1-D plasma lens by laser-driven elongated wakefield.

Apurva Gaikwad

Advisor: Prof. Navid Vafaei-Najafabadi

Stony Brook University | Department of Physics and Astronomy

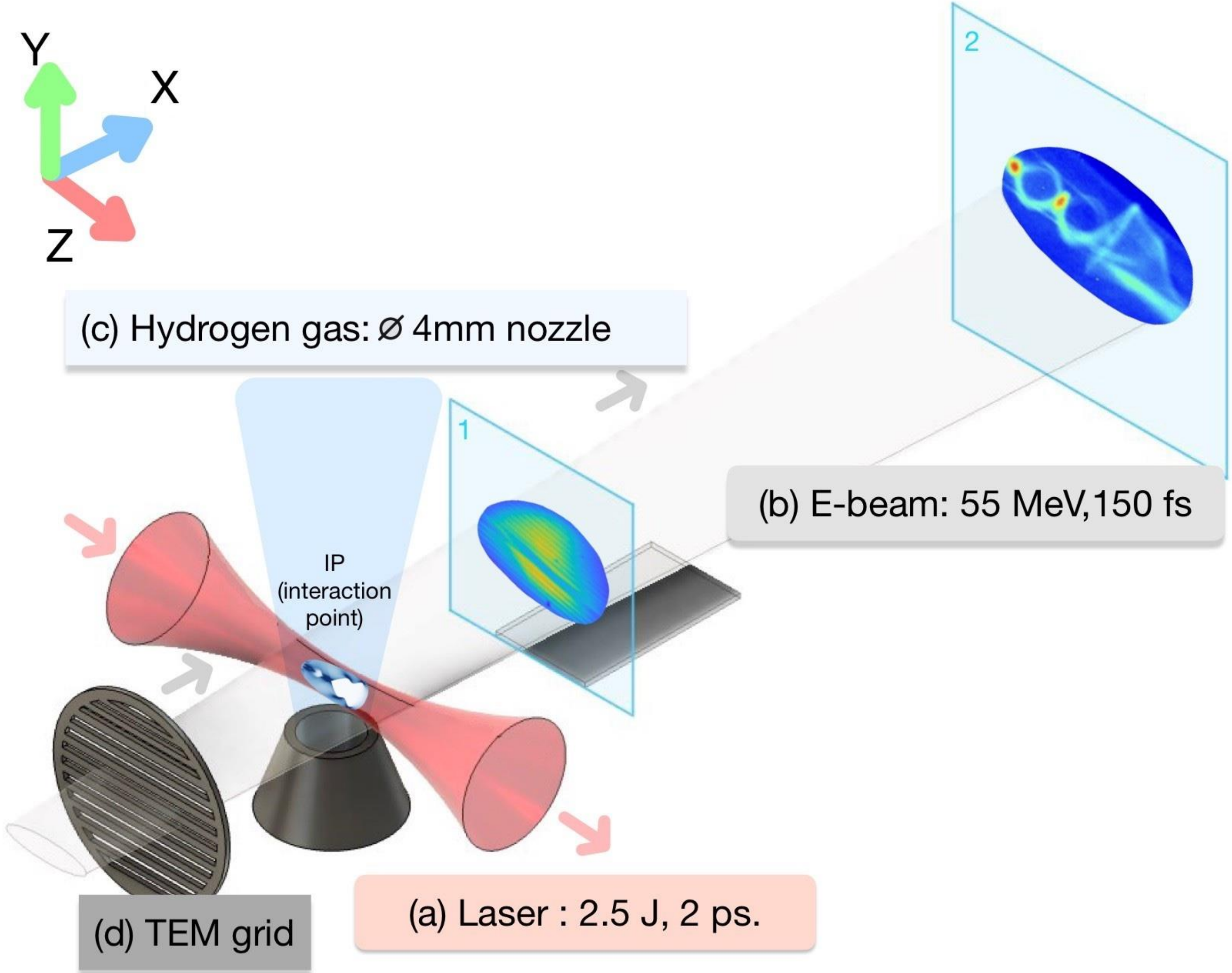
Stony Brook University

- Stony Brook University : Apurva Gaikwad, I. Petrushina, E. Trommer, B. Romasky, V.N. Litvinenko, R. Samulyak, N Manzella, N. Pathak, N. Vafaei-Najafabadi.
- University of Texas at Austin : M. Downer, R. Zgadzaj.
- Accelerator Test Facility, Brookhaven National Laboratory: I. Pogorelsky, K. Kusche, W. Li, M. Babzien, M. Palmer, M. Fedurin, M. Polyanskiy.
- Lawrence Livermore National Laboratory: R. Kupfer.
- University of Rochester/ Laboratory of Laser Energetics : K. Miller.
- University of California Los Angeles : A. Farrell, C. Joshi, C. Zhang,Y. Wu.
- University of Colorado Boulder : M. Petrusky.

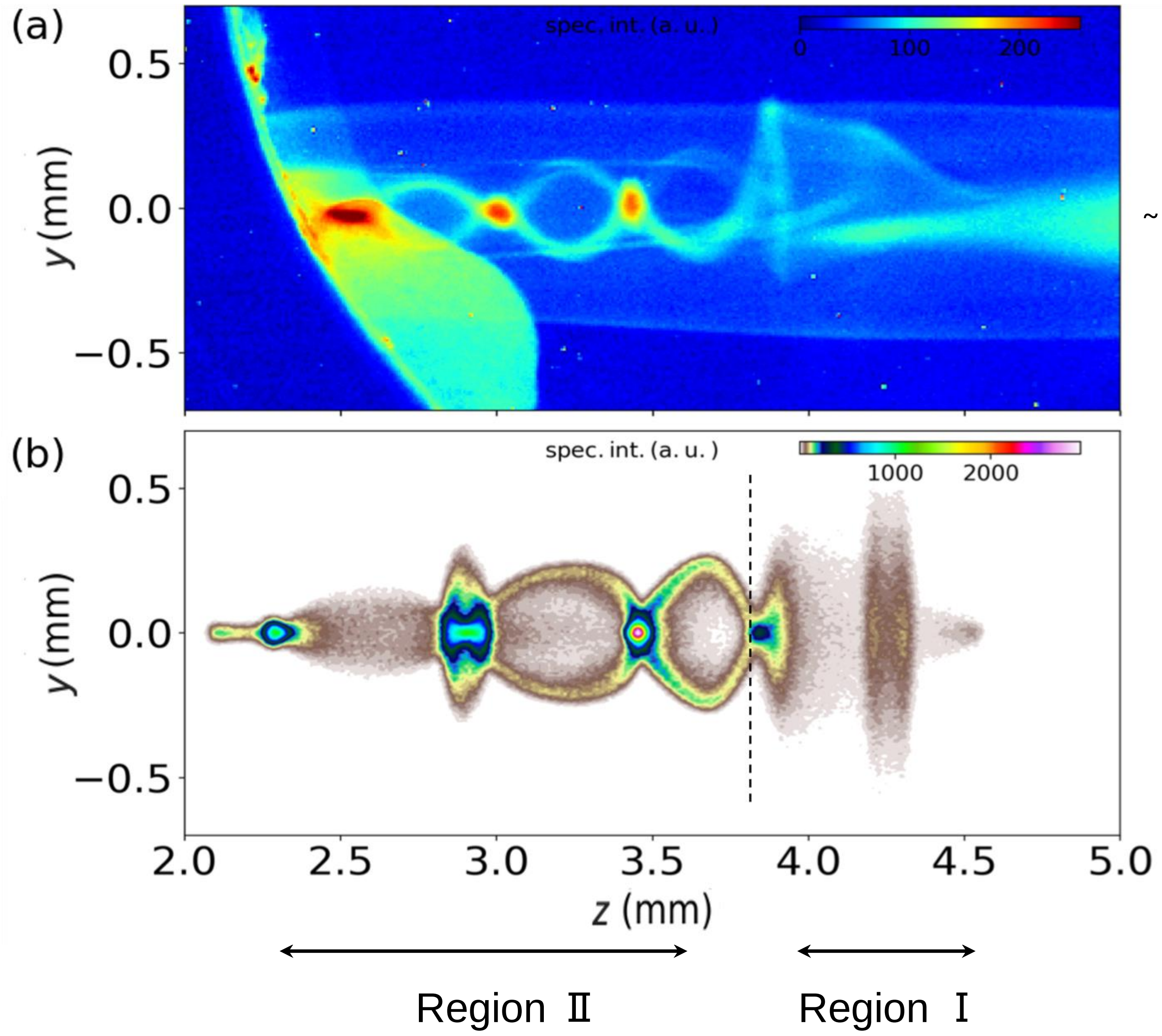
Motivation

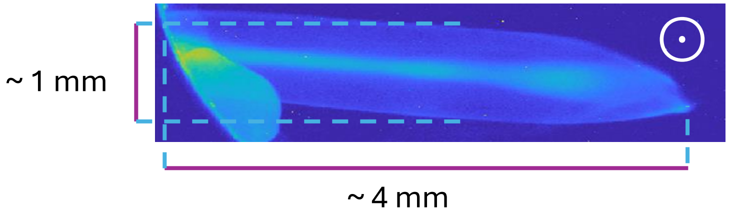
- Optimal operation in future linear colliders depends on resolving the luminosity-beamstrahlung trade-off.
- A definitive physical solution is operating with "flat beams” ($\sigma_x >> \sigma_y$).
- Hence a tool for flat beam creation is highly desired.
- Unlike conventional quadrupoles or capillary discharge lenses, plasma lenses offer focusing gradients orders of magnitude stronger.
- Standard passive plasma lenses can have "transverse coupling," which leads to resonant emittance mixing. This degrades the beam quality and reduces luminosity.
- We propose that the cylindrical electron-depleted ion cavity observed during our experiment provides a strong, linear focusing in only one direction.
  - Acting as a 1D focusing optical tool.
- This inherently decoupled plasma optic provides extreme focusing required for flat beam generation and helps mitigate beamstrahlung and energy spread at the interaction point.

ATF Experimental Setup



Comparison between experimental and simulated probe profile





Unperturbed electron beam captured on YAG screen

Q_e ~ 0.5 nC, $\boldsymbol{\varepsilon}_n$ ~ 1- 3 mm mrad

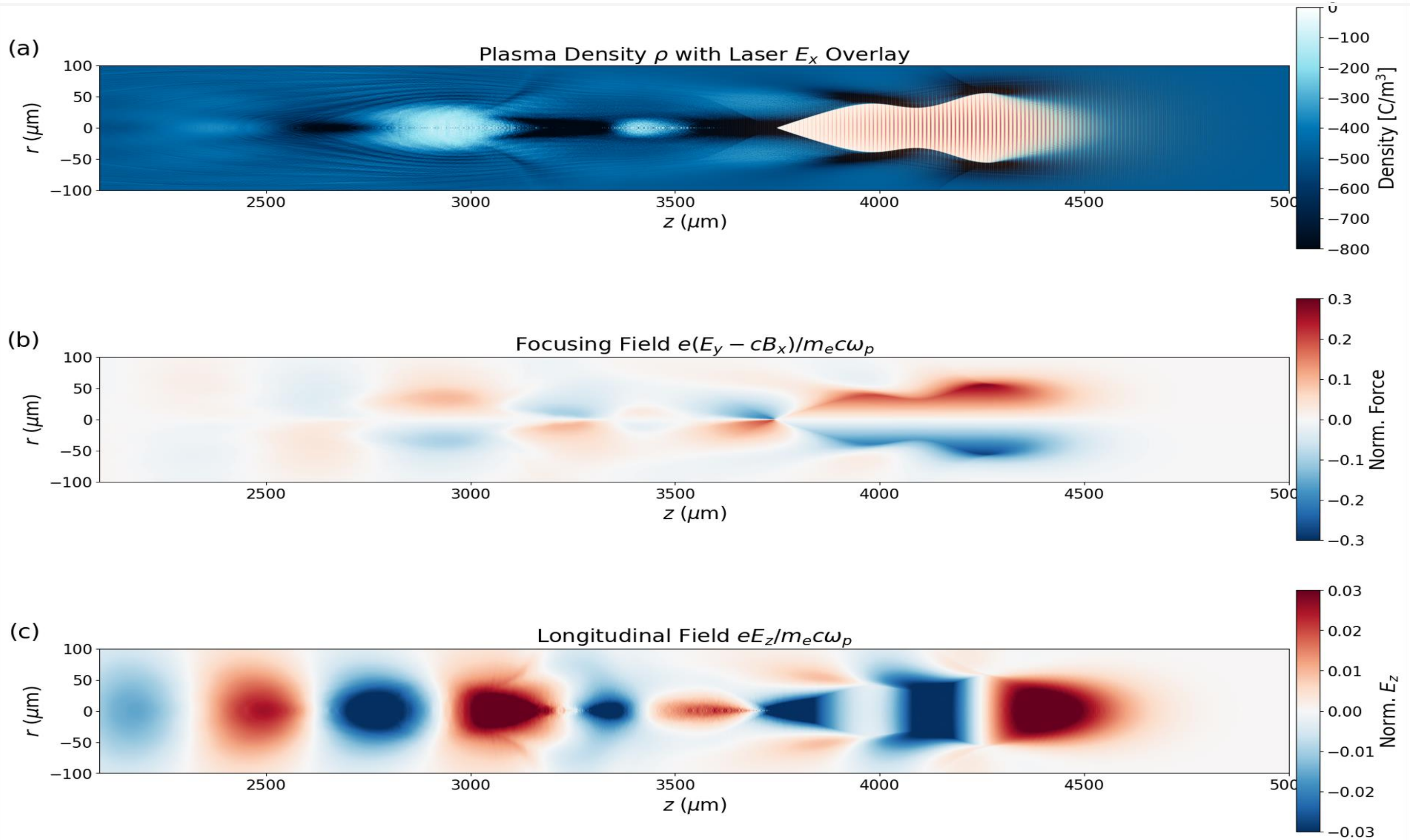
Experiment 2019; Irina Petrushinax
Simulations by Dr. Pathak

FBPIC simulation details and parameters

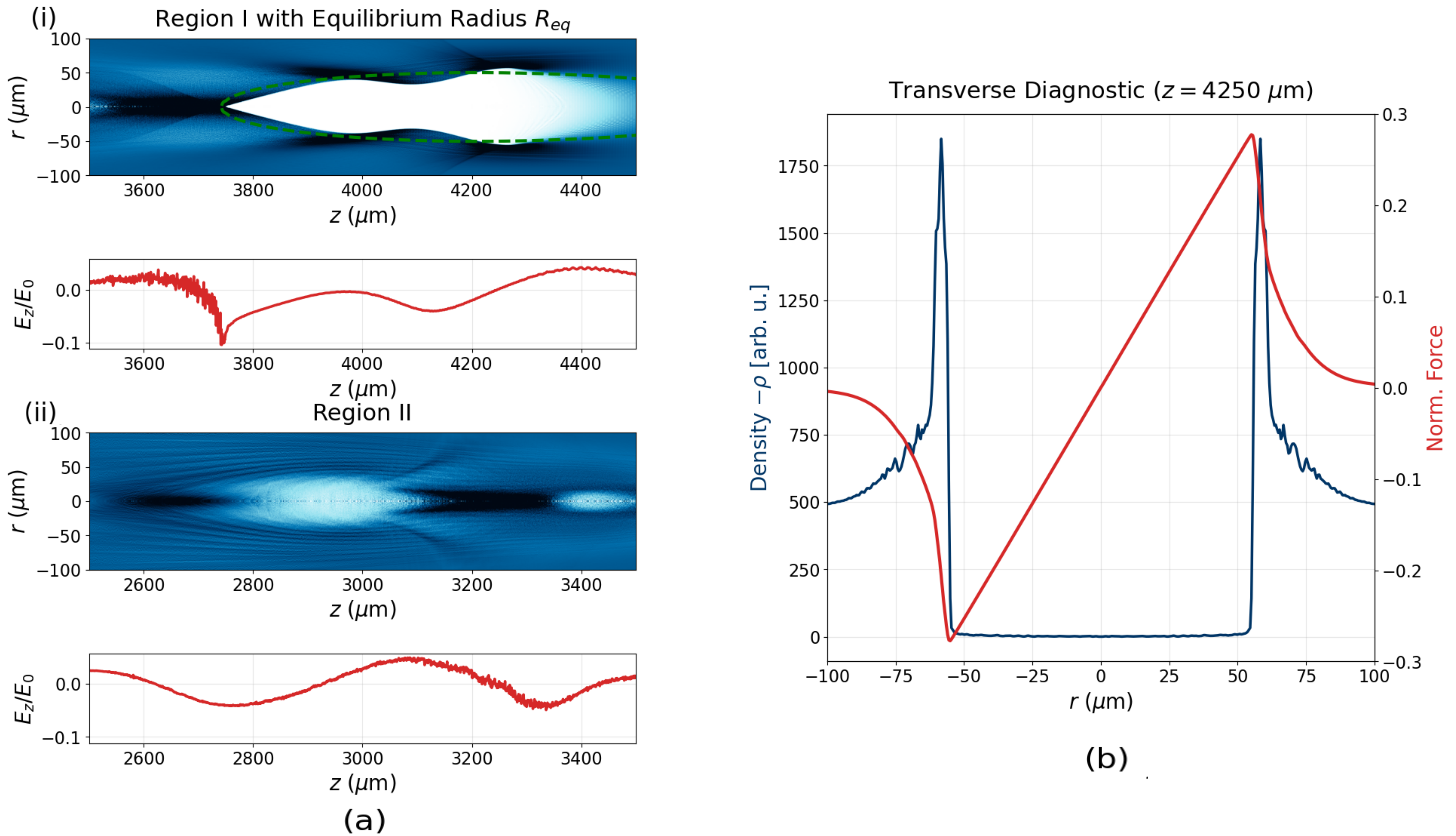
- To study the probe density modulation, FBPIC (Fourier-Bessel Particle-In-Cell) was used.
- Using parameters close to the experiment.

Laser plasma interaction conditions	
Plasma density	3e15 cm-3
τ (laser pulse length)	2 ps (FWHM)
a0	1.0
w0 (laser waist size)	40 μm
Laser pulse wavelength	10 μm

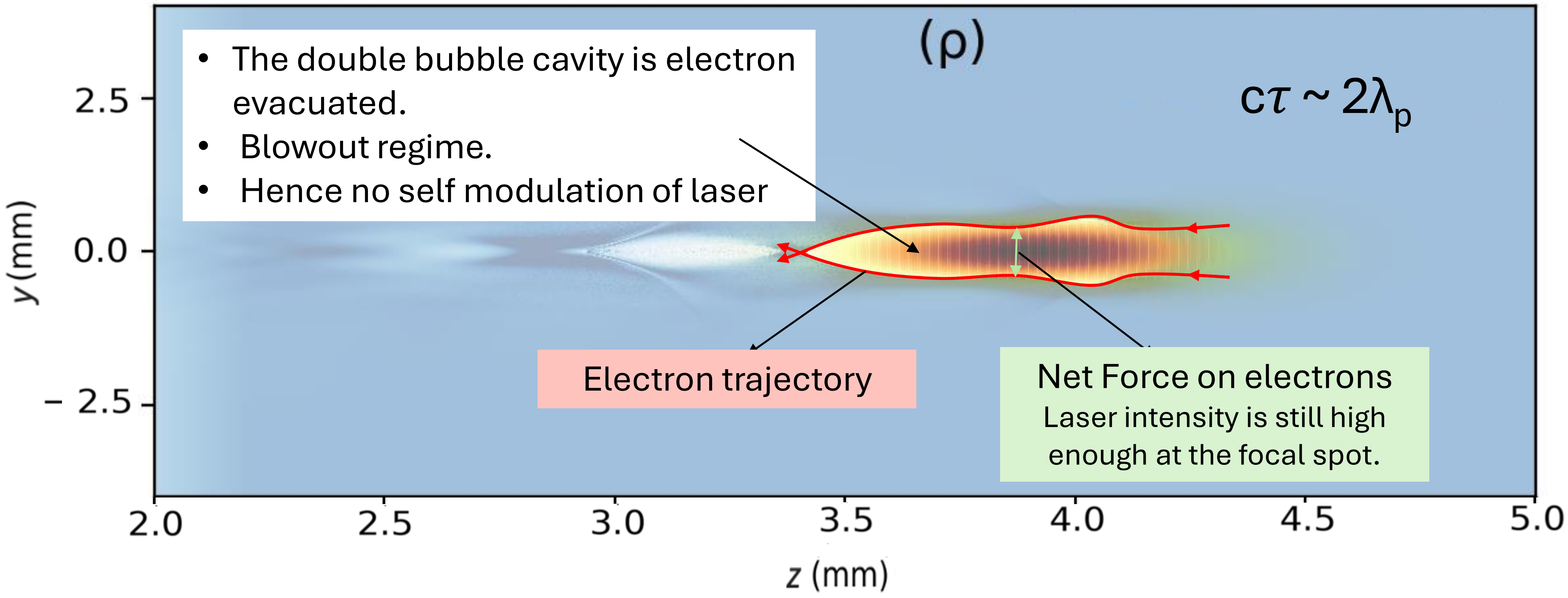
Exploration of simulated wakefield



Wakefield longitudinal and transverse diagnostics



Dynamics of the Interaction Regime



- At lower densities, restoring force of ion column is weaker compared to the pondermotive force of the focused laser. This doesn’t let the electrons reach back to the axis and forms an open wake structure.

Force Balance between Laser and Ion cavity

Bi-Gaussian Laser Pulse in time and space

$$a(\mathrm{r},\xi,t) = a_0 e^{-r^2/w_0(\xi)^2} \underbrace{e^{-(\xi-\xi_0)^2/(c\tau)^2}} \underbrace{\cos(k_0\xi - \omega_0 t)}$$

(assumption Laser Pulse is Static; t = 0, at z = 0) **Averaged out**

The transverse gradient of laser is considered for calculating the ponderomotive force as the longitudinal gradient has minimal effect.

Ponderomotive Force

$$F_p = -\nabla\left(\frac{a^2}{2}\right)$$

Restorative Force of Ions

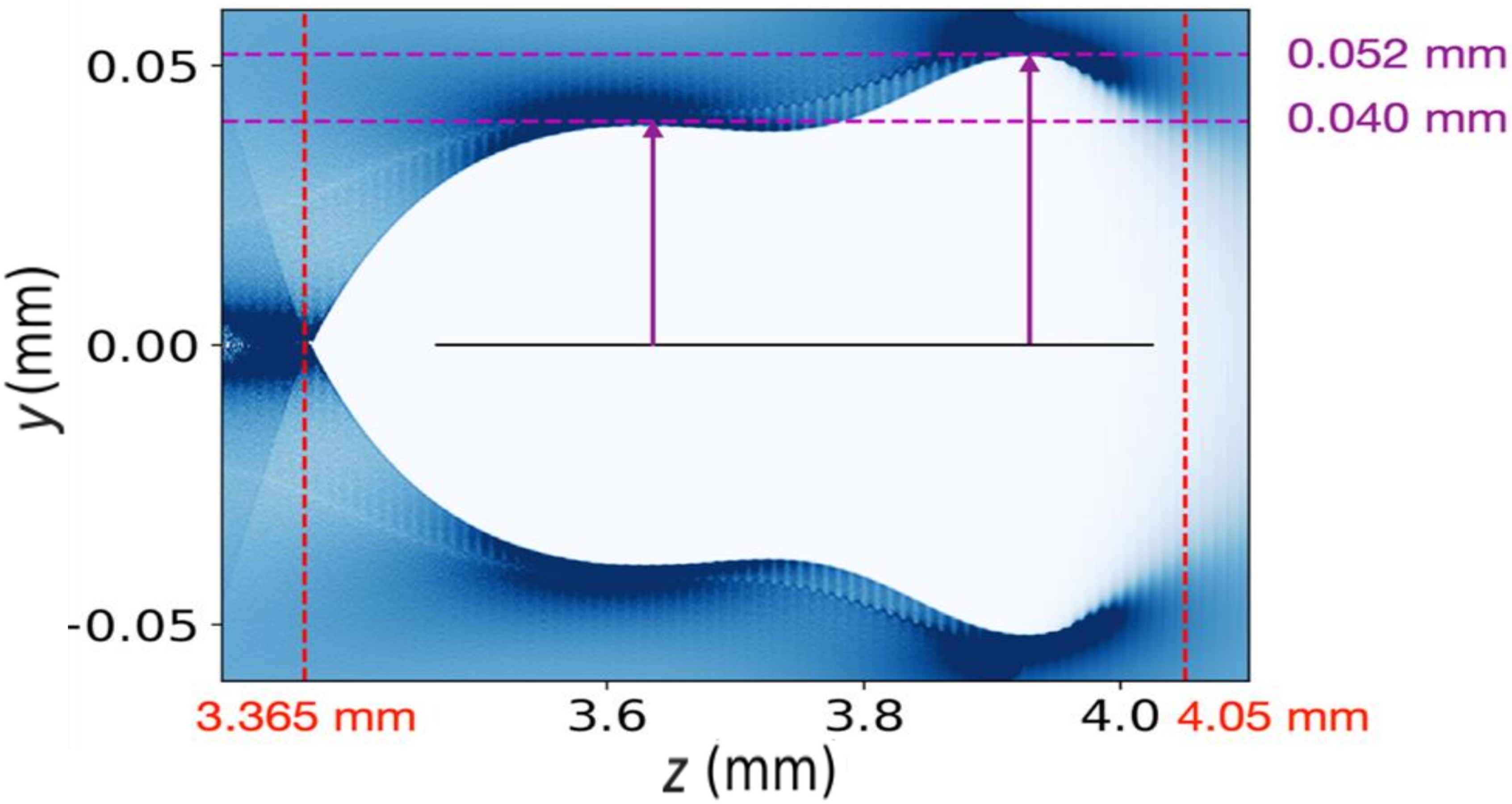
$$F_r(r) = -kr\ , \quad k = 0.5$$

$$\left|F_p\left(r_{eq}\right)\right| = \left|F_r\left(r_{eq}\right)\right|$$

$$\frac{r_{eq}}{w_0} = \frac{1}{\sqrt{2}}\sqrt{\ln\left(\frac{a_0^2}{0.125 w_0^2}\right)}$$

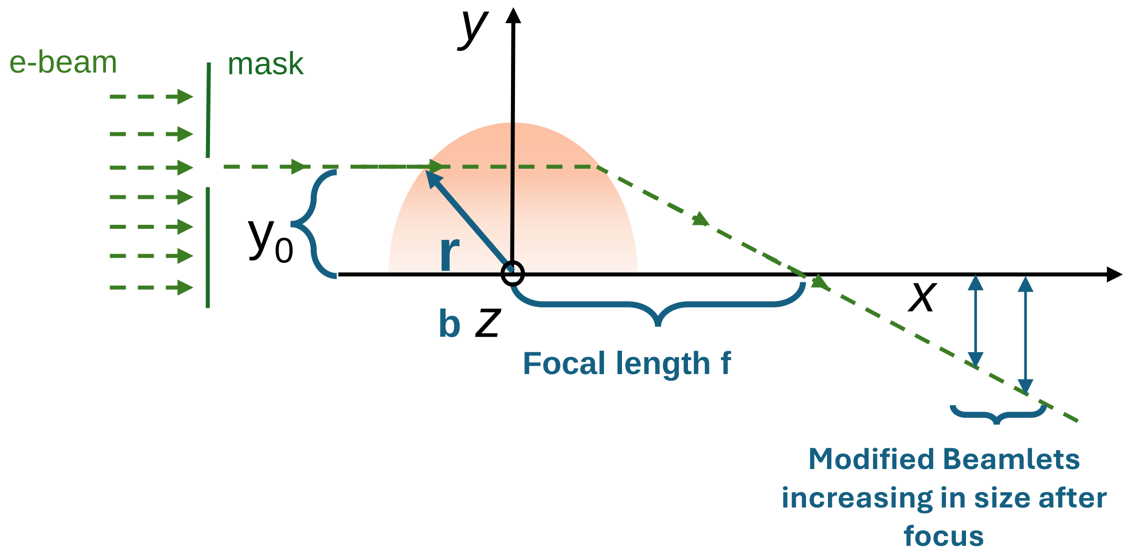
Verification of equation

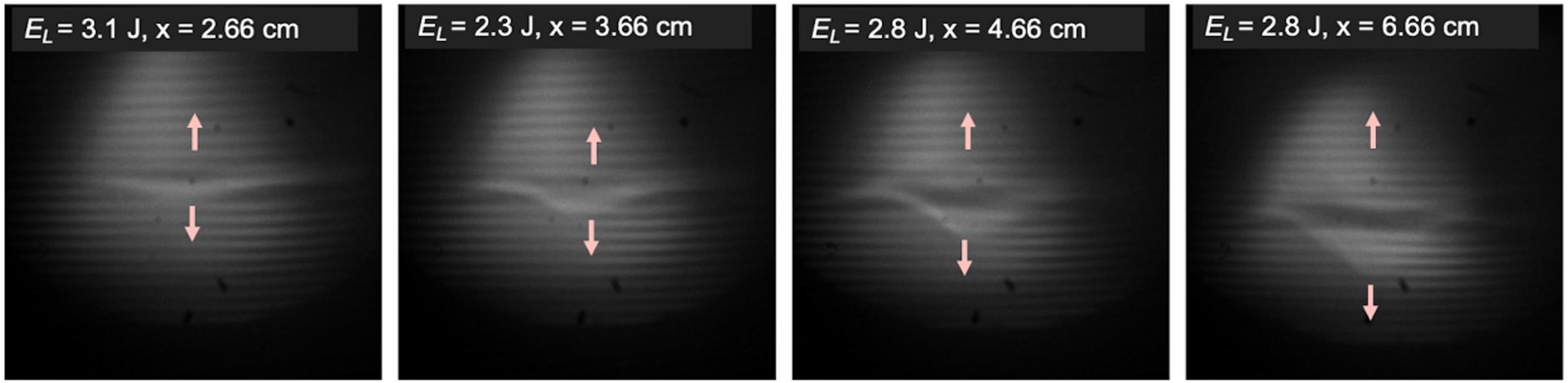
- For our case, calculated r_{eq} ~ 49.79 μm.



Experimental verification of focal length

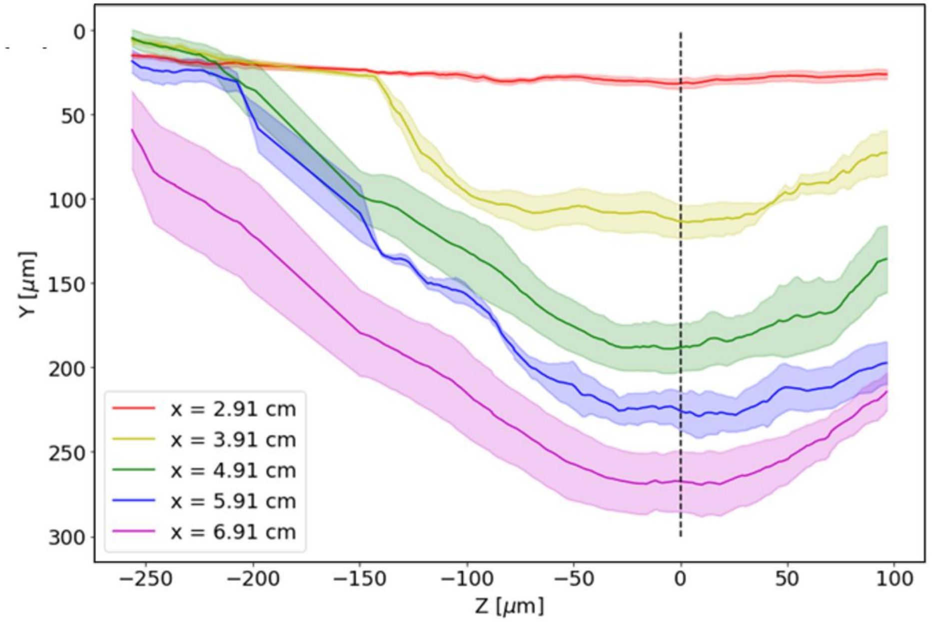
Wake treated as a simple thin lens



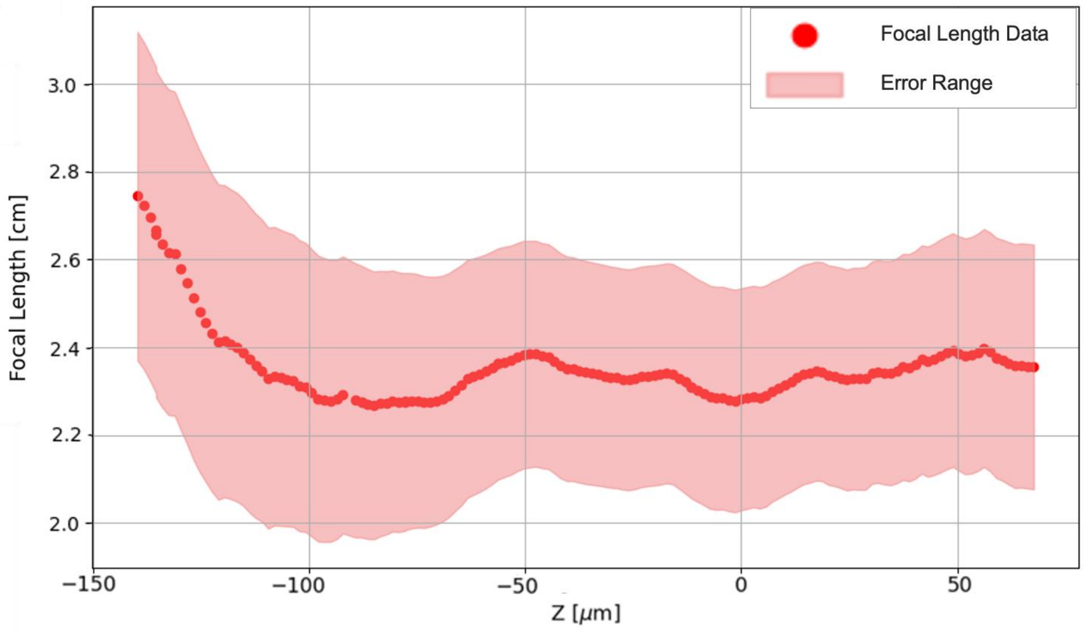


Experimentally captured beamlet expansion at BPM 1

Experimental verification of focal length



Digitized beamlets



Focal length along the ion channel

Plasma Lens Candidate

- The novel blowout regime exhibits a near-flat accelerating field along the length of the ion channel.

- The transverse focusing force of the elongated cylindrical cavity dominates the interaction with electron beam in orthogonal configuration.

- By combining these characteristics we propose this interaction regime as a candidate for 1 D focusing plasma optic.

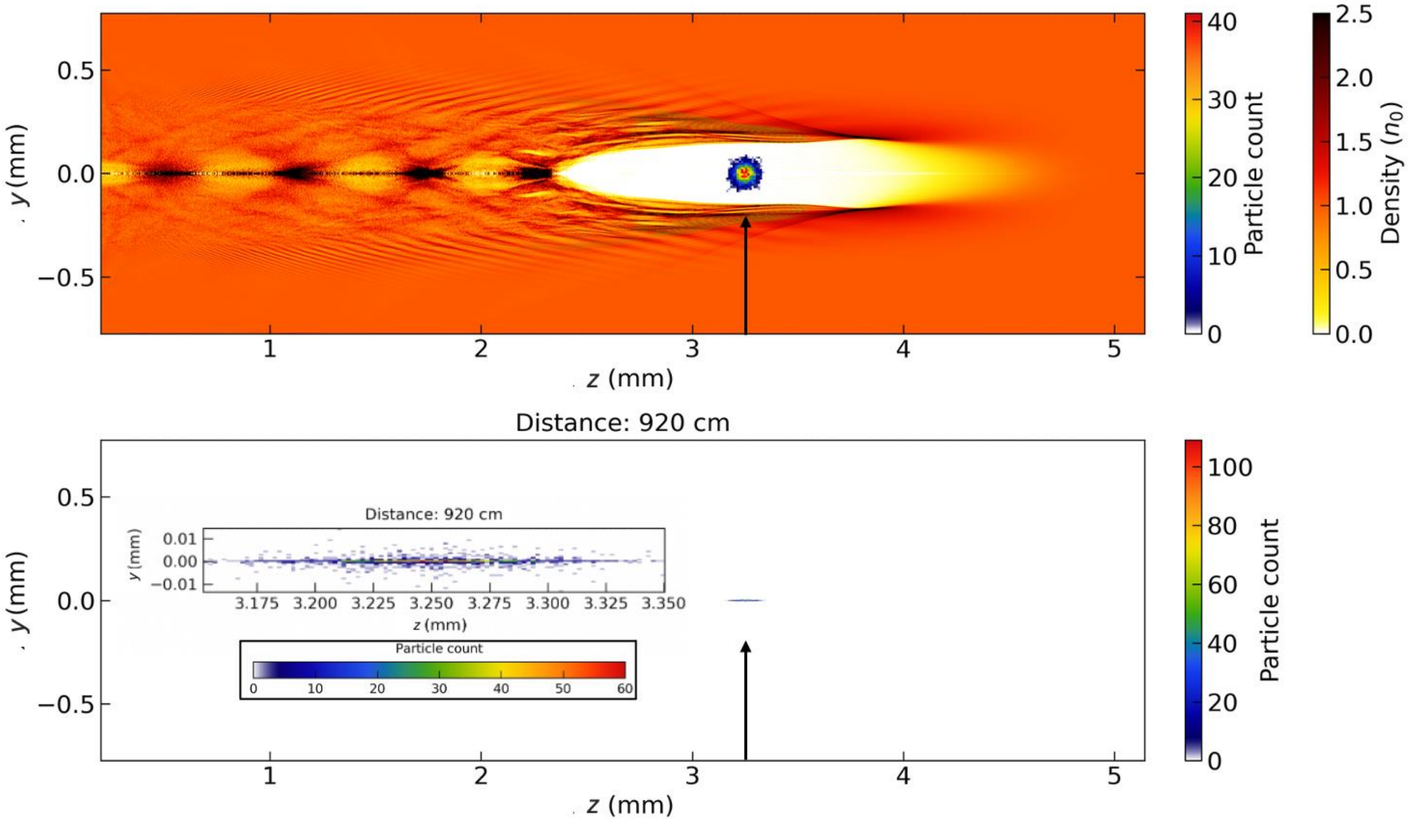
Scaling focusing optic for 100 GeV beam

Simulation parameters

$a_0 = 3$, $\lambda = 10$ µm, $w_0 = 200$ µm , $\tau = 4$ps, $n_e = 3 \times 10^{15}$ cm^{-3}

Navid Vafaei-Najafabdai talk
WG1 Tuesday.

$$E_z = \frac{1}{2} r b \frac{dr_b}{d\xi}$$



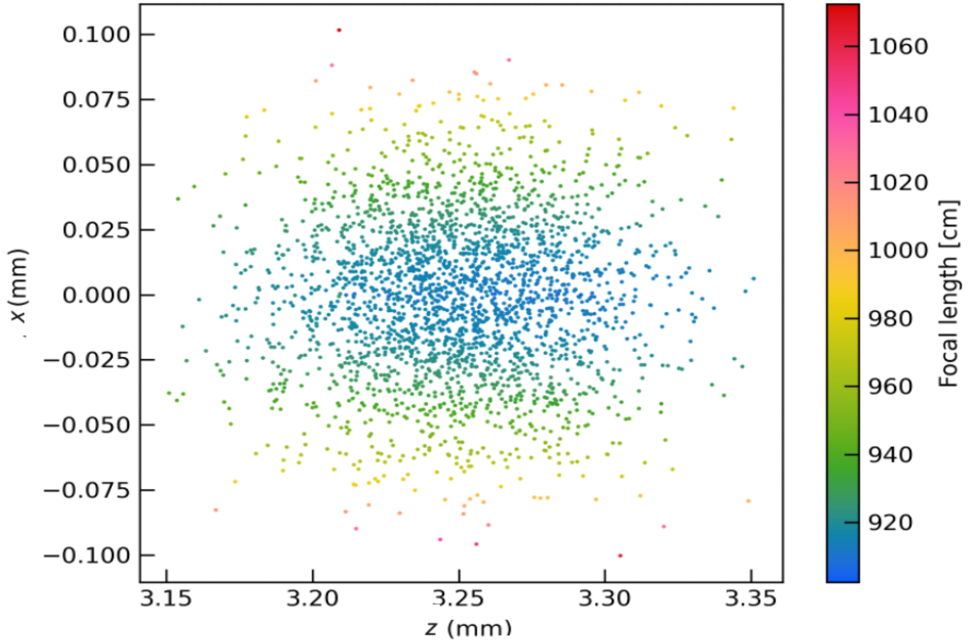
The focal length is ~9.2 m. It's a competitive comparison with a high-gradient quadrupole of G = 100 T/m (l ~ 18 cm) with a focal length of 18.5 m

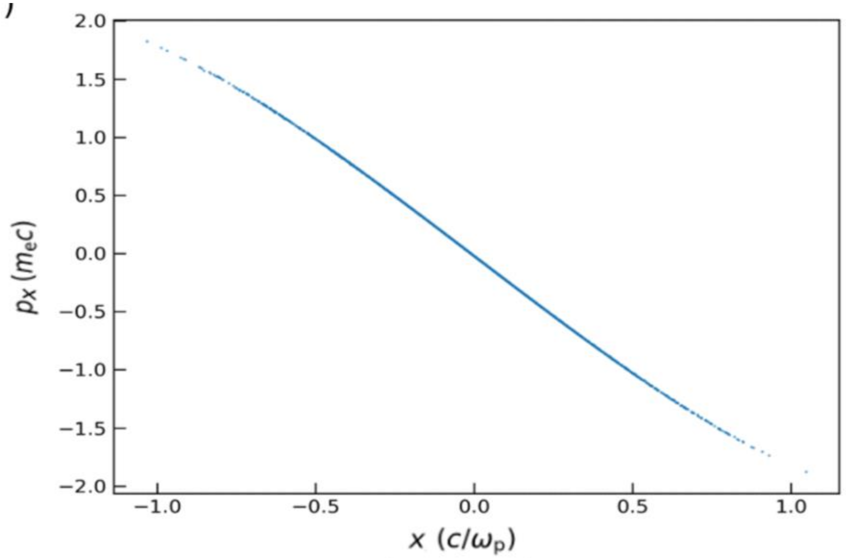
W. Lu 2006

Simulations by Dr. Miller

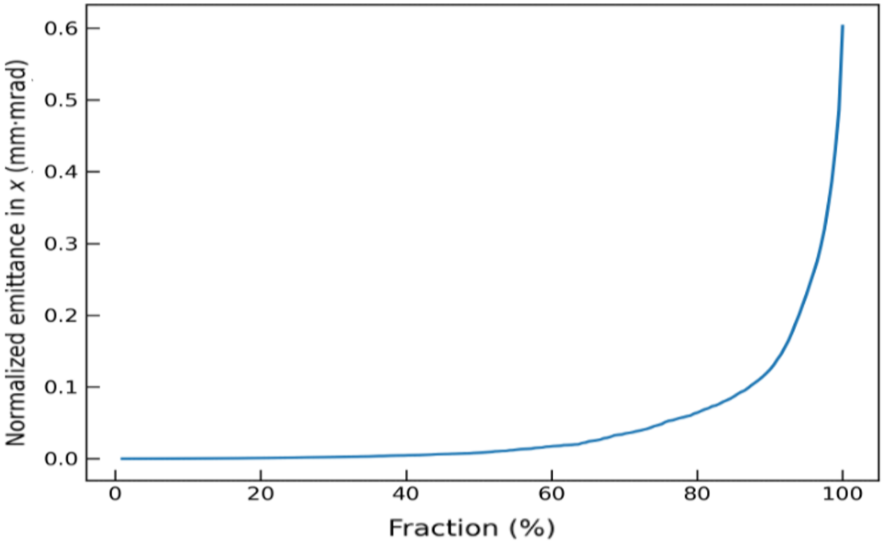
Test probe electron beam diagnostics

Focal length of the central beam slice





Phase space



Normalized fractional emittance curve

Conclusion

- Orthogonal probe beam interaction confirms a line focus entirely decoupled from the cross-plane coordinate.

- Simulations demonstrate core fractional emittance remains unperturbed (< 0.06 mm.mrad) across 80% of the beam profile.

- Achieved focal lengths under 10 m, competing directly with state-of-the-art 100 T/m conventional quadrupoles for 100 GeV test beam.

- Confirms potential for compact, flexible, high-gradient optics tailored for the beam asymmetry requirements of future linear colliders.