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First observation of Current Filamentation Instability (CFI)

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Brookhaven National Laboratory Accelerator Test Facility

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INSTITUTO SUPERIOR TÉCNICO Universidade Técnica de Lisboa

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ATF User Meeting

May 26, 2012

– Brian Allen –

Agenda

- Overview
- PIC Simulations
- Experiment
  - Setup
  - Results
- Conclusion

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Current Filamentation Instability (CFI)

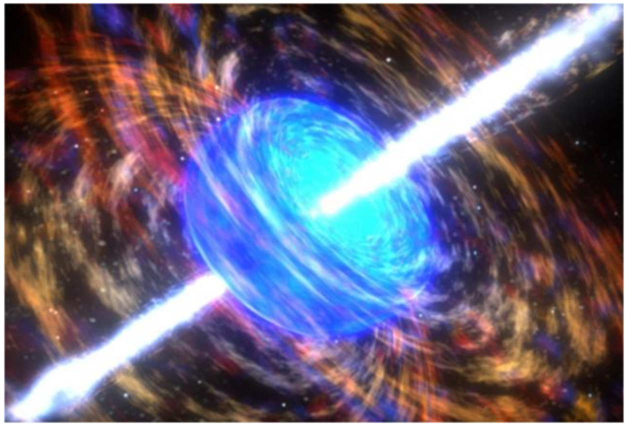
What is CFI?

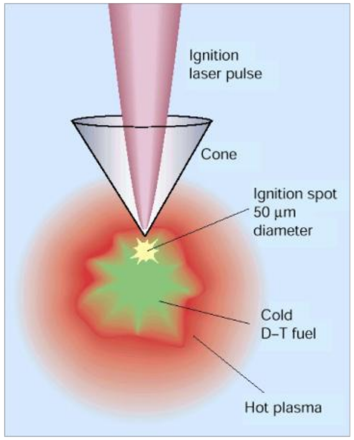
- Particle beam transport in plasmas is subject to Current Filamentation Instability (CFI)
- CFI results in breakup of the beam into narrow high current filament
- Enhances/generates magnetic fields and generates radiation

Why is it interesting?

- Basic plasma instability
- Potential relevance to Astrophysics and Inertial Confinement Fusion (ICF)

Afterglow of gamma ray bursts





Hot electron transport for Fast Igniter - ICF

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Characteristics of CFI

Characteristics

- Particular case of the Weibel instability[1] (Temperature anisotropy)
- Plasma return current
  - $\sigma_r > c/\omega_{pe}$ flows through beam, CFI regime
  - $\sigma_r << c/\omega_{pe}$ return current outside beam, PWFA wakefields
- Purely transverse electromagnetic instability of relativistic beams - purely imaginary frequency

How it occurs

- Non-uniformities in the transverse beam/plasma profile lead to unequal opposite currents (beam and plasma) and magnetic fields
- Opposite currents repel each other, leading to instability and filamentation

Effects

- Beam filaments
- Plasma density perturbations
- Magnetic field enhancement (or generation)
- Radiation generation

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[1]E. Weibel - Phys. Rev. Lett. 2, 83 (1959)

Criteria for CFI

Criteria for CFI

- $\sigma_r >> c/\omega_{pe}$ ($k_p\sigma_r >> 1$)
- $\gamma_0 >> 1$

Filament size and spacing $\sim c/\omega_{pe}$

Growth rate[1] (infinite transverse size):

$$\Gamma = \beta_0 \sqrt{\frac{\alpha}{\gamma_0}}\,\omega_{pe} \quad \text{or} \quad \Gamma = \beta_0 \omega_{pb} \Big/ \sqrt{\gamma_0} \quad \sim n_b \sim Q/(\sigma_r^2 \sigma_z)$$

σ_r - Transverse beam size, σ_z - bunch length, n_e - plasma density, n_b beam density

Q - beam charge, c - speed of light in vacuum, γ_o - relativistic beam factor

Plasma-electron angular frequency: $\omega_{pe} = (n_e e^2/\varepsilon_o m_e)^{1/2}$

Collisionless skin depth: $k_p^{-1} = c/\omega_{pe}$

Ratio of beam to plasma density: $\alpha = n_b/n_e$

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[1] Bret et al., Phys. Rev. Lett. 94, 115002 (2005)

CFI with ATF Beam

ATF Beam Parameters

Parameters	Value
Charge (nC)	1.00
Typical Bunch Transverse Waist Size - $\sigma_{0x,y}$ (μm)	50 to 100
Bunch Length (ps)	5
Bunch Density (cm^{-3})	$6\text{x}10^{13}$
Energy (MeV)	58
Normalized Emittance (mm-mrad)	1 to 2(?)

- γ_0=117
- Growth length estimate:

Γ=4.2x10^{10} s^{-1} or 7.1 mm at *c*

γ_0>>1, σ_{0y}>> c/ω_{pe} for n_e > 1.6x10^{16} cm^{-3}

CFI should be observable on a cm-length plasma scale

(plasma length, L_p = 2 cm)

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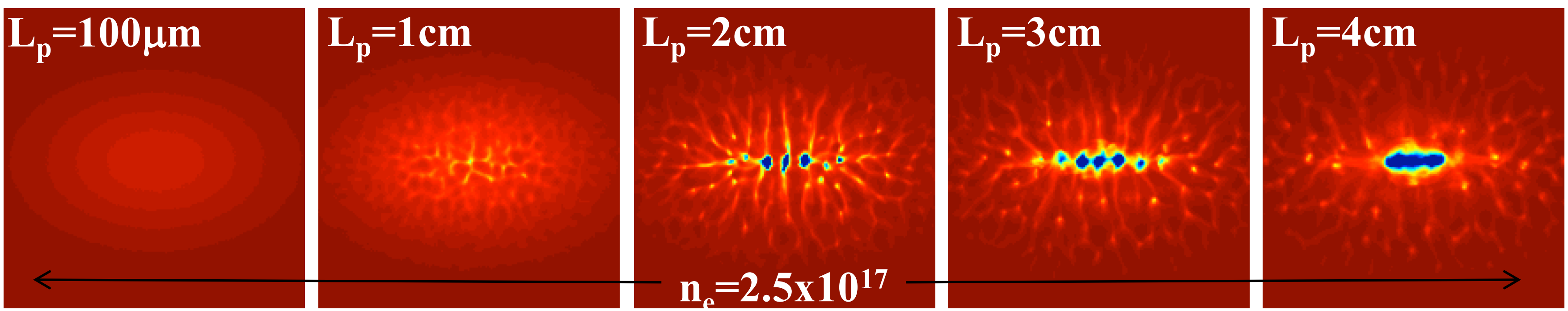
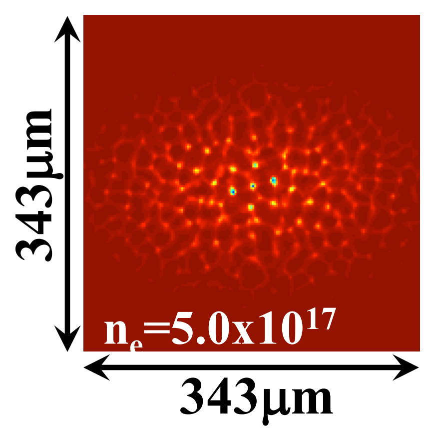
PIC Simulations – Transverse Images

- Size and number of filaments scales with c/ω_p
- Merging of filaments





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Simulations with QuickPIC

Warren Mori

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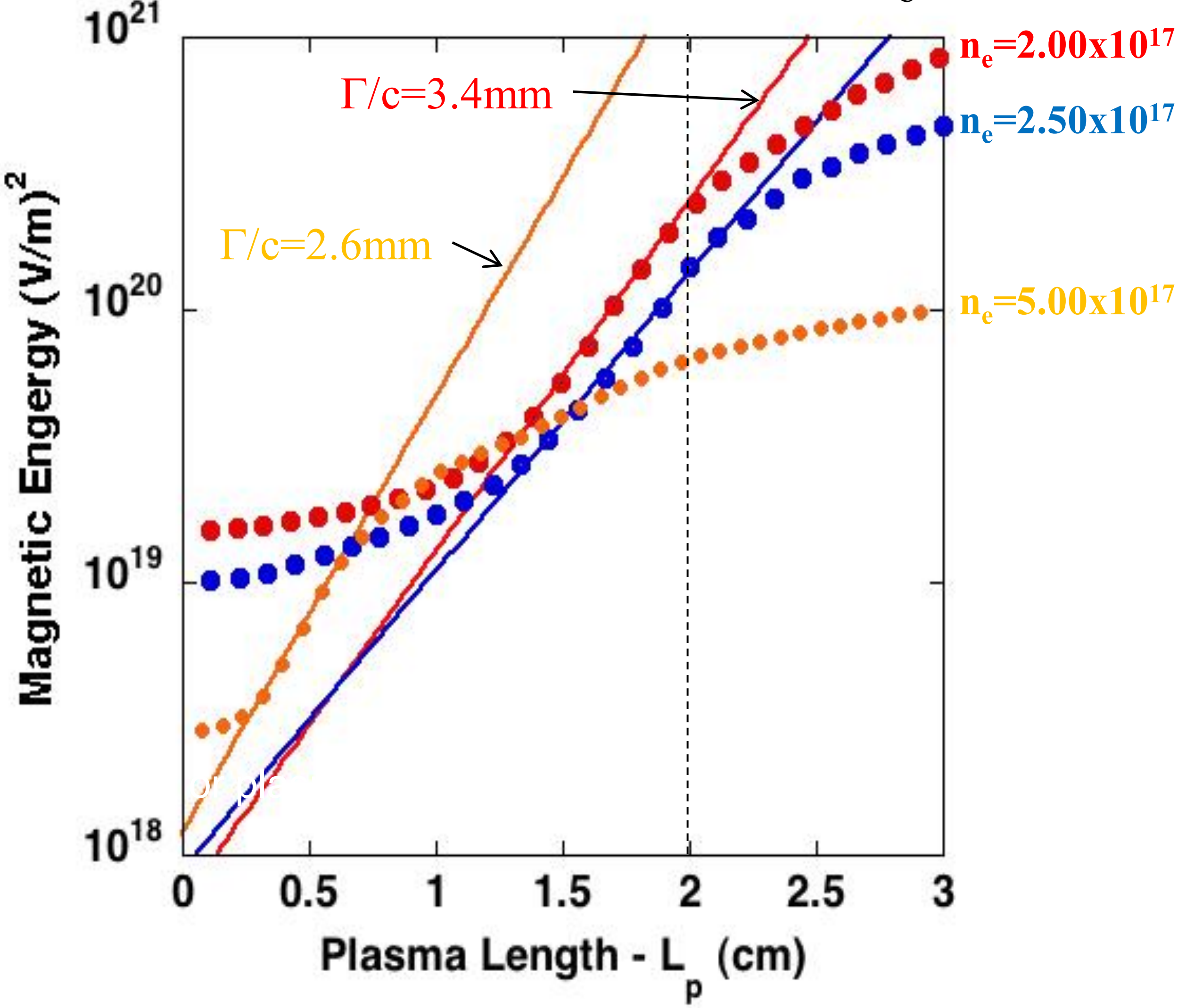
PIC Simulations – Growth Rate

- Theory
  - For infinite transverse size: $\Gamma \sim n_b^{1/2}$
  - Independent of n_e
- Simulations
  - Dependence on n_e
  - Earlier saturation

Growth Rate with constant n_b



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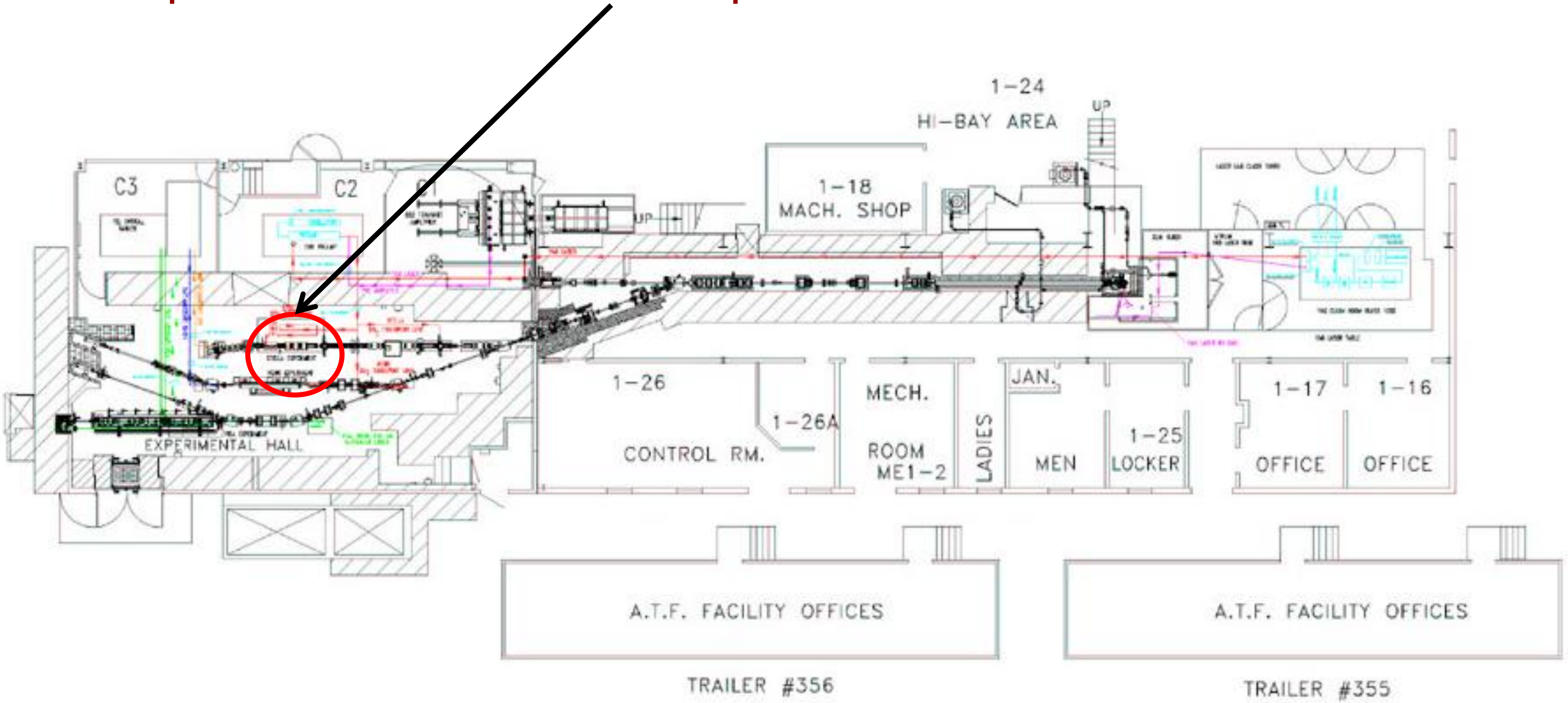
Experiment

- Experiment on BL #1 – Compton Chamber



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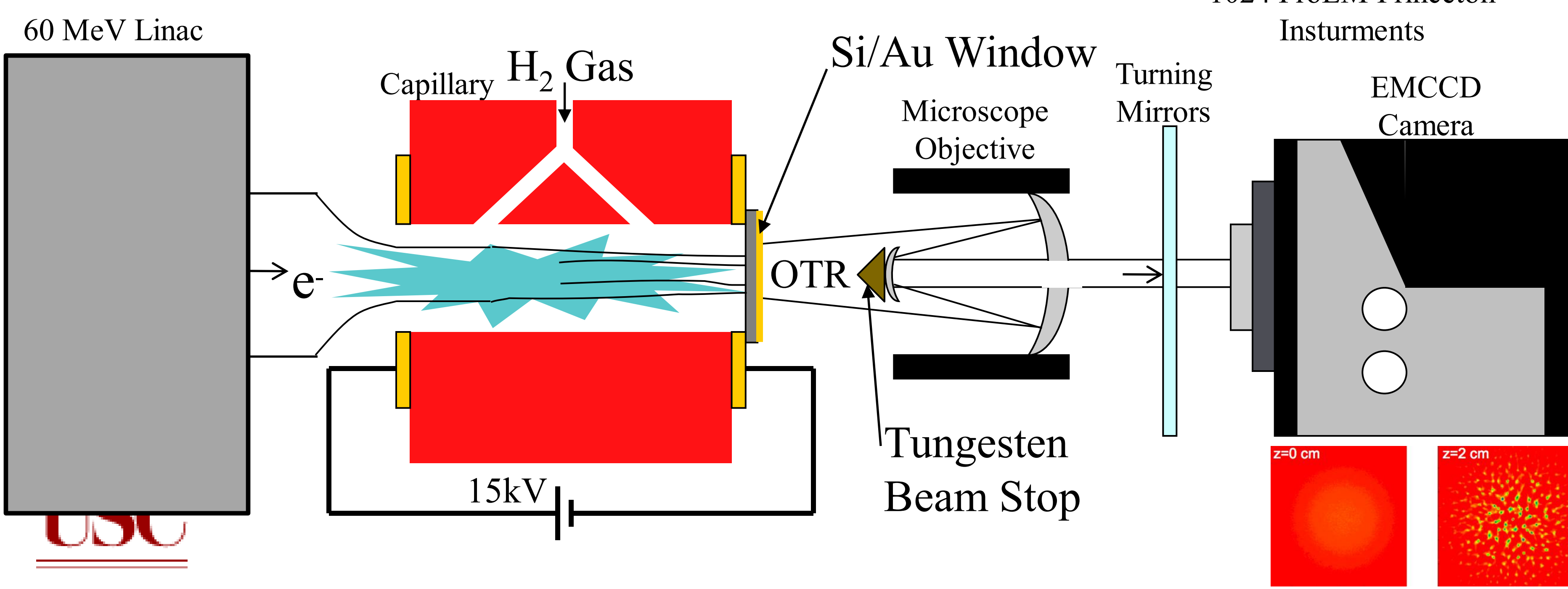
Direct Filament Imaging

- Micron resolution of transverse bunch
  - Si-window - low scattering, terminates plasma
  - Au coating for Optical Transition Radiation Generation
  - Resolution 3.9μm/line (USAF 1951 Target – 50% MTF)

1024 ProEM Princeton Insturments



Summary

- Designed imaging system for transverse bunch size measurement with micron resolution
- CFI observed and studied at the ATF
  - Transverse imaging of multiple (1-5) filaments
  - Multiple filaments observed for $k_p\sigma_{0y}$>2.2 (theory $k_p\sigma_r$>1)
  - Filament size and position vary event to event
  - Scaling of filament size with plasma skin depth
  - Suppression of CFI with reduced charge ($\Gamma \sim n_b^{1/2}$)
  - Focusing for $k_p\sigma_r$<<1
- Paper in preparation

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THANK YOU ATF!

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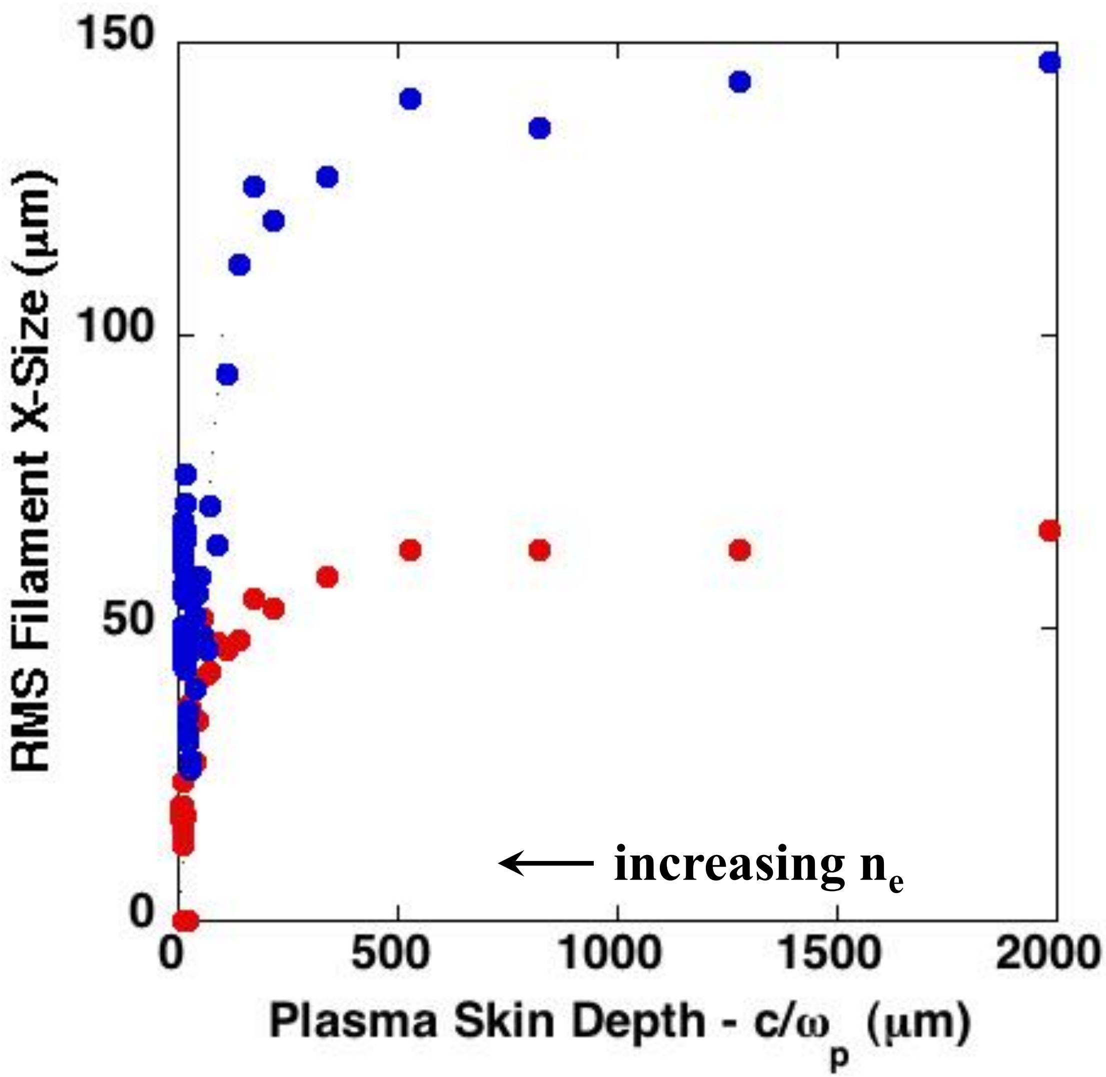
FOCUSING?

- Red – High Charge (1.0nC)
  - σ_{0x}=80μm, σ_{0y}=53μm
- Blue – Low Charge (0.54nC)
  - σ_{0x}=95μm, σ_{0y}=49μm
- Similar trends but scaling with charge!



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