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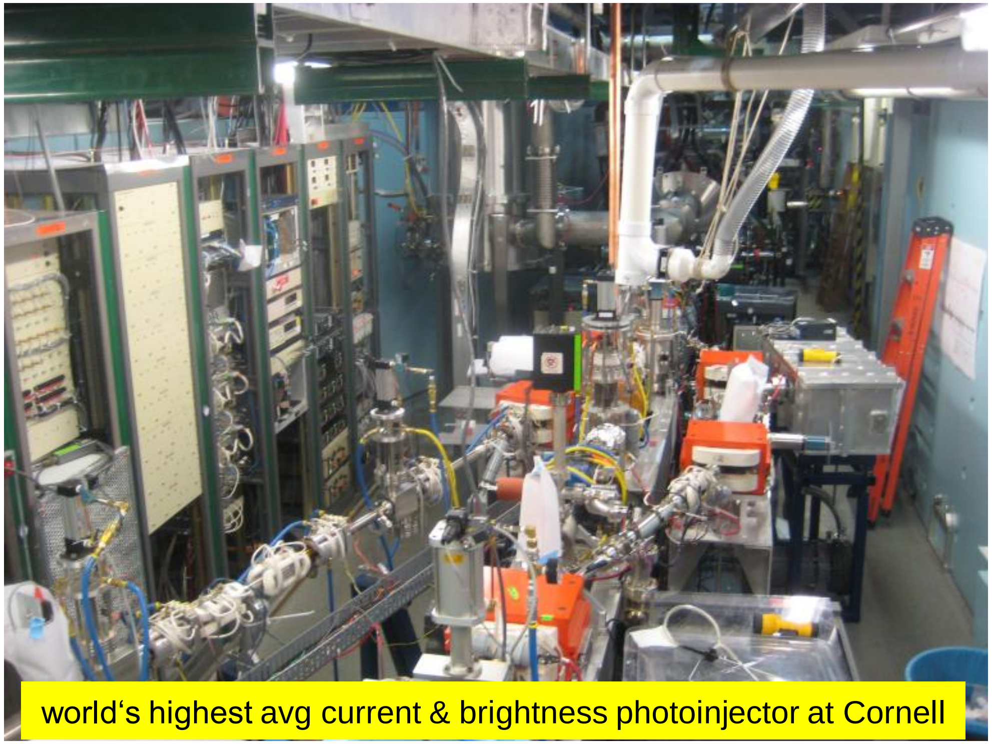
High Brightness Photoinjectors of Tomorrow: Physics of Beam Brightness at the Frontier

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

Ivan V. Bazarov
Cornell University



world's highest avg current & brightness photoinjector at Cornell

Research objectives

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- **Goals:**
  - **Understand fundamental physics and technology limits to high brightness beam production in photoinjectors;**
  - **Cathode research:**
    - **Photoemission physics modeling & measurements of intrinsic mean transverse energy (MTE), response time, and quantum efficiency (QE) of non-metal photocathodes (QE ≥ 5%);**
    - **Explore and engineer novel photocathode materials in real-life accelerator conditions of a high average current photoinjector**
  - **Beam dynamics:**
    - **Realization of the brightness limit from the photoinjector as set by space charge and the photocathode mean transverse energy spread**
    - **Among the physics issues being tackled: virtual cathode instability & adaptive laser shaping for lowest emittance**

Need for high brightness beams

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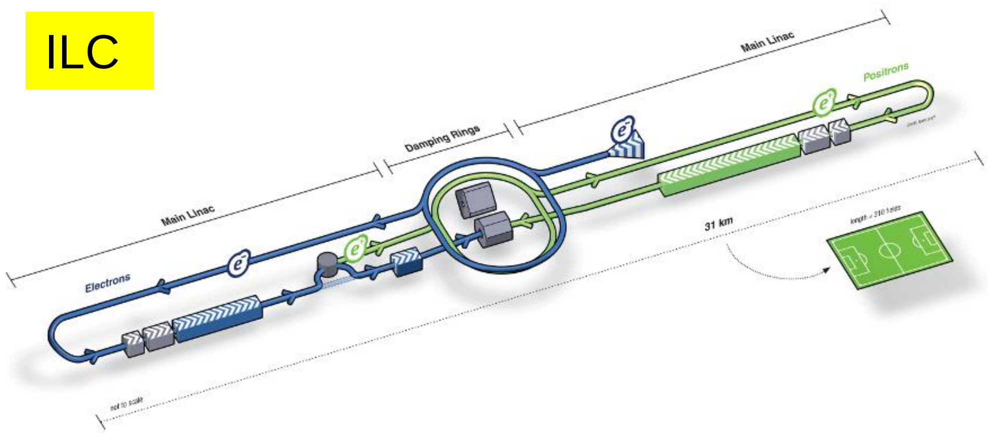
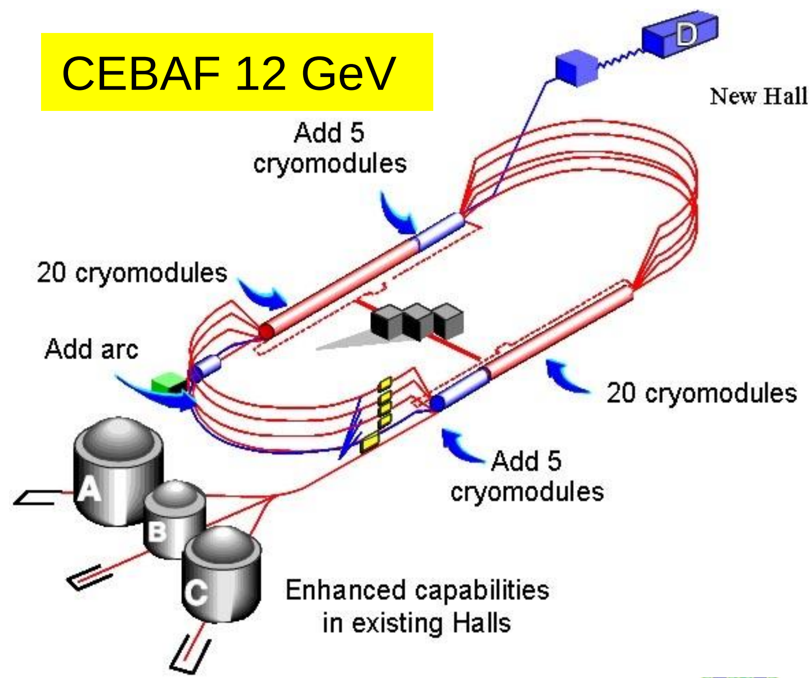
- Powerful probes of matter
  - Colliders, fixed target experiments

ILC



CEBAF 12 GeV



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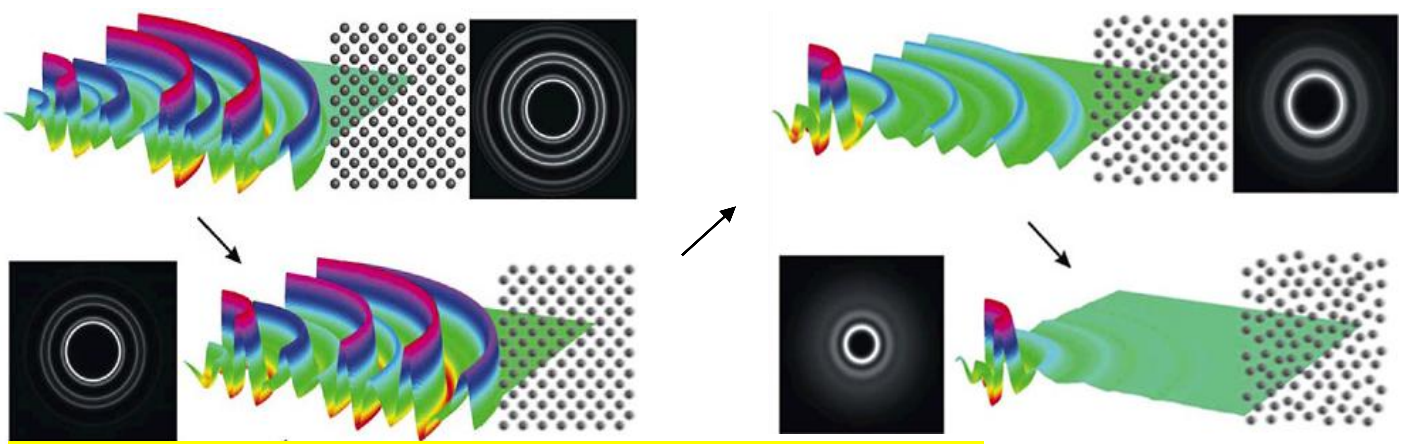
  - **Small lab scale probes (e.g. ultrafast electron diffraction)**



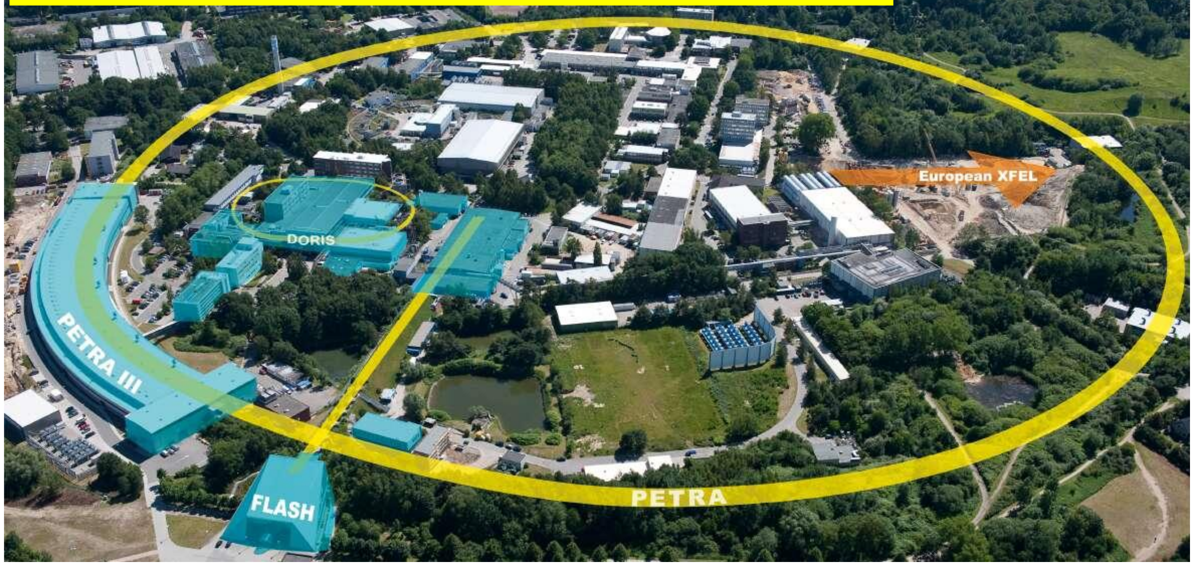
600 fs snapshots of Al melting, Dwayne Miller, U Toronto

Need for high brightness beams

CLASSE

- **Powerful probes of matter**
  - **Colliders, fixed target experiments**
  - **Small lab scale probes (e.g. ultrafast electron diffraction)**
- **Sources of secondary beams**
  - **Synchrotron radiation sources: storage rings, free electron lasers, energy recovery linacs**

Petra-III – world's brightest storage ring



Need for high brightness beams

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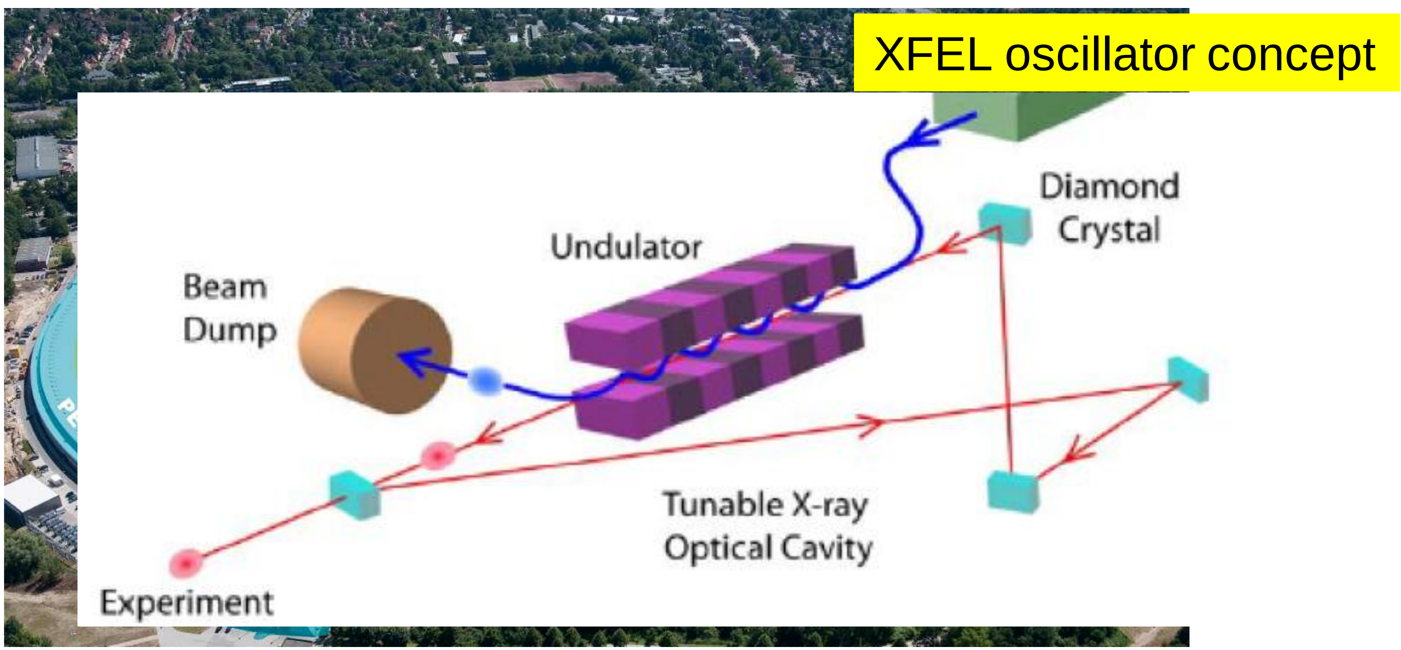

Need for high brightness beams

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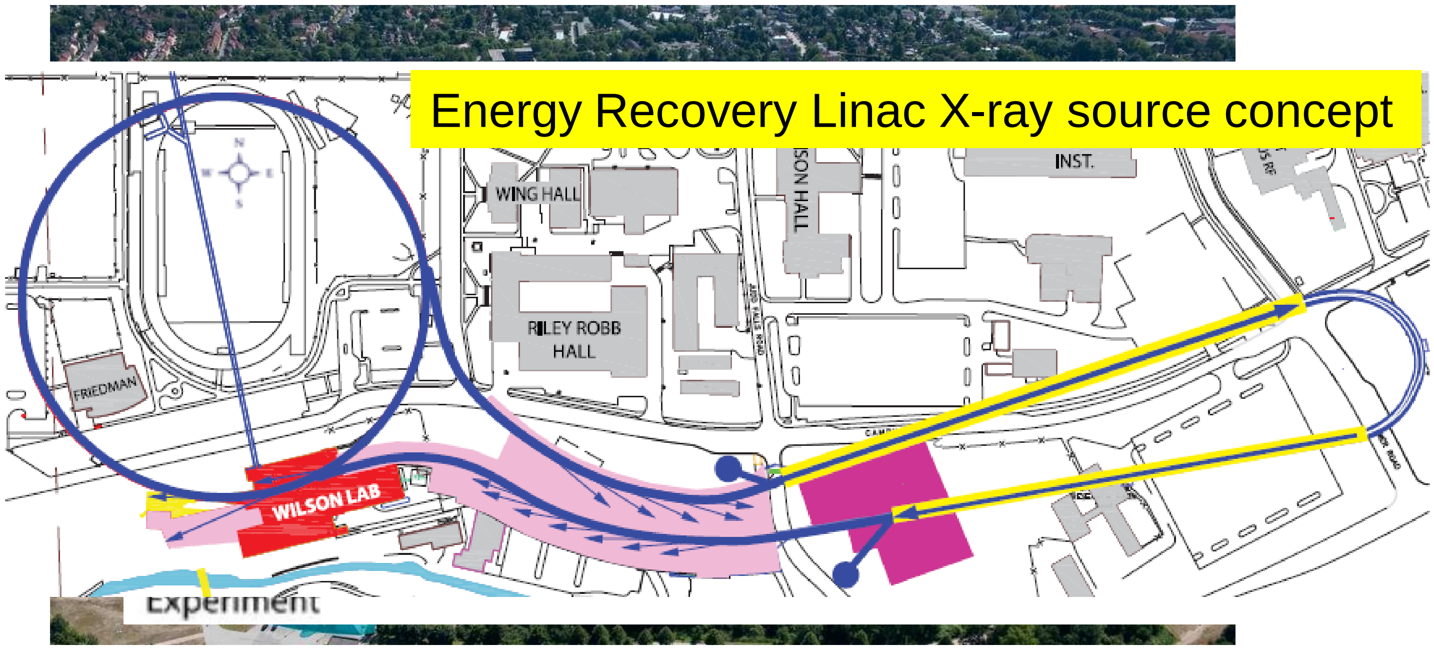

Need for high brightness beams

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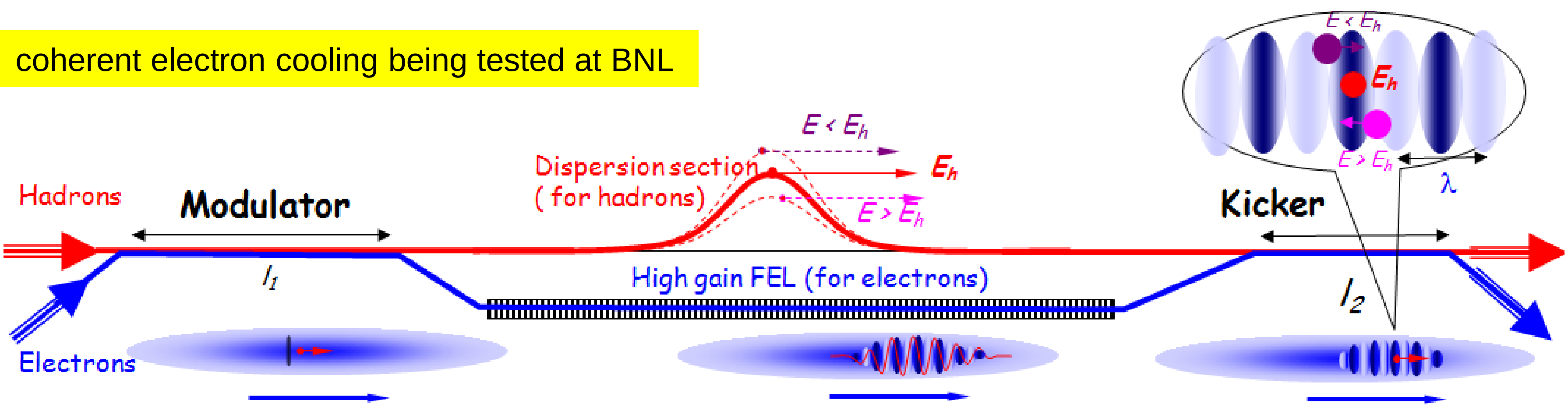
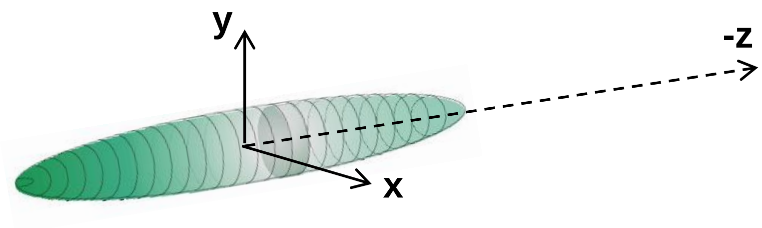
- Powerful probes of matter
  - Colliders, fixed target experiments
  - Small lab scale probes (e.g. ultrafast electron diffraction)
- Sources of secondary beams
  - Synchrotron radiation sources: storage rings, free electron lasers, energy recovery linacs
- Cooling of hadron beams

coherent electron cooling being tested at BNL



What is brightness?

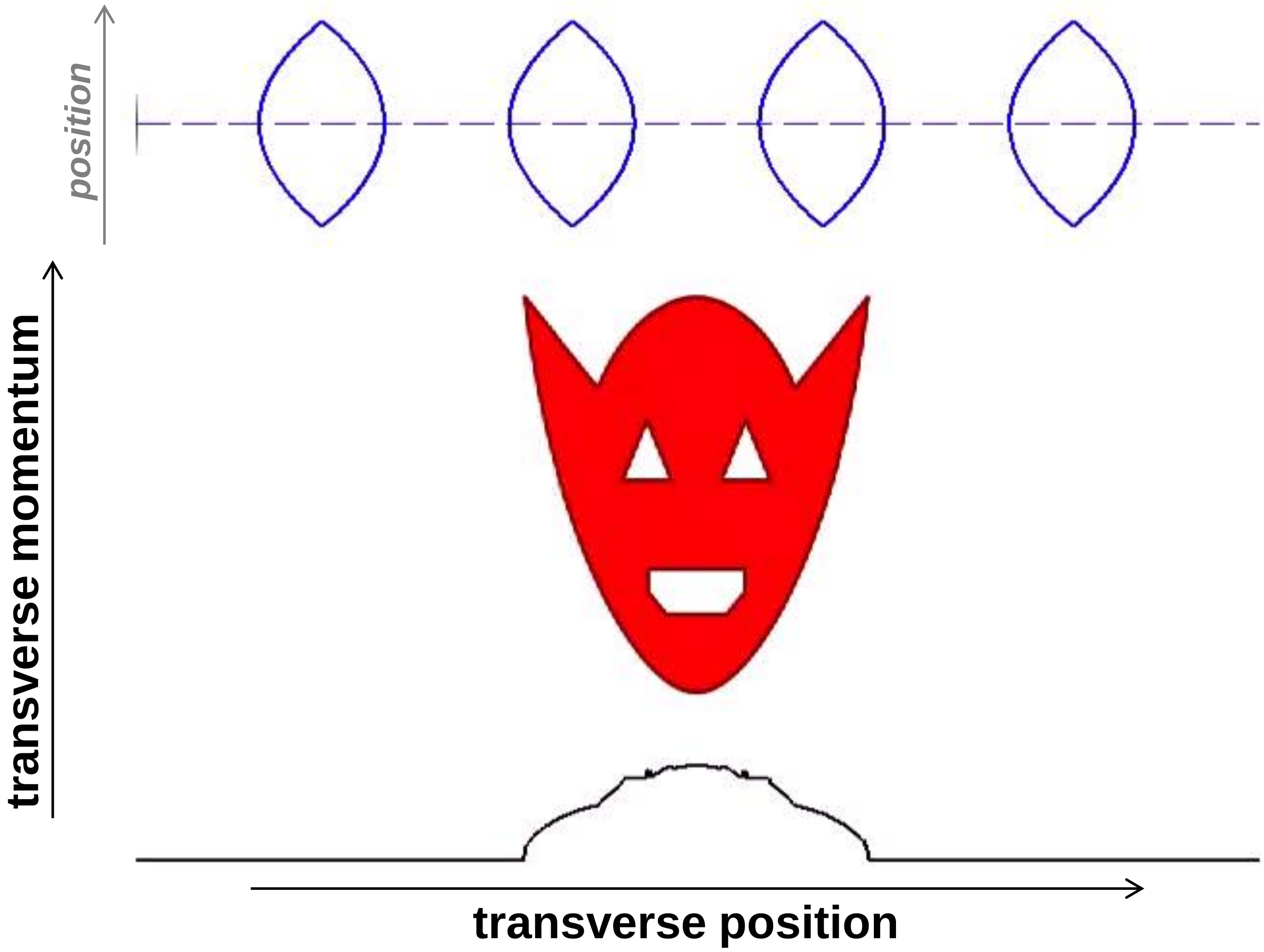


- **6D phase space**
  - **{x, p_x, y, p_y, E, t}**

- $$\mathcal{B}_{4\mathrm{D}} = \frac{\text{flux or current}}{\text{4D phase space volume}}$$

- **Connection to:**
  - **Liouville theorem, beam temperature, entropy, coherence**

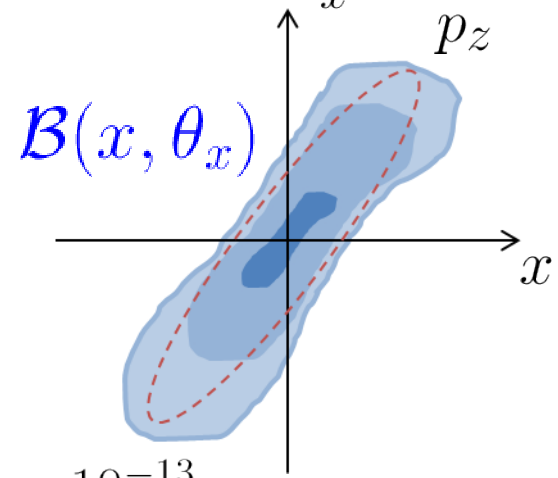
Example: linear optics beamline of non-interacting particles



Some definitions

- **Micro-brightness**: $\mathcal{B}_{\mathrm{2D}}(x,p)$
  - **Flux:** $\mathcal{F} = \iint \mathcal{B}\, dx dp$

$\theta_x \approx \frac{p_x}{p_z}$



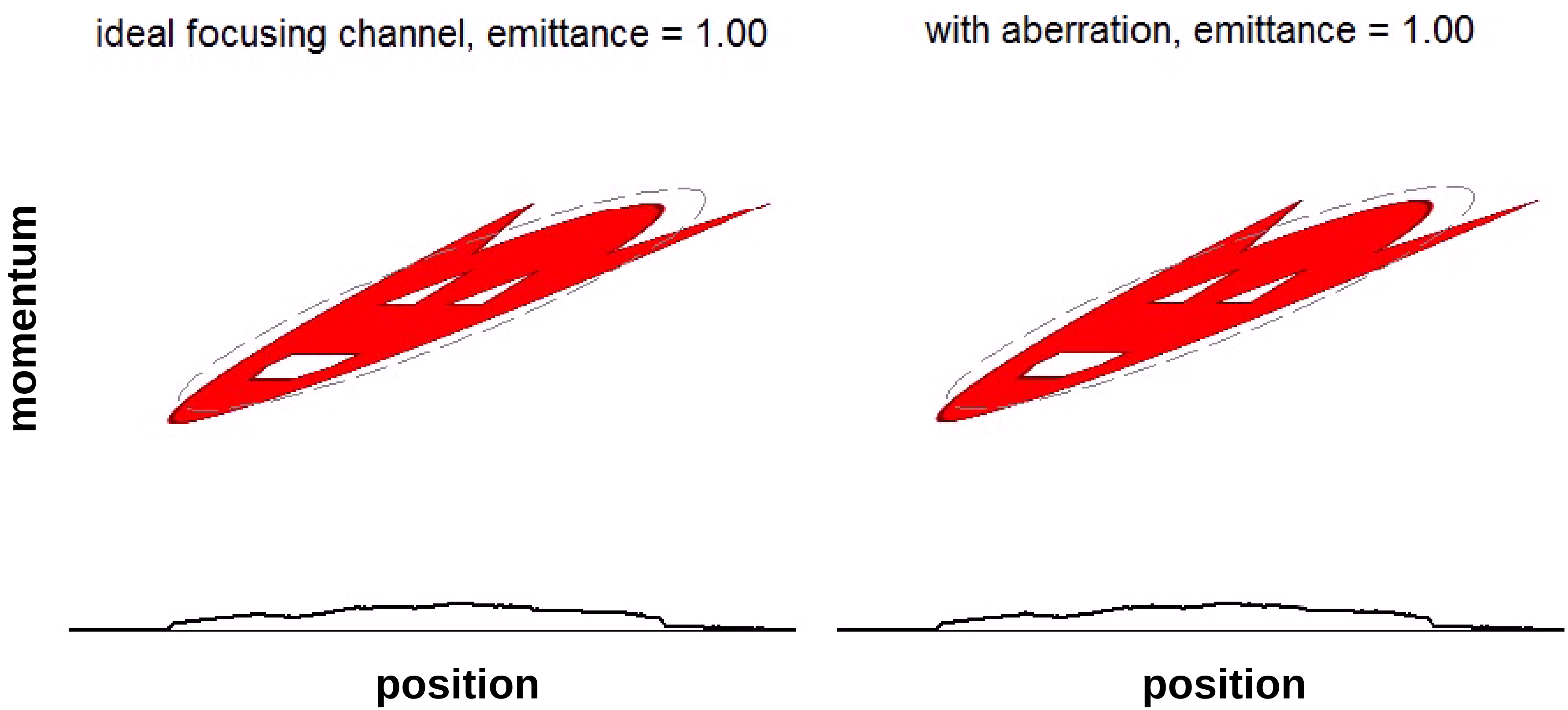
- **Normalized emittance (phase space area)**:

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

  - **e.g. quantum limit for e⁻:** $\epsilon_{\mathrm{norm}} = \frac{\hbar/2}{m_e c} = 1.93\times 10^{-13}\,\mathrm{m}$

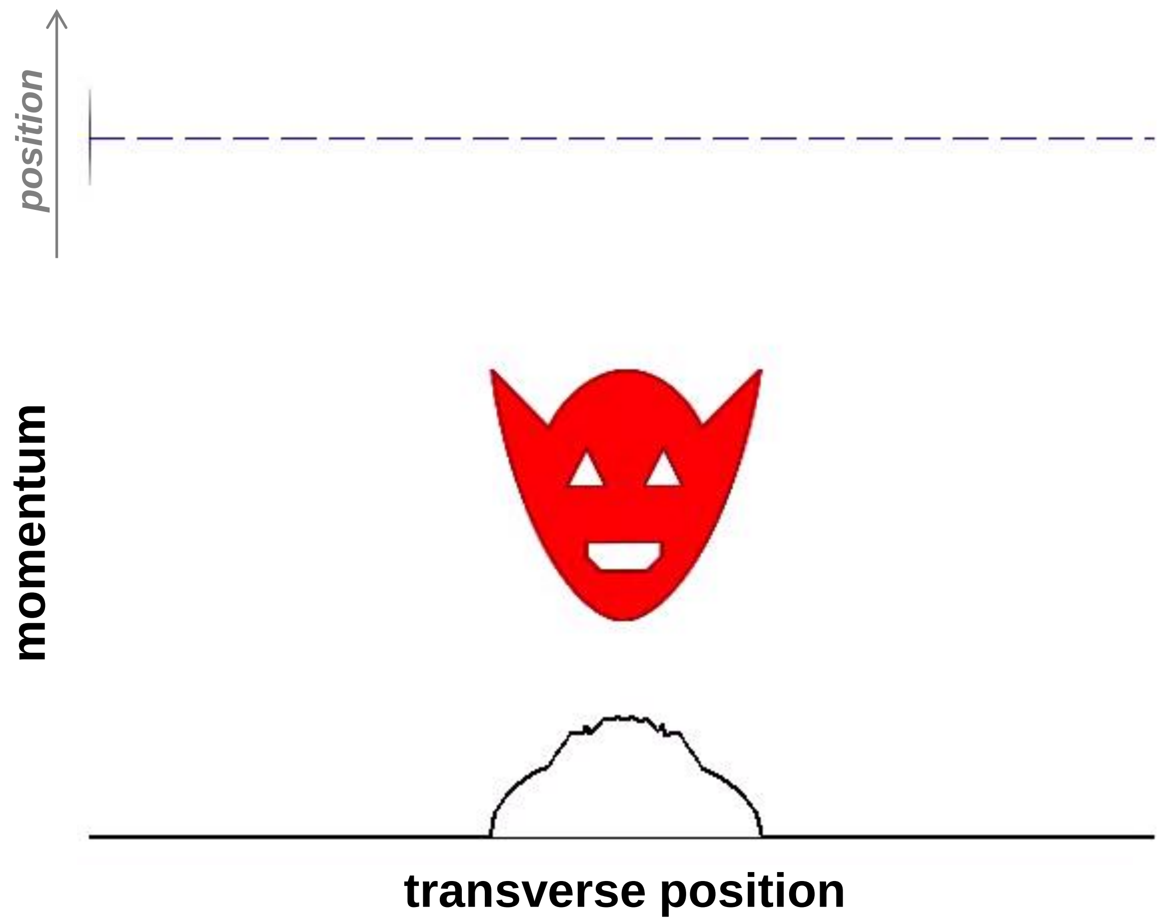
- **Alternative definition of phase space area (volume)**
  - **"Liouville's emittance"**: $\epsilon_{\mathrm{Liouville}} = \left[\frac{4\pi}{mc}\iint\left(\frac{\mathcal{B}}{\mathcal{F}}\right)^2 dx\, dp\right]^{-1}$
  - **coherence length**: $L_\perp = \frac{\hbar}{m_e c}\frac{\sigma_x}{\epsilon_{\mathrm{norm}}}$

Linear and non-linear motion (continuous focusing channel)

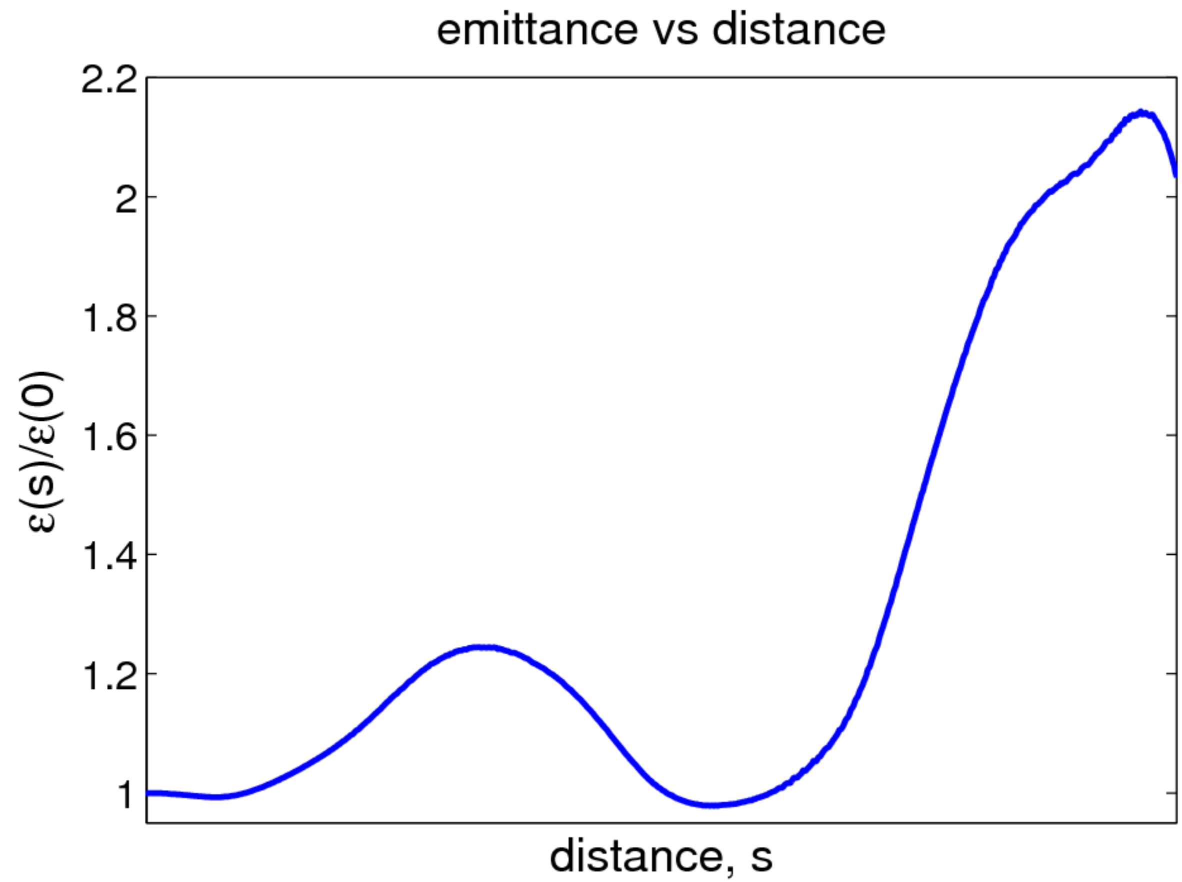


- **Liouville's emittance: const in both cases**

Space charge in a continuous focusing channel



Space charge in a continuous focusing channel



- **But Liouville's emittance stays const**

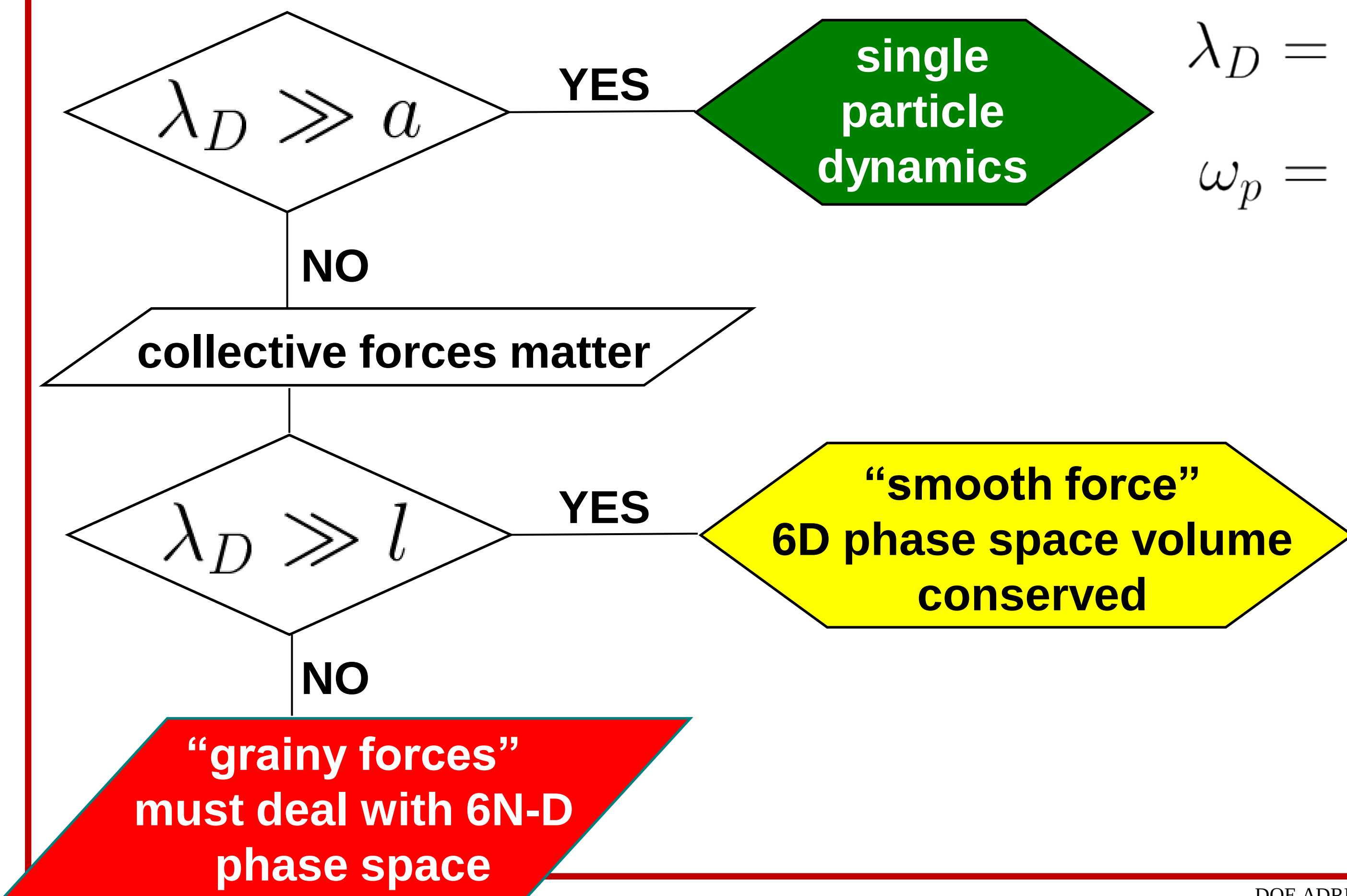
Tricky space charge

- **Beam as non-neutral plasma: 3 characteristic lengths**

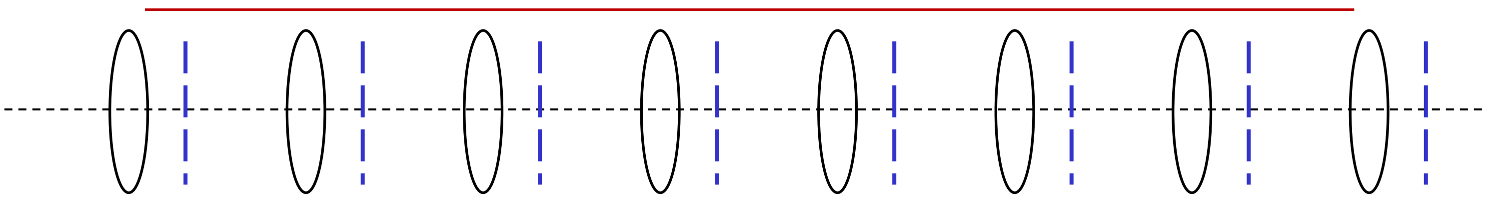
  a **beam diameter;** l **inter-particle distance;** λ_D **Debye length**

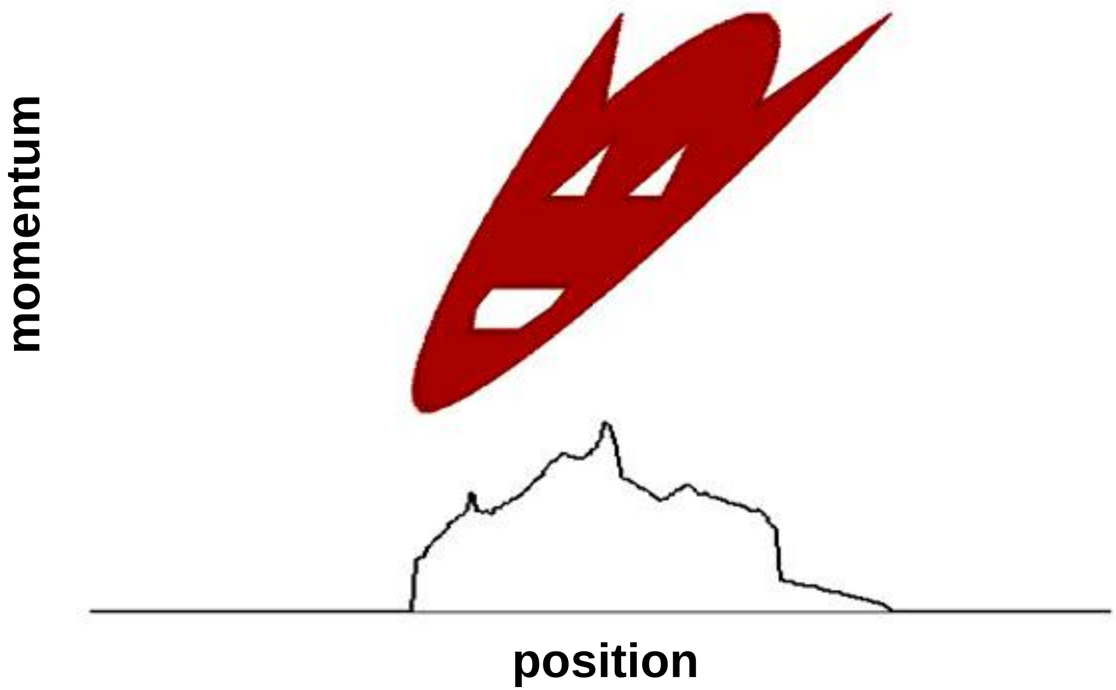
$$\lambda_D = \frac{\sigma_{v_\perp}}{\omega_p} = \frac{\sqrt{k_B T_\perp / \gamma m}}{\omega_p}$$

$$\omega_p = \sqrt{\frac{e^2 n}{\epsilon_0 m \gamma^3}}$$

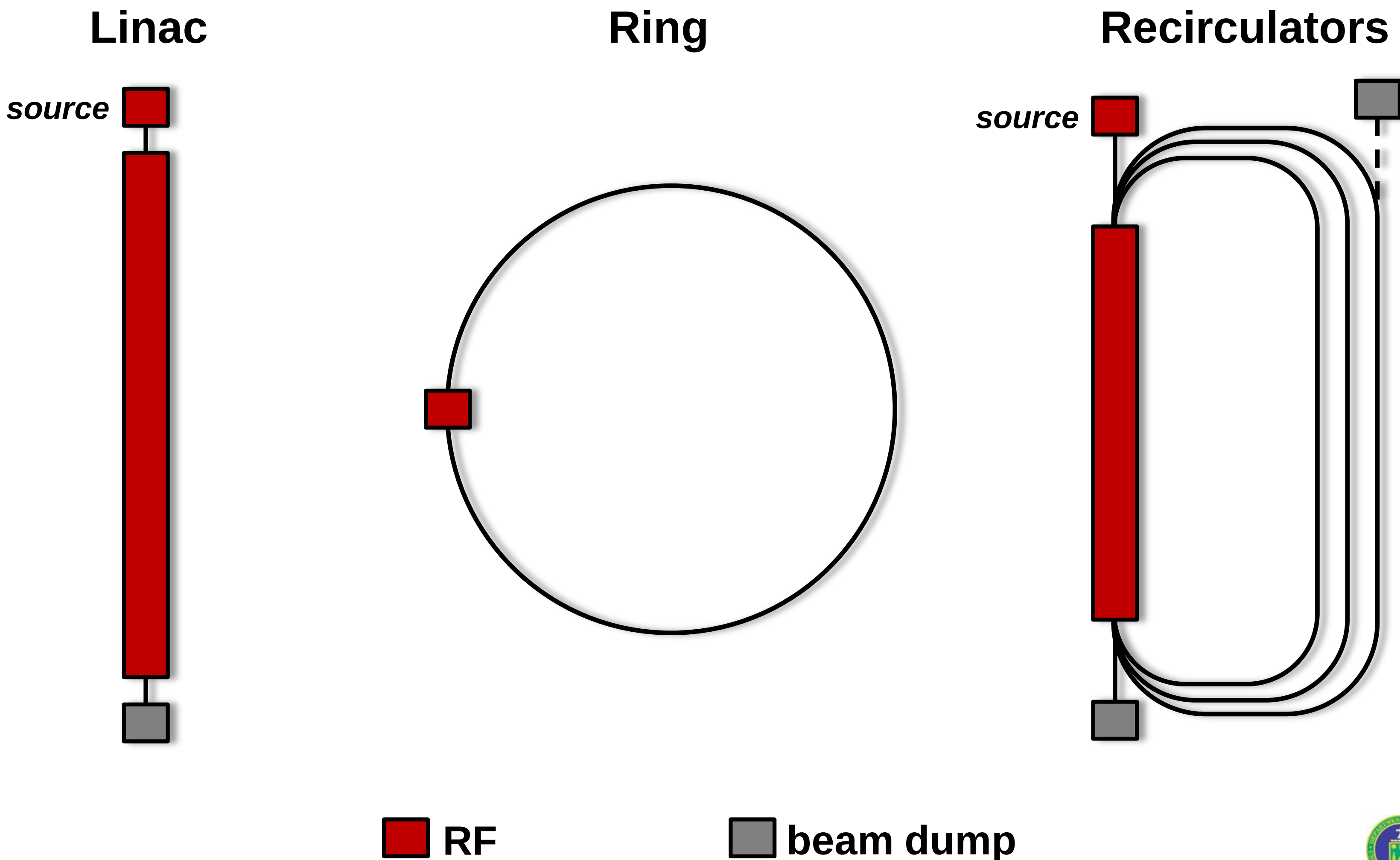


Information loss in phase space



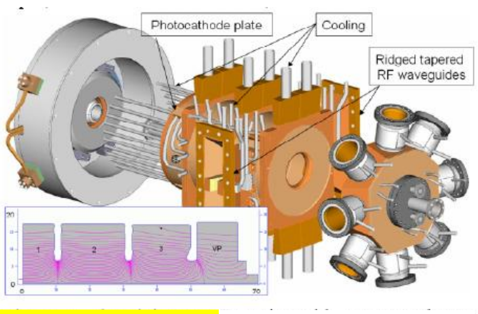


Accelerator topologies



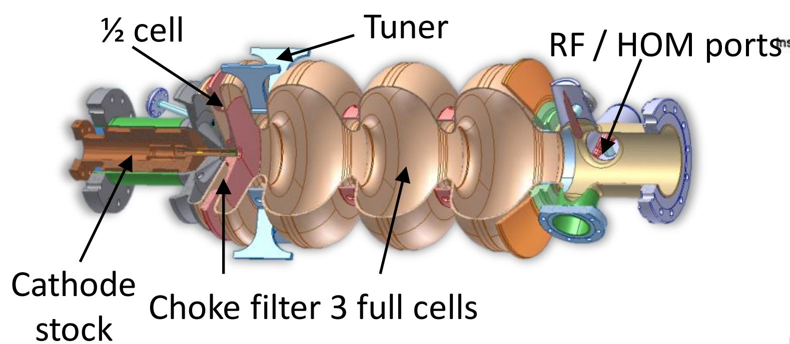
Photoinjectors = marriage of physics and technology

normal conducting RF gun



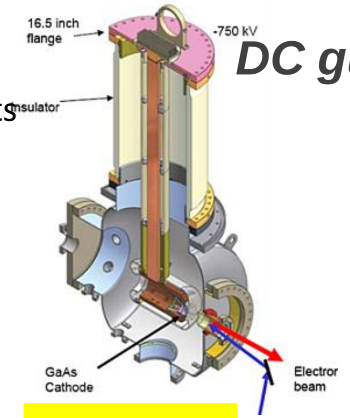
LANL RF gun

SRF gun



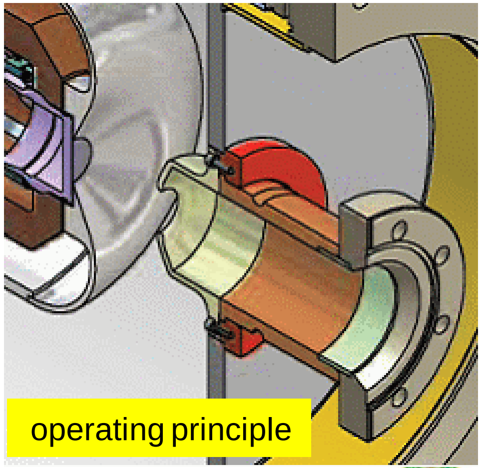
ELBE SRF gun

DC gun



Cornell gun

plus variants…



operating principle

- **CW operation: max cathode fields: (DC ≤10 MV/m), NCRF (≤ 20 MV/m), best promise for SRF (≤ 30 MV/m)**

Physics 101: basic limit to beam brightness from photoinjectors

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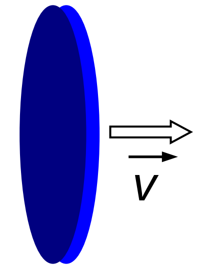
- Each electron bunch assumes a **'pan-cake' shape** near the photocathode for short (≤ 10ps) laser pulses



- Maximum **charge density** determined by the electric field:

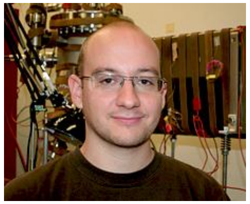
$$dq/dA = \varepsilon_0 E_{cath}$$

- **Angular spread** set by mean transverse energy (MTE) of photoelectrons

$$\Delta p_\perp \sim (m \times MTE)^{1/2}$$

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

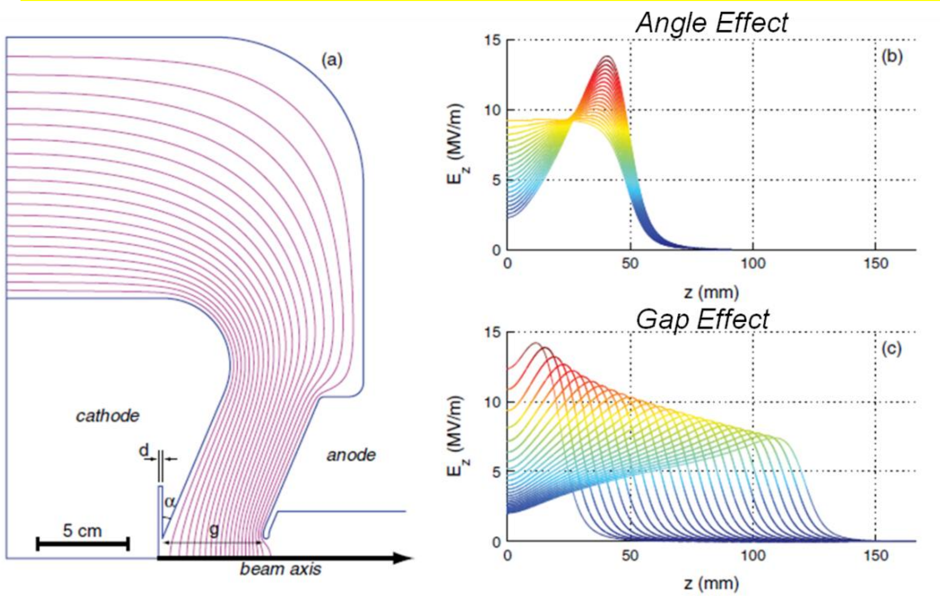
IVB, et al., Phys. Rev. Lett. 102 (2009) 104801



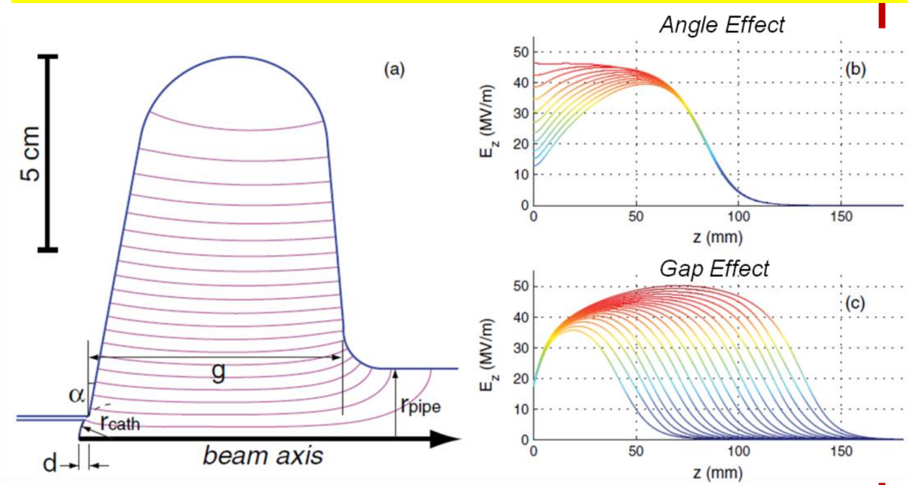
Optimization study: SRF vs DC guns

- Vary gun geometry while realistically constraining the voltages
- Full beam dynamics with 3D space charge
- Multiobjective parallel genetic optimization

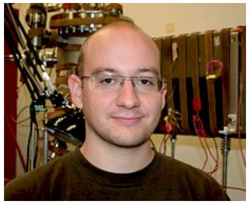
DC gun, 3 geometry parameters: gap, cathode angle & recess



SRF gun, 4 parameters: gap, cath angle & recess, pipe dia



IVB, J. Maxson, et al., Phys Rev ST-AB 14 (2011) 072001



Optimization study: SRF vs DC guns

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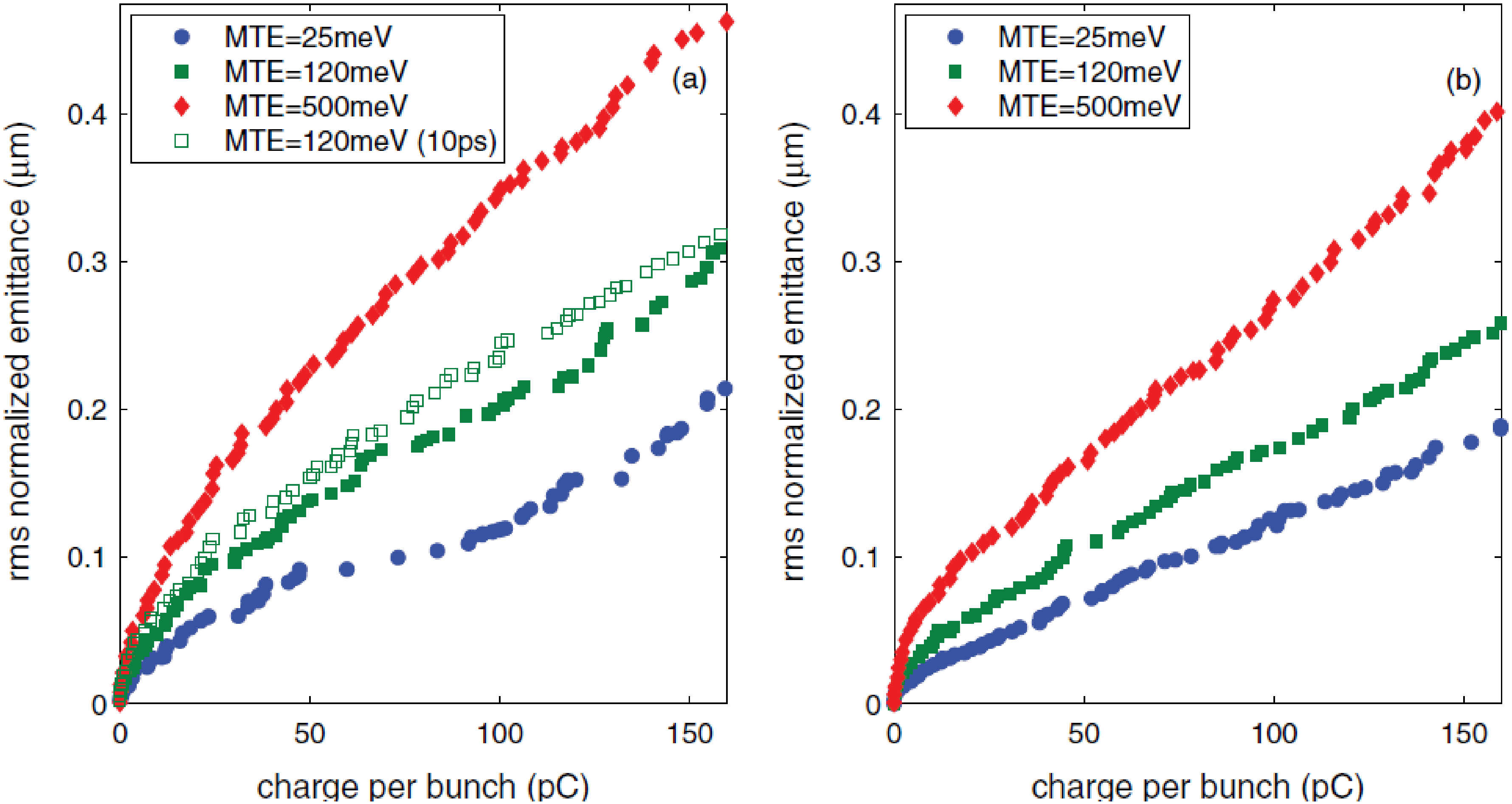
DC Gun SRF Gun



IVB, J. Maxson, et al., Phys Rev ST-AB 14 (2011) 072001

Accelerator test-beds at Cornell

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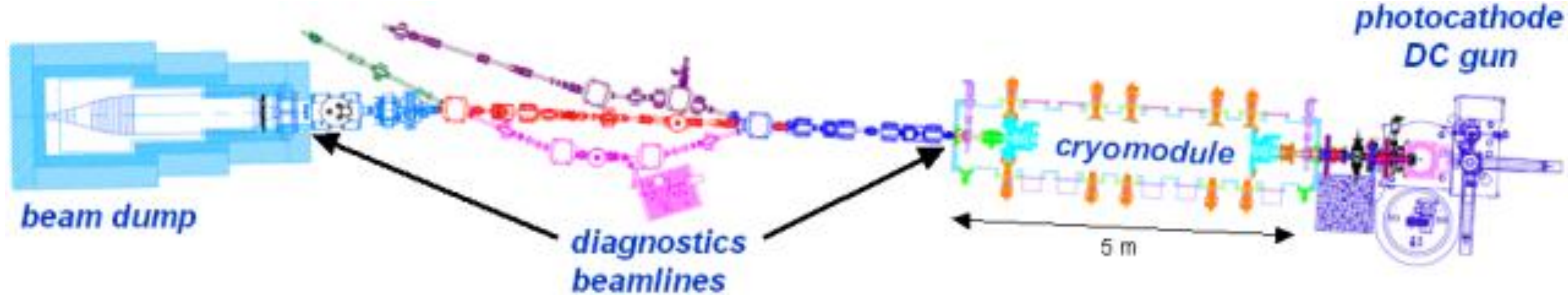
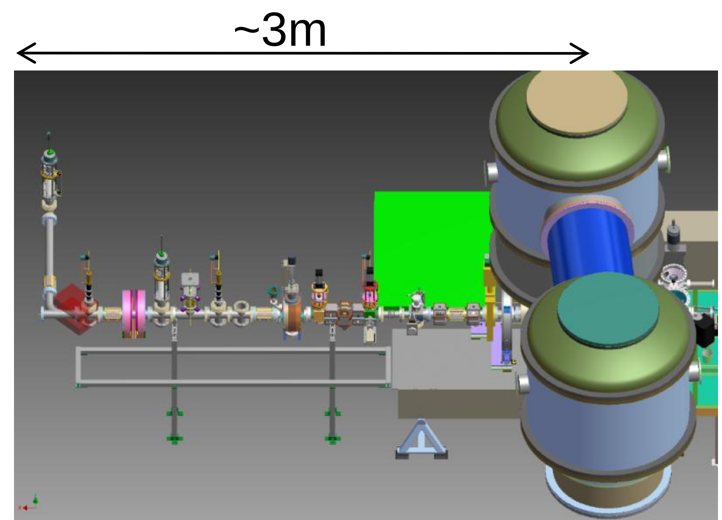
- **Two accelerators make this CAREER work possible: NSF supported 100mA 5-15 MeV photoinjector;**



- **New 500kV photoemission gun & diagnostics beamline (processed to 400kV and ongoing): the main 'playground' for a PhD student (J. Maxson)**



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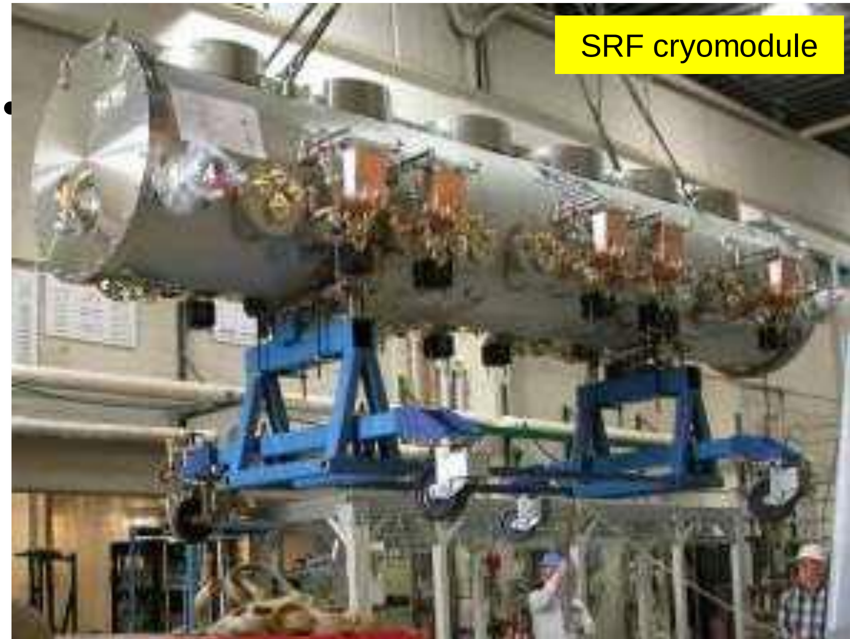
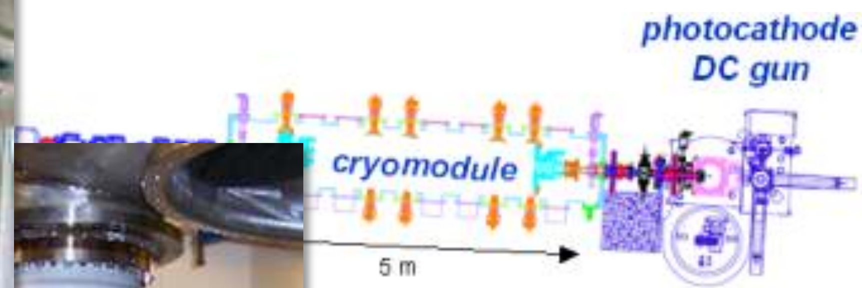


• REER work possible: NSF
otoinjector;



Accelerator test-beds at Cornell

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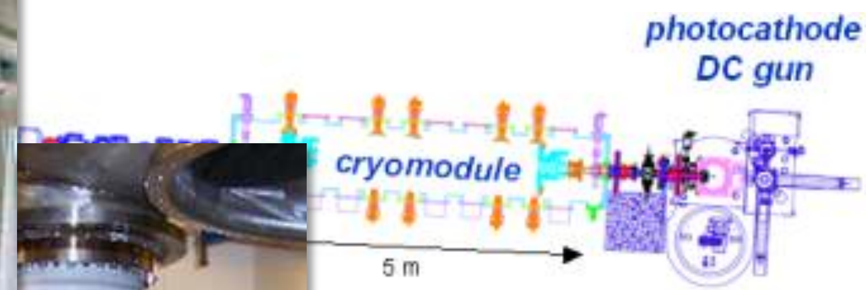

Accelerator test-beds at Cornell

NSF CLASSE

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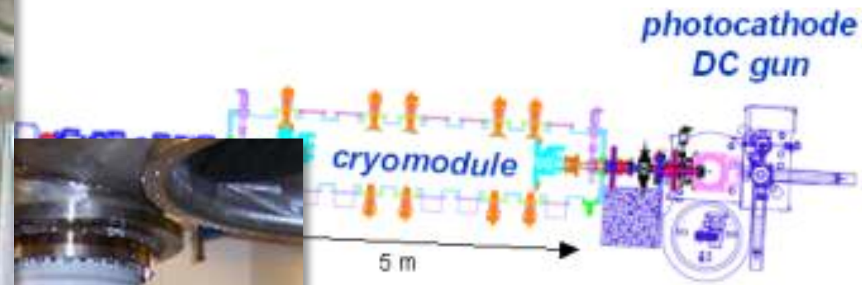
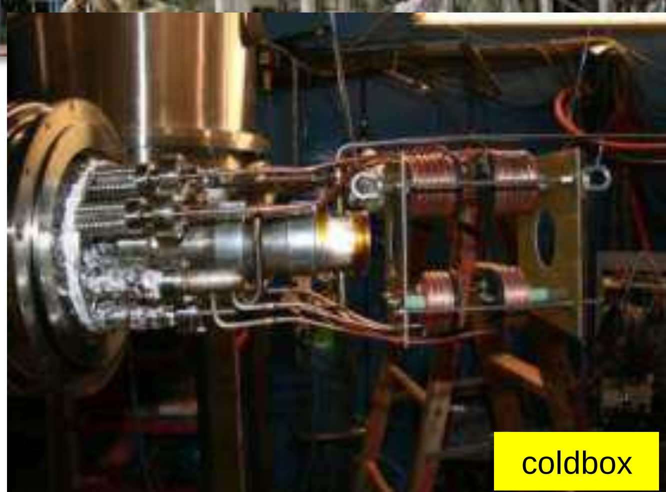
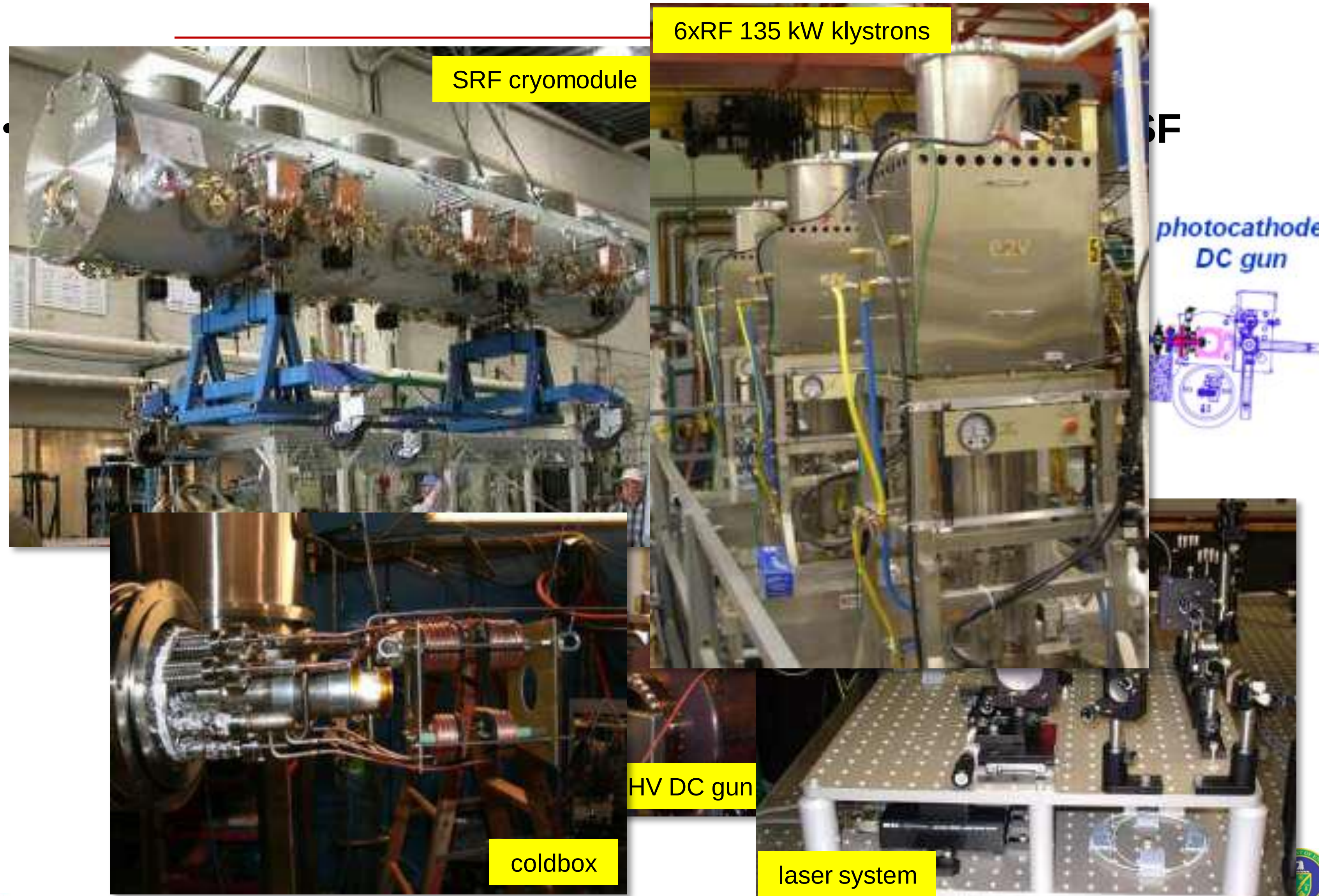




Accelerator test-beds at Cornell



Accelerator test-beds at Cornell

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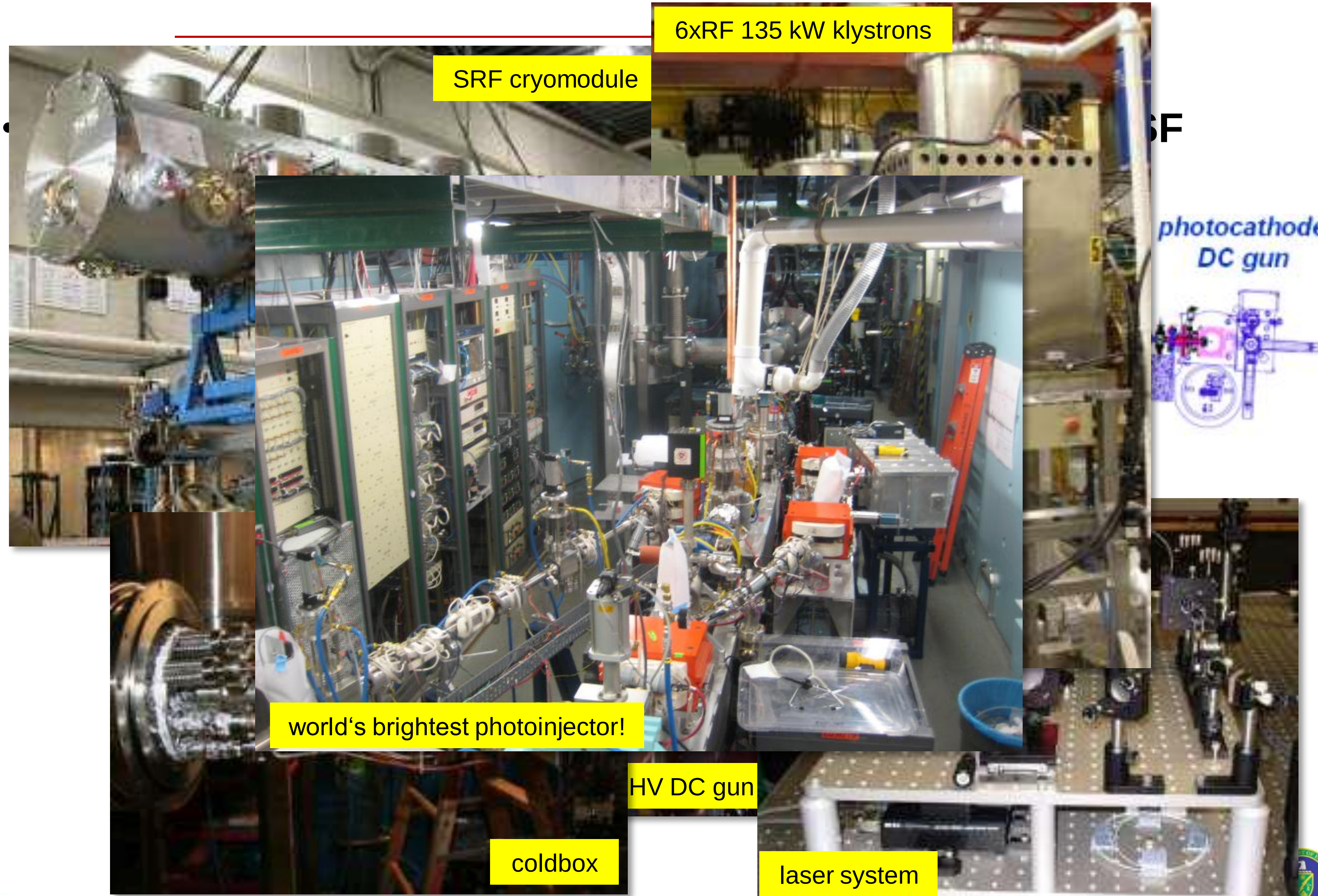

Photocathode research at Cornell: some results

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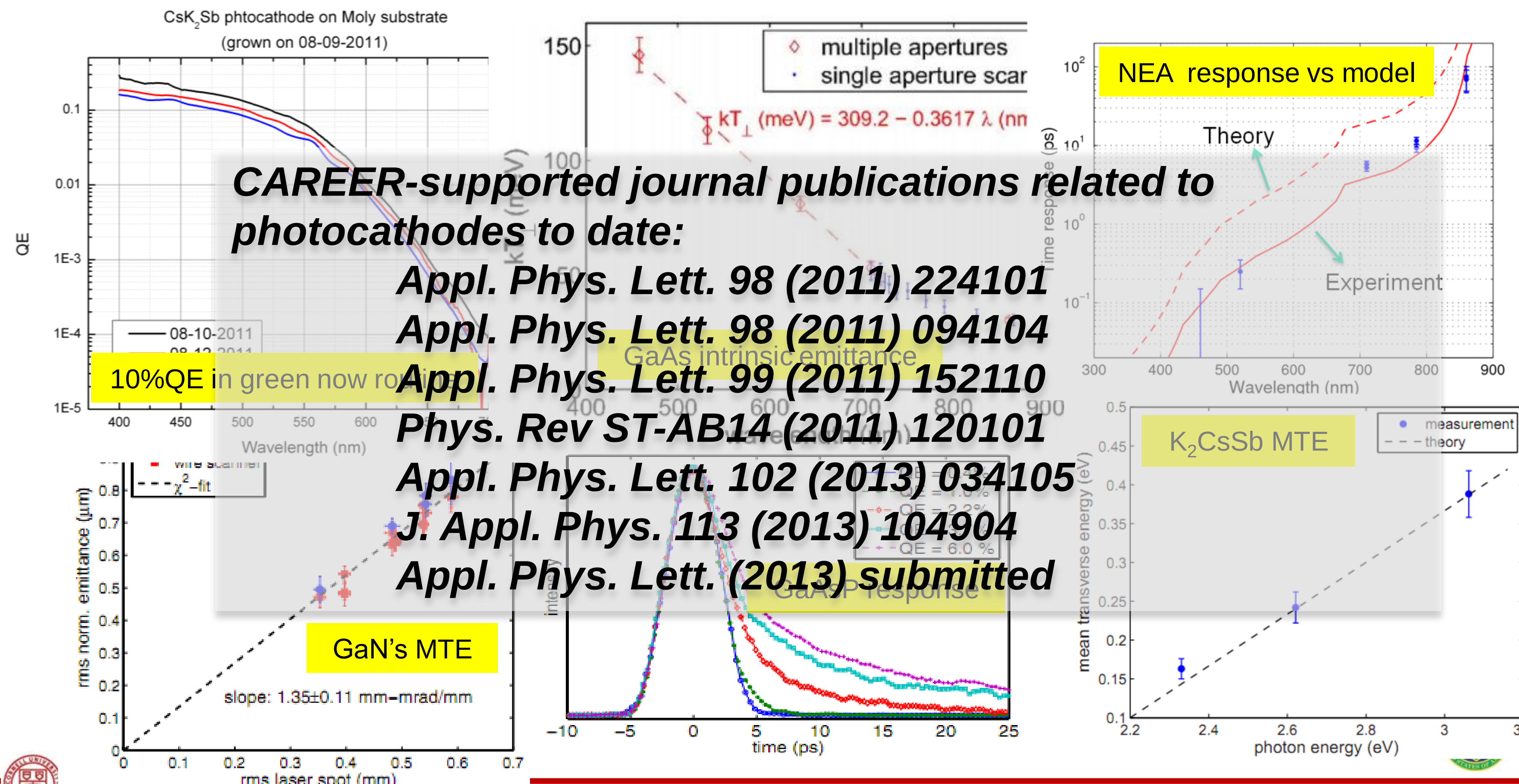
- **Wide selection of photocathodes experimentally evaluated for the first time (MTE, response time, accelerator performance): GaAs, GaAsP, GaN, Cs_3Sb, K_2CsSb, Na_2KSb**



CAREER-supported journal publications related to photocathodes to date:

- ***Appl. Phys. Lett. 98 (2011) 224101***
- ***Appl. Phys. Lett. 98 (2011) 094104***
- ***Appl. Phys. Lett. 99 (2011) 152110***
- ***Phys. Rev ST-AB14 (2011) 120101***
- ***Appl. Phys. Lett. 102 (2013) 034105***
- ***J. Appl. Phys. 113 (2013) 104904***
- ***Appl. Phys. Lett. (2013) submitted***

Cornell cathode facilities: low MTE, high QE, robustness

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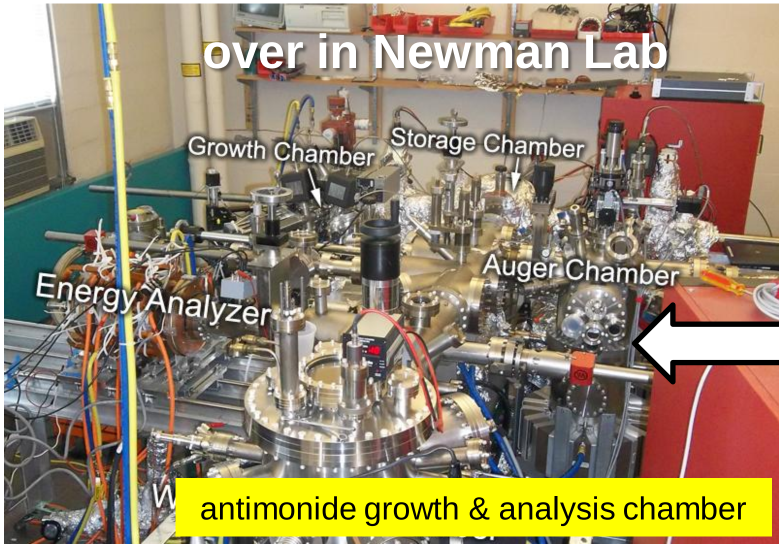
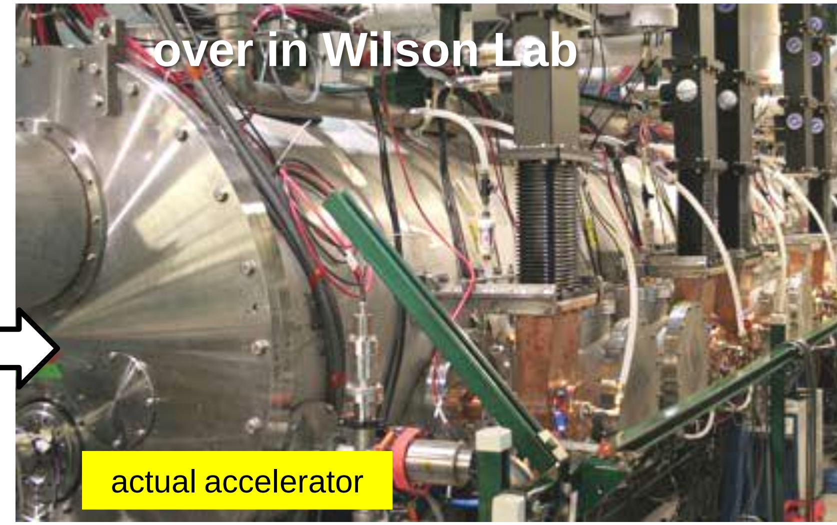
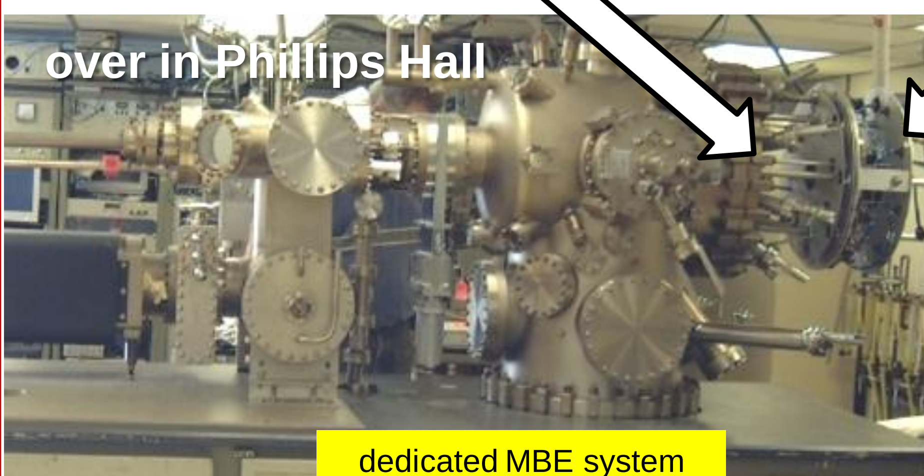
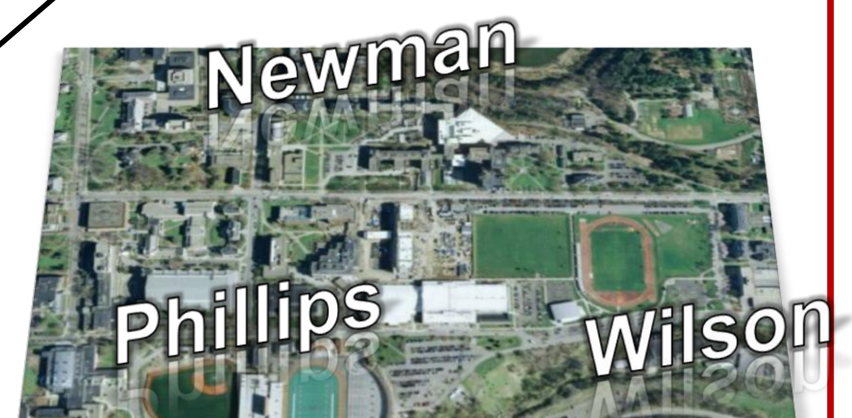
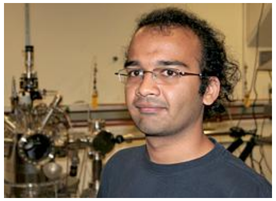






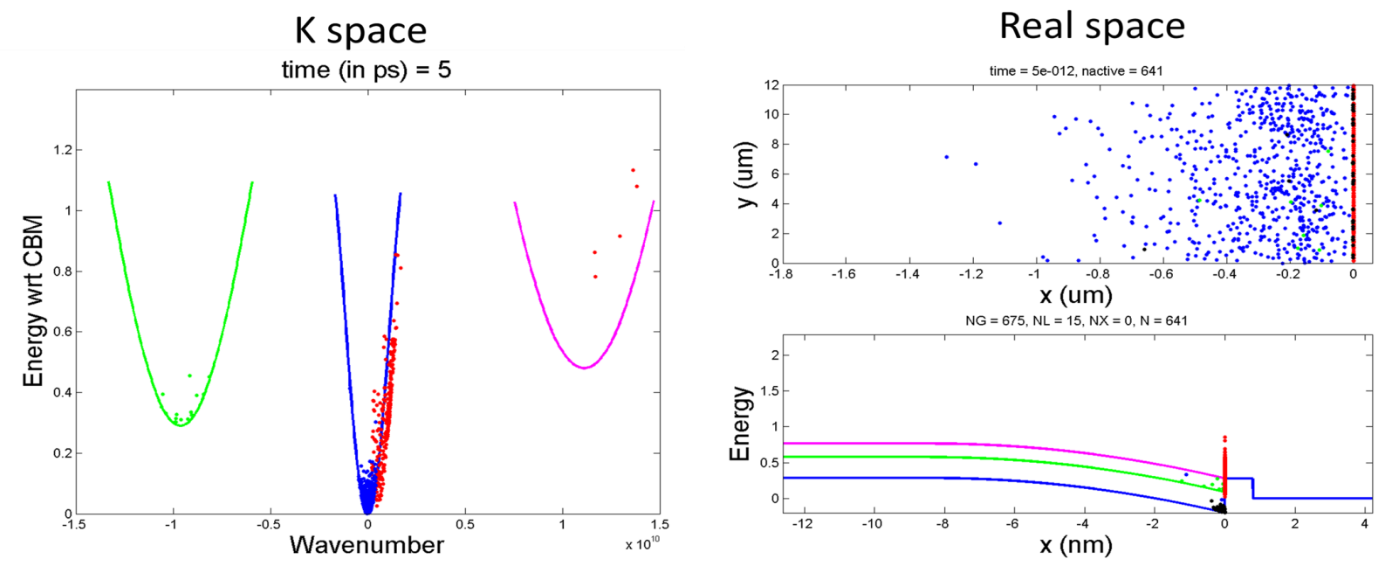


Cornell Campus



Breakthrough in modeling

Simulation snapshot



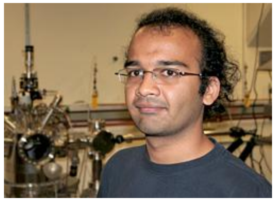
BLUE – Electrons in Gamma Valley

GREEN – Electrons in L Valley

PURPLE – Electrons in X Valley

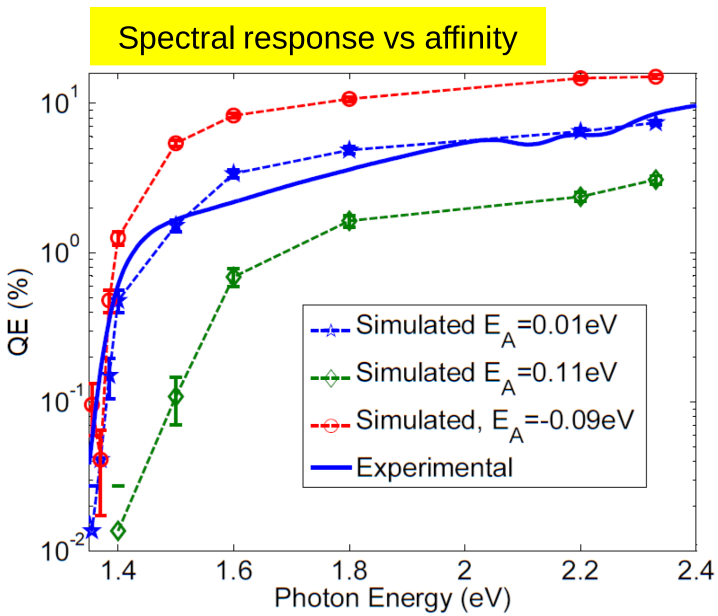
RED– Emitted electrons

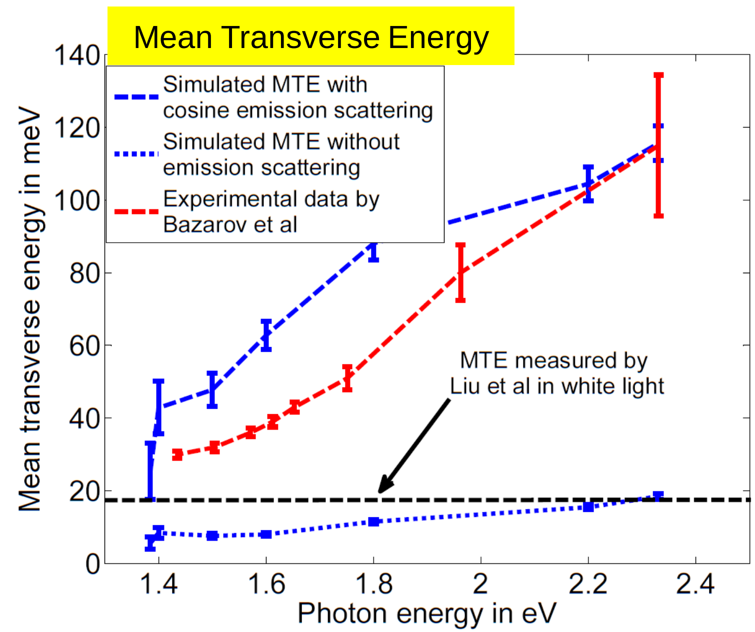
- **Monte-Carlo simulation tool for III-V family photocathodes**
  - **Fully developed for both non-layered reflective cathodes as well as layered & transmission mode structures**



Modeling of photocathodes: a predictive tool in hand

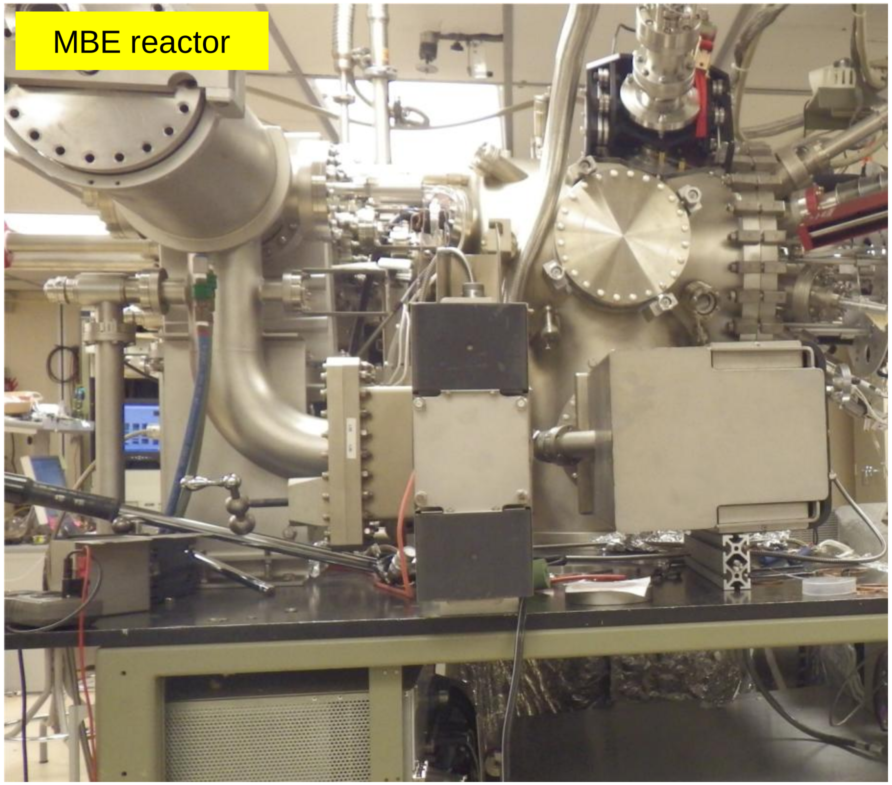
- **Simulations explain existing experimental data for bulk GaAs taken by our group without free fit parameters**
- **Next, will extend this tool to antimonides & cryogenically cooled materials**

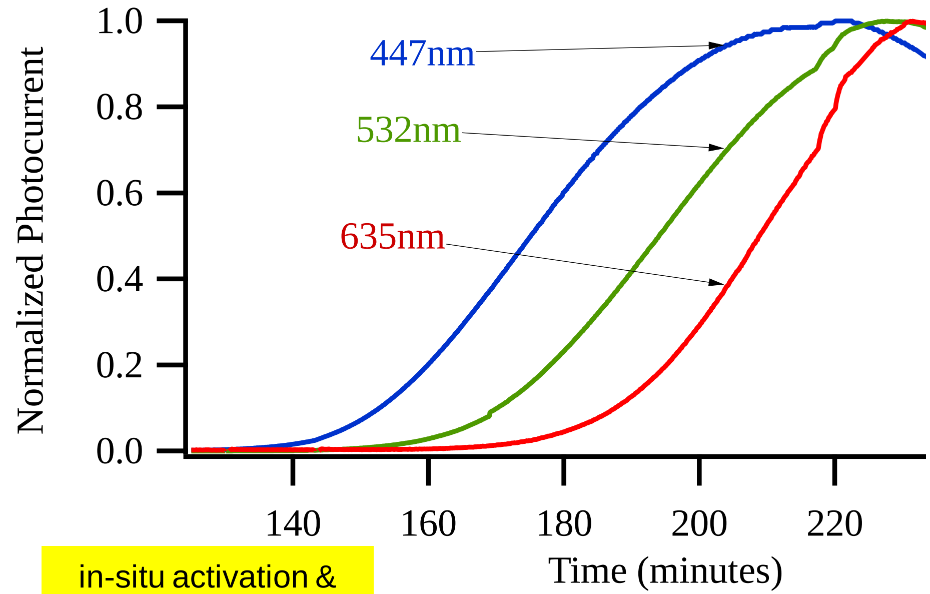




S. Karkare, IVB, et al., J. Appl. Phys. 113 (2013) 104904

Molecular Beam Epitaxy: towards ultra-cold photoemitters





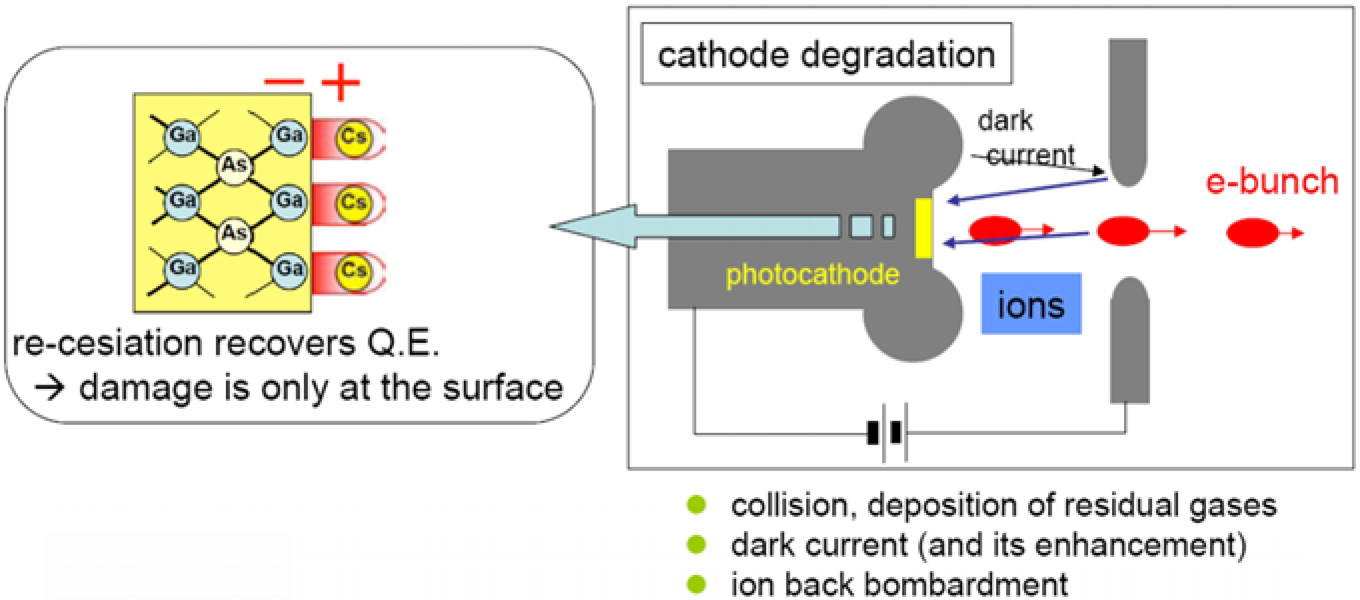
in-situ activation & T-meter (emittance)

- **MBE: ultimate tool for photocathodes**
  - **Lowest emittance cathode grown (x2 improvement over bulk GaAs!)**
- **Starting to "engineer" new types of MBE photocathode structures**

W. Schaff, IVB, et al. (2013) in preparation

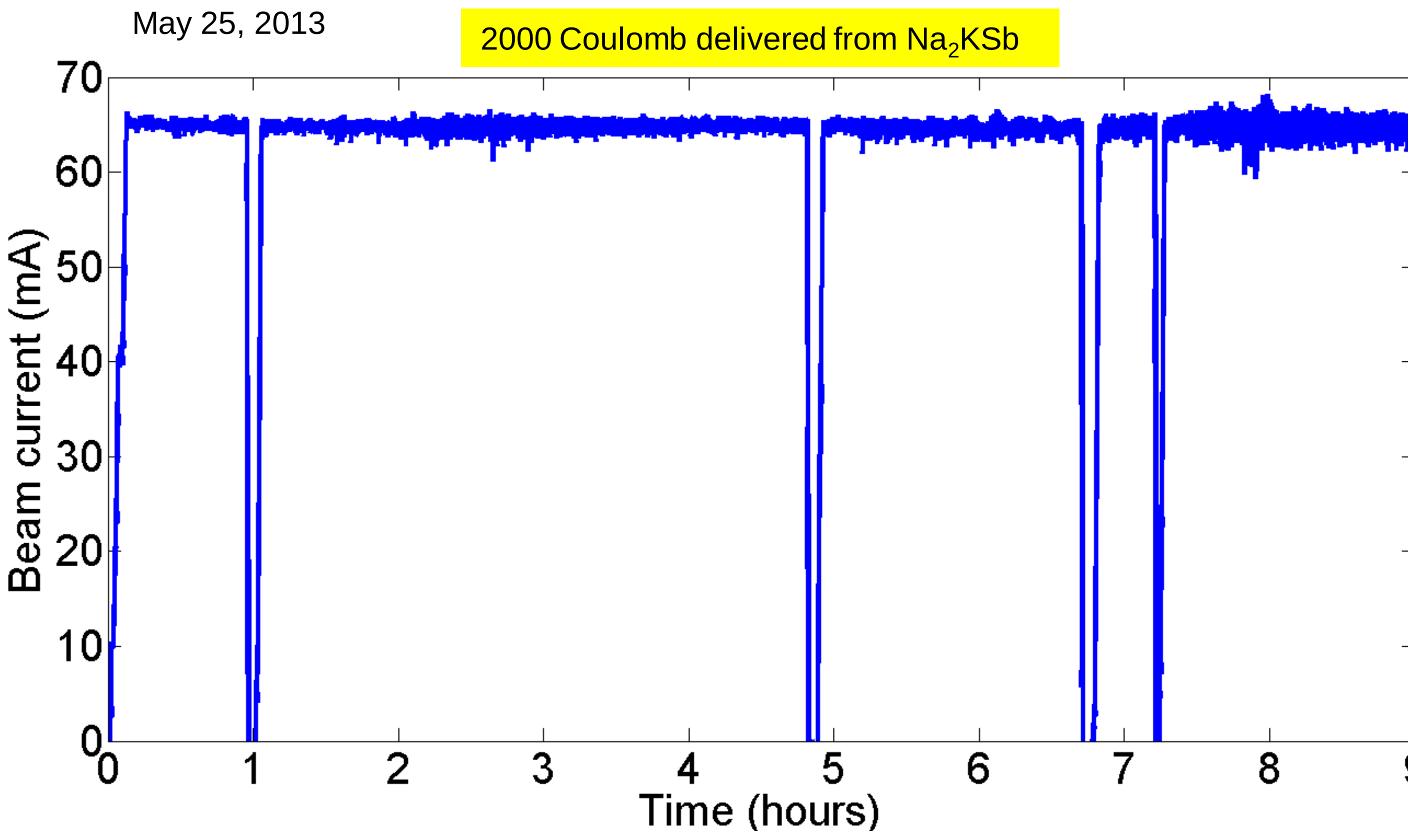
Getting high average current

- **Ion back-bombardment: a sure killer of sensitive photocathodes**



- **Best prior achievements**
  - **Boeing FEL RF gun 32 mA avg (25% d.f.)**
  - **JLAB FEL DC gun 9.1 mA avg (100% d.f.)**

Robust photocathodes at Cornell



Practical lifetimes for ~100 mA operation

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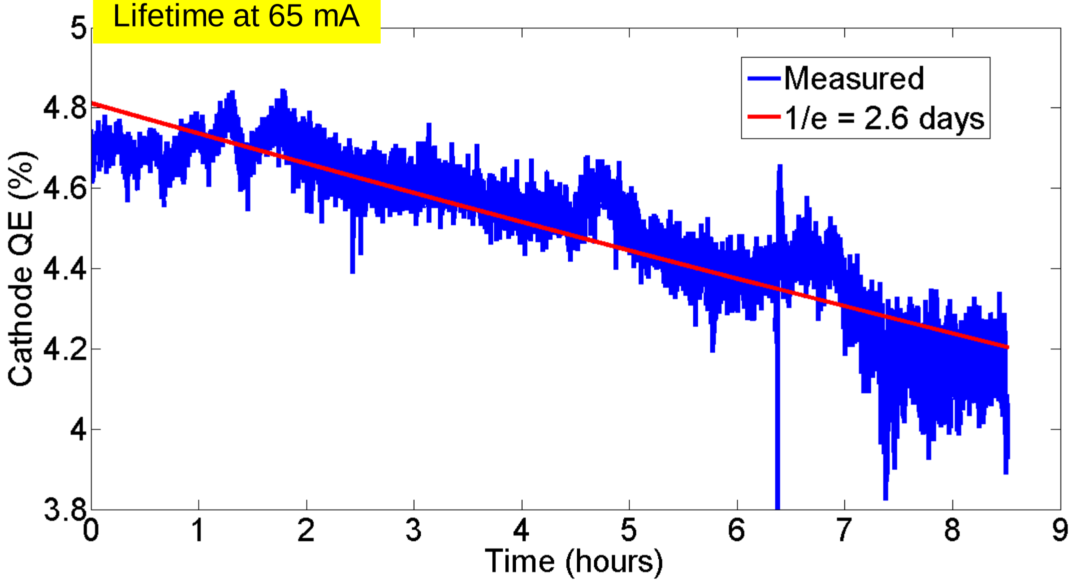
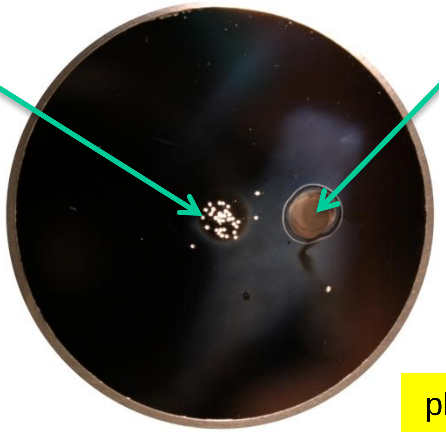


- Lifetime good enough to operate for ~ week without interruption at 65 mA!
- Highest avg current so far 75 mA (limited by RF processing in input couplers)

Ion damage limited to the central area



Active area is offset from the center

photocathode after use

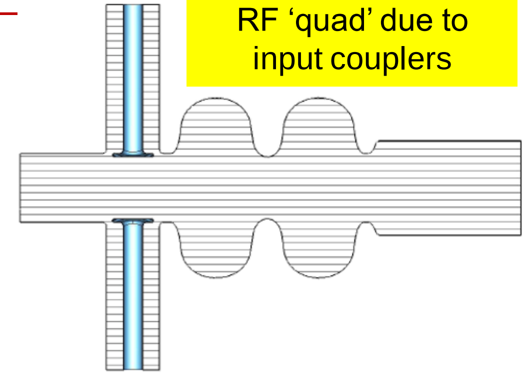
- Exceeded the 1993 Boeing results by >x2!

L. Cultrera, IVB, et al., Appl. Phys. Lett (2013) submitted

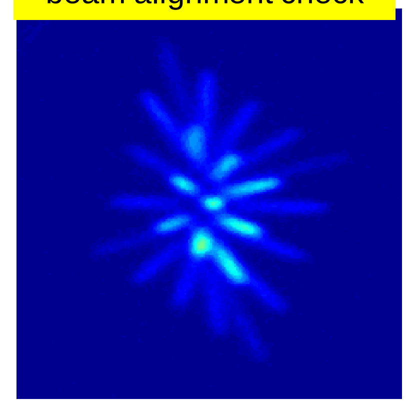
Ultralow emittance: many 'tricks' needed to get there

- **6D phase space diagnostics!**
- **'Virtual accelerator': 3D space charge, 3D RF cavity field models, quads, dipoles, etc.**
- **Beam-based alignment via beam response matrices from fieldmaps**
- **Improved 3D laser shaping**
- **And many others…**

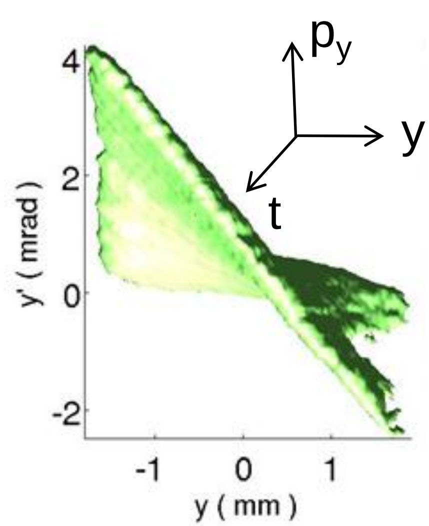
RF 'quad' due to input couplers



beam alignment check



Phys. Rev. ST-AB 15, 024002 (2012)
Phys. Rev. ST-AB 14, 032002 (2011)
Phys. Rev. ST-AB 14, 112802 (2011)
Nucl. Instr. Meth. A 614, 179 (2010)
…



slice emittance with 0.1ps resolution

Emittance results after 'merger'

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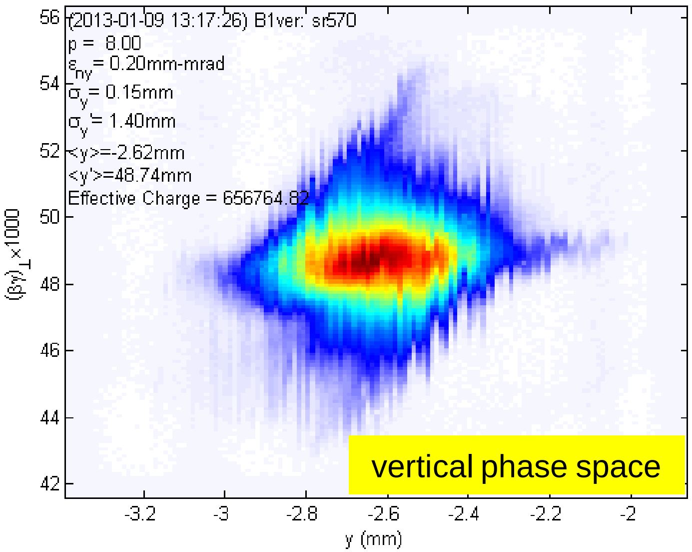
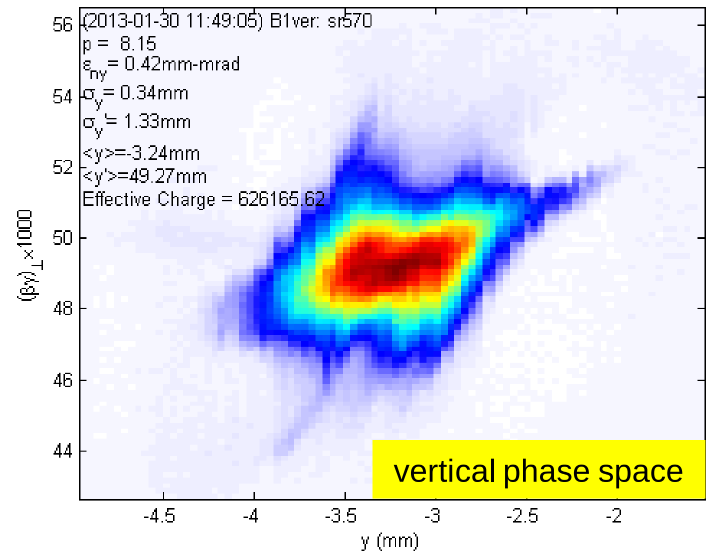
20 pC/bunch | **80 pC/bunch**





Normalized rms emittance (horizontal/vertical) 90% beam, E ~ 8 MeV, 2-3 ps rms

0.22/0.15 mm-mrad | **0.49/0.29 mm-mrad**

Normalized rms core* emittance (horizontal/vertical) @ core fraction (%)

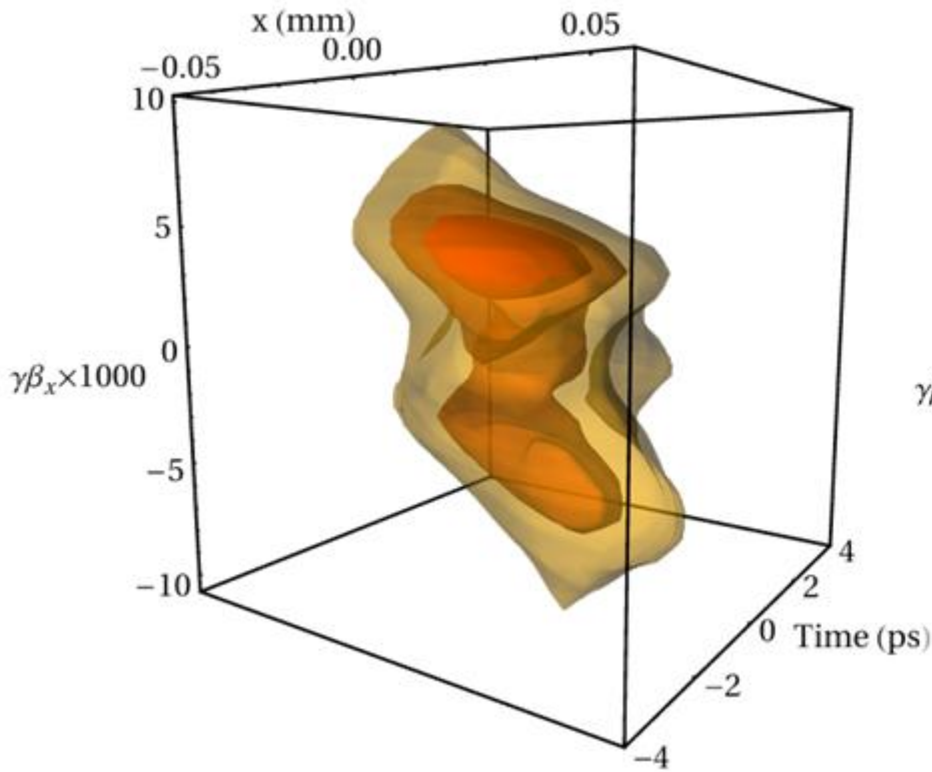
0.14/0.09 mm-mrad @ 68% | **0.24/0.18 mm-mrad @ 61%**

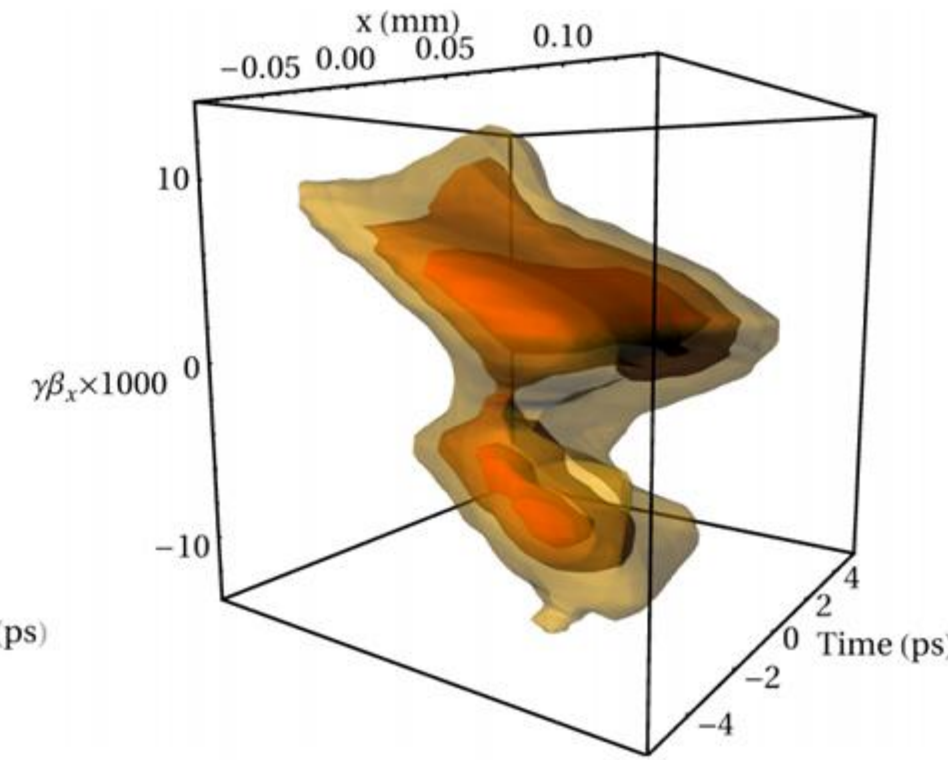
20x the brightness at 5 GeV of the best storage ring (1nm-rad hor. emittance 100 mA)!
Similar to the best NCRF guns emittance but with > 10^6 repetition rate (duty factor = 1)

C. Gulliford, IVB, et al., Phys Rev ST-AB (2013) submitted

Measured time-resolved phase space distribution

20 pC/bunch **80 pC/bunch**



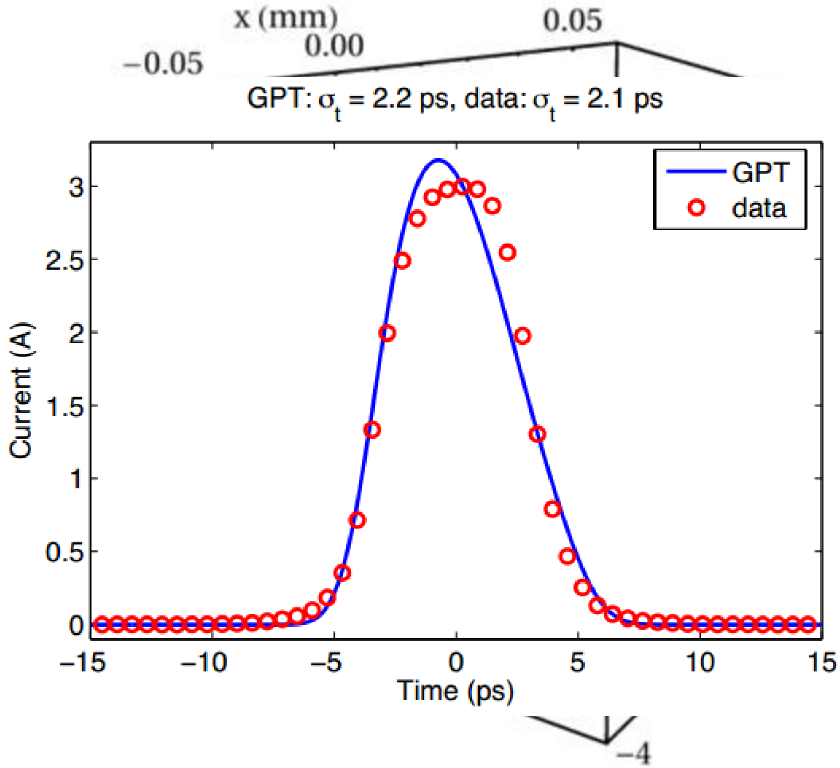


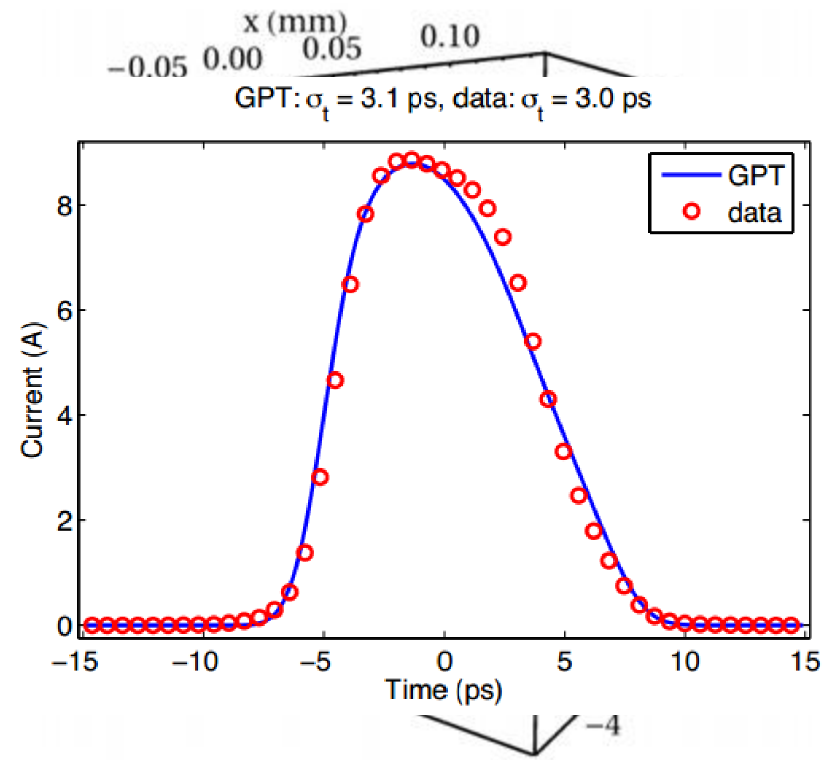
2.1±0.1 ps **3.0±0.2 ps**

Energy spread: 0.1-0.2%

Measured time-resolved phase space distribution

20 pC/bunch **80 pC/bunch**





2.1±0.1 ps **3.0±0.2 ps**

Energy spread: 0.1-0.2%

To the fundamental brightness limit…

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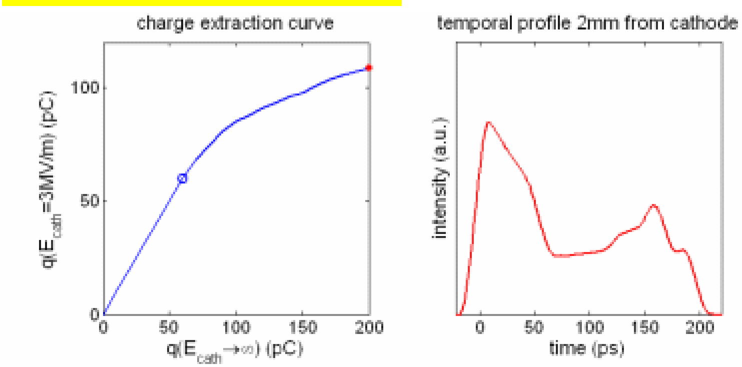
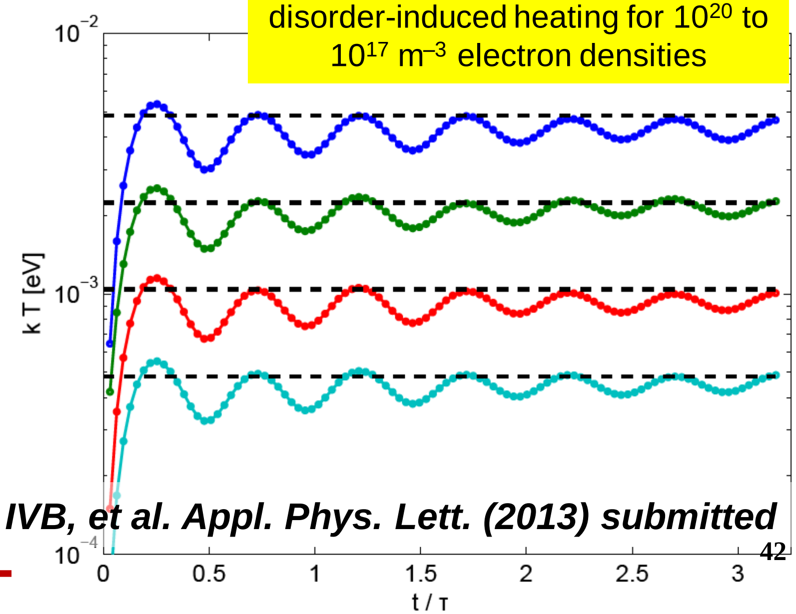
- **Fundamental limit to emittance compensation?**
  - **~90% final emittance can be due to thermal (cathode) emittance according to simulations; ~70% according to the latest measurements**
- **Main physics issues for reaching cathode emittance**
  - **'virtual cathode' instability → longitudinal breaking of the bunch at the cathode**
  - **control of non-linear space charge forces → better 3D laser shaping**
- **Fundamental limit to the lowest cathode emittance (from beam physics point of view)?**
  - **Set by 'disorder-induced-heating' to cryogenic temperatures (depends on beam density)**

'virtual cathode' instablity



disorder-induced heating for 10^{20} to 10^{17} m^{-3} electron densities



J. Maxson, IVB, et al. Appl. Phys. Lett. (2013) submitted

Key CAREER Crew

CLASSE

Siddharth Karkare
PhD student
CAREER 100% support

Dr. Luca Cultrera
Research Associate
CAREER 50% support

Jared Maxson
PhD Student
(NSF PhD fellowship)

(will be supported by CAREER 100% starting 2014)

Support & Our Team

CLASSE

- **NSF DMR-0807731 for ERL R&D support**
  - **2 M$/year funds the photoinjector and gun development providing a unique accelerator test-bed and infrastructure**
- **DOE DE-SC0003965 CAREER grant**
  - **0.15M$/year mostly supporting the CAREER personnel and some of the photocathode work**

PhD students

Summary

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- World's brightest high rep rate electron source at Cornell, e.g. can be used to drive x-ray FELs and ERLs (if a 5 GeV ERL were built today, x20 better beam than Petra-III and x200 than APS); another x10 straightforward improvement in photoinjector brightness anticipated over the next few years;
- New parameter space for accelerators, new beam physics challenges in view;
- Photocathode research in full steam, photoemission physics insights now drive new material selection;
- Virtual photocathode instability and new adaptive laser shaping work starting now as the new photoemission gun comes online;
- Future beyond 2014 (the current NSF grant) is uncertain;