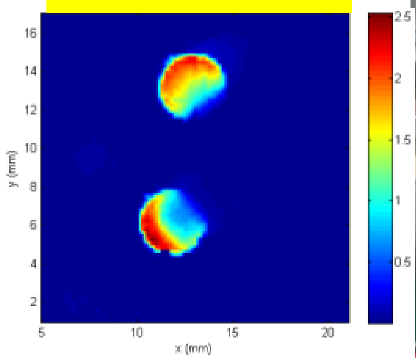
CLASSE

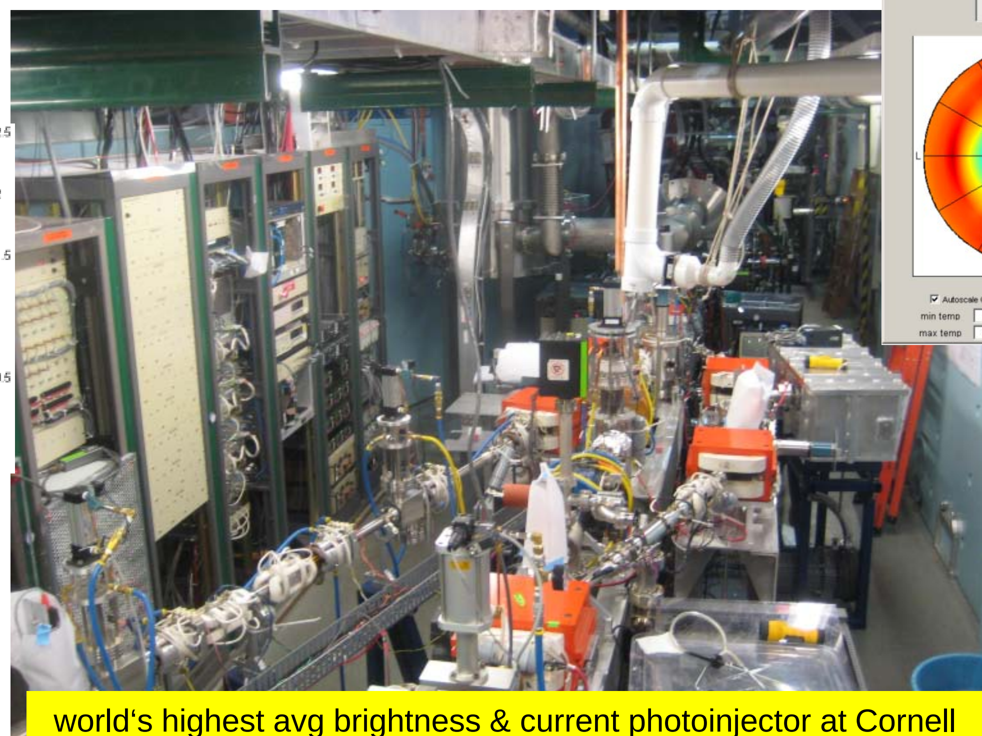
# Overview of Photoinjectors for Future Light Sources

Ivan Bazarov

Cornell University

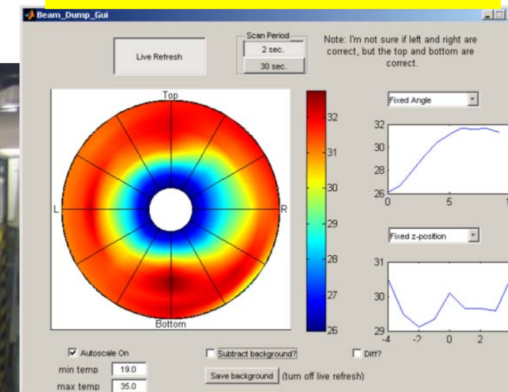
GaAs QE(%) map after 50 mA run



world's highest avg brightness & current photoinjector at Cornell

Main dump T-map during 35 mA high current running




damaged optics after 10's W of laser power

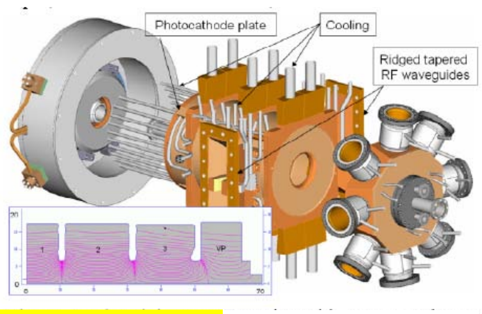
# Today's talk

CLASSE

- Needs for linac-based light sources
- Different approaches, same goals
- Recent progress (incomplete survey)
- Moving beyond the state-of-the-art

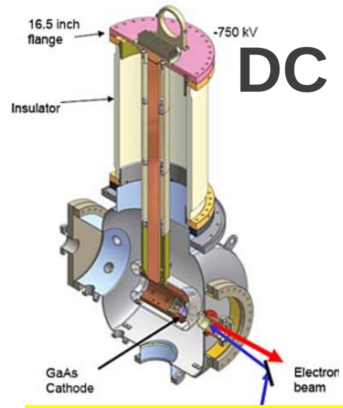
# DC, RF, SRF guns

## NCRF



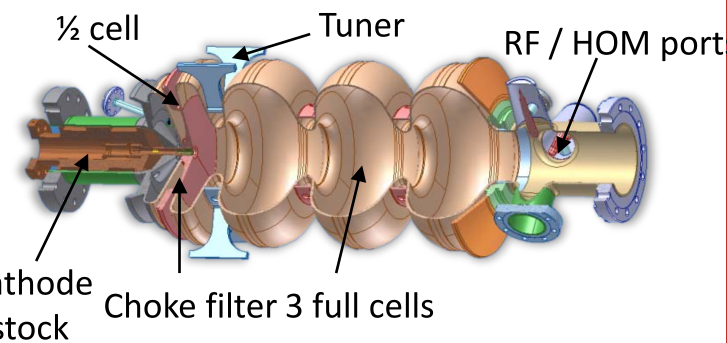

LANL RF gun

## DC




Cornell gun

## SRF




ELBE SRF gun

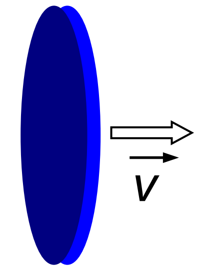
**plus variants…**

- **Pulsed machines (FELs): NCRF a success story**
  - **can always improve emittance → lower machine energy**
- **CW operation: cathode fields reduced (DC ≤10 MV/m), NCRF (≤ 20 MV/m), best promise for SRF (≤ 30 MV/m)**
  - **Main push is for increased avg current (ERLs), emittance desired several 0.1 um rms normalized range for ~100 pC**

# Physics of high brightness photoguns made simple

CLASSE

- Given a laser, photocathode cathode, and accelerating gradient $\rightarrow$ max brightness is set




- Each electron bunch assumes a "pan-cake" shape near the photocathode for short (~10ps) laser pulses, max 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 (MTE = mean transverse energy), $\Delta p_\perp \sim (m \times MTE)^{1/2}$

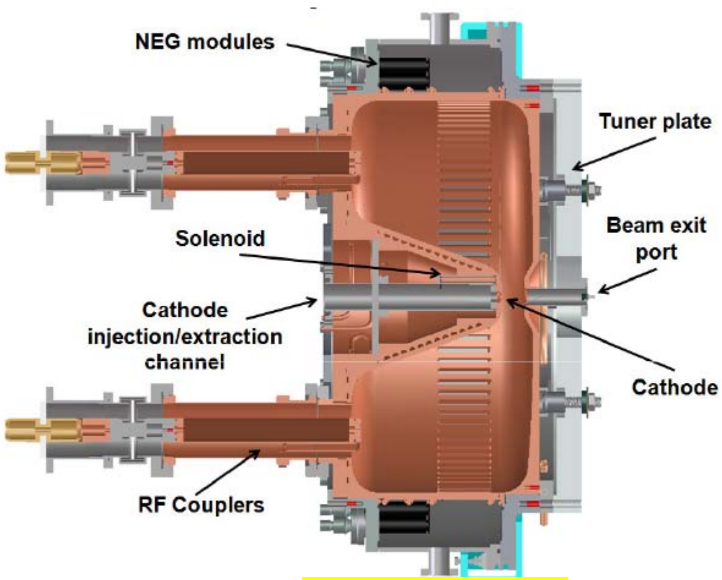
- Combining these two yields the maximum (normalized) beam brightness achievable from a photoinjector – defined by only two key parameters: cathode field $E_{cath}$ and MTE of photoelectrons

achievable brightness:

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

# RF guns

- No ceramic to worry about, no cryoplant
- BUT huge losses for CW operation, questionable vacuum
  - BOEING RF gun & renewed LANL effort: it can be made to work!
- VHF gun (LBNL): reduce operating frequency, increase cooling area, introduce plenty of pumping slots
  - nice solution when << GHz rep rate is acceptable



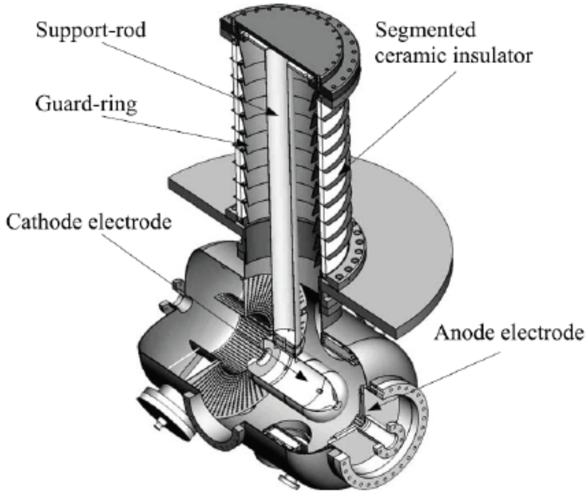

VHF LBNL gun

| | |
|---|---|
| Frequency | 187 MHz |
| Operation mode | CW |
| Gap voltage | 750 kV |
| Field at the cathode | 19.47 MV/m |
| $Q_0$ (ideal copper) | 30887 |
| Shunt impedance | 6.5 MΩ |
| RF Power | 87.5 kW |
| Stored energy | 2.3 J |
| Peak surface field | 24.1 MV/m |
| Peak wall power density | 25.0 W/cm$^2$ |
| Accelerating gap | 4 cm |
| Diameter/Length | 69.4/35.0 cm |
| Operating pressure | ~ $10^{-11}$ Torr |

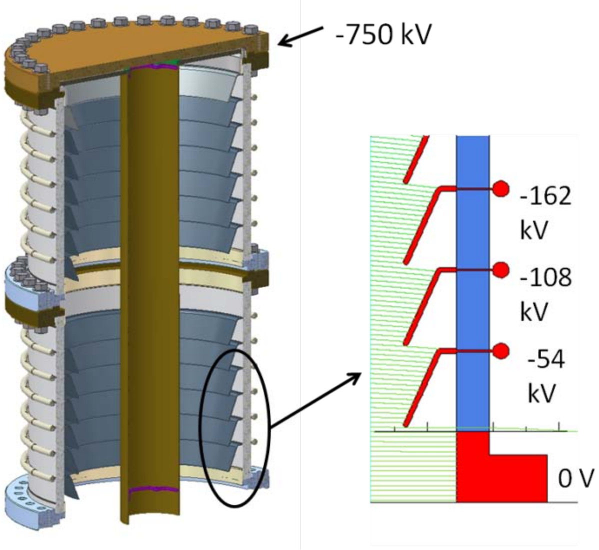
# DC guns

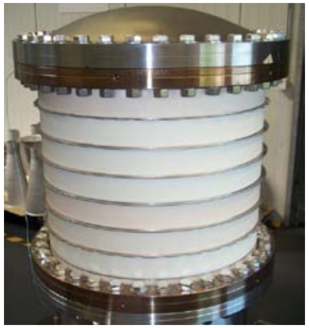
- Highest average current (50mA) operation today of the 3 choices
- Very high voltages (≥ 500kV) are still difficult, despite DC guns being around for a while
- New generation of guns to resolve ceramic puncture problems

JAEA/KEK gun with shielded ceramic




Cornell ceramic design & photo



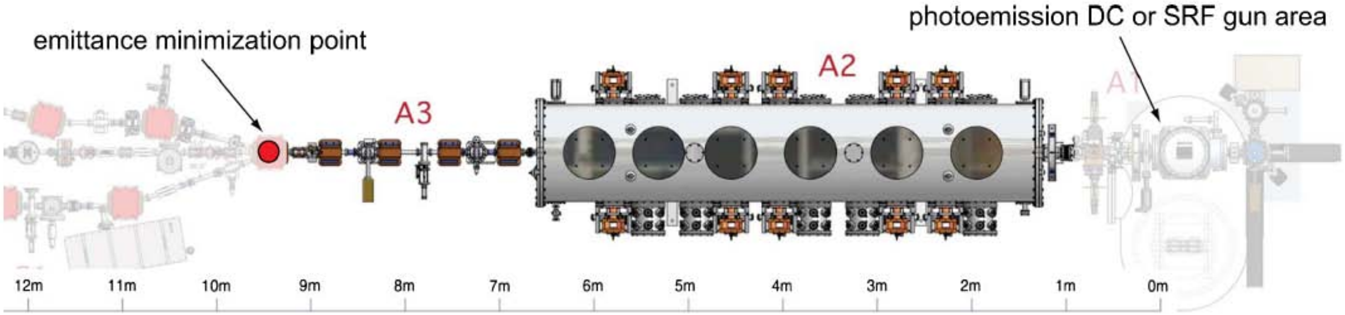



# SRF guns

- **A lot of R&D in the community**
  - **Great promise, lots of issues**
- **Elliptical cavities and quarter wave resonator (QWR) structures**
  - **Elliptical cavities ≥ 700 MHz**
  - **QWR ≤ 500 MHz (operates as a quasi-DC gap, similar to VHF NC gun)**
- **Best result so far: ELBE ~18MV/m pk with 1% $Ce_2Te$ for > 1000h**


# Example of one detailed comparison: DC vs SRF

- **GOAL: using multiobjective genetic algorithms compare two technologies**
- **Use Cornell injector beamline as a basis**



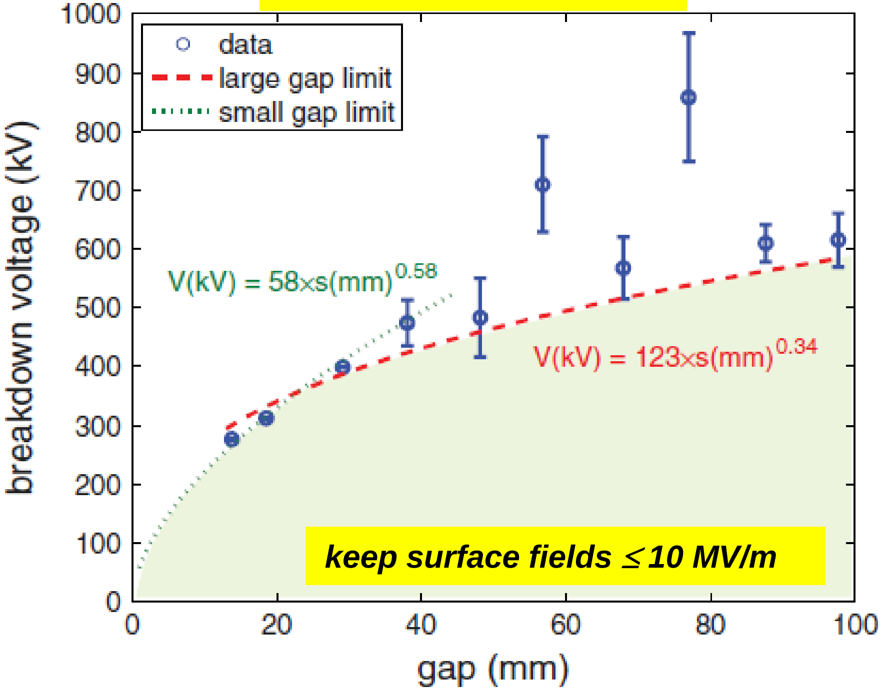

- **Realistically constrained DC gun voltages, SRF gun fields**
- **Vary gun geometries, laser, beam optics**

***IVB et al., PRST-AB 14 (2011) 072001***

# DC gun geometry & field constraints

- **Use empirical data for voltage breakdown**

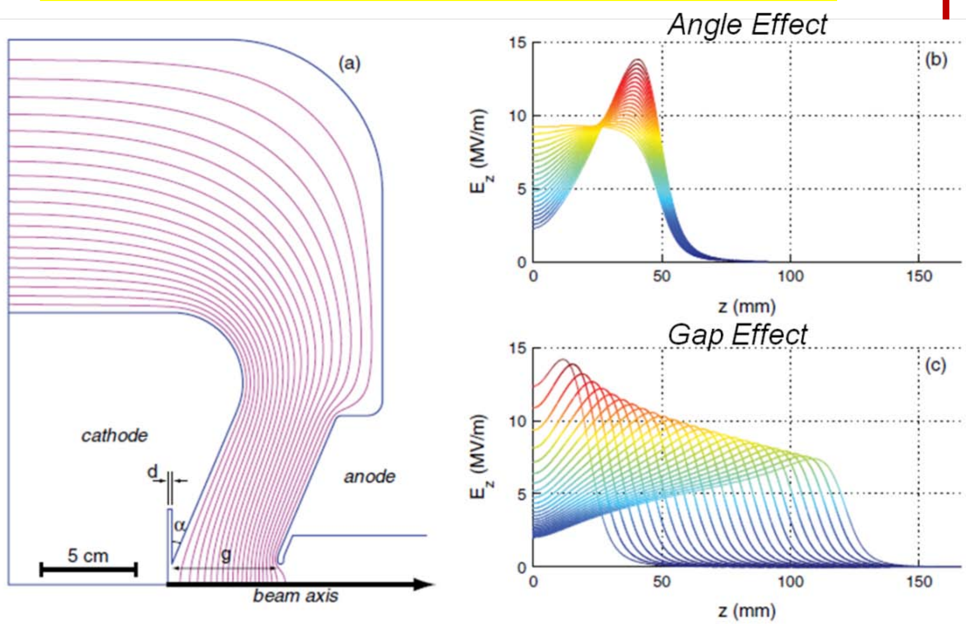
breakdown voltage vs gap




***keep surface fields ≤10 MV/m***

- **Vary gun geometry while constraining the voltage**

3 geometry parameters: gap, cathode angle & recess

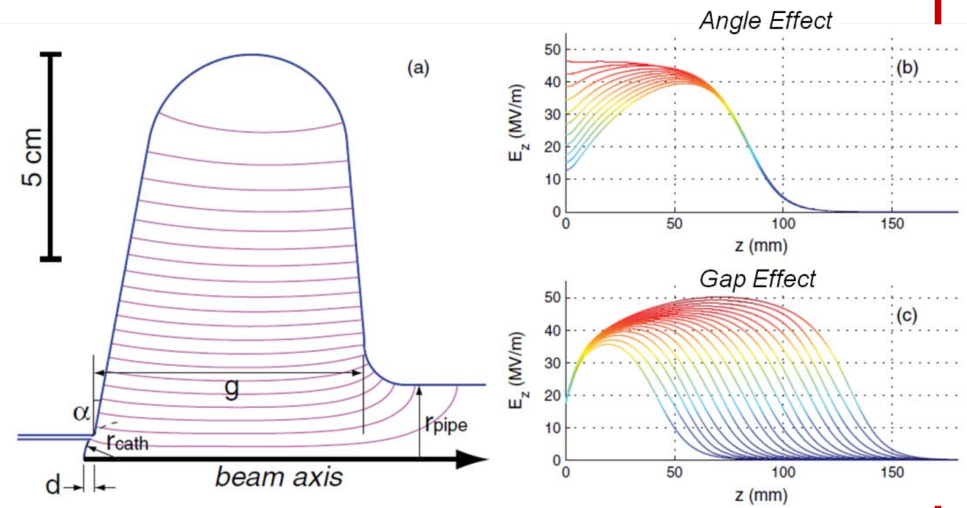


# SRF gun geometry & field constraints

- **1.3 GHz 0.5-cell elliptical cavity**
- **Constrained surface fields according to TESLA spec**
  - **$E_{acc} \leq 25$ MV/m**
  - **$E_{pk}/E_{acc} \leq 2$**
  - **$H_{pk}/E_{acc} \leq 4.26$ mT/(MV/m)**

- **Equator radius used for frequency tuning**

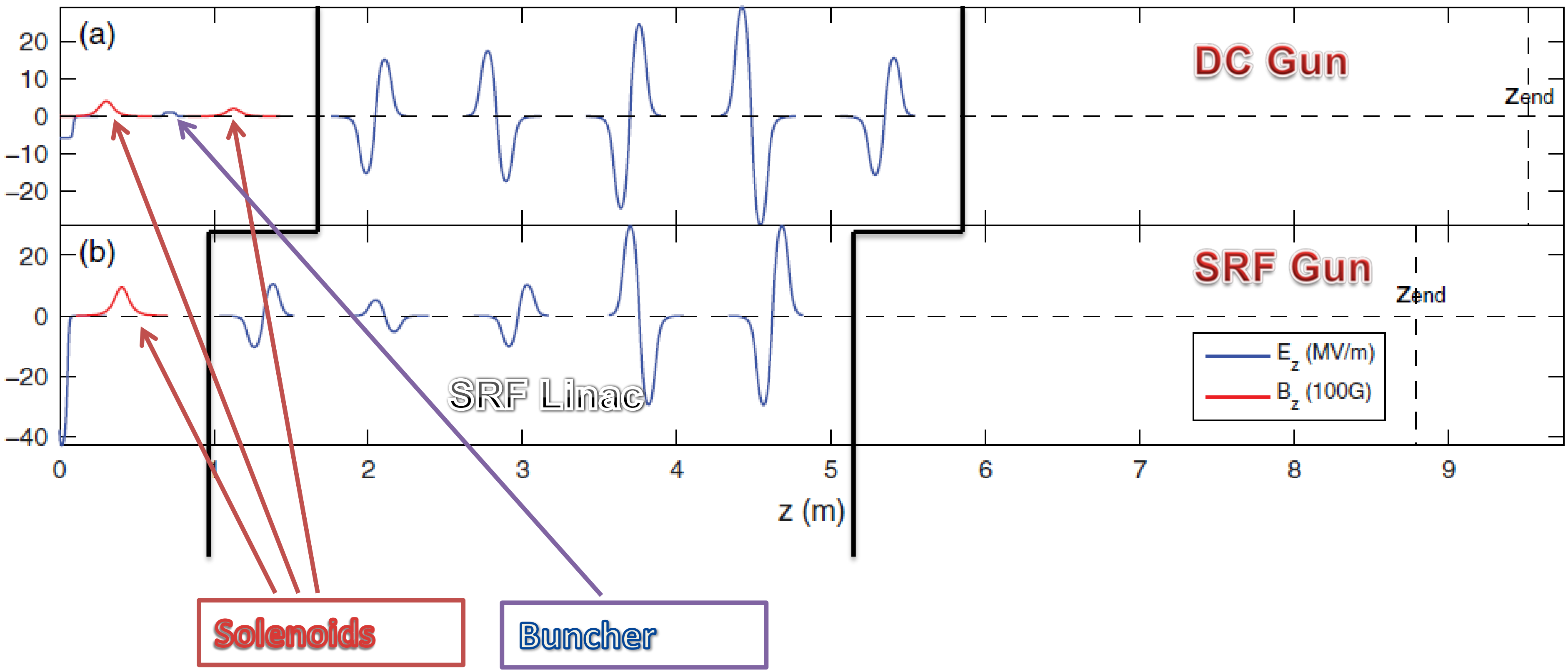
4 parameters: gap, cathode angle & recess, pipe dia




***Most solutions $E_{pk} \leq 50$ MV/m***

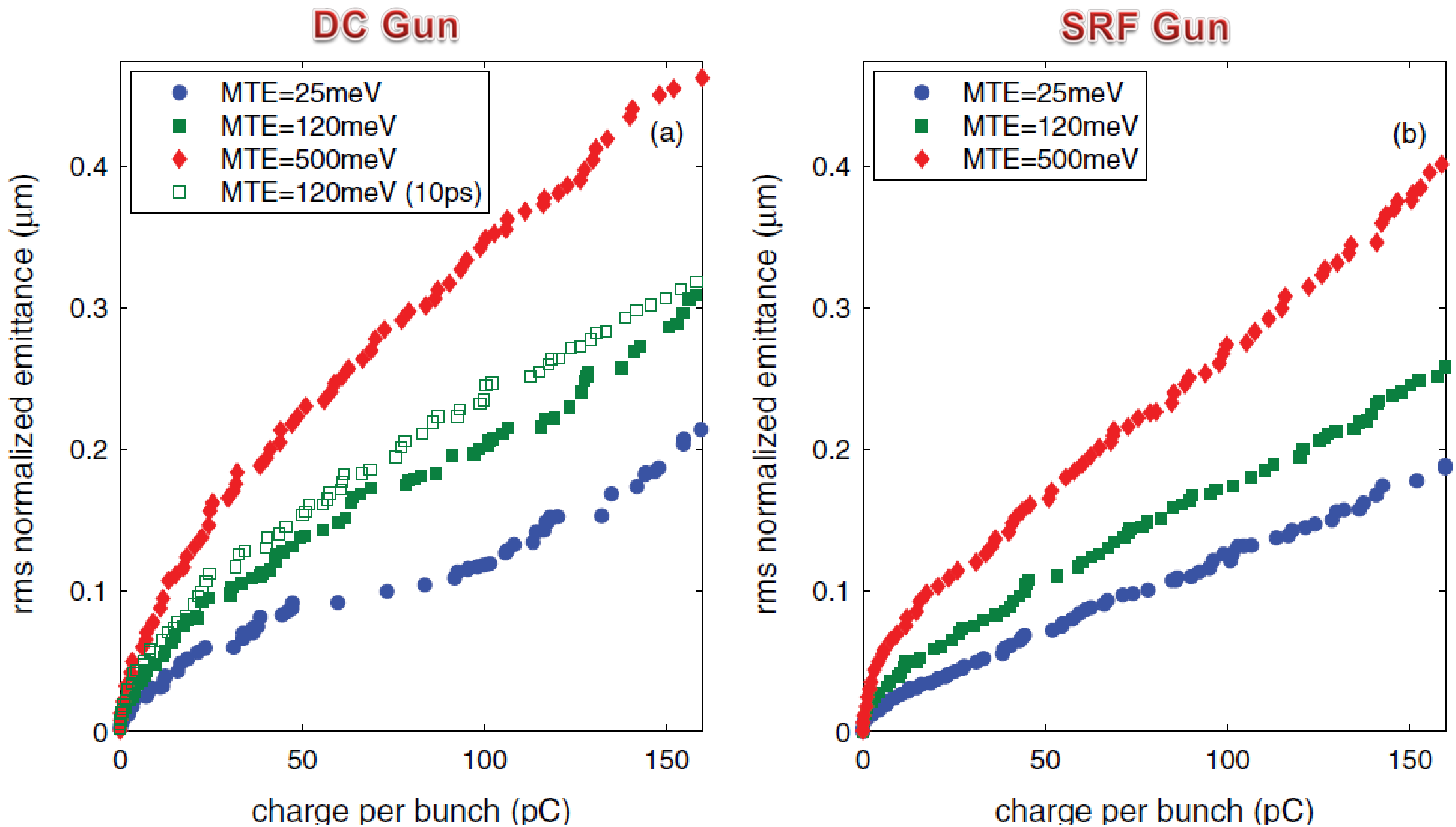
- **Vary beam current 0-200 mA**
- **Final bunch length ≤ 3 ps rms**

# Beamline parameters

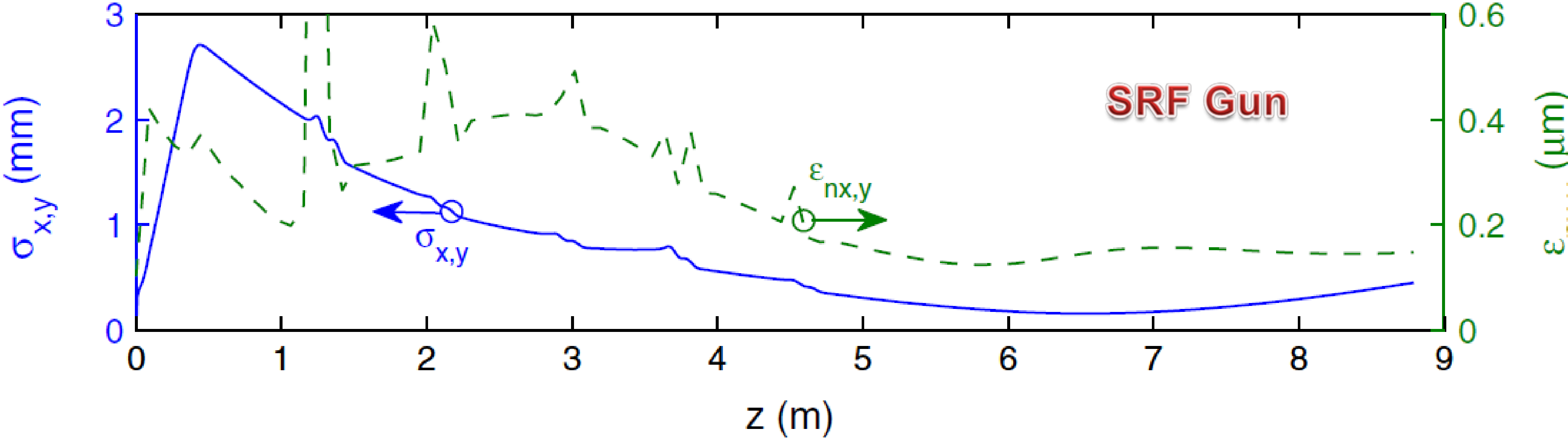



- The SRF beamline is simplified:
  - NC buncher cavity is ineffective at high beam energy
  - Only one solenoid included

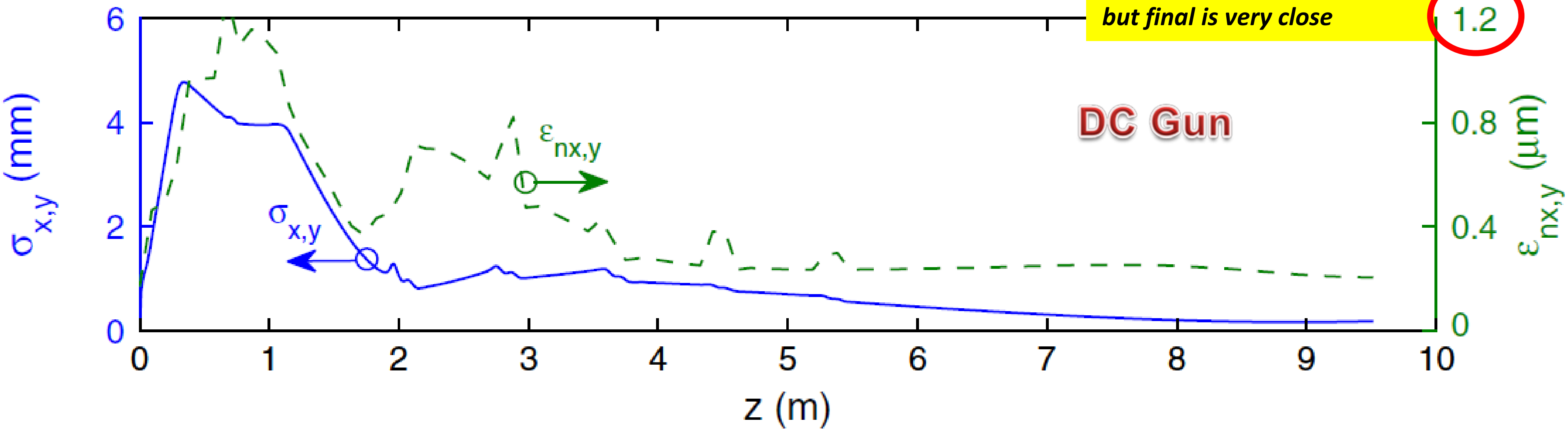
# Emittance Performance



# A closer look at 80pC case




*X2-3 larger peak emittance!*
*but final is very close*

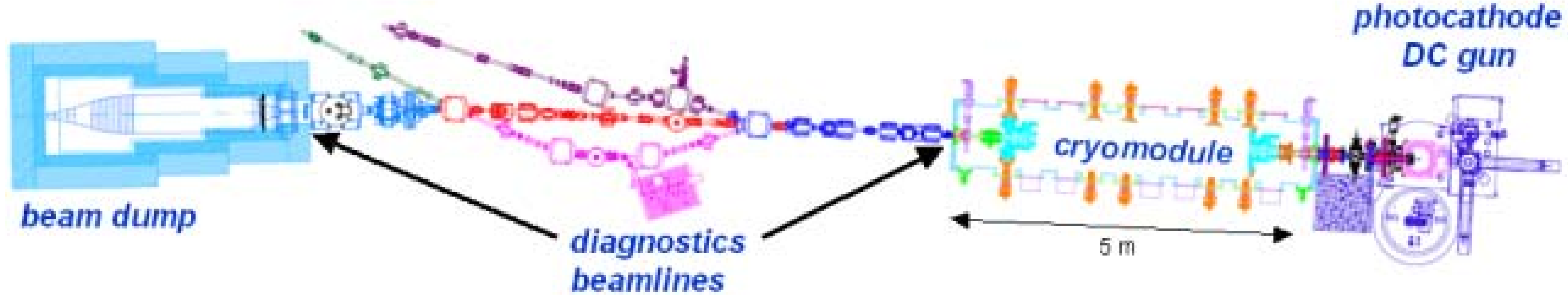


# Comparison results recap

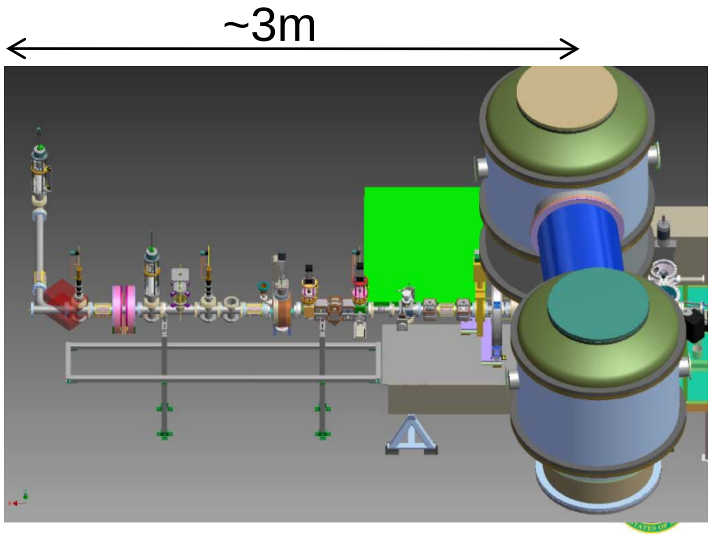
- The two technologies did not show much difference in the final 100% rms emittance in these simulations ***despite > x3 larger field at the cathode for SRF case*** (the beam core must be brighter for SRF)
- DC gun case requires more cancellations to get to small emittances at the end – how well can it be done in real life?
- ***Space charge energy chirp after the gun:***
  - leaves a nasty chromatic aberration through the solenoids!
  - Far more ***prominent in DC case***. Must anti-chirp with buncher!
- Perhaps cathodes **(MTE)** are more important than the field (beyond a certain point)!
- Recent alignment & emittance run @ Cornel ERL injector:
  - Measured: 1.3-1.4 x model (so far)

# Photoemission source development @ Cornell

- **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): shoot to have HV by this summer**



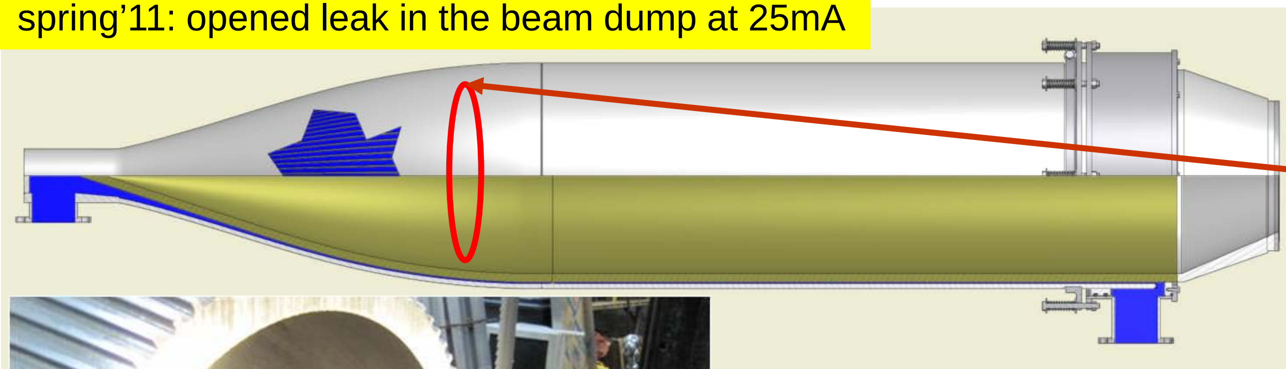
# Cornell ERL photoinjector highlights

- **Over the last year:**
  - **Maximum average current of 52 mA from a photoinjector demonstrated**
  - **Demonstrated feasibility of high current operation (~ kiloCoulomb extracted with no noticeable QE at the laser spot)**
  - **Original emittance spec achieved: now getting x1.8 the thermal emittance values, close to simulations (Sept 2011)**

# *it happens…

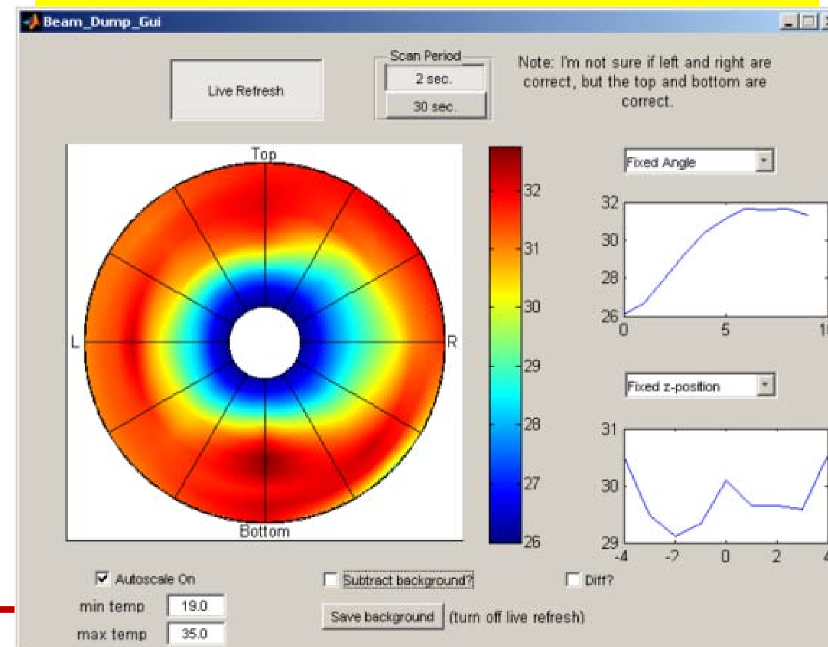
CLASSE

spring’11: opened leak in the beam dump at 25mA



Designed for 600 kW average power


*Now 80 thermocouples monitor the repaired dump temperature over its entire surface*

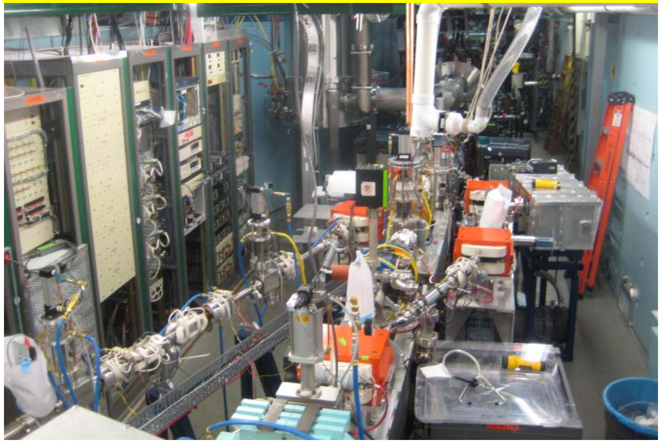


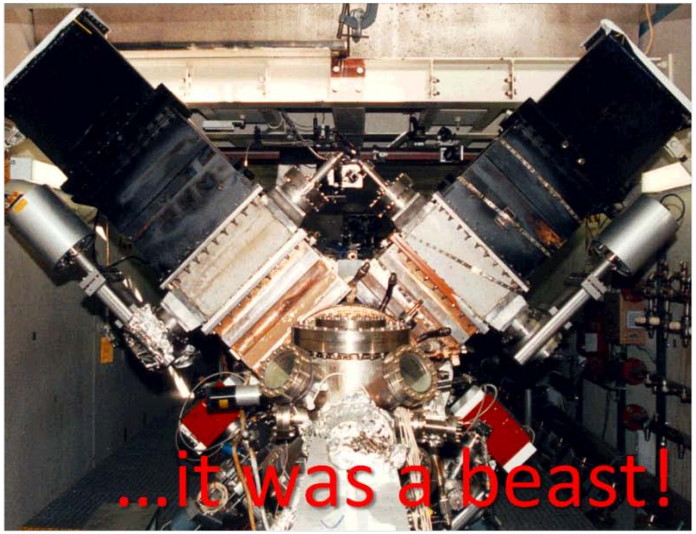

- **‘Dramatic accelerator physics’ – drilled a hole in the dump (1” Al) with electron beam!**
- **Raster/quad system wired/set incorrectly**

# BOEING gun tribute

**The Boeing 433 MHz RF Photocathode Gun**

Cornell photoinjector: 52 mA (Feb 9, 2012)





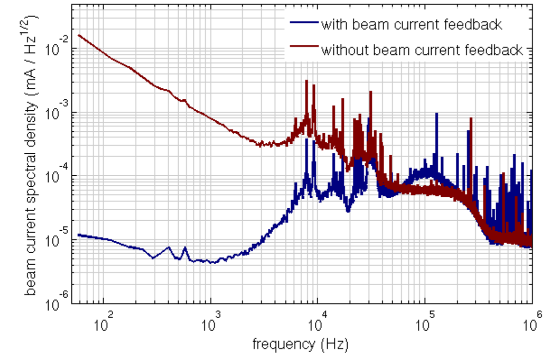

D.H. Dowell/MIT Talk, May 31, 2002

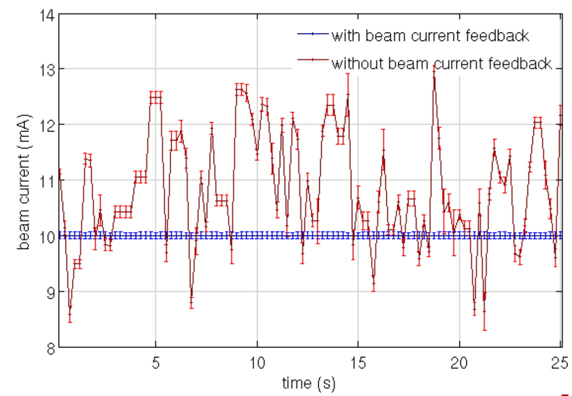
- **New current record is 52 mA (Feb 9, 2012) at Cornell using GaAs!!**
  - **beats Dave Dowell's 32 mA record of 20 years!**

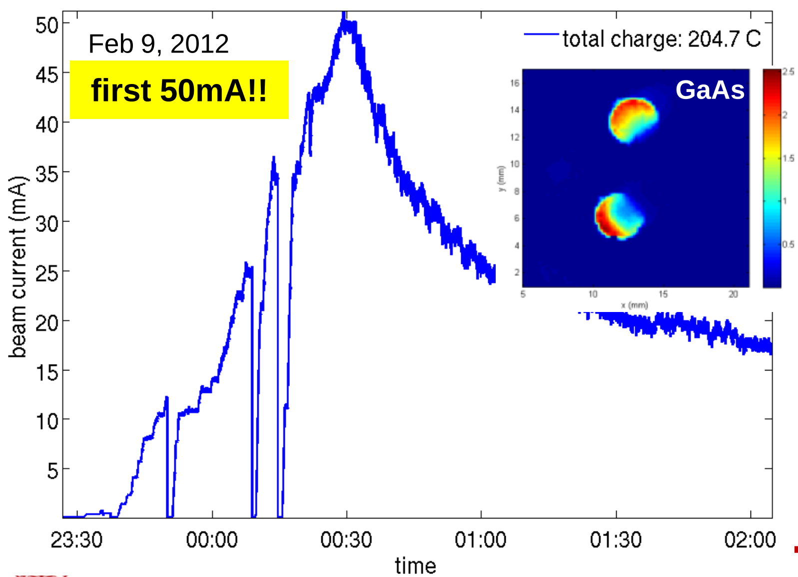
# Pushing for high current

CLASSE

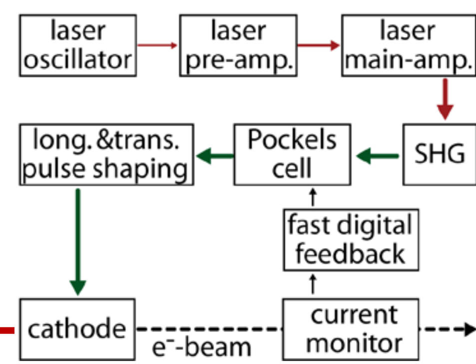
- **Key developments:**
  - **Expertise in several different photocathodes (both NEA and antimonides)**
  - **Improvements to the laser (higher power)**
  - **Feedback system on the laser**
  - **Minimization of RF trips (mainly couplers)**
  - **Minimizing radiation losses**



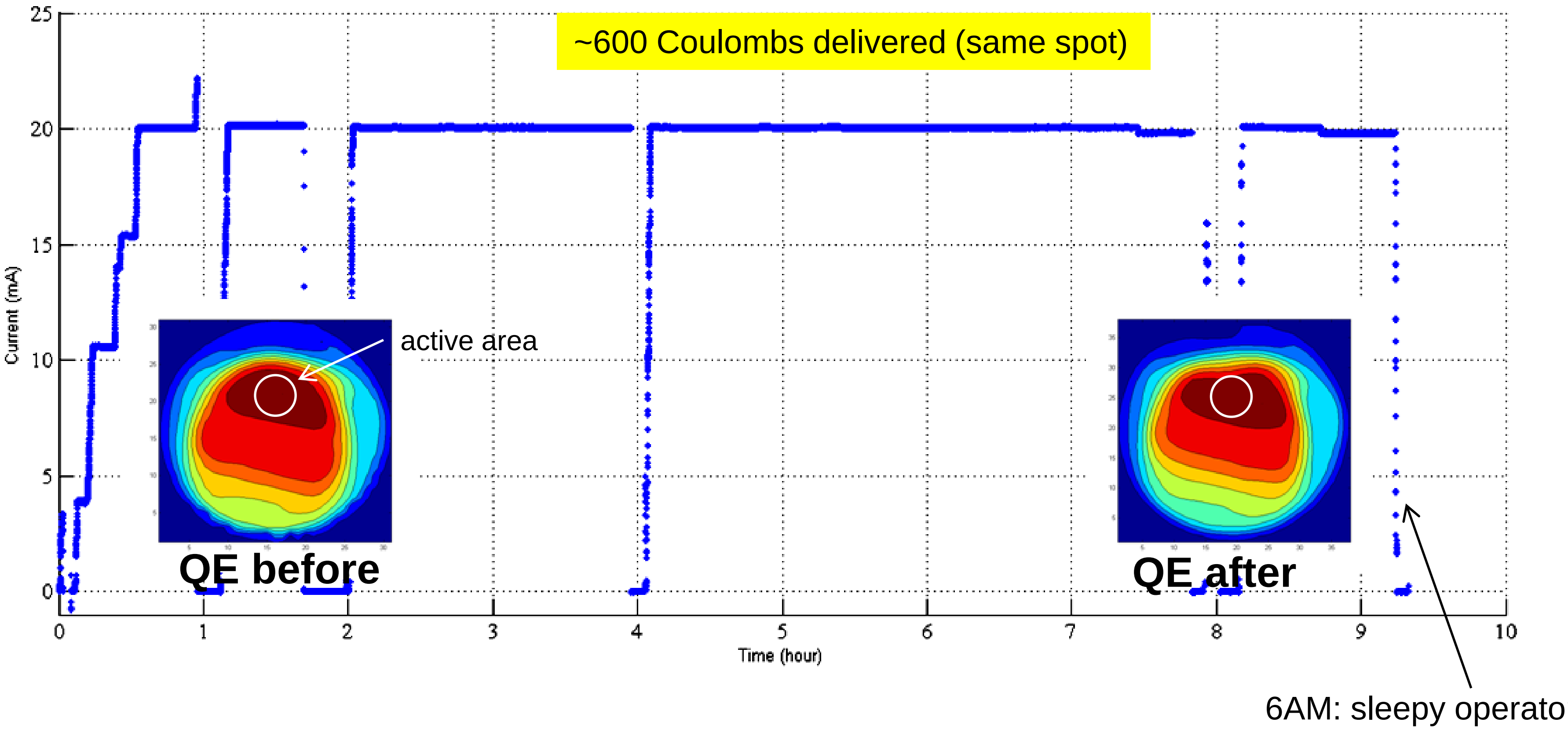




Laser intensity feedback system (developed by F. Loehl)



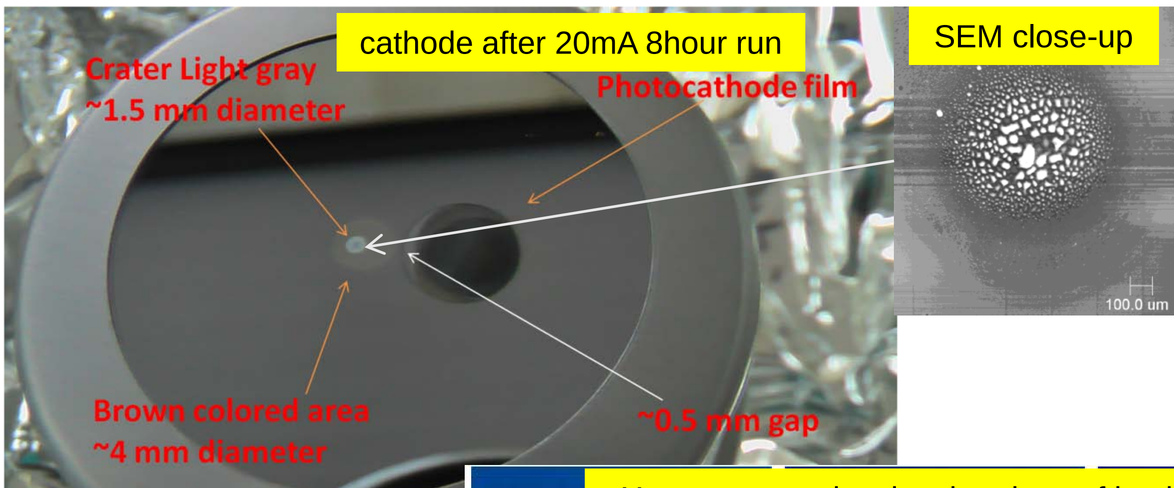

# High current operation (offset CsKSb gives excellent lifetime)

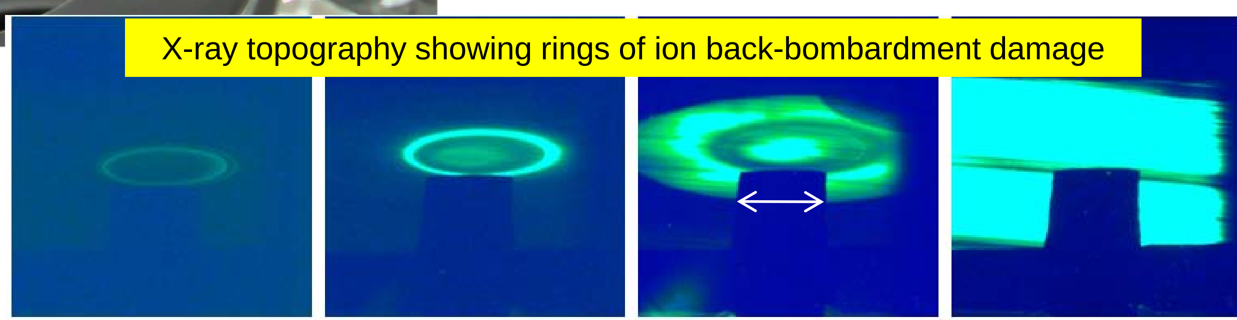



**L. Cultrera, et al., PRST-AB 14 (2011) 120101**

# Real-life accelerator testing for photocathodes: high average current

- **Main message: moving off-axis gives many kiloCoulombs 1/e lifetime from K2CsSb or Cs3Sb (same spot)**
- **Now understand that pits in EC are the result of machine trips**

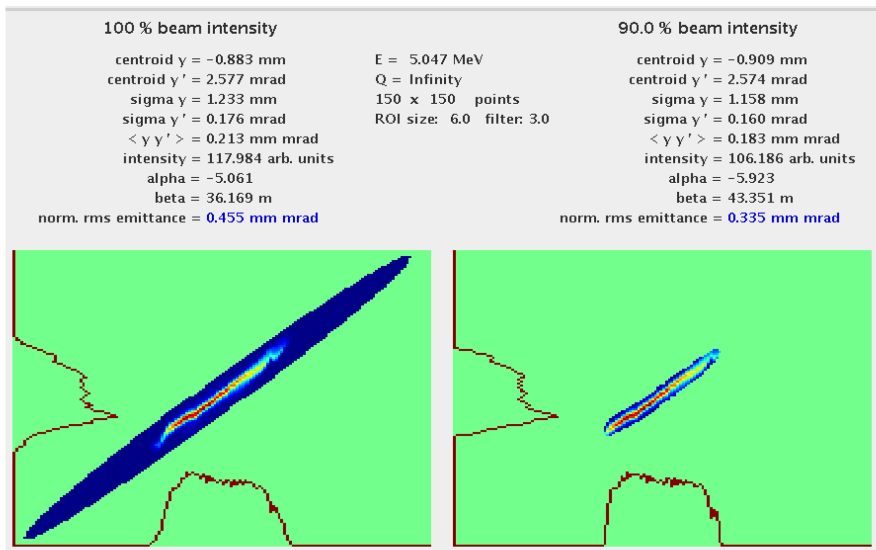



17.4560 degree | 17.4880 degree | 17.4960 degree | 17.5000 degree

# Laser off-center

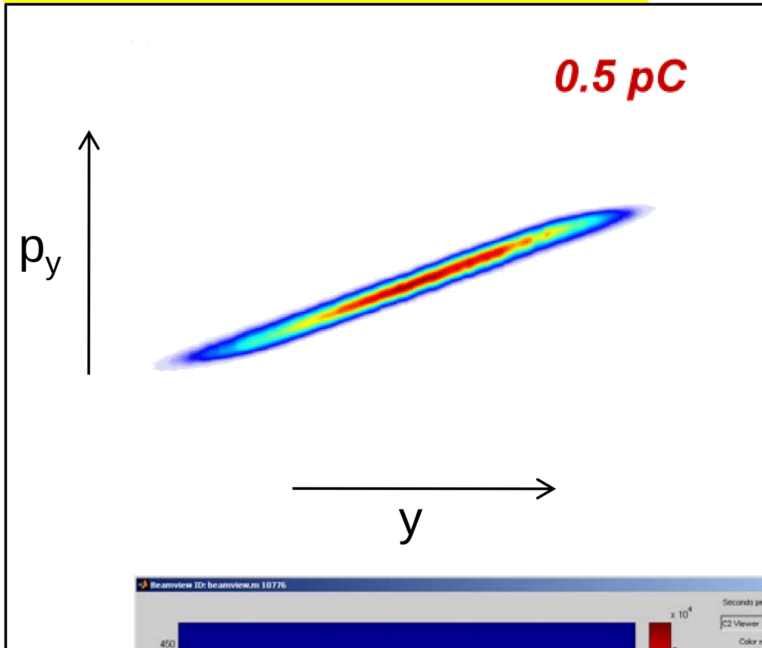
Good news: running 5 mm off-center on the photocathode gives the same emittance (20pC/bunch) due to intrinsically low geometric aberrations in the DC gun




This is very important, as we know that we cannot run with the laser at the center of the cathode due to cathode damage issues.

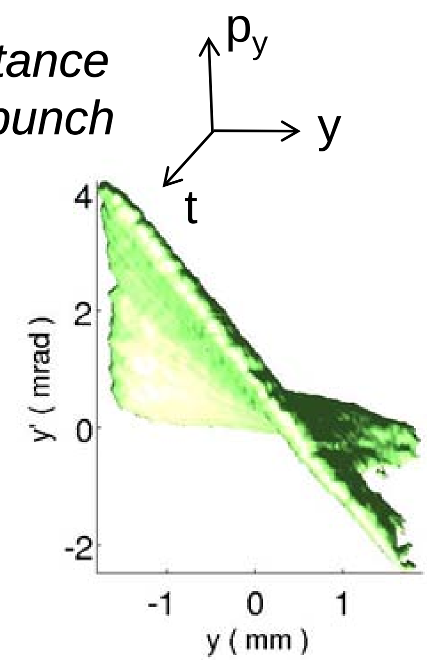
# 6D beam diagnostics: key to low emittance

transverse phase space (animation)

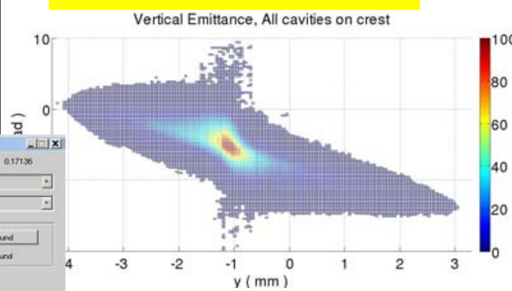


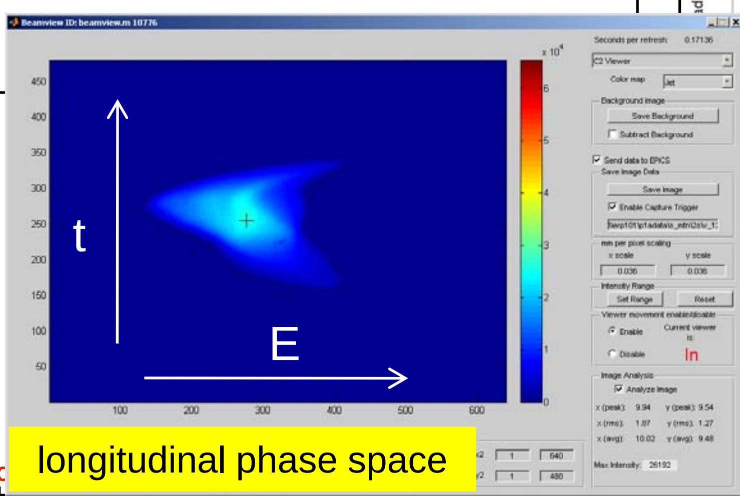

slice emittance with resolution of few 0.1ps

*So far the smallest emittance 0.7 mm-mrad at 80 pC/bunch (rms, 100%)*




projected emittance

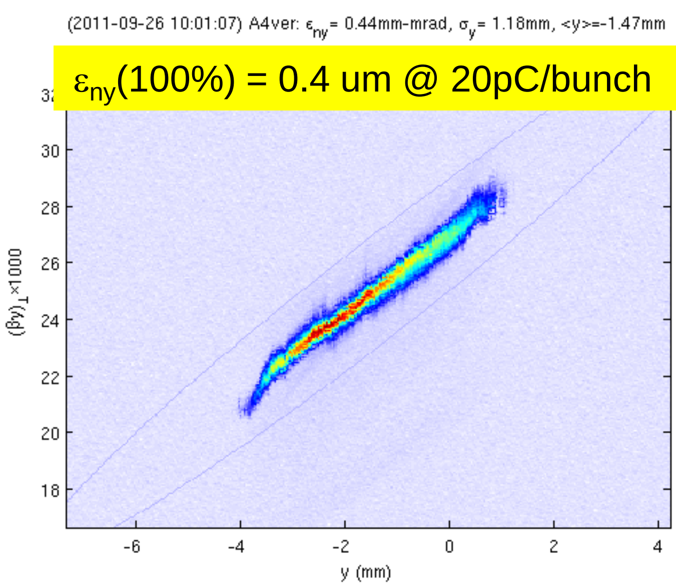


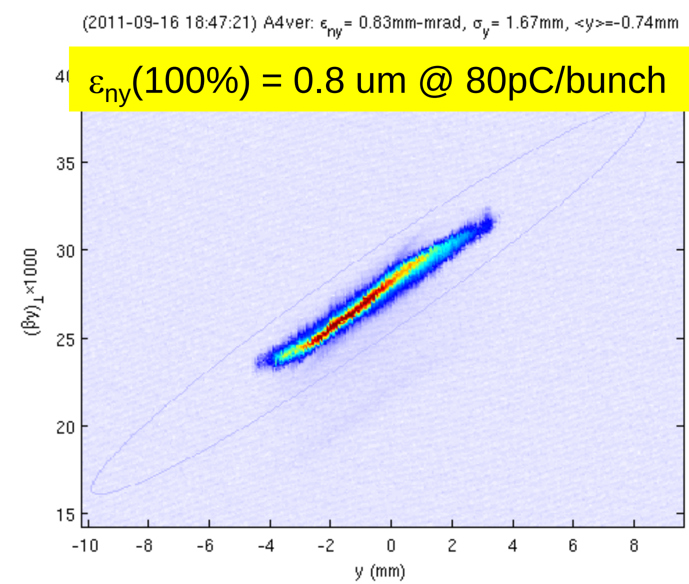




longitudinal phase space

# Sept 2011: initial emittance spec achieved!

- **Keys to the result**
  - **Beam-based alignment (took us a couple of months)**
  - **Working diagnostics**
  - **Fight jitters in the injector**

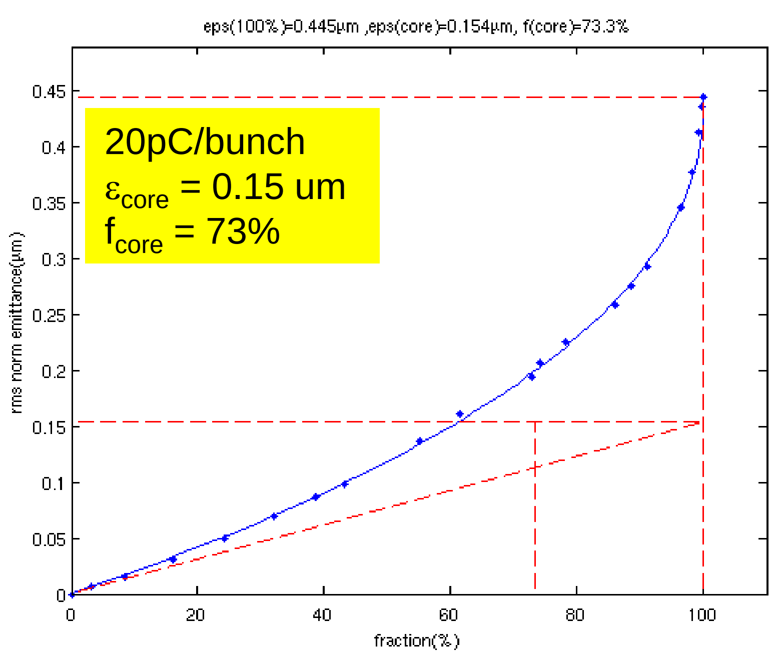


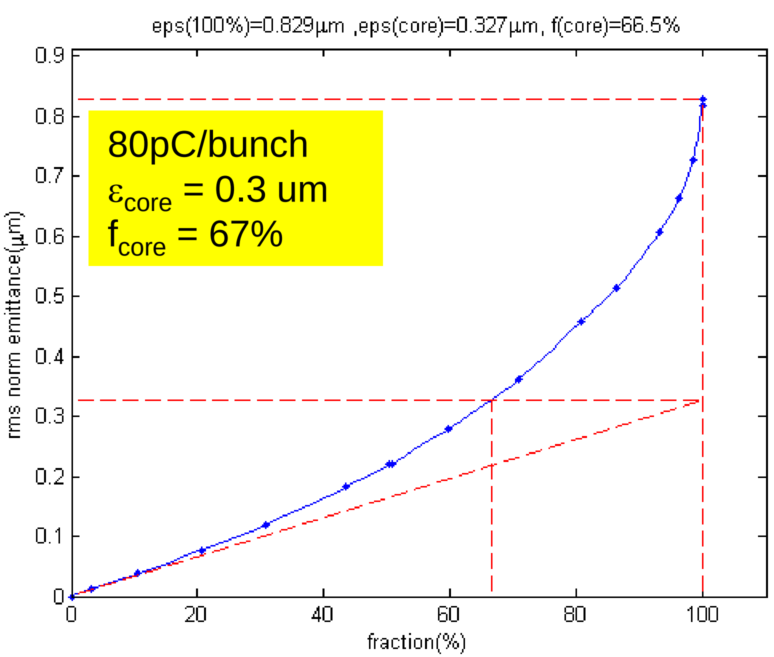




- **x1.8-2.0 thermal emittance! x1.4 simulated emittance**
- **correct scaling with bunch charge**

# 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%)



# Single rms emittance is inadequate for comparisons

- **Better to quote 3 numbers**
  - **100% rms emittance (or 95% or 90%)**
  - **core emittance (essentially peak brightness)**
  - **core fraction**

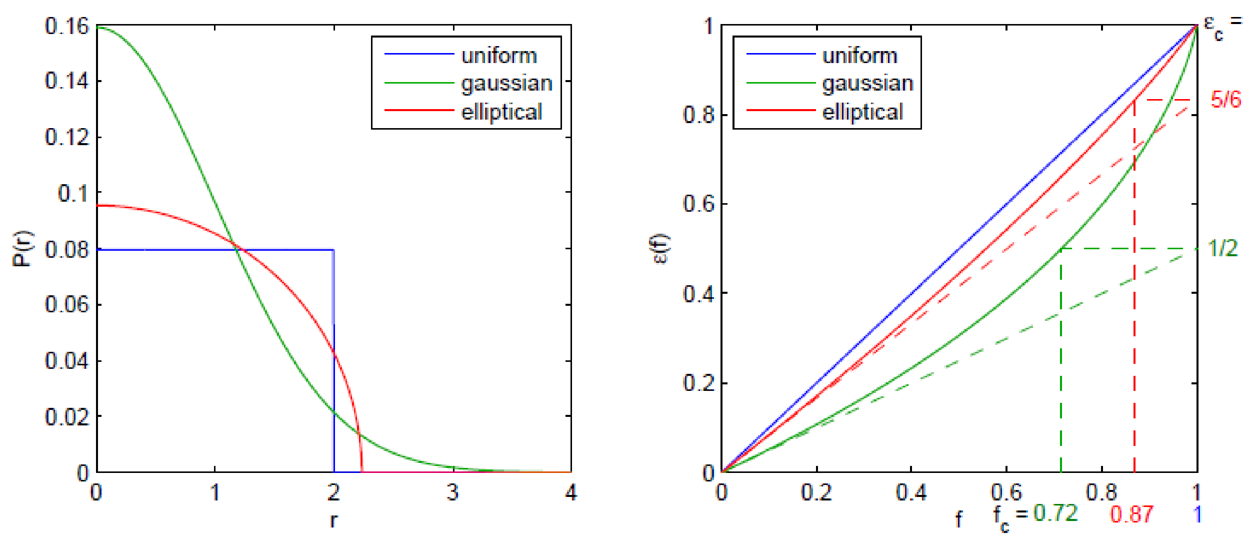
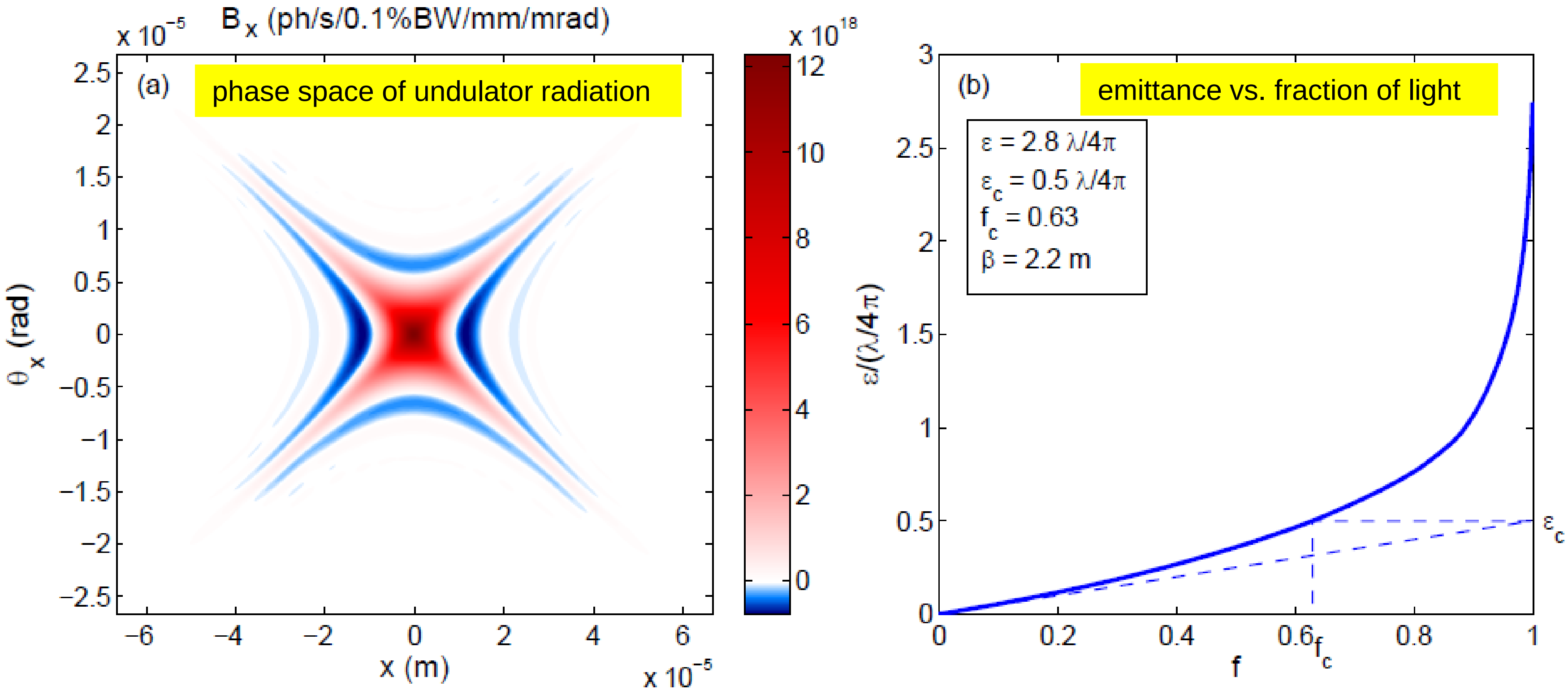



FIG. 8. Radial phase-space distributions (left) and corresponding emittance vs. fraction curves (right). All distributions are scaled to have $\epsilon = 1$. Core fraction and emittance for different distribution types are shown as well.

# Emittance vs. fraction for light
## Wigner distribution = phase space density




- **There are fewer Gaussians around than one might think**
- **More about it in my afternoon talk in joined SR&ERL WG**

***IVB, arXiV 1112.4047 (2011)***

# Measured beam brightness so far…

- **Effective brightness (for comparison)**

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

- **E.g. demonstrated at 20mA ERL injector beam, if accelerated to 5GeV, is as bright as 100mA 50 × 50 pm-rad Gaussian beam!**

- **The result can only improve!**

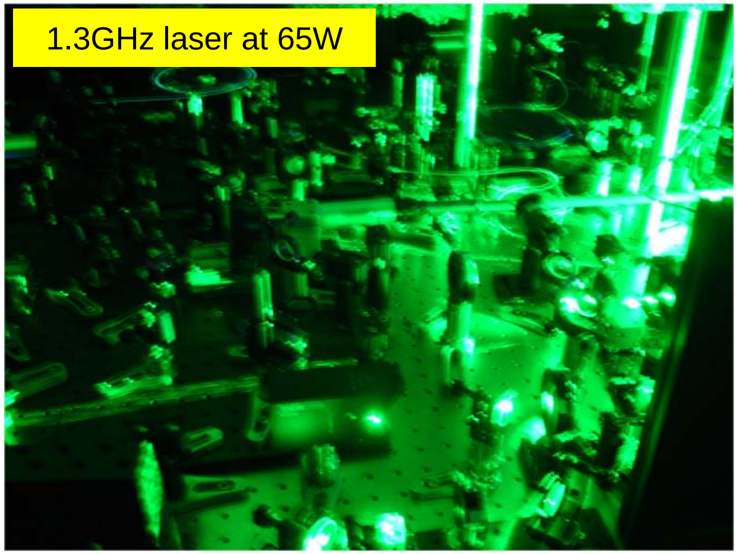
# Lasers & cathodes

- **Laser/gun/cathode is really one package**
- **New guns = load lock chamber (a must for high current operation, debugging)**

- **Great interest in cathodes & developing new materials**
  - **Mirror success of polarized photocathodes: started with <50% polarization from strained GaAs, now >90% polarization is routine**
  - **Need more material science experts**
  - **Fertile research area = better cathodes immediately translate into better photoinjectors**
  - **Several proposals for ultracold photoelectrons**

# Lasers

Z. Zhou et al., Opt. Express 20 (2012) 4850




- Plenty of laser power when coupled with good cathodes
- Next steps:
  - better 3D shaping
  - engineering and integration into the machine via stabilization loops (all degrees of freedom)
- Practical shaping techniques
  - Temporal stacking (uniform)
  - Transverse clipping (truncated Gaussian)

  better than "beer-can"; only ≤ 20% emittance increase compared to highly optimized shapes

  - Blowout regime if $E_{cath}$ is high enough

# Building collaboration on photocathodes for accelerators

- **Collaboration with**
  - ANL, BNL, JLAB
  - Cornell, SLAC
  - Berkeley, more…
- **Excitement and momentum in the community;**
- **Cathode workshops at BNL in 2010; in Europe 2011; coming up at Cornell in 2012**

*1st workshop*


*2nd workshop*

**Photocathode Physics for Photoinjectors 2012**
*Cornell University, 8-10 October 2012*

http://www.bnl.gov/pppworkshop/

http://photocathodes2011.eurofel.eu

http://www.lepp.cornell.edu/Events/Photocathode2012

# Conclusions

- **Accelerator community investing into photoinjector R&D**
- **Dividends *will follow* (already happening)**
- **Much remains to be done with *conventional approaches* (no emittance exchange tricks, field emission tips to enhance field, etc.), but there is always room for brand new ideas**
- **Practical (turn-key) photoinjectors with greatly improved parameters becoming a reality**

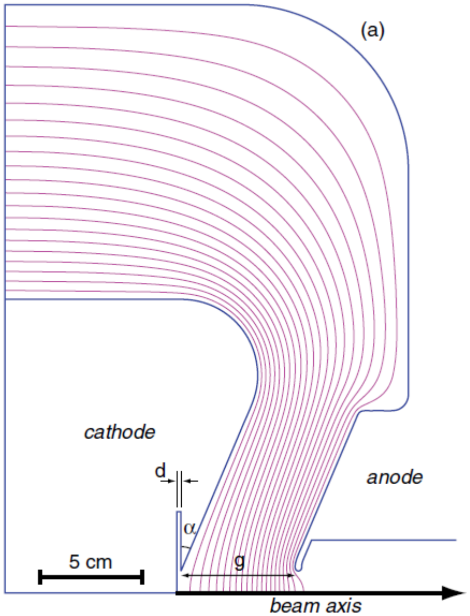
# Acknowledgements (for the Cornell team)


- **Photoinjector team:**
  - 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, Charlie Strohman, Zhi Zhou, and more.

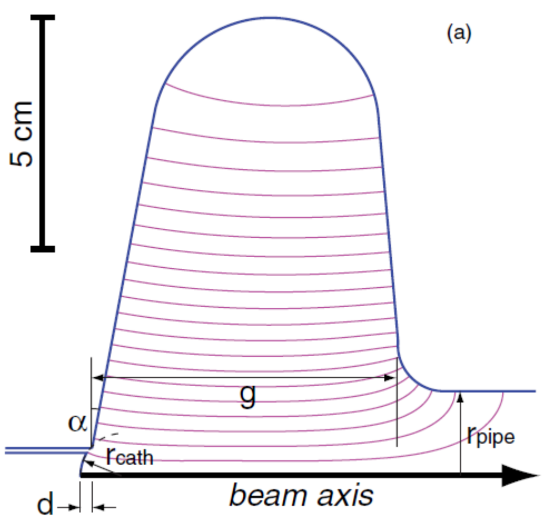
- **Main support NSF DMR-0807731 for ERL R&D**
  - also DOE DE-SC0003965 CAREER grant

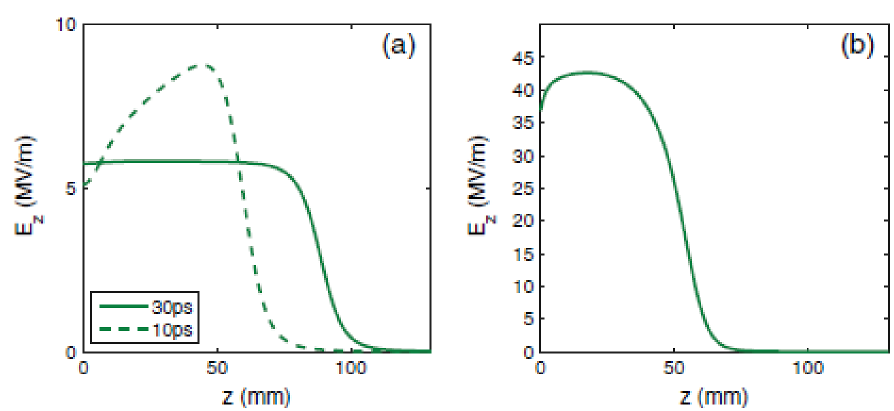
# END

# 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

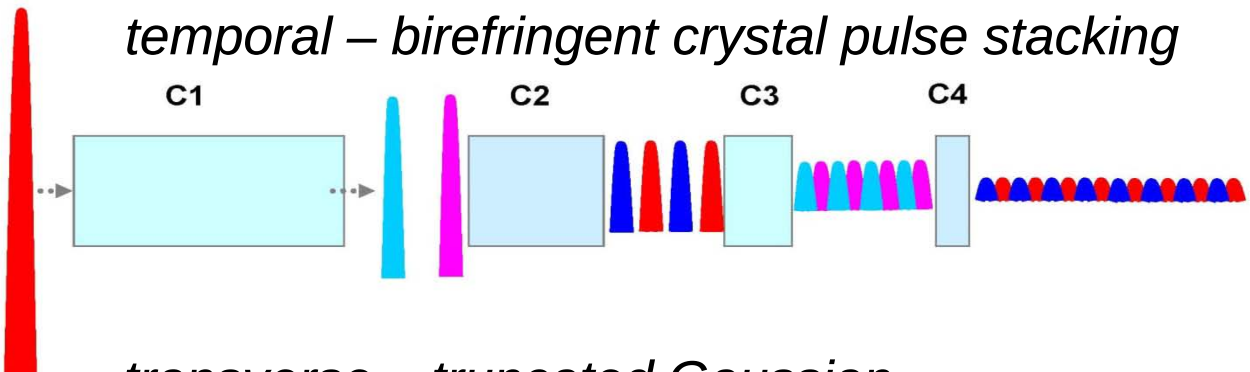
TABLE I. Main injector parameters after optimization.

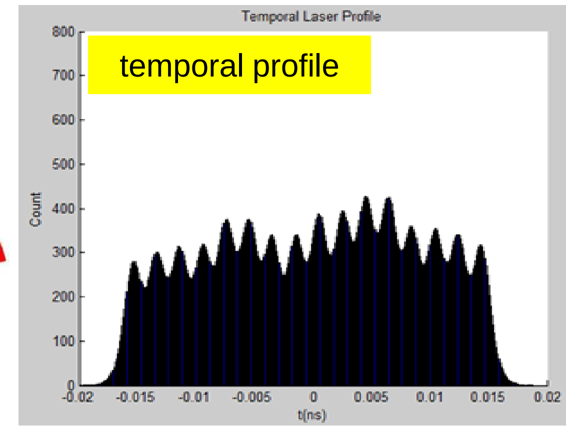
| Parameter | dc gun | SRF gun |
|---|---|---|
| Charge | 80 pC | 80 pC |
| Laser spot size (rms) | 0.35 mm | 0.21 mm |
| Laser pulse (rms) | 10 ps | 9 ps |
| Thermal emittance (rms) | 0.17 $\mu$m | 0.10 $\mu$m |
| Cathode field ($t = 0$) | 5.1 MV/m | 16.6 MV/m |
| Kinetic energy after the gun | 0.47 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 $\mu$m | 0.15 $\mu$m |
| 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 |

# 3D laser shaping for space charge control

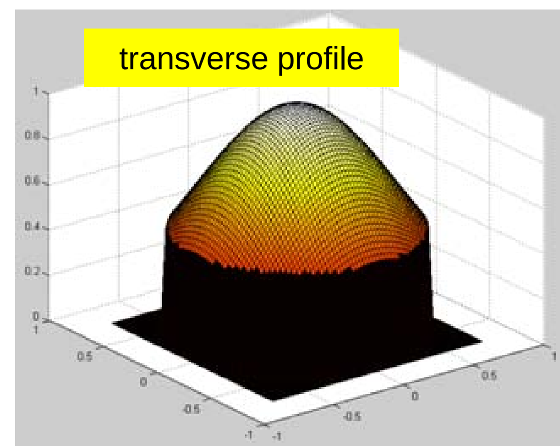
- **Optimal 3D laser shape: practical solutions identified**

*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*