

Round-to-Flat Beam Transformation and Applications

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Outline

- Introduction;

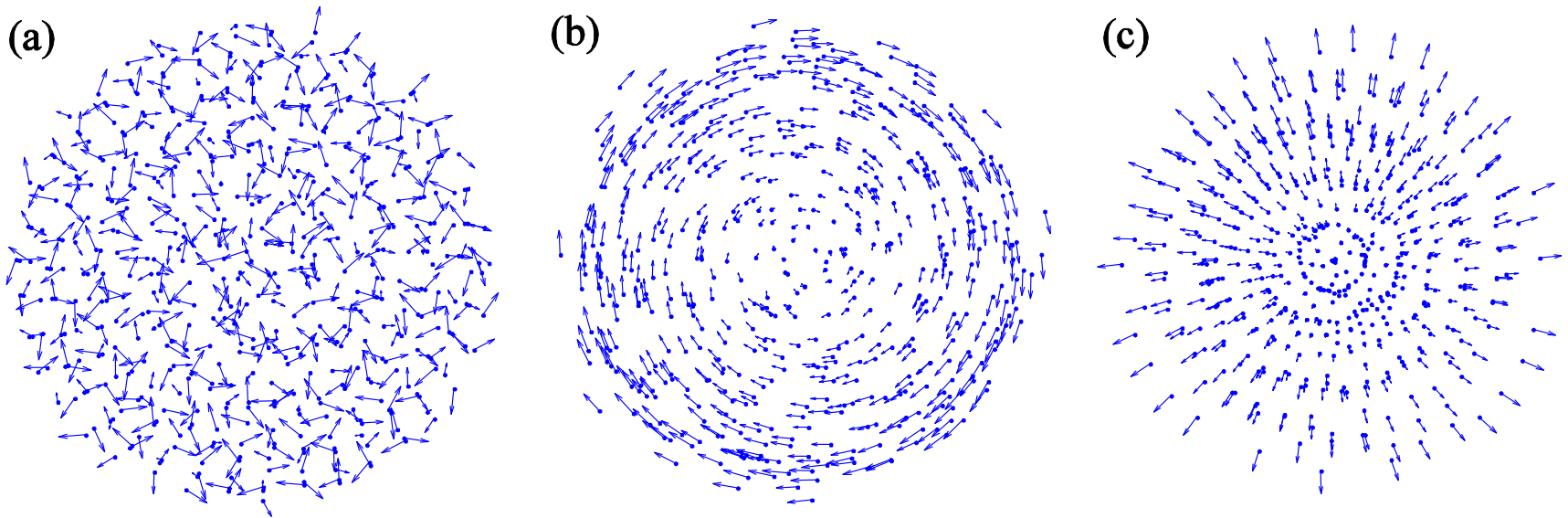
- Generation of magnetized electron bunches from a high-brightness RF photo-injector;

- Parameterization and measurements of the magnetized beam;

- Experimental demonstration of the removal of the angular momentum and the generation of a flat beam:
 - theory;
 - measurement method;
 - data analysis and results;
 - comparison with simulations.



Beam dynamics: three different regimes



↑
emittance

Magnetized
(canonical angular momentum)

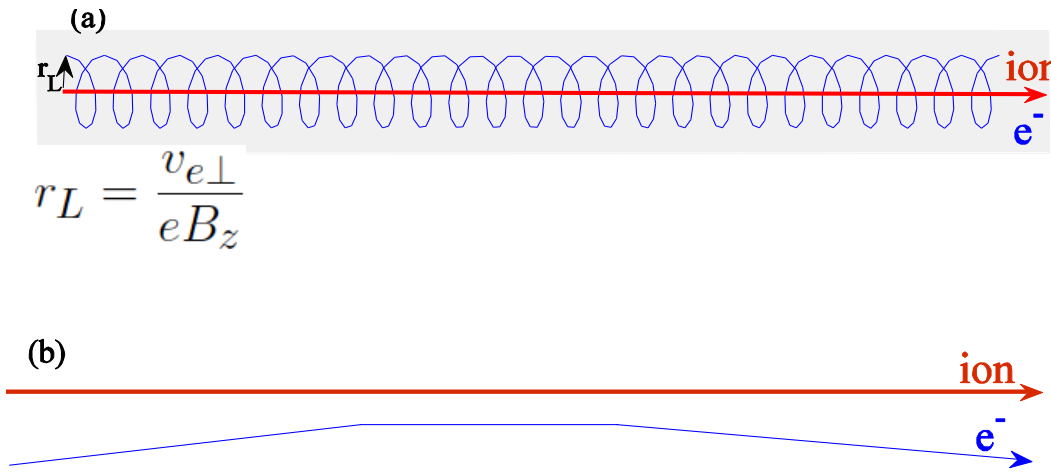
↑
space charge

envelope equation in a drift: $\sigma'' - \frac{\varepsilon^2}{\sigma^3} - \frac{L^2}{\sigma^3} - \frac{K}{4\sigma} = 0$ where $K = \frac{2I}{I_0 \beta^3 \gamma^3}$

is the generalized perveance.

Applications of magnetized beam and flat beam

□ Electron cooling for heavy ion: cooling interaction Time



$$\tau_c^{mag} \approx \rho / (v_z^{ion} - v_z^e)$$

magnetized

$$\tau_c^{free} \approx \rho / v_e^\perp$$

non - magnetized

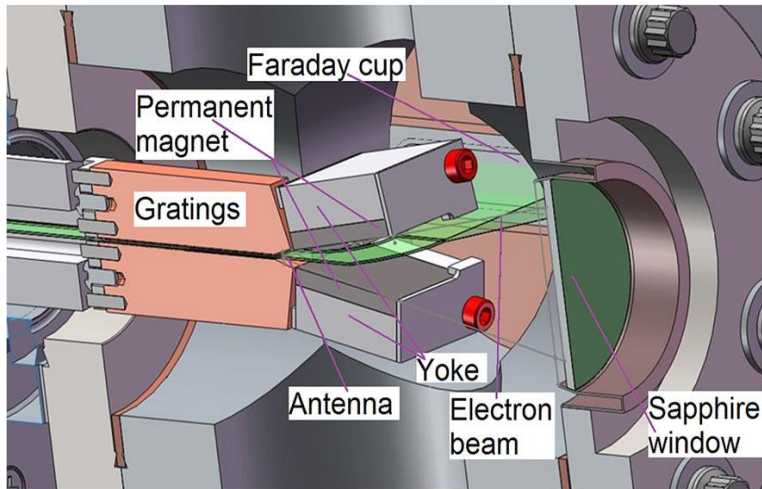
□ Flat beam for linear e^+e^- collider: reduce beamstrahlung

$$\text{luminosity} \propto \frac{1}{\sigma_x \sigma_y} \quad \delta_E \propto \frac{1}{(\sigma_x + \sigma_y)^2}$$

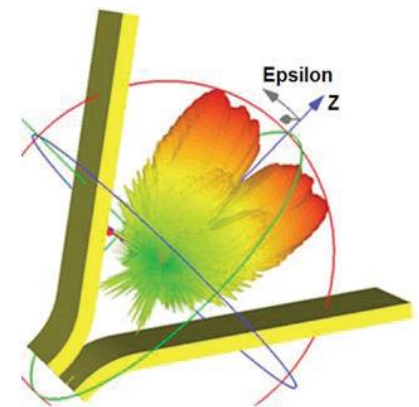
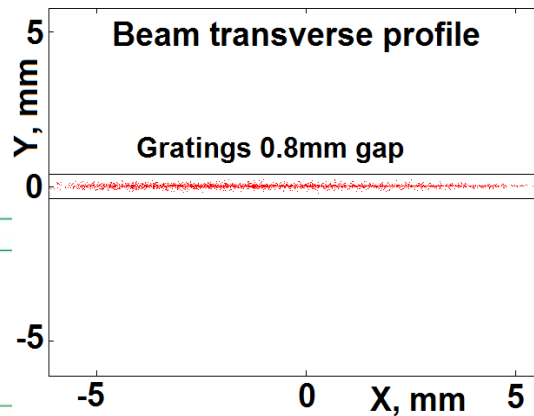
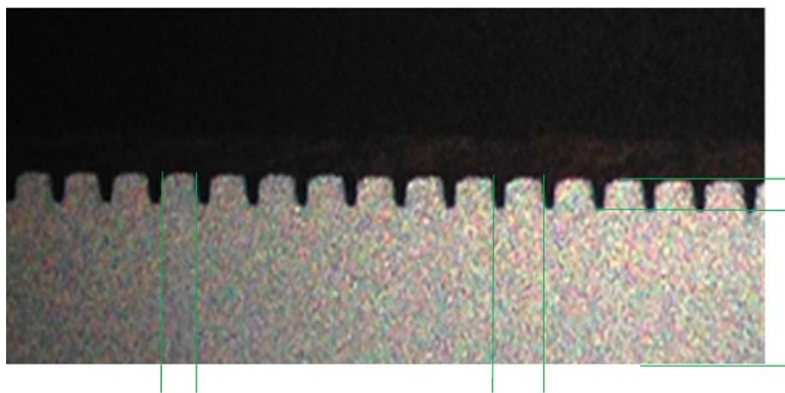
Applications of magnetized beam and flat beam

Flat beam for light sources

Radiators of planar geometry such in the Radiabeam-APS THz generation experiment carried out at the Injector Test Stand in APS/ANL.



(a)



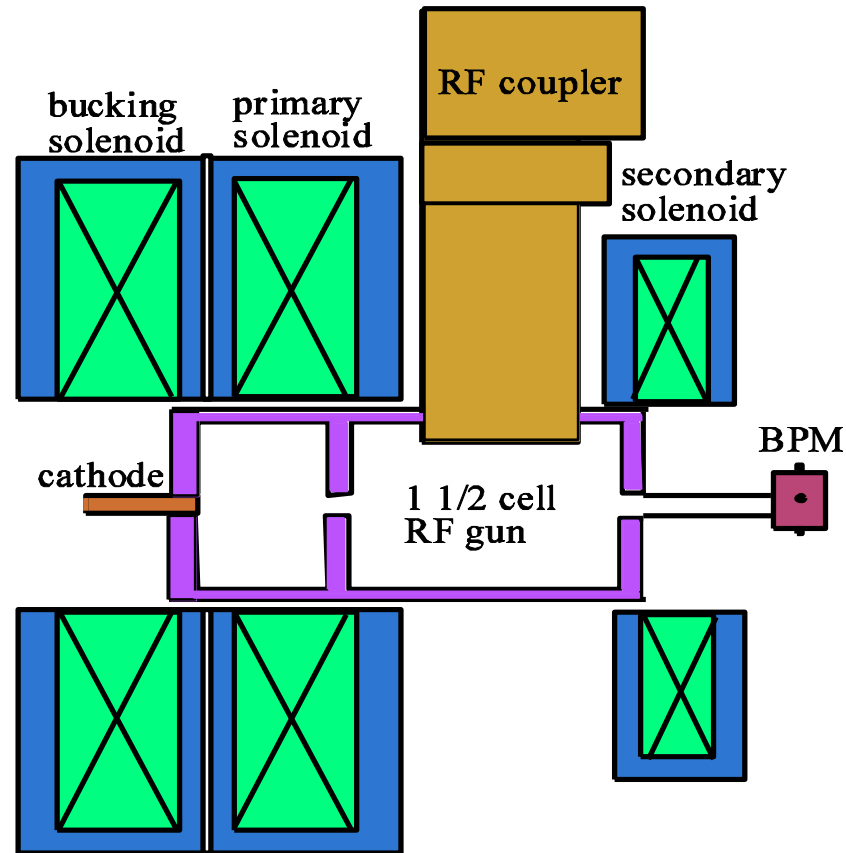
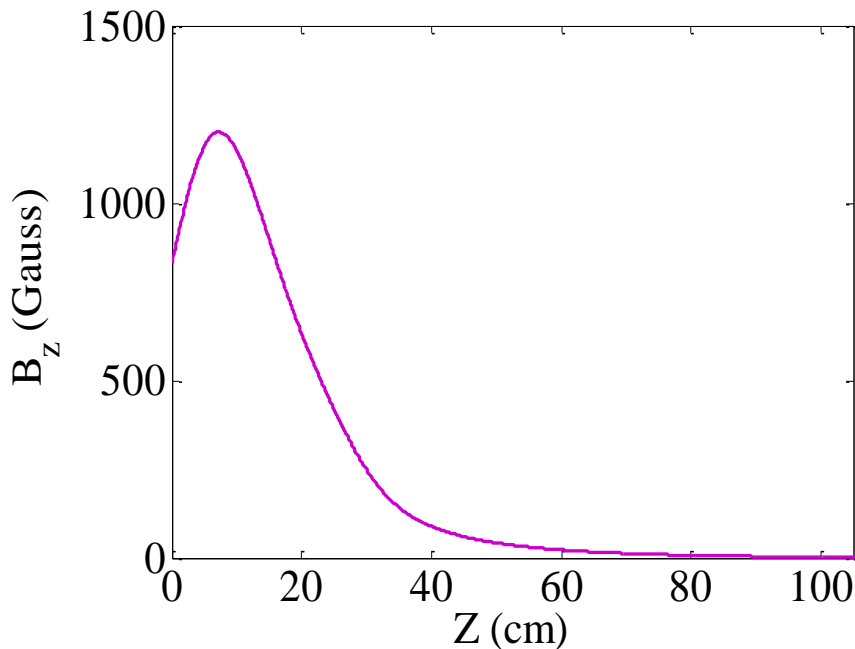
(A. Smirnov, Phys. Rev. ST Accel. Beams 18, 090703 (2015).)

Generation of magnetized electron beam From a high-brightness RF photo-injector

$$L = \gamma m r^2 \dot{\phi} + \frac{1}{2} e B_z r^2$$

On the cathode: $\langle L \rangle = e B_0 \sigma_c^2$

Solenoidal end field applies a torque to the beam. When $B_z=0$, canonical equals to the mechanical angular momentum.



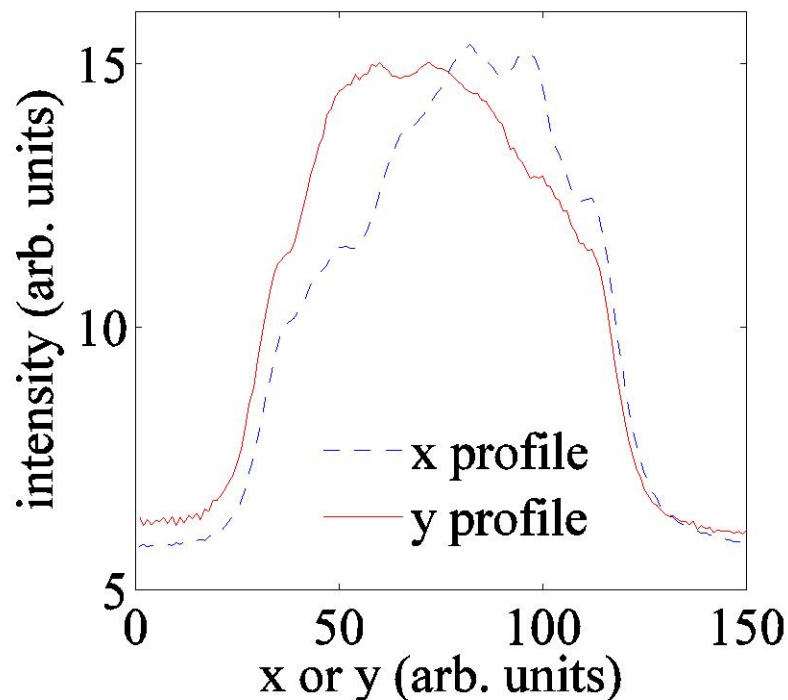
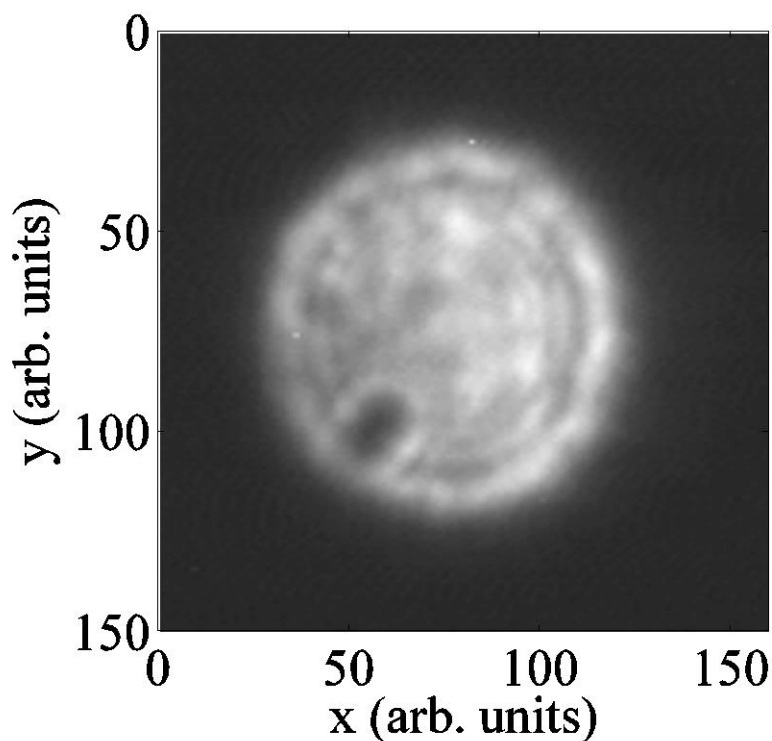
FNPL 1.625-cell RF gun, 1.3 GHz

Measurement of canonical angular momentum on the photocathode

$$\langle L \rangle = eB_0\sigma_c^2$$

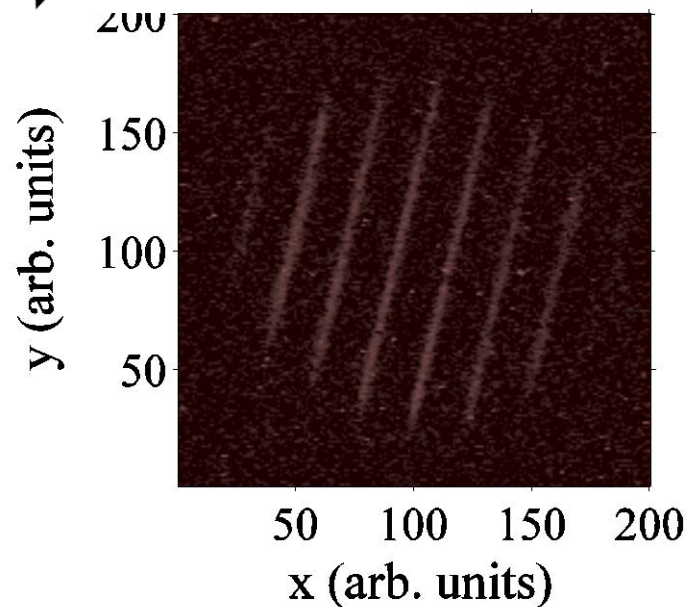
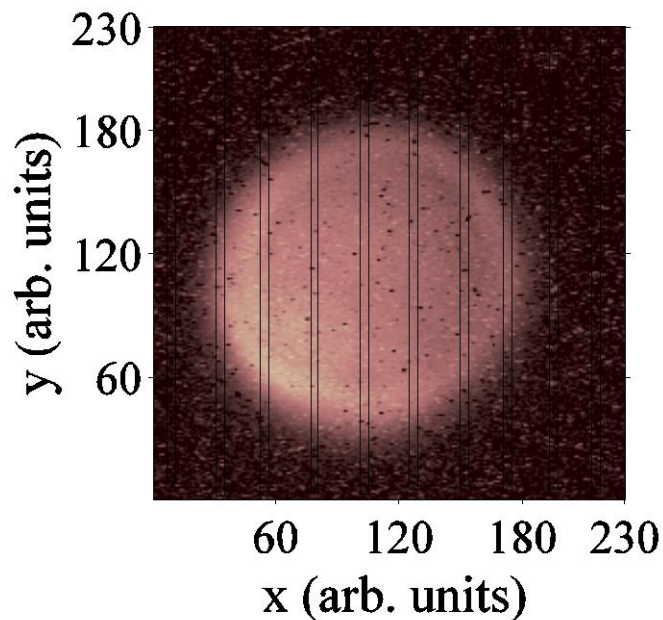
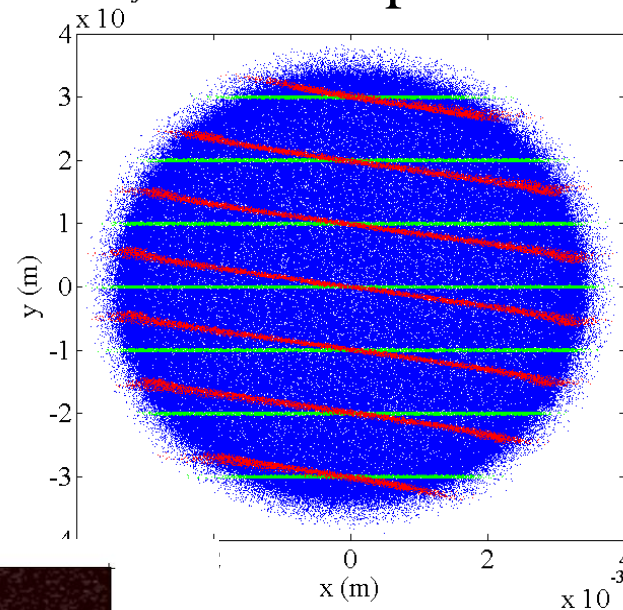
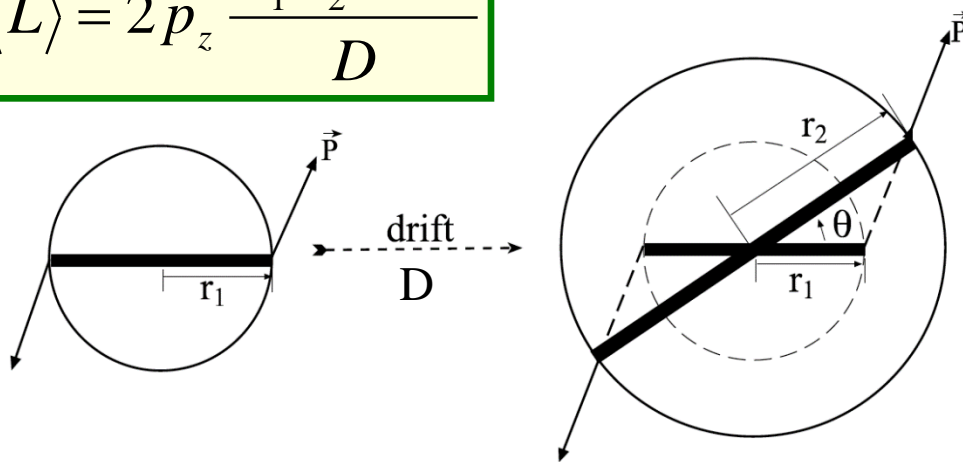
B_0 : B-field on cathode

σ_c : RMS beam size on cathode

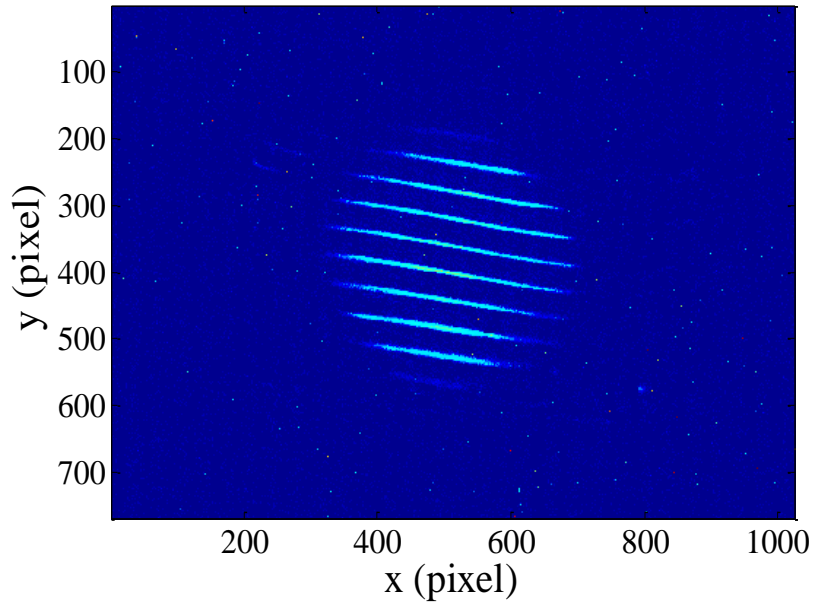


Measurement of mechanical angular momentum in a drift space

$$\langle L \rangle = 2p_z \frac{\sigma_1 \sigma_2 \sin \theta}{D}$$

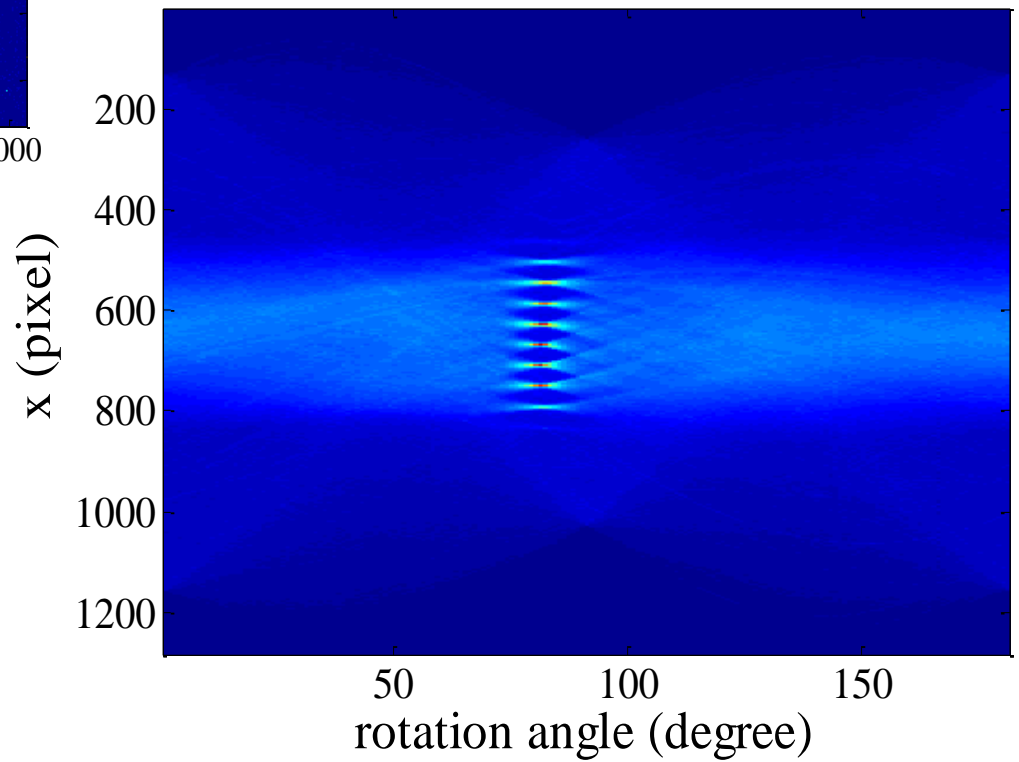


Measurement of rotation angle

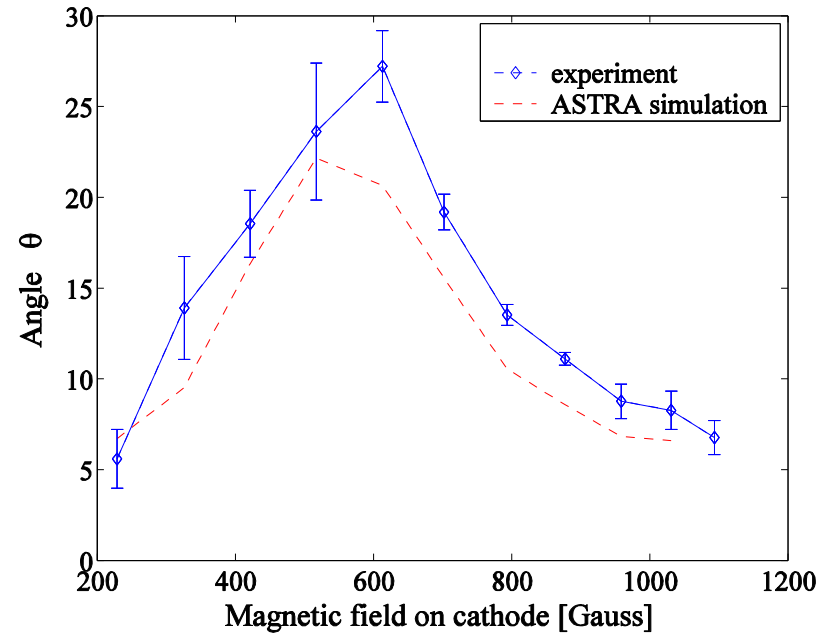
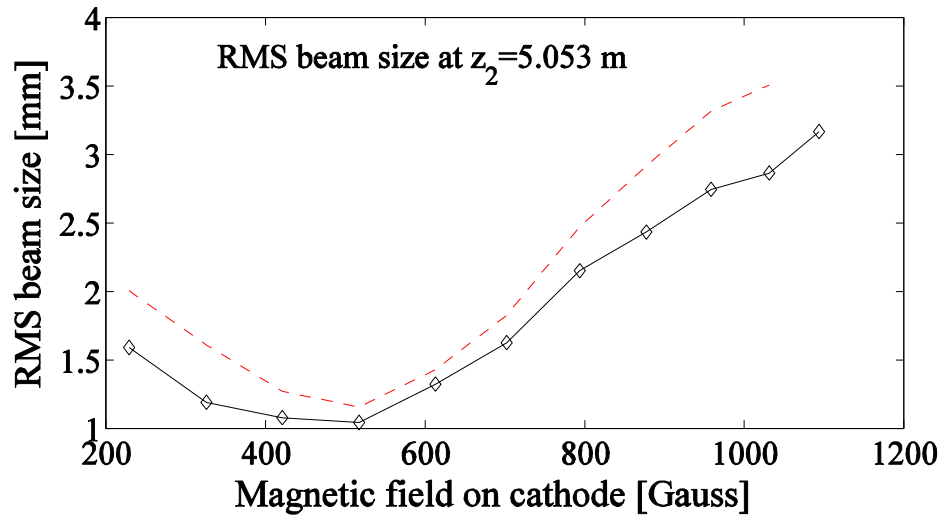
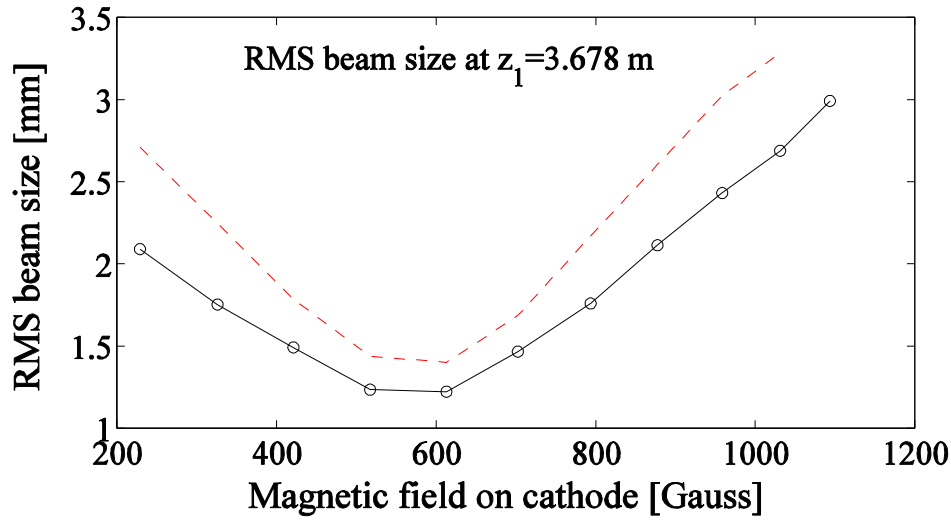


↑
slit image

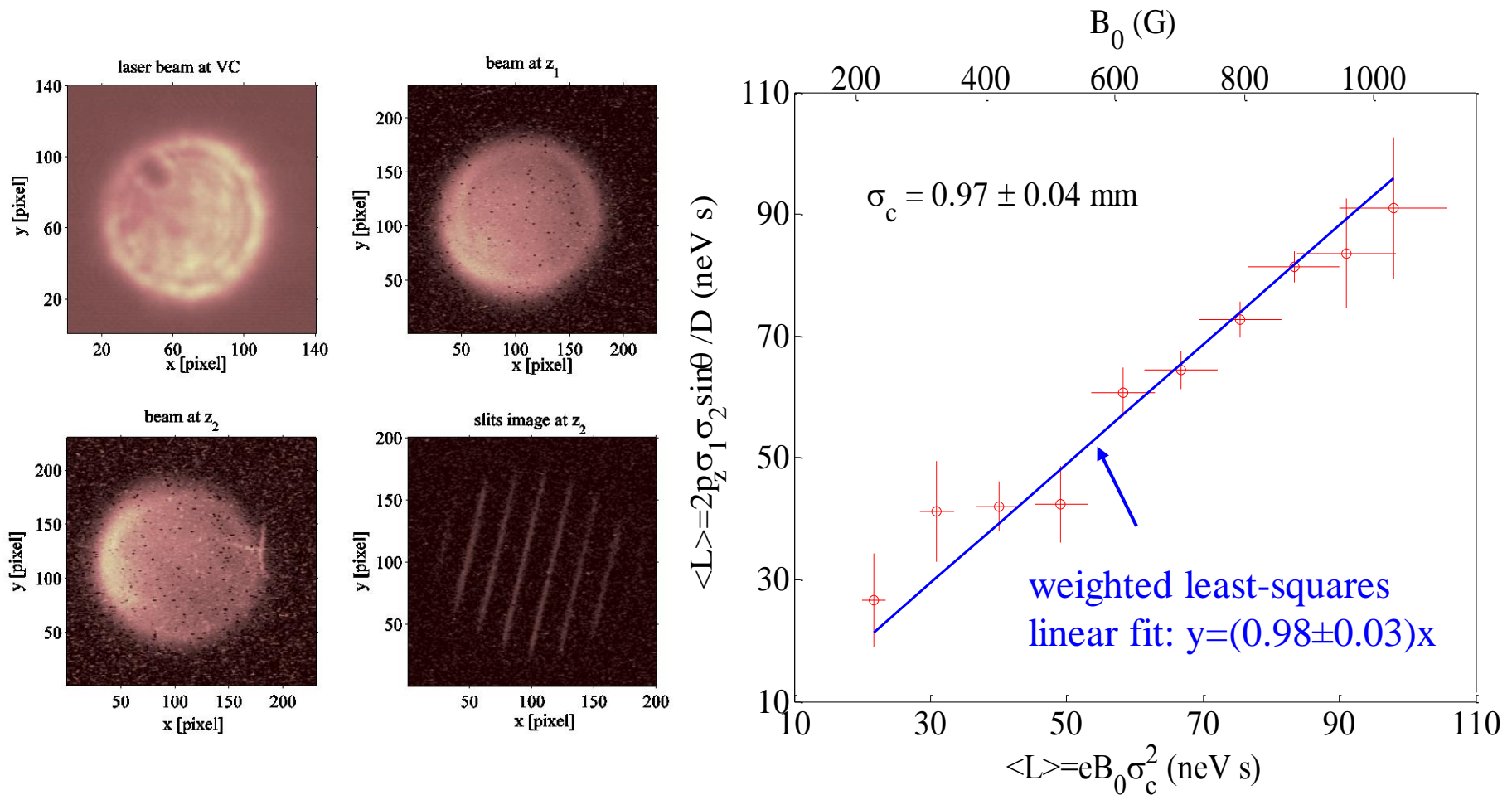
rotation of the slit image



Measurement of mechanical angular momentum vs B-field



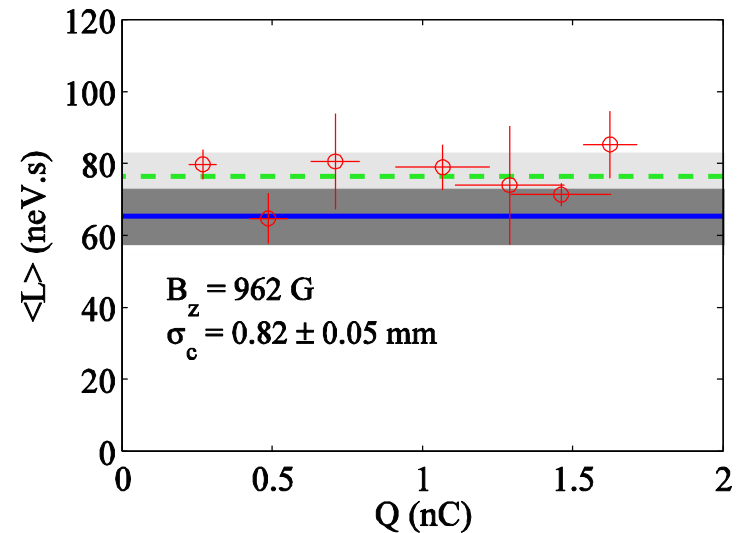
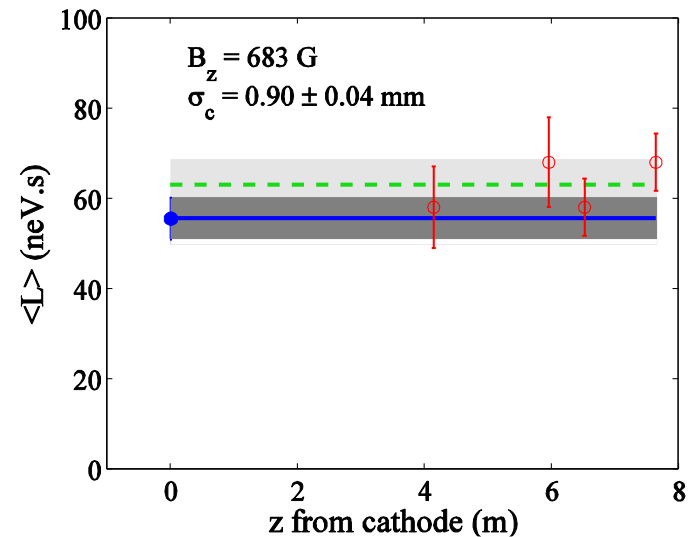
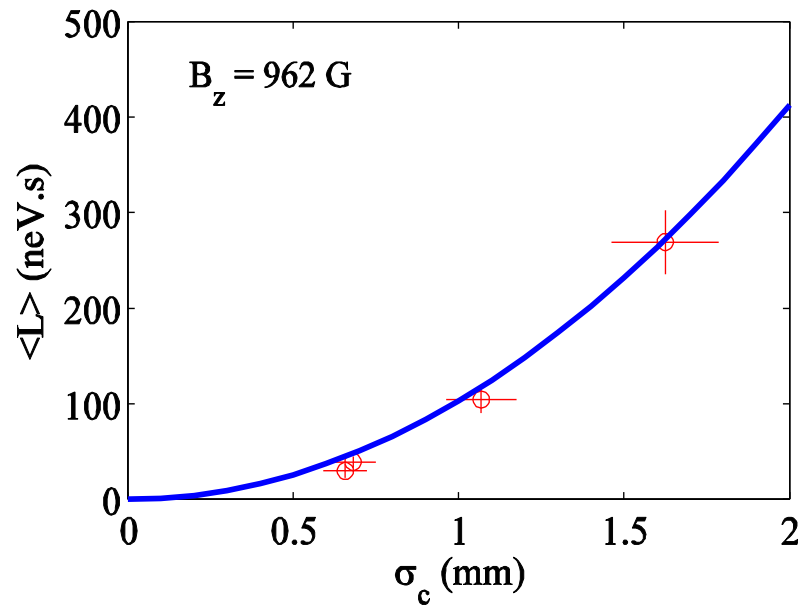
Demonstration of conservation of canonical angular momentum as a function of magnetic field on cathode



Parametric dependencies of angular momentum

Angular momentum versus

- beam longitudinal position z
- bunch charge
- beam size on the cathode



From magnetized beam to flat beam

Ya. Derbenev, “Adapting Optics for High Energy Electron Cooling”,
University of Michigan, UM-HE-98-04, Feb. 1998.

Ya. Derbenev, “Matched Electron Cooling”, WEWAUD02, COOL’15.

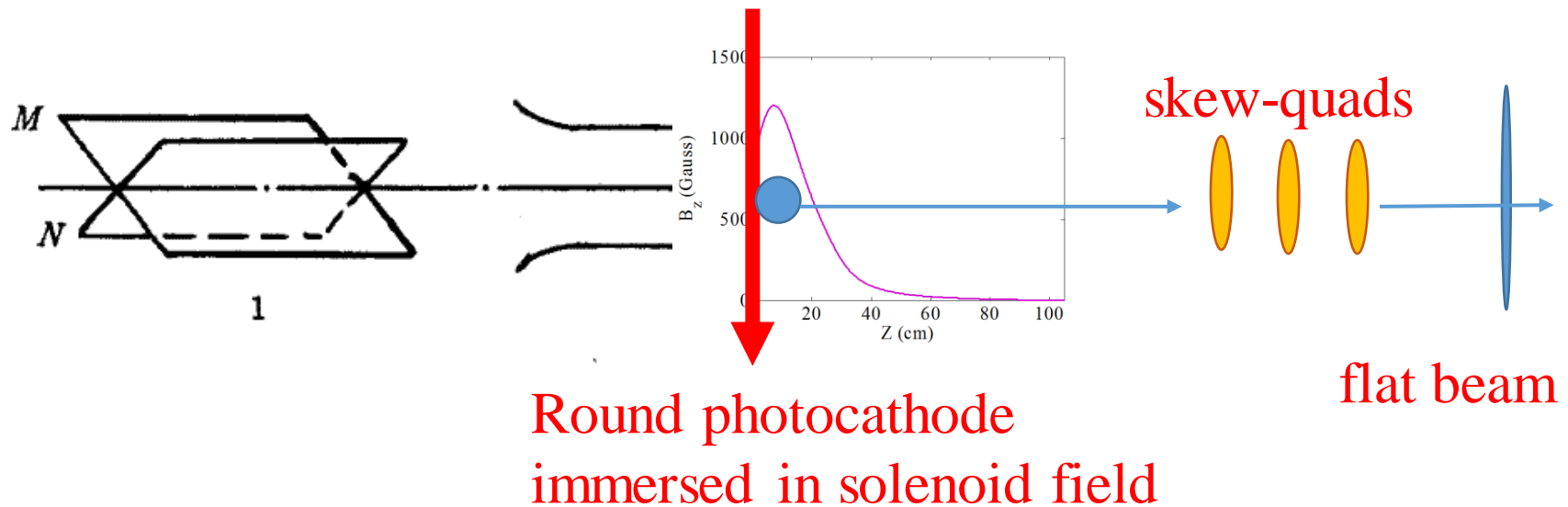
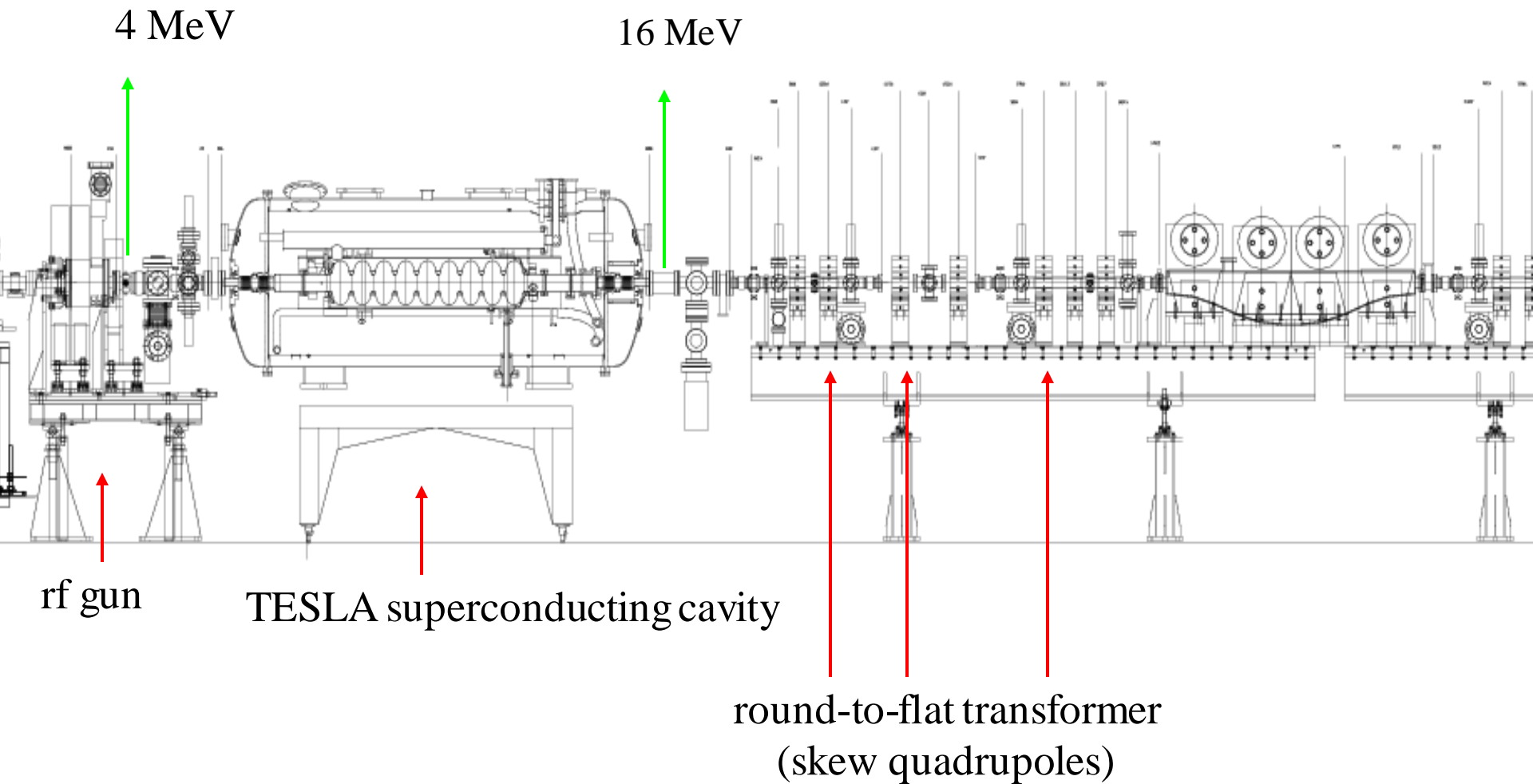


Figure 2: Schematic of adapting optics for electron beam: 1) plane-vortex skew quadrupole transformer; 2) solenoid to stop the x -vortex; 3) vortex-plane transformer.

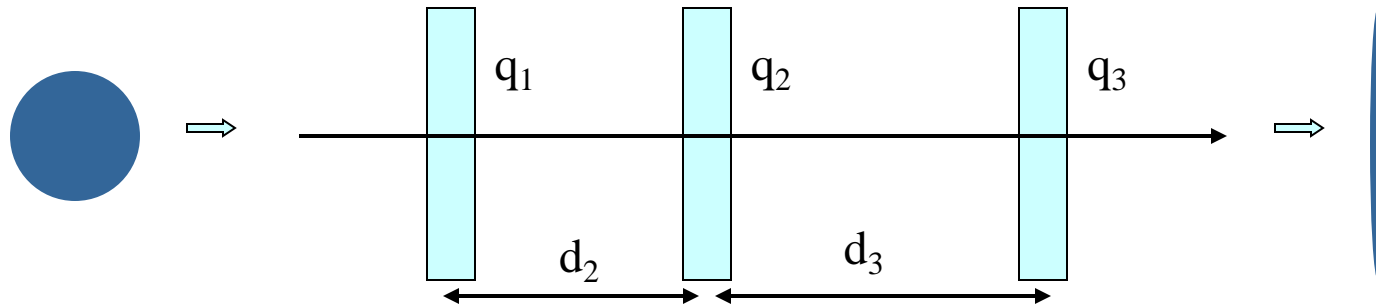
See also: A. Burov, S. Nagaitsev and Ya. Derbenev, Phys. Rev. E 66, 016503 (2002).

Fermilab/NICADD Photoinjector Lab. (FNPL)

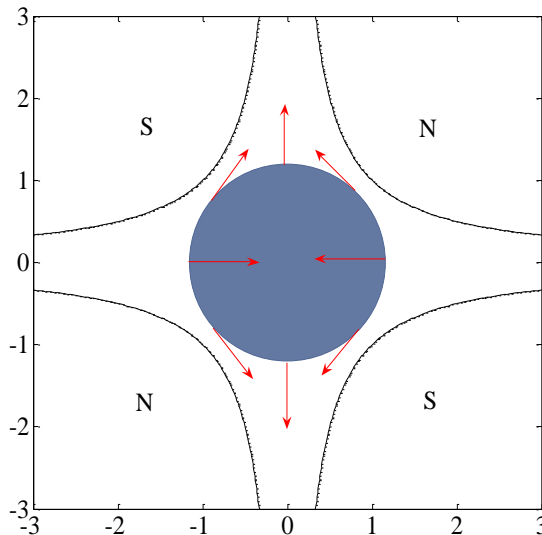


Round-to-flat beam transformation using skew quadrupoles

Flat beam: large transverse emittance ratio, zero average angular momentum.



$$\langle \tau \rangle_{total} = 2 \cdot \sum q_i \langle x_i y_i \rangle$$



Two sets of solutions:

$$q_1 = \pm \sqrt{\frac{-d_2 S_{11} + S_{12} - d_2 d_T S_{21} + d_T S_{22}}{d_2 d_T S_{12}}}$$

$$q_2 = -\frac{S_{12} + d_T S_{22}}{d_2 d_3 (1 + S_{12} q_1)}$$

$$q_3 = -\frac{q_1 + q_2 + d_2 S_{11} q_1 q_2 + S_{21}}{1 + (d_T q_1 + d_3 q_2) S_{11} + d_2 d_3 q_2 (S_{21} + q_1)}$$

(D. Edwards)

Round-to-flat beam transformation

$$\Sigma_{round} = \begin{bmatrix} \varepsilon_{eff} \beta & 0 & 0 & L \\ 0 & \varepsilon_{eff} / \beta & -L & 0 \\ 0 & -L & \varepsilon_{eff} \beta & 0 \\ L & 0 & 0 & \varepsilon_{eff} / \beta \end{bmatrix}$$

General form of a round beam at beam waist location

(K.-J. Kim)

$$\varepsilon_{eff} = \sqrt{\varepsilon_u^2 + L^2}$$

uncorrelated emittance

“normalized” canonical angular momentum

$$\Sigma_{flat} = M \Sigma_{round} \tilde{M}$$

Transfer matrix of the round-to-flat beam transformer (skew quadrupoles)

$$\Sigma_{flat} = \begin{bmatrix} \varepsilon_- \beta & 0 & 0 & 0 \\ 0 & \varepsilon_- / \beta & 0 & 0 \\ 0 & 0 & \varepsilon_+ \beta & 0 \\ 0 & 0 & 0 & \varepsilon_+ / \beta \end{bmatrix}$$

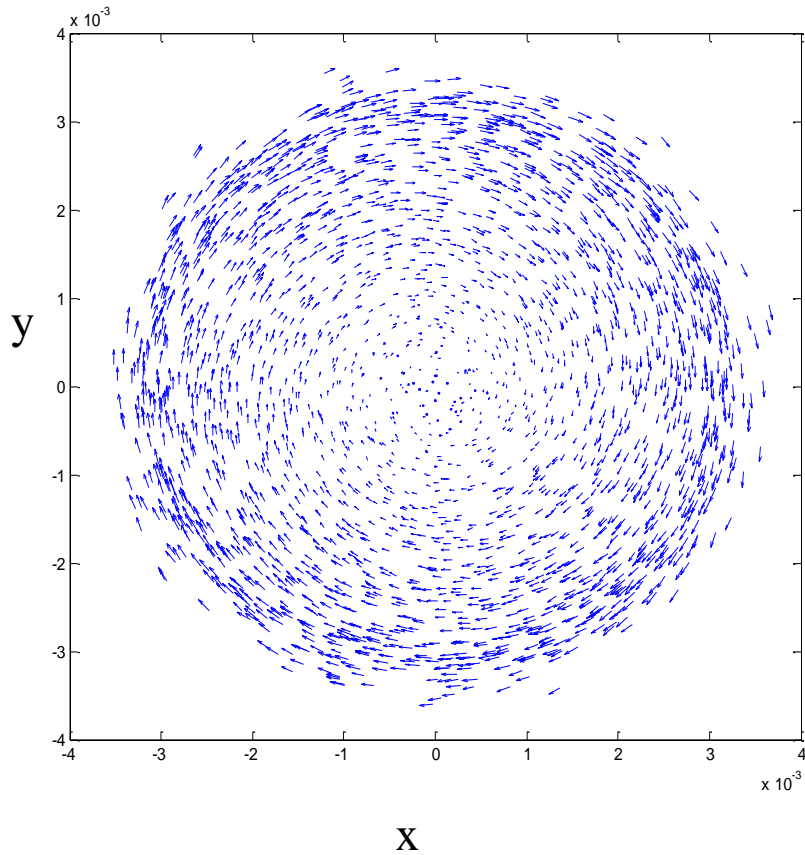
Flat beam emittances given by:

$$\varepsilon_{\pm} = \sqrt{\varepsilon_u^2 + L^2} \pm L$$

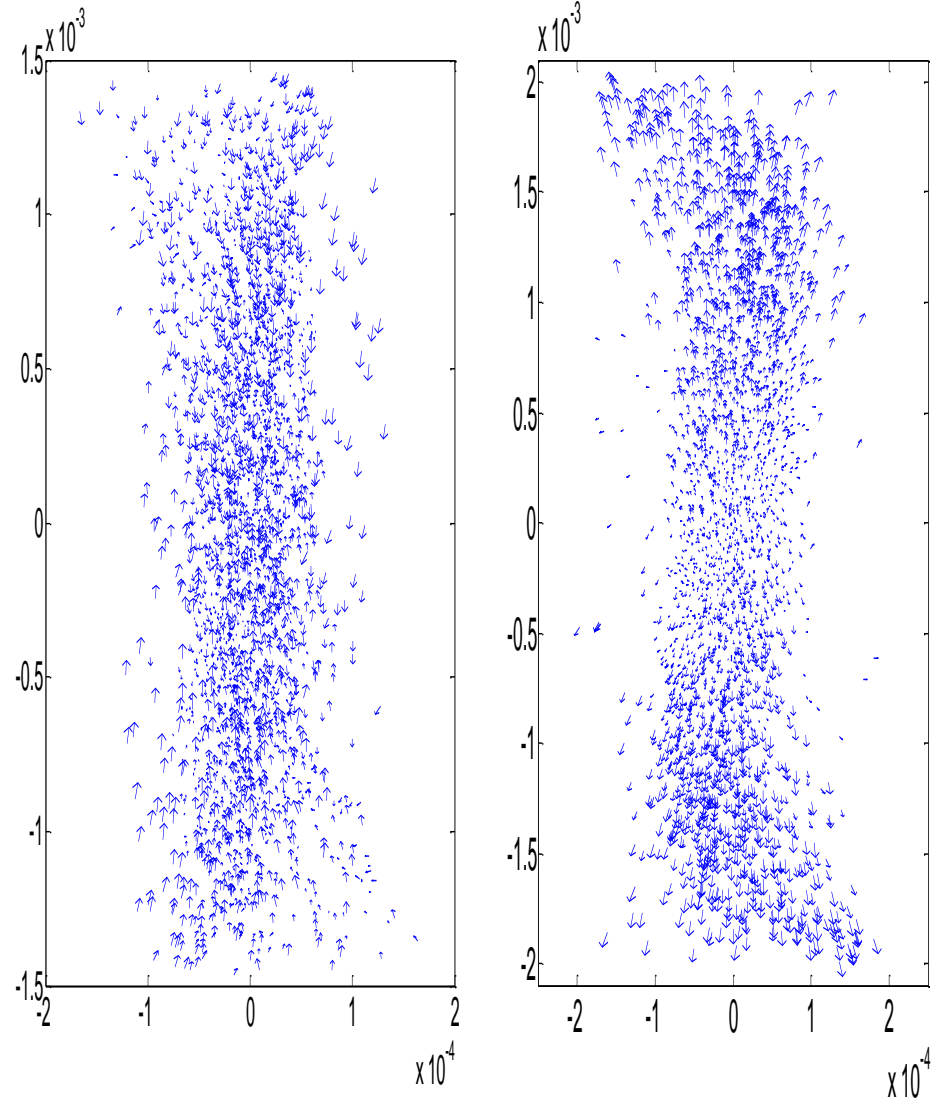
e.g. $L=20$ mm mrad, $\varepsilon_u=1$ mm mrad
 $\varepsilon_+=47$ mm mrad; $\varepsilon_-=0.02$ mm mrad



Position and velocity snap shots at the entrance/exit of the transformer (ASTRA simulations)



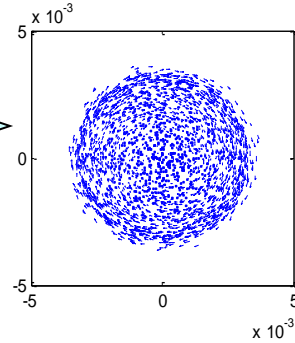
Round beam



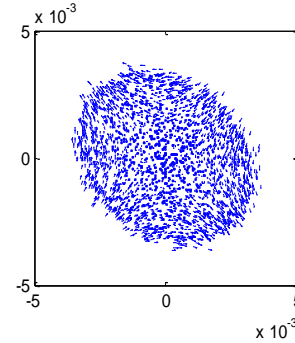
flat beam

Beam evolution through the transformer for the first solution

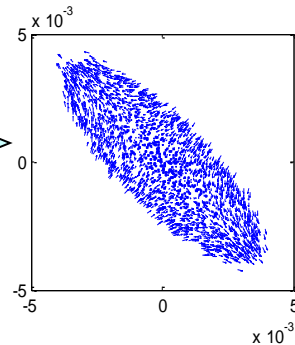
10 mm



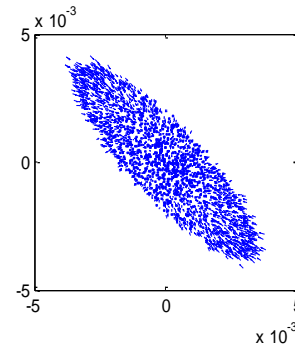
Right before 1st quad →



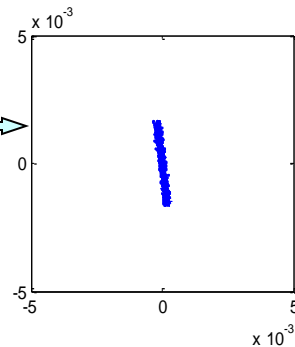
← Right after 1st quad



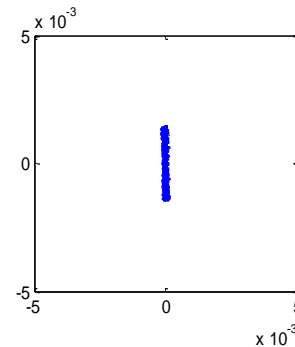
Right before 2nd Quad →



← Right after 2nd Quad



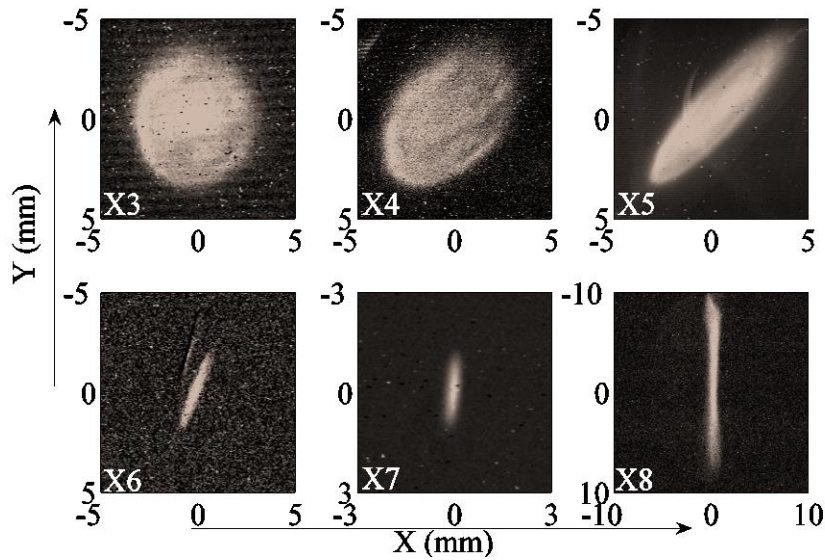
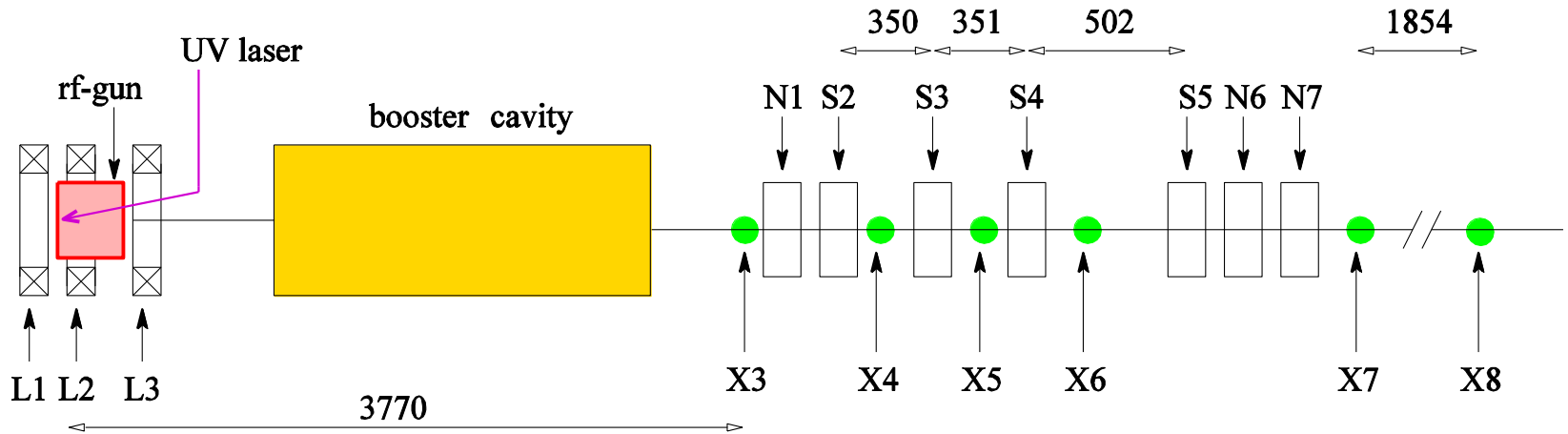
Right before 3rd quad →



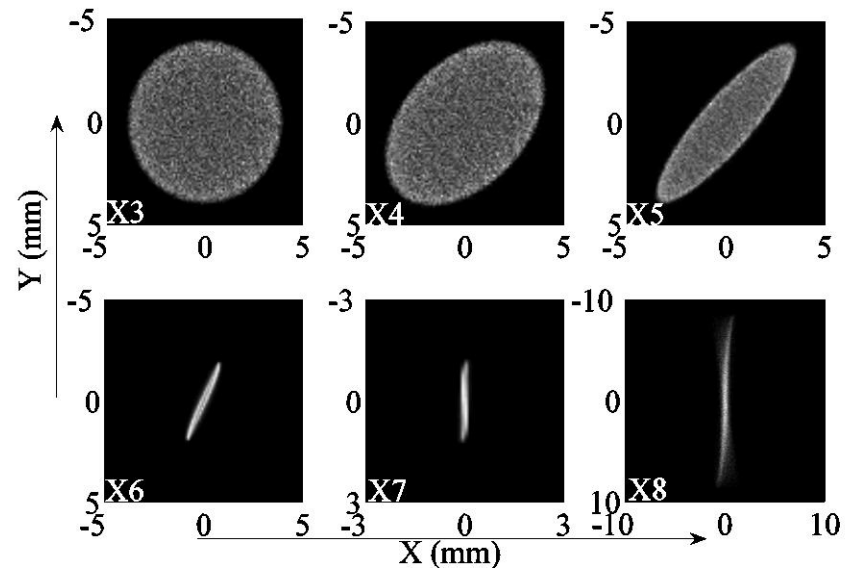
← Right after 3rd quad



Removal of angular momentum and generating a flat beam



experiment



simulation

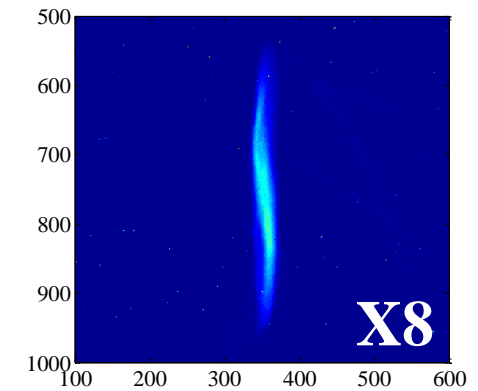
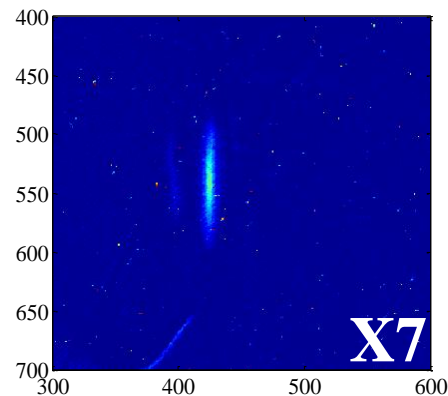
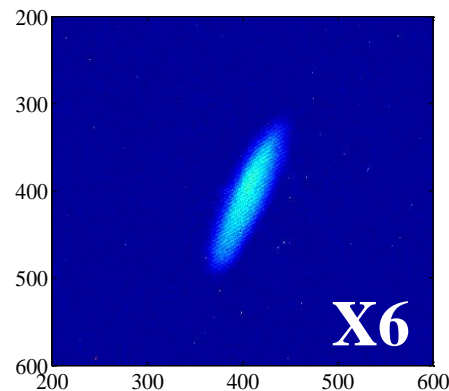
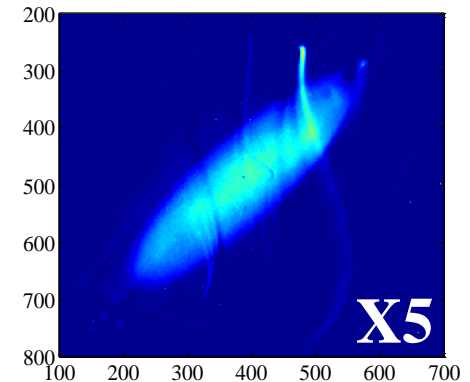
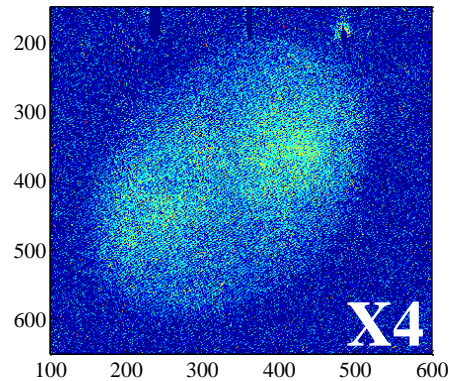
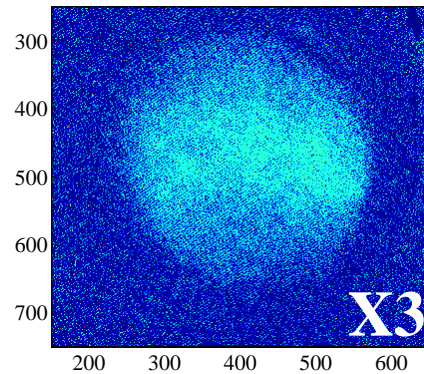
Flat beam measurements: beam images

Solenoid setting: main=195A, buck=0A, secondary=75A

$\sigma = 0.97$ mm, $\sigma_t = 3$ ps

$E = 15.86$ MeV

$Q = 0.51 \pm 0.17$ nC

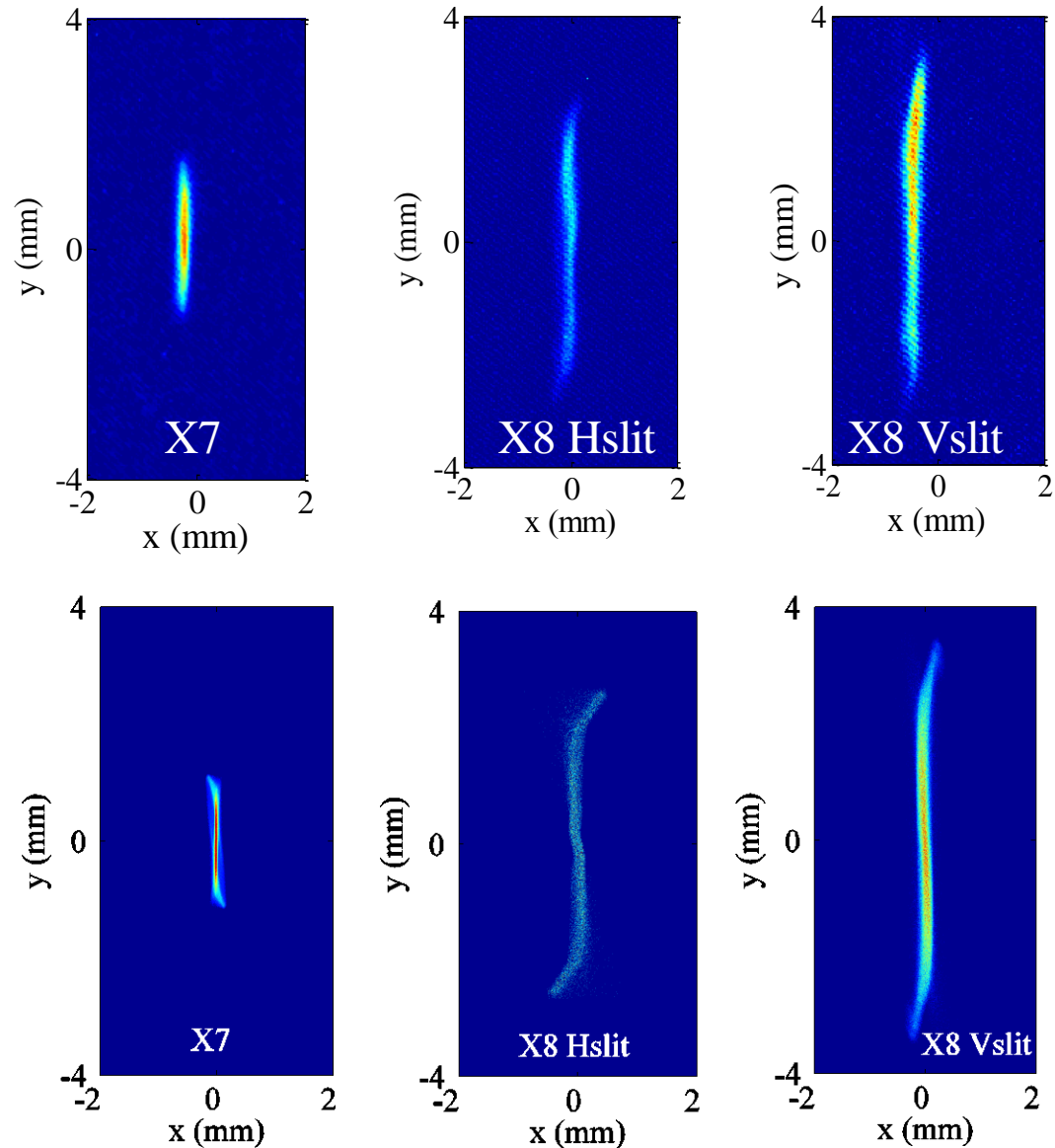


Flat beam experiment: emittance measurements

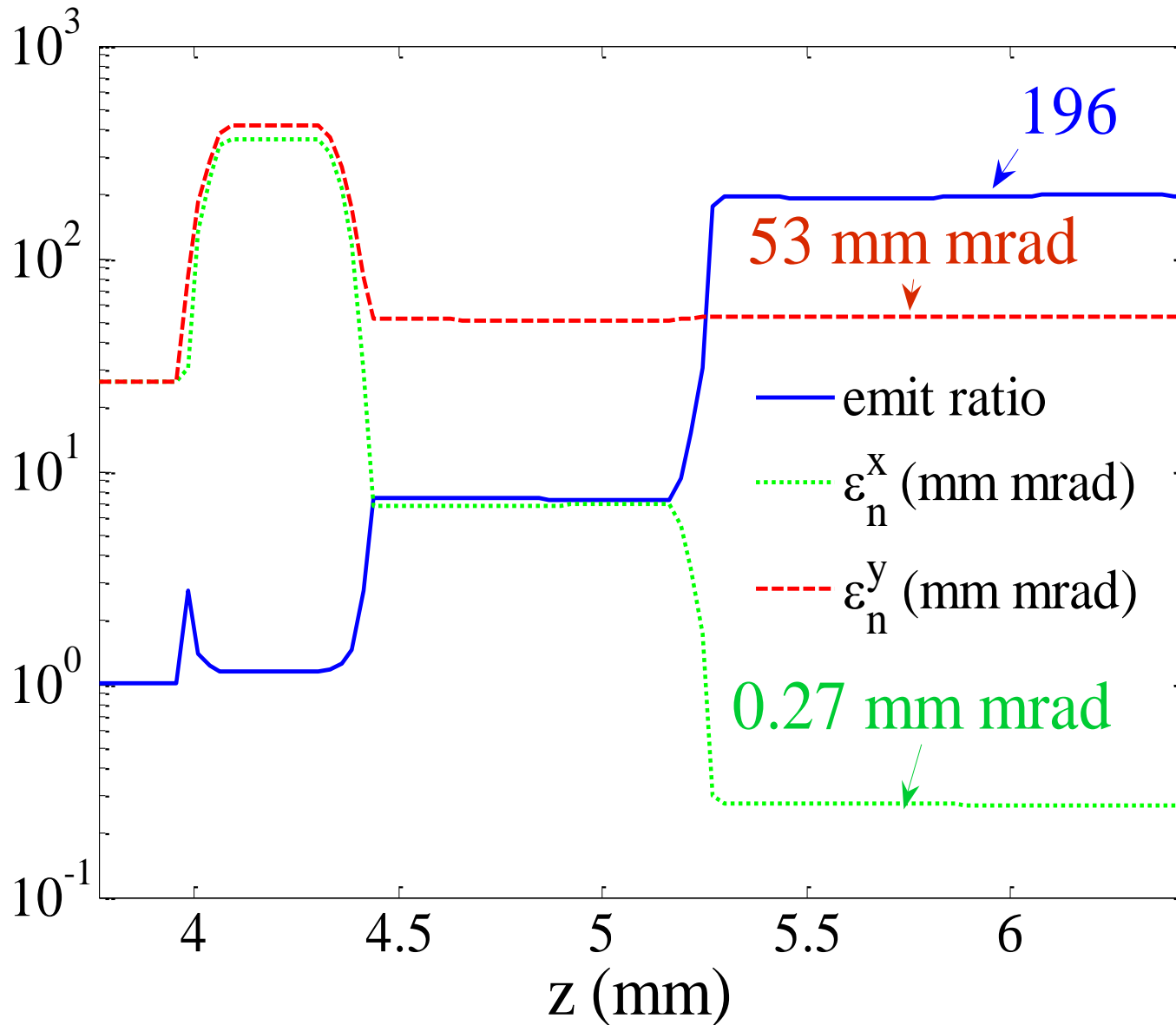
Solenoid setting:
main=190A,
buck=0A,
secondary=75A

Laser $\sigma = 0.76$ mm
 $\sigma_t = 3$ ps

E = 15.8 MeV
Q = 0.50 ± 0.05 nC



ASTRA Simulation with experimental conditions



Experimental results compared with numerical simulations (0.5 nC)

Parameter	Experiment	Simulation	Unit
σ_x^{X7}	$0.088 \pm 0.01 (\pm 0.01)$	0.058	mm
σ_y^{X7}	$0.63 \pm 0.01 (\pm 0.01)$	0.77	mm
$\sigma_x^{X8,v}$	$0.12 \pm 0.01 (\pm 0.01)$	0.11	mm
$\sigma_y^{X8,h}$	$1.68 \pm 0.09 (\pm 0.01)$	1.50	mm
ϵ_n^x	$0.41 \pm 0.06 (\pm 0.02)$	0.27	μm
ϵ_n^y	$41.1 \pm 2.5 (\pm 0.54)$	53	μm
$\epsilon_n^y / \epsilon_n^x$	$100.2 \pm 20.2 (\pm 5.2)$	196	

P. Piot, Y.-E Sun, K.-J. Kim, Phys. Rev. ST Accel. Beams 9, 031001 (2006).

Summary

- ❑ Magnetized photo-injector electron beams are generated and dependences on various parameters are studied. The angular-momentum-dominated electron beams are characterized;
- ❑ The magnetized electron beam is converted into a flat electron beam using a skew-quadrupole channel;
- ❑ The emittances of the flat beam are measured and at 0.5 nC, normalized emittance of **0.4 mm mrad** was measured; emittance ratio of **100** was achieved.

