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Update-Current Filamentation Experiment

ATF User Meeting

October 7, 2010

- Brian Allen –

Brookhaven National Laboratory
Accelerator Test Facility

UCLA

INSTITUTO SUPERIOR TÉCNICO
Universidade Técnica de Lisboa

Work supported by DoE and NSF

Agenda

- CFI Overview
- Experimental program
- Progress to date
- Future work
- Summary

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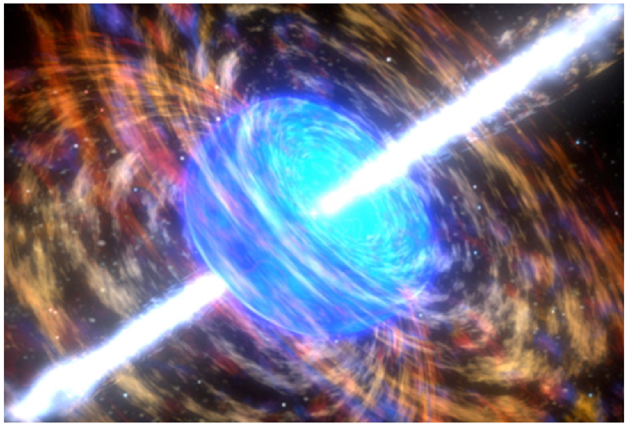
Current Filamentation Instability (CFI)

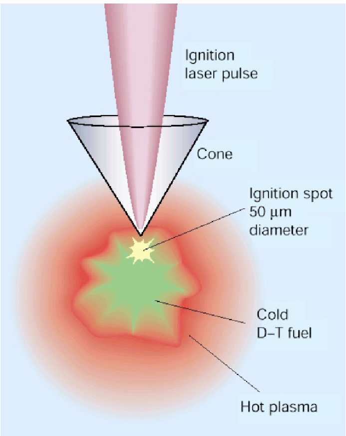
What is CFI?

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

Why is it interesting?

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





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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

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

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

Growth rate[1]:

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

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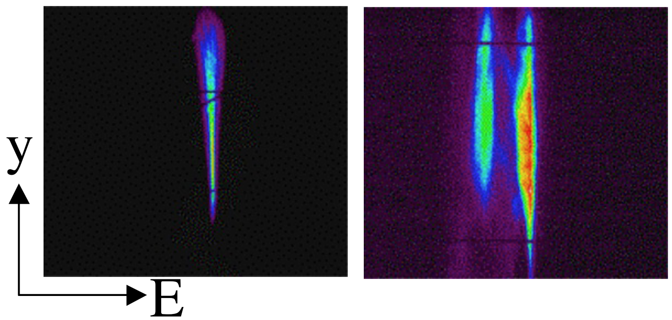
[1] Bret et al., Phys. Rev. Lett. 94, 115002 (2005)

CFI with ATF Beam



- Over-compression in the magnetic chicane results in breakup into two higher density bunches
  - Breakup due to spacecharge + coherent synchrotron radiation (CSR)
- Select bunch with high energy slit

ATF Over-Compressed Beam Parameters

Parameters	Value
Charge (pC)	180 or 300
Beam Transverse Waist Size (μm)	100
Bunch Length (fs)	~100
Beam Density (cm^{-3})	1.0×10^{14}
Energy (MeV)	58
Normalized Emittance (mm-mrad)	1 to 2 (?)

- W.D. Kimura et. al, AIP Conference Proceedings Volume 877, 527 (2006)
- E. Kallos et. al., Physical Review Letters, 100, 074802 (2008)

- γ_0=117
- Growth length estimate:

$\Gamma=8.6\times10^{10}$ s^{-1} or 3.5 mm at *c*

$\gamma_0 >> 1$, $\sigma_r >> c/\omega_{pe}$ for $n_e > 2.8\times10^{15}$ cm^{-3}

CFI should be observable on a cm-length plasma scale

(capillaries of length L_p = 1 or 2 cm are available)

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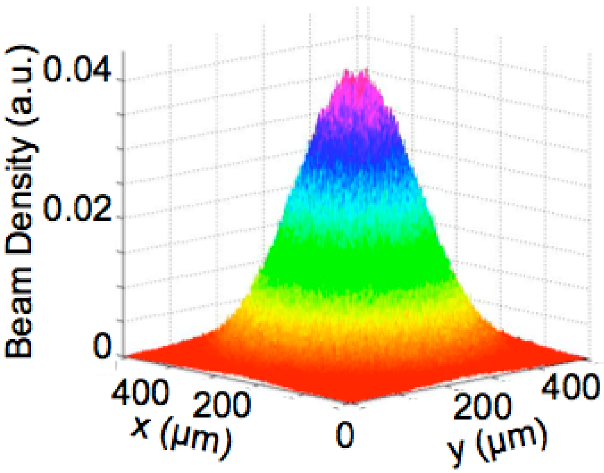
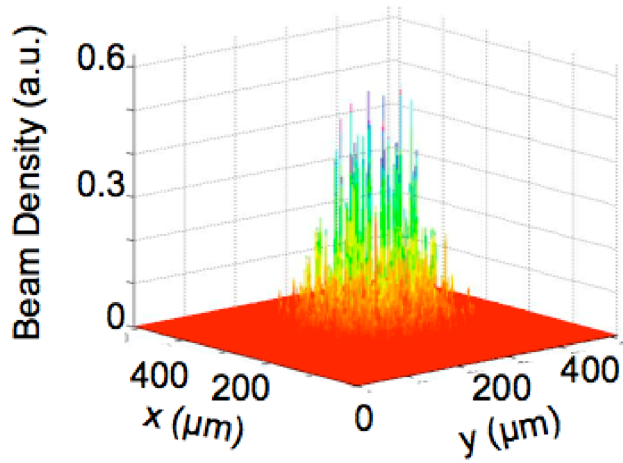
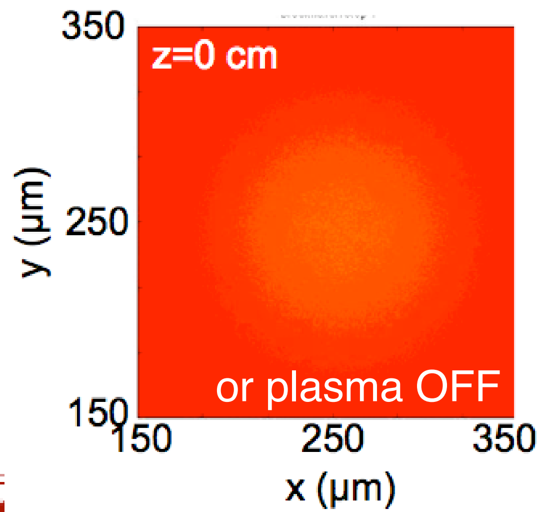
Simulations - Beam Filamentation

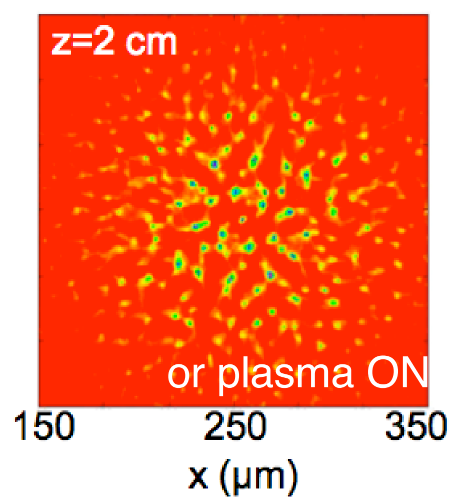




ATF Beam and Plasma Simulation Parameters

Parameters	Value	Value
Simulation Box - X (μm, # grids)	1100	512
Simulation Box - Y (μm, # grids)	1100	512
Simulation Box - Z (μm, # grids)	160	128
Plasma Particles/Cell	1	
3-D Time Step (μm)	34	
Beam Particles - X (#)	512	
Beam Particles - Y (#)	512	
Beam Particles - Z (#)	128	
Relativistic Factor	117	
Beam Transverse Waist Size (μm)	100	
Bunch Length (μm)	30	
Charge (pC)	200	
Plasma Density (cm^{-3})	2.5×10^{17}	
Capillary Length (cm)	2	
Skin Depth (c/w_{pe}) (μm)	10.6	





Filament size 10 μm
Filament spacing 20 μm
$c/\omega_{pe} \sim 10.6\mu m$

Simulations with QuickPIC - Warren Mori

Experimental Program

Phases

1. Imaging of beam filaments (beam/current density) at plasma exit
2. Measure/image plasma density gradients and magnetic field
3. Identify & measure radiation and spectrum
4. Evolution of instability along z (growth rate)

Phase 1 progress

- Integrated EMCCD camera into image capture system at ATF
- Imaging system resolution analysis
- Currently
  - Initial setup for imaging of beam filaments
  - Design and manufacture of components
  - First (beam & plasma) run scheduled for next week

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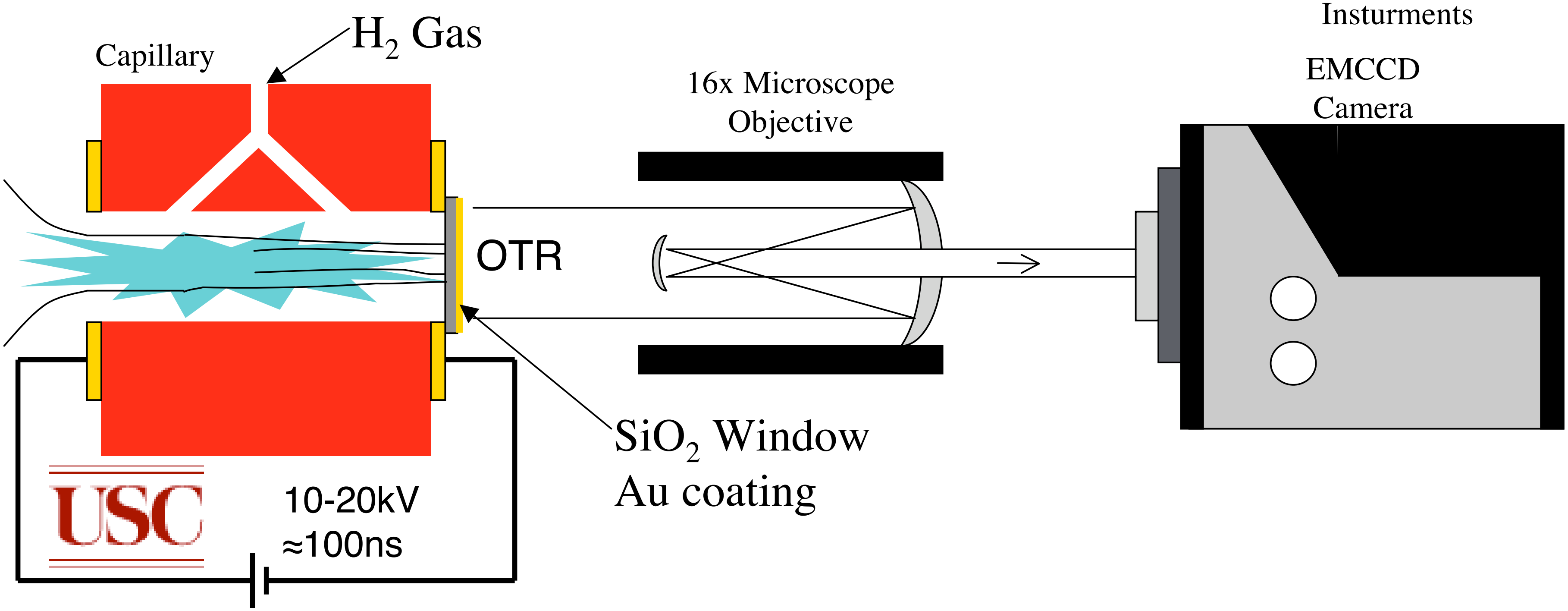
Direct Filament Imaging

- Si-window - low scattering, terminates plasma
- Au coating for Optical Transition Radiation Generation
- Challenge with low number of photons and high resolution

1024 ProEM Princeton Insturments



Filament Size Due to Scattering

- Filament exiting the plasma through window creates OTR
- Scattering due to SiO_2 window

$$\theta_o^{(1)} = (13.6\ \mathrm{MeV}/\beta cp)\ z\ (x/Xo)^{1/2}\ [1+.038\ \ln(x/Xo)]$$

βc – velocity, p – momentum, z – charge number, x – thickness, Xo[2] – radiation length

Filament Size After Scattering in Si

Window Thickness	Original Size	Si Window
100μm	10.6μm	11.7μm
200μm	10.6μm	13.9μm

- 100μm Window tested in test chamber for gas and plasma pressure up to 350 Torr at 15kV (Typical is 100 Torr)

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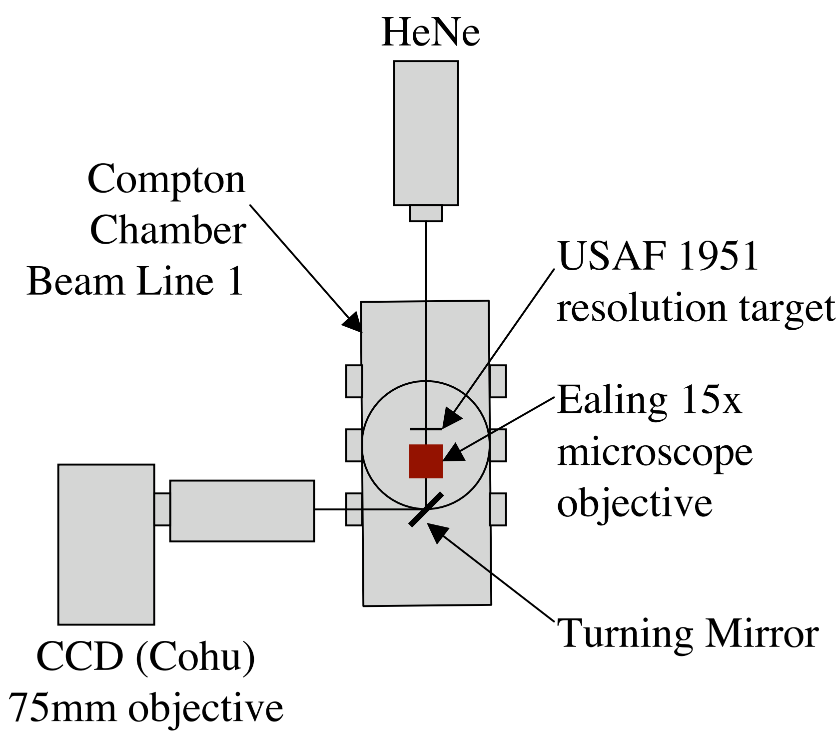
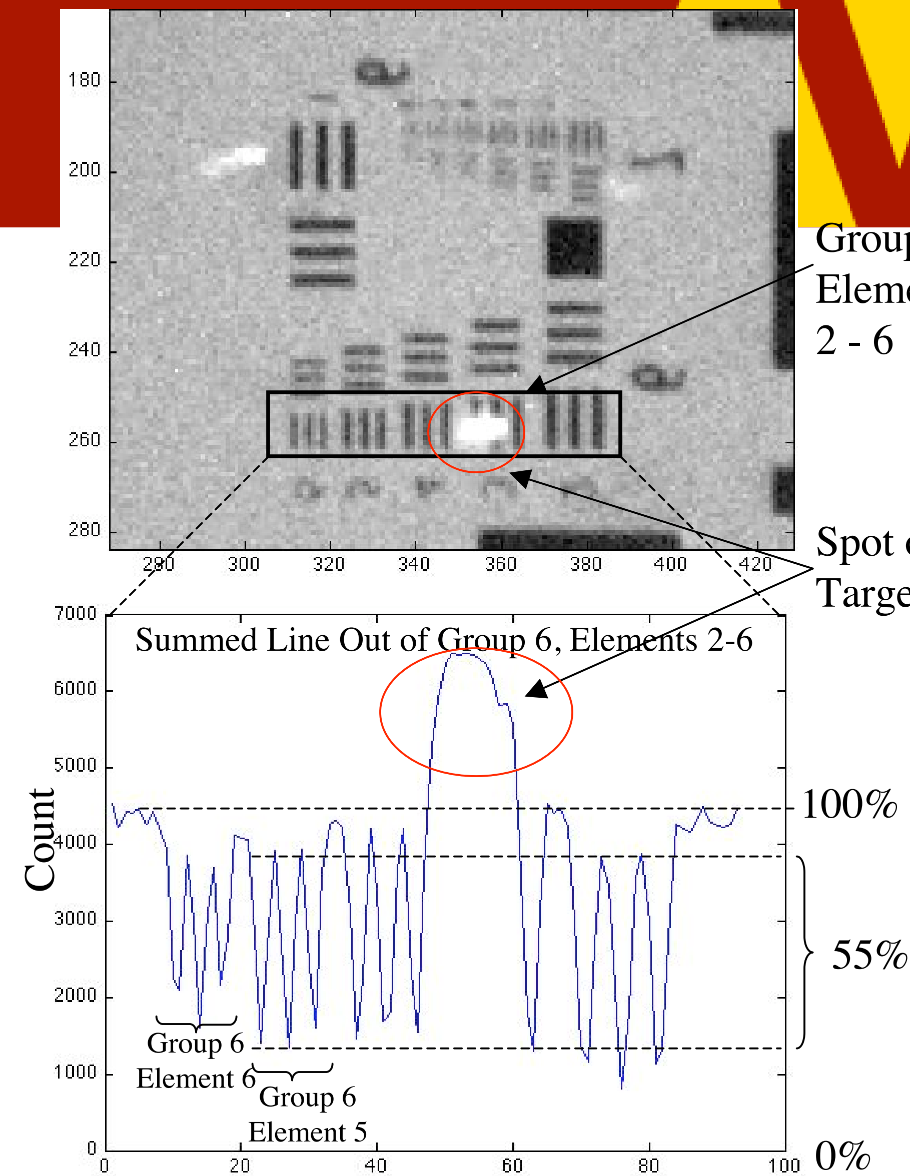
(1) Equation 27.12 - Phys. Letters B Vol. 667/1-5 (2008) 1-1340
(2) Table 6.1 - Phys. Letters B Vol. 667/1-5 (2008) 1-1340

Resolution Analysis - Inside Chamber





Non-uniform illumination of target

Better resolution with finer focusing adjustment

Camera pixel size limited

Group/Element	CCD Count Max	CCD Count Min	100% Level	% Modulation	# Line Pairs/mm	Resolution µm/Line Pair	Resolution µm/Line
6/2	3859	1031	4530	62.4%	71.8	13.9	7.0
6/3				-----No Data, spot on target -------			
6/4	4207	1568	4530	58.3%	90.5	11.0	5.5
6/5	3927	1451	4530	54.7%	102	9.8	4.9
6/6	3770	1955	4530	40.1%	114	8.8	4.4

Current Status

- Use ATF over-compressed beam
- Capillary discharge with ne=10^{15} - 10^{18} cm^{-3}
    - $n_e \sim 2.5 \times 10^{17}$ for experiment
    - Capillary length: L_p=1 or 2 cm
- Window/imaging system with ~5μm resolution

Ready for first phase - Imaging Filaments!

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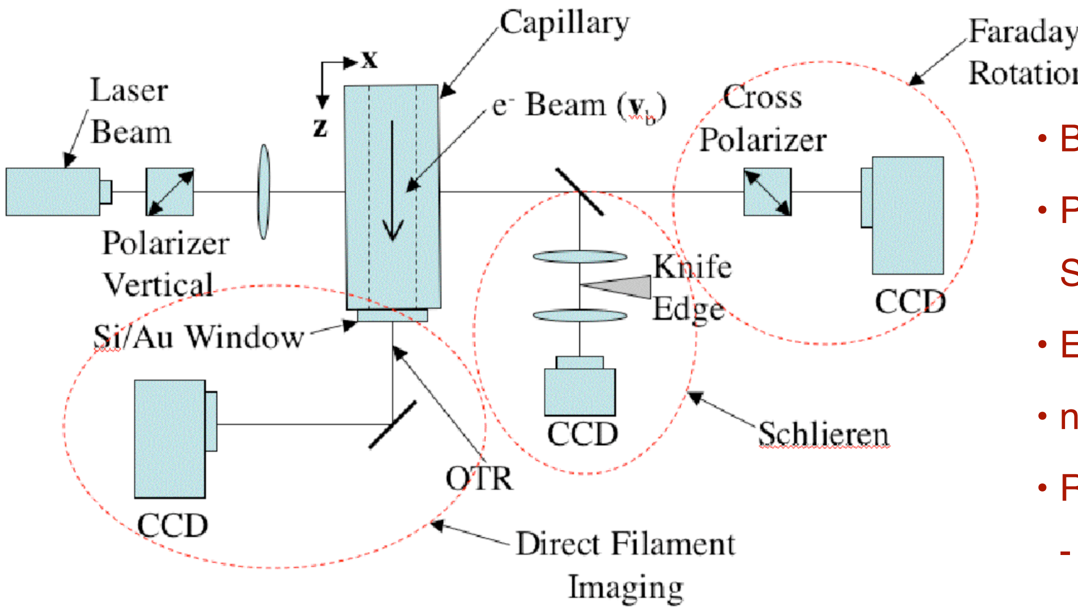
Future Phases

Phase 2) B-field and plasma density gradient



- B-Field - Faraday Rotation
- Plasma density (n_e) gradient - Schlieren/Shadowgraphy
- Evolution along z-axis (growth rate)
- n_e measurement (not shown)
- Require optically transparent capillary - Sapphire

Phase 3) Radiation

- Identify frequency of radiation - Collaborating with IST Portugal for simulations
  - Correlate filaments, magnetic field and resulting radiation
- Setup for radiation diagnostic
  - Use 90° spectrometer already on beam line 1, just after Compton Chamber
  - Detector/spectrometer to be determined

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Summary

- Simulations show CFI at ATF
- Resolution of imaging system sufficient
- Completed initial setup for imaging of beam filamentation
- First run with (beam and plasma) scheduled for next week
- Preliminary design for future stages underway
  - Correlation of plasma (n_e) perturbation and B-field generation with filaments
  - Growth Rate
  - Radiation

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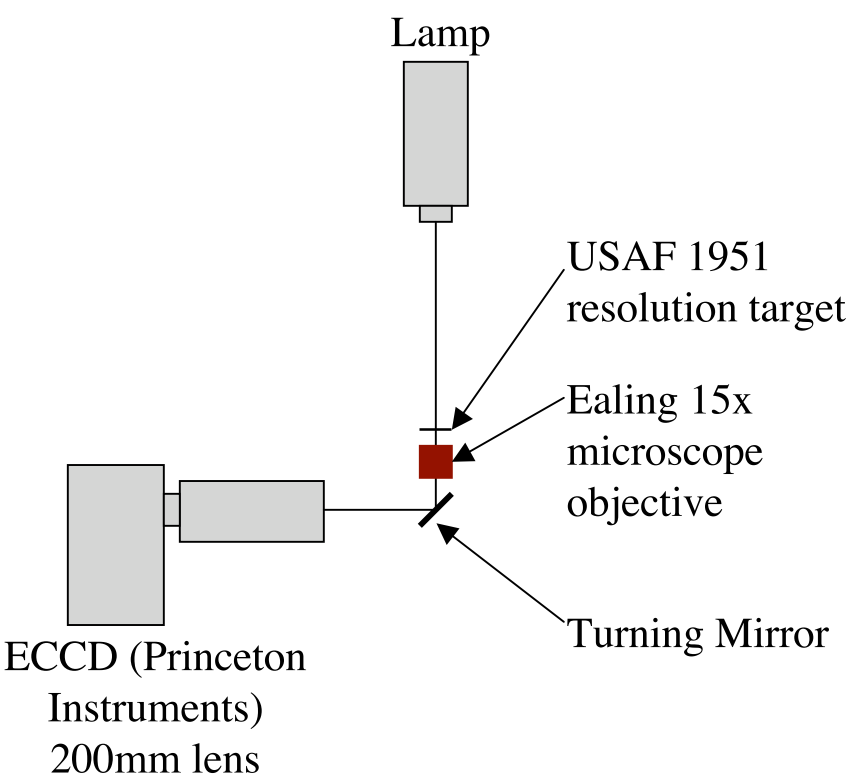
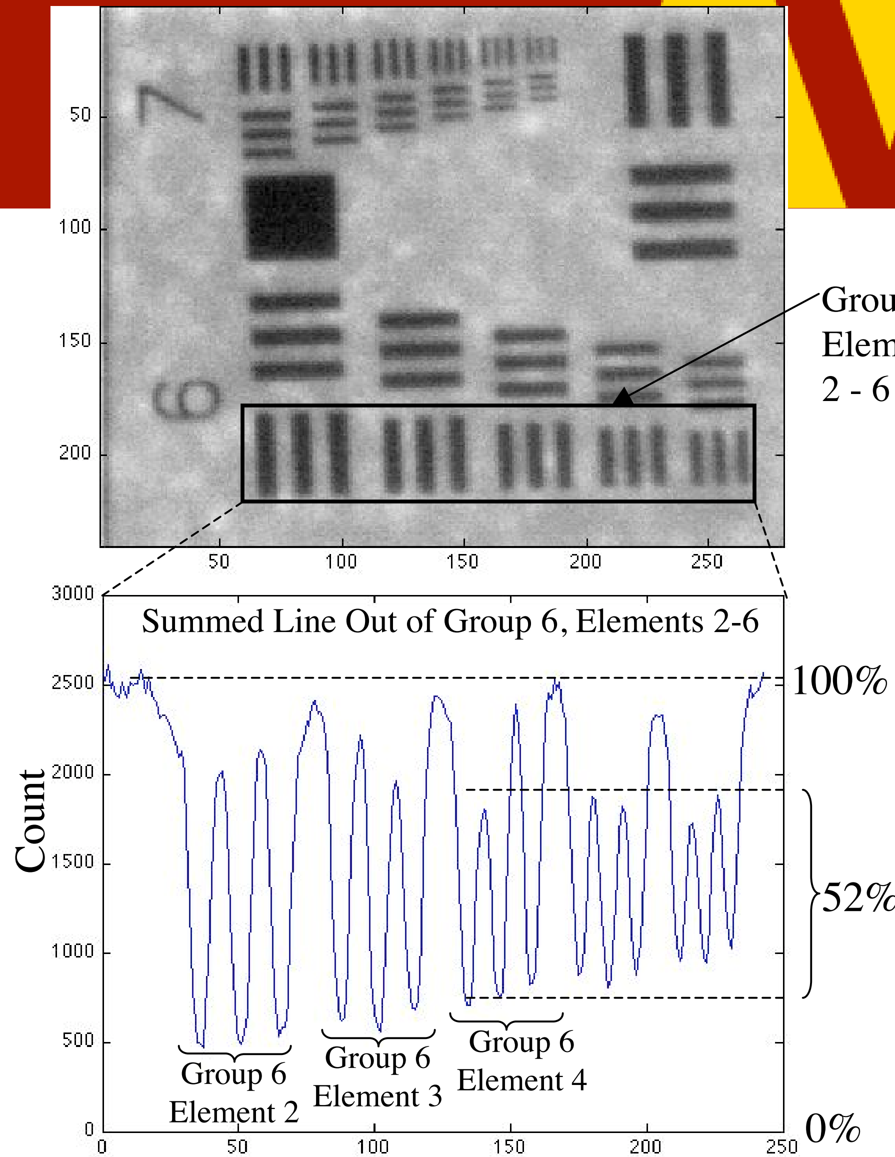
Thank You ATF!

Resolution Analysis
- Outside Chamber





	CCD Count				Resolution		
Group/Element	Max	Min	100% Level	% Modulation	# Line Pairs/mm	µm/Line Pair	µm/Line
6/2	2076	490	2585	61.4%	71.8	13.9	7.0
6/3	2085	620	2585	56.7%	80.6	12.4	6.2
6/4	2100	760	2585	51.8%	90.5	11.0	5.5
6/5	1865	851	2585	39.2%	102	9.8	4.9