Extending science and technology behind high brightness and duty-factor photoinjectors

DOE Early Career: Investigation of Fundamental Limits to Beam Brightness Available From Photoinjectors

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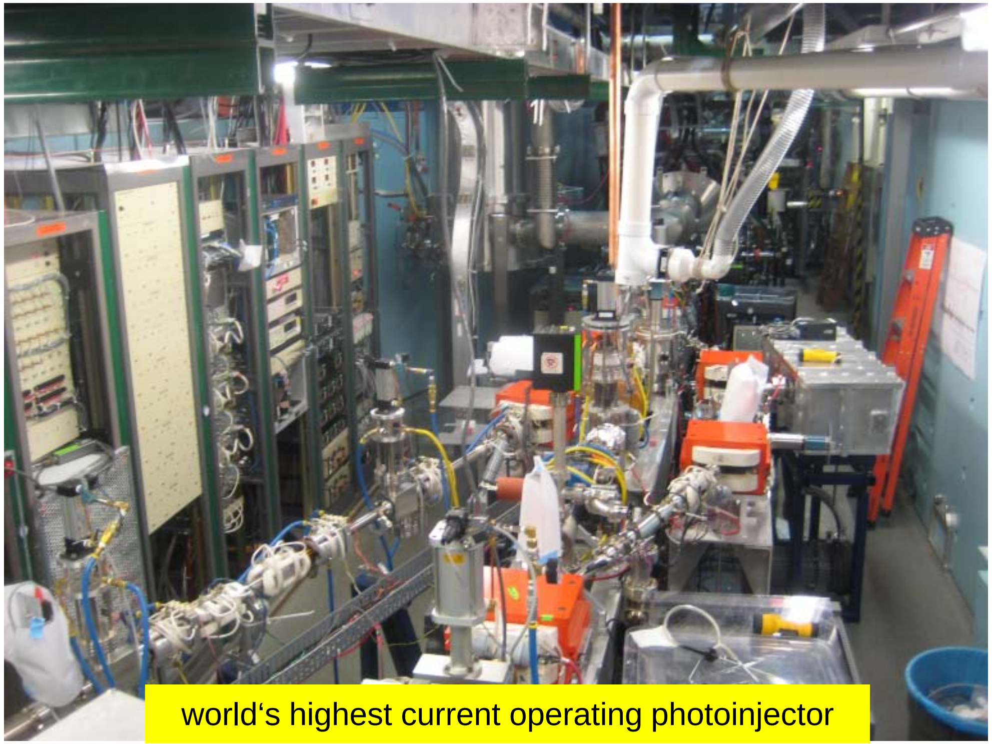
Cornell University



world's highest current operating photoinjector

Research objectives

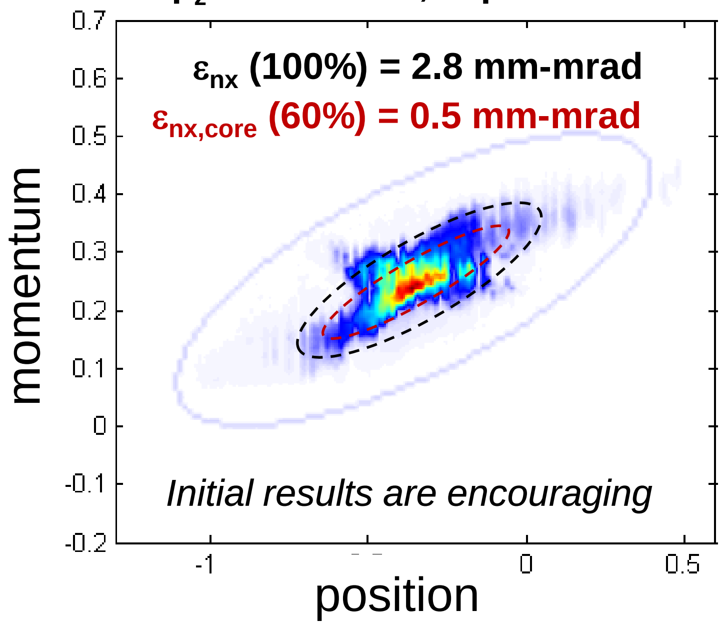
- **Goals:**
  - **Understand fundamental physics and technology limits to high brightness beam production in photoinjectors;**
  - **Cathode research:**
    - **measure and model intrinsic mean transverse energy (MTE) of high QE photocathodes;**
    - **explore novel photocathode materials in real-life accelerator conditions of a high average current photoinjector**
  - **Beam dynamics:**
    - **space charge control via advanced laser shaping in the gun's vicinity;**
    - **implications of virtual cathode instability for transverse phase space.**

Avg. beam brightness: current/flux density in phase space

Transverse phase space: key to CW coherent x-ray generation

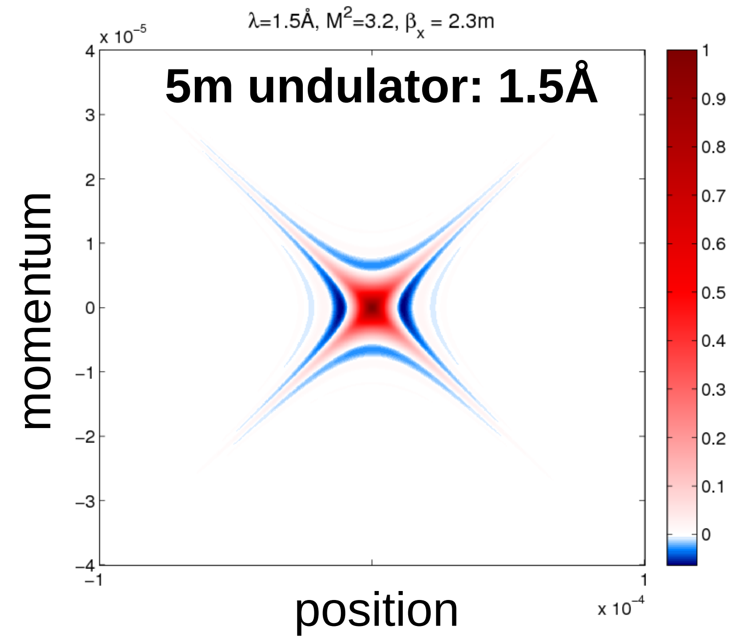
Electron beam

p_z = 5.2 MeV/c, 80pC/bunch



+

X-ray beam



Physics 101: basic limit to beam brightness from photoinjectors

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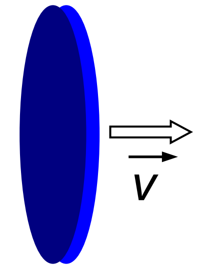
- Each electron bunch assumes a 'pan-cake' shape near the photocathode for short (≤ 10ps) laser pulses



- Maximum charge density determined by the electric field:

$$dq/dA = \varepsilon_0 E_{cath}$$

- Angular spread or transverse momentum footprint is set by intrinsic momentum spread of photoelectrons leaving the photocathode: $\Delta p_\perp \sim (m \times MTE)^{1/2}$
- Combining these two yields the maximum (normalized) beam brightness achievable from a photoinjector – defined only by two key parameters: electric field at the cathode E_{cath} and MTE of the photoelectrons:

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

PRL 102, 104801 (2009)

Photocathode research capabilities at Cornell

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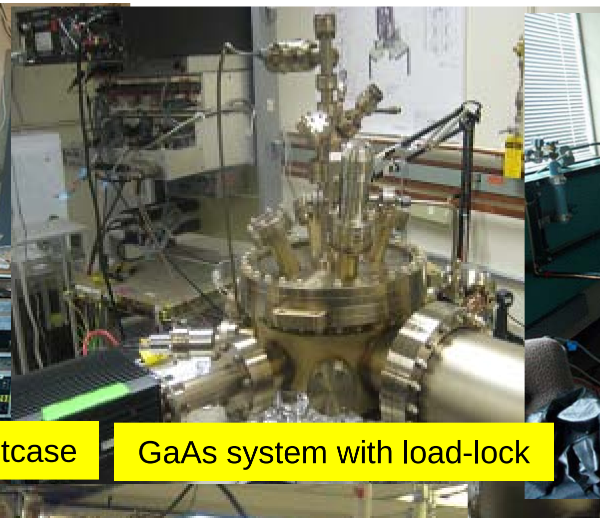
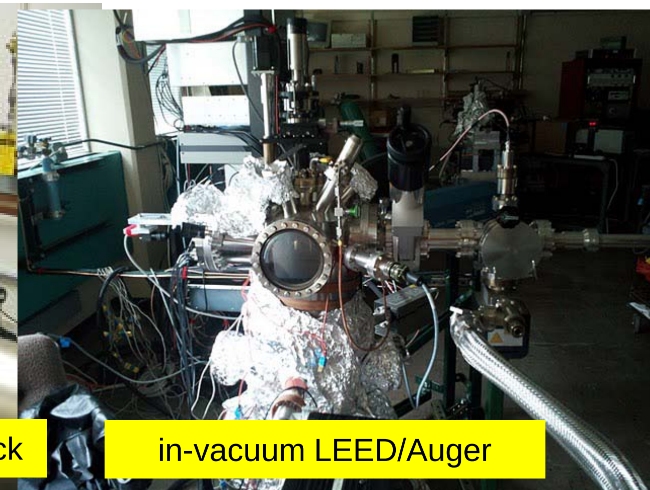
multialkali growth chamber with vacuum suitcase


GaAs system with load-lock

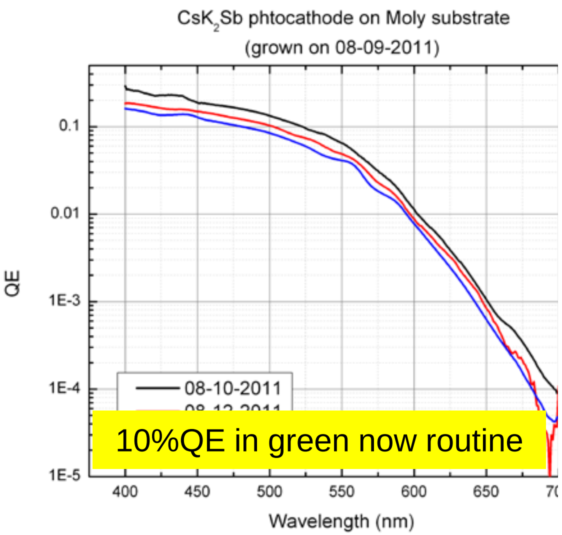

in-vacuum LEED/Auger

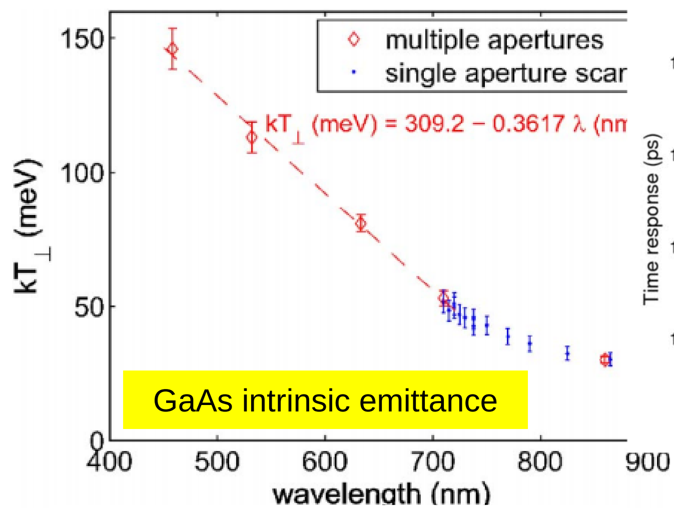

MBE III-V system (work in progress, looking for personnel support funds)

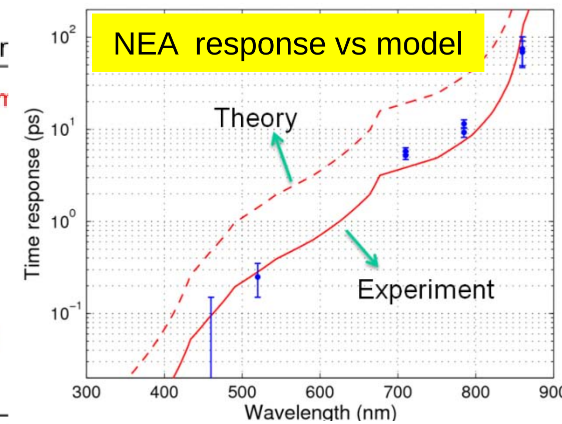
- **Also on campus AFM, EDX, SEM, STM, SIMS, ARPES**
- **+ CHESS (XRF, x-ray topography, EXAFS, and much more)**

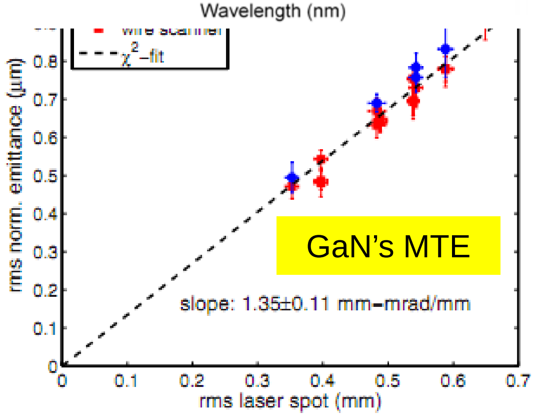
Photocathode research some results

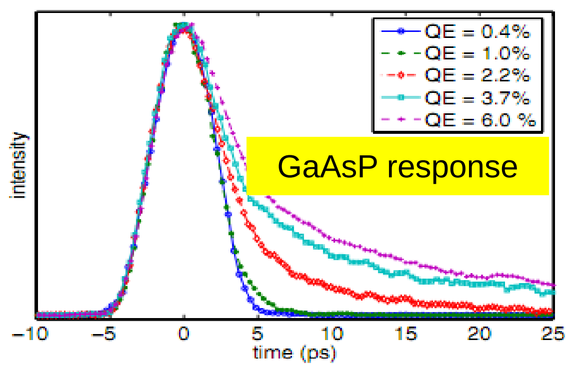
- **Wide selection of photocathodes evaluated for MTE and response time: GaAs, GaAsP, GaN, Cs_3Sb, K_2CsSb**

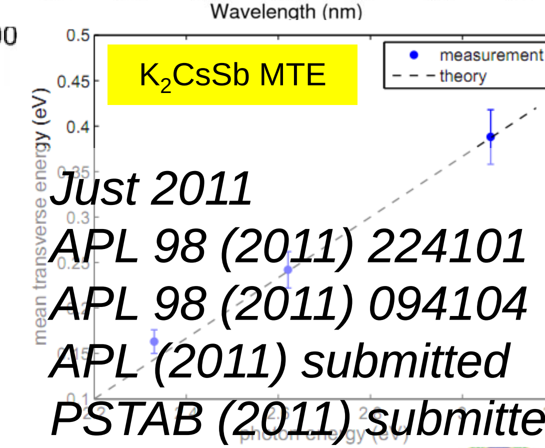












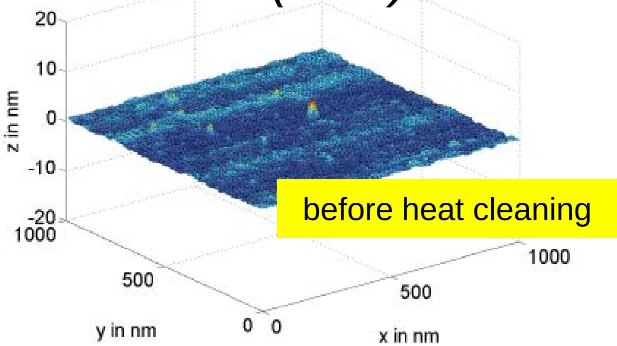
Just 2011
APL 98 (2011) 224101
APL 98 (2011) 094104
APL (2011) submitted
PSTAB (2011) submitted

Photocathode physics: some mysteries

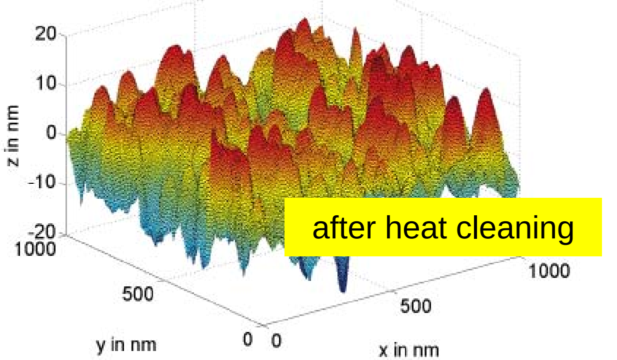
- **Due to small effective mass of Γ valley electrons, theory predicts MTE as low as 2meV in at 800nm for GaAs**
- **Some groups have observed these small MTE values, but most do not (including us). Why??**
- **Possible causes – surface roughness and different structure of Cs/F layer**

PAC'11, THP192

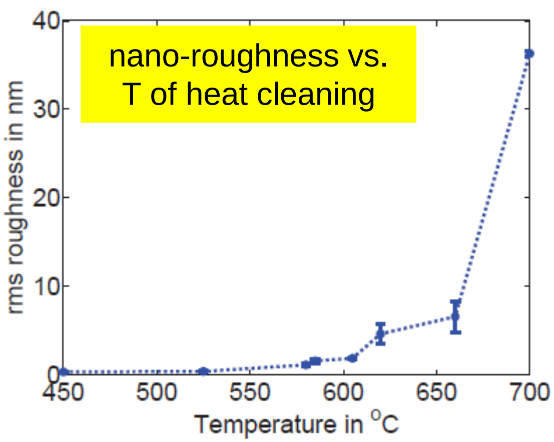
APL 98 (2011) 094104

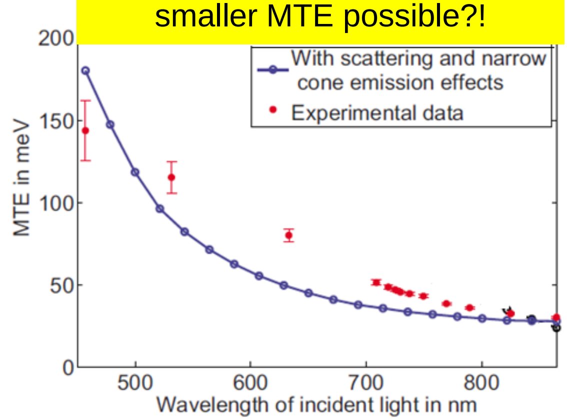


(a) Surface of atomically polished GaAs crystal before heat cleaning (smooth surface)



(b) Surface of heat cleaned and activated GaAs crystal used in the Cornell dc photoemission gun (rough surface)





Photocathode research: putting experiment & theory together

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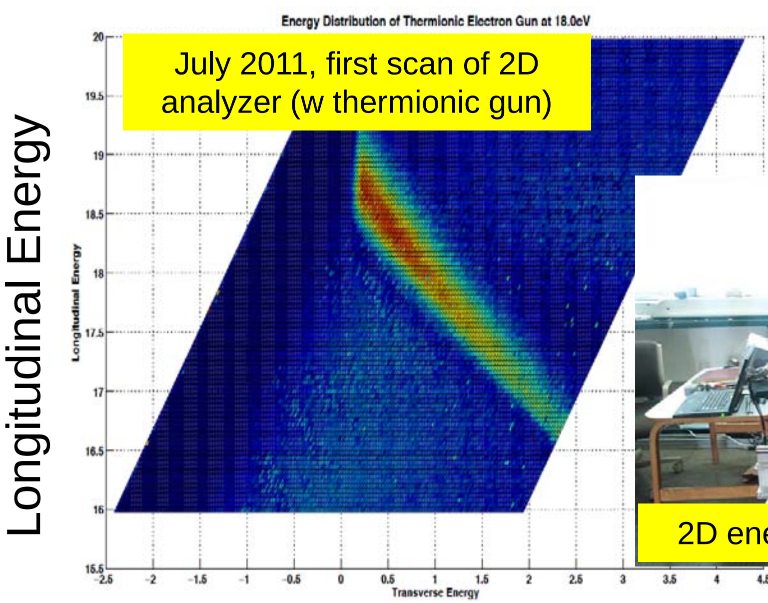
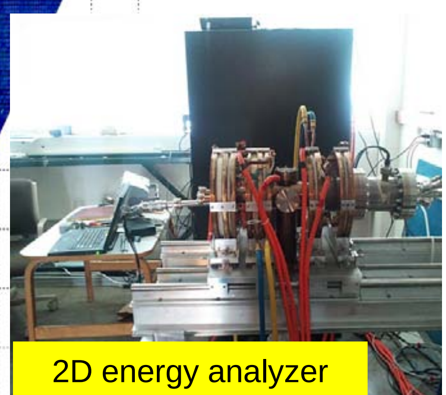
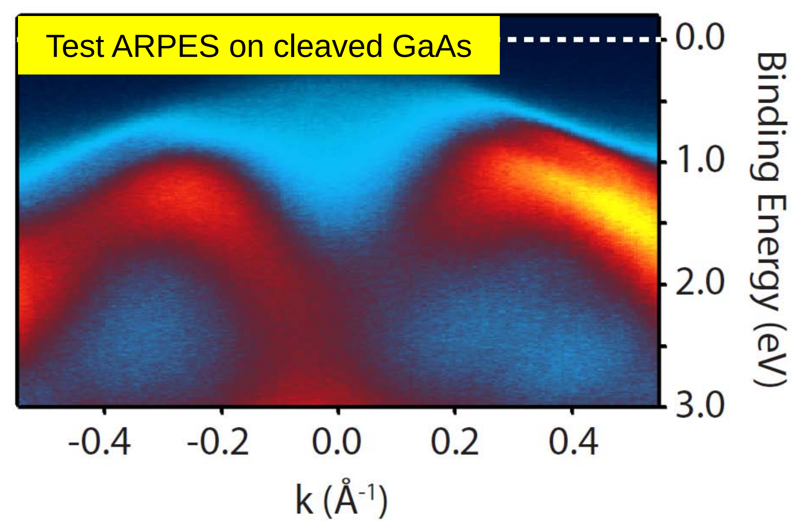
- PhD student (Karkare) has built and commissioned 2D energy analyzer (improved version of APL 78 (2001) 2721): measures longitudinal and transverse electron distributions simultaneously using magnetic field immersion & adiabatic invariant (can do 2meV);
- Collaboration with ARPES (K. Shen) group on campus;



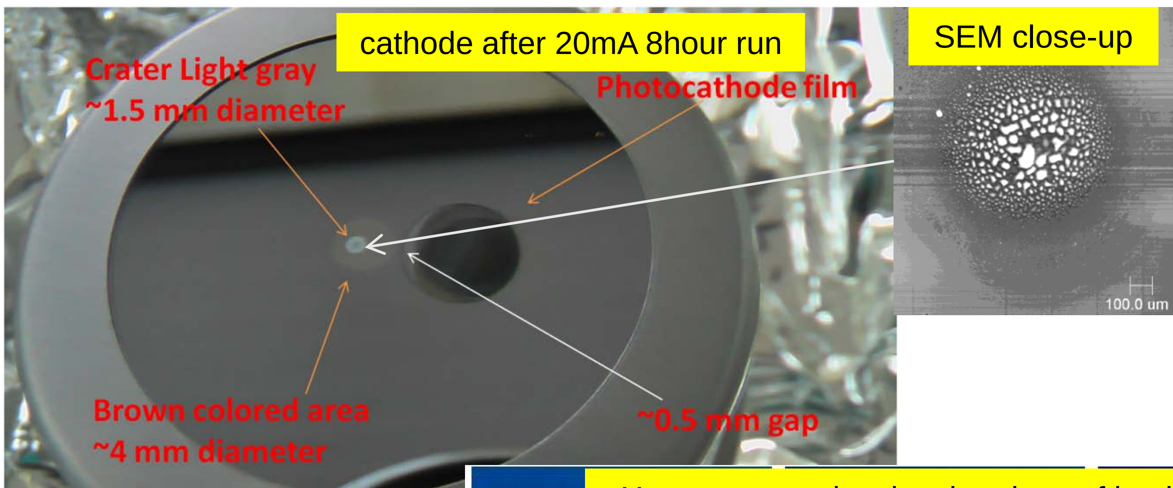


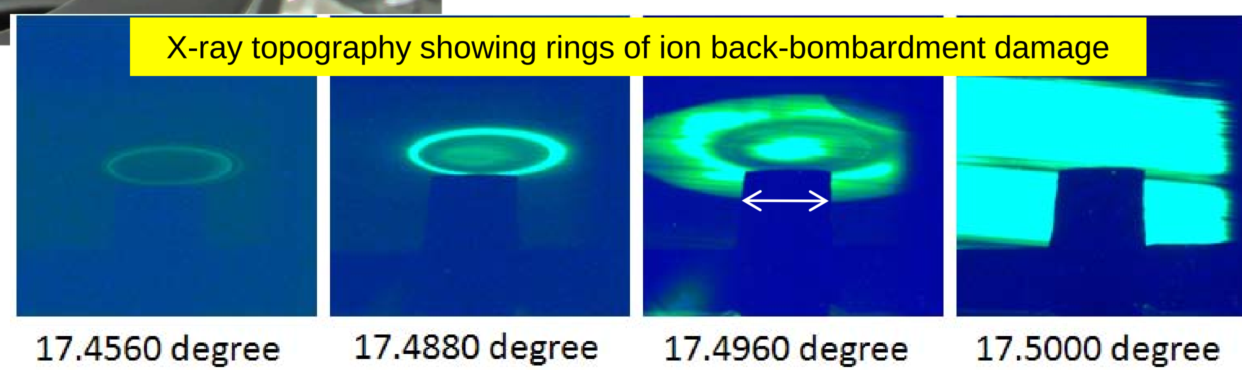
- New collaborative effort with Tech-X (SBIR) on NEA theory



Real-life accelerator testing: high average current

- **Always remember where these cathodes end up (i.e. it's not enough to write papers, our job is to make the accelerator work!). Example of a *real* cathode that delivered ~1000C.**

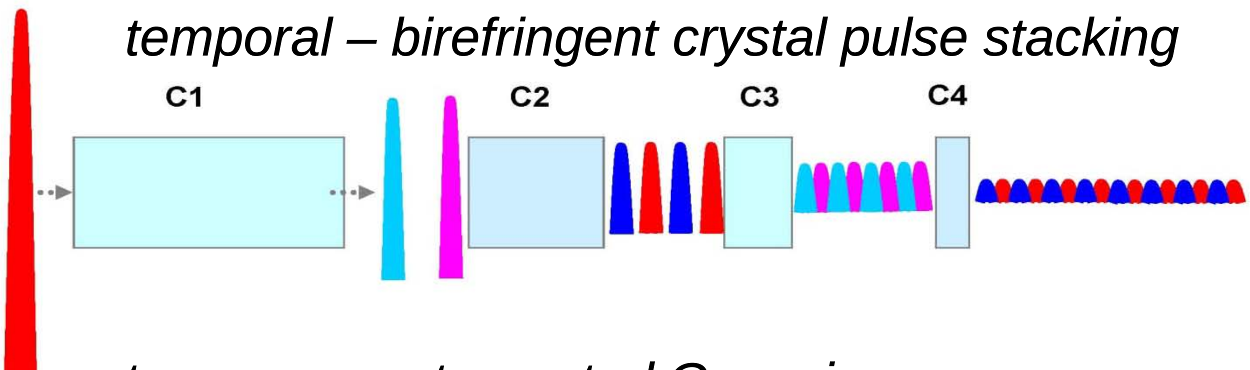




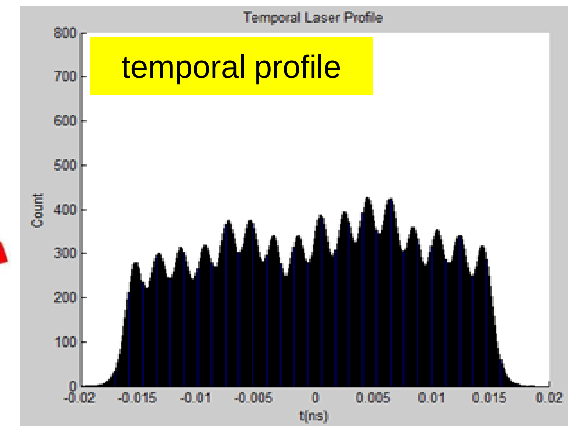
3D laser shaping for space charge control

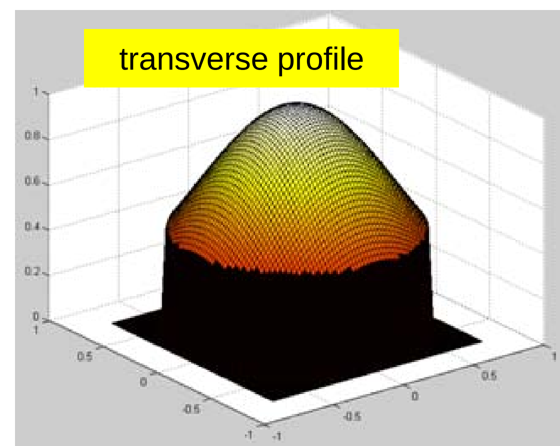
- **Space charge can quickly ruin beam brightness; full 3D space charge simulations are used to arrive at an optimal laser shape**
- **Practical solution identified:**

temporal – birefringent crystal pulse stacking



transverse – truncated Gaussian



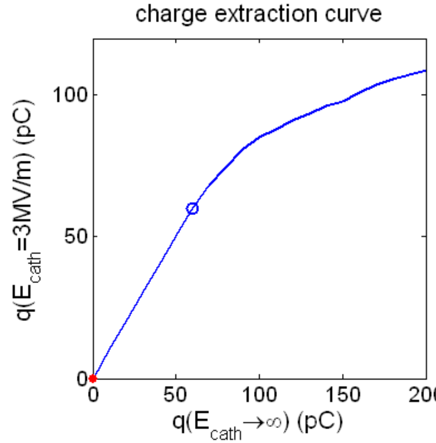


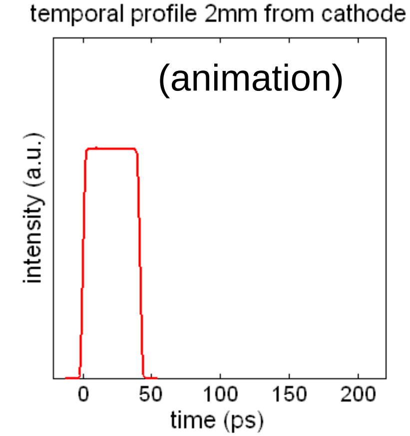
- **>50% of light gets through, emittance (sims) <20% higher than the optimal**

PRSTAB 11 (2008) 040702
Appl. Opt. 46 (2011) 8488

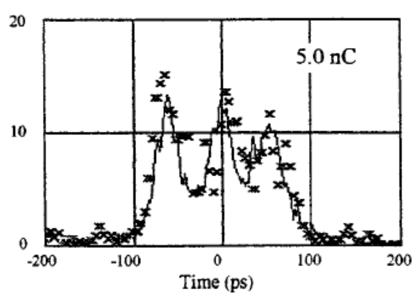
Virtual cathode instability

- Regime in which created charge exceeds charge induced on the surface of the photocathode by external electric field;
- Initial work by Dowell and UMD, very little known about transverse dynamics implications;
- Need both transverse and longitudinal diagnostics to unravel the phenomenon.

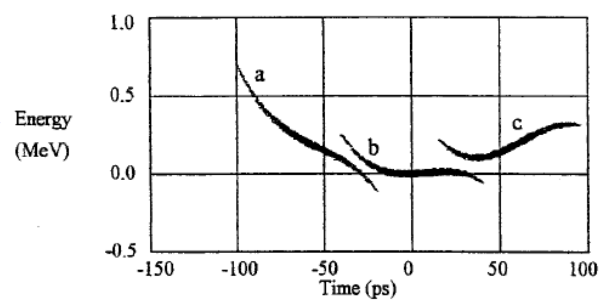




e.g. Phys. Plasmas 4 (1997) 3369



smart guesswork →



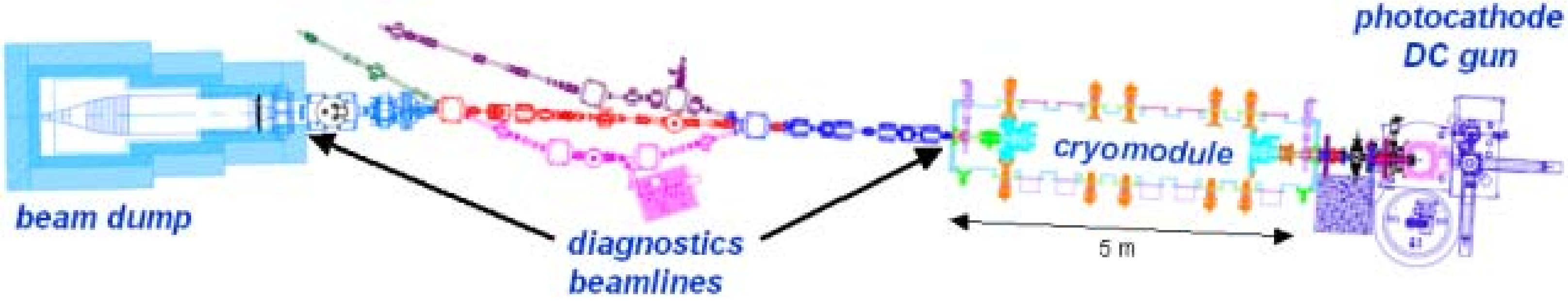
5 nC per micropulse
1300 amperes/cm^2 Peak Current Density

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

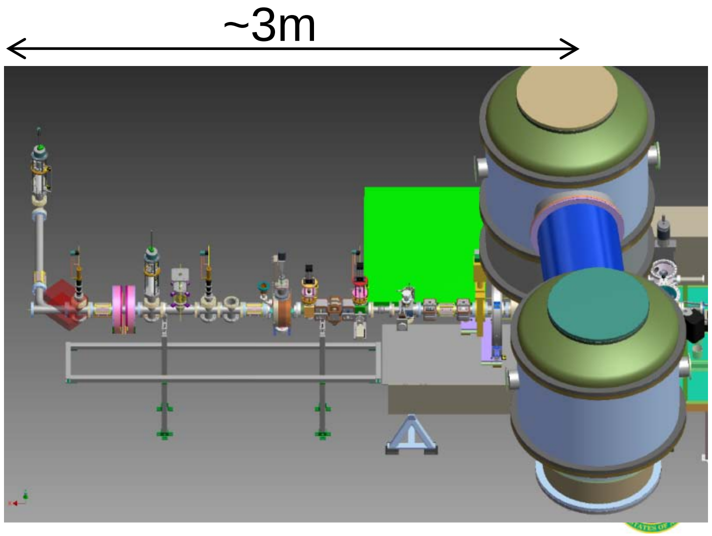
a = 5.9x10-5 MeV/ps^2
b = -2.8x10-6 MeV/ps^3

Accelerator test-beds

- **Two accelerator facilities @Cornell to make these studies possible: NSF supported 100mA 5-15 MeV photoinjector;**



- **New 500kV photoemission gun & diagnostics beamline (under construction): the main playground for a PhD student (Maxson)**



Diagnostics capabilities + sim (showing those relevant to this project)

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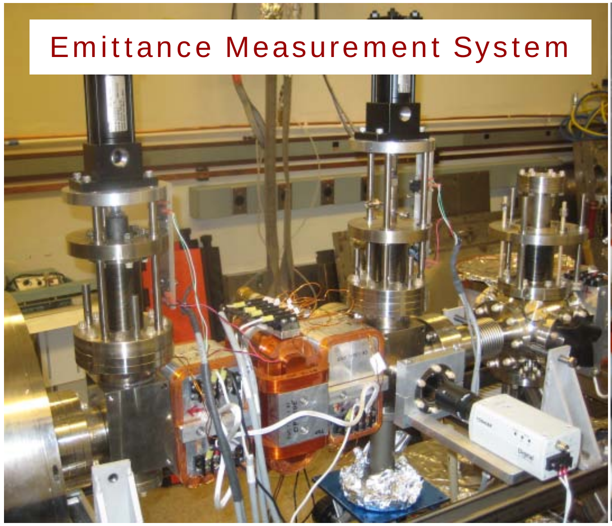
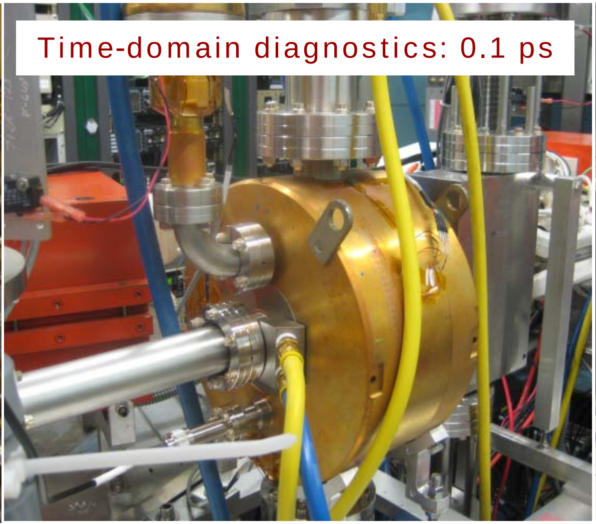
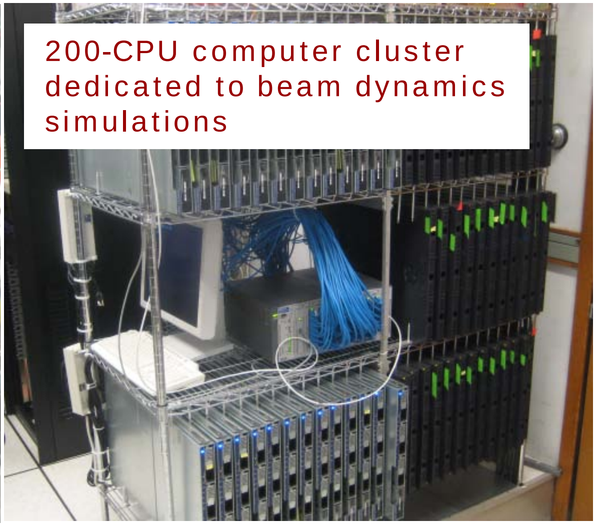
- Simultaneous 6D (transverse + longitudinal phase space) diagnostic

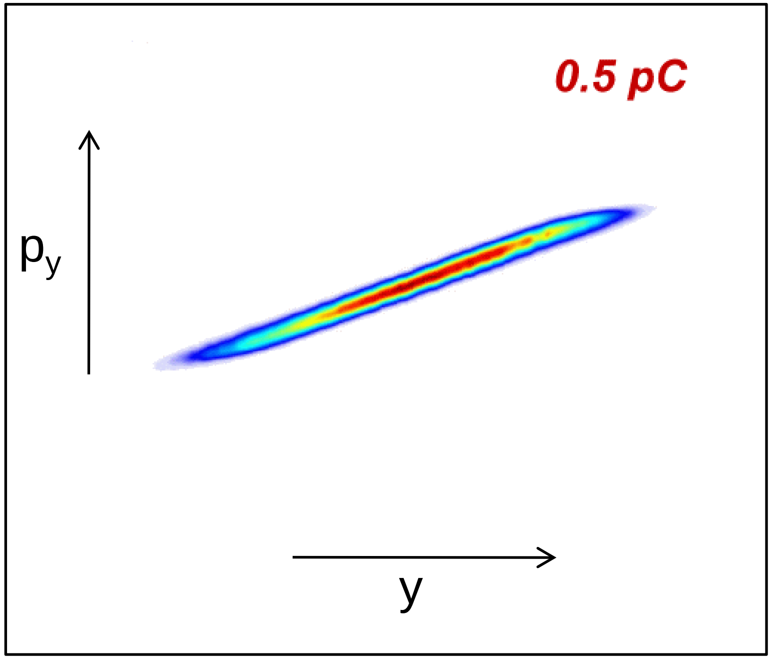




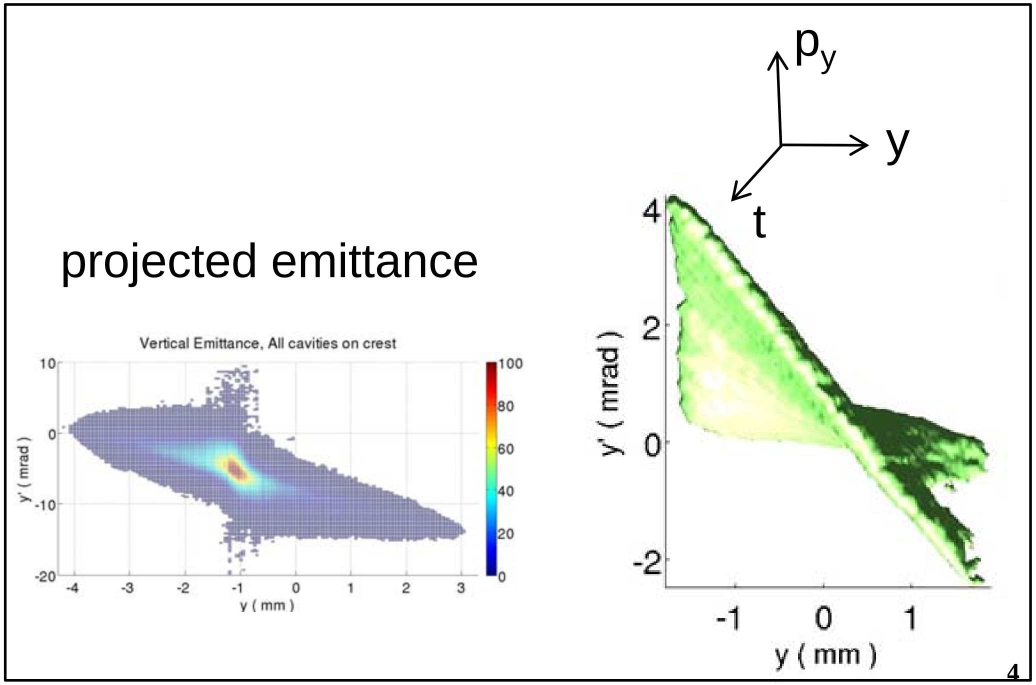


Some examples of measurements

transverse phase space (animation)



slice emittance with resolution of few 0.1ps



Education:
training the future work force

- **Cornell maintains a strong PhD program in accelerator physics (presently 11 PhD students, 2 of them enabled by this CAREER grant);**
- **50 undergrads/year go through CLASSE, vast majority of them moves on to other places in the country after they graduate (5 undergrads involved this year in this CAREER research, and 2 REUs this summer);**
- **A long list of former Cornell graduates who are now in leadership positions throughout the DOE labs.**

It matters…

Building collaboration on photocathodes (and not only) for accelerators

CLASSE

- **Collaboration with**
  - ANL
  - BNL
  - JLAB
  - SLAC
  - Berkeley
- **Co-organized first workshop "Photocathode Physics for Photoinjectors" at BNL;**
- **Excitement and momentum in the community;**
- **Next workshop at Cornell;**
- **Leading the effort on creating collaborative community-driven Internet resource;**

Key CAREER Crew

CLASSE

Siddharth Karkare
PhD student
CAREER 100% support

Dr. Luca Cultrera
Research Associate
CAREER 40% support

Jared Maxson
PhD Student
(NSF PhD fellowship)

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  - John Barley, Adam Bartnik, Joe Conway, John Dobbins, Bruce Dunham, Colwyn Gulliford, Xianhong Liu, Yulin Li, Heng Li, Florian Loehl, Roger Kaplan, Val Kostroun, Tobey Moore, Vadim Vescherevich, Peter Quigley, John Reilly, Karl Smolenski, Zhi Zhou, and more.
- Undergrads
  - Yoon Woo Hwang, Rick Merluzzi, Ben Pichler, Ashwathi Iyer, William Roussel, Morgan Dixon, Matt Nichols
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