Proposal: Experimental Investigation of the Current Filamentation Instability

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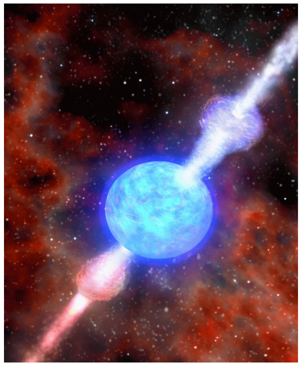
Work Supported by US DOE

Motivation

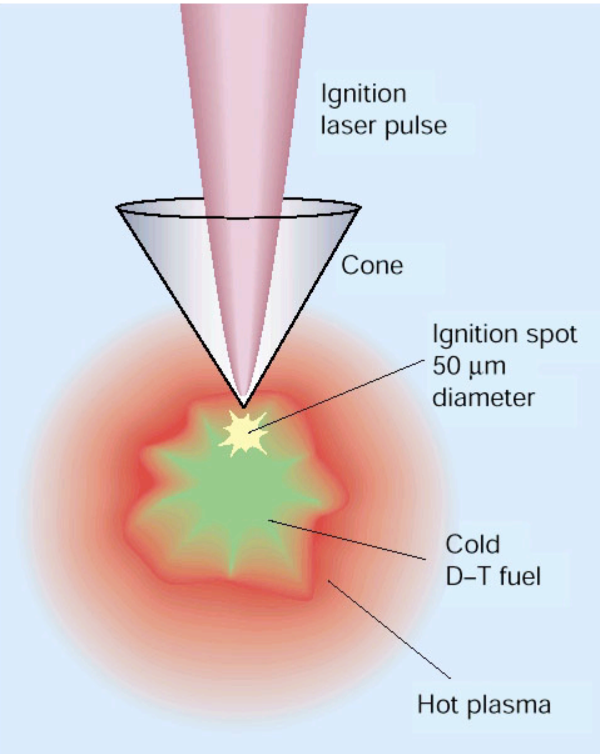


- Particle beam transport in plasmas is subject to Current Filamentation Instability (CFI)
- CFI results in breakup of the beam into narrow high current filament
- Generation of magnetic fields
- Gamma Ray Bursts (GRBs)
  - Phenomena which creates GRBs, afterglow and associated magnetic fields is unknown
  - Fireball theory - relativistic, collisionless shocks of electrons, positrons and ions
  - Energy Spectrum of GRB's - radiation produced by synchrotron radiation in random tangled magnetic fields (jitter radiation)

Ref: (image) http://astroguyz.com

Motivation

- Fast Igniter - Inertial Confinement Fusion (ICF)[1][2][3]
  - Contribute to generation of magnetic fields
  - Affect energy transport and deposition in fusion pellet



[1]Sentoku et al., Phys. Rev. Lett. 90, 155001 (2003)
[2]Bret et al., Phys. Rev. Lett. 94, 115002 (2005)
[3]Deutsch et al., Transport Theory and Statistical Physics, Volume 34, Issue 3 - 5, 353 (2005)
(image) M. Key Nature 412, 775-776 (23 August 2001)

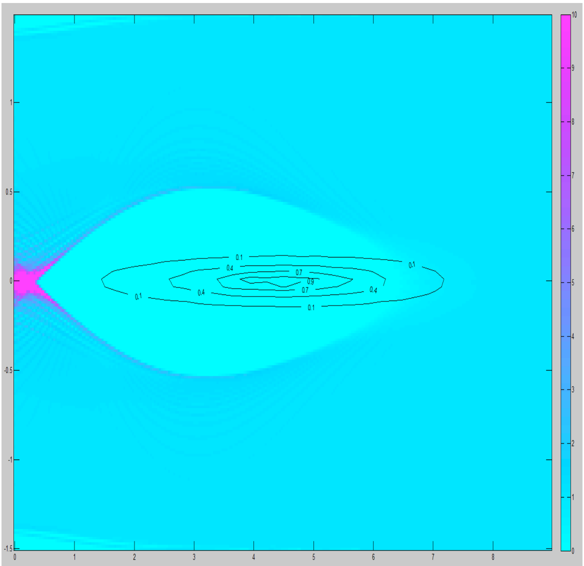
Proposal

- Directly and systematically study Current Filamentation Instability (CFI)
  - Previous measurements yielded inconclusive results[1]
  - ATF offers independent control of both beam and plasma
  - Basic plasma instability, potential impact on Astrophysics and Inertial Confinement Fusion[2]
  - Interdisciplinary: Simulations and Experiments
    - Plasma physics
    - Beam physics
    - Radiation physics
  - With ATF parameters simulations show CFI should unambiguously be observed
  - Study CFI as function of beam and plasma parameters

(1) Tatarakis et al., Phys. Rev. Lett. 90, 175001 (2003); (2) Honda, Phys. Rev. E 69, 016401 (2004)

CFI Overview

- Two regimes for electron beam/plasma interactions based on ratio of transverse beam size (σ_r) to collisionless skin depth (c/ω_{pe})
- Regime 1: $\sigma_r << c/\omega_{pe}$ ($k_p\sigma_r << 1$) - wakefield generation
  - Plasma return current flows <u>outside</u> of beam
  - Drives <u>wakefields</u>, used in PWFAs
  - Dominant instability - hosing, $\sigma_z >> c/\omega_{pe}$ ($k_p\sigma_z >> 1$)



Defintions:

Plasma/Electron angular frequency: $\omega_{pe}=(n_e e^2/\varepsilon_0 m_e)^{1/2}$

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

CFI Overview

- Regime 2: $\sigma_r \gg c/\omega_{pe}$ ($k_p\sigma_r \gg 1$), CFI Regime
  - Plasma return current flows <u>inside</u> beam
  - Dominant instability dependent on relativistic beam factor (γ_0)
    - $\gamma_0 \sim 1$ - two stream instability (parallel instability)
    - $\gamma_0 \gg 1$ - CFI (transverse instability)
      - Particular case of the Weibel instability[(1)]
        - » Temperature anisotropy
      - Purely transverse electromagnetic instability - purely imaginary frequency
      - Non-uniformities in the transverse beam/plasma profile lead to unequal opposite currents and magnetic fields
      - Opposite currents repel each other -> instability and filamentation
      - Filament size and spacing $\sim c/\omega_{pe}$
      - Growth rate[(2)]:

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

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

[(1)]E. Weibel - Phys. Rev. Lett. 2, 83 (1959); [(2)]Bret et al., Phys. Rev. Lett. 94, 115002 (2005)

CFI with ATF Beam

ATF Over-compressed Beam Parameters

Parameter	Value
Charge (pC)	150 to 200
Beam Transverse Waist Size (μm)	100 to 200
Bunch Length (fs)	100
Beam Density (cm^{-3})	10^{14}
Energy (MeV)	59
Emittance (mm-mrad)	1 to 2

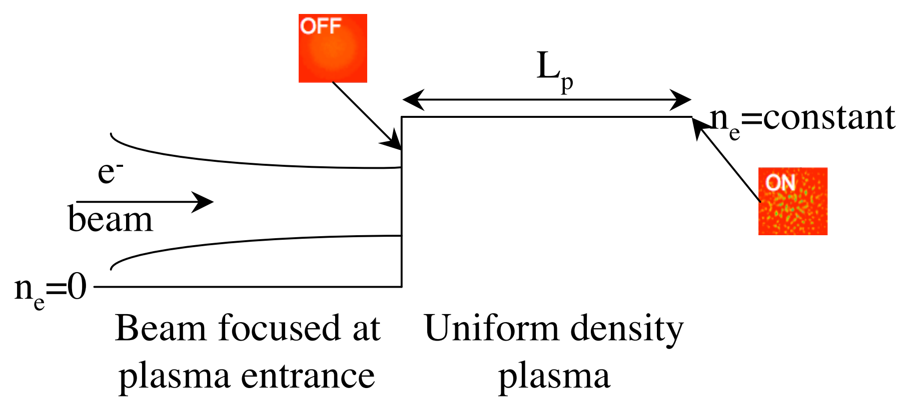
W.D. Kimura et. Al, AIP Conference Proceedings Volume 877, 534

- γ_0=117, CFI regime
- Growth rate estimate: Γ=8.6x10^{10} s^{-1} or 3.5 mm at *c*
- $\gamma_0 \gg 1$, $\sigma_r \gg c/\omega_{pe}$ and $\Gamma \sim n_b$
  – Need large σ_r and large n_b

CFI should be observable on a cm-length plasma scale

Simulation - Tools/Resources

- Simulation Tools: Particle-in-cell codes
  - OSIRIS
  - QuickPIC
  - PWFA and ICF
  - Both codes have been benchmarked against other codes and with experimental results
- Hardware Resources:
  - NERSC supercomputer
  - USC HPCC 30 Tflops cluster
- Simulation Setup



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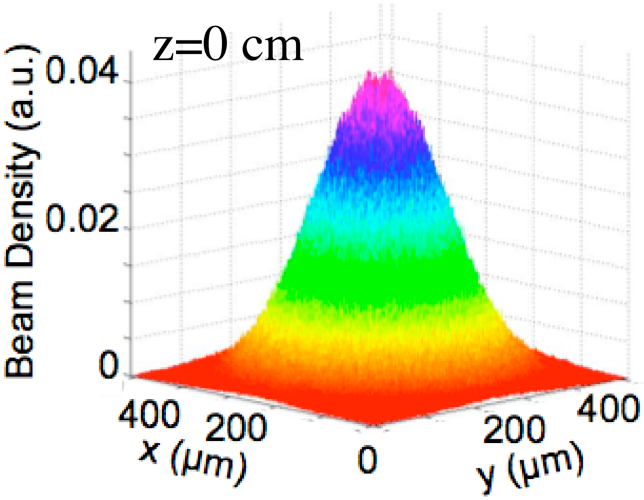
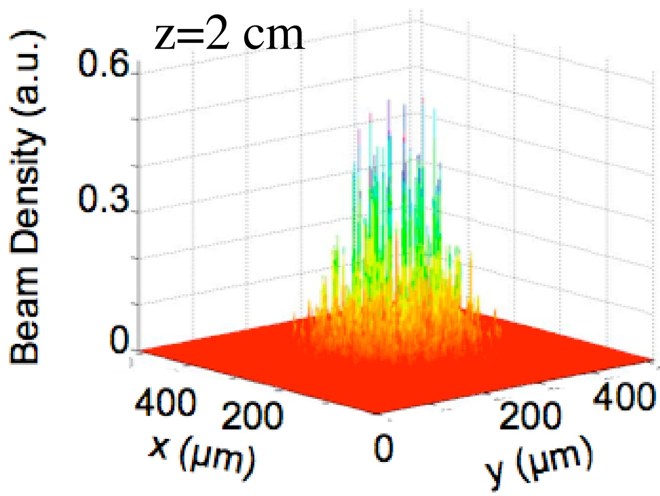
Simulation - Filamentation

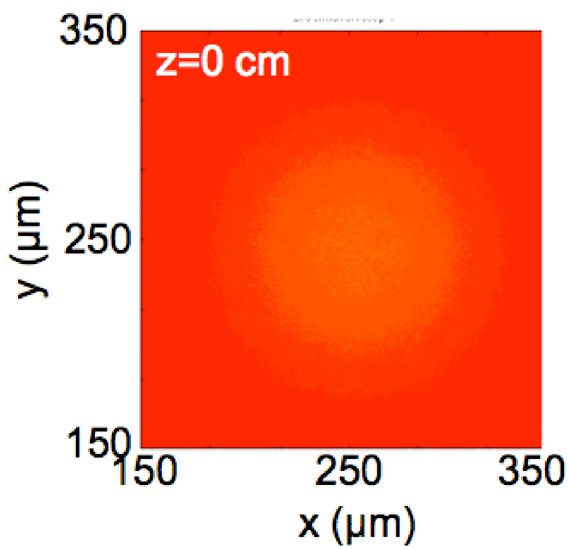
Beam focused at the entrance of a uniform density plasma

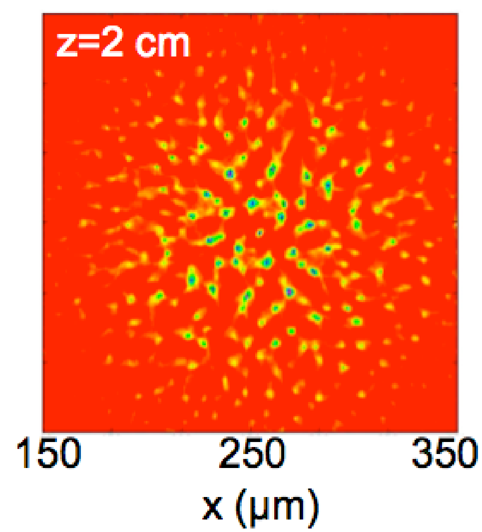




ATF Beam and Plasma Simulation Parameters

Parameter	Value	Value
Simulation Box – X	548 μm	512 cells
Simulation Box – Y	548 μm	512 cells
Simulation Box – Z	136 μm	128 cells
Plasma Particles/Cell	4.0	
3-D Time step (μm)	100	
Number Beam Particles -X	128	
Number Beam Particles -Y	128	
Number Beam Particles -Z	512	
Relativistic Factor	100	
Beam Transverse Waist Size (μm)	100	
Bunch Length (μm)	15	
Charge (pC)	200	
Plasma Density (cm^{-3})	$5x10^{17}$	
Capillary Length (cm)	2	
Skin depth (c/ω_{pe}) (μm)	7.5	





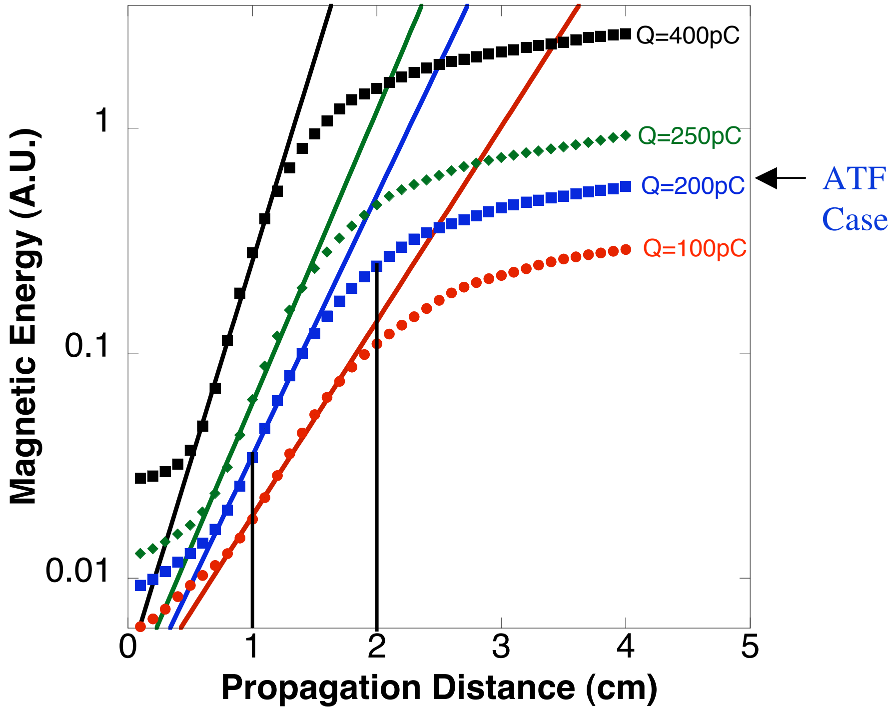
Filament size 4 μm
Filament spacing 20 μm
Both ≈ c/ω_p

These images are similar to those we expect to measure in the expt.

CFI Growth Rate (Γ)

Characterize instability by the resulting magnetic energy $\approx \int B_{perp}^{2} dv$

- Growth rate is ~ beam density (n_b) ~ charge
- For Q=200 pC, Γ = 8.0×10^{10} s^{-1} or 3.8 mm, agrees with estimated (Γ=8.6×10^{10} s^{-1} or 3.5 mm)

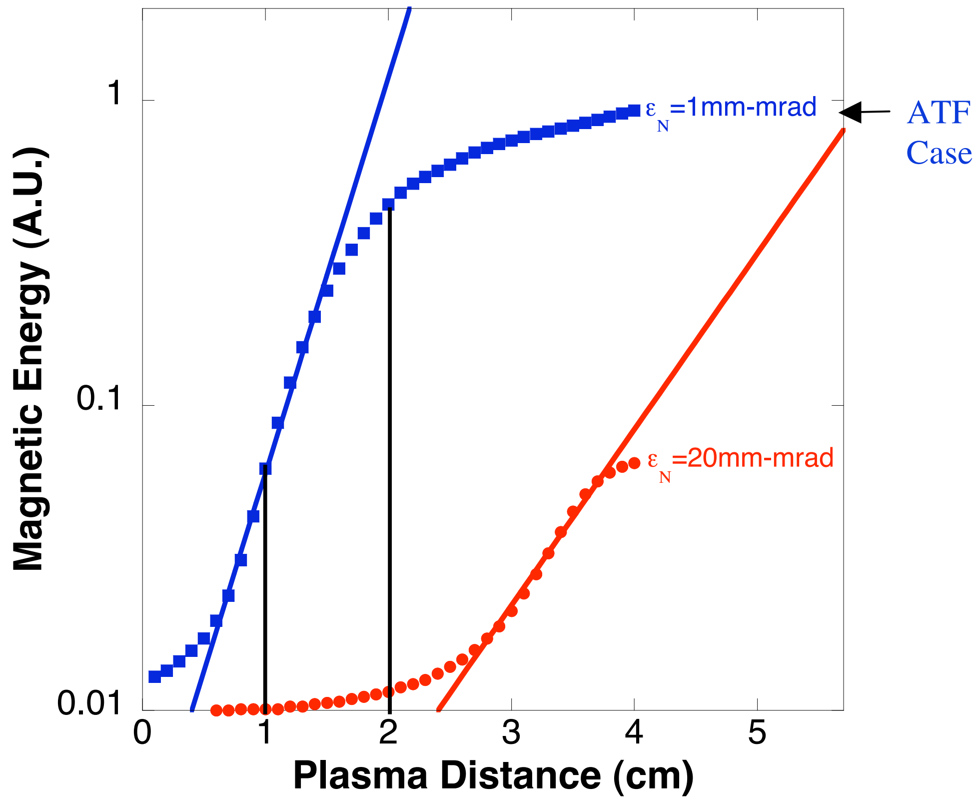


Instability appears over available plasma lengths (1 and 2 cm)

Parameters: $\varepsilon_{x,y}$ = 1mm/mrad, all other parameters as shown in simulation parameters table

Emittance Effects

- Emittance competes with CFI [1]
- Increased emittance reduces CFI growth rate
- Similar to temperature effect in Weibel instability [2]



Transverse emittance not an issue for ATF parameters (ε_N=1 - 2 mm-mrad)

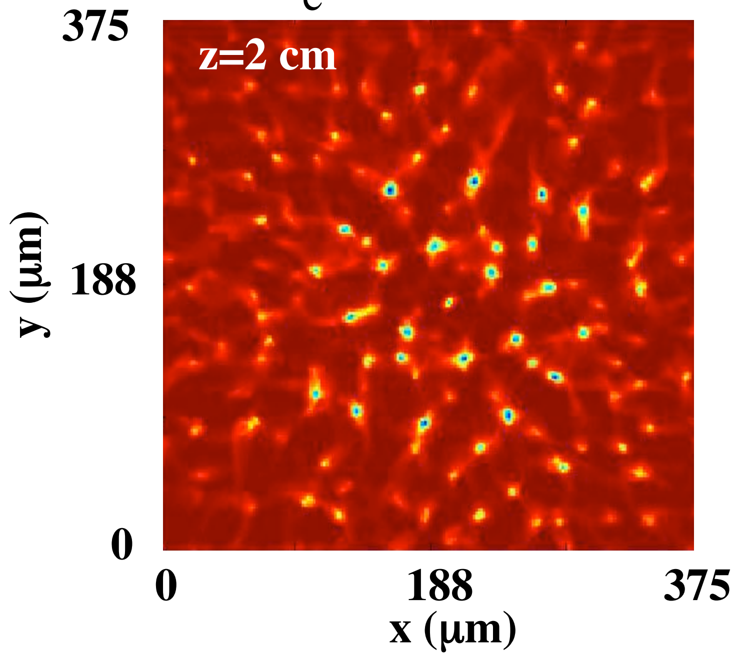
Parameters: $\varepsilon_{x,y}$ = 1mm-mrad and 20 mm-mrad, all other parameters as shown in simulation parameters table

[1] J.R. Cary et al., Phys. Fluids 24, 1818 (1981); [2] L. Silva et. al - Phys. of Plasmas 9, 2458 (2002)

Plasma Density Effects

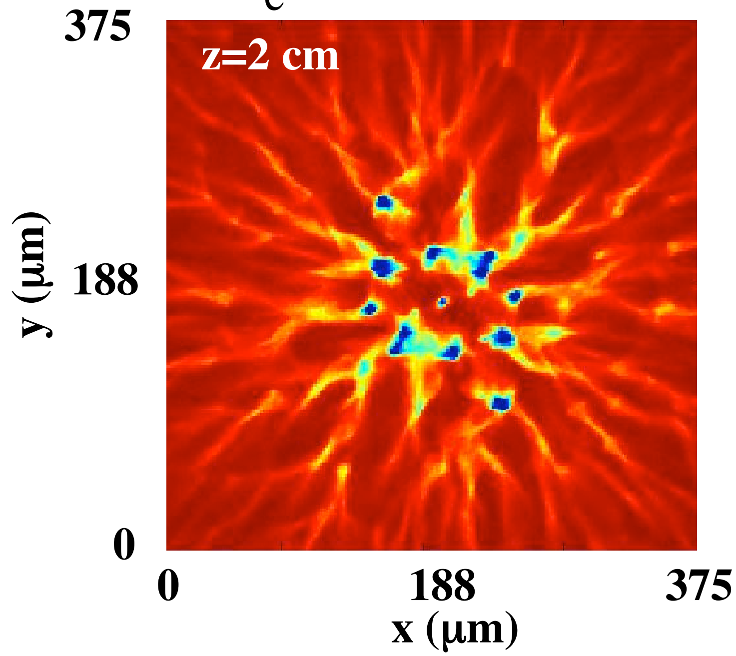
- Filament size ~ $c/\omega_{pe} \sim 1/\sqrt{n_e}$
- Filament size increases with decreased n_p

$n_e = 5 \times 10^{17}\ \mathrm{cm}^{-3}$



Filament size ~4 μm

$n_e = 2.5 \times 10^{17}\ \mathrm{cm}^{-3}$



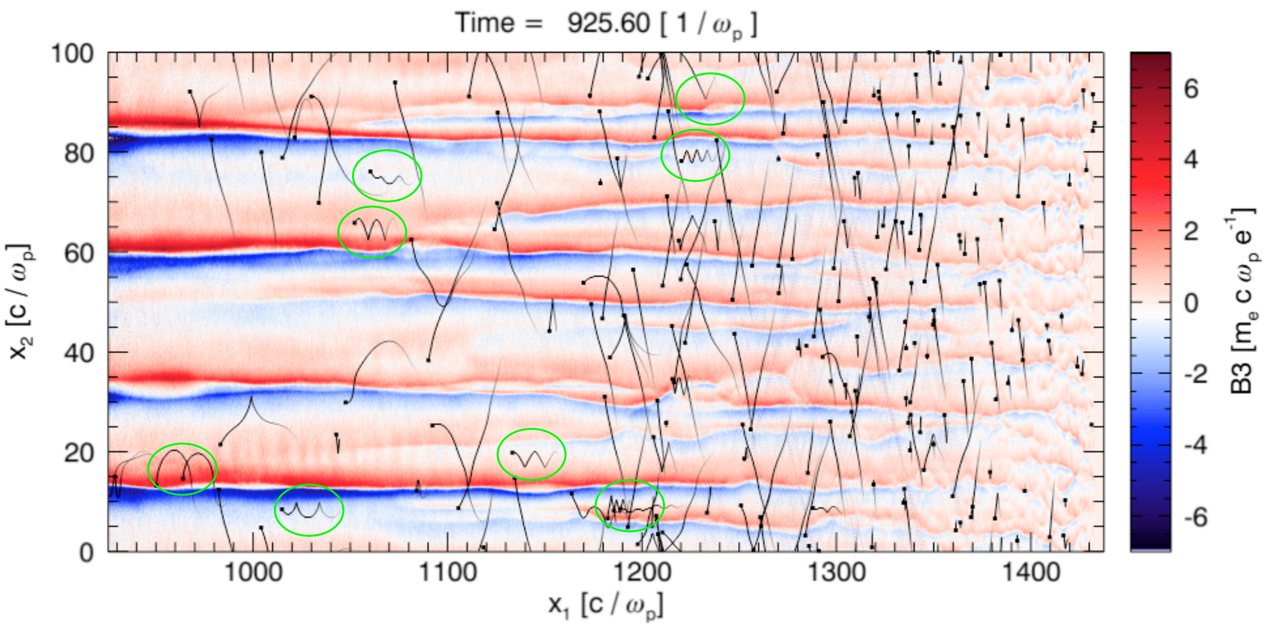
Filament size ~6 μm

At $n_e = 1 \times 10^{17}\ \mathrm{cm}^{-3}$ no filamentation observed

Radiation Simulations

- CFI generates magnetic fields
- Beam and plasma particles oscillate and radiate
- Example of simulation result

Particle tracks in magnetic field strength contours in plasma/plasma collision

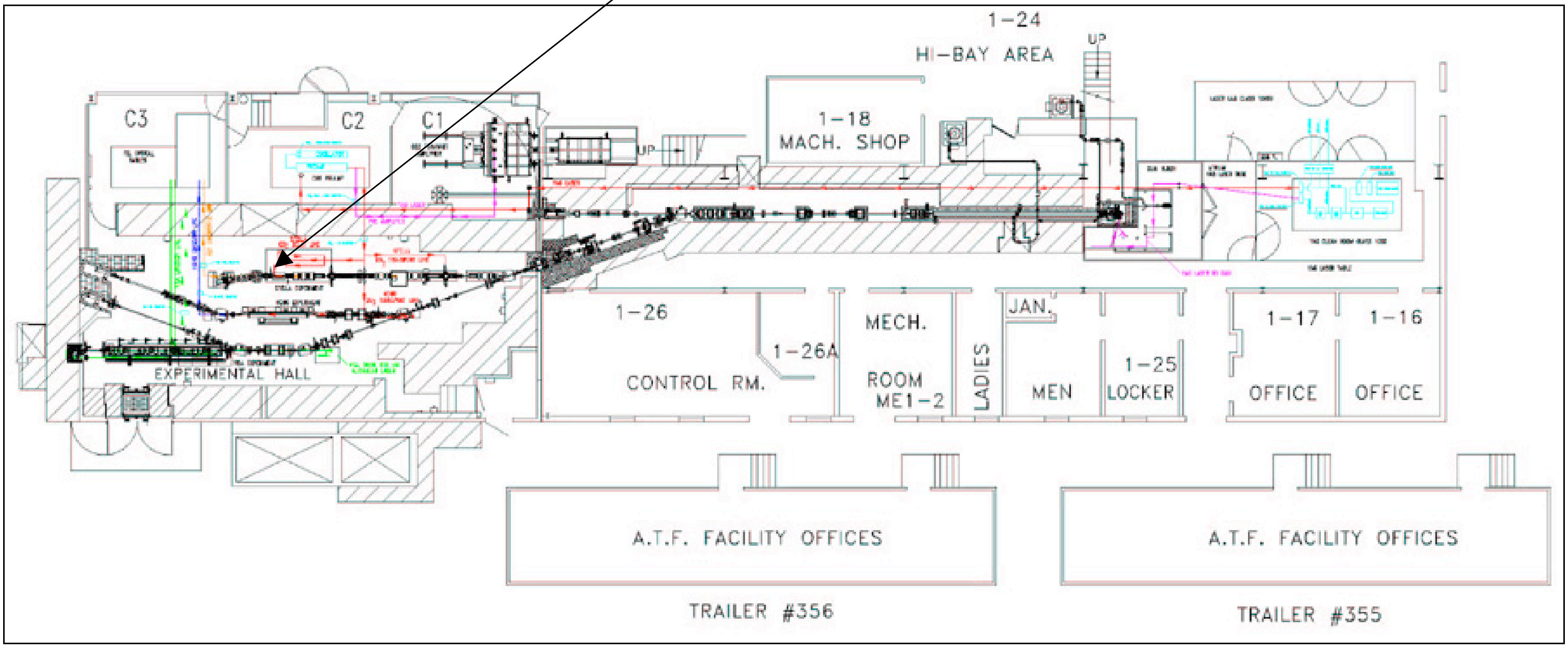


•Radiation parameters can be calculated from particle trajectories

Appearance of radiation indicates appearance of CFI

Experimental Setup - Beam Line 1

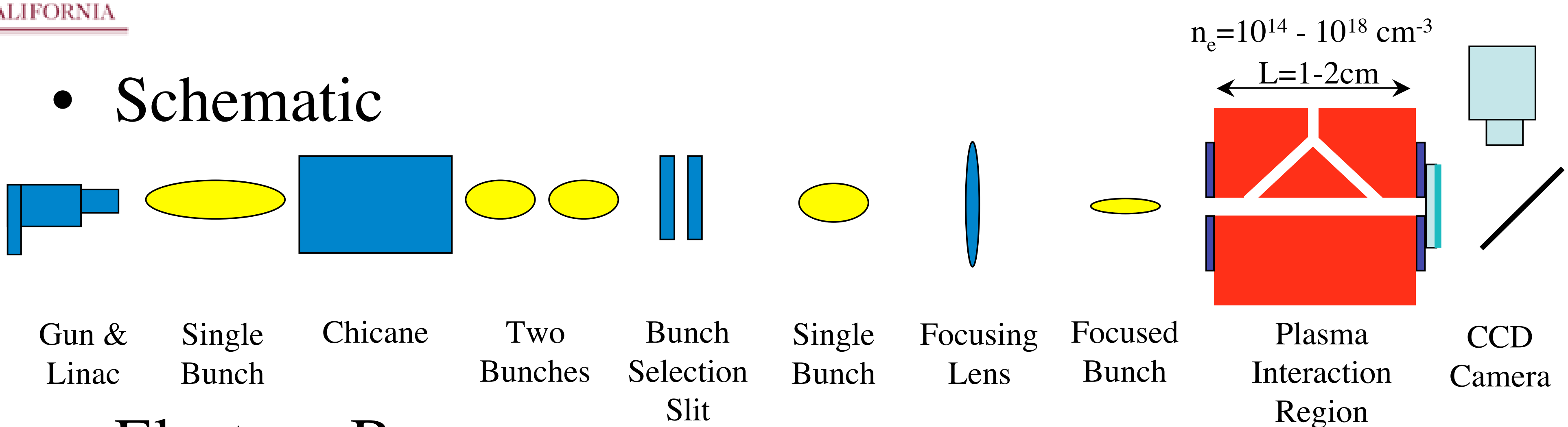
Experiment Beam Line 1 (Compton Scattering)



Ref: (image) http://www.bnl.gov/atf/core_capabilities/images/ATF_Layout.pdf

Experimental Setup

- Schematic



- Electron Beam
  - Focused to σ_r=100 μm at capillary entrance
  - Compressed density(1): 2.6×10^{14} cm^{-3}
  - Uncompressed density: 4.4×10^{13} cm^{-3}
    - Simulations show no instability
  - Variable beam parameters:
    - Beam radius (σ_r)
    - Emmitance ($\varepsilon_{x,y}$)
    - Charge (with x-band cavity)

(1) E. Kallos et. al - Phys. Rev. Lett. 100, 074802 (2008)

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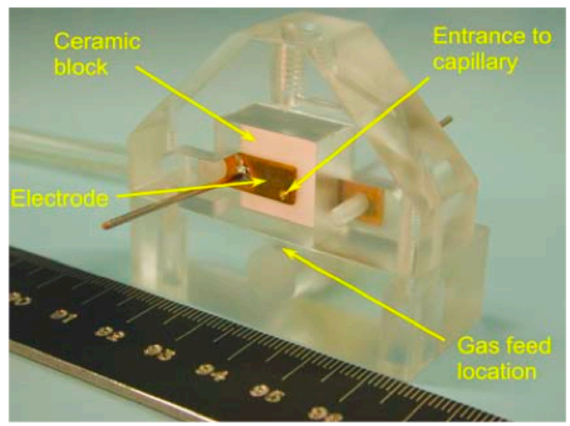
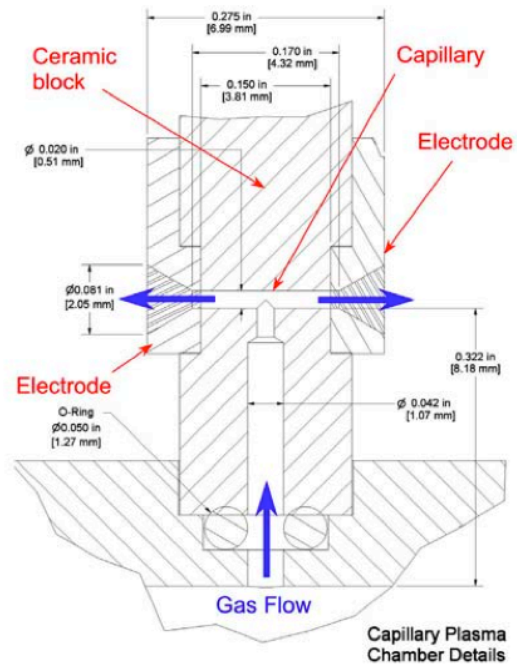
Experimental Setup - Plasma Source

- Plasma Source
  - H_2 capillary discharge
  - Capillary/plasma have radius of ~ 500 μm
  - Variable plasma parameters:
    - Capillary length (1cm and 2cm)
    - Plasma density: H_2 pressure and beam arrival time



(a)



(b)

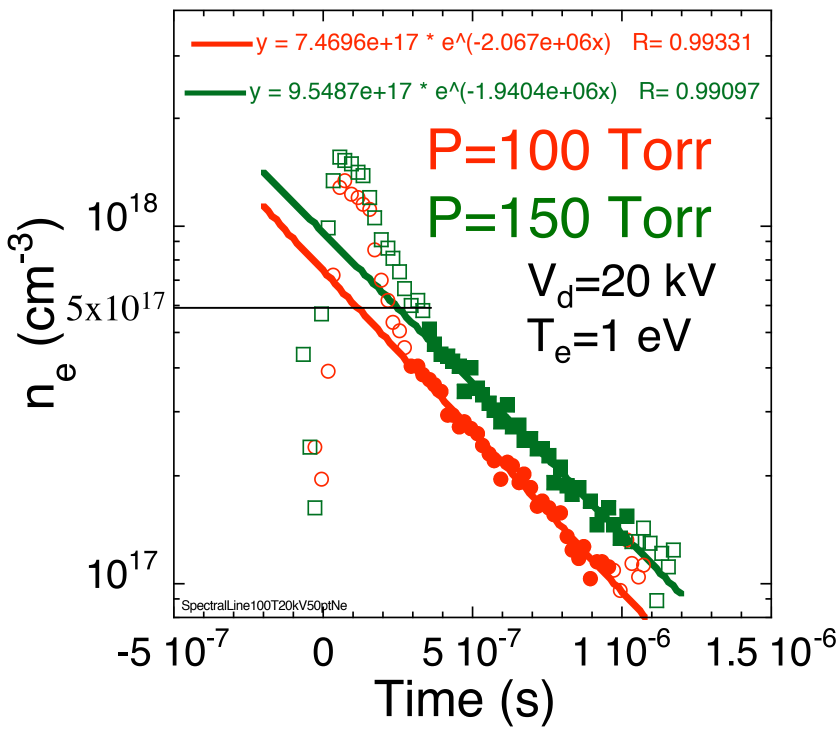
Ref: (image) W.D. Kimura et. Al, AIP Conference Proceedings Volume 877, 534

Experimental Setup - Plasma Density

- Plasma Density
  - Density controlled by delay between plasma and beam
  - Measured as function of time with Stark broadening of the hydrogen H_α line at 656nm[1]

$$n_e\left[cm^{-3}\right] \cong 8 \times 10^{12}\left(\frac{\Delta\lambda_{1/2}[A]}{\alpha_{1/2}}\right)^{3/2}$$

$$n_e(t),\ \Delta\lambda_{1/2}(t)$$

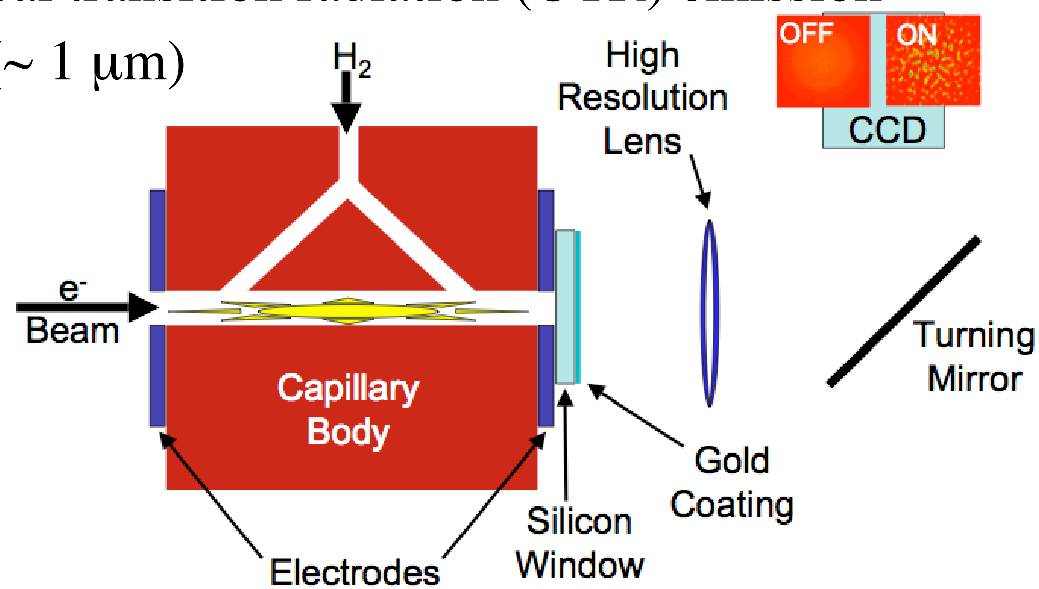


Plasma density actually measured

[1] R.C. Elton, H.R. Griem - Phys. Rev. 135, A1559 (1964)

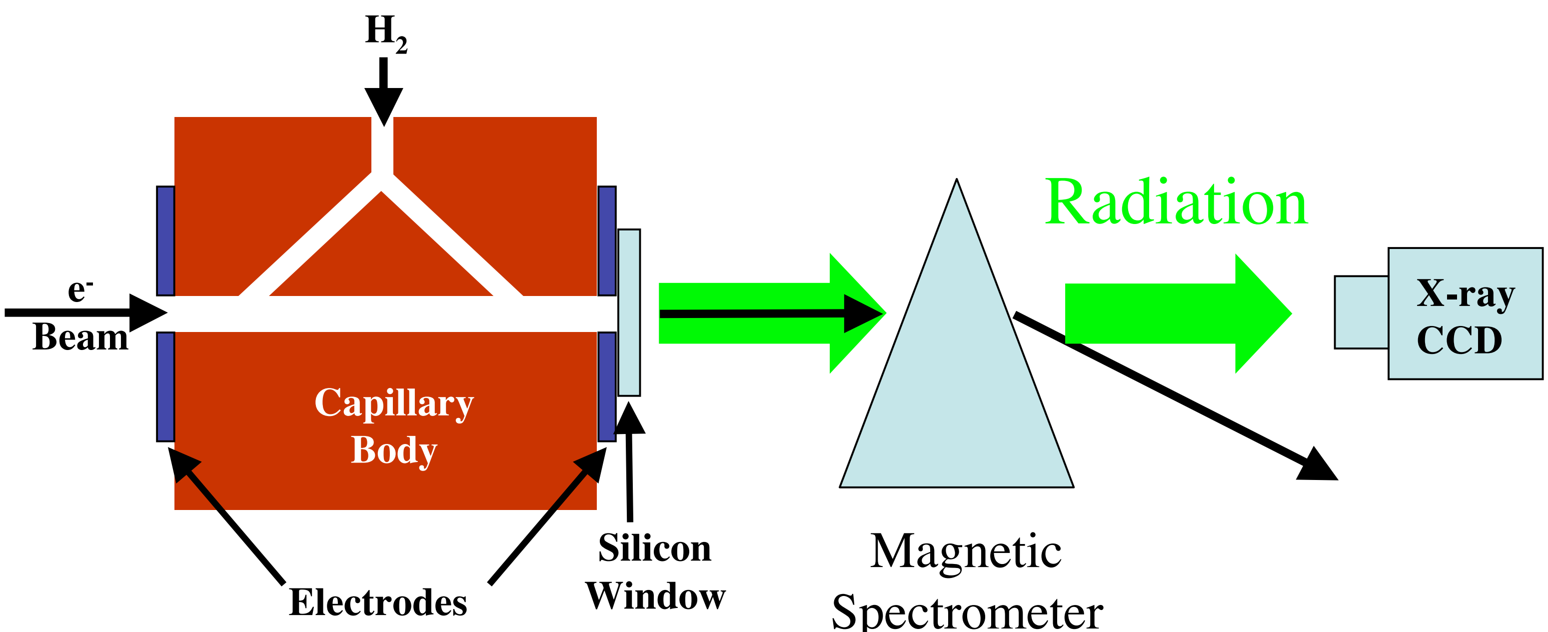
Experimental Setup - Diagnostics

- CFI Imaging Diagnostic
  - Measure: filament size, spacing and number
    - Need to resolve on the scale of c/ω_p (~4μm)
  - Setup
    - Silicon window at capillary exit (~100μm, for minimun scattering)
    - Gold coating for optical transition radiation (OTR) emission
    - High resolution lens (~ 1 μm)
    - Turning mirror
    - CCD camera



Experimental Setup - Diagnostics

- Radiation Diagnostic
  - Compton scattering experiment diagnostic, CCD-camera - shad-o-snap 1024 sensitive in the 10-50 keV range
  - Beam-plasma interaction background
  - Look for increased radiation level at CFI onset
  - Beam/radiation separated by magnetic spectrometer
  - Radiation parameters to be determined from simulations



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Summary

- Systematically study instability as function of beam and plasma parameters
  – Experimentally and through simulations
- Beam and plasma parameters are independently and well controlled
- Most hardware and experience available
- CFI has not been convincingly observed before
- Basic plasma instability, impact on Astrophysics and ICF
- Different regime than PWFA
- Calculations and simulations indicate that with ATF parameters CFI should be unambiguously observed

Thank You