Flat beam plasma wakefield experiment at the AWA facility

Pratik Manwani[1], Alex Ody[3], Nathan Majernik[2], Derek Chow[1] Yunbo Kang[1], Joshua Mann[1], Gerard Andonian [1,4], Seongyeol Kim[3], Phillipe Piot[3], John Power[3], Doran Scott[3], and James Rosenzweig[1]

1: University of California, Los Angeles

2. Stanford Linear Accelerator Center (SLAC)

3: ANL, Lemont, Illinois

4: Radiabeam

UCLA College | Physical Sciences Physics & Astronomy

Argonne NATIONAL LABORATORY

Outline

- Motivation
- General formalism
  - Beam and plasma blowout ellipticity
  - Matching conditions
  - Simulations – Beam plasma interaction
- Experiment at Argonne Wakefield Accelerator(AWA)
  - Plasma source development
  - Beamline design
- Conclusion and future work

Motivation

- Plasma wakefields using asymmetric beams ($\sigma_x > \sigma_y$) with highly asymmetric emittances ($\epsilon_x \gg \epsilon_y$) have not been investigated.
  - These beams yield a blowout cavity that is elliptical in cross section which leads to interesting physics.

- Promising to use asymmetric drivers in hollow channel plasmas to accelerate positrons (Zhou et al, 2021)

- For colliders, beams with highly asymmetric emittance are expected to mitigate beam-beam effects (beamstrahlung) at the interaction point.

$$\frac{U_{flat}}{U_{round}} \propto \frac{\sigma_y}{\sigma_x}$$

Important to check how these beams will behave in plasma afterburner scenarios

First simulations ($n_b \ll n_0$)

- We can start with a beam having an arbitrary profile:

$$n_b = n_{b0} X(x) Y(y) Z(z)$$

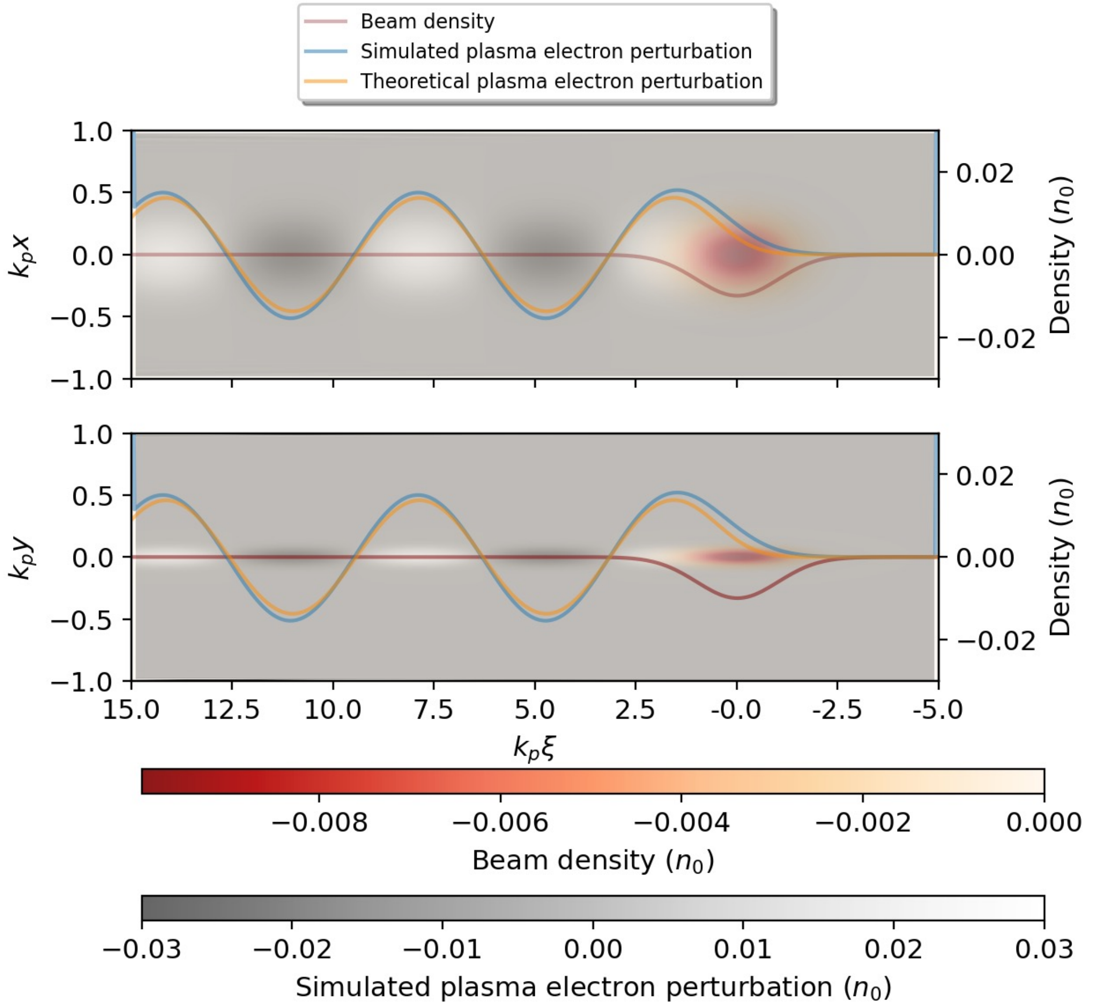
- Using the linearized wake equation ($\xi = ct - z$), we can get the perturbed plasma density :

$$\left(\frac{\partial^2}{\partial \xi^2} + k_p^2\right) n_1 = -k_p^2 n_b$$

- For a Gaussian beam, this gives

$$n_1(r,\xi) = -k_p n_{b0} e^{\left(-\frac{x^2}{2\sigma_x^2}\right)} e^{\left(-\frac{y^2}{2\sigma_y^2}\right)} \int_{\epsilon}^{\infty} e^{\left(-\frac{z^2}{2\sigma_z^2}\right)} \sin\left(k_p(\xi - \xi')\right) d\xi$$

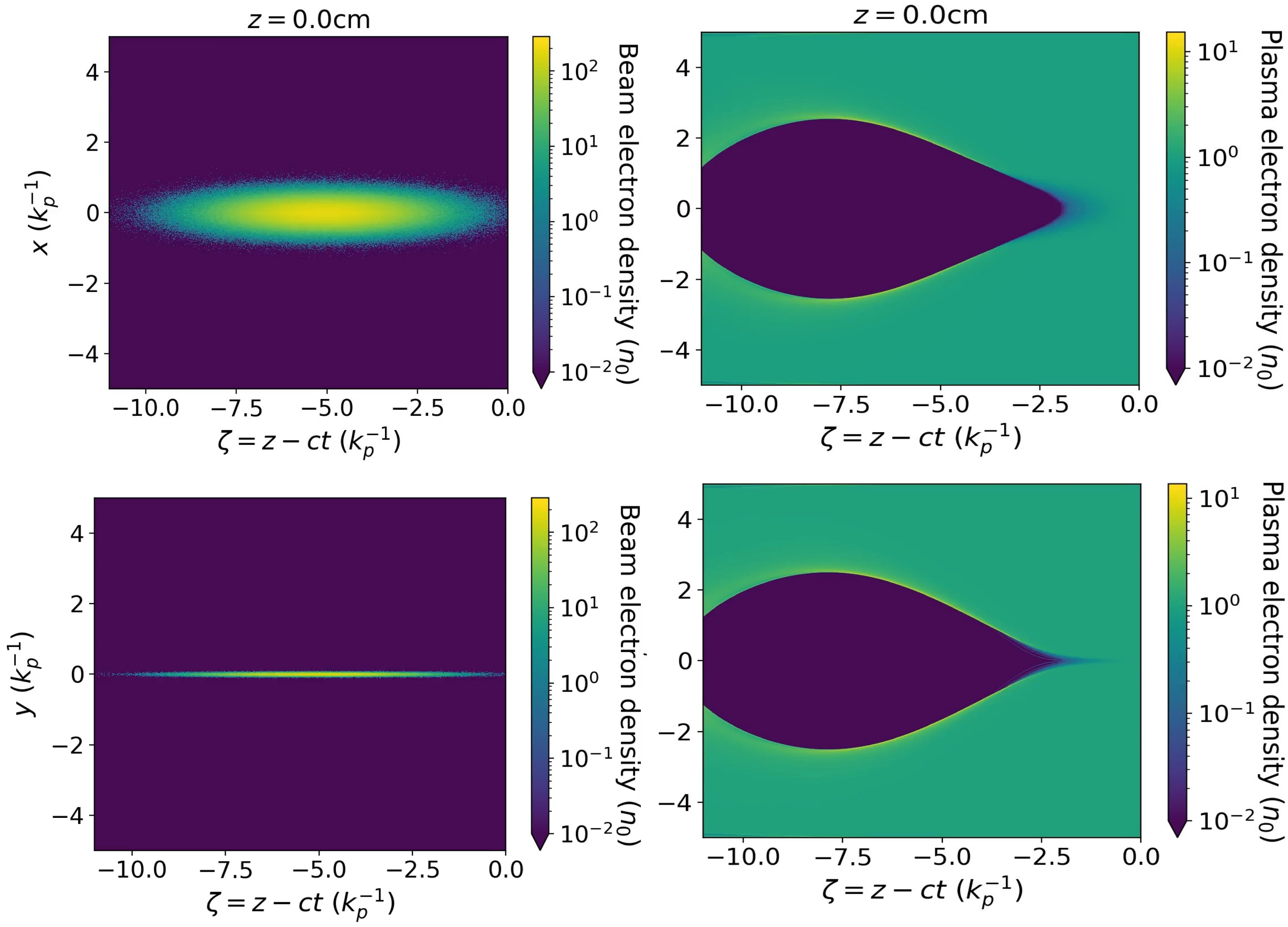
- The linear regime can be accessed at the AWA with higher plasma densities



First simulations ($n_b \gg n_0$)

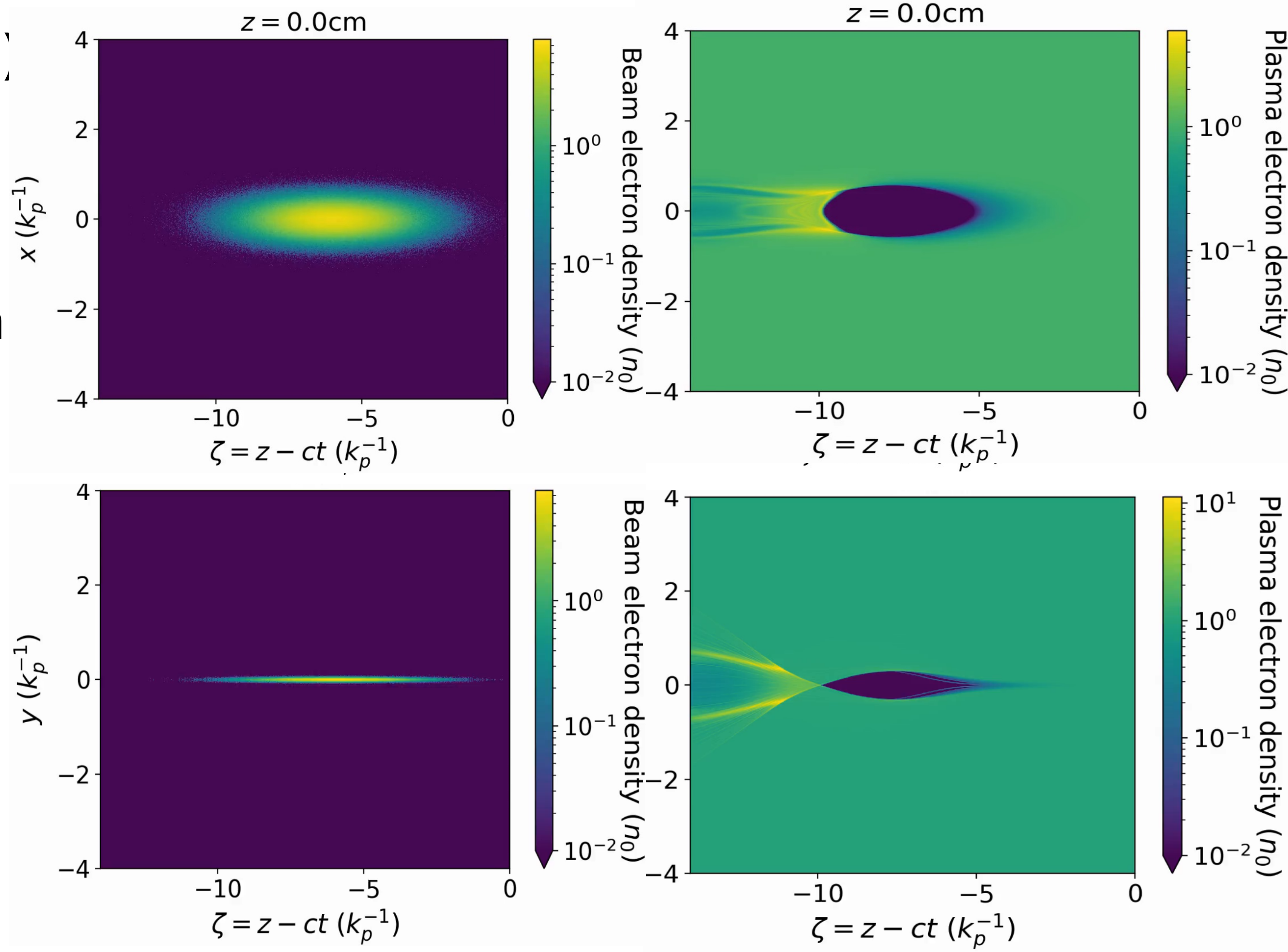
- For high beam densities ($\frac{n_b}{n_0} \gg 1$), there is a formation of an axisymmetric blowout cavity

- Example of a strong blowout ($\sigma_x = 10\ \sigma_y, n_b = 100$)



First simulations ($n_b > n_0$)

- For high beam densities ($1 < n_b < 20$) there is a formation of an elliptical blowout cavity
- The ellipticity reduces with increase in beam density.
- Example of a weak blowout ($\sigma_x = 10\ \sigma_y$)
  - Can be accessed at AWA
- The ellipticity (a_p/b_p) needs to be properly taken into account



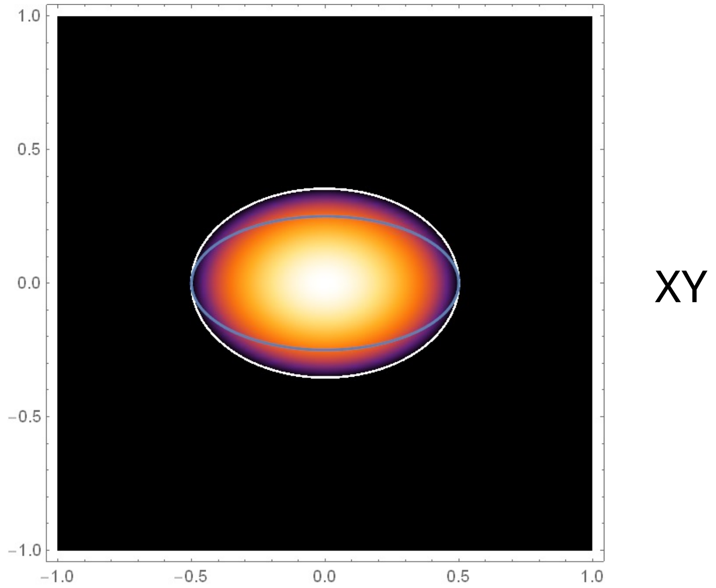
Quasi-potential ($\psi = \phi - A_z$)

- The quasi-potential ($\psi = \phi - A_z$) gives the complete description of fields on a relativistic beam

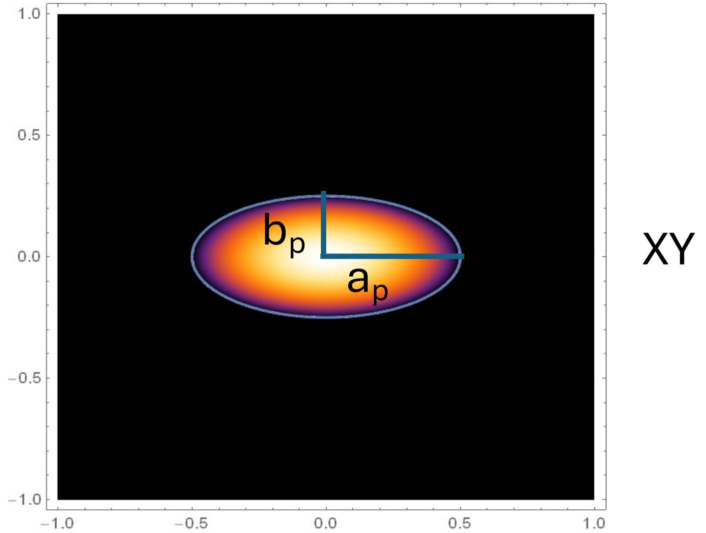
- We set $\psi = 0$ at the boundary. Our argument is that there are no electromagnetic fields outside.

- We have a poisson's equation with boundary condition:
  - $\nabla^2 \psi = -1; \;\; \psi|_{\partial\Omega} = 0$

  - Solution: $\psi = -\frac{x^2 b_p^2 + y^2 a_p^2 - a_p^2 b_p^2}{2(a_p^2 + b_p^2)}$



ϕ_i

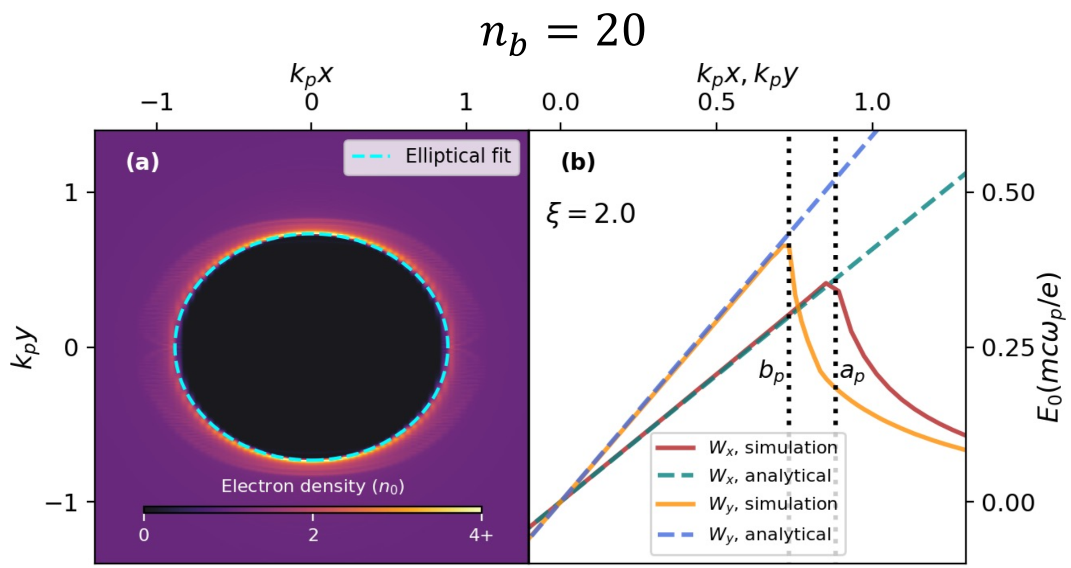


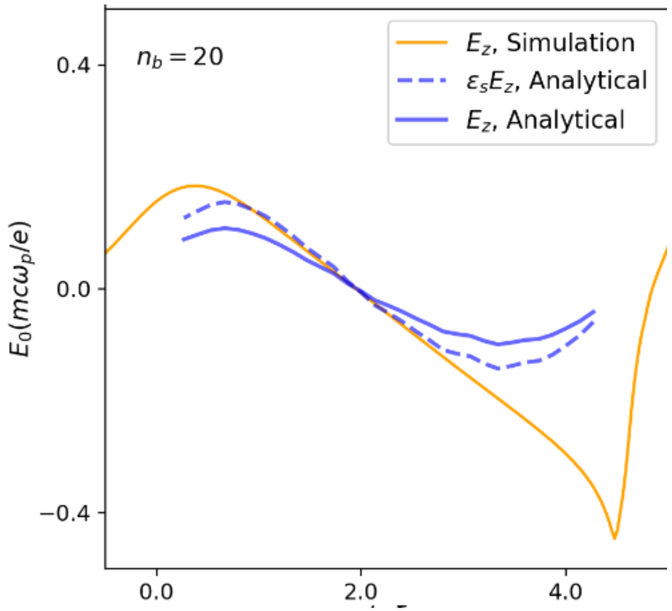
$\psi = \phi_i + \phi_{e,sheath} - A_{z,sheath}$

Wakefields

- We can test this model by fitting for the elliptical sheath boundaries generated using PIC simulations

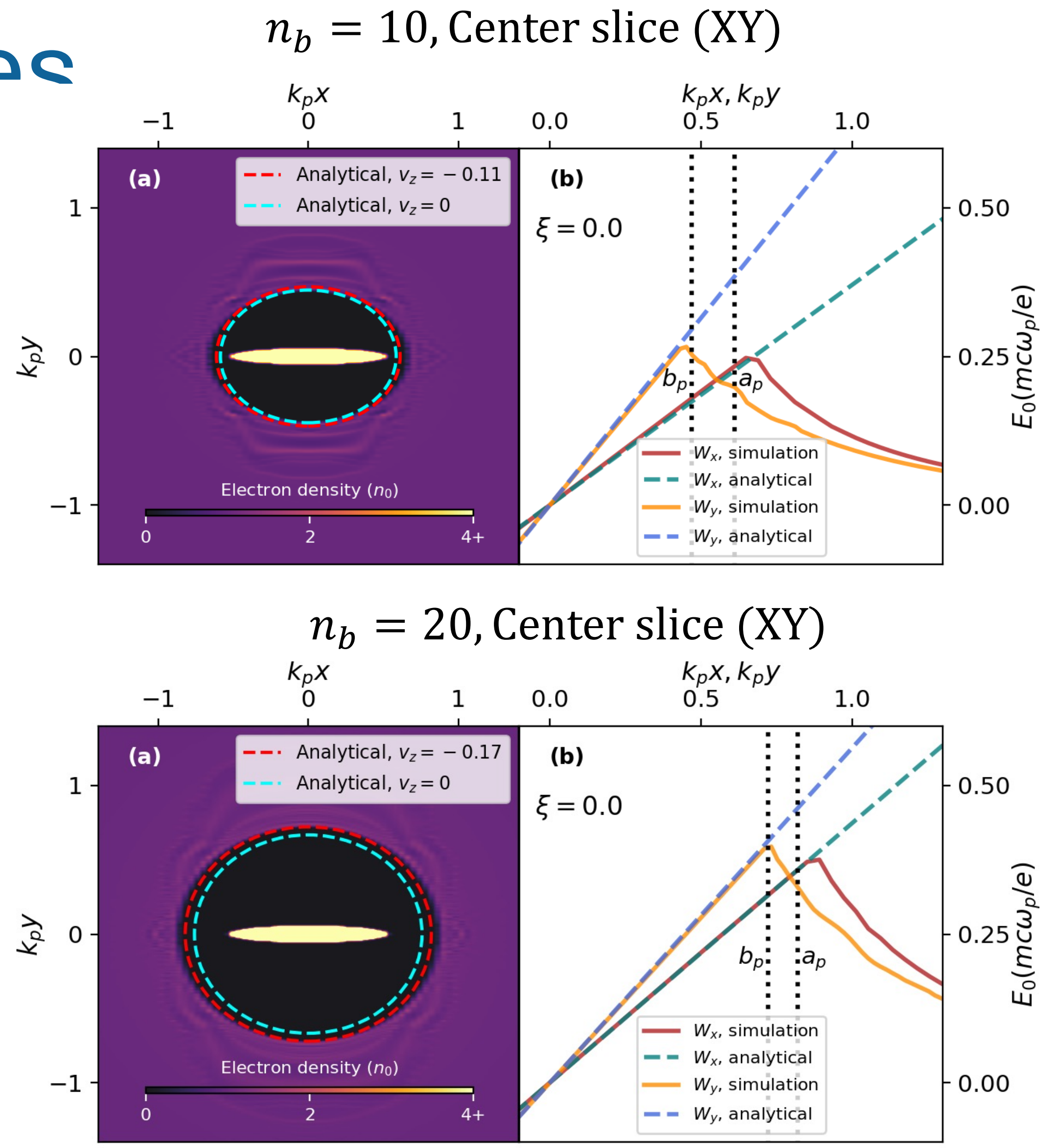
- This can be used to find the wakefields:
  - $F_x = E_x - B_y = -\frac{\partial \psi}{\partial x} = \frac{x a_p^2(\xi)}{a_p^2(\xi)+b_p^2(\xi)}$
  - $F_y = E_y + B_x - \frac{\partial \psi}{\partial y} = \frac{y a_p^2(\xi)}{a_p^2(\xi)+b_p^2(\xi)}$
  - $F_z = E_z = \ -\frac{\partial \psi}{\partial \xi} = \frac{a_p b_p((x^2-y^2+b_p^2)b_p a_p' + (x^2-y^2-a_p^2)a_p b_p'\ )}{(a_p^2+b_p^2)\hat{}2}$





Finding the blowout boundaries

- In the long beam limit ($r \ll \gamma\sigma_z$), we neglect the longitudinal variation of the fields
- By neglecting the plasma return velocity ($v_z = 0$) and equating the forces at the boundaries, we get:
  - $\frac{\partial \psi(x\,,0,\xi_0)}{\partial x} = \frac{\partial \phi_b(x,0,\xi_0)}{\partial x}$
- We can add back the electromagnetic character to the wake by adding back the longitudinal velocity:
  - $v_z = \frac{\lambda_b}{\pi(x_p+1)(y_p+1)}$



Analysis of the blowout plasma wakefields produced by drive beams with elliptical symmetry

P. Manwani,* Y. Kang, J. Mann, B. Naranjo, G. Andonian, and J. B. Rosenzweig
Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA

(Dated: July 22, 2024)

Finding the matched beam parameters

- Input: Beam charge, Beam bunch length (σ_z), emittance (ϵ_{nx},ϵ_{ny})
- Output: Blowout size (a_p, b_p), Matched beam size (σ_x, σ_y)

$$W_\perp(a_p, b_p) + E_b(n_b, \sigma_x, \sigma_y, a_p, b_p) = 0$$

→

Substitute: $K_x = \dfrac{2K_r}{1 + a_p^2/b_p^2}$ $\quad K_y = \dfrac{2K_r a_p^2/b_p^2}{1 + a_p^2/b_p^2}$

$$I_b = 2\pi\sigma_x\sigma_y n_b \quad K_r = \frac{1}{2\gamma} \quad \sigma_\perp = \sqrt{\frac{1}{\sqrt{K_\perp}}\epsilon_\perp}$$

↓

$$\mathrm{f}(\epsilon_x, \epsilon_y, a_p, b_p) = W_\perp(a_p, b_p) + E_b(n_b(I_b, \dots), \sigma_x(\epsilon_x, a_p, b_p), \sigma_y(\epsilon_y, a_p, b_p), a_p, b_p)$$

←

Minimize the function to obtain the blowout size and matched spot size

$$(a_p, b_p, \sigma_x, \sigma_y)$$

↑

Plug back to verify

PWFA Experiment at the AWA facility

Flat beam PWFA experiment (AWA)

- Asymmetric emittances can be used to yield elliptical blowouts
  - 1 nC, 200: 2 um ratio at 42 MeV have been created

- Aim would be to increase energy to 58 MeV and charge to 2-3 nC

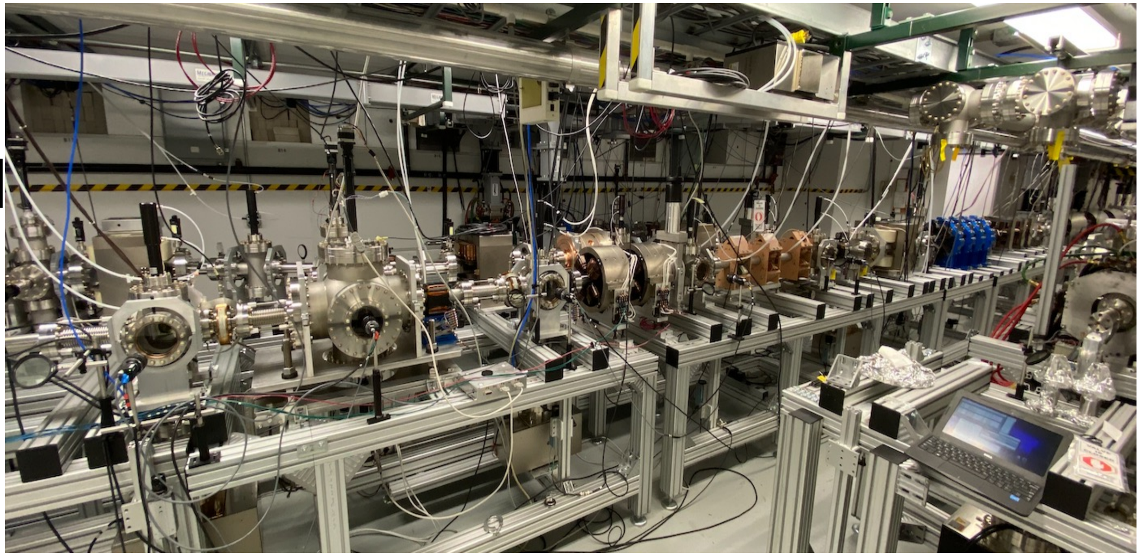
- Weak nonlinear regime can be accessed
  - Plasma source with $10^{14} - 10^{15}\ cm^{-3}$ (developed at UCLA)

- First runs performed at 45 MeV, 1 nC

TABLE I. Beam parameters measured at slab location.

Parameter	Value	Unit
Charge	2 ± 0.3	nC
Energy	42 ± 0.2	MeV
Horizontal emittance (ε_x)	$196 \pm XX$	µm
Vertical emittance (ε_y)	$2.5 \pm XX$	µm
rms bunch length σ_z	610 ± 70	µm

Flat beam parameters at AWA

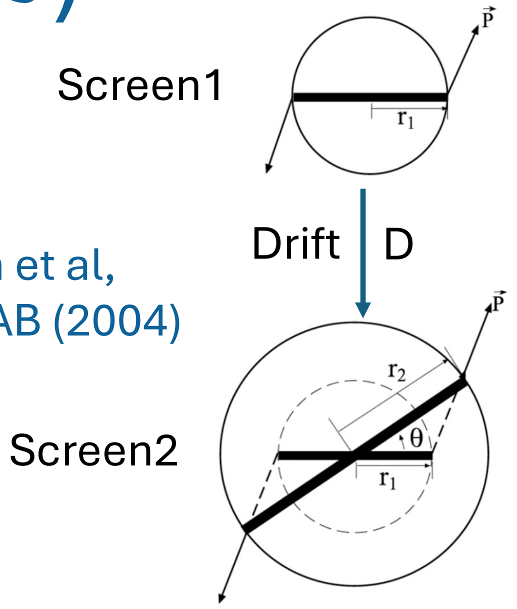


AWA facility

First runs - Magnetized beam ($\mathcal{L}$)

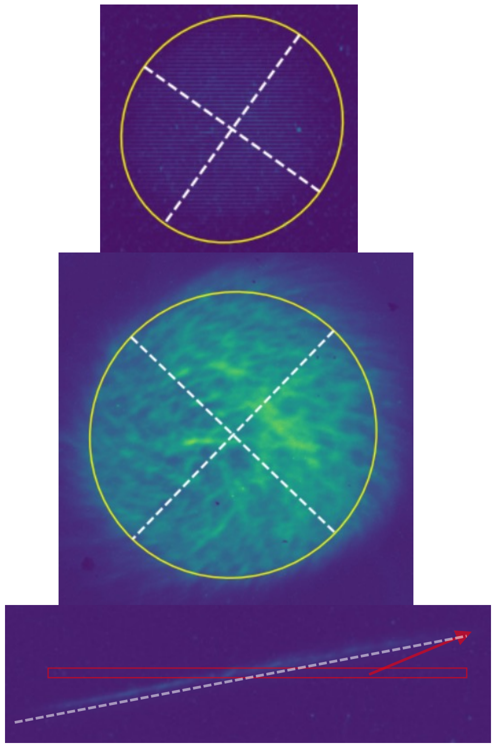
- Beam parameters – 1 nC, 45 MeV
- Canonical angular momentum
  - $L = \gamma m r^2 \dot{\phi} + \frac{1}{2} e B_z r^2$
- Inside solenoid at photocathode
  - $\dot{\phi} = 0, < L > = e B_0 \sigma_c^2$
- This is converted to mechanical angular momentum
  - $< L > = \frac{p_z r_1 r_2 sin\theta}{D}$
- Magnetization
  - $\mathcal{L} = \frac{<L>}{2 m_e c}$
- The effective emittance is: $\varepsilon_{eff} \equiv \sqrt{\varepsilon_u^2 + \mathcal{L}^2} \simeq \mathcal{L}$

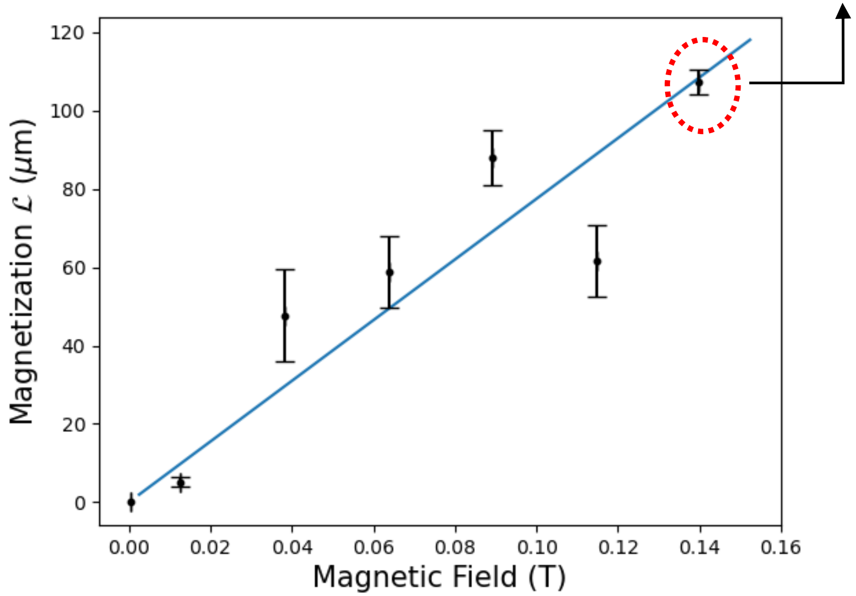
Uncorrelated emittance



Y. Sun et al, PRSTAB (2004)

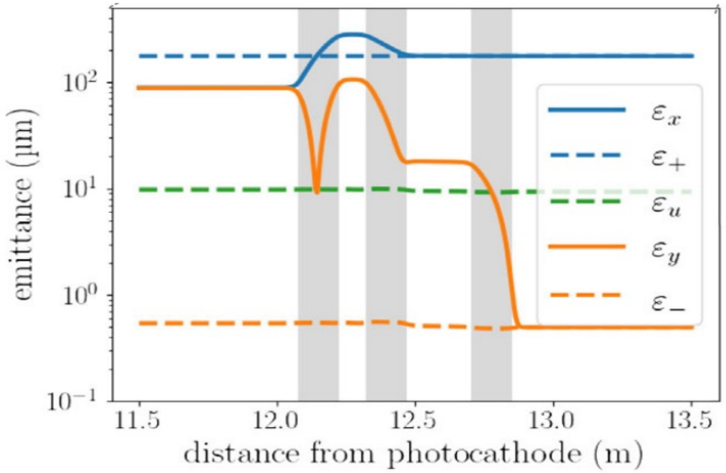
CAM dominated beam





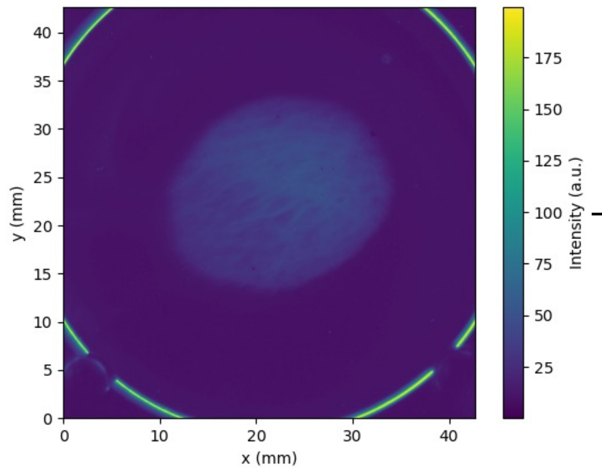
First runs - Round-to-Flat beam transformation

- The round to flat beam transformation is done using a set of three skew quadrupoles to remove the angular momentum of the beam
- This splits the emittance
  - $\varepsilon_x \rightarrow \ \varepsilon_+ = \varepsilon_{eff} + \mathcal{L} \simeq 2\mathcal{L}$
  - $\varepsilon_y \rightarrow \varepsilon_- = \varepsilon_{eff} - \mathcal{L} \simeq \dfrac{\varepsilon_{eff}^2}{2\mathcal{L}}$

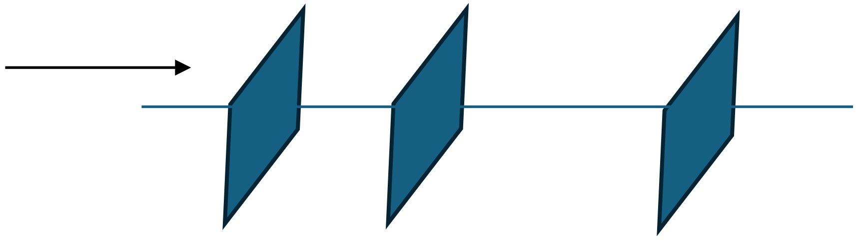


$\epsilon_x, \epsilon_y \rightarrow$ 200:2 um rad

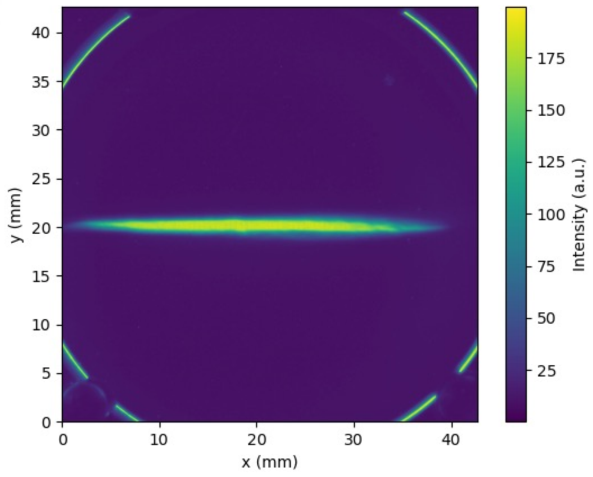
T. Xu et al, PRAB 2022



YAG

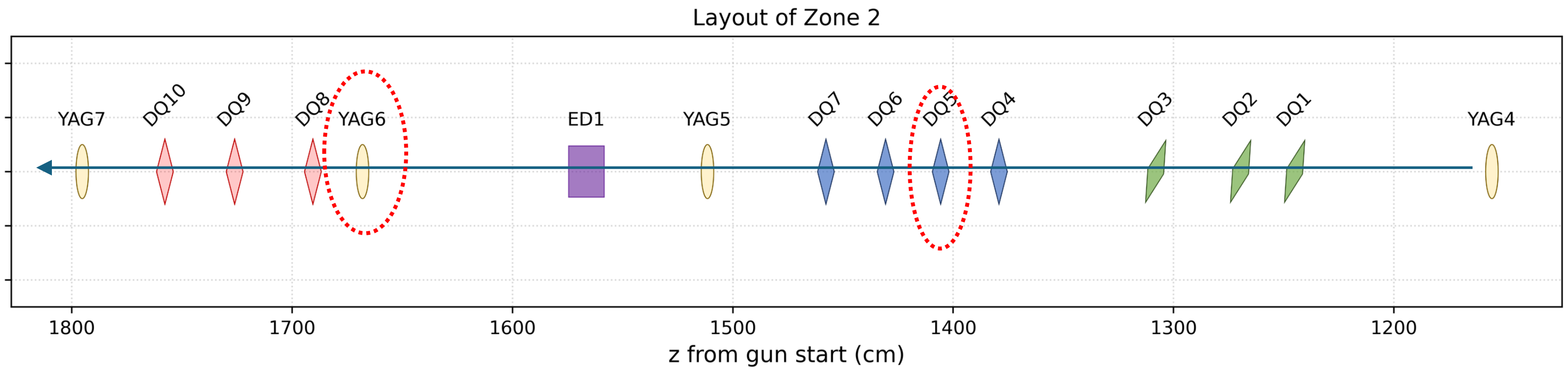


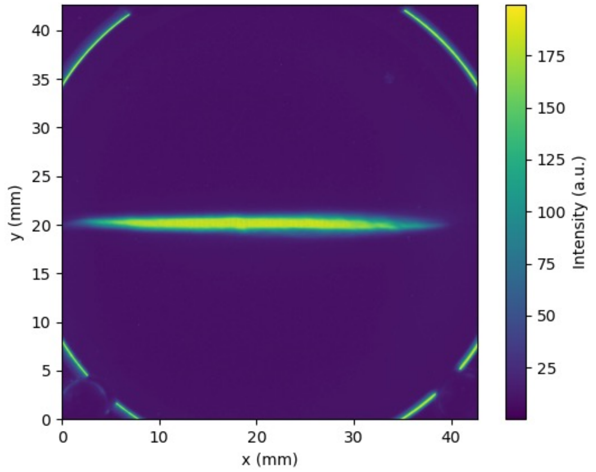
Skew quadrupoles

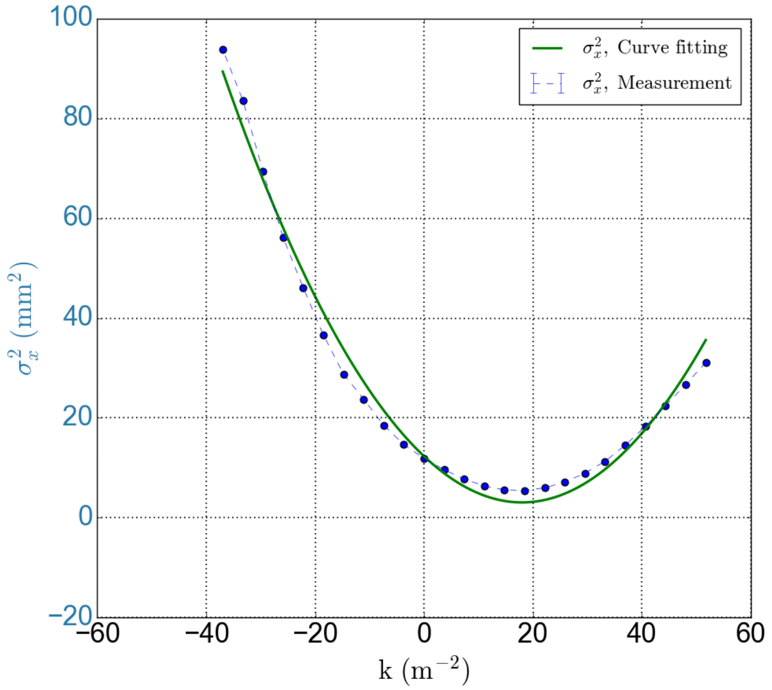


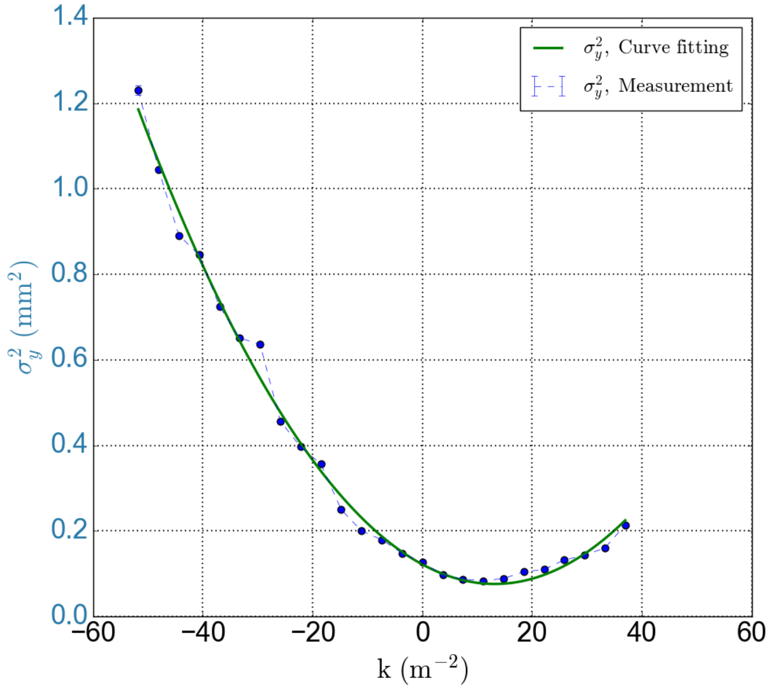
YAG

First runs - Quad scan measurement







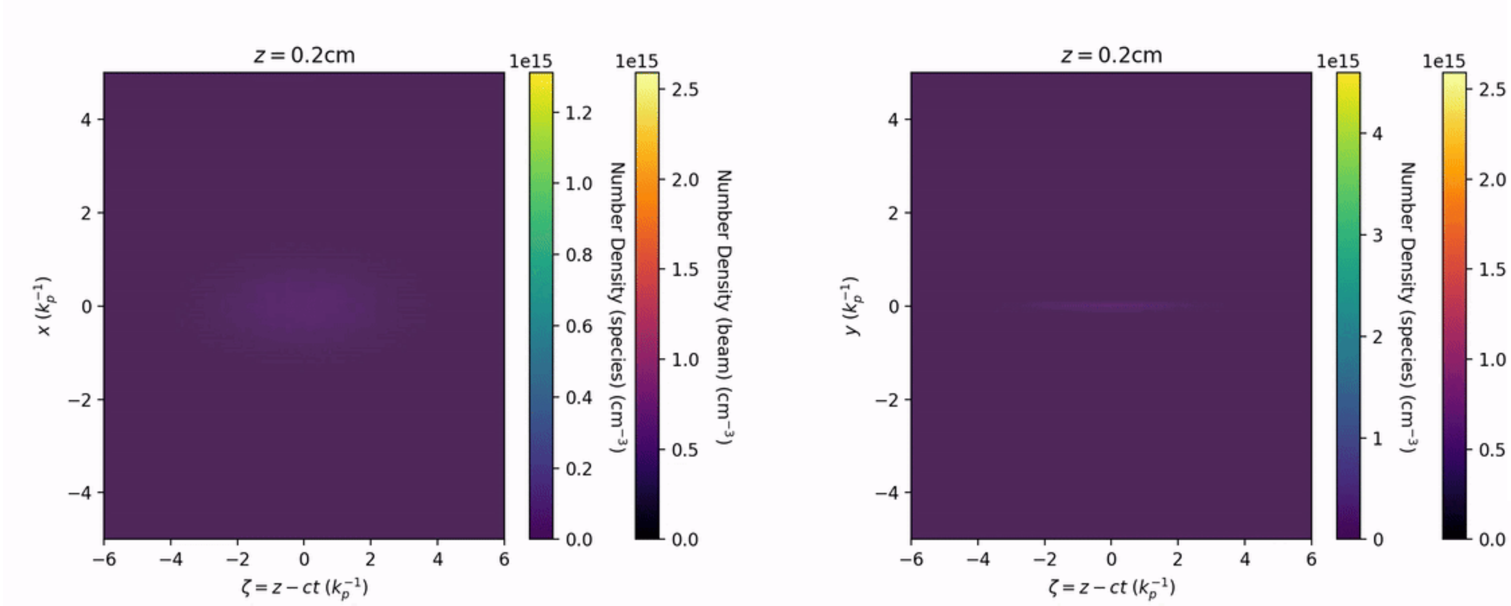


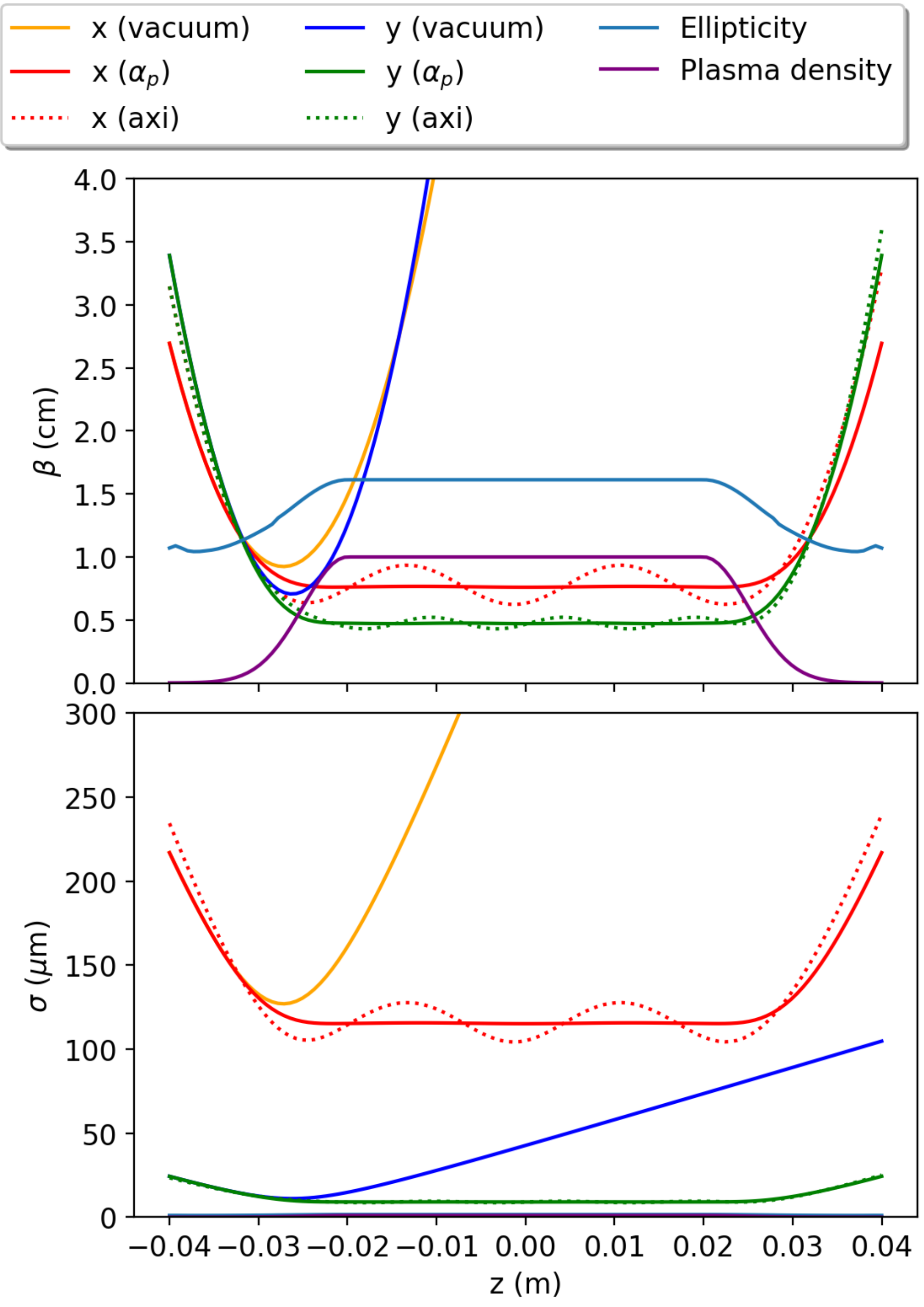
<u>Preliminary analysis</u>

$$\epsilon_x, \epsilon_y \rightarrow 335.25, 5\ um\ rad$$

Beam – plasma interaction

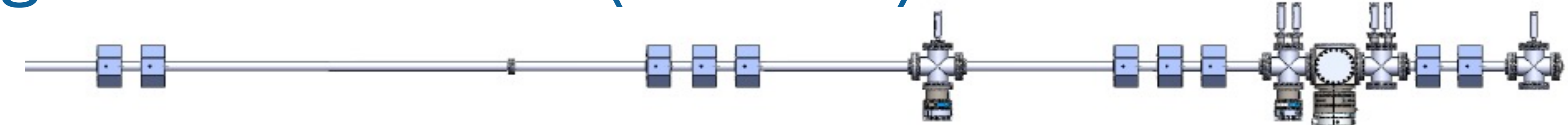
- We can use our long beam model for the vacuum-plasma transport
- The ellipticity increases with increase in plasma density ($\alpha_p \propto n_p$)
- The ellipticity is about 1.4 for a 3 nC and 2 for a 2 nC beam



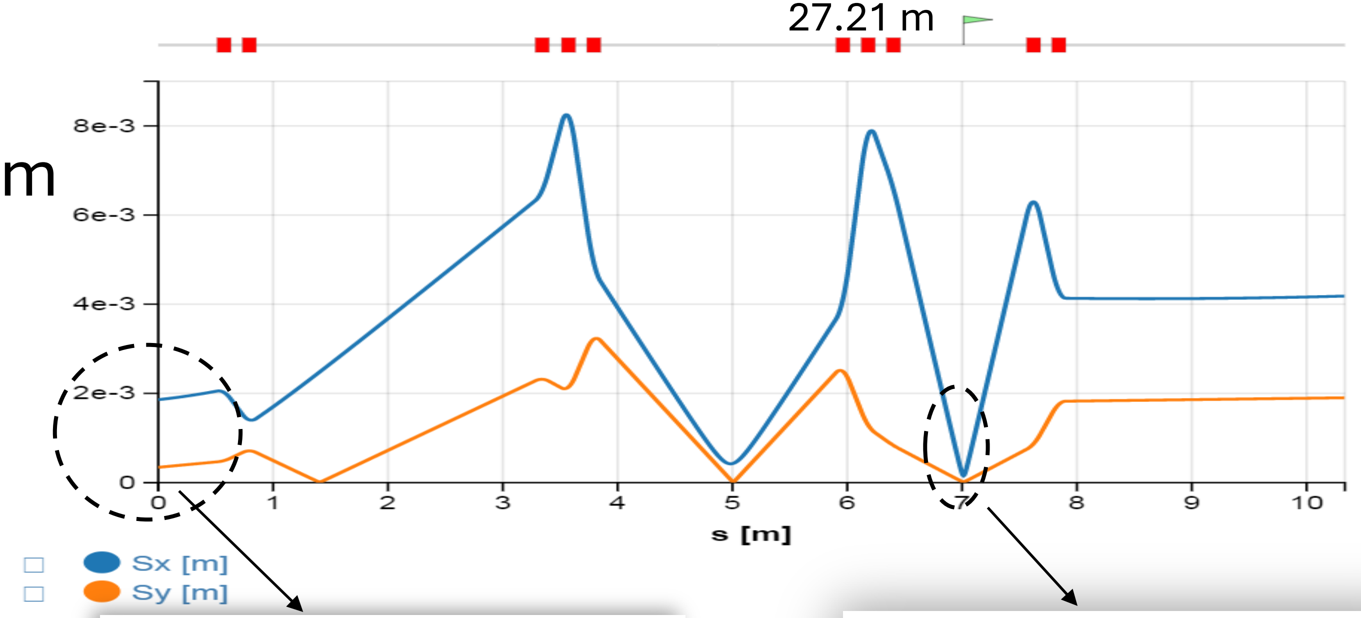


Analytical results

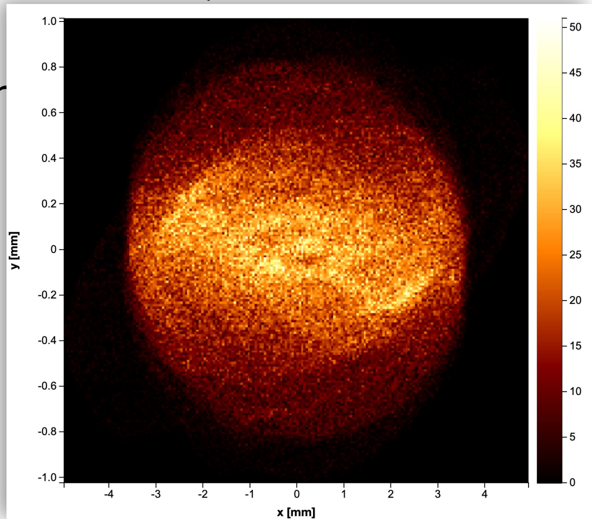
Elegant simulations (58 MeV)

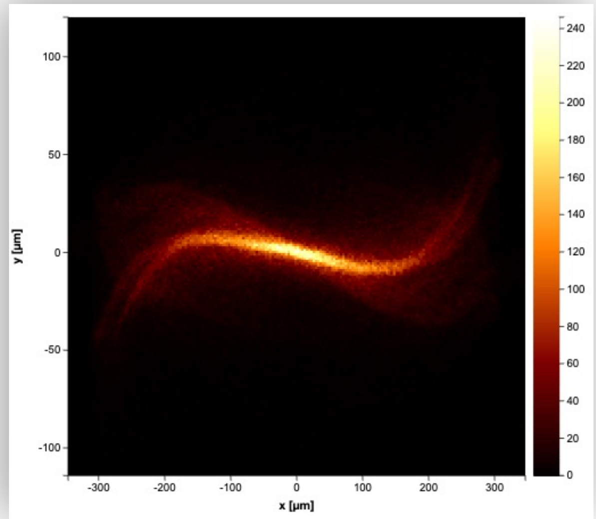


20.3 m



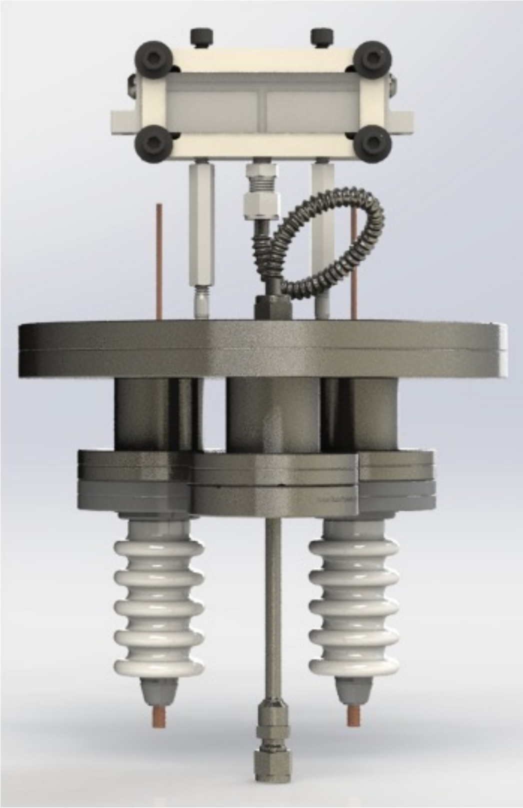
- Input twiss parameters (20.3 m) from OPAL
- We focus the beam at two different locations
  - Ante chamber
  - Plasma chamber
    - β_x(needed): 0.009 m , β_y(needed): 0.0071 m
- Emittance changes due to chromatic spread (3rd order tracking)
  - ϵ_x = 188 .7 -> 189.5 (I.P) um rad
  - ϵ_y =1.6 -> 2.8 (I.P)um rad

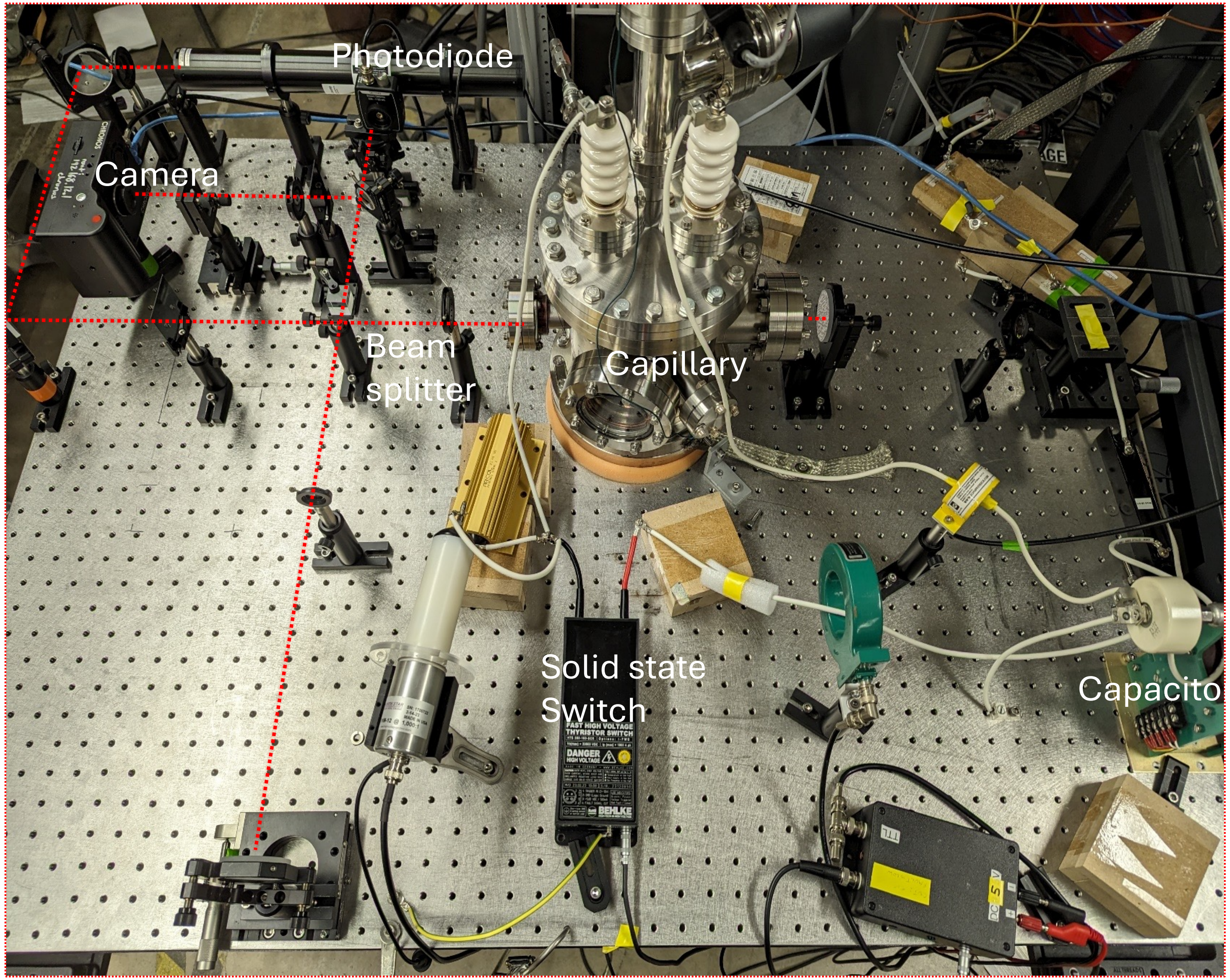




Capillary discharge plasma source at UCLA

- 4 mm diameter x 8 cm length
- 1 cm holder on either side
- 10 kV, 60 A peak current, Argon gas, 50 psi, 5 ms window





Plasma source diagnostics - Interferometer

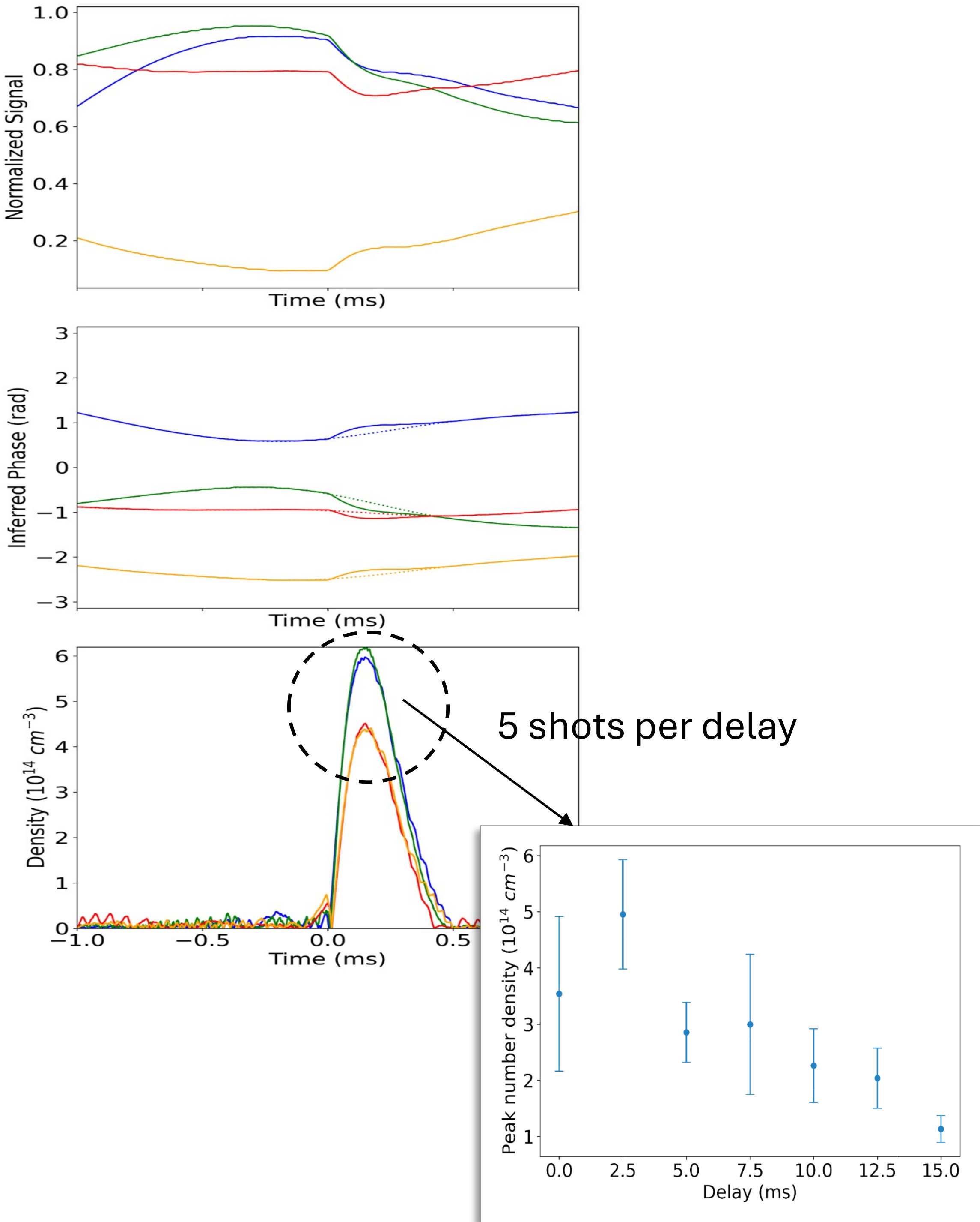
- Change in phase can be estimated from the signal at the photodiode

$$V_p = \frac{1}{2}(V_{max} - V_{min})(1 + cos\phi) + V_{min}$$

- Plasma density can be estimated from this change in phase

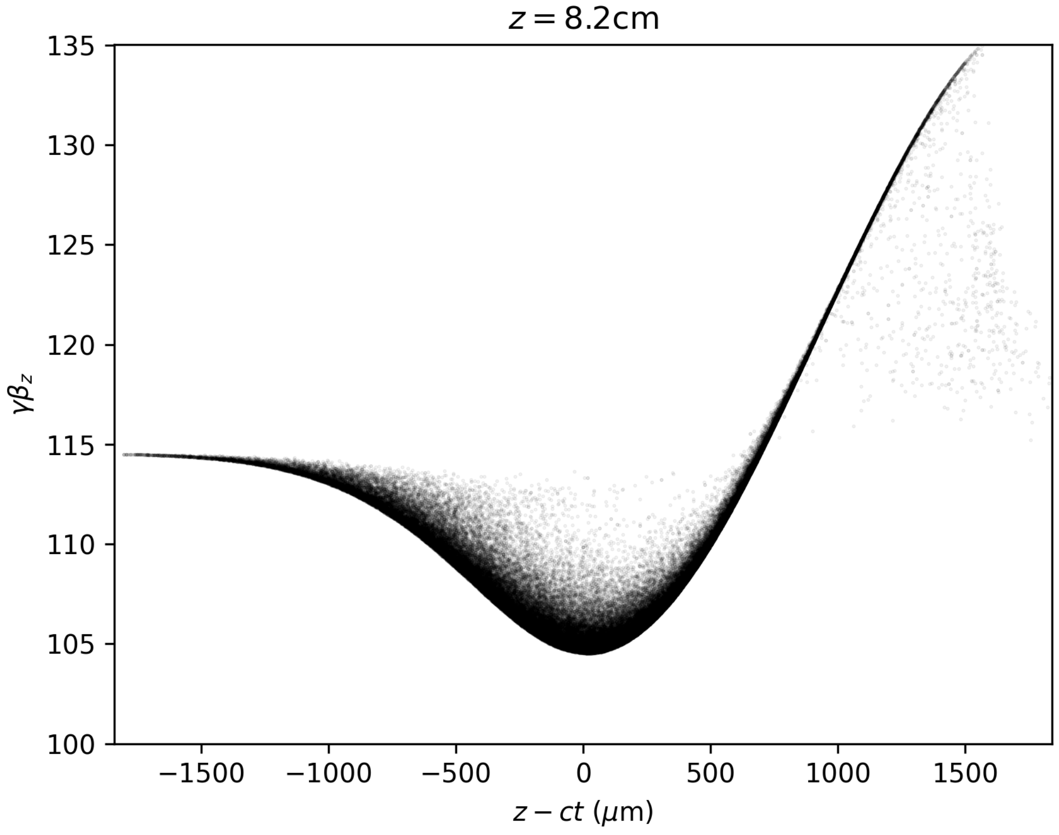
$$2\int_0^d N_e(z)dz = \frac{4\pi c^2 m_e \epsilon_0}{\lambda e^2}\Delta\phi$$

- Changing the delay between the gas injection and the electrical discharge changes the peak density

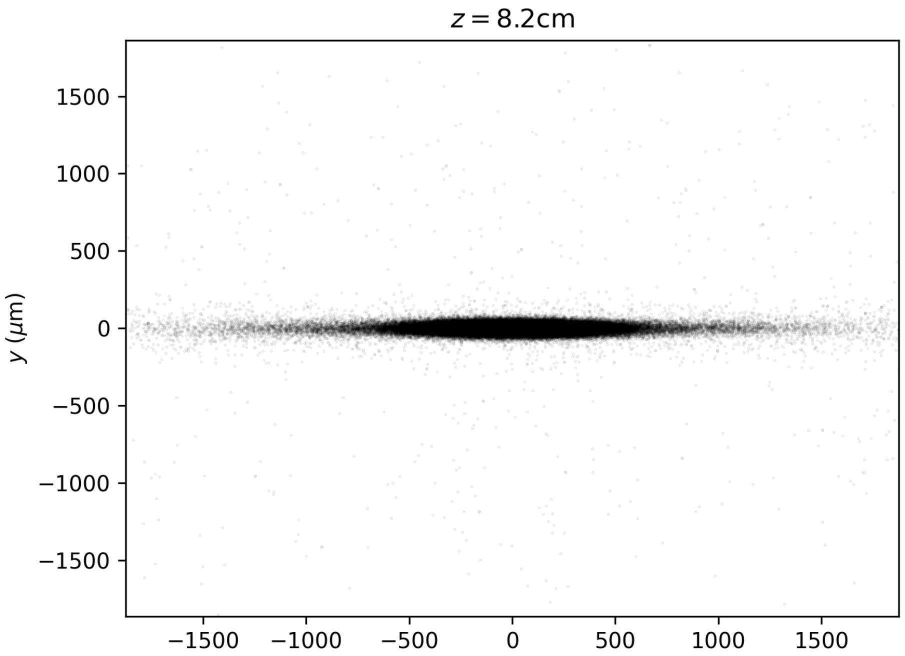


Observables - PWFA

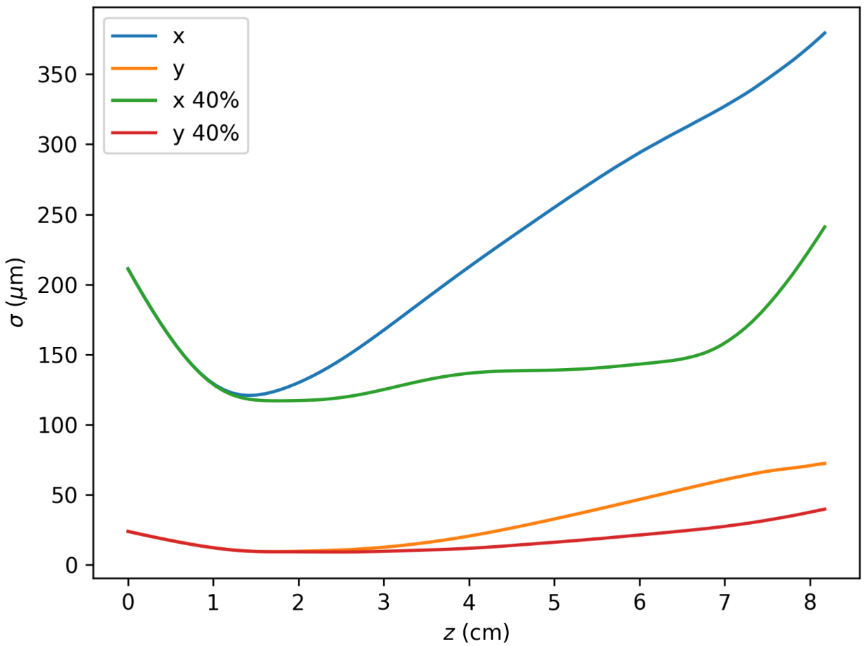
- Energy spread and plasma focusing visible on spectrometer and YAG
- Diagnostics for mismatch would be



p_z-z



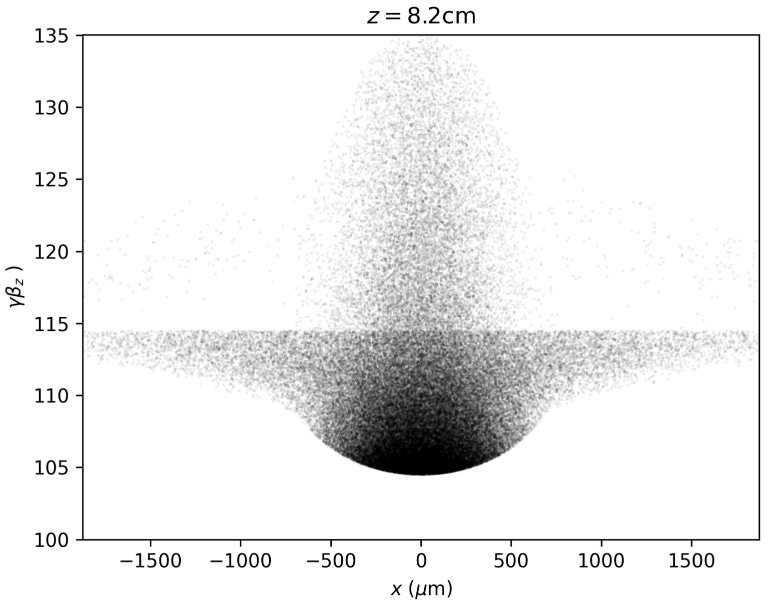
X-Y



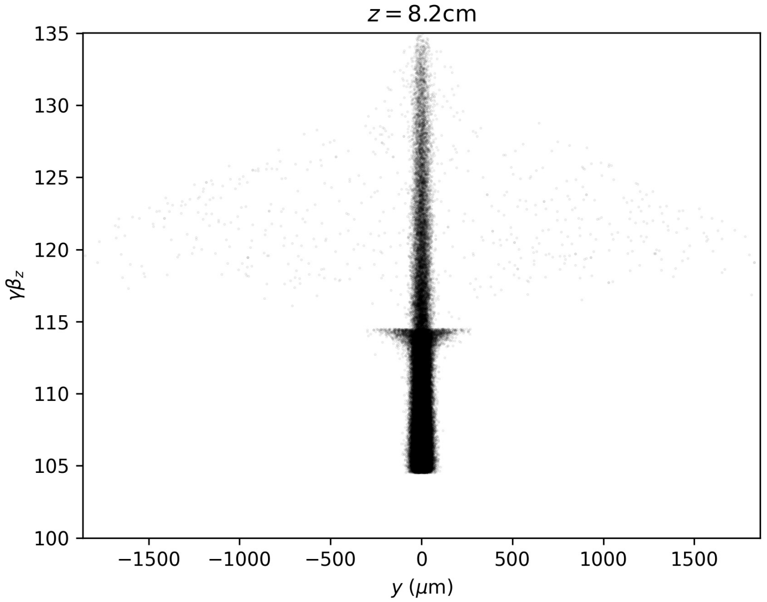
Spot size evolution (QuickPIC)

Observables – Elliptical blowout

Asymmetric case ($\epsilon_x : 200, \epsilon_y : 2\ um\ rad$)



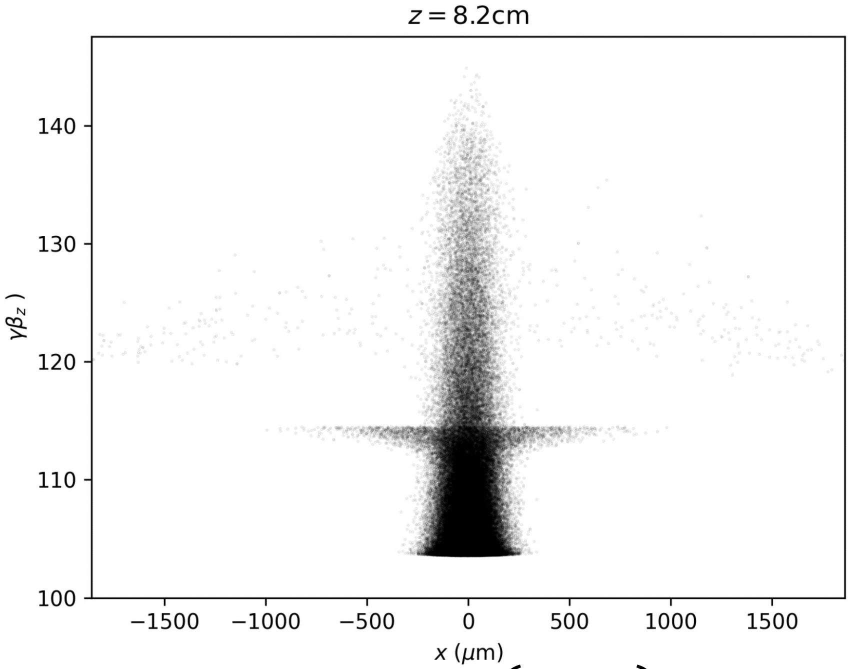
p_z-x



p_z-y

- Transverse dependence of the longitudinal field
- Curvature is observed
- This might be sign of elliptical blowout

Axisymmetric case ($\epsilon_{x,y} : 20\ um\ rad$)



p_z-(x, y)

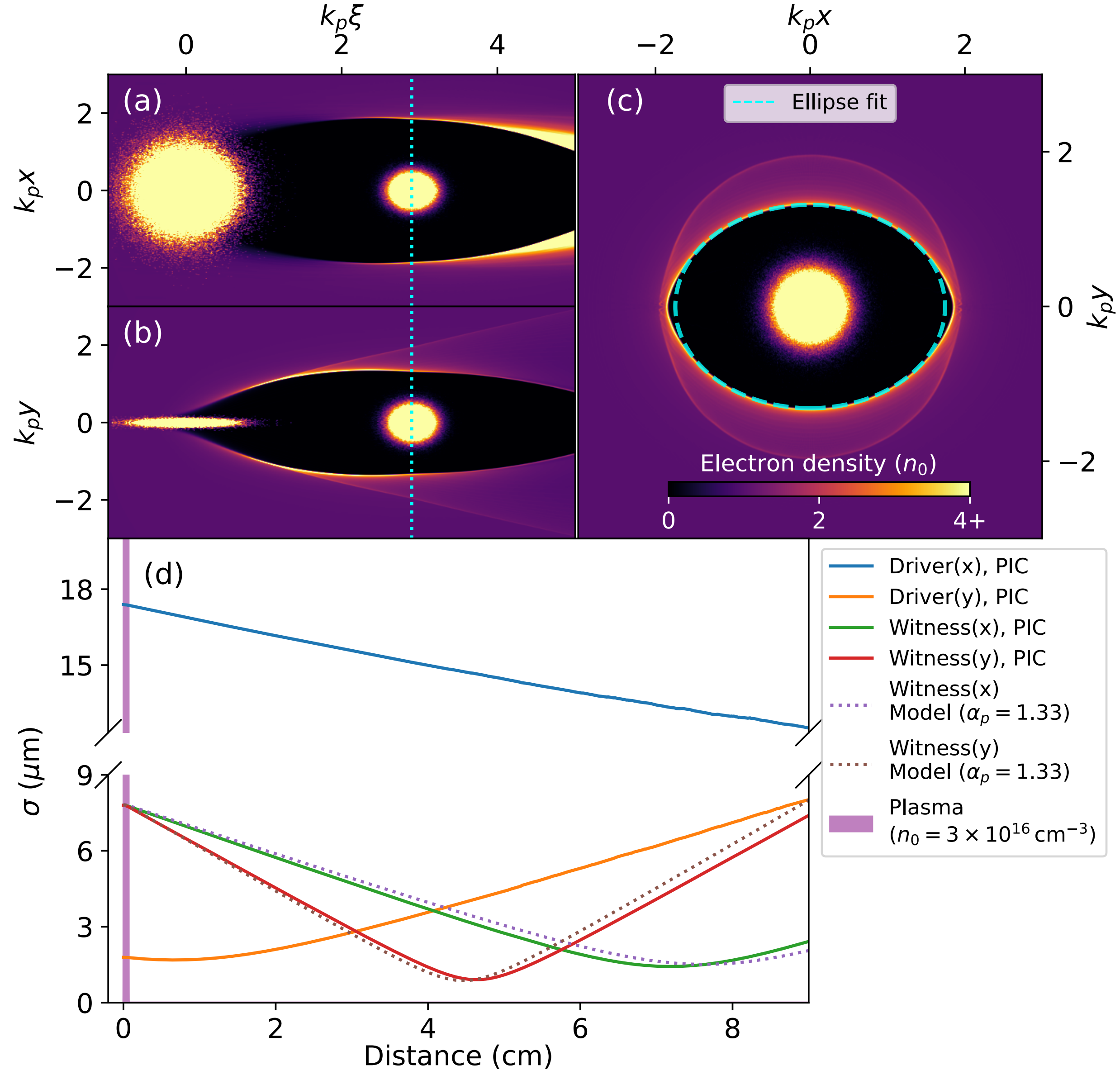
- No transverse dependence
- No curvature is observed

Asymmetric passive lens (FACET-II)

- Ellipticity of the blowout will yield an asymmetric focusing kick on the witness

- Can be produced by creating a high aspect ratio drive beam using quadrupoles

- Proof of principle experiment to show ellipticity of blowout



Conclusion and next steps

- We have shown the asymmetric wakefields that are driven by flat beams
- Beams with highly asymmetric emittance in the ratio 1:100 are possible at AWA

- The key next steps are:
  - Plasma source characterization and automation at UCLA
  - Finalizing the differential pumping setup and beamline design

References and Acknowledgements

- Manwani, P., Kang, Y., Mann, J., Naranjo, B., Andonian, G., & Rosenzweig, J. B. (2024, June 4). *Analysis of the blowout plasma Wakefields produced by drive beams with elliptical symmetry*. arXiv.org. https://arxiv.org/abs/2406.02719
- W.Kellog, Foundations of Potential Theory, (Dover Publications,New York,1953), p. 192
- Xu, T., Conde, M., Ha, G., Kuriki, M., Piot, P., Power, J., & Wisniewski, E. (2019). Generation High-Charge of Flat Beams at the Argonne Wakefield Accelerator. In *10th International Particle Accelerator Conference*. 10.18429/JACoW-IPAC2019-WEPTS094
- W. Lu, C. Huang, M. Zhou, W. B. Mori, and T. Katsouleas, Nonlinear theory for relativistic plasma wakefields in the blowout regime, Phys. Rev. Lett. 96, 165002 (2006).
- Barov, N., Rosenzweig, J., Conde, M., Gai, W., & Power, J. (2000). Observation of plasma wakefield acceleration in the underdense regime. *Phys. Rev. ST Accel. Beams, 3, 011301*. https://link.aps.org/doi/10.1103/PhysRevSTAB.3.011301
- Mihalcea, Daniel & Piot, P. & Stoltz, P.. (2012). Three-Dimensional Analysis of Wakefields Generated by Flat Electron Beams in Planar Dielectric-Loaded Structures. Physical Review Special Topics - Accelerators and Beams. 15. https://doi.org/10.1103/PhysRevSTAB.15.081304
- Yakimenko, V., Alsberg, L., Bong, E., Bouchard, G., Clarke, C., Emma, C., Green, S., Hast, C., Hogan, M., Seabury, J., Lipkowitz, N., O'Shea, B., Storey, D., White, G., & Yocky, G. (2019). FACET-II facility for advanced accelerator experimental tests. *Phys. Rev. Accel. Beams, 22, 101301*. 10.1103/PhysRevAccelBeams.22.101301

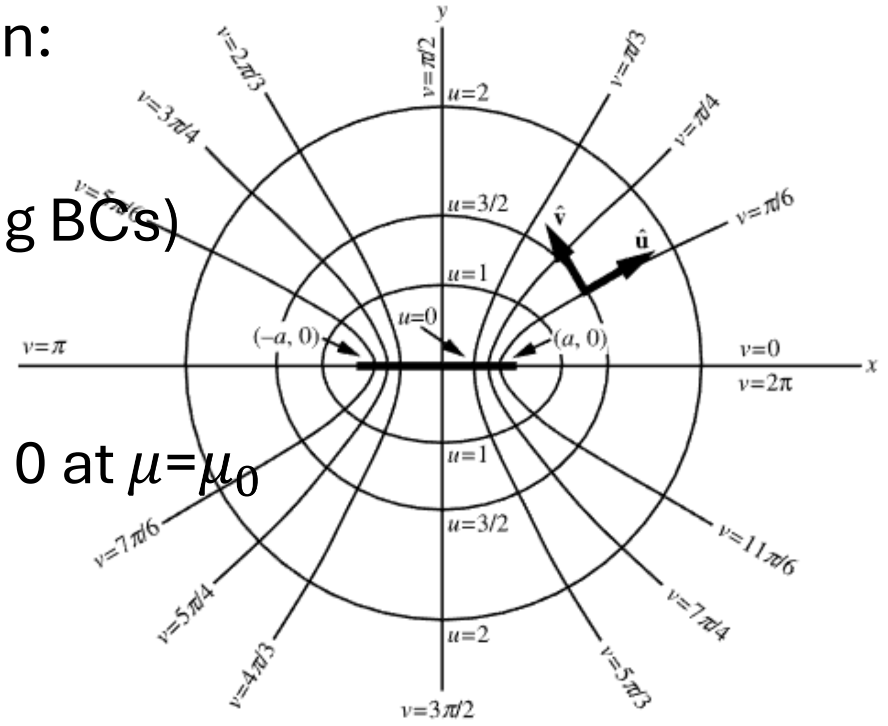
Funded by DOE Grant No. DE-SC0017648

Thank you for your time!

Backup Slides

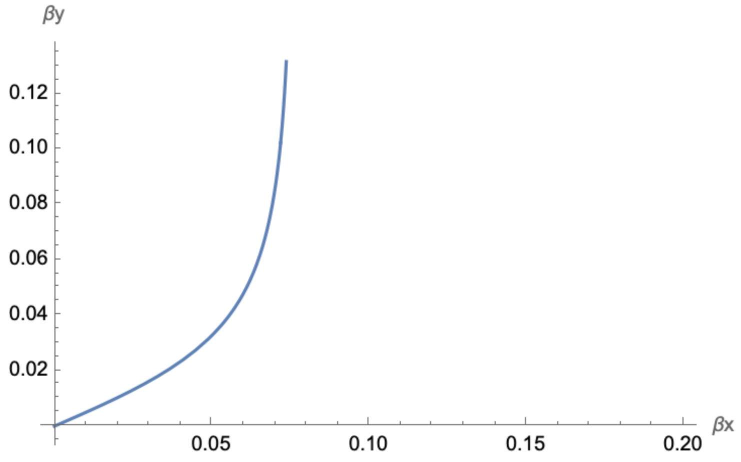
Elliptical wake potential

- We have a poisson's equation with boundary condition:
  - $\nabla^2\psi = -1; \;\; \psi|_{\partial\Omega} = 0; a = \sqrt{x_p^2 - y_p^2}$
- We can use the particular solution to the PDE (Ignoring BCs)
  - $\psi_p = -\frac{a^2}{8}(\cosh(2\mu) - \cosh(2\mu_0) + \cos(2\nu))$
- We add a homogenous solution such that potential is 0 at μ=μ_0
  - $\psi_h = \frac{a^2}{8}\left(\frac{\cosh(2\mu)}{\cosh(2\mu_0)}\right)\cos(2\nu))$
- Using elliptical coordinates:
  - $\psi = \psi_p + \psi_h = \; -\frac{a^2}{8}(\cosh(2\mu) - \cosh(2\mu_0) + \left(1 - \frac{\cosh(2\mu)}{\cosh(2\mu_0)}\right)\cos(2\nu))$
- Converting back to Cartesian coordinates:
  - $\psi = -\frac{x^2y_p^2+y^2x_p^2-x_p^2y_p^2}{2(x_p^2+y_p^2)}$

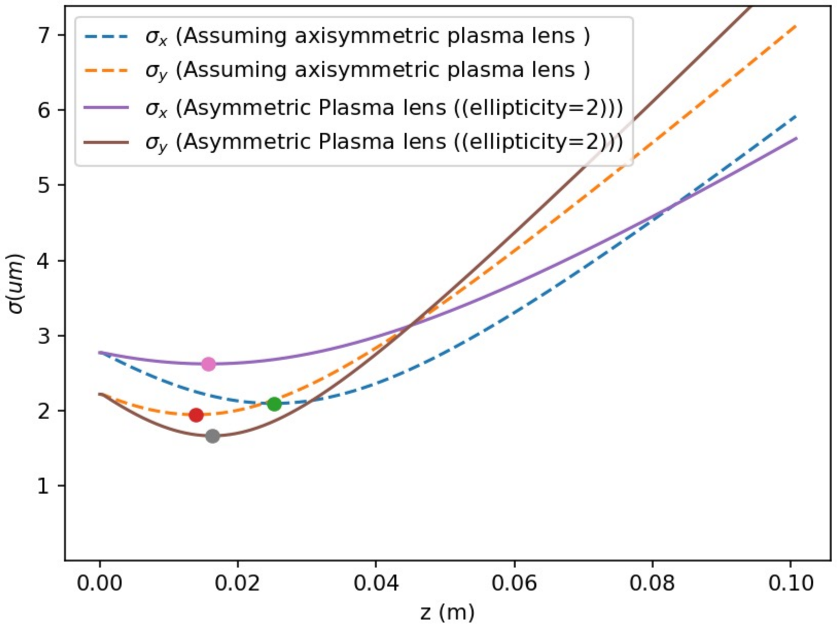


Application – Asymmetric Plasma Lens

- Location of waist:
  - $z_{wx} = \frac{K_x L \beta_{0x} + \alpha_{0x} - L\gamma_{0x}}{K_x^2 L^2 \beta_{0x} + 2K_x L \alpha_{0x} + \gamma_{0x}}$
  - $z_{wy} = \frac{K_y L \beta_{0y} + \alpha_{0y} - L\gamma_{0y}}{K_y^2 L^2 \beta_{0y} + 2K_y L \alpha_{0y} + \gamma_{0y}}$
  - We can solve for $z_{wx} = z_{wy}$



Solution for $z_{wx} = z_{wy}$ and $\beta_{0x} \neq \beta_{0y}$



Solution for $z_{wx} = z_{wy}$ and $\beta_{0x} = \beta_{0y}$