Underdense, Passive Plasma Lens for Focusing Electron Beams

HKUST IAS Program on High Energy Physics

1/14/2021

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Introduction

- Plasma lenses are capable of strong, axisymmetric focusing.
- Active plasma lenses use an applied current in a plasma capillary to provide focusing.
- Passive plasma lenses use fields present in the wakes generated by a driving beam
  - Overdense and underdense regimes.
- In this talk:
  - Quick overview of different plasma lens regimes
  - Closer look at underdense passive plasma lens focusing
  - Applications and current experimental plans for underdense passive plasma lenses

Active Plasma Lenses

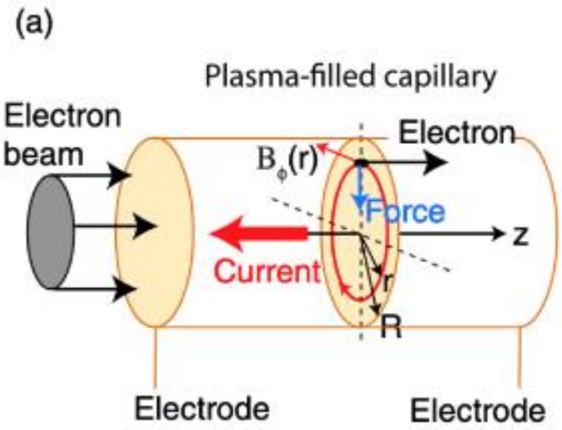
- APL's use a gas-filled capillary with electrodes on the ends. A current is driven through the plasma and this produces focusing magnetic field.

$$g_{APL} = 200 \frac{I[\mathrm{kA}]}{(R[\mathrm{mm}])^2} \mathrm{T/m}$$

Using parameters from the APL in
S. Steinke et. al., Nature **530**, 190-193 (2016):

$$I = 650\mathrm{A}$$
$$R = 250\mu\mathrm{m}$$

$$g_{LBNL} = 2080\ \mathrm{T/m}$$



- Even a weak APL is comparable to the strongest PMQ's.
- **Focusing doesn't depend on beam shape.**
- **Works for electrons and positrons.**

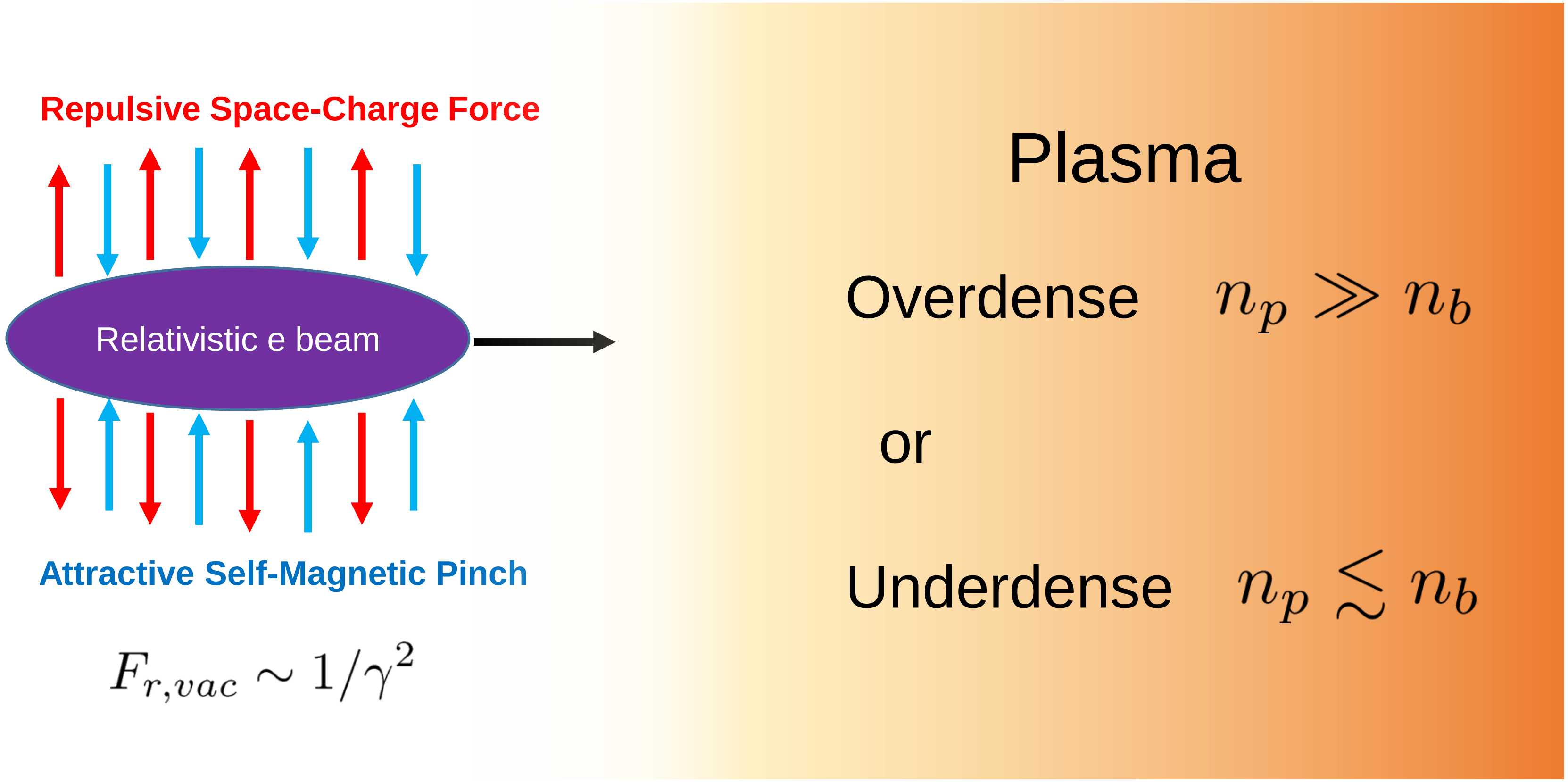
J. van Tilborg et. al., PRL **115**, 184802 (2015)

Active Plasma Lenses

- APL’s work well in experiment
  - S. Steinke et. al., Nature **530**, 190-193 (2016)
- Preserve emittance growth
  - C. A. Lindstrøm et. al., PRL **121**, 193801 (2018)
- Allow for compact diagnostics
  - S. K. Barber et. al., Appl. Phys. Lett. **116**, 234108 (2020)
- However, requires small beam density compared to plasma.
  - Otherwise a wake is driven in the plasma and this leads to aberrations.
  - Would require a large transverse beam size.
  - C. Lindstrøm, E. Adli, [arXiv:1802.02750] (2018)

Passive Plasma Lens Focusing

- In vacuum, forces on an ideal beam cancel
- Passive plasma effects depend on relative density



Su, J. J., et al. "Plasma Lenses for Focusing Particle Beams." Physical Review A, vol. 41, no. 6, Mar. 1990, pp. 3321–31. APS, doi:10.1103/PhysRevA.41.3321.

Overdense Regime

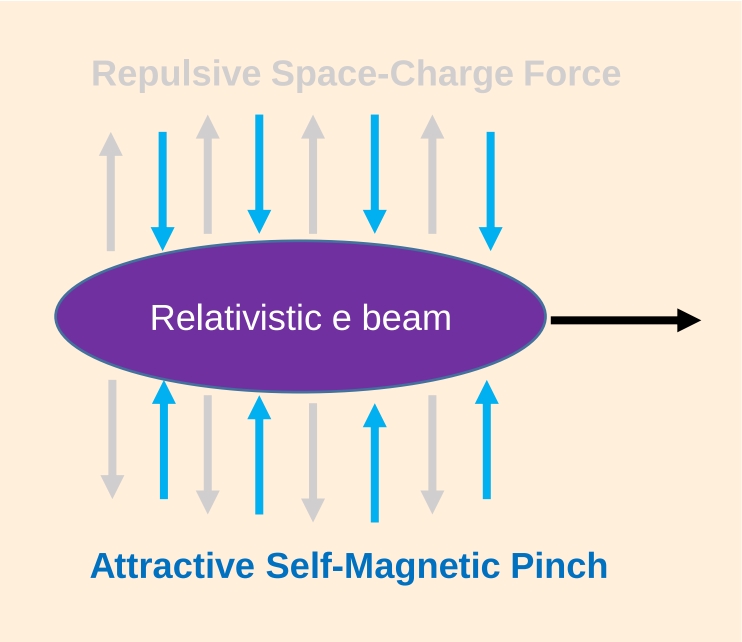
- The beam is a perturbation to the high plasma density.
- Assuming adiabatic motion, plasma e's cancel beam's charge but not its current.
- Ampere's Equation:

$$\oint \vec{B} \cdot \vec{dl} = \mu_0 J_{enc} = \mu_0 \pi r^2 v n_b e$$

$$v/c \approx 1$$

$$B_\theta = 2\pi n_b e r$$

$$n_{plasma} \gg n_{beam}$$



$$F_r / r = 2\pi n_b e^2$$

Overdense Plasma Lenses

- The overdense, passive regime was used in early plasma lens experiments due to this regime being more straightforward to access.

- These days, active plasma lenses do a better job in the overdense regime, and the underdense plasma lenses (next slide) do a better job in the passive regime.

Underdense Passive Plasma Lens

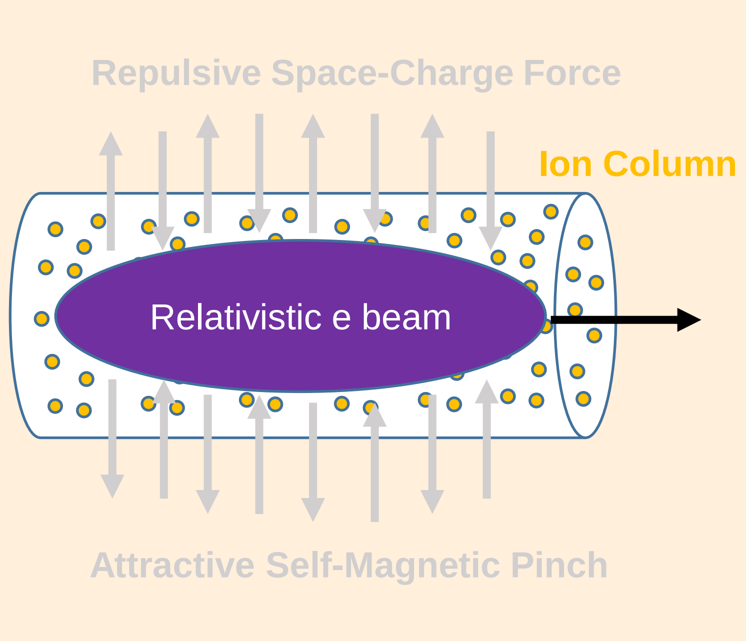
- High density beam blows out plasma electrons, creating an ion column.
- Ion column provides focusing force on beam
- Gaussian cylinder:

$$\oint \vec{E} \cdot d\vec{A} = \frac{1}{\epsilon_0}\rho_{enc}$$

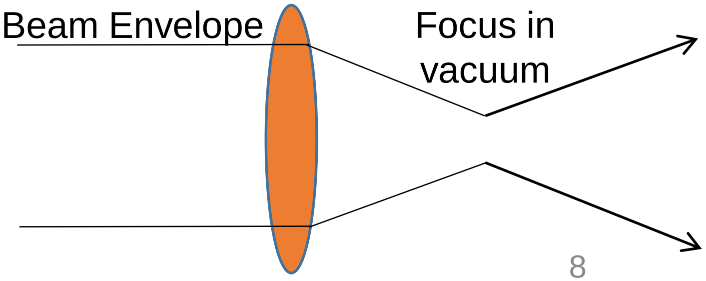
$$E_r = 2\pi n_p e r$$

- <u>Linear</u> focusing force which depends on uniform background plasma density

$$n_{plasma} \lesssim n_{beam}$$



$$F_r/r = 2\pi n_p e^2$$



Beam Dynamics of Thin Plasma Lens

- Consider an x, x' transfer matrix for thick lens

$$M_{thick} = \begin{bmatrix} \cos\sqrt{K}L & \frac{1}{\sqrt{K}}\sin\sqrt{K}L \\ -\sqrt{K}\sin\sqrt{K}L & \cos\sqrt{K}L \end{bmatrix}$$

- Take thin limit:

$$M_{thin} = \begin{bmatrix} 1 & 0 \\ -KL & 1 \end{bmatrix}$$

- A focal length can be derived and interpreted using focusing strength of plasma on e$^-$ beam

$$f = \frac{1}{KL} \simeq \frac{\gamma_L mc^2}{2\pi e^2 n_p}\frac{1}{L}$$ where $$K = \frac{2\pi e^2 n_p}{\gamma_L mc^2}$$

Beam Dynamics of Thin Plasma Lens

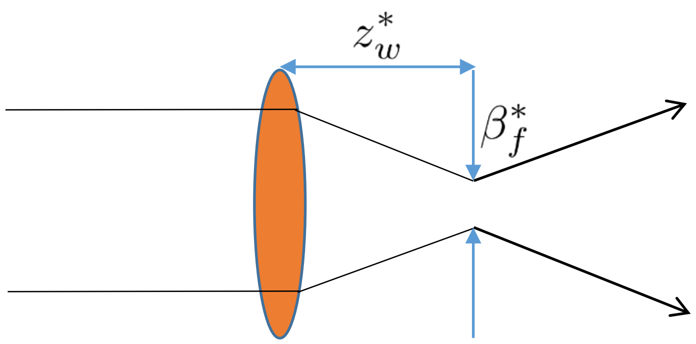
- Include the lens and a drift into a transfer matrix for the collective CS parameters:

$$\begin{bmatrix}\beta(z)\\ \alpha(z)\\ \gamma(z)\end{bmatrix} = \begin{bmatrix} M_{11}^2 & -2M_{11}M_{12} & M_{12}^2 \\ -M_{11}M_{21} & M_{11}M_{22}+M_{12}M_{21} & -M_{12}M_{22} \\ M_{21}^2 & -2M_{21}M_{22} & M_{22}^2 \end{bmatrix}\begin{bmatrix}\beta_0\\ \alpha_0\\ \gamma_0\end{bmatrix}$$

- Then we can find the beam size at focus and the location of the focus:

$$\beta_f^* = \frac{1}{\beta_0 K^2 L^2 + 2\alpha_0 K L + \gamma_0}$$

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



- A similar expression can be found for thick lenses but is slightly less analytically tractable.

C. Doss et. al., PRAB **22**, 111001 (2019)

Applications/Motivations for Plasma Lenses

- Underdense passive plasma lenses are very promising for focusing high-density electron beams.
- Many applications of plasma lenses to be explored at SLAC's FACET-II:
  - Matching beams into Plasma Wakefield Accelerators to preserve emittance.
  - Possibility as a strong final-focus optic and/or tool to study hard synchrotron radiation and the Oide limit.
  - Assist with many other planned experiments at FACET-II and beyond.
    - Who doesn't want smaller beam spot sizes!?

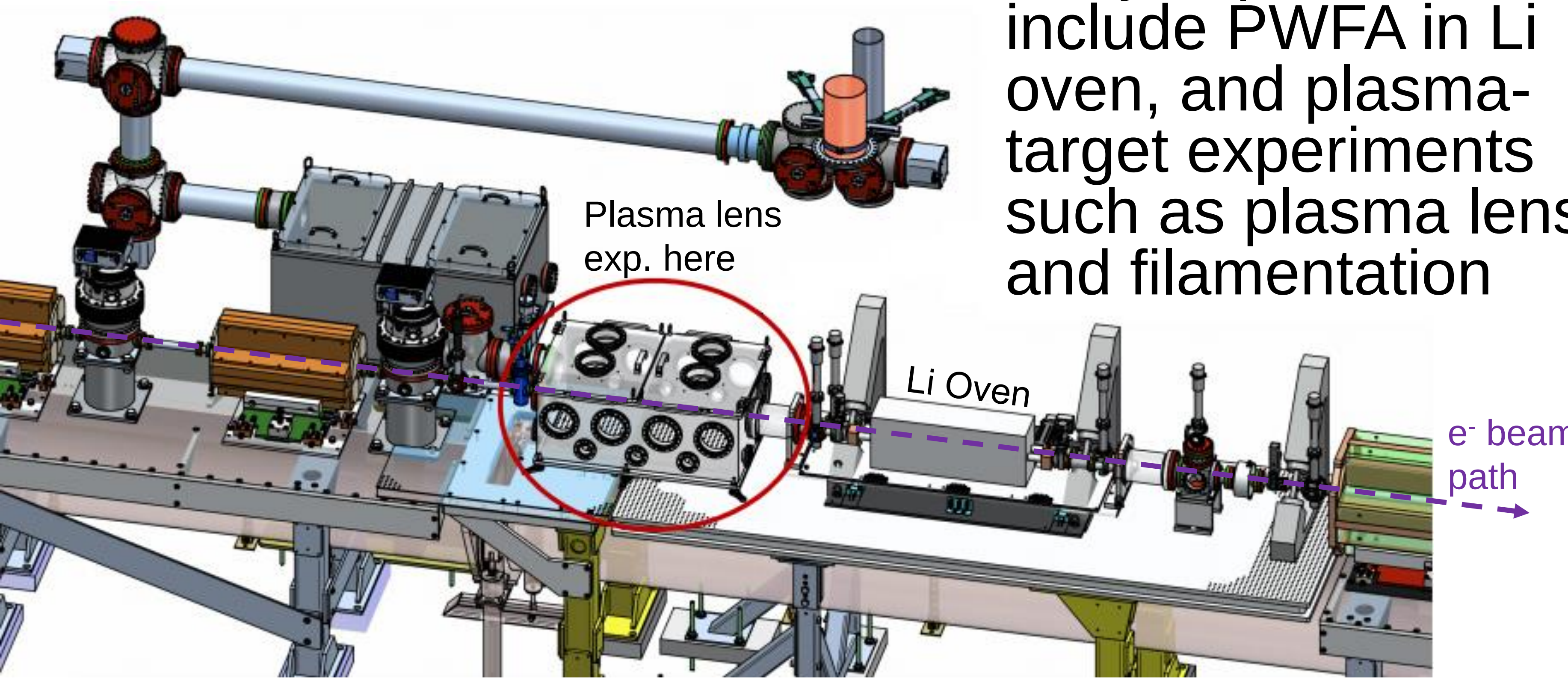
FACET-II Overview

Electron Beam Parameter	Operational Ranges
Final Energy [GeV]	4.0 – 13.5
Charge per Pulse [nC]	0.7 – 5
Repetition Rate [Hz]	1 - 30
Norm. Emittance [µm-rad]	3 – 6
Spot Size at Experiments [µm]	5 – 20
Min. Bunch Length rms [µm]	0.7 – 20
Max Peak Current [kA]	10 - 200

- 1 km in length
- Photo-injector generates single- or two-bunch beams
- Imaging spectrometer and other diagnostics in experimental area

FACET-II Experiments

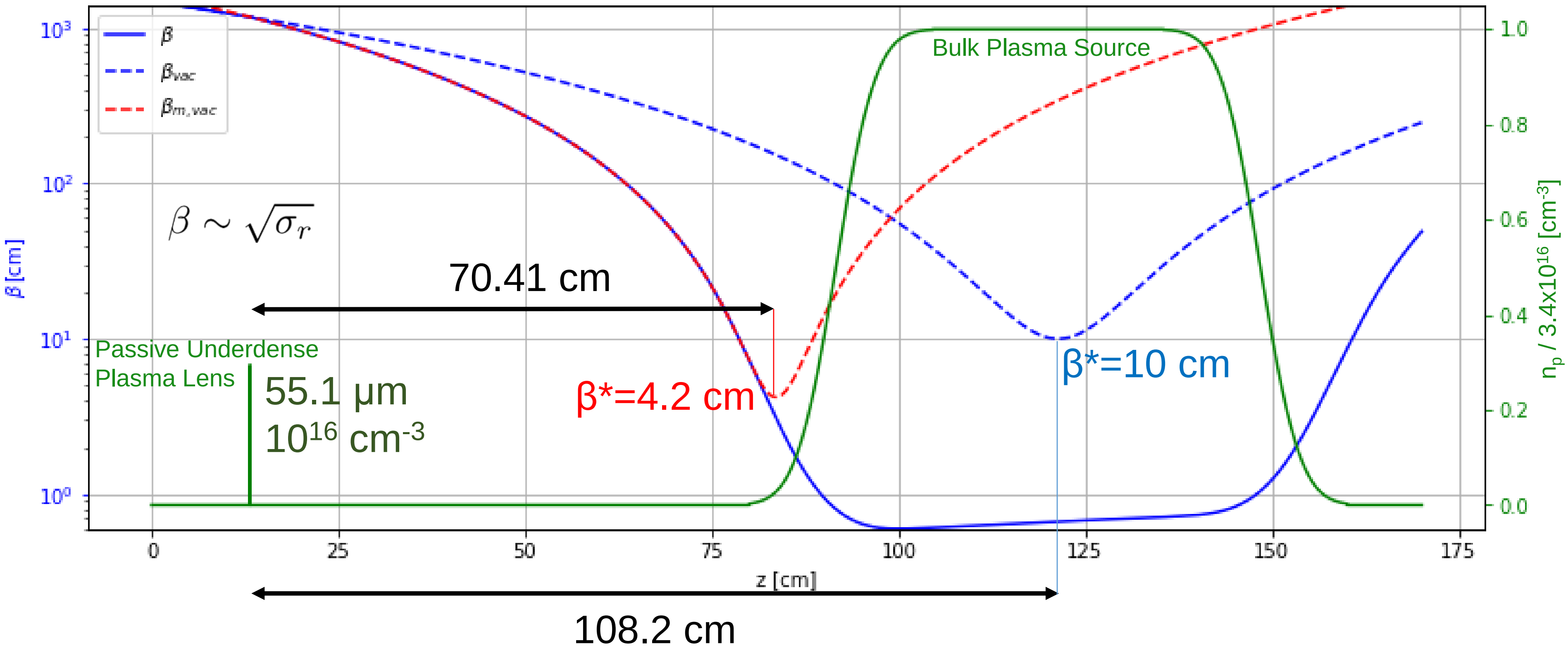
- Experimental area features compressed, ≤0.6 J, 800 nm laser; compressed probe beams; gas jets; and a bypass-able Lithium vapor oven.



- Early experiments include PWFA in Li oven, and plasma-target experiments such as plasma lens and filamentation

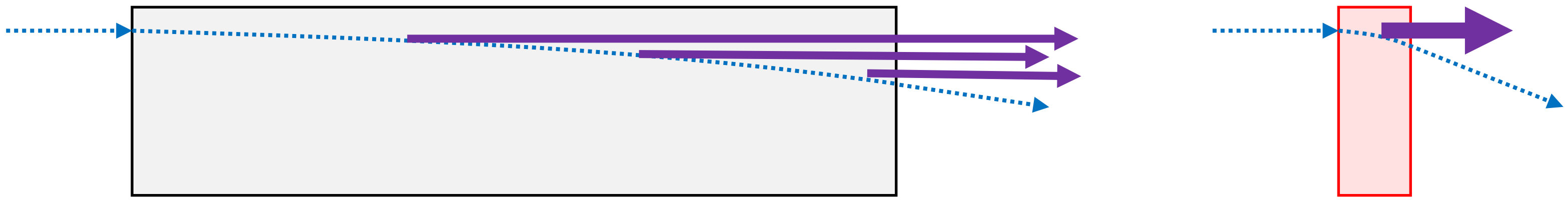
PWFA Matching Example

- Matching into a PWFA requires extremely small beam size for emittance preservation.
- Plasma lenses are one option to reach this goal.



Synchrotron Radiation and Oide Limit

- Underdense plasma lenses could be used either as a potential final focus optic or as a proxy for studying Physics present in other strong focusing optics.
- For example: electrons in focusing optics emit synchrotron radiation adiabatically (left) or non-adiabatically (right).



- The non-adiabatic emission of hard photons can significantly affect transverse momentum and final focus spot size.

Theory on Synchrotron Radiation

- Analytic theory for how non-adiabatic emission of synchrotron radiation introduces aberrations at the focus.
  - K. Oide, "Synchrotron-Radiation Limit on the Focusing of Electron Beams," Phys. Rev. Lett., vol. 61, no. 15, pp. 1713–1715, Oct. 1988.

$$\underbrace{\sigma^{*2} = \beta^*\epsilon}_{\text{Ideal Behavior}} + \underbrace{\frac{110}{3\sqrt{6\pi}} r_e \lambda_e \gamma_L^5 F(\sqrt{K}L, \sqrt{K}l^*) \left(\frac{\epsilon}{\beta^*}\right)^{5/2}}_{\text{New Synch. Rad. Effects}}$$

$$F(\sqrt{K}L, \sqrt{K}l^*) \equiv \int_0^{\sqrt{K}L} |\sin\phi + \sqrt{K}l^* \cos\phi|^3 \left[\int_0^{\phi} (\sin\phi' + \sqrt{K}l^* \cos\phi')^2 d\phi'\right]^2 d\phi$$

$$l^* \equiv f - \frac{1}{2}L$$

Theory on Synchrotron Radiation

- The previous equation can be solved to find a minimum possible spot size for a given focusing optic.

$$\sigma^*_{min} = \left(\frac{7}{5}\right)^{1/2} \left[\frac{275}{3\sqrt{6\pi}} r_e \lambda_e F(\sqrt{K}L, \sqrt{K}l^*)\right]^{1/7} (\epsilon_N)^{5/7}$$

$$\beta^*_{opt} = \left[\frac{275}{3\sqrt{6\pi}} r_e \lambda_e F(\sqrt{K}L, \sqrt{K}l^*)\right]^{2/7} \gamma_L (\epsilon_N)^{3/7}$$

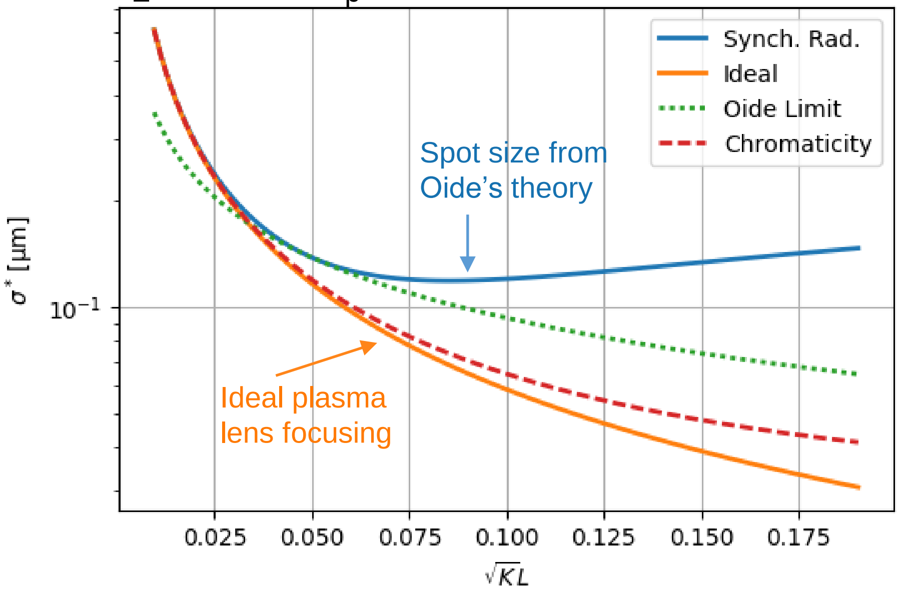
- This minimum spot size is achieved when the beam’s betafunction at focus is β^*_{opt}

Synchrotron Radiation and Oide Limit

- Understanding the Oide Limit will be important for future colliders, but this limit has yet to be reached experimentally.

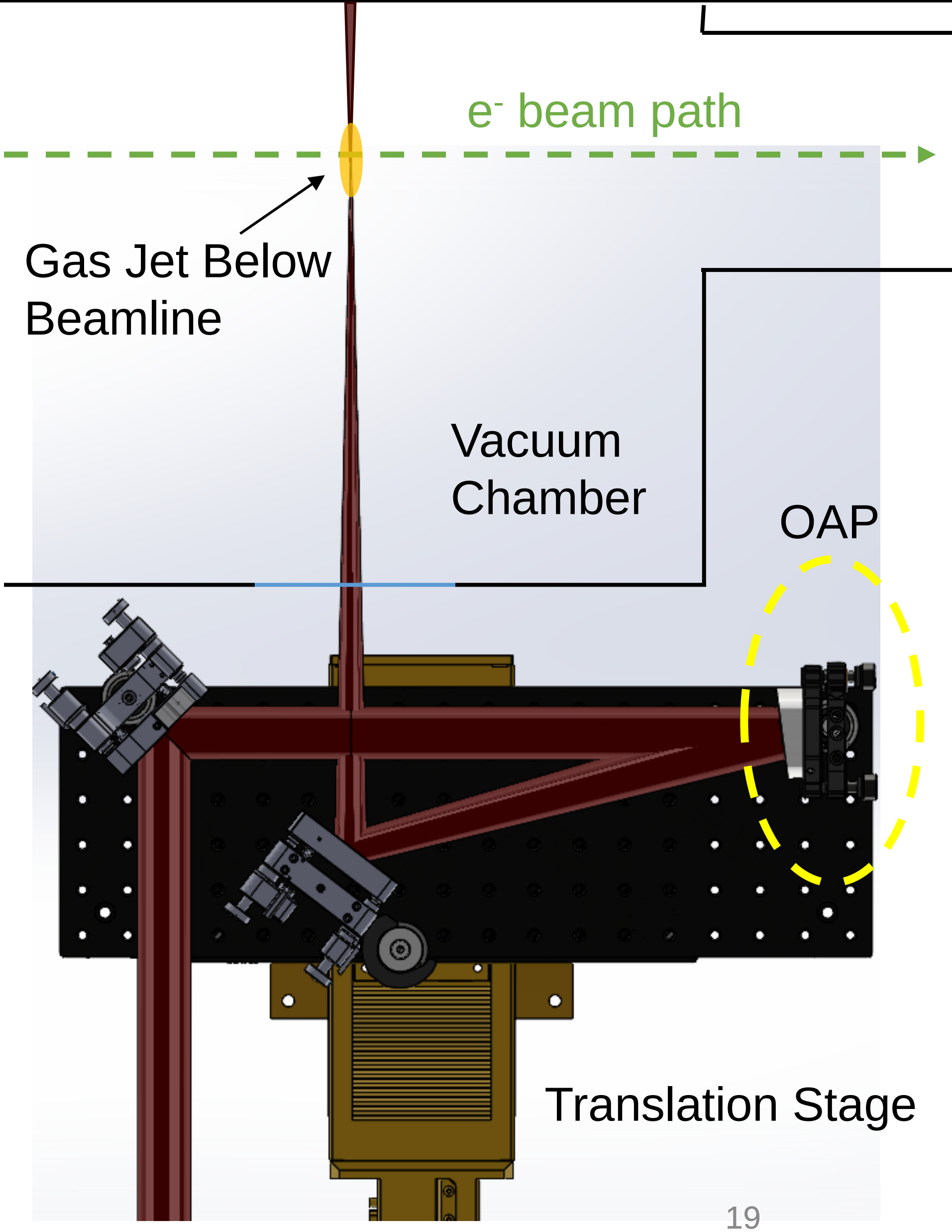
- We expect to be able to study this experimentally at FACET-II using underdense plasma lenses.

$E = 10$ GeV, $\beta_i = 5$ m, $\varepsilon_N = 3$ μm-rad, $\sigma_E = 0.1\%$, $n_p = 10^{18}$ cm^{-3}, L = 20-200 μm



Plasma Lens at FACET-II

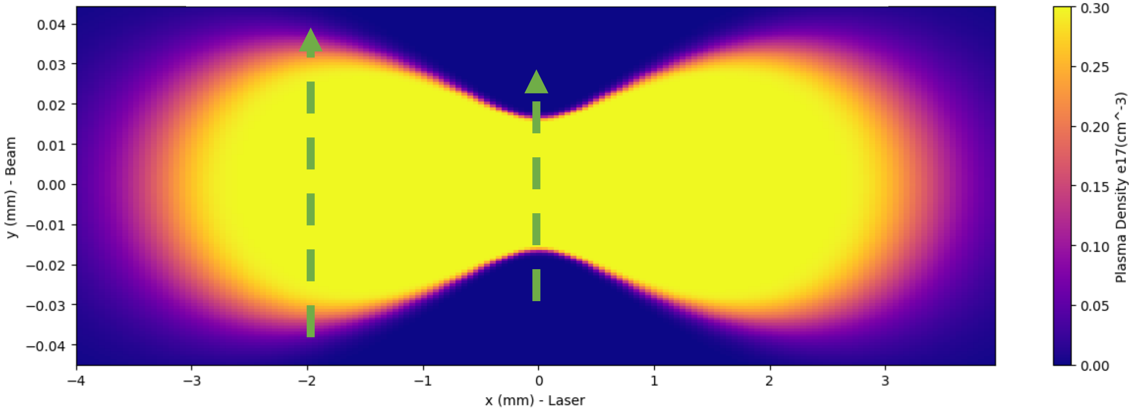
- Hydrogen gas jet in the path of the electron beam.
- Compressed laser pulse of up to 20 mJ ionizes the gas jet at the focus of an OAP.
- Opto-mechanics allow for plasma to be shifted and adjusted.
- Downstream magnetic lattice for imaging the beam's vacuum focus.

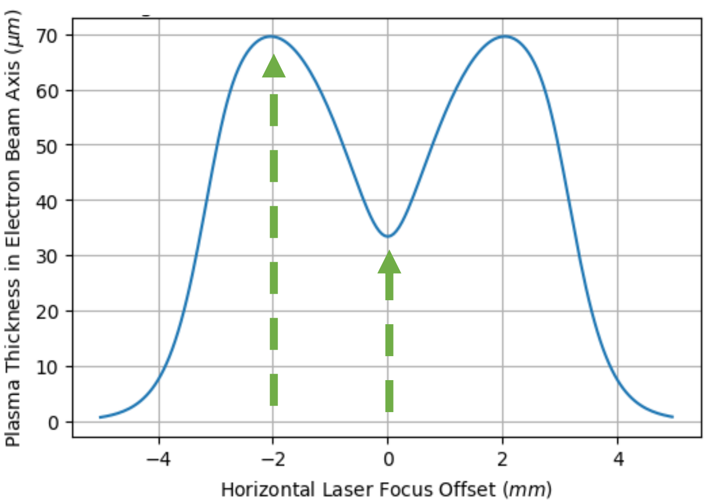


Plasma Lens at FACET-II

- Can scan plasma lens thickness by horizontally shifting the laser focus with respect to the electron beam axis.
- Gas jet pressure can adjust plasma lens density: currently planning for $10^{16} \rightarrow 10^{18}$ cm^{-3}.
- With 1 mJ, access thickness range 35 μm -> 70 μm
- Plasma density to be experimentally measured with shadowgraphy and afterglow techniques.

Plasma Density: ~1/50 Aspect Ratio

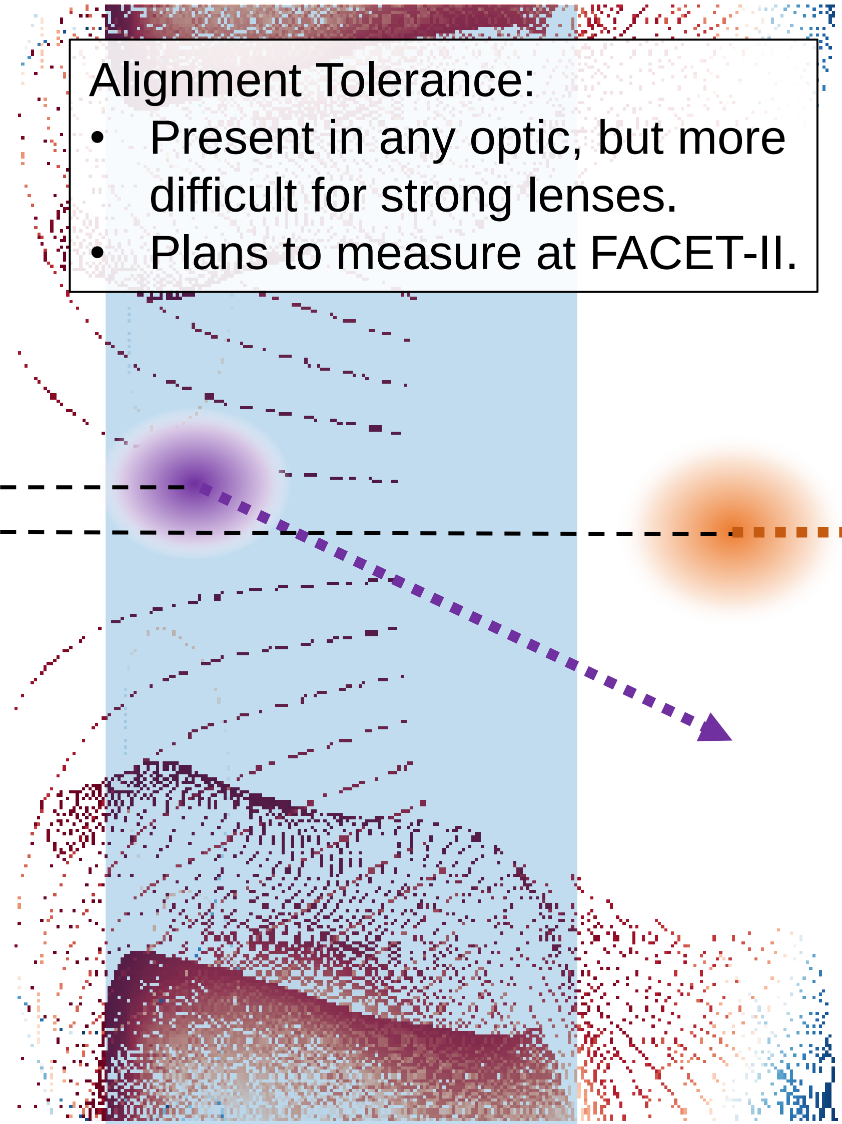


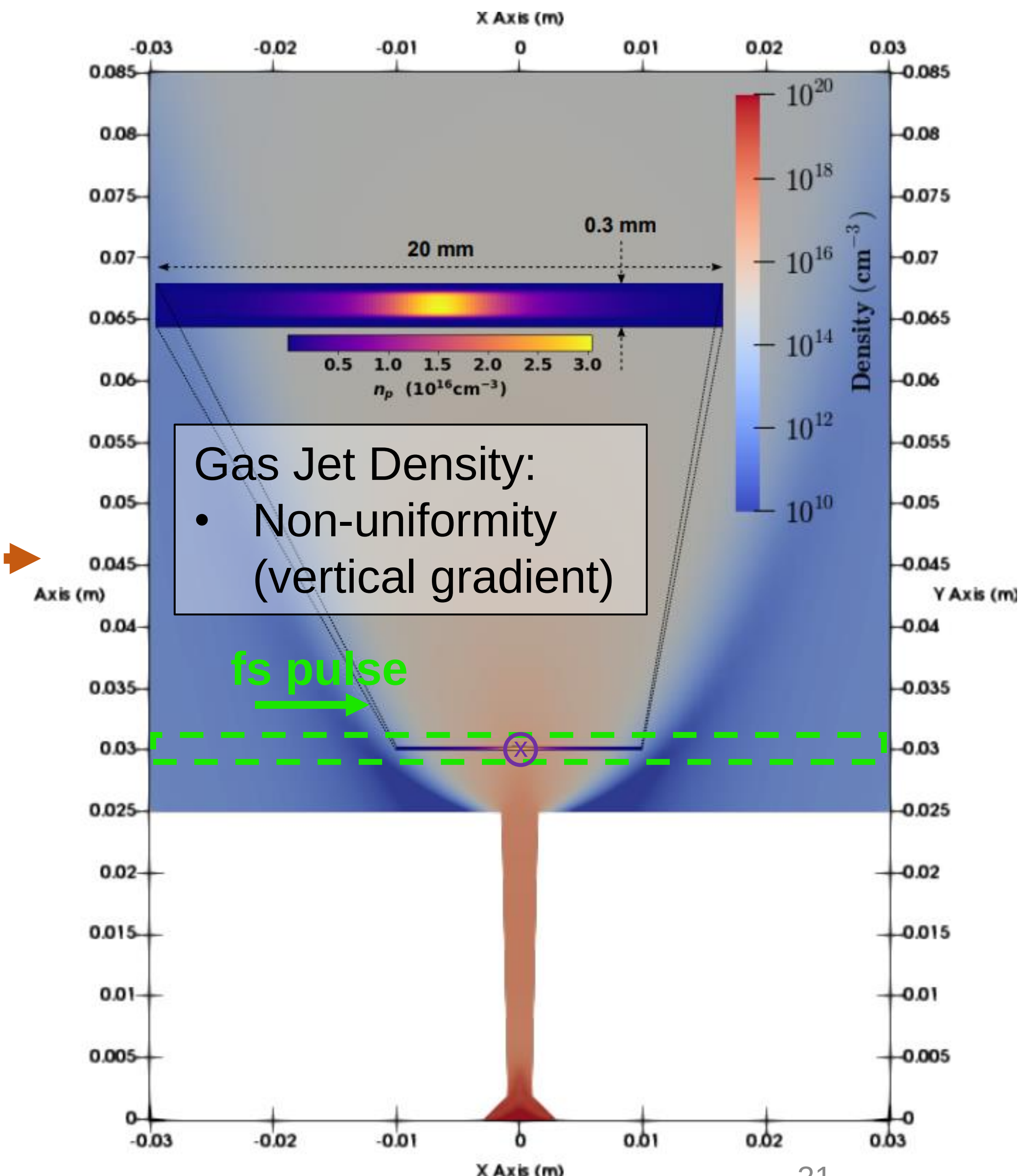


Expected Experimental Challenges

Alignment Tolerance:

- Present in any optic, but more difficult for strong lenses.
- Plans to measure at FACET-II.





Gas Jet Density:

- Non-uniformity (vertical gradient)

Summary and Outlook

- Active plasma lenses have demonstrated their usefulness in experiments, and underdense passive plasma lenses show promise in the future.

Underdense Plasma Lenses at FACET-II:

- Test accuracy of plasma lens model and reliability of electron beam focusing using laser-ionized underdense passive plasma lens.
  - Plasma lens thicknesses from as low as 35 μm to as large as 350 μm
  - Gas densities around 10^{16} – 10^{18} cm^{-3}
- Apply plasma lens towards PWFA matching and studying effects of strong focusing.

Thanks!

This work was funded by the U.S. Department of Energy grant number DE-SC0017906.