Generation and Dynamics of Magnetized Beams for High-Energy Electron Cooling*

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Outline

- Introduction
- Features and parameterization of magnetized beams
- Formation of magnetized bunches:
  - methods and limitations,
  - experiments in rf gun.
- Transport and Manipulation:
  - transverse matching,
  - longitudinal manipulations,
  - decoupling into flat beams.
- Outlook

Required Electron-Beam Parameters

- Cooling interaction time

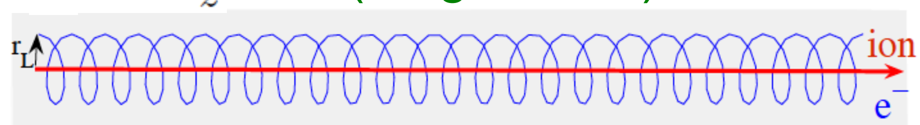
$$\tau \approx \rho / v_{e\perp}$$ (not magnetized)

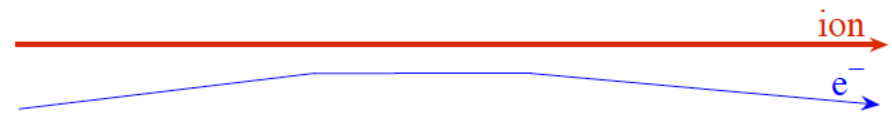
$$\tau \approx \frac{\rho}{v - v_{e\parallel}}$$ (magnetized)

- magnetized cooling less dependent on e- beam transverse emittance (to what extent?)

$$r_L = \frac{v_{e\perp}}{eB_z}$$

(magnetized)





(not magnetized)

- electron-cooling accelerator provides beam eventually matched to cooling-solenoid section

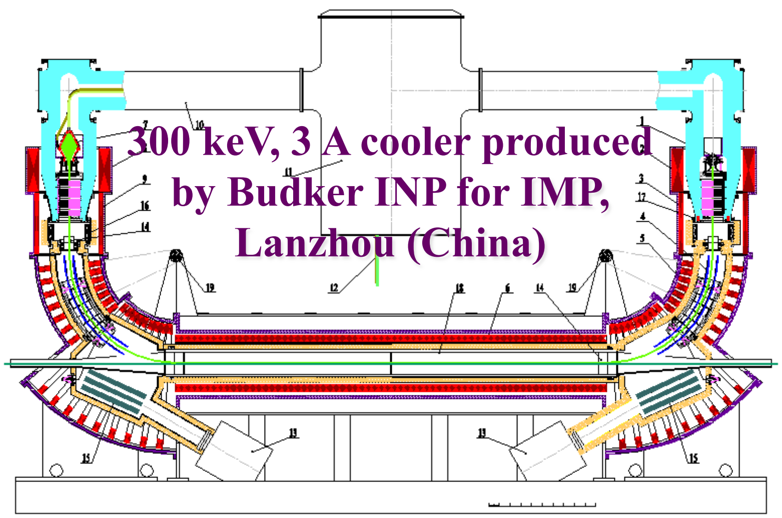
Cooler configurations

e.g. see S. Nagaitsev, et al, PRL96, 044801 (2006)

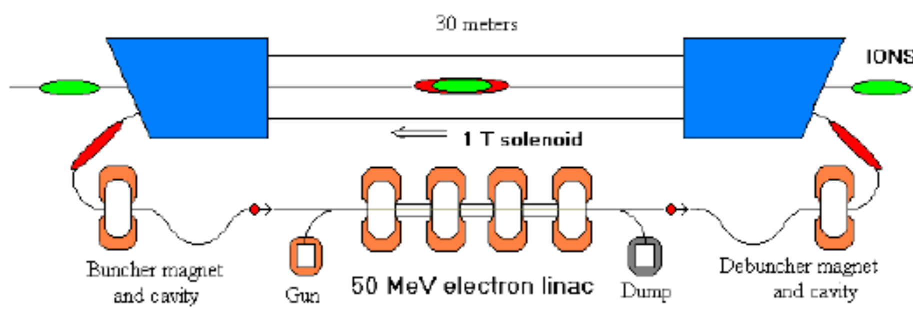
- low-energy coolers:
  - lattice (bends) embedded in magnetic fields,
  - based on DC electron sources,
  - no further acceleration or bunching, needed.

- high-energy coolers:
  - medium energies required (50-100 MeV),
  - acceleration in SCRF linac → bunching
  - lumped solenoidal fields → matching

e.g. see I. Ben-Zvi, et al., Proc. PAC2001, p. 48 (2001)

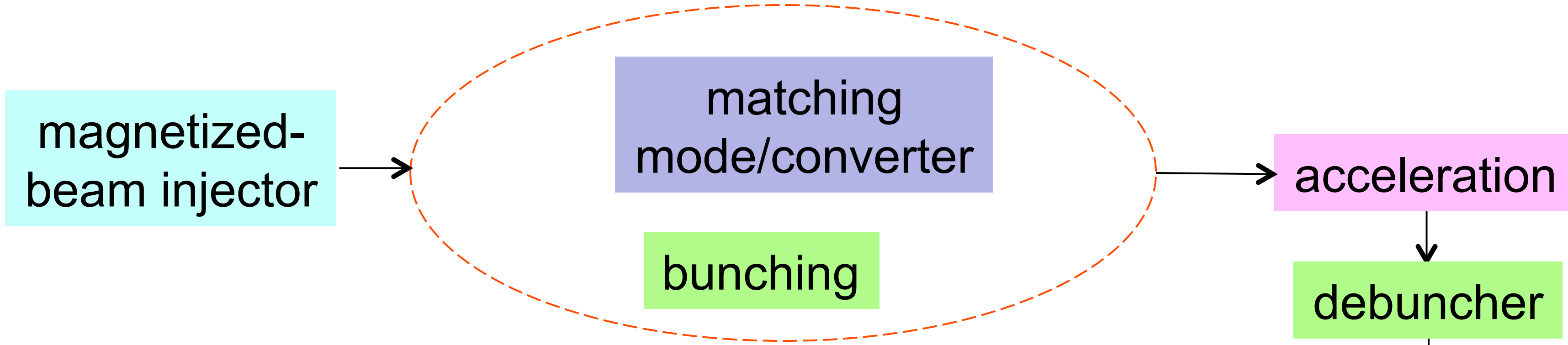


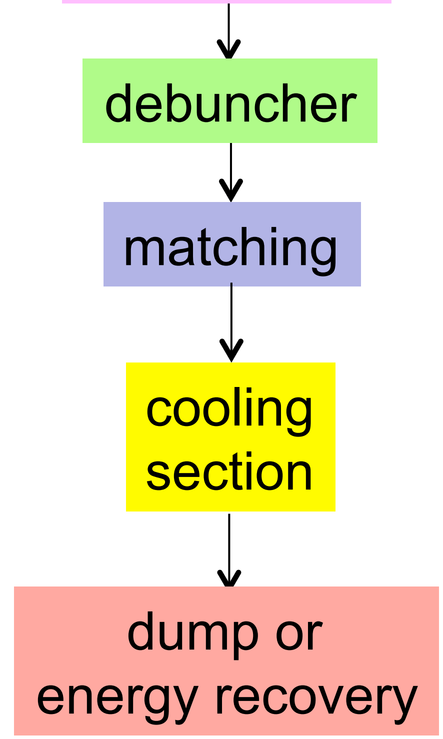
300 keV, 3 A cooler produced by Budker INP for IMP, Lanzhou (China)



early concept for RHIC e-cooling

High-energy coolers



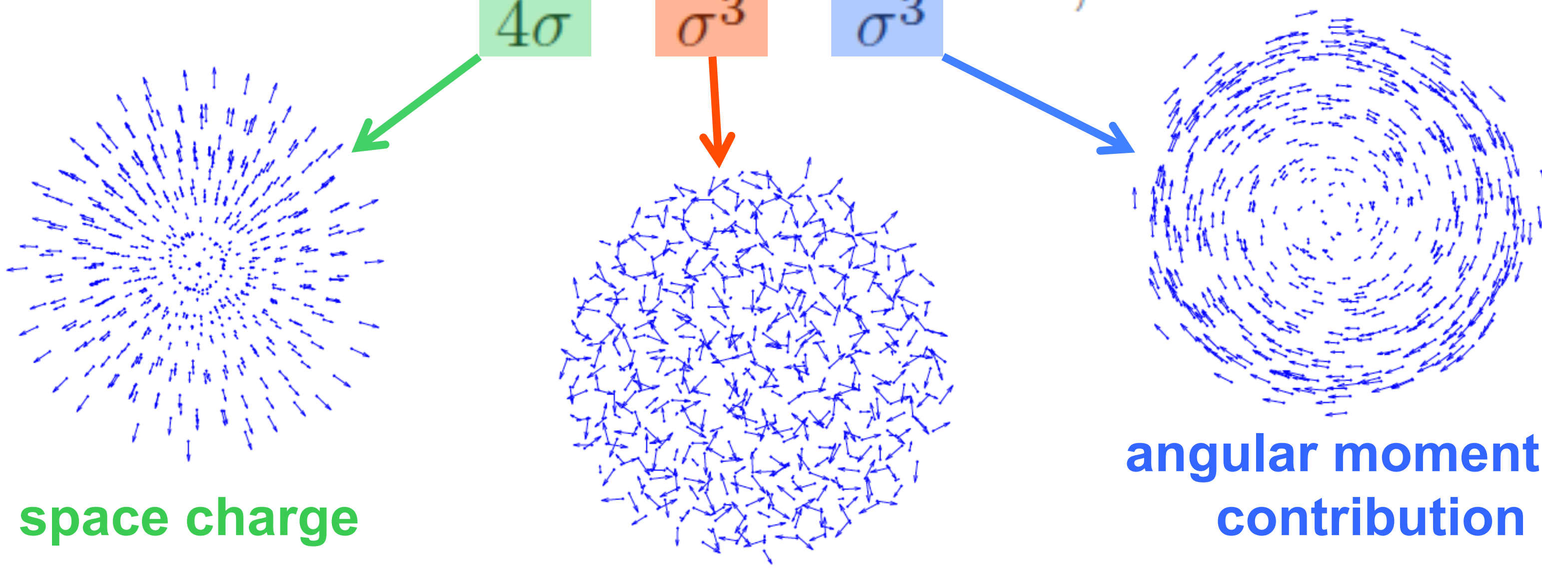


- injector: produces bunched beam for RF acceleration
- debuncher: matched electron bunch length to ion-beam's,
- matching + mode/converter sections: repartition "physical" emittances, match in cooling-solenoid section.

Beam dynamics regimes (round beams)

- Radial envelope (σ) equation in a drift (Lawson):

$$\sigma'' - \frac{K}{4\sigma} - \frac{\epsilon_u^2}{\sigma^3} - \frac{\mathcal{L}^2}{\sigma^3} = 0,$$



K: generalized perveance

ϵ_u : uncorrelated geometric emittance

$\mathcal{L}$: magnetization

adapted from Y.-E Sun, Dissertation U. Chicago (2005)

Features & Parameterization

- possible parameterization of coupled motion between 2 degrees of freedom has been extensively discussed; see:
  - D.A. Edwards and L.C. Teng, IEEE Trans. Nucl. Sci. 20, 3, pp. 885-889 (1973).
  - I. Borchardt, E. Karantzoulis, H. Mais, G. Ripken, DESY 87-161 (1987).
  - V. Lebedev, S. A. Bogacz, ArXiV:1207.5526 (2007).
  - A. Burov, S. Nagaitsev, A. Shemyakin, Ya. Derbenev, PRSTAB 3, 094002 (2000).
  - A. Burov, S. Nagaitsev, Ya. Derbenev, PRE 66, 016503 (2002).
- Simpler description that provides the necessary insights..

A simple description of coupled motion

- Consider the 4x4 beam matrix

$$\Sigma \equiv \begin{bmatrix} \langle \mathbf{X}\widetilde{\mathbf{X}} \rangle & \langle \mathbf{X}\widetilde{\mathbf{Y}} \rangle \\ \langle \mathbf{Y}\widetilde{\mathbf{X}} \rangle & \langle \mathbf{Y}\widetilde{\mathbf{Y}} \rangle \end{bmatrix} \qquad \text{where} \qquad \begin{matrix} \widetilde{\mathbf{X}} \equiv (x, x') \\ \widetilde{\mathbf{Y}} \equiv (y, y') \end{matrix}$$

- Introduce the "correlation" matrix: $C \equiv \langle \mathbf{Y}\widetilde{\mathbf{X}} \rangle \langle \mathbf{X}\widetilde{\mathbf{X}} \rangle^{-1}$
- Beam matrix takes the form:

$$\Sigma = \left(\begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix} + \begin{bmatrix} 0 & C^{-1} \\ C & 0 \end{bmatrix} \right) \begin{bmatrix} \langle \mathbf{X}\widetilde{\mathbf{X}} \rangle & 0 \\ 0 & \langle \mathbf{Y}\widetilde{\mathbf{Y}} \rangle \end{bmatrix}$$

- The correlation subjects to $R = \begin{bmatrix} H & G \\ U & V \end{bmatrix}$ transforms as $C_0 \to C$

$$C = (U + VC_0)(H + GC_0)^{-1}$$

- C provides information on the coupling only.

Beam matrix for a round magnetized beam

- At a waist, the matrix of a magnetized (round) beam is

$$\Sigma_0 = \begin{bmatrix} \varepsilon T_0 & \mathcal{L}J \\ -\mathcal{L}J & \varepsilon T_0 \end{bmatrix}.$$

where $T_0 = \begin{bmatrix} \beta & -\alpha \\ -\alpha & \frac{1+\alpha^2}{\beta} \end{bmatrix}$

and the magnetization is

$$\mathcal{L} = \langle xy' \rangle = -\langle x'y \rangle = \frac{L}{2p_z}$$

- The eigen-emittances of this beam matrix are:

$$\varepsilon_\pm = \varepsilon \pm \mathcal{L}. \quad \text{where } \varepsilon^2 = \mathcal{L}^2 + {\varepsilon_u}^2 = |\Sigma|$$

- the eigen-emittances can be mapped into "physical" emittances using a skewed beamline $\begin{bmatrix} M_+ & M_- \\ M_- & M_+ \end{bmatrix}$

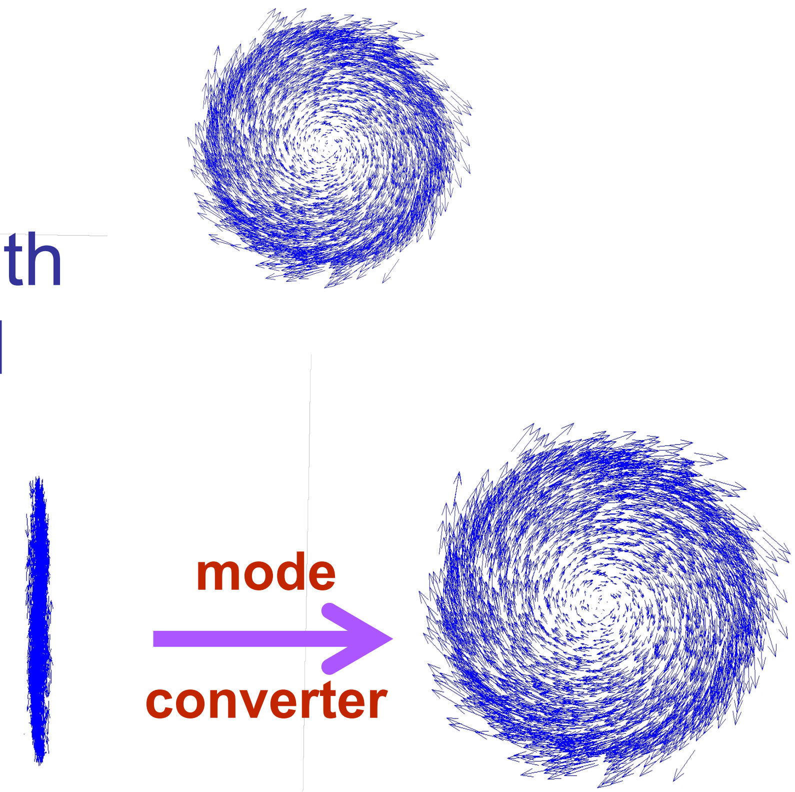
decoupling when

$$M_- + M_+ C_0 = 0.$$

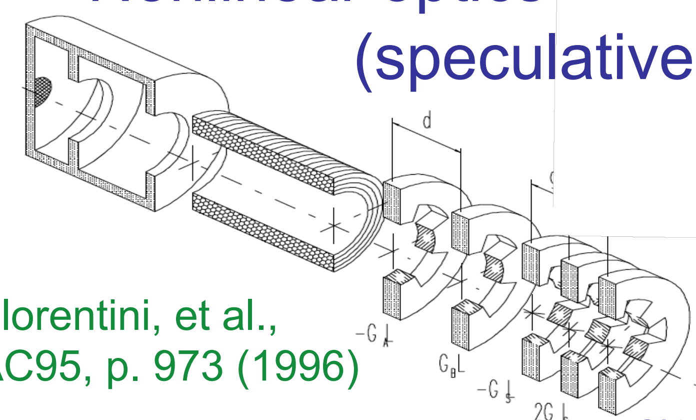
K.-J. Kim, PRSTAB 6, 104002 (2003)
D. A. Edwards, unpublished (2001)

Formation of magnetized bunches

- Cathode immersed in an axial **B** field
- Sheet beams at birth (with subsequent flat-to-round beam converter)
  - shaped cathode,
  - line-laser focus
  - Nonlinear optics (speculative)



Y. Derbenev, University of Michigan report UM-HE-98-04 (1998)



G. Florentini, et al., Proc. PAC95, p. 973 (1996)

Cathode in a magnetic field

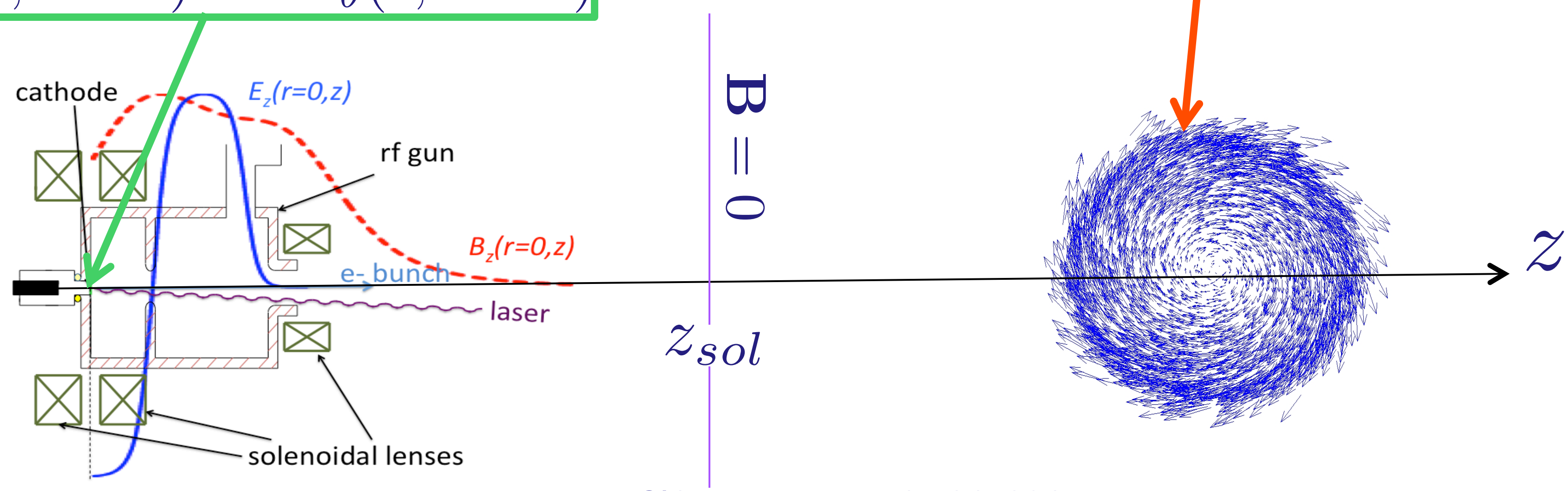
- electrons born in an axial B field $B_z \rightarrow$ CAM

$$L(r) = erA_\theta \simeq \frac{er^2}{2} B_{z,0} + \mathcal{O}(r^4)$$

- upon exit of solenoid field ($A_\theta = 0$): CAM becomes purely kinetic.

$$P_\theta(r, z=0) = eA_\theta(r, z=0)$$

$$p_\theta(r, z > z_{sol}) = P_\theta(r, z=0)$$



Emittance vs magnetization

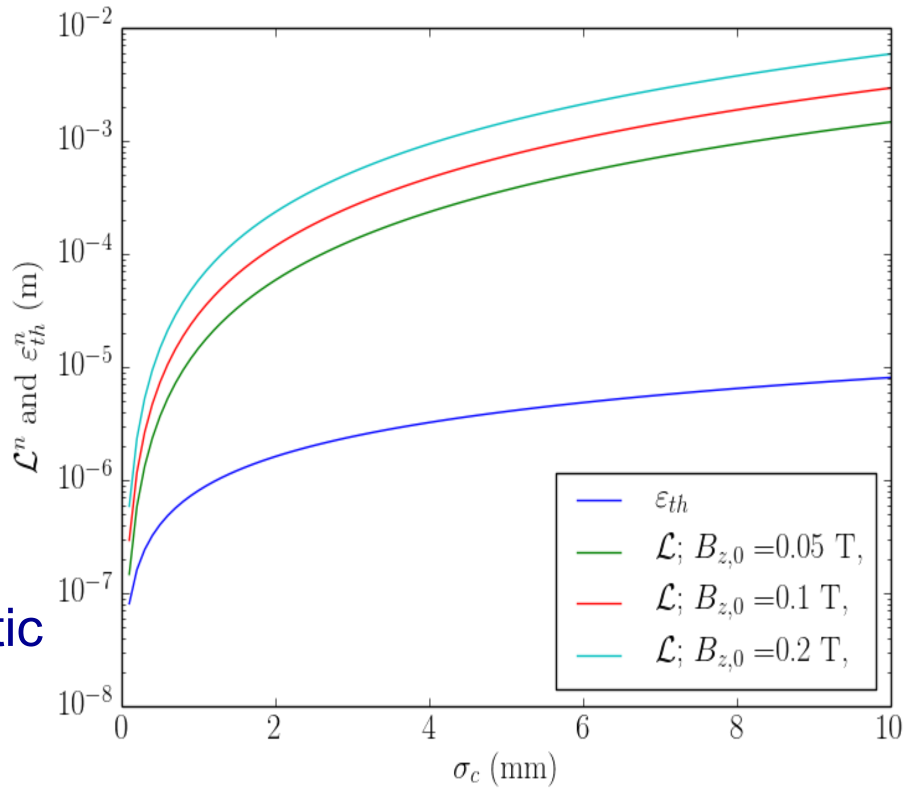
- "effective emittance" $\varepsilon^2 = \mathcal{L}^2 + {\varepsilon_u}^2$
- magnetization

$$\mathcal{L} = \frac{eB_0}{2mc}\sigma_c^2$$

- The emittance has a lower-bound value :

$$\varepsilon_u^n \equiv \beta\gamma\varepsilon_u \geq \varepsilon_{th} = \sigma_c \left(\frac{2\delta E}{3mc^2}\right)^{1/2}$$

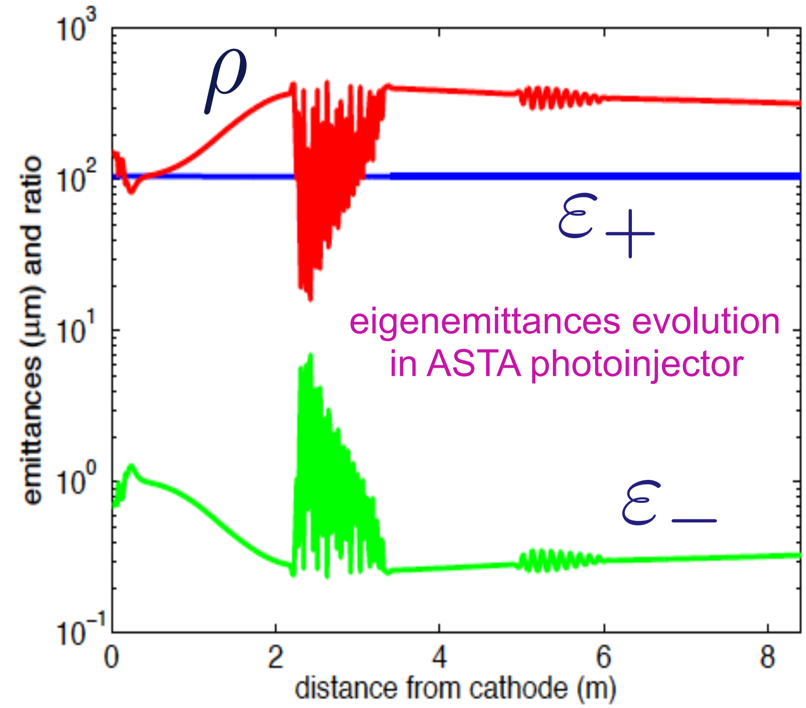
where δE is the excess in kinetic energy during emission

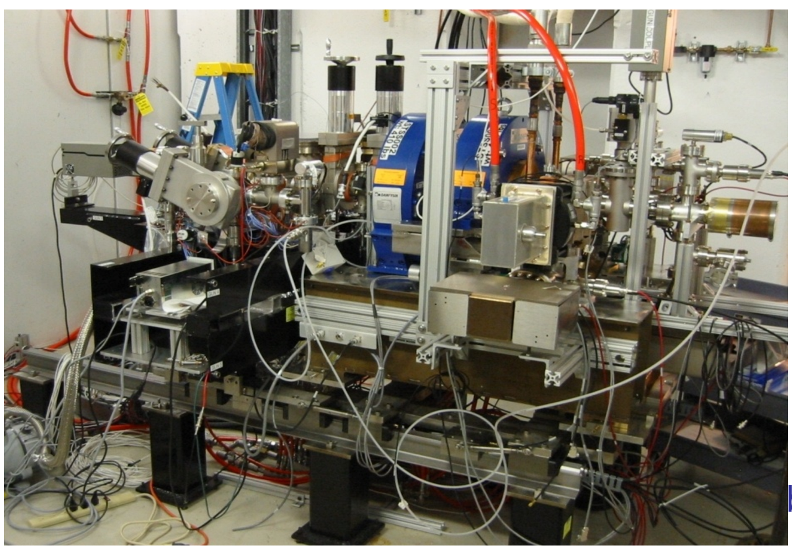


- Practically, ε_u includes other contributions.

Example of 3.2-nC magnetized bunch

- high-charge bunch subject to emittance degradation
- proper optimization (emittance compensation) $\longrightarrow$ 4-D emittance comparable to round beams.



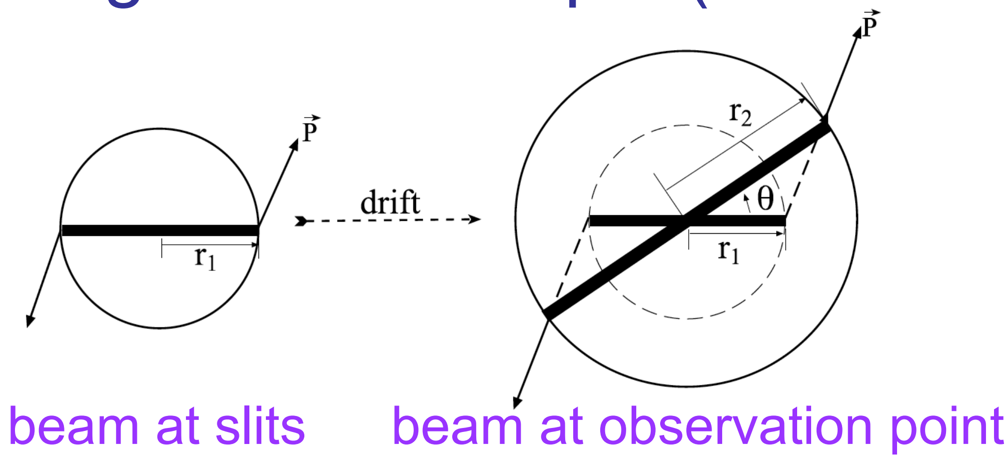


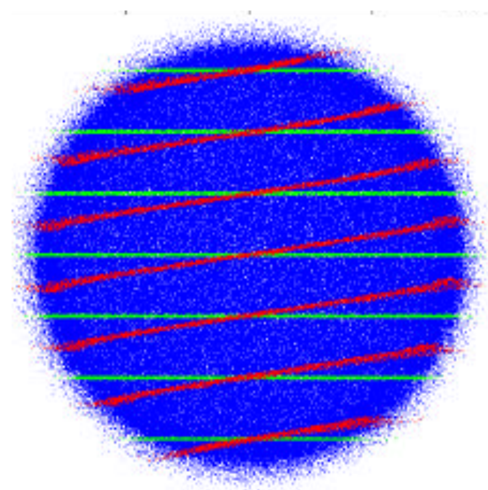
parameter	flat-beam configuration	round-beam configuration	units
Q	3.2	3.2	nC
E	47.18	48.77	MeV
ε_x	105.04	5.43	μm
ε_y	0.31	5.44	μm
ε_{4D}	5.53	5.44	μm
ρ	$\simeq 334$	$\simeq 1$	–

P. Piot et al. IPAC13; C-X. Wang, FEL06, 721 (2006)
X. Chang, I. Ben-Zvi, J. Kewisch AAC04 (2004)

Measuring (kinetic) angular momentum

- Kinetic angular momentum can be measured using a slit technique (similar to emittance)





Y.-E Sun et al, PRSTAB 7, 123501 (2004)

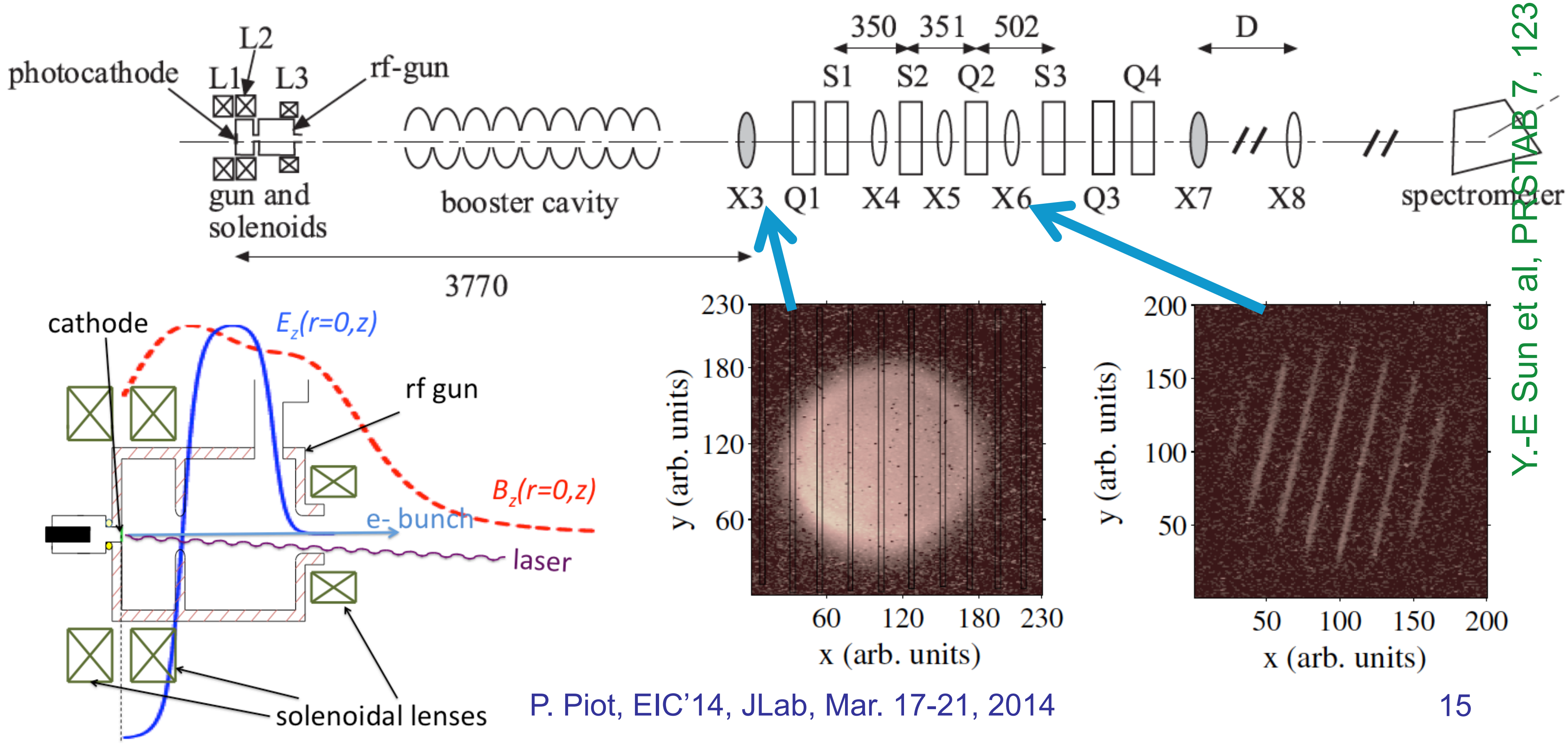
- The beam's average angular momentum is given by

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

$\sigma_{1,2}$: rms beam size at slit (1) and observation screen (2),
P_z : axial momentum
D : drift length between locations (1) and (2).

Experimental generation in a photoinjector

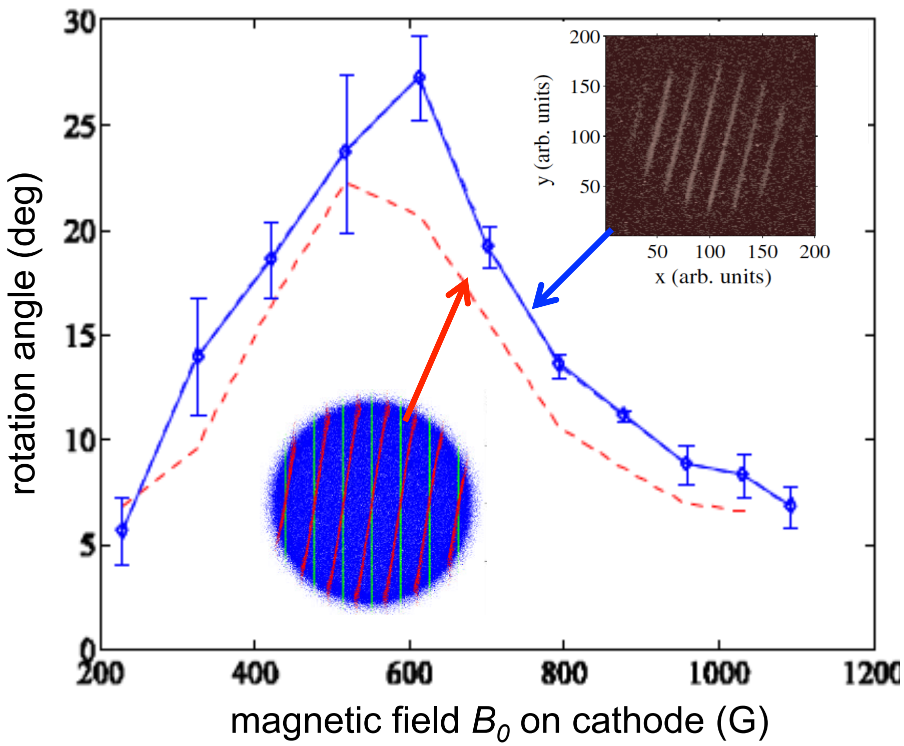
- Fermilab A0 normal-conducting photoinjector (decommissioned),
- 15 MeV, charge up to 2 nC,~3-10 ps bunch

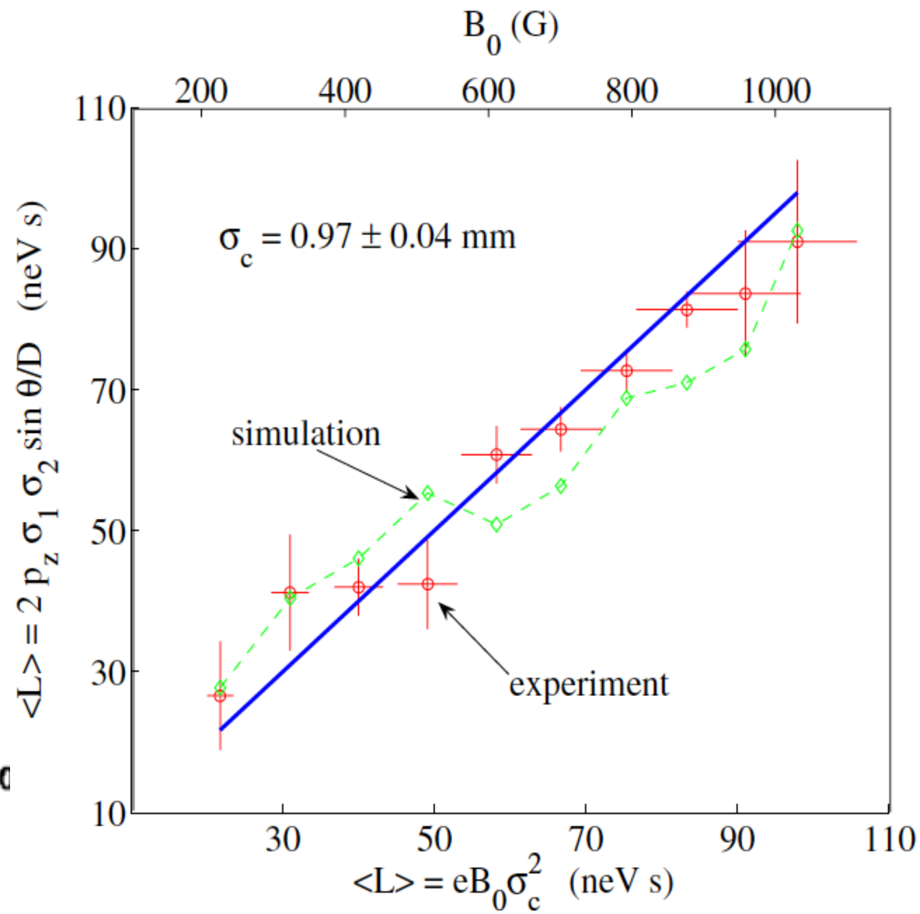


Y.-E Sun et al, PRSTAB 7, 123501 (2004)

Experimental generation in a photoinjector

- linear scaling with B field on photocathode

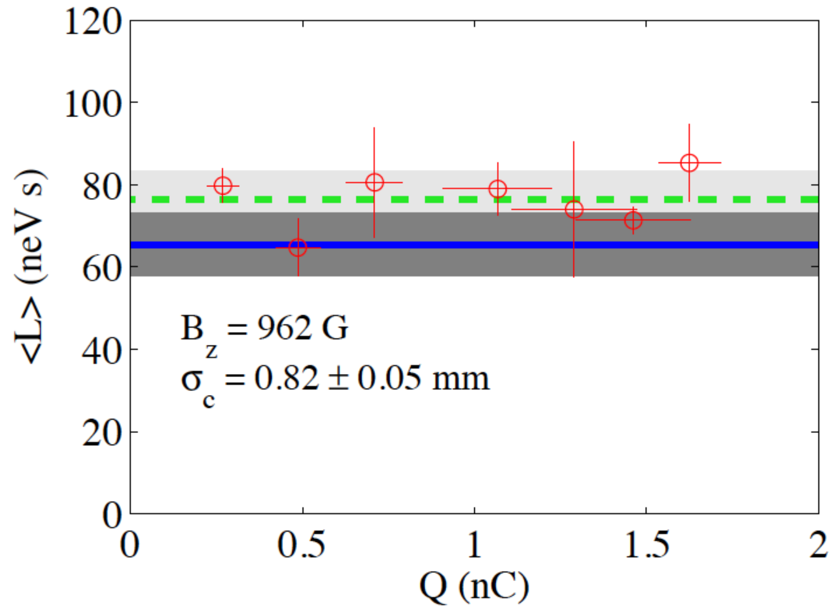


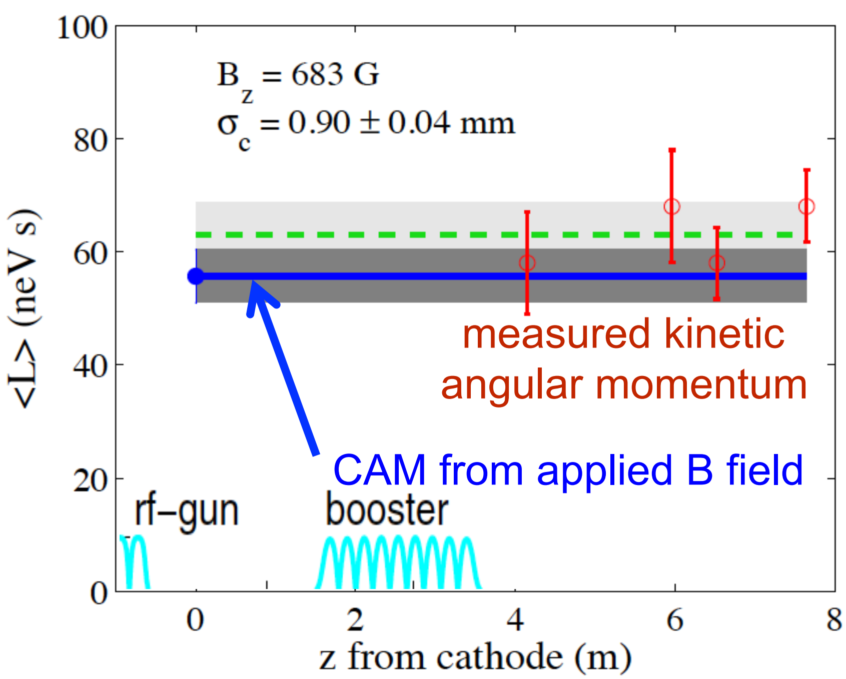


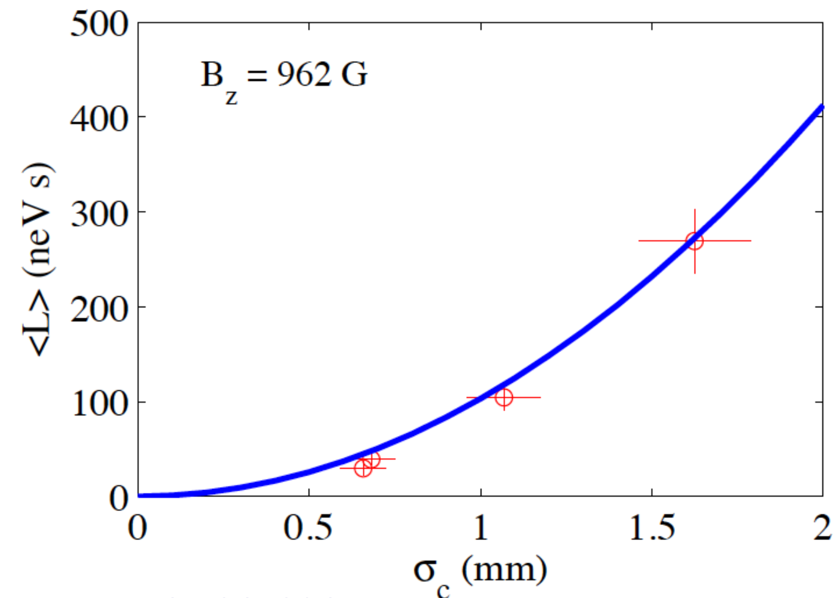
Y.-E Sun et al, PRSTAB 7, 123501 (2004)

Experimental generation in a photoinjector

- weak Q dependence,
- quadratic scaling with laser spot size σ_c on photocathode.







Y.-E Sun et al, PRSTAB 7, 123501 (2004)

Decoupling into flat ($\varepsilon_x/\varepsilon_y \neq 1$) beam

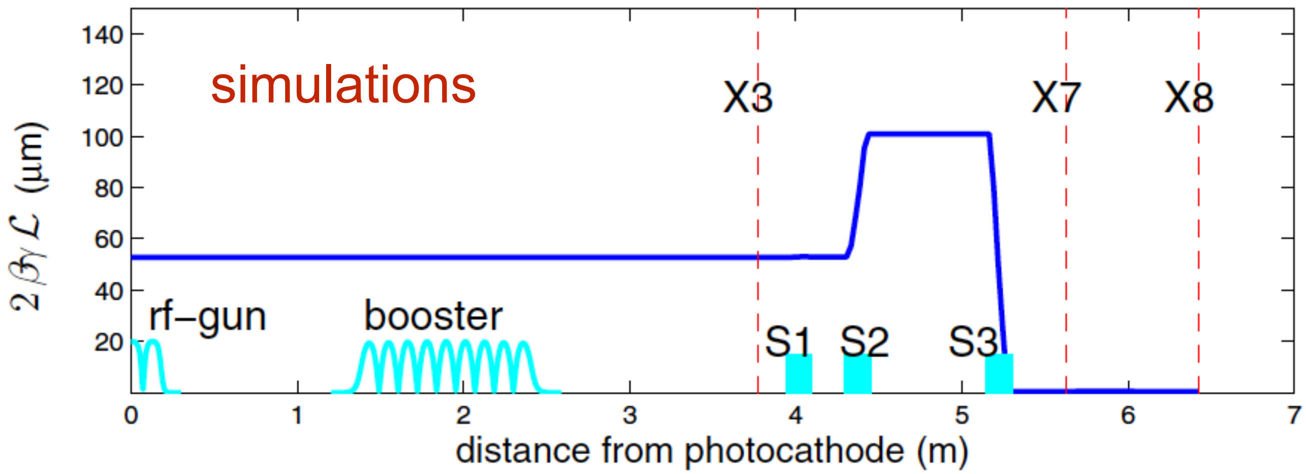
- Transport of magnetized bunches while preserving $\mathcal{L}$ is challenging,
- Use of round-to-flat beam transformer to convert into uncoupled (flat) beam
  $\longrightarrow$ eigen-emittances maps into "physical" transverse emittances:

$$\varepsilon_n^{\pm} = \sqrt{(\varepsilon_n^u)^2 + (\beta\gamma\mathcal{L})^2} \pm (\beta\gamma\mathcal{L}) \overset{\beta\gamma\mathcal{L} \gg \varepsilon_n^u}{\longrightarrow} \begin{cases} \varepsilon_n^{+} \simeq 2\beta\gamma\mathcal{L}, \\ \varepsilon_n^{-} \simeq \frac{(\varepsilon_n^u)^2}{2\beta\gamma\mathcal{L}}, \end{cases}$$

R. Brinkmann et al., PRSTAB 4, 053501 (2001)
Y. Derbenev, University of Michigan report UM-HE-98-04 (1998)

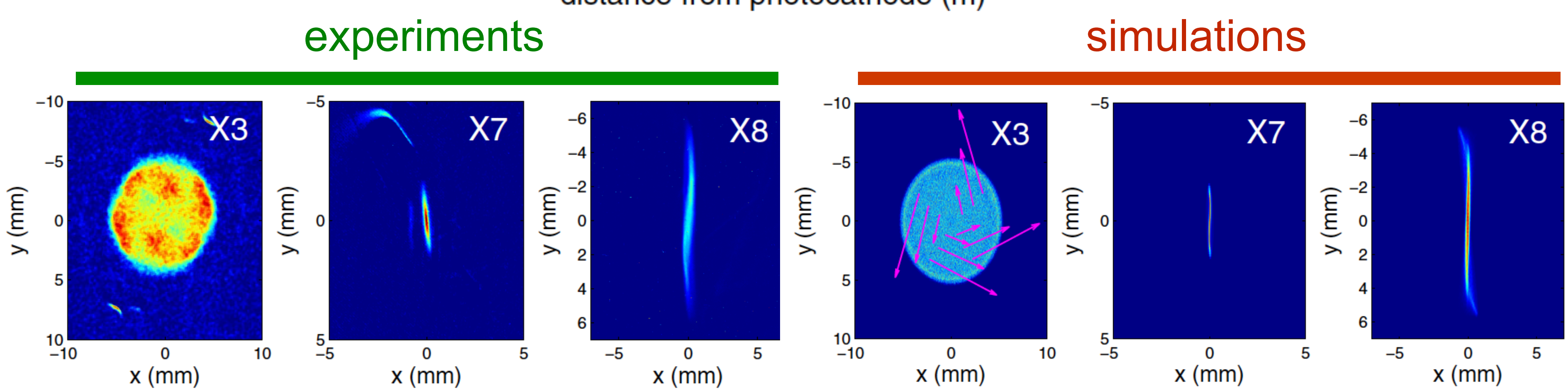
Decoupling into flat beam: experiments (1)

- Same experimental setup as used for generation of CAM-dominated beams



0.5 nC

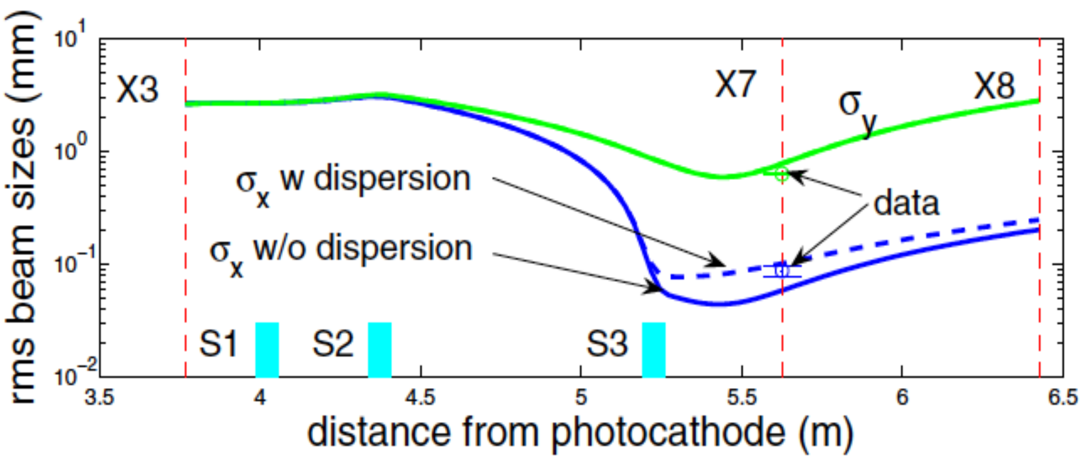
P. Piot, et al, PRSTAB 9, 031001 (2006)

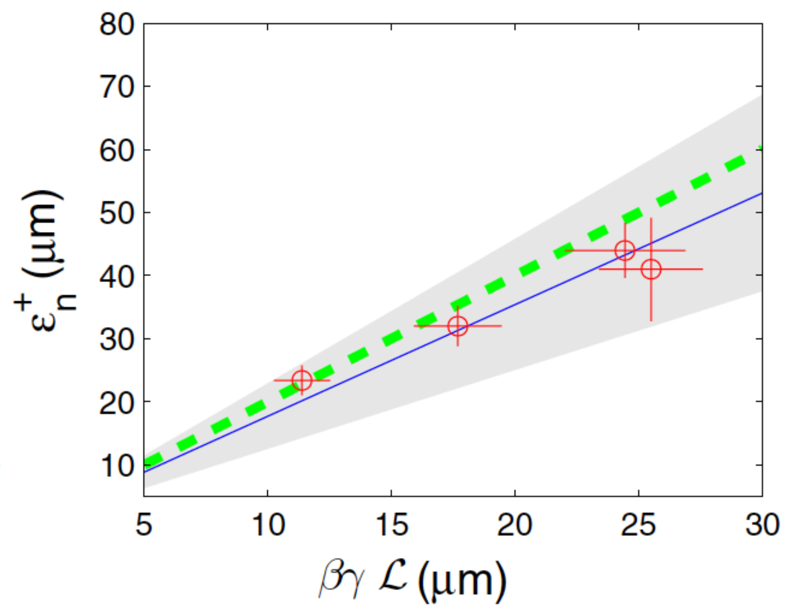


Decoupling into flat beam: experiments (2)

- normal emittances map into the flat-beam emittance
- large experimental uncertainties for smallest emittance meas.

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





Outlook + open questions

- magnetized beam from a SCRF gun:
  - flux concentrator around cathode?
  - flat beam at cathode
    [J. Rosenzweig, PAC93 showed $(\varepsilon_+,\varepsilon_-)$=(95,4.5) μm]
- needed ϵ_u and $\mathcal{L}$? and limit on 4-D emittance?
- planned future experiment at ASTA