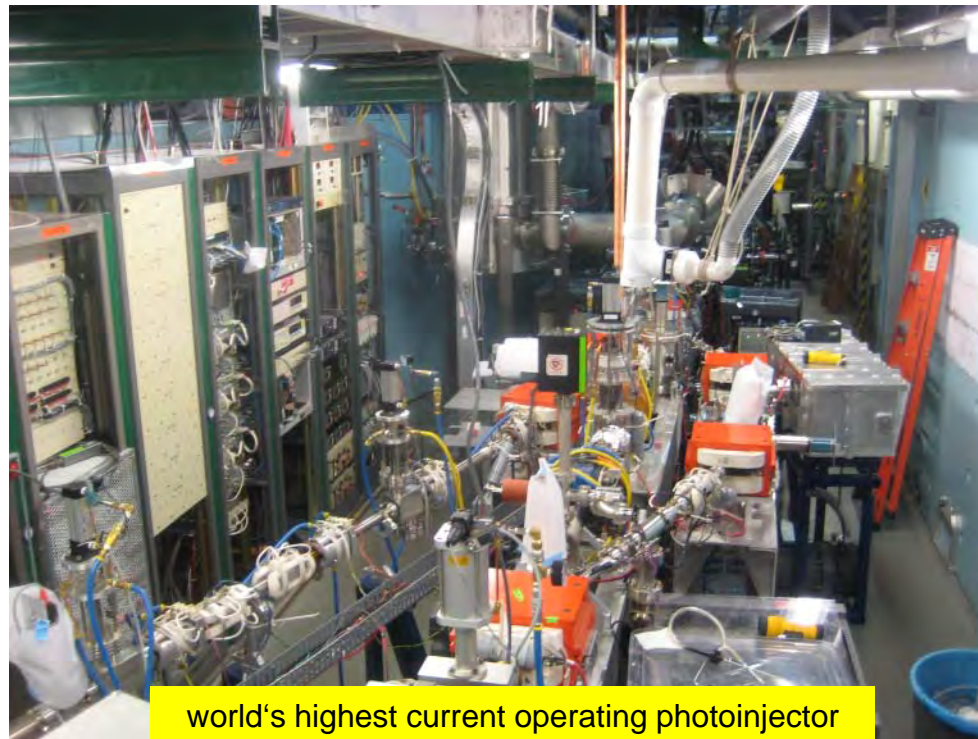


## Extending science and technology behind high brightness and duty-factor photoinjectors

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

**Ivan Bazarov**  
**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.



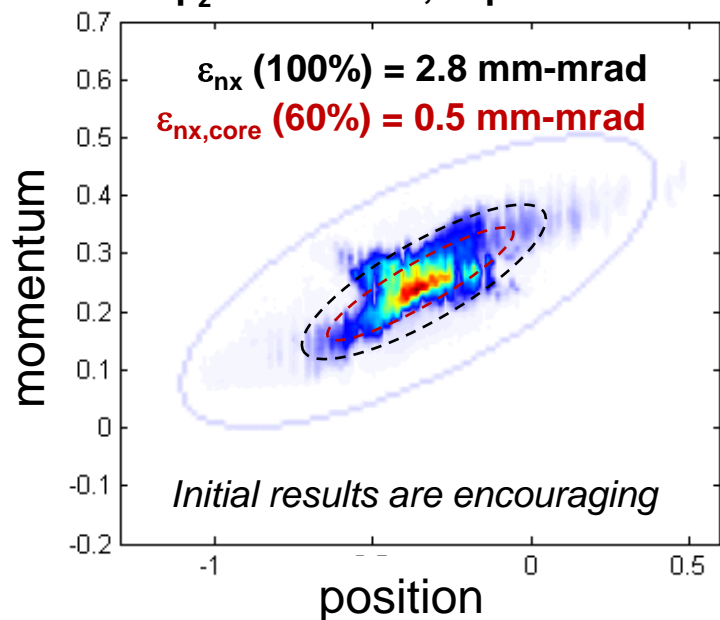
# Avg. beam brightness: current/flux density in phase space



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

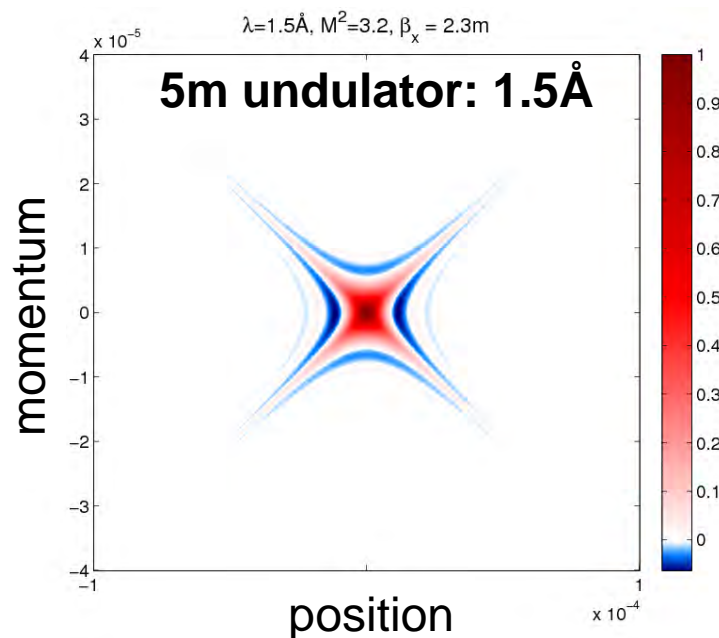
## *Electron beam*

$p_z = 5.2 \text{ MeV/c}$ , 80pC/bunch



+

## *X-ray beam*



# Physics 101: basic limit to beam brightness from photoinjectors



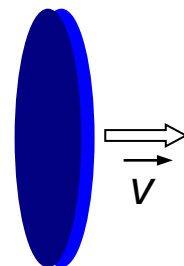
- Each electron bunch assumes a **'pan-cake' shape** near the photocathode for short ( $\leq 10\text{ps}$ ) laser pulses
- Maximum **charge density** determined by the electric field:

$$dq/dA = \epsilon_0 E_{\text{cath}}$$

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

$$\left. \frac{B_n}{f} \right|_{\text{max}} = \frac{\epsilon_0 mc^2}{2\pi} \frac{E_{\text{cath}}}{\text{MTE}}$$

$$\epsilon_{n\perp} = \sqrt{\frac{3}{10\pi\epsilon_0 mc^2} q \frac{\text{MTE}}{E_{\text{cath}}}}$$

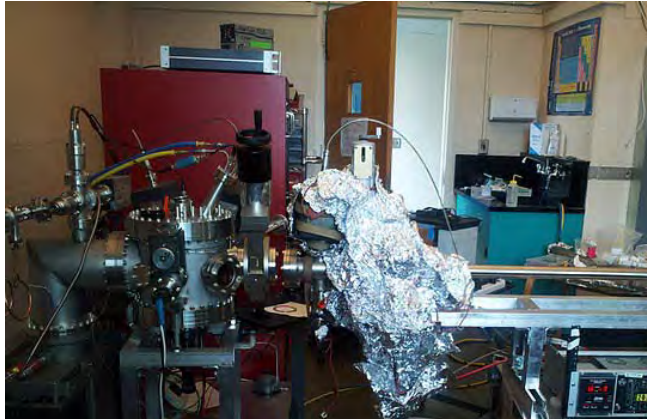


PRL 102, 104801 (2009)

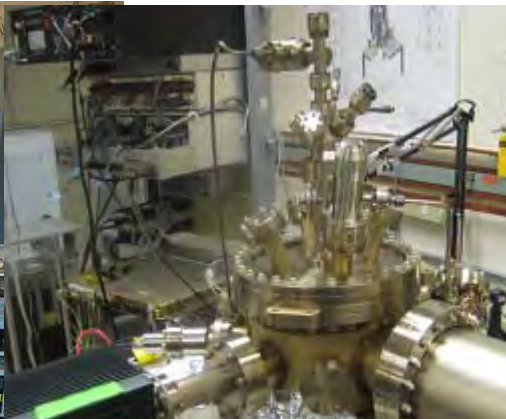




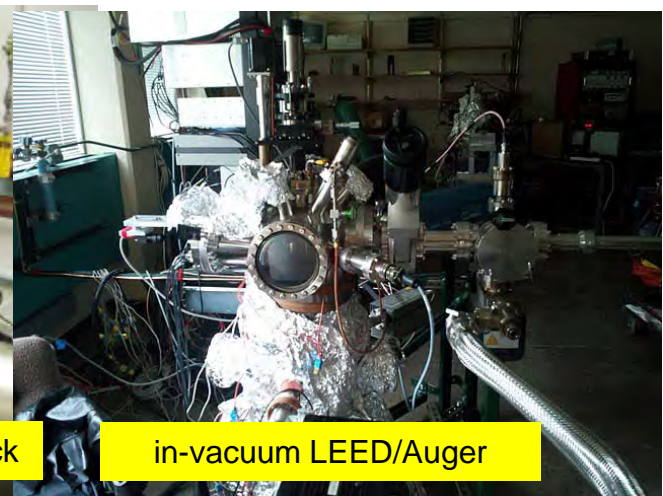
# Photocathode research capabilities at Cornell



multialkali growth chamber with vacuum suitcase



GaAs system with load-lock



in-vacuum LEED/Auger



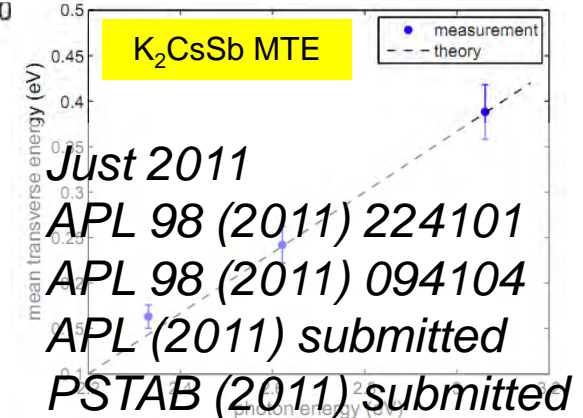
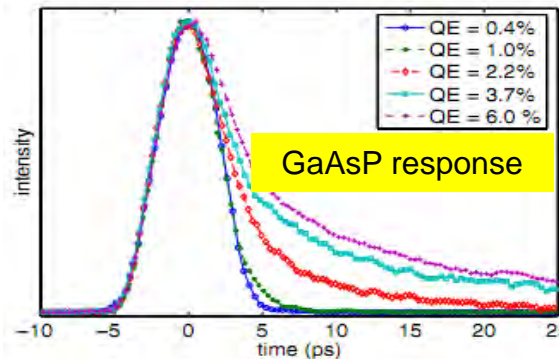
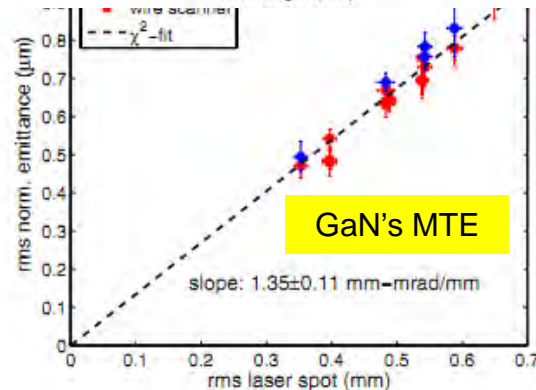
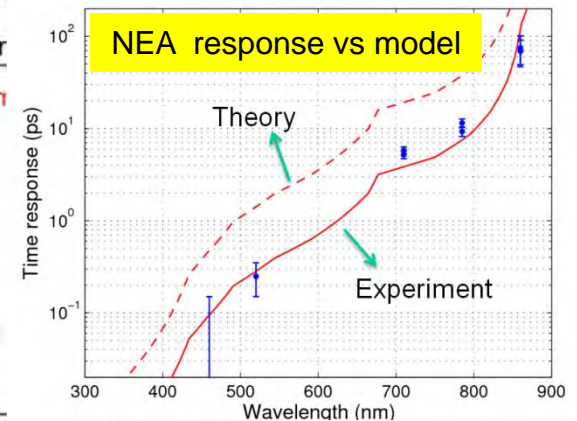
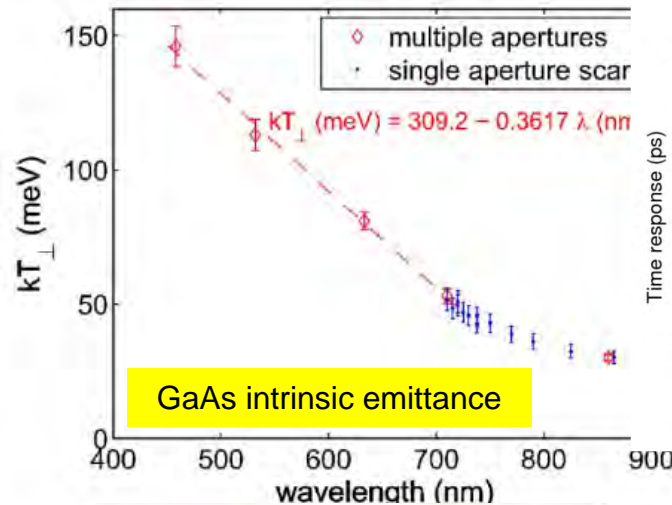
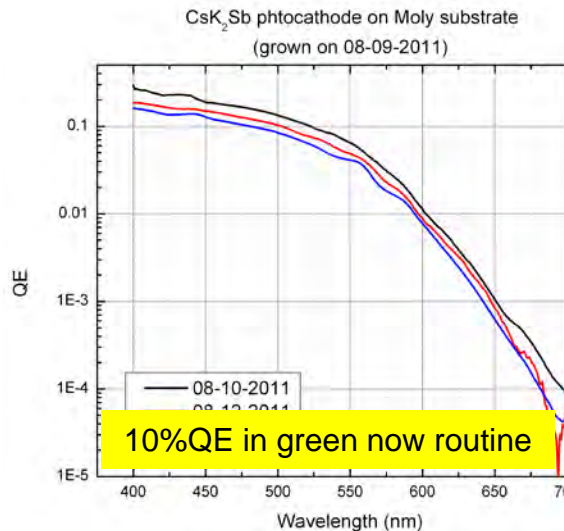
MBE III-V system (work in progress, looking for personnel support funds)

- Also on campus  
AFM, EDX, SEM,  
STM, SIMS, ARPES
- + CHES (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<sub>3</sub>Sb, K<sub>2</sub>CsSb



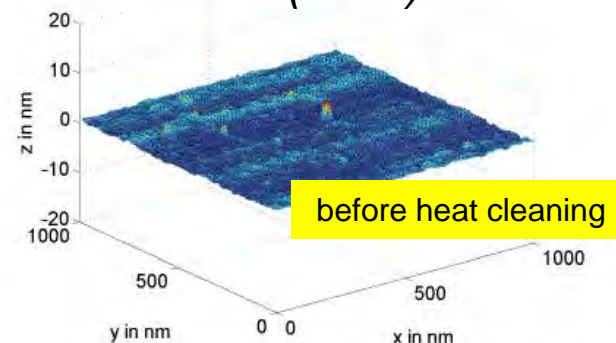


# Photocathode physics: some mysteries

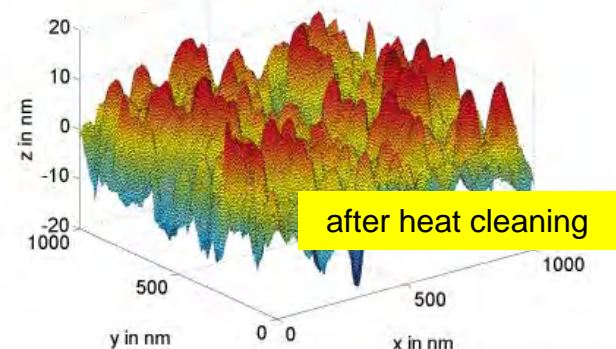
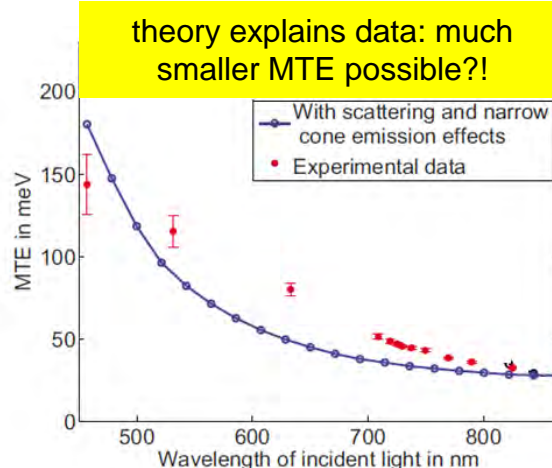
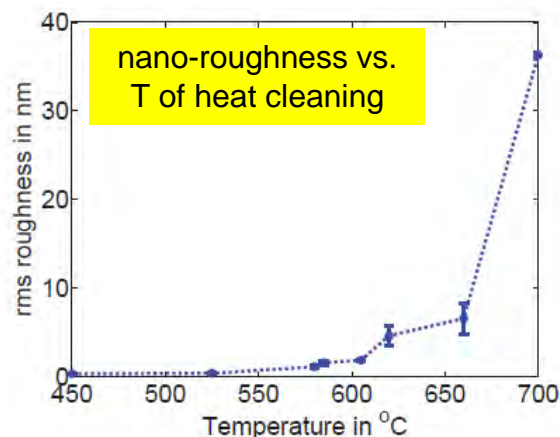


- Due to small effective mass of  $\Gamma$  valley electrons, theory predicts MTE as low as 2meV in at 800nm for GaAs
- Some groups have observed these small MTE values, but most do not (including us). Why??
- Possible causes – surface roughness and different structure of Cs/F layer

PAC'11, THP192  
APL 98 (2011) 094104



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



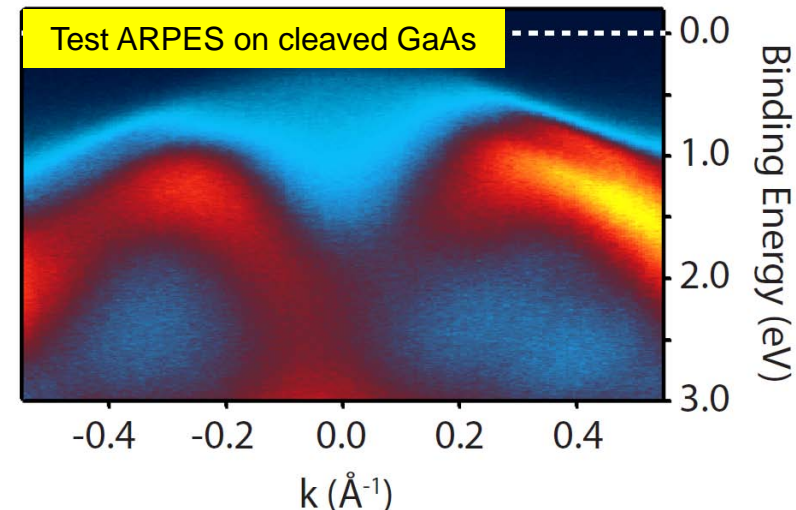
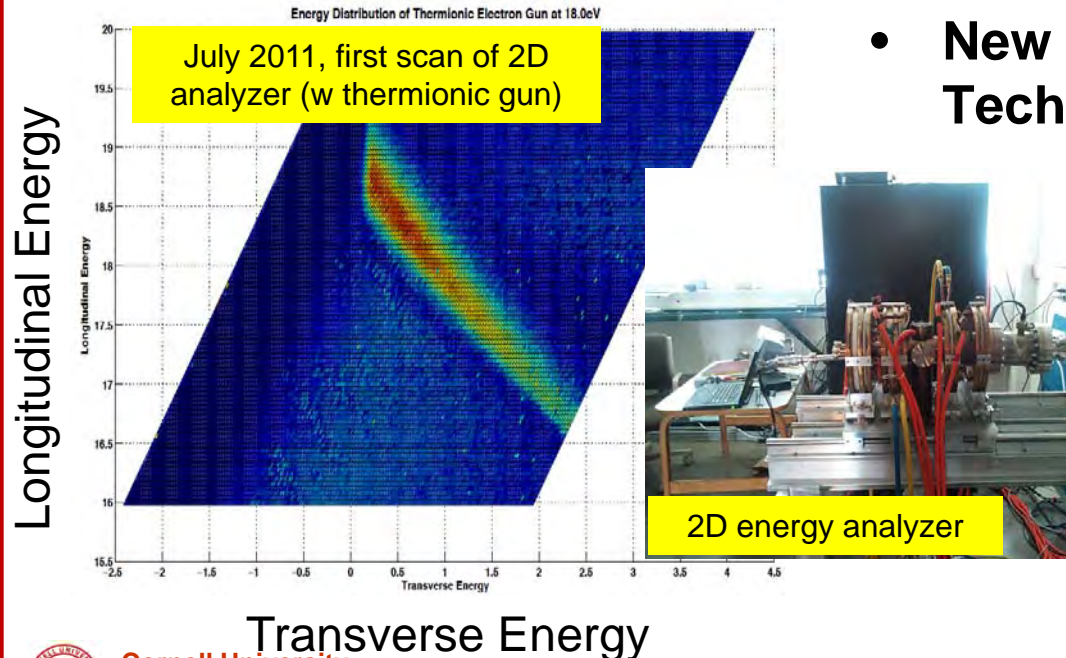
(b) Surface of heat cleaned and activated GaAs crystal used in the Cornell dc photoemission gun (rough surface)



# Photocathode research: putting experiment & theory together



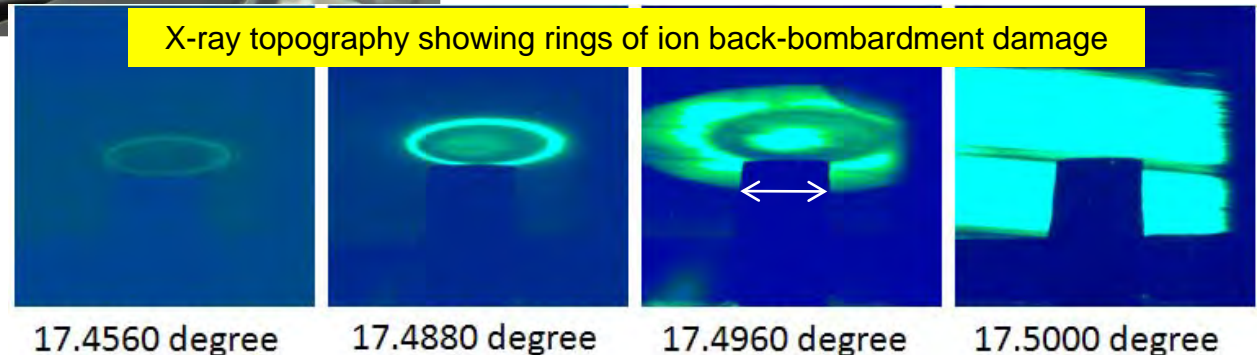
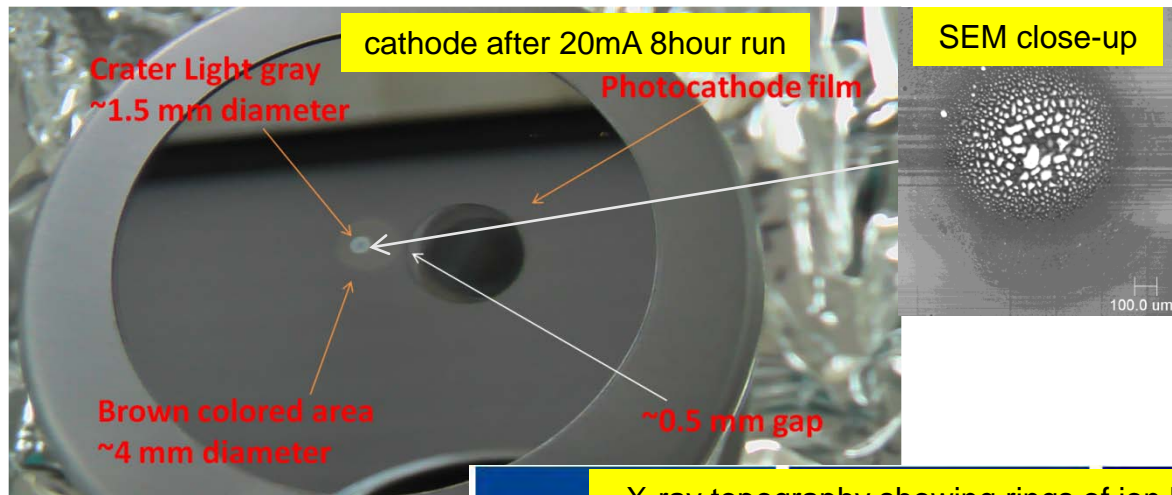
- PhD student (Karkare) has built and commissioned **2D energy analyzer** (improved version of APL 78 (2001) 2721): measures longitudinal and transverse electron distributions simultaneously using magnetic field immersion & adiabatic invariant (can do 2meV);
- Collaboration with ARPES (K. Shen) group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





# Real-life accelerator testing: high average current

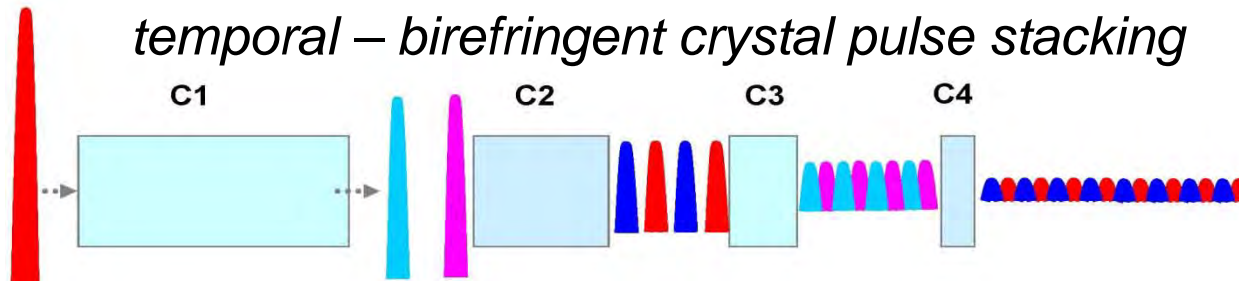
- Always remember where these cathodes end up (i.e. it's not enough to write papers, our job is to make the accelerator work!). Example of a real cathode that delivered ~1000C.



# 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*

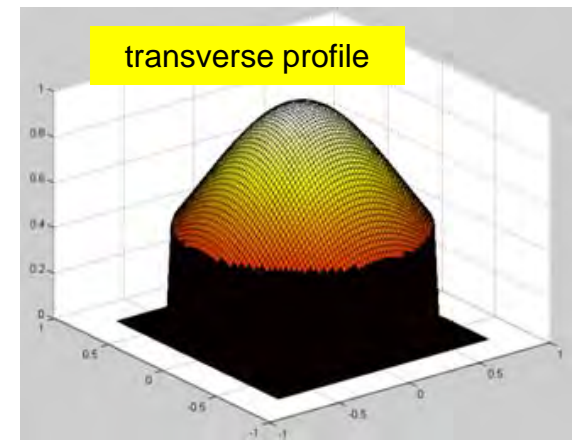
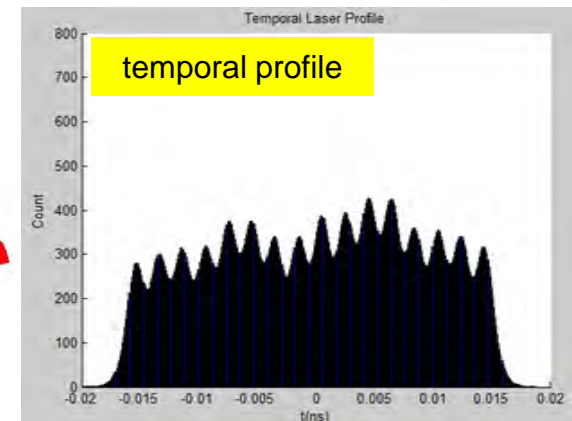


*transverse – truncated Gaussian*

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

PRSTAB 11 (2008) 040702

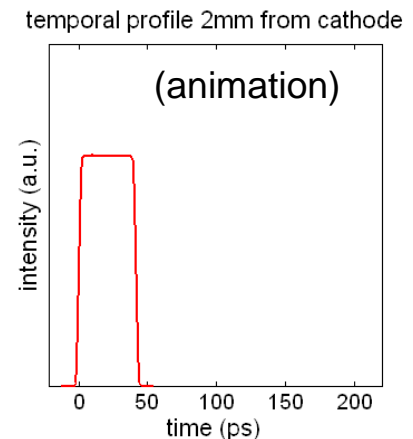
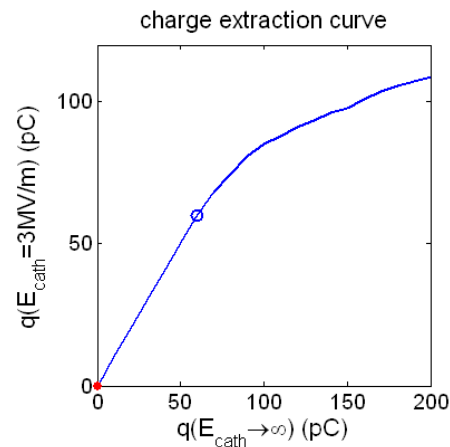
Appl. Opt. 46 (2011) 8488



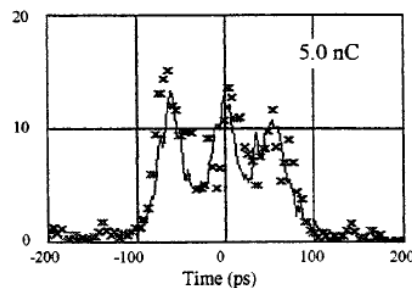
# Virtual cathode instability



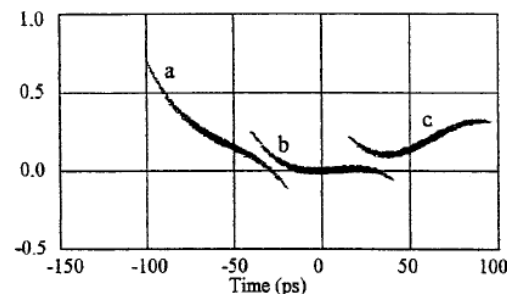
- Regime in which created charge exceeds charge induced on the surface of the photocathode by external electric field;
- Initial work by Dowell and UMD, very little known about transverse dynamics implications;
- Need both transverse and longitudinal diagnostics to unravel the phenomenon.



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



smart  
guesswork → Energy (MeV)



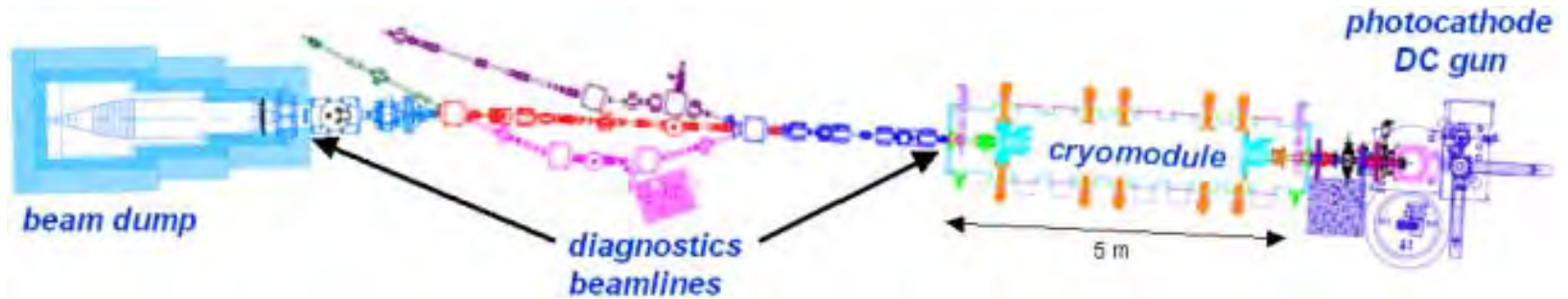
5 nC per micropulse  
1300 amperes/cm<sup>2</sup> Peak Current Density

$\tau_{11}^a = 1600$	$\tau_{11}^b = 1600$	$\tau_{11}^c = 1600$	ps <sup>2</sup>
$\tau_{12}^a = -9$	$\tau_{12}^b = 1$	$\tau_{12}^c = 9$	ps-MeV
$\tau_{22}^a = 0.051$	$\tau_{22}^b = 0.0012$	$\tau_{22}^c = 0.051$	MeV <sup>2</sup>
$a = 5.9 \times 10^{-5} \text{ MeV/ps}^2$			
$b = -2.8 \times 10^{-6} \text{ MeV/ps}^3$			

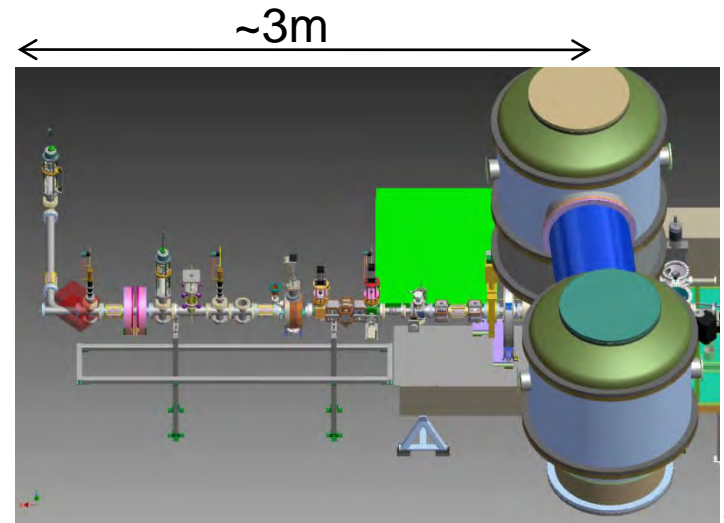


# Accelerator test-beds

- 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)

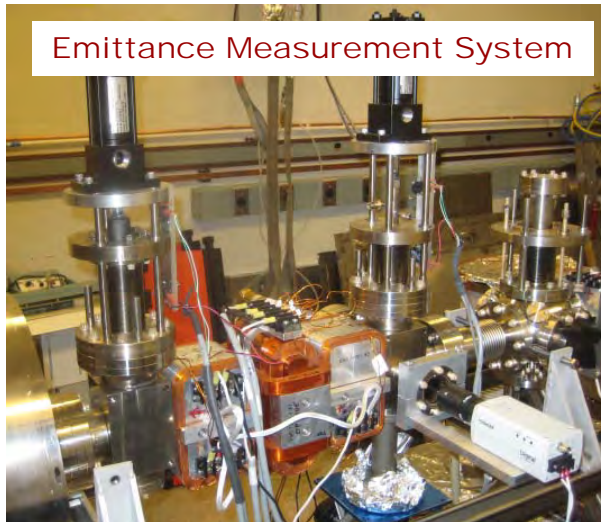




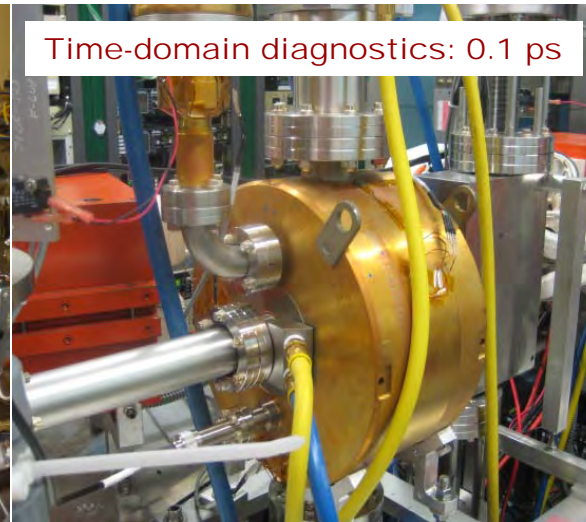
# Diagnostics capabilities + sim (showing those relevant to this project)



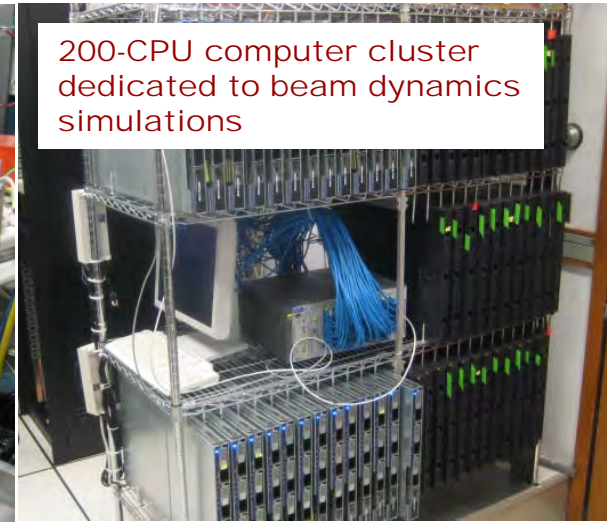
- **Simultaneous 6D (transverse + longitudinal phase space) diagnostic**



Emittance Measurement System



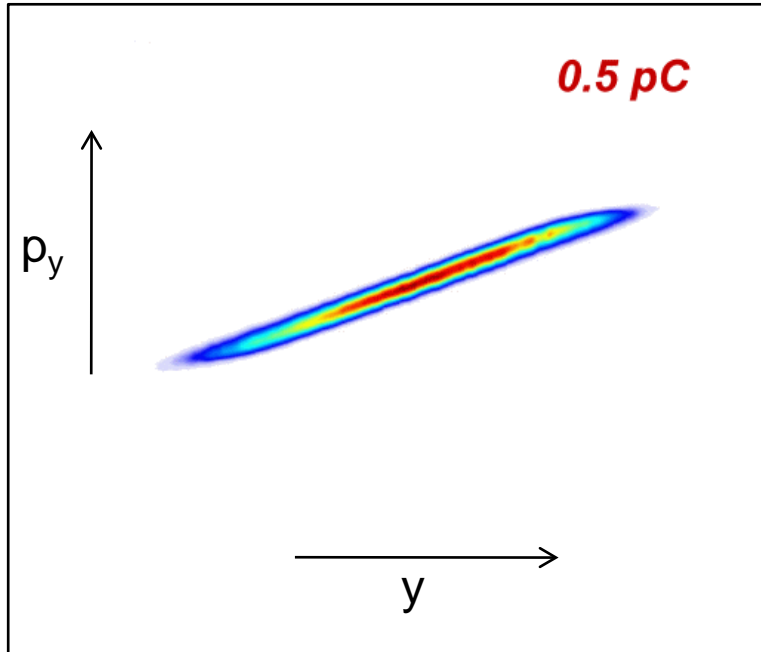
Time-domain diagnostics: 0.1 ps



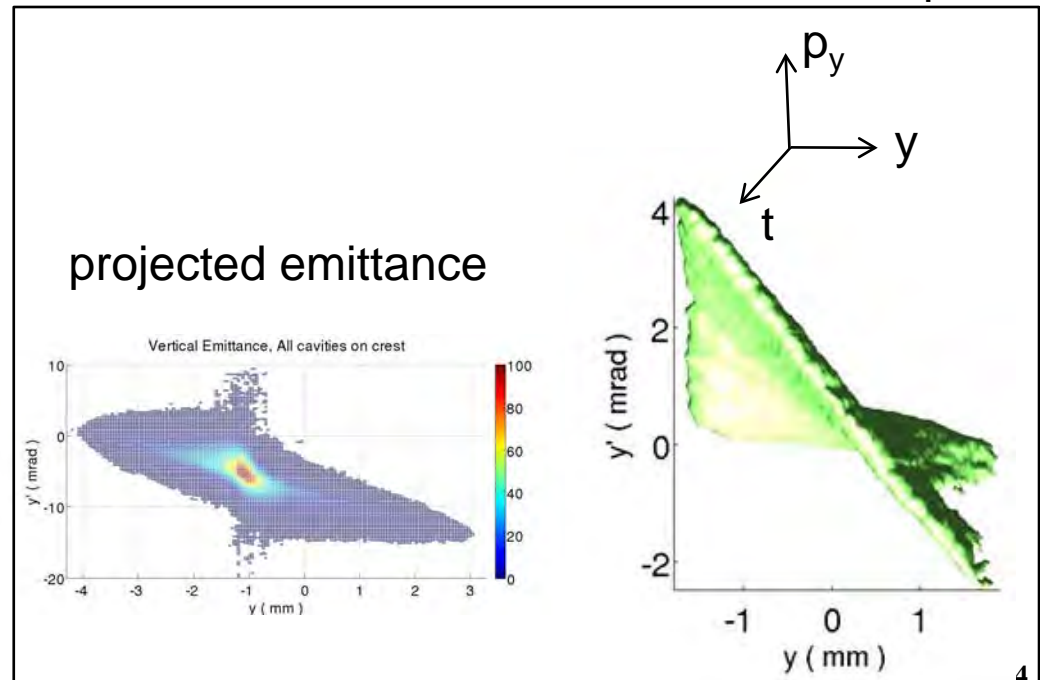
200-CPU computer cluster  
dedicated to beam dynamics  
simulations

# Some examples of measurements

transverse phase space (animation)



slice emittance with resolution of few 0.1ps



# Education: training the future work force

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- 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



- 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;



## Photocathode Physics for Photoinjectors

Registration is now closed...  
Motivation

Photoinjectors are a critical research area for modern accelerators, from ultra-high peak brightness machines to the next generation of these devices. These devices are required to provide temporal and spatial response and polarization control. The workshop (October 12-14, 2010) will explore the current state of the art, provide a theoretical and a practical overview, and discuss future opportunities for cathode research.

Event Date  
October 12-14, 2010  
Event Location

## 2nd workshop





# Key CAREER Crew



**Siddharth Karkare**  
PhD student  
CAREER 100% support



**Dr. Luca Cultrera**  
Research Associate  
CAREER 40% support



**Jared Maxson**  
PhD Student  
(NSF PhD fellowship)



# Acknowledgements



- **The entire ERL injector team**
  - 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
- **NSF DMR-0807731 for ERL R&D support**
- **And of course, DOE DE-SC0003965 CAREER grant**

