Experimental Progress of Passive Plasma Lens at FACET-II

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On behalf of E-308 collaboration

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(Apologies if incomplete!)

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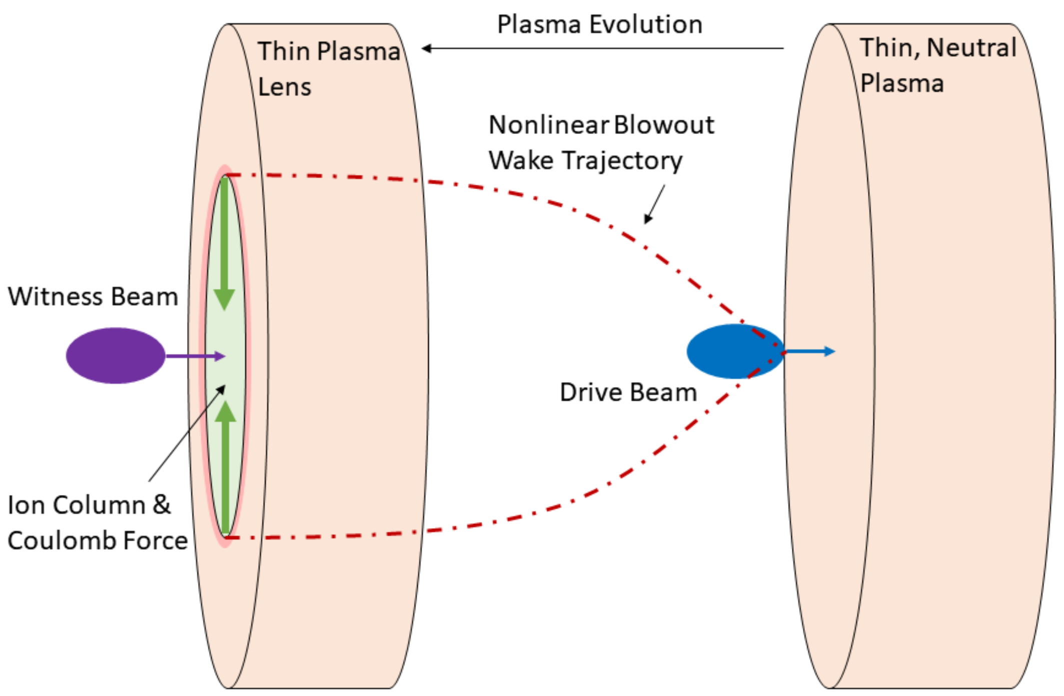
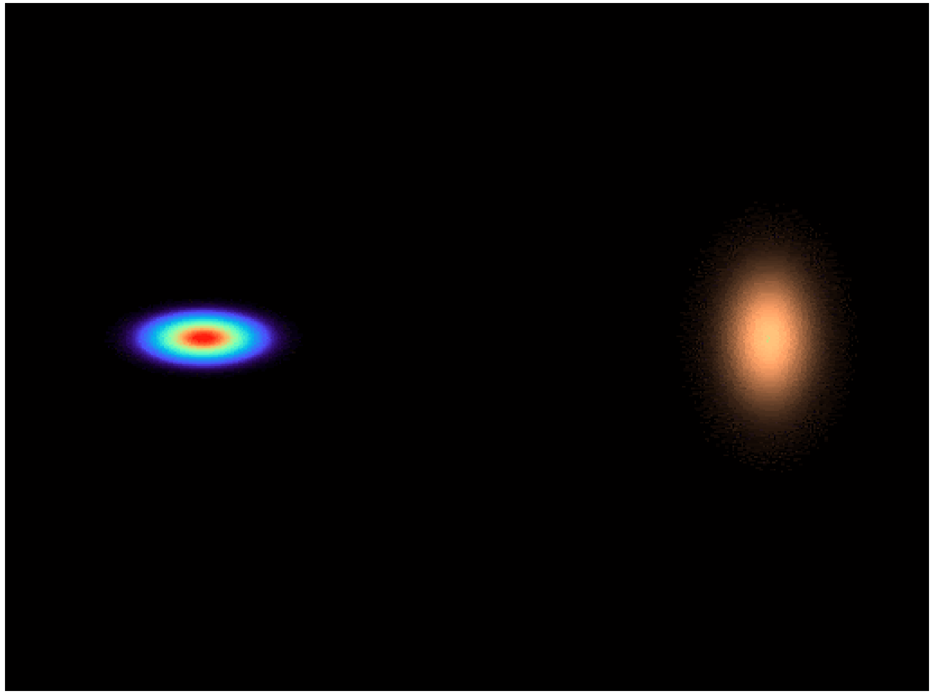
Thin, Underdense, Passive Plasma Lens (TUPPL)

- 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





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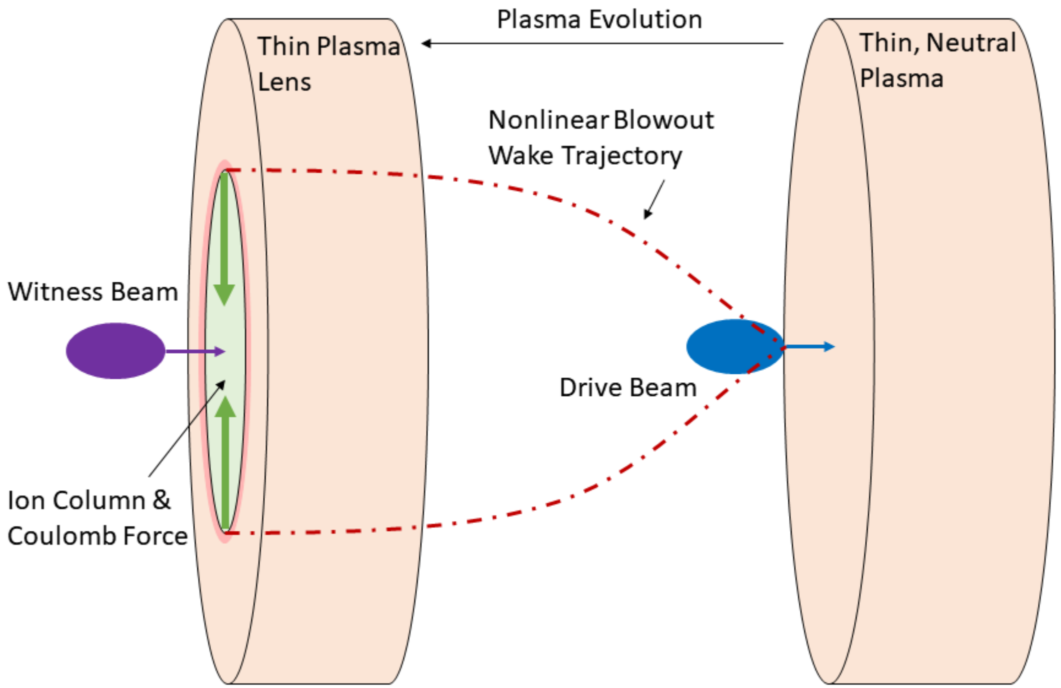
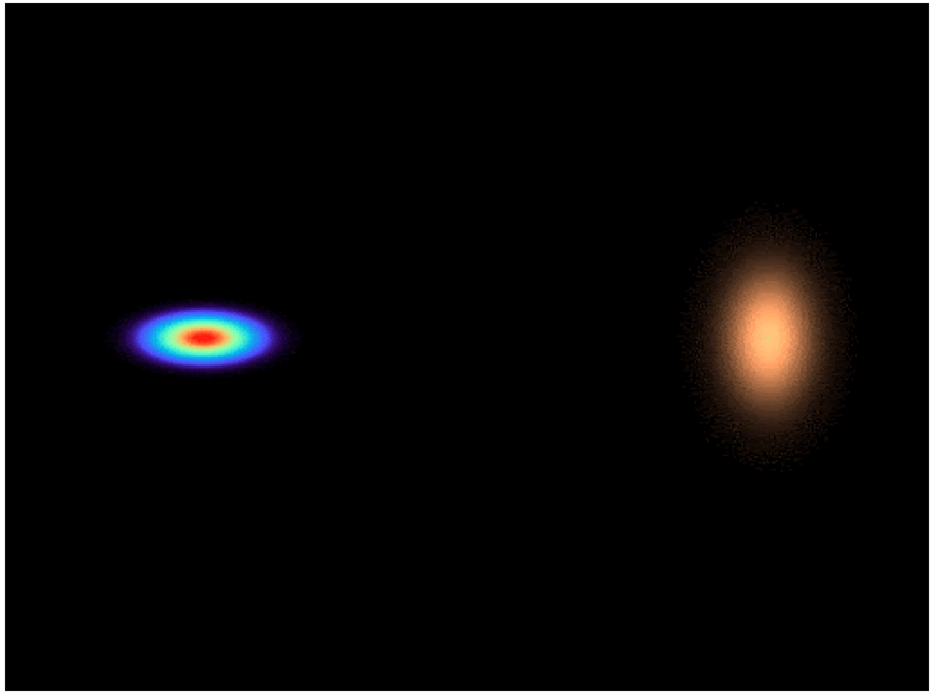




Attractive Features of TUPPL

Extremely strong focusing

- Orders of magnitude beyond electromagnets, PMQs, APL

Axisymmetric focusing

- Single lens can achieve symmetric focus in x & y

Ultra-compact

- Plasma lens itself: ~400 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/ height above gas jet
- Density length product → plasma expansion

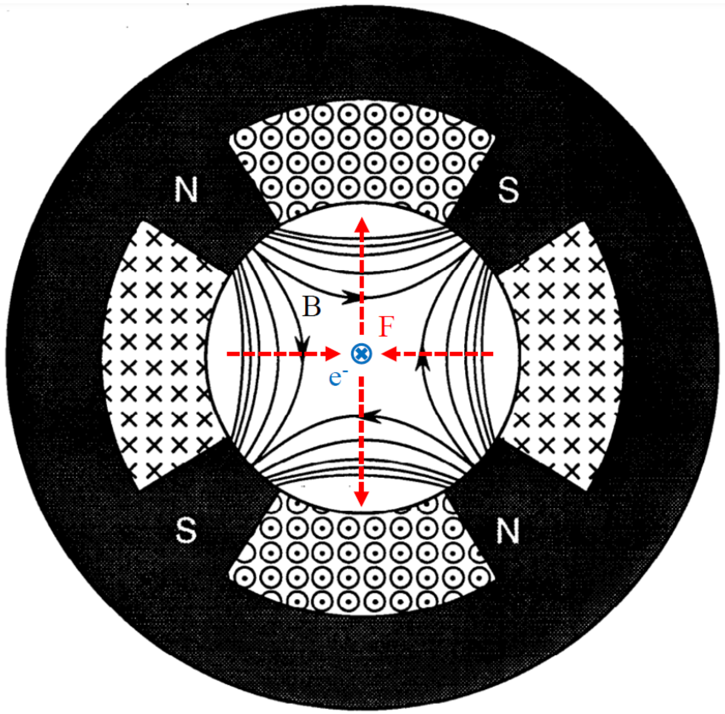
Self-aligning

- Central axis of blowout determined by electron beam

Comparison to other focusing optics

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

Quadruple Magnet



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

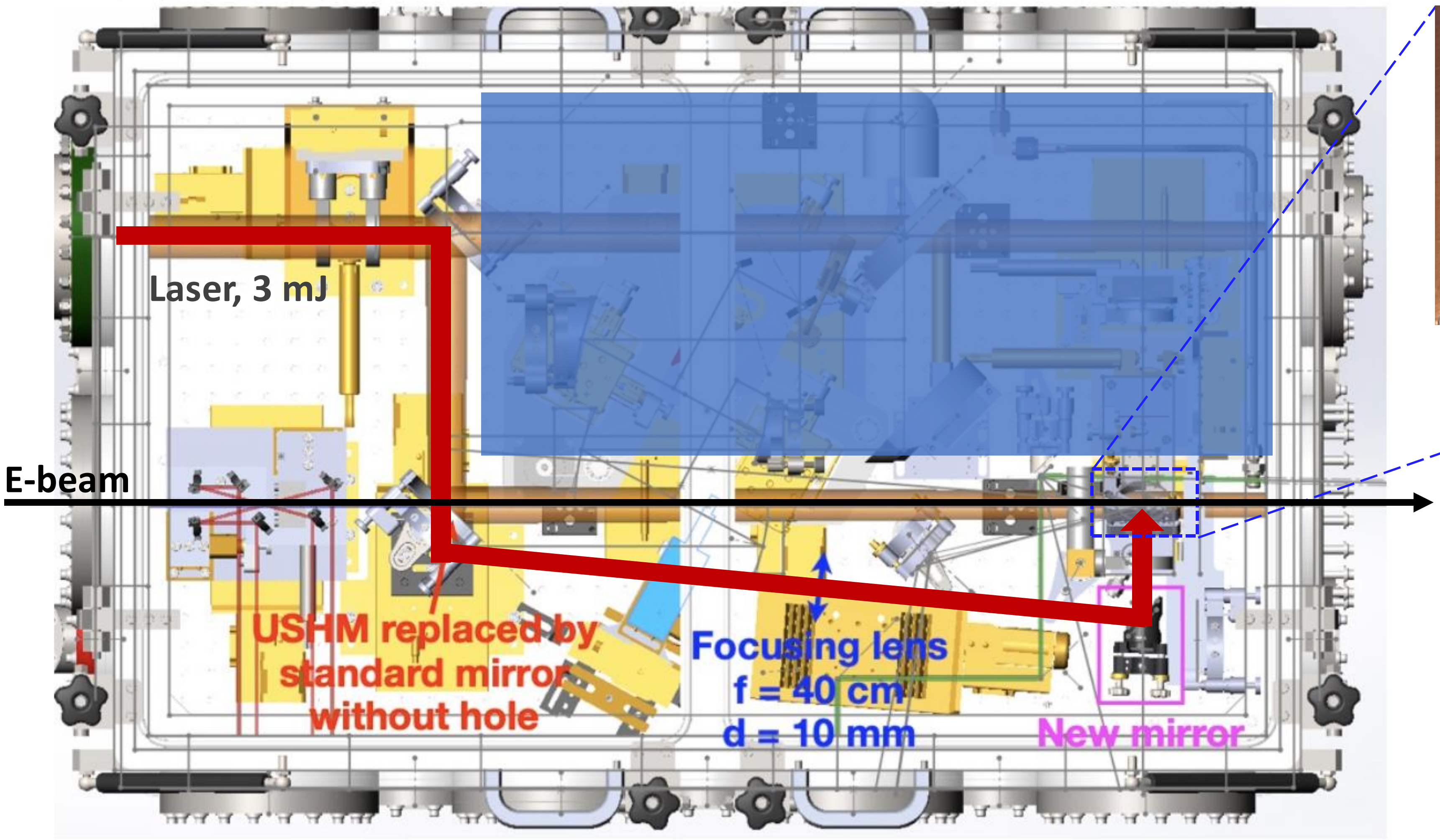
Phase advance (normalized length): $\Delta\psi = \sqrt{K}L = 0.0458$

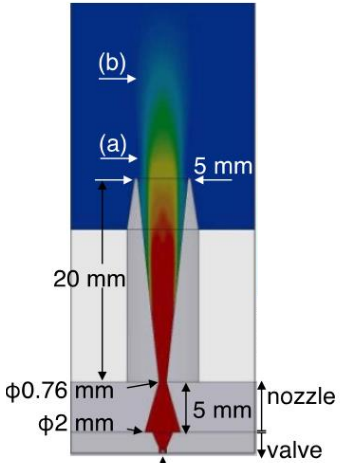
Type	g [kT/m]	K [m^{-2}]	L [mm]	f [cm]
Quadrupole Electro-magnet	**0.01**	**0.3**	**84**	**3990**
Permanent Magnetic Quadrupole	**0.5**	**15**	**12**	**564**
Active Plasma Lens	**3.6**	**108**	**4.4**	**210**
Thin PPL (blowout theory, $5 \times 10^{16}\ cm^{-3}$)	**1468**	**44000**	**0.22**	**10.4**
Thin PPL (June 2025 exp., preliminary)	**437**	**13100**	**0.4**	**19**

E-308 Experimental Setup

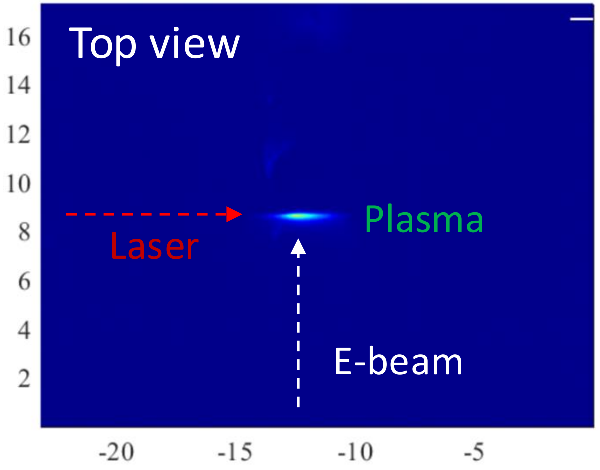
Laser-ionized H_2 gas jet

Chaojie Zhang *et al* 2021 *Plasma Phys. Control. Fusion* **63** 095011





5mm D_{exit}; ~50 psi



Plasma Requirements

1. Maximize focusing strength: minimize focal length → maximize $n_p L$

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

2. Remain in thin lens regime: keep phase advance $\lesssim 0.2$ → keep sqrt(n_p)L low

$$\Delta\psi = \sqrt{K}L = \sqrt{\frac{2\pi r_e n_p}{\gamma_b}} L$$

3. Remain in underdense blowout regime: $2\, n_p \lesssim n_b$ → keep n_p sufficiently low

Summary: Requirements push toward lower density and longer length.

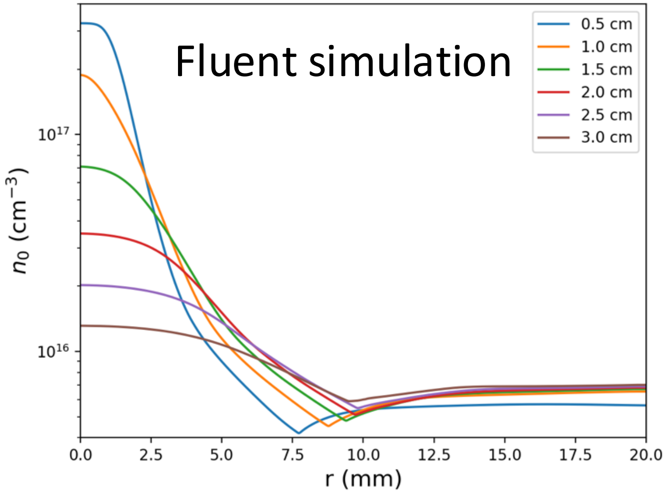
- Experimental conditions made it challenging to optimize n_p and L.
- Result: operated in overdense thin lens regime during previous run.
- Improved modeling, diagnosis, and control of plasma source expected next run.

Plasma Source Modelling

University of Colorado Boulder

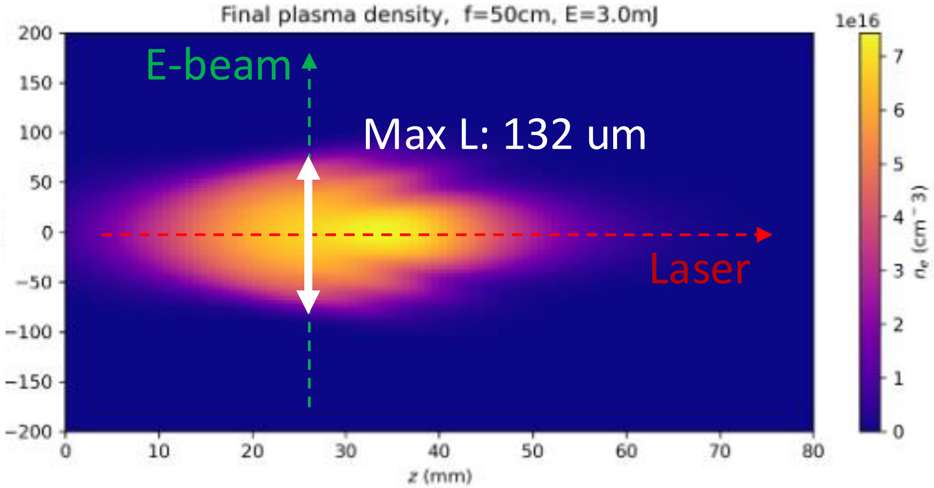
- Laser energy was limited to 3 mJ to avoid damaging final mirror
  → limited initial plasma lens length
- Fluid models used to estimate gas density above jet nozzle, but large uncertainty on backing pressure in experimental device (no local gauge)
- Challenging to reach low densities with minimum operating backing pressure
- **Solution: ionize small volume at high density and allow plasma to expand**

Radial neutral density profile



assume 1e17

Split-step Fourier ionization code



Need to rely on plasma expansion to reach target plasma length ~ 500 um.

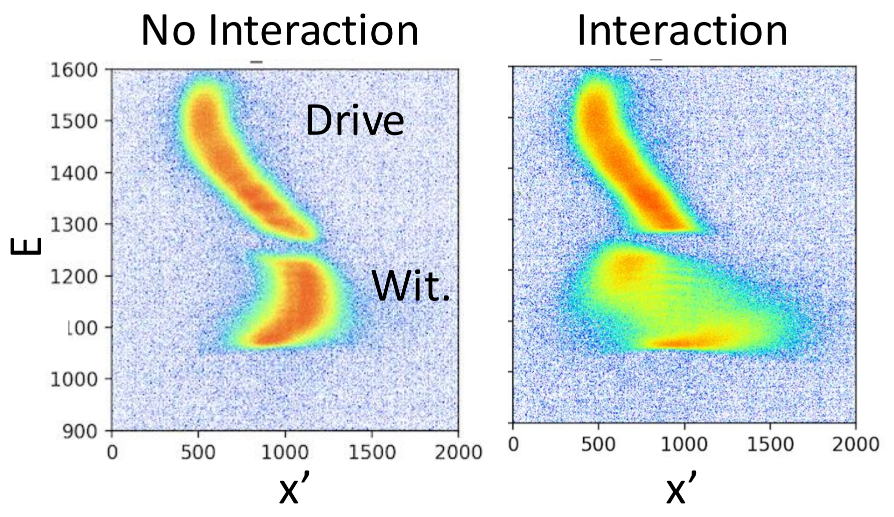
Plasma Length Estimation

- Laser / e-beam arrival delay scan performed to find good working point
  - Set electron imaging spectrometer to parallel-to-point
  - Scanned delay and looked for strong divergence increase of witness beam

- Two different Working Points (WP) studied:

	Working Point 1	Working Point 2
Nozzle Height	-1.5 cm	-1.0 cm
Delay Time	3 ns	20 ns

Both produced very similar results



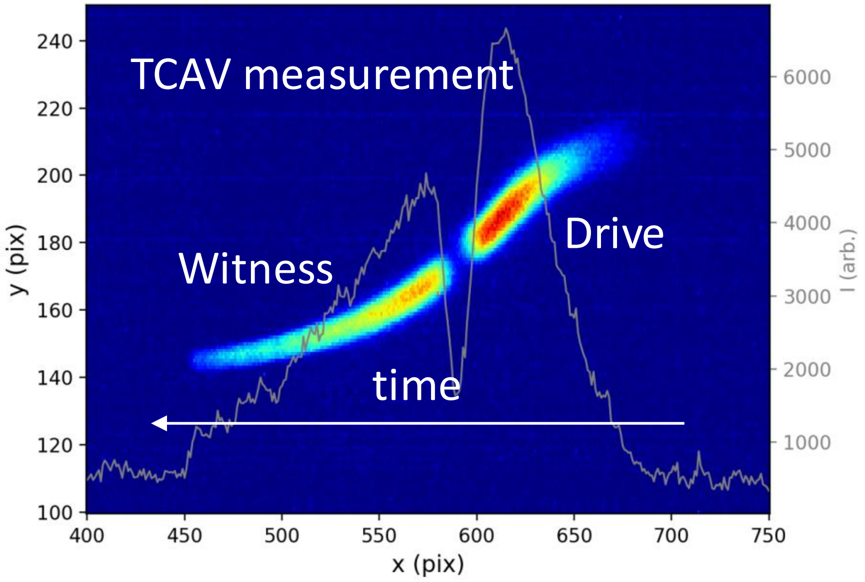
- Laser position scan performed to estimate plasma lens length
  - Assumed azimuthally symmetric plasma profile w.r.t. laser axis, perp. to e-beam
  - Translated laser above/below e-beam axis until interaction ended
  - Measured movement of laser to find the plasma length **L ≈ 400 µm** for both WP's

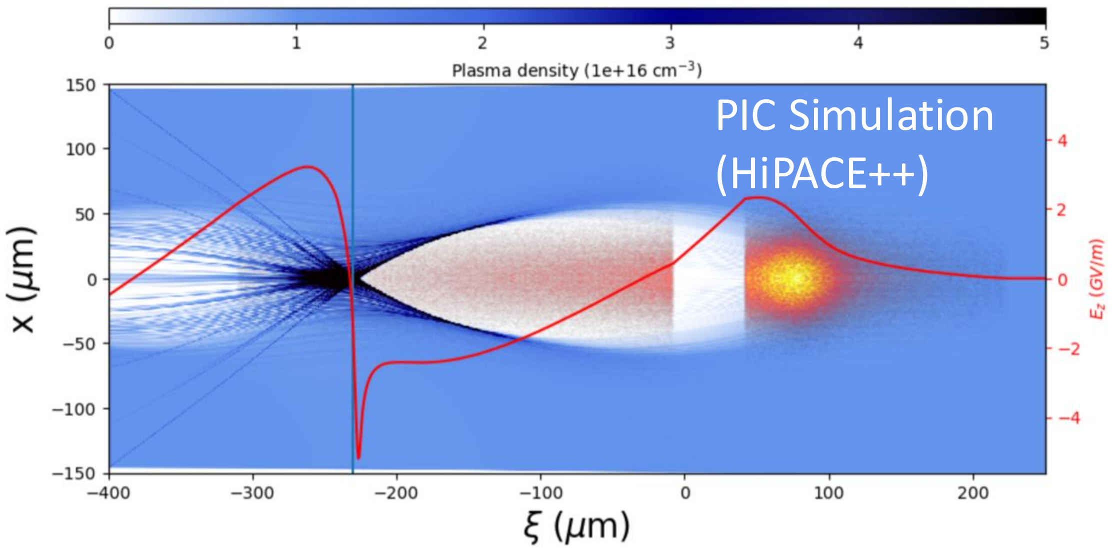
Electron Beam Configuration: Two Bunches

Two-bunch configuration generated using notch collimator with chirped beam

Long, roughly linearly chirped witness beam

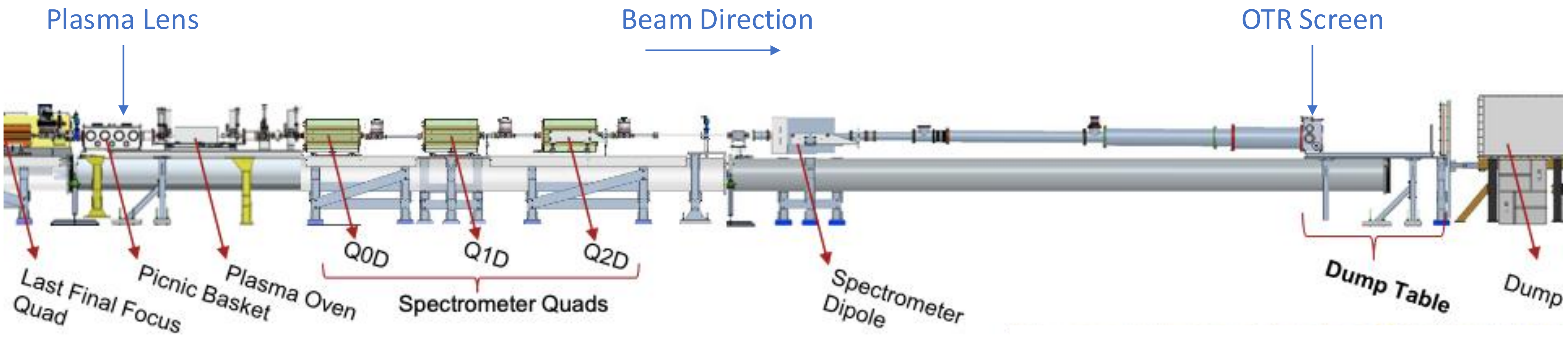
- Can sample long region inside wake
- Chirp permits longitudinally resolved measurement of focusing with imaging spectrometer





Drive Bunch: ~780 pC
Witness Bunch: ~650 pC
Δz gap: ~40 μm

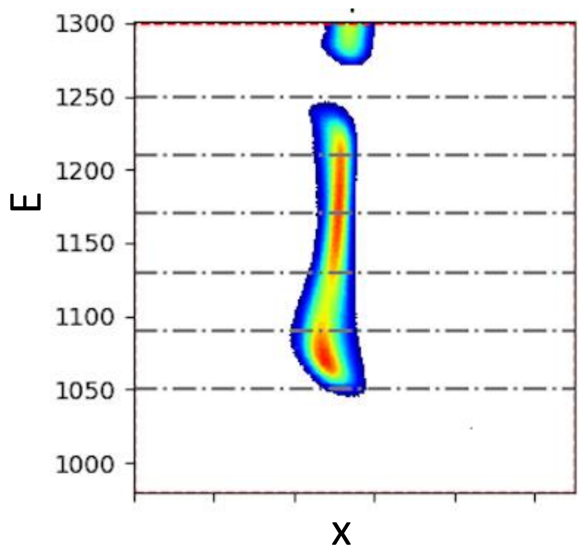
FACET-II Electron Imaging Spectrometer



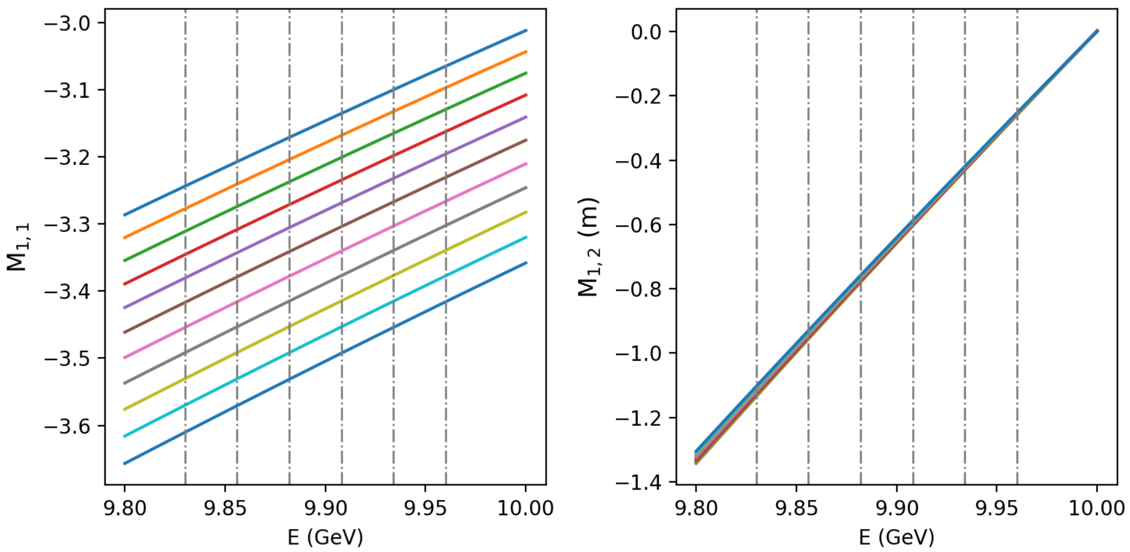
Point-to-Point scans of object plane and Parallel-to-Point scans of M_{12} were performed to analyze beam dynamics.

Chromaticity of imaging spectrometer must be taken into account during analysis.

Dispersed beam after Imaging Spectrometer



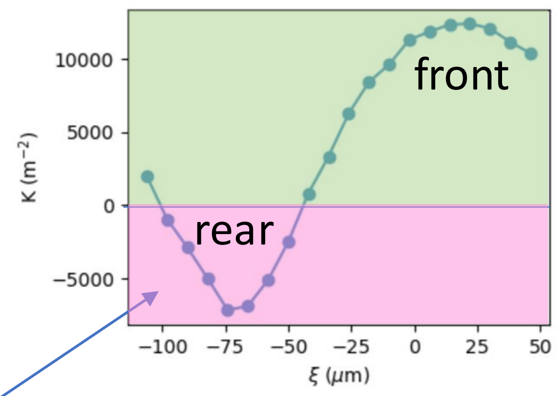
Chromaticity for object plane scans from z_{lens} to z_{lens} + 50 cm



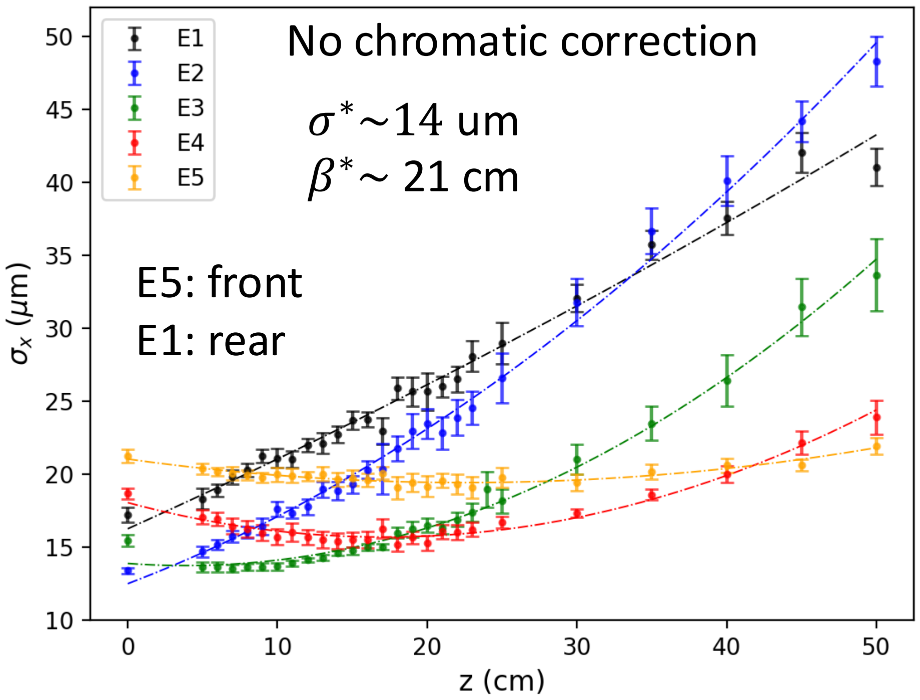
Strong Focusing of Witness Beam

- Object plane scan preliminary results (still need chromatic correction)
- Observed strong focusing of 200-300 pC witness bunch
- Reduced min. spot size to $\sigma^* \approx$ 11-14 µm from initial value of 20 µm
- Reduced min. beta function to $\beta^* \approx$ 14-21 cm from initial value of 75 cm
- Moved waist upstream by 20-30 cm
- Rear of witness beam was beyond first wake period and defocused

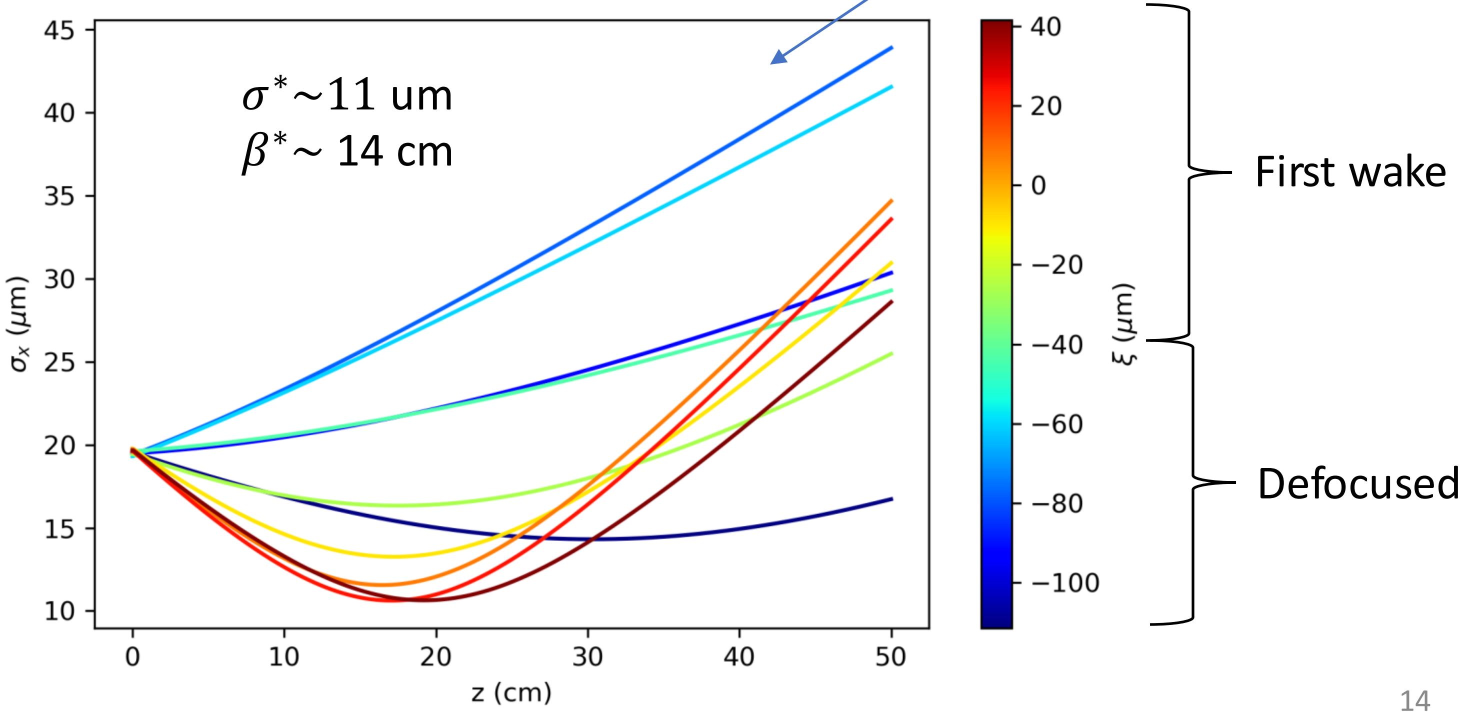
Focusing along bunch



WP1 Data



PIC simulation results



Witness Bunch Emittance Analysis

Data Analysis:

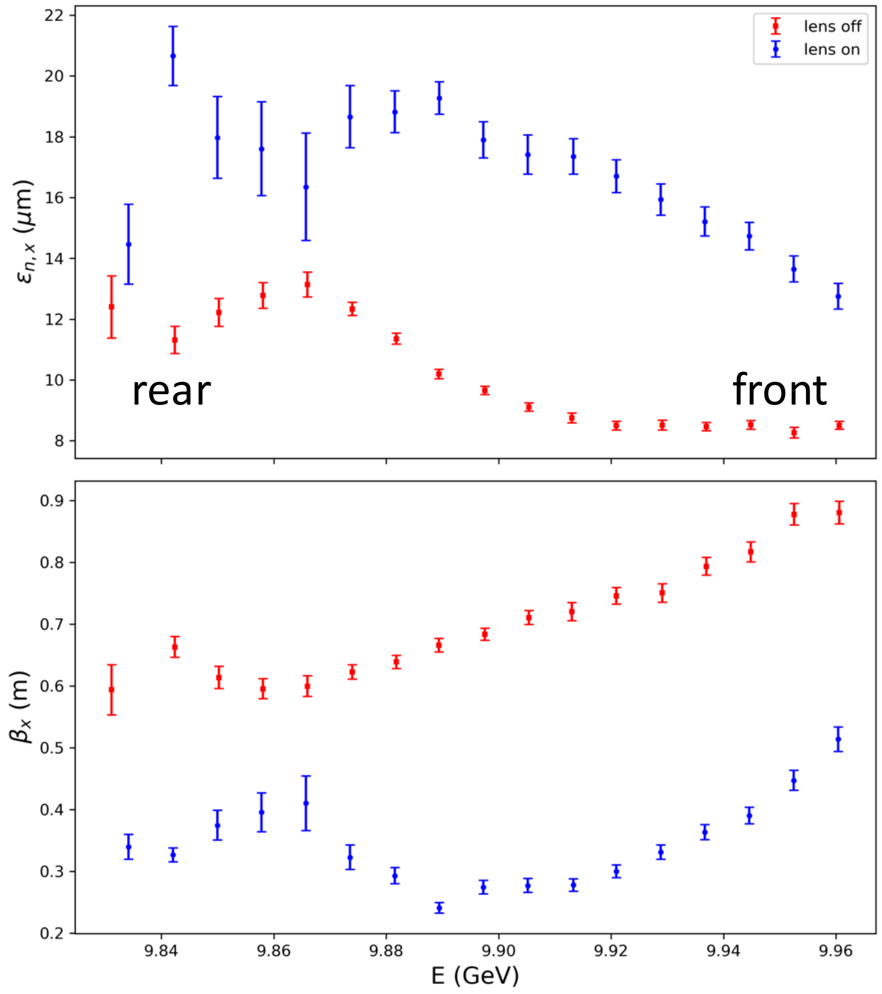
- Analyzed emittance of 20 energy slices of ~10 MeV
- Used object plane and M_{12} scan data
- Fit to equation:

$$\sigma_x(E)^2 = \frac{\epsilon_n}{\gamma}\left[M_{11}^2\beta_0 - 2M_{11}M_{12}\alpha_0 + M_{12}^2\left(\frac{1+\alpha_0^2}{\beta_0}\right)\right]$$

Preliminary Observations

- Significant emittance growth in plasma lens
  - Roughly factor of 2
  - Not in underdense regime
  - $k_p \sigma_r \gtrsim 1$
- Beta function reduced due to emittance growth in addition to focusing

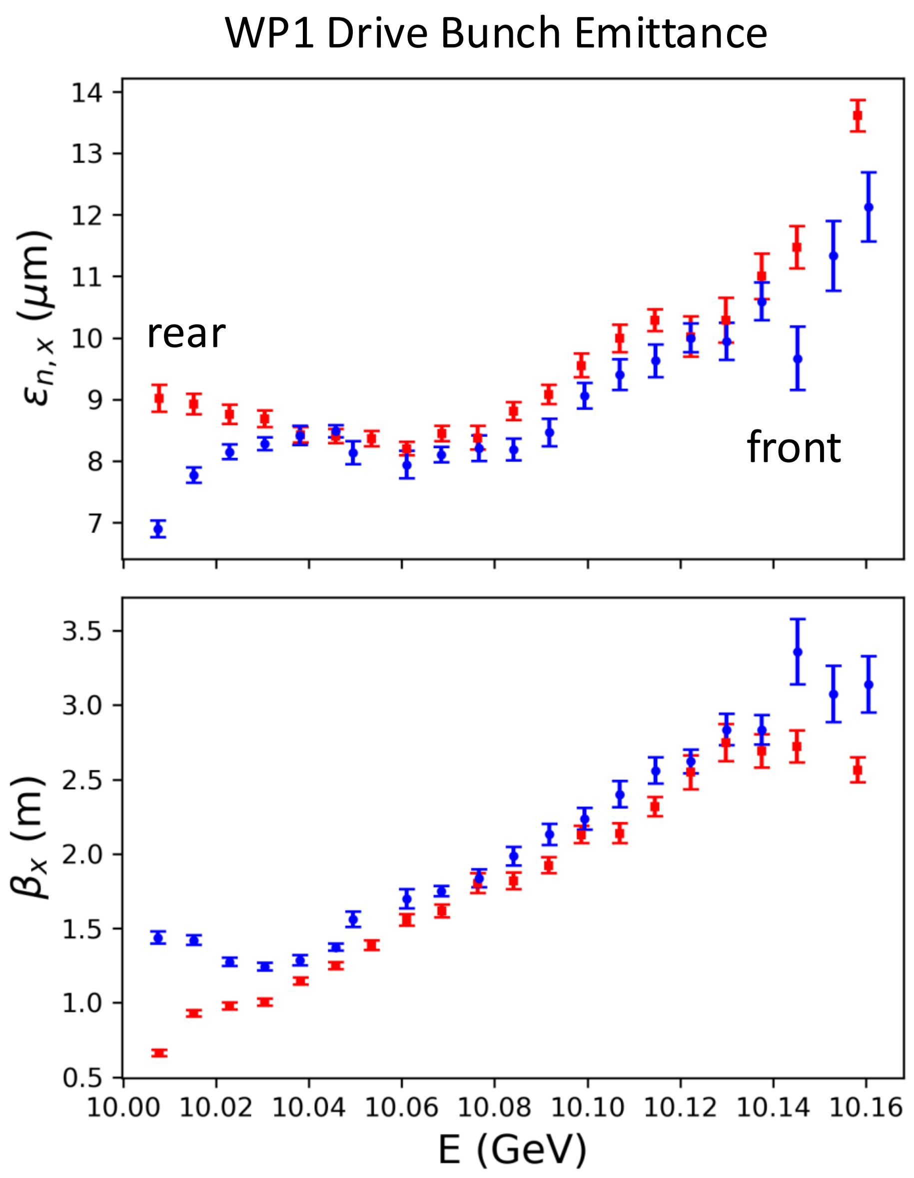
WP1 Witness Bunch Emittance



Drive Bunch Emittance Analysis

Preliminary Observations

- No appreciable growth for most of the bunch
- Small emittance growth at very tail of bunch
- Strong wake must start to develop near tail of drive bunch
- Agrees well with simulations



Summary

- Observed strong focusing of witness bunch in a thin, passive plasma lens
  - 200-300 pC, σ^*: 20 µm → 11-14 µm, β^*: 75 cm → 14-21 cm, Δz^*: 2-30 cm
  - Preliminary results – chromatic correction required
- Did not reach the underdense blowout regime
  - Emittance growth by factor of ~2 due to nonlinear focusing fields
  - Tail of bunch extended beyond first wake period
- Expect optimized performance in underdense regime next run
  - Better plasma source modeling, diagnostics, and control
  - Will lower plasma density and increase length
- Will eventually use in combination with other experiments at FACET-II
  - Strong focusing for matching into a PWFA
  - Focusing boost prior to multi-foil transition radiation focusing device
  - Asymmetric driver and blowout (w/ Pratik Manwani, UCLA)
  - Transverse gradient TUPPL
  - Divergence control of plasma-injected beams

Publications

1. S. Meng, et al., [*strong focusing with a passive plasma lens, in preparation*]

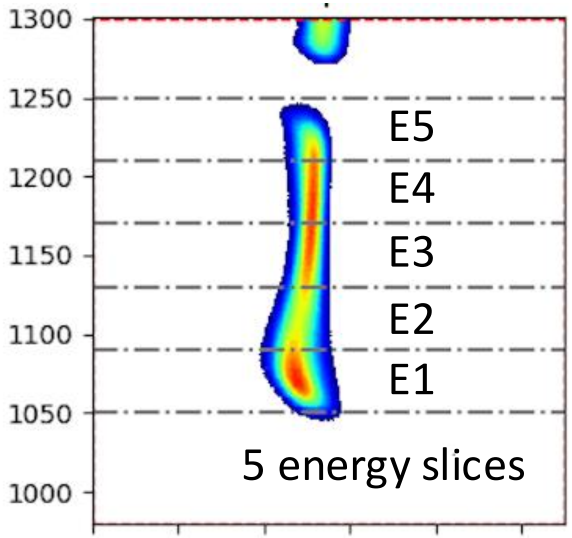
2. C. E. Doss, et al., "Laser-ionized, beam-driven, underdense, passive thin plasma lens", Phys. Rev. Accel. Beams 22, 111001 (2019) https://doi.org/10.1103/PhysRevAccelBeams.22.111001

3. C. E. Doss, et al., "Underdense plasma lens with a transverse density gradient", Phys. Rev. Accel. Beams 26, 031302 (2023) https://doi.org/10.1103/PhysRevAccelBeams.26.031302

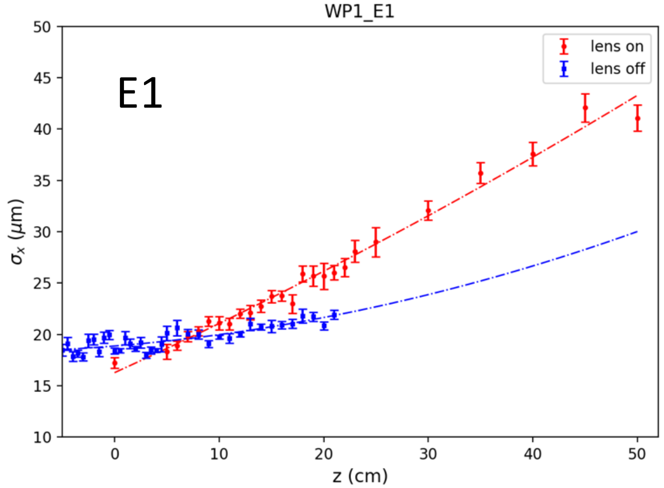
Publications

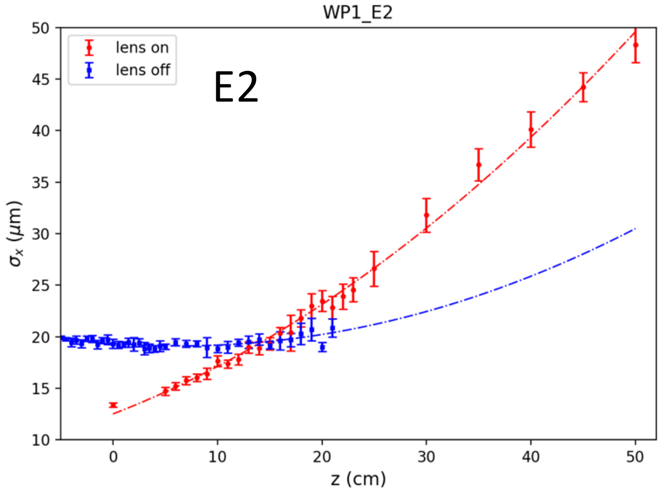
Evidence of passive plasma lensing

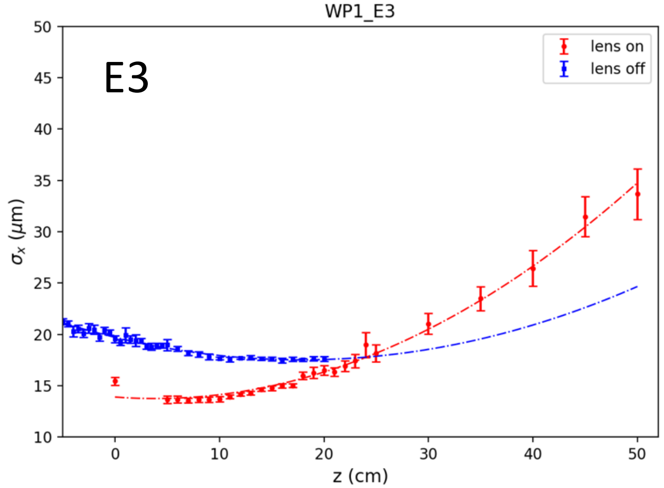
- Object plane scan with **no chromaticity correction**
- E1 → E5 with increasing energy

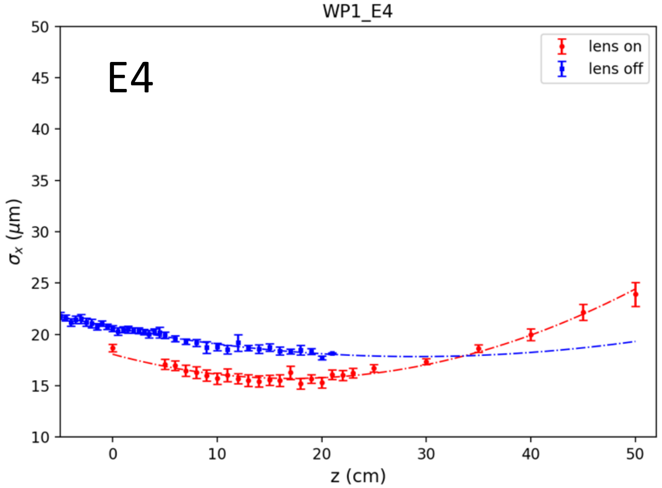


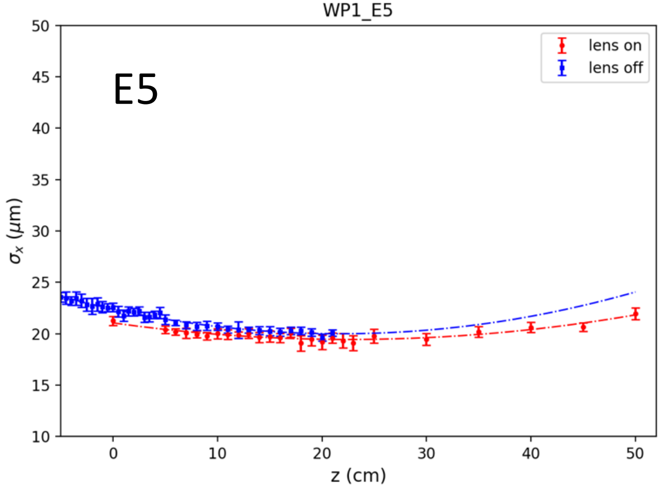
Very clear upstream shift of z^* and reduction in σ^*!



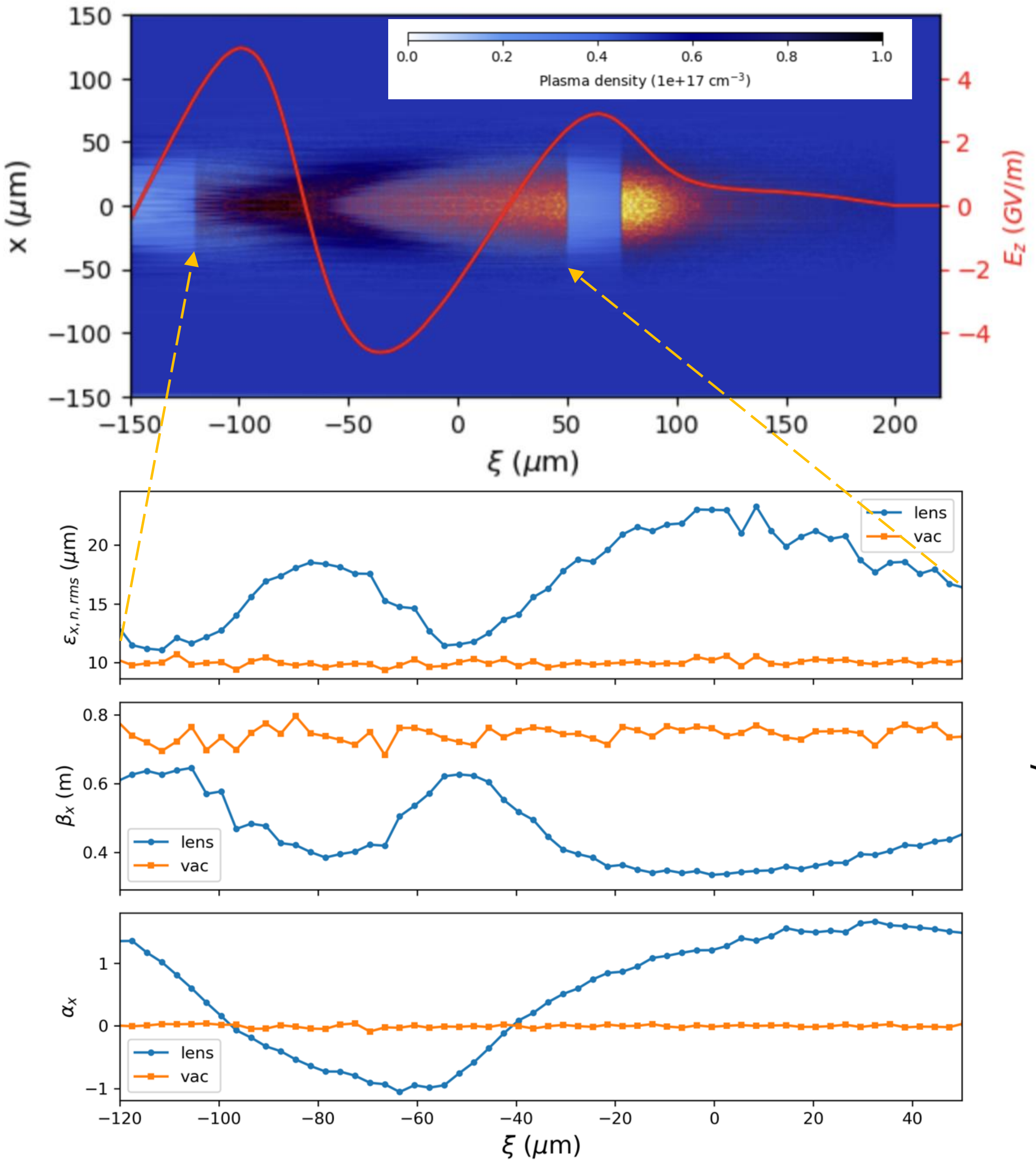






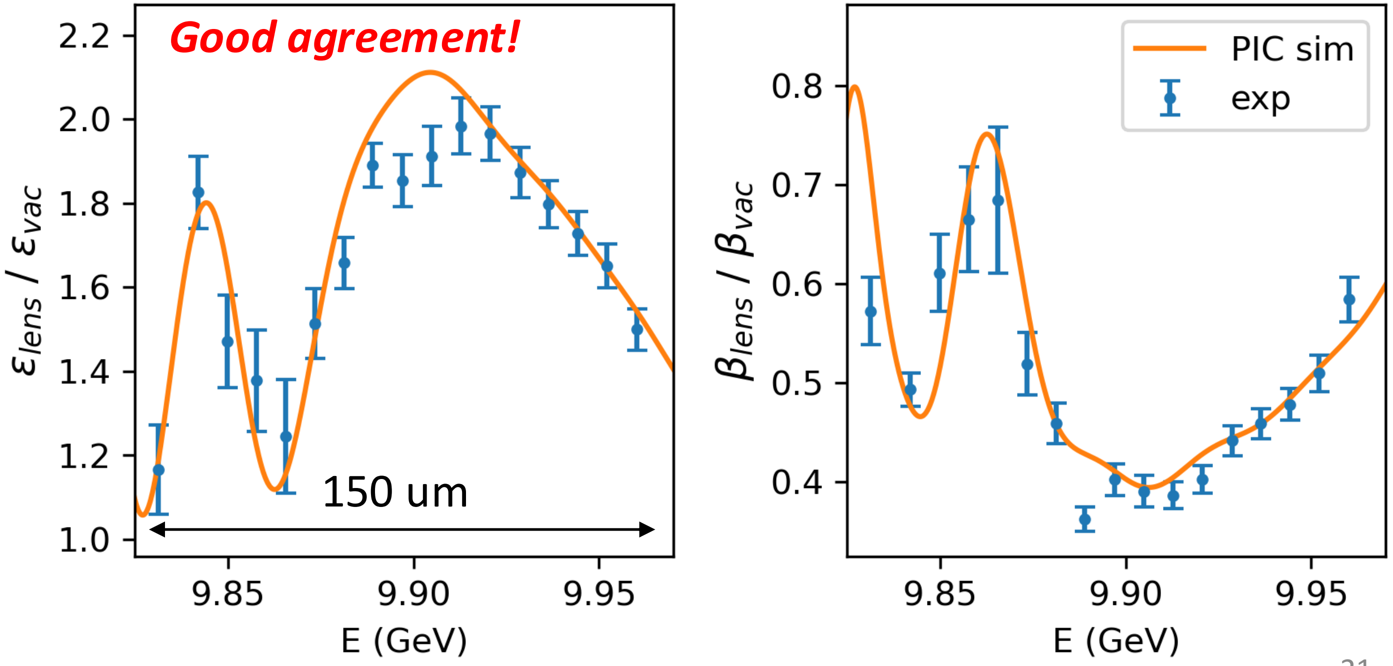


Preliminary PIC simulation studies

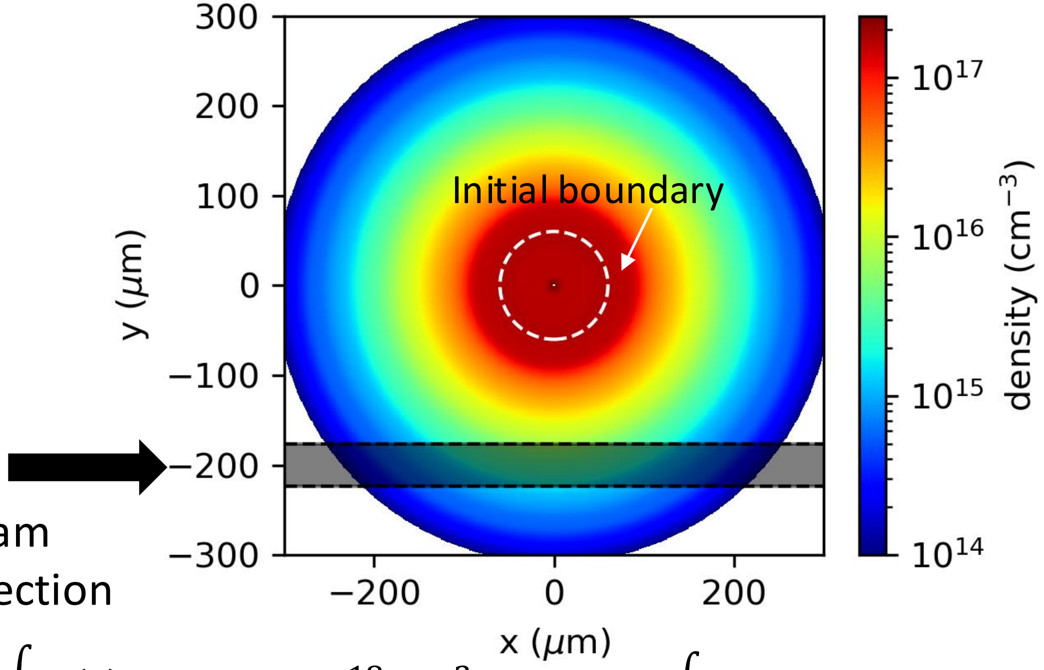


- Simulation parameters:
  - Gaussian transverse profile with 20 um spot size and 75 cm beta that match x-plane measurement.
  - Current profile from BMAD simulation generated by Claudio, similar to TCAV measurement.
  - Plasma density ~ $5 \times 10^{16}\ cm^{-3}$; plasma length ~ 400 um.
- Witness beam samples three regions: first wake, defocusing region, front of the second wake.

Simulation value scaled by 6%



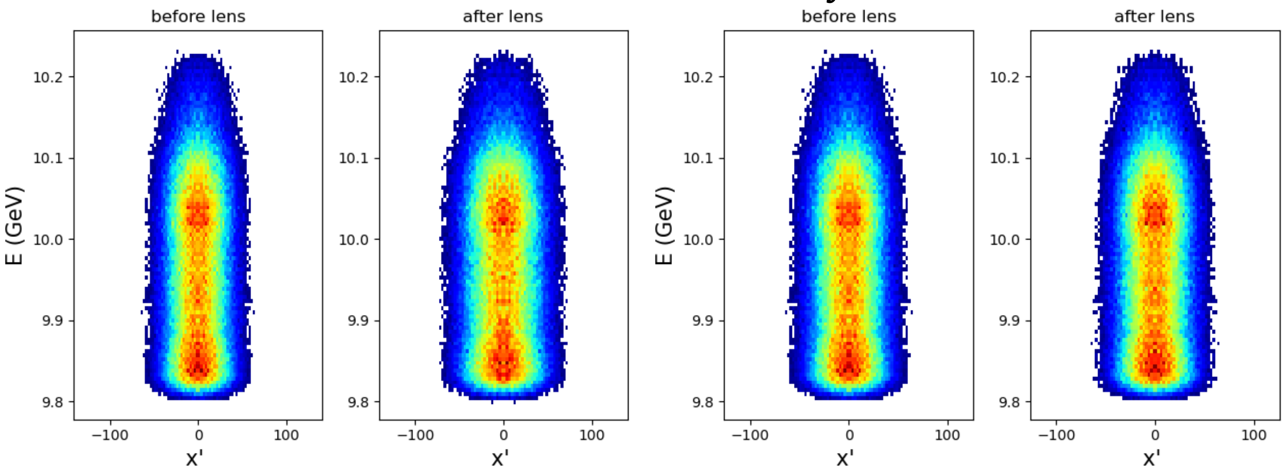
Plasma Expansion Simulation



Beam direction

$\int n(z)dz = 1 \times 10^{18}\ m^{-2}$

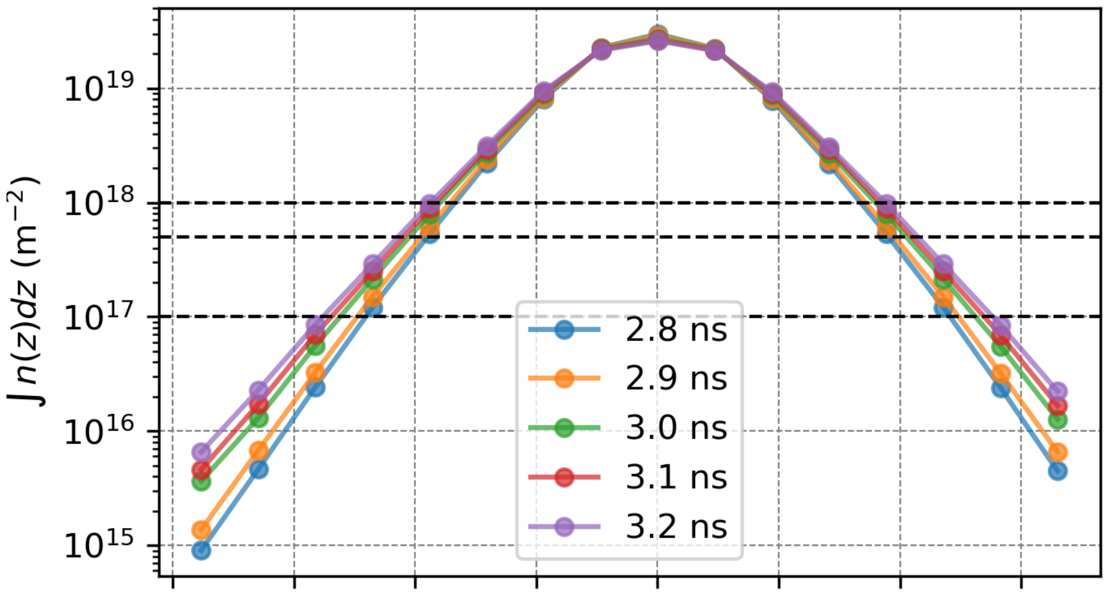
$\int n(z)dz = 1 \times 10^{17}\ m^{-2}$



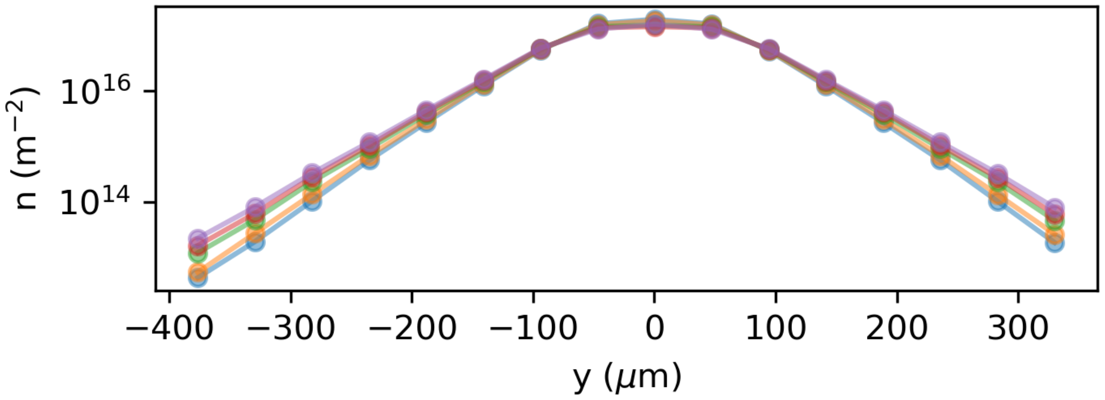
Some magnification

No magnification

Initial density: $4 \times 10^{17}\ cm^{-3}$



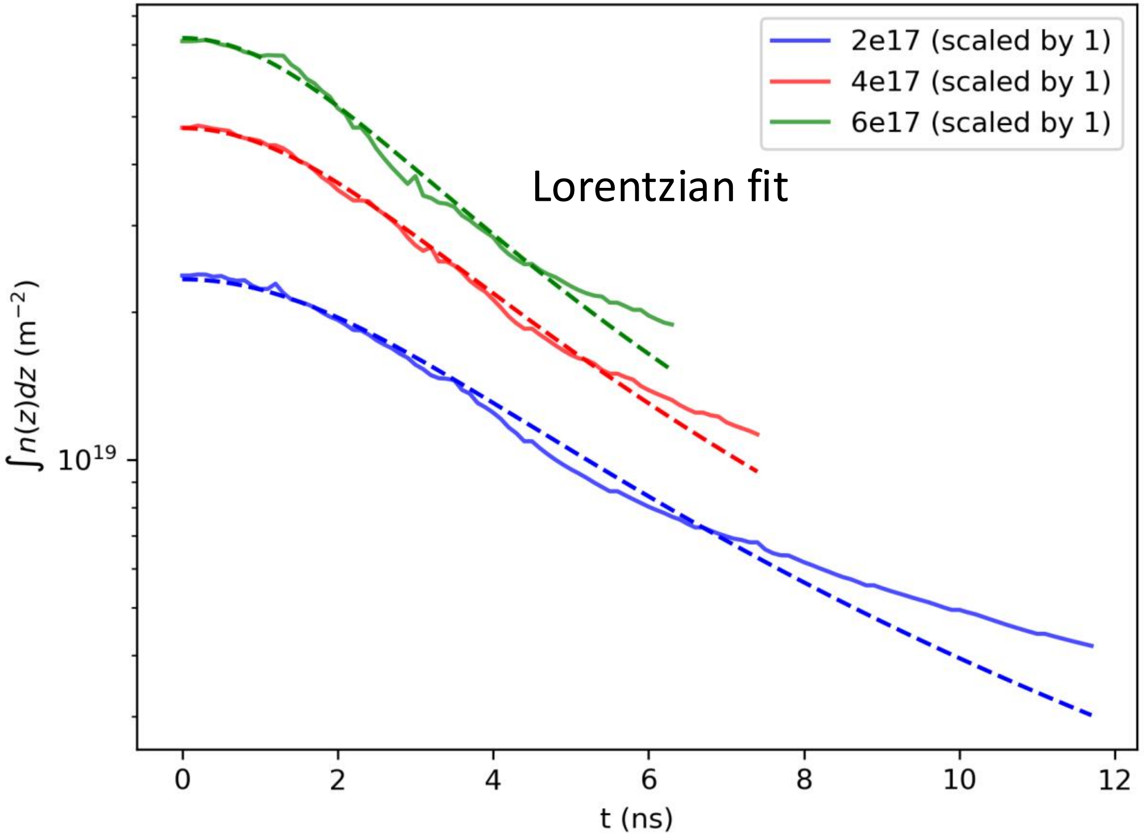
Agrees well with the 400 μm measurement!



Density Length Product Evolution

University of Colorado Boulder

Not scaled



scaled