Ivan Bazarov
*for the ERL team*

# Initial Beam Results from the Cornell ERL Injector Prototype

# Contents

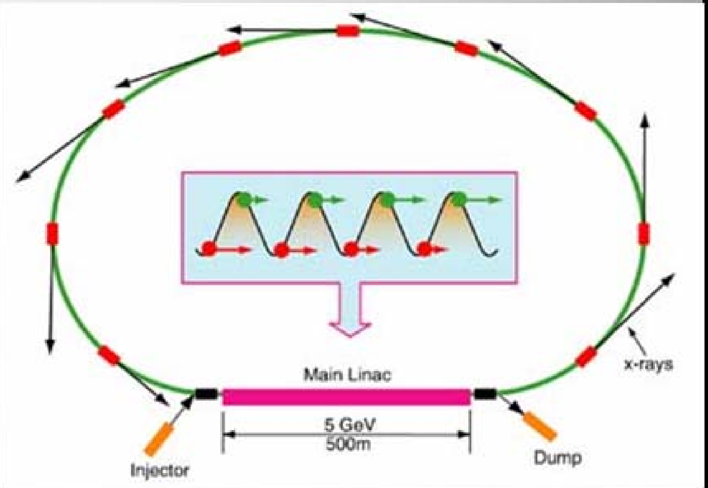
- Parameters
- ERL phase1a timeline
- Main technical areas
- Space charge limit to beam brightness
- Laser & photocathodes
- RF effects on the beam
- Present status and outlook

# Parameters

Table 1: ERL parameter list.

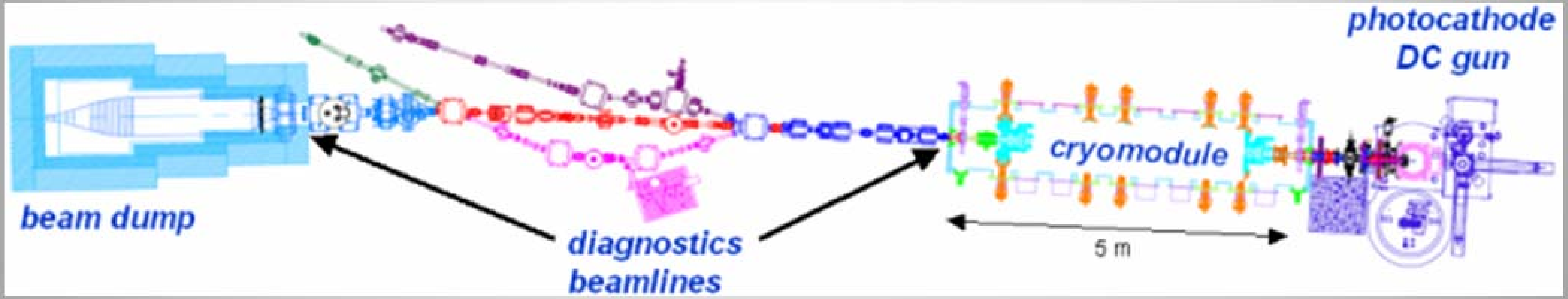
| Parameter | Value | Unit |
|---|---|---|
| Beam Energy | 5-7 | GeV |
| Average Current | 100 / 10 | mA |
| Fundamental frequency | 1.3 | GHz |
| Charge per bunch | 77 / 8 | pC |
| Injection Energy | 10 | MeV |
| Normalized rms emittance | ≤2 / 0.2 | mm-mrad |
| Energy spread (rms) | 0.02-0.3 | % |
| Bunch length in IDs (rms) | 0.1-2 | ps |
| Total radiated power (typical) | 400 | kW |
| X-ray brilliance | $10^{22}$ | ** |

** Photon / (sec·mrad$^2$·mm$^2$·0.1% BW)




- ERL as a quasi-continuous source of bright x-rays
- Cornell ERL prototype (phase1a): to address outstanding source and high avg. current issues

# ERL Phase1a: source R&D



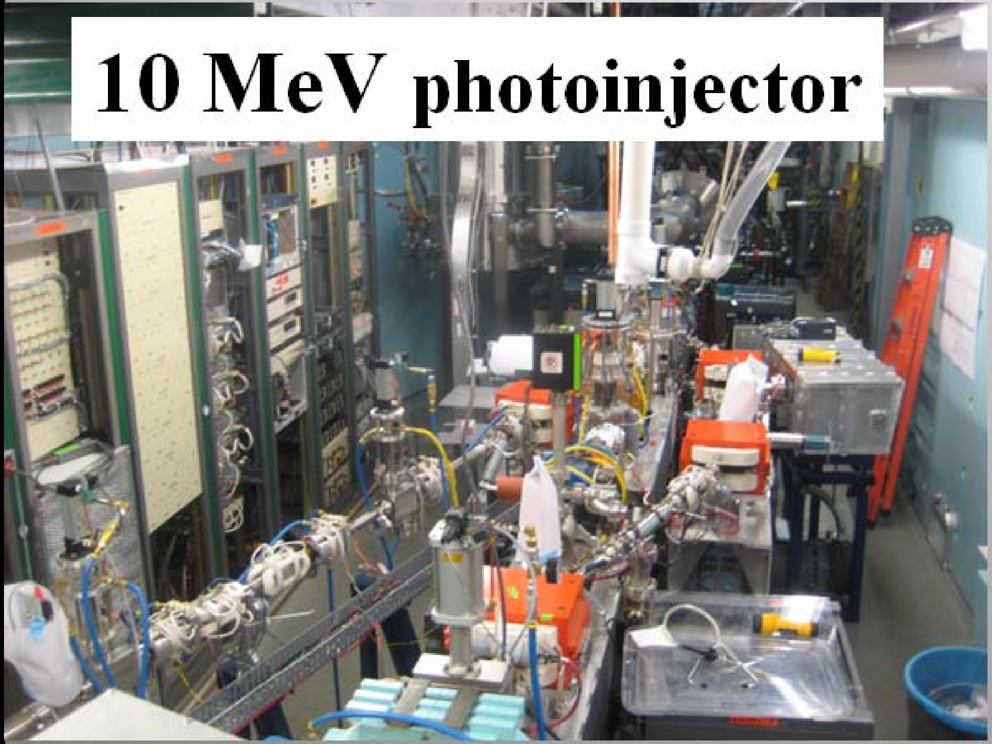

| | |
|---|---|
| Beam energy | 5-15MeV |
| Max average current | 100 mA |
| RMS norm. emittance | ≤2 mm-mrad |
| Max beam power | 0.6 MW |
| RMS pulse duration | 2-3 ps |

# Timeline

- 2001: ERL prototype proposal submitted
- 2005: NSF funds the injector part (~45%) of the proposal, $$$ received on Valentine's day
- 2006: Sept 7, 1st beam time out of DC gun
- 2007-8: Photocathode studies and space charge characterization underway using 50MHz laser
- 2008: Spring. Completion of the SRF injector cryomodule
- 2008: Summer. Accelerator installation finished. July 9, 1st beam with all SRF cavities on

# Phase1a ERL beam work

- Beam studies after the DC gun till 03/2008
- Thereafter, commissioning the 10MeV injector




*before 03/2008*

# Technical area: DC gun & laser

- ***DC photogun*** operational for over 2 years
- Strong points: quick photocathode removal & activation, excellent vacuum (necessary for good cathode lifetime)
- Major issue: *field emission & ceramic puncture* (425→250 kV)
- ***Laser system***: individual pulse characteristics demonstrated at ×26 lower rep. rate (50MHz)

- Ran into several (thermal handling) difficulties when trying to extend avg. power to 20W green (>50 W IR)

# Technical area: SRF

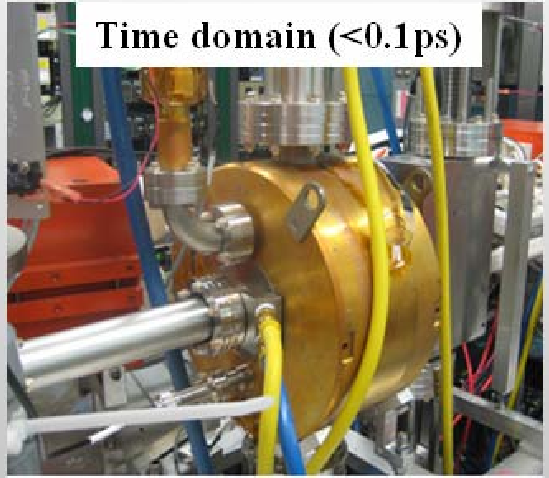
- Talk later today by M. Liepe
- RF installation beam ready as of May 2008
- SRF cavities processed to allow 14MeV operation, further processing underway to reach 15MeV (some issues with low $Q_0$'s)
- Good field stability
- Discovered problems with stray magnetic fields inside the module

# Technical area: beam instrument.

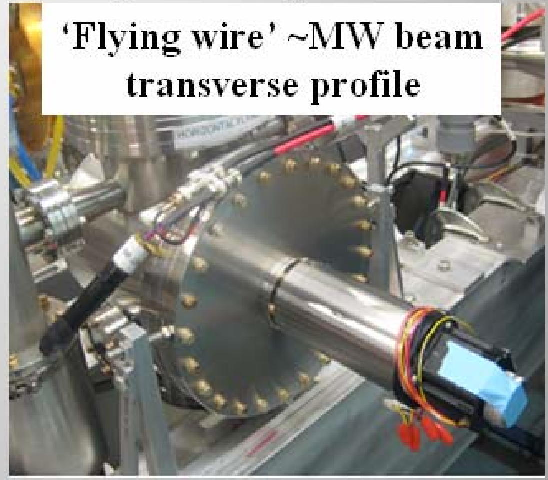
## *Beam instrumentation to characterize 6D phase space*

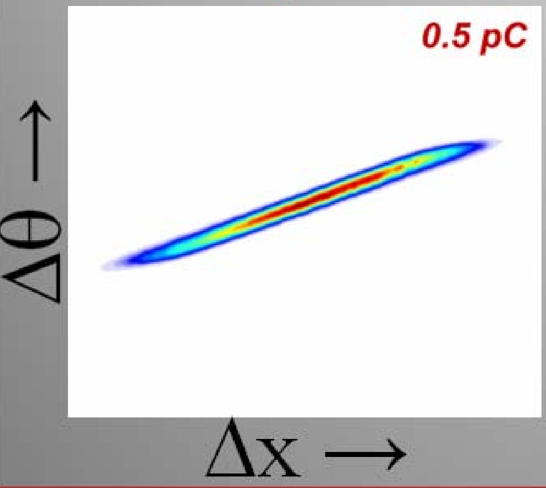
**Emittance measurement**

**Time domain (<0.1ps)**



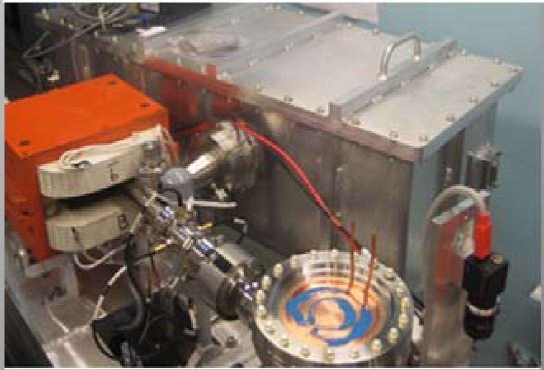
**'Flying wire' ~MW beam transverse profile**






**BPMs, Timing & Control System**

**THz interferometer for bunch profile characterization**



Cornell University
Laboratory for Elementary-Particle Physics

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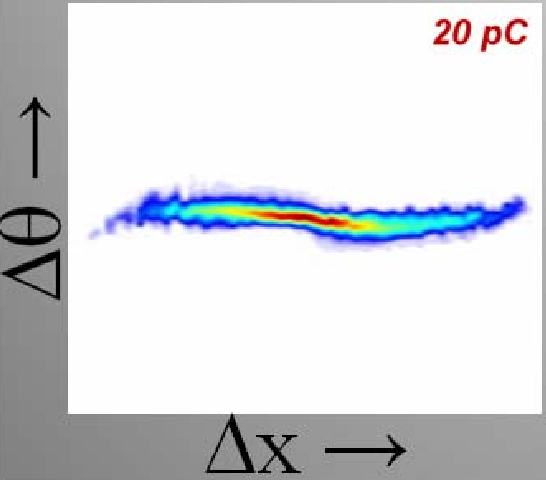


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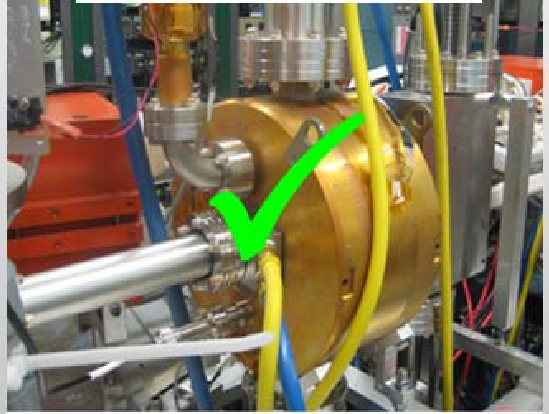

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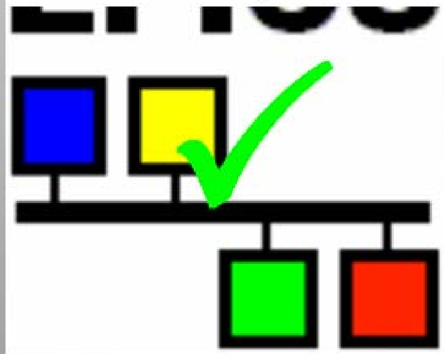

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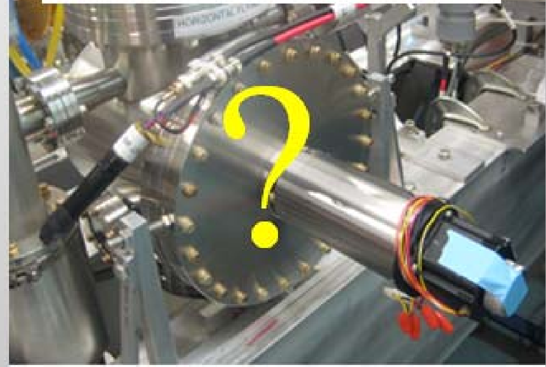

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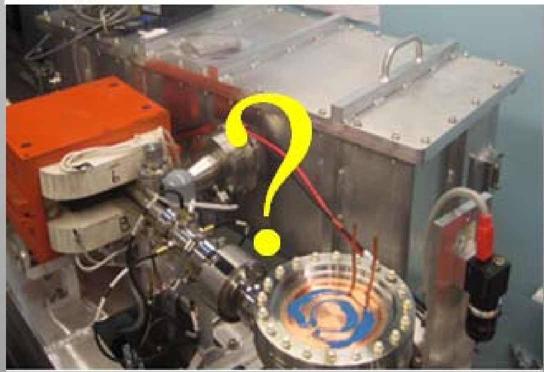


# Space charge brightness limit

- For *short* laser pulse (pancake beam after emission), ***max charge density*** is defined by $\varepsilon_0 E_{cath}$
- Solid angle is set by transverse momentum spread of photoelectrons characterized by ***trans. temperature***
- Combining these two leads to normalized brightness and emittance limits

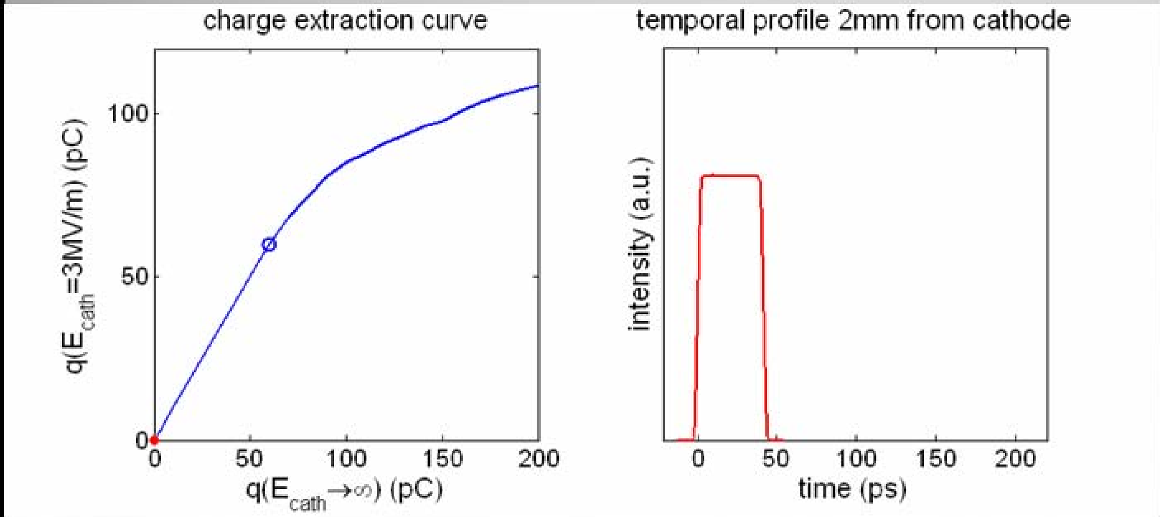
$$\left.\frac{B_n}{f}\right|_{max} = \frac{\varepsilon_0 mc^2}{2\pi} \frac{E_{cath}}{kT_\perp} \qquad \epsilon_{n\perp} = \sqrt{\frac{3}{10\pi\varepsilon_0 mc^2} q \frac{kT_\perp}{E_{cath}}}$$

# Space charge considerations

- Space charge forces must be controlled at all stages in the injector (*space charge dominated*)
- Virtual cathode instability: quenching of accelerating gradient due to excessive charge extracted from the photocathode
- Stay away from this limit ($q/q_{vc} < ⅓ – ½$) to avoid brightness degradation at the photocathode

# Space charge dominated

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



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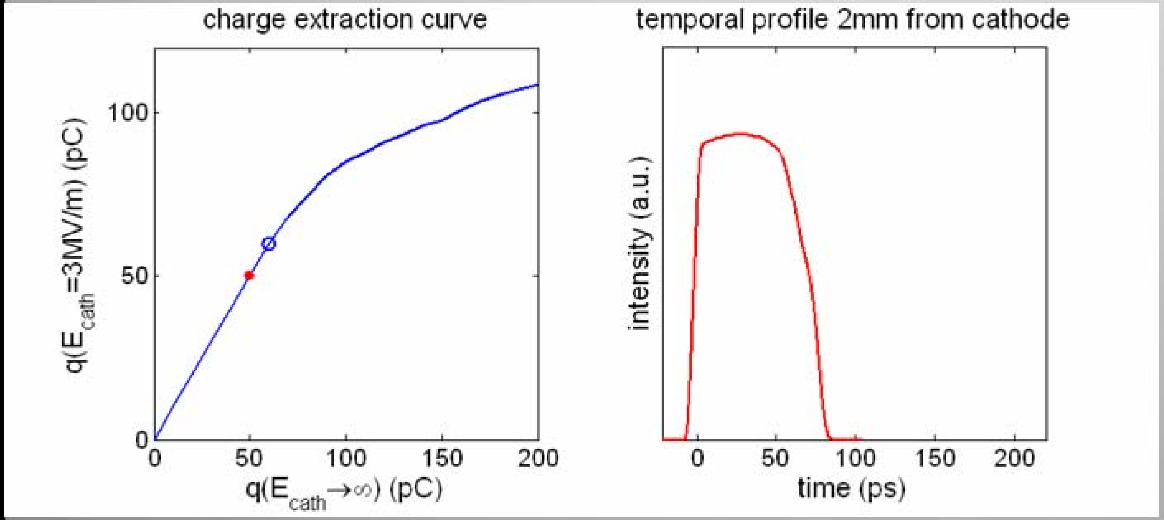

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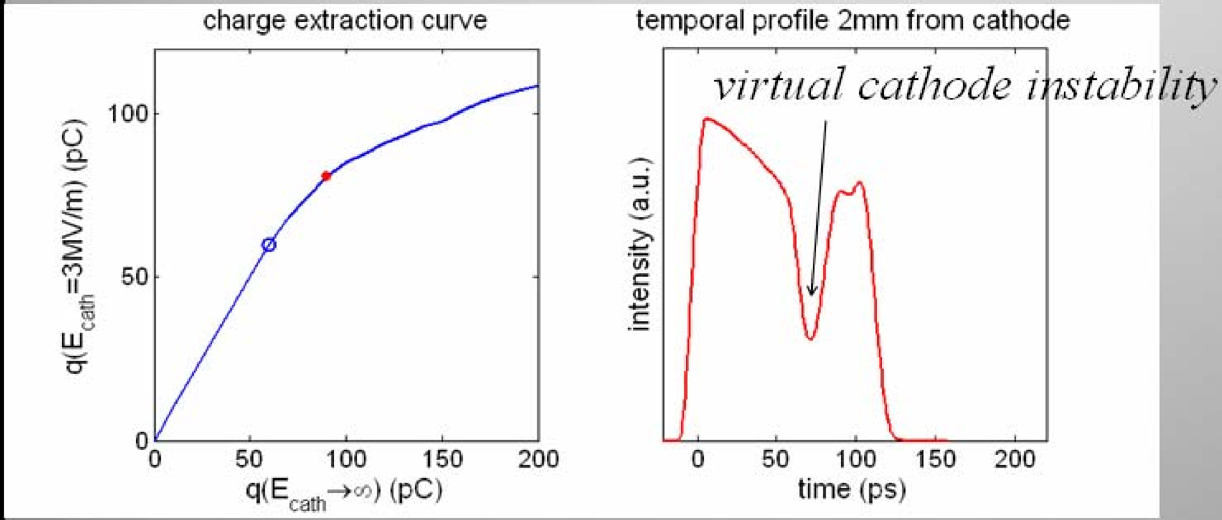

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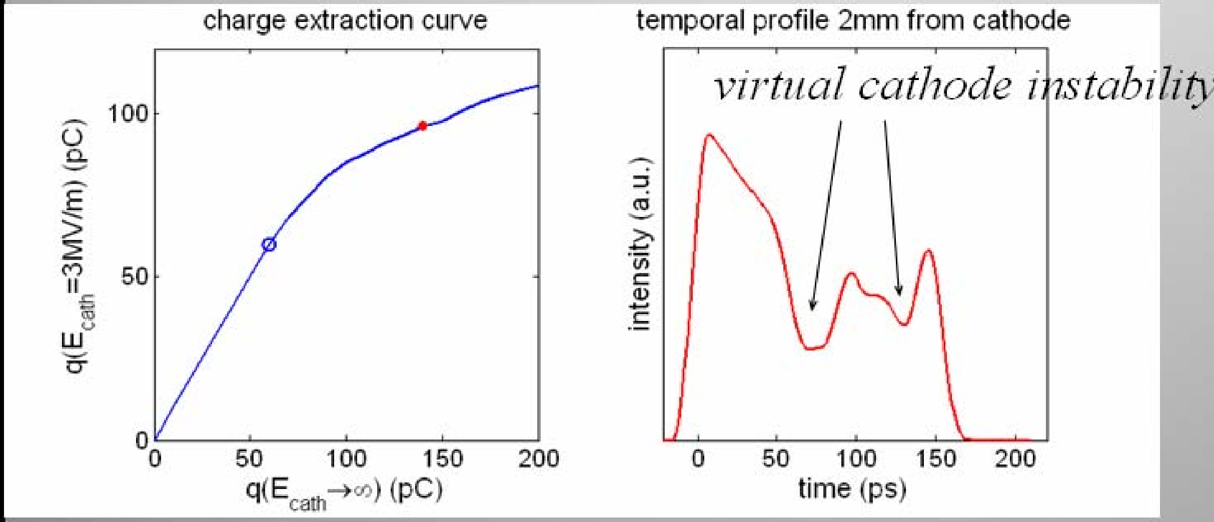
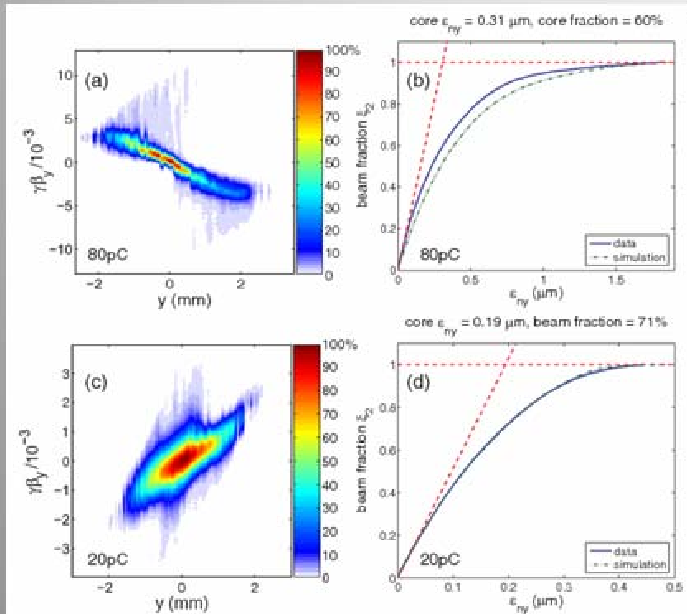
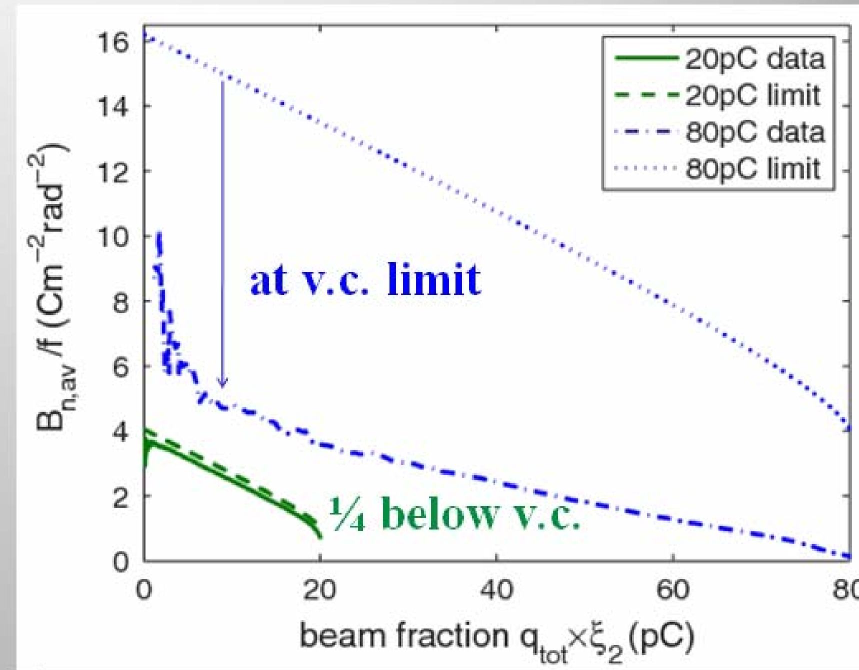


# 250kV DC gun data

*80 pC,* $\varepsilon_{nx} = 1.8 \pm 0.2\ \mu m$




*20 pC,* $\varepsilon_{nx} = 0.43 \pm 0.05\ \mu m$




**PRL, 102 (2009) 104801**

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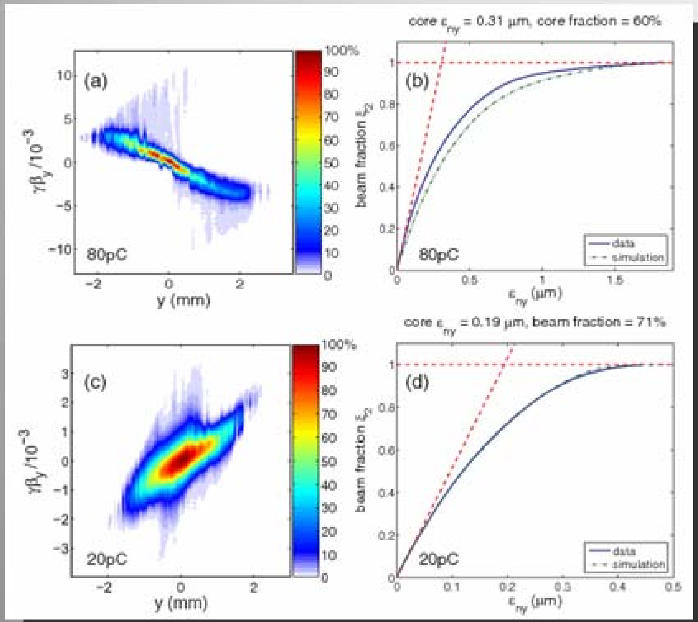


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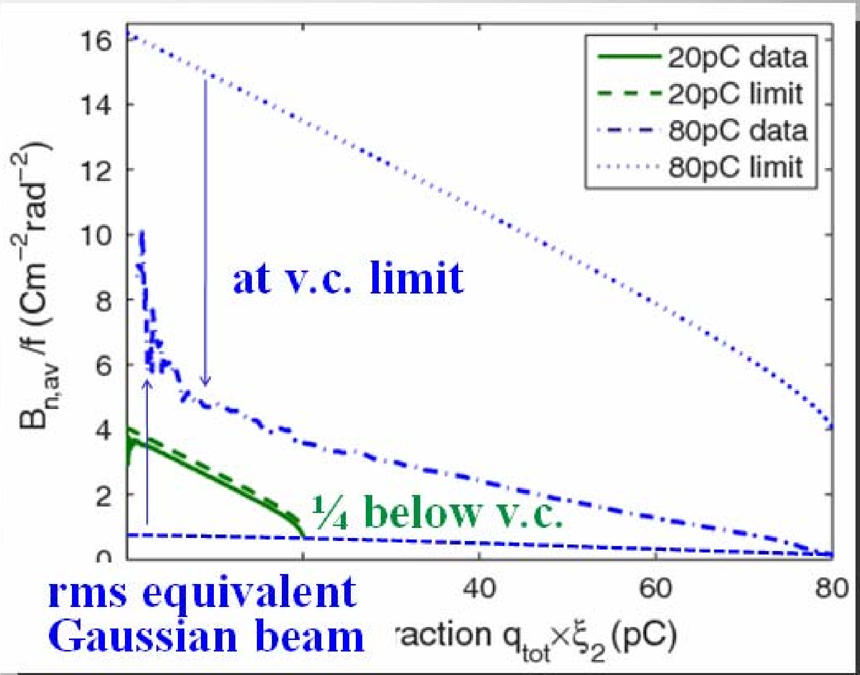
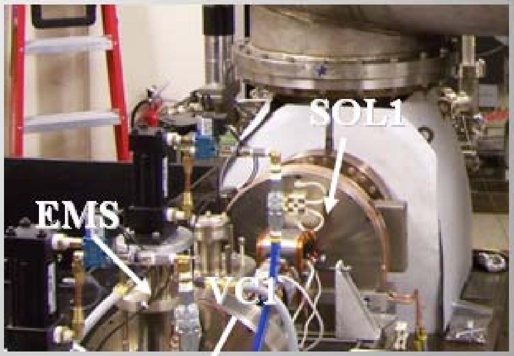
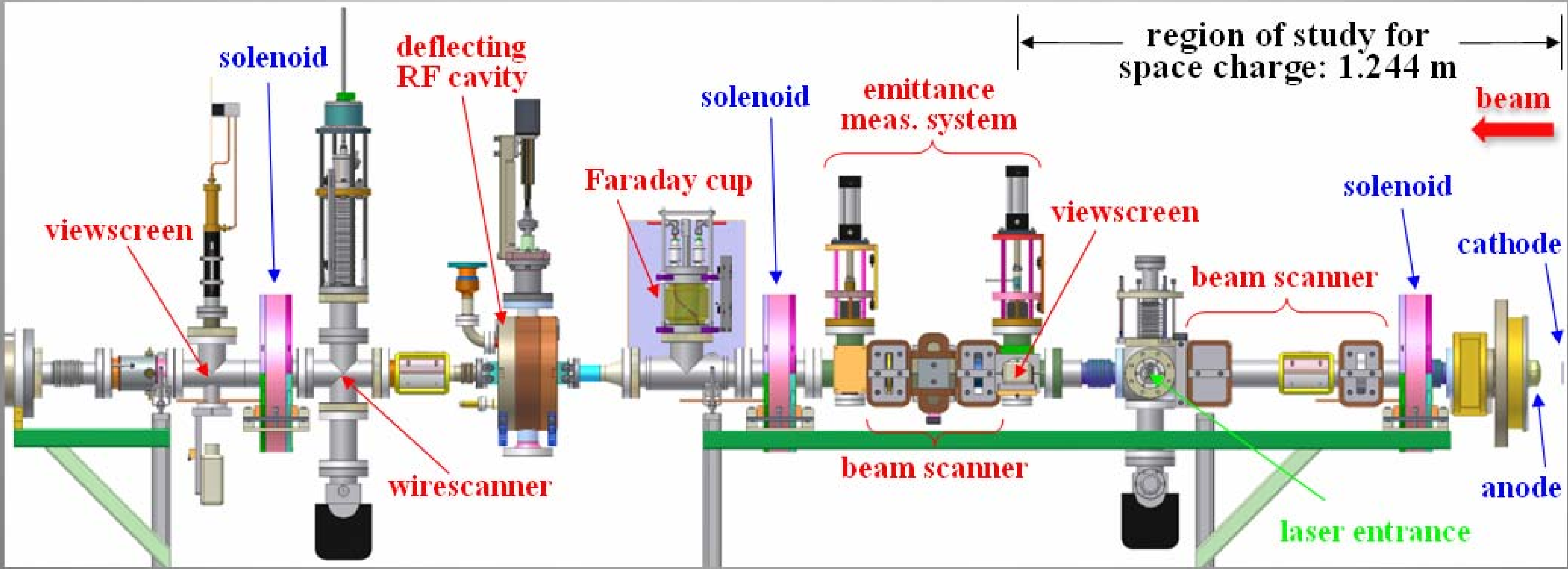



**PRL, 102 (2009) 104801**

# Gun beamline studies

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

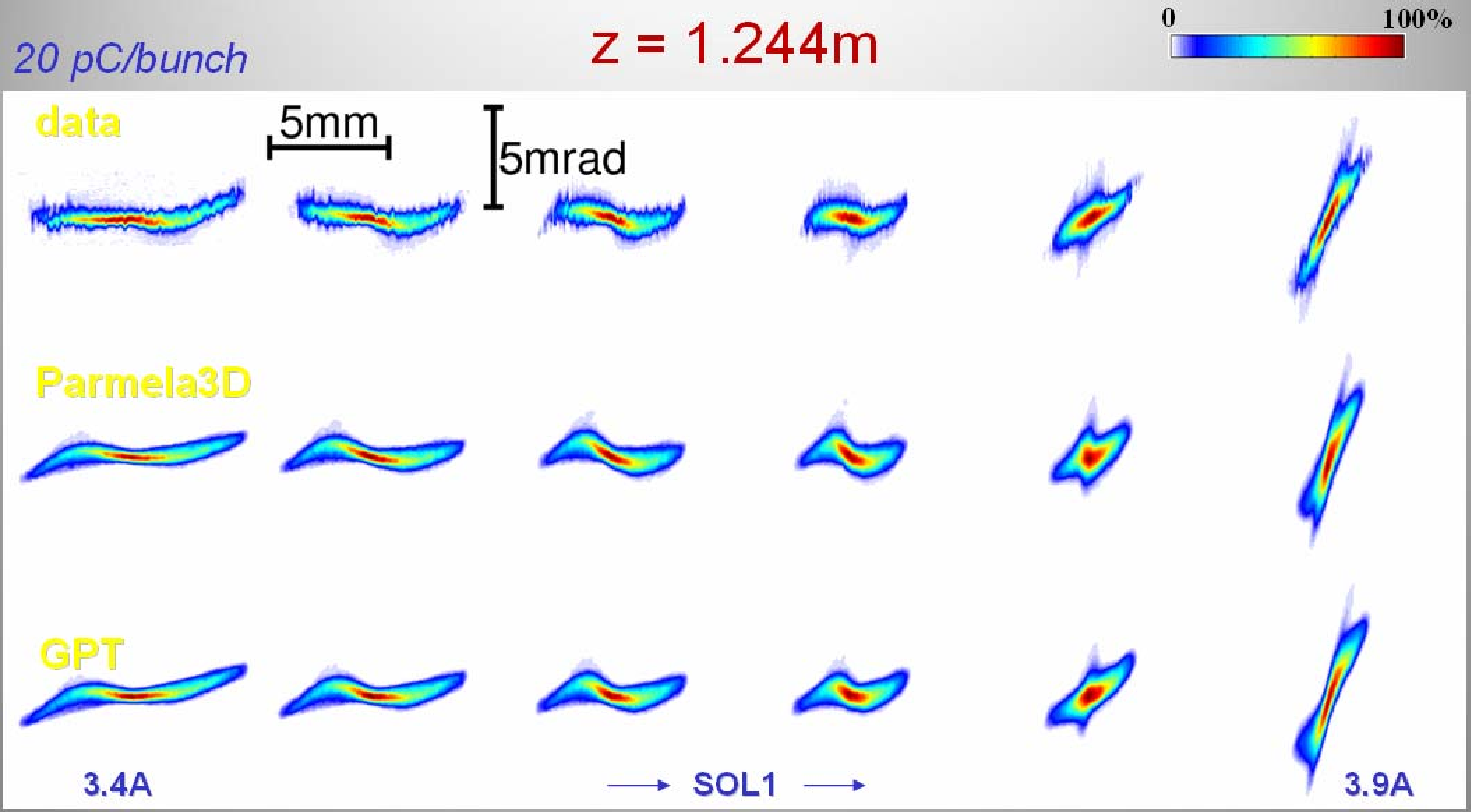


# Space charge code validation

*20 pC/bunch*

z = 1.244m

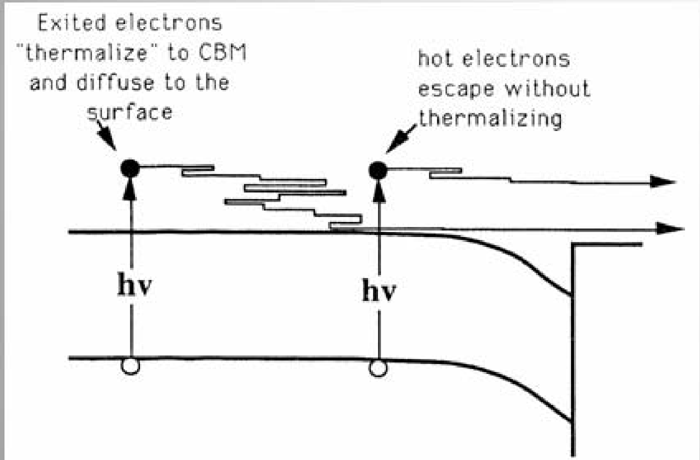



***PRSTAB, 11 (2008) 100703***

# Photocathode studies

- Beam quality-wise, two important figures of merit
  - Effective transverse thermal energy → brightness limit
  - Response time → one's ability to shape laser and linearize space charge forces
- Limiting our study to NEA photocathodes: GaAs, GaN, and GaAsP
- GaAs remains the best out of what we looked into (no perfect photocathode)

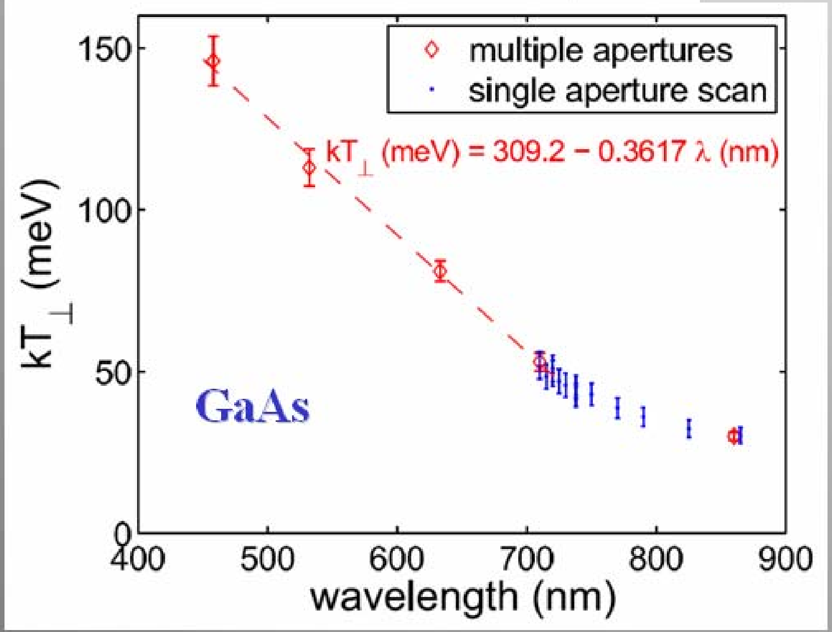
# kT vs. wavelength

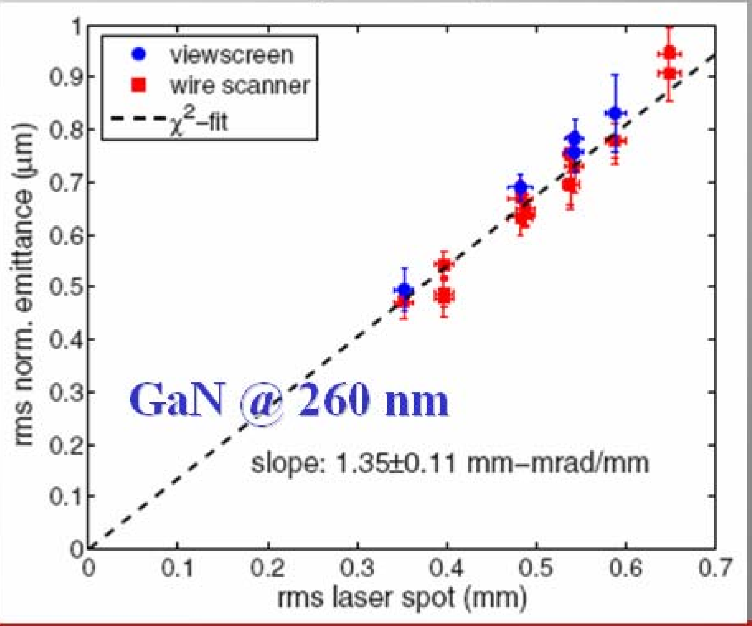



## relates spot size to emittance

$$\varepsilon_{n,th} = \sigma_{\perp}\sqrt{\frac{kT}{mc^2}}$$

***JAP, 103 (2008) 054901***
***JAP, 105 (2009) 083715***

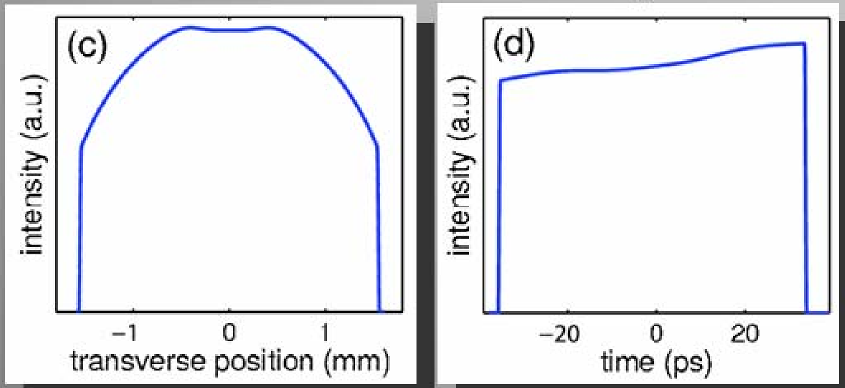


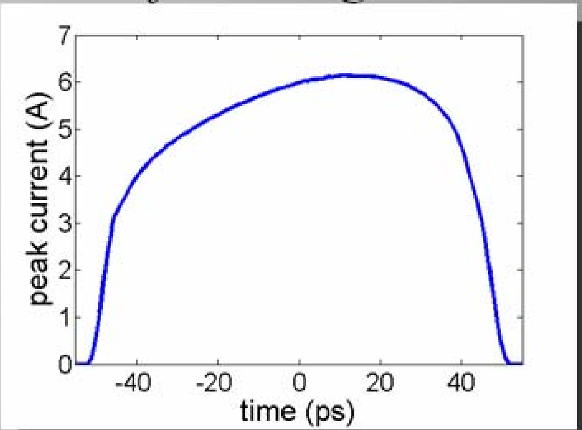
# Laser shaping

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

desired laser shape

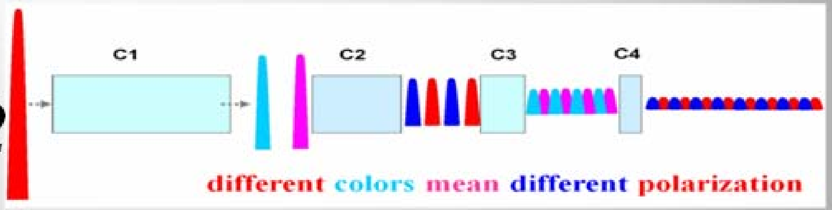



after the gun

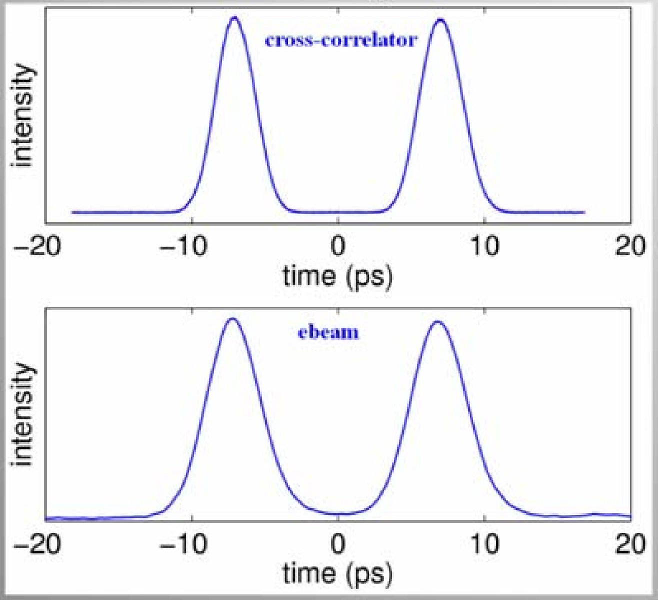


# One robust method

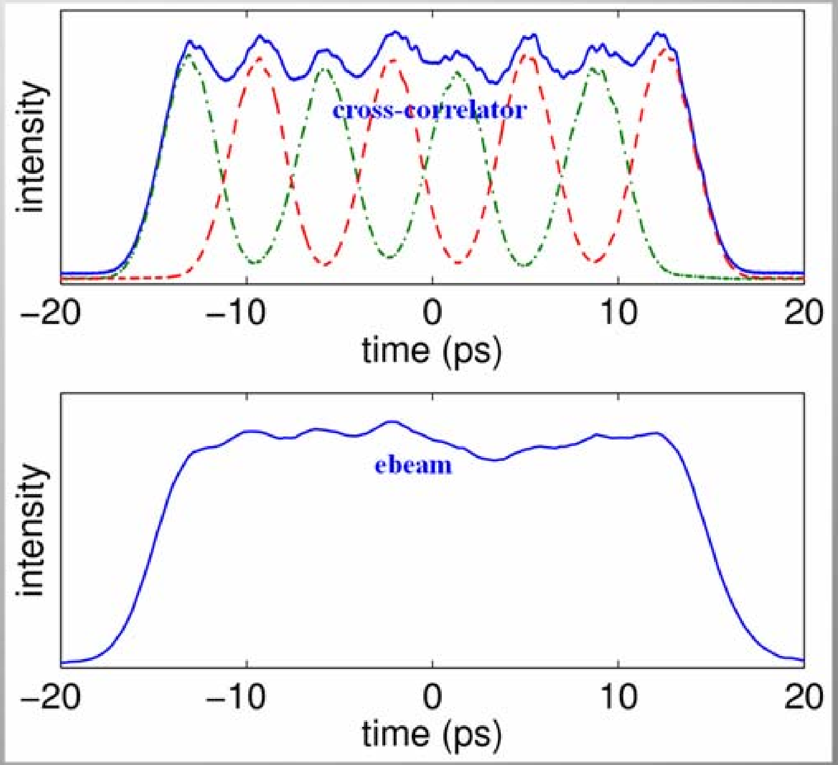
***App Opt, 46 (2007) 8488***
***PRSTAB, 11 (2008) 040702***




One crystal




Three crystals



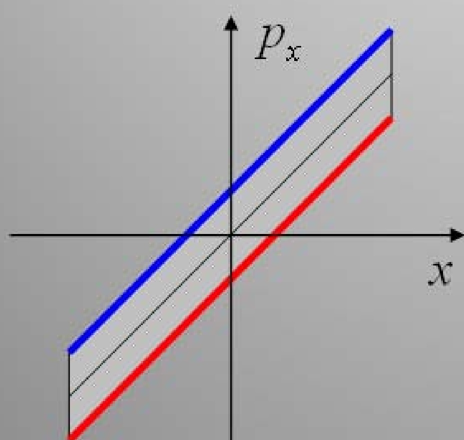

*useful diagnostics tool with RF on*

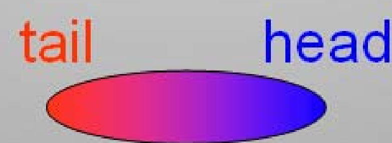
# Beam dynamics with RF

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

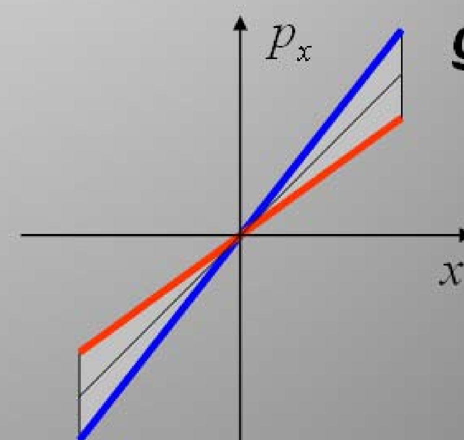
$$p_x(x,z) = p_x(0,0) + \frac{\partial p_x}{\partial x}x + \underbrace{\frac{\partial p_x}{\partial z}z}_{kick} + \underbrace{\frac{\partial^2 p_x}{\partial x \partial z}xz}_{focusin\ g} + \mathrm{K}$$

***kick***




***focusin g***



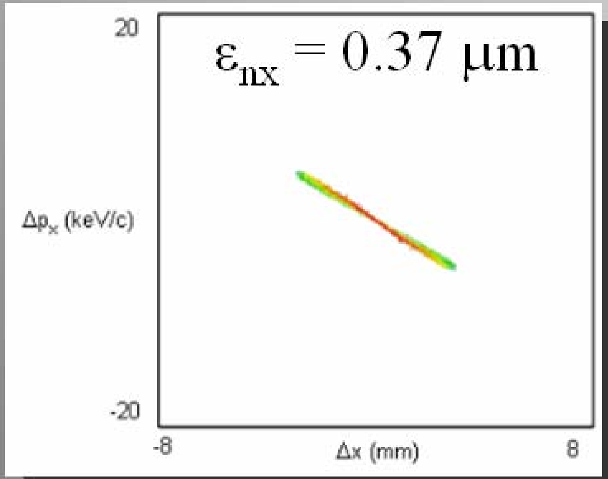
# RF focusing

- If space charge is kept in check (force is linear), RF induced emittance dominates

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

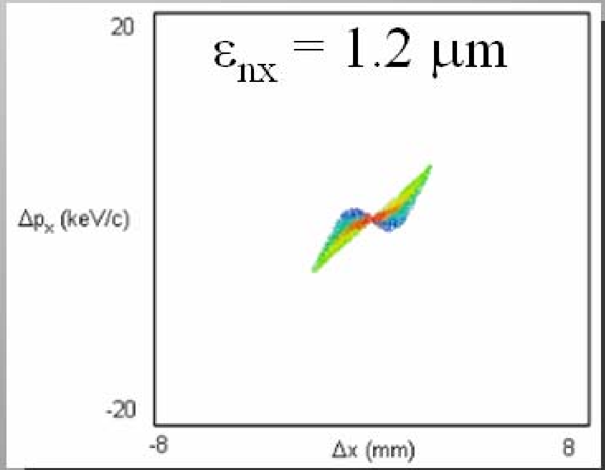
- RF cavities focus or defocus the beam depending on phase, kinetic energy and gradient

*Before 1st cavity*




*rf emittance growth "bow-tie" pattern*

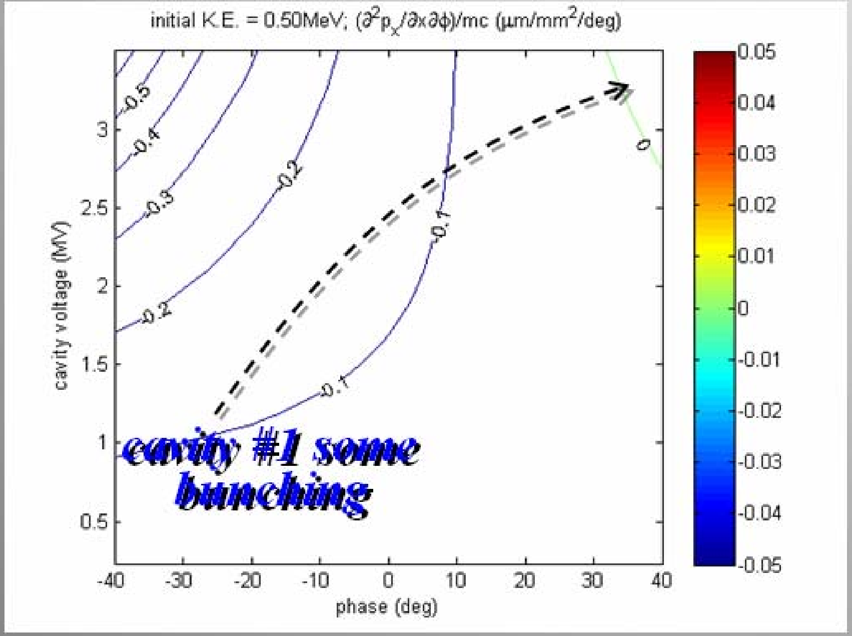
*After 1st cavity*



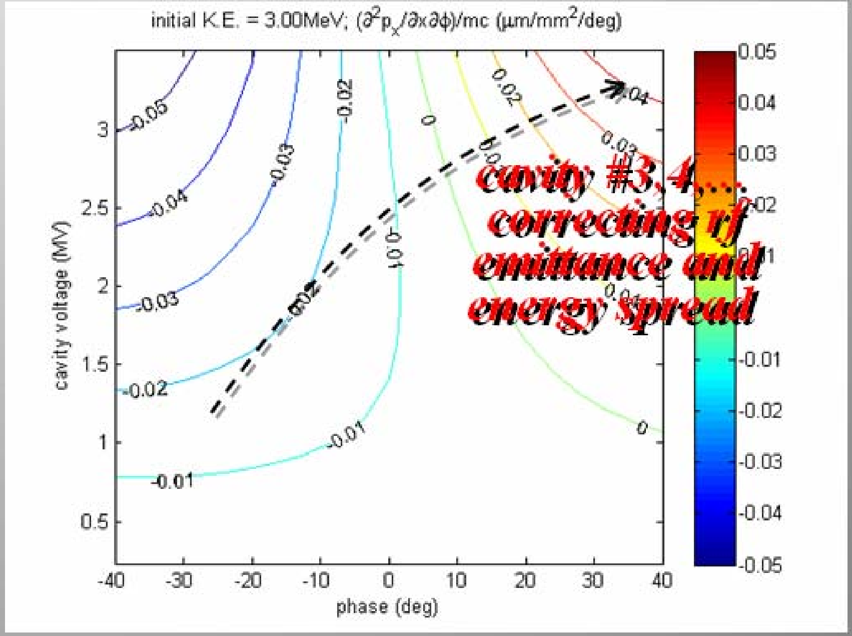
# RF emittance cancelation

- RF induced emittance growth can be cancelled (yet to be demonstrated with beam)

*K.E. = 0.5 MeV*

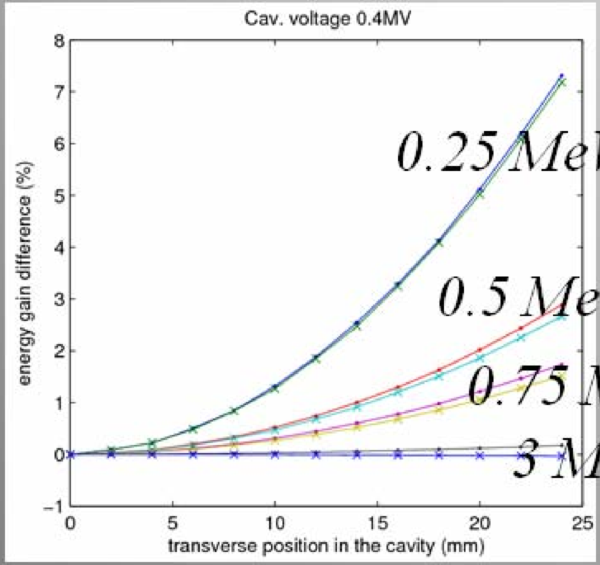


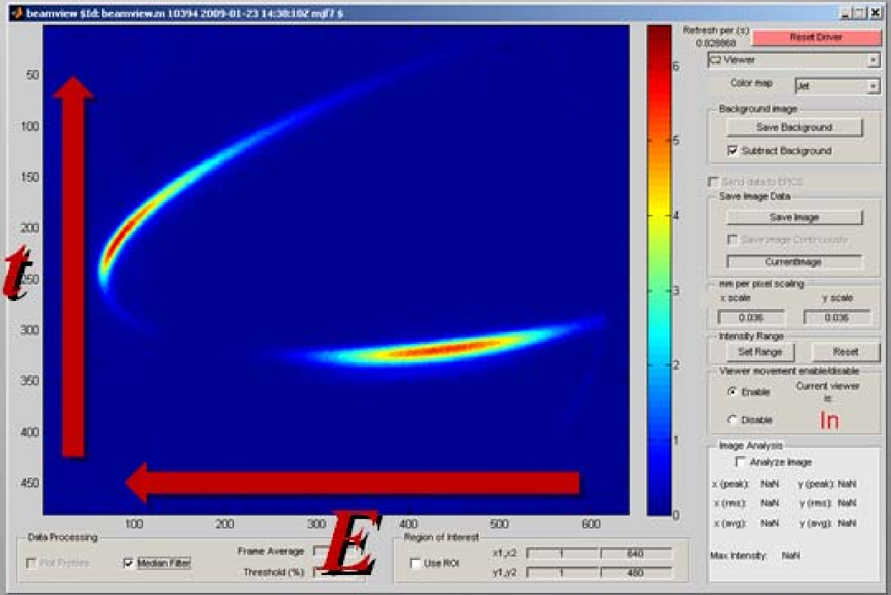

*K.E. = 3 MeV*



# Low gun voltage implications

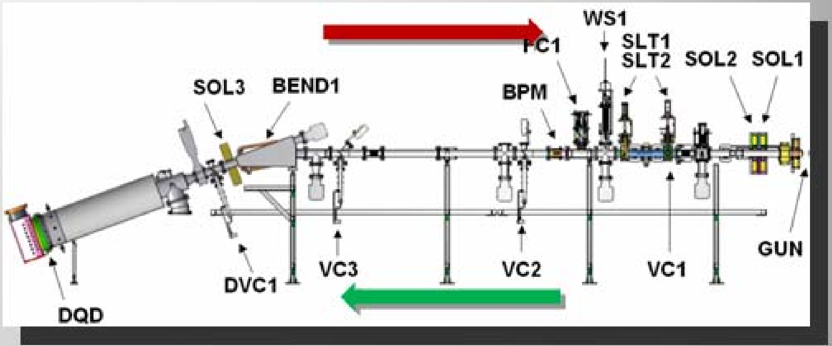
- Low gun voltage introduces several challenges in the 1st cavity
  - Energy gain is transverse position dependent
  - 1st cavity acts as a phase shifter
- Time & energy diagnostics proves very useful



# High current status

*gas backstream from the dump*



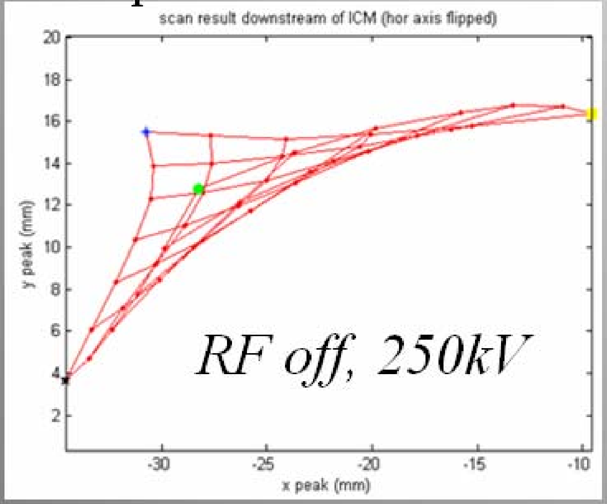

*beam direction*

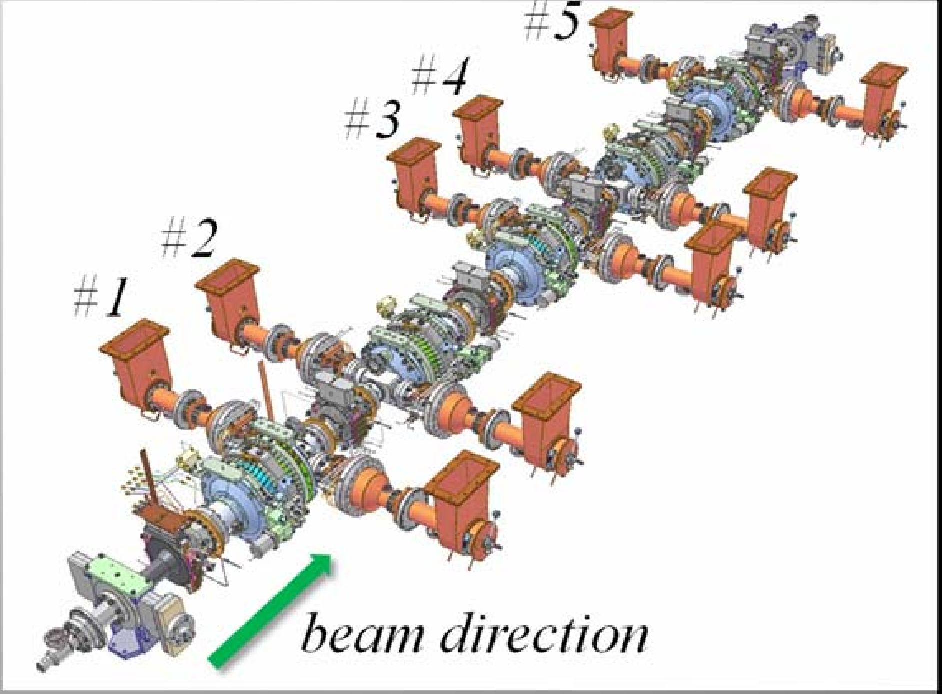
- 20 mA DC current demonstrated from the gun as limited by gas backstream from the dump (~5m away)
- 5MeV beam running so far reached 4mA as limited by our ability to generate low-loss beam (radiation)

# Problem with the cryomodule

- Stray magnetic fields inside the cryomodule increase beam losses and thwart beam based alignment
- Planning to open the cryomodule to eliminate the problem

Grid pattern downstream



# Summary

- Cornell project: unique testbed for high-current low emittance injector R&D
- Learned many valuable lessons from the gun operation despite low voltage & ceramic woes
- 11 months after 10 MeV injector installation complete and 10 months of initial beam running we are in the thick of the commissioning
- Found some problems that require action
- Work in parallel on improved gun to reach ≥500kV and 20W 1.3GHz laser (presently ran ~7W max)

# Acknowledgements

- John Barley, Sergey Belomestnykh, Mike Billing, Eric Chojnacki, John Dobbins, Bruce Dunham, Richard Erhlich, Mike Forster, Steve Gray, Colwyn Gulliford, Georg Hoffstaetter, Heng Li, Yulin Li, Matthias Liepe, Xianghong Liu, Florian Loehl, Valery Mejdidzade, Dimitre Ouzounov, Hasan Padamsee, Peter Quigley, David Rice, Hisham Sayed, Valery Shemelin, Charles Sinclair, Eric Smith, Karl Smolensky, Charlie Strohman, Maury Tigner, Alexander Temnykh, Vadim Vescherevich, Frank Wise, and more…