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Novel emittance measurement combining foil focusing and pepper-pot techniques

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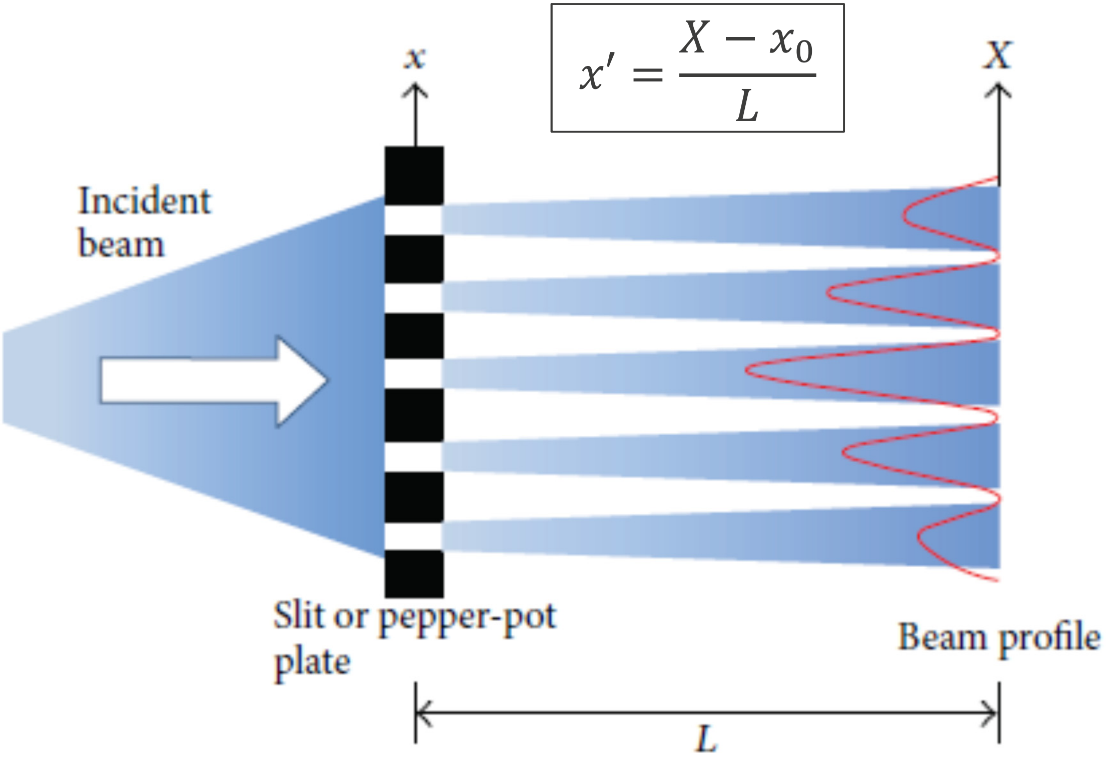
Pepper-pot emittance measurements



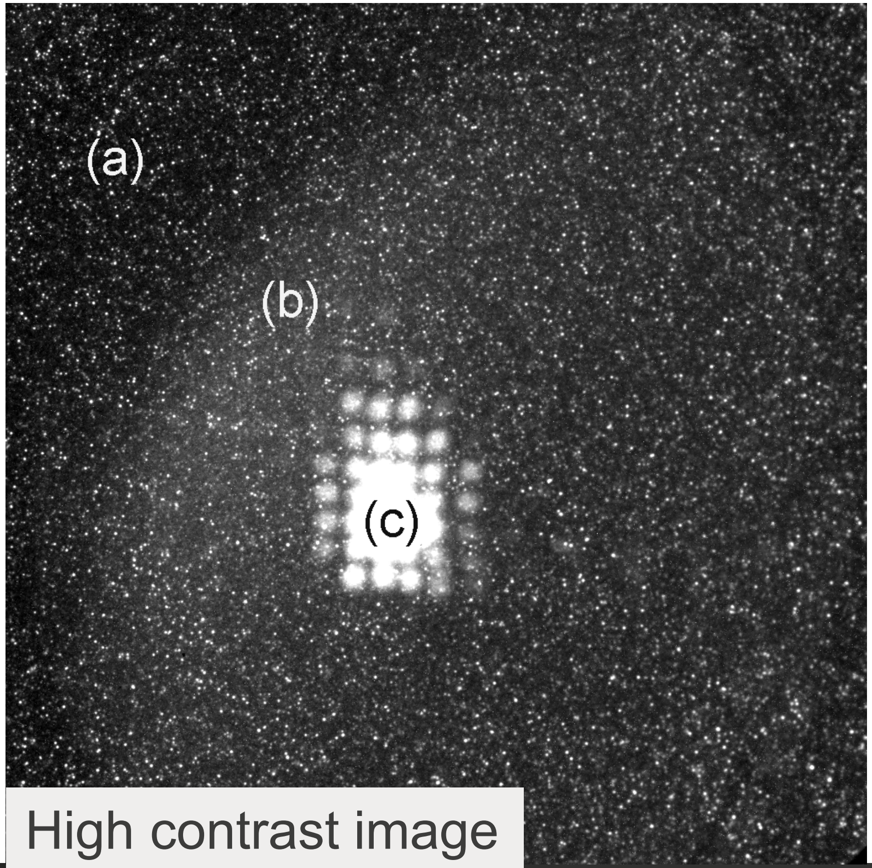
- A pepper-pot mask separates the beam into individual beamlets.
  - Typically a range-thick mask to reduce background counts.
- The beamlets are imaged after a drift.
  - Divergence is determined from the drifted centroid location.
  - RMS beamlet size is a measure of the beam's spread in divergence.
- Emittance is calculated from the beamlet distribution

$$\varepsilon_x = 4\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

Image: Park, Sae-Hoon & Lee, Sang-Hoon & Kim, Yu-Seok, Science and Technology of Nuclear Installations, 2016, 1-4 (2016).

Use Multiple Coulomb scattering to reduce background at imaging screen instead of a range-thick mask.

- No vignetting introduced by a thin pepper-pot mask.
- Average scattering angle is 156 mrad for 254-μm thick Mo.
- Sufficient signal-background ratio to resolve spots.



High contrast image

(a) Background (no OTR target)
(b) Background due to scattered beam on target
(c) Foil focused pepper-pot image

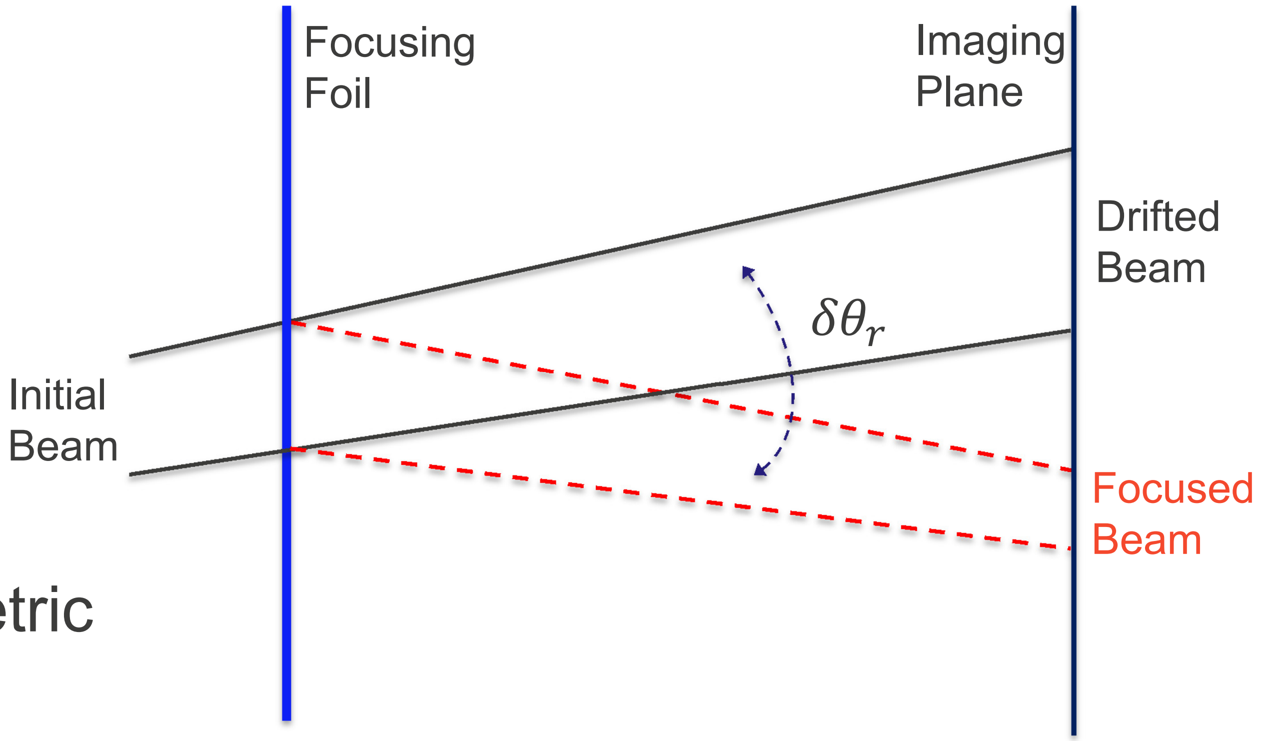
Thin foils focus IREBs.

- A relativistic beam experiences a transverse 'kick' when passing through a thin, conducting, grounded foil.
- For an axisymmetric, uniform beam, this kick* is

$$\frac{\delta p_r}{p_z} = \delta\theta_r = -16\frac{I_b}{I_A}\frac{b}{a}\sum_{n=1}^{\infty}\frac{J_1\left(\frac{\chi_{0n}a}{b}\right)J_1\left(\frac{\chi_{0n}r}{b}\right)}{\chi_{0n}^3 J_1(\chi_{0n})^2}$$

  - I_b is the beam current (1.65 kA)
  - $I_a = 17.05\beta\gamma$ is the Alfven current in kA
  - a is the beam radius
  - b is the beam pipe radius (10 cm)
  - χ_{0n} is the nth root of the Zero-order Bessel function $J_0(x)$

- Can be extended to any axisymmetric beam distribution.**



*Adler, R. J. *Part. Accel.* **12**, 39–44 (1982).
R. F. Fernsler, R. F. Hubbard, and S. P. Slinker, J. Appl. Phys., **68, 5985–5994 (1990).

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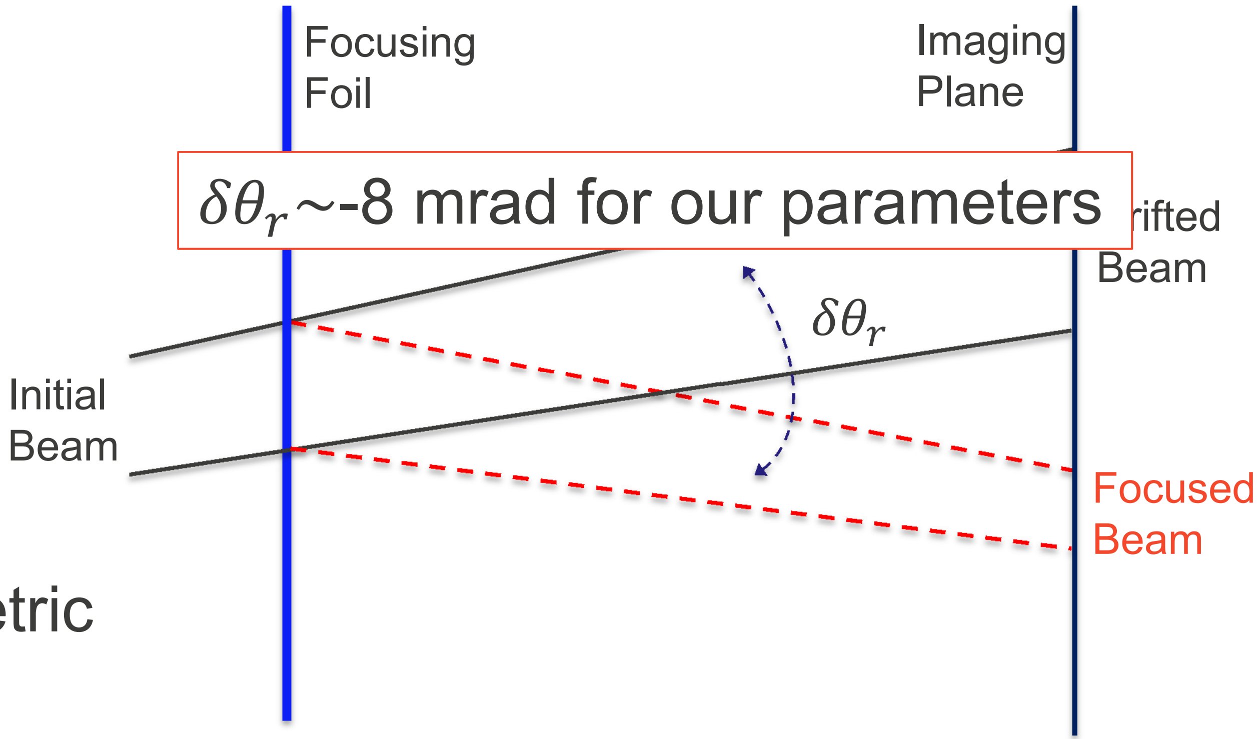

$\delta\theta_r$~-8 mrad for our parameters

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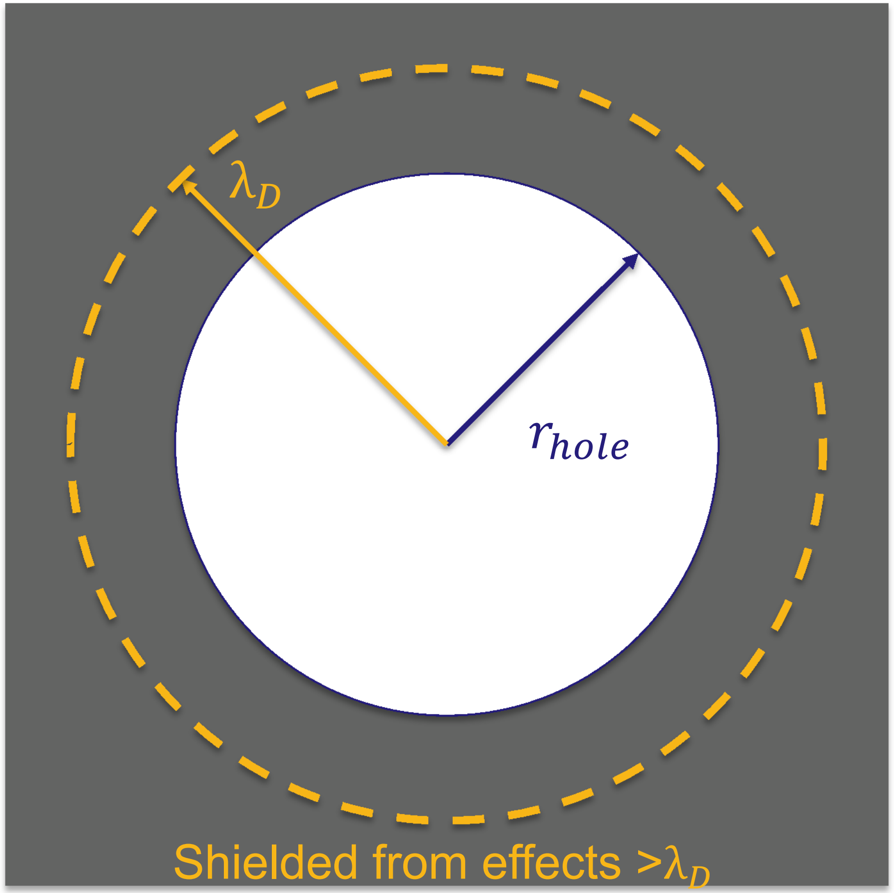
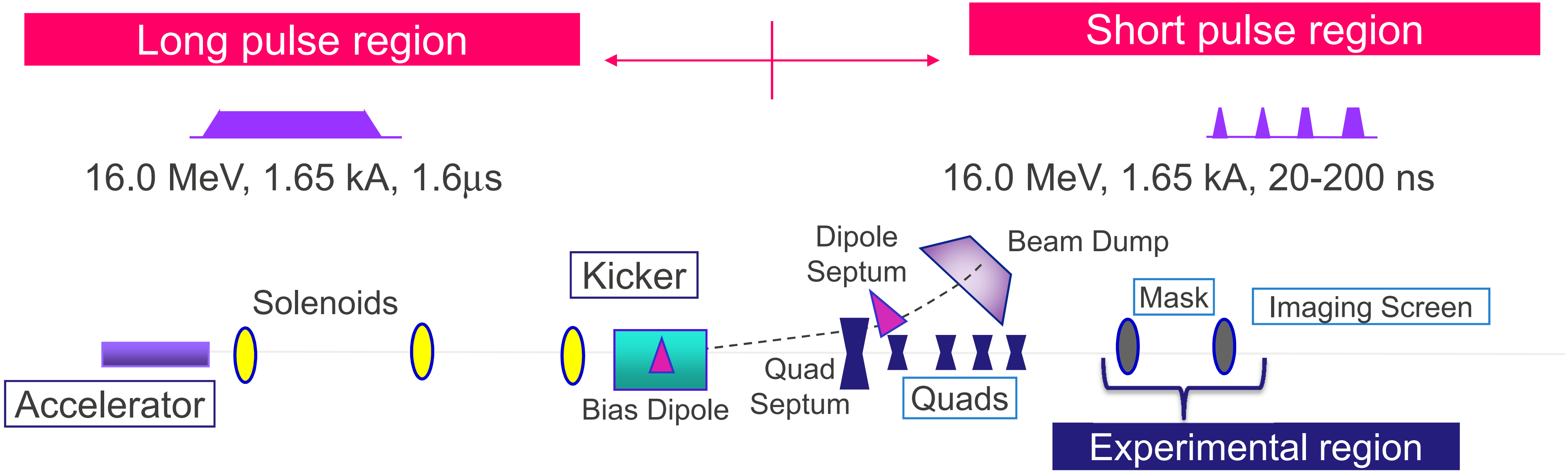
Debye length and foil focusing

- Beam passing through foil (not holes) experiences foil focusing and scattering deflections.
  - Scattering is dominant force.
  - 156 >> -8 mrad
- Beamlets **only** experience foil focusing as long as the hole radius is smaller than the Debye length.
  - Hole radius .75 mm
  - Debye length $\lambda_D = \frac{\varepsilon_n}{4}\sqrt{\frac{I_A}{I_b}} \sim 2mm$ for DARHT Axis-II



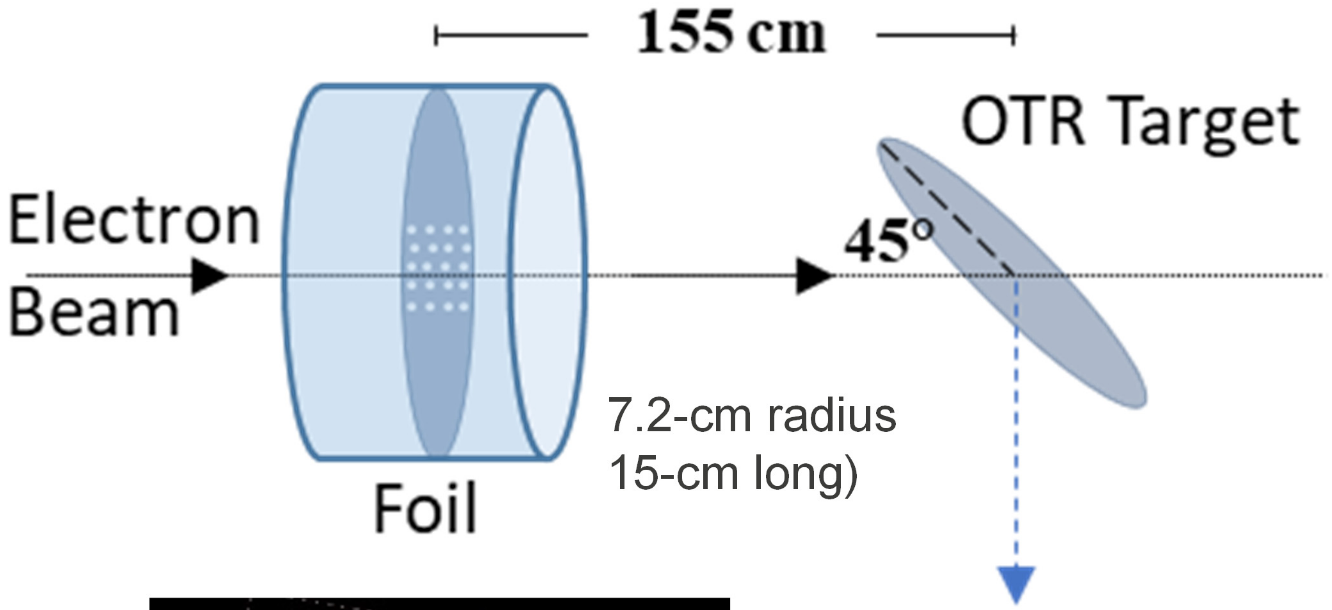
Dual-Axis Radiographic Hydrotest Facility: DARHT Axis-II

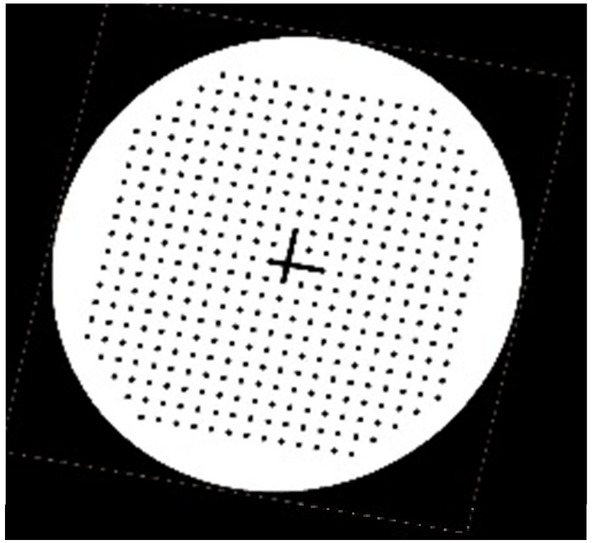


- Completed 2008
- Linear induction accelerator
- 16-MeV electron kinetic energy
- Programmable pulse widths

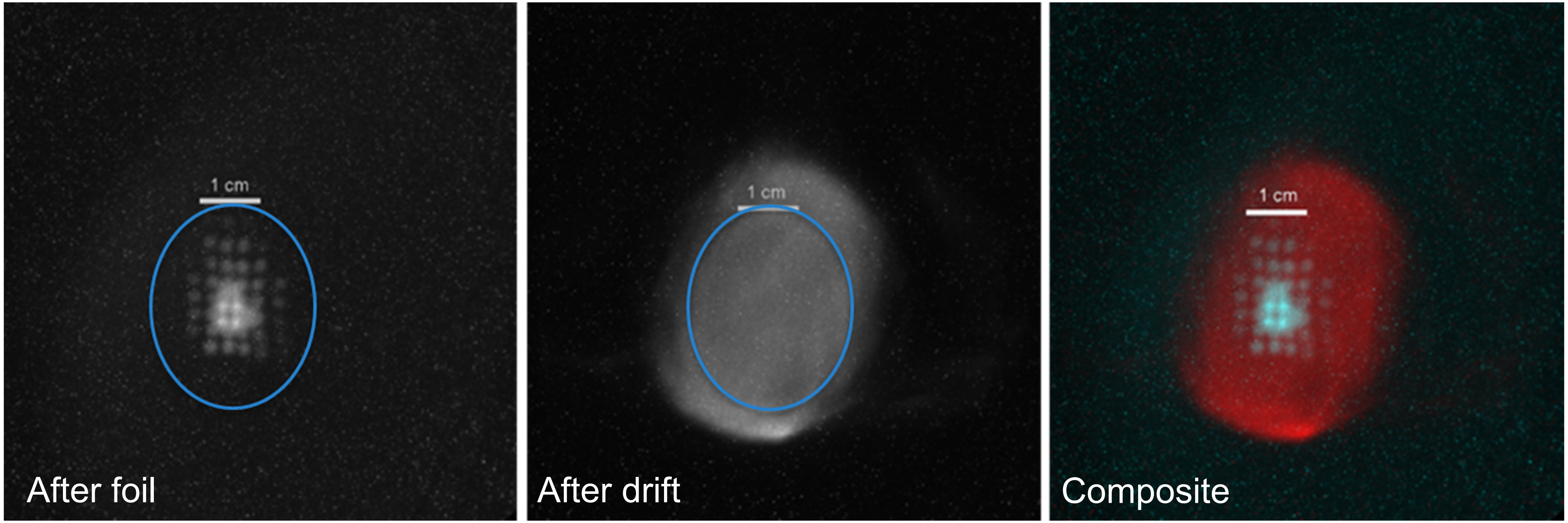
Experimental setup

- DARHT Axis-II Beam
  - 16 MeV
  - 1.65 kA
  - 40-ns pulse kicked from the 1.6-μs flattop
- Mo pepper-pot/focusing mask
  - 254 μm thick
  - 1.5 mm diameter holes
  - 5 mm center-to-center spacing
- NB: Mask fiducial length (17 mm) is much greater than the Debye length (2 mm)



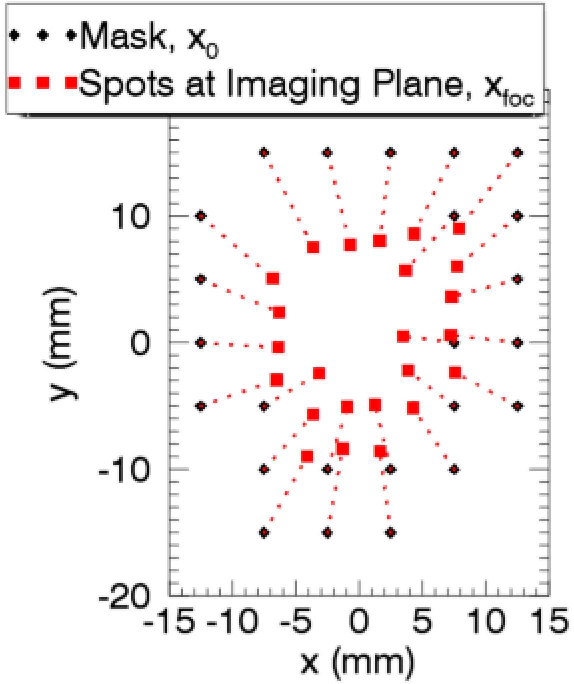


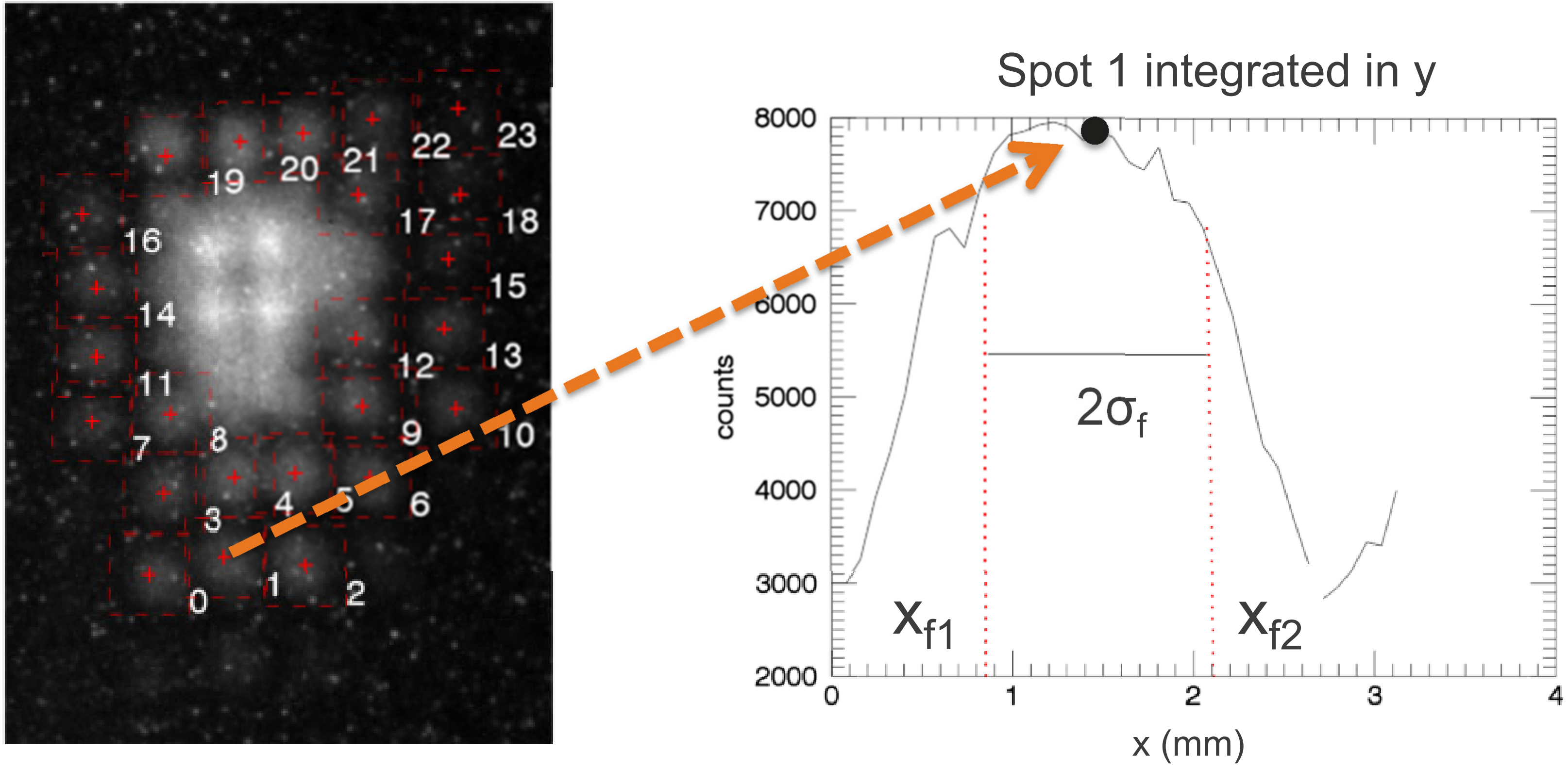
Evidence of Foil Focusing on DARHT-II.



Beam radius at (mm)	X (mm)	Y (mm)	
Mask 6x7.5 holes	13	16	
After foil	6	8	Converging beam!
After drift	20	25	Diverging beam!

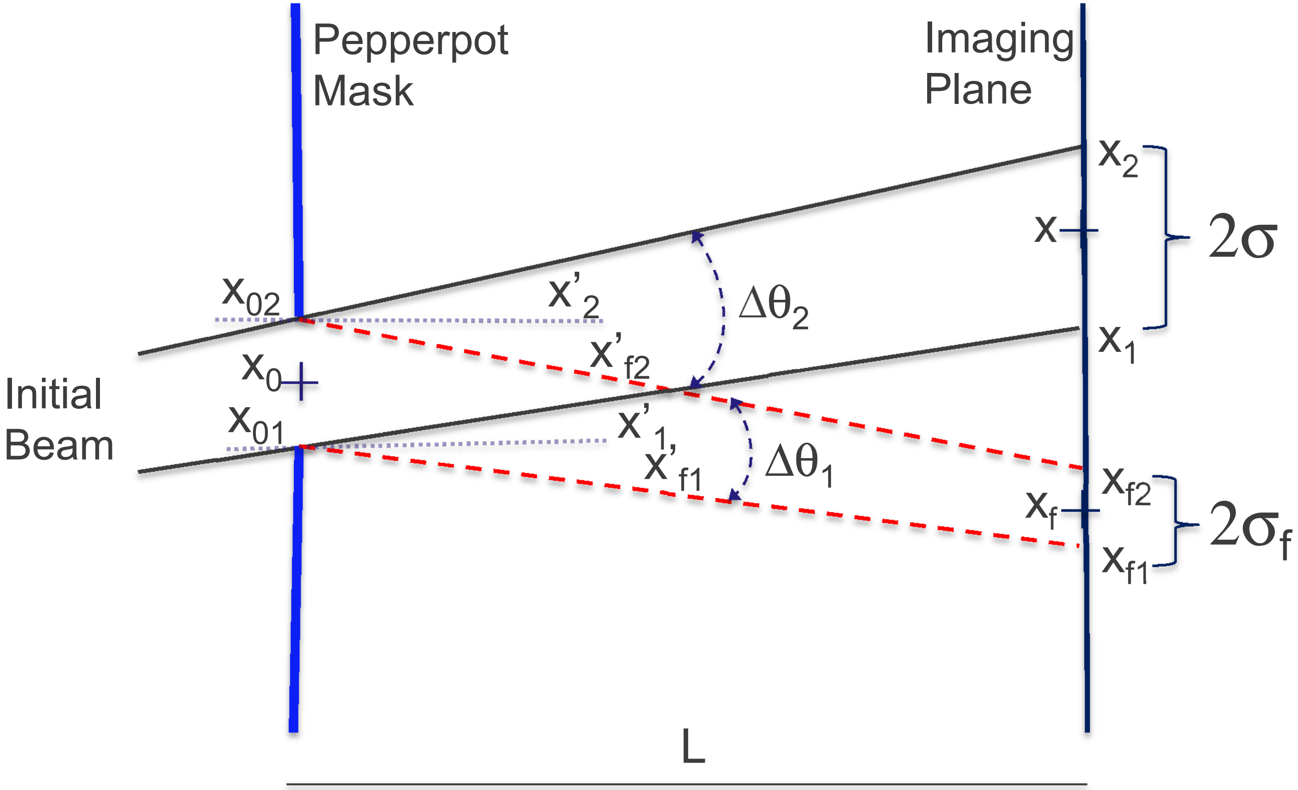
Spot Analysis





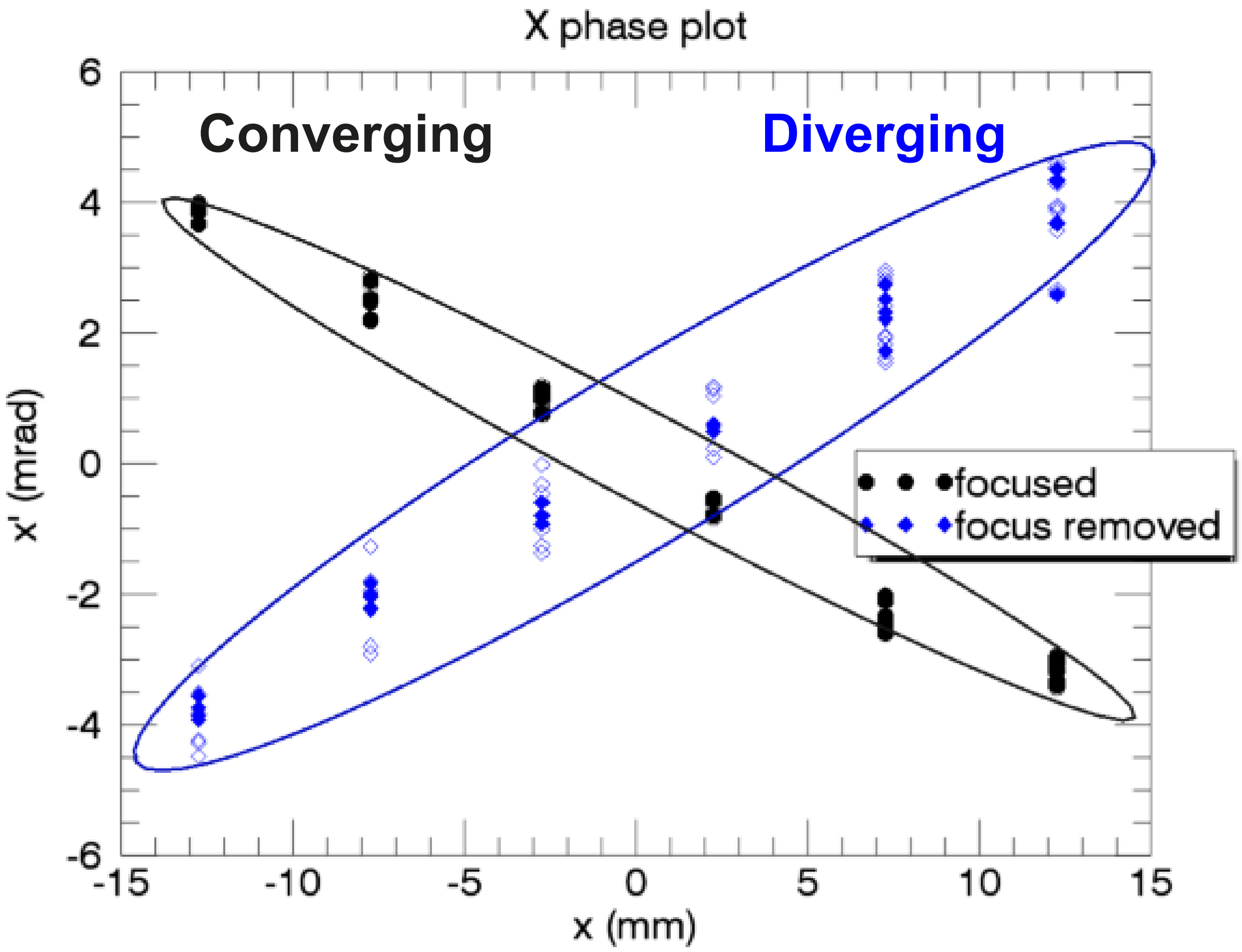
- Subtract constant background with 5-pix median smoothing
- Spot size: $\sigma_f{}^2 = \langle x_{beamlet}{}^2 \rangle = \frac{\sum counts(x - \langle x \rangle)^2}{\sum counts}$
- RMS edges of beamlet: $x_{f1}, x_{f2} = x_f \pm \sigma_f$
- $f \rightarrow$ focused beamlet pattern

Accounting for foil focusing of beamlets



- Beamlet envelopes are also foil focused.
  - $\Delta\theta_i = \theta_{r0}\, {}^{x_{0i}}/_{r_{0i}}$, kick in x-direction
  - $x'_i = x'_{fi} - \Delta\theta_i$, corrected divergence
  - $x_i = x_{0i} + x'_i L$, corrected beamlet edges
- Beam sizes before and after accounting for focusing
  - σ_f is 0.78 mm
  - σ is 1.3 mm

Accounting for foil focusing changes beam convergence angle and the measured emittance



in π-mm-mrad	ε_x	ε_y
Focused	147	306
Corrected	226	415

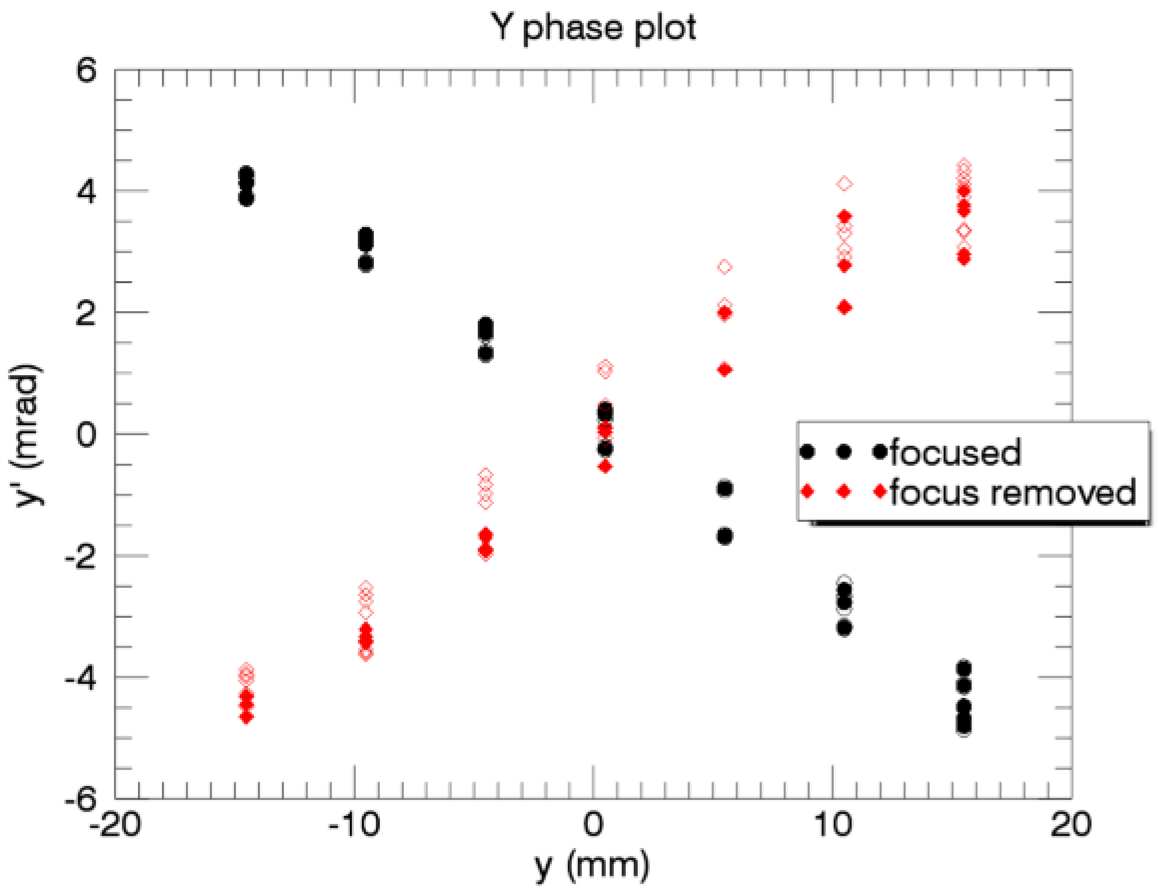
- Analysis of another shot with a different quadrupole tune gives ε_x=300 and $\varepsilon_{x,corrected}$=423 π-mm-mrad.
- Solid-centroid locations.
- Open-edge locations.

Conclusion

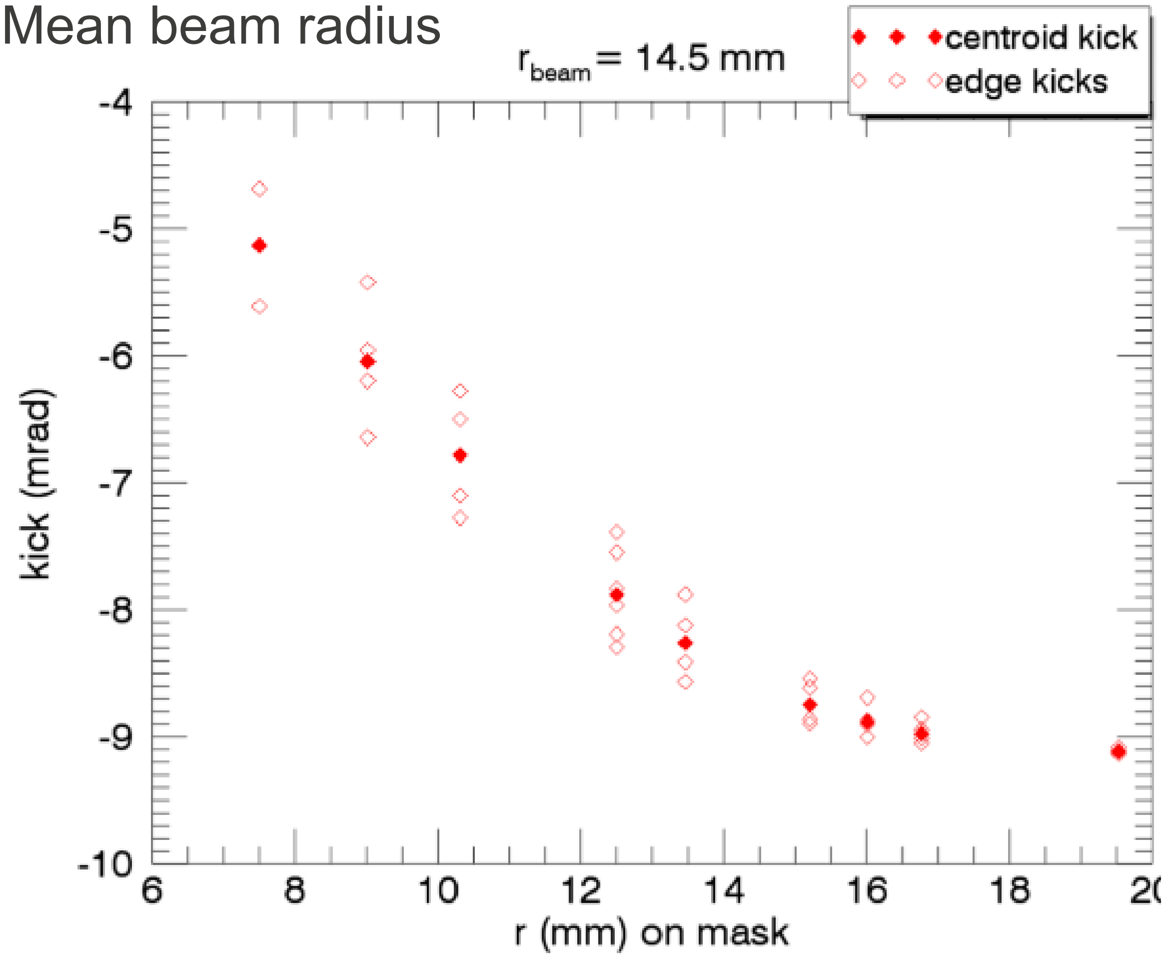
- Foil focusing must be taken into account when using a thin pepper-pot foil to measure a relativistic beam's emittance.
  - More important for beams that are close to pipe radius
- Future direction
  - Optimize mask
  - Automatic spot detection
  - Elliptical beams
  - Off-center beams
  - Background
  - Error analysis
  - Space charge

Thank you.

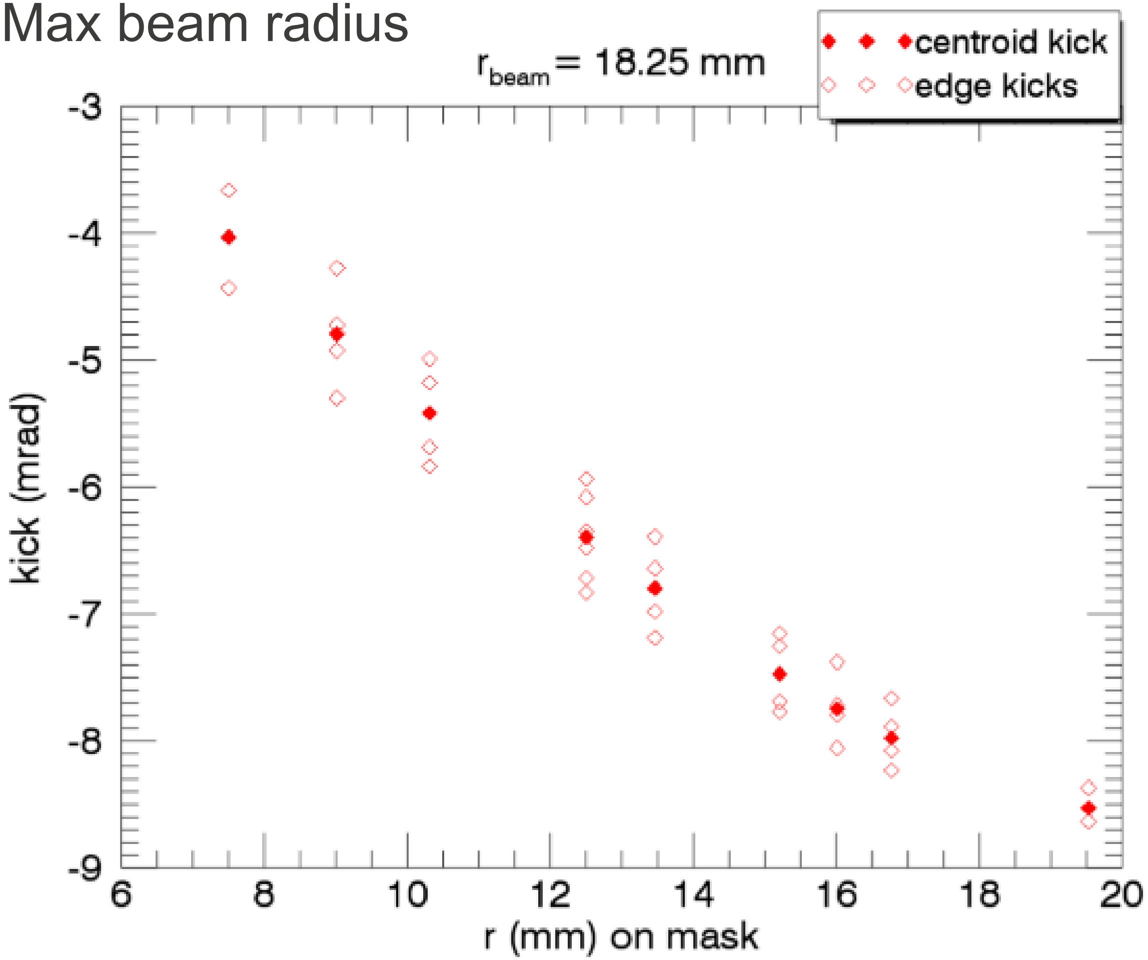
kimberlys@lanl.gov


Y phase plot
6
4
2
0
-2
-4
-6
y' (mrad)
-20
-10
0
10
20
y (mm)
focused
focus removed

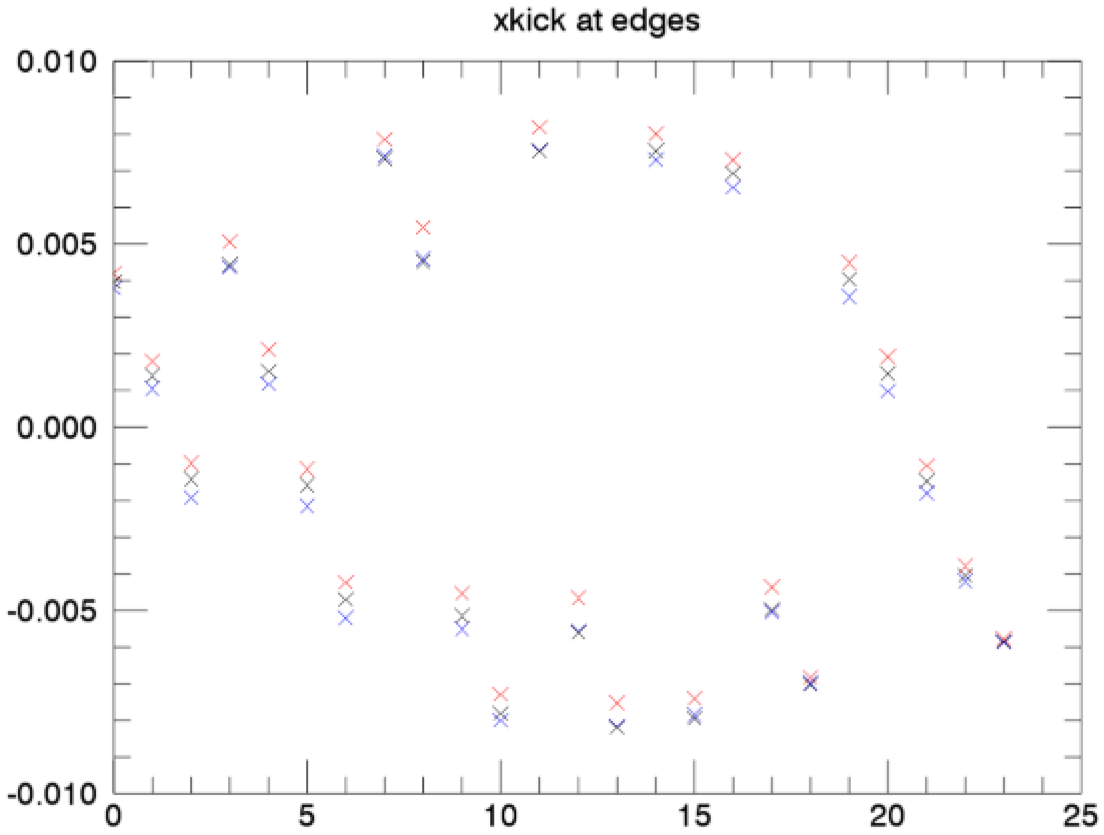
Mean beam radius

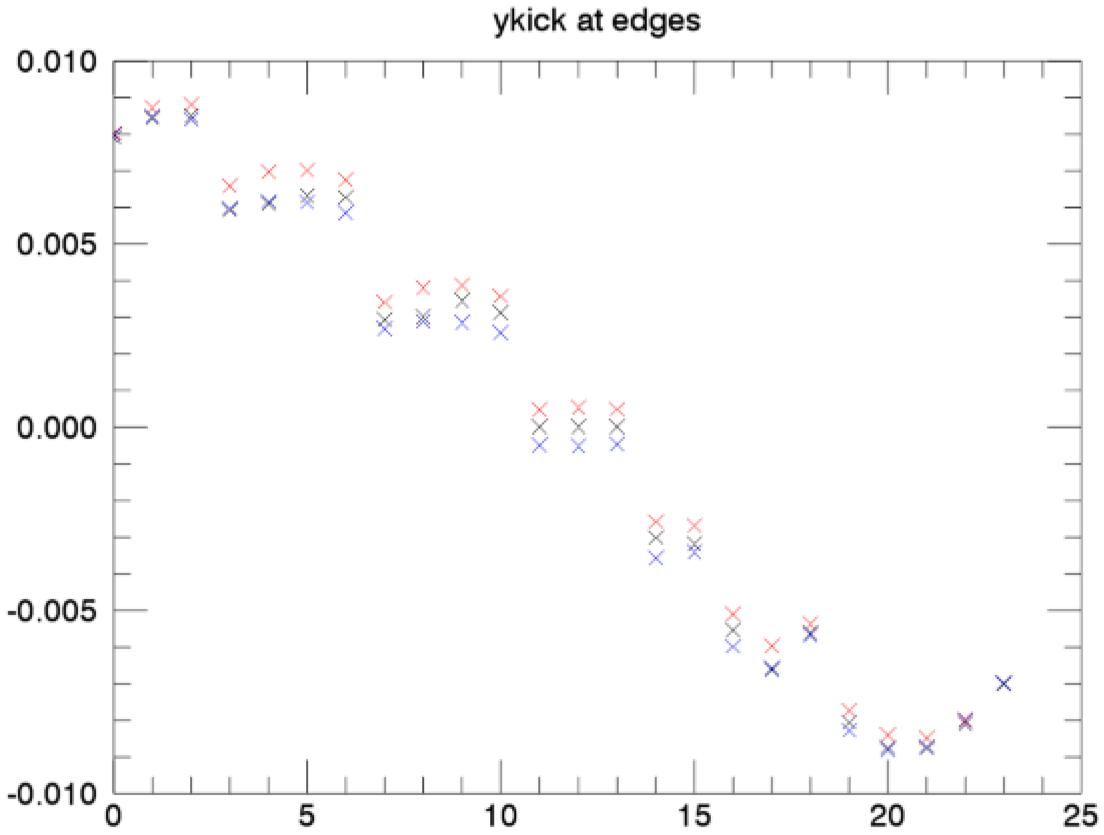


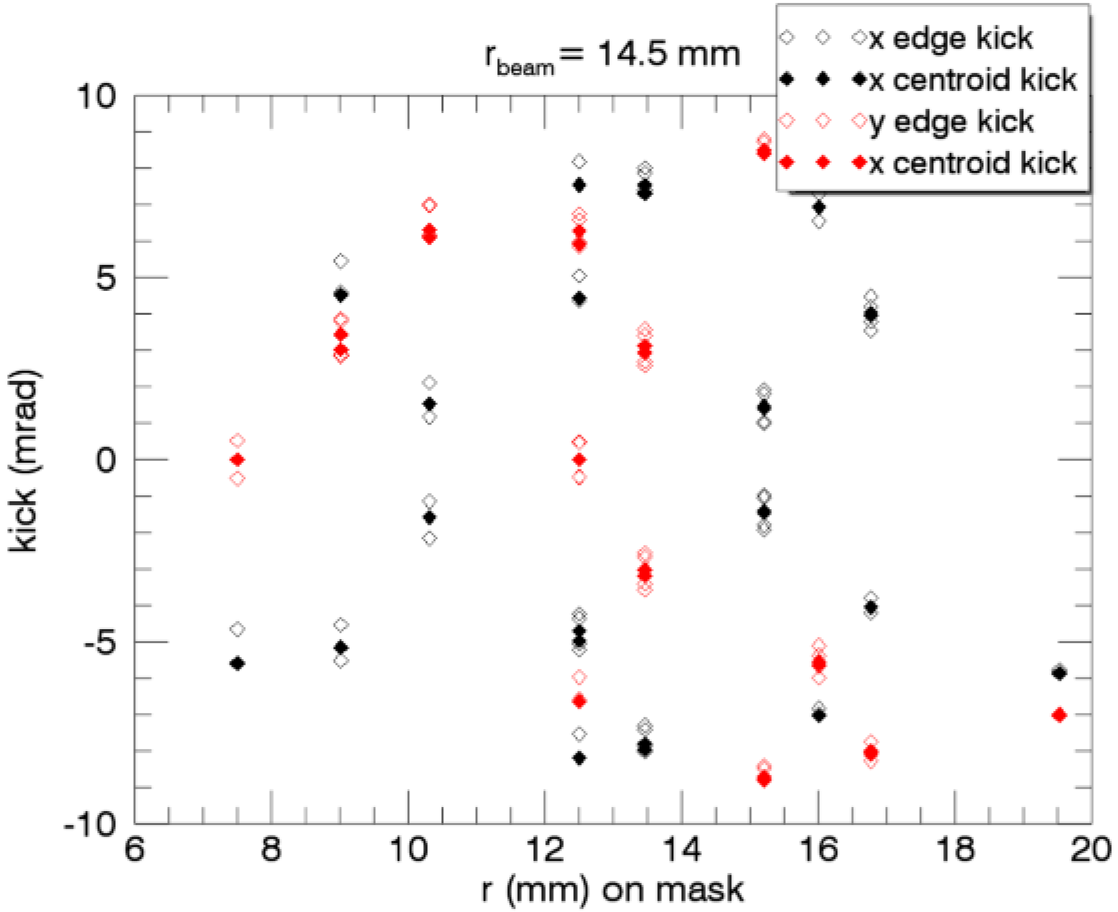
Max beam radius



Kick (in rad) as a function of spot






r_{beam} = 14.5 mm
x edge kick
x centroid kick
y edge kick
x centroid kick
10
5
0
-5
-10
kick (mrad)
6
8
10
12
14
16
18
20
r (mm) on mask

RMS spot values

$$\langle x\rangle = \frac{\sum_i I_i x_i}{\sum_i I_i}$$

$$\langle x'\rangle = \frac{\sum_i I_i x'_i}{\sum_i I_i}$$

$$\langle x^2\rangle = \frac{\sum I(x - \langle x\rangle)^2}{\sum I}$$

$$\langle x'^2\rangle = \frac{\sum I(x' - \langle x'\rangle)^2}{\sum I}$$

$$\langle xx'\rangle = \frac{\sum I(x - \langle x\rangle)\,(x' - \langle x'\rangle)}{\sum I}$$

$$\varepsilon_x = 4\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$