# Progress on the Flat beam PWFA experiment at AWA

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# Outline

- Motivation
- Theory and features of the Flat beam PWFA
- Experiment at Argonne Wakefield Accelerator(AWA)
  - Plasma source development
  - Beamline setup and diagnostics
  - Experimental results
- Conclusion and future steps

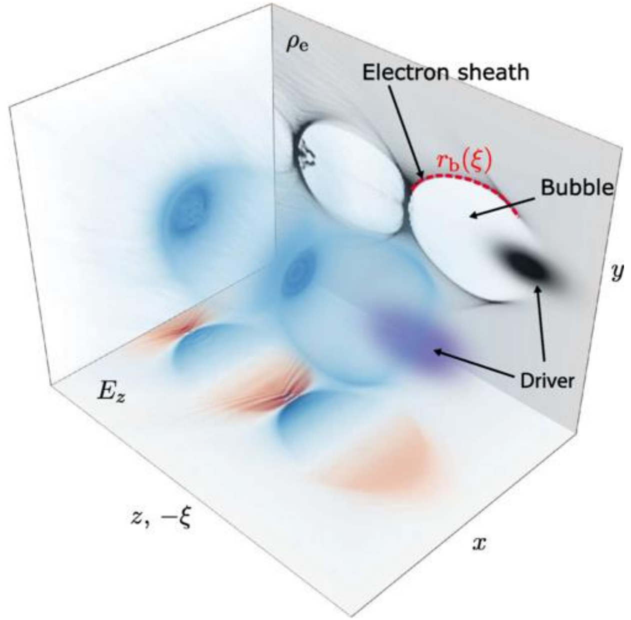
# Motivation

- Plasma wakefields driven by flat beam is an underdeveloped topic in current research
  - Flat beams - Asymmetric spot sizes and emittance : $\sigma_x \gg \sigma_y$ , $\epsilon_x \gg \epsilon_y$
  - These beams yield a blowout cavity that is **elliptical** in cross section

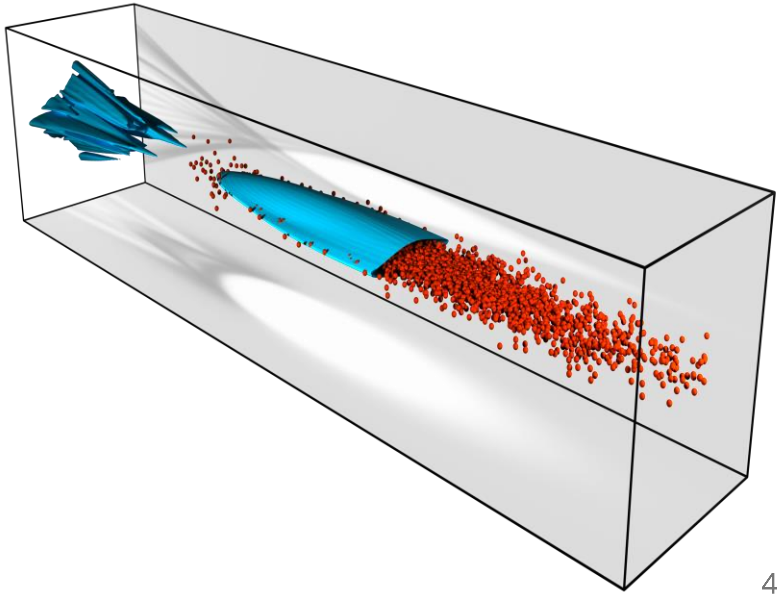
- In colliders, these beams mitigate beam-beam effects (beamstrahlung) at the interaction point.

$$\text{Beamstrahlung} \propto \frac{1}{\sigma_x+\sigma_y}, \ \text{Luminosity} \propto \frac{1}{\sigma_x\sigma_y}$$

- Direct applications for:
  - Plasma afterburners
  - Asymmetric plasma lenses




*A. Golovanov et al, PRL 2023*



# Elliptical Blowout

- Given the elliptical boundaries ($a_p(\xi)$, $b_p(\xi)$ and $\Delta_s(\xi)$ )

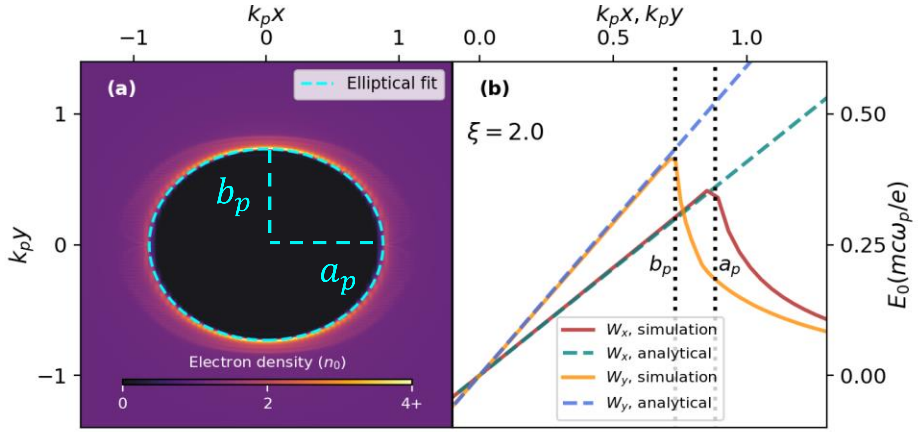
- $\psi = -\frac{x^2 b_p^2 + y^2 a_p^2 - a_p^2 b_p^2}{2(a_p^2+b_p^2)} - \frac{\Delta_s a_p b_p}{(a_p^2+b_p^2)^2}[(x^2-y^2)c_p^2 - a_p^4 \; - b_p^4]$

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

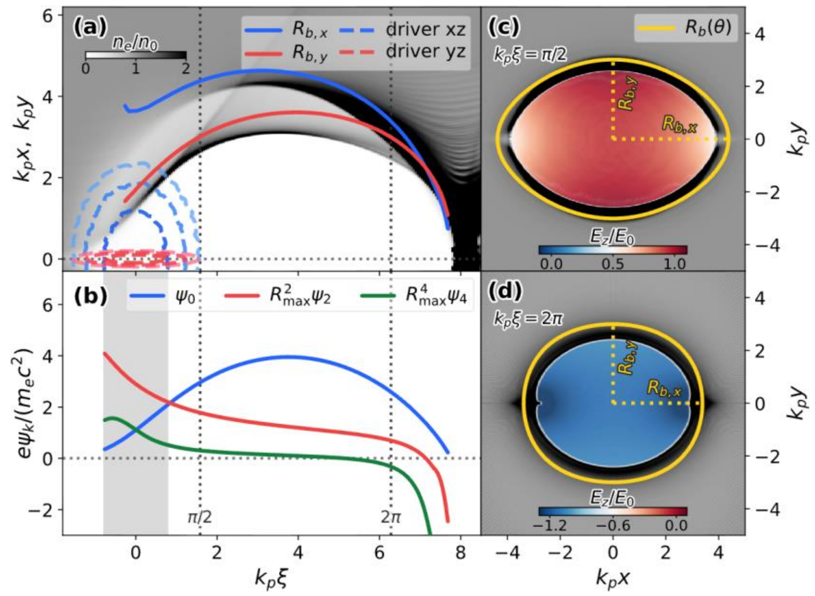
**Asymmetric but linear!**

- $F_z = E_z = -\frac{\partial\psi}{\partial\xi} = \frac{a_p b_p((x^2-y^2+b_p^2)b_p a_p' + (x^2-y^2-a_p^2)a_p b_p')}{(a_p^2+b_p^2)\text{^}2}$

**No longer uniform**




Adding more moments and using variational approach: General solution



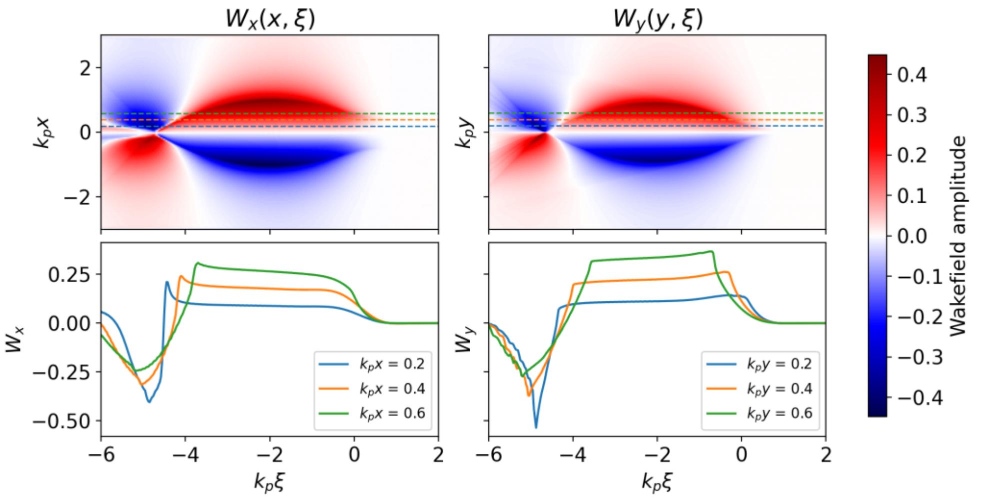

Check out Yunbo Kang's talk and poster: T22

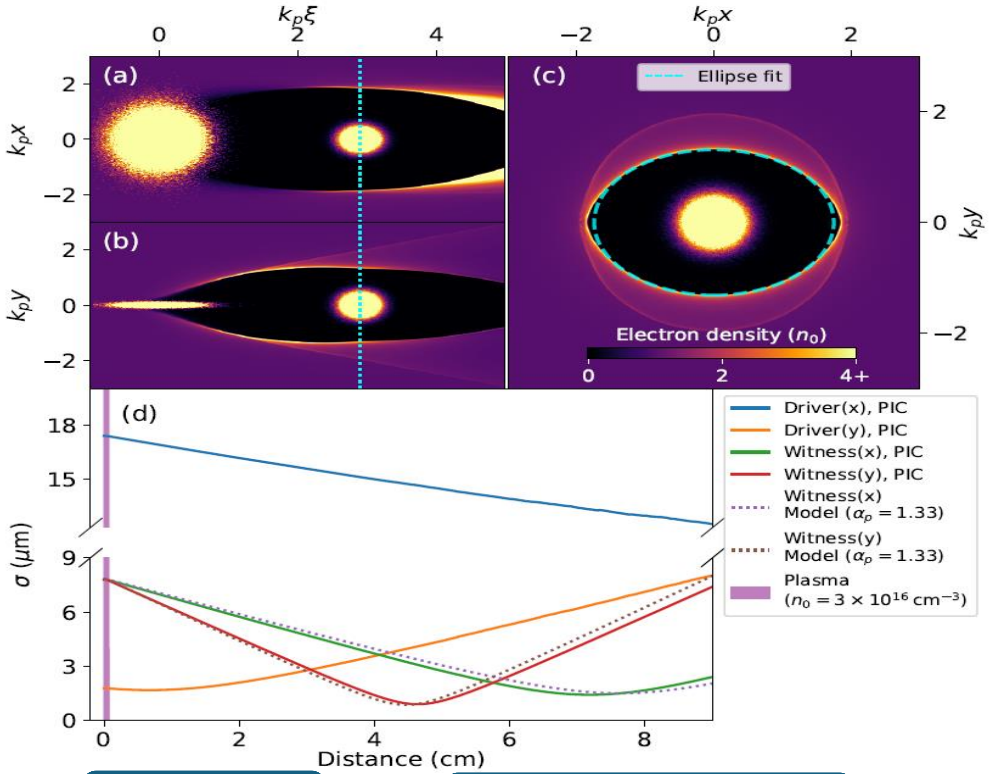
# Features

- Longitudinally varying focusing
  - Mitigates hosing instability (resonance between head and tail)

- Asymmetric linear fields
  - Can be slice-by-slice emittance matched
  - Leads naturally to asymmetric plasma lenses
  - Asymmetry can break resonant x-y emittance mixing in presence of nonlinearities ($K_x \neq K_y$)

*S. Diederichs et al, PRL(2024)*




*Solid: PIC*

*Dotted: Equations*

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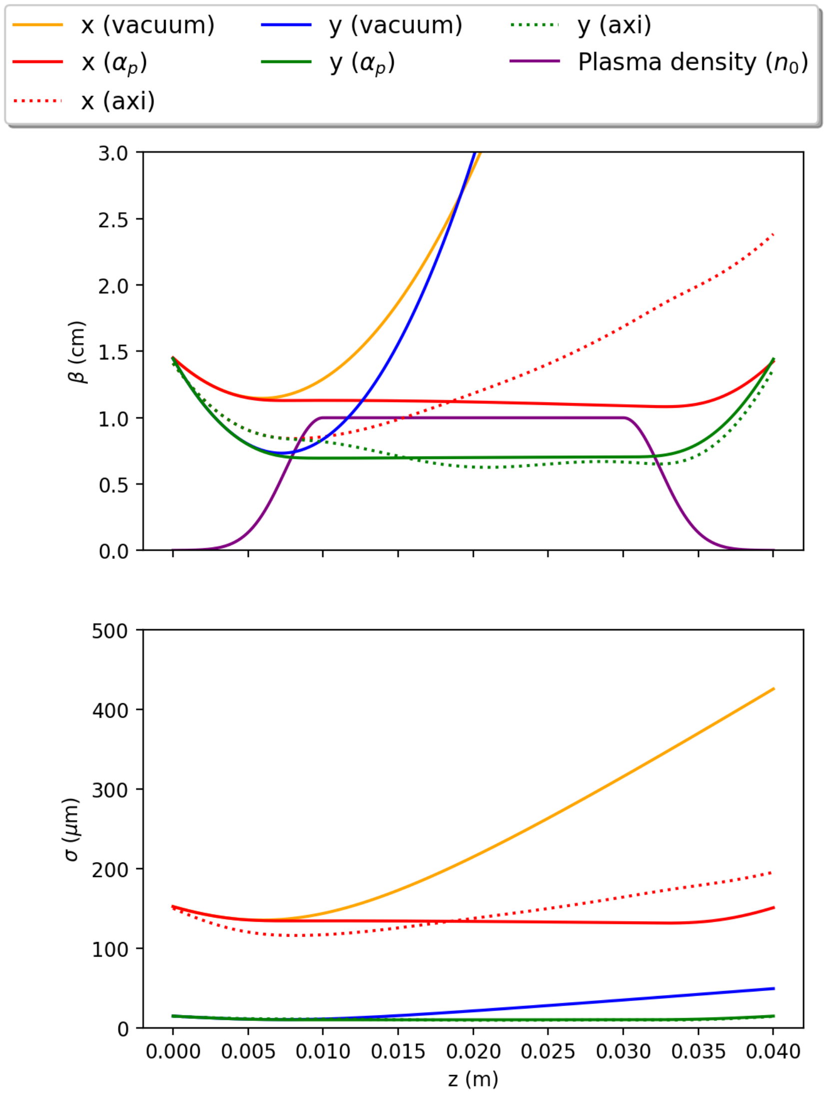
*S. Diederichs et al, PRL(2024)*

- Modified Quadrupole instability – Blowout keeps getting asymmetric if mismatched
  - $Kx, Ky = K_r\left(1 \pm \frac{\alpha_p^2 - 1}{\alpha_p^2 + 1}\right)$
  - Significant head erosion in one dimension

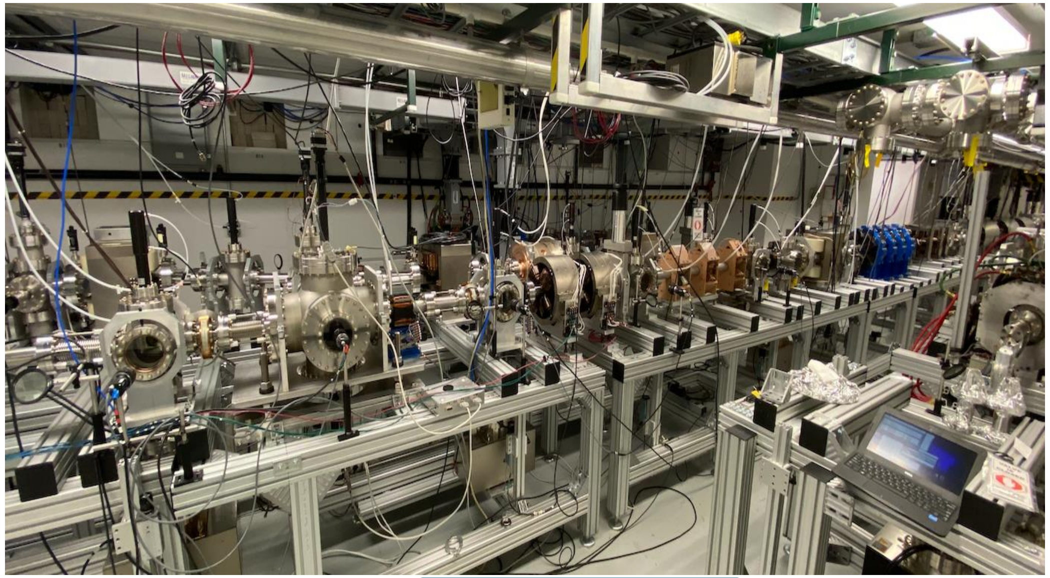



*Using long beam model*

# Flat beam PWFA Experiment at the AWA facility

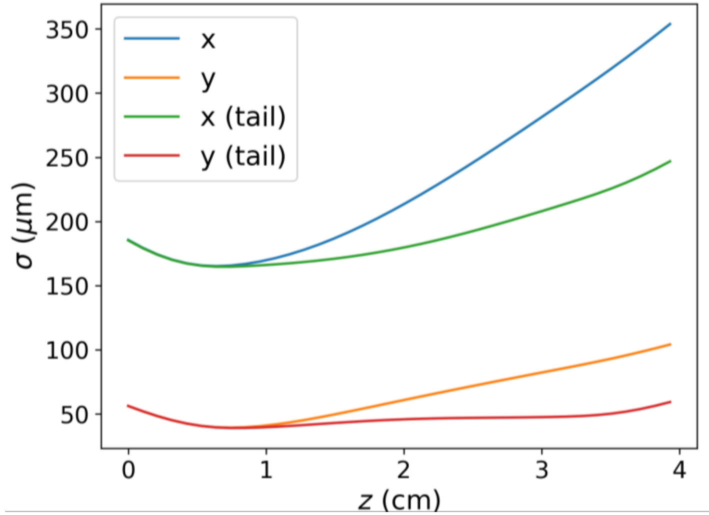
# Flat beam PWFA experiment at AWA

- Argonne Wakefield Accelerator Facility (AWA) has capabilities to produce flat beams
- Weak blowout can be accessed($n_b > n_0$)
  - Beam
    - Charge: 2-4 nC
    - Energy: 62.5 MeV
    - Bunch length: 2 ps (1.5 $k_p^{-1}$)
    - Expected emittances at IP : 220,20 um rad
  - Plasma source with peak density of $10^{15}\ cm^{-3}$ (developed at UCLA)
- **Goal: Measure asymmetric focusing**



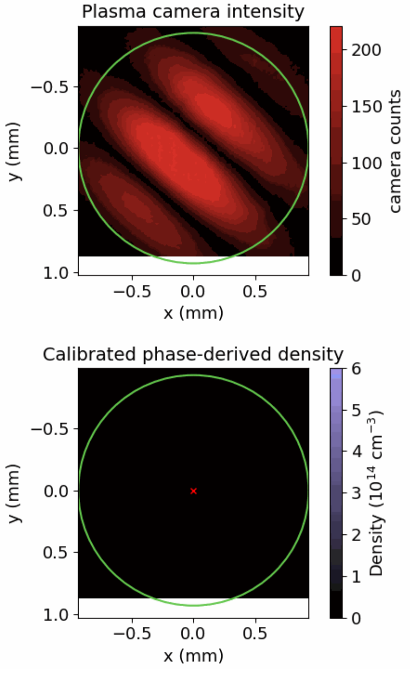
*AWA facility*

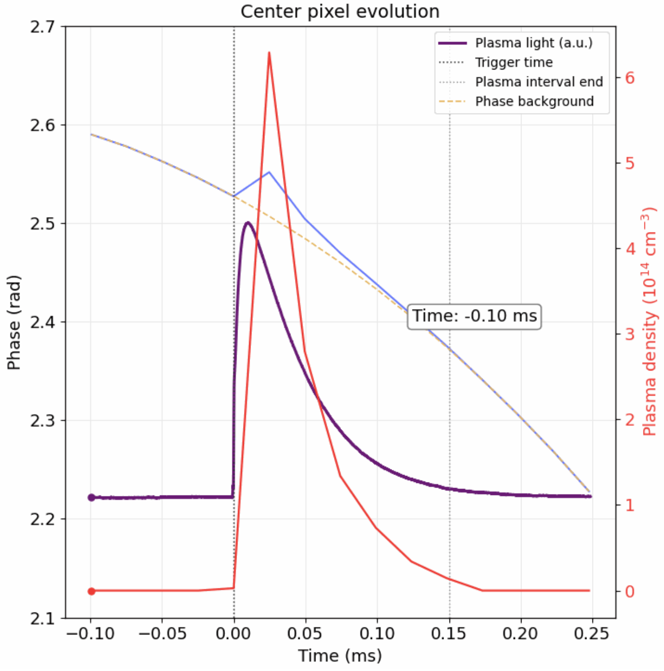
*Expected beam-plasma interaction at $n_0 = 10^{14}\ cm^{-3}$ (QuickPIC)*

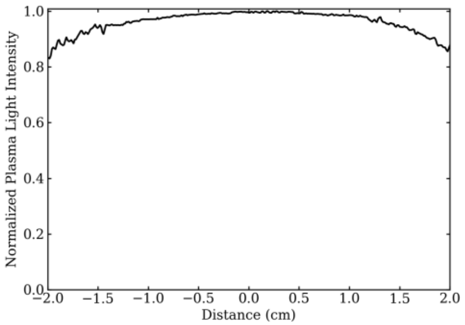


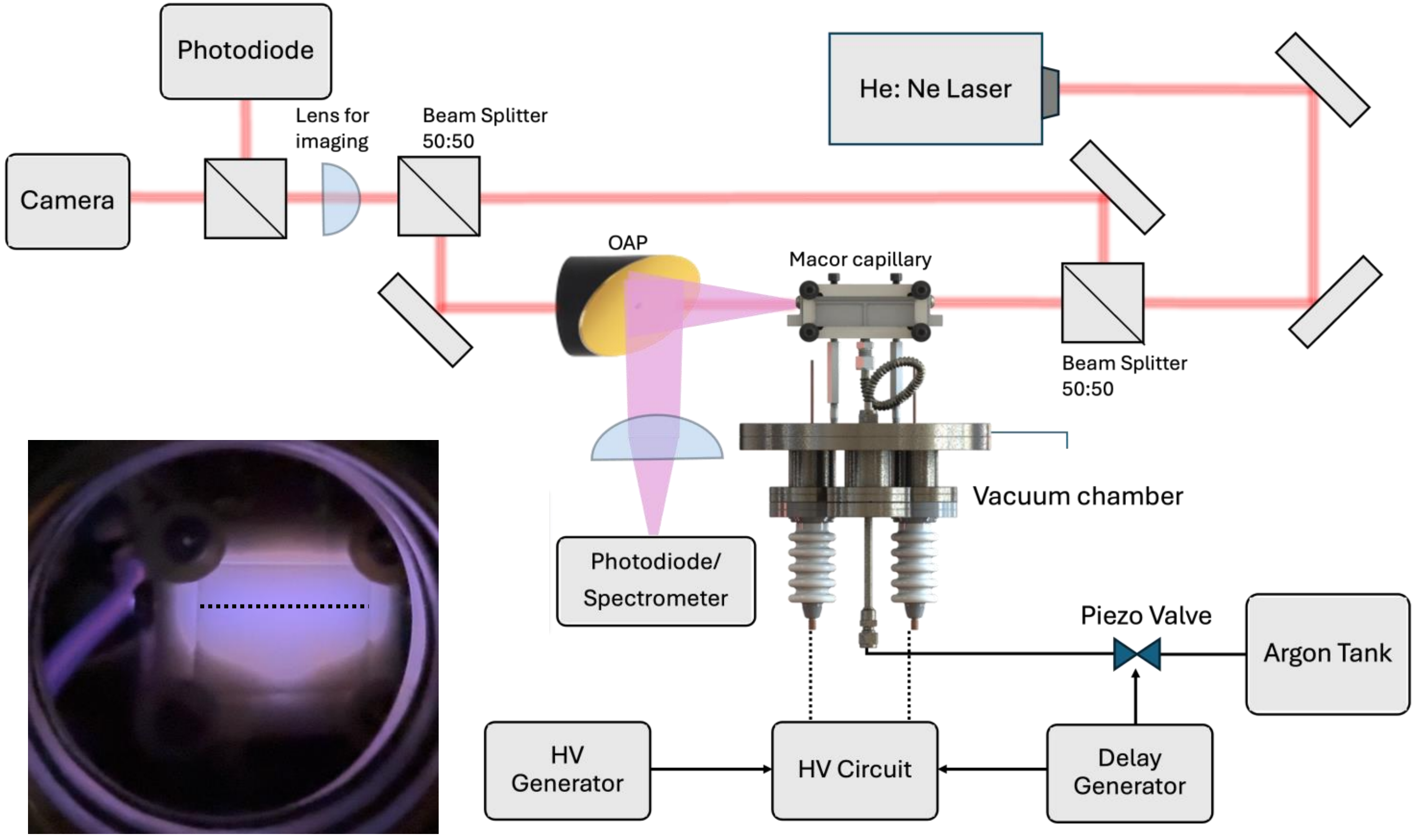
# Capillary discharge-based plasma source

- Macor - 4 mm diameter, 4 cm length
- 5 kV, 50 A (1 $\mu$s) peak current
- Argon gas, 100 psi, 1.5 ms injection time
- Peak density ~ $10^{15}\ cm^{-3}$
- Limited by Camera frame rate : 24.5 us



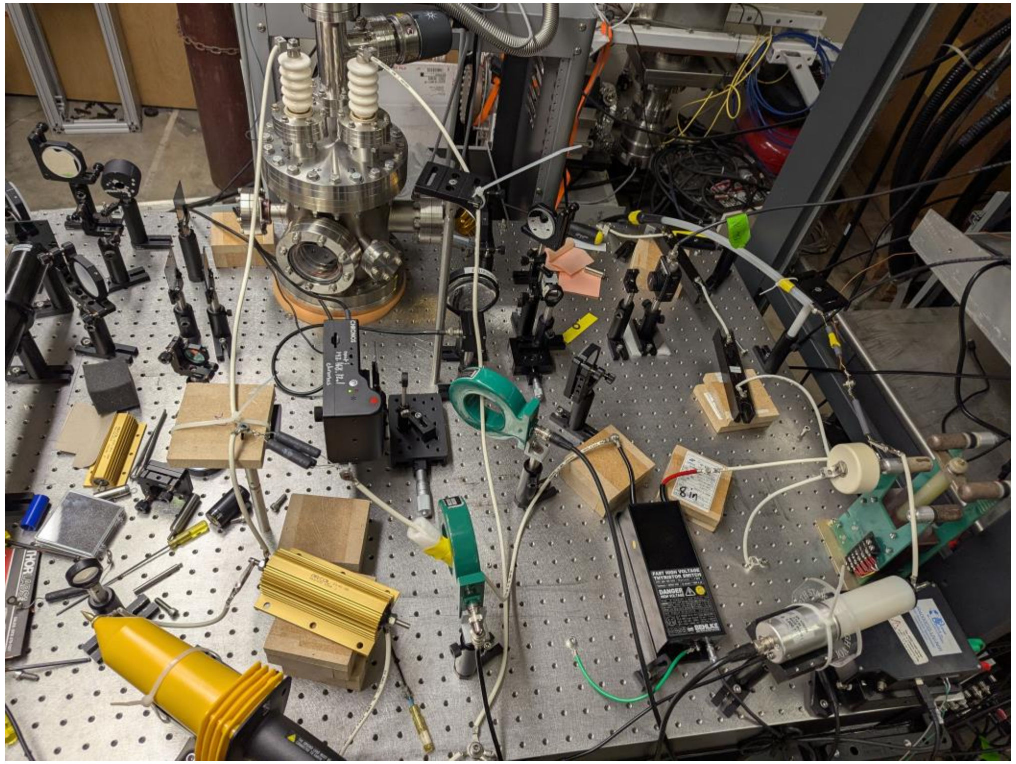



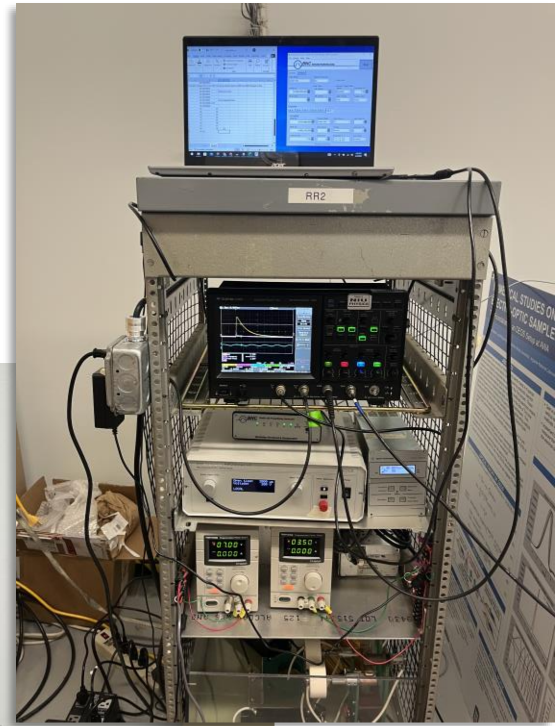



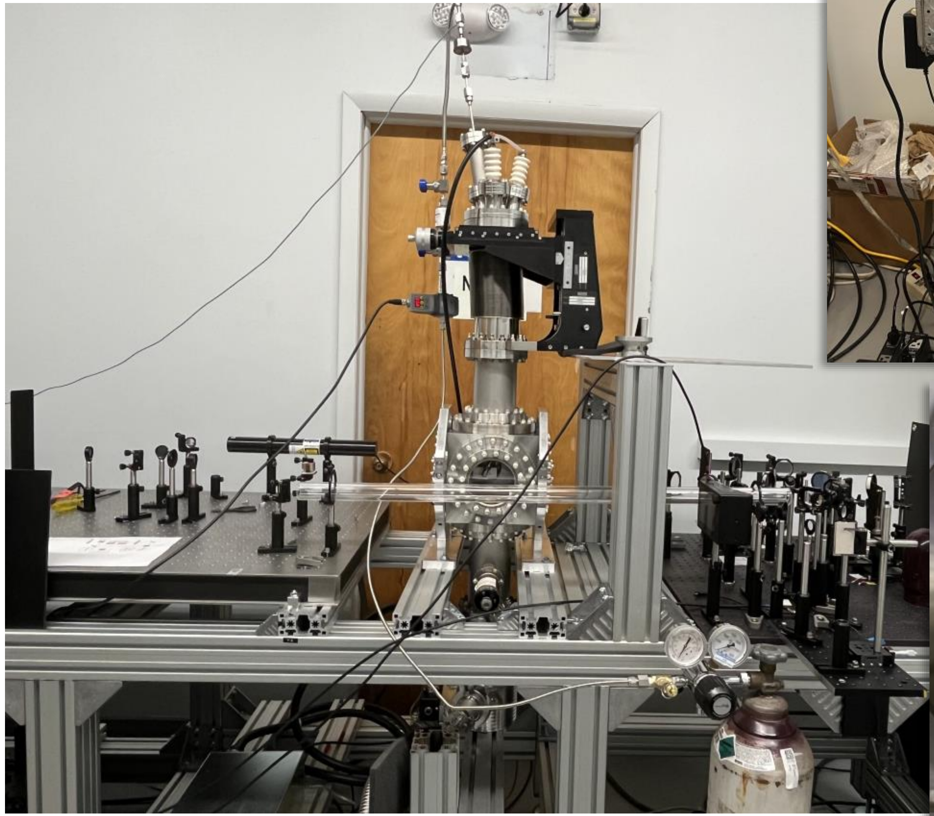

*Mach Zehnder based HeNe interferometer*

# Capillary discharge-based plasma source - Photos

- Plasma source (Recommissioned at AWA)
  - External rack for power and diagnostics
  - XYZ mount was added for movement of capillary (xyz: $\pm 0.5, 0.5, 2$ in)
  - Interferometer measurements were reconducted





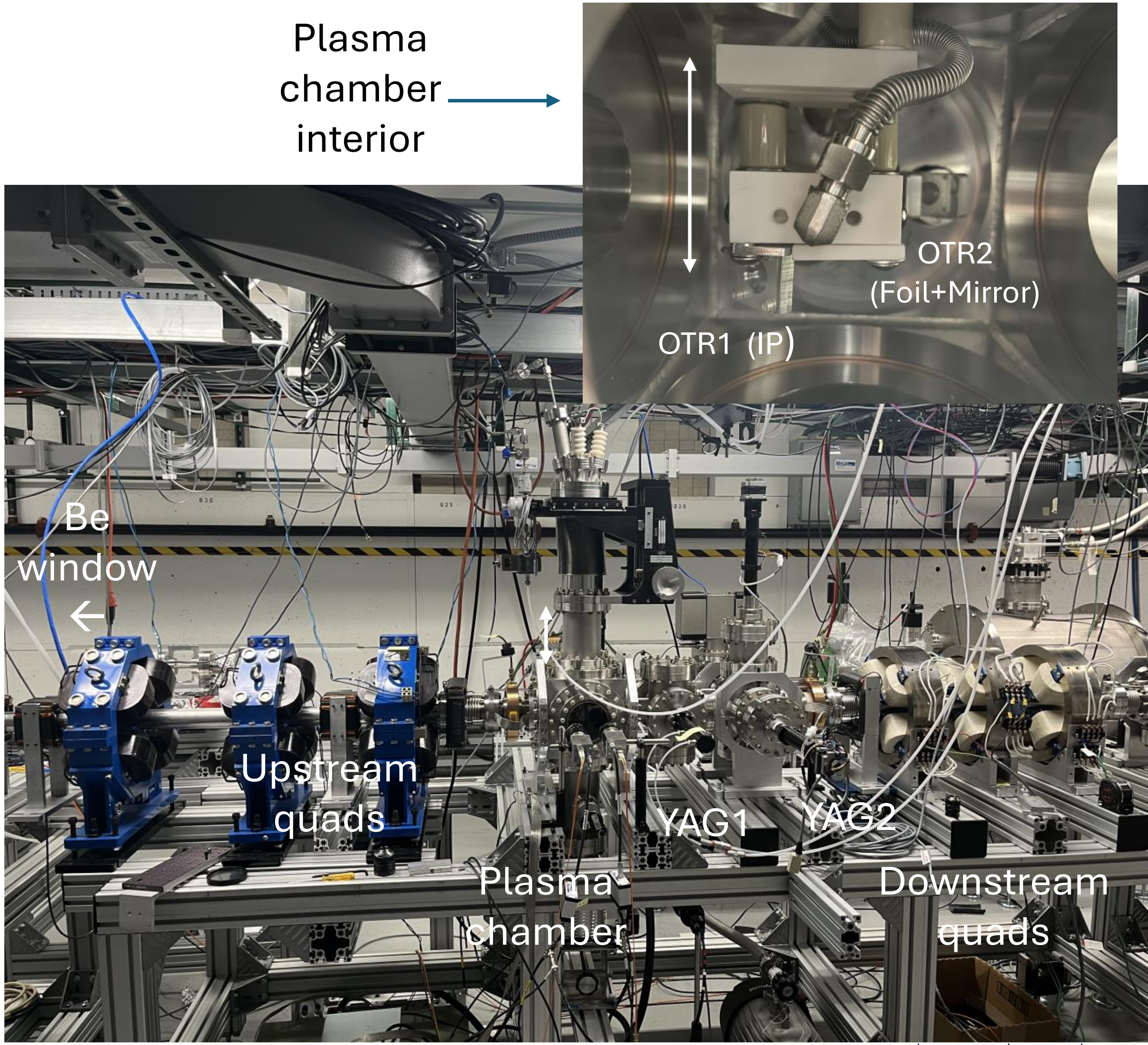


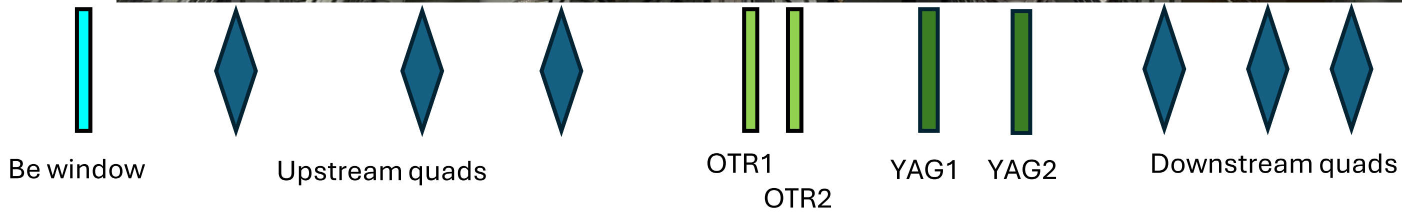
Plasma source @ UCLA

Plasma source @ AWA

# Beamline install

- Strong focus required ($\beta_x,\ \beta_y \sim 1\ cm$)
  - Upstream quads are close to chamber
- Be window (50 um) was added
  - Used for gas-vacuum separation
  - Disproportionate emittance increase ($\Delta\epsilon_y \gg \Delta\epsilon_x$)
- Discharge current and voltage for each plasma shot were recorded
- Beam Diagnostics were added (Three screens)
  - Two OTR screens were added inside chamber
    - OTR1: 45 degree foil
    - OTR2: Foil + Mirror to block off plasma light
  - Two YAGs were added downstream of the plasma chamber



# Experimental runs - Flat beam generation

- Axial magnetic field at photocathode inside solenoid results in a magnetized beam : $\mathcal{L} = \frac{eB_0\sigma_c^2}{2m_e c}$
- This is converted to mechanical angular momentum → CAM dominated beam
- Three skew quads remove the correlation and split the emittances
  - $\varepsilon_x \rightarrow \ \varepsilon_+ = \varepsilon_{eff} + \mathcal{L} \simeq 2\mathcal{L},$
  - $\varepsilon_y \rightarrow \varepsilon_- = \varepsilon_{eff} - \mathcal{L} \simeq \frac{\varepsilon_u^2}{2\mathcal{L}}$

*Y. Sun et al, PRSTAB (2004)*

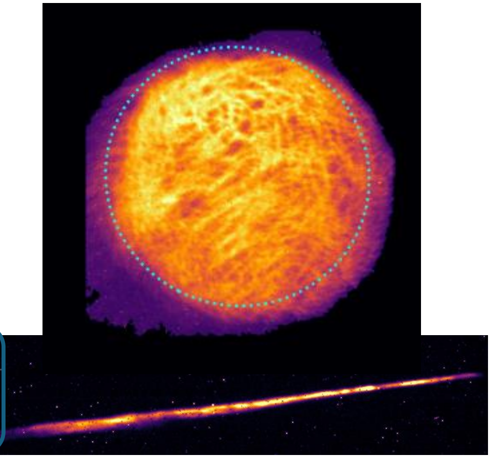
CAM dominated beam

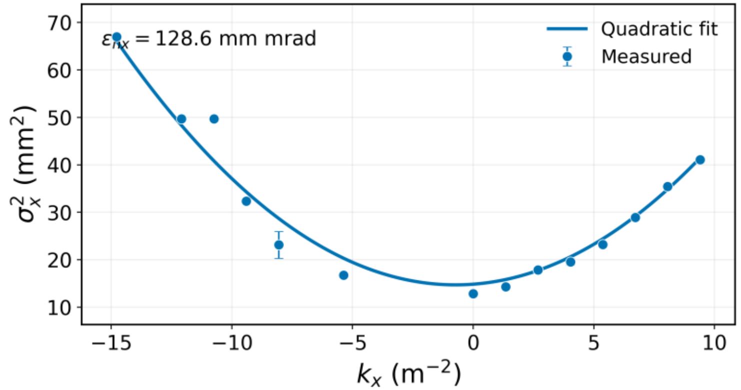
<u>Magnetization</u>

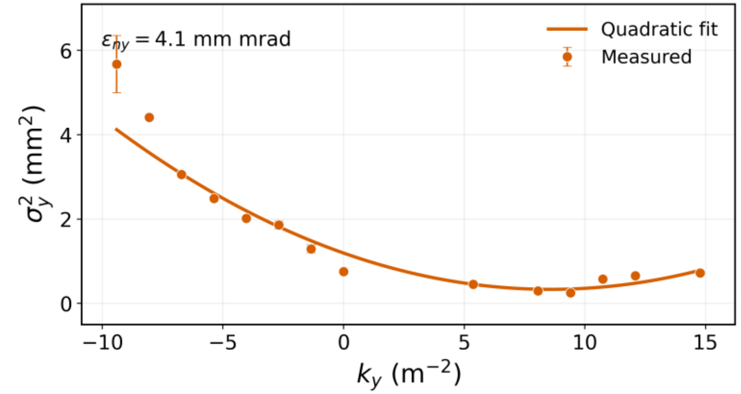
$\mathcal{L} \rightarrow 83\ um\ rad$

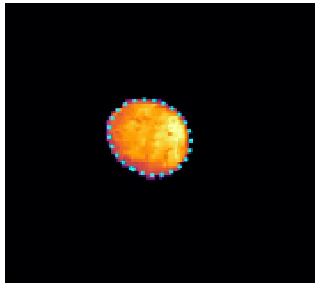
<u>Quad scan</u>

$\epsilon_x, \epsilon_y \rightarrow 129, 4.1\ um\ rad$

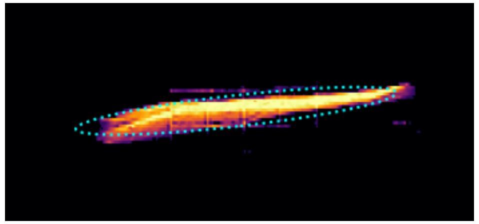




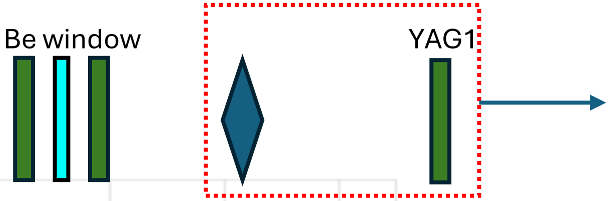
YAG4

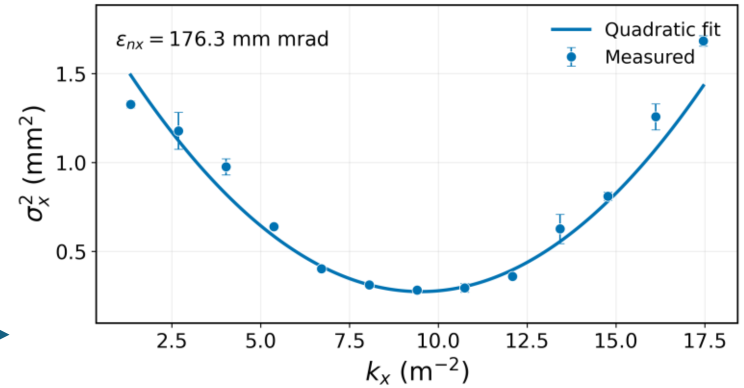



YAG5

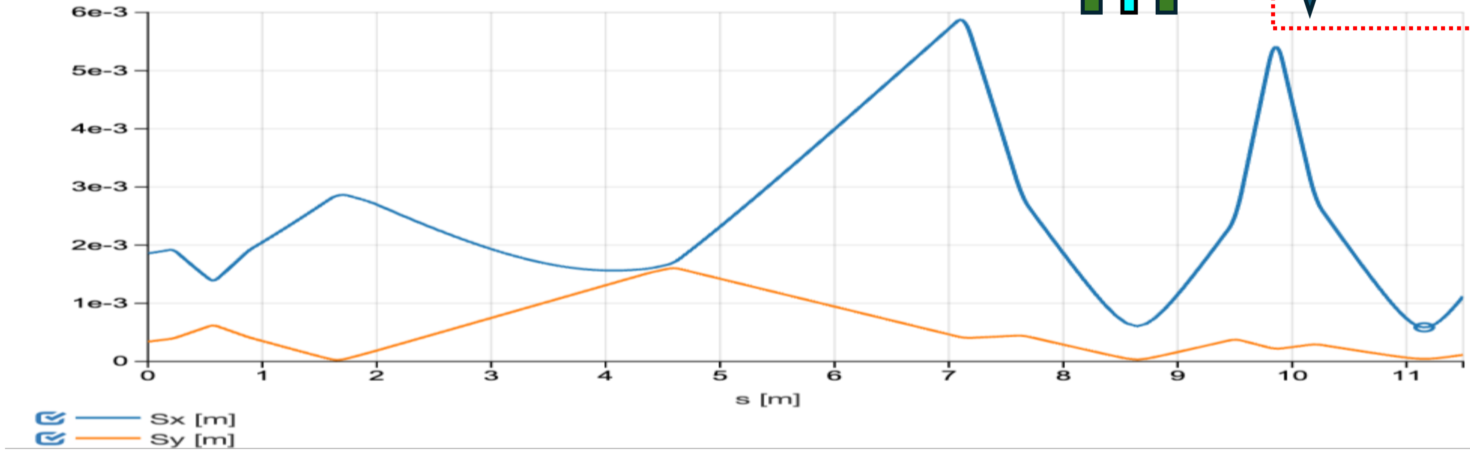
# Experimental runs – Twin foci

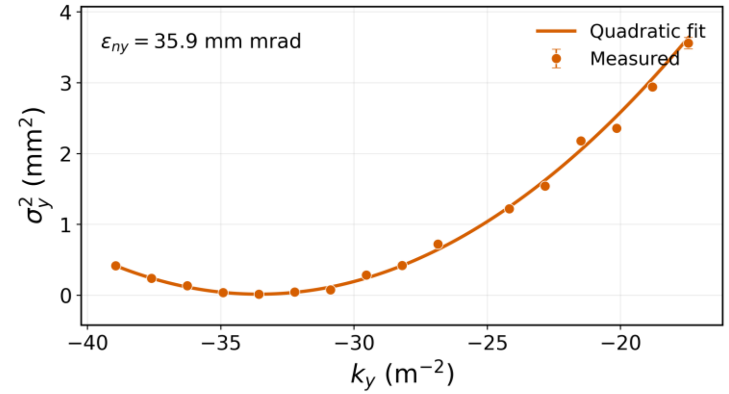
- Beam needs to be focused at the window to reduce emittance increase due to scattering



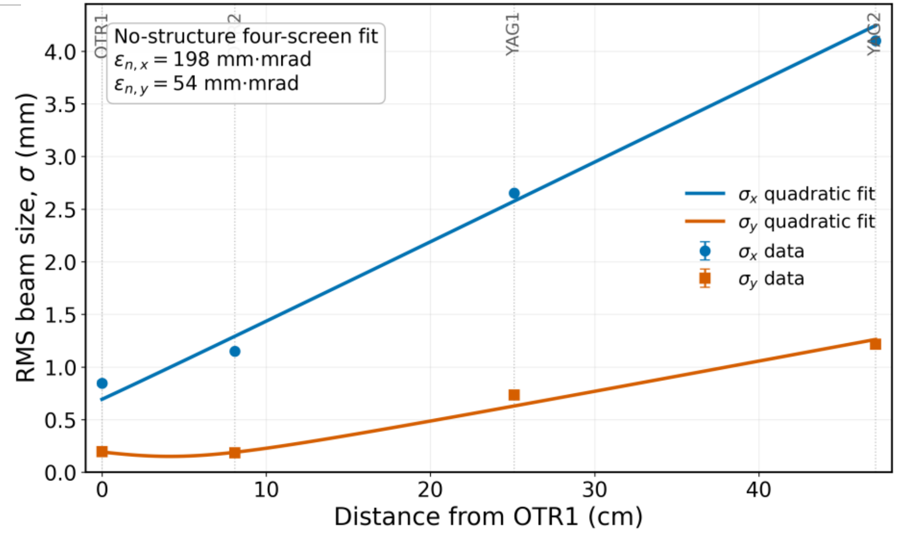

Elegant simulations



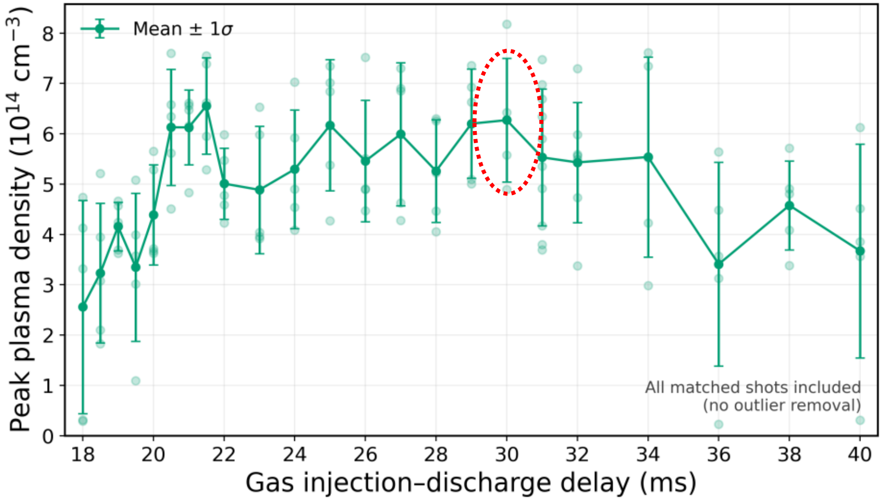

- A quad scan measurement was conducted to get the beam emittances near the IP
  - $\epsilon_{nx}, \epsilon_{ny}$: 176.3, 35.9 um rad (Quad screen measurement)

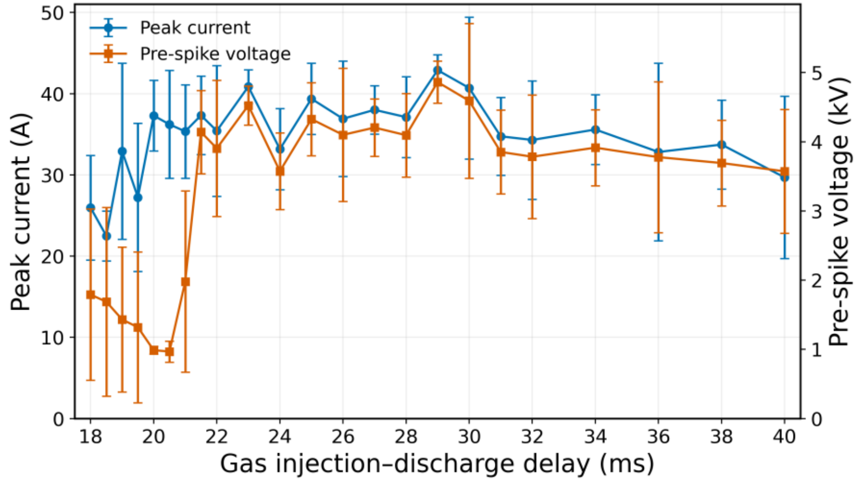
- The beam was then focused using the last downstream quad
  - Strong focusing (No capillary)
  - $\epsilon_{nx}, \epsilon_{ny}$: 198,54 um rad (Three screen measurement)



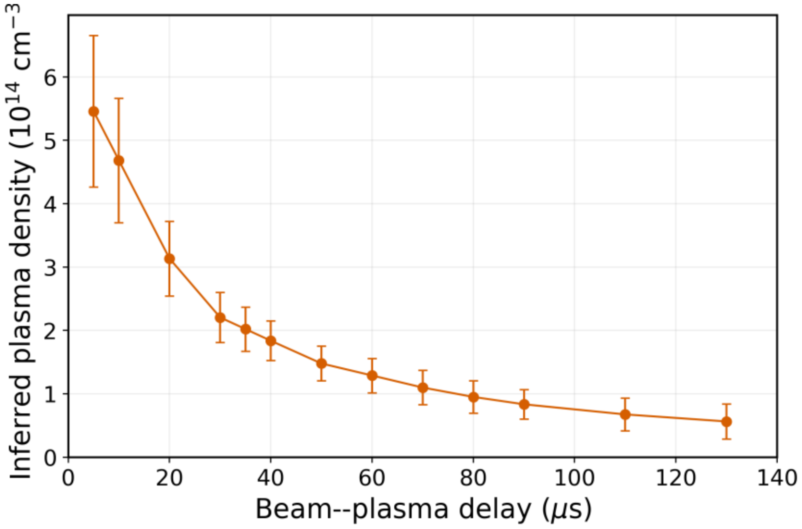
# Experimental runs – Plasma runs

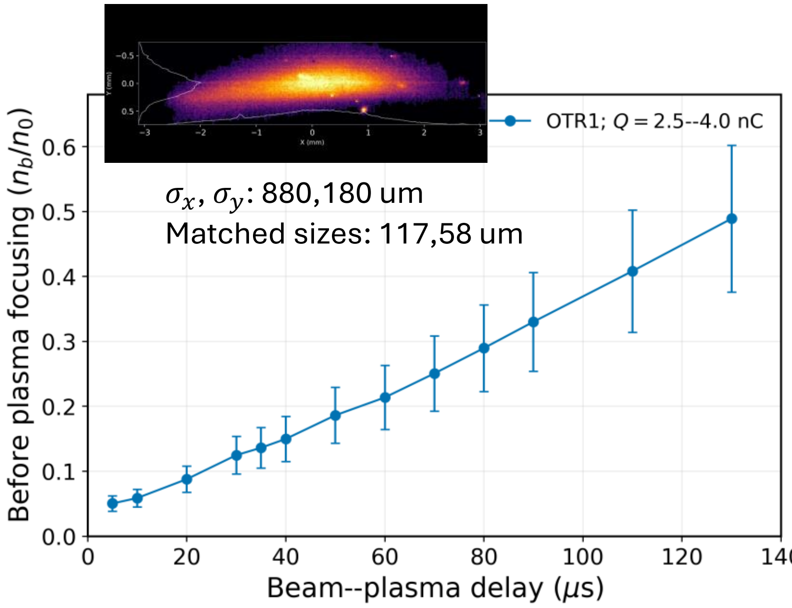
- Gas injection-Discharge delay was set at 30 ms
- Beam repetition rate>Plasma repetition rate
  - Current fluctuations: Electrode erosion or capillary charging?
- Beam was large in x at IP
  - ~ 50 % transmission through capillary



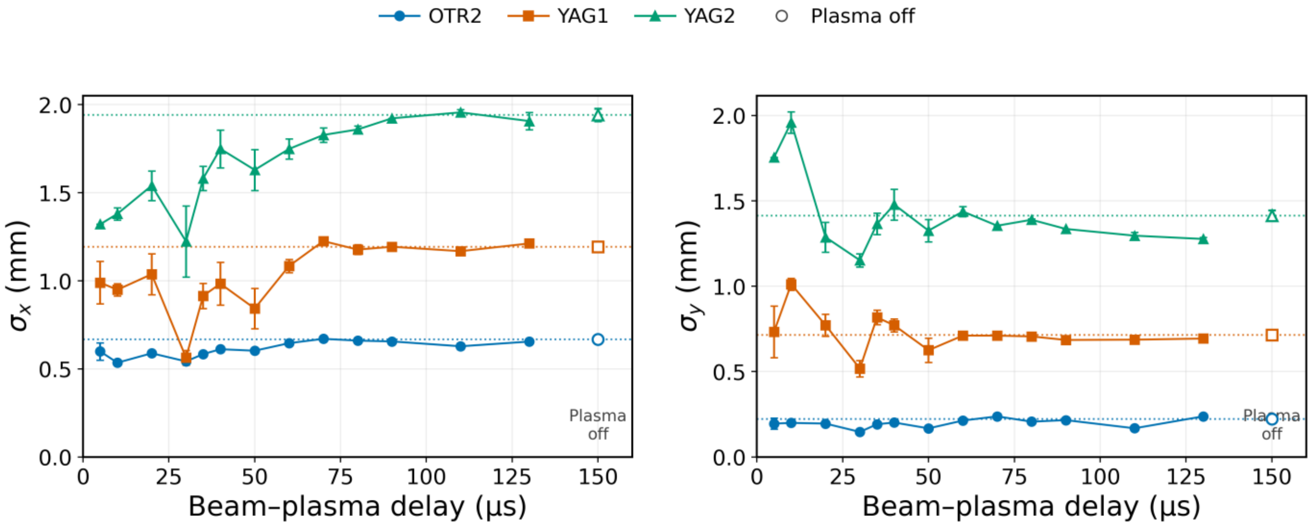

Preinstallation measurements

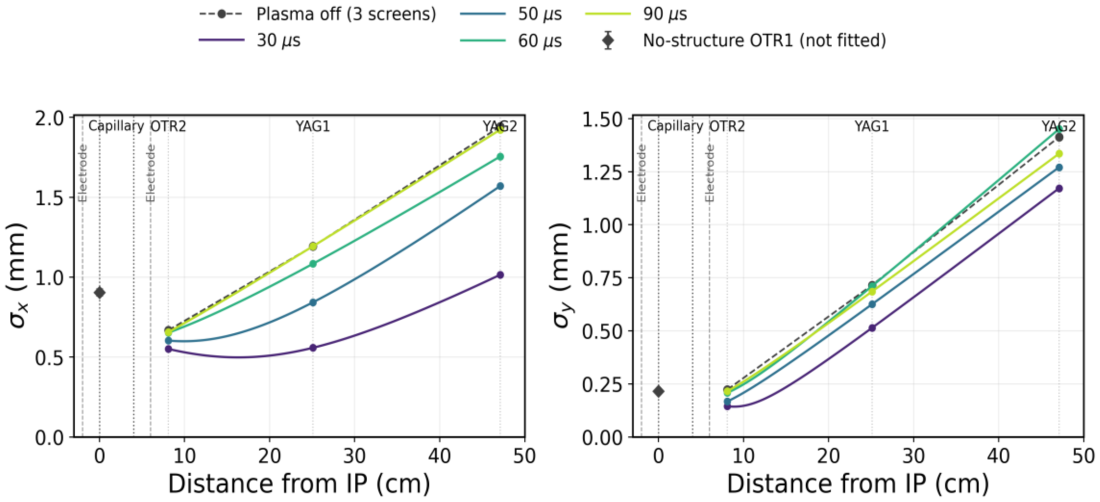


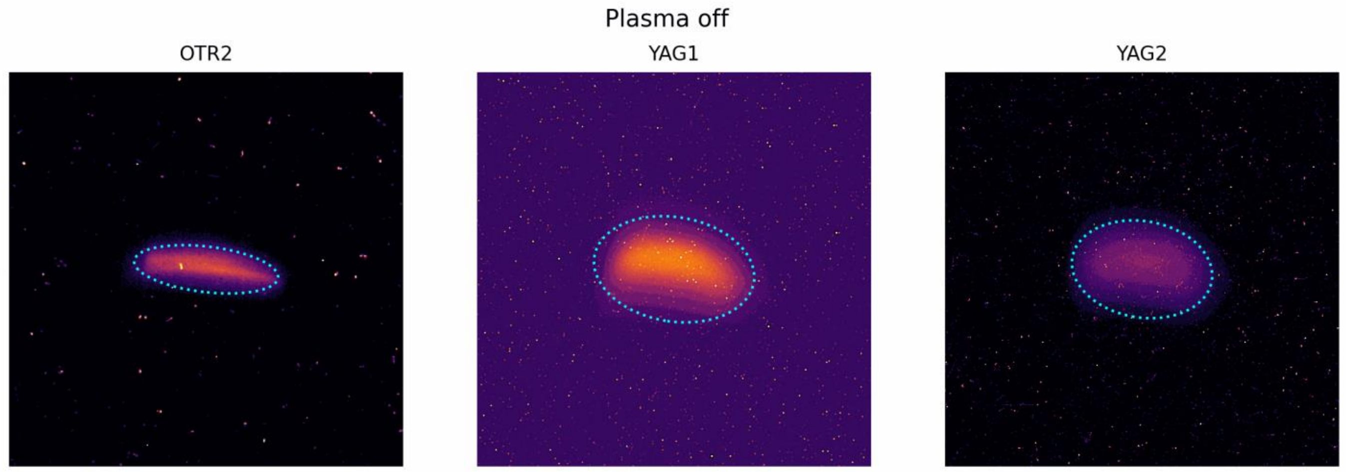



# Preliminary analysis – Plasma focusing

- $\sigma_x$ is larger than the matched spot size
  - Shows a monotonic reduction in size with plasma density (pinching)
- $\sigma_y$ is on the order of the matched spot size
  - Shows more oscillatory mismatch behavior



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- $\sigma_x$ is larger than the matched spot sizes
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- $\sigma_y$ is on the order of the matched spot size
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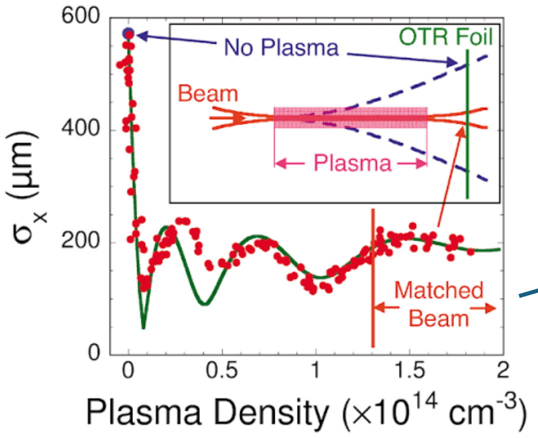
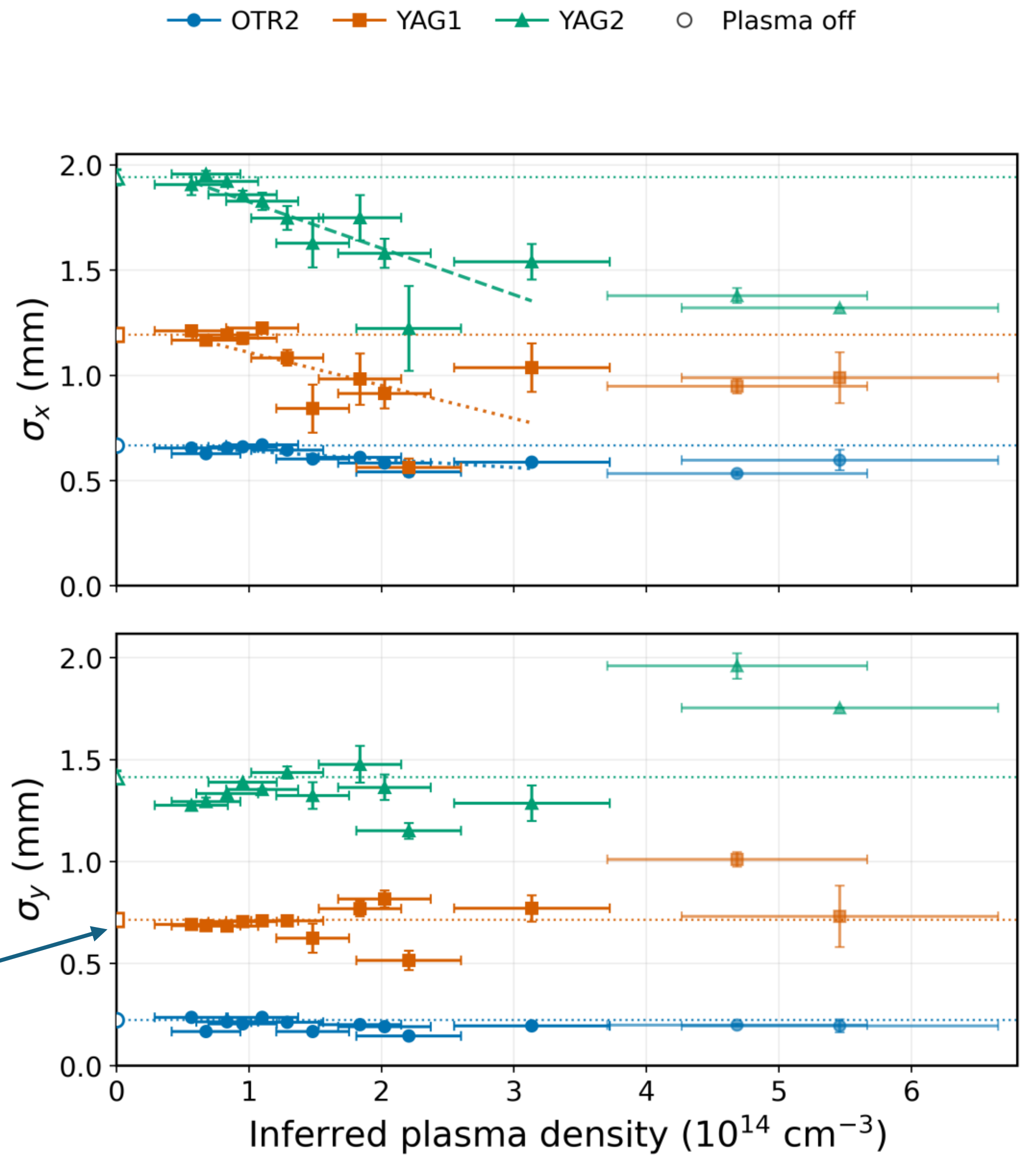
- Dashed lines show correlation of spot size and plasma density




*P. Muggli et al, PRL 2004*

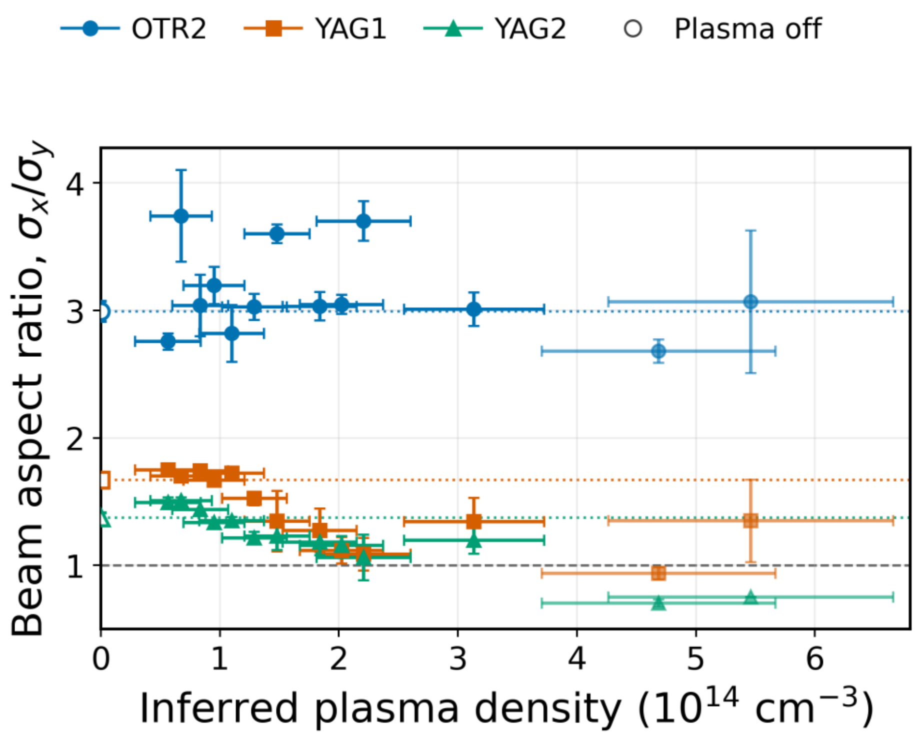


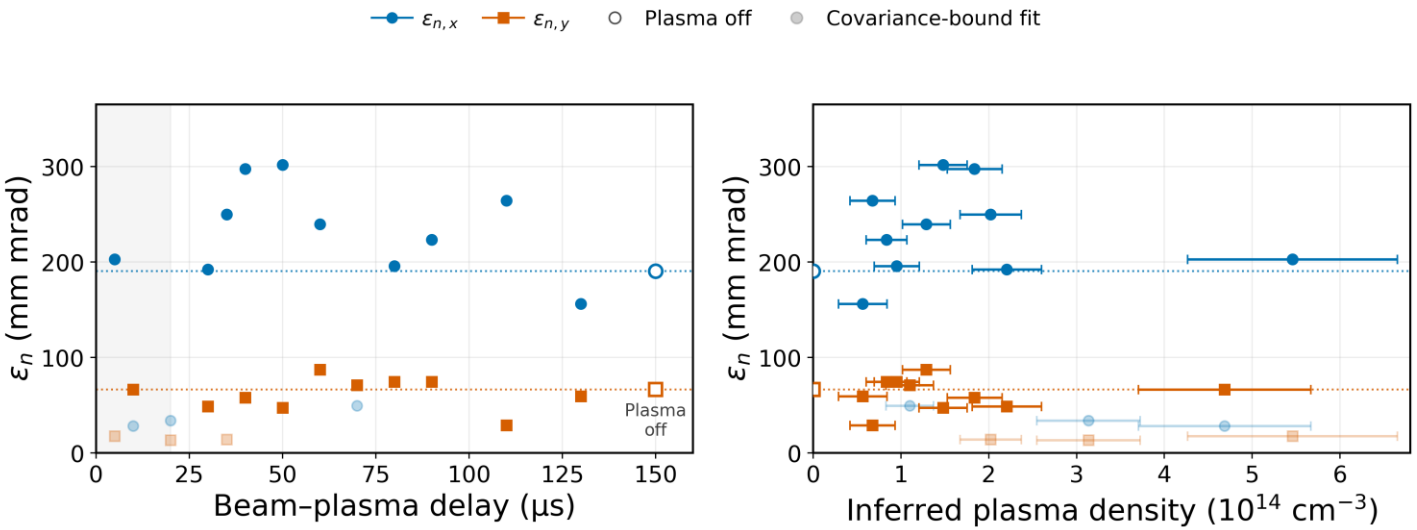
# Preliminary analysis – Emittance and asymmetry

- Beam asymmetry fluctuates at OTR2 but is typically greater than no plasma shots

- Same trend seen for low densities on YAG1 and YAG2 and they tend to reduce at higher densities

- Emittance measurements: Three screen measurements are highly sensitive to small changes in spot sizes(To be analyzed)



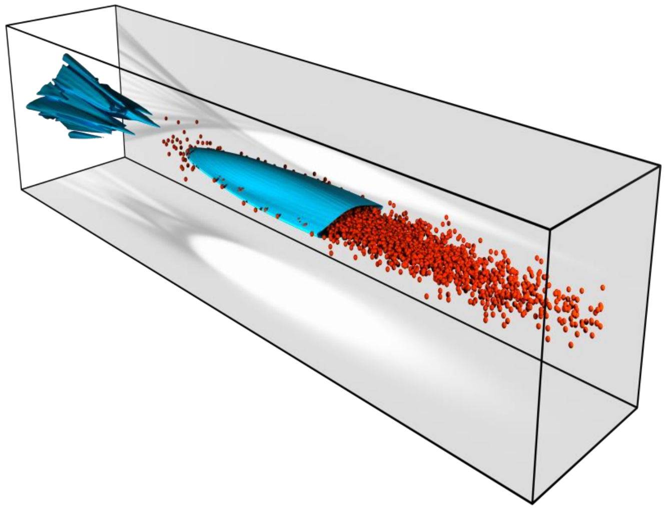



# Conclusion and Future steps

- The beam–plasma propagation experiment was successfully proposed and demonstrated at AWA.

- Three screen measurements indicate asymmetric focusing, but needs to be investigated with simulations

- Future Steps
  - Improve final focus and perform longitudinal measurements
  - Implement differential pumping to preserve the beam emittance ratio
  - Asymmetric plasma thin and adiabatic lens with well characterized plasma profiles



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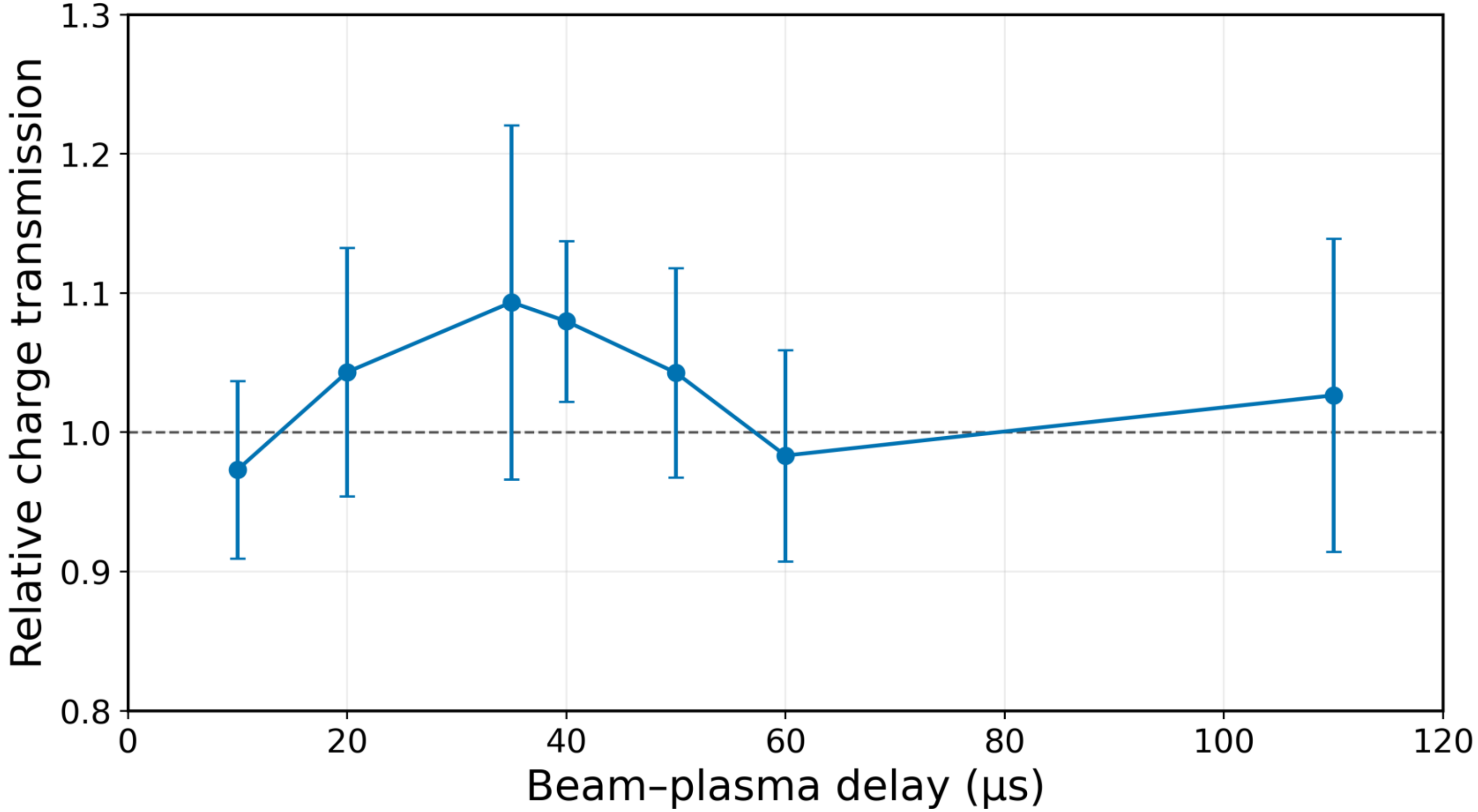
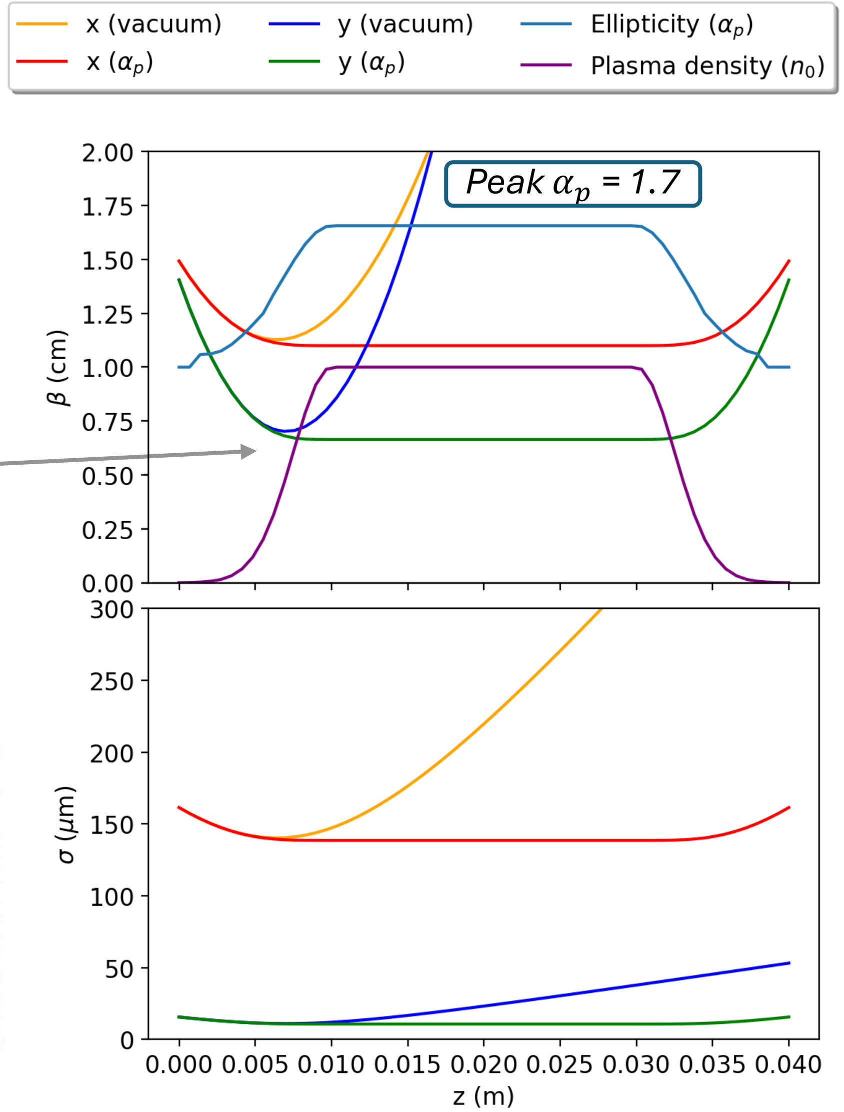
Thank you for your time!

# Charge transmission (Preliminary)

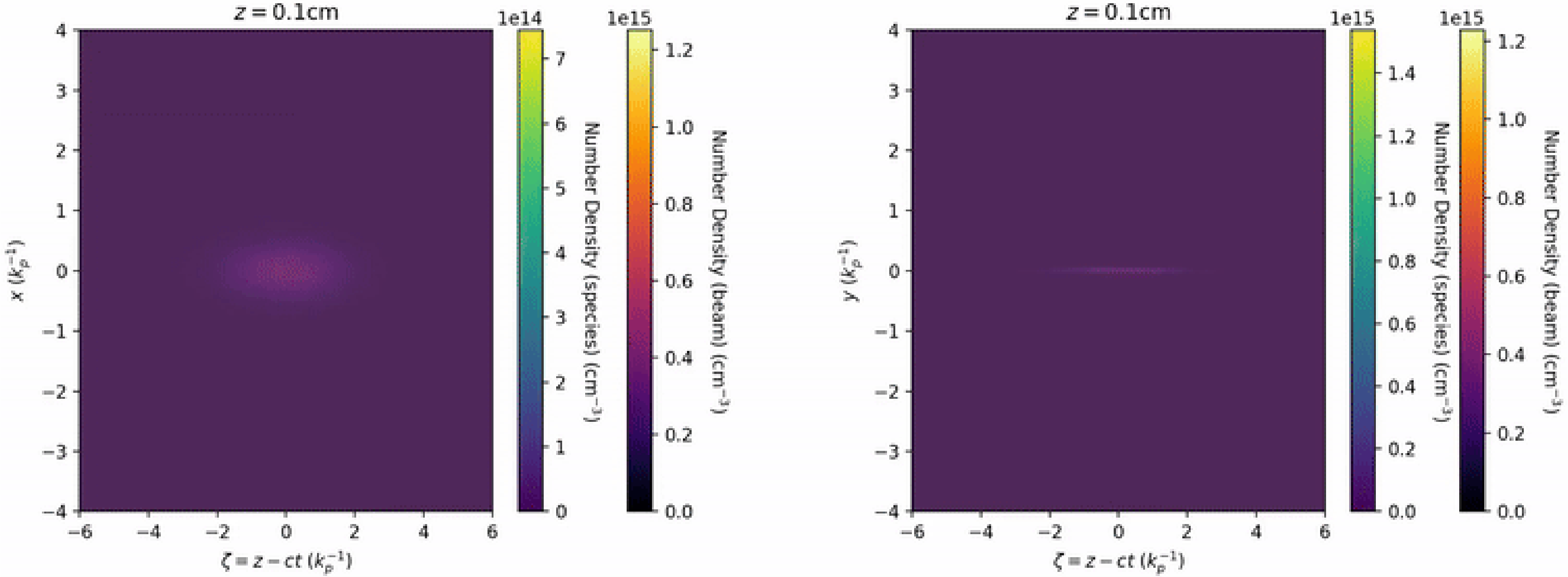


# Beam-plasma interaction

- We can use our long beam model for the vacuum-plasma transport
- The ellipticity ($\alpha_p$) increases with increase in plasma density
- **Note: Matched beta functions depend on $\alpha_p \left(\frac{a_p}{b_p}\right)$**



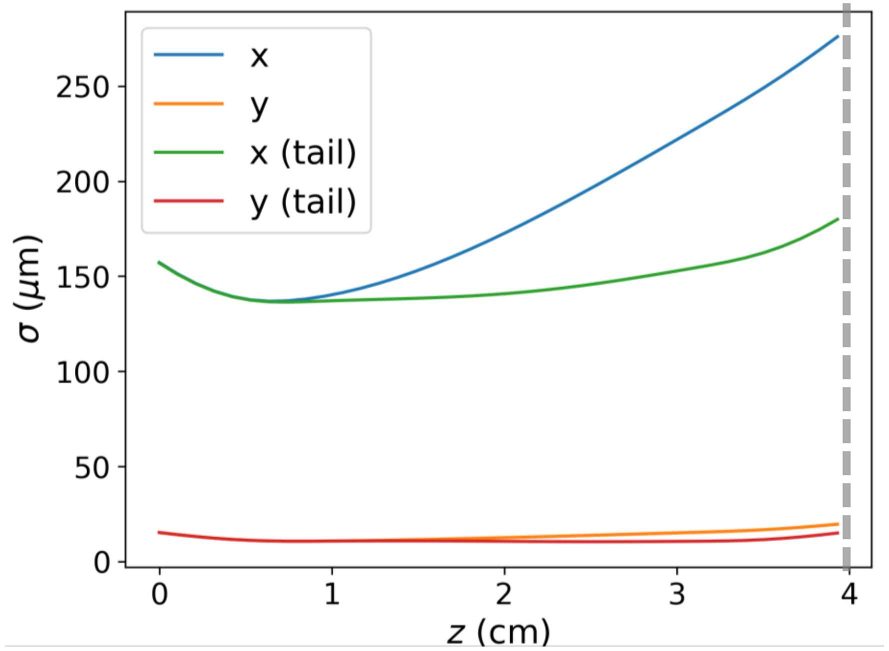

*Using long beam model*



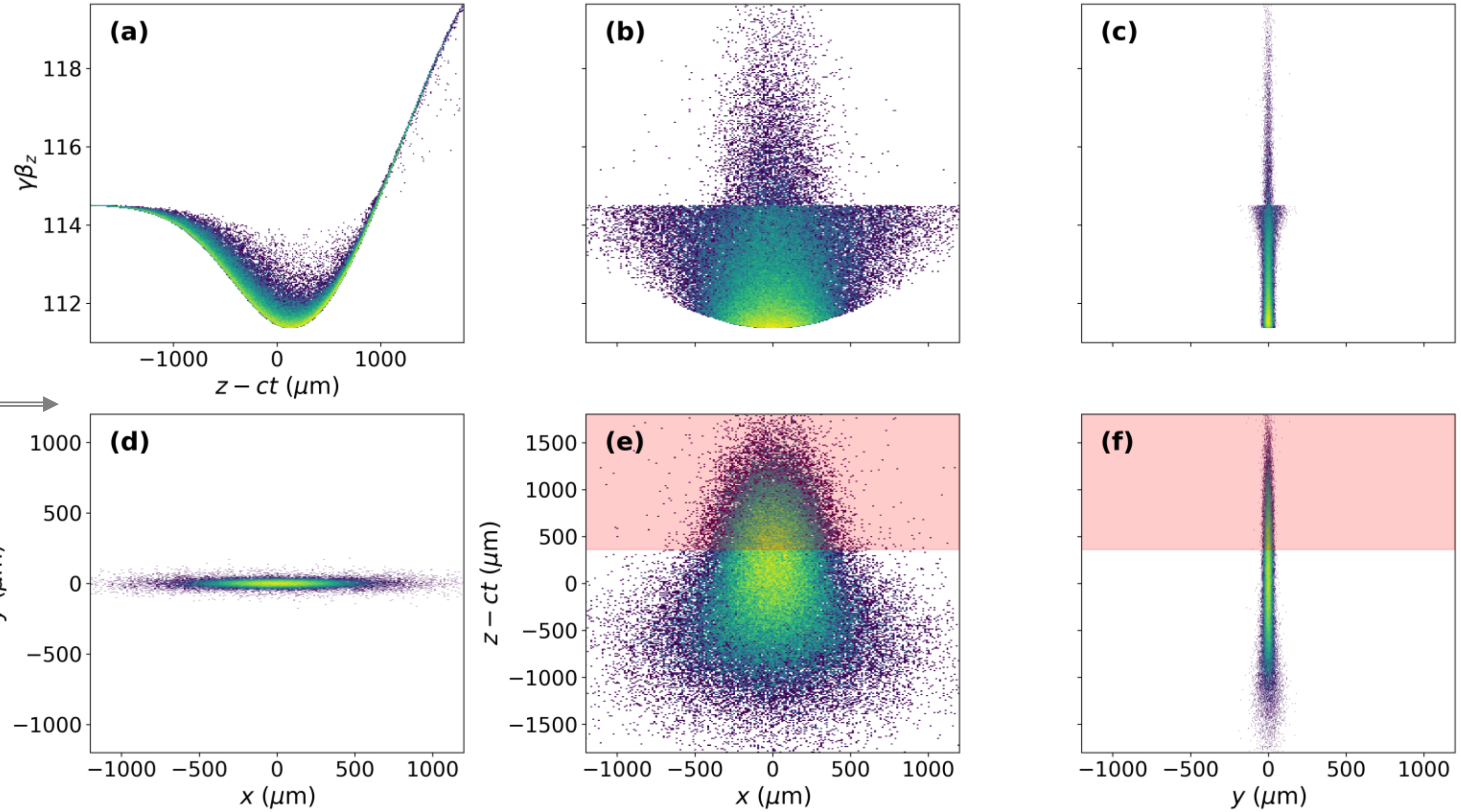

*AWA beam parameters at $n_0$ of $1 \times 10^{14}$ $cm^{-3}$ (QuickPIC)*

# Experiment observables

- Longitudinally varying focusing
  - OTR foil at entrance and exit of capillary viewed by streak camera
  - Two screens downstream for angle and emittance measurements
- Energy spread will be measured using a transverse deflecting cavity and a dipole spectrometer




*Spot size evolution(QuickPIC)*




*After beam – plasma interaction (QuickPIC)*