Photoemission research at Cornell University: recent advances and future perspectives

Luca Cultrera

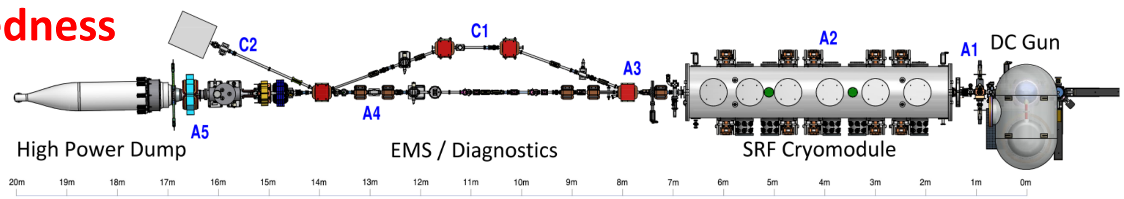
R&D areas

- **Photocathode lab hardware upgrades and modifications**
  - Alkali antimonides growth chambers;
  - New High Voltage DC cryogun;
  - New substrates holders (INFN miniplug REF/TRANS , Omicron-like);
  - Mott polarimeter;
- **Numerical simulations**
  - Alkali-antimonide Monte Carlo photoemission simulation;
  - Micro-sized tips;
- **Cathode growth and characterization**
  - La:$BaSnO_3$;
  - CsTe over GaAs;

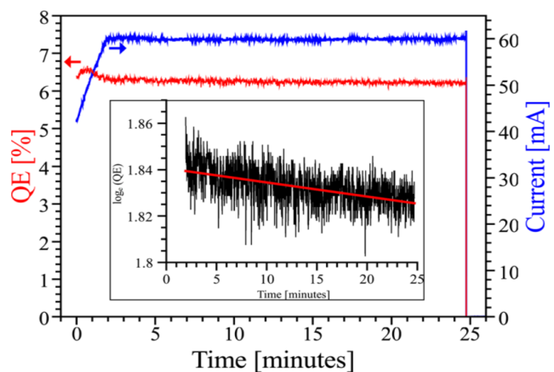
- **High Brightness**
  - **X-FELs;**
  - **UED;**
- **High intensity**
  - **ERLs;**
  - **Electron cooling;**
- **Polarized sources**
  - **Colliders;**

ERL R&D aimed at high average currents

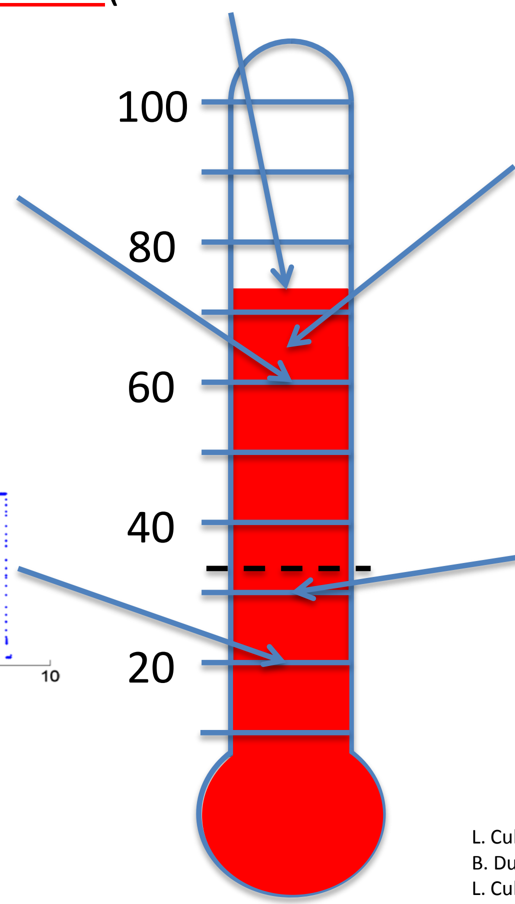
Alkali antimonides proved their ruggedness in the ERL injector prototype

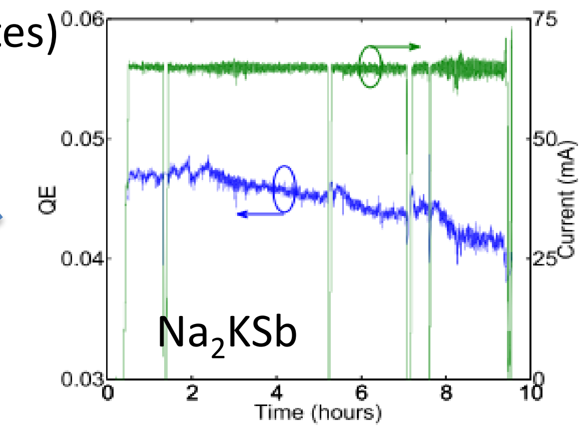


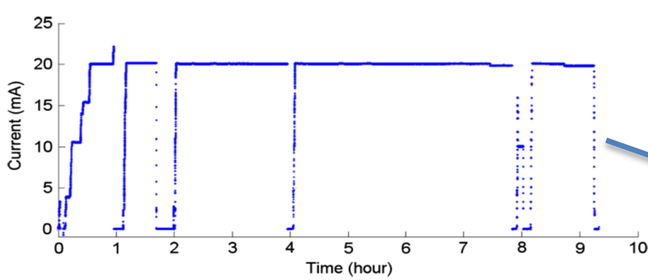
Up **75 mA** (held for a few minutes)



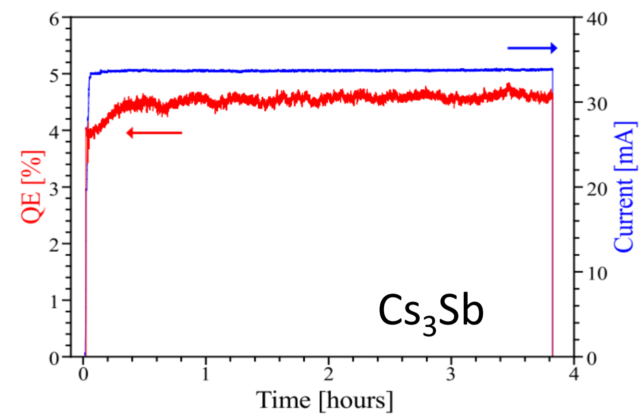
CsK_2Sb







CsK_2Sb

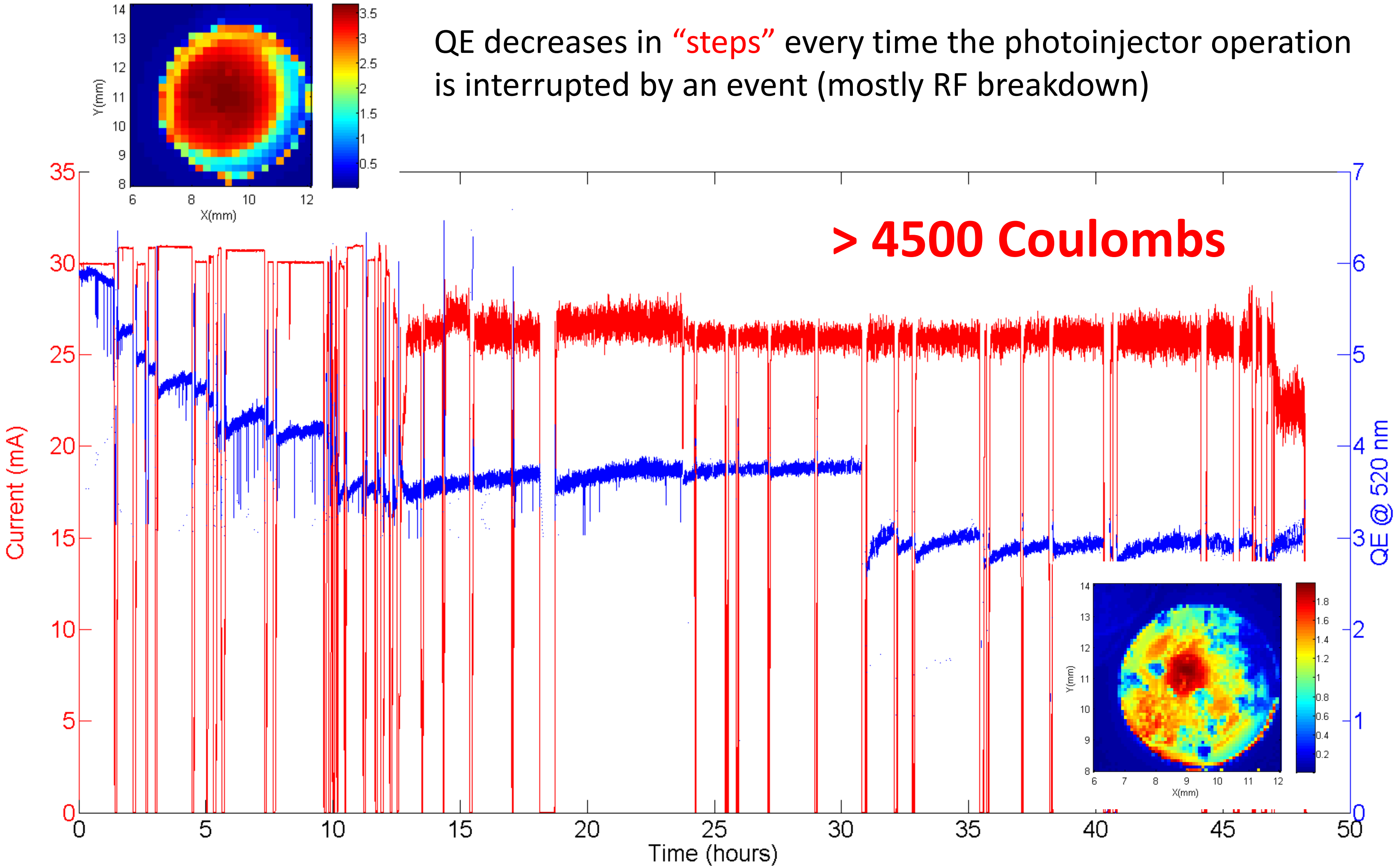


L. Cultrera et al., *Physical Review ST- Accelerators and Beams* **14** (2011) 120101
B. Dunham, et al., *Appl. Phys. Lett.* **102** (2013) 034105
L. Cultrera et al, *Appl. Phys. Lett.* **103** (2013) 103504

Na_2KSb: 48 hours long run

QE decreases in "steps" every time the photoinjector operation is interrupted by an event (mostly RF breakdown)

> 4500 Coulombs

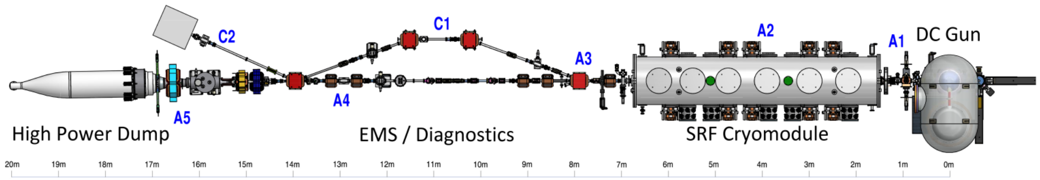


…and high brightness for X-FELs.

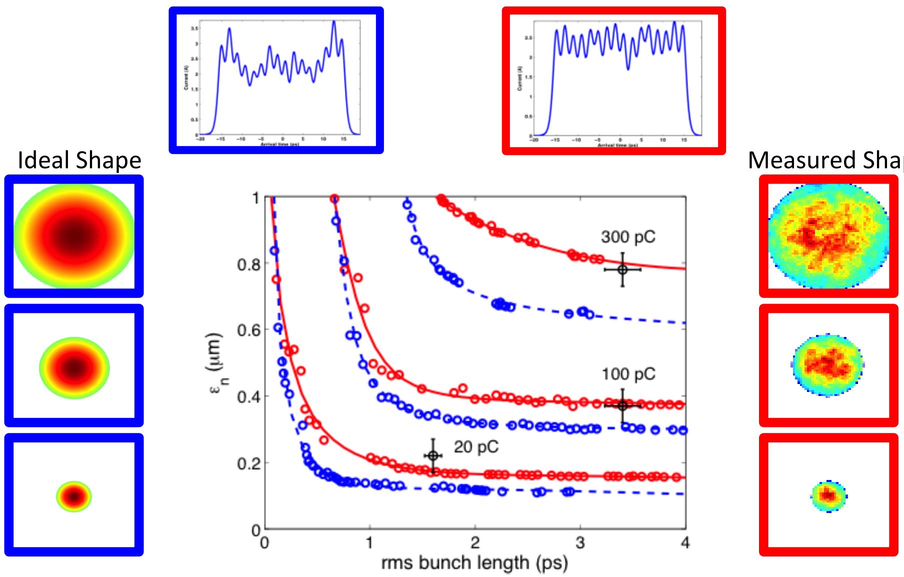
High rep. rate FEL (LCLS-II) injector requirements

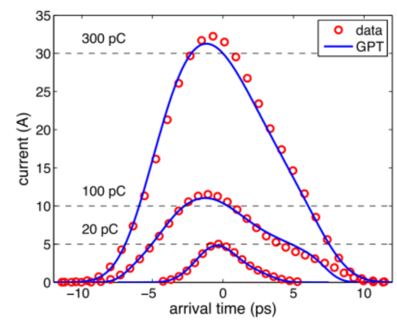
Q (pC)	I_{peak} Target (A)	ε_n Target (95%, μm)
20	5	0.25
100	10	0.40
300	30	0.60

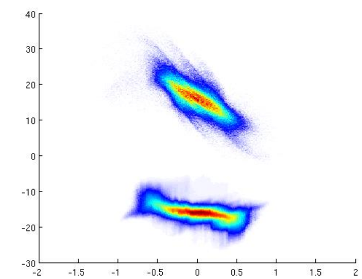
- Vary all relevant magnet, cavity settings
- Vary laser shaping: truncation fraction, crystal angles



Q (pC)	I_{peak} (A)	ε_n (95%, μm)	$\varepsilon_{n,th}/\varepsilon_n$
20	5	H: 0.18, V: 0.19	60%
100	11.5	H: 0.32, V: 0.30	80%
300	32	H: 0.62, V: 0.60	70%



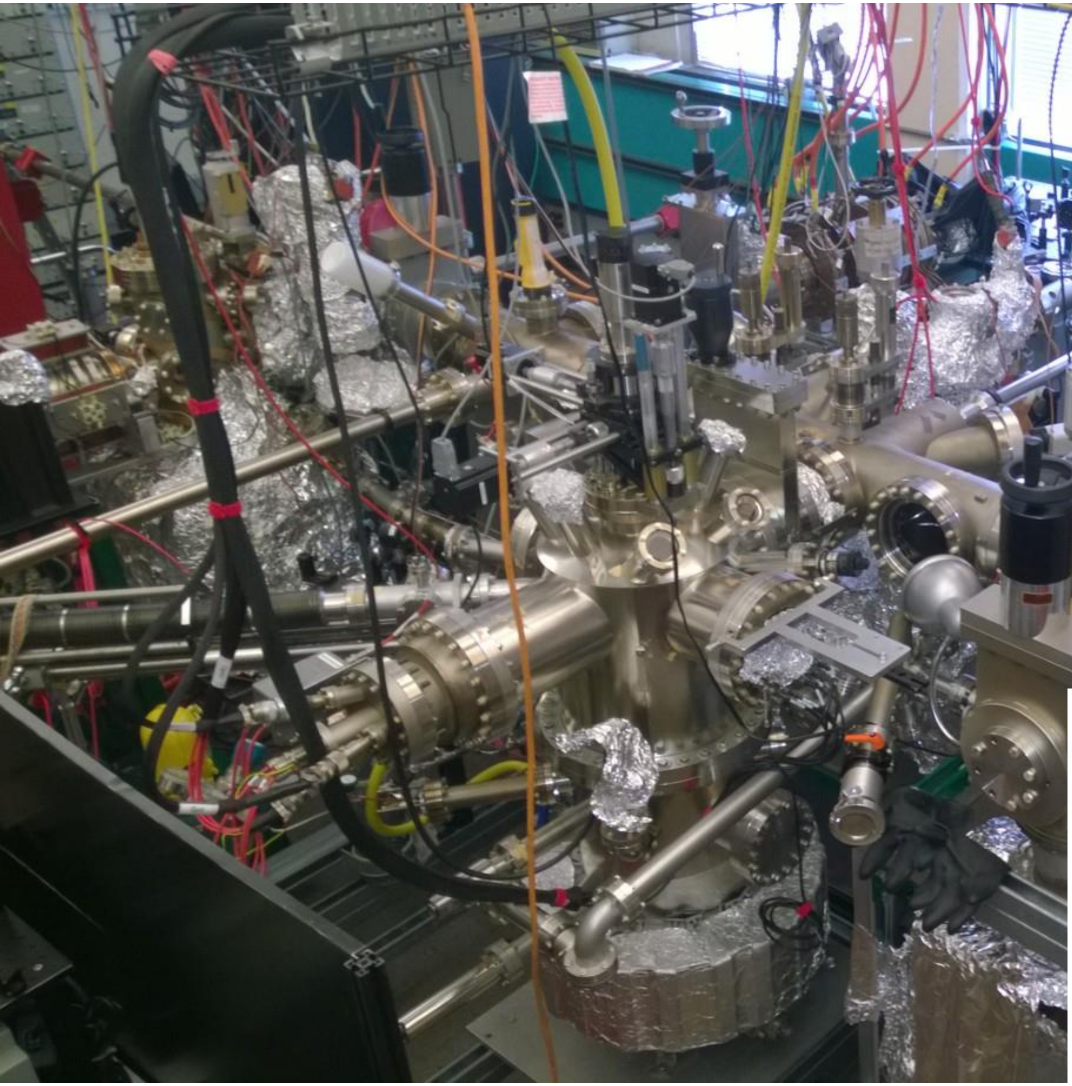


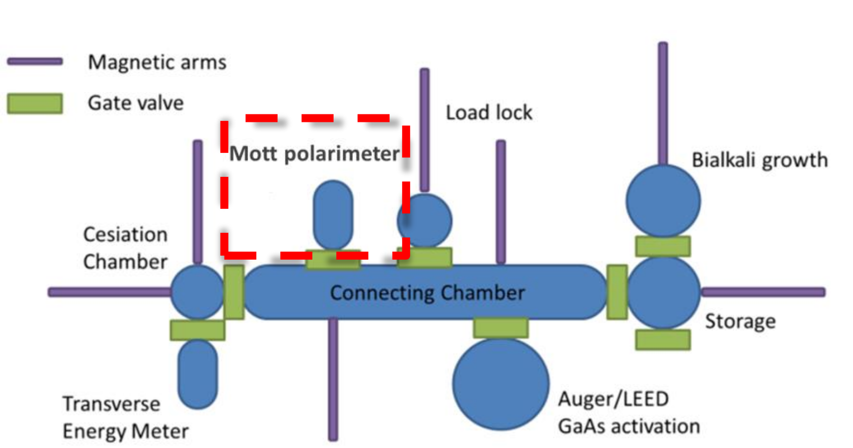


The transverse laser shape can make a difference

C. Gulliford, A. Bartnik, I. Bazarov, B. Dunham, L. Cultrera, *Appl. Phys. Lett.* **106** (2015) 094101

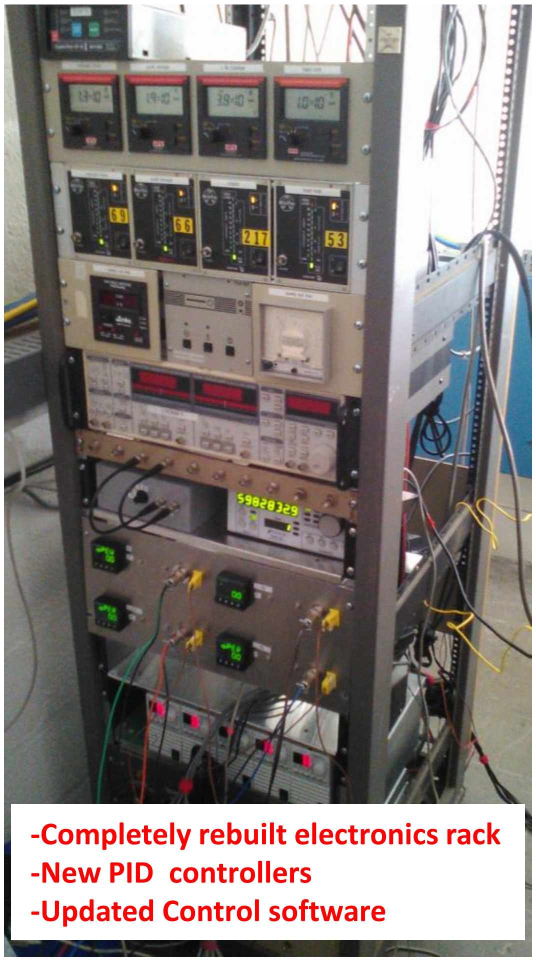
Photocathode Lab





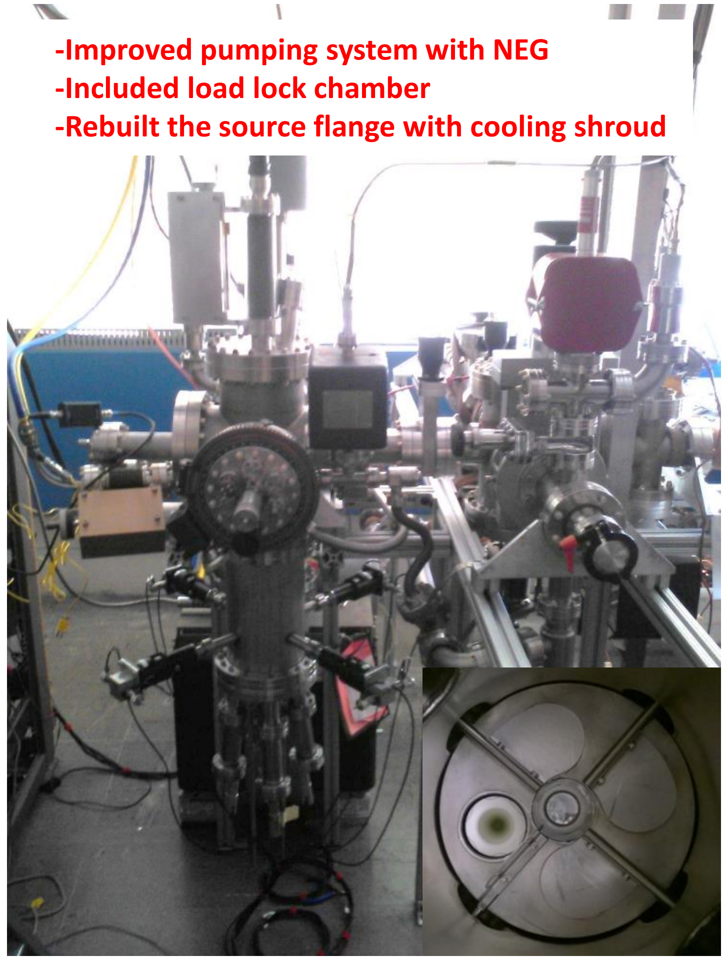
2nd growth system

Our 2nd growth chamber has been completely rebuilt and recommissioned and is now our production chamber to deliver cathodes for our electron guns **(Cs_3Sb, CsK_2Sb, Na_2KSb)**



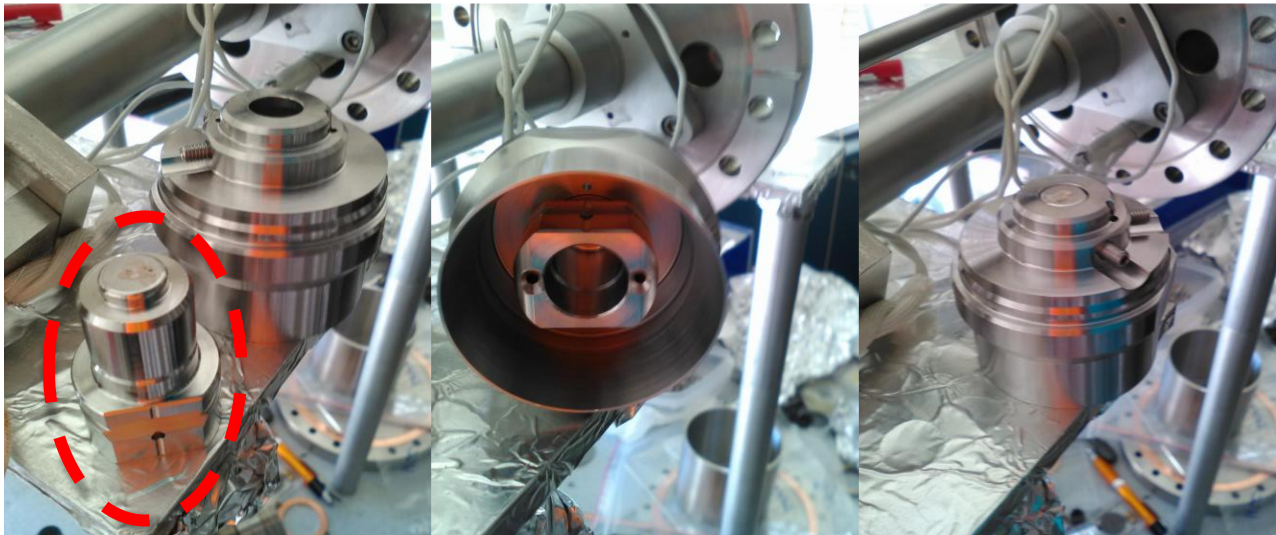
-Completely rebuilt electronics rack
-New PID controllers
-Updated Control software

-Improved pumping system with NEG
-Included load lock chamber
-Rebuilt the source flange with cooling shroud



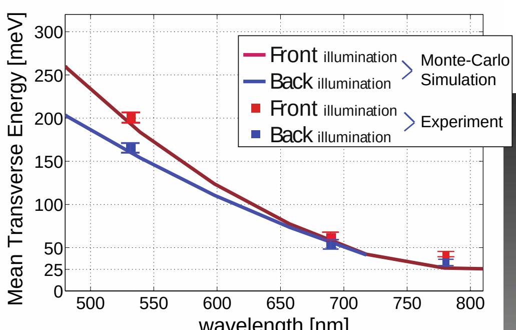
-Included a new movable mask to growth off-center cathodes

INFN/DESY/LBNL miniplug



Interface to grow on the "miniplug" in use at INFN/DESY/LBNL and in our new Cornell HV DC cryogenic gun

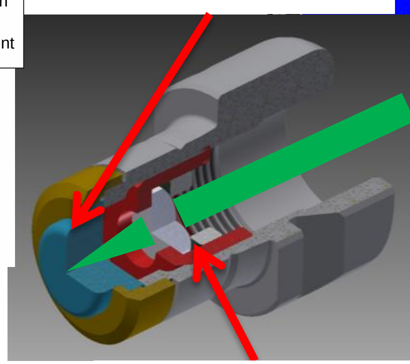
Prototype of transmission mode



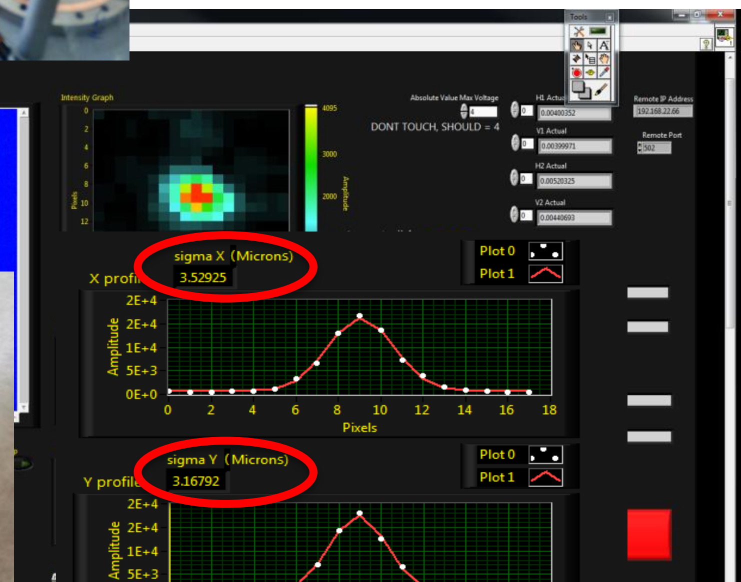
Back illumination makes brighter electron beams!

Appl. Phys. Lett. 108, 124105 (2016)

Glass substrate



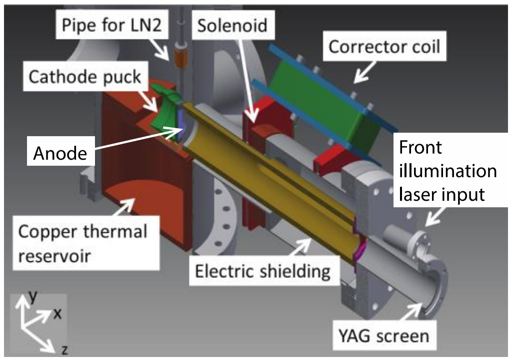
Focusing lens

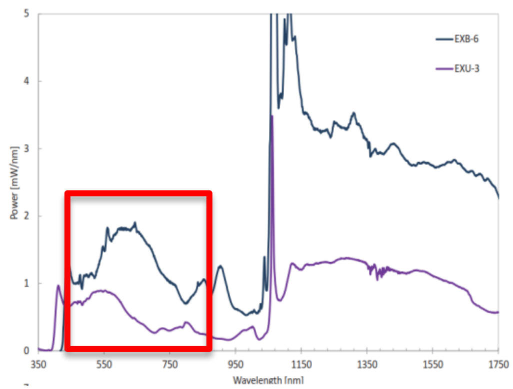


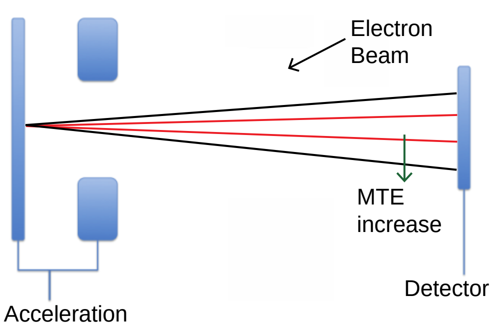
~3 micron laser spot size

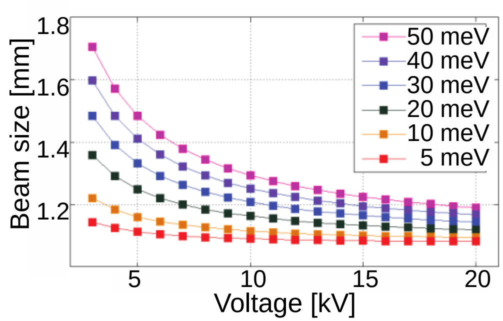
Transverse Energy Meter (TEmeter)

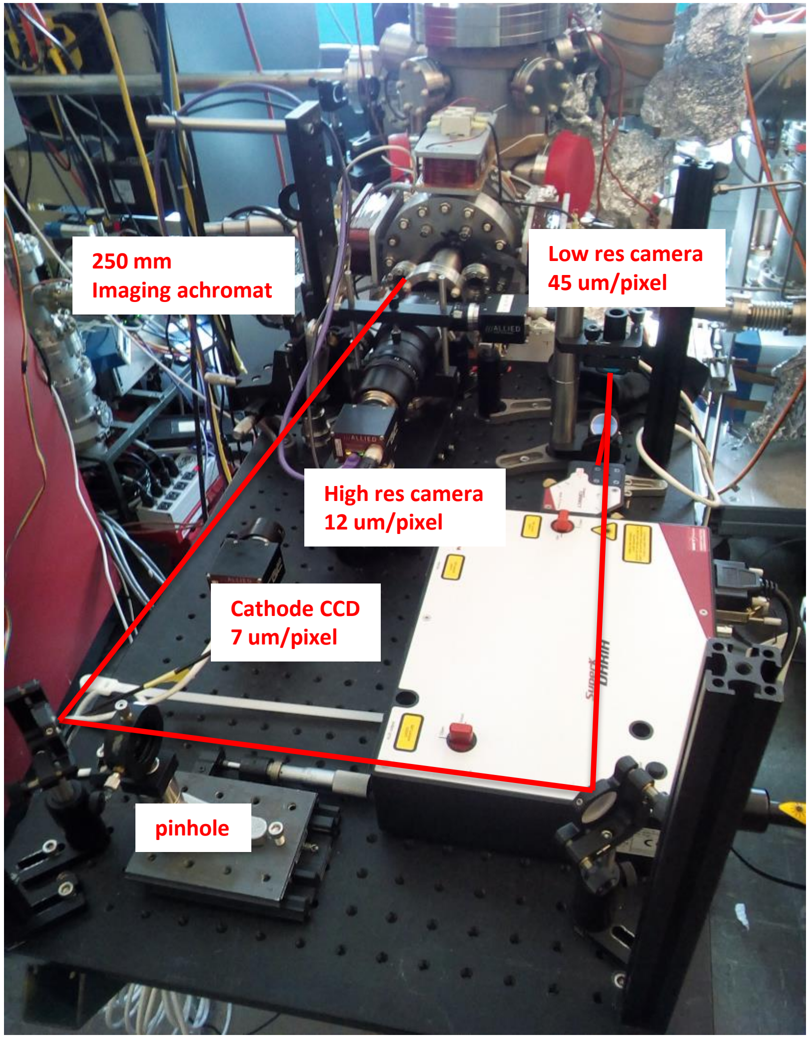
- Measure Mean Transverse Energy (MTE)
- Cryogenically cooling capacity @ 90K with LN2
- Voltage up to 20kV (~4-5MV/m) with gap (4-5mm)
- Compact device – ~ 30'' tall and 20'' long



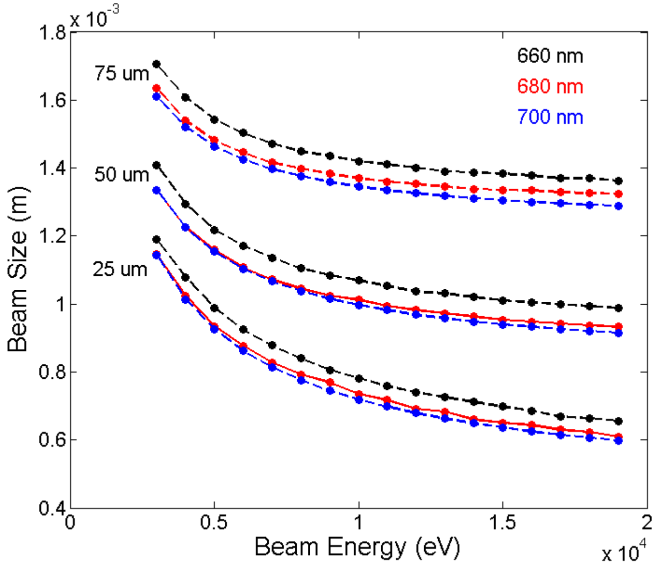


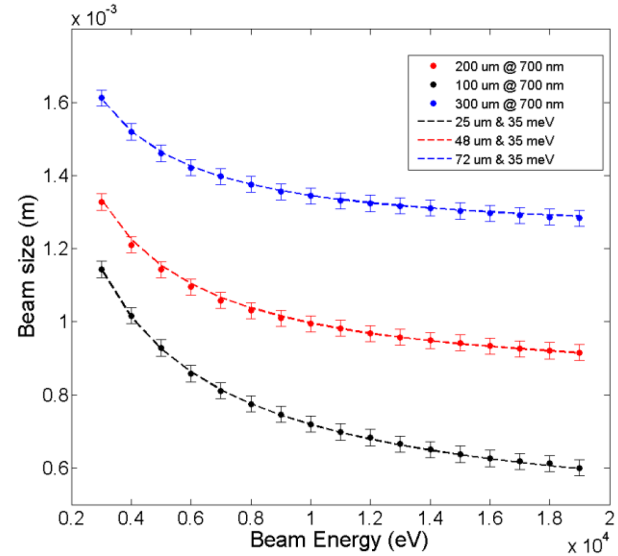


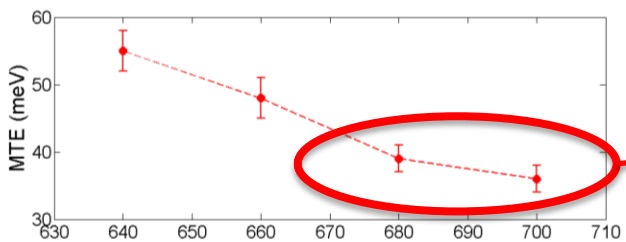


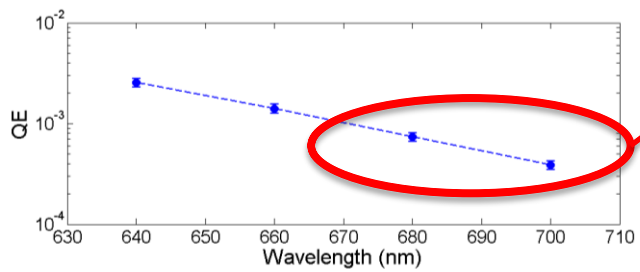


Alkali antimonide near threshold of emission (TEmeter voltage scan example)









Electron beams are produced near threshold using alkali antimonide (Cs_3Sb)

MTE as low as 35 meV are measured

QE is larger than that of metals

The intrinsic emittance is **0.26 mm mrad/mm rms**

3 times smaller than the one of Cu and CsTe

Immediate benefit for X-FELs

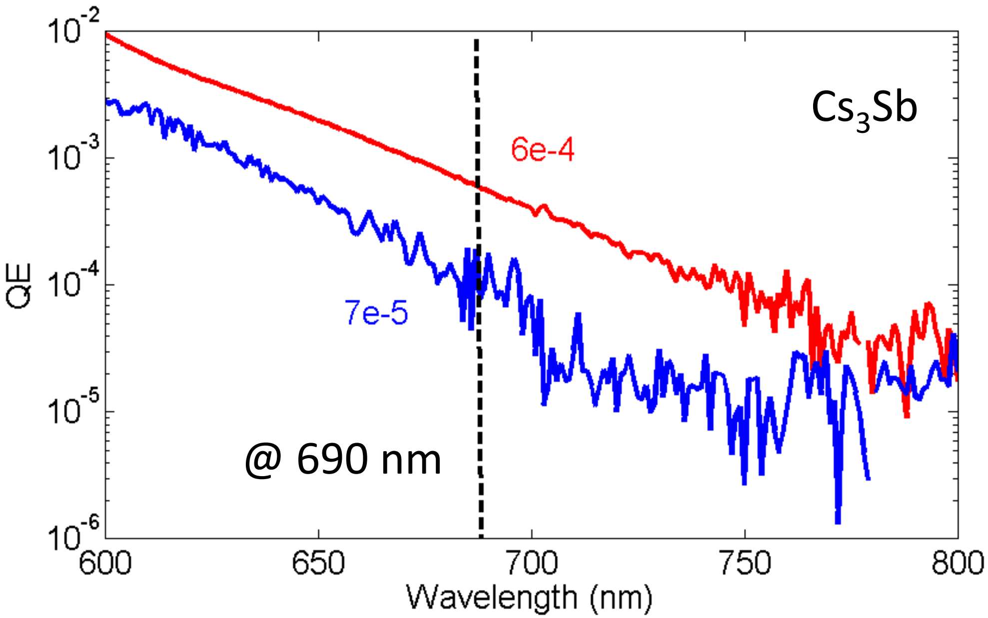
300 pc @ 1MHz require 2 W IR laser!

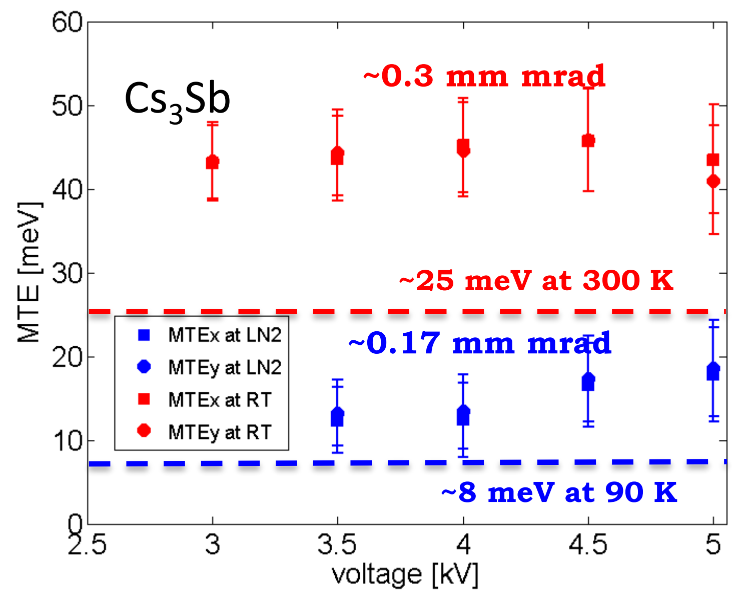
Cool the cathode to cool the beam

At about 0.25 μm/mm rms we almost touched the bottom of QE… **Electron finite temperature sets a lower limit to the minimum intrinsic achievable emittance (0.22 μm/mm rms)**

What happen if we cool the cathode to cryogenic temperature?

As ***T* lowers from 300 K to 90 K**, MTE should lowers from **25** to **8** meV
and the minimum intrinsic emittance from **0.22** to **0.12** μm/mm rms





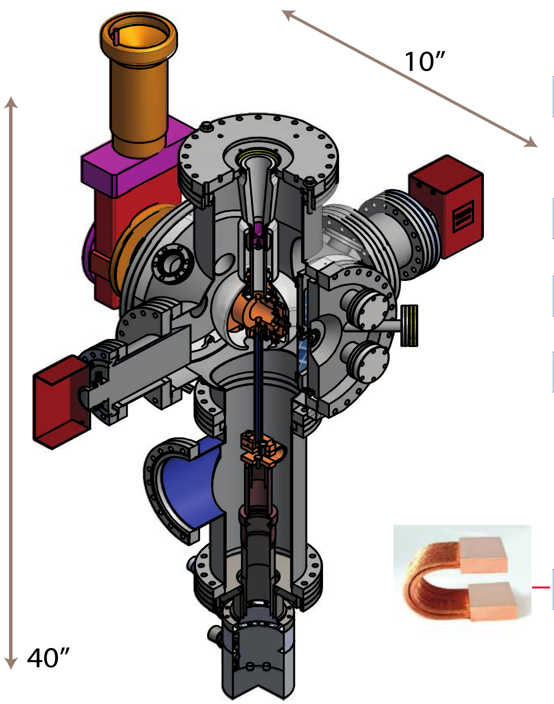
200 K equiv. temp.

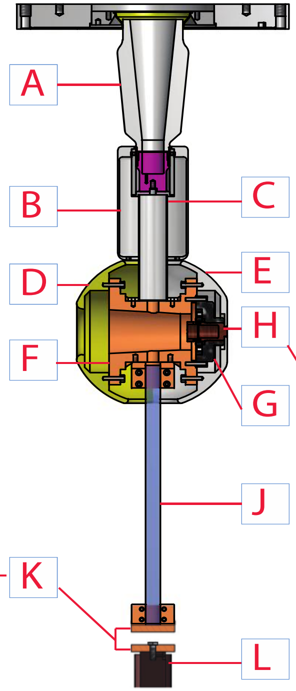
Combining the benefit of
"near threshold"+ "cryo-temperature"+ "transmission"
to minimize initial electron beam phase space

L. Cultrera et al., Phys. Rev. ST – Acc. Beams **18** (2015) 113401
H. Lee et al., Rev. Sci. Instrum. **86** (2015) 073309

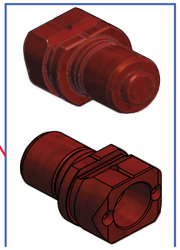
Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

HV DC Cryogun @ 20 K

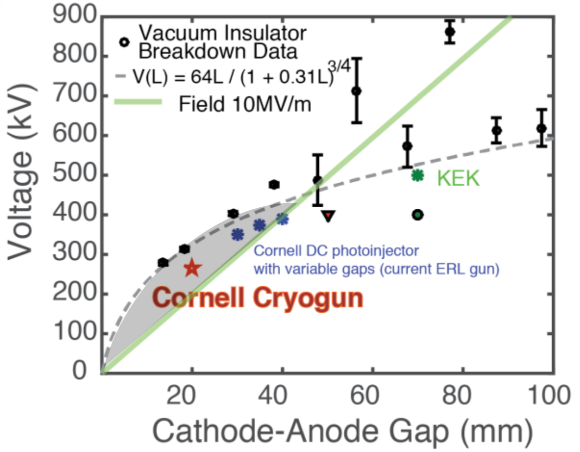




(A) Insulator
(B) Screening electrode
(C) HV stalk
(D) Back electrode
(E) Front electrode
(F) Copper core
(G) Puck holder
(H) Minipuck
(J) Sapphire rod
(K) Copper strap
(L) Cryopump

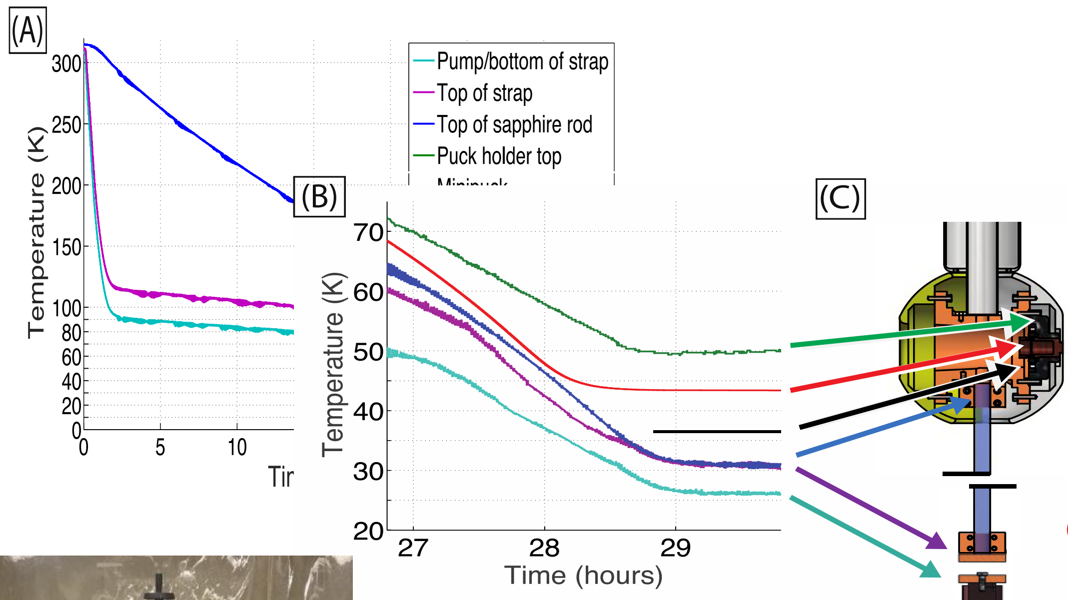


≥10 MV/m DC field doable



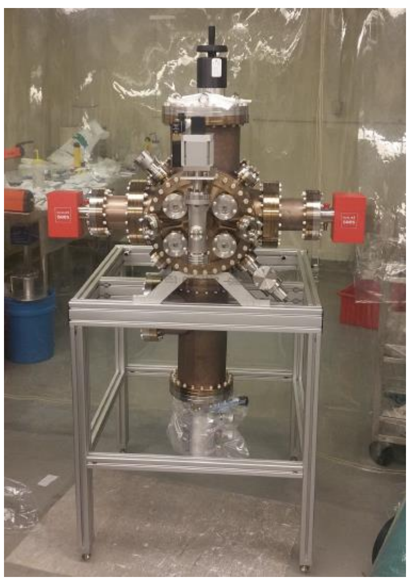
- **The gun was designed to reach 20 K at the cathode**
- **Electric field at or larger than 10 MV/m**
- **Beam energy above 200 keV**

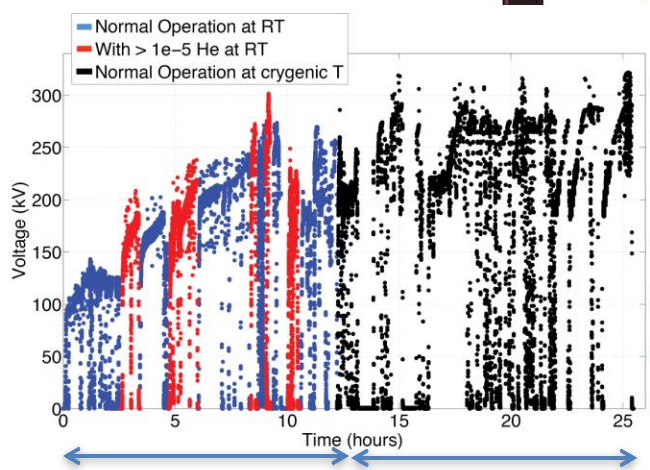
HV DC Cryogun @ 43 K



Cryopump
(~6W at 15K)

At the cathode 43±1K

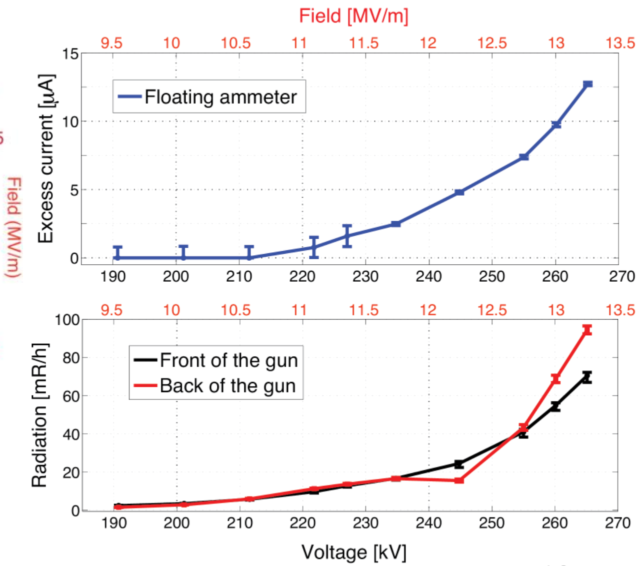




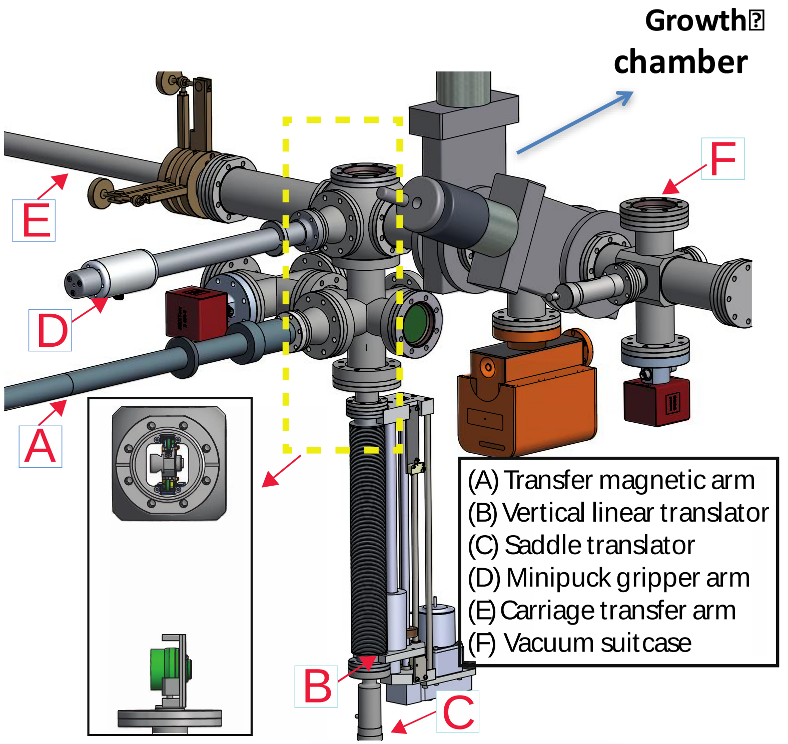
RT

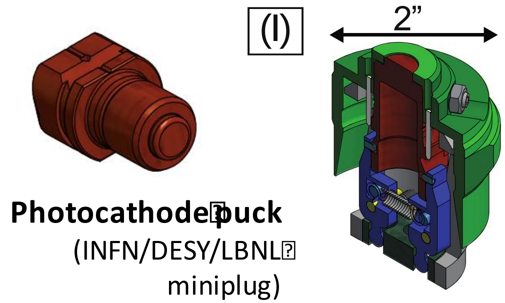
Cryogenic▯temp

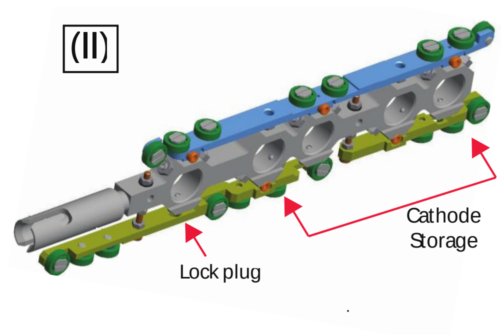
Performance▯at▯cryogenic▯temp

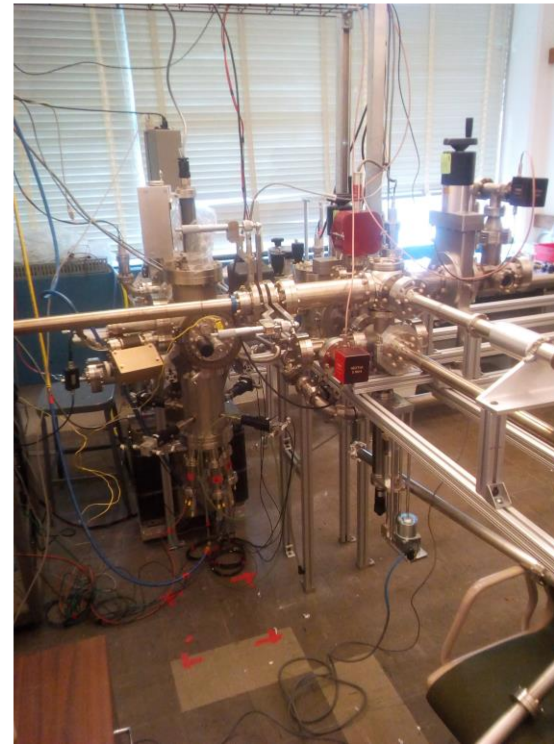


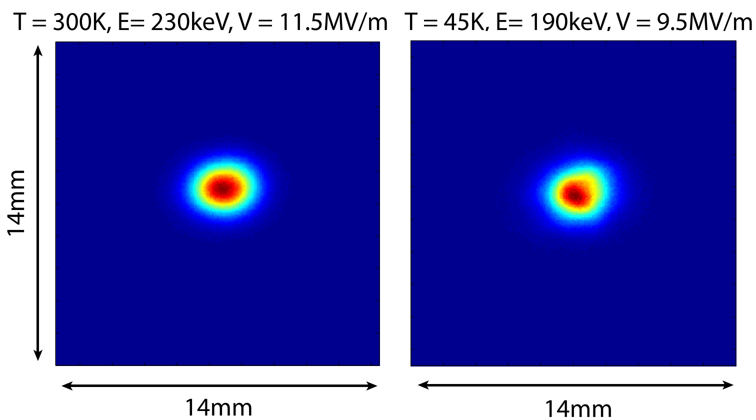
Cs_3Sb first beam







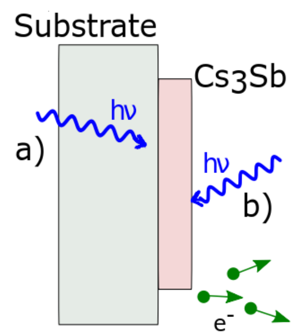


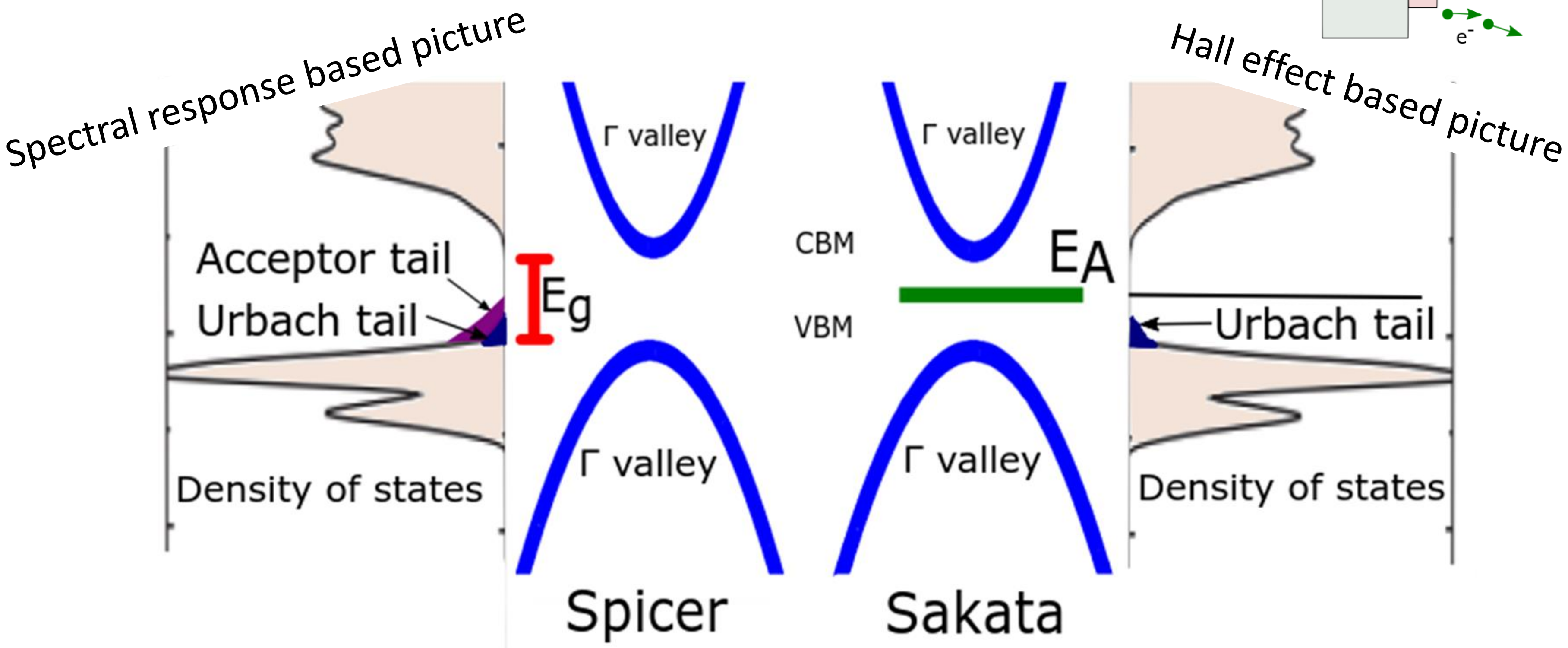


- **Cs_3Sb** grown with sequential growth over polished SS;
- Time constraints delayed detailed emission studies;
- Demonstrated the **first beam** at RT and **45 K**;
- Gun is being relocated in a new lab;
- Cathode loading mechanism is being revisited;

Cryocooling alkali antimonides

- ***What should we expect at cryo T?***
  - *QE? MTE? Response time?*





Which one is the real picture?
How does affect photoemission?

W. Spicer, Phys. Rev. **112**, 114 (1958).

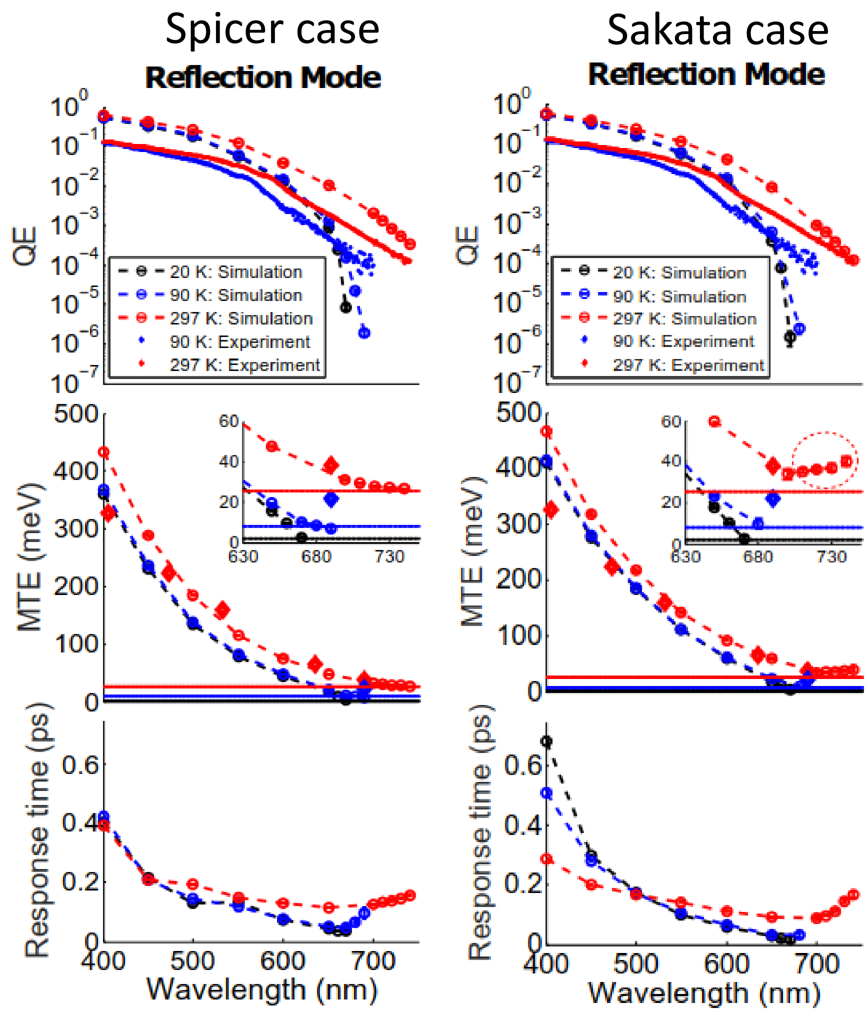
T. Sakata, J. Phys. Soc. Jpn. **9**, 1031–1032 (1954)

Comparison with experiment and predictions

Difficult to treat electron emission at electron energies well below 1 eV. Sudden approximation is not valid anymore.

Many non-uniformities (roughness, ϕ) can affect MTE

Parameter	Symbol	Value
Band gap at room temperature (297 K)	$E_g(297\text{ K})$	1.6 eV[4]
Bulk electron affinity	χ	0.45 eV[4]
Conduction band effective mass (Γ valley)	$m^*_{\Gamma,c}$	0.23 m_e *[8]
Valence band effective mass (Γ valley)	$m^*_{\Gamma,v}$	0.36 m_e *[8]
Longitudinal optical phonon energy	$\hbar\omega_{LO}$	0.022 eV[5,23]
Doping density (Sakata)	N_{A0}	$7.5\times10^{20}\text{cm}^{-3}$ [10]
Doping density (Spicer)	N_{A0}	10^{19}cm^{-3} [10]
Acceptor energy level (Sakata)	$E_A - E_V$	0.29 eV[10]
Static dielectric constant (Spicer)	ϵ_s	8.2 ϵ_0[2]
Static dielectric constant (Sakata)	ϵ_s	11.4 ϵ_0
High frequency dielectric constant	ϵ_∞	5 ϵ_0[2]
Damping coefficient	Γ	$1.58\times10^{15}\ \frac{\text{rad}}{\text{s}}$ [2]
Resonance angular frequency	ω_T	$4.22\times10^{15}\ \frac{\text{rad}}{\text{s}}$ [2]
Acceptor level resonance angular frequency	ω'_T	$1.23\times10^{15}\ \frac{\text{rad}}{\text{s}}$
VBM at surface (with respect to E_F)	B	-0.35 eV (ad-hoc)
Substrate refractive index	n_s	1.5
Substrate work function	ϕ_S	4.4 eV[24]
Electron-phonon coupling strength	ΔE_{ZP}	0.1 eV[14]



Interplay of a large number of parameters

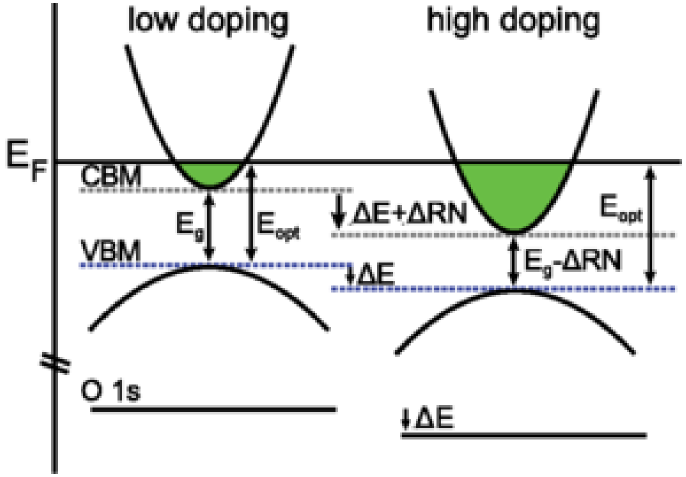
Qualitative agreement with experiment

Pristine surfaces

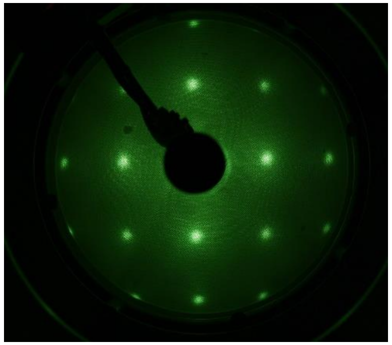
Enormous progresses have been made in realizing smooth surfaces of alkali antimonides
Their surface still cannot be considered atomically flat and uniform

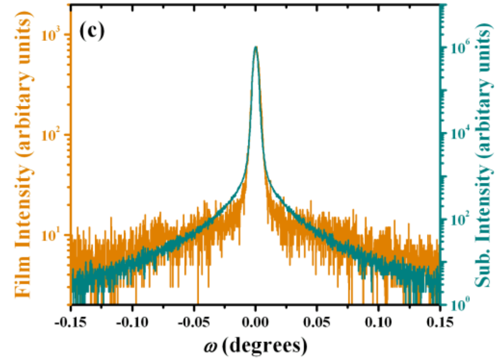
$BaSnO_3$

- Transparent conducting oxide
- Can be n-doped with La up to 10^{20} cm^{-3} (x=4%, degenerate semiconductor)
- Stable in air

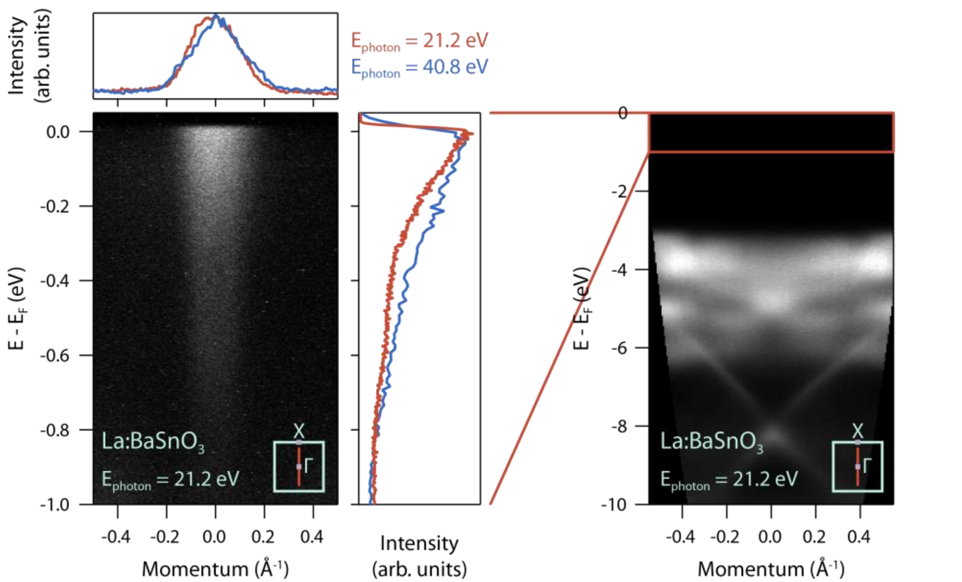


ARPES measurements revealed faint signals from non dispersive states near the Fermi Energy (surface states? Defects?)





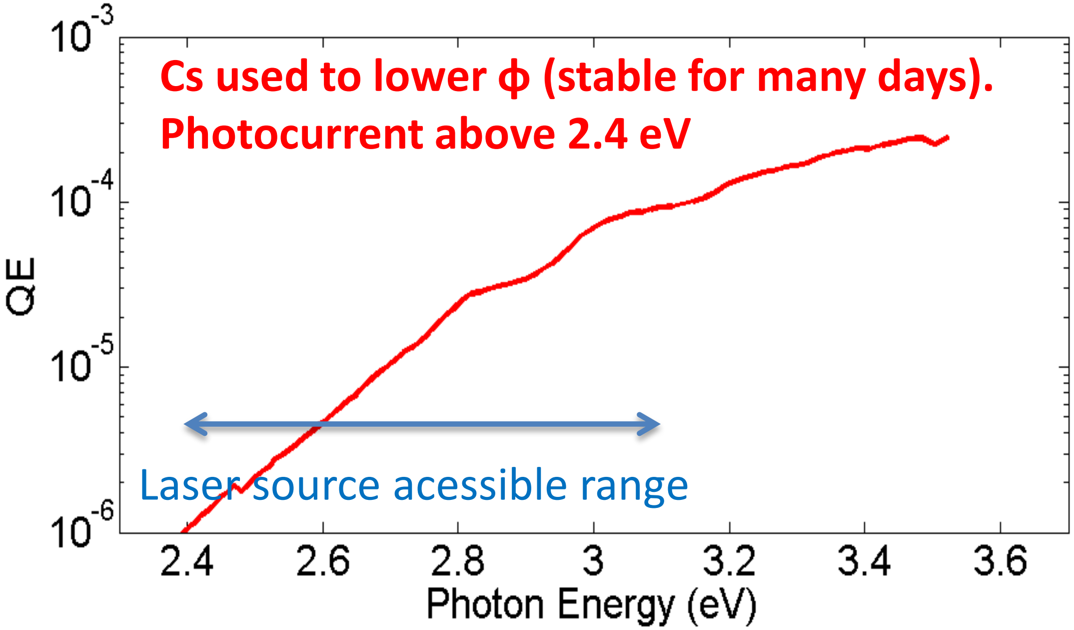
Epitaxially grown using MBE => pristine surfaces



(data courtesy of Ed Lochocki and Hanjong Paik)

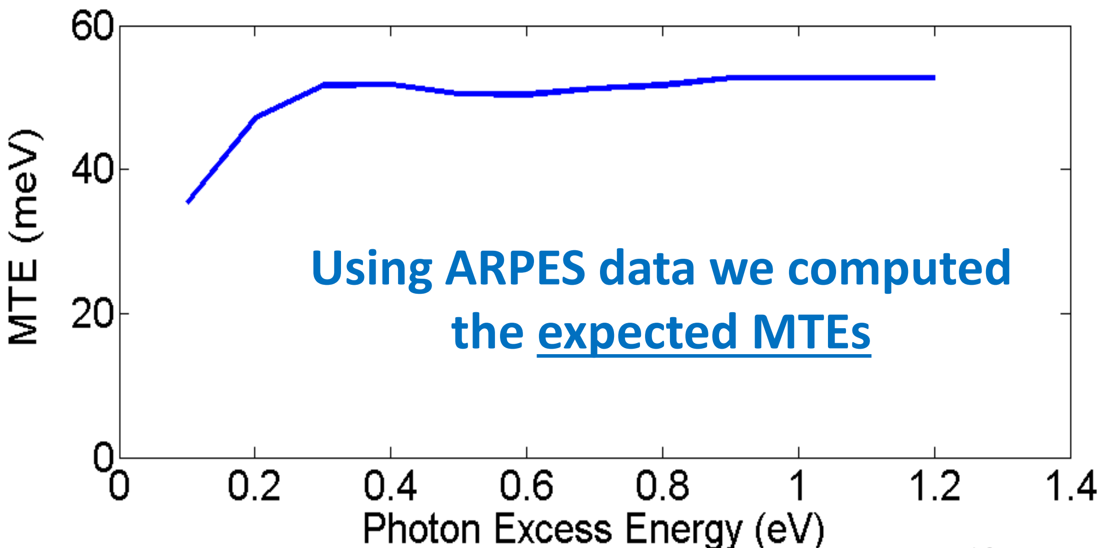
QE and MTE

- The very sample used to collect the ARPES spectrum was moved into our UHV system;
- Light sources photon energies are below the required range (ϕ >4.3 eV)

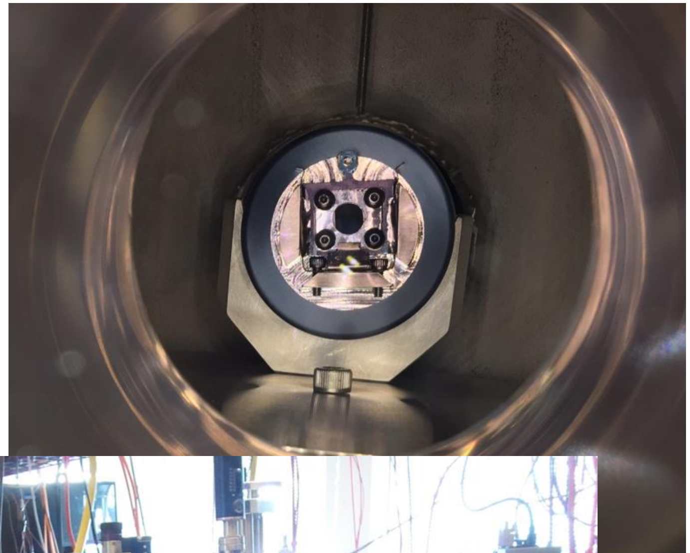


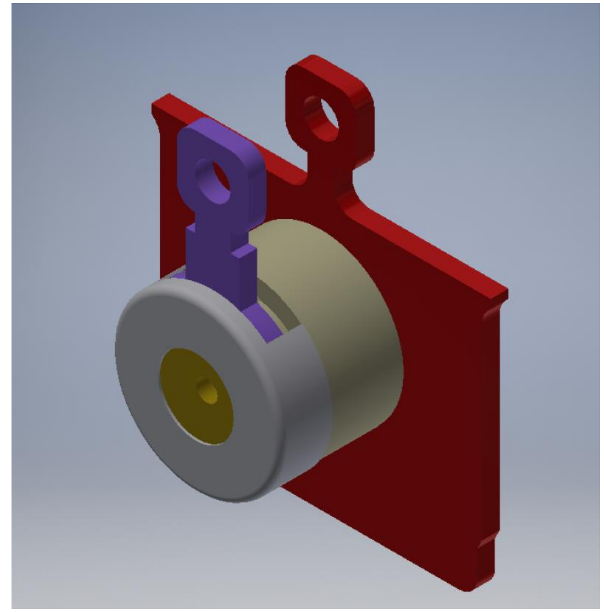
So far MTEs measurements have been difficult to perform because of the <u>poor s/n ratio</u> due to:

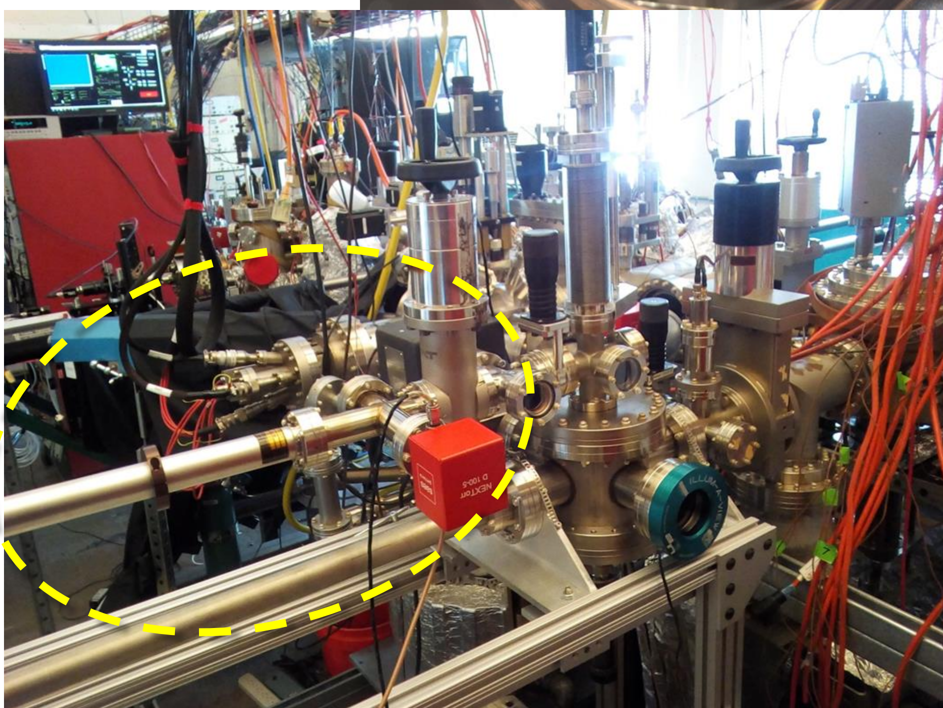
- low intensity of the electron beam signal;
- insufficient filtering of the diffuse laser light;
- Field emitter;



Need more surface science….







Mk-II Omicron like sample holder is compatible with 3 systems

ARPES

New TEmeter (under development)

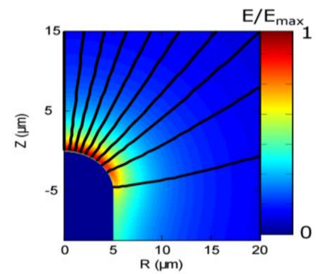
UHV STM-XPS

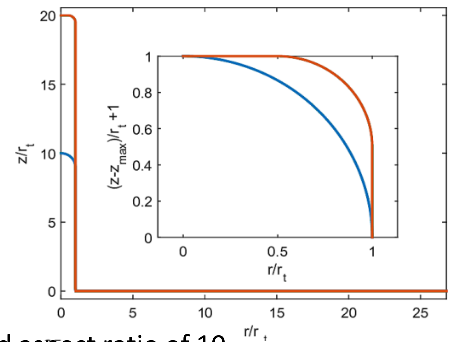
Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

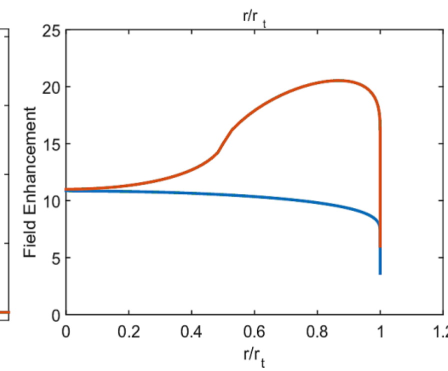
Leverage the electric field

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

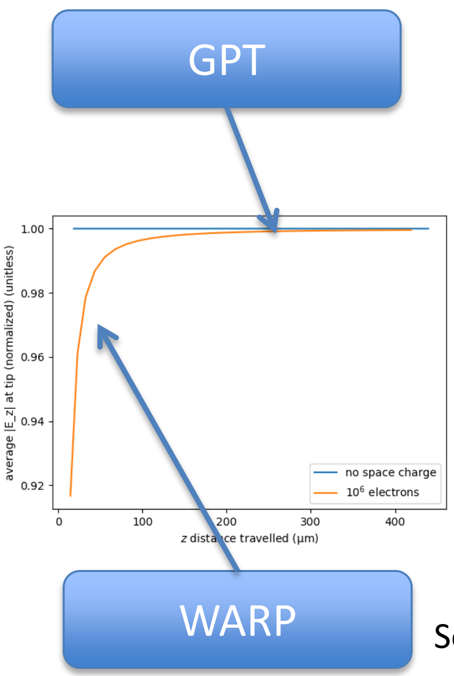
Can we keep aberration under control?

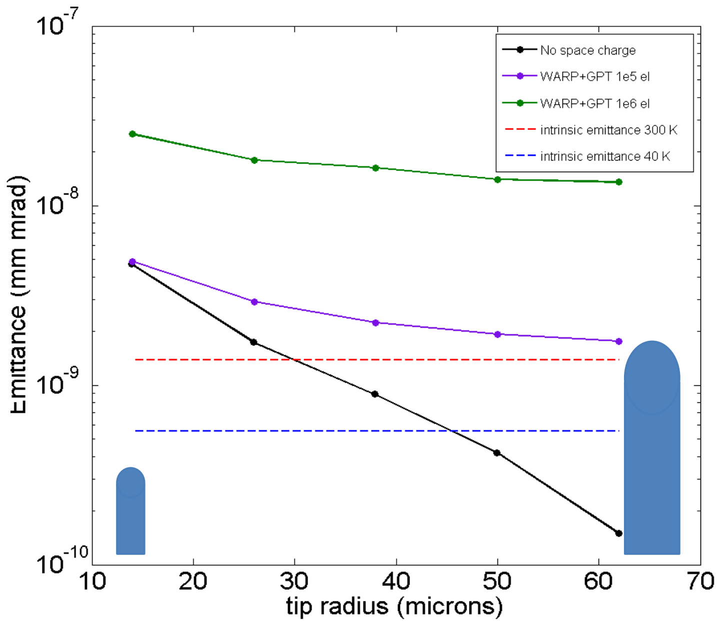




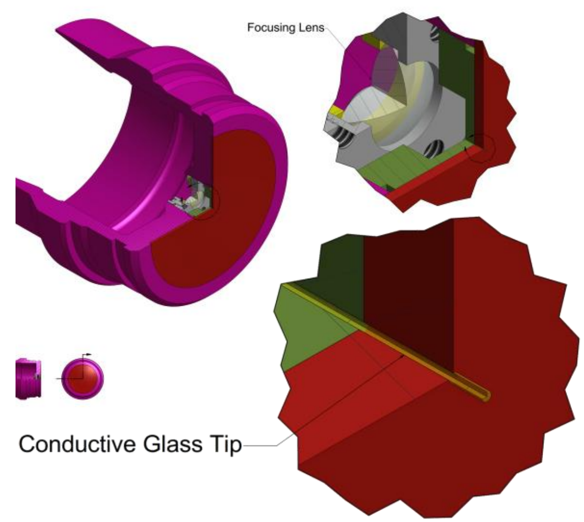


Modeled on DC cryogun
Fully round tip, variable radius, fixed aspect ratio of 10
10 MV/m gradient
100 MV/m at tip
Fixed spot size (5 μm)





Solves image charge, computes fields, track particles



Field emission???

ERL FFAG Experiment

- Cornell DC gun – **alkali antimonide photocathodes**
- 100mA, 6MeV SRF injector (ICM)
- 600kW beam dump
- 100mA, 6-cavity SRF CW Linac (MLC)

Tested

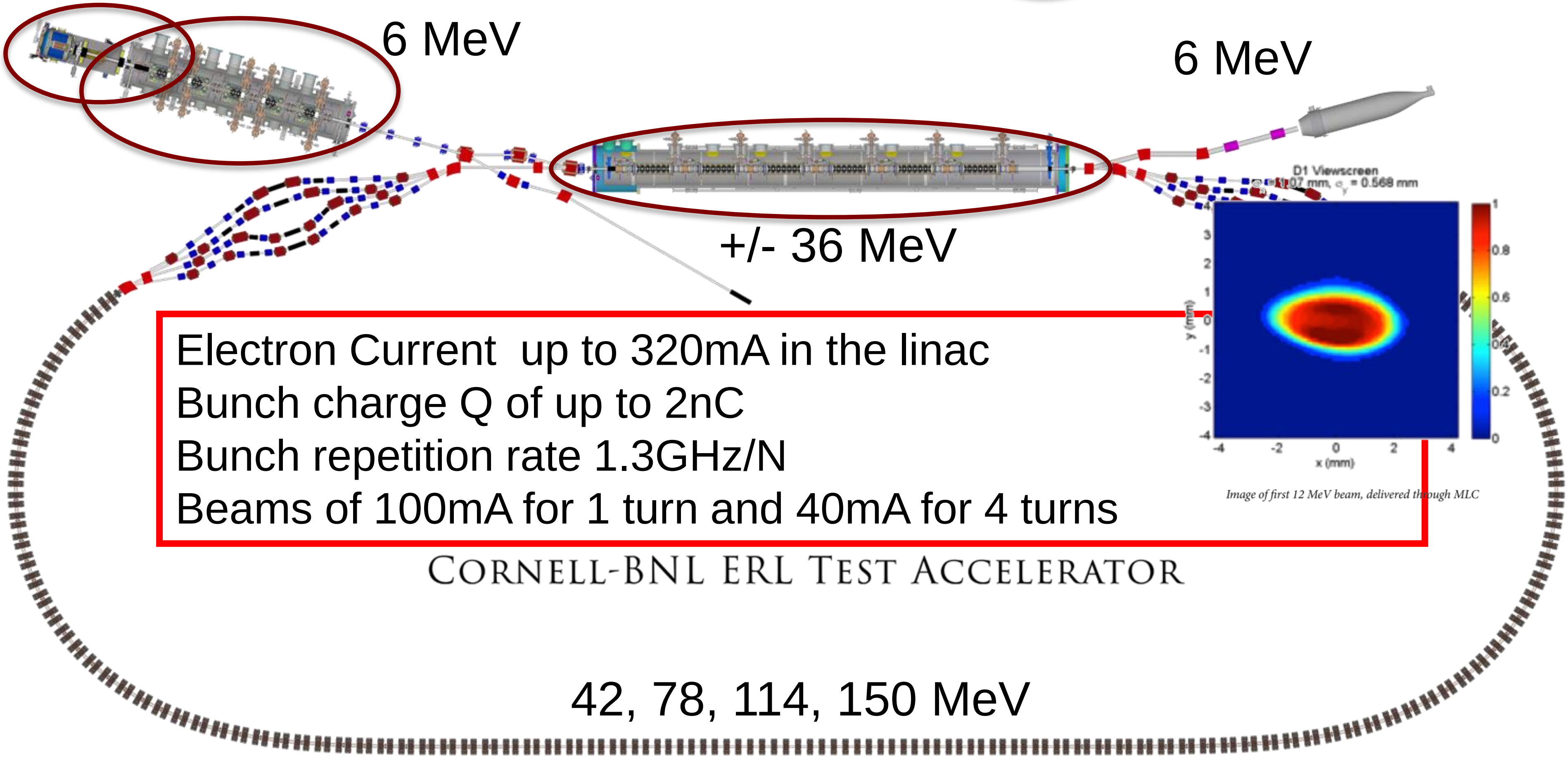
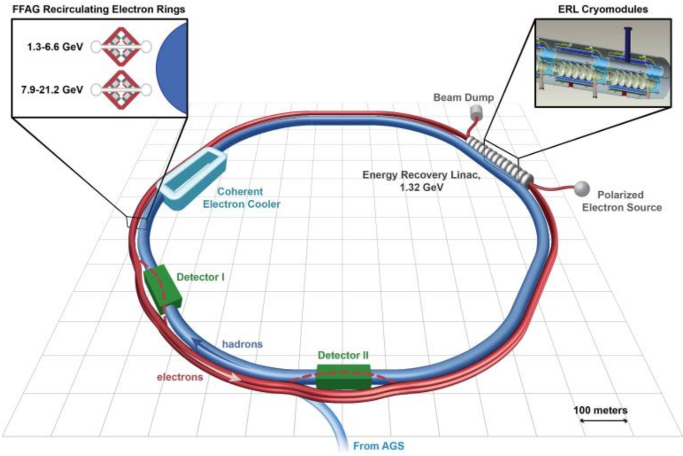


Image of first 12 MeV beam, delivered through MLC

Electron Current up to 320mA in the linac
Bunch charge Q of up to 2nC
Bunch repetition rate 1.3GHz/N
Beams of 100mA for 1 turn and 40mA for 4 turns

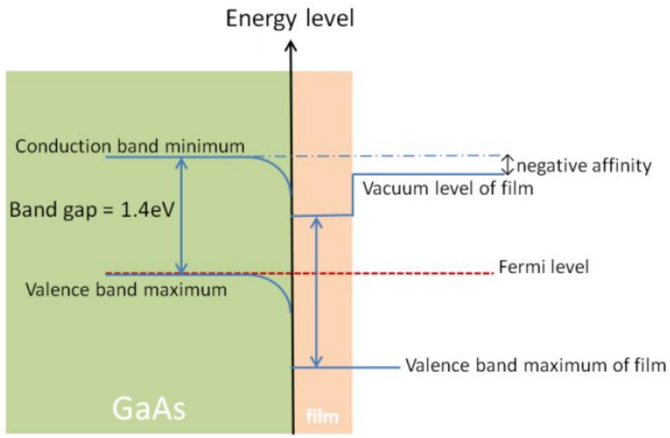
CORNELL-BNL ERL TEST ACCELERATOR

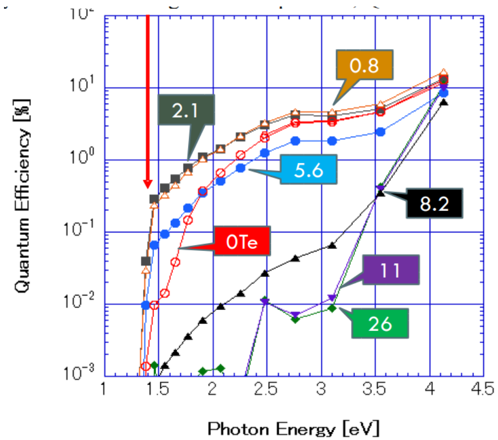
CsTe on GaAs and polarized electron beams



The BNL Linac-Ring option for EIC need electron beams with:

- larger than **70% polarization**
- Average electron currents up to **50 mA**
- **GaAs cannot provide such intensities**



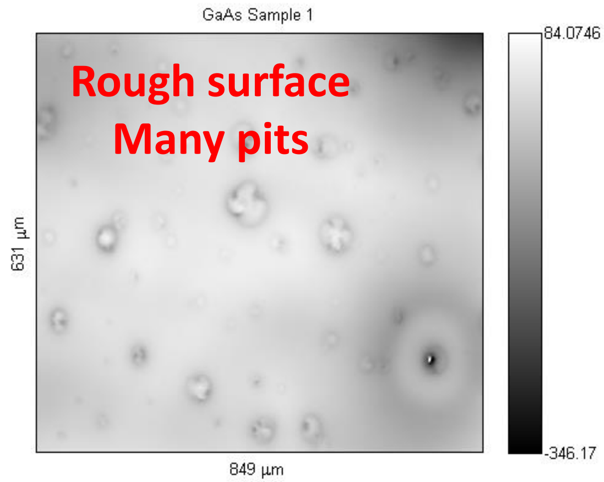


M. Kuriki, P3 Workshop 2014, Berkeley

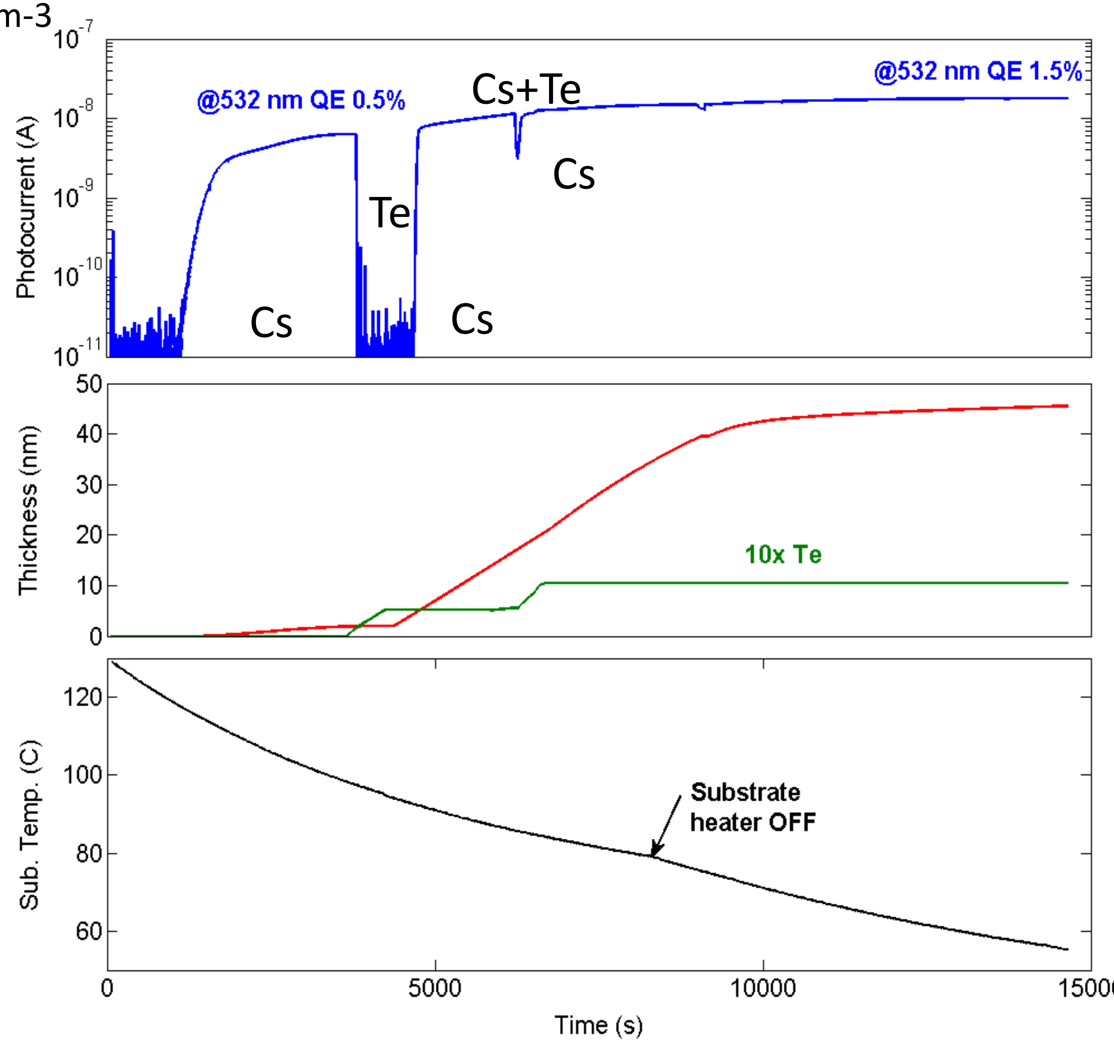
- LESS VACUUM SENSITIVE COMPARED TO Cs-O?
- WHAT HAPPEN TO THE ELECTRON BEAM POLARIZATION?
- CAN BE STORED/TRANSPORTED IN A SUITCASE?

CsTe on GaAs

GaAs substrate samples p-type Zn doped 1e18 cm-3
Wet etch to remove oxide and passivate surface
-H_2SO_4:H_2O_2:H_2O (20:1:1) 2 min @ RT
-HCl:iPA (20:80) 3 min @ RT



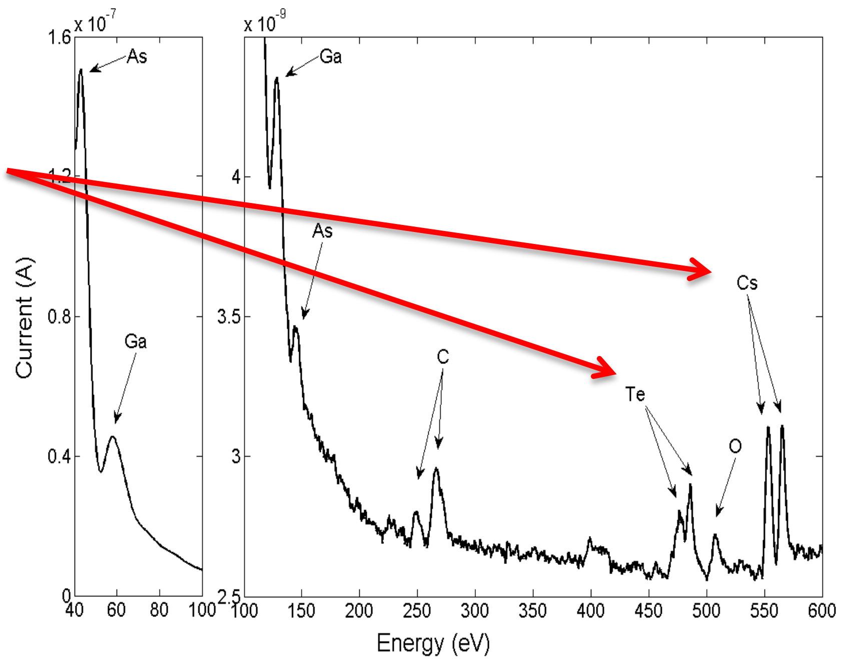
Heat cleaning at 400 C overnight
Room Temperature Cs activation yields ~3% QE @ 532nm
Surface is clean enough to perform activation!!

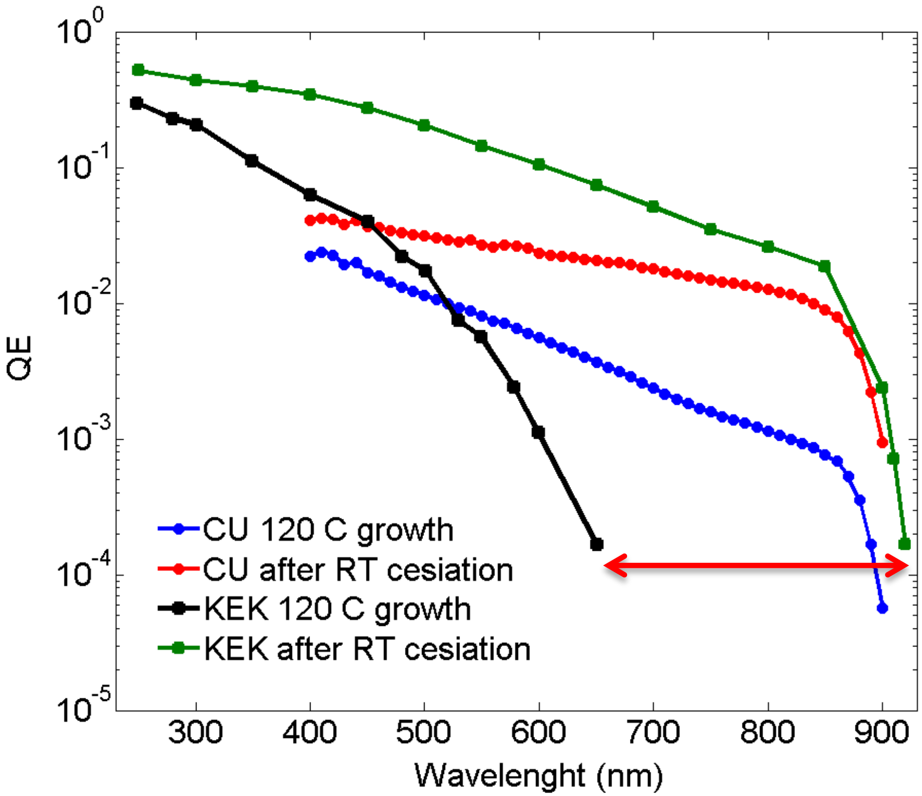


We now skip the first step of etching…
QE after Cs is lower but we have no more surface pitting

CsTe on GaAs

- **Auger spectroscopy confirms the presence of Cs and Te over the GaAs surface**
- Ga ans As peaks are still visible meaning that the CsTe layer is thinner than few nm
- C and O peaks likely coming from the e-gun filament





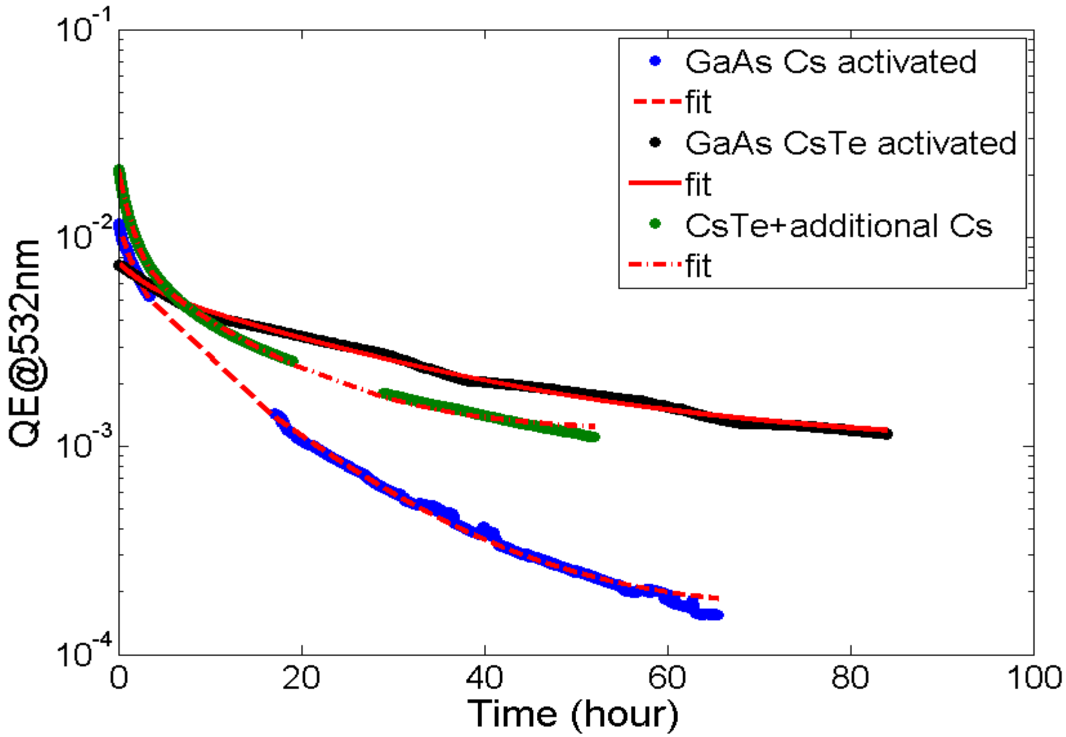
- We do **NOT** see an emission threshold shift
- We do **NOT** get the high QE previously reported by Japanese group

Patchy coverage of the surface?

CsTe on GaAs

Vacuum level is below 1e-10 Torr

Alkali antimonide do not experience QE degradation



Fit with 2 exponential decay (fast< 1hour, slow several hours):

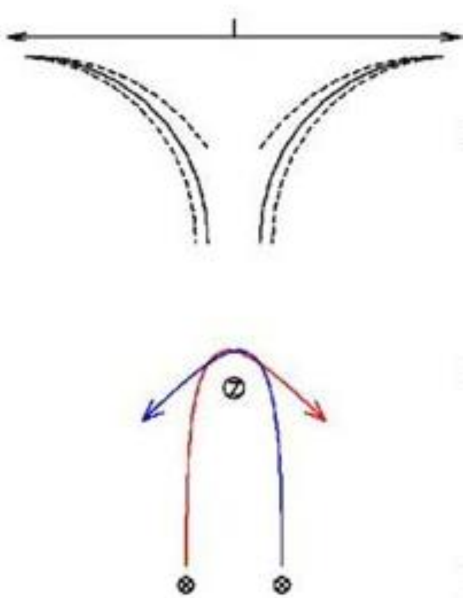
-fast decays have same order of magnitude;

-**slow decays component time constant improved by a factor 3 (~24 hours)**;

Mott scattering polarimeter

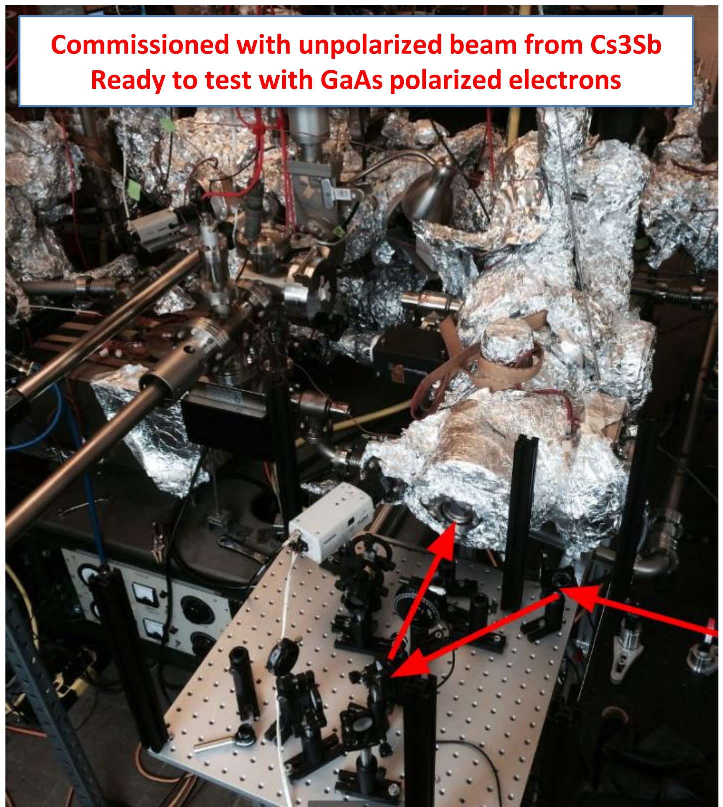
We loan from Jlab a retarding field Mott polarimeter that was designed and used at SLAC to study the generation of polarized electron beam from strained GaAs and other III-V superlattices.

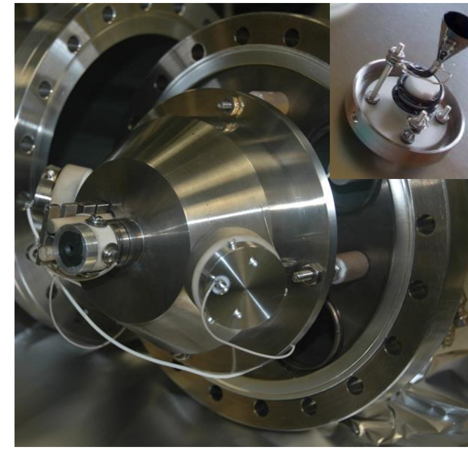
Spin-orbit interaction => asymmetry in scattering

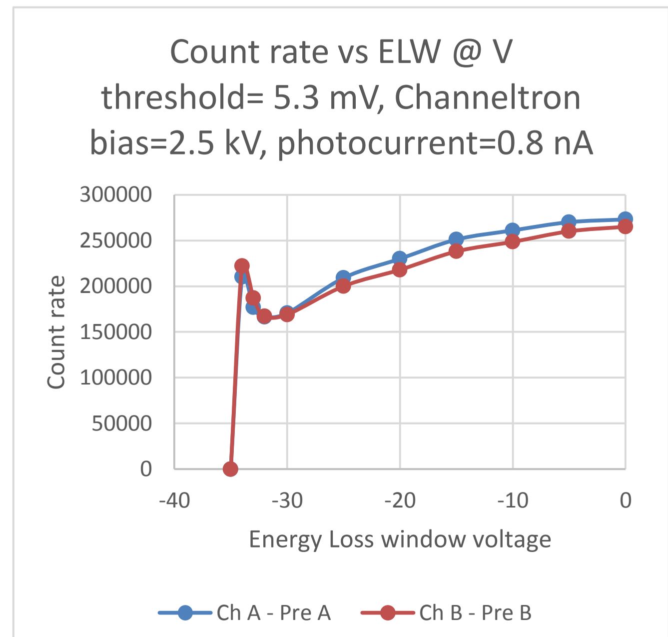


$$A(\theta) = \frac{I_L - I_R}{I_L + I_R},$$

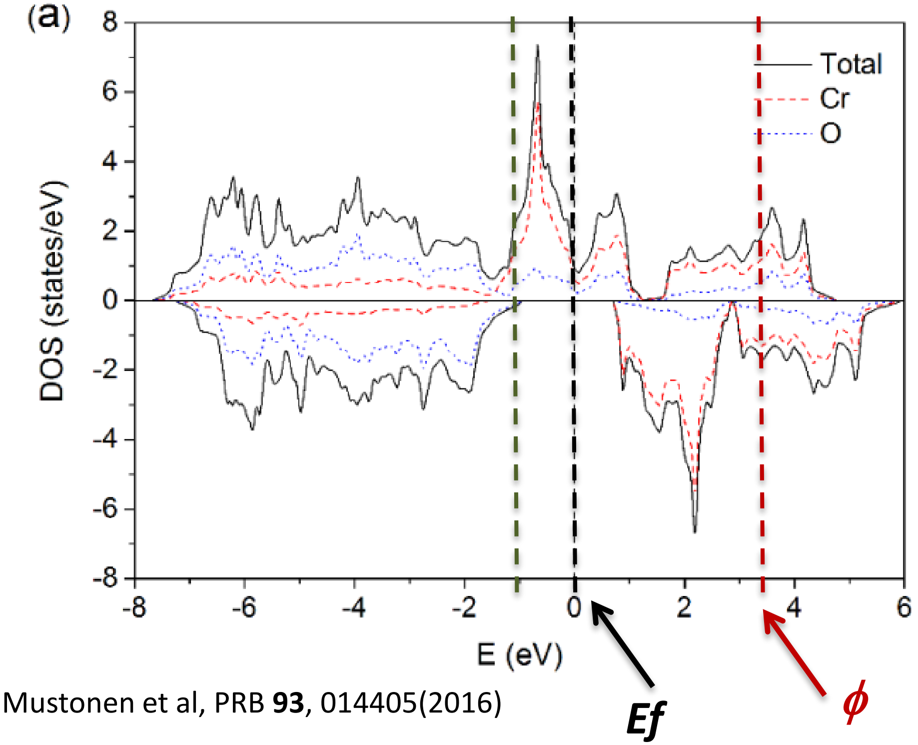
$$A = S_{eff} P_e,$$







CrO_2



Mustonen et al, PRB **93**, 014405(2016)

Kamper et al, PRL **59**, 2788 (1987)

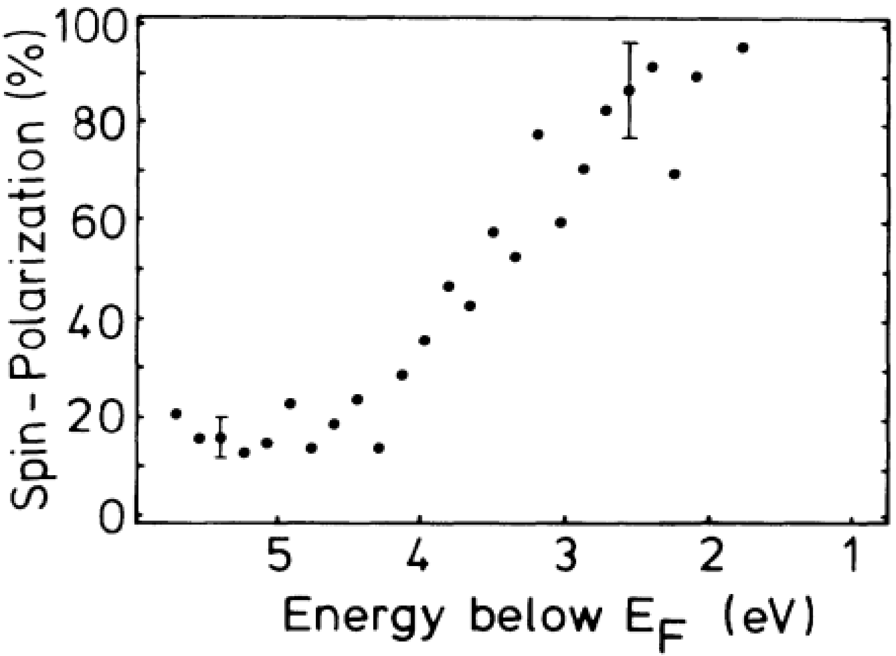


TABLE II. Work functions for CrO_2 surfaces.

	$\Phi_{unrelaxed}$ (eV)	$\Phi_{relaxed}$ (eV)
(100) Cr	3.64	3.40
(100) O	6.38	6.23

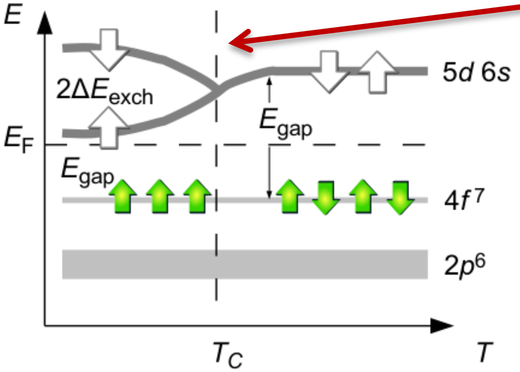
Attema et al, PRB **77**, 165109 (2008)

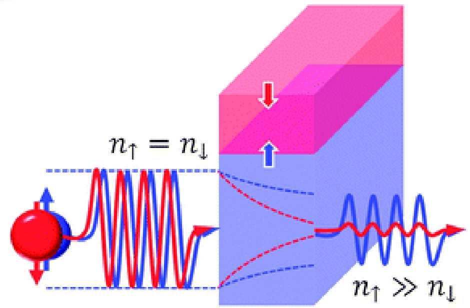
Stable material
Lowest workfunction is 3.4eV
Require UV light

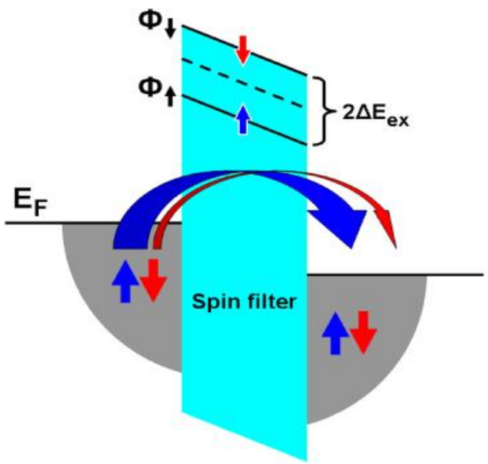
Up to 4.4 eV photon energy only one spin can be photoexcited => 100% polarization

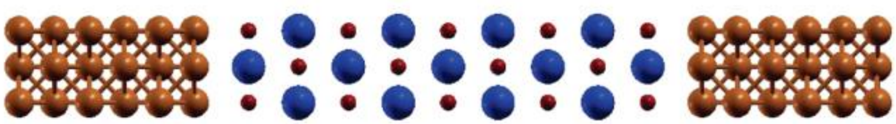
Spin filters

Spin dependent barrier below Tc

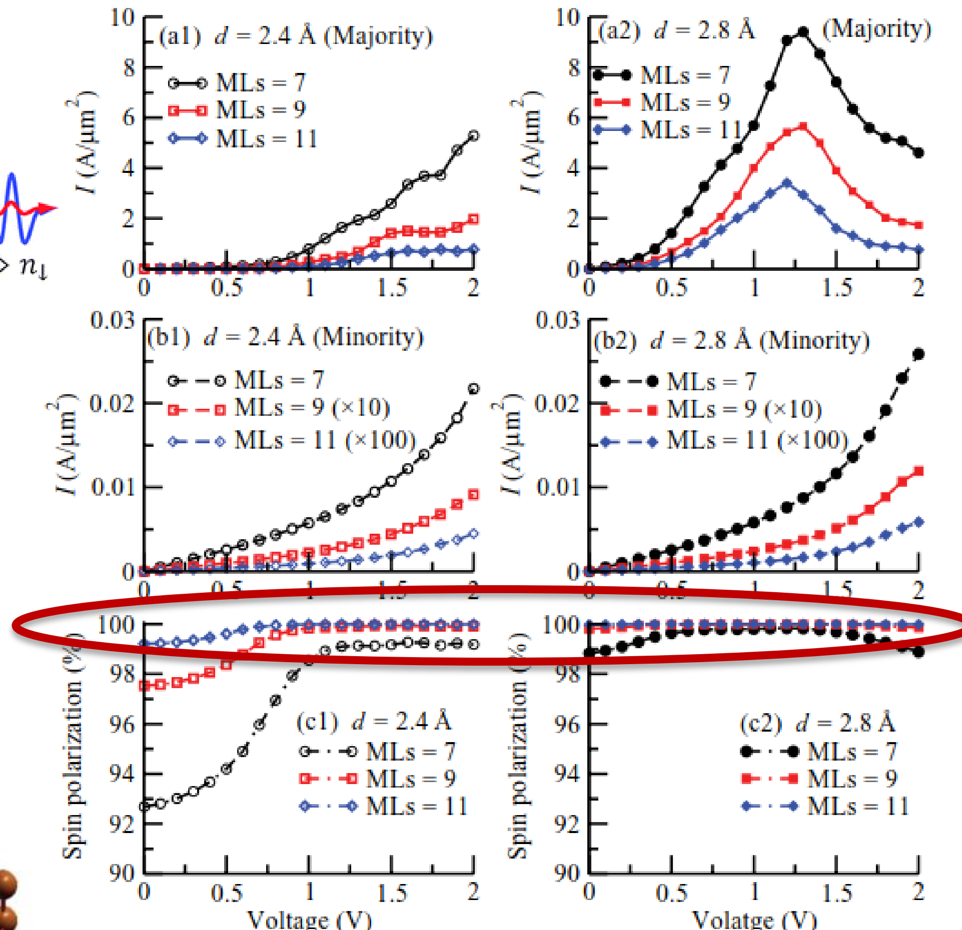








Cu EuO Cu



Jutong et al, **PRB** 86, 205310 (2012)

Can we make real electron beams?

Muller et al, PRL **29**, 1651 (1972)

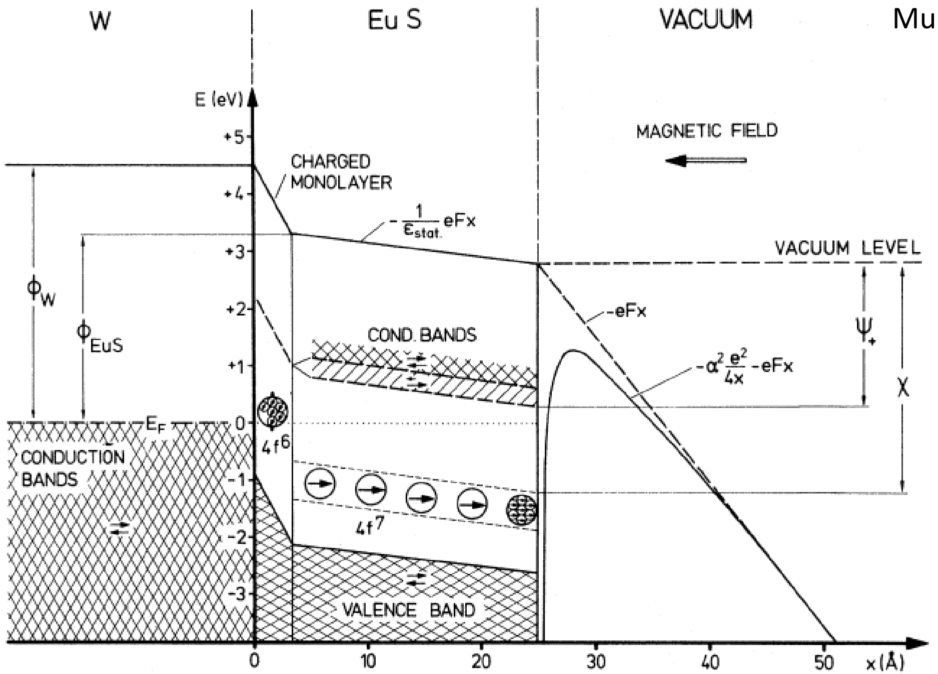


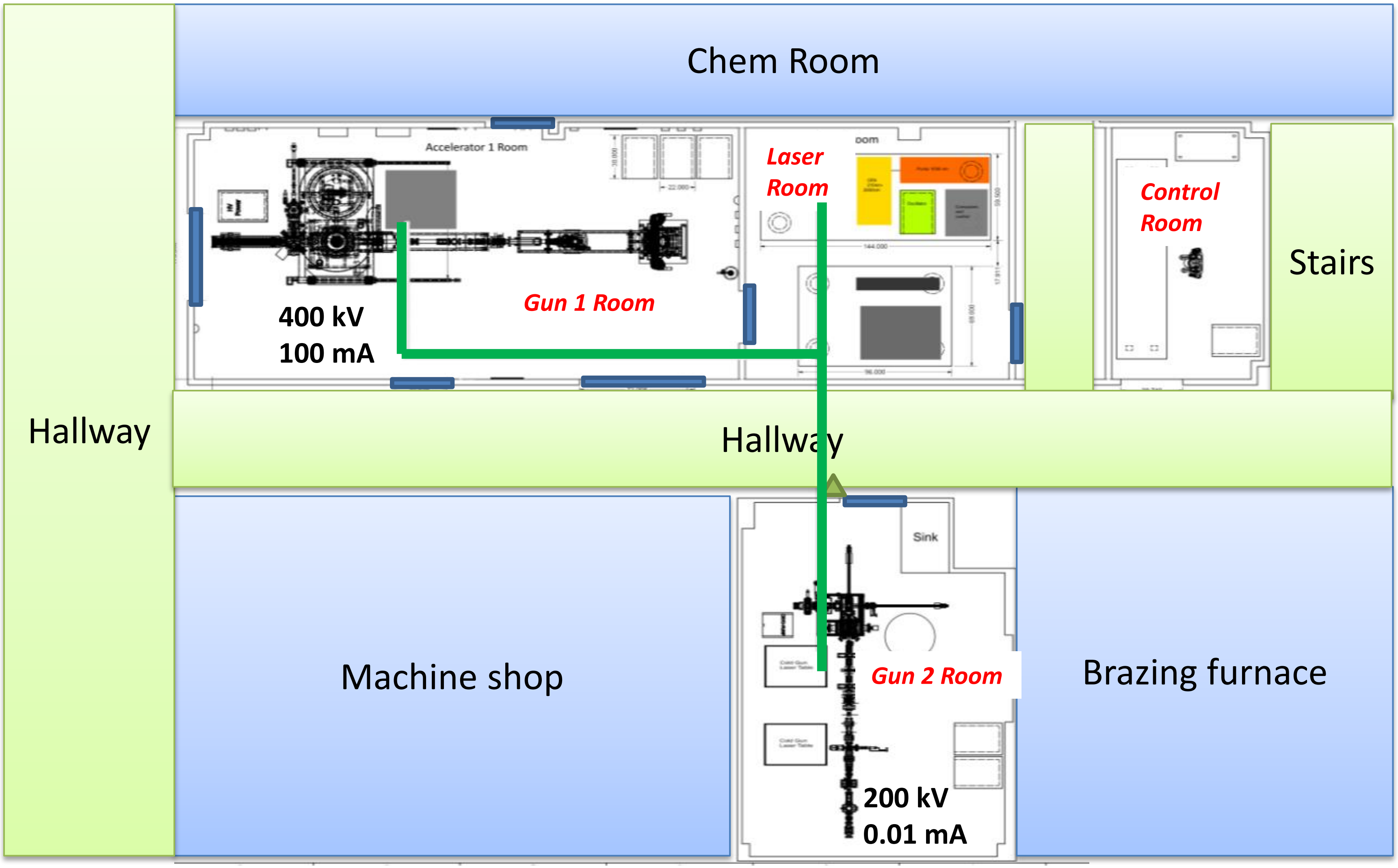
FIG. 3. Field-emission model for EuS on W for a typical field $F = 2.5\times10^7$ V/cm. In the image force potential α is $(\epsilon_{opt}-1)/(\epsilon_{opt}+1)$ with $\epsilon_{opt}=5.2$ (Ref. 22). ψ_+ is the electron affinity of the lower split conduction band, χ the photothreshold, and φ_W and φ_{EuS} the work functions of W and EuS.

Field emission experiment W/EuS date back in 1972

Required operation at **cryo-temperatures to get EuS<Tc**

Polarization of **89±7 %** was measured at **21K**

Upcoming Photogun Laboratory



Summary

- Identified venues producing immediate benefits for existing/future X-FELs and UED;
  - ***Near threshold operation;***
  - ***Cryocooling, micron sized laser spot;***
- Cornell infrastructure provide closed loop:
  - ***Photocathode lab ⇔ Photo-injectors;***
- Looking forward to new materials for improved performances
  - ***Improve our interactions with material scientist***

Thanks for your attention!

The Cornell team:

I. Bazarov, J. Maxson, A. Bartnik, C. Gulliford,
H. Lee, A. Galdi, J. Kwan Bae, W. Li, C. Pierce,
T. Moore, S. McBride, C. Xu, R. Doane

Beam Brightness

Motion along longitudinal (acceleration) and transverse direction is decoupled

$$\frac{B_{n,av}}{f} = q^{-1}\frac{1}{(mc)^2}\int \rho_4{'}^2 dxdydp_xdp_y$$

$$\boldsymbol{MTE = kT_e = m_e c^2 (\varepsilon_{n,x})^2}$$

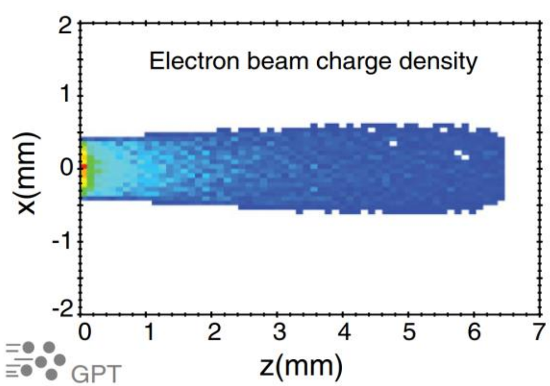
For **"pancake"** distribution (transverse >> longitudinal size) it can be shown that

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

Electric field at photocathode surface and **equivalent temperature** of electrons are limiting the maximum microscopic brightness

I. V. Bazarov et al., *Phys. Rev. Lett.* **102**, 104801 (2009)

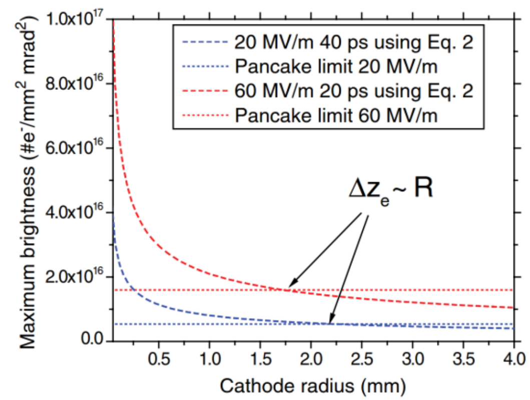
If the bunch charge is sufficiently low that no virtual cathode instability effect will be induced, further improvement of the 4D brightness can be achieved by using relatively long laser pulses (10s of ps) and very small laser spot sizes (<100 μm)



"cigar" distribution

$$B_{\perp} \propto \frac{E_{cath}{}^{3/2}\Delta t}{\sqrt{R}\sigma_{p_\perp}{}^2}$$

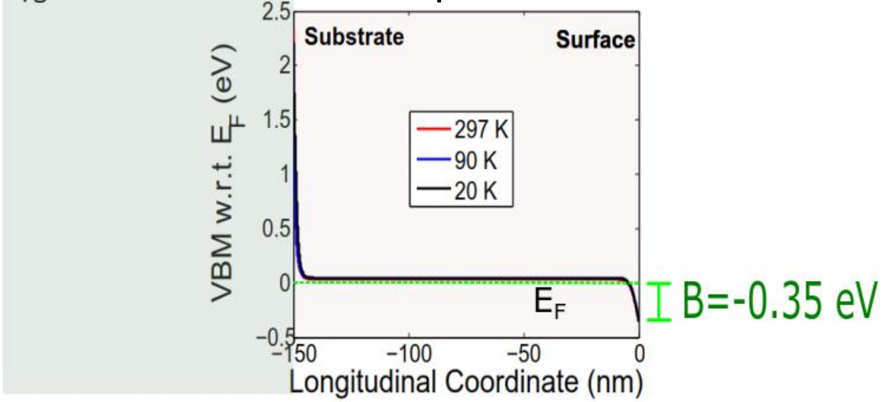
D. Filippetto et al. *Phys. Rev. ST Accel. Beams* **17**, 024201 (2014)



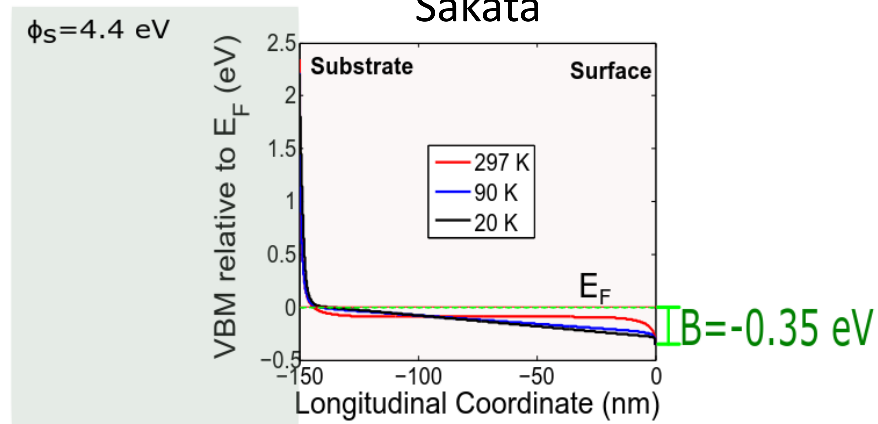
Two different problems

Solving the Poisson equation….

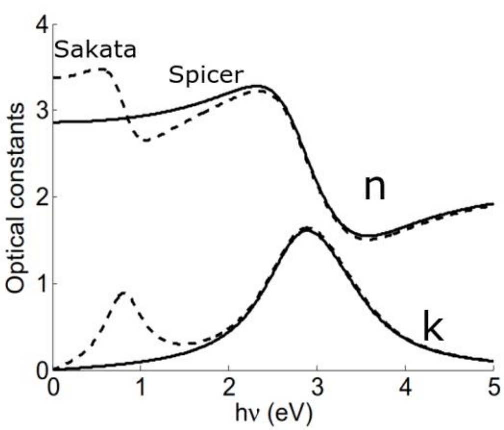
Spicer



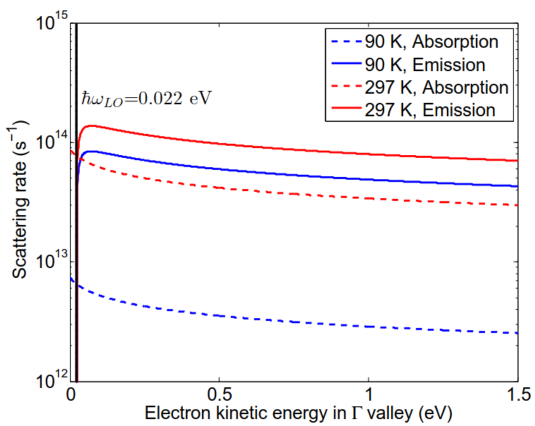
Sakata



3 steps Monte Carlo is used to compute photoemission



Absorption



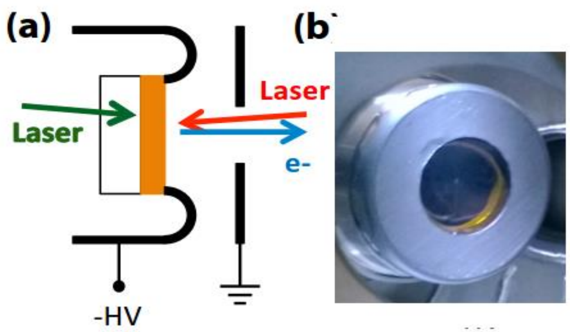
Transport/Relaxation

Difficult to treat electron emission at electron energies well below 1 eV. **Sudden approximation is likely not valid anymore** and different types of **non-uniformities** can affect the transverse momentum of electrons;

Emission

Transmission mode cathodes

H. Lee et al., *Appl. Phys. Lett.* **108**, (2016) 124105



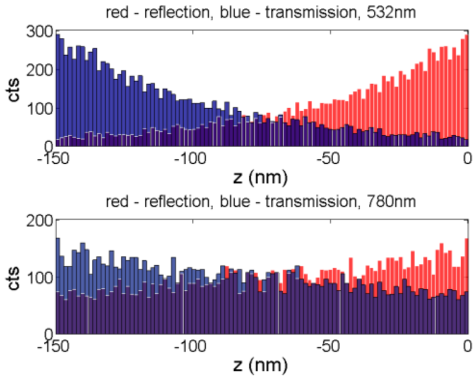
Increase the number of e-ph scattering

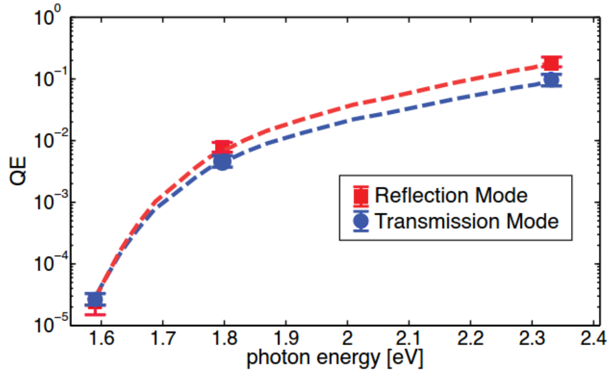
lower MTE (and intrinsic emittance)

Increase the average e- travel distance

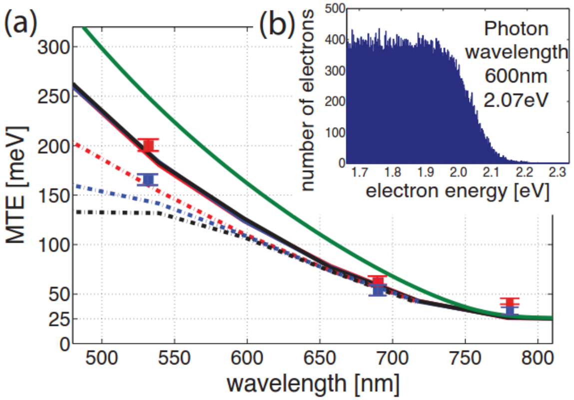
by operating them in transmission rather than reflection mode

$$P(z) \propto e^{\left(-\alpha(\lambda)/z\right)}$$



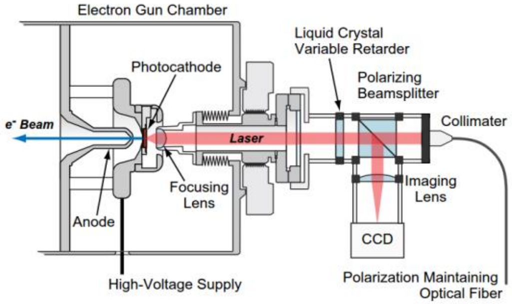


QE is 2 times smaller!!



MTE is 20% smaller !!

transmission mode configuration easily allows the realization of **very small laser spot** on the cathode surface



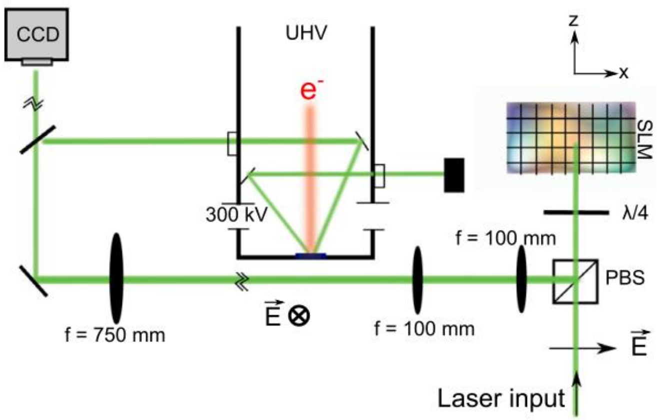
M. Kuwahara et al., *Appl. Phys. Lett.* **101**, 033102 (2012)

UED beam case

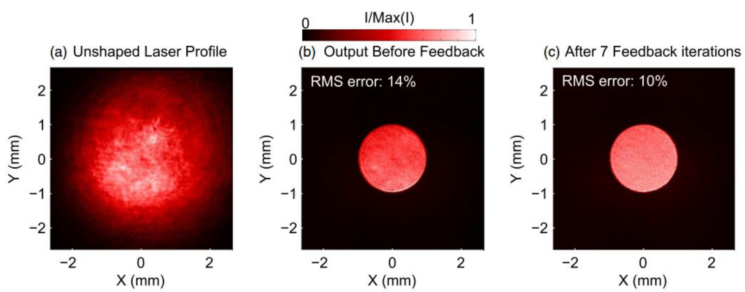
- 60 MV/m
- 10 ps laser
- **2 μm diameter**
- **2x10⁵ electrons**

$$\varepsilon_i = 10^{-4}\ mm\ mrad$$

How well can we shape the laser beam?

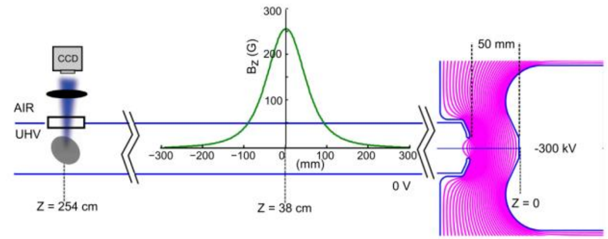


Liquid crystal array is used as mask to attenuate the transverse distribution of the laser "point to point" to match the desired laser profile

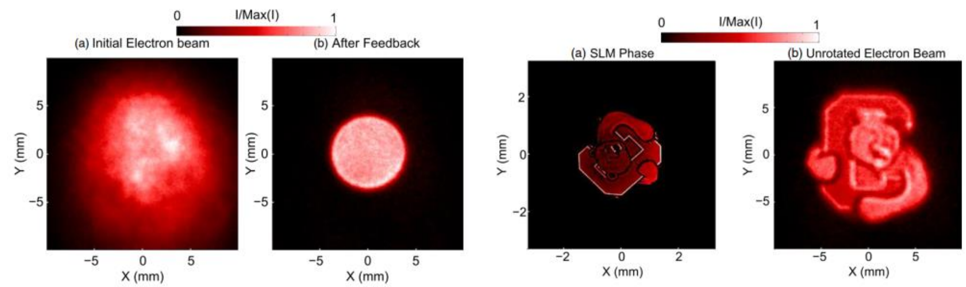


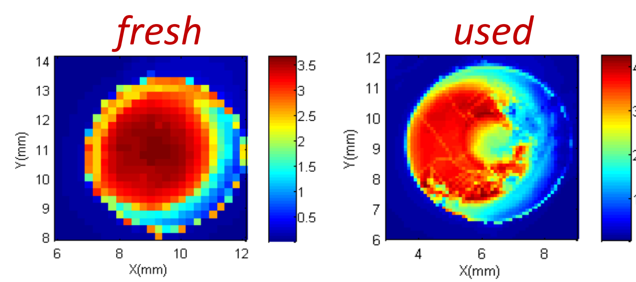
- **Easy to implement**
- **Fast feedback**
- **Above 30% efficiency (flat top)**

Damage threshold
2.6 W/cm² average power
101 MW/cm² peak power

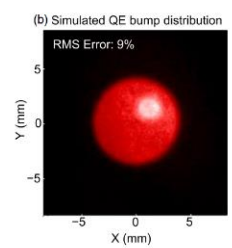


But we can also directly shape the e-beam!!

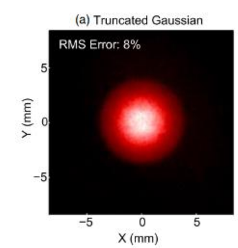




Real QE maps



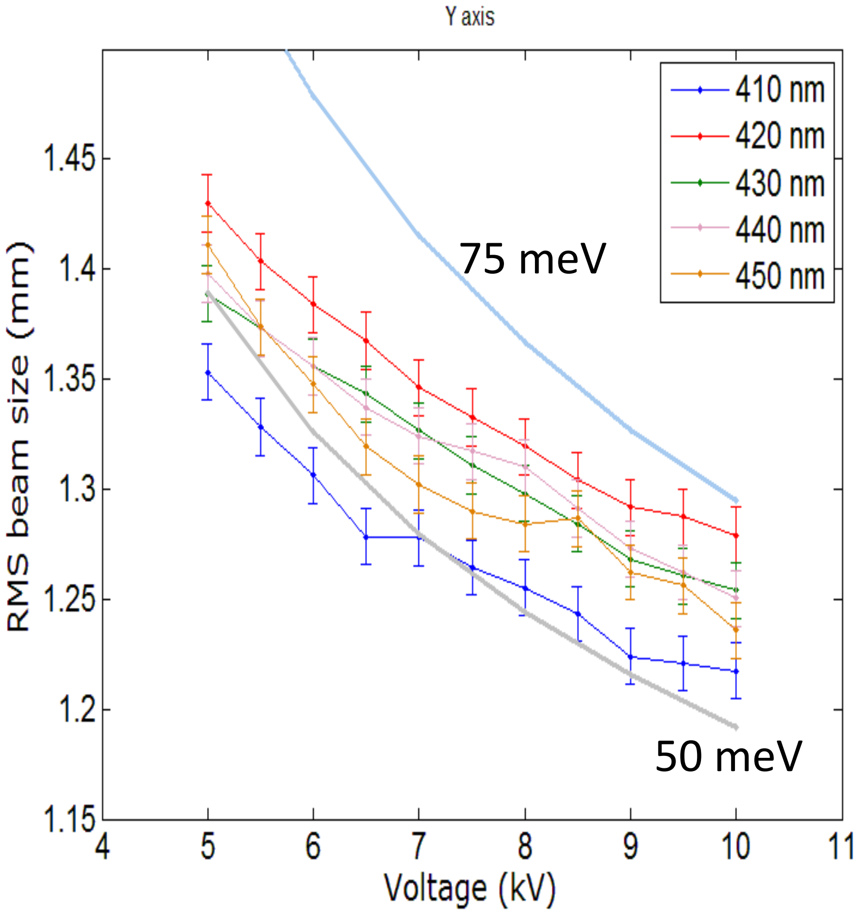
Shape the laser beam to compensate for QE using e-beam feedback



J. Maxson, A. Bartnik, I. Bazarov, Applied Physics Letters **105** (2014) 171109
J. Maxson, H. Lee, A. C. Bartnik, J. Kiefer, and I. Bazarov, Phys. Rev. ST Accel. Beams **18**, 023401 (2015)

La:BaSnO3

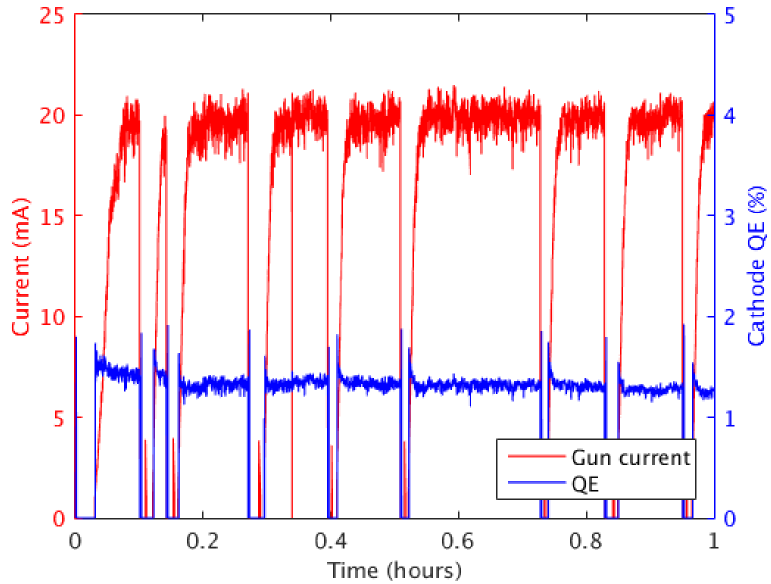
- Preliminary TE meter measurements with 410 nm-450 nm wavelength
- The voltage scans have been performed using a 200 um pinhole
- We plan to repeat the measurement on a second sample.

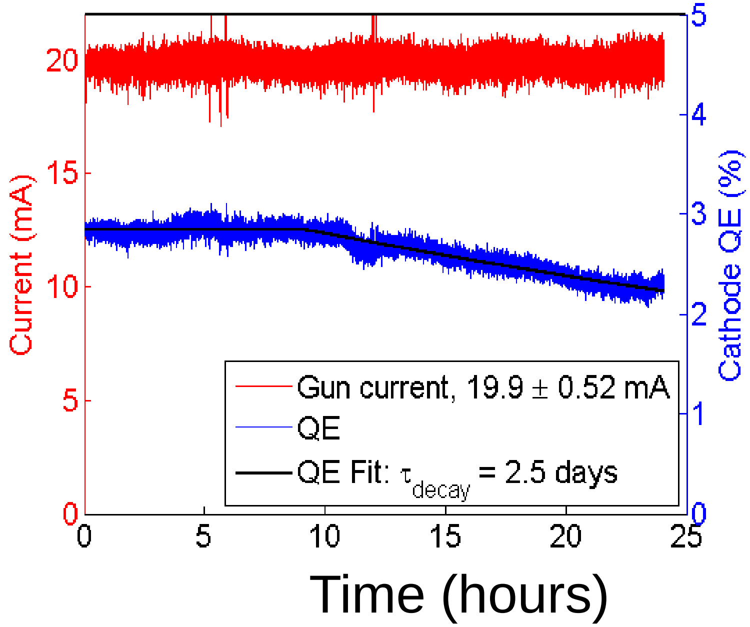


Gun Test Beamline

Surprise! The machine tripped **10x more often** with only the gun.

- Upon further inspection, an error was discovered in our previous reasoning– it was possibly always the gun.





With ion clearing electrode
24 hours at 20 mA with no trips!!