Potential for Astrophysics Experiments in the Laboratory Using High-Brightness Particle Beams

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POSSIBLE EXPERIMENTS

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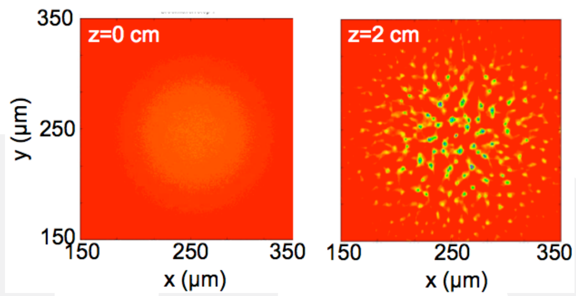
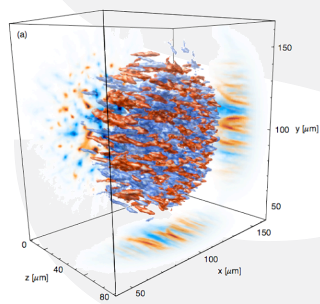
CALIFORNIA

1. Current Filamentation Instability (CFI) of the BNL-ATF e^{-}-beam



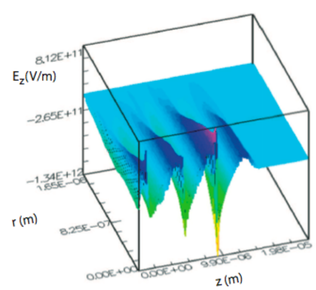
Experiment under way

2. CFI instability of the SLAC e^{-}/e^{+} “fireball beam”



To be proposed

3. SLAC-LCLS fs e^{-}-beam for TV/m beam/plasma interaction



To be proposed

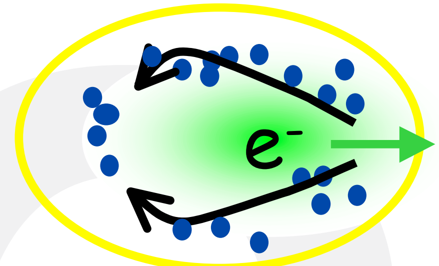
MOTIVATION

- Why is Current filamentation instability (CFI) important?
  - Relativistic outflows are ubiquitous in astrophysics
  - CFI likely plays an important role in flow/ambient plasmas interaction
  - Relatively few experiments to test CFI
  - CFI also has important laboratory applications (ICF)

- Plan:
  - Take advantage of PWFA experiments/experience
  - Develop new and appropriate diagnostics
  - Measure CFI-quantities (σ_r, Δ, B, δn_e, γ, Γ, …)
  - Set up strong experimental/simulation synergy

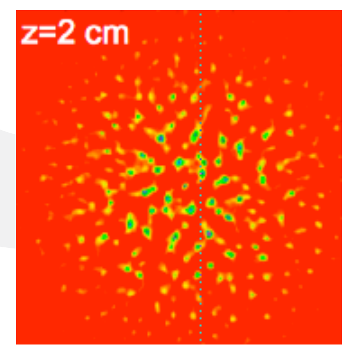
TWO REGIMES OF BEAM-PLASMA INTERACTION

1) $\sigma_r << c/\omega_{pe}$



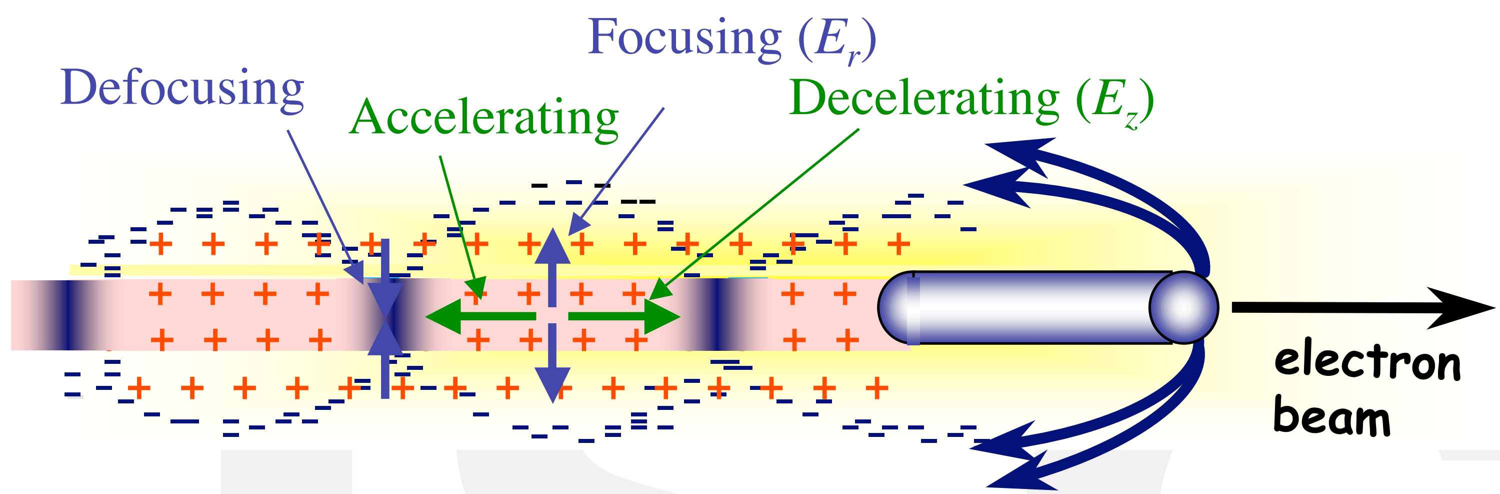
- Return current outside of the bunch
- Plasma wakefield regime $\sigma_z \cong c/\omega_{pe}$
- Blow-out regime $n_b \geq n_{pe}$
- Large decelerating, accelerating, focusing fields
- Hose instability

2) $\sigma_r >> c/\omega_{pe}$



- Return current outside of the bunch
- CFI, two-stream, oblique instabilities

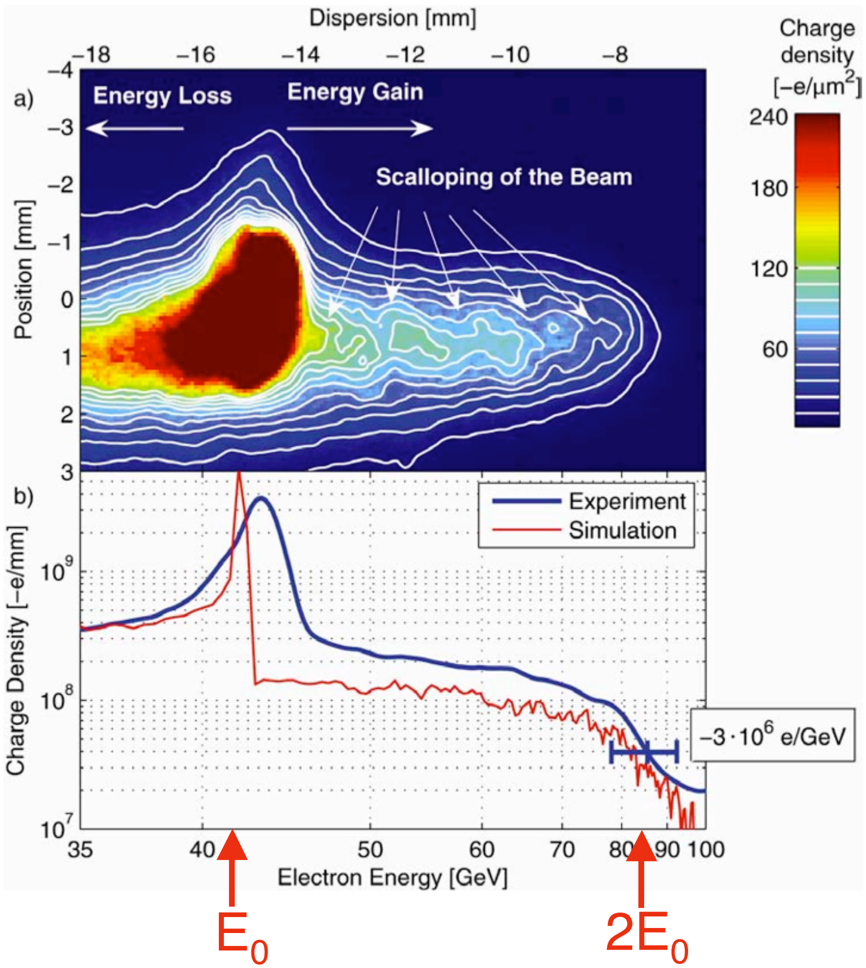
Plasma Wakefield (e^-)



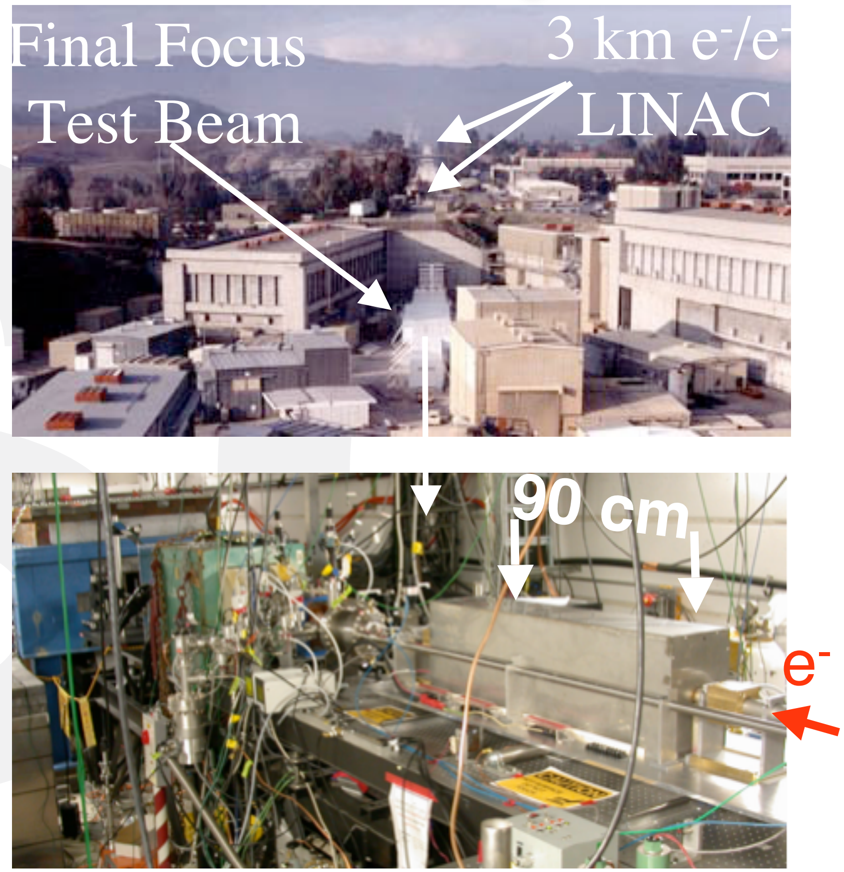
- Plasma wave/wake excited by a relativistic particle bunch
- Plasma e^- expelled by space charge forces => energy loss + focusing
- Plasma e^- rush back on axis => energy gain

e^- ENERGY DOUBLING

I. Blumenfeld *et al.*, Nature 445, 2007



E_0=42 GeV



- Energy doubling of e^- over L_p≈85 cm, 2.7x10^{17} cm^{-3} plasma
- Unloaded gradient ≈52 GV/m (≈150 pC accel.)

CFI @BNL-ATF

- Regime 2: $\sigma_r >> c/\omega_{pe}$ ($k_p\sigma_r >> 1$), Current Filamentation Instability
  - Plasma return current flows inside beam
  - Dominant instability dependent on relativistic beam factor (γ_0)

    $\gamma_0 >> 1$ - CFI (transverse instability)
    - Filament size and spacing $\sim c/\omega_{pe}$
    - Growth rate(1):

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

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

BNL-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

– γ_0=117, CFI regime

- Growth rate estimate:

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

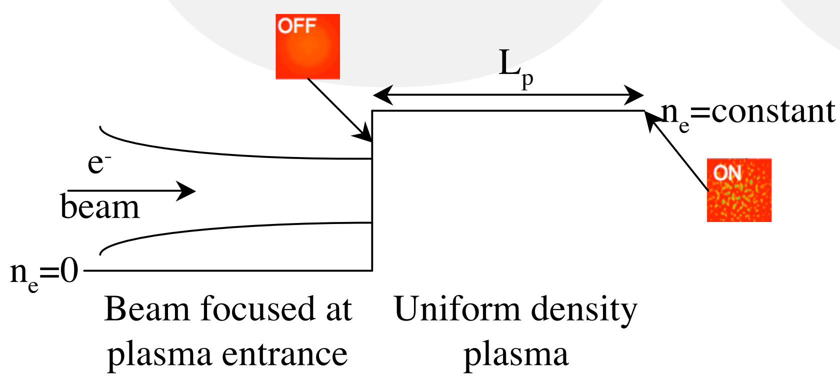
➢CFI should be observable on a cm-length plasma scale

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

SIMULATIONS TOOLS

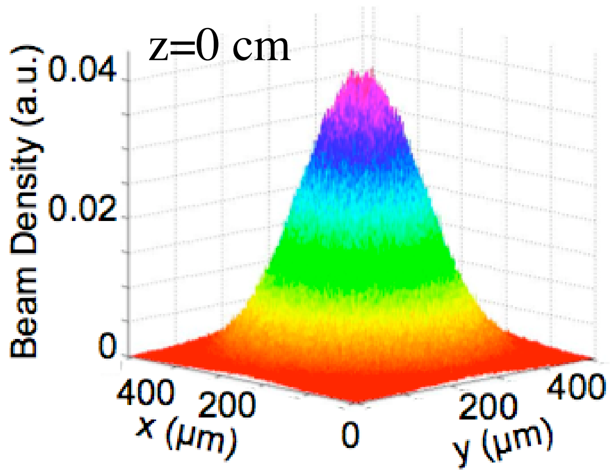
- Simulation Tools: Particle-in-cell codes
  - OSIRIS
  - QuickPIC
  - PWFA, ICF
  - Both codes have been benchmarked against other codes and with experimental results

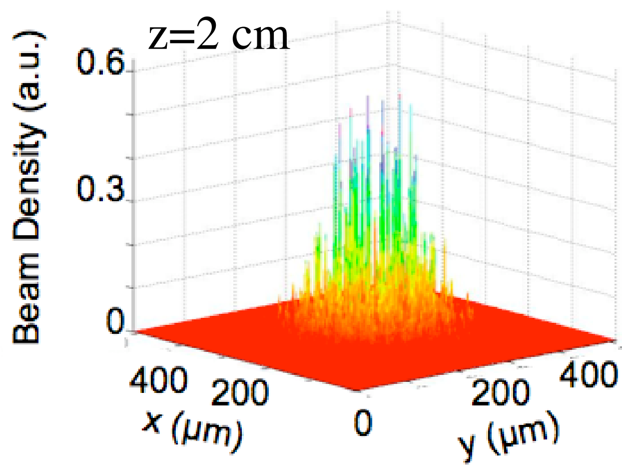
- Simulation Setup



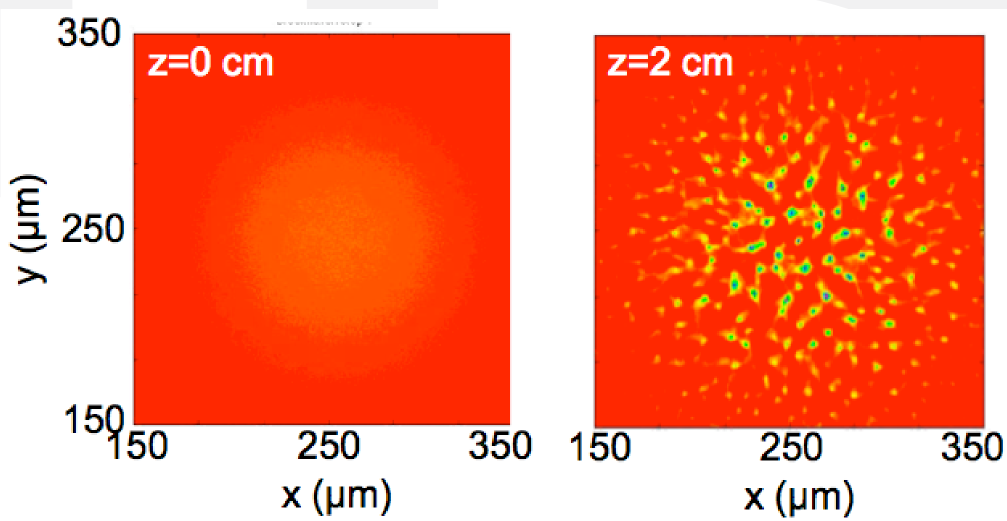
FILAMENTATION SIMULATION

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

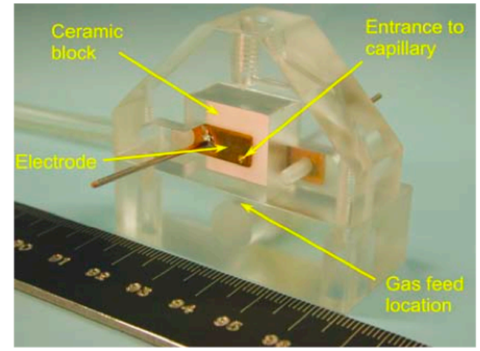
Filament spacing ≈20 μm

Both ≈ c/ω_p

These images are similar to those we expect to measure in the experiments

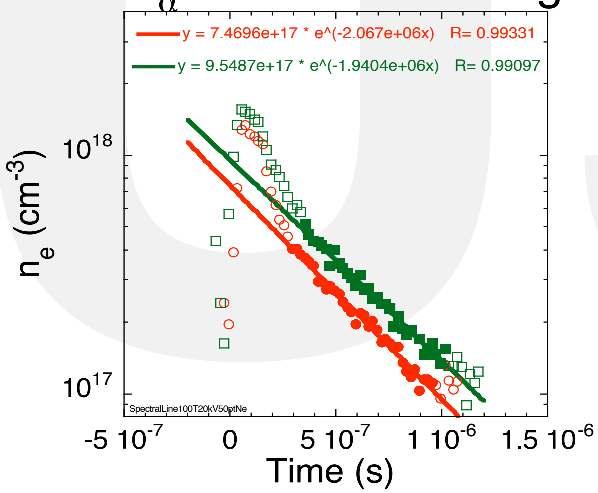
Experimental Setup

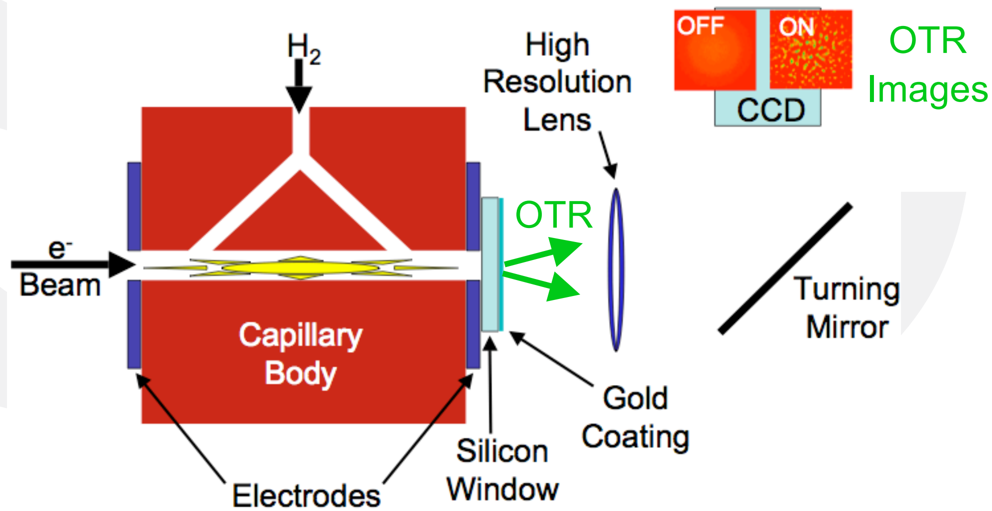
- Plasma Source
  - H_2 capillary discharge, radius of ~ 500 μm
  - Variable plasma parameters:
    - Capillary length (1cm and 2cm >L_G=3.5mm)
    - Plasma density: H_2 pressure and beam arrival time
  - Variable beam parameters:
    - Charge, length, radius (n_b)



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

H_α Stark Broadening



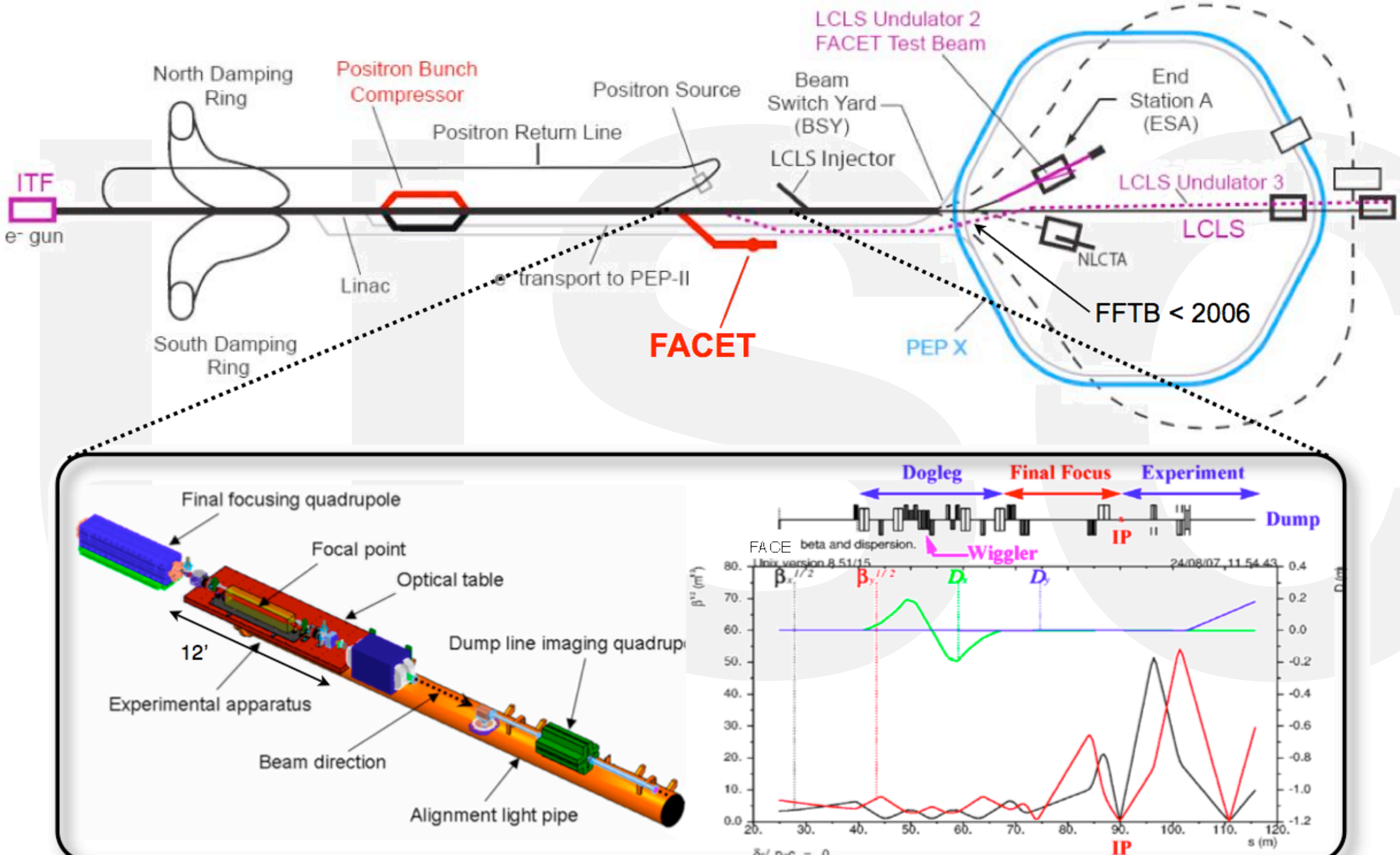


➡ Diagnostics: OTR for filaments, radiation

➡ Measure filaments size, spacing, growth rate, etc.

➡ Experiment approved at BNL-ATF, program funded by NSF

FACET is a new facility to provide high-energy, high peak current e⁻ & e⁺ beams for PWFA experiments

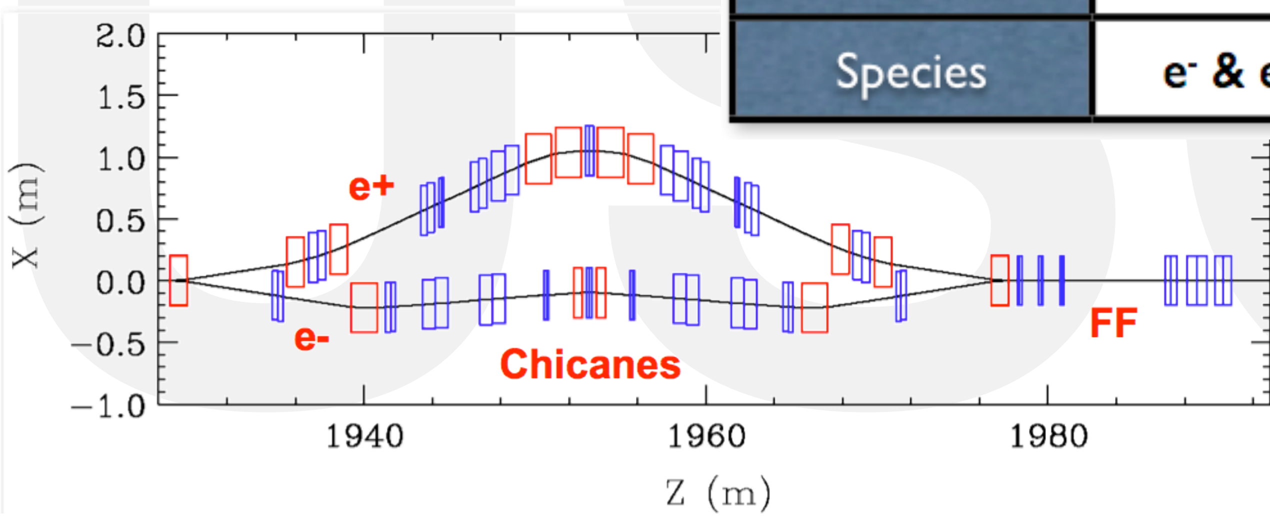


NEUTRAL RELATIVISTIC BEAM

- Extract e- & e+ from damping rings on same linac pulse
- Accelerate bunches to sector 20 5cm apart
- Use 'Sailboat Chicane' to put them within 100μm at entrance to plasma

Energy	24 GeV
Charge	3 nC
Sigma z	17 µm
Sigma r	< 10 µm
Peak Current	22 kAmps
Species	e^- & e^+

$\gamma \approx 5 \times 10^4$
E_0=80J
P=1PW
$I = 4.4 \times 10^{20} W/cm^2$
$E_{r\,max}$=61GV/m
$B_{\theta max}$=2MG
$n_b = 7 \times 10^{17} cm^{-3}$

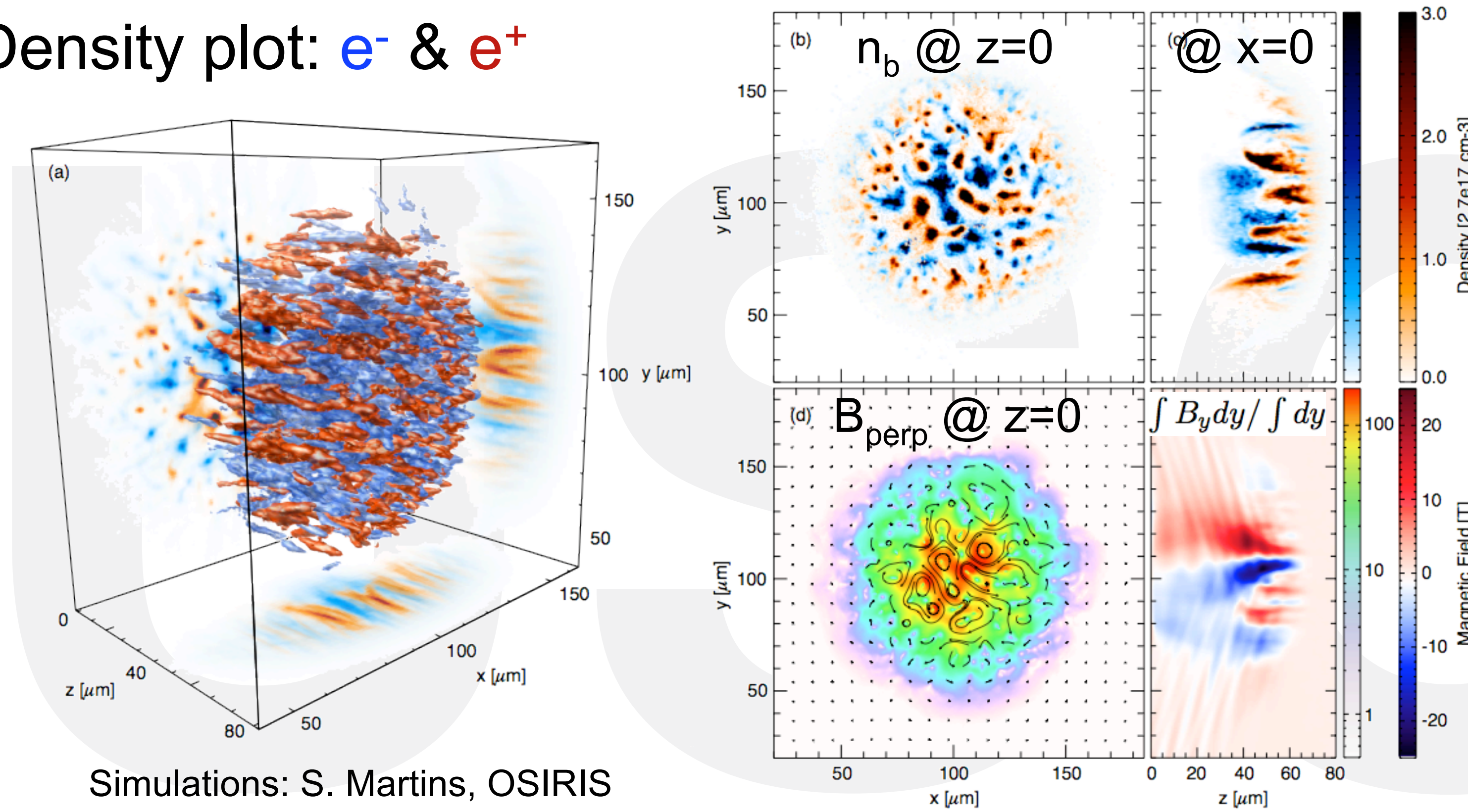


→ "Fireball Beam": Neutral Ultra-relativistic e^-/e^+ beam

- ➡ Space-time overlap of equal e^-/e^+ for "fireball beam"
- ➡ Beam at 10Hz, very stable, Li plasma(?)
- ➡ Collision of relativistic "fireball beam" with lab plasma

SIMULATION: FILAMENTATION

Density plot: e^- & e^+

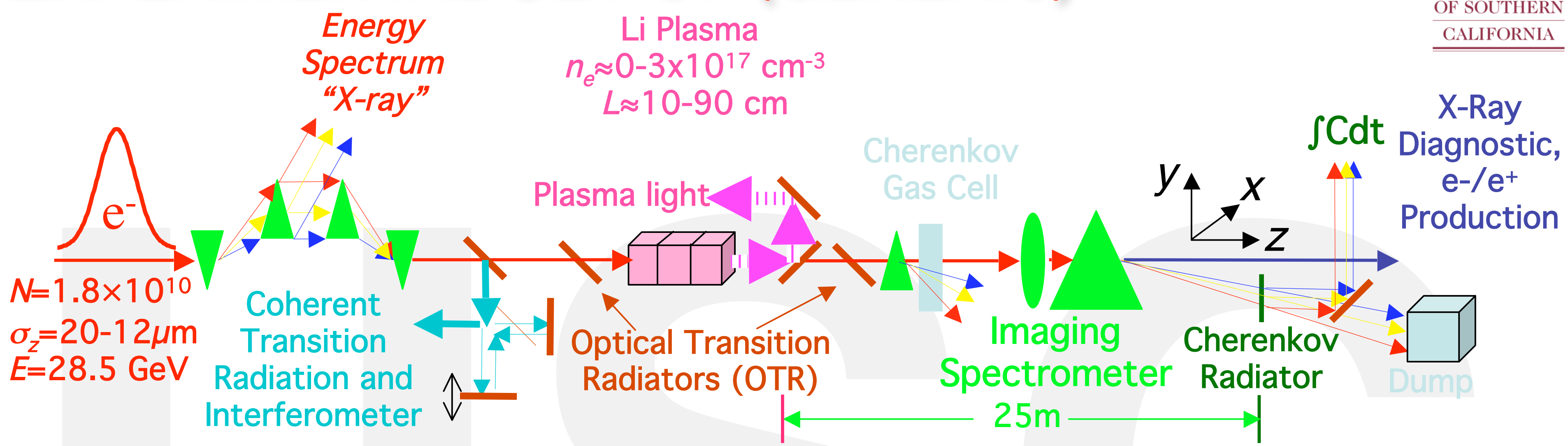


Simulations: S. Martins, OSIRIS

L_p=10cm
n_e=2.7x10^{17}cm^{-3}
ε_N=2x10^{-5}m-rad

- "Fireball beam" CFI after 10cm of plasma!
- Same beam parameters as for PWFA, very different result with neutral beam

EXPERIMENTAL SET UP (GENERIC)



- Li-plasma source similar to PWFA experiments
- Diagnostics:

  δn_e: shadowgraphy, Schlieren } as a fct of plasma length
  B: Faraday rotation }
  Radiation
  Energy loss
  ...

SUMMARY

- Accelerators produce high quality particle beams that could be used for astrophysics-relevant experiments: opportunities!
- CFI of BNL-ATF e^- beam and SLAC e^-/e^+ ultra-relativistic "fireball beam"
- Experiments benefit from PWFA experience/setup
- Other experiment possible? Beam-driven relativistic shocks?
- Input welcome!

Thank you!