Adiabatic Plasma Lens Experiments at SPARC

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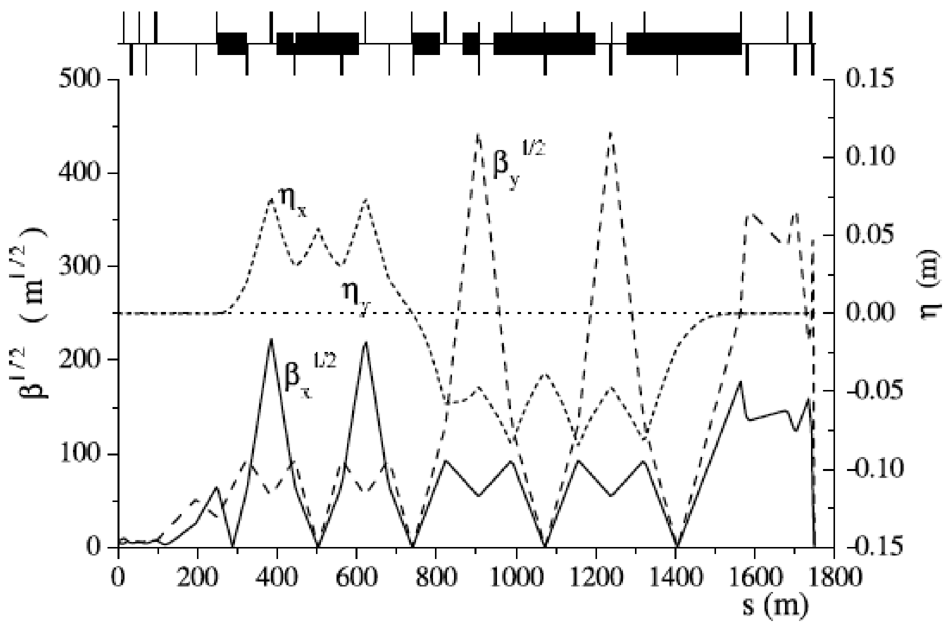
Abstract

- Plasma lenses in the underdense regime have been shown to give extremely strong linear focusing, with strength proportional to the local plasma ion density. This technique has been proposed as the basis of an scheme for future linear colliders that mitigates the Oide effect through adiabatic focusing. In this scenario the plasma density in the lens is ramped slowly on the scale of betatron motion, to funnel the beam to its final focus while forgiving chromatic aberrations.
- We present to the physics design of an adiabatic plasma lens experiment to be performed at SPARC_LAB.
  - We illustrate the self-consistent plasma response and associated beam optics for both symmetric and asymmetric beams in plasma, simulated by QuickPIC using density profiles obtained from experiment.
  - We discuss experimental plans including plasma source development and betatron-radiation-based beam diagnostics.

Adiabatic Plasma Lens for Linear Collider Final Focus

- Plasma collider accelerator at 10 GeV/m is 100's of m long
- Advanced linear final focus design ~ 2km long for chromatic aberration correction
- Limited also by Oide effect – radiation in final quads
- Need two things:
  - Stronger focusing
  - *Adiabatic* focusing
- Use plasmas!

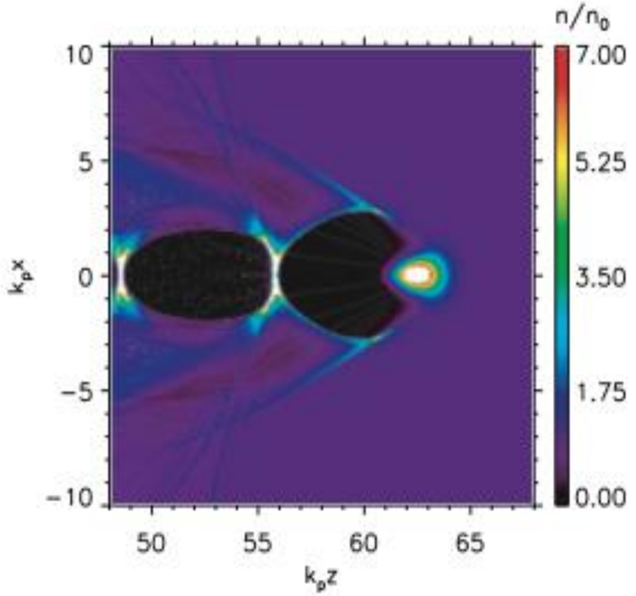


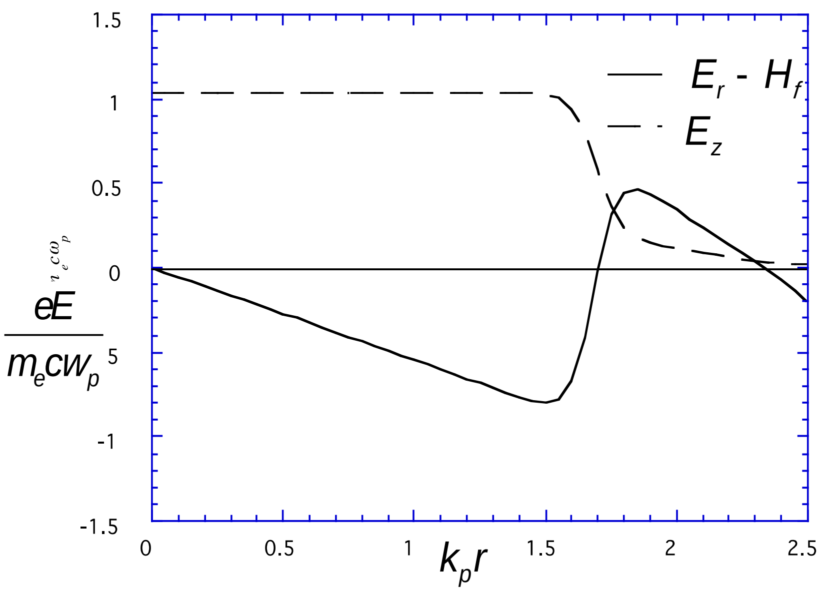
Raimondi and Seryi, PRL 86 3779 (2001)

The PWFA Underdense “Blowout” Regime

J. B. Rosenzweig, *et al.*, *Phys. Rev. A -- Rapid Comm*. 44, R6189 (1991).

- Beam much denser than plasma $\boxed{n_b >> n_0}$
- Very nonlinear plasma waves
  - Plasma electrons exit beam channel



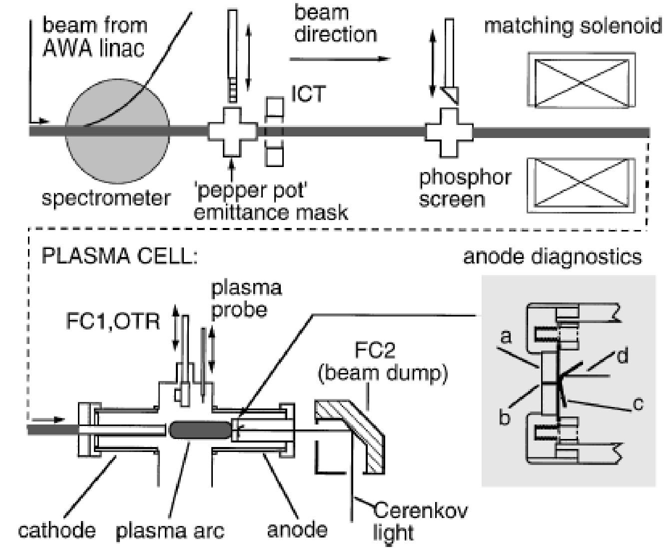


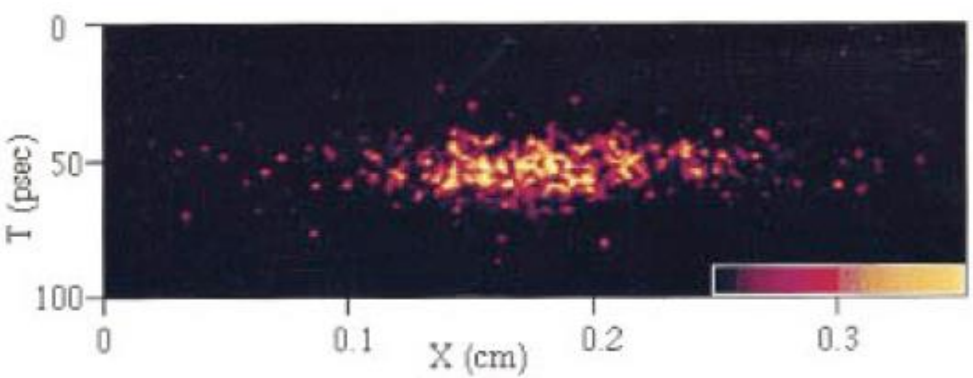
Plasma wake (E_z) w: radial dependence of fields in beam region. Linear in *r*!

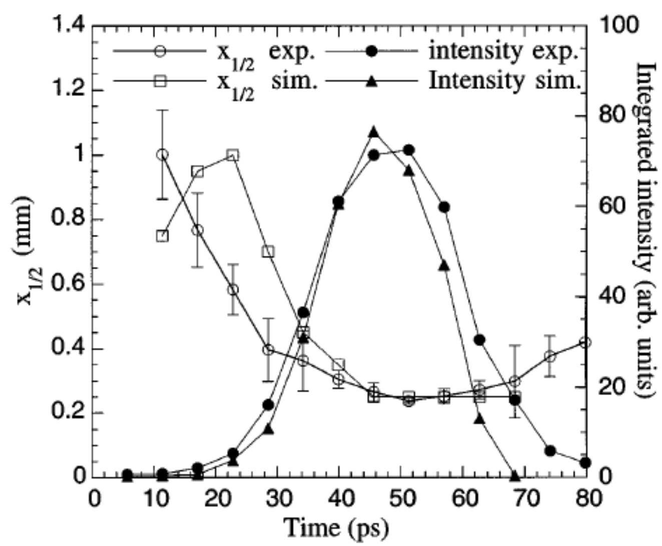
- “Linear” *wakefields,* stable beam propagation
- E_z (accel) constant in r (EM wave)
  - ***Focusing linear* in *r* (ES ion field)**

Guiding in a Blowout Regime PWFA

- Match beam to focusing
  - Exploit finite ramp
- Measurements challenging
- 1st streak camera -> now RF deflector







N. Barov and J.B. Rosenzweig, *Phys. Rev. E* 49 4407 (1994)
N. Barov, et al., *Physical Review Letters.* 80, 81 (1998)

The underdense lens case

- Would like to focus *without* longitudinal wakes; transverse effects dominant
- The conditions of interest are

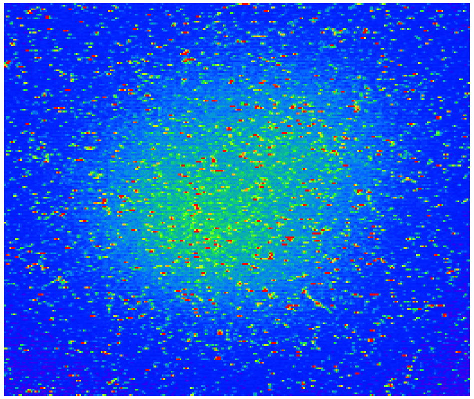
$$\boxed{n_b >> n_0} \qquad \boxed{k_p s_r < 1} \qquad \boxed{k_p s_z > 2}$$

- Similar to PWFA but with longer beam, higher charge
  – Ex: Q=600 pC, τ=600 fsec (400 A). "Full beam"
  – Plasma densities controls equilibrium beta…

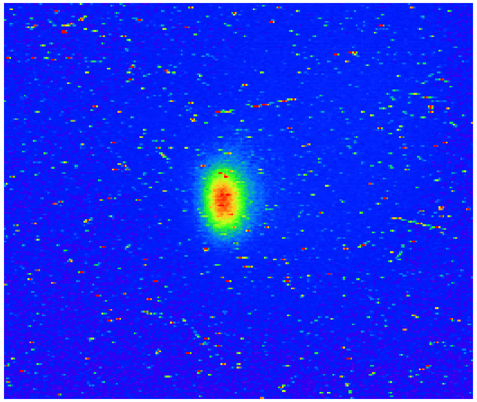
Blowout regime focusing: underdense thin plasma lens

- Use as thin lens (*non-equilibrium* case)
- "**Mismatch**" beam size to focusing in plasma
- Remove most aberrations of linear focusing regime if

$$\boxed{n_b > n_0 / 2}$$



Unfocused – 5 electron pulses

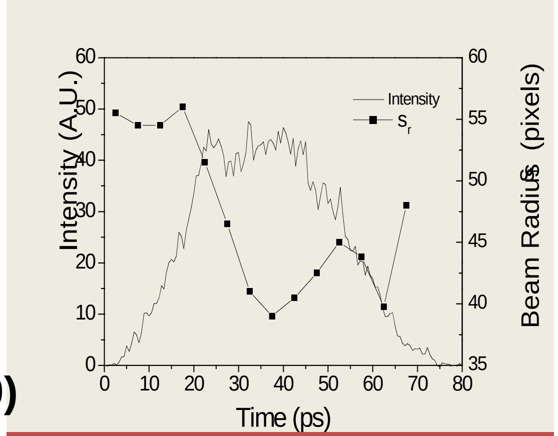


Plasma focused – 1 pulse

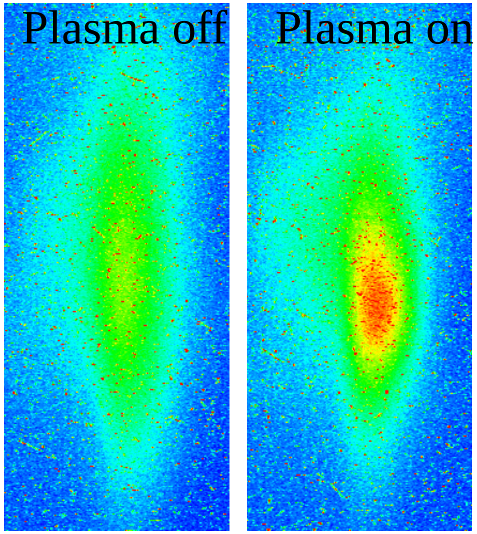
The beam area is reduced by a factor of 22. Equivalent to *luminosity enhancement*

Also demonstrated:
- *t*-dependent focusing
- focusing w/**asymmetric beam for LC**

***M.C. Thompson, et al., Phys. Plasmas*, 17, 073105 (2010)**



Time-resolved intensity profile (w/streak camera)



1 : 3.5 Beam Aspect Ratio

Adiabatic plasma lens

- Use adiabatically **increasing** focusing strength through ramping density slowly

$$k_b^2(z) = 2pr_e n_0(z)/g = k_p^2(z)/2g$$

- This define a quasi-equilibrium βετα-function

$$b_{qeq}(z) » k_b^{-1}(z)$$

when the change is slow enough…

$$L_s\ ^{\text{o}}\ n_0(z)/n_0^{\text{¢}}(z) >> b_{qeq}(z)$$

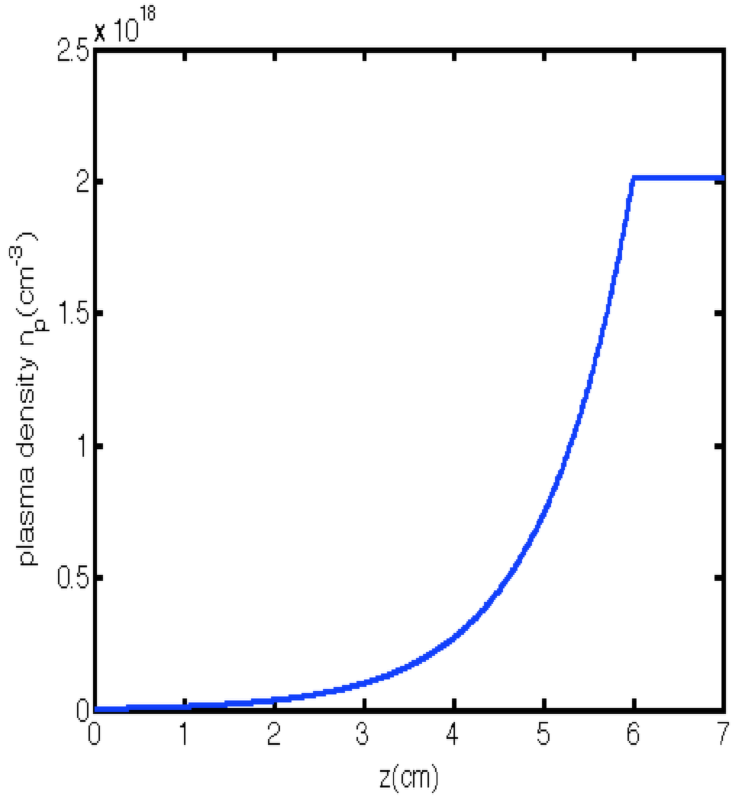
- Mitigates synchrotron energy loss aberrationsl

Ramped focusing with strong aberrations, a bit like a Winston-cone in optics

Adiabatic plasma lens at SPARC

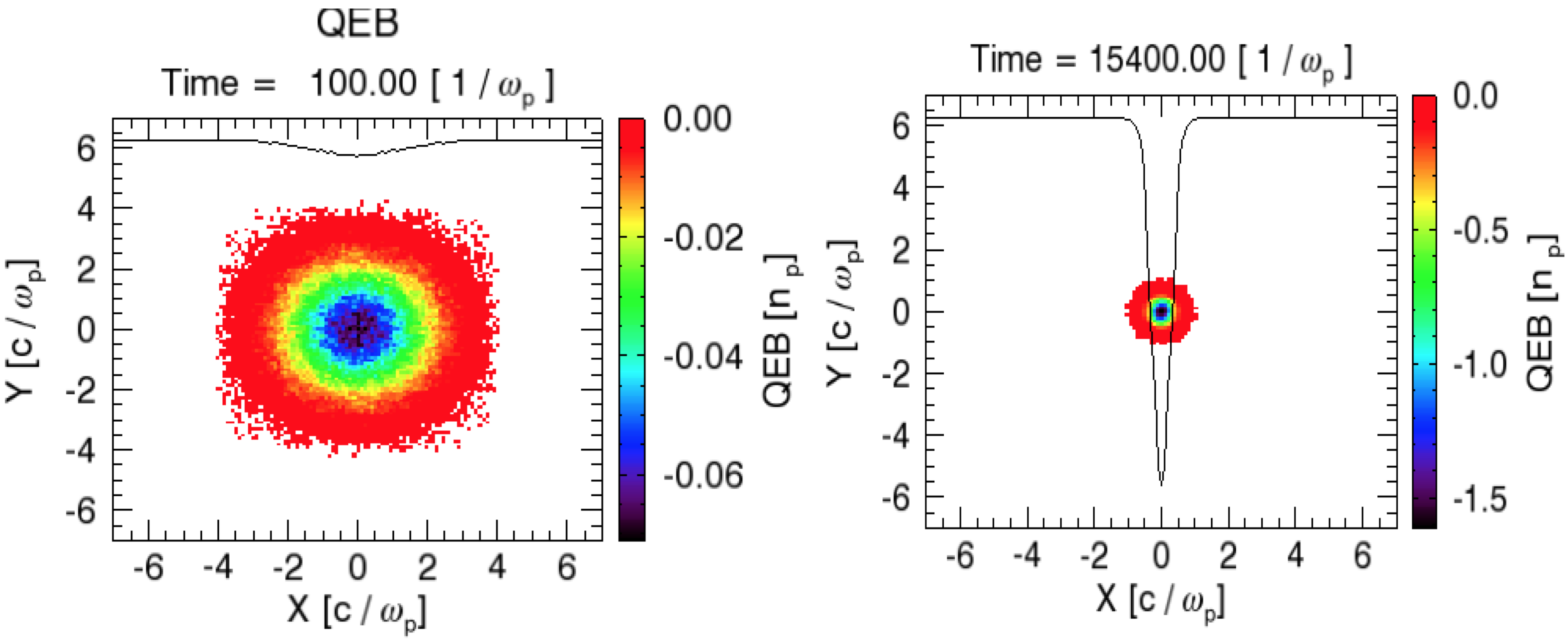
- Path to compact linear collider final focus
  - Mitigate Oide effect
  - Open the door to plasma compensation of beam-beam interaction?
- Collaboration on plasma source
  - Filippi, LNF; Zigler, Hebrew Univ.
- Experimental team/infrastructure at SPARC

Beam parameters for simulation	
Energy	110 MeV
RMS bunch length (σ_z)	75 microns
Normalized emittance	2 mm-mrad
Bunch charge	600 pC
Initial plasma density, n_p	5 x 10^{15} cm^{-3}
Matched beta_eq	1.6 mm
Ramp scale Ls	τ_l=1 cm
Sigma x,y Ramp length, L	5 um 6 cm



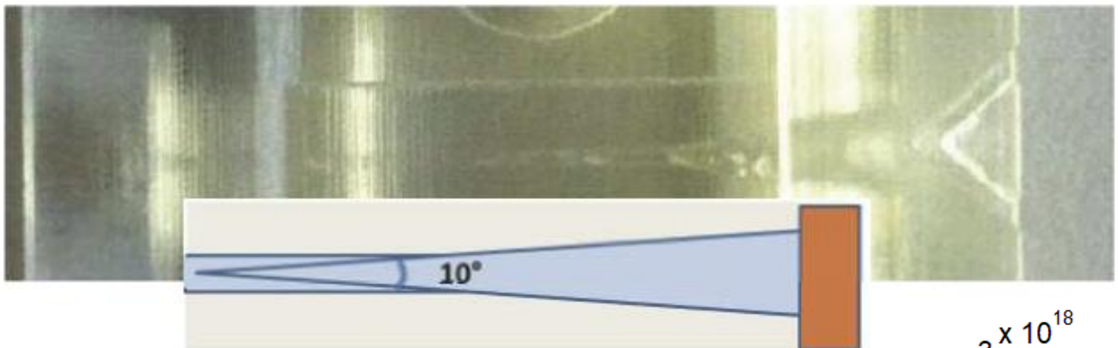
Exponential rise over 400x

Beam density and spot evolution

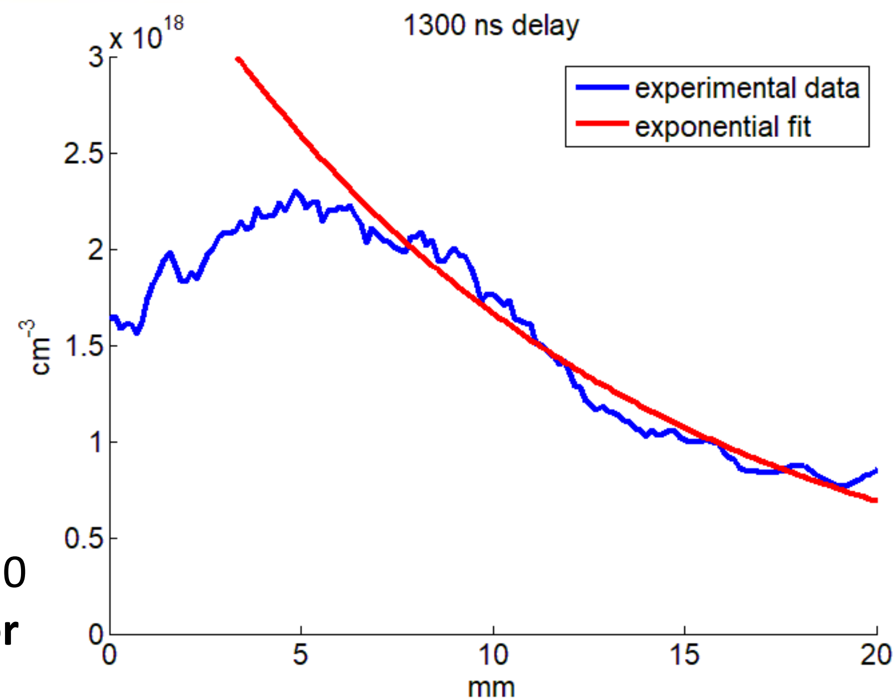


Plasma source development

- Use tapered plastic capillary to control expansion of plasma at entrance



- Tapered edge density (spectroscopic measure)



More details: Wednesday poster session 19:30
“Tapering of plasma density ramp profiles for adiabatic lens experiments”

Beam measurements

- Too small to measure optically
- Use *betatron radiation* instead, in flat density region after ramp
- Method already utilized at LWFA facilities
- Short wavelength radiation (nm)

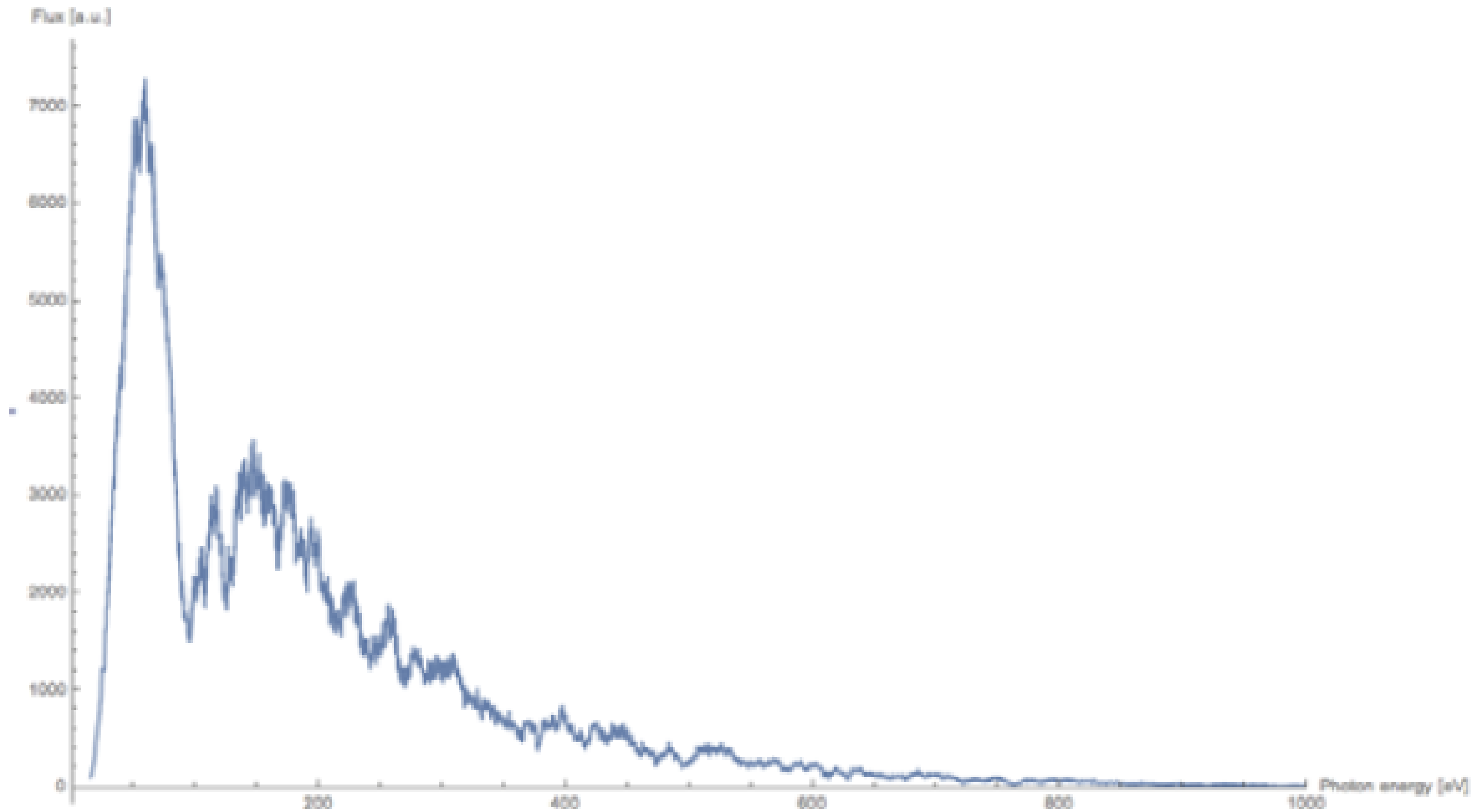
$$K_u = k_\beta \gamma x_0 = 1.33 \times 10^{-2} \gamma^{-0.5} n_0 \left(10^{16} / \mathrm{cc}\right) x_0 (\mu\mathrm{m})$$

$$\lambda_r(\theta) = \lambda_\beta / 2\gamma^2 \cdot \left[1 + \frac{1}{2} K_u^2 + (\gamma\theta)^2\right]$$

- In 2 cm, lots of it! $N_b = L_f / l_b$ $N_g \text{ » } \left(a / 4p\right) N_b a_b^2 \text{ » } 10^7$
- Spectroscopic determination of emittance

$$\Delta\lambda_{rms} = 2\varepsilon_{rms,n} / \gamma$$

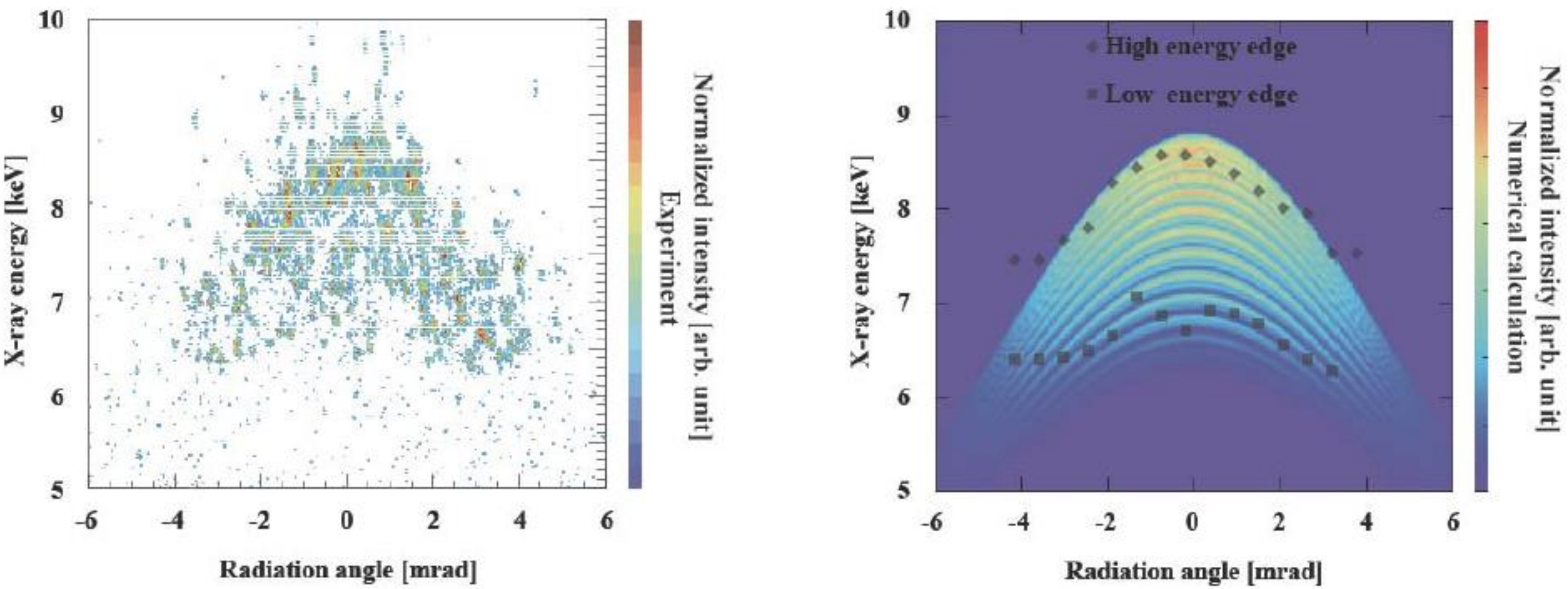
Spectral structure of betatron radiation



From SPECTRA simulations

Single shot X-ray spectrometer

- UCLA-BNL inverse Compton scattering



Full results in Sakai, et al., PRAB 20 060701 (2017)

Future work

- Examine asymmetric beams
  - Highly relevant to LC final focus
- Optimize plasma source
- Upgrade crystal spectrometer
- Layout completion for SPARC
- Experiments!