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Maximum Brightness from Photoinjectors

Contents

- Definitions
- Space charge limit
- Additional considerations (briefly)

Definitions

- Microbrightness ρ_6 = density in 6D phase space (invariant in Hamiltonian systems)
- Decoupled motion in transverse, longitudinal planes $\Rightarrow$ consider transverse projection $\boldsymbol{\rho_4}$
- Also, consider ***average*** (ERL forte), ***normalized***

$$\mathcal{B}_{n,\mathrm{av}} = I_{\mathrm{av}}^{-1} \frac{1}{(mc)^2} \int \rho_4^2 dx dy dp_x dp_y,$$

e.g.

$$\mathcal{B}_{n,\mathrm{av}} = \frac{I_{av}}{(4\pi\epsilon_{nx})(4\pi\epsilon_{ny})},$$

- Or normalized ***brightness/bunch***

for 4D Gaussian

$$\frac{\mathcal{B}_{n,\mathrm{av}}}{f} = q^{-1} \frac{1}{(mc)^2} \int \rho_4'^2 dx dy dp_x dp_y,$$

$$\frac{\mathcal{B}_{n,\mathrm{av}}}{f} = \frac{q}{(4\pi\epsilon_{nx})(4\pi\epsilon_{ny})},$$

Phys. Fluids B 4, 1674 (1992)

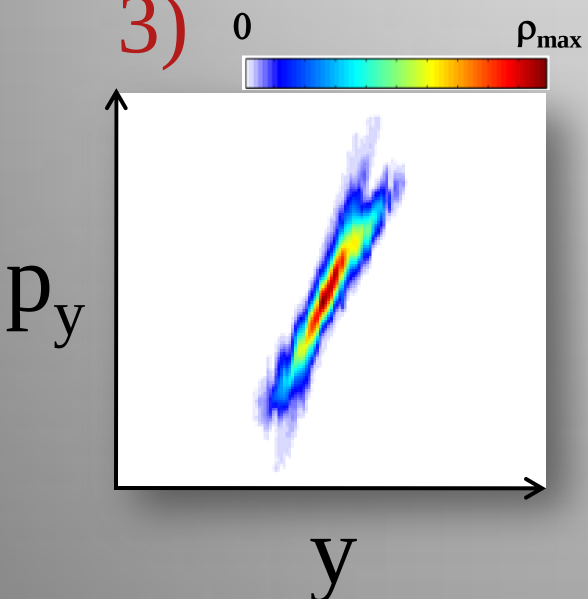
Beam fraction

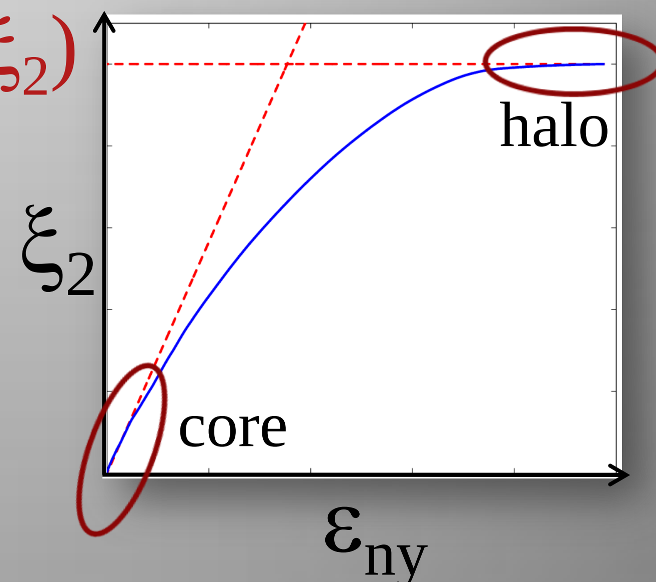
- Ways to represent phase space information

1) 100% (or 95%, or xx%) rms emittance, beam moments

2) rms emittance vs. beam fraction: $\varepsilon_{ny}(\xi_2)$

3)





C. Lejeune and J. Aubert, Adv. Electron. Phys. Suppl. 13, 159 (1980)

Brightness vs. beam fraction

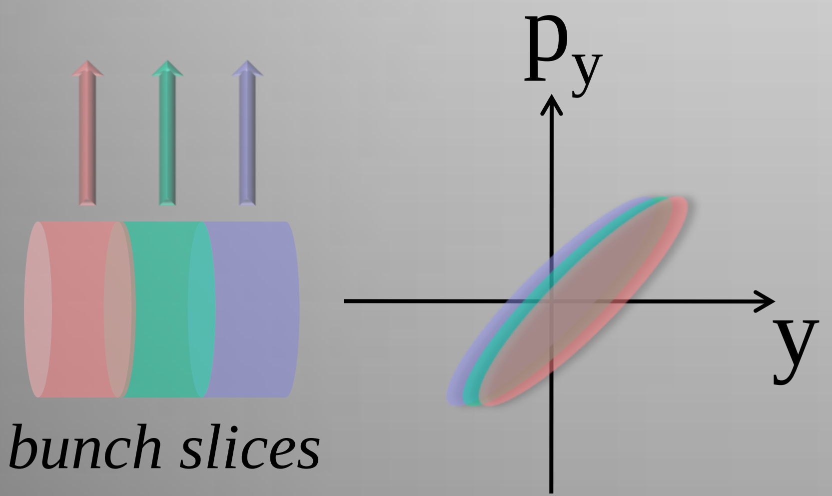
- If round beam with $\varepsilon_{ny}(\xi_2)$, one can write

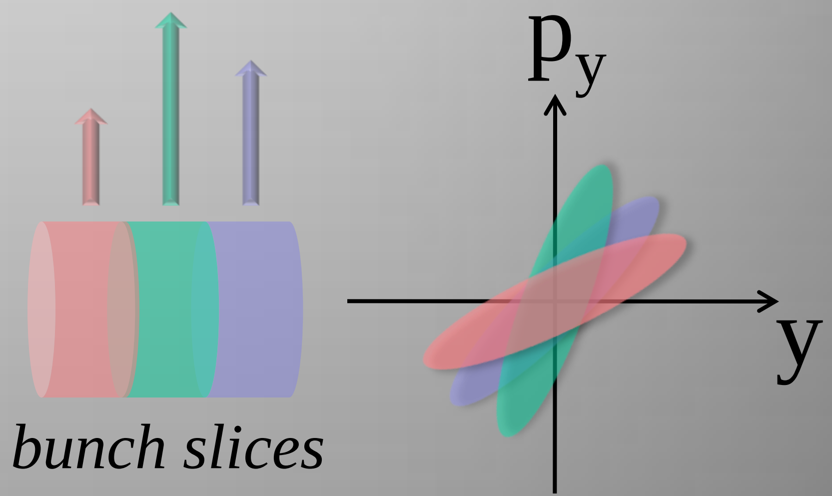
$$\frac{\mathcal{B}_n(\xi_2)}{f} = q\left(\frac{\xi_2}{4\pi\epsilon_{ny}(\xi_2)}\right)^2,$$

- Strictly speaking true only for Gaussian or uniform elliptical distributions
- Nevertheless, the factor $4\pi(\varepsilon_{ny})$ is same within 5% for water-bag, rectangular, etc.

Invariant when?

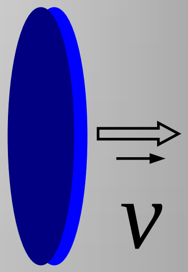
- Brightness so defined is invariant for linear forces uniform along the bunch slices
- ***Core brightness*** should remain the same even if the forces vary along the bunch slices (e.g. space charge) provided no slice sheering occurs





Brightness limit

- For short laser pulse (i.e. pancake beam after emission), ***max charge density*** ~ $\varepsilon_0 E_{cath}$, i.e. sets the min beam ***area at the photocathode***

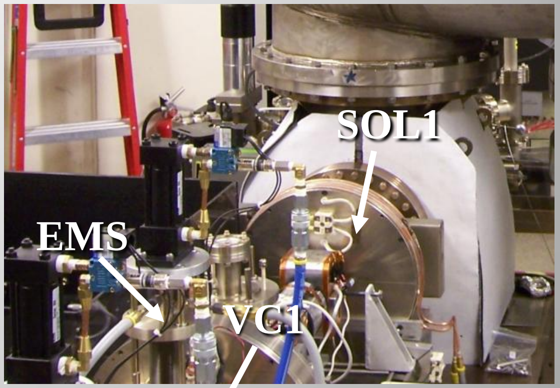


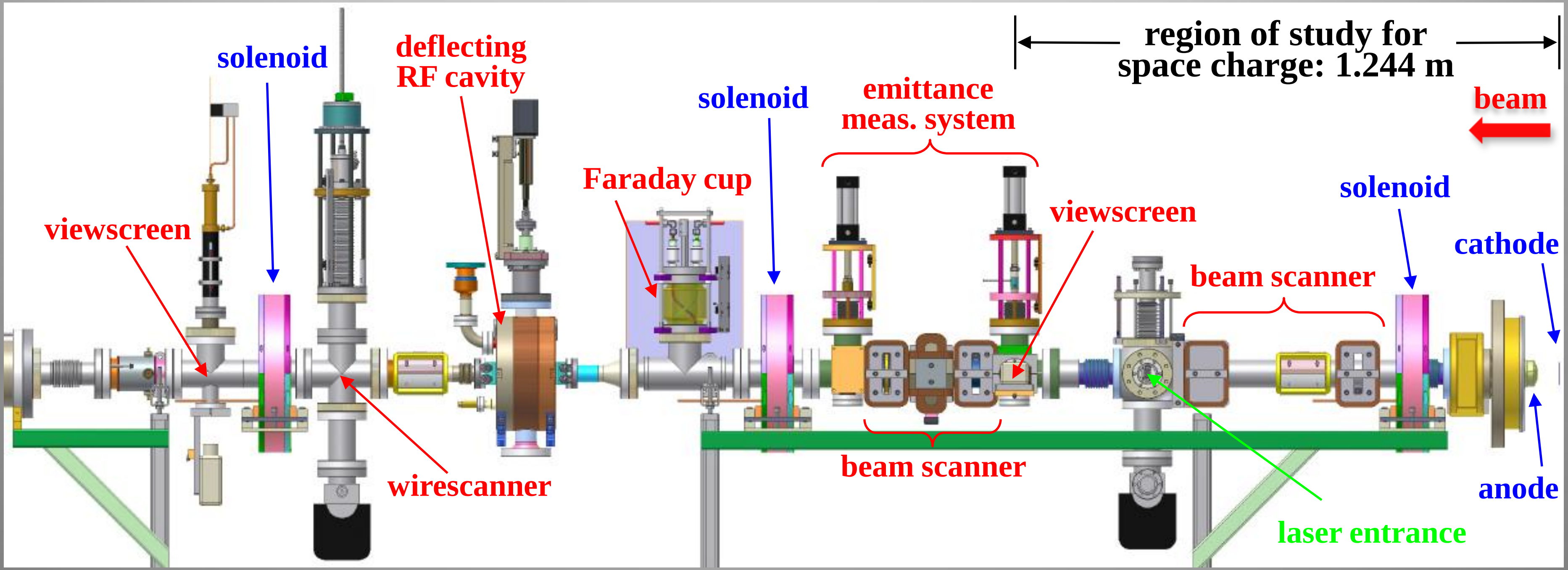
- The ***solid angle*** is set by transverse momentum spread of photoelectrons characterized by ***cathode effective temperature:*** $\Delta p_\perp \sim (mkT_\perp)^{1/2}$
- Combining the two, one finds (assuming maxwellian distribution in momentum):

$$\left.\frac{B_n}{f}\right|_{max} = \frac{\varepsilon_0 mc^2}{2\pi}\,\frac{E_{cath}}{kT_\perp}$$

Beam measurements

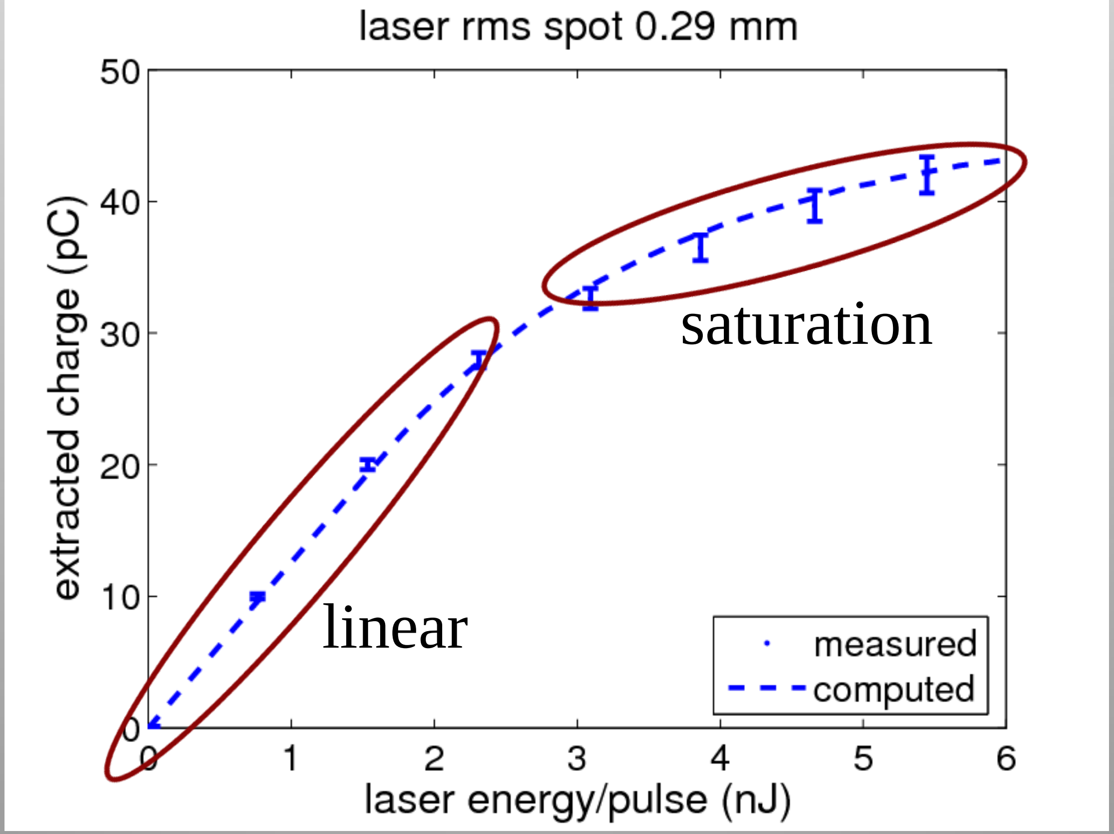
- Benchmarking space charge codes
- Photocathode characterization
- Laser shaping and temporal characterization



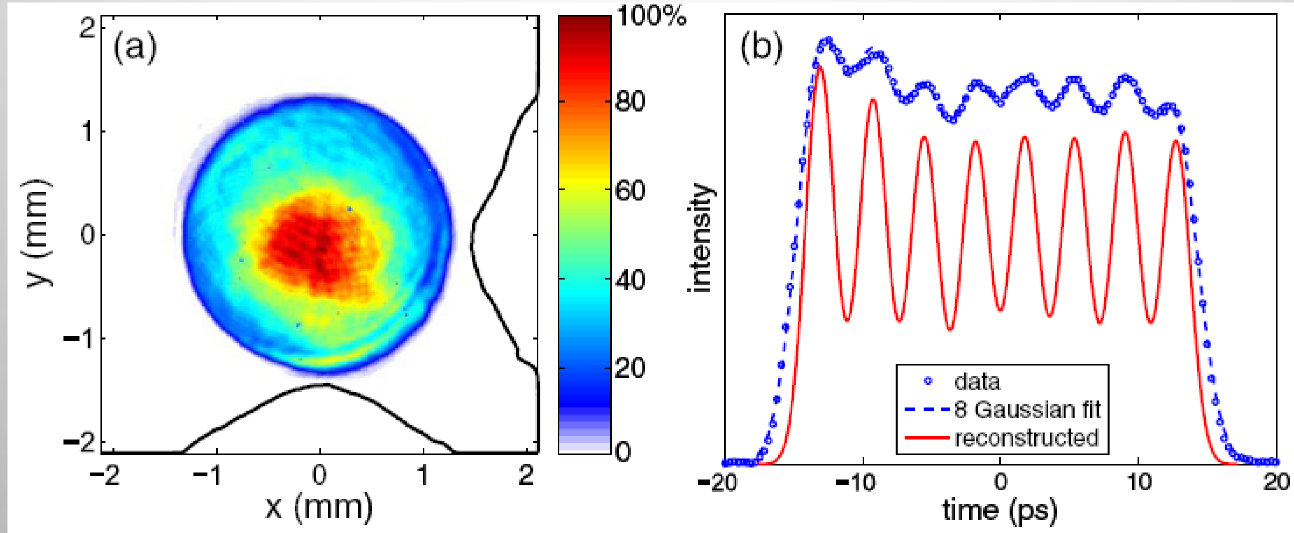


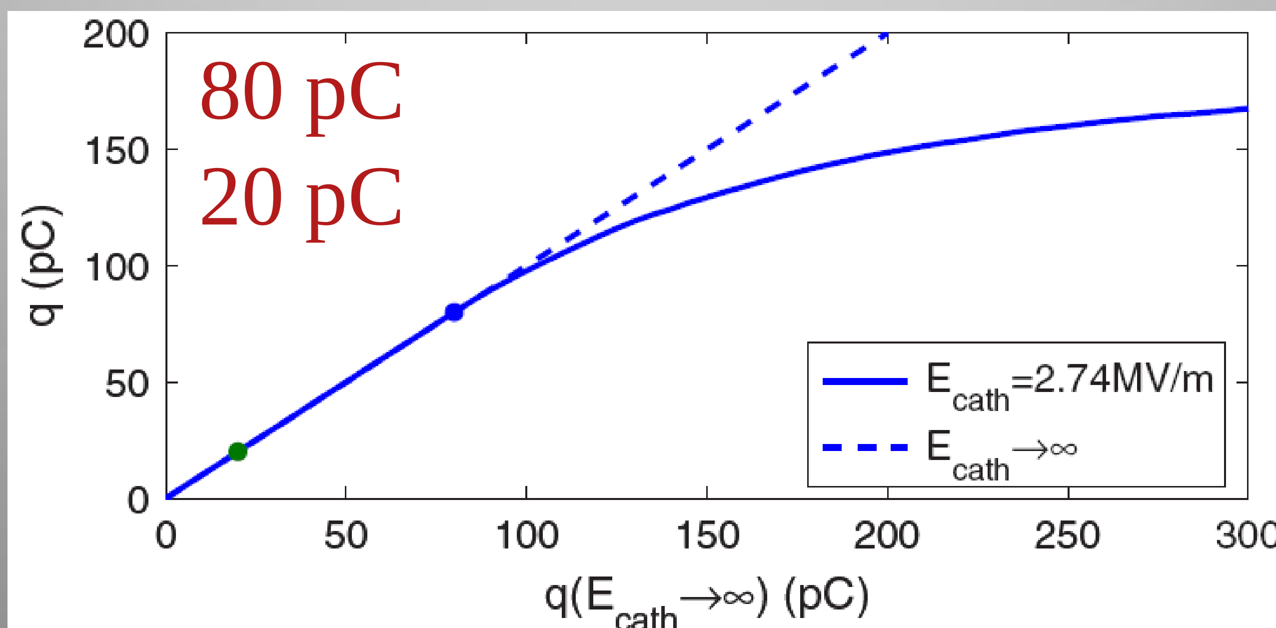
Charge extraction

- Increasing the laser intensity: linear charge extraction followed by saturation in charge/bunch



Laser distributions & charge extraction curve

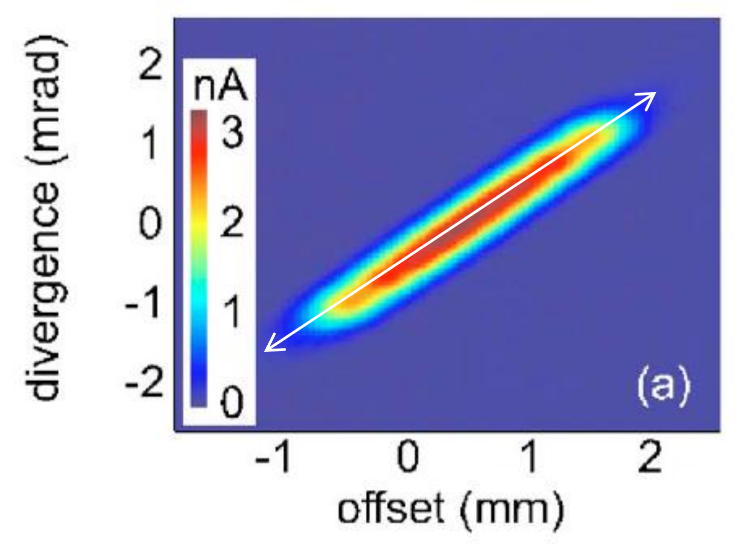




Tying loose ends…

- Laser pulse shortness $A \equiv \sigma_{x,y} m / \sigma_t^2 E_{\text{cath}} e,$
  A >> 1 for pancake approximation
  - for our operating parameters A ~ 17
- Photoelectron transverse momenta distribution

GaAs (no space charge)

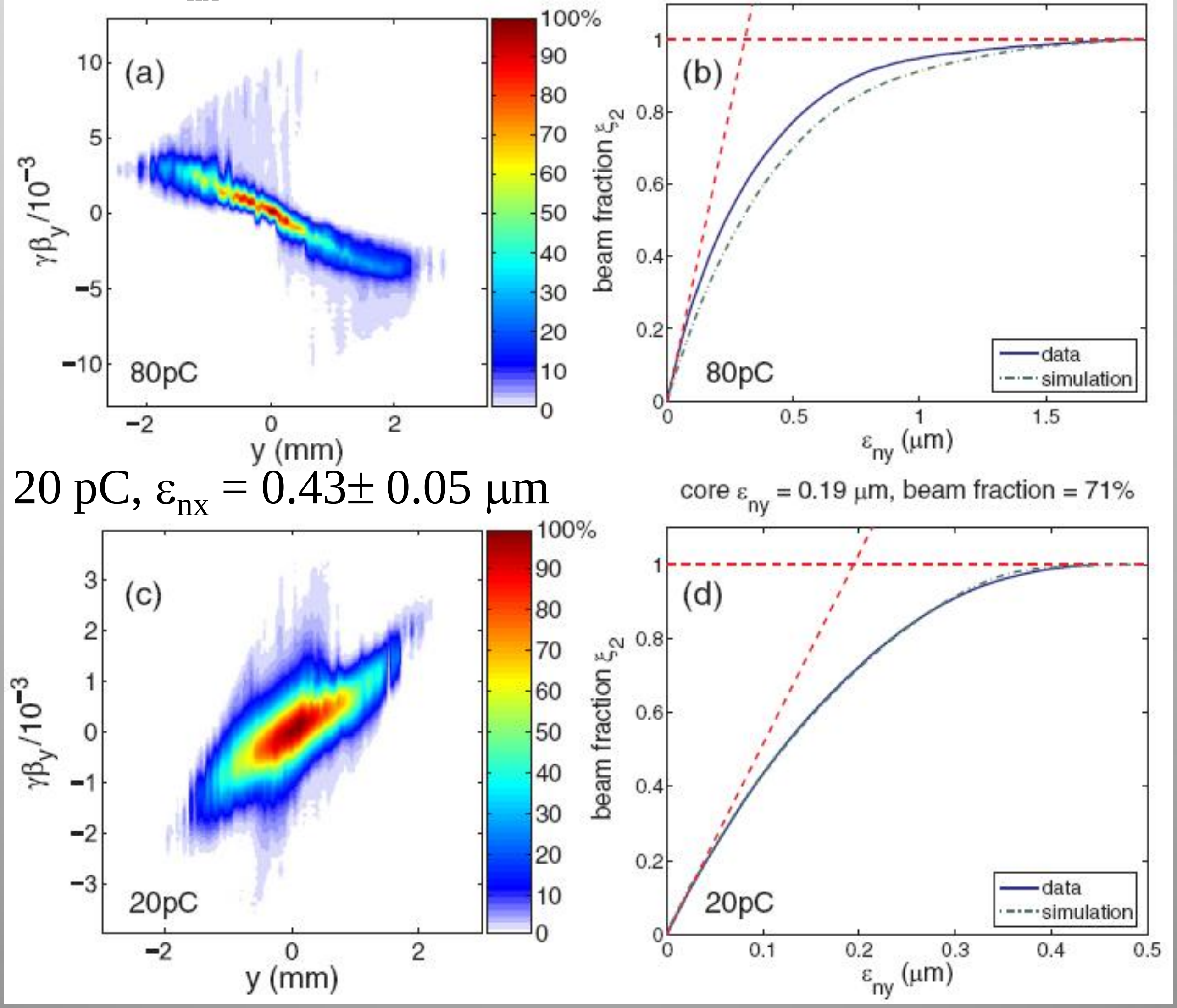


Close to Gaussian distribution @ 520 nm

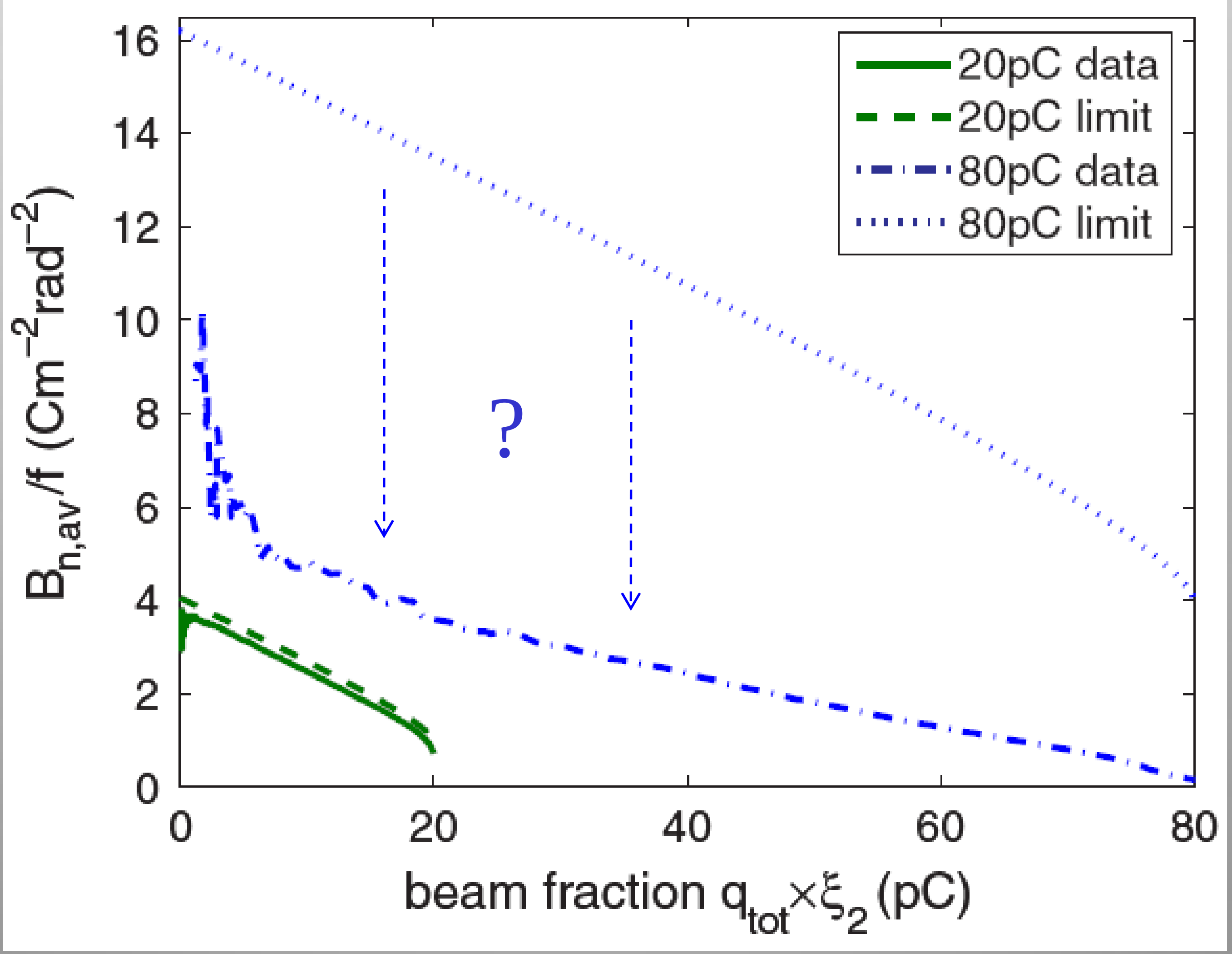
Measurement results

80 pC, ε_{nx} = 1.8± 0.2 μm

20 pC, ε_{nx} = 0.43± 0.05 μm



Brightness comparison to theory



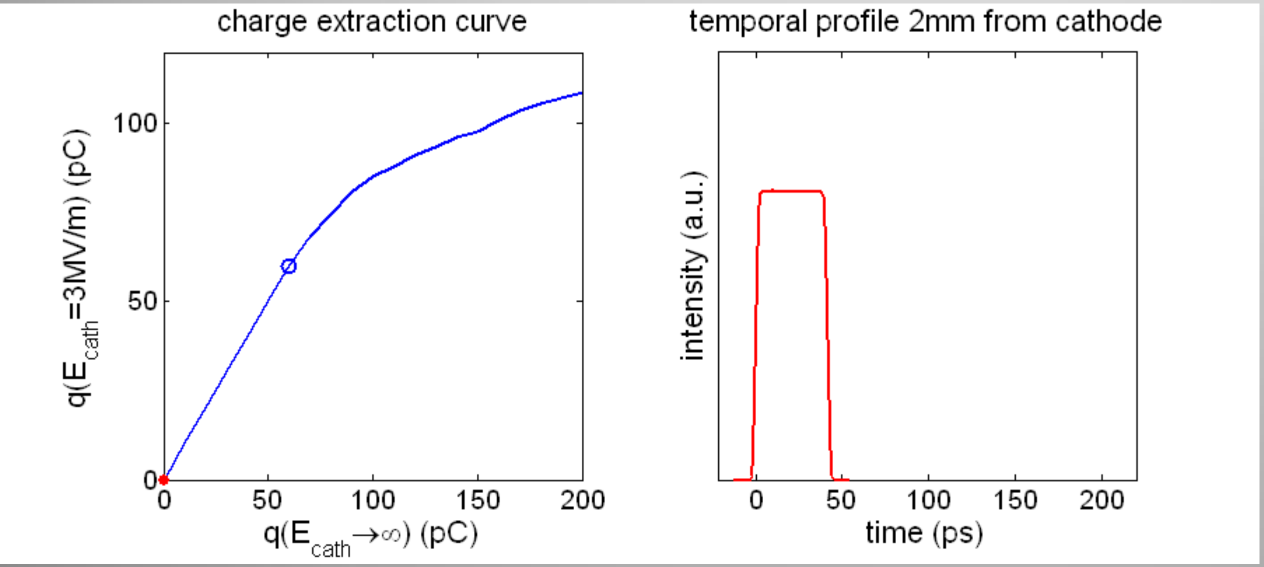
PRL 102, 104801 (2009)

Another limit

- 20 and 80pC data represents space-charge dominated beams by roughly same amounts ($R = I\sigma_x^2/(I_0\beta\gamma\varepsilon_{nx}^2)$, $\langle R \rangle \sim 43$ and 56 respectively) $\Rightarrow$ deviation from the theoretical value in 80pC case cannot be due to the space charge *after the gun*
- How about the space charge at the photocathode?
- *Virtual cathode*: quenching of the accelerating gradient (and photocurrent) at the tail of the bunch $\Rightarrow$ bunch deforms and breaks apart

Virtual cathode

- ***Pack a bunch smartly***: putting as many electrons in each bunch as possible does not work…



Virtual cathode

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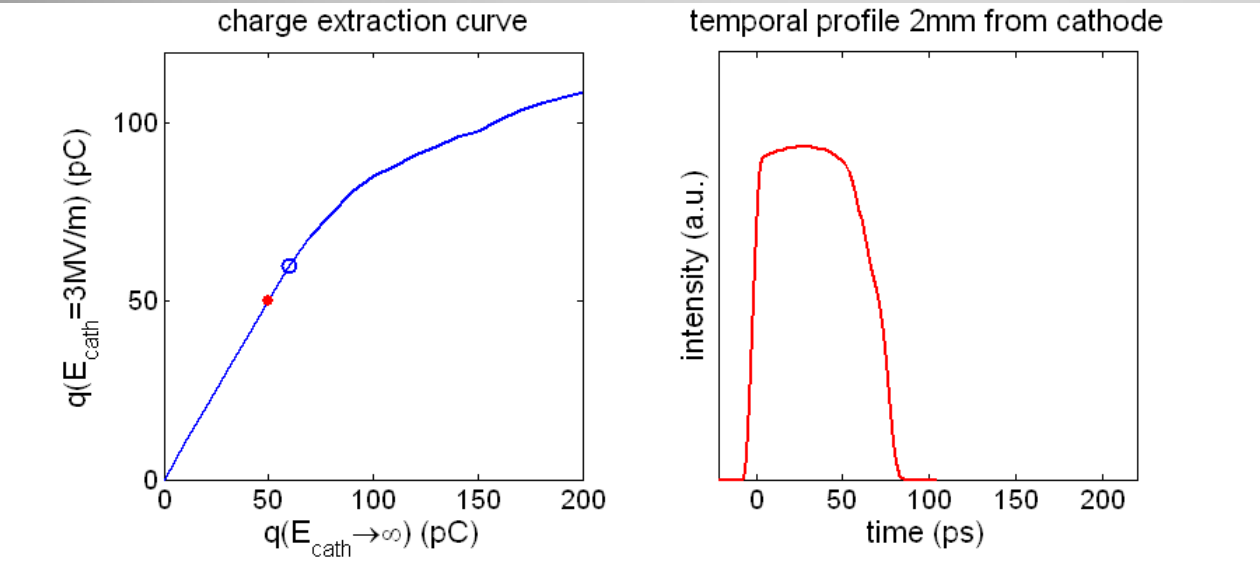

Virtual cathode

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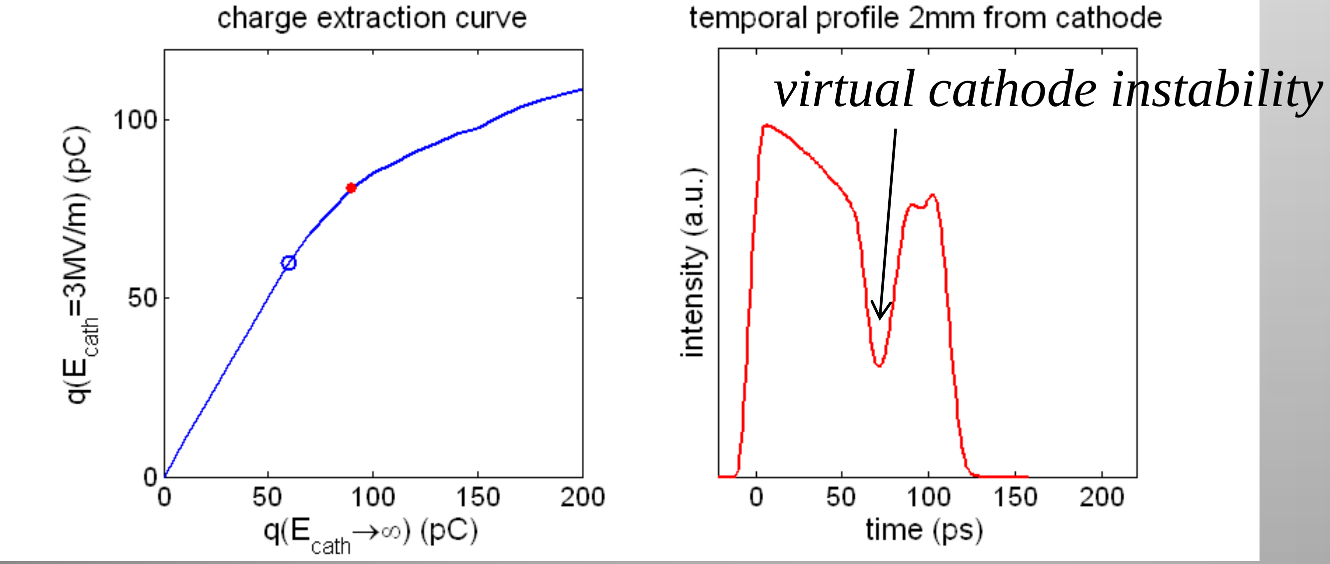

Virtual cathode

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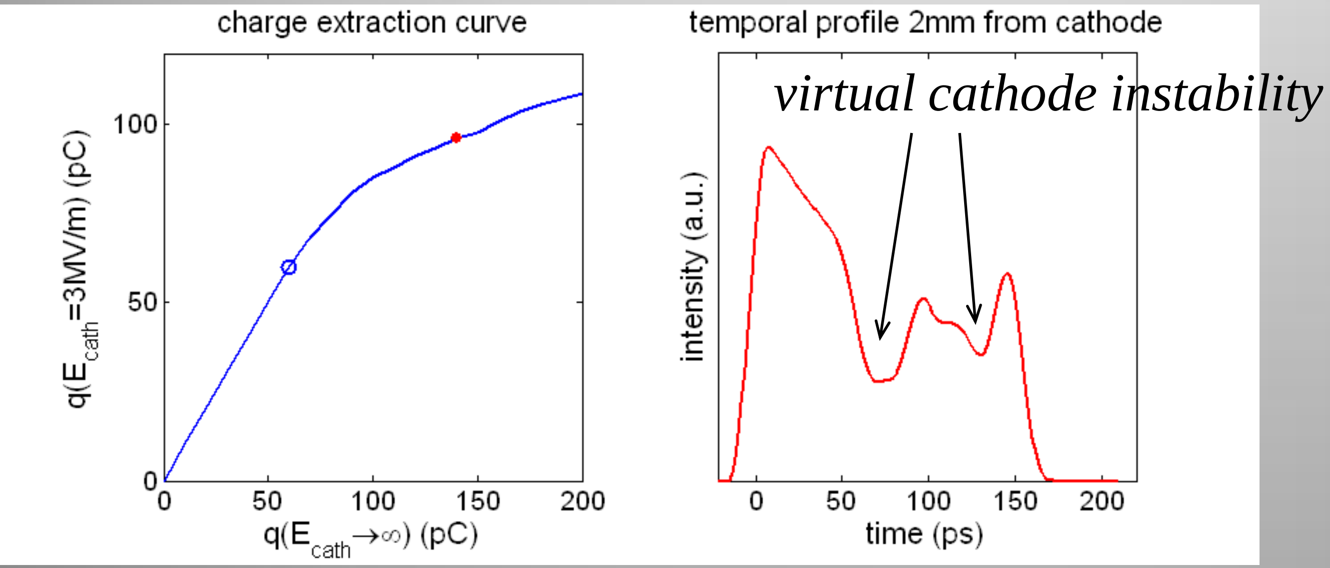
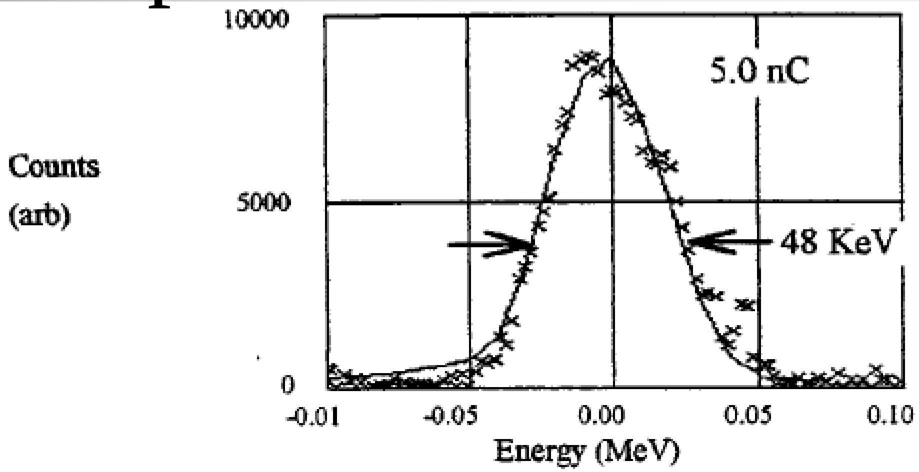
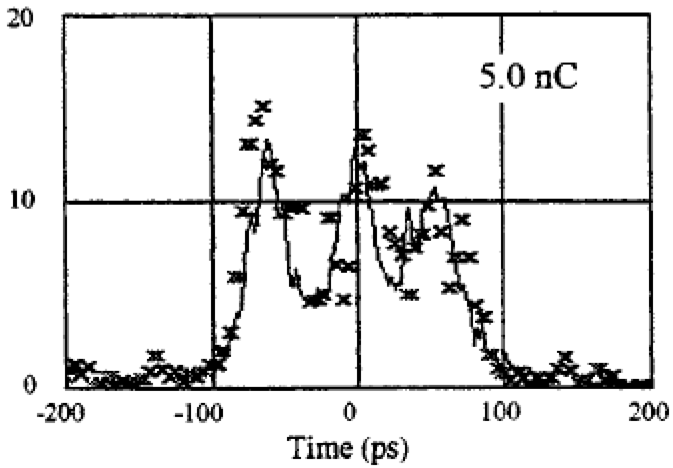


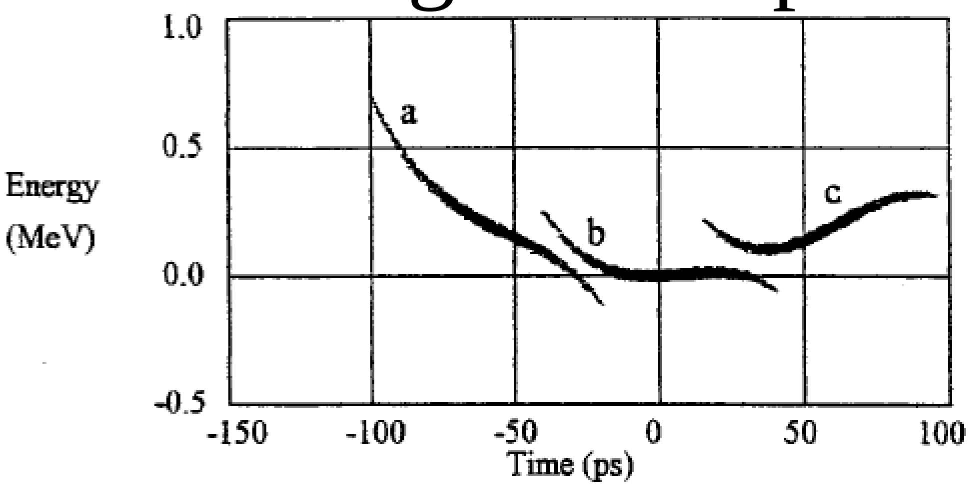
ELSA measurements

Dispersion + streak camera measurements





Fitted longitudinal phase space



5 nC per micropulse

1300 amperes/cm^2 Peak Current Density

τ^a_{11} = 1600	τ^b_{11} = 1600	τ^c_{11} = 1600	ps^2
τ^a_{12} = -9	τ^b_{12} = 1	τ^c_{12} = 9	ps-MeV
τ^a_{22} = 0.051	τ^b_{22} = 0.0012	τ^c_{22} = 0.051	MeV^2

a = 5.9x10-5 MeV/ps^2

b = -2.8x10-6 MeV/ps^3

Phys. Plasmas 4, 3369 (1997)

Space charge considerations

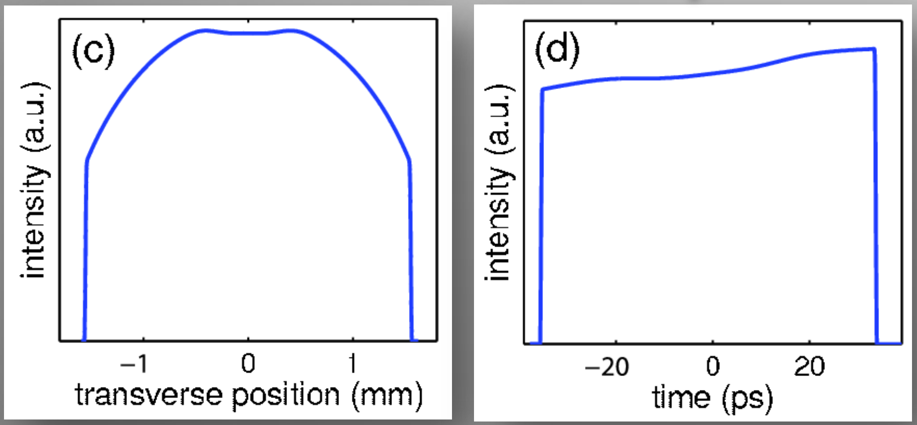
- Stay away from the limit ($q/q_{vc} < ¼ – ½$)
- Make the pulse length as long as tolerably possible (e.g. 1.3 GHz DC gun injector: 12 ps rms for the laser, then compressed down to 3 ps)
- Well-designed injector will have

$$\epsilon_{n\perp} \sim \sqrt{\frac{1}{\varepsilon_0 mc^2} q \frac{kT_{\perp}}{E_{cath}}}$$

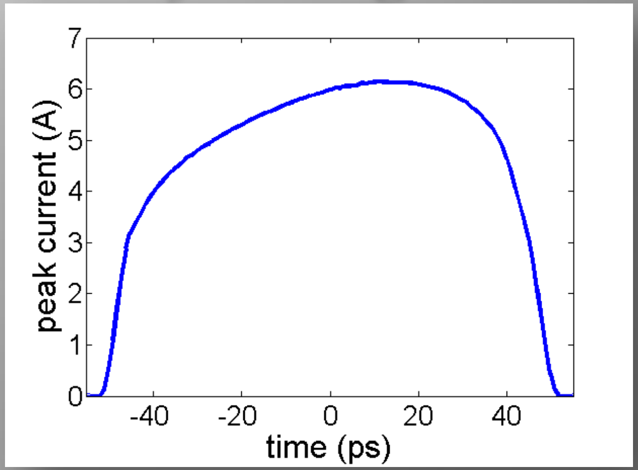
Laser shaping

- Desired 3D distribution in free space is a uniformly filled ellipsoid → linear space charge forces
- Actual ideal laser shape is altered by
  - The boundary condition of the cathode
  - Nonrelativistic energy / bunch compression

desired laser shape



after the gun

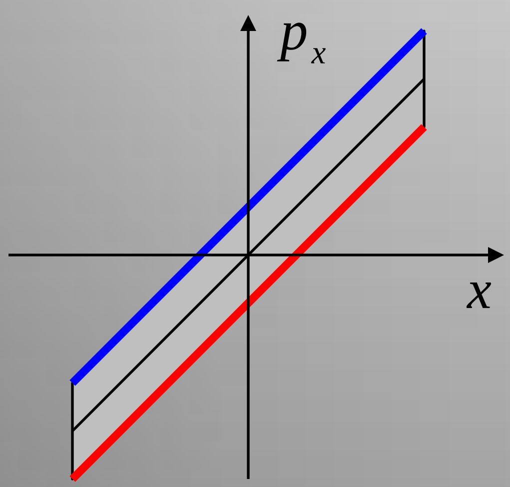


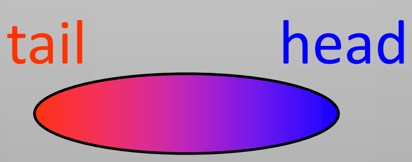
Beam dynamics with RF

$$\varepsilon_n = \frac{1}{mc}\sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle xp_x\rangle^2}$$

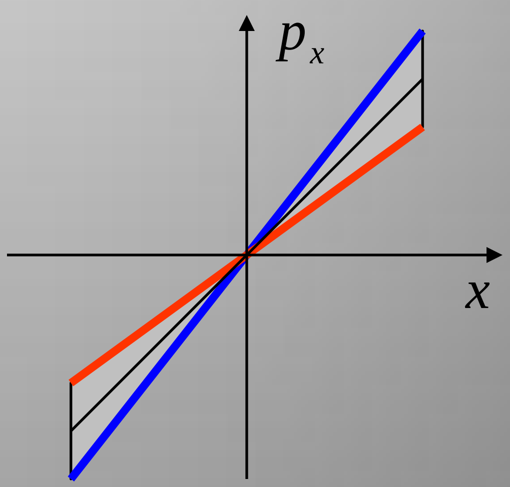
$$p_x(x,z) = p_x(0,0) + \frac{\partial p_x}{\partial x}x + \underbrace{\frac{\partial p_x}{\partial z}z}_{kick} + \underbrace{\frac{\partial^2 p_x}{\partial x \partial z}xz}_{focusing} + \ldots$$

kick





focusing



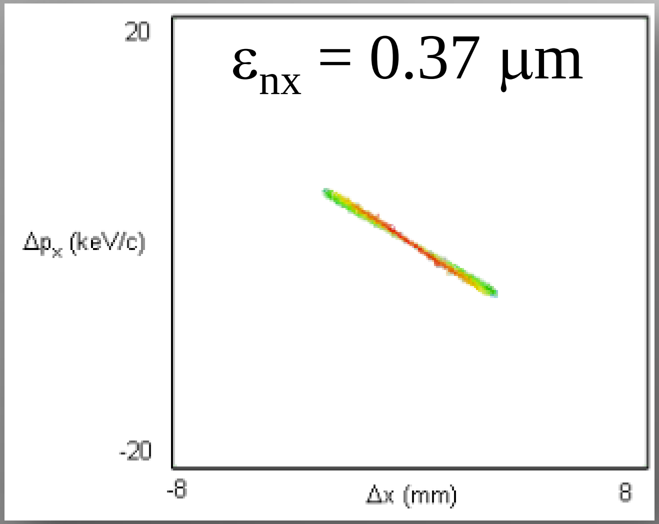
RF focusing

- If space charge is kept in check, RF induced emittance dominates

$$\varepsilon_{rf} = \frac{1}{mc}\left|\frac{\partial^2 p_x}{\partial z \partial x}\right| \sigma_x{}^2 \sigma_z$$

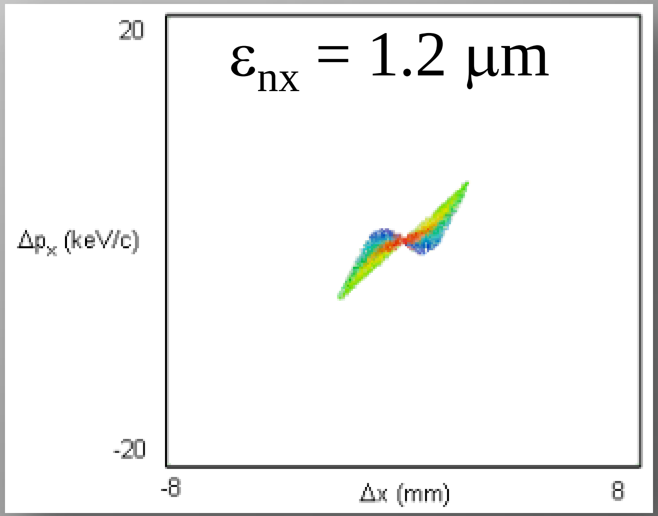
- RF cavities focus or defocus the beam depending on phase, kinetic energy and gradient

Before 1st cavity



rf emittance growth "bow-tie" pattern

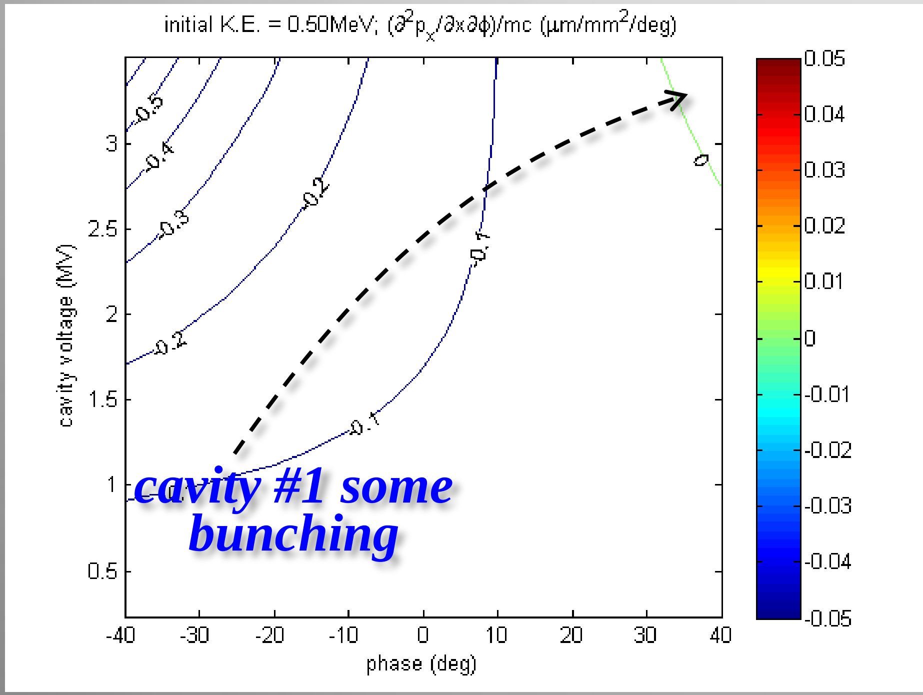
After 1st cavity



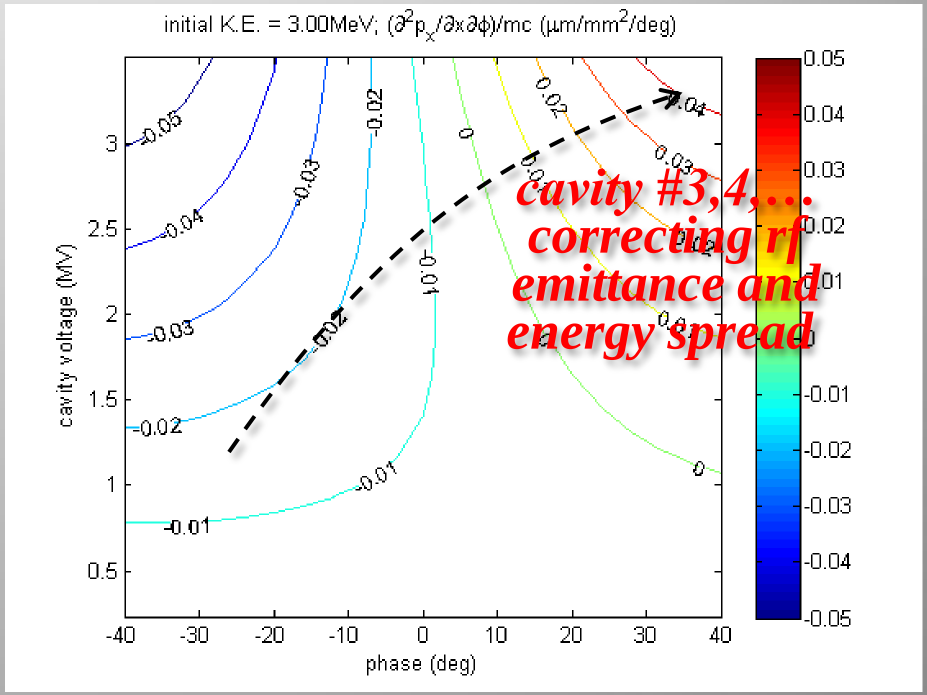
RF emittance cancelation

- RF induced emittance growth can be cancelled

K.E. = 0.5 MeV



K.E. = 3 MeV



Summary

- Brightness limit as set by the accelerating gradient and the transverse thermal energy of photoelectrons was discussed
- The basic figure of merit: $\boldsymbol{E_{cath}/kT_{\perp}}$, should apply to both DC and (S)RF guns
- The injector beams distributions are non-Gaussian, have higher local beam brightness than Gaussian beams
- Need more than a single number to describe the beam quality

Some other numbers of interest

- 100% (90%) emittance, core emittance, core fraction