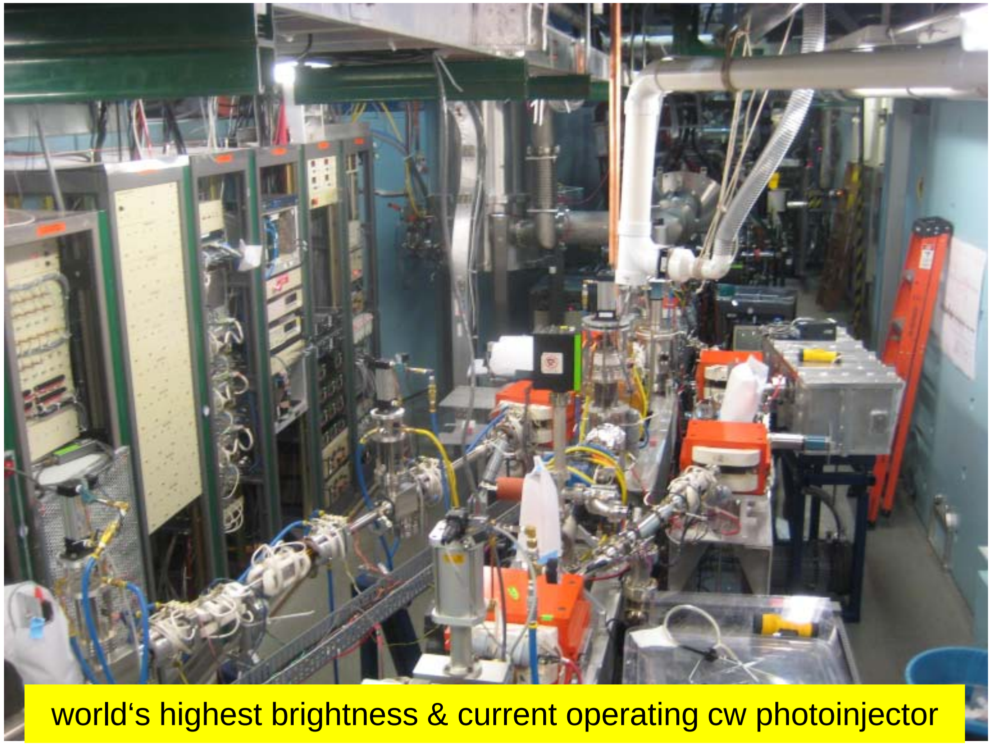
ERL photoinjector R&D at Cornell

Ivan Bazarov and Jared Maxson

Cornell University



world's highest brightness & current operating cw photoinjector

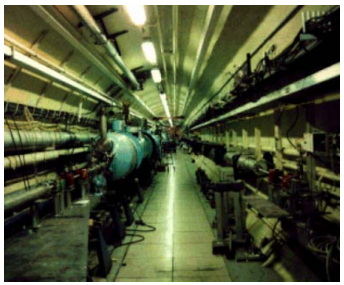
Today's talk

- **Part I: ERL R&D @ Cornell**

- **Part II: ultimate beam brightness from DC/SRF guns**

ERL development timeline

CLASSE



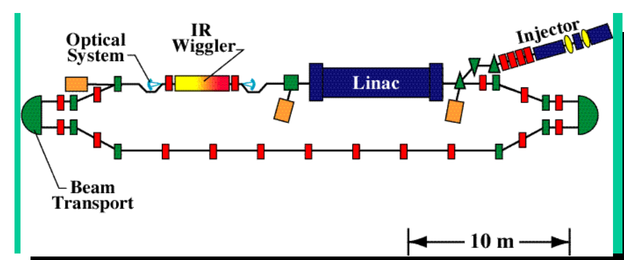
1965: M. Tigner
Nuovo Cimento
37 (1965) 1228

1986: Stanford SCA
T. Smith et al.
NIM A 259 (1987) 1

1960 1970 1980 1990 2000 2010

1990: S-DALINAC
(Darmstadt)

1998: BINP FEL
1999: JLAB DEMO-FEL
2002: JAERI FEL
2004: JLAB FEL Upgrade



2004: ERL-P
2004: BNL R&D ERL
2005: Cornell gets $

KEK, BESSY

Cornell ERL R&D effort

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- CHESS
  - X-ray science case (XDL'11 series of 6 workshops in Ithaca, NY for diffraction limited X-rays) , undulator R&D
- SRF group
  - Manufactured the first main linac 7-cell cavities, main linac cryomodule prototype
- ERL photoinjector facility
  - Operating the world's highest current and brightness CW photoinjector
- Gun development lab
  - Laser lab, beamline diagnostics, and Mark-II gun under construction (more from Jared)
- Photocathode lab
  - Material science of high QE photocathodes, cathode engineering

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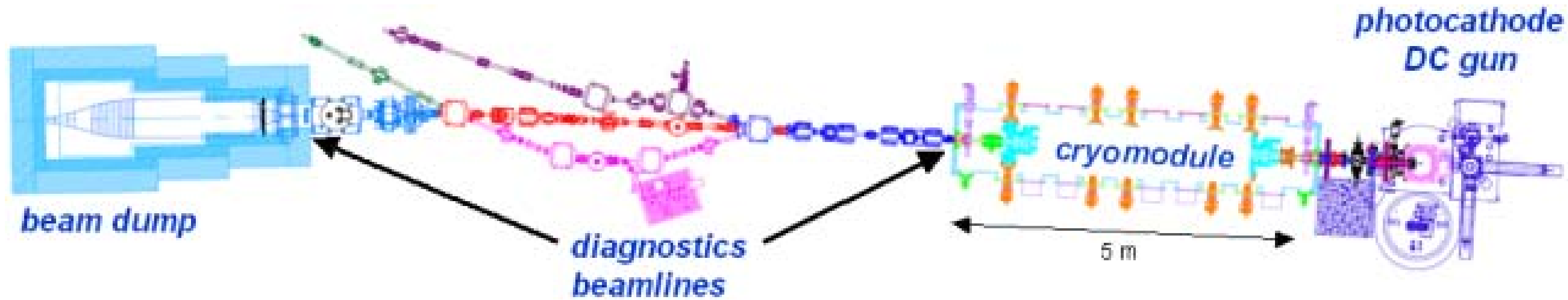
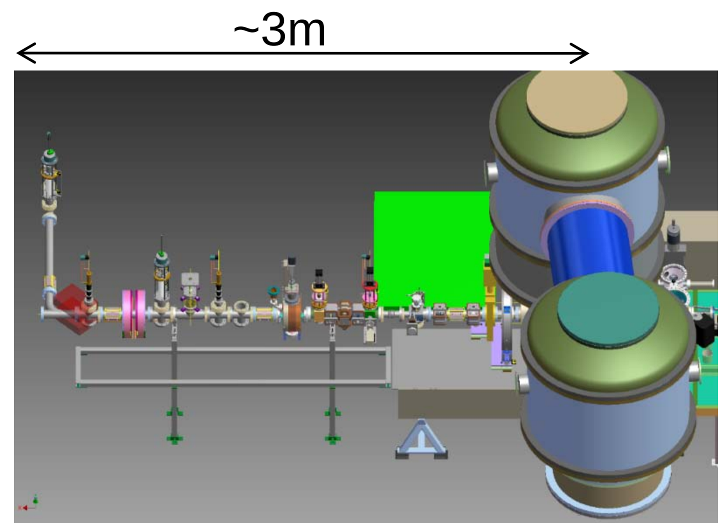
Photoemission source devepment

- **Two accelerator facilities @Cornell to push photoinjector state-of-the-art: NSF supported 100mA 5-15 MeV photoinjector;**



- **New 500kV photoemission gun & diagnostics beamline (under construction): the main 'playground' for Jared**



ERL photoinjector highlights

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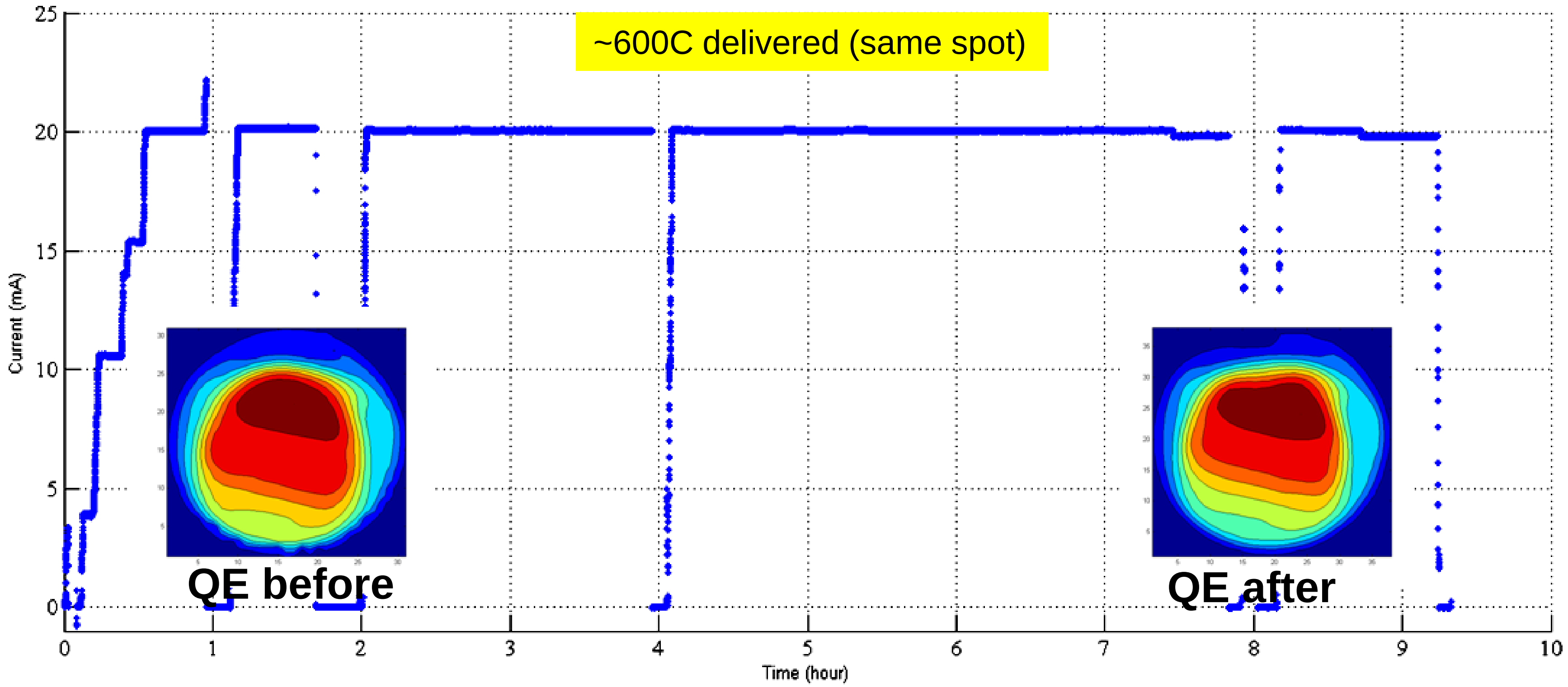
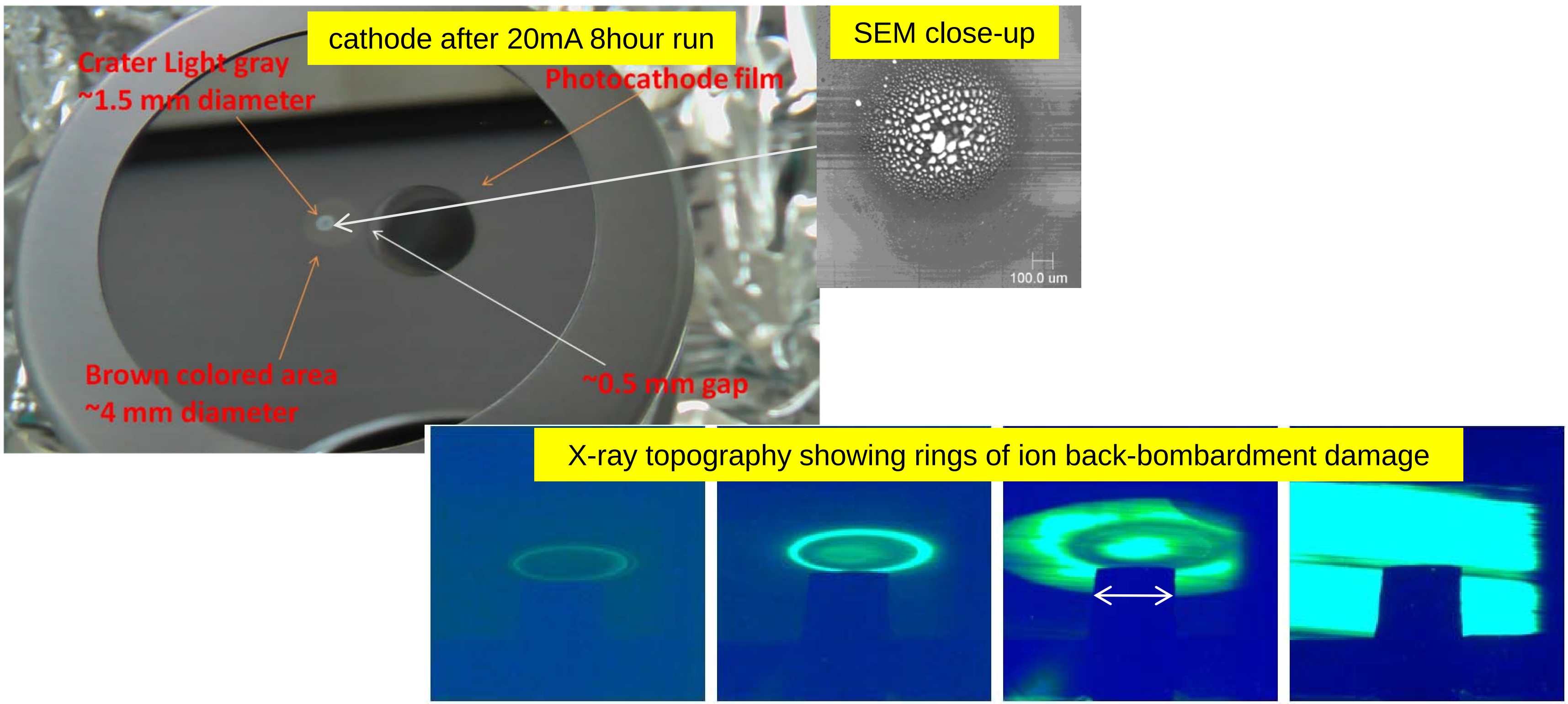
- **Over the last year:**
  - **Demonstrated feasibility of high current operation (hundreds of Coulomb extracted with minimal degradation to QE)**
  - **Original emittance spec achieved: now getting x2 the thermal emittance values, very close to simulations (Sept 2011)**

High current operation



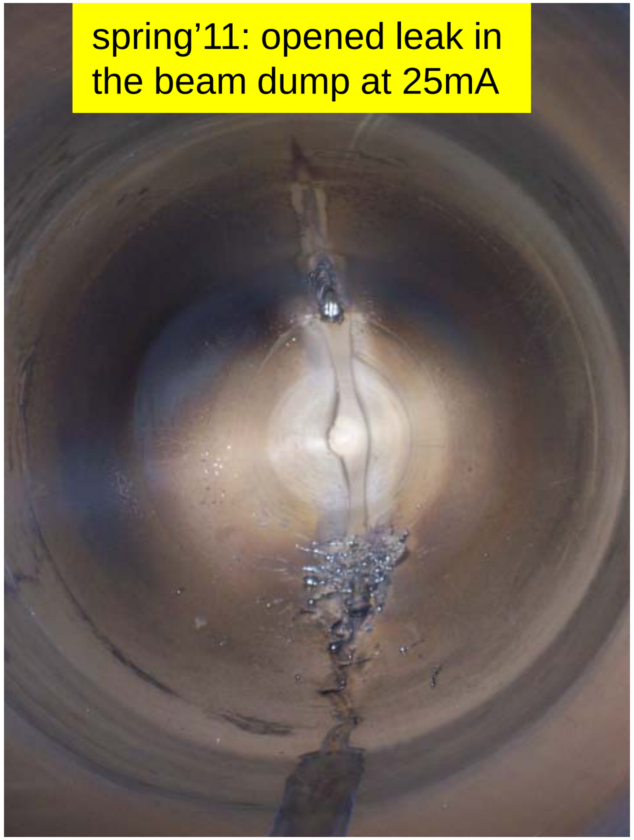
Real-life accelerator testing for photocathodes: high average current

- **CsKSb cathode after delivering ~600C.**



17.4560 degree | 17.4880 degree | 17.4960 degree | 17.5000 degree

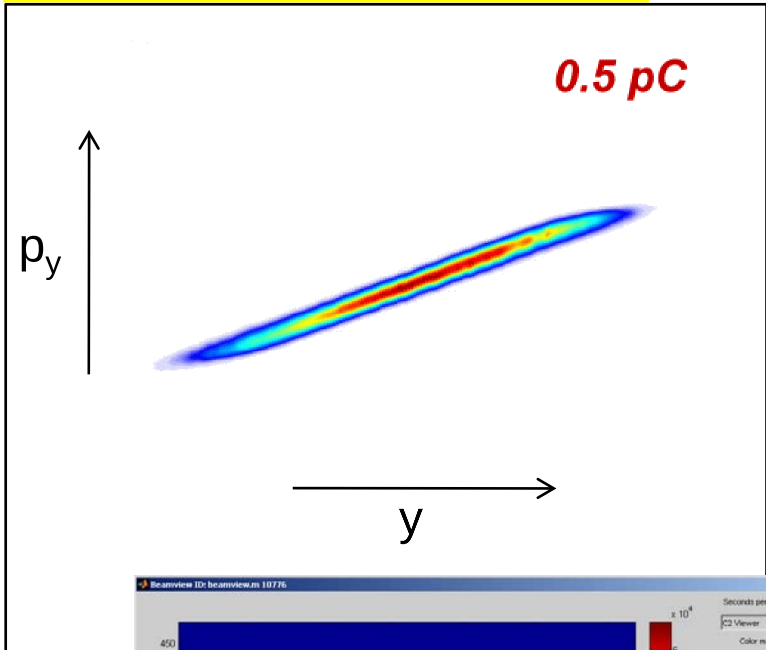
Old Boeing RF gun record still stands! But I bet not for long…



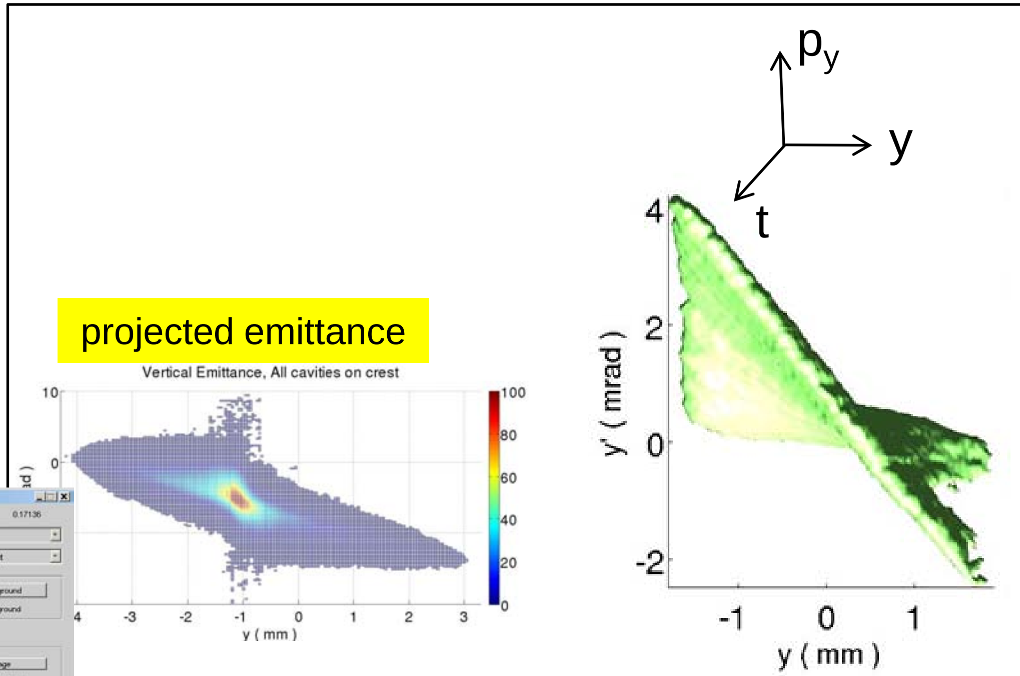
- **'Dramatic accelerator physics' – drilled a hole in the dump (1" Al) with electron beam!**
- **Raster wired incorrectly, (de)focusing quad setting off**
- **The dump is being repaired, back to Cornell in 2 weeks**

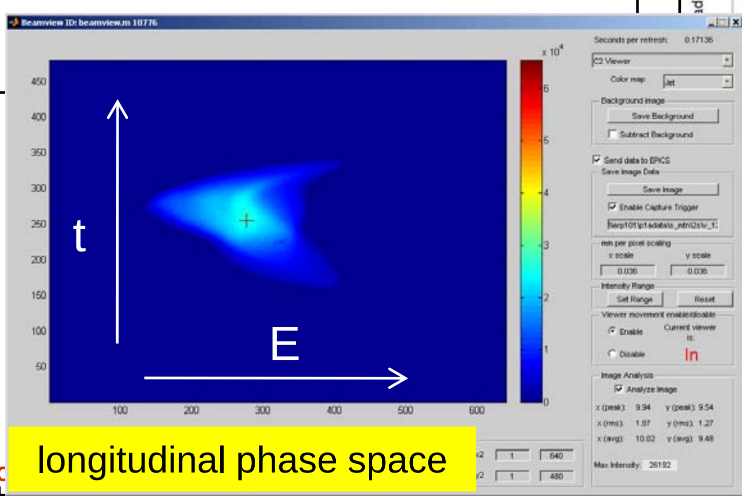
6D beam diagnostics: key to success

transverse phase space (animation)



slice emittance with resolution of few 0.1ps

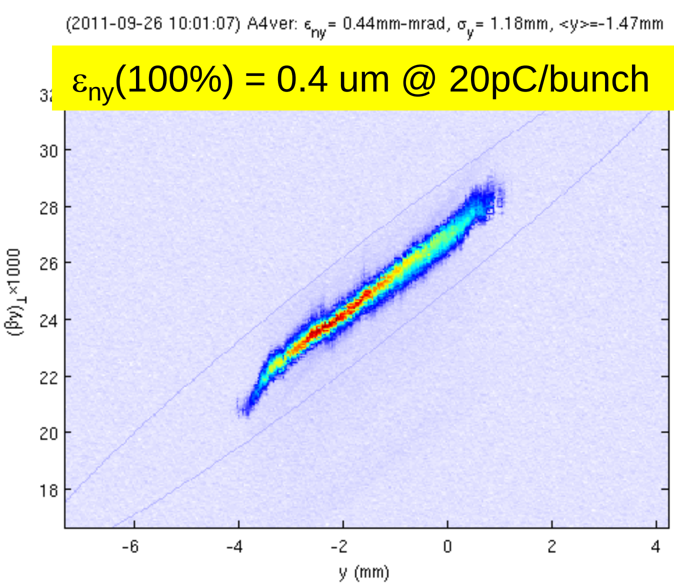


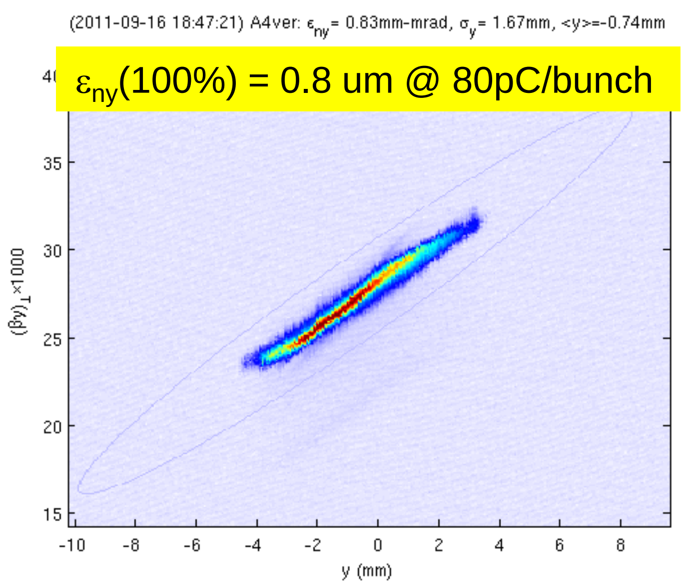


longitudinal phase space

Just last month: emittance spec achieved!

- **Keys to the result**
  - **Beam-based alignment (took us a couple of months)**
  - **Fantastic diagnostics!! (one of the reasons we are here)**
  - **Fight jitters in the injector**

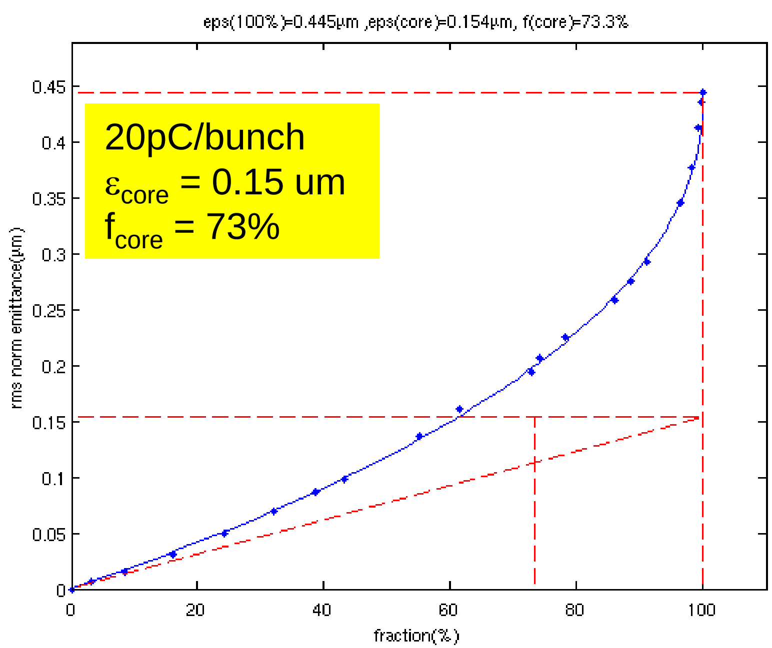


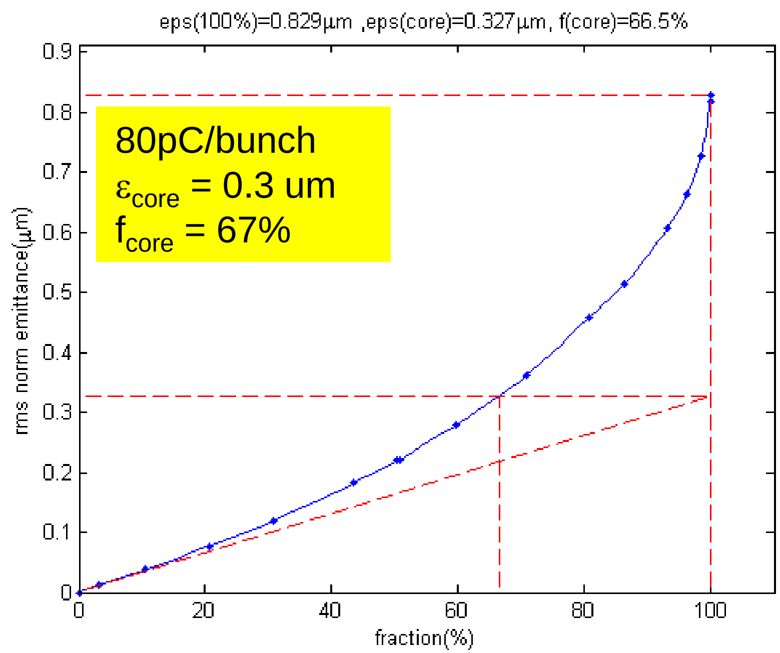


- **x2 thermal emittance! x1.3 simulated emittance**
- **correct scaling with bunch charge**

Some proselytizing: which emittance is right to quote

- **Single RMS emittance definition is inadequate for linacs**
  - **Beams are not Gaussian**
  - **Various groups report 95% emittance or 90% emittance (or don’t specify what exactly they report)**
- **The right approach**
  - **Measure the entire phase space, then obtain emittance of the beam vs. fraction (0 to 100%)**





But the undulator radiation in central cone is Gaussian… or is it?

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animation: scanning around 1st harm. ~6keV (zero emittance)

Spectral flux (ph/s/0.1%BW/mm^2) at 50m from undulator (5GeV, 100mA, λ_p = 2cm)

Light in phase space

animation: scanning around 1st harm. ~6keV (zero emittance)

Phase space near middle of the undulator (5GeV, 100mA, λ_p = 2cm)

Emittance vs fraction for light

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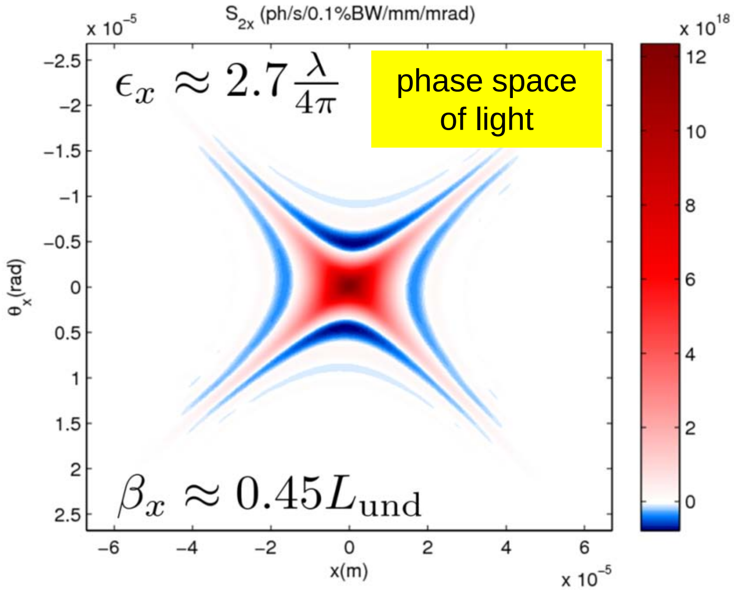

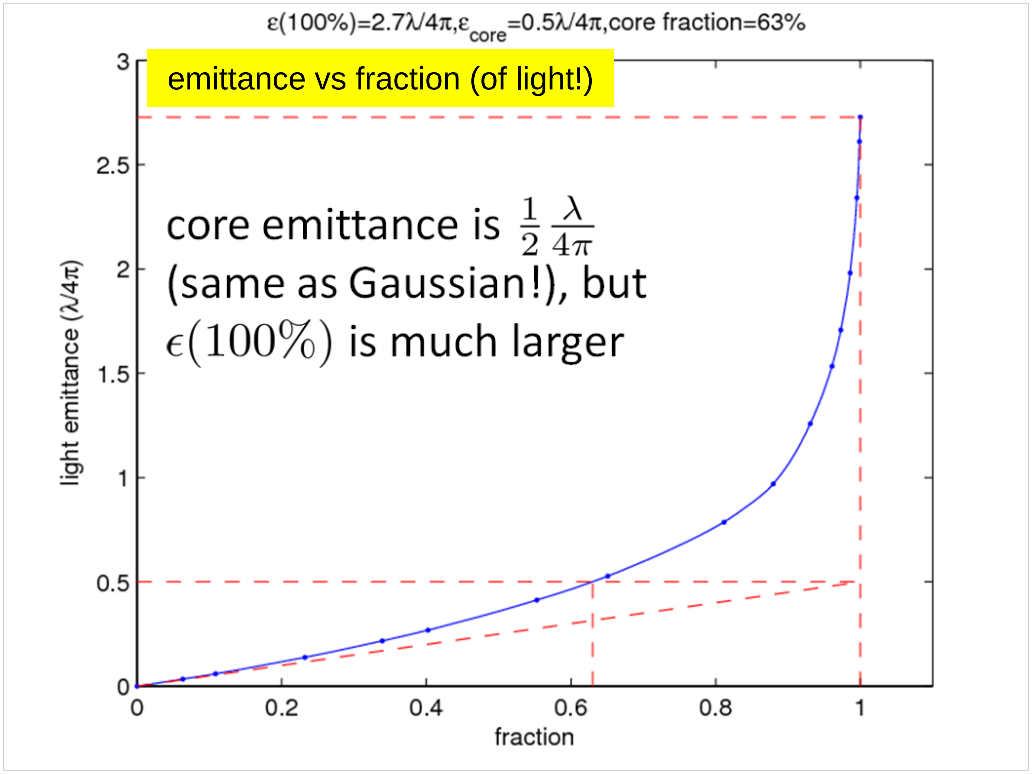

Bazarov, Synchrotron radiation in phase space (in preparation)

Just how bright is Cornell ERL injector beam?

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- **Effective brightness (for comparison)**

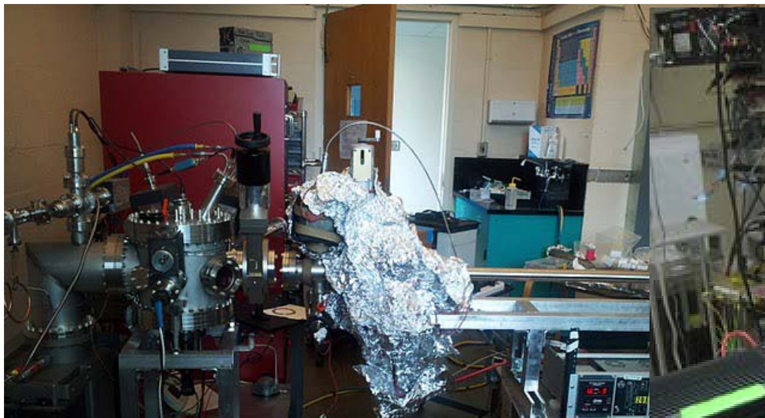
$$B_0 \propto I \frac{f_{x,core} f_{y,core}}{\epsilon_{x,core} \epsilon_{y,core}}$$

- **Today's 20mA ERL injector beam is as bright as 100mA 0.6nm-rad × 0.006nm-rad storage ring Gaussian beam!**

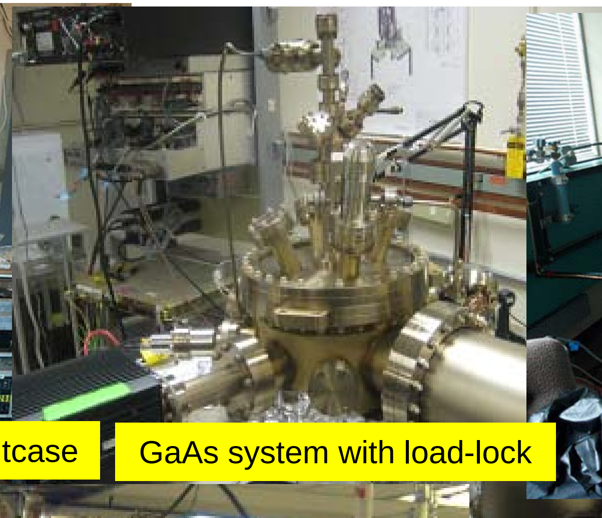
- **Parity in transverse brightness with the very best rings is already achieved; the result can only improve**

Photocathode research at Cornell

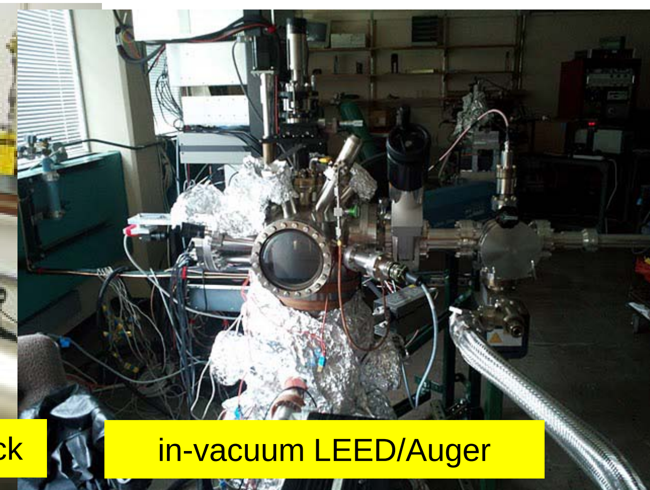
CLASSE



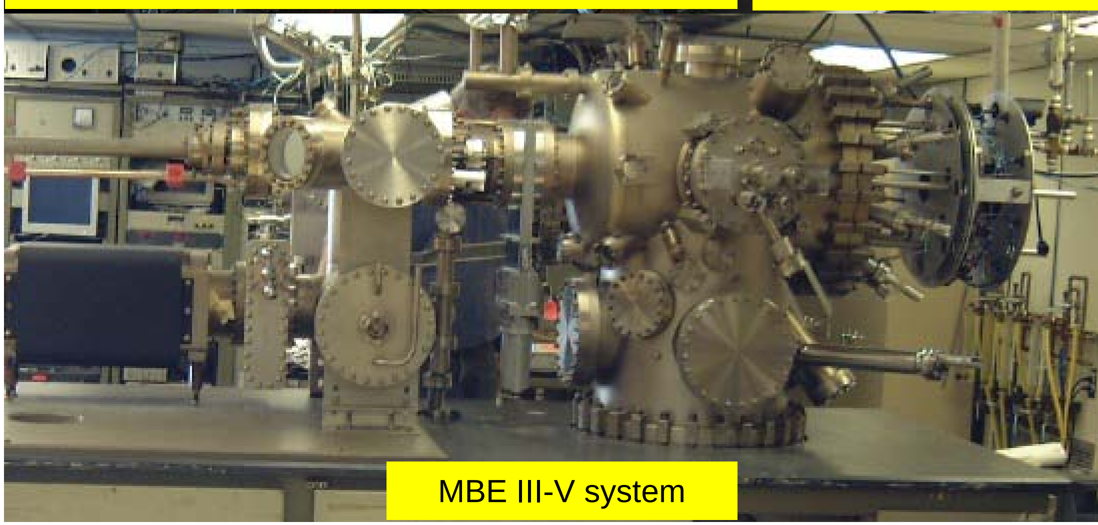
multialkali growth chamber with vacuum suitcase



GaAs system with load-lock



in-vacuum LEED/Auger

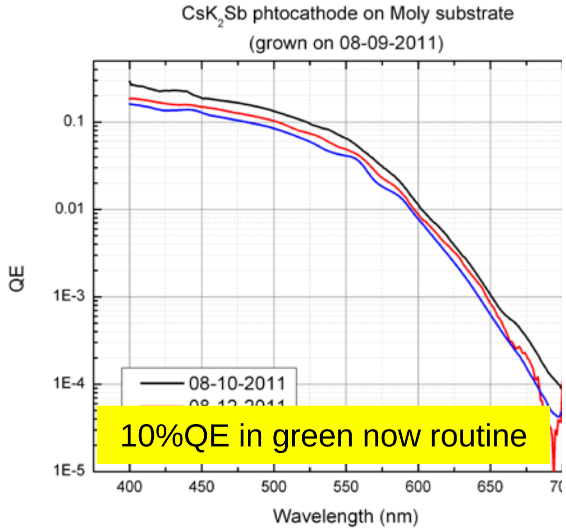


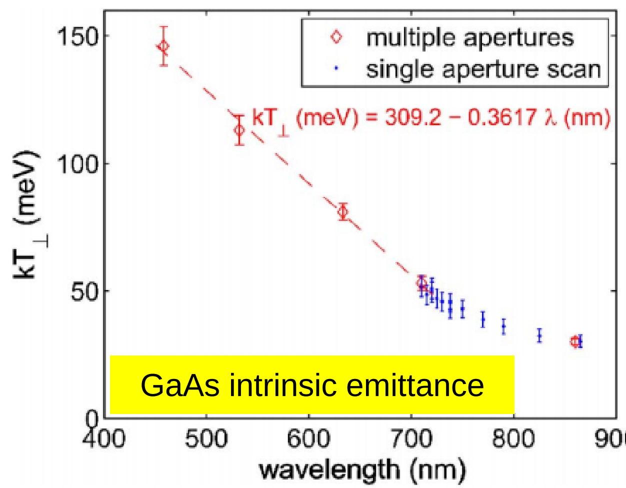
MBE III-V system

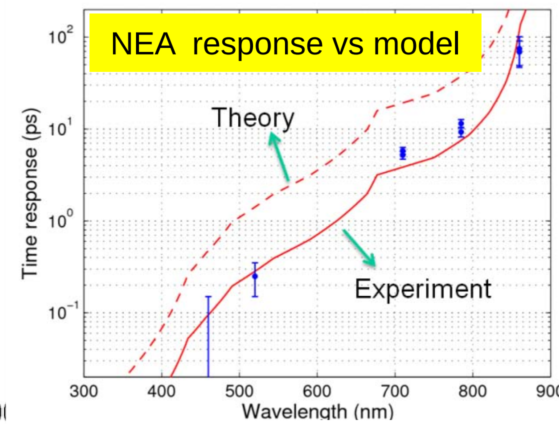
- **Also on campus AFM, EDX, SEM, STM, SIMS, ARPES**
- **+ CHESS (XRF, x-ray topography, EXAFS, and much more)**

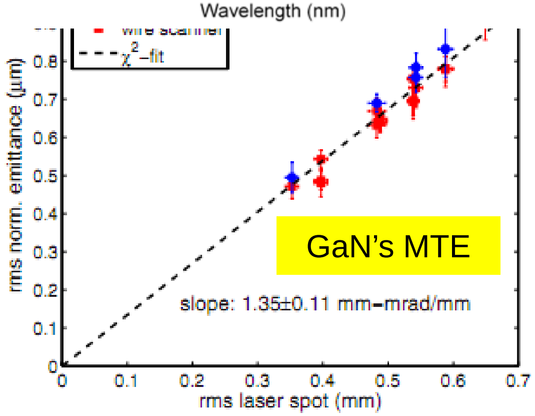
Photocathode research: some results

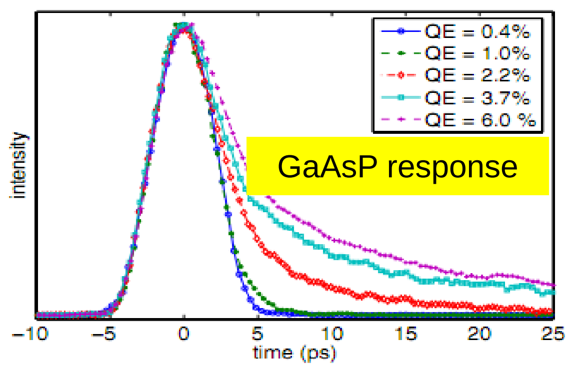
- **Wide selection of photocathodes evaluated for MTE and response time: GaAs, GaAsP, GaN, Cs_3Sb, K_2CsSb**

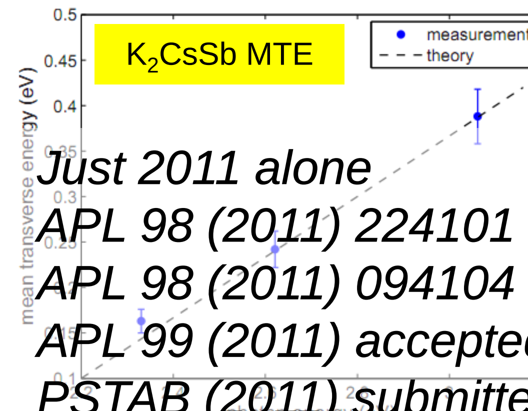








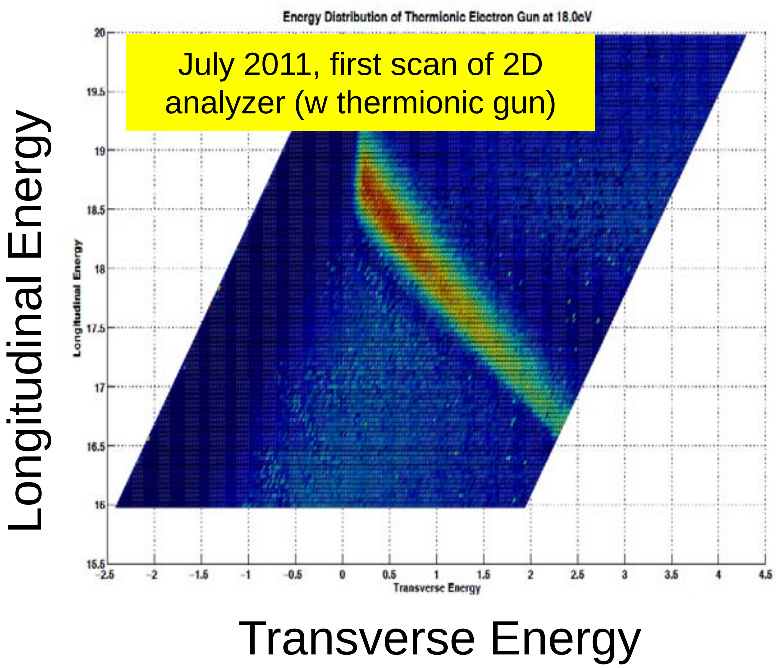


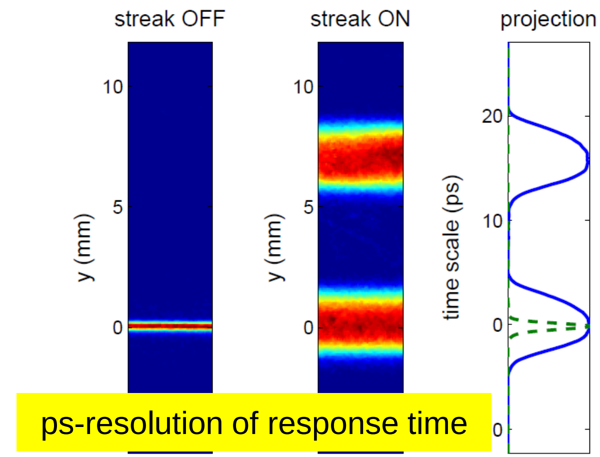


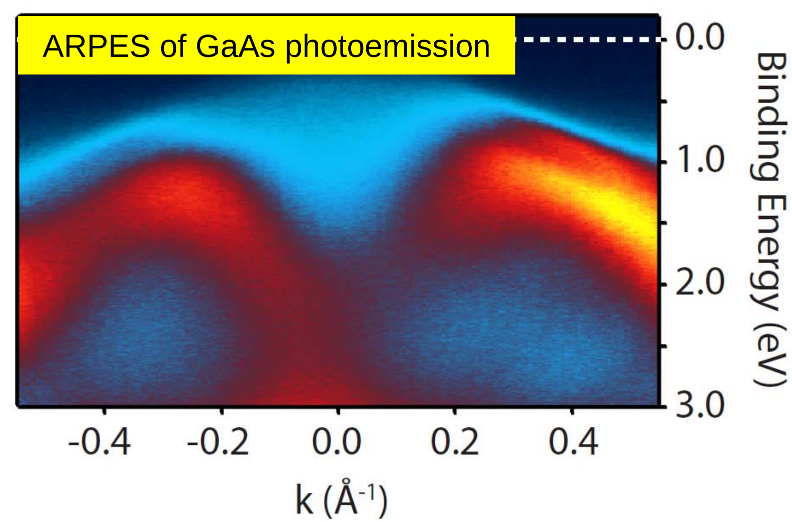
Just 2011 alone
APL 98 (2011) 224101
APL 98 (2011) 094104
APL 99 (2011) accepted
PSTAB (2011) submitted
PRL (2011) in preparation

Photocathode research: moving forward

- **Exciting prospects of generating sub-thermal (ultracold) photocathodes, i.e. photocathodes with essentially zero thermal emittance;**
- **About to grow our first MBE III-V with tuned parameters!**







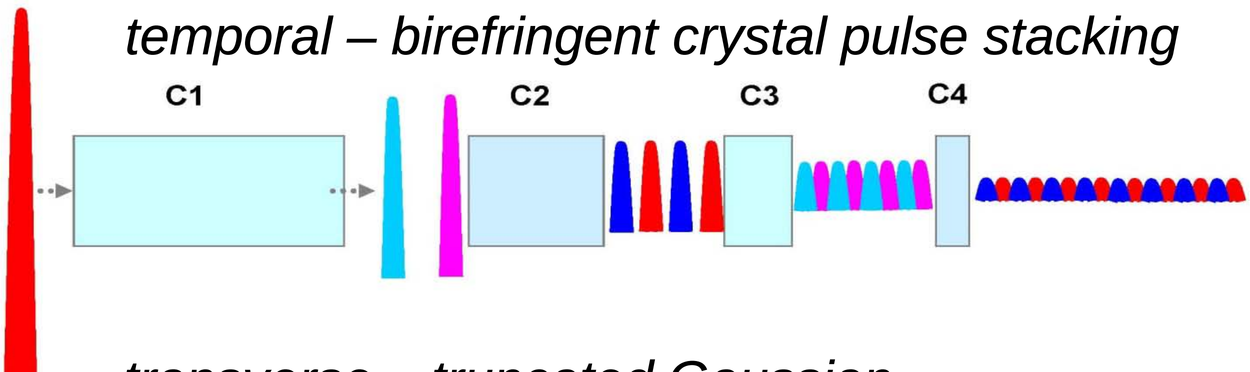
Building collaboration on photocathodes for accelerators

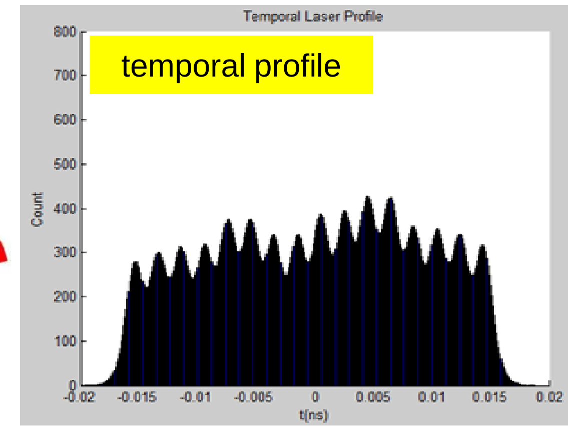
- **Collaboration with**
  - ANL
  - BNL
  - JLAB
  - SLAC
  - Berkeley
- **Excitement and momentum in the community;**
- **Cathode workshop at Cornell in 2012;**
- **Leading the effort on creating collaborative community-driven Internet resource;**

3D laser shaping
for space charge control

- **Optimal 3D laser shape: practical solutions identified**

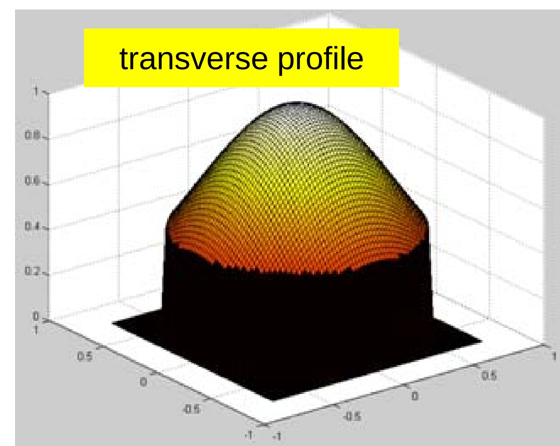
temporal – birefringent crystal pulse stacking





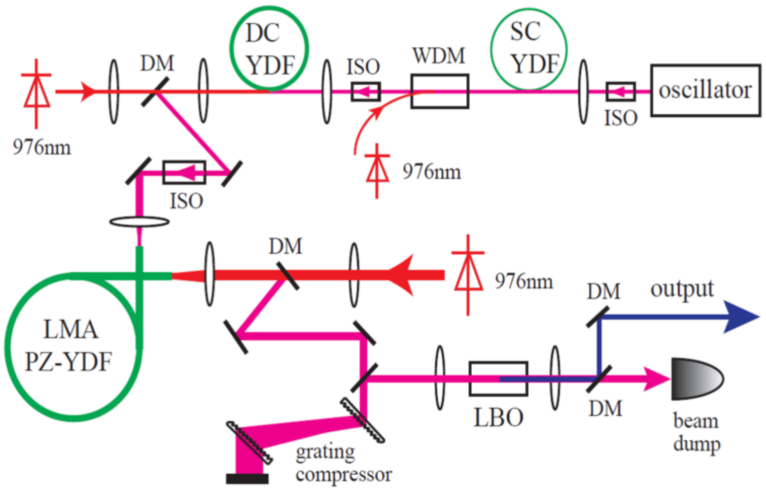
transverse – truncated Gaussian

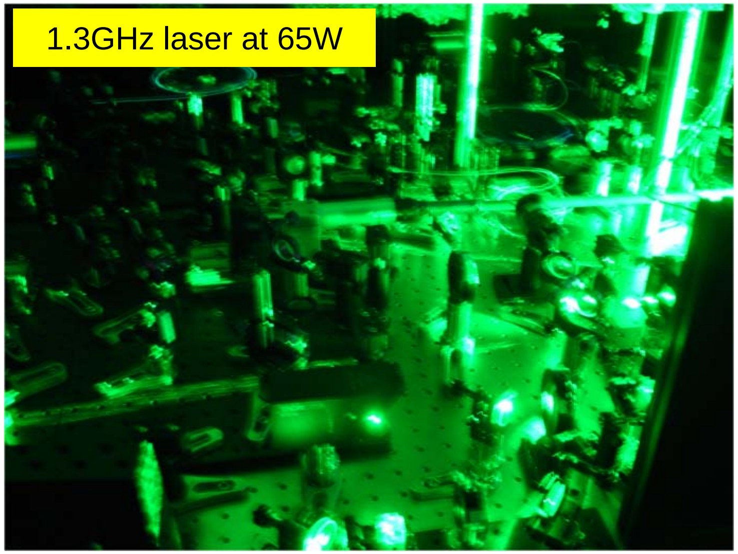
- **>50% of light gets through, emittance (sims) ~20% higher than the optimal**



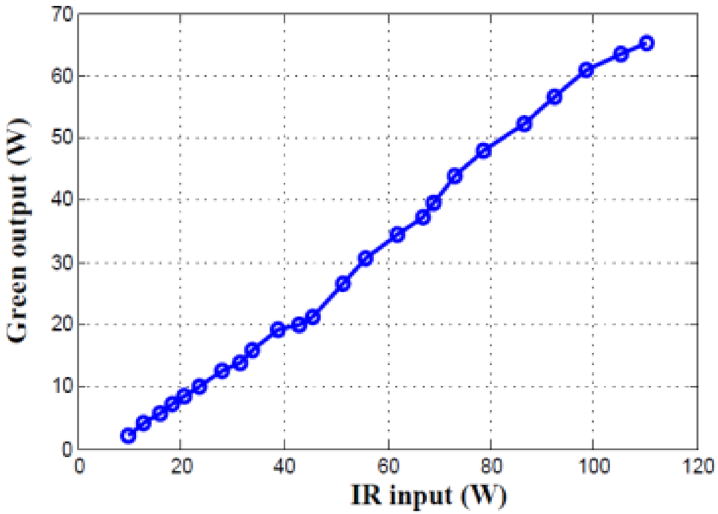
PRSTAB 11 (2008) 040702
Appl. Opt. 46 (2011) 8488

Plenty of laser power now!





should operate reliably at ~40W



Z. Zhou et al, Opt. Express (2011) submitted

Future outlook: towards ultimate brightness from DC/SRF guns

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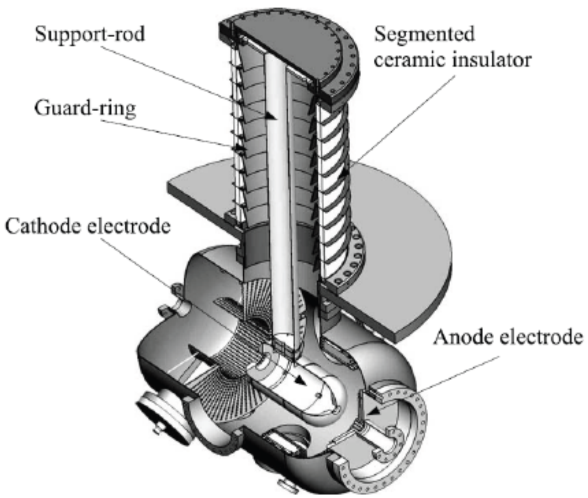
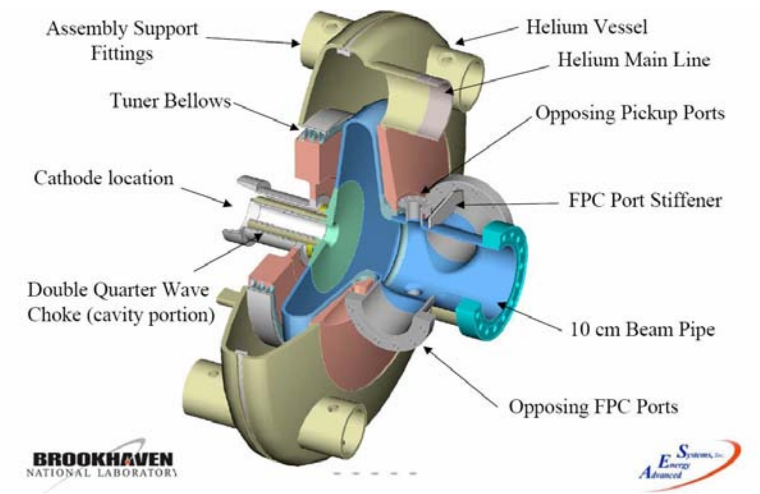
- **Jared Maxson (part II)**

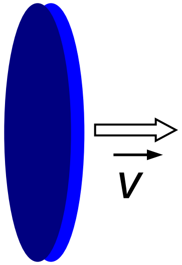
Comparing DC and SRF guns





Photoemission: Ultimate Brightness

- The final answer:
  - Given a laser, photocathode, and accelerating gradient→ Max. beam brightness is set!
- Take a short laser pulse, < 10 ps:
  - Beam assumes pancake distribution
  - There is a *max charge density supportable!*



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

- Take a particular photocathode & laser:
  - Transverse momentum spread intrinsic to photoemission
  - There is a *minimum emittance achievable!*

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

$$\epsilon_{nx,y} = \sigma_{x,y}\sqrt{\frac{MTE}{m\,c^2}}$$

Photoemission: Ultimate Brightness

- Transverse brightness:

$$B_{n,ave} \sim \frac{I}{\epsilon_{nx}\epsilon_{ny}} = \frac{q_b f}{\epsilon_{nx}\epsilon_{ny}}$$

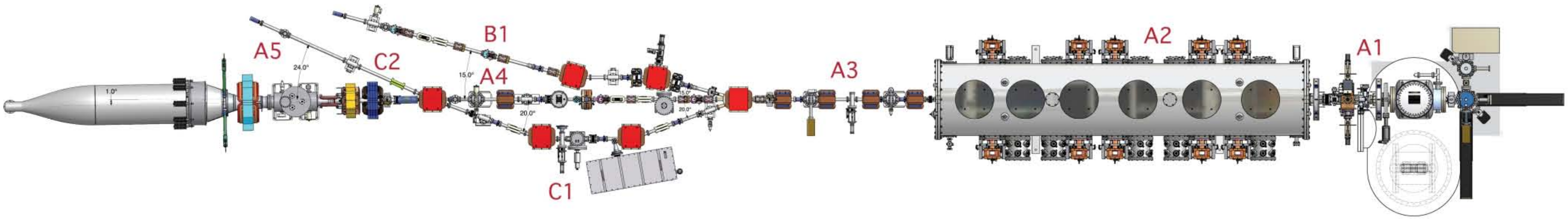
- Or:

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

- **q**: (Determined by E_{cath})
  - What are the ***largest gradients achievable*** with existing technology, pushed to its limits?
- **f:**
  - What are the technologies that best support ***CW operation?***
- ϵ_{nx}:
  - Can we transport the thermal emittance, wrangling ***space charge dilution*** and ***element abberations?***

High Brightness Sources

- A host of high brightness photoinjectors are being built for various ERL/FEL applications.
- For the Cornell ERL, we need:
  - **100 mA** average current
  - **< 1 mm-mrad** norm emittance
- Once upon a time…
  - DC guns were a viable (stable!) CW option at the time
  - Local expertise in negative affinity GaAs
  - …so an injector was born!

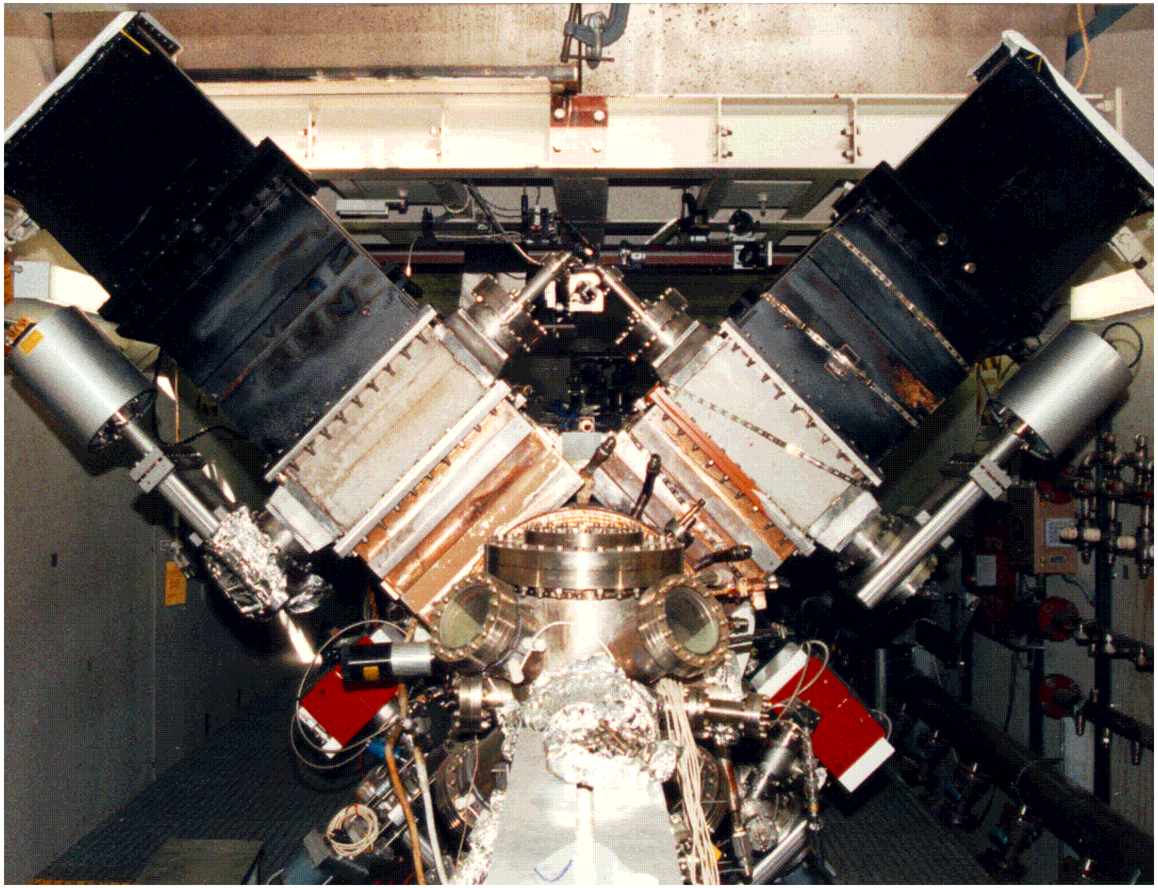


N.C. RF Photoguns

- What about normal conducting RF guns?
  - Much success in for pulsed applications (SLAC, LCLS)
  - **Large field** at the photocathode
  - **Stable, pulsed** operation
- CW operation not so easy:
  - Field emission →poor vacuum
  - Poor vacuum quality→Poor photocathode lifetime
  - Lots of power, heat→ Limited to lower frequency
- Can be done!
  - Dave Dowell and the Boeing RF gun
  - 1992 demonstration of 32 mA average current (running at 25% duty factor)
  - Limited by vacuum quality, and…

…it was a beast!

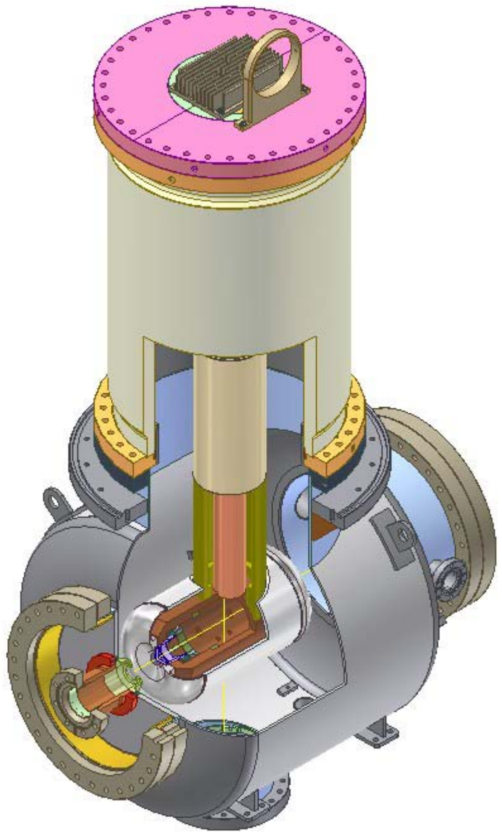
The Boeing 433 MHz RF Photocathode Gun

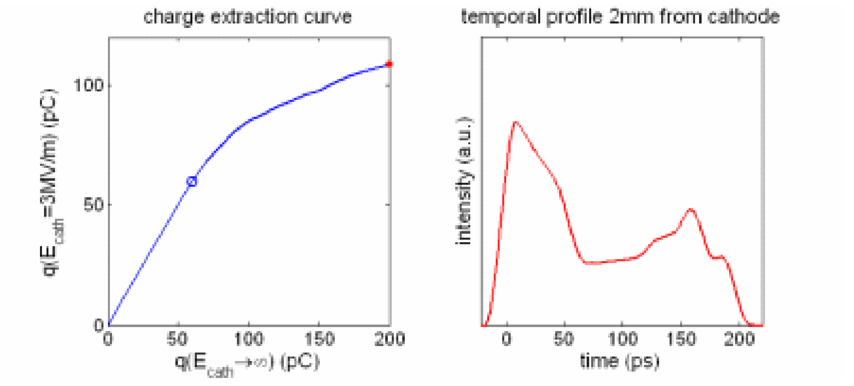


D.H. Dowell/MIT Talk, May 31, 2002

DC Photogun Issues

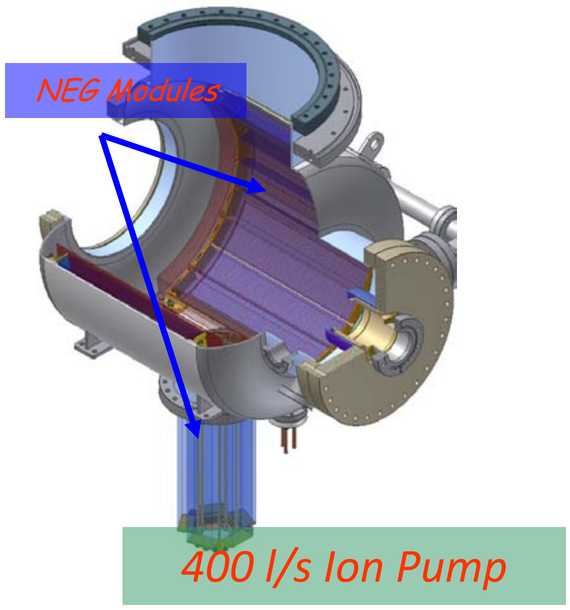
- DC guns are deceptively simple:
  - HVPS, Stalk, Ceramic, and electrodes
- Voltage limited by ceramic puncture
  - Field emission from HV stalk bores holes through alumina HV vacuum envelope.
- Lower beam energy:
  - Emittance dilution
  - Large charge beam instability
  - Hard to transport, sensitive to element aberrations.

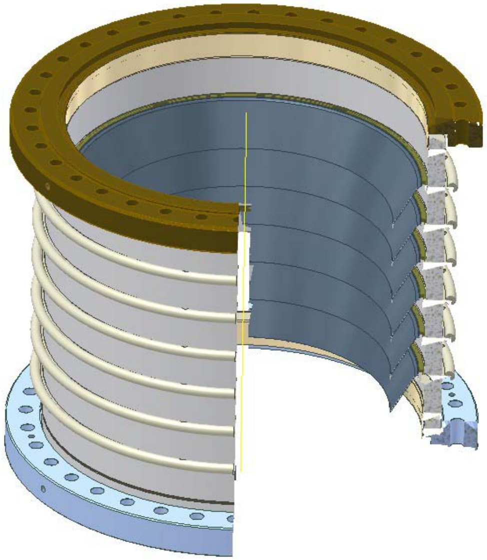




The Brighter Side

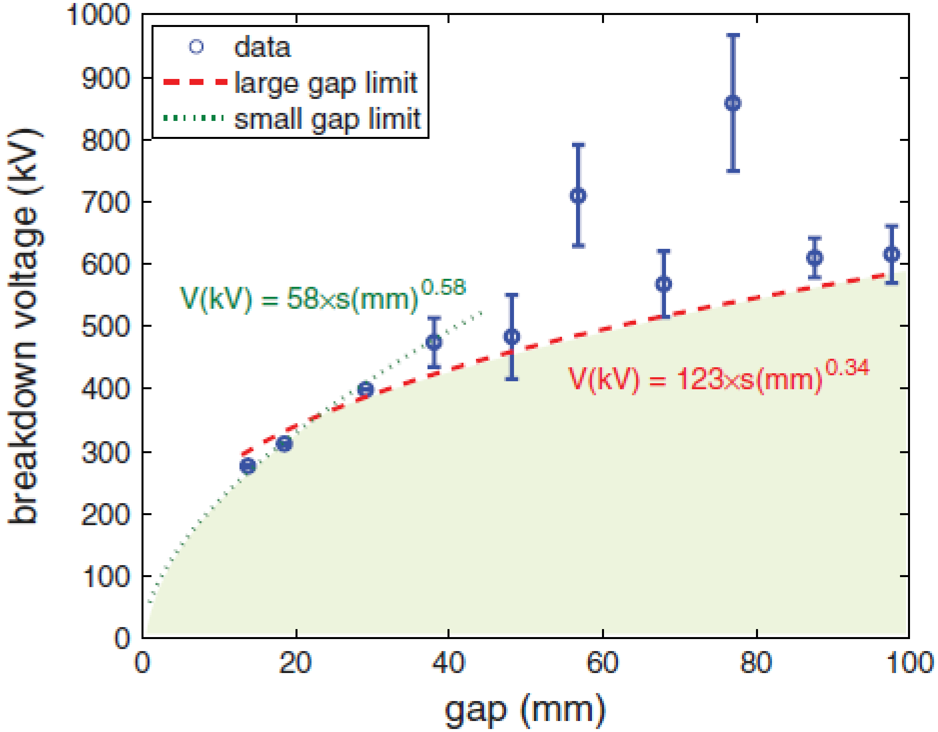
- But you get:
  - Inherent CW operation
  - Excellent vacuum
  - Design simplicity, small inherent aberration.
- Overcoming ceramic puncture
  - KEK segmented insulator
  - Define voltage on each segment with metallic guard rings.
  - MK II gun @ Cornell: my PhD
- MK II will also feature:
  - Adjustable cathode/anode gap
  - Biased anode?





Ultimate DC performance

- With ceramic puncture mitigated…
  - Still limited by UHV breakdown in beam region.



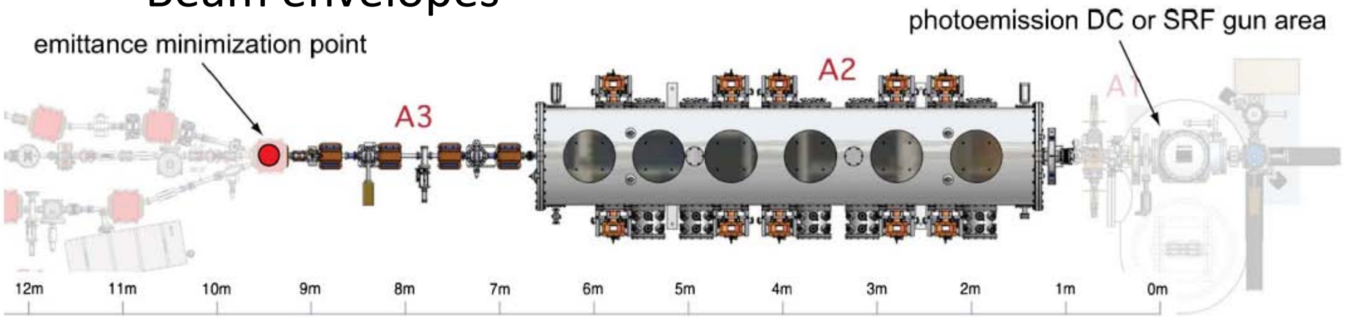
  - Inherent tradeoff between energy, field at the cathode, and focusing strength.

Enter SRF Guns

- Also (conceptually) simple:
  - **n+1/2 cell** SRF cavity, with a photocathode at position of max gradient
  - Quarter wave resonator is another option
  - **Low RF losses** means CW operation is viable
  - Huge (**>30 MV/m**) cathode gradients
  - MeV beam direct from the gun!
- Practical limitations:
  - High QE photocathode load lock, puck insertion mechanism challenging
  - Lots of places for **field emission!**
- Fields only limited fundamentally by SRF quenching.

Performance Comparison

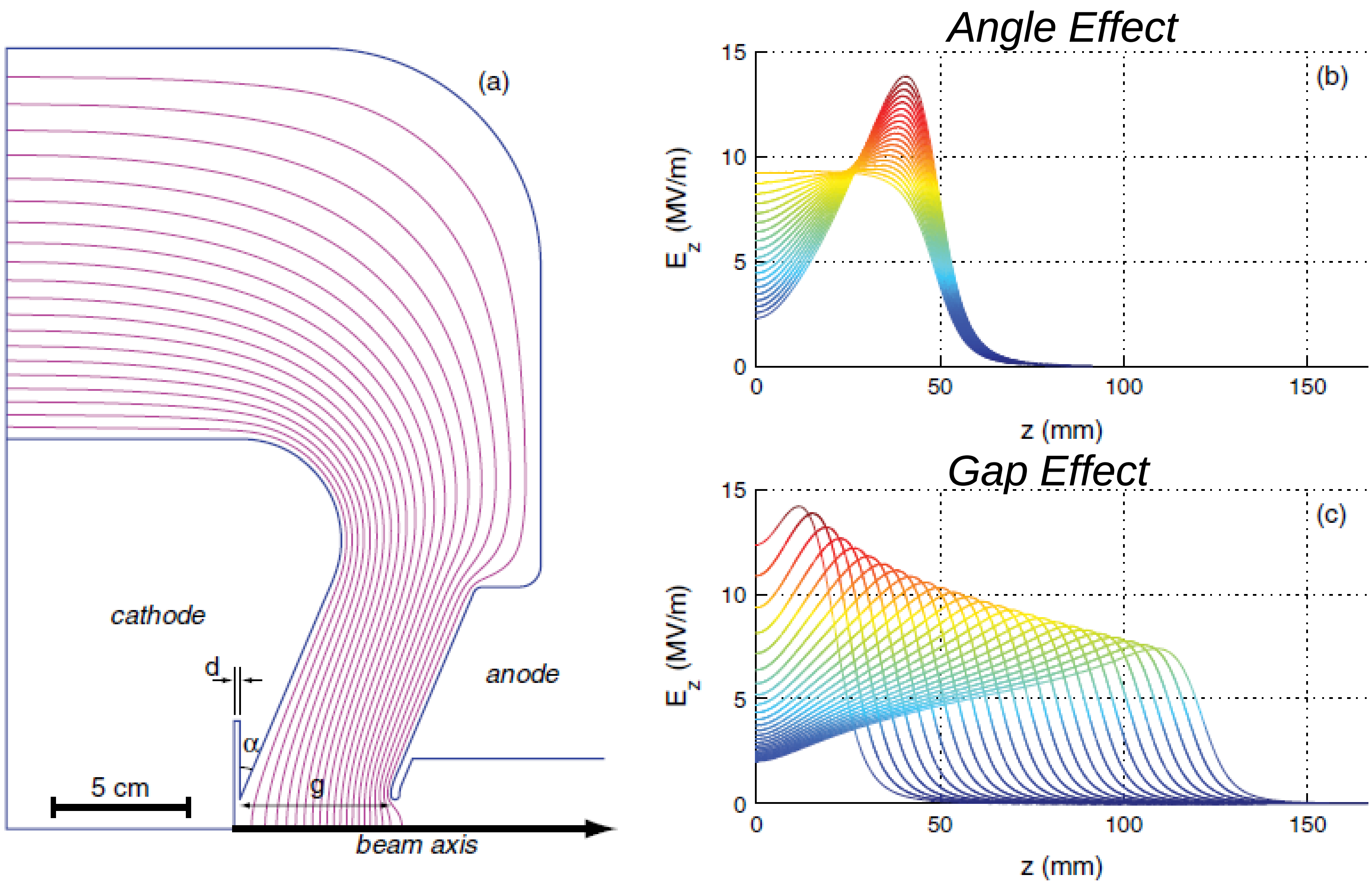
- SRF guns promise to deliver high brightness beams with only a few fundamental drawbacks.
- But how much better is better?
- Let's consider the ultimate (ideal) gun design for both types:
  - Subject to only **fundamental constraints**
  - **Simulate** them on the same linac (ERL inj. Prototype)
  - Performance:
    - Emittance vs. Bunch charge
    - Beam envelopes



Ideal Gun Design?

- Ultimate performance=(ultimate gun design) + (fully optimized beamline)
- Utilizing multi-objective genetic optimizer + 100 node computer cluster:
  - **Specify**: RF frequency (1.3 GHz), cathode intrinsic emittance, current (0-200mA, or 0-154 pC/bunch), beamline elements.
  - **Vary:** gun geometry, gun voltages, laser temporal profile, solenoids, SRF cavity voltages & phases
  - **Minimize:** emittance after 10m.
  - **Constrain:** fields to be within “fundamental limitations”.
- Specifics:
  - Calculate discrete set of gun geometries (Poisson/Superfish)→export 1D field map
  - Optimizer requests from continuous gun geometry parameter set→interpolate field map in multi-D space.

DC Gun Geometry

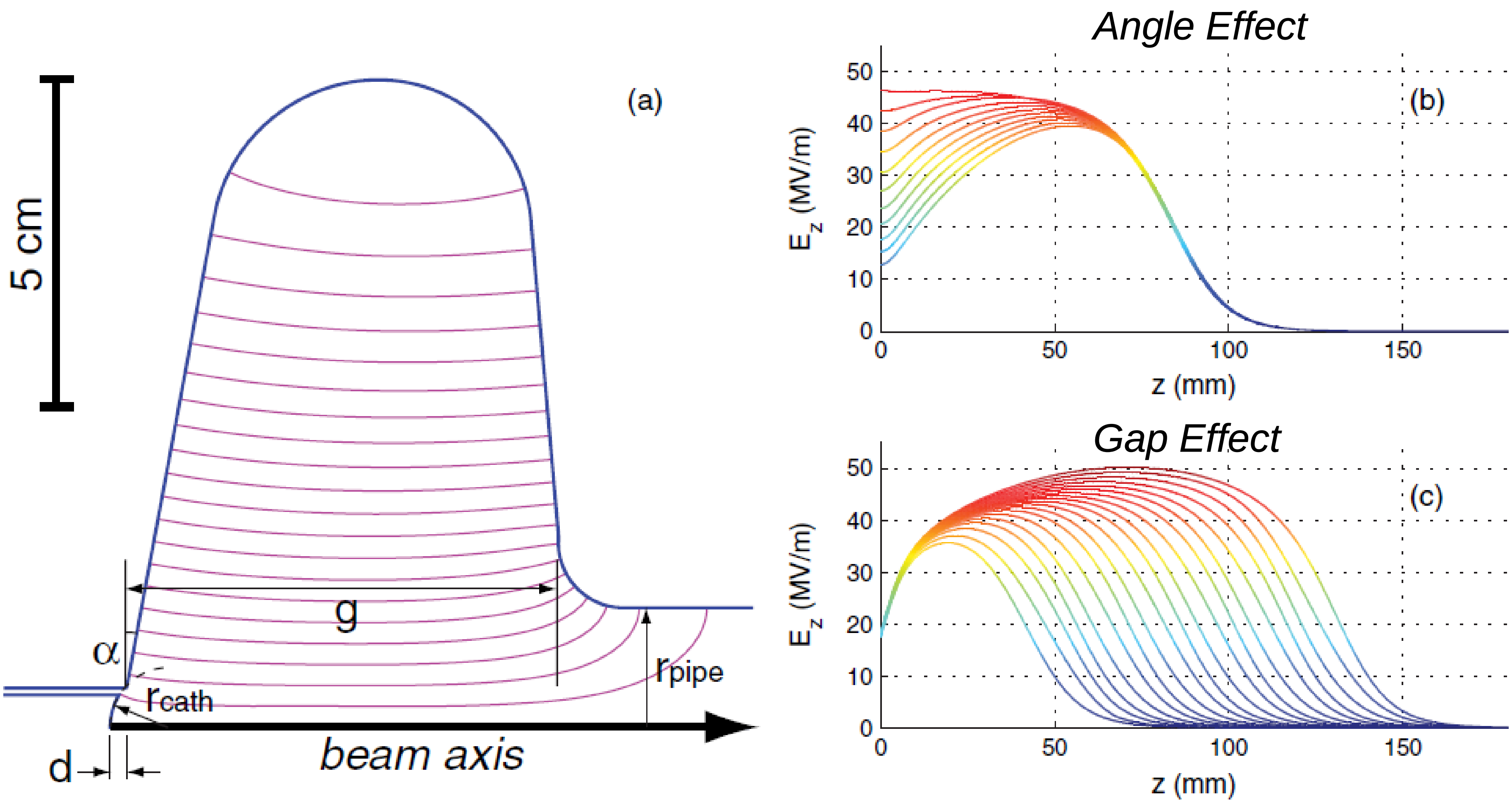


- Field constraint: Voltage, given a min cathode-anode gap, must be below breakdown.

SRF Gun Design

- Select: 1.3 GHz, ½ cell
  - Only one (half) cell! 200mA (beam)→ 400kW coupler power—tough at 1.3 GHz.
- Use optimistic field constraints (TESLA nine cell)
  - $E_{acc} \leq 25\ \mathrm{MV/m}$
  - $E_{peak}/E_{acc} \leq 2$
  - $H_{peak}/E_{acc} \leq 4.26$ mT/(MV/m)
- Majority of possible solutions were constrained by E_{pk}($\leq$ 50 MV/m).

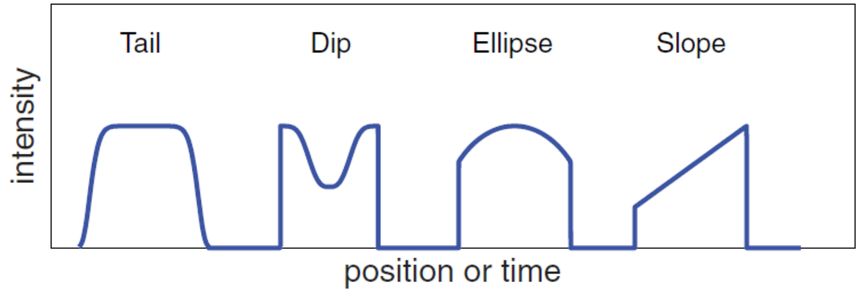
SRF Gun Geometry

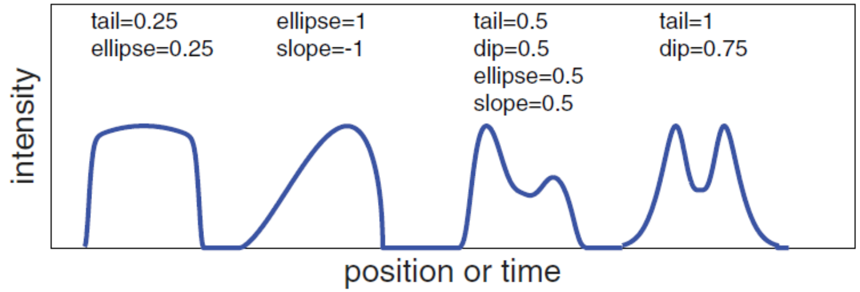


- Equatorial radius used as the tuning parameter.

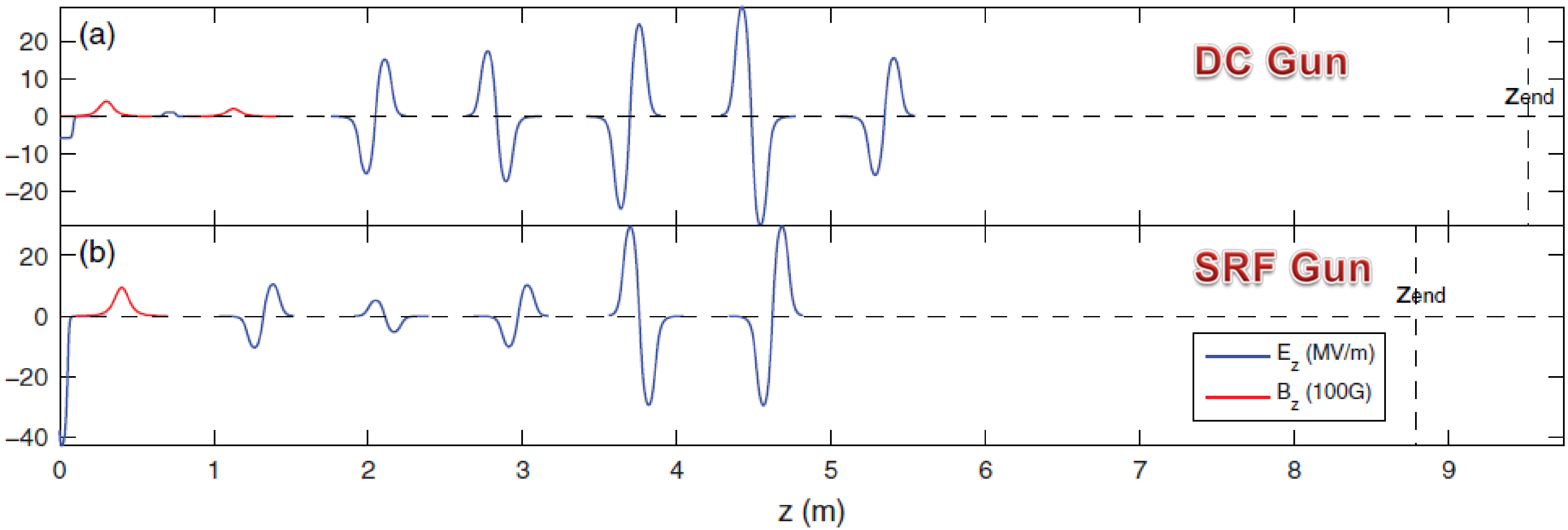
Laser Temporal Shaping

- The effect of space charge at the photocathode will be different for each gun:
  - The temporal pulse shape should have a strong effect on the final emittance:
- Optimizer can use combinations of archetypical shapes:

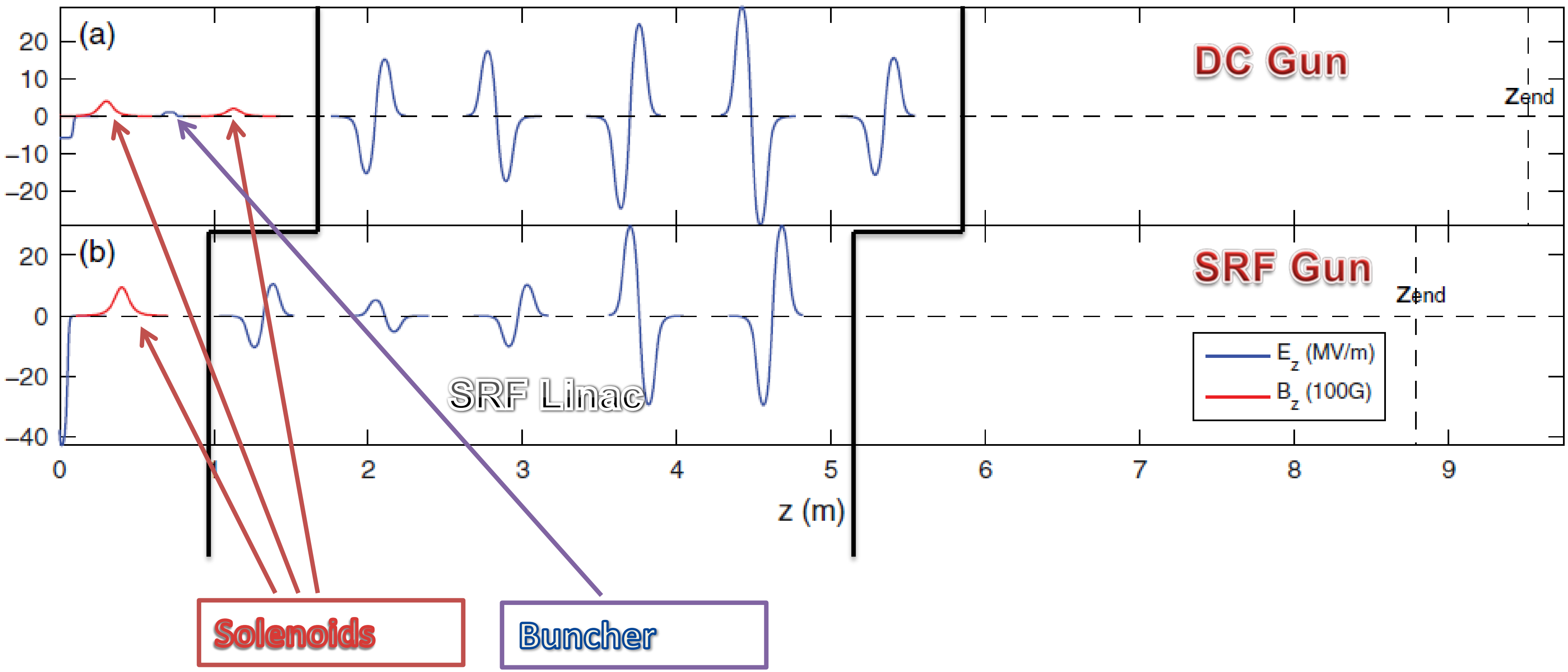




Beamline parameters



Beamline parameters

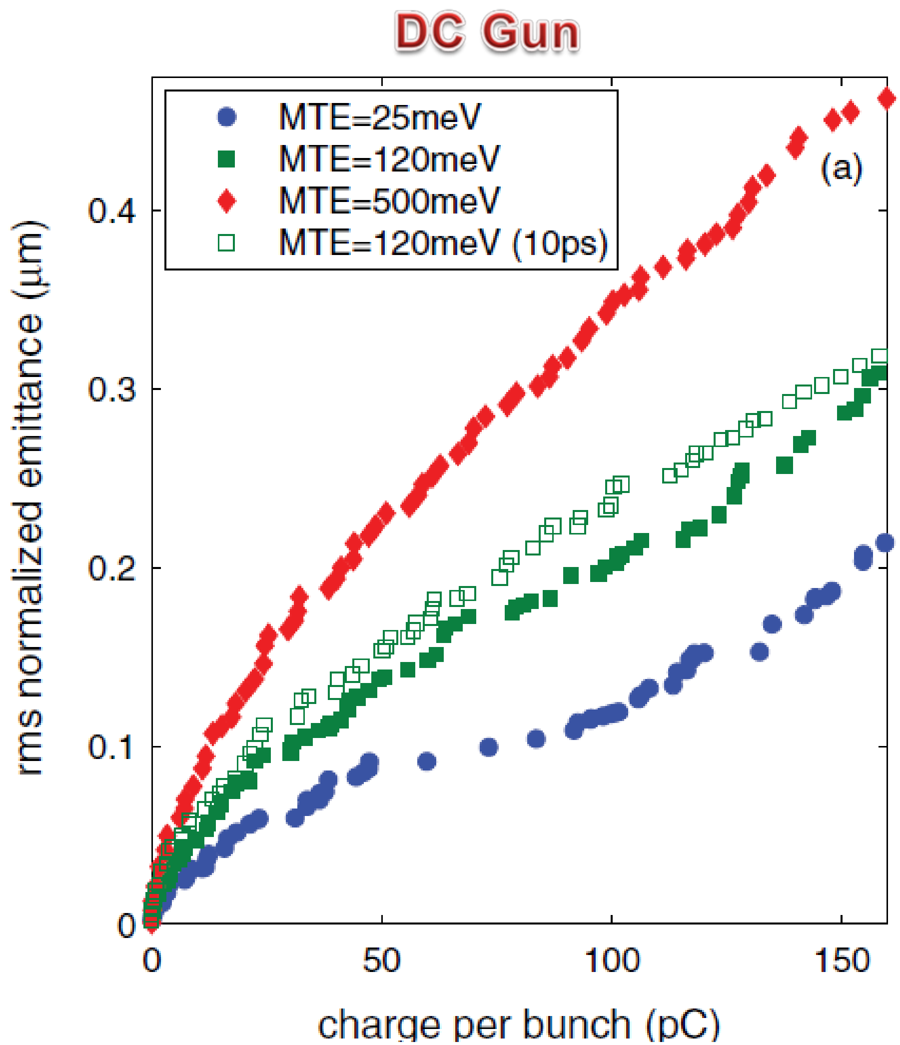


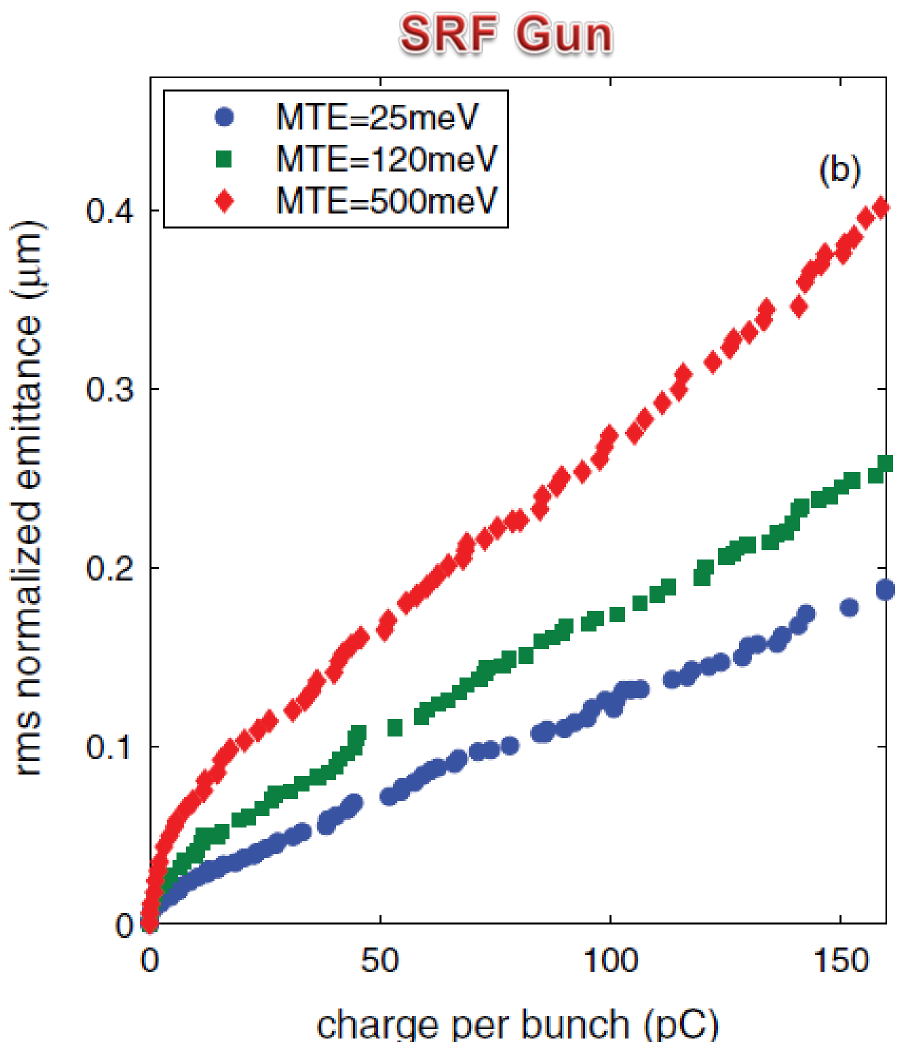
- The SRF beamline is simplified:
  - NC buncher cavity is ineffective at high beam energy
  - Only one solenoid included

Emittance Performance

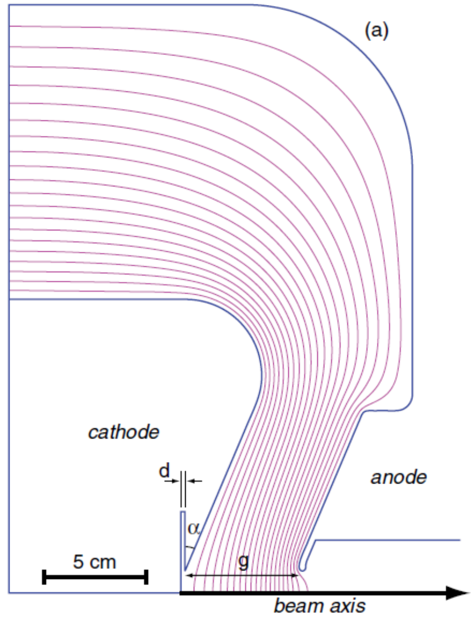
- Cathode Mean Transverse Energy:
  - Thermal (intrinsic) emittance:
    - $\epsilon_{nx} = \sigma_x \sqrt{\frac{MTE}{m\, c^2}}$
  - 25 meV:
    - Lowest MTE for NEA GaAs (room temp!)
    - vacuum cleaved
  - 120 meV:
    - Cornell's MTE for NEA GaAs @ 520 nm
    - *in operando.*
  - 500 meV
- Note: Initial sims request long (~100 ps) DC gun laser pulse length
  - Keep solutions, but this is hard to do!
  - Subsquent run: constrain pulse to <10 ps

Emittance Performance

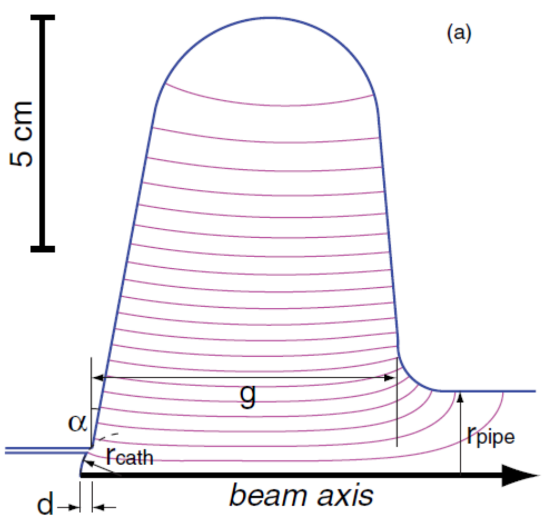


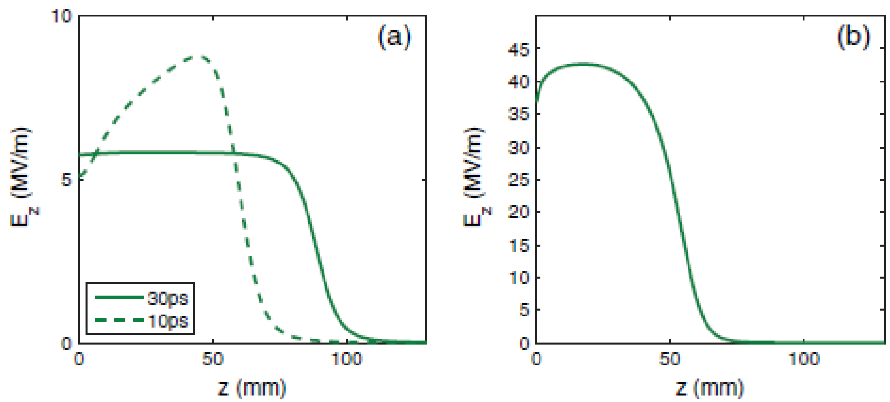


Optimal Gun Geometry:



- DC Gun:
  - $\alpha \approx 0$, $g = 9$ cm, V=470 kV
  - Pushed for ***max field*** over focusing.
  - Cathode recess unimportant.
- SRF gun:
  - $\alpha = 2.3$, $g = 4.4$ cm
  - $r_{pipe} = 0.9$ cm, $r_{cath} = 0.4$ cm
  - r_{pipe} and cathode recess seemed unimportant.



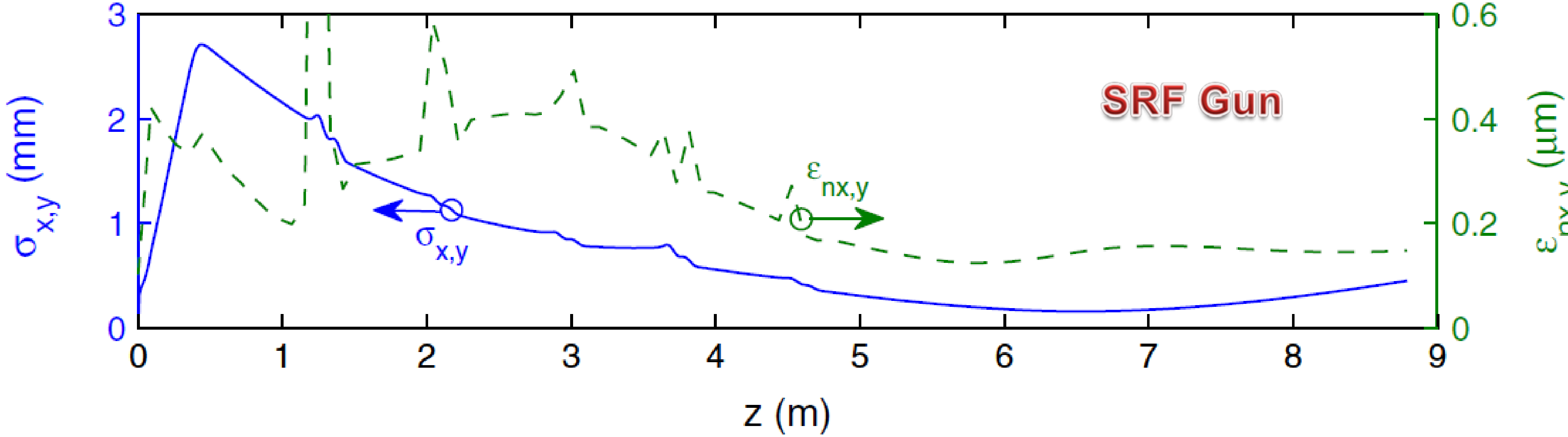


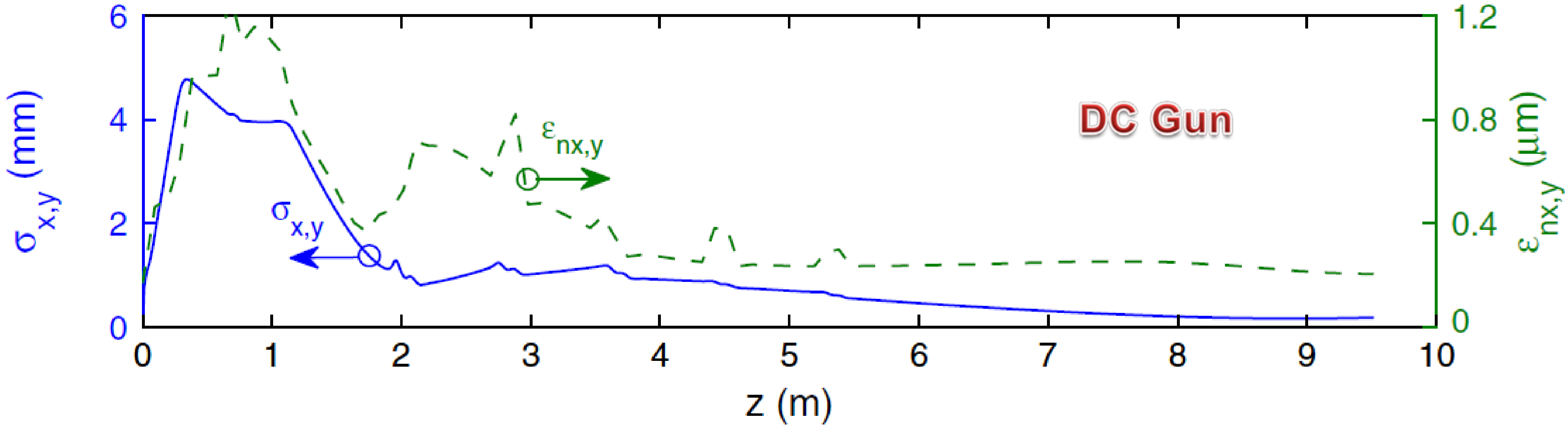
Beamline Specifics

TABLE I. Main injector parameters after optimization.

Parameter	dc gun	SRF gun
Charge	80 pC	80 pC
Laser spot size (rms)	0.35 mm	0.21 mm
Laser pulse (rms)	10 ps	9 ps
Thermal emittance (rms)	0.17 μm	0.10 μm
Cathode field ($t = 0$)	5.1 MV/m	16.6 MV/m
Kinetic energy after the gun	0.47 MeV	1.91 MeV
Buncher peak field	1.2 MV/m	⋯
SRF cavities1,2 peak E_z	20, 22 MV/m	11, 6 MV/m
SRF cavities1,2 phase	−25, −37°	−60, −40°
Solenoid1 peak field	0.038 T	0.094 T
Solenoid2 peak field	0.023 T	⋯
Transverse emittance (rms)	0.21 μm	0.15 μm
Bunch length (rms)	0.89 mm	0.86 mm
Longitudinal emittance (rms)	8.2 mm keV	9.2 mm keV
Kinetic energy	12.4 MeV	10.3 MeV

…But can it be done?





…But can it be done?

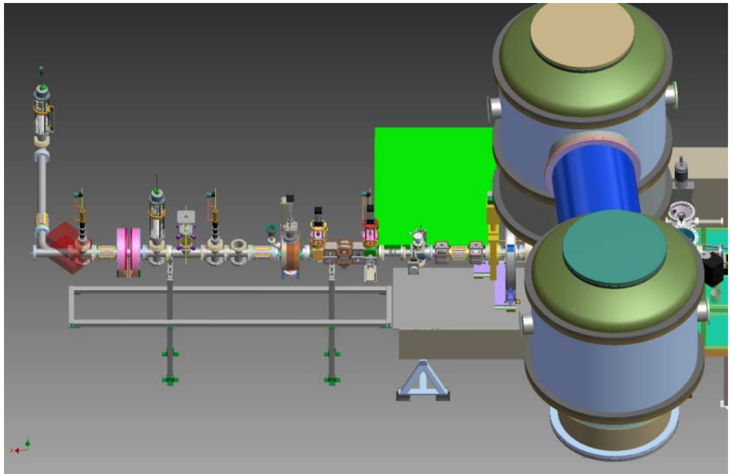
- ***Space charge energy chirp @ photocathode:***
  - leaves a nasty chromatic aberration through the solenoids!
  - Far more ***prominent in DC case***. Must anti-chirp with buncher!
- Space charge dominated ***emittance evolution:***
  - Difficult to quantify analytically!
  - Precise knowledge of orbits and phases (read alignment, calibration, and sims) required to compensate!
  - Just beyond state of the art
- Recent alignment run @ Cornel ERL injector:
  - Sim: 1.1 x thermal; Measured: 2x thermal.

"The proof of the pudding"

- For cool cathodes, optimization suggests comparable DC/SRF performance.
  - SRF beamline clearly more forgiving.
- Critical areas for preserving beam brightness ***common to both SRF/DC***:
  - Single particle dynamics: element aberrations/ scaling laws.
  - Space charge dynamics: simulating vetting/agreement
  - 3D laser pulse control
- Both technologies must be concurrently pursued!
- Beamline collaboration a natural consequence

"…Is in the eating"

- BNL a leader in SRF gun development.
- Cornell's construction of the MK II DC Gun:
  - Adjustable cathode/anode gap→ ***"dial-in" a field!***
  - Segmented insulator: pushing the voltage limits.
  - Full 6D phase space characterization:
    - Understand implications real beam orbit and optics on phase space growth
    - Induce & study ***space charge instability at photocathode***: how longitudinal breakup impacts the transverse phase space.



Summary

CLASSE

Part I

- **Cornell ERL photoinjector project has achieved beam brightness that exceeds that of the best existing storage rings;**
- **Diverse and aggressive program to improve beam brightness and injector performance further;**

Part II

- **Two potent technologies for high current low emittance photoinjectors discussed;**
- **“The proof of the pudding is in the eating”**
  - **Exciting time to push both DC and SRF guns to their ultimate limit (as set by photocathode & peak electric field)**

Acknowledgements

CLASSE

- **This is a team effort:**
  - **John Barley, Adam Bartnik, Joe Conway, Luca Cultrera, John Dobbins, Bruce Dunham, Colwyn Gulliford, Siddharth Karkare, 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.**

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