile



FACET-II Electron Imaging Spectrometer

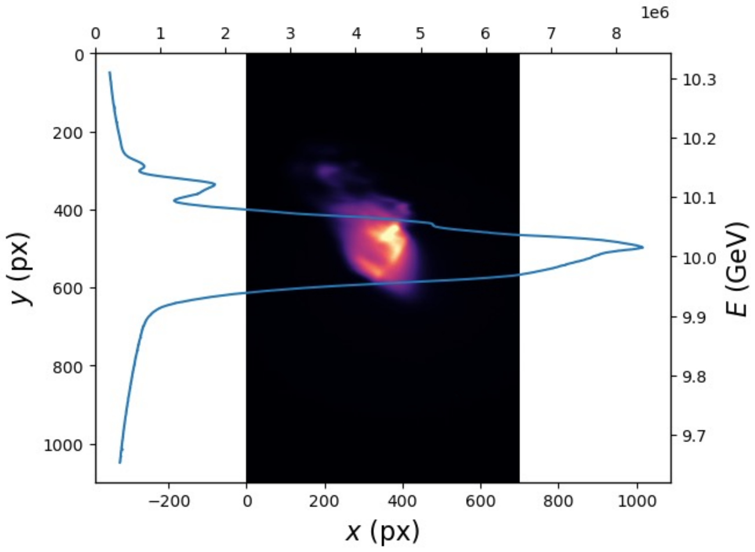


- Quadrupole magnet triplet and spectrometer dipole magnet
- Disperses in y, images in x
- Image plane at OTR screen near dump
- Object plane scanned around location of gas jet (plasma lens)

Focusing with the Plasma Lens

Plasma Lens Off

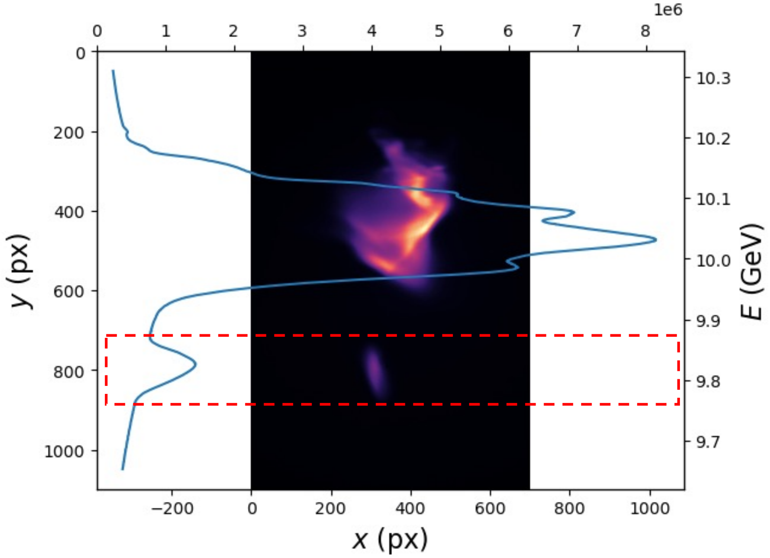
Vacuum



Imaging Spectrometer Screen
Object Plane: Plasma Lens
Total Charge: 1.6 nC
Centroid Energy: 10 GeV

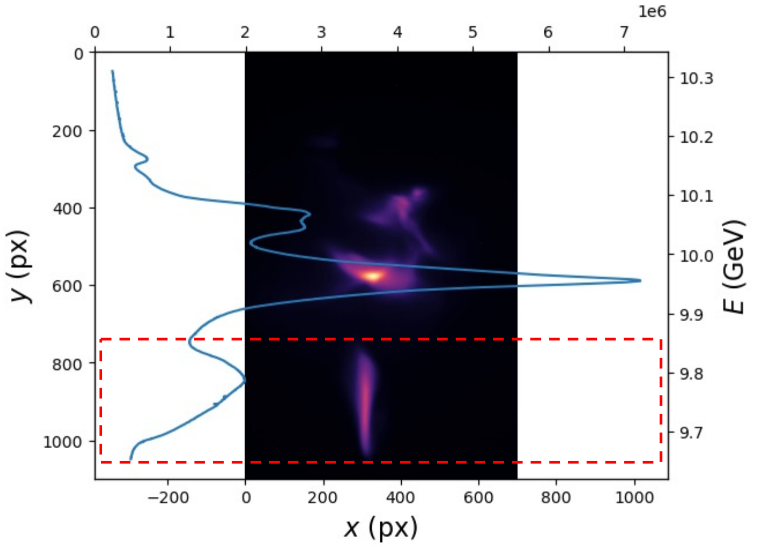
Plasma Lens On

3 PSI



Imaging Spectrometer Screen
Object Plane: Plasma Lens
Focused Charge: 70 pC
Energy Loss: ~200 MeV

7.5 PSI

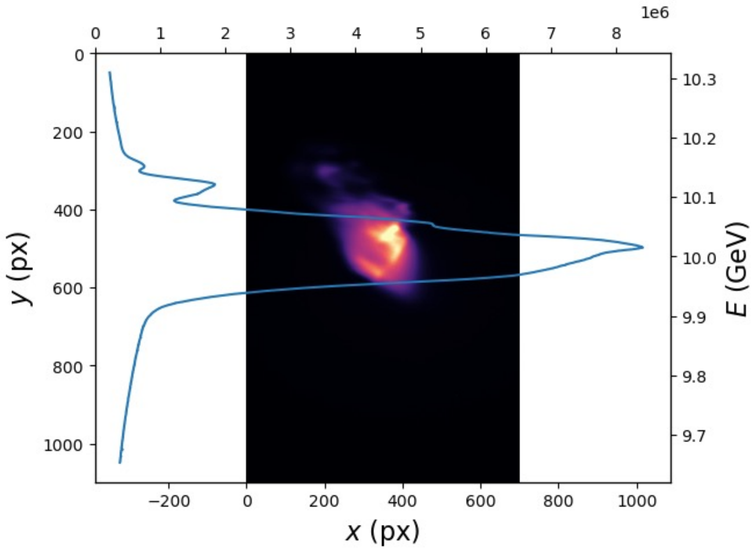


Imaging Spectrometer Screen
Object Plane: Plasma Lens
Focused Charge: 300 pC
Energy Loss: ~250 MeV

Focusing with the Plasma Lens

Plasma Lens Off

Vacuum



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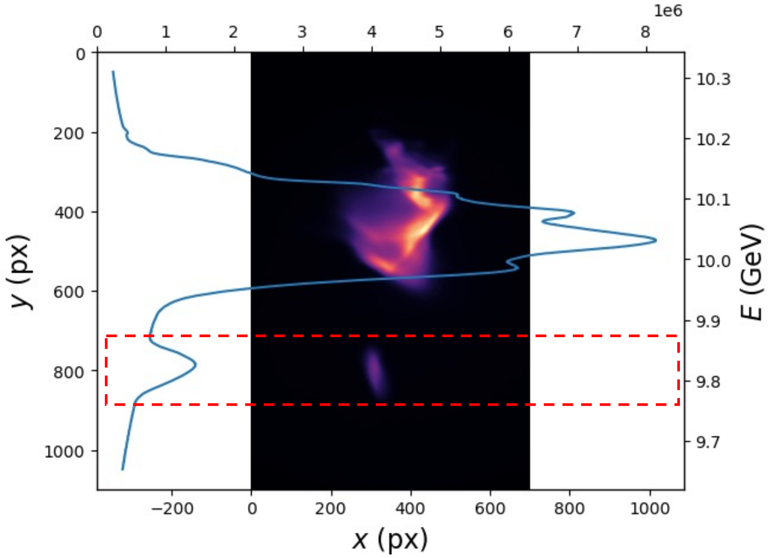
Plasma Lens On

3 PSI



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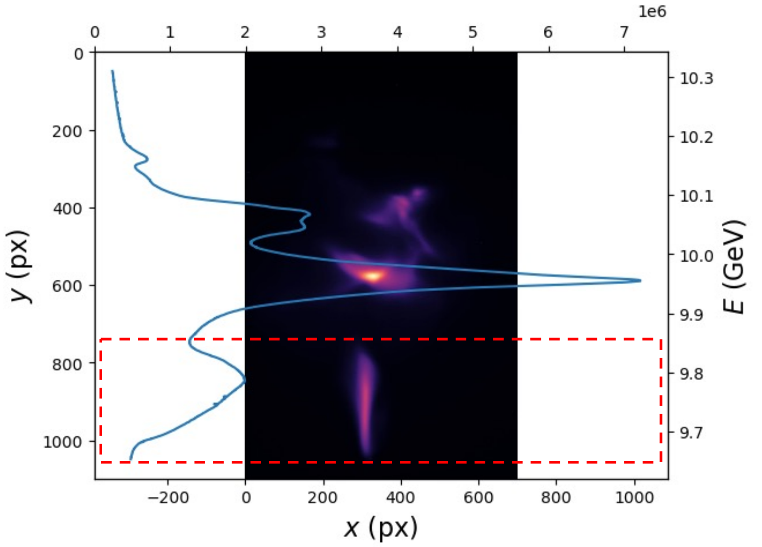
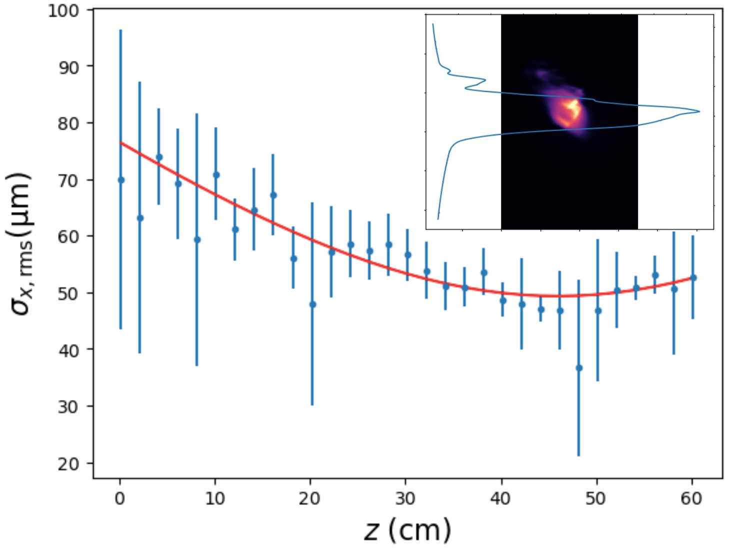


Imaging Spectrometer Screen
Object Plane: Plasma Lens
Focused Charge: 300 pC
Energy Loss: ~250 MeV

Imaging Spectrometer Object Plane Scan

Plasma Lens Off

Vacuum

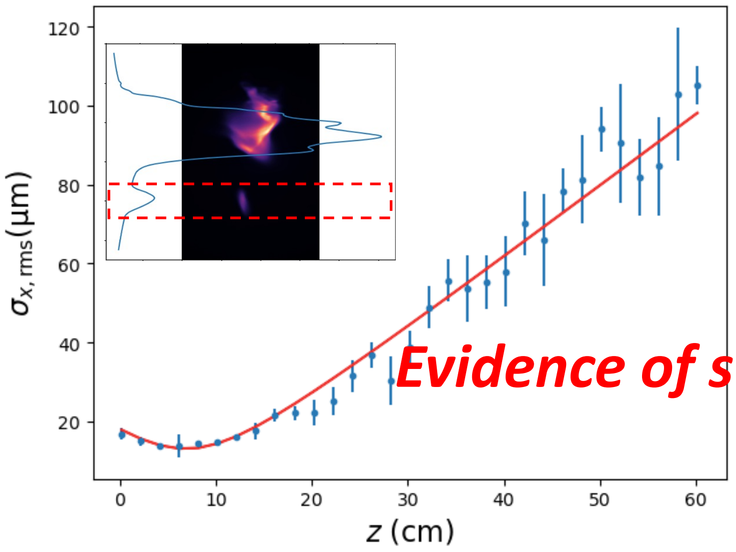


Fit Params:
$z^* = 46$ cm
$\beta^* = 39$ cm
$\sigma^* = 49$ μm
Q = 1.6 nC

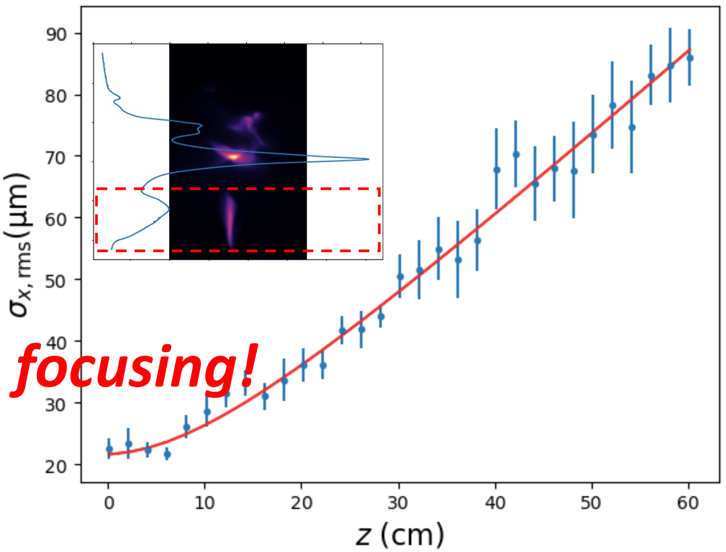
Plasma Lens On

Strongly Interacting (Focused) Charge

3 PSI



7.5 PSI



Evidence of strong focusing!

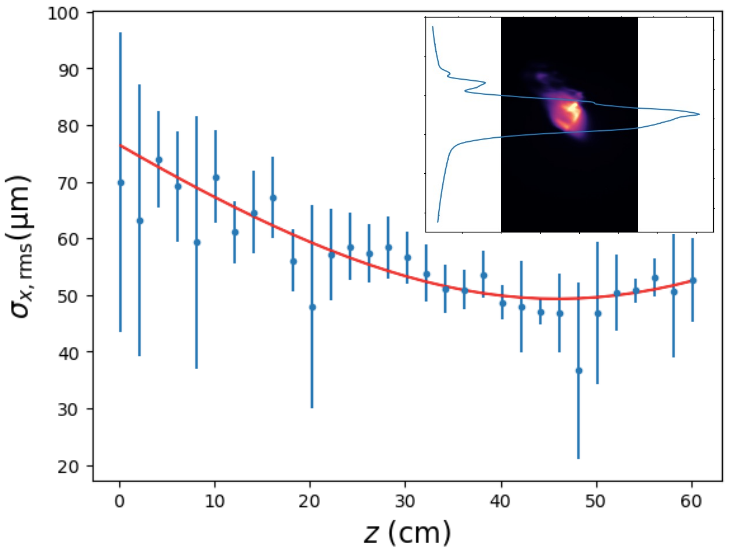
Fit Params:
$z^* = 6.8$ cm
$\beta^* = 7.2$ cm
$\sigma^* = 13$ μm
Q = 70 pC

Fit Params:
$z^* = <2$ cm
$\beta^* = 16$ cm
$\sigma^* = 22$ μm
Q = 300 pC

Imaging Spectrometer Object Plane Scan

Plasma Lens Off

Vacuum

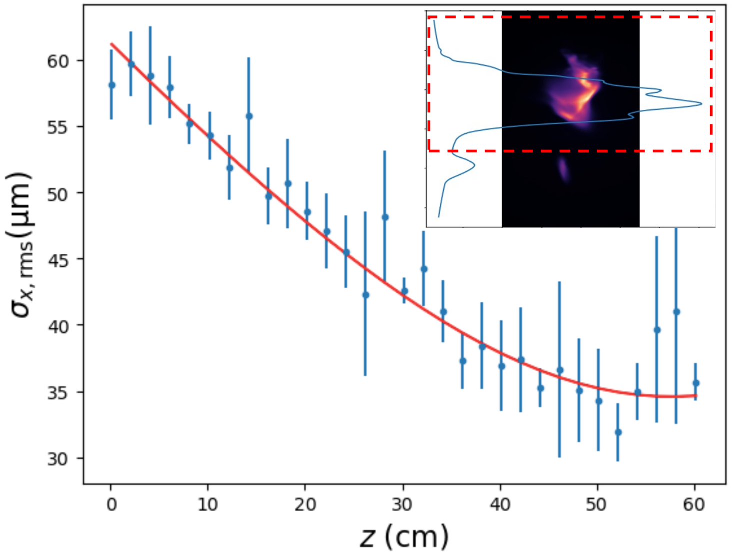


Fit Params:
$z^* = 46$ cm
$\beta^* = 39$ cm
$\sigma^* = 49$ μm
Q = 1.6 nC

Plasma Lens On

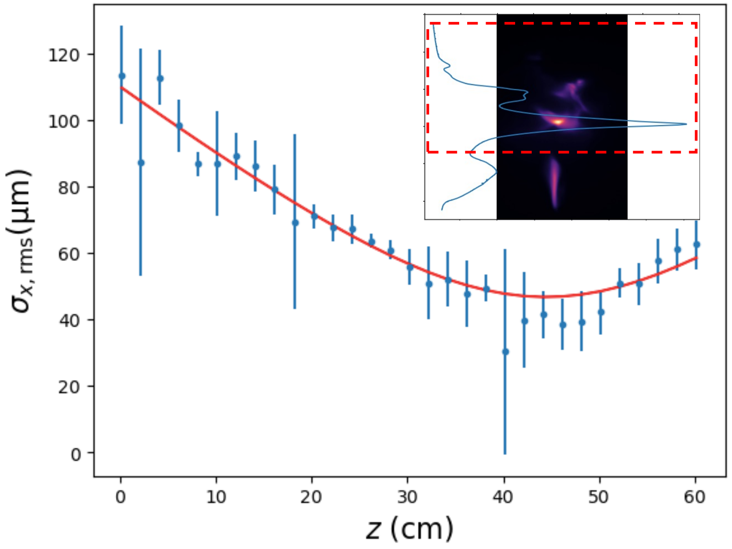
Weakly Interacting (Unfocused) Charge

3 PSI



Fit Params:
$z^* = 58$ cm
$\beta^* = 39$ cm
$\sigma^* = 35$ μm
Q = 1.5 nC

7.5 PSI



Fit Params:
$z^* = 44$ cm
$\beta^* = 21$ cm
$\sigma^* = 47$ μm
Q = 1.3 nC

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)

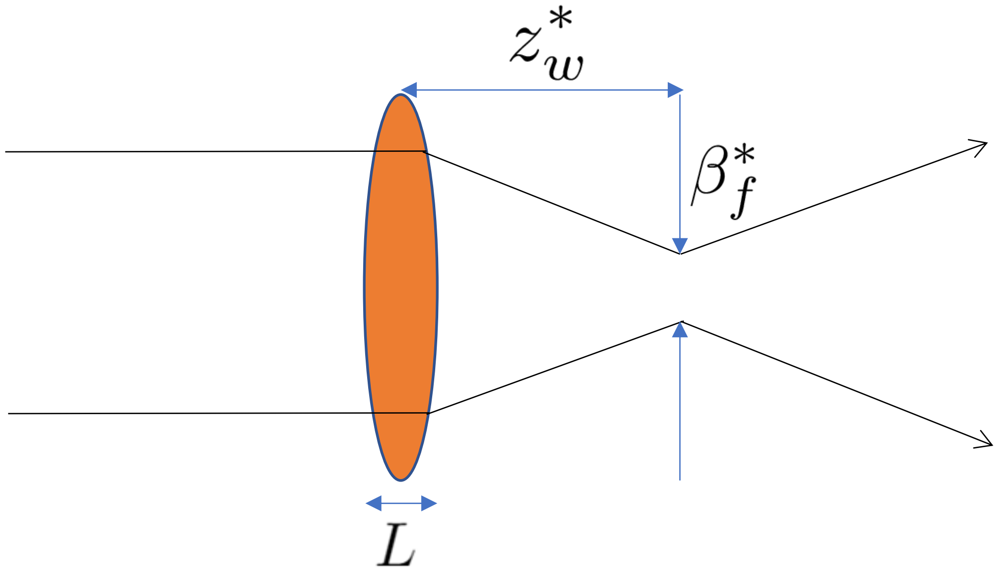
- Beam Energy
- Plasma Density
- Plasma Length

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)



Estimating Plasma Lens Conditions

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

Pressure	Length	β_o	α_0	γ_o	z_w^*	n_p	$\Delta\phi$
3 PSI	2 mm	93 cm	1.2	0.026 cm^{-1}	6.8 cm	**7.6x10^{15} cm^{-3}**	**0.16 rad**
7.5 PSI	2 mm	93 cm	1.2	0.026 cm^{-1}	~2 cm	**2.8x10^{16} cm^{-3}**	**0.31 rad**

- Assuming L = 2 mm, and Twiss params from vacuum beam we can solve for plasma density using z^*
- Distance to focus z^* better than β^* because it is less sensitive to chromaticity
- 7.5 PSI plasma density a few times larger than 3 PSI, as expected (though not exact ratio)

We find plasma lens to be in the thin, underdense regime for both pressures.

June 2024 Experimental Summary

- **First evidence of thin, underdense, passive plasma lens behavior!**
  - 70 pC and 300 pC strongly focused in 2mm plasma lens of density O(10^{16} cm^{-3})
  - Focal point shifted more than 40 cm upstream while still in vacuum after plasma lens
  - Apparent β^* of 7cm and 16cm reduced from 39 cm
  - Scaling of focal strength with gas pressure roughly follows model
- **Non-ideal setup:**
  - Axial ionization → long plasma → very low pressure → difficult to characterize directly
  - Electron beam very large (~100 µm emittance, 80 µm spot size at plasma lens)
- **Only a portion of the beam interacted strongly:**
  - Likely only rear of bunch inside blowout wake
  - Lost few percent energy
  - Weakly interacting portion behaved similarly to vacuum beam

Future Outlook

- **Simulation studies:**
  - Perform PIC simulations to enhance understanding of experimental results
- **Improve setup:**
  - Transverse propagation of ionization laser
    - Plasma length controlled by laser focus: short and tunable
    - Shorter length allows higher backing pressure → better characterized gas & plasma
  - Higher quality incoming e-beam
    - Increase amount of interacting charge
    - Allow operation at higher plasma density
- **Broader parameter scans:**
  - Vary density with gas jet pressure
  - Vary length with laser properties
  - Vary incoming beam parameters by shifting vacuum waist

Thank You!