Photoinjector Production of Flat Electron Beams

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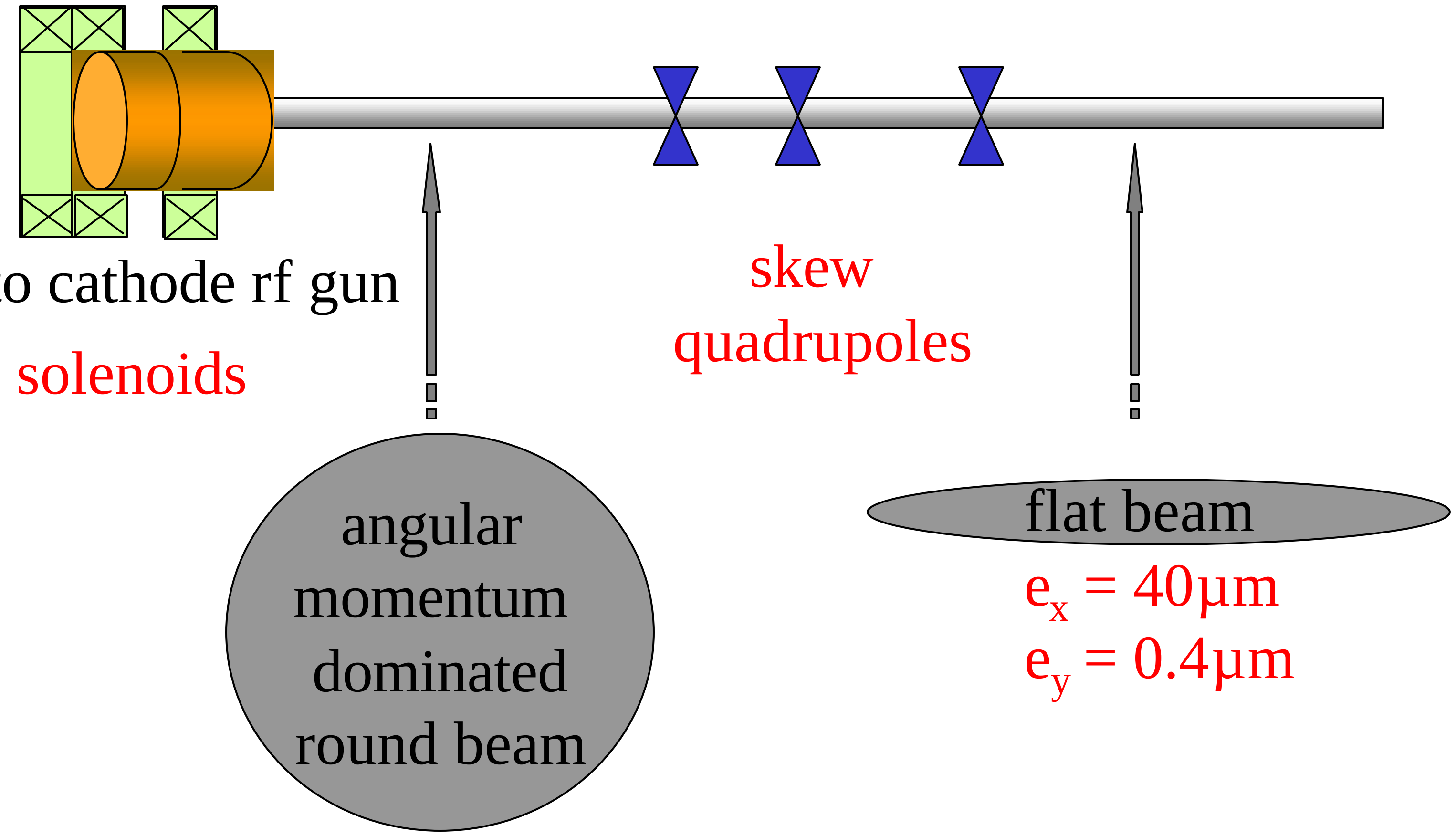
the short story



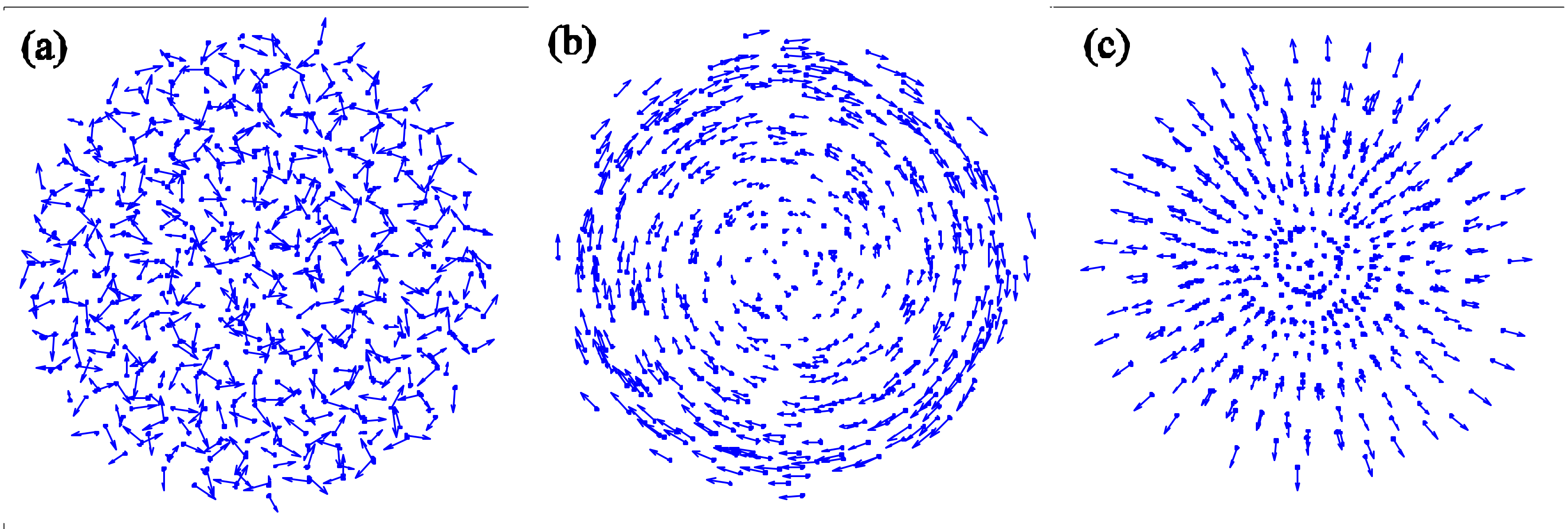
e_x=4μm
e_y=4μm

Derbenev (1998); Burov & Danilov (1998); Brinkmann, Derbenev & Flöttmann (2001); Kim (2003);

Outline

- angular-momentum-dominated electron beams;
- production and measurements of angular-momentum-dominated beam;
- removal of the angular momentum and generation of flat beam:
  – theory;
  – measurement method;
  – data analysis and results;
  – comparison with simulations;
- conclusions.

Beam dynamics: three different regimes



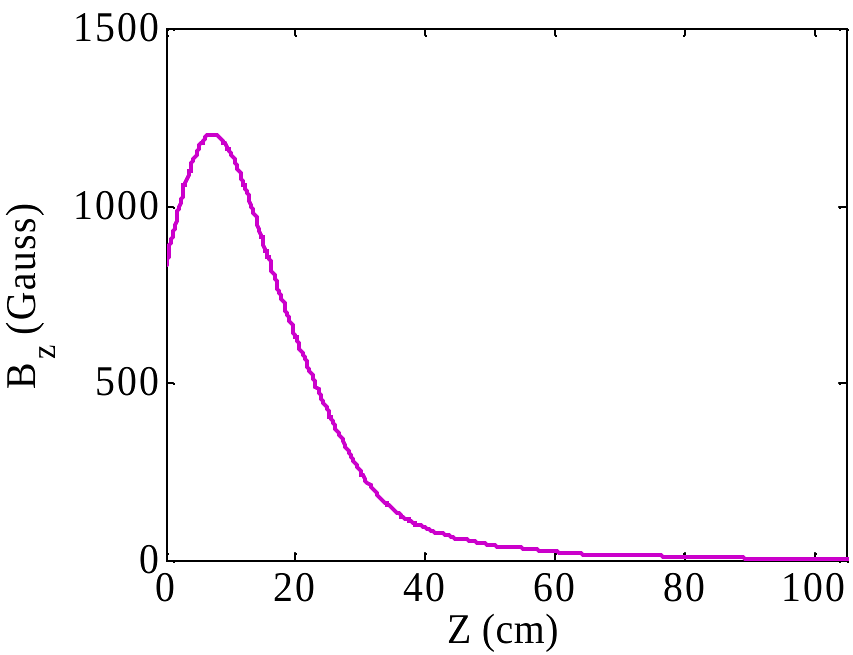
emittance | canonical angular momentum | space charge

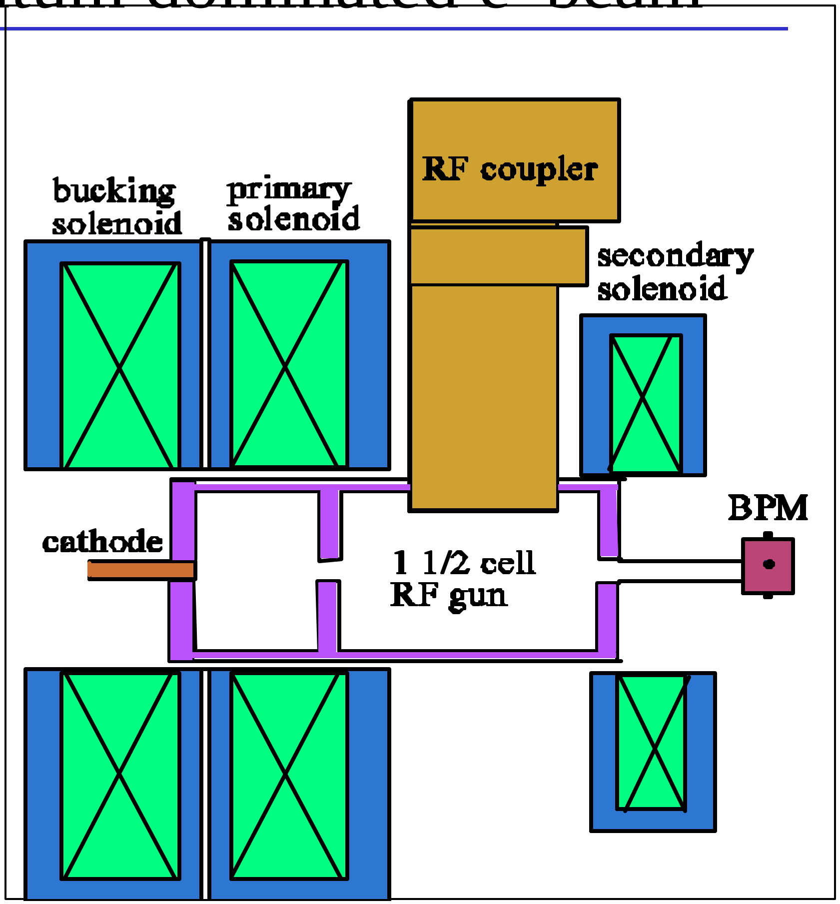
envelope equation in a drift: $s'' - \frac{e^2}{s^3} - \frac{L^2}{s^3} - \frac{K}{4s} = 0$ where $K = \frac{2I}{I_0 b^3 g^3}$.

Generation of angular momentum dominated e$^-$ beam

$$L = gmr^2\dot{f} + \frac{1}{2}eB_z r^2$$

On the photocathode: $\langle L \rangle = eB_0 s_c^2$

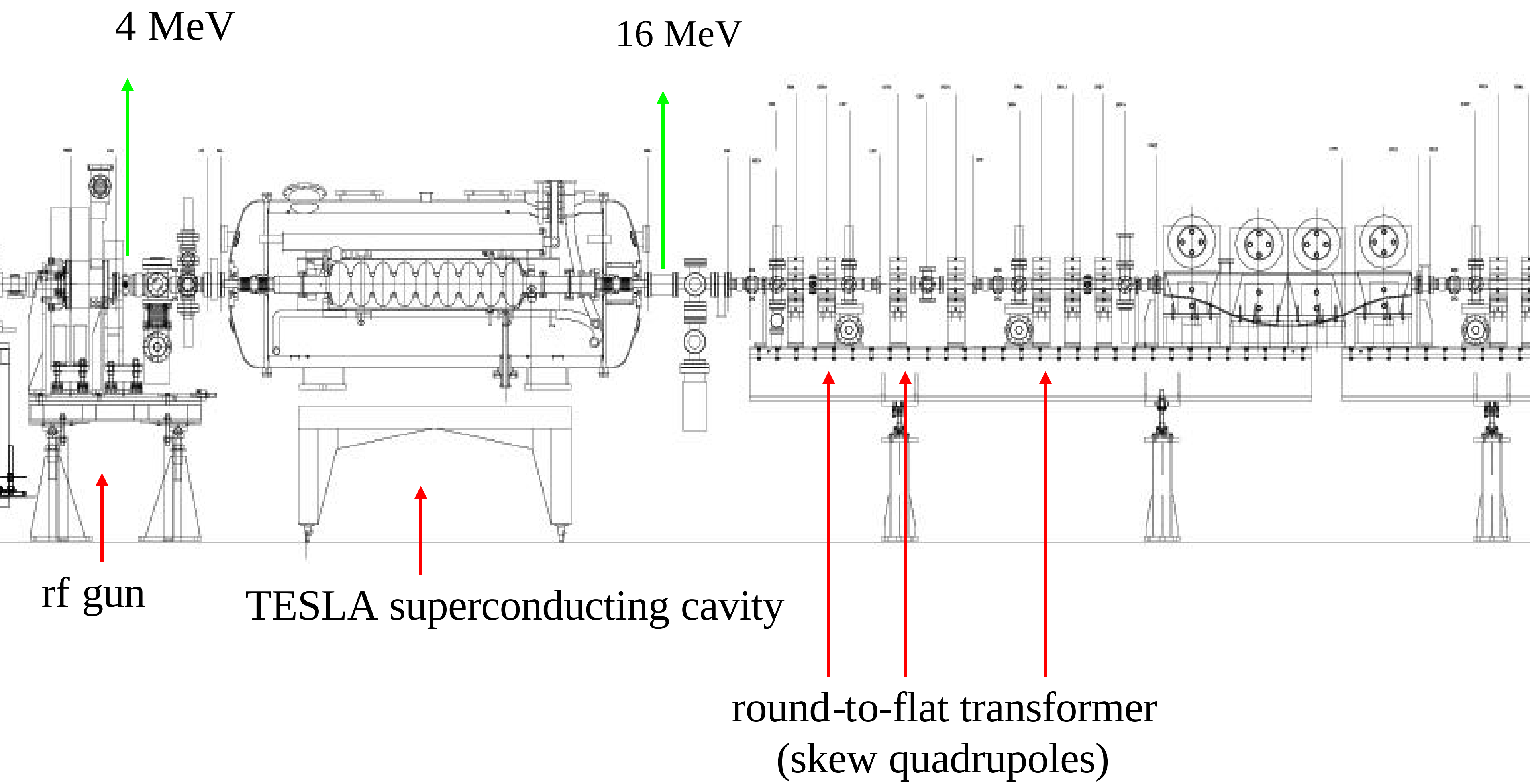




FNPL 1.625-cell RF gun, 1.3 GHz

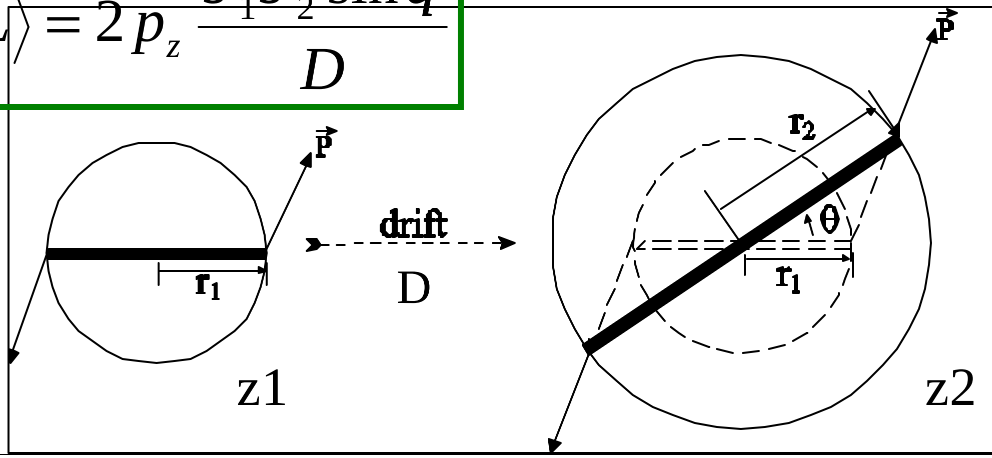
Solenoidal end field applies a torque to the beam. When Bz=0, canonical = mechanical angular momentum

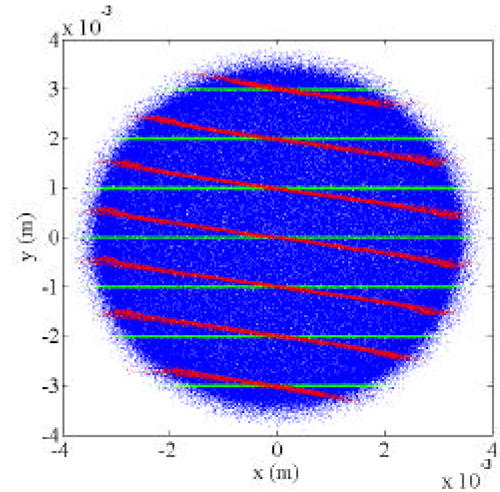
Fermilab/NICADD Photoinjector Lab. (FNPL)

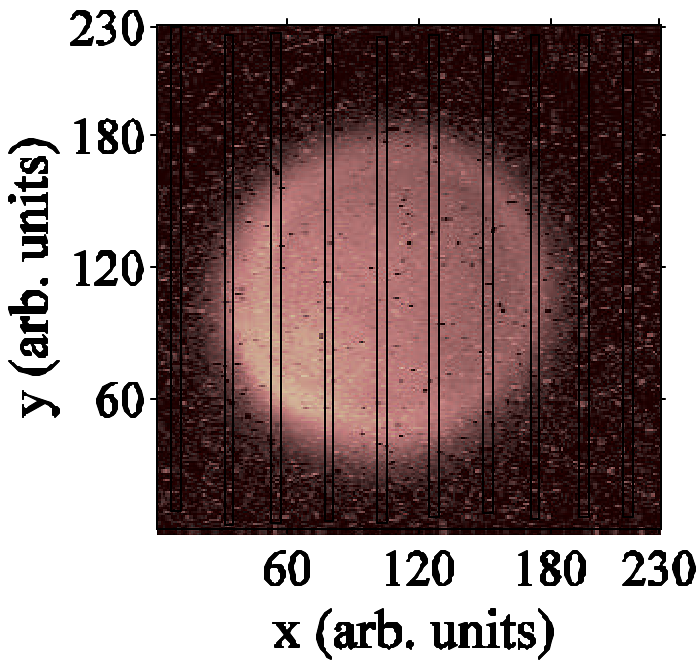


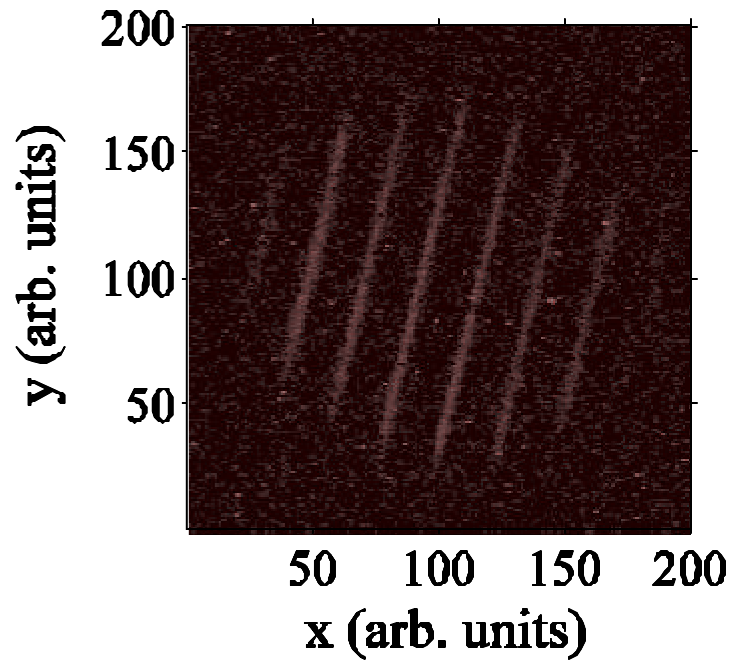
Measurement of mechanical angular momentum in a drift space

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



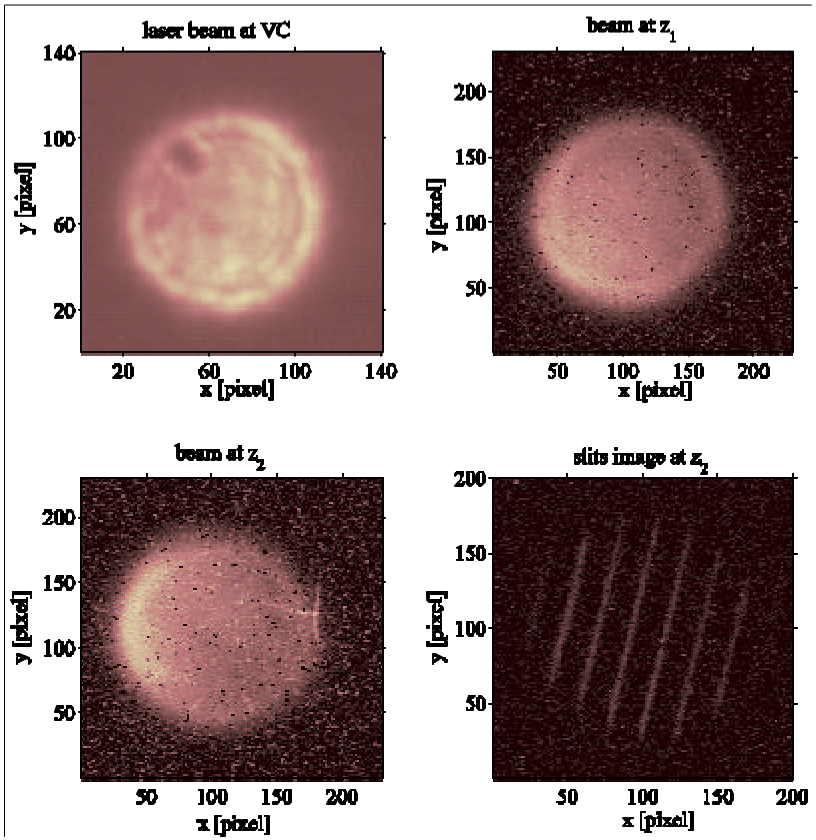


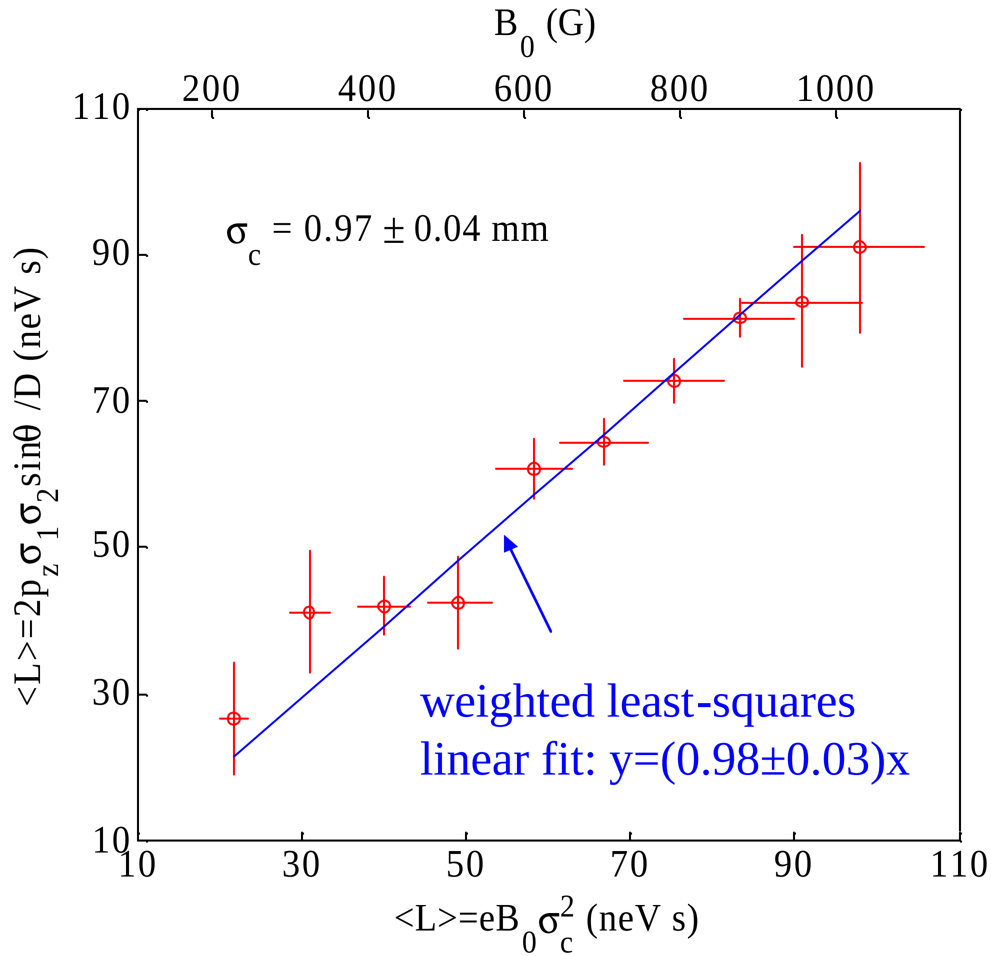




Demonstration of conservation of canonical angular momentum

as a function of magnetic field on cathode





Round-to-flat beam transformation

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

General form of a round beam at beam waist location

(K.-J. Kim)

$$e_{eff} = \sqrt{e_u^{\;2} + L^2}$$

uncorrelated emittance

"normalized" canonical angular momentum

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

Transfer matrix of the round-to-flat beam transformer

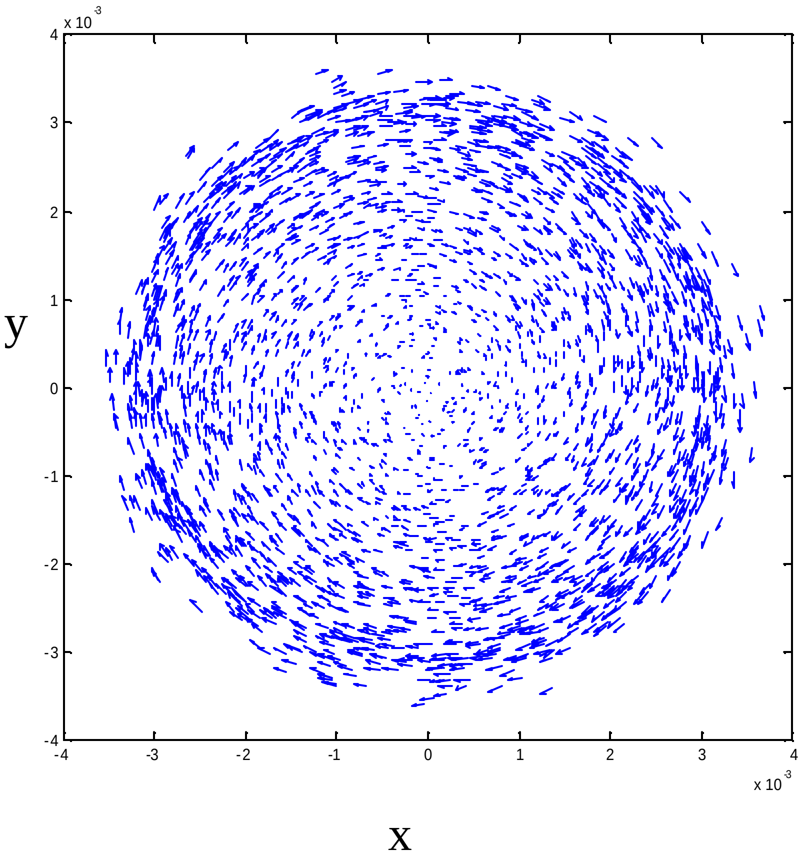
$$\Sigma_{flat} = \begin{bmatrix} e_{-}b & 0 & 0 & 0 \\ 0 & e_{-}/b & 0 & 0 \\ 0 & 0 & e_{+}b & 0 \\ 0 & 0 & 0 & e_{+}/b \end{bmatrix}$$

Flat beam emittances given by:

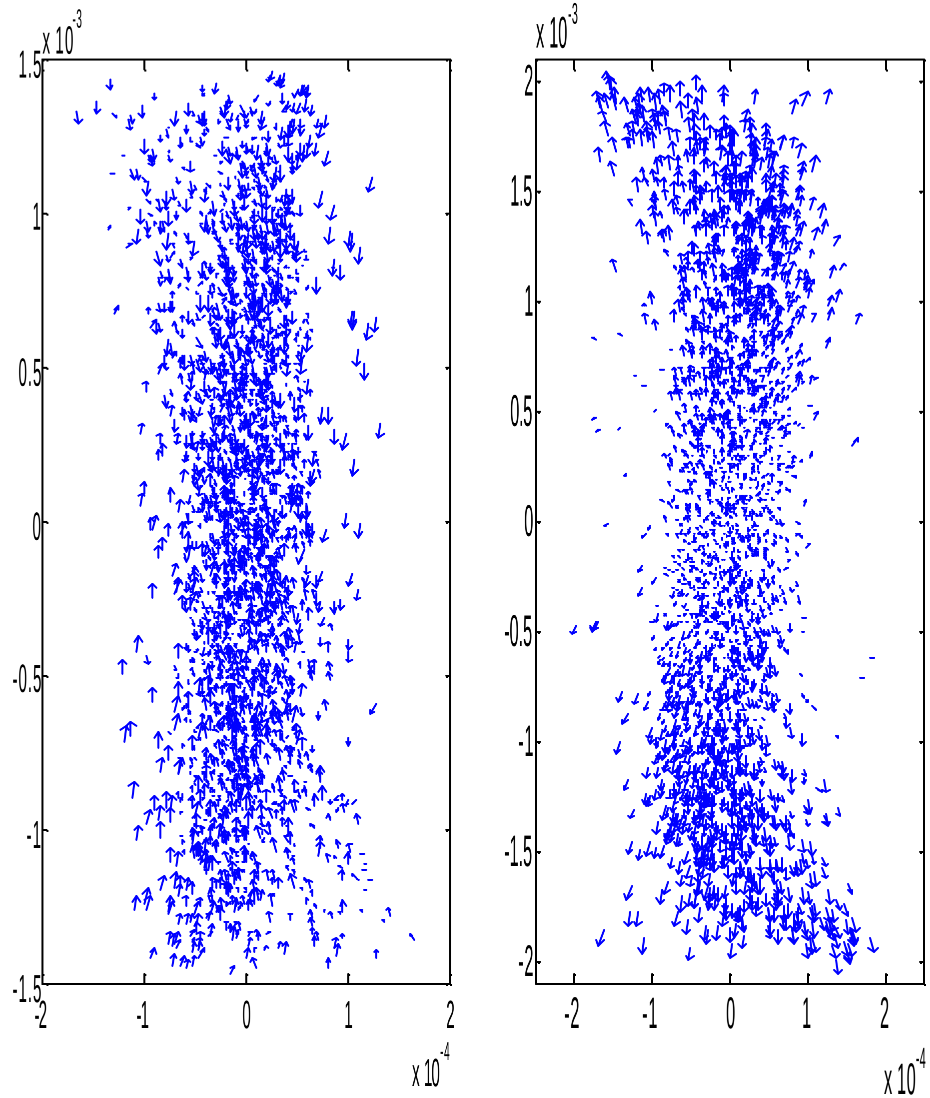
$$e_{\pm} = \sqrt{e_u^{\;2} + L^2} \pm L$$

e.g. L=20 mm mrad, e_u=4 mm mrad
e_+=40 mm mrad; e_-=0.4 mm mrad

Position and velocity snap shots at the entrance/exit of the transformer



Round beam



flat beam

Beam evolution through the transformer for the first solution

Right before 1st quad

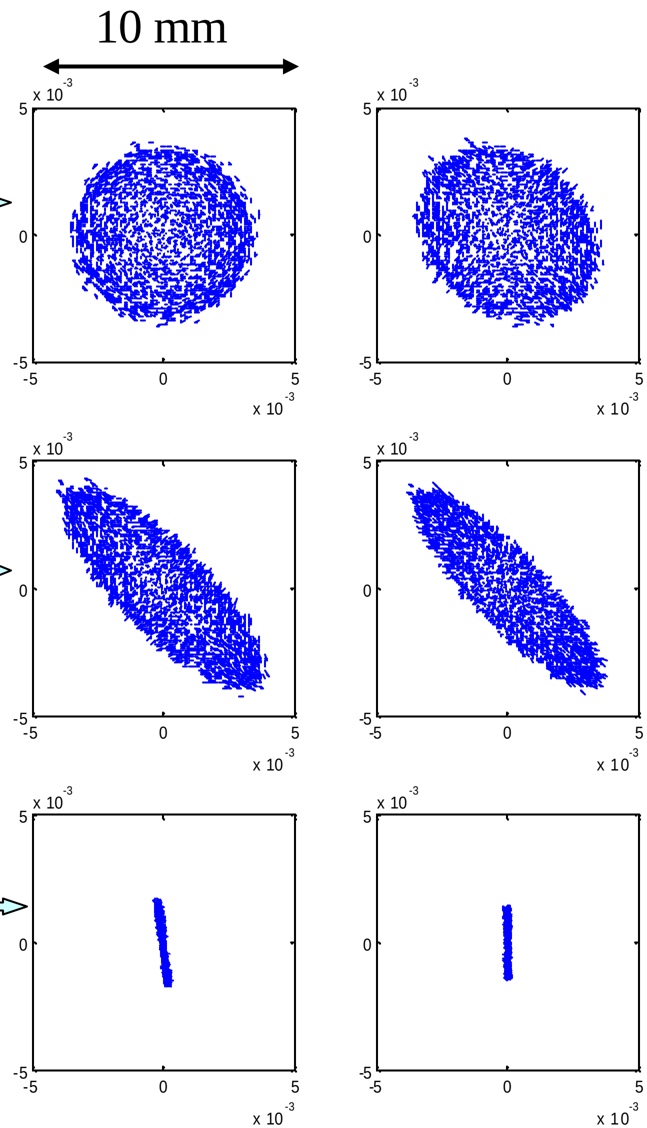
Right after 1st quad

Right before 2nd Quad

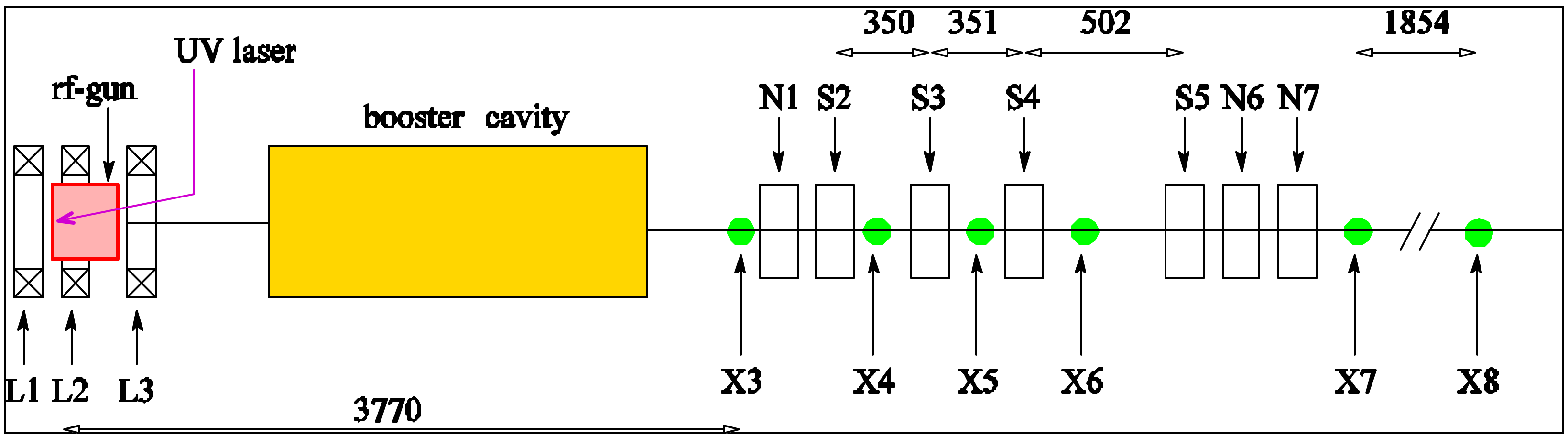
Right after 2nd Quad

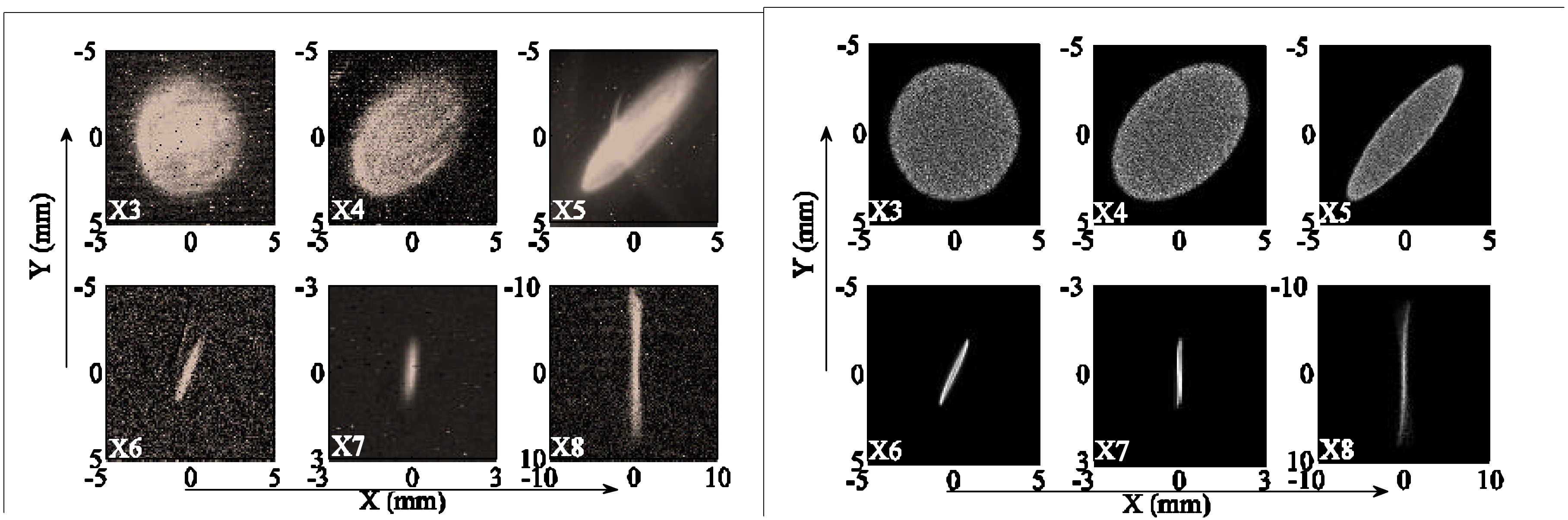
Right before 3rd quad

Right after 3rd quad



Removal of angular momentum and generating a flat beam





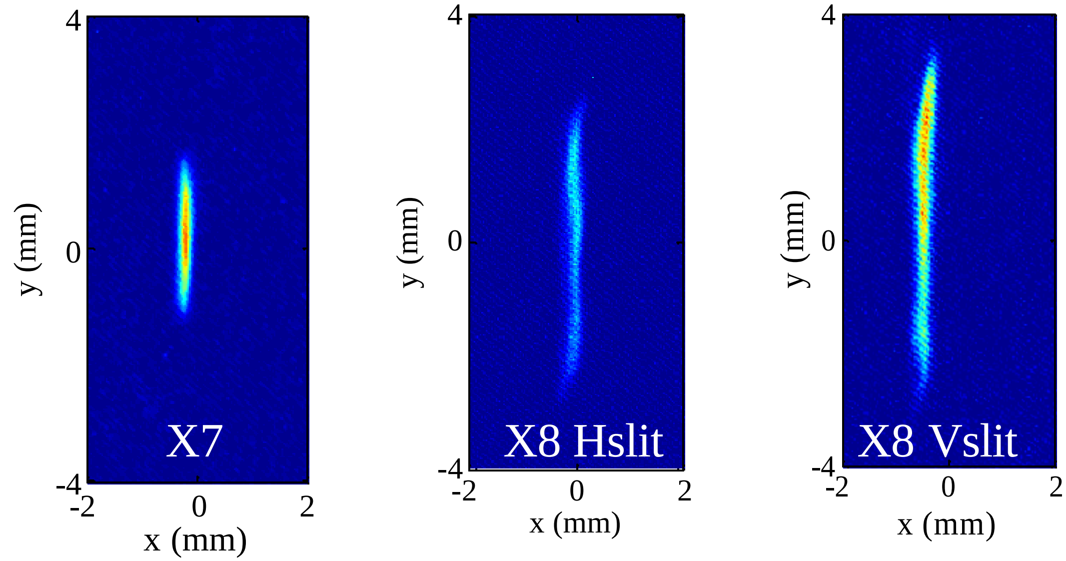
experiment simulation

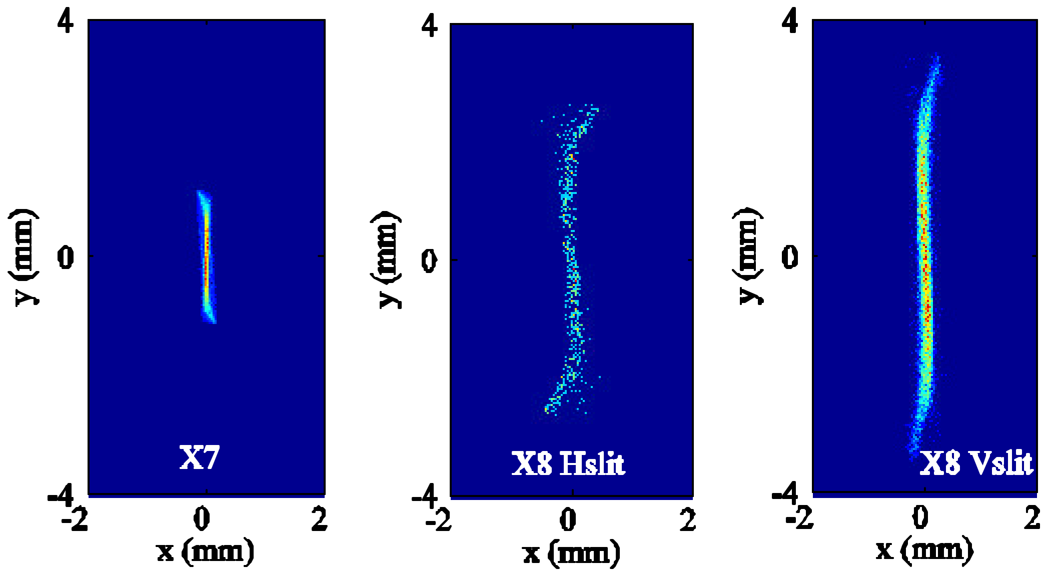
Flat-beam experiment

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

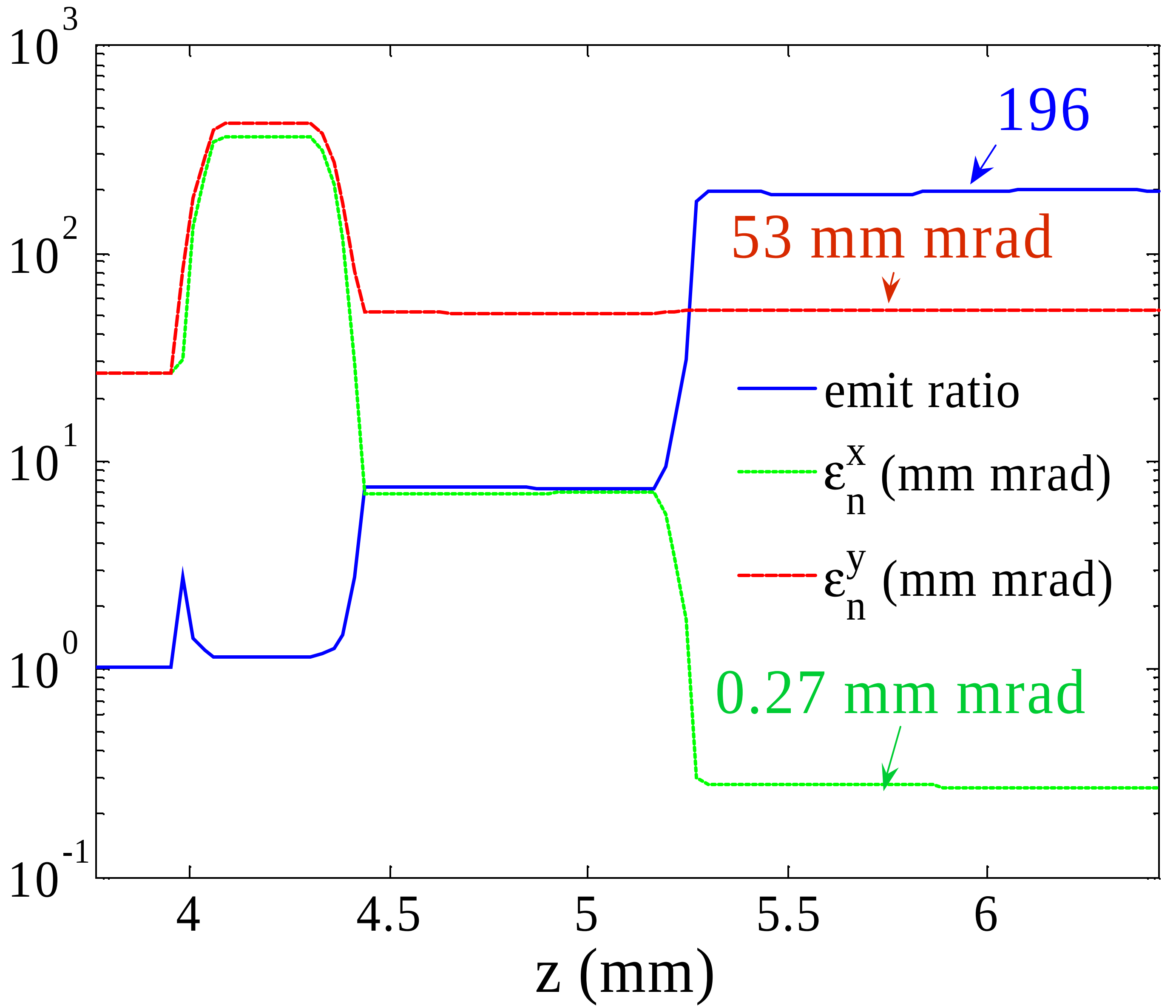
Laser s = 0.97 mm
s_t = 3 ps

E = 15.8 MeV
Q = 0.50 ± 0.05 nC





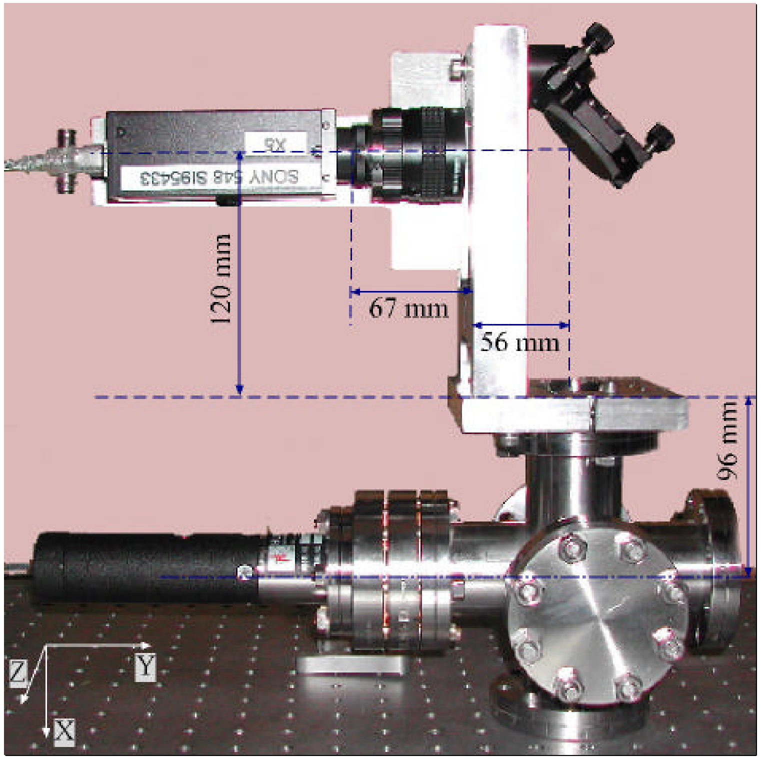
ASTRA Simulation with experimental conditions



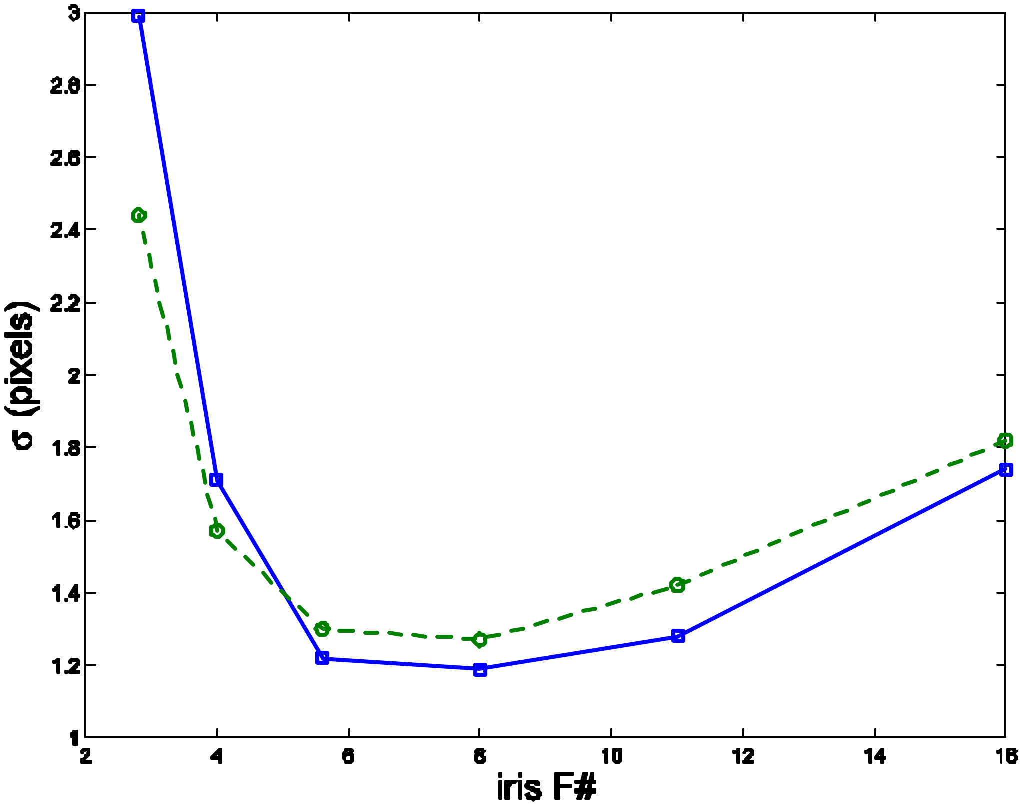
Compare measurement with simulation

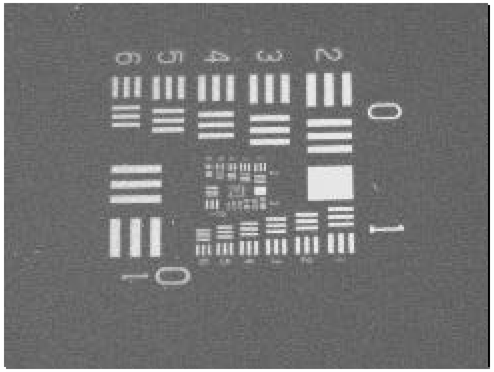
	Experiment 90%	Experiment 95%	Simulation (ASTRA)
rms_cathode(mm)	0.97		0.97
B_cathode(Gauss)	898		898
I_Quad1 (A)	-1.97		-1.98
I_Quad2 (A)	2.56		2.58
I_Quad3 (A)	-4.55		-5.08
rms_X7y (mm)	0.58±0.01	0.63±0.01	0.77
rms_X7x (mm)	0.084±0.001	0.095±0.001	0.058
rms_X8_hslit (mm)	1.57±0.01	1.68±0.01	1.50
rms_X8_vslit (mm)	0.12±0.01	0.13±0.01	0.11
Lcath (mm mrad)		24.5±0.7	
Lmech (mm mrad)		26.6±0.5	
Emit-uncorrelated (mm mrad)		5.1±0.7	
e_+ (mm mrad)	53.8±0.9		
e_- (mm mrad)	0.49±0.13		
e_x (mm mrad)	**0.39±0.02**	**0.49±0.02**	**0.27**
e_y (mm mrad)	35.2±0.5	41.0±0.5	53
e_y/e_x	90±5	83±4	196
$(e_x \cdot e_y)^{0.5}$	3.7	4.5	3.8 mm mrad

Camera resolution



Calibration: 29 µm/pixel
Resolution: [35 ~ 50] µm





Upper limit of the "true" flat beam emittances

$$s_0 = \sqrt{s^2 - s_{res}^2}$$

- s_0: upper limit of true rms size
- s: directly measured
- s_{res}: best measured camera resolution

	90%	**95%**
rms_X7y (mm)	0.58±0.01	0.63±0.01
rms_X7x (mm)	0.076±0.001	0.088±0.001
rms_X8_hslit (mm)	1.57±0.01	1.68±0.01
rms_X8_vslit (mm)	0.11±0.01	0.11±0.01
e_x (mm mrad)	**0.32±0.02**	**0.41±0.02**
e_y (mm mrad)	35.2±0.5	41.0±0.5
e_y/e_x	**110±7**	**100±5**
$\sqrt{e_x e_y}$ (mm mrad)	3.35	4.1

summary

- experimental investigation of angular-momentum-dominated electron beams was carried out.

- The result of flat-beam emittance measurements:
  - at 0.5 nC, normalized emittance of **0.4 mm mrad** was measured;
  - emittance ratio of **100** was achieved.

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rf: Markus hüning, Peter Prieto, Rene Padilla, John Reid, Tim Berenc

controls: Mike Kucera, Jason Wennerberg

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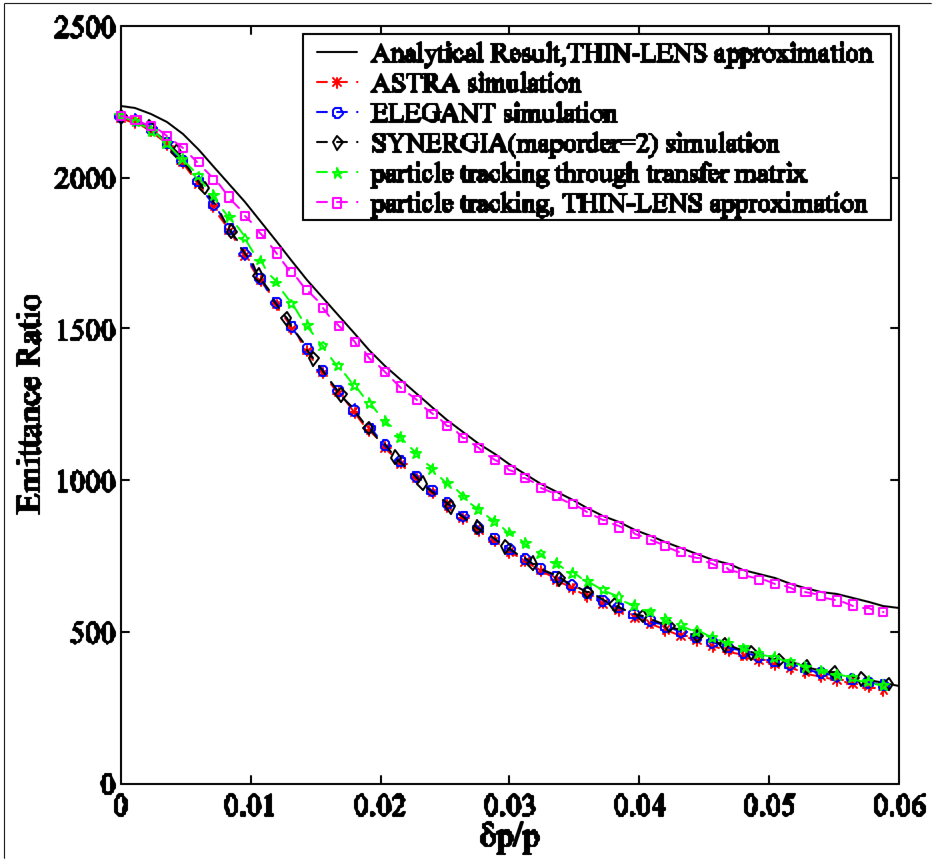
Chromatic effects

q? $q_0(1 - \delta + \delta^2)$, transfer matrix? $M(q_1, q_2, q_3, d_2, d_3) \approx M_0 + \delta\Delta_1 + \delta^2\Delta_2$,

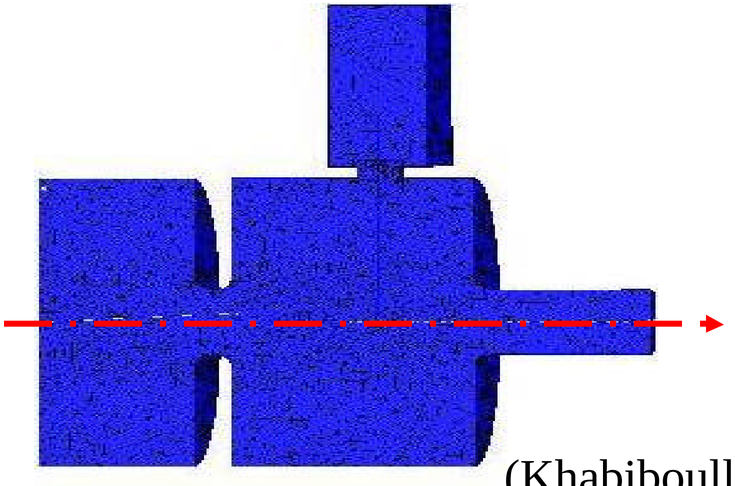
$$\varepsilon_{x,y} = \sqrt{(\varepsilon_{eff} \mp \mathcal{L})^2 + \langle\delta^2\rangle^2[|\Delta_{11 \text{ or } 22}| + (\varepsilon_{eff} \mp \mathcal{L})^2 \mathrm{Tr}(T\Delta^{\dagger}_{11 \text{ or } 22})]}.$$



thermal emittance =1 mm mrad.

space charge force is turned off.

RF asymmetry caused by gun RF coupler kick

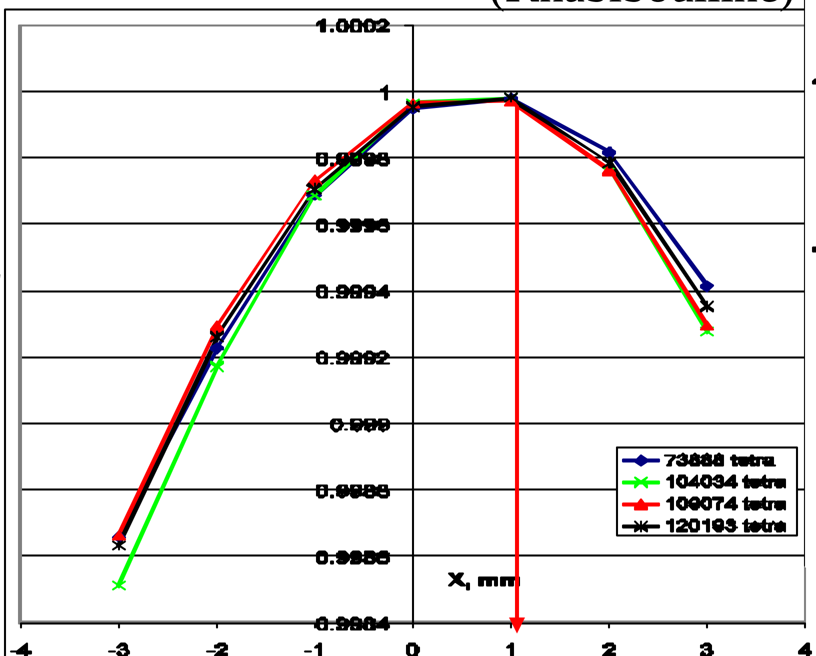


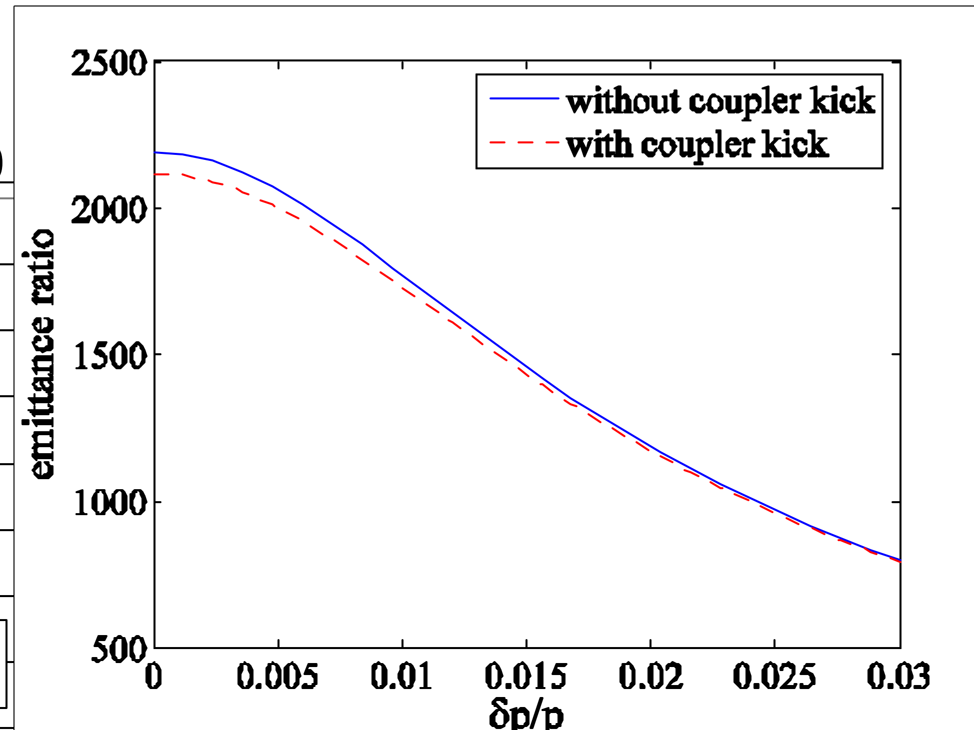
(Khabiboulline)

Accelerating mode center is shifted

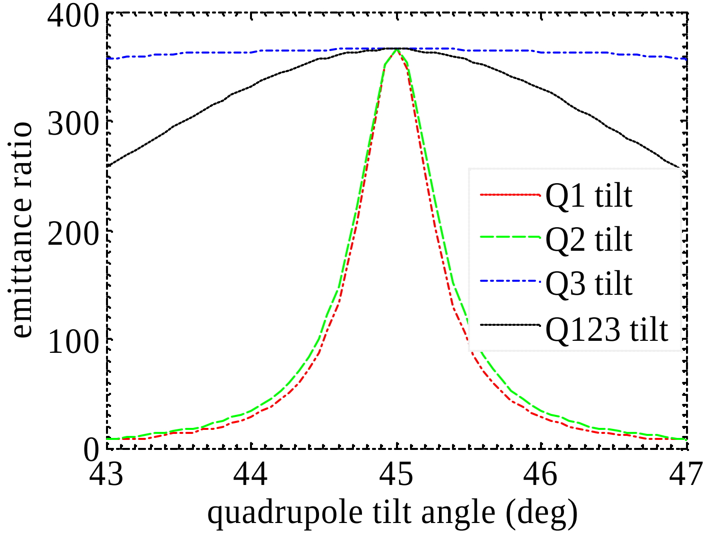
? time-dependent dipole kick

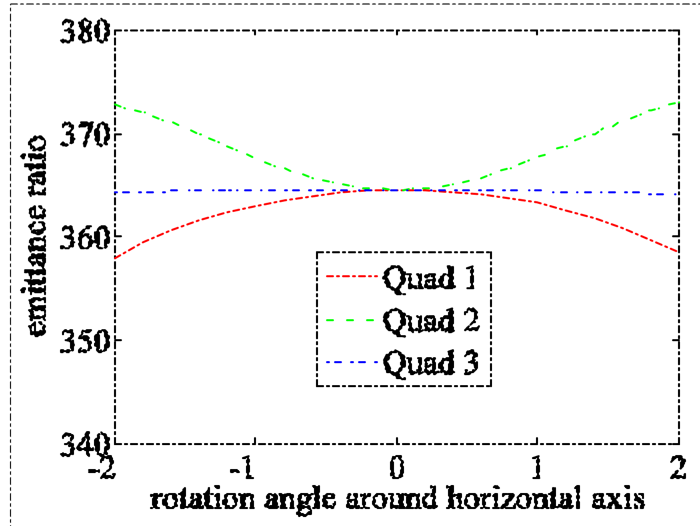
? vertical emittance growth

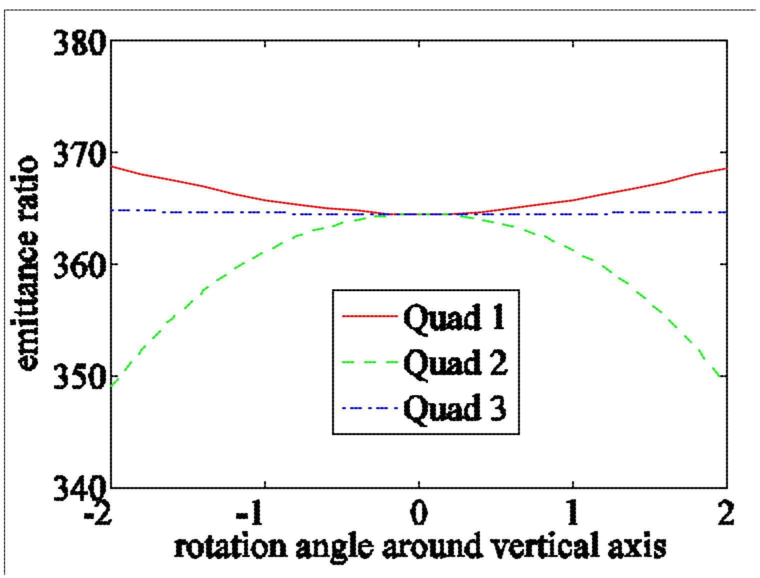


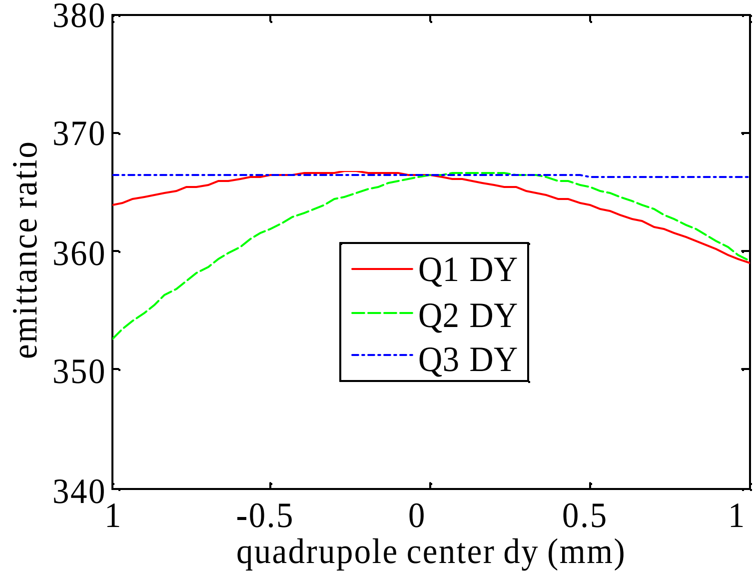


Quadrupole alignment: rotation and displacement around each axis









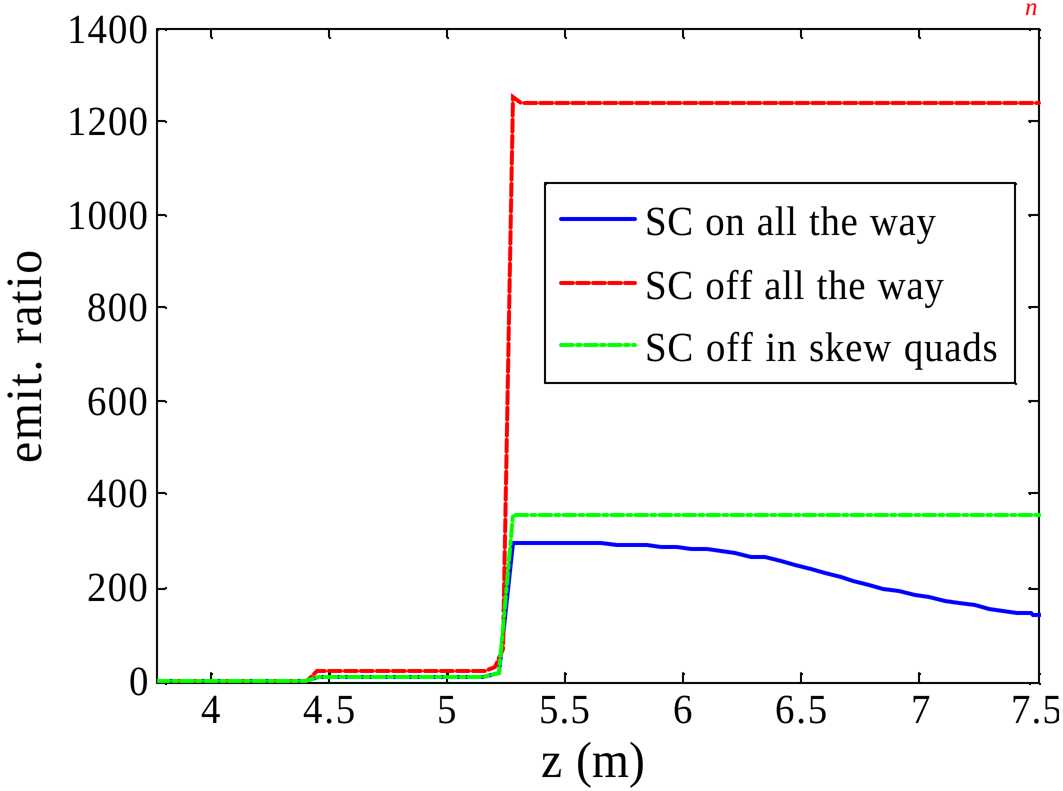
Space-charge effects in rf gun

Space charge in the rf gun is the main limiting factor in flat-beam generation.

$$e_n^{sc} \approx \sqrt{\left(b \frac{I}{I_0} \frac{1}{16\sqrt{2}}\right)^2 + e_n^2}$$

$$e_n = 1\,\mu\text{m} \Rightarrow e_n^{sc} = 3.5\,\mu\text{m}$$

$$e_n^- = 0.02\,\mu\text{m} \Rightarrow e_n^{-,sc} = 0.30\,\mu\text{m}$$



emittance ratio decreases from 10^3 to 10^2 as a result of the non-linear space-charge effects in the rf gun area.

Upper limit of the "true" flat beam emittances

$$s_0 = \sqrt{s^2 - s_{res}^2}$$

upper limit of true rms size

directly measured

best measured camera resolution

	95%	-dispersion at 95%	simulation
rms_X7x (mm)	0.088±0.001	0.065±0.001	0.058
rms_X8_vslit (mm)	0.11±0.01	0.11±0.01	0.11
e_x (mm mrad)	**0.41±0.02**	**0.30±0.02**	**0.27**
$\sqrt{e_x e_y}$	**4.1±0.1**	**3.5±0.1**	**3.8**
e_y/e_x	**100±5**	**137±15**	**196**