Angular momentum dominated electron beam and flat beam generation

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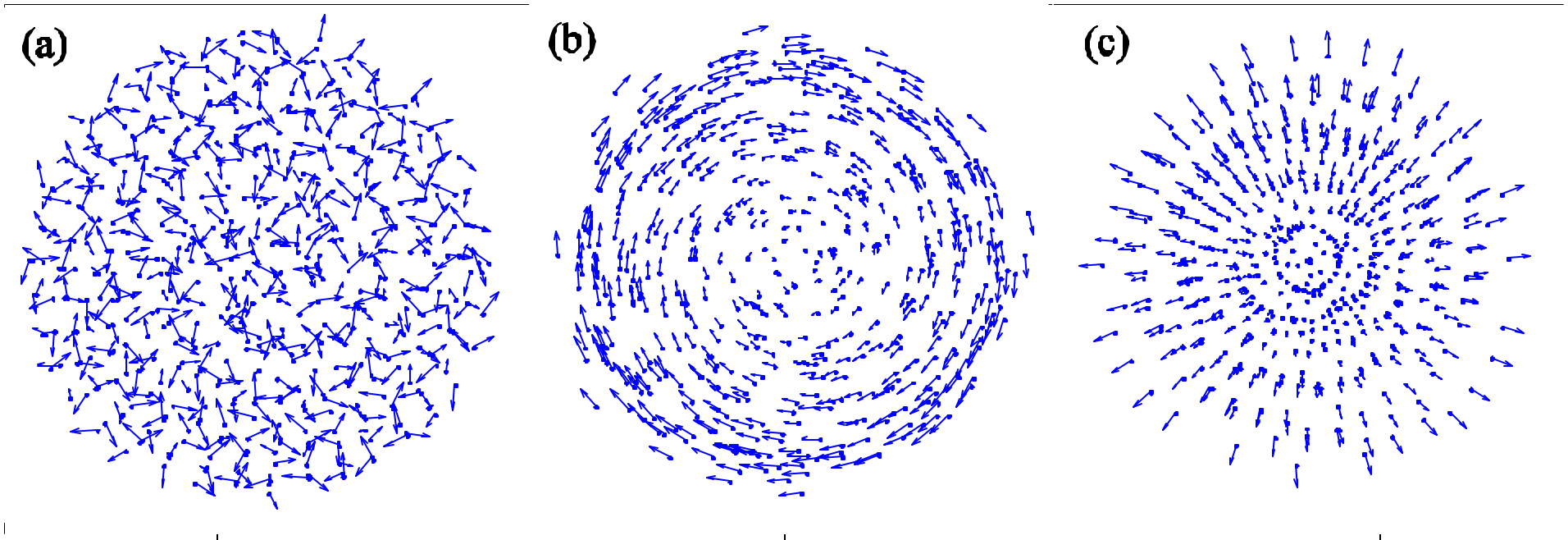
outline

- angular momentum dominated electron beam and its applications
- production and measurements of angular momentum dominated beam
- removal of the angular momentum and generation of flat beam:
  - a bit of theory
  - measurement method
  - data analysis and recent results
  - comparison with simulations
- conclusion

beam dynamics: three different regimes

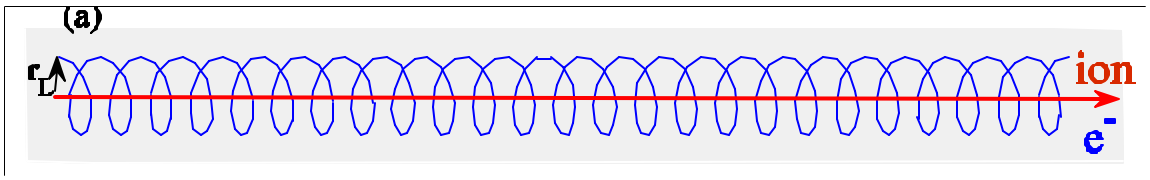


emittance canonical angular momentum space charge

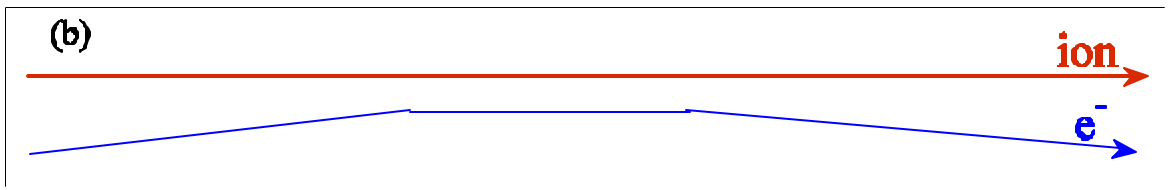
envelope equation in a drift: $s'' - \frac{e^2}{s^3} - \frac{L^2}{s^3} - \frac{K}{4s} = 0$ where $K = \frac{2I}{I_0 b^3 g^3}$.

Applications of angular momentum dominated beam

- electron cooling for heavy ion



$$t_c^{mag} \approx r \Big/ \left(v_z^{ion} - v_z^{e}\right)$$



$$t_c^{free} \approx r \Big/ v_e^{\perp}$$

- flat beam for linear e^+e^- collider: reduce beamstrahlung

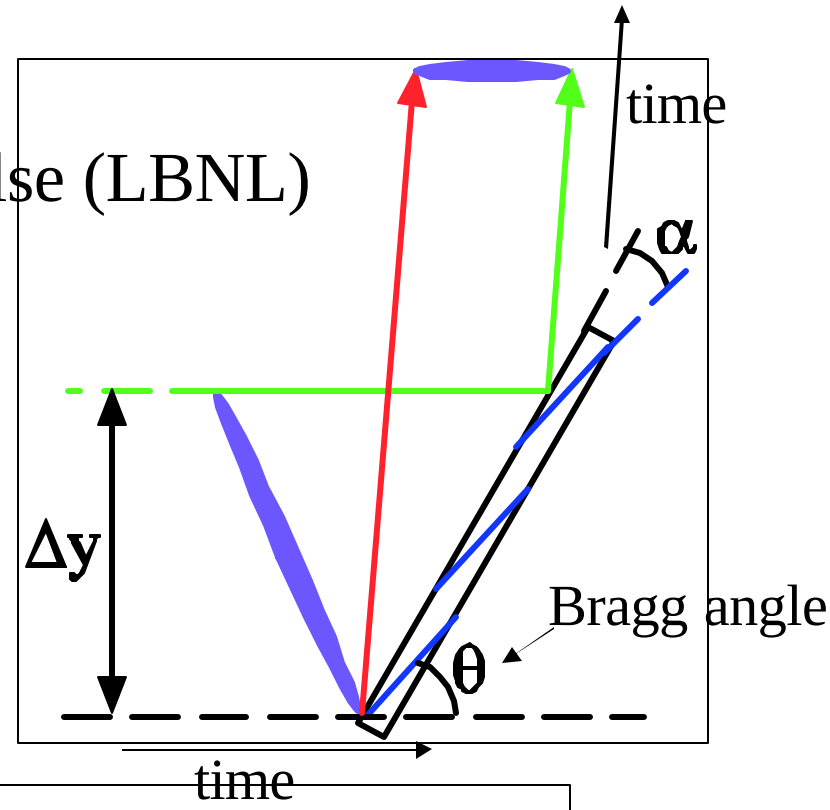
$$\text{luminosity} \propto \frac{1}{s_x s_y} \qquad d_E \propto \frac{1}{(s_x + s_y)^2}$$

e.g. TESLA 500GeV 10/0.03 mm mrad for 3 nC

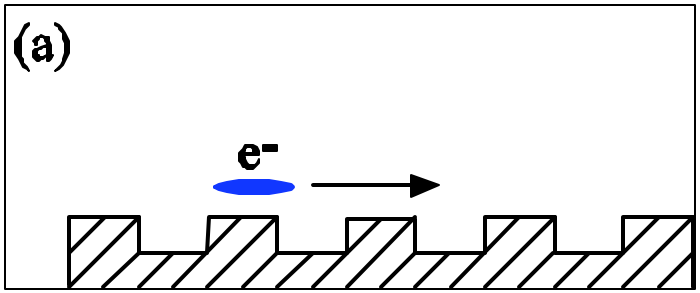
Applications of angular momentum dominated beam

- flat beam for light sources
  - Linac based ultra-short X-ray pulse (LBNL)

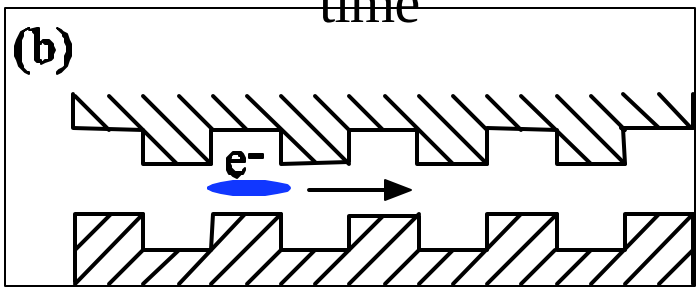
$$\Delta l = \Delta y \frac{2 \sin q \sin a}{\sin(q + a)}$$



  - Smith-Purcell radiator
    or image charge undulator



U of Chicago, Dartmouth U.



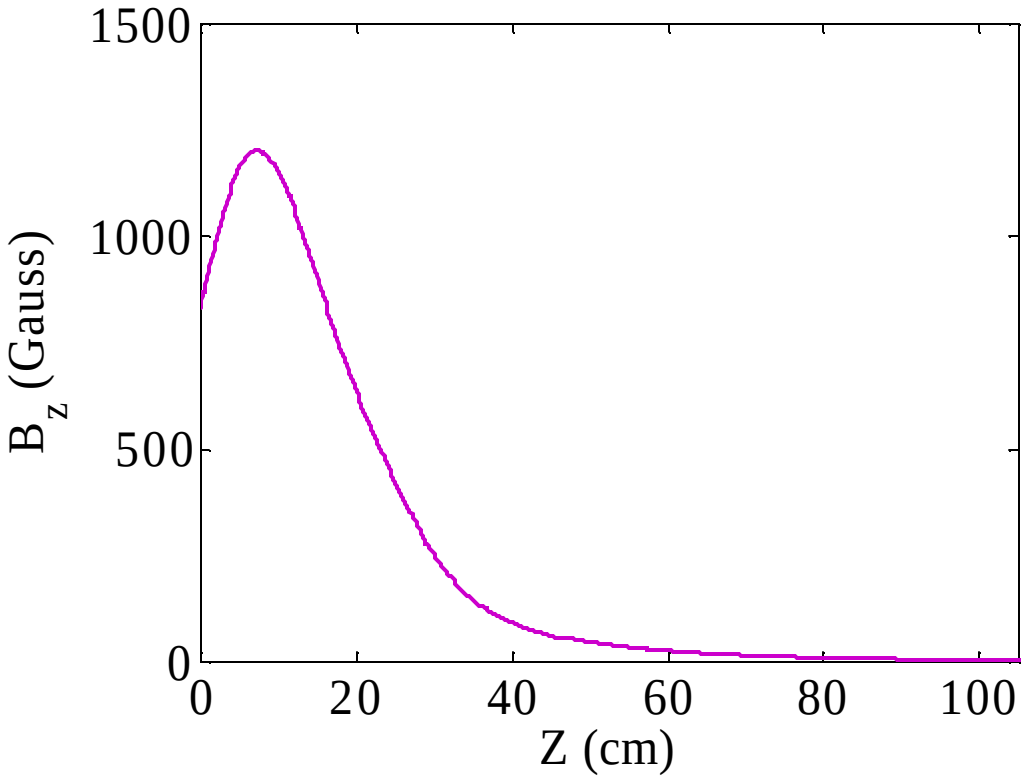
JLab.

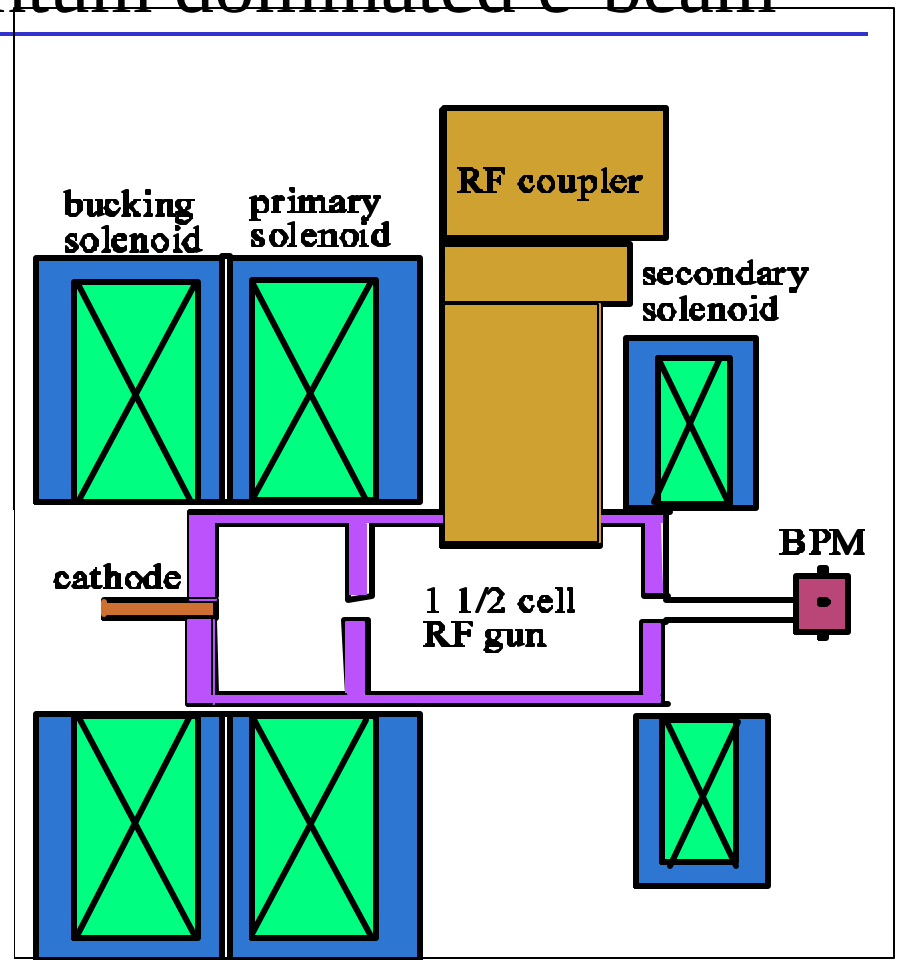
Generation of angular momentum dominated e⁻ beam

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

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

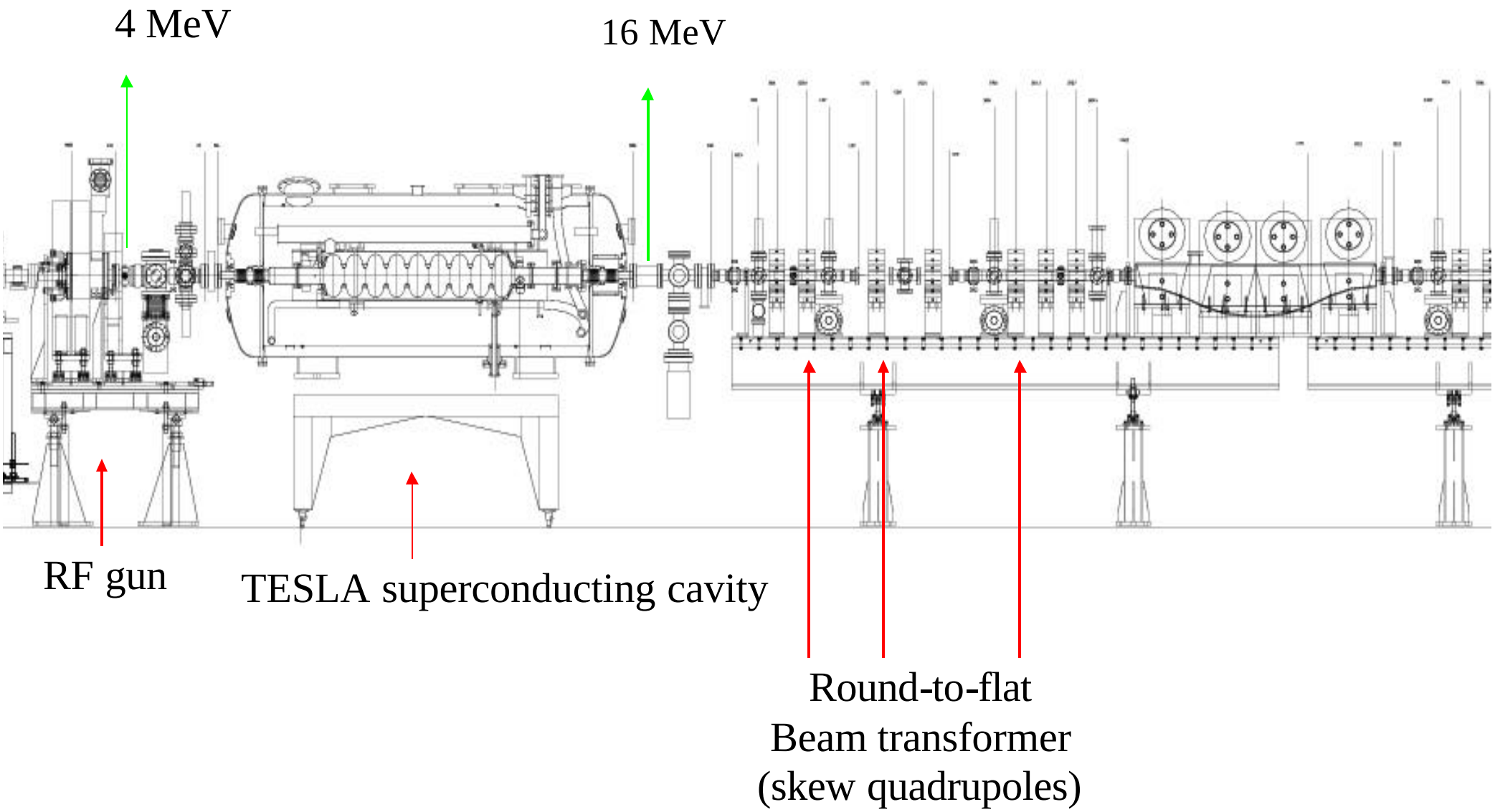
$B_z = 0$: mechanical angular momentum





FNPL 1.625-cell RF gun, 1.3 GHz

Fermilab/NICADD Photoinjector Lab. (FNPL)

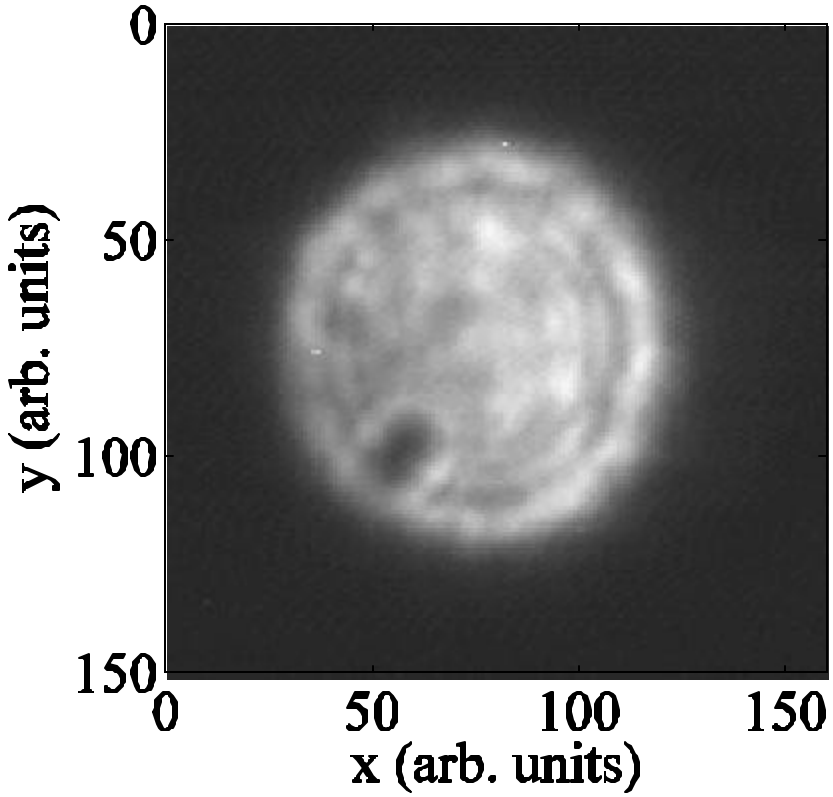


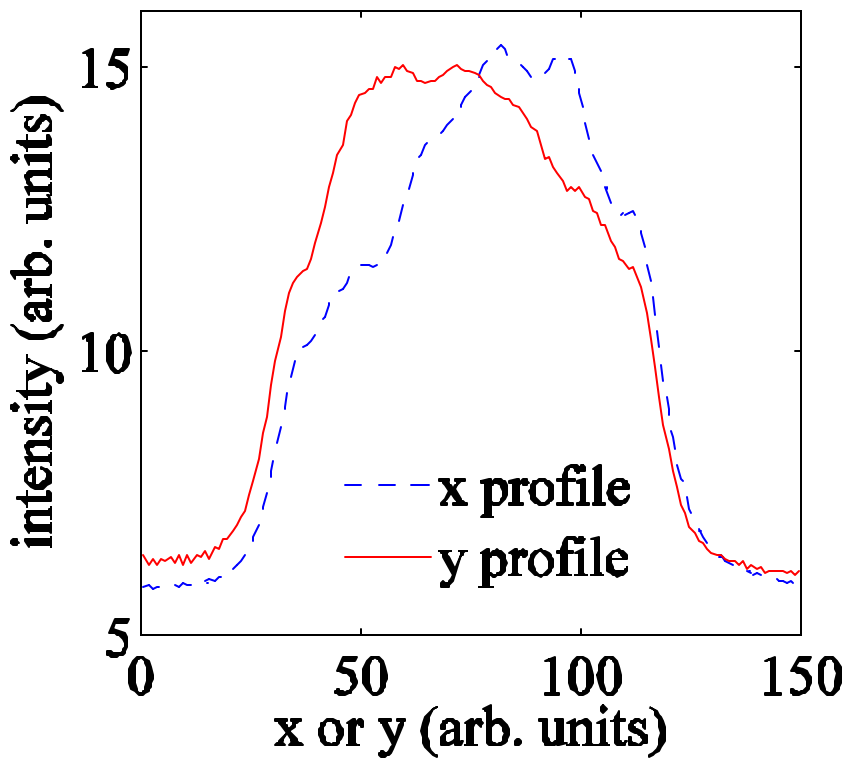
Measurement of canonical angular momentum on the photocathode

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

B_0: B-field on cathode

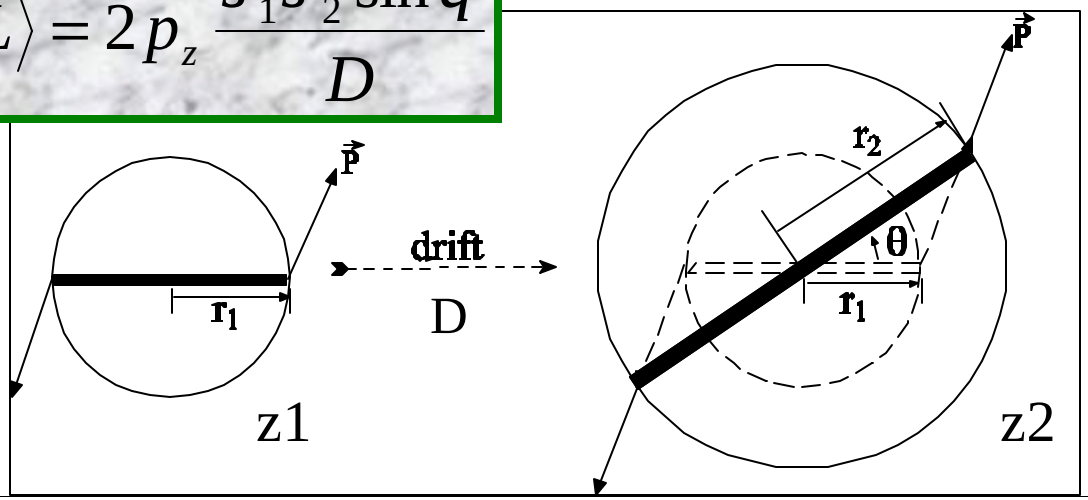
s_c :RMS beam size on cathode

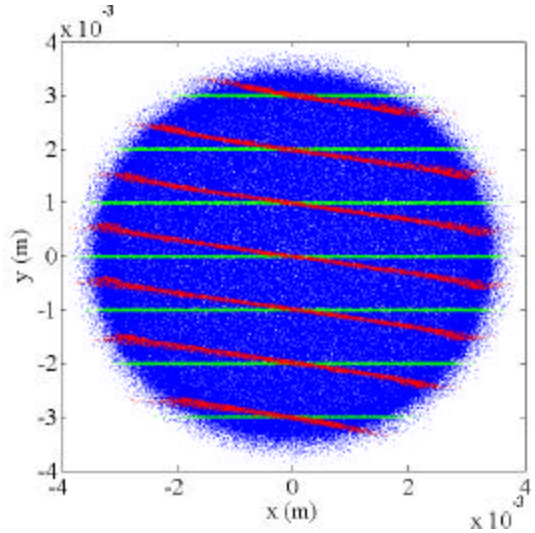


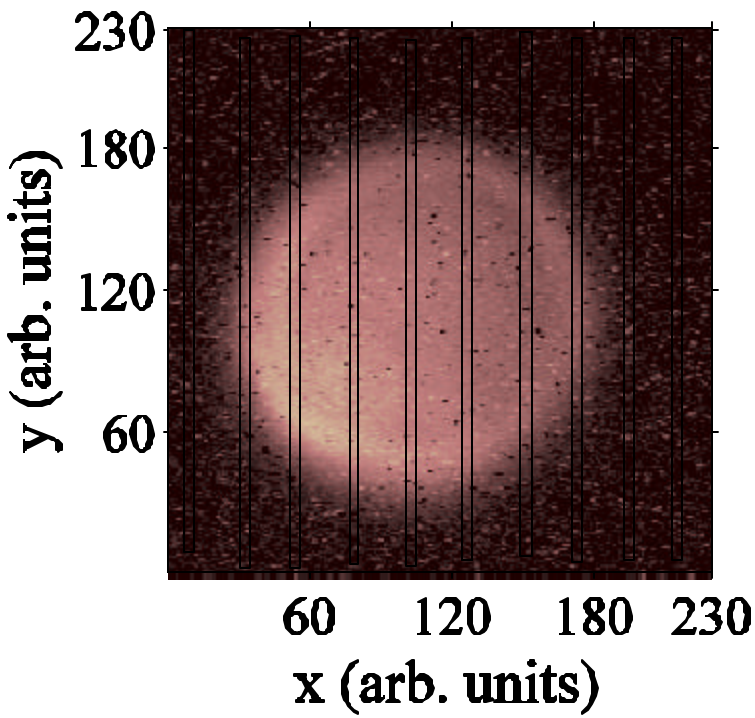


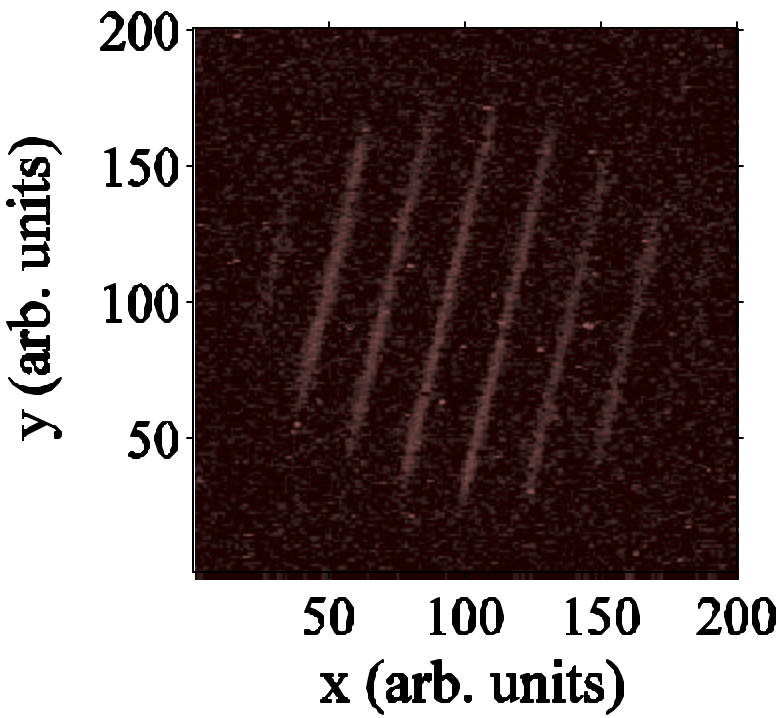
Measurement of mechanical angular momentum in a drift space

$$\langle L \rangle = 2 p_z \frac{s_1 s_2 \sin q}{D}$$

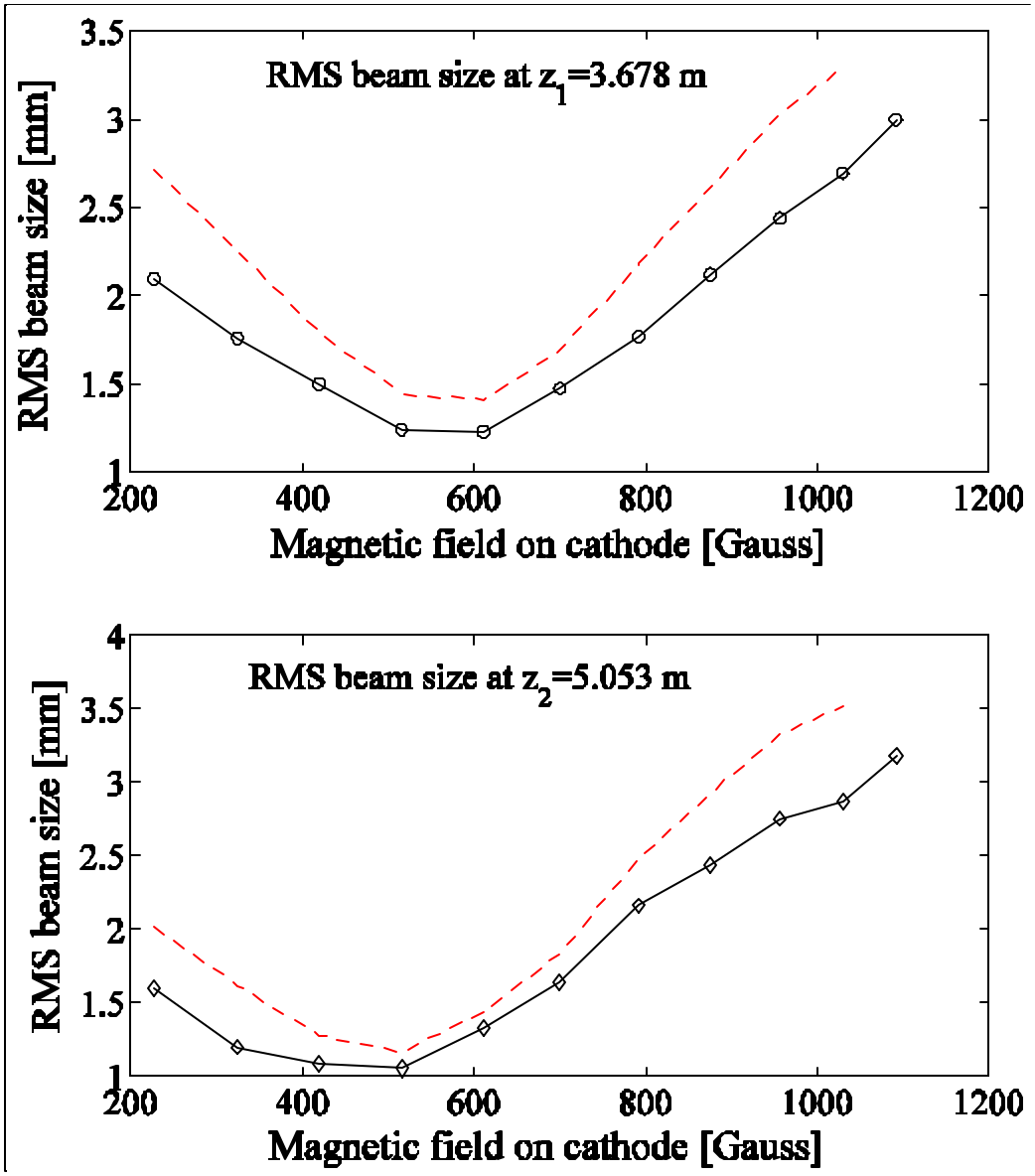


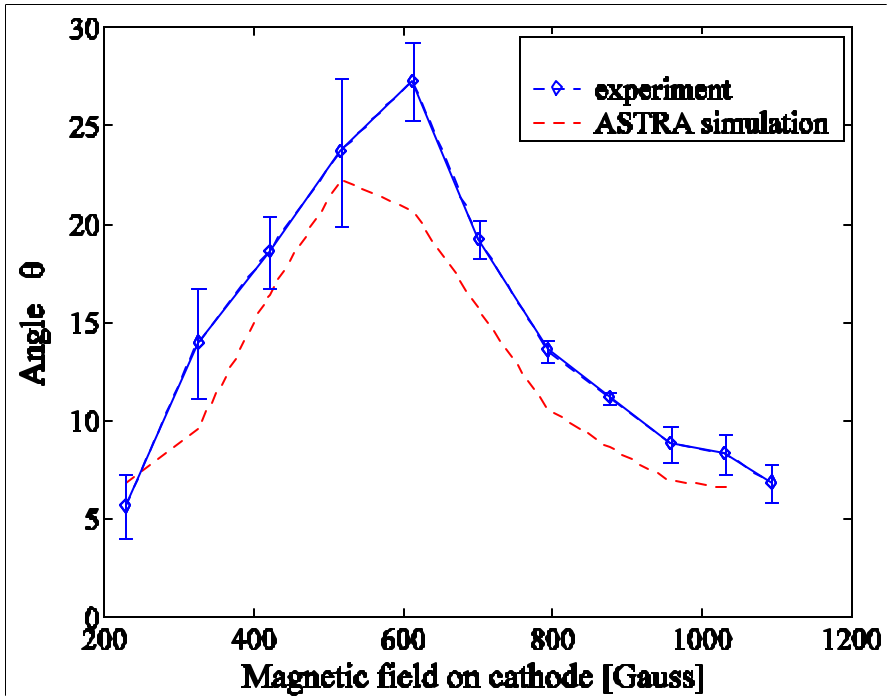






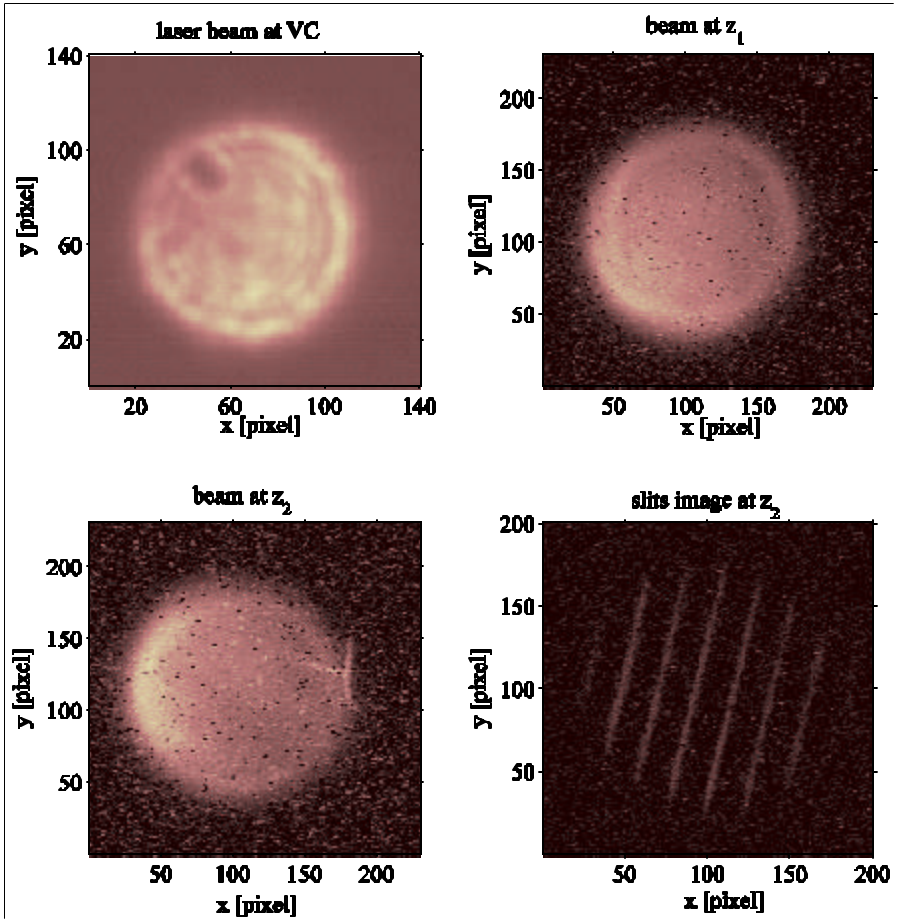
Measurement of mechanical angular momentum vs B-field

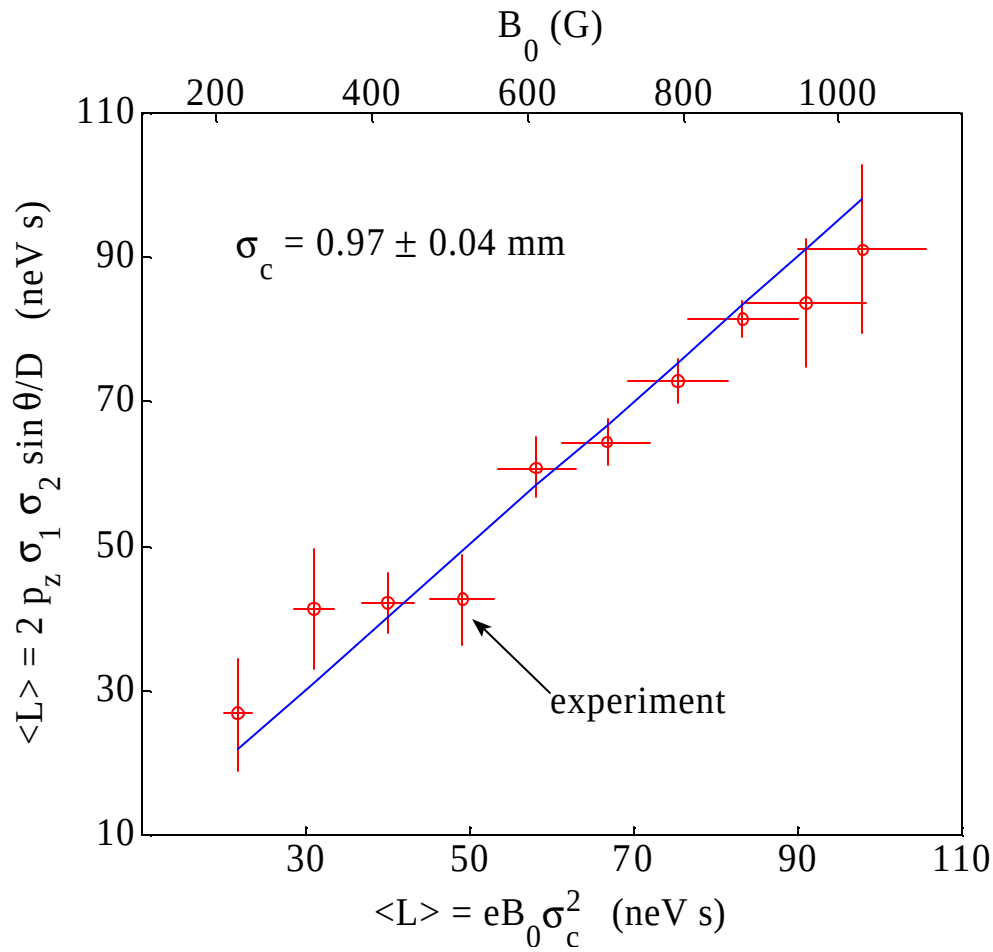




Demonstration of conservation of canonical angular momentum

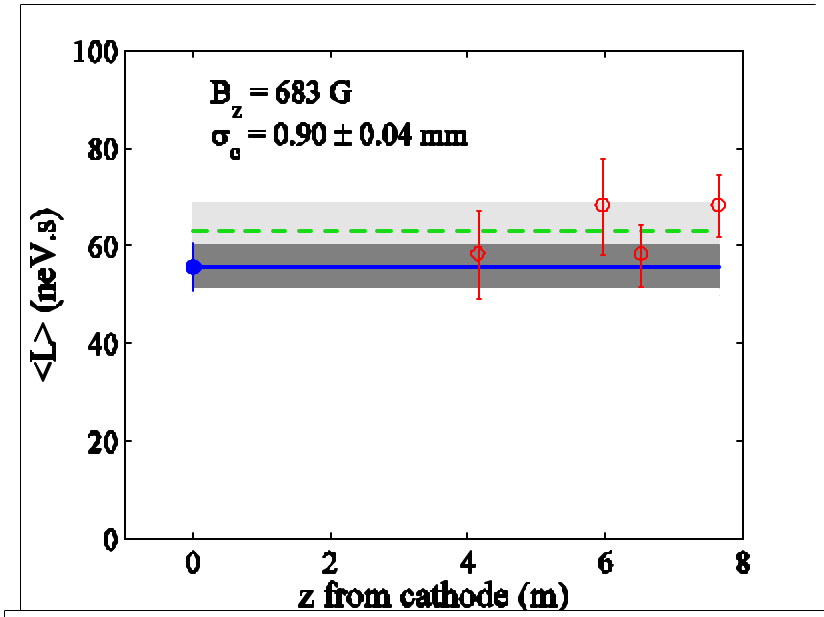
as a function of magnetic field on cathode

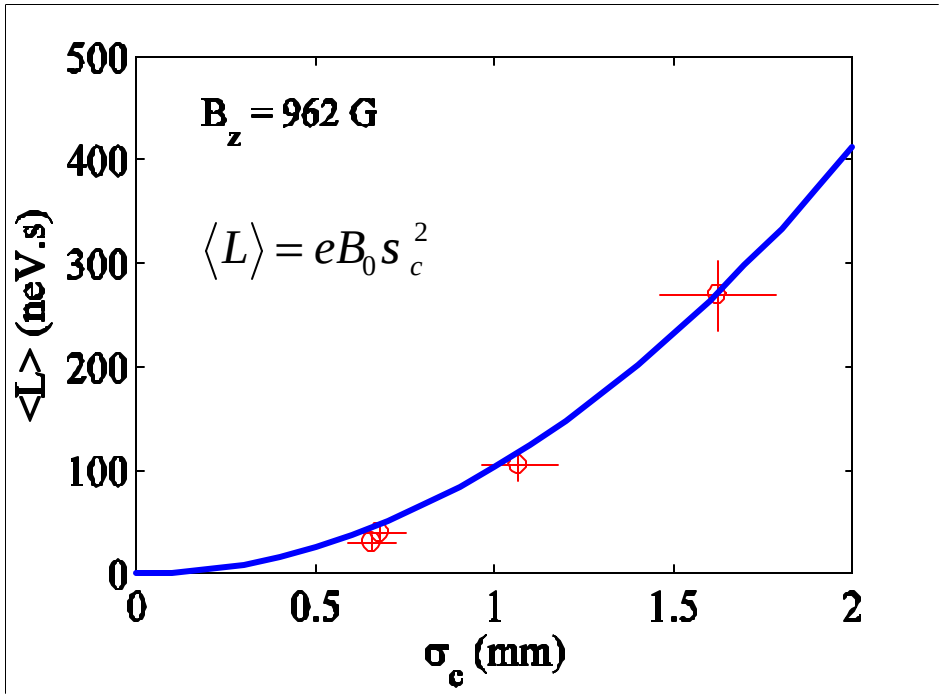


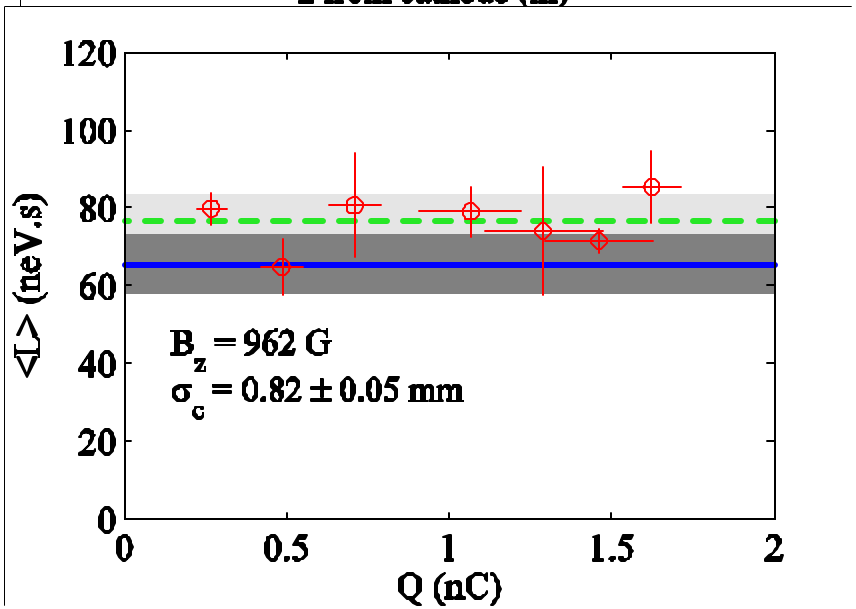


Parametric dependencies of angular momentum

- Angular momentum versus
  - beam longitudinal position z
  - bunch charge
  - beam size on the cathode







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
(K.-J. Kim)

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

Un-correlated emittance

"normalized" canonical angular momentum

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

Transfer matrix of the round-to-flat beam transformer

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

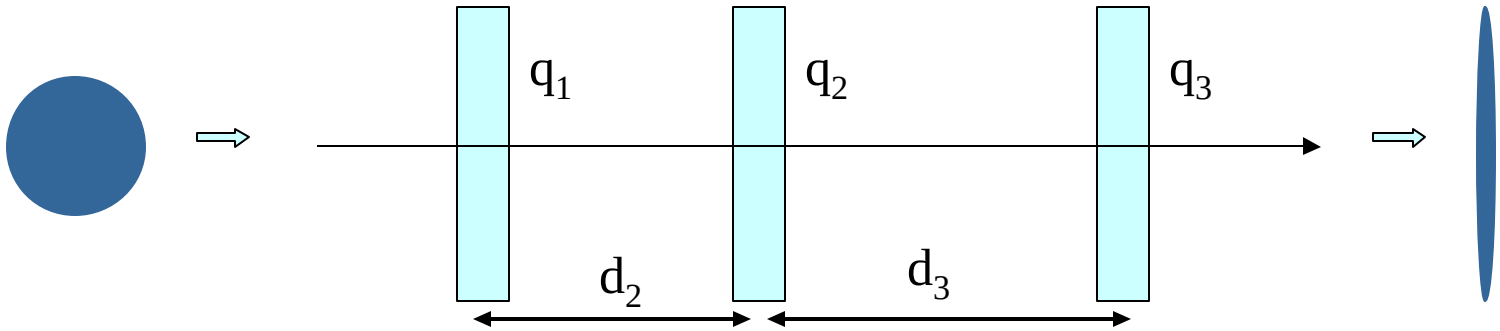
Flat beam emittances given by:

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

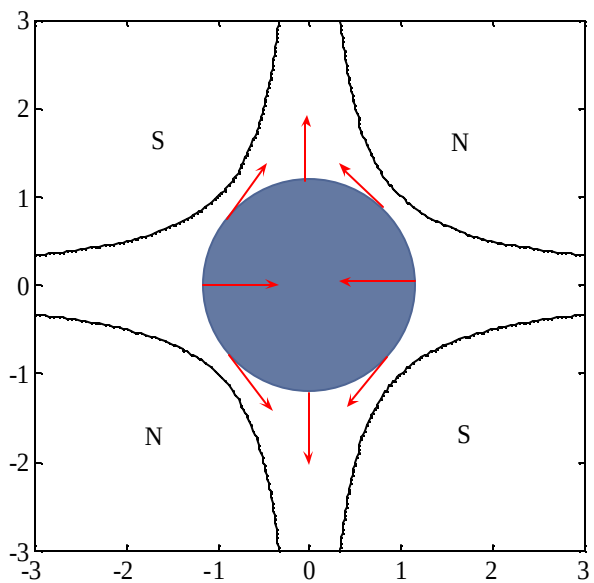
e.g. L=20 mm mrad, e_u=1 mm mrad
e_+=47 mm mrad; e_-=0.02 mm mrad

Round-to-flat beam transformation using skew quadrupoles

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



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



Two sets of solutions:

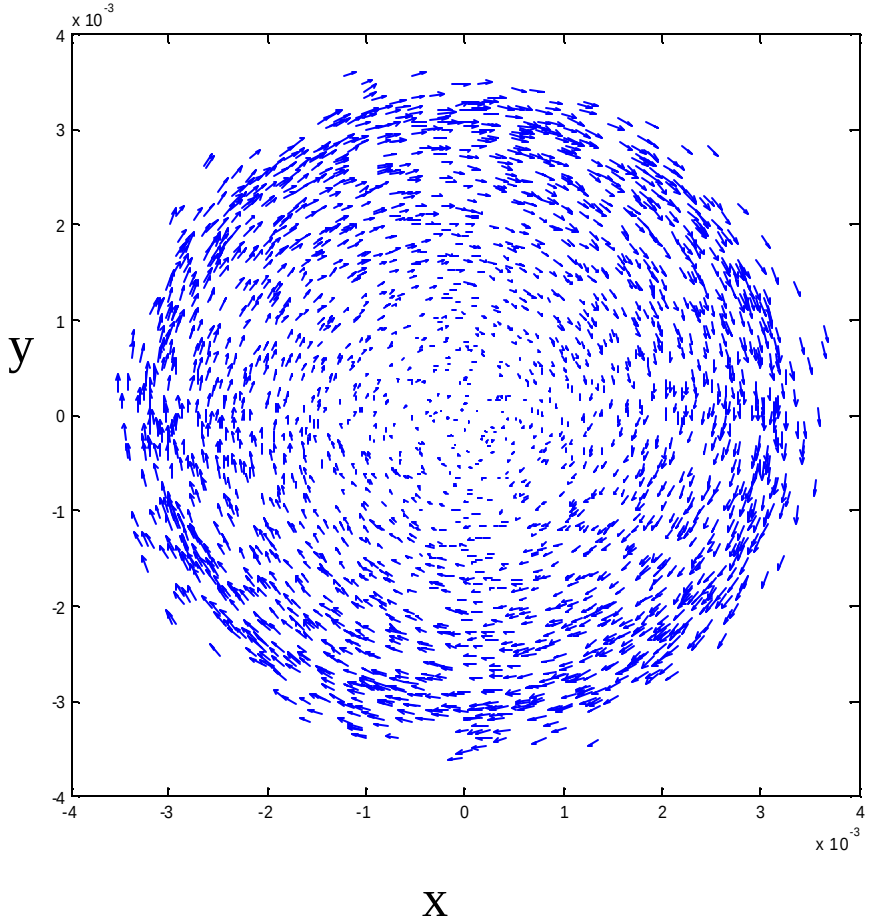
$$q_1 = \pm\sqrt{\frac{-d_2 S_{11} + S_{12} - d_2 d_T S_{21} + d_T S_{22}}{d_2 d_T S_{12}}}$$

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

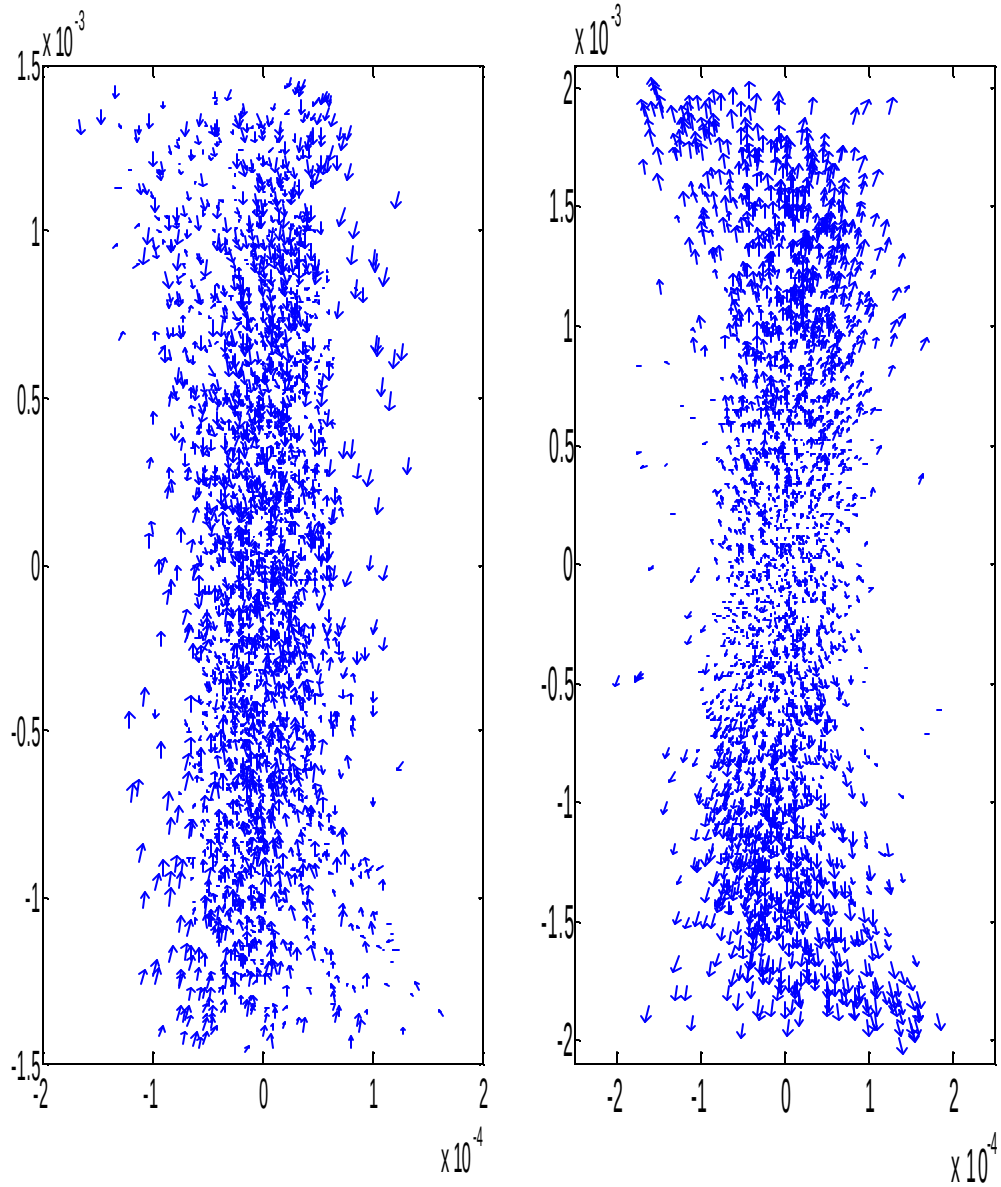
(D. Edwards)

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

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

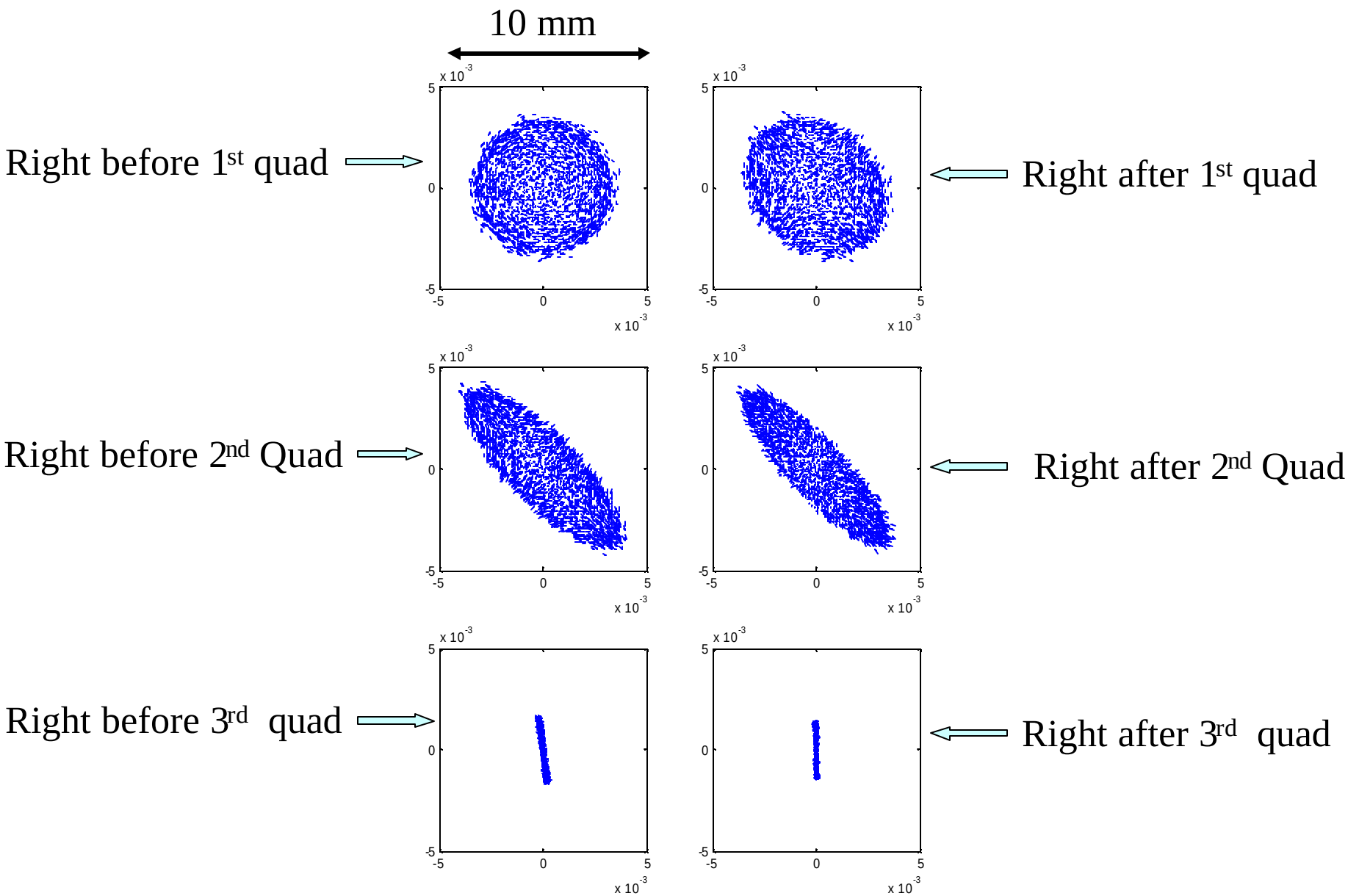


Round beam

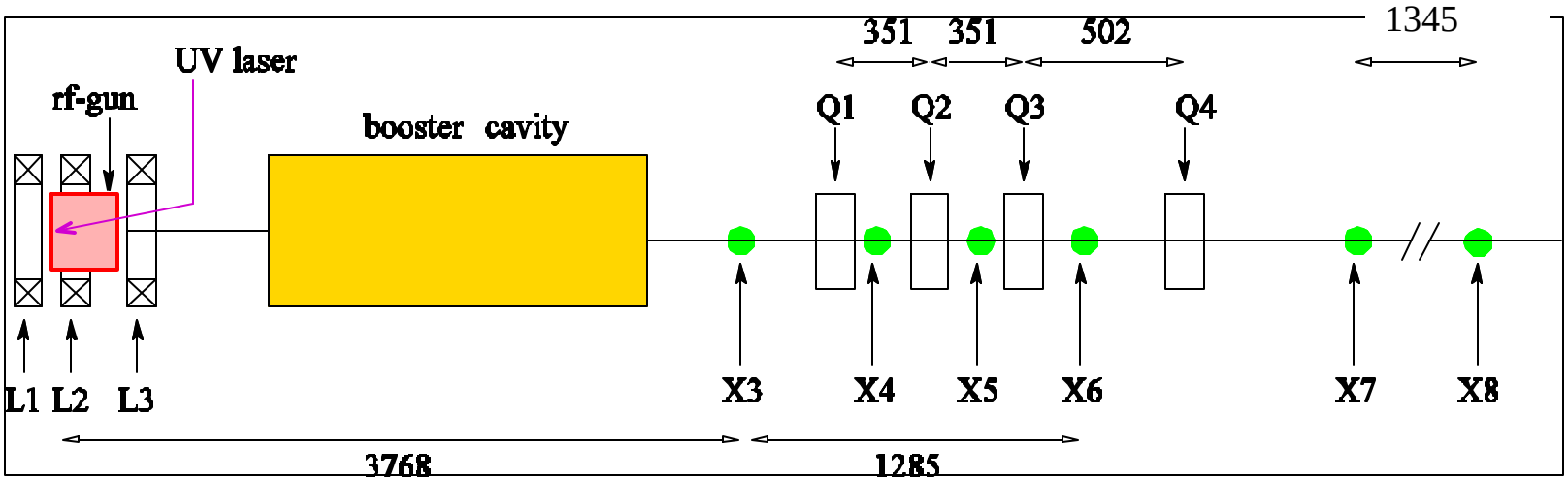


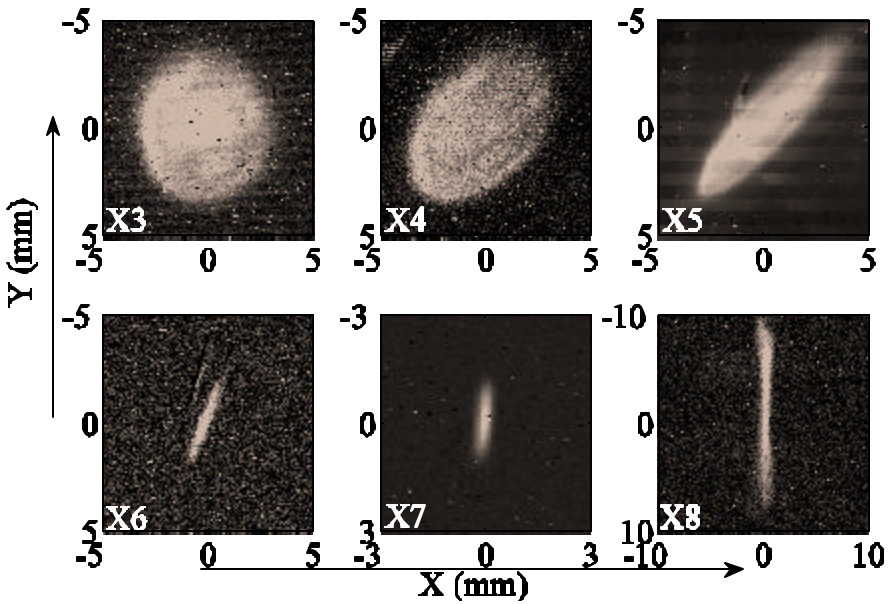
flat beam

Beam evolution through the transformer for the first solution

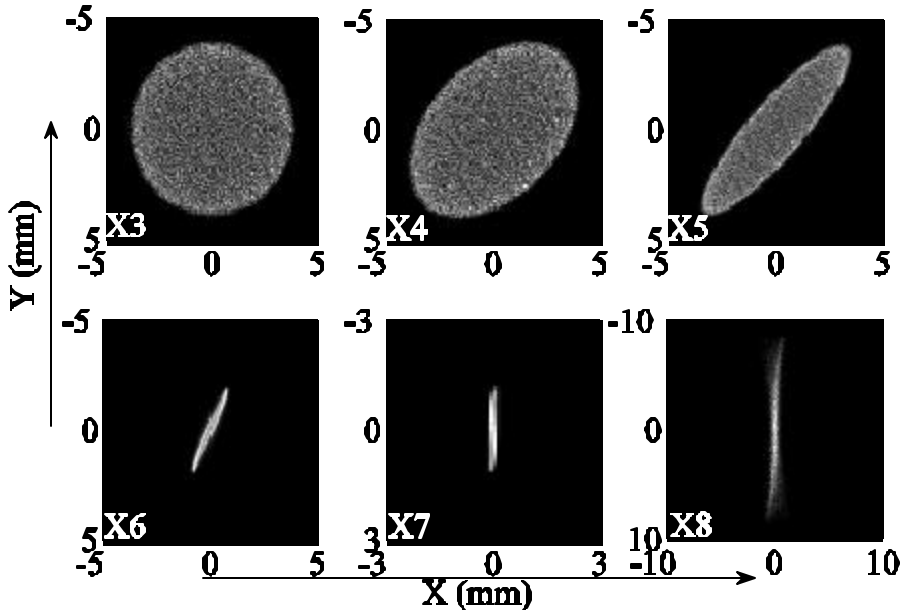


Removing of angular momentum and generating a flat beam





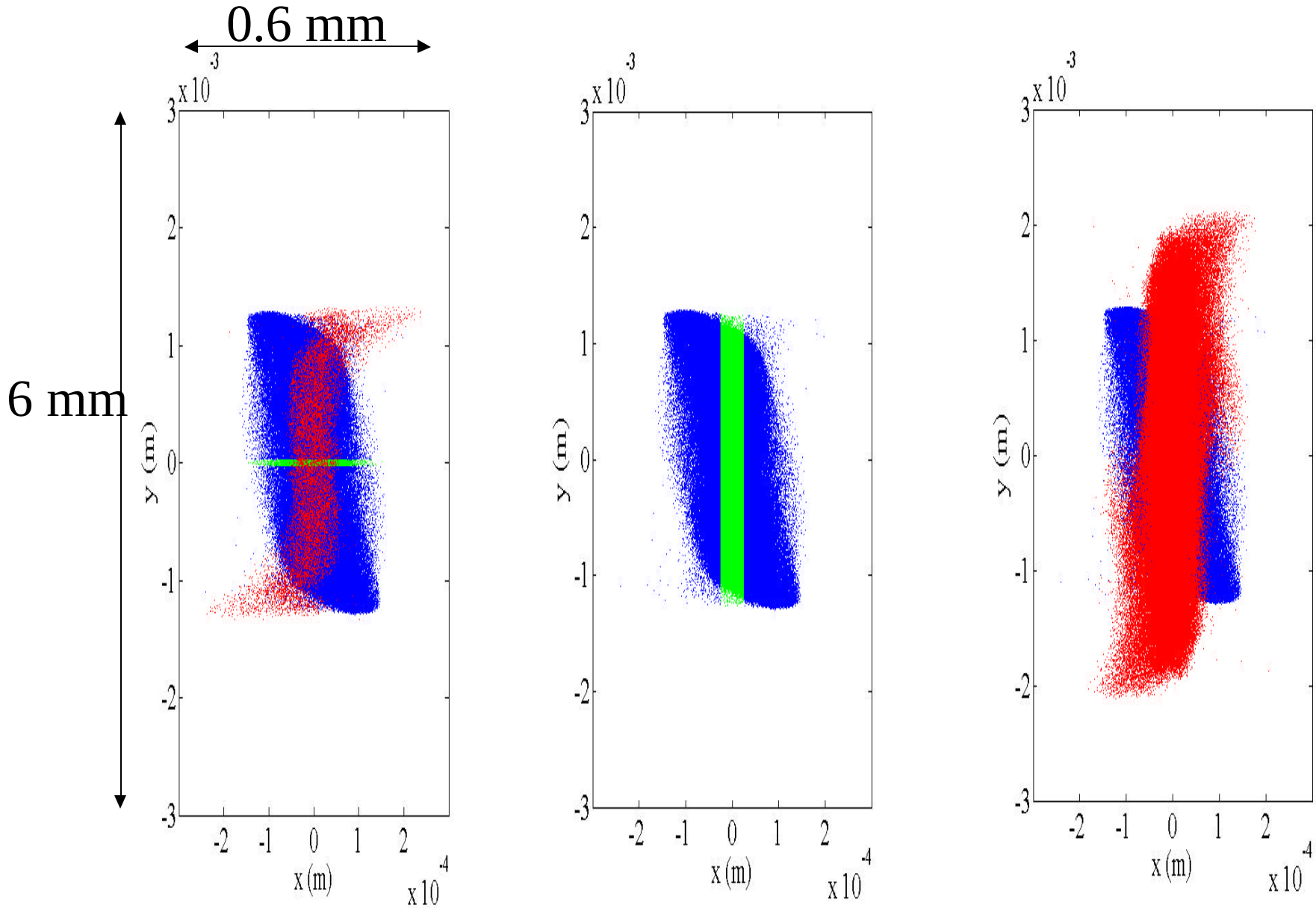
experiment



simulation

single slit emittance measurement method

Blue: flat beam at X7; green: H or V slit inserted at X7; red: slit image at X8.



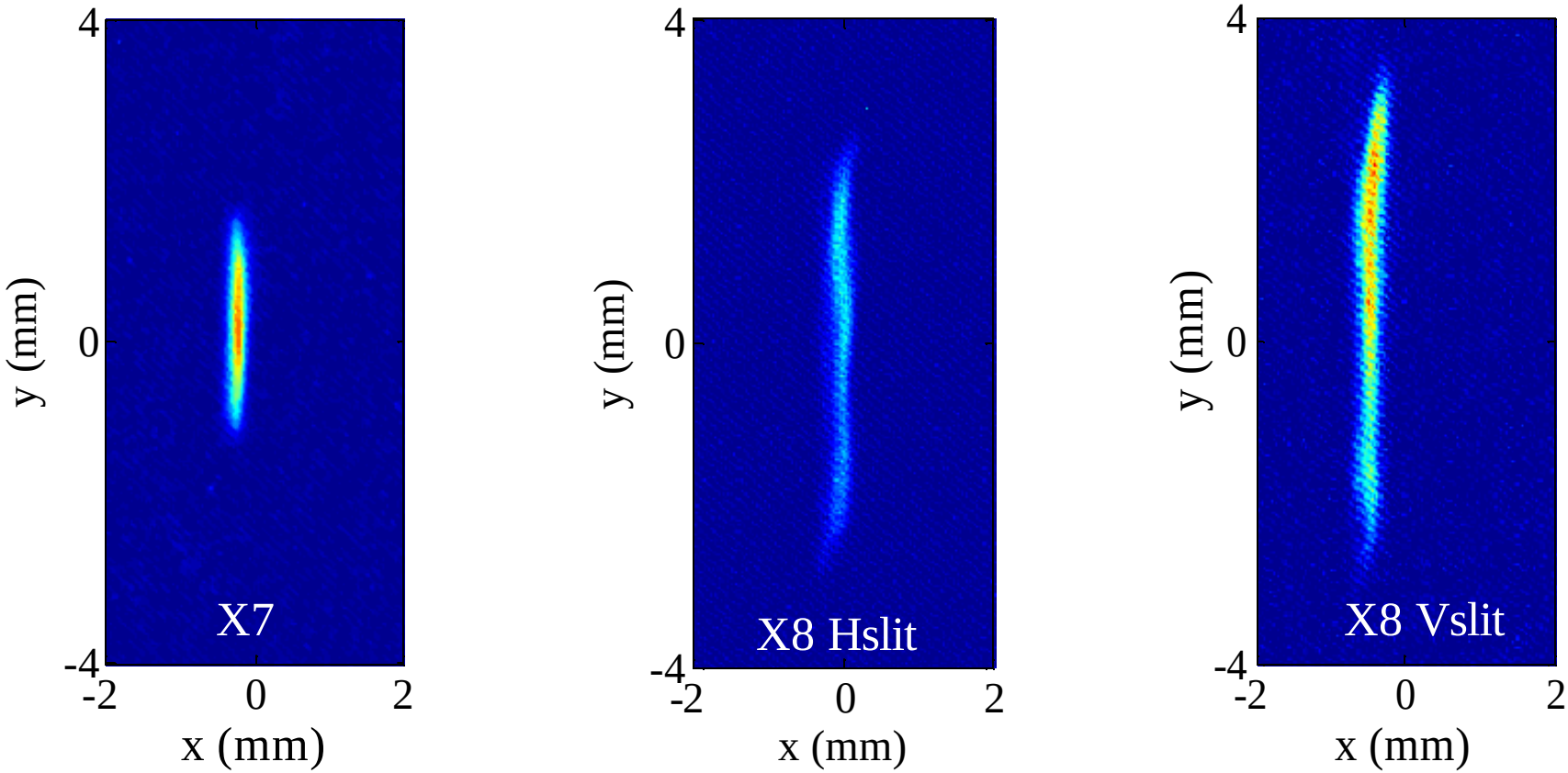
Recent flat beam experiment 1

Data of Jan. 6, 2005

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

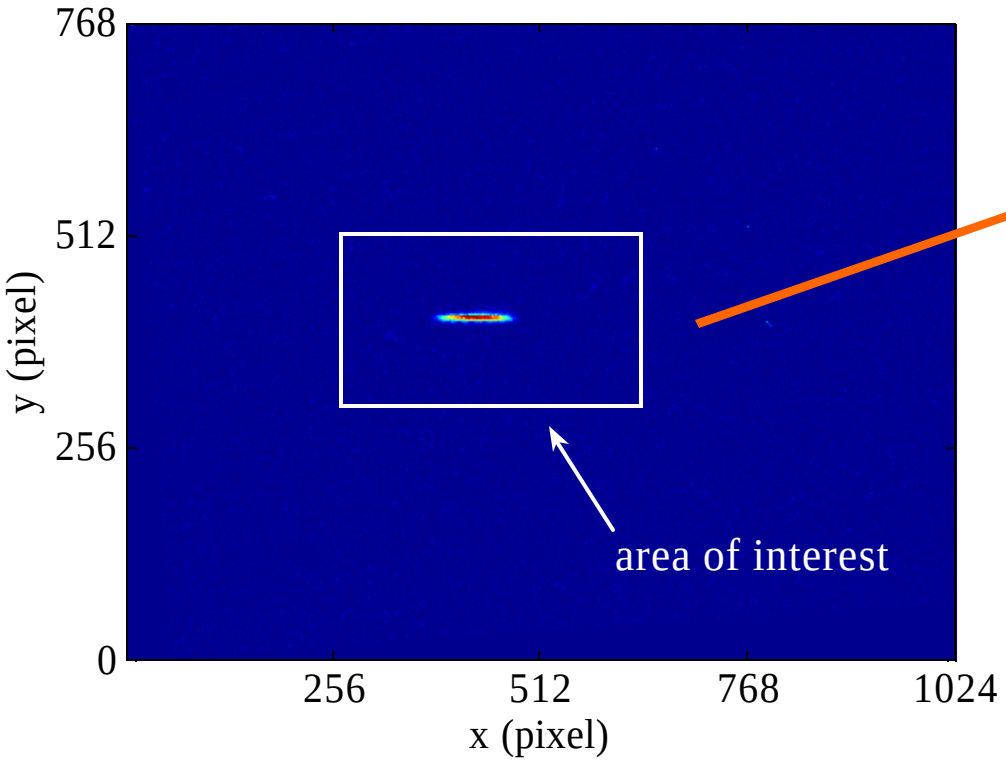
UV drive-laser rms size = 0.76 mm, rms pulse length = 3 ps

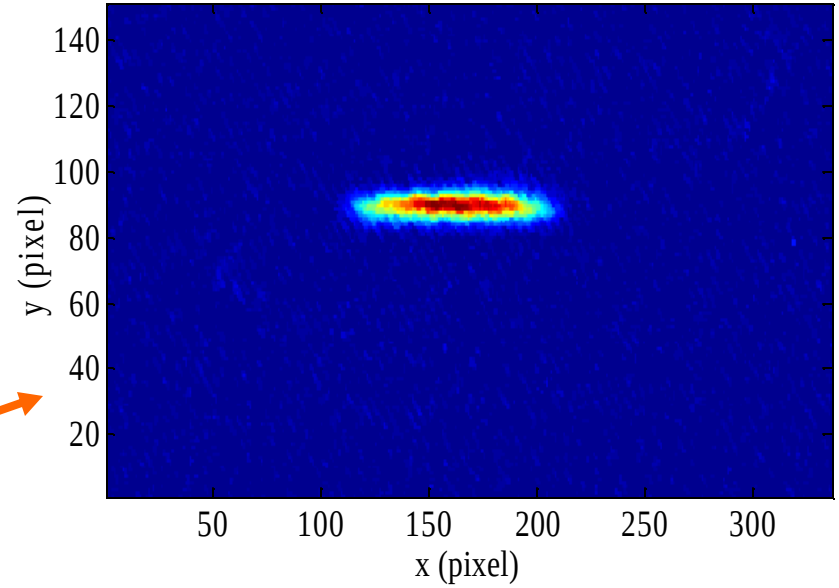
beam energy = 15.8 MeV bunch charge = 0.50 ± 0.05 nC



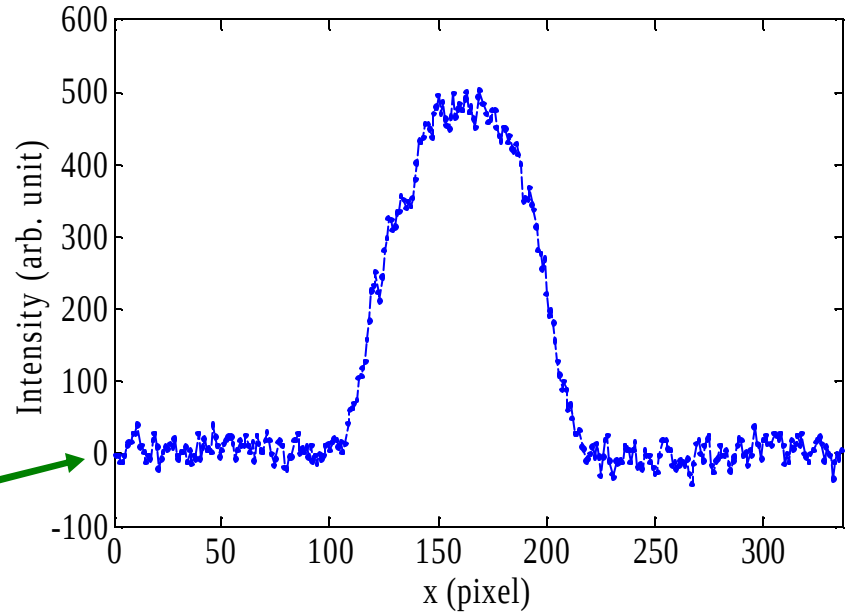
Data analysis: RMS beam size calculation

1. Choose area of interest



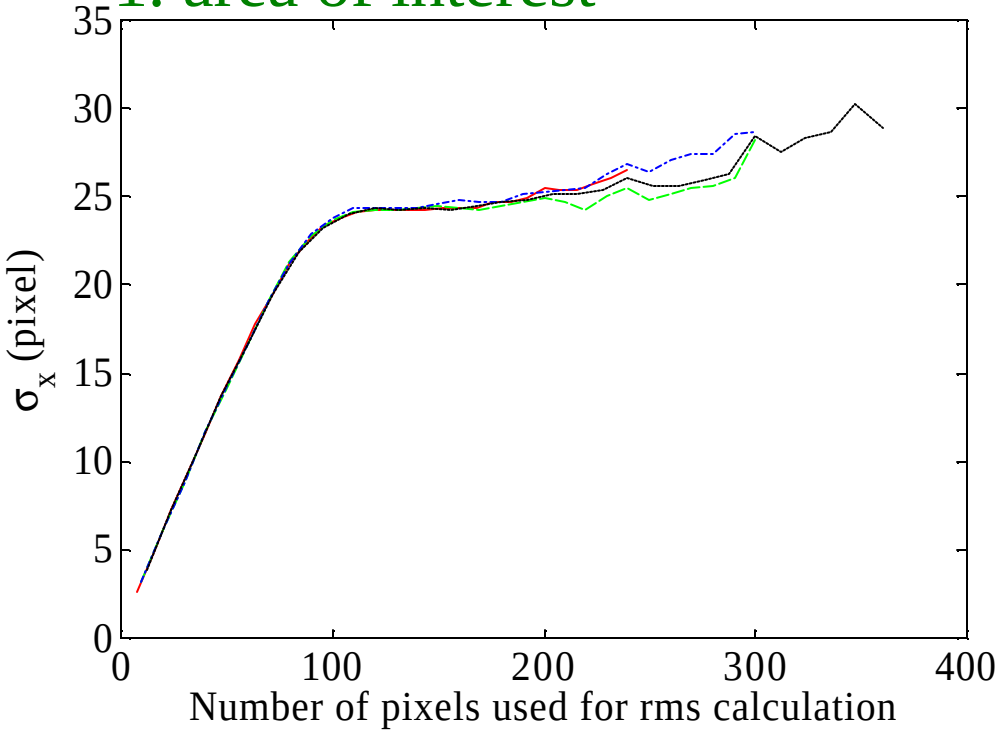


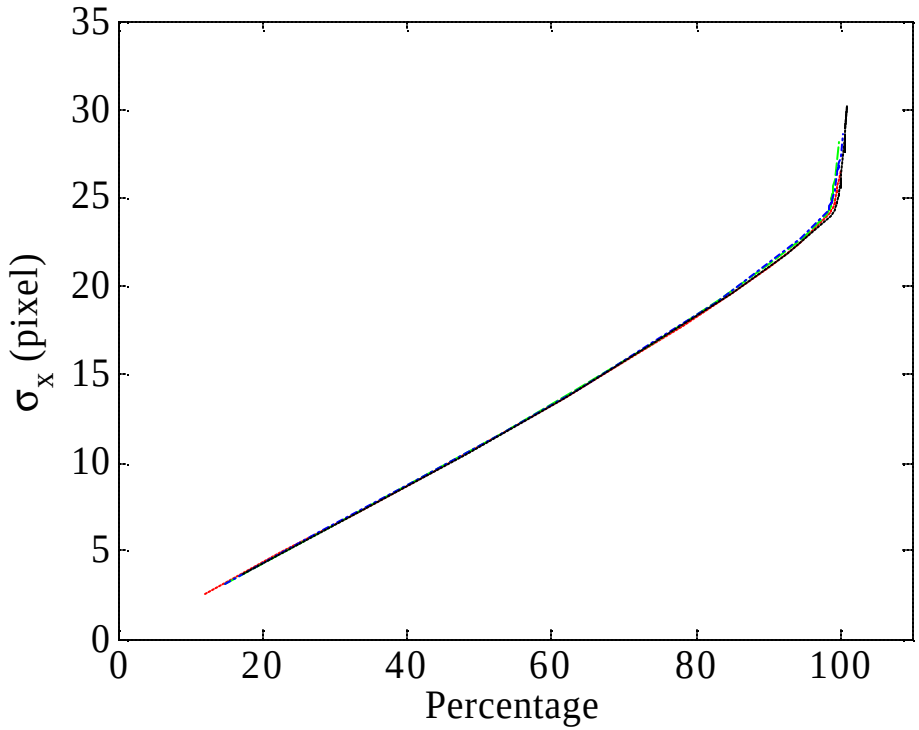
2. Decide the background level



Data analysis: RMS beam size calculation

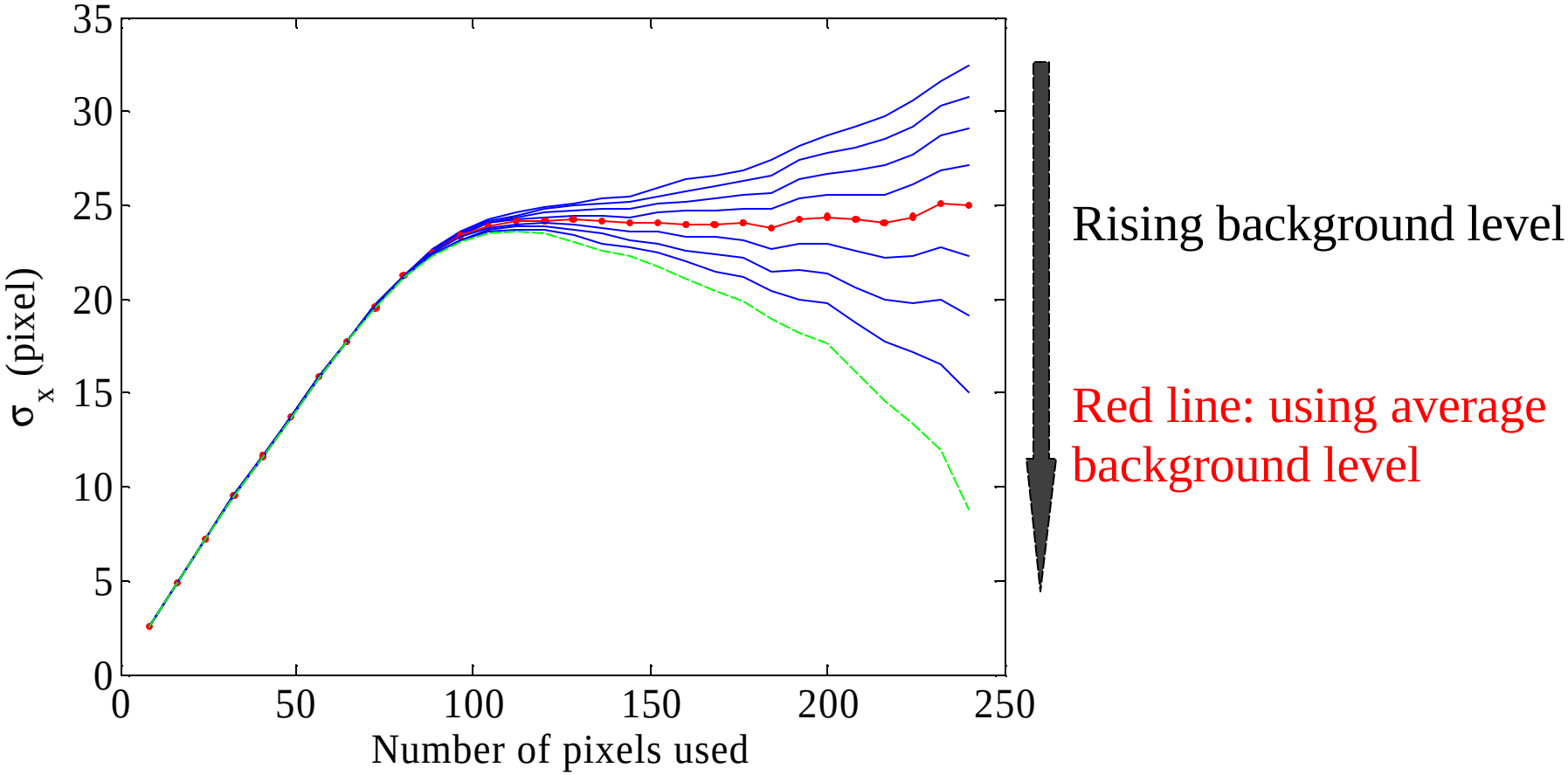
1. area of interest





Data analysis: RMS beam size calculation

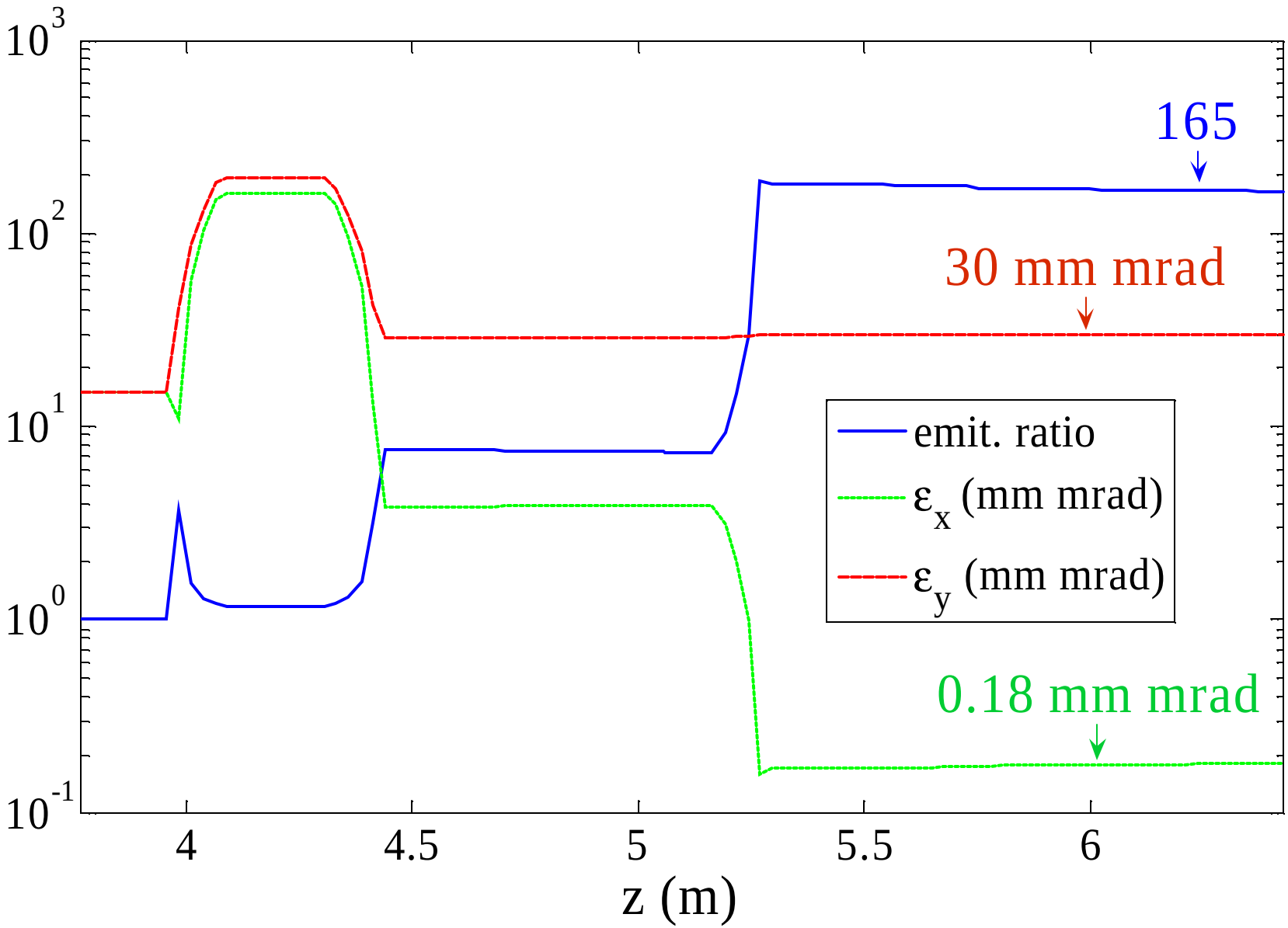
2. background level



Compare experiment 1 with simulation

	Experiment		Simulation
	90%	**95%**	**(ASTRA)**
rms_cathode(mm)	0.71±0.05	0.76±0.06	0.76
B_cathode(Gauss)	876		876
I_Quad1 (A)	-1.92		-2.03
I_Quad2 (A)	2.40		2.57
I_Quad3 (A)	-2.99		-4.01
rms_X7y (mm)	0.59±0.03	0.63±0.04	0.56
rms_X7x (mm)	0.077±0.005	0.087±0.006	0.047
rms_X8_hslit (mm)	1.15±0.02	1.24±0.02	1.50
rms_X8_vslit (mm)	0.12±0.01	0.13±0.01	0.081
emitx (mm mrad)	**0.36±0.04**	**0.45±0.06**	**0.18**
emity (mm mrad)	26±2	30±2	30
emit ratio	73±10	68±10	165
$(\text{emitx}\cdot\text{emity})^{0.5}$	3.1	3.7	2.3 mm mrad

ASTRA Simulation with 01/06/2005 experiment conditions



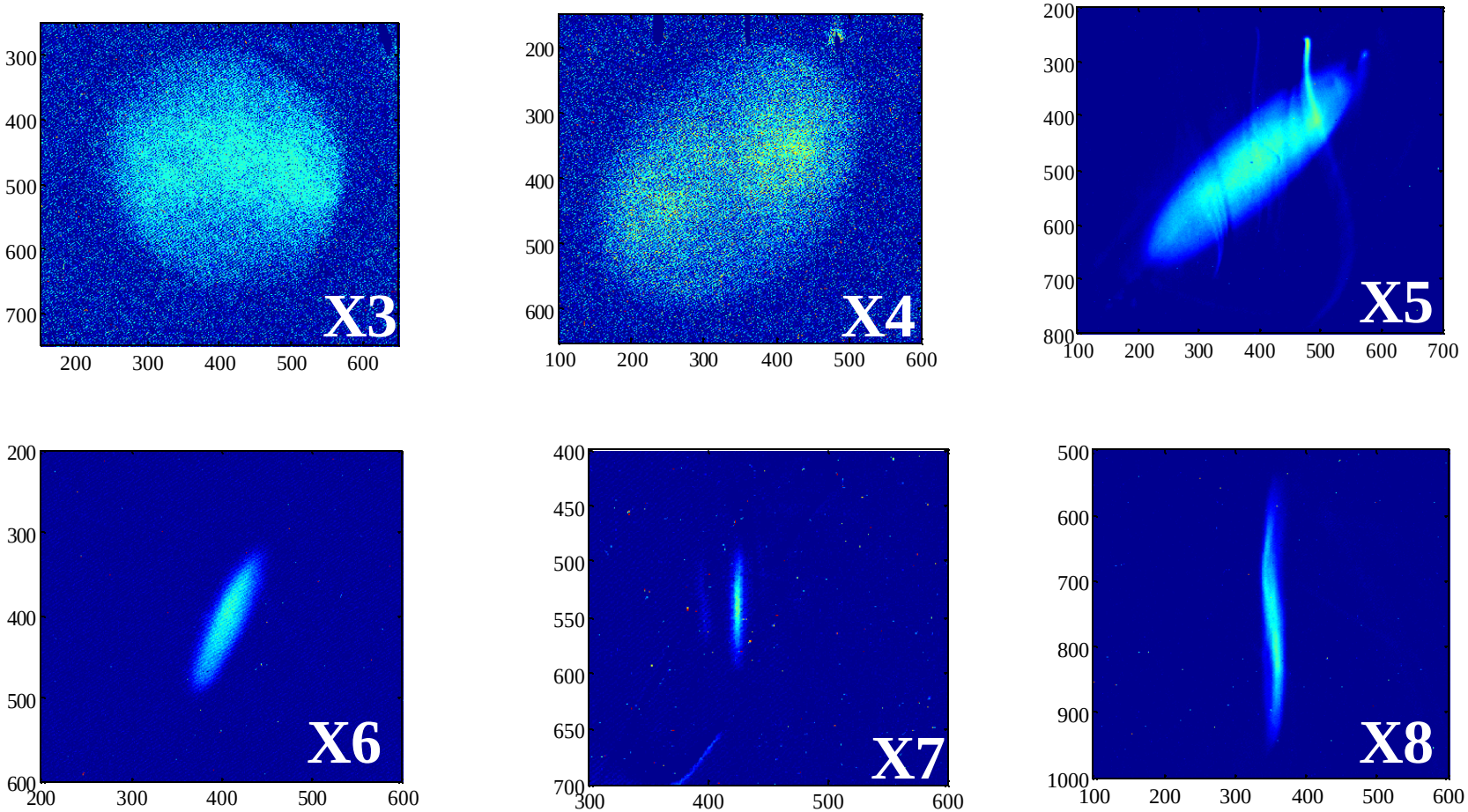
Recent flat beam experiment 2

Data of Feb. 25, 2005

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

UV drive-laser rms size = 0.97 mm, rms pulse length = 3 ps (?)

beam energy = 15.86 MeV bunch charge = 0.51 ± 0.17 nC



Compare experiment 2 with simulation

	Experiment		Simulation
	90%	**95%**	**(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
emitx (mm mrad)	**0.39±0.02**	**0.49±0.02**	**0.27**
emity (mm mrad)	35.2±0.5	41.0±0.5	53
emit ratio	90±5	83±4	196
$(\text{emitx}\cdot \text{emity})^{0.5}$	3.7	4.5	3.8 mm mrad

conclusion

- A series of experimental investigation of angular momentum dominated electron beam was carried out;
- Simulations show that an emittance ratio >100 is possible when the chromatic effect and space charge are taking into account.
- Recent flat beam emittance measurements are very encouraging
  - at 0.5 nC, normalized emittance of **0.4 ~ 0.5 mm mrad** was measured (LUX design value but at 1nC);
  - emittance ratio of **70 ~ 90** was achieved;
  - ideas and simulations of further improving the emittance ratio is underway.
- However as beam size approaches to 10's of μm, dispersion and camera resolution come to play.
- laser pulse length and temporal profile

acknowledgements

Contributors to the work presented here:

Guidance and leadership
Helen Edwards, Don Edwards, Kwang-je Kim, Philippe Piot

Laser work:
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Cryogenics and vacuum:
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RF:
Markus huening, Peter Prieto, Renee Padilla, John Reid

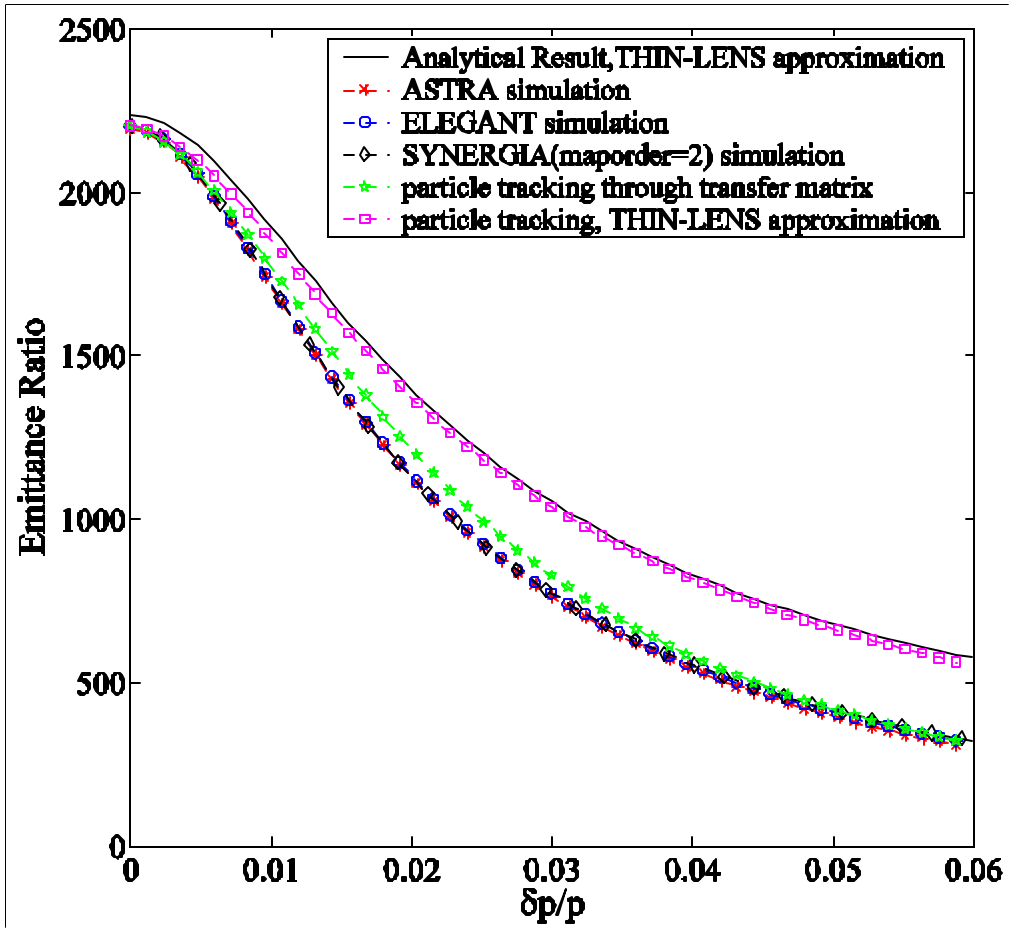
Software:
Jason Wennerberg

Discussions:
Court Bohn, Klaus Flöttmann

Chromatic effects

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

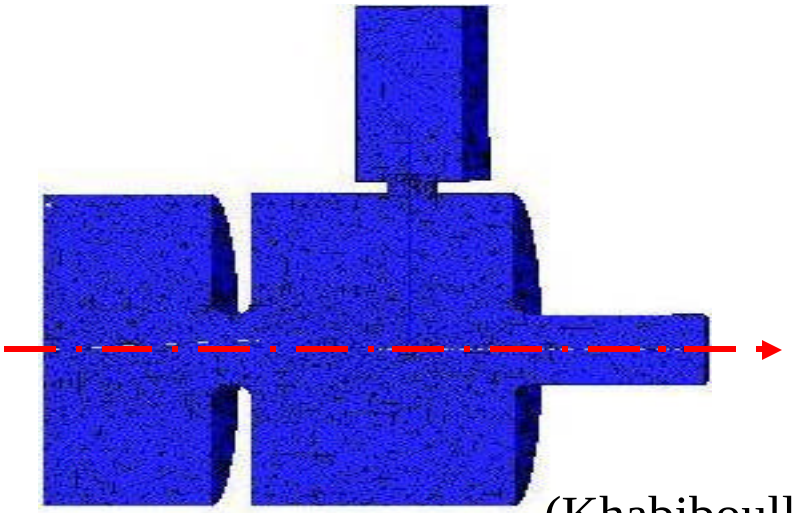
$$\varepsilon_{x,y} = \sqrt{(\varepsilon_{eff} \mp \mathcal{L})^2 + \langle\delta^2\rangle^2[|\Delta_{11 \text{ or } 22}| + (\varepsilon_{eff} \mp \mathcal{L})^2 \mathrm{Tr}(T\Delta^{\dagger}_{11 \text{ or } 22})]}.$$



thermal emittance =1 mm mrad.

space charge force is turned off.

RF asymmetry caused by gun RF coupler kick

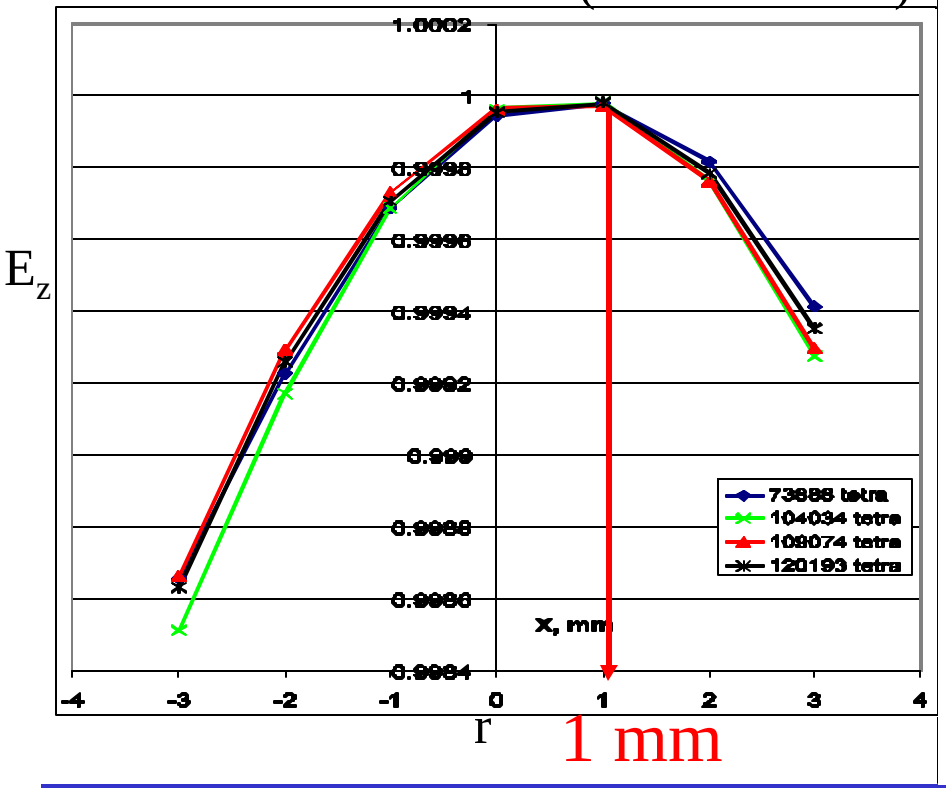


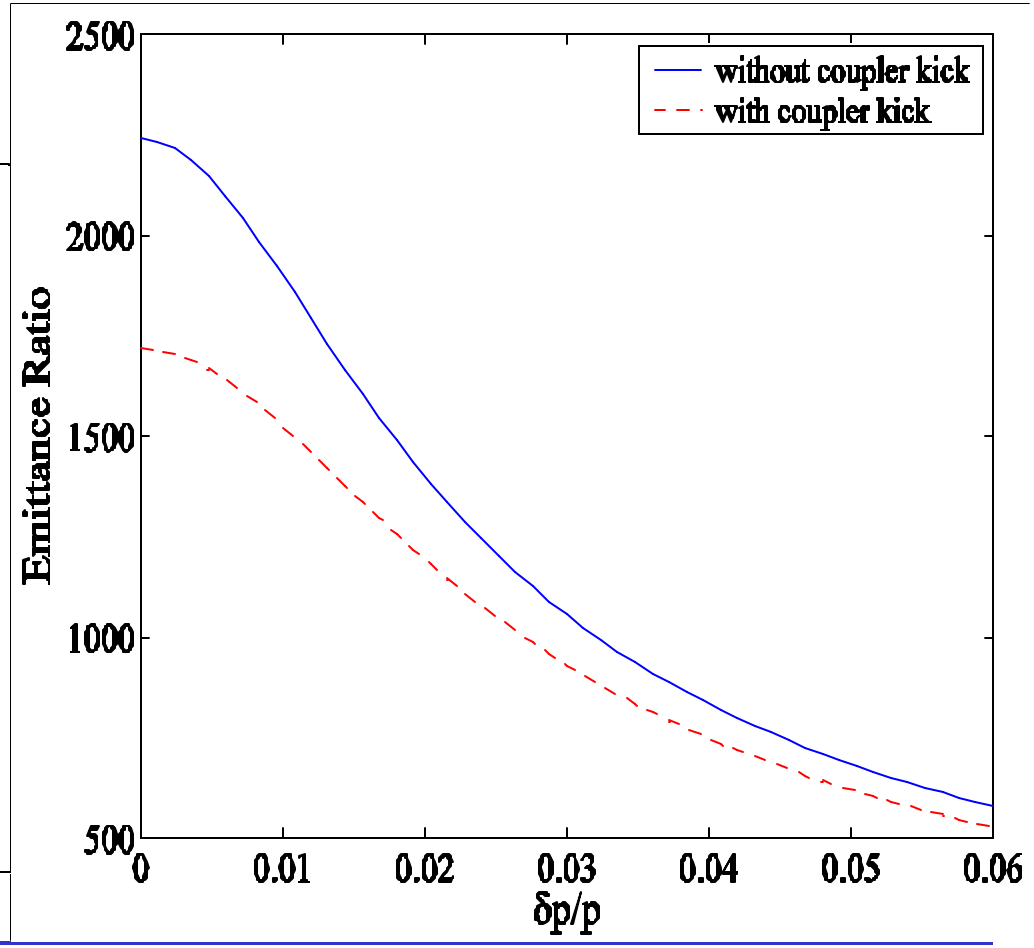
(Khabiboulline)

Accelerating mode center is shifted

? time-dependent dipole kick

? vertical emittance growth





Quadrupole alignment: rotation and displacement around each axis