X-ray Radiation and Electron Injection from Beam Envelope Oscillations in Plasma Wakefield Accelerator Experiments at FACET

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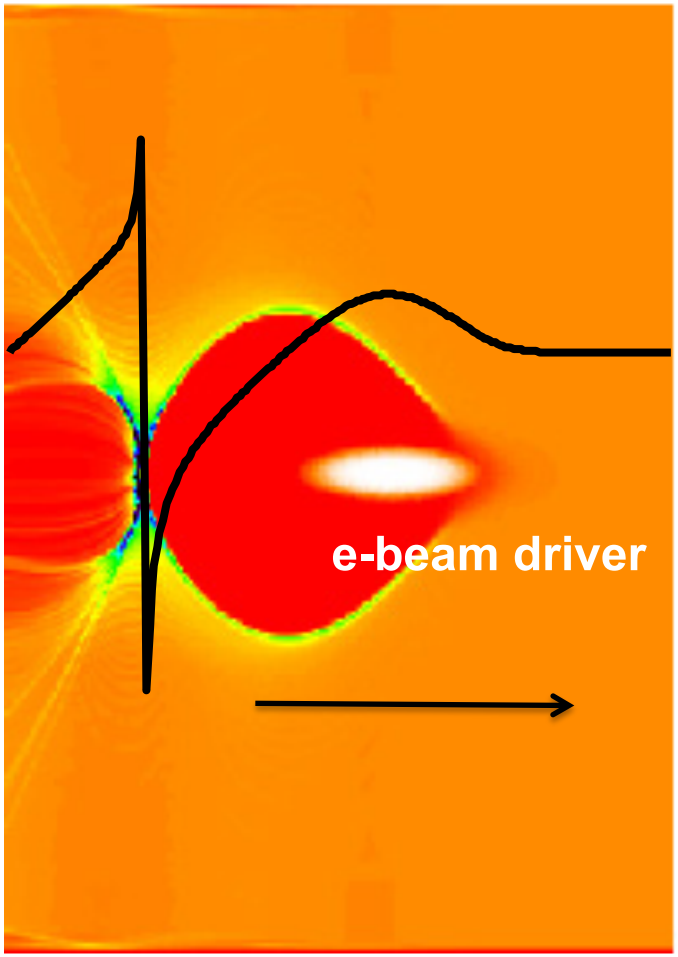
Beam Driven Blowout Regime

For $n_b > n_p$ under dense

- A short electron pulse traveling in an underdense plasma where the 3D radiation pressure causes complete electron cavitation
- Creates a stable self-guiding structure with large accelerating wake



Experimental parameters

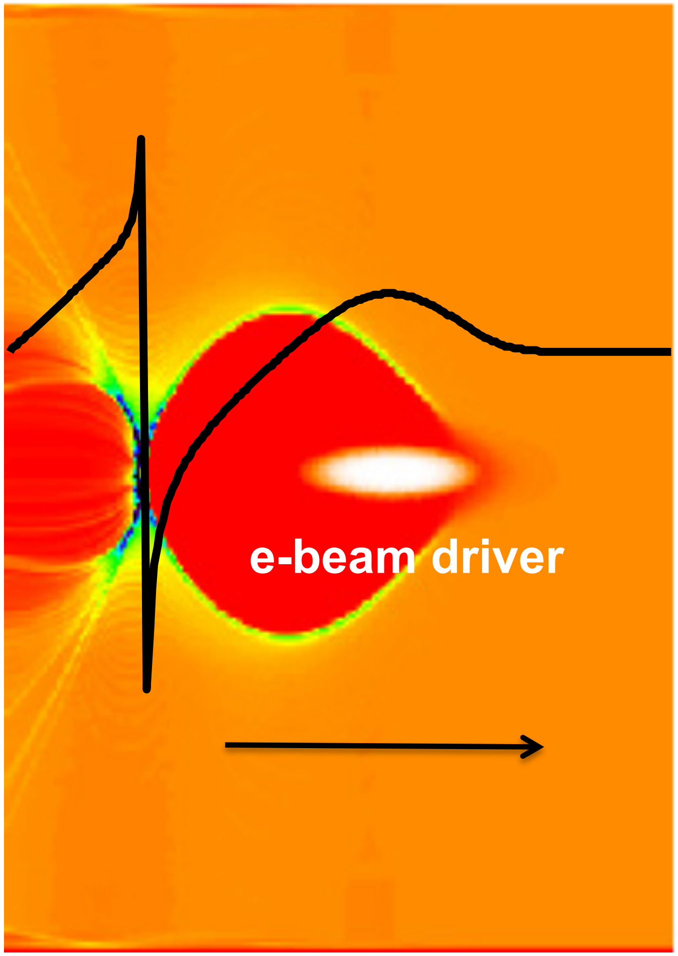
Electron Beam

20.3 GeV
ε_x = 50-100 mm-mrad
ε_y = 5-10 mm-mrad
β_x = 10 cm
β_y = 100 cm
$\sigma_z \cong$ 40 um
charge = 2×10^{10}
Current = 10-20 kA

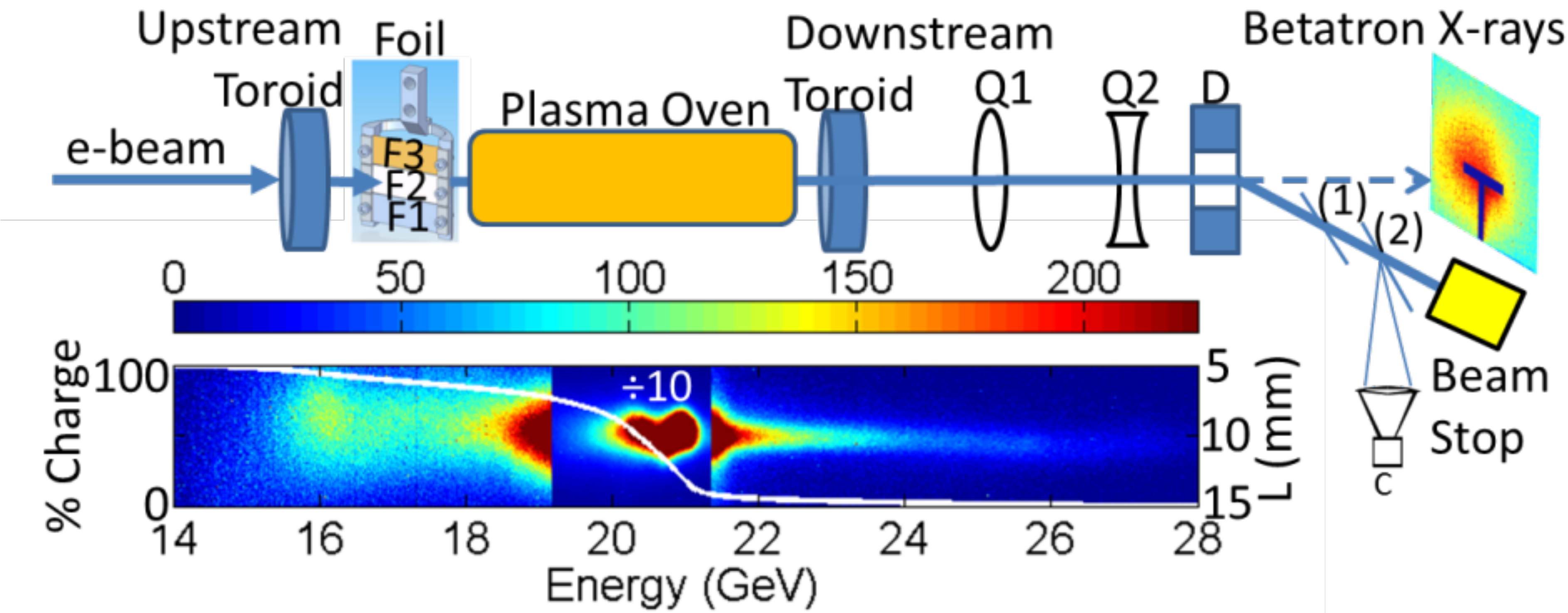
$k_p \sigma_z > 2$
$K_p \sigma_x \leq 1$
$k_p R_b \cong 2$
ionization radius > R_b
$n_b \geq n_p$

Plasma Source

self ionized Rubidium vapor
2.7×10^{17} cm^{-3}
Argon buffer gas containment
nominal ramps 10 cm
flat center 30 cm



Experimental Setup



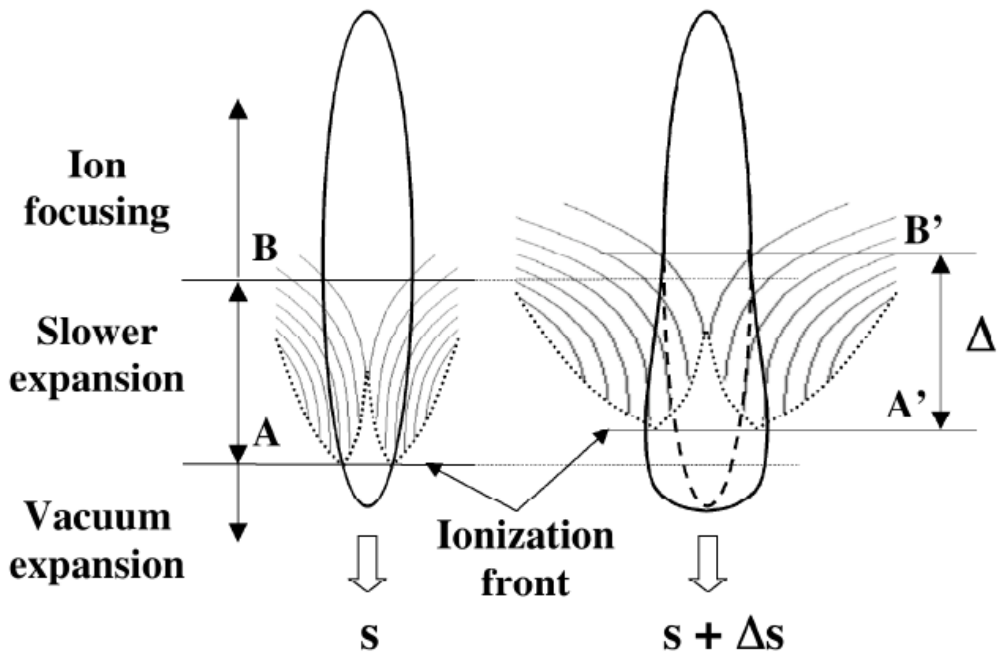
The Experiment was Designed to Study the Effects of Emittance Spoiling Foils on:

- Head erosion
- Betatron oscillations
    - -x-ray yield
    - -excess charge (aka secondary ionization)
- E_{loss} and E_{gain}

Head Erosion in Self Ionized Plasma

$$L_{HE} \sim \sigma_z / v_{etch}$$

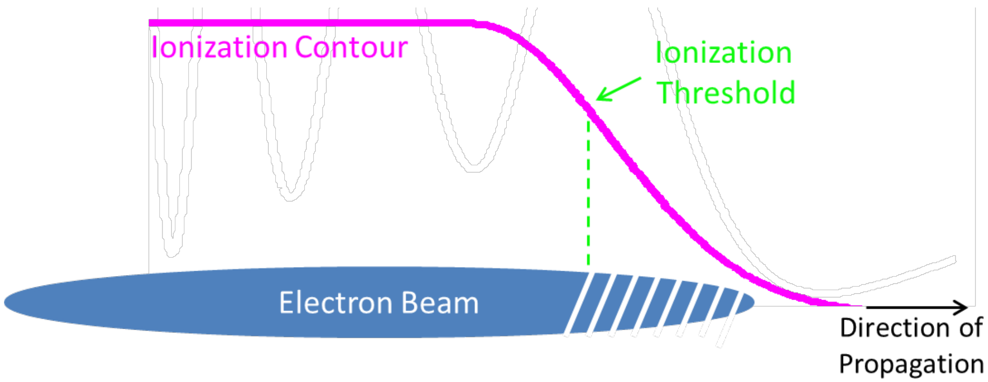
$$v_{etch} \sim \frac{\varepsilon_N}{\gamma} I^{3/2} IP_{eV}^{1.73}$$

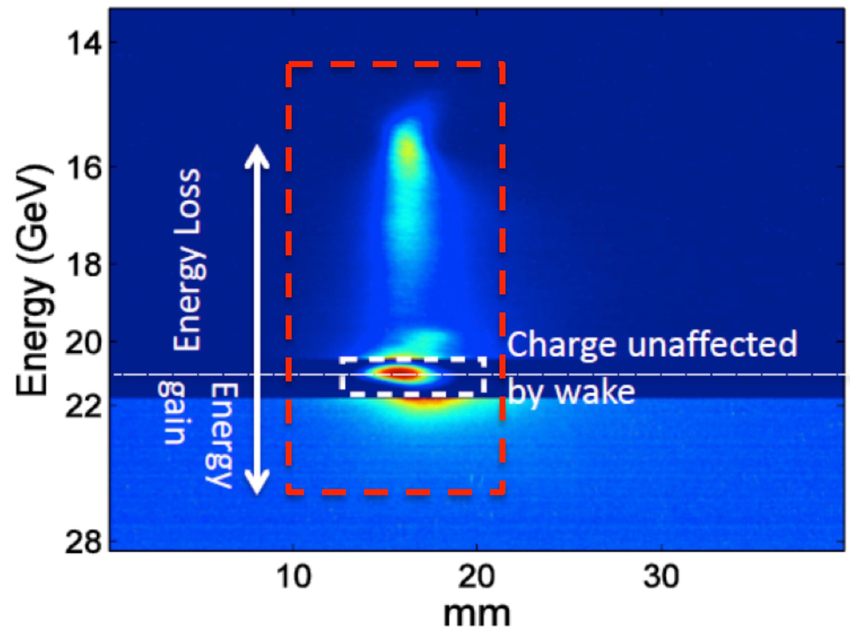


M. Zhou thesis, Ian Blumenfeld thesis

Unaffected Charge

If the head of the beam is not dense enough to ionize, those electrons will not drive the wake, reducing σ_z





Analysis method

- Counts in the white box are summed to give unaffected charge.
- Red box shows the extent of the electron signal, summed to give total charge

Betatron Oscillation and X-rays

- Critical photon energy $h\nu_c \sim \gamma^2 n r_0$

$$\frac{d^2 r_0}{dz^2} + k_b^2 r_0 = 0$$

22 MeV*

- Radiated power of a single electron $P \sim \gamma^2 n^2 r_0^2$

$$k_b = \frac{\omega_p}{c} \frac{1}{\sqrt{2\gamma}}$$

- Average number of photons per electron with mean energy $h\nu_c$

$$N_{ave} = 5.6 \times 10^{-3} N_{osc} K$$

Photons* ≈ 10^{11}

very bright source!

Ref. Kostyukov

*assumes k_b= const r_0 = 10 um

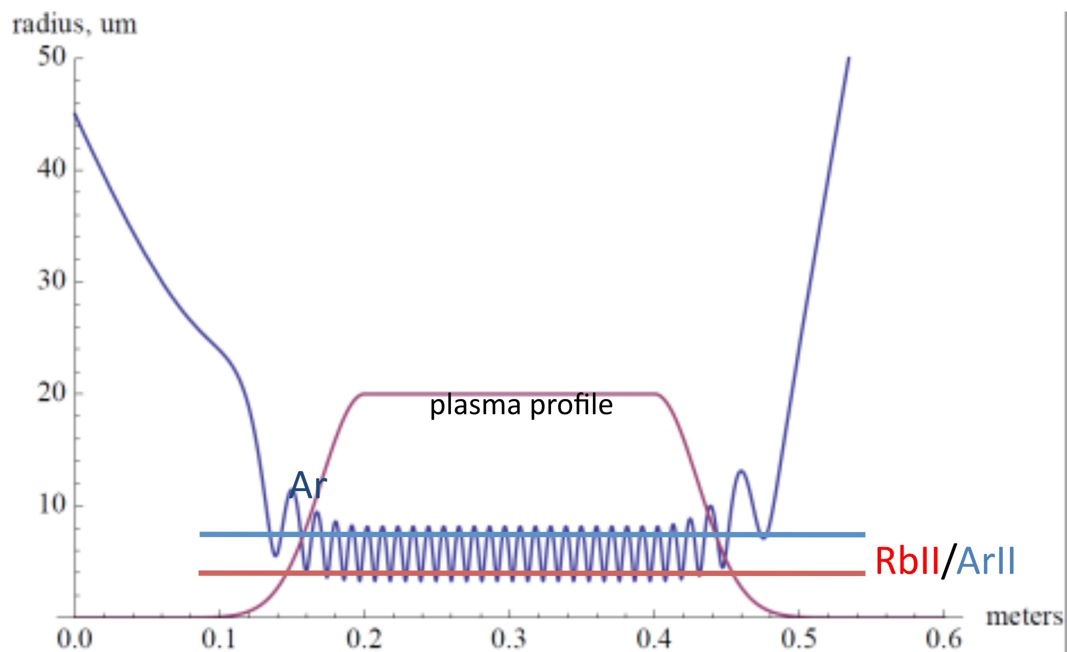
Beam Envelope Oscillation and Excess Charge

Beam Envelope Equation

$$\frac{d^2\sigma}{dz^2} + k_b^2\sigma = \frac{\varepsilon_N^2}{\gamma^2\sigma^3}$$

$$k_b(z) = \frac{\omega_p}{c}\frac{1}{\sqrt{2\gamma}}$$

Large beam fields create
secondary ionization,
excess charge,
and beam loading



Ionization and Secondary Ionization

- Maximum electric field of an electron beam is

$$E_{max} = 10.4 \left[\frac{GV}{m}\right] \frac{N}{10^{10}} \frac{10}{\sigma_r} \frac{50}{\sigma_z}.$$

- For σ_z= 40 μm, $N = 2 \times 10^{10}$, the threshold radius for 10% ionization is

	IP (eV)	E_{th} (GV/m)	σ_r (μm)
Rb	4.17	3.0	88
Li	5.39	4.7	56
Ar	15.8	29	8.8
Rb II	27.3	52	5
Ar II	27.6	53	4.9
He	24.6	61	4.2

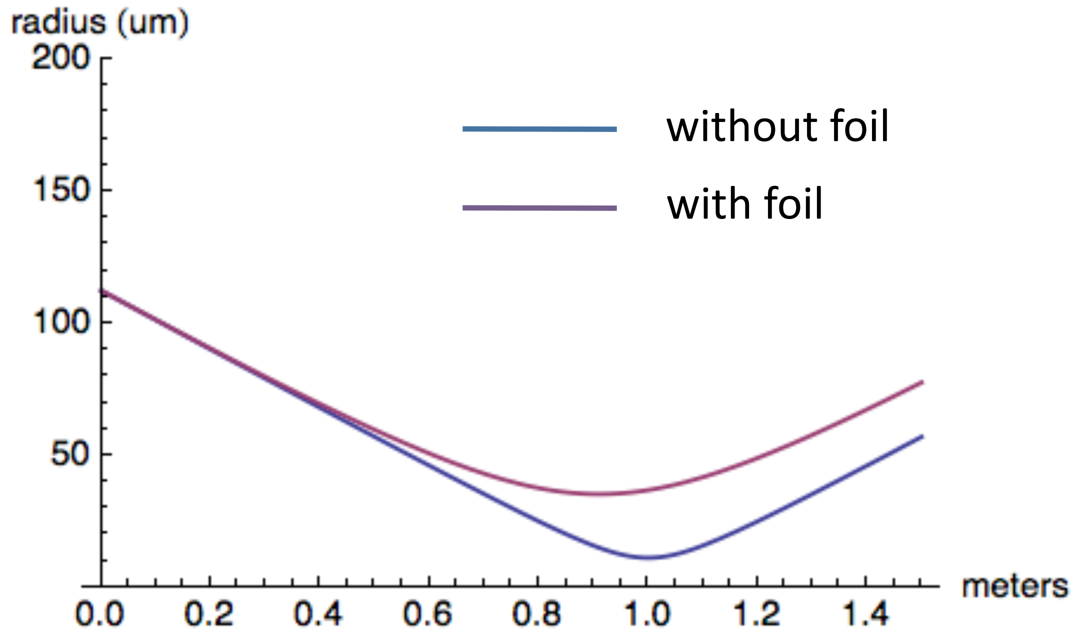
Beam propagation with spoiler foil in vacuum

$$\varepsilon^2 = \varepsilon_0(\varepsilon_0 + \beta_0\theta^2)$$

$$\beta^2 = \beta_0^2\varepsilon_0 / (\varepsilon_0 + \beta_0\theta^2)$$

$$\alpha^2 = \alpha_0^2\varepsilon_0 / (\varepsilon_0 + \beta_0\theta^2)$$

Θ = 35 urad

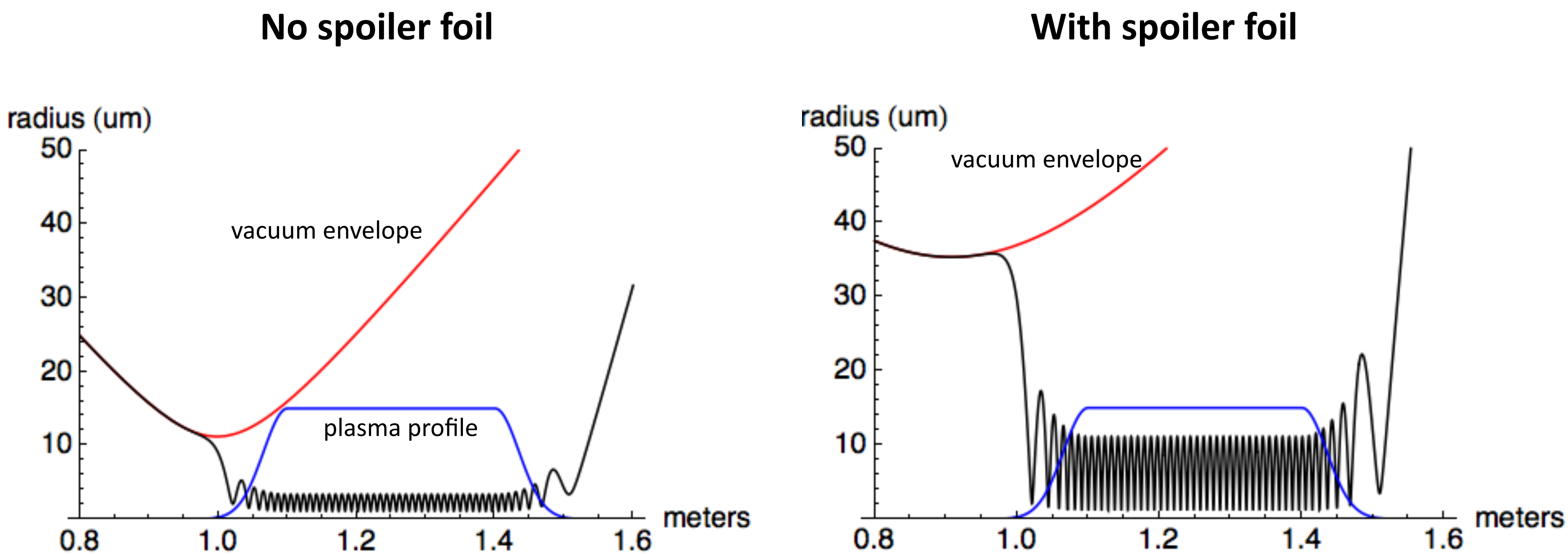


Without foil
ε_0 = 50 mm-mrad
β = 10 cm
σ_r = 11 μm

With foil
ε = 164 mm-mrad
β= 30 cm
σ_r = 35 μm

J.R. Rosenzweig and P. Chen, Phys. Rev. D 39 (1989) 2039

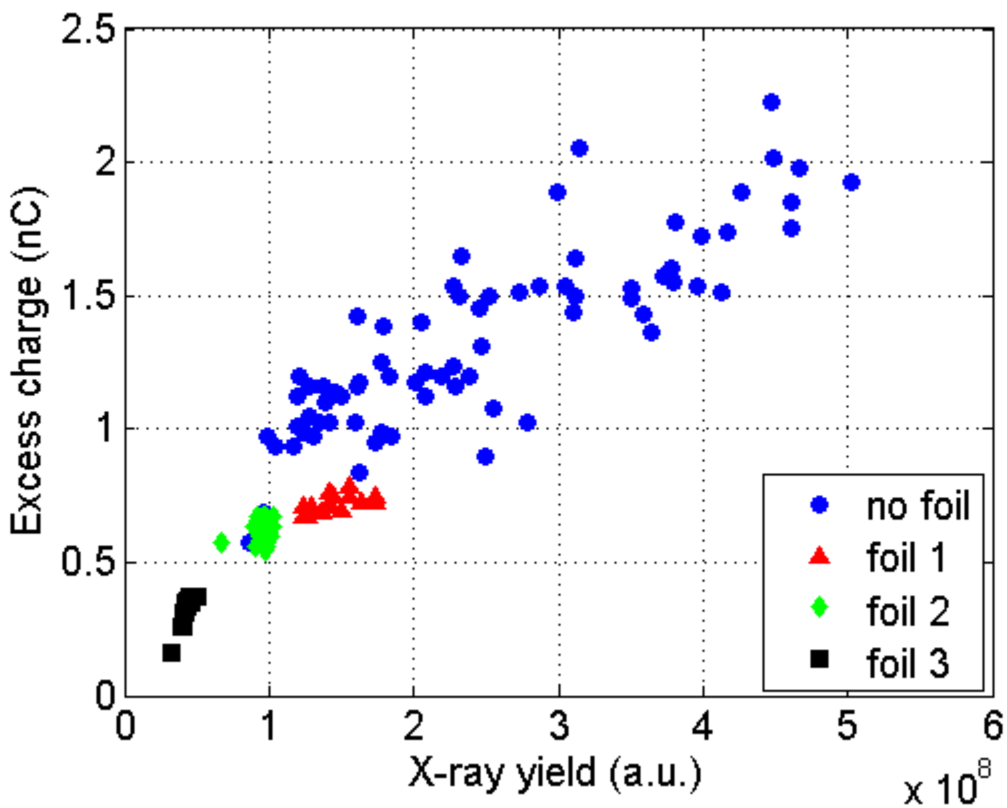
Beam propagation with spoiler foil in plasma*



Enlarged oscillation amplitude
Beam size minimum does not change with enlarged emittance

* Assumes full blow out

Excess charge correlated with x-ray yield

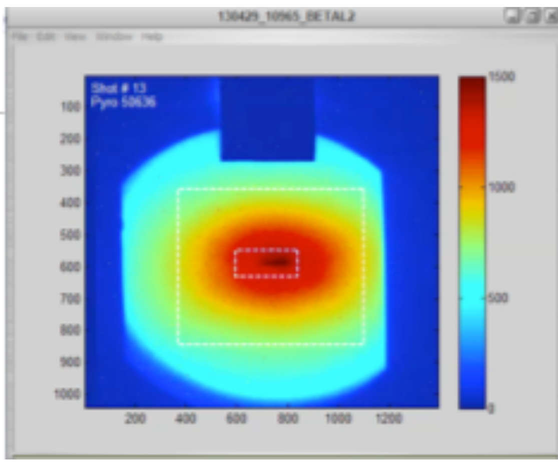


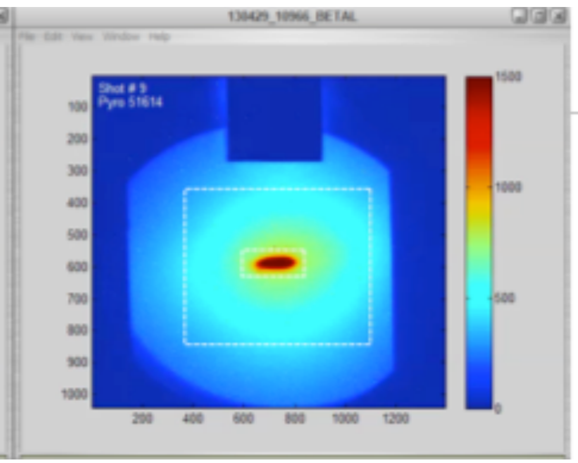
drive beam has 3 nC

Experimental Data

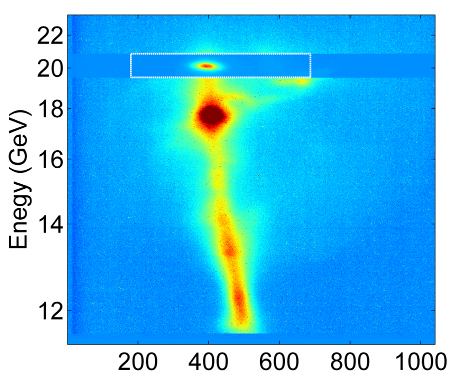
Without spoiler foils: **With spoiler foil:**

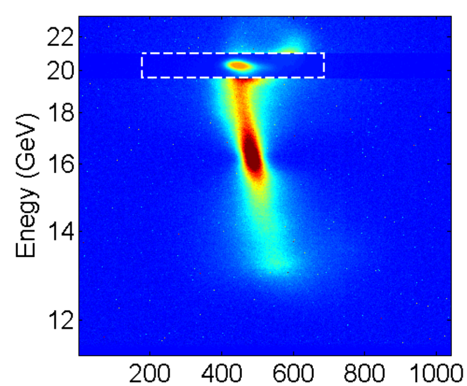
X-ray signal



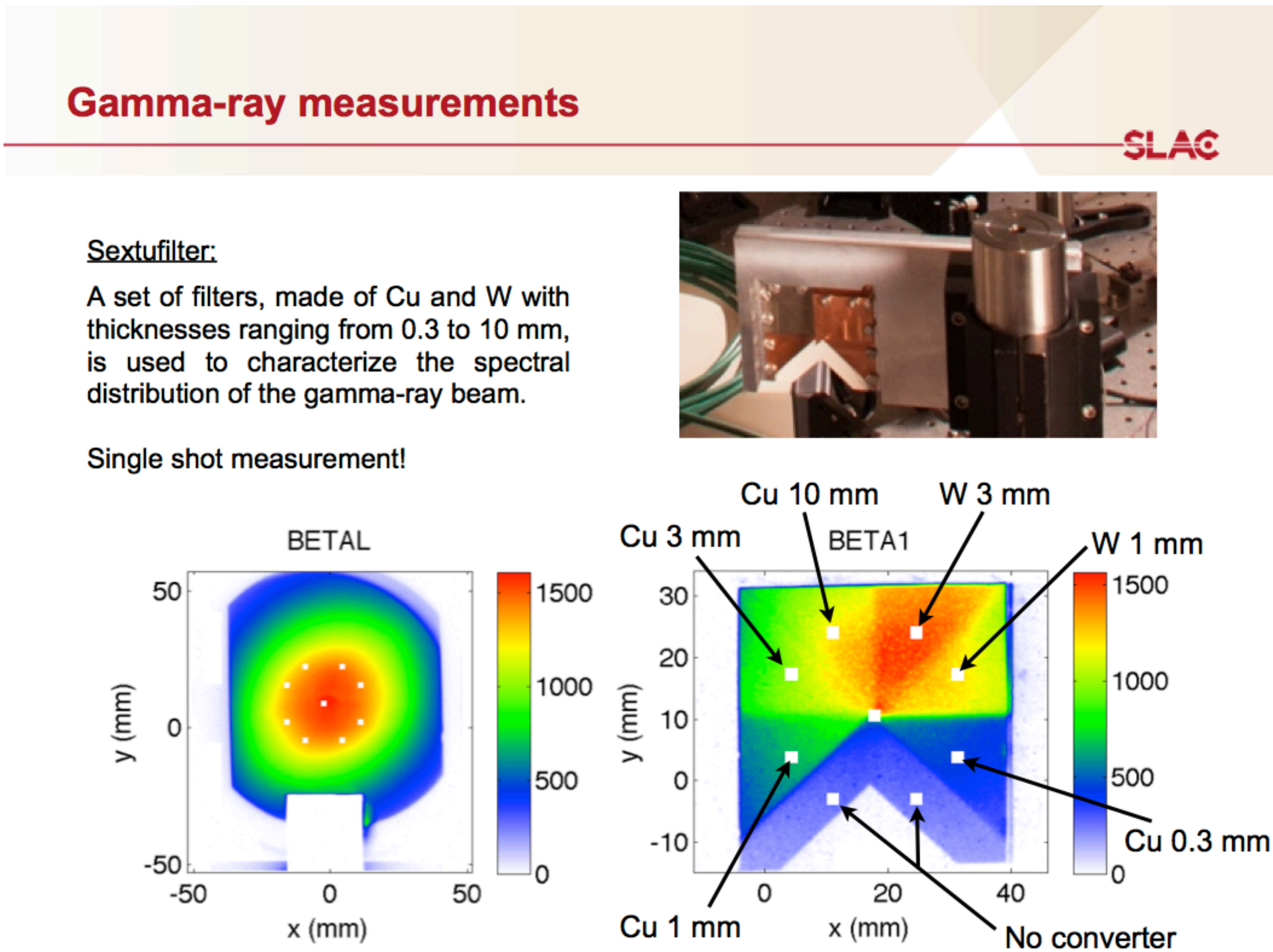


Energy loss





X-ray diagnostics to measure divergence and critical energy



Results of betatron x-ray studies

- Head erosion limits the x-ray yield that can be produced. $L_{HE} \sim \sigma_z / \varepsilon$
- Preformed plasma would allow propagation large radius beams for the production of high yield multi MeV x-rays.
- For accelerator you want a matched beam where the x-rays signatures would be used to minimize the critical energy and divergence.

Secondary Ionization and Trapped Charge

- Trapped charge limits the accelerating gradient (see N. Vafaei, these proceedings)
- Solution is to select a vapor or gas where secondary ionization is not a concern, H_2.
- Ionization trapping studies are important because
  - we have found it can be used to produce ultra-short electron pulses with narrow energy spread (see W. An and C. Clayton these proceedings)

Self-ionization vs Pre-ionization*

- Head erosion limits the distance the beam can propagate before transferring all its energy to wake formation.
- Results show we are nearly HE limited.
- Preformed plasma solves the participating charge problem (recent experiments show up to 100% participation)
- Preformed plasma solves the HE problem.

*See M. Litos these proceedings

E200 Collaboration

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