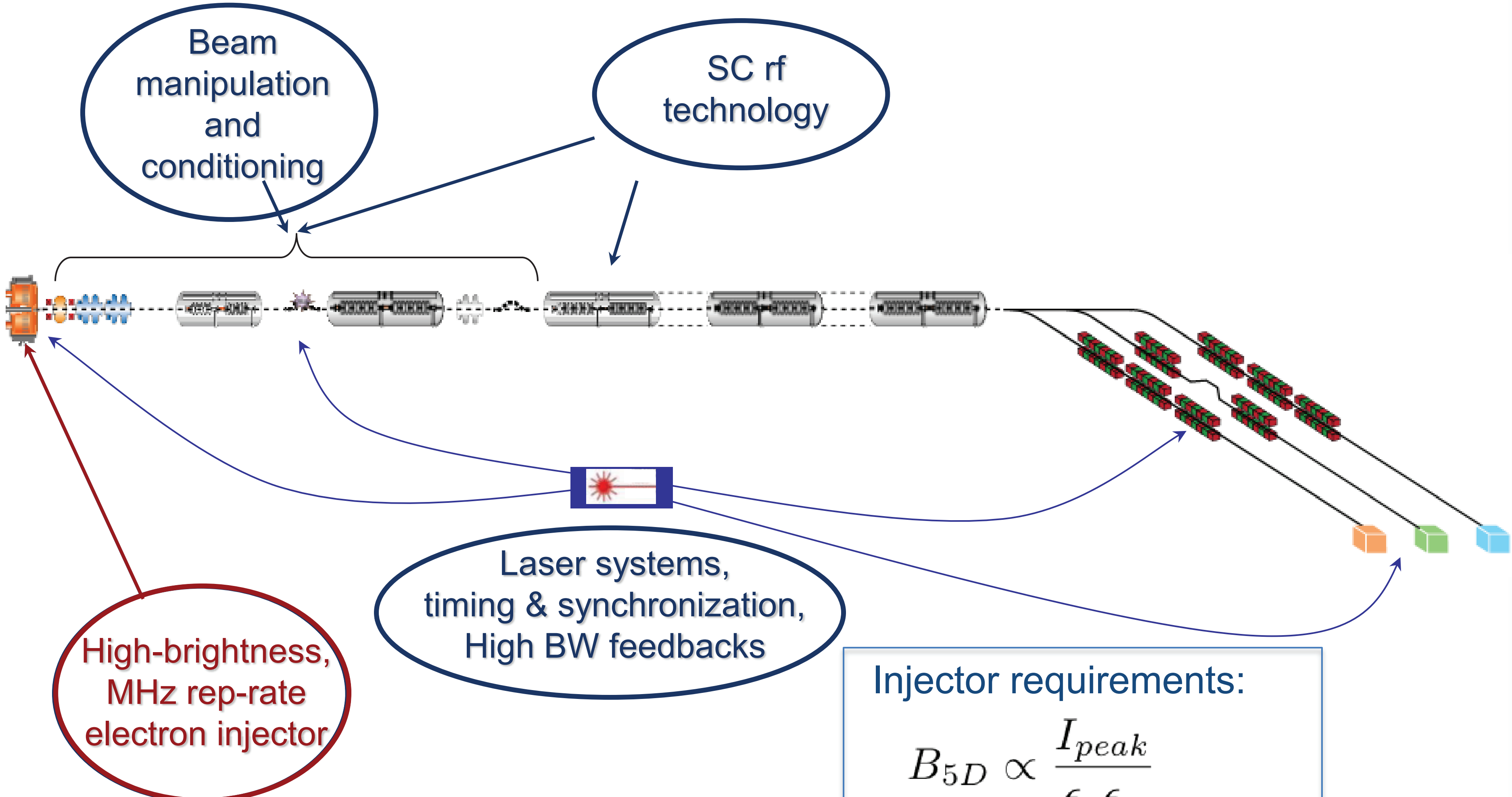
D. Filippetto, LBNL

APEX

A photo-injector for high average power light sources and beyond

Accelerators for High average power FELs

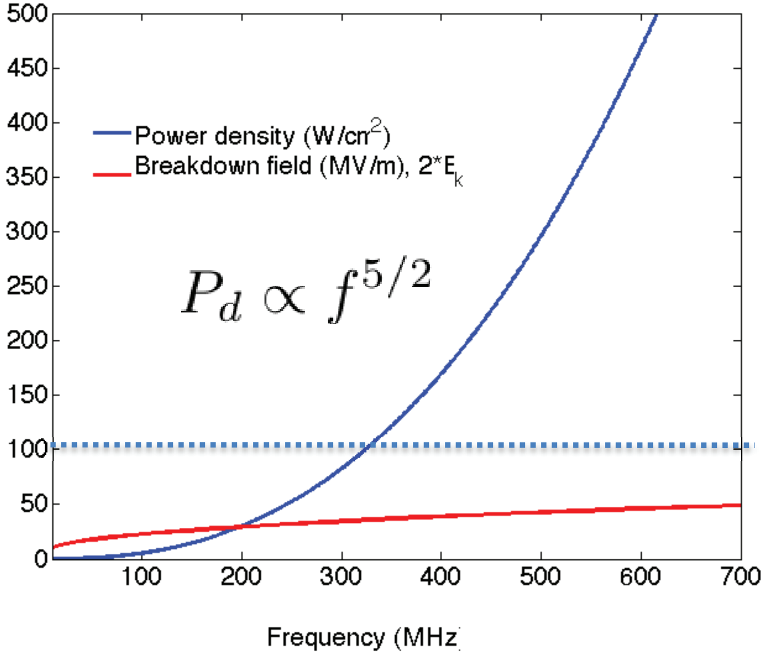


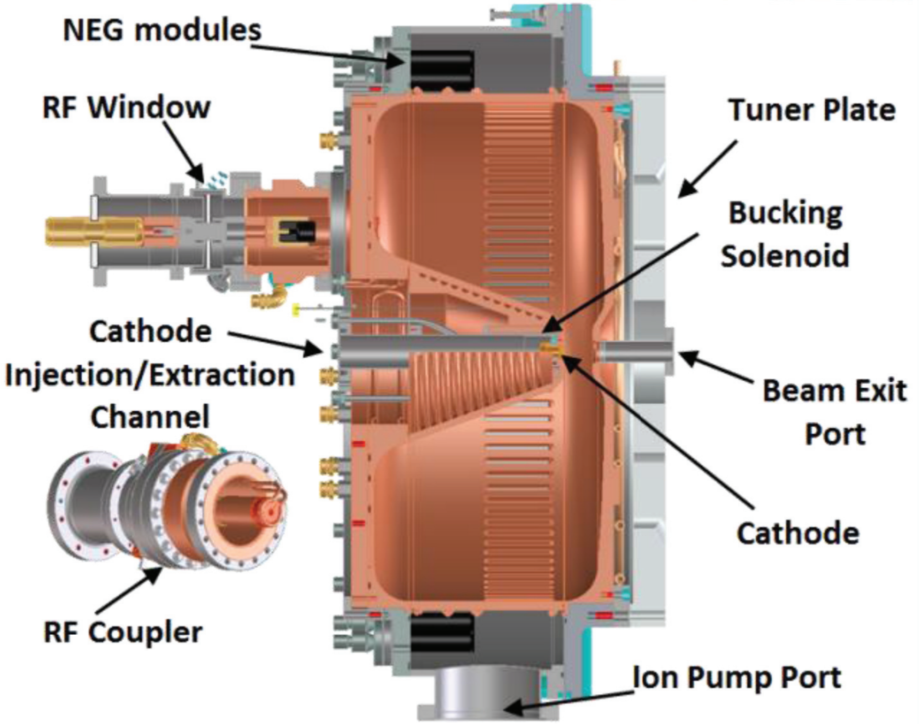
Injector requirements:

$$B_{5D} \propto \frac{I_{peak}}{\epsilon_x \epsilon_y}$$

$$B_{5D,av} \propto \frac{Q_{bunch} \cdot f_{rep}}{\epsilon_x \epsilon_y}$$

The LBNL VHF Gun





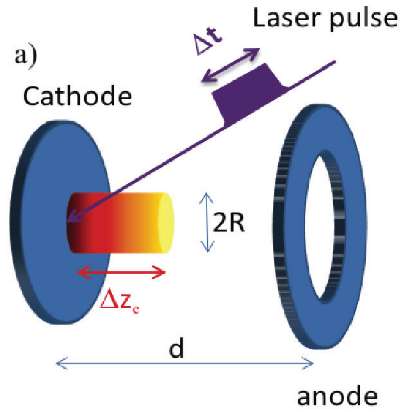
K. Baptiste, et al, NIM A 599, 9 (2009)

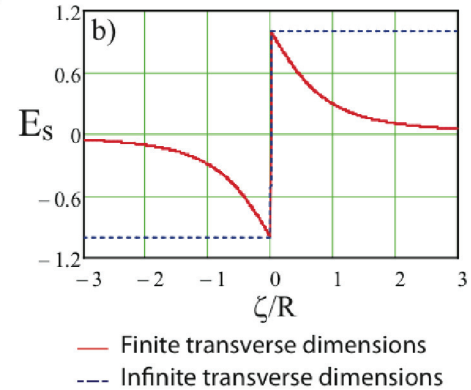
- Tolerable Dark current
- Technology readiness and reliability
- Overall system complexity (rf, compression)
- Space constraints

Frequency	186 MHz
Operation mode	CW
Gap voltage	Up to 800 keV
Field at the cathode	> 20 MV/m
Peak wall power density	25.0 W/cm^2
base pressure	~ 10^{-11} Torr

Cigar beams:

- The long λ_{rf} allows small aspect ratio R/L
- Only electrons at z<R contribute to $E_{cathode}$
- Increase extracted charge for a given emittance, at expenses of output current

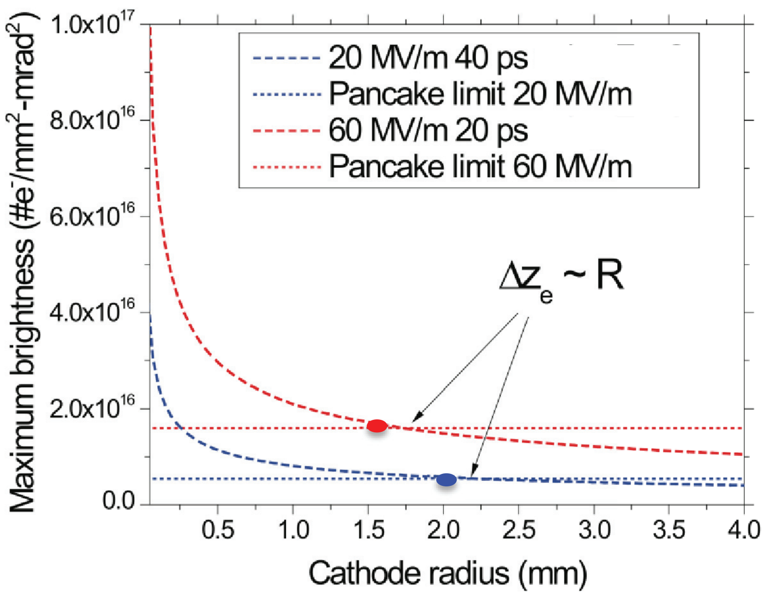




2D C-L law for cigar-shaped beams

$$I_{sat,2D} = I_0 \frac{\sqrt{2}}{9} \left(\frac{eE_0R}{mc^2} \right)^{\frac{3}{2}}$$

$$B_{\perp}^{max} \propto \frac{E_0^{3/2} \Delta t}{\sqrt{R} \sigma_{p_\perp}^2}$$

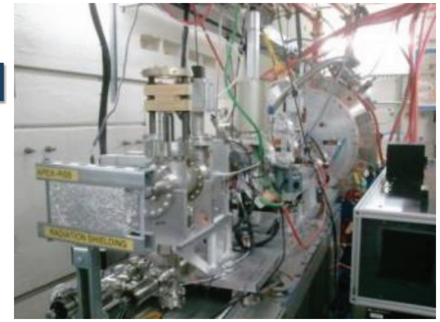


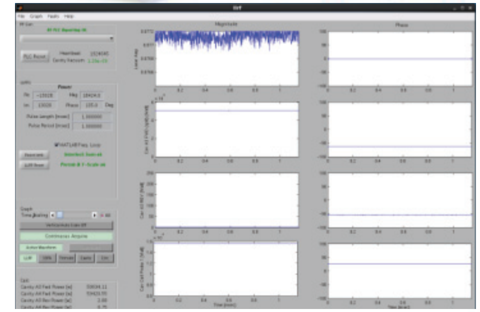
D. Filippetto et al., Phys. Rev. ST Accel. Beams 17, 024201 (2014).

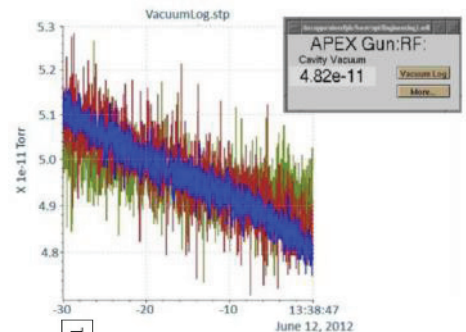
VHF Gun performances (Phase-0)

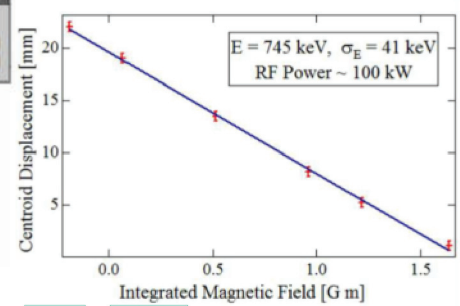
- Gun and Phase 0 beamline installed
- Gun reliably and routinely operated in CW at the nominal RF power.
- Required vacuum performance demonstrated.
- 1 MHz laser system commissioned. Transfer line pulse shaping done.
- First photo-emitted electron beam with low QE cathode generated.
- Photo-emitted electron beam nominal+ energy demonstrated.

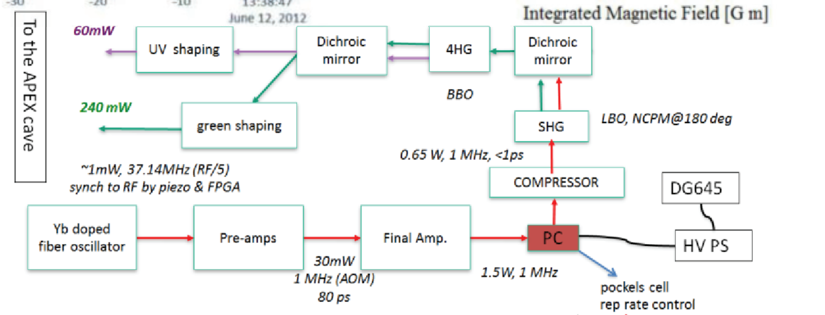
Gun technology demonstrated!

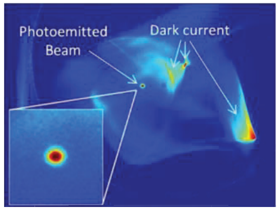


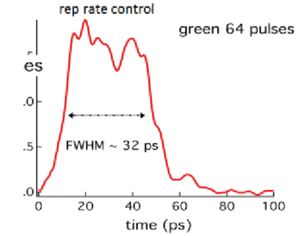










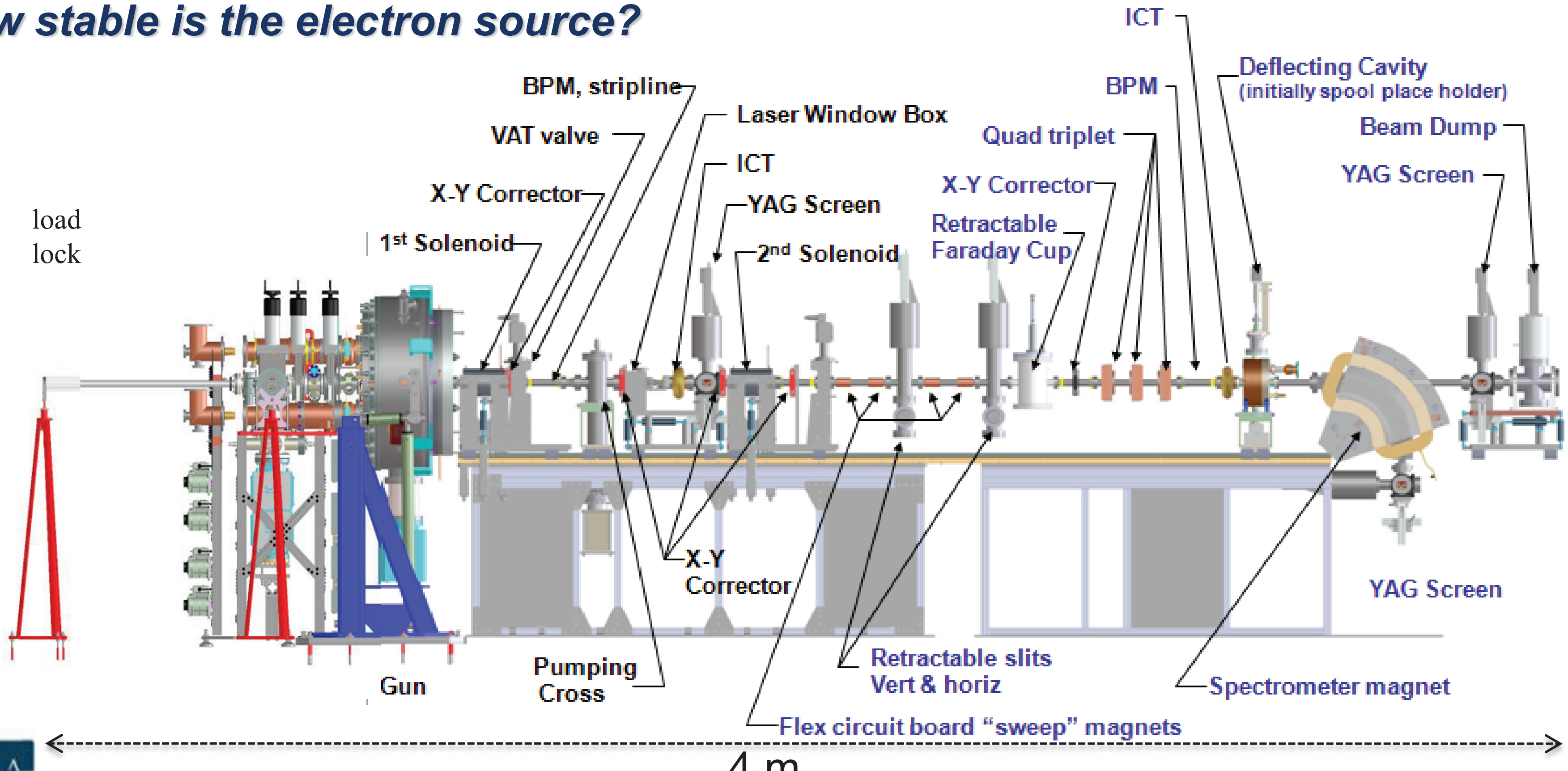


F. Sannibale, *et al.*, PRST-AB 15, 103501 (2012)

The APEX Phase I:

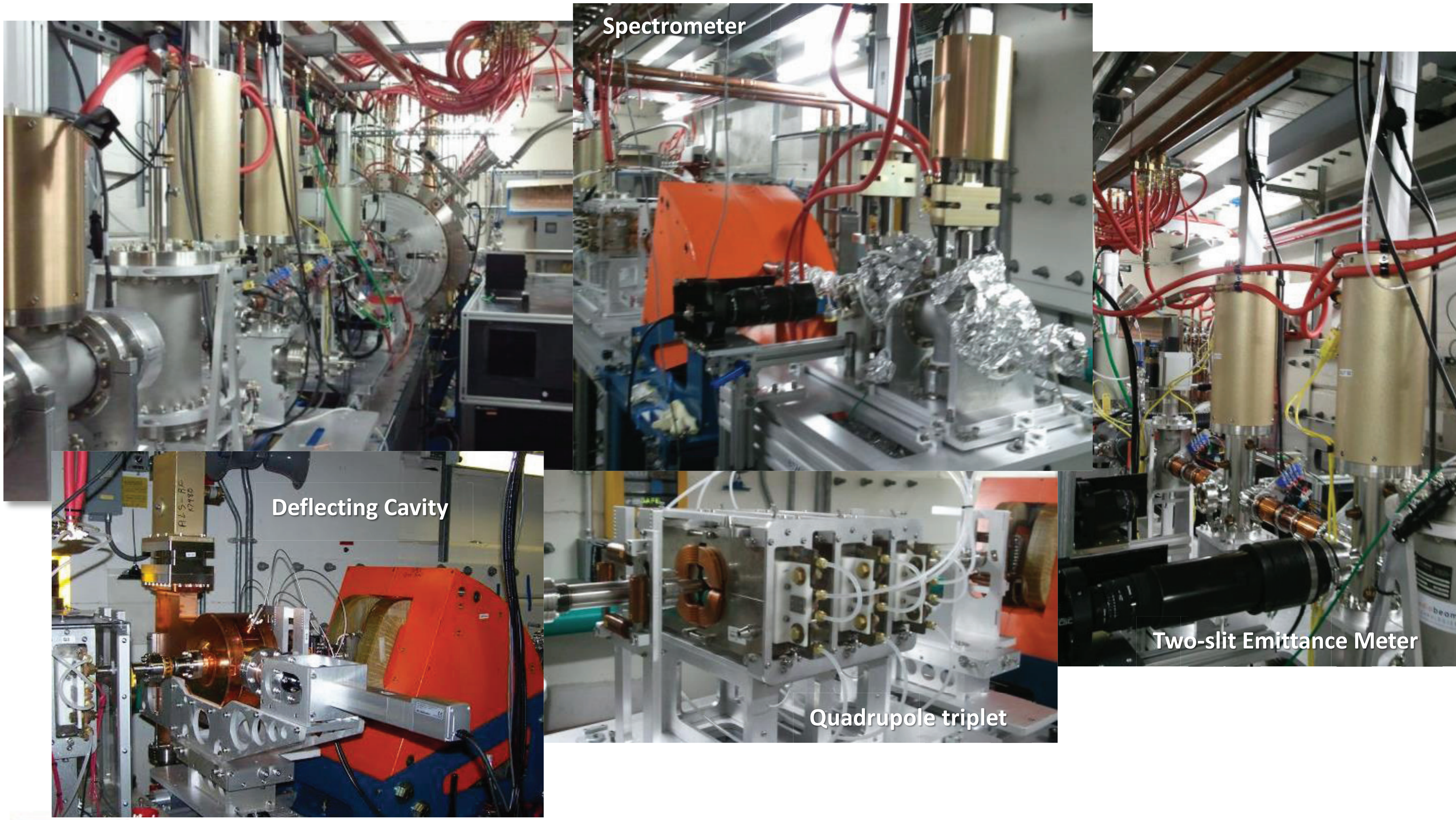
VFAQ (Very Frequently Asked Questions):

- How much is the dark current? What/Where are the sources
- What can we do for mitigating DC?
- Will the DC limit the max gradient and/or cathode lifetime?
- How long is the Cathode lifetime in a CW rf gun?
- How stable is the electron source?

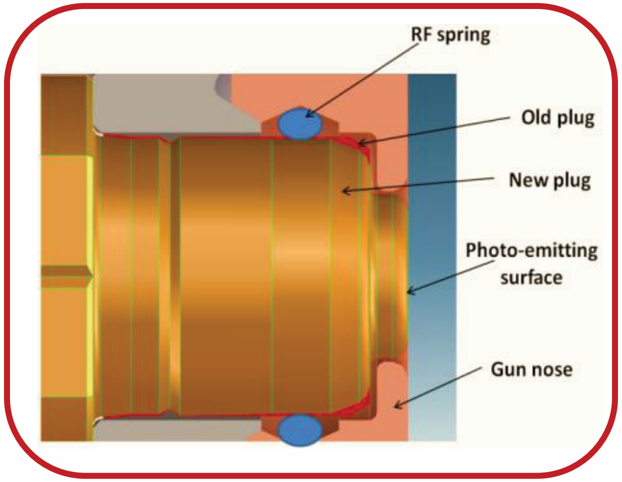


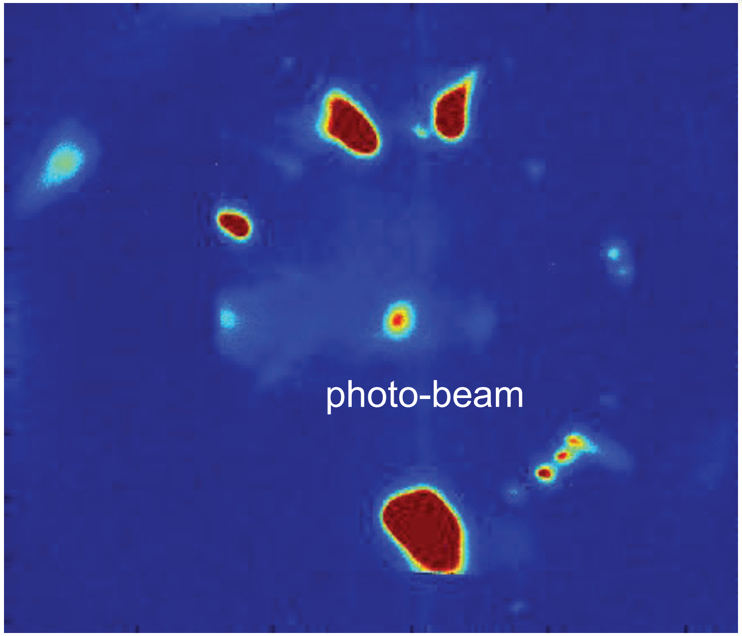
PHASE I installed

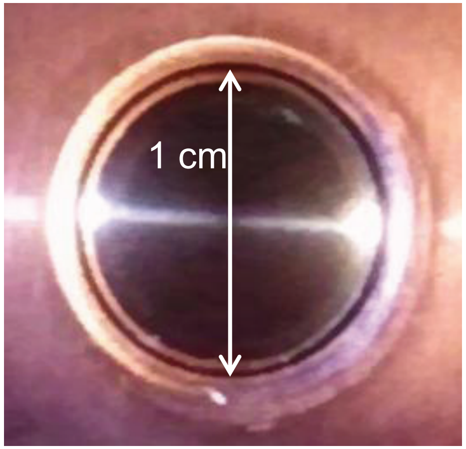
- **All Phase I beamline installed and now under commissioning.**

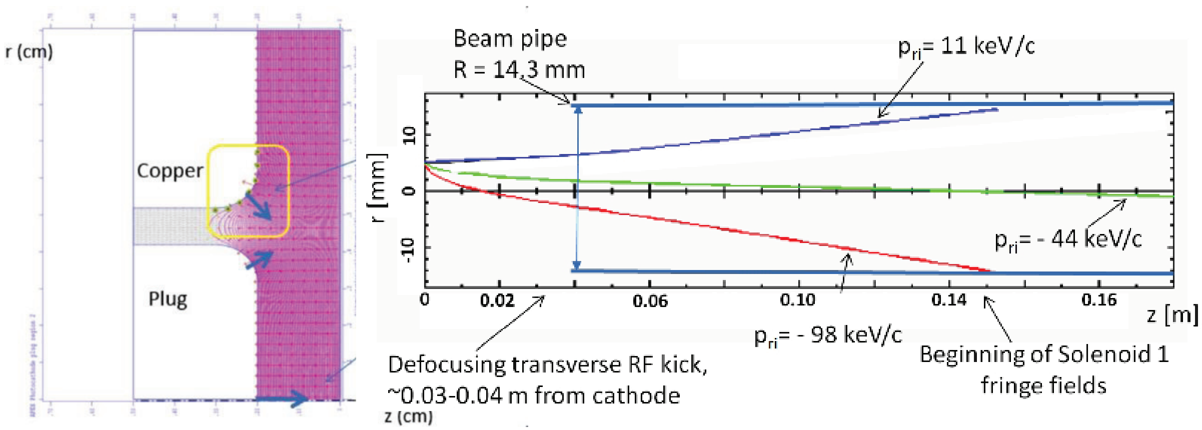


Sources of dark current





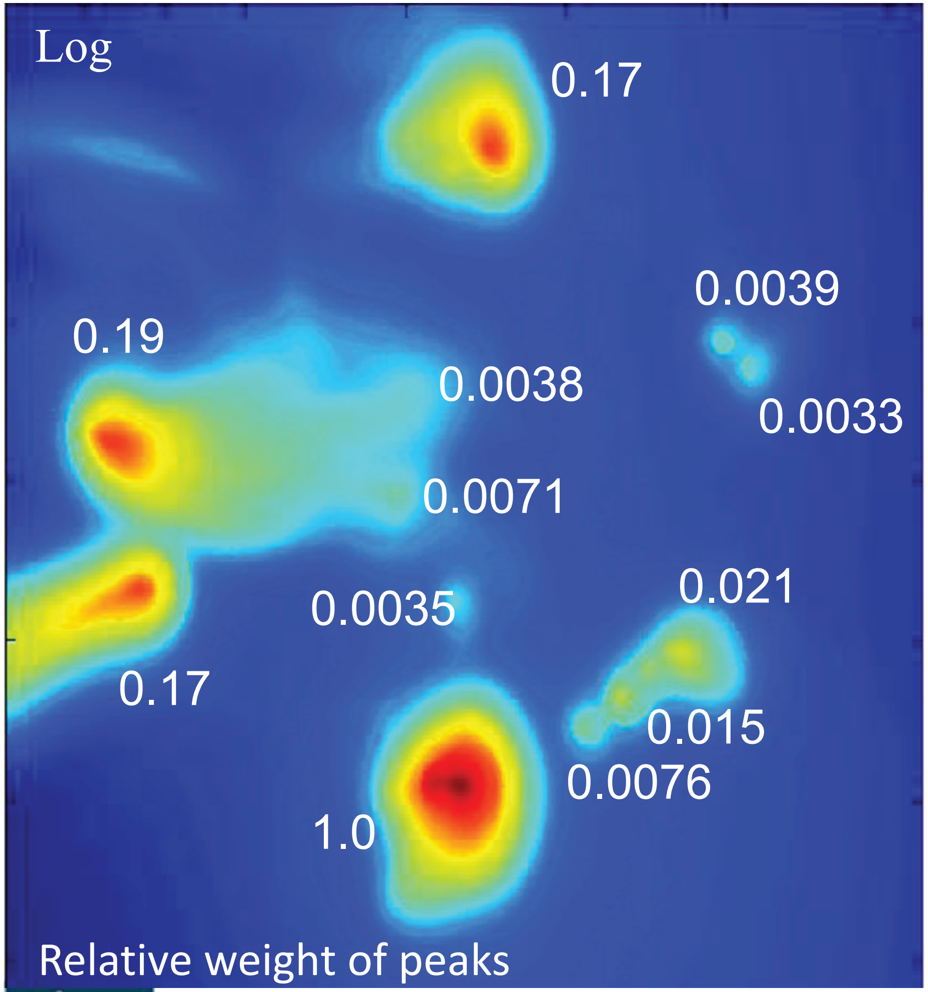


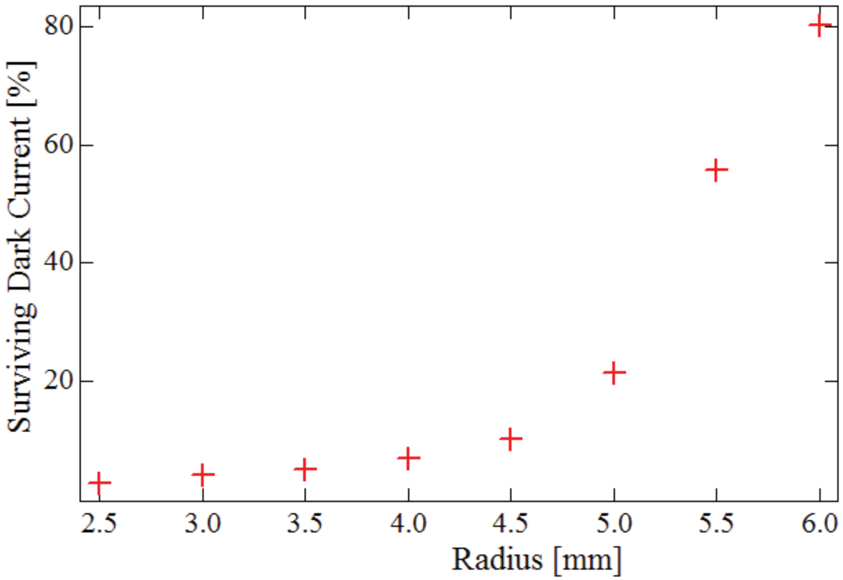


$$\alpha k r \approx 50\ mrad = 35 keV$$

DC imaging

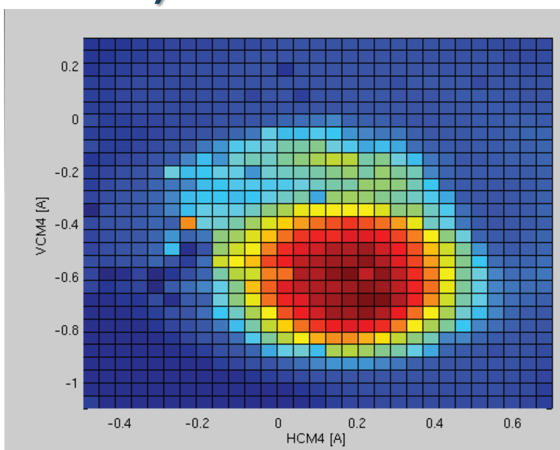
Sum of 12 images with different integration times, 10^5 dynamic range

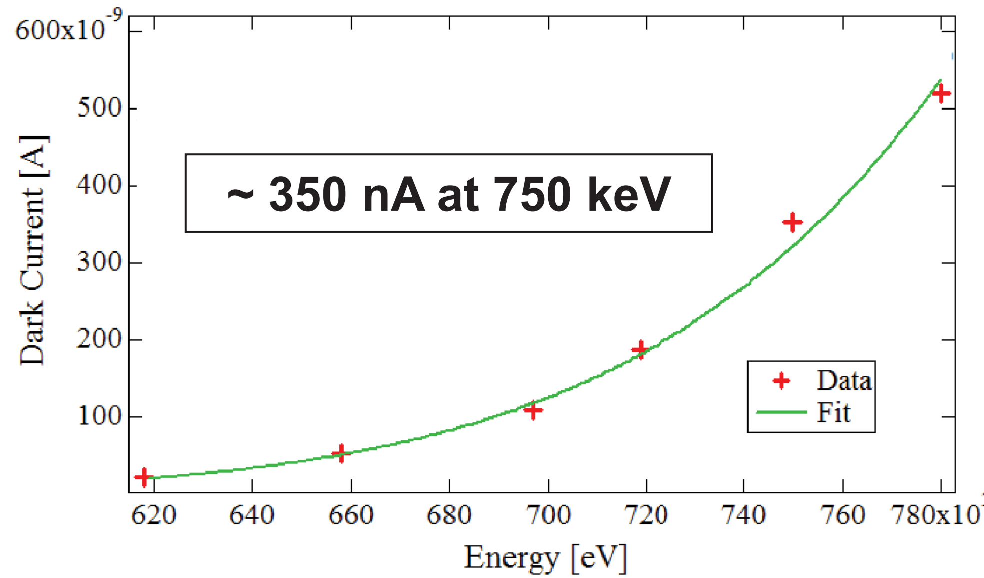


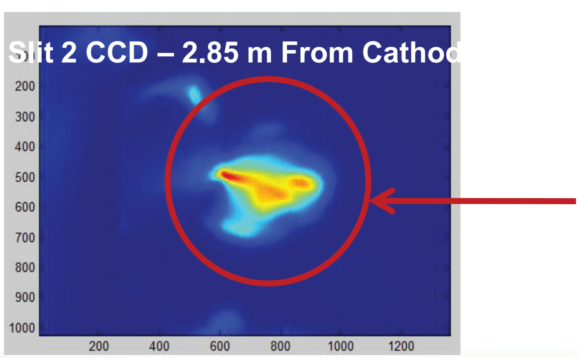


Dark Current scans

- Dark Current measurements performed in various solenoid configurations.
- Up to 2.5 uA transported in "cathode imaging configuration"
- Dark Current scans for solenoids optimized for injection at 100 pC
- (Solenoids scaled with energy. Solenoids for 20 pC and 300 pC are very similar)
- More than 97% of DC was in the center (DC map scanning Hor and Vert correctors)







Faraday Cup Diameter (1.5 cm)

Fowler-Nordheim fits

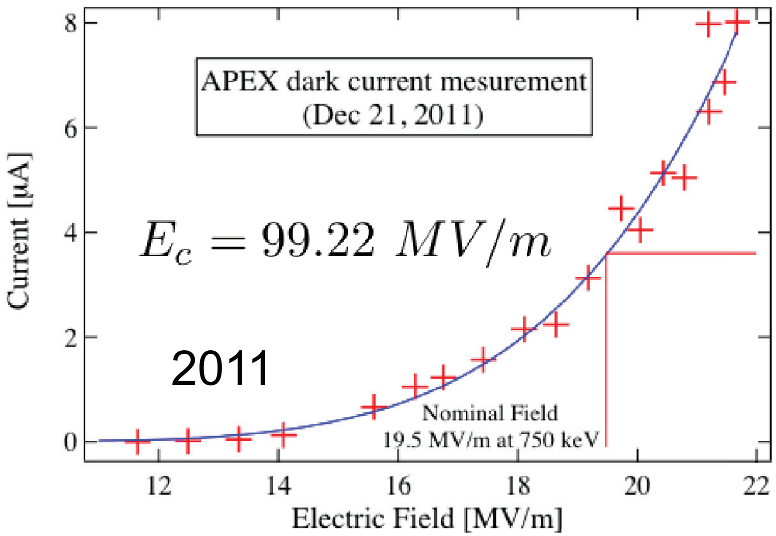
Field emission is generated by surface protrusions (high β) and/or inclusions and particulates (low Φ)

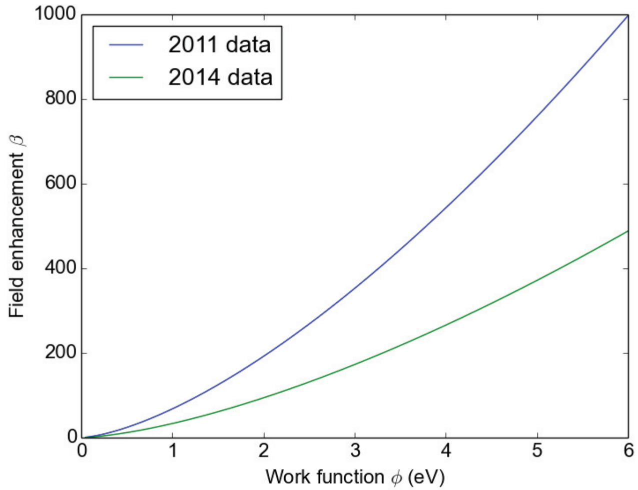
$$I_{FN} = I_c \frac{E^2}{E_c^2} \exp\left(-\frac{E_c}{E}\right)$$

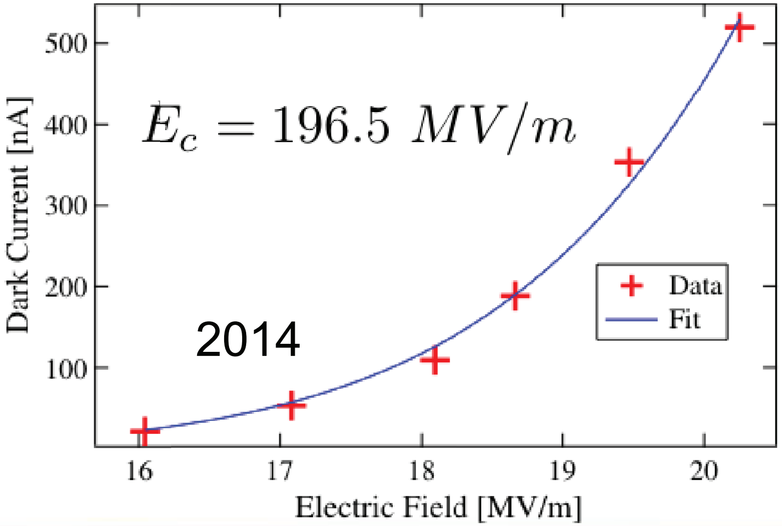
$$\bar{I}_{FN} = \frac{1}{\sqrt{2\pi}} I_c \left(\frac{E_0}{E_c}\right)^{2.5} \exp\left(-\frac{E_c}{E_0}\right)$$

$$E_c = 6.53 \times 10^9 \frac{\phi^{1.5}}{\beta}$$

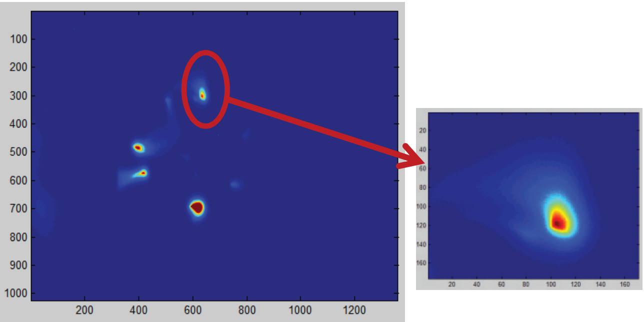
$$I_c = 65.67 \times 10^{-6} \times 10^{4.52/\sqrt{\phi}} \times A_e[nm^2] \times \phi^2$$

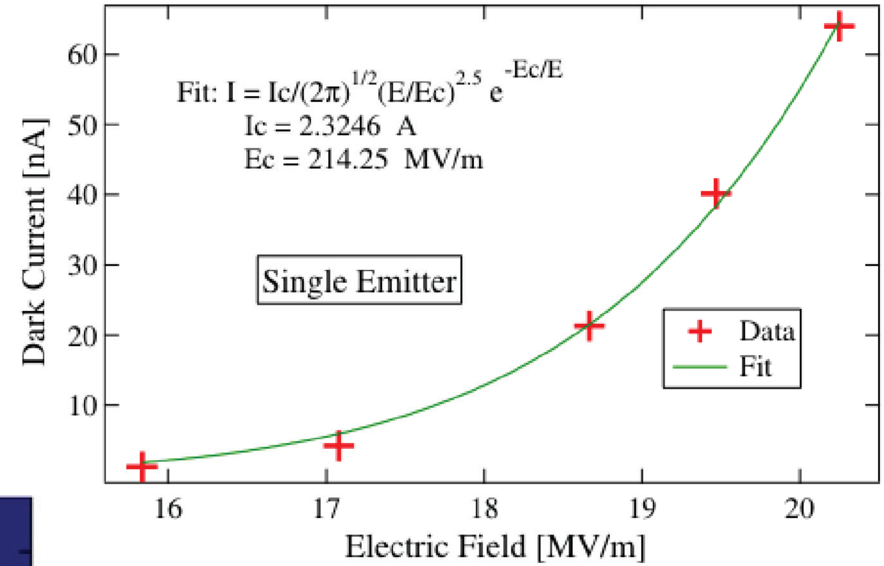


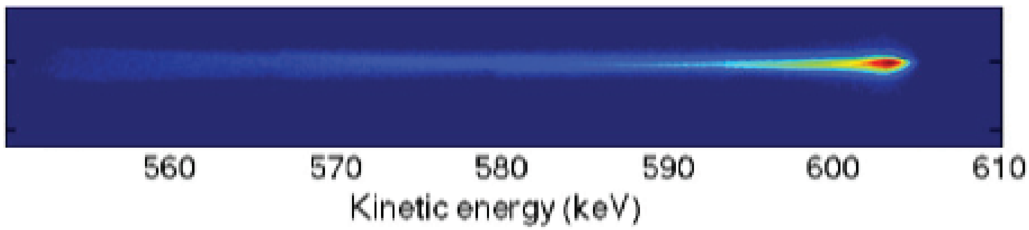


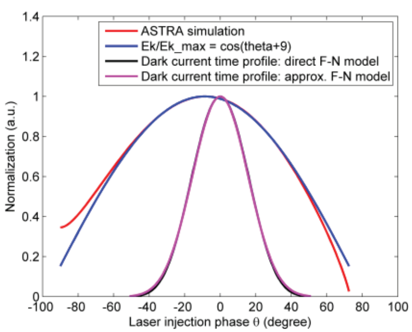


Single emitter fit and energy distribution



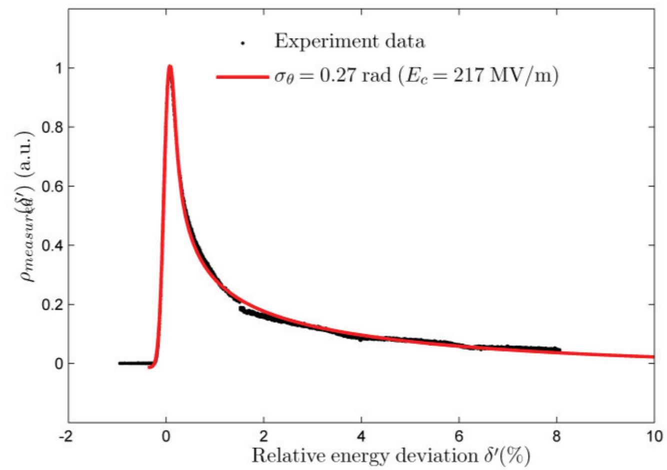






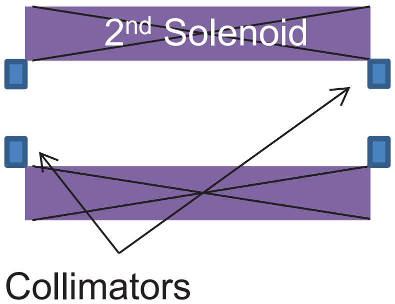
$$\rho(\delta) \propto \frac{1-(\sqrt{2\delta}-\theta_0)^2}{\sqrt{2\delta}} \exp\left(-\frac{(\sqrt{2\delta}-\theta_0)^2}{2\sigma_\theta^2}\right) + \frac{1-(\sqrt{2\delta}+\theta_0)^2}{\sqrt{2\delta}} \exp\left(-\frac{(\sqrt{2\delta}+\theta_0)^2}{2\sigma_\theta^2}\right)$$

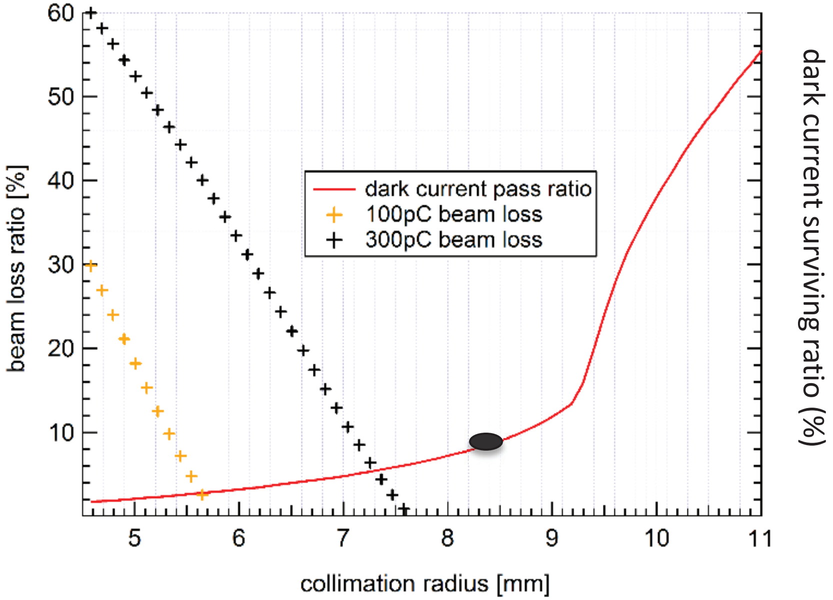
$$\rho_{measured}(\delta') \propto \int_0^\infty \rho(\delta)\, e^{-\frac{(\delta'-\delta)^2}{2\delta_\varepsilon^2}}\, d\delta + \rho_{floor}$$



Dark Current reduction

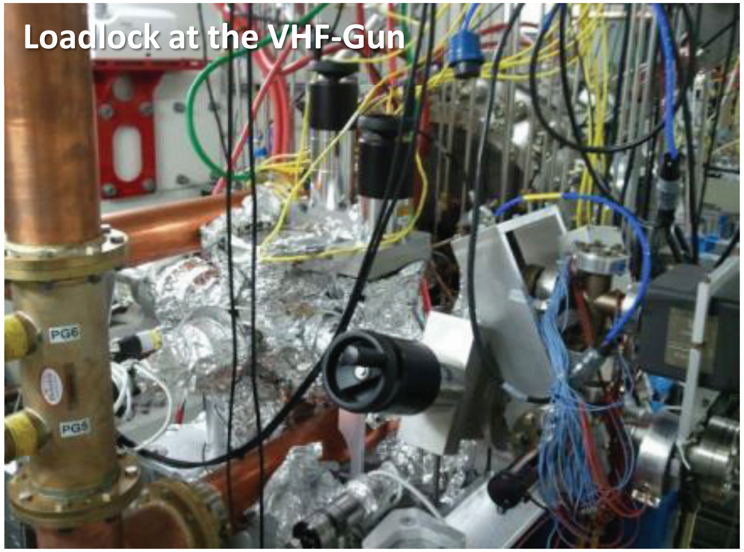
- **A simple scheme that works for both low and high charge: collimators at the 2nd solenoid**
- **Effective scheme: no beam loss and more than a factor 10 dark current reduction.**





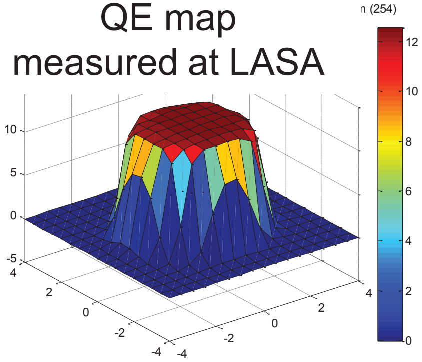
- **Active dark current kicker option has been studied (stringent requirements on field flatness)**
- **Cavity surface treatment for DC emission decrease (Dry-Ice).**

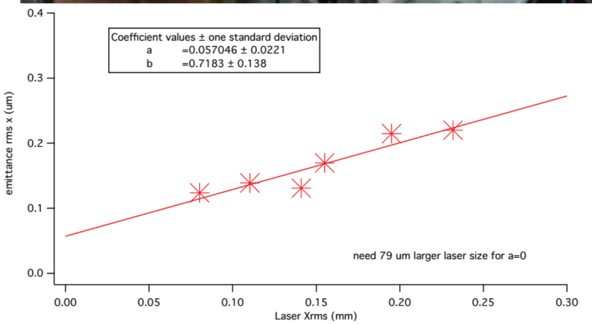
Cathode physics: Cs_2Te

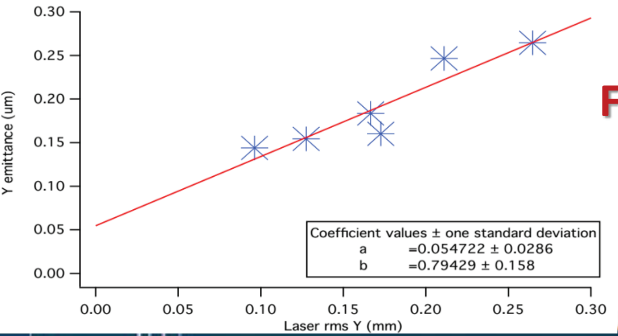


(deposited at INFN-LASA, 2011)

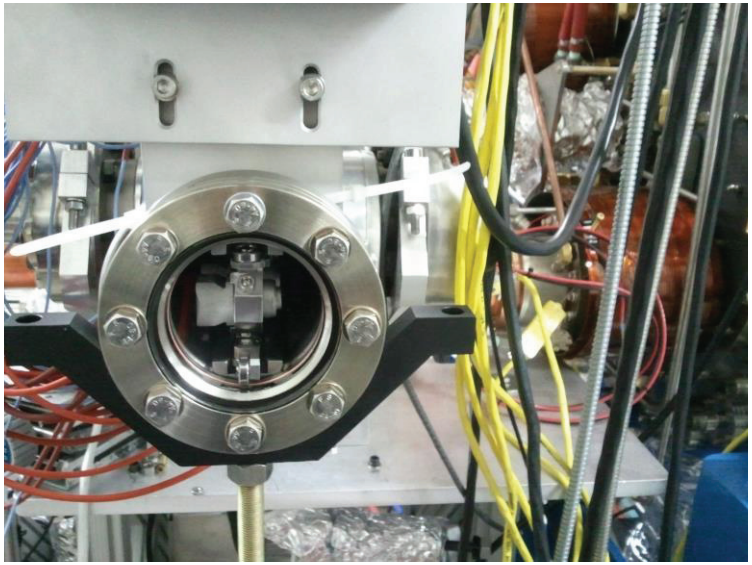
QE map
measured at LASA





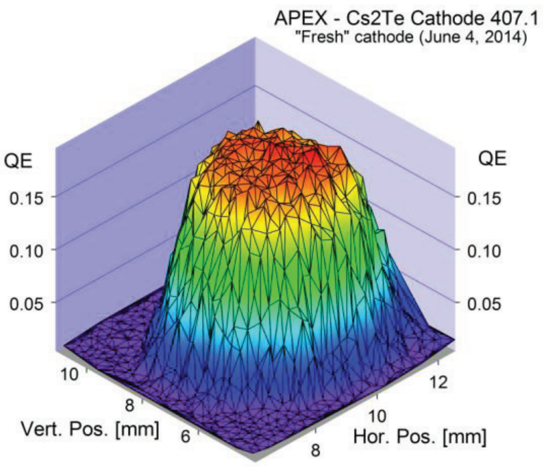


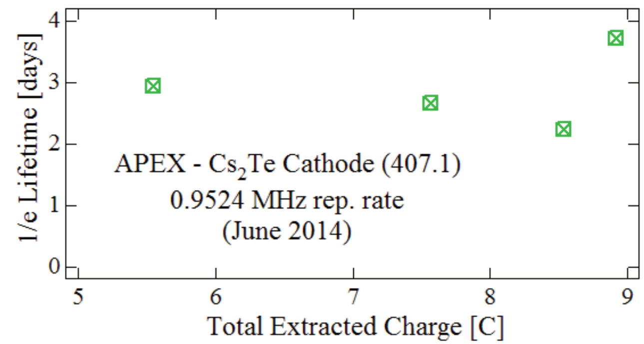
First thermal emittance data:
0.76 μm/mm rms

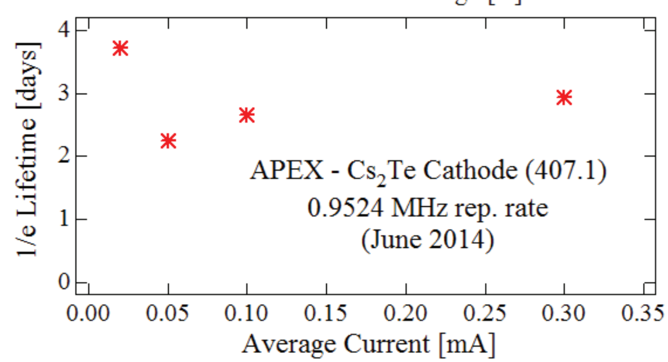


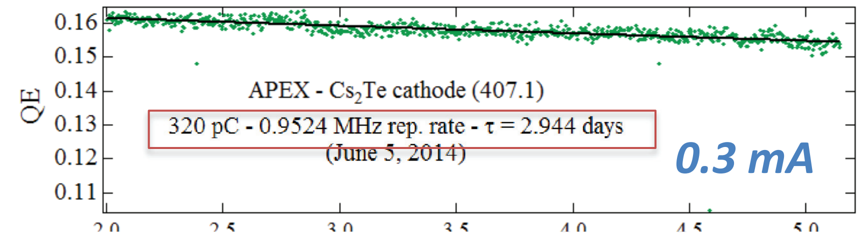
Cs_2Te Fresh Cathode QE Measurements

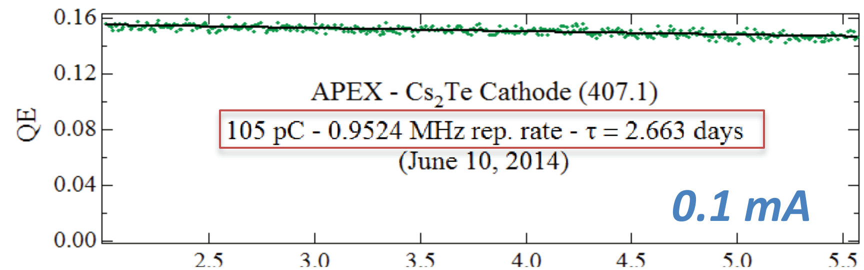
@ Berkeley Lab

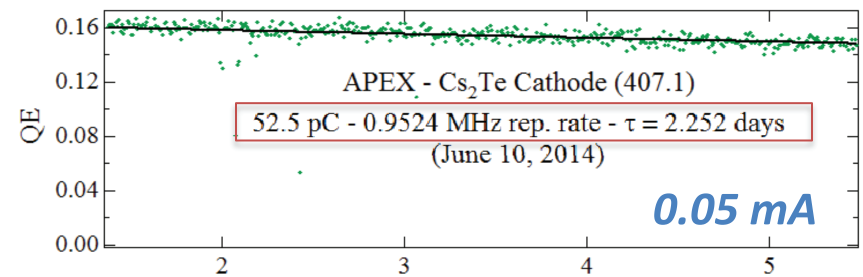


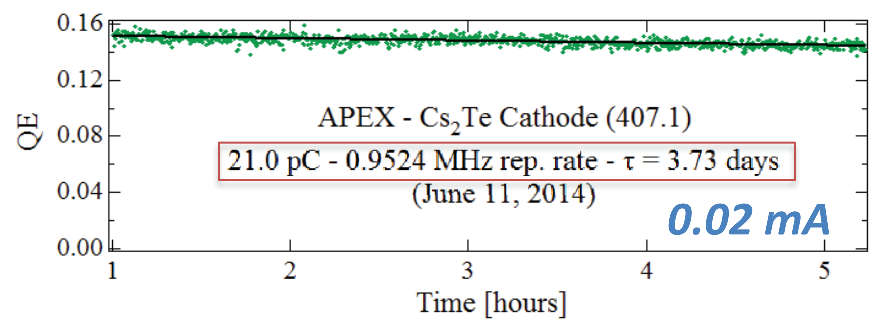




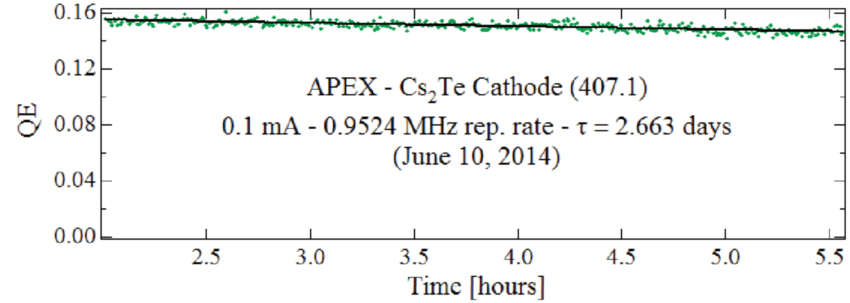


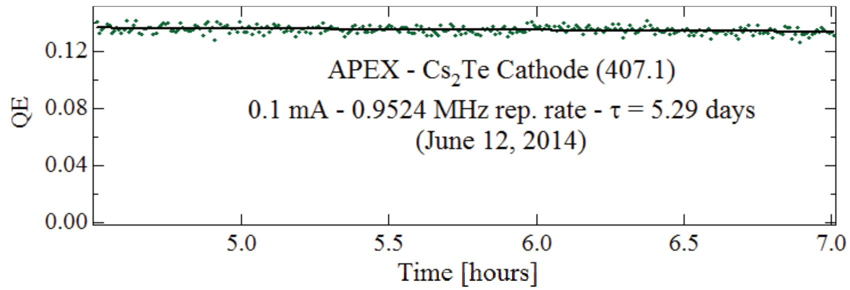


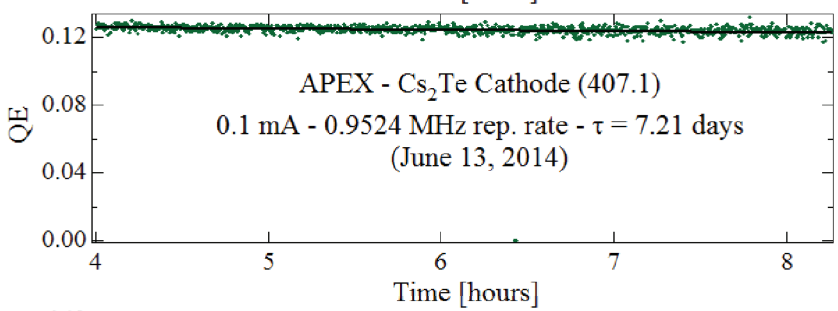


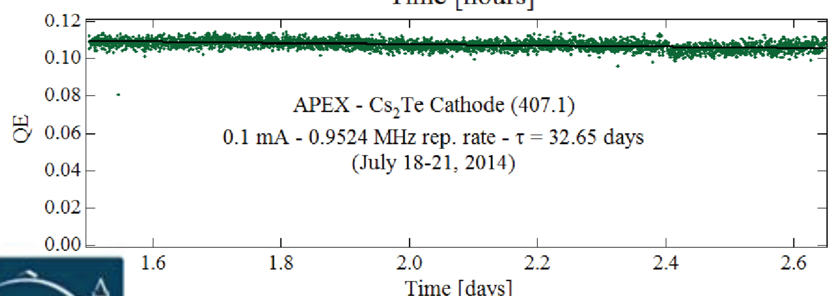


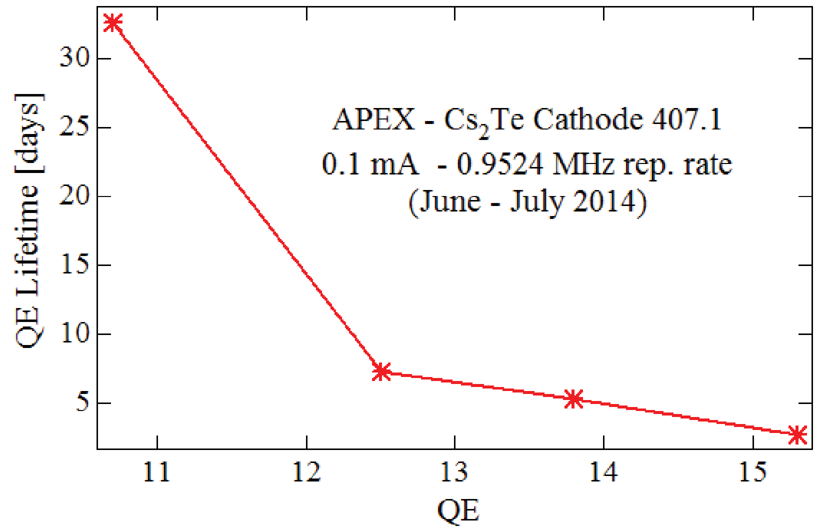
Cs_2Te Lifetime vs. QE





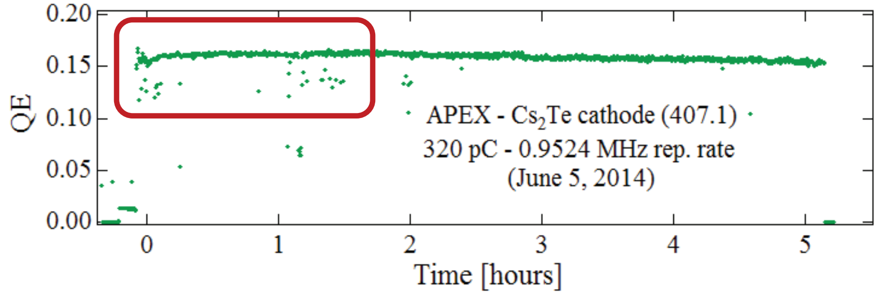


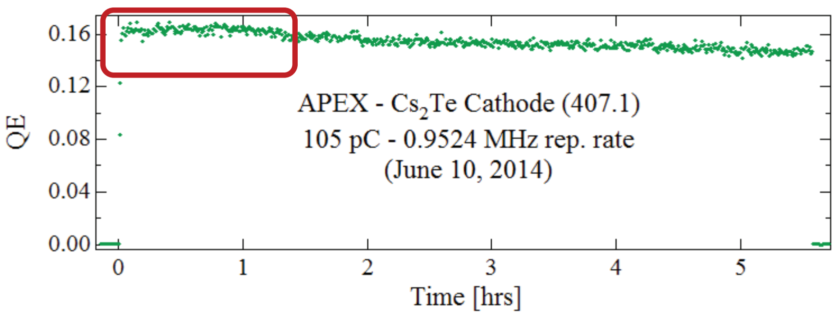


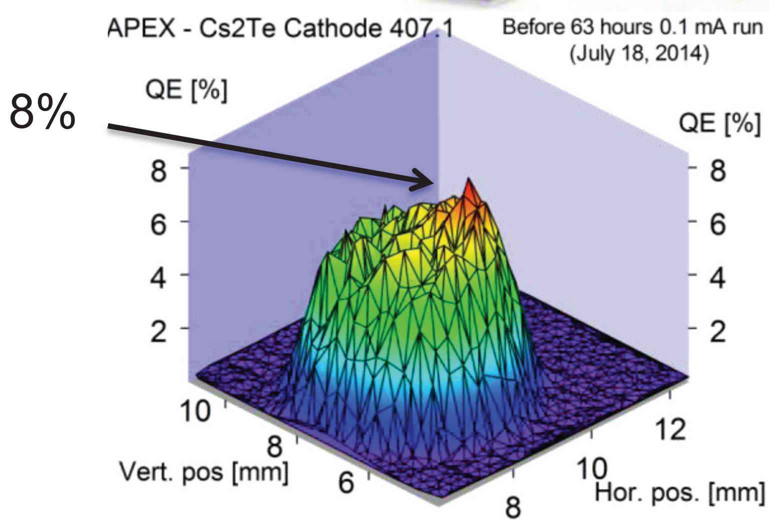


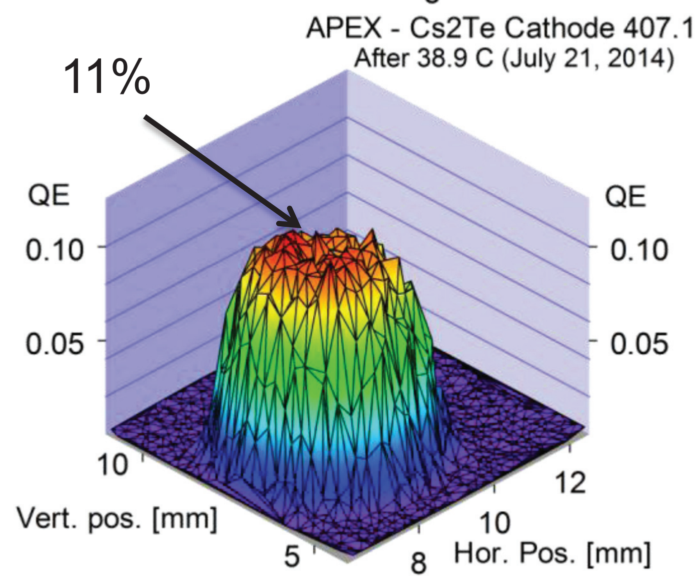
- **Cathode lifetime depends on the absolute value of QE.**

Cathode rejuvenation









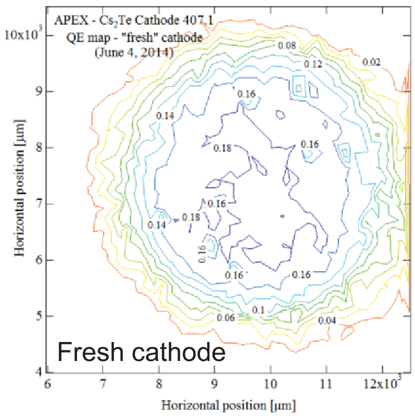
- Laser cleaning of molecules with weak bonds
- Rejuvenation with Temperature (RF heating)

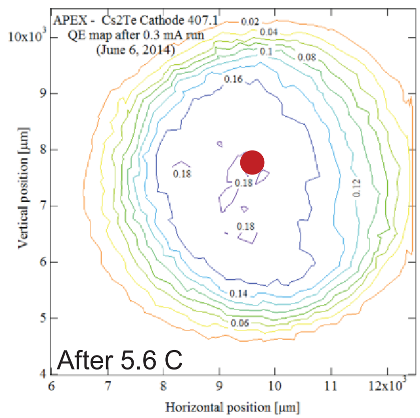
(See for example H. Kong et al., Nucl. Instr. and Meth. A **358, 276 (1995)).**

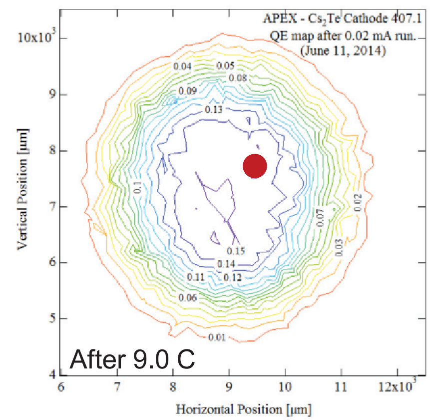
- After 38.9 C the QE degraded from ~16% vs. ~11%

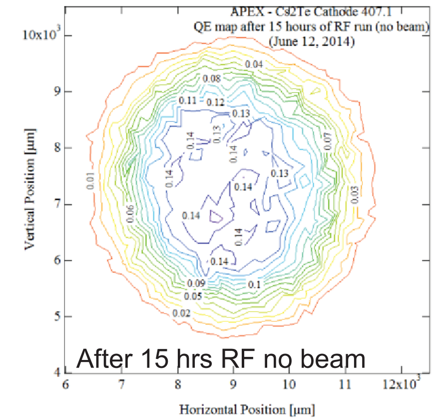
Cs_2Te 407.1 QE Maps

1 sigma laser beam Size and position

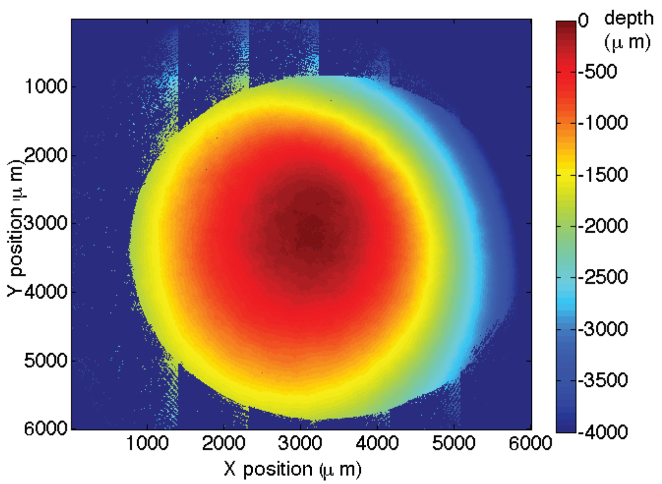


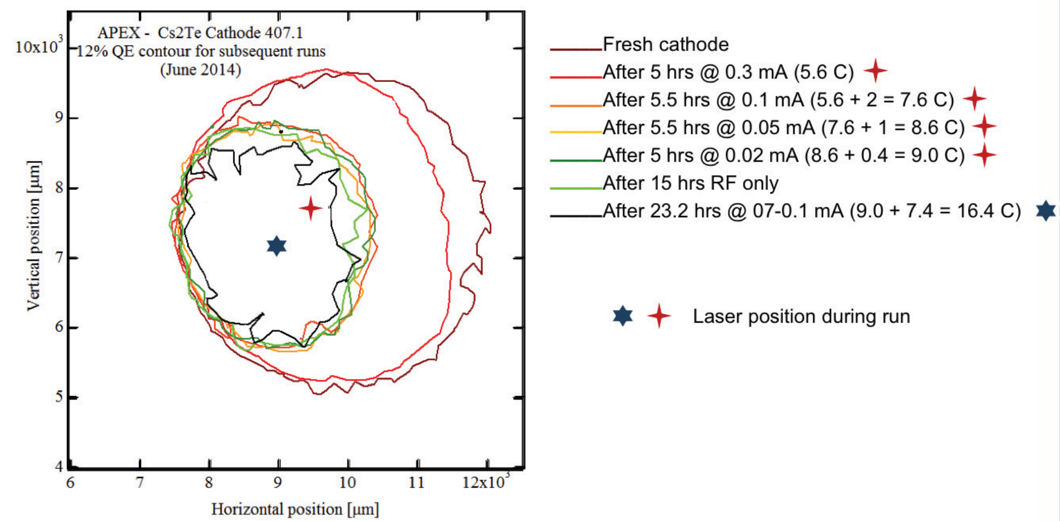






Post-mortem interferometry on cathode surface





APEX Synchronization Plan

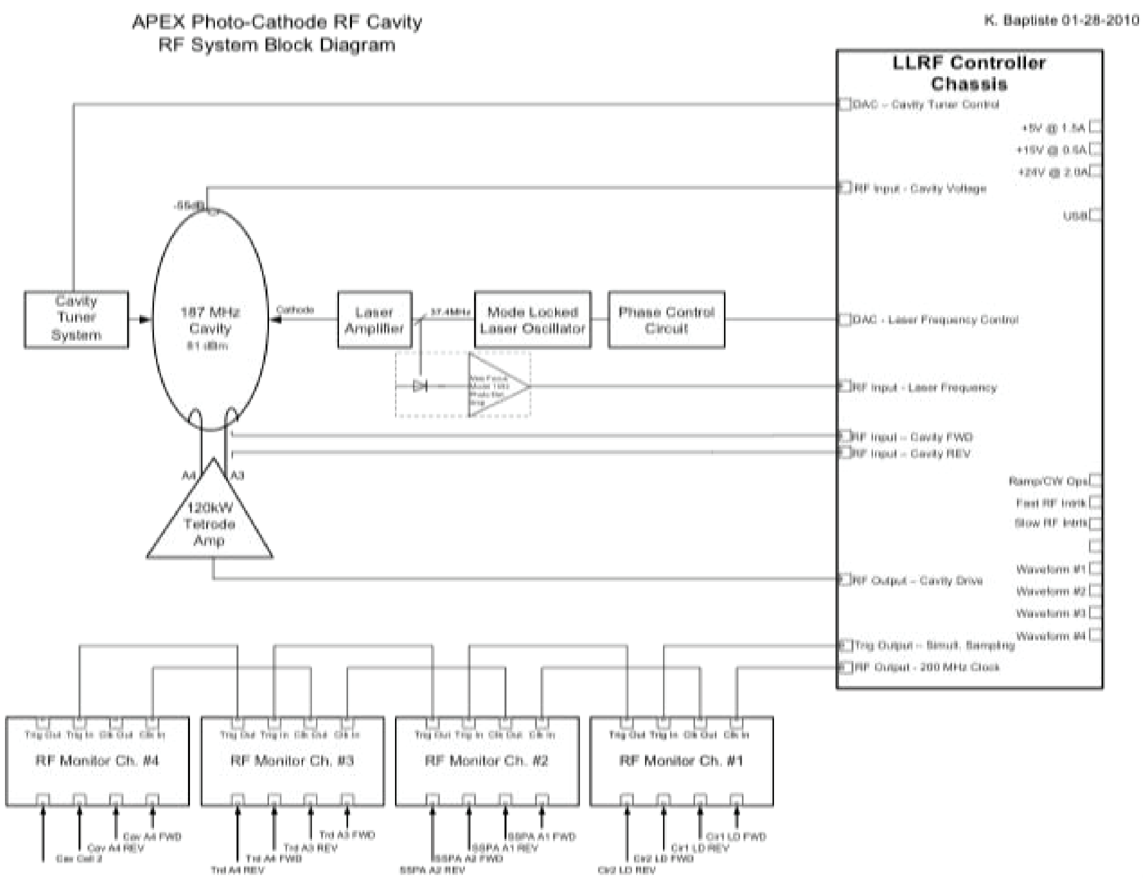
Target:

Laser-to-rf time jitter < 100 fs

Rf amplitude fluctuations < 10^{-4}

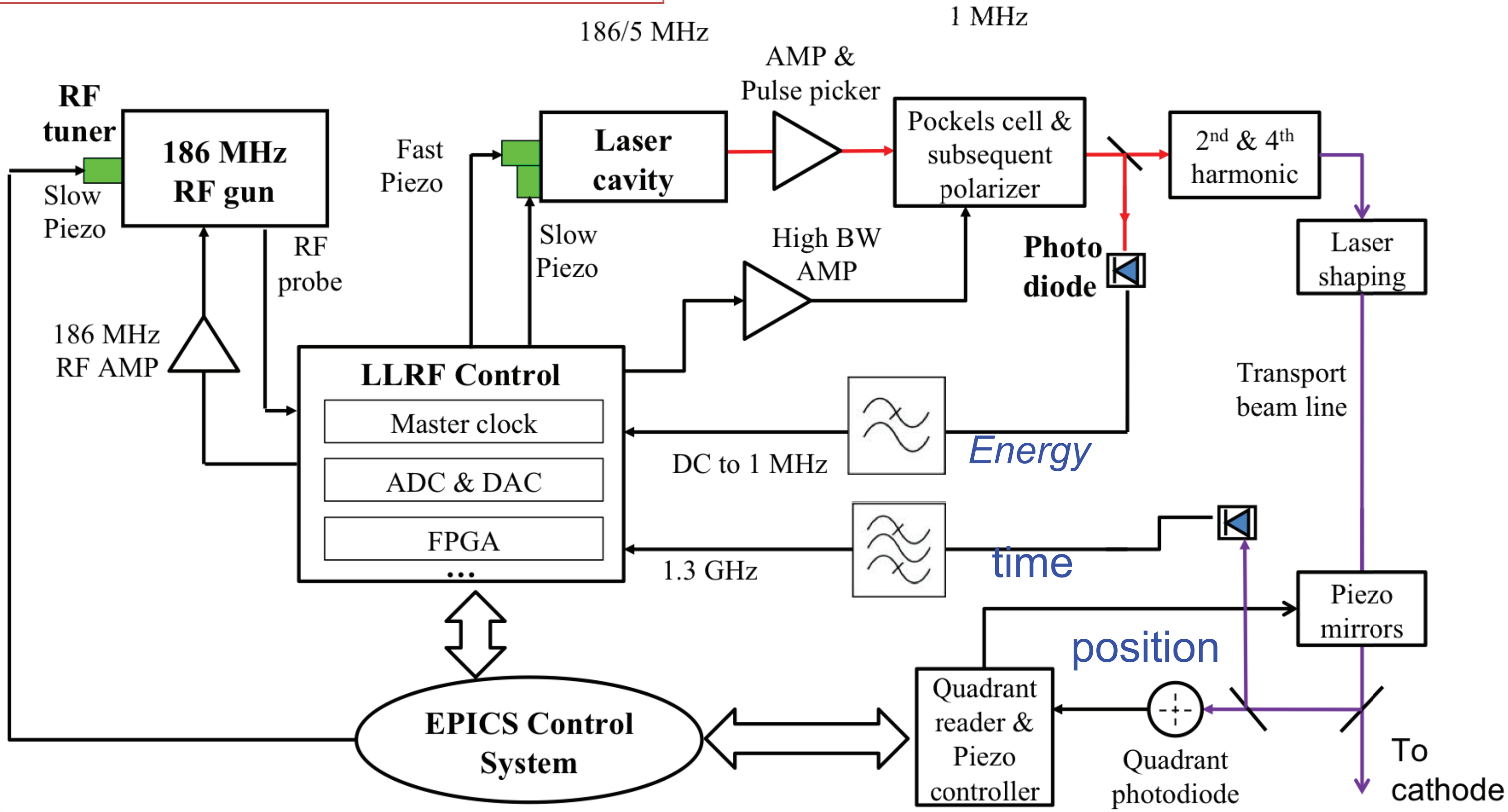
Beam pointing at the cathode < 10 μm

Charge fluctuations < 0.5%



APEX Synchronization Plan

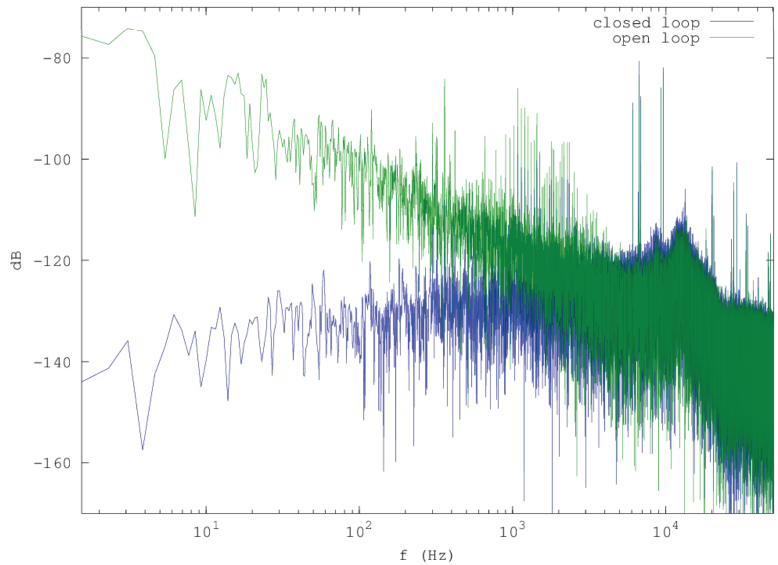
Target:
Laser-to-rf time jitter < 100 fs
Rf amplitude fluctuations < 10^{-4}
Beam pointing at the cathode < 10 µm
Charge fluctuations < 0.5%



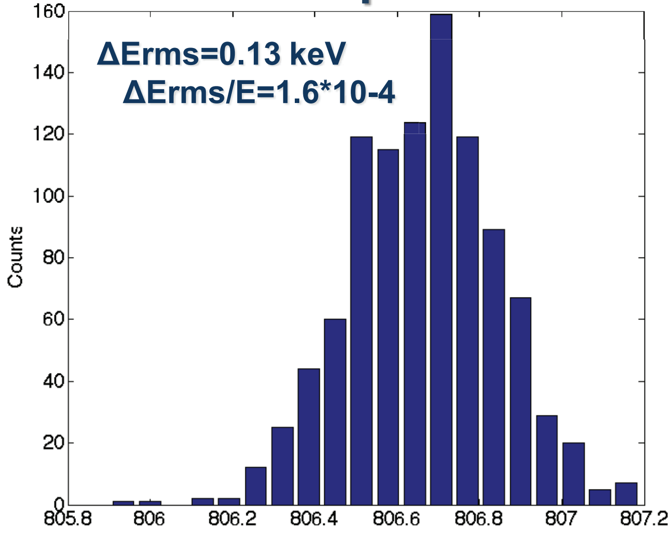
RF Jitter with LLRF Amp./Phase Feedback

@ Berkeley Lab

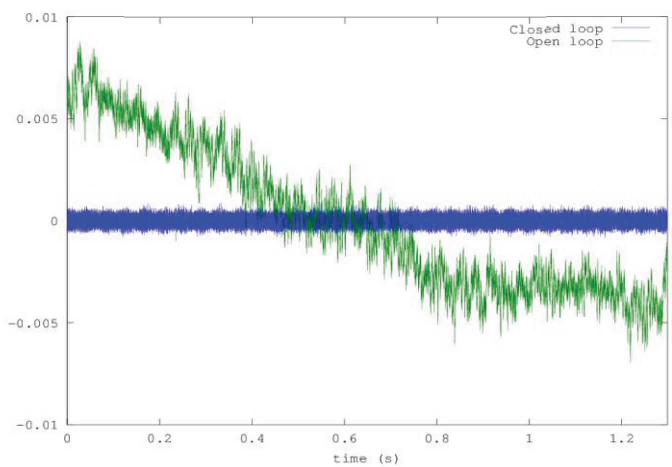
RF Amplitude noise spectrum



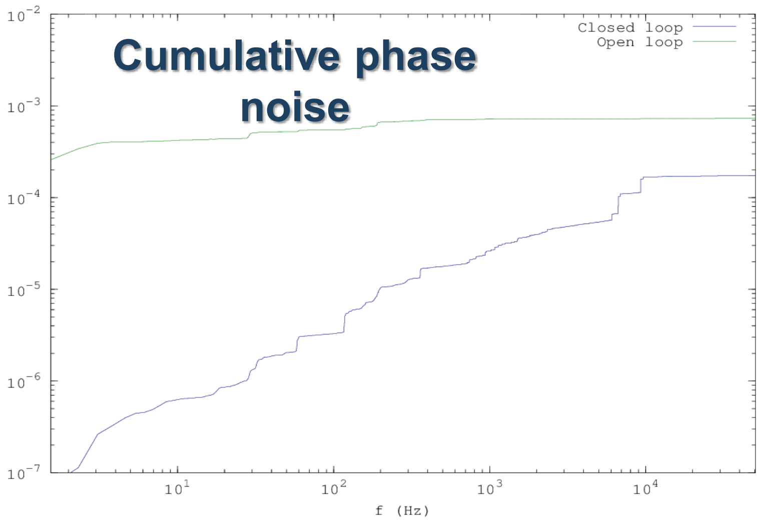
Dark current energy peak measured at the APEX spectrometer.



RF Phase error



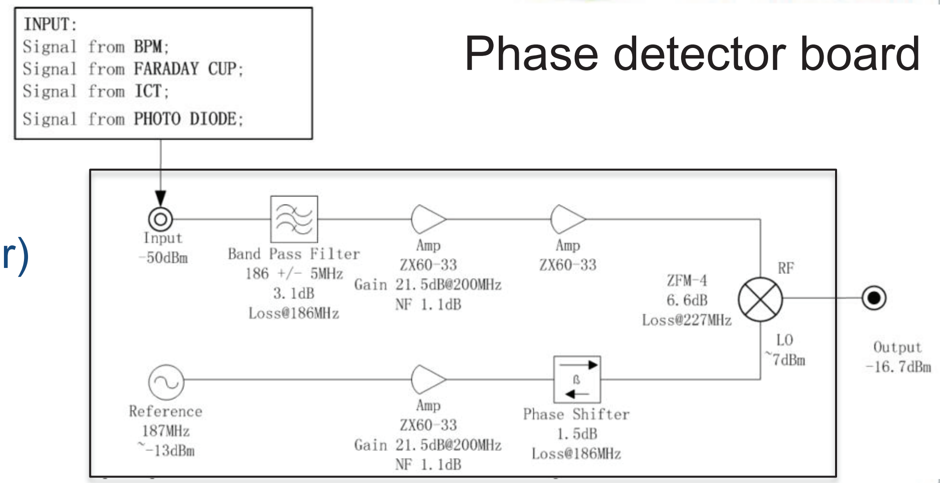
Cumulative phase noise

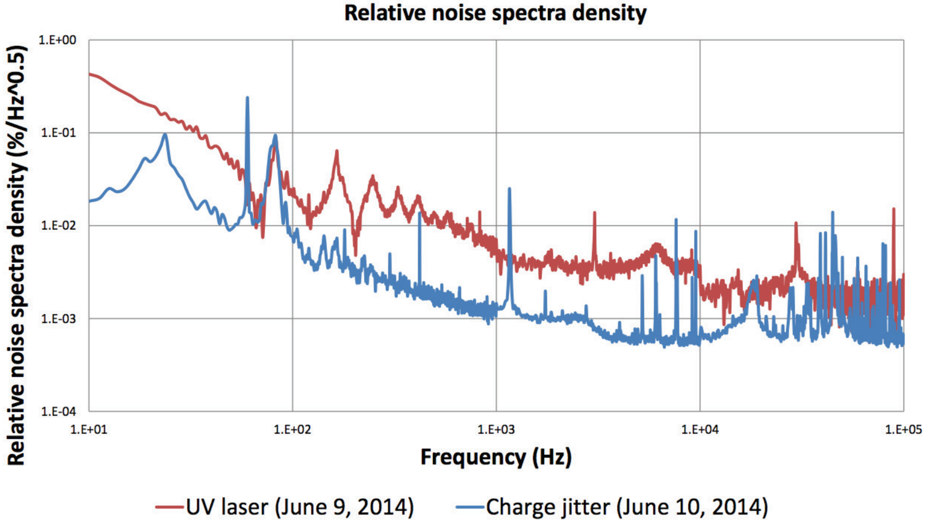


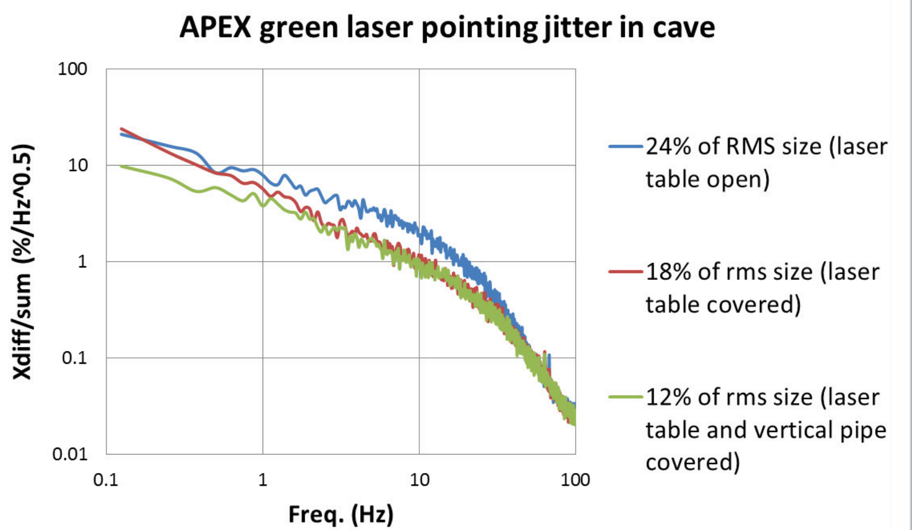
Laser and e-beam jitter measurements

- Phase detector built in house (need 2nd for xcorr)
- Measured IR,Green and UV energy fluctuations
- Starting the measurements on the e beam (Q,t)
- Installing a pointing feedback system (>5X better)

Phase detector board





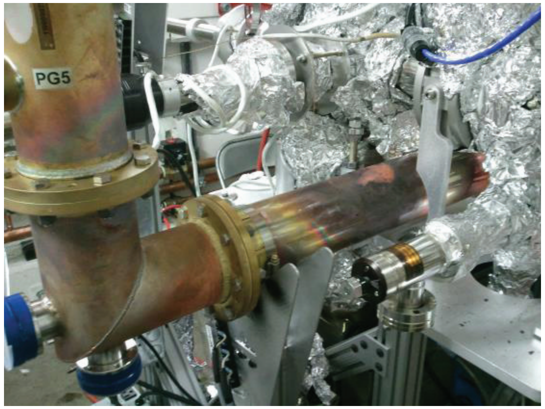


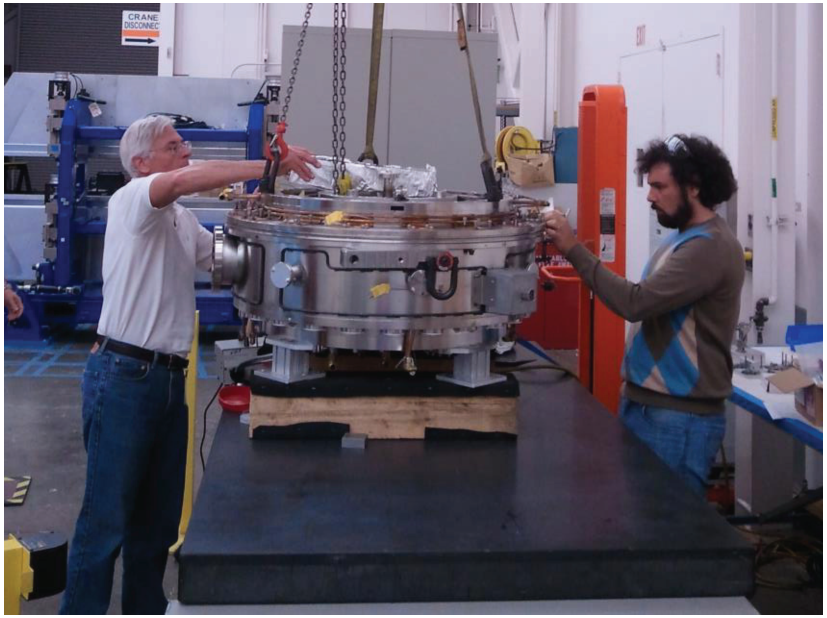
	10 Hz – 100 kHz
UV (June 9)	1.49%
Charge (June 10)	0.64%

RF accident:

- Experienced serious overheating of one coax waveguide
- The temperature went high enough to melt teflon bushings in the cavity vicinity creating black power (carbon + Cu oxides)+perfluorate gases
- The vacuum window cracked (temperature, over-pressure…)
- The gun has been un-installed and sent to the LBNL machine shop for cleaning
- Gun design allow opening and closing (no brazing between the cathode and the anode plates)
- The cleaning is already started (chemical bath is being performed as we speak)

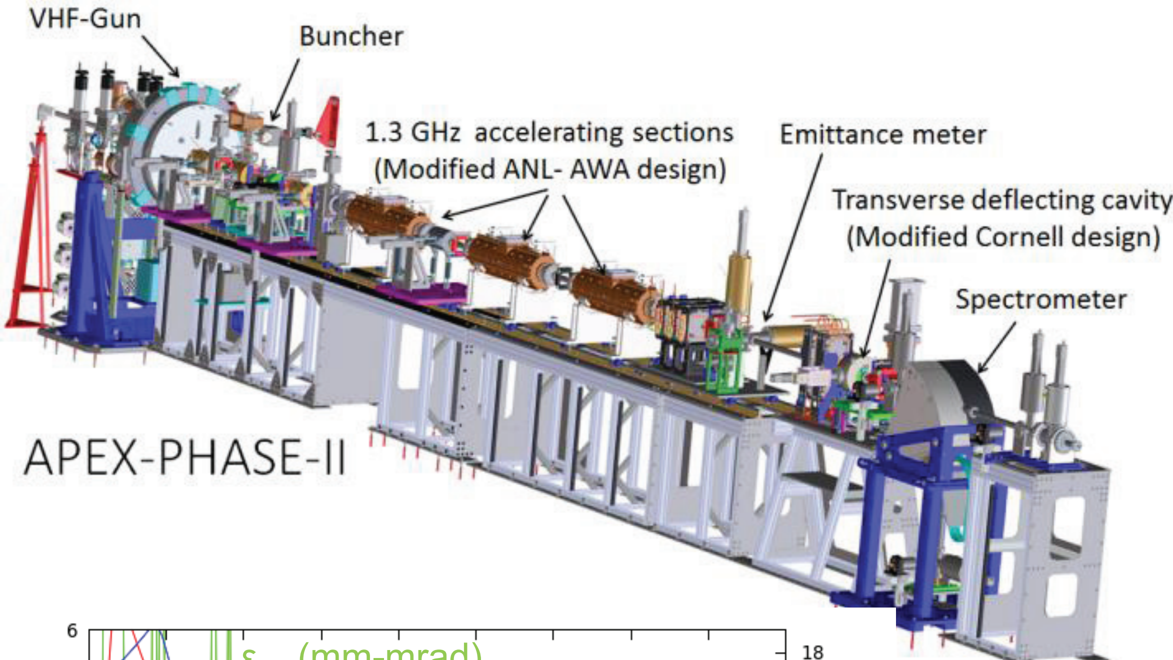
- No signs of discharge/multipacting inside the cavity.
- Will perform dry-ice cleaning of the cavity and pay particular attention to the machining of the cathode area.
- Foreseen 6 weeks shut-down period

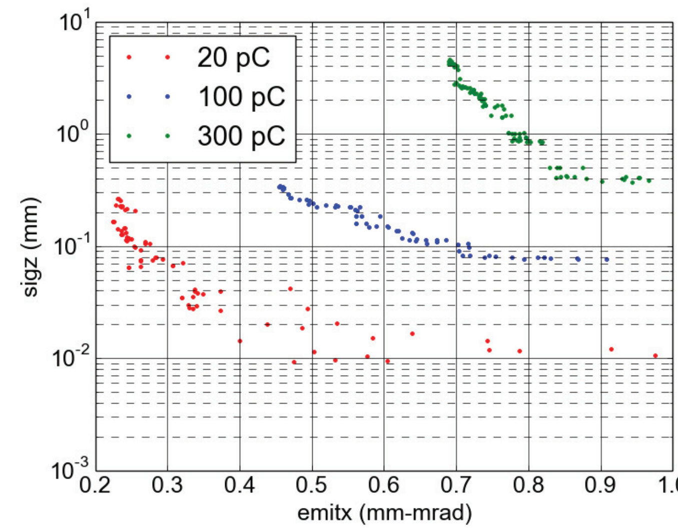




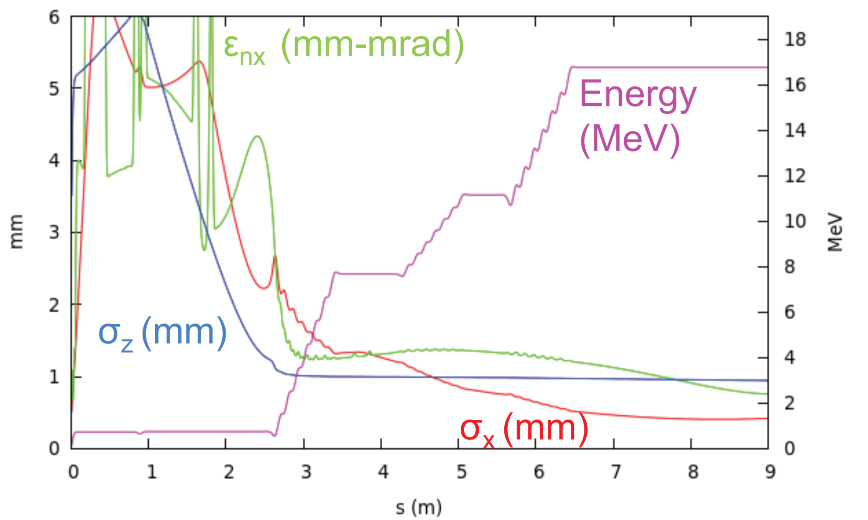
Phase II

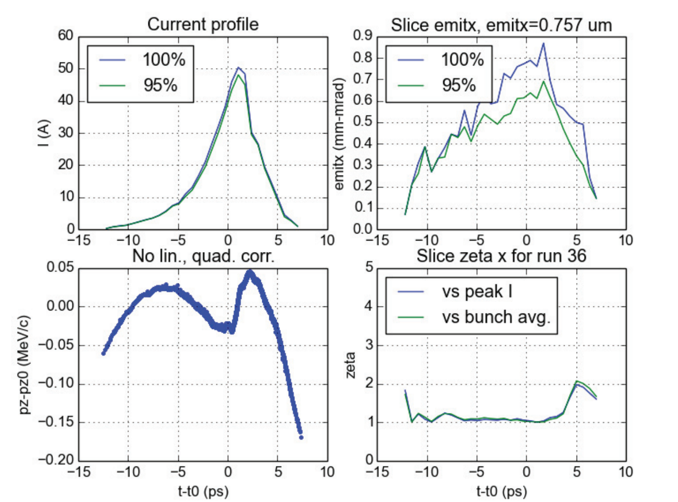
Prove the beam brightness. Measure emittance Vs bunch current.





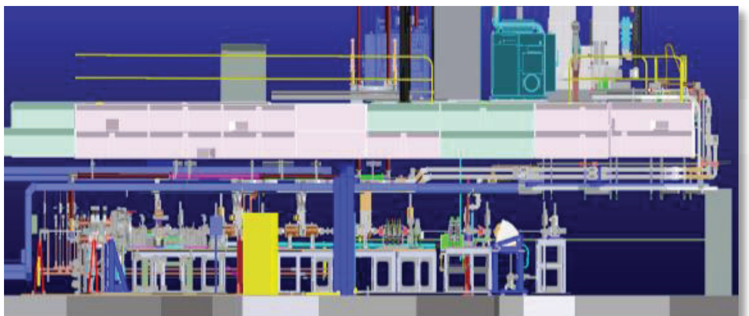
Beam at exit of APEX (9m, ~17 MeV)

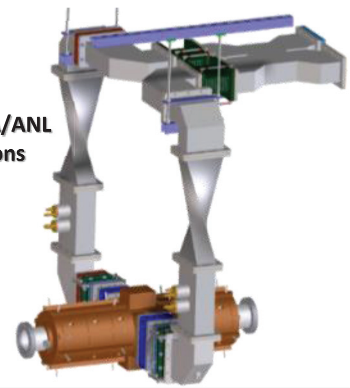




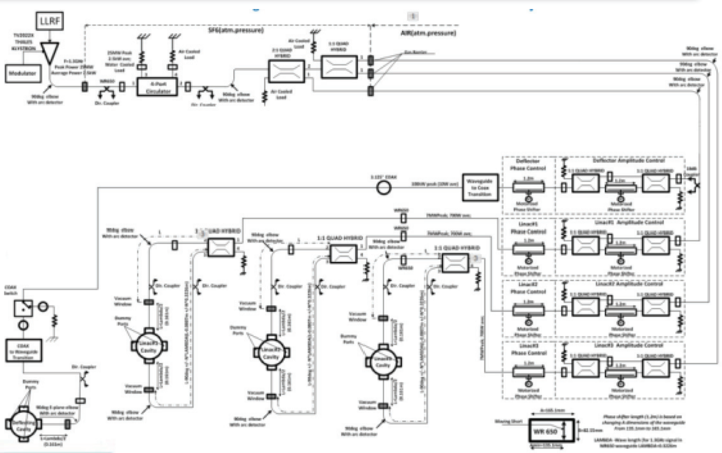
Phase II Main Activities

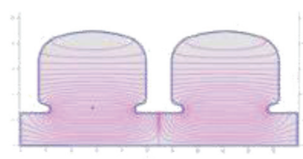
- 1.3 GHz Klystron LBNL and Modulator delivered to LBNL (acceptance test on September 8, 2014).
- Modified (multipole-free) AWA/ANL-like 1.3 GHz accelerating section being fabricated by HiTech.
- RF distribution completely designed and most component at LBNL.
- 1.3 GHz CW Buncher design finished.





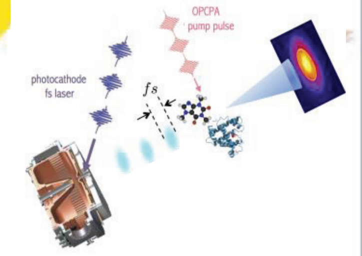
Modified AWA/ANL
Accel. Sections





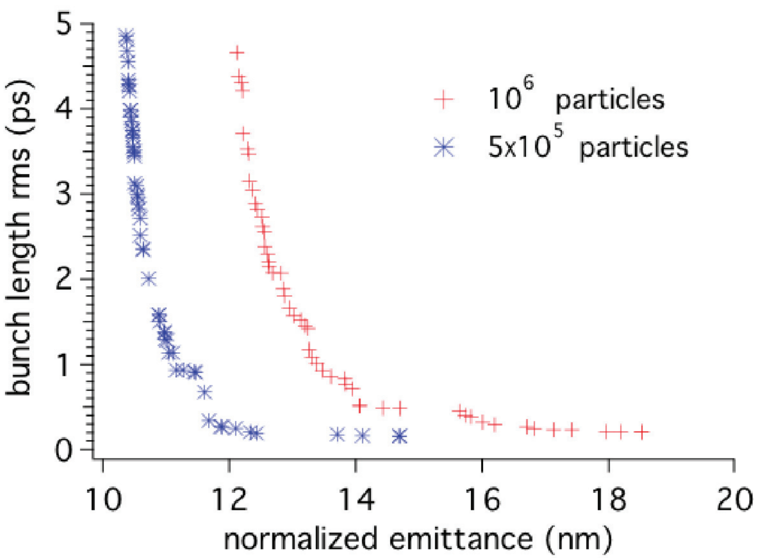
CW NC 1.3 GHz Buncher

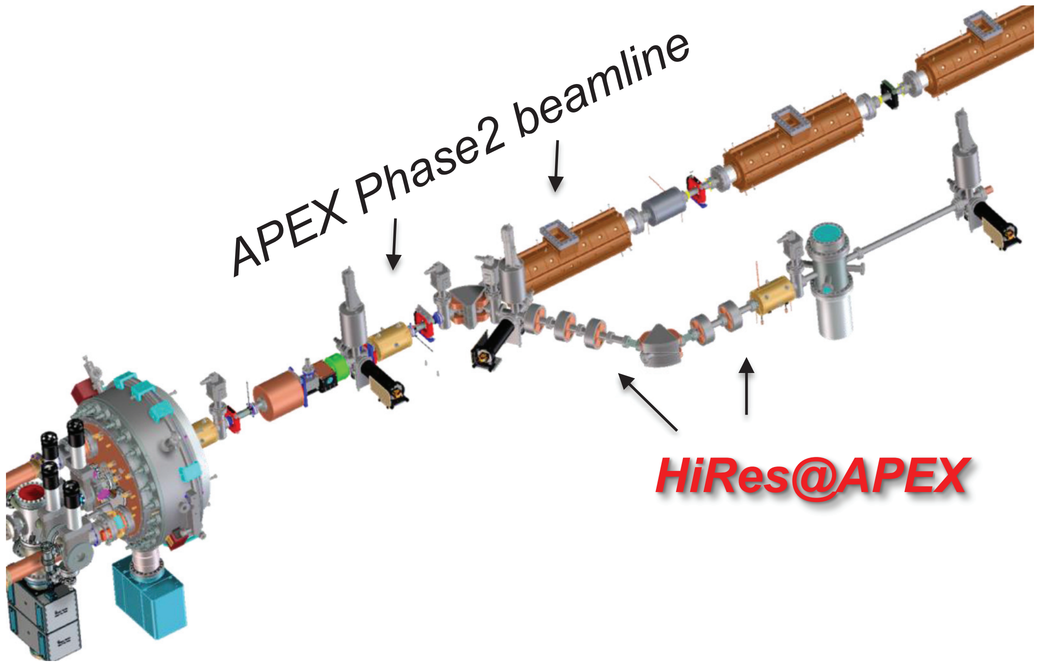
HiRes: High Rep. rate Electron Scattering



The HiRes beamline @ APEX will focus on UED, providing:

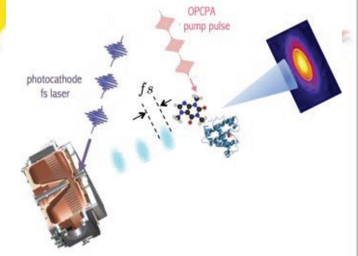
- time and space resolution**: from 100 fs to 100 ps**, ultralow emittance
- **Very high electron flux (10^{12} e/s):** ultrafast dynamics of complex molecules in gas/liquid phase with atomic resolution
- **Tunable electron energy:** up to 800 keV
- **Ultra-stable system**: noise suppression up to $f_{rep}/2$, high. res. stroboscopic measurements



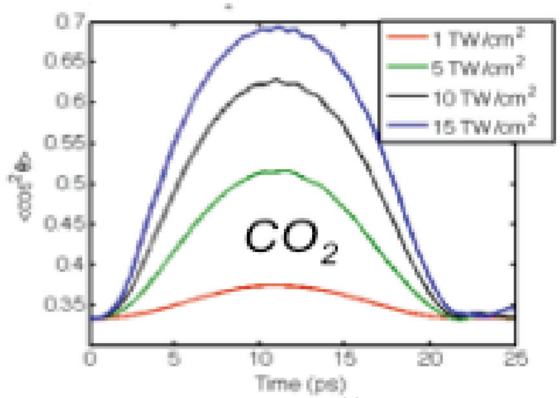


HiRes@APEX is funded by DOE-BES, through the Early Career Award

Science drivers

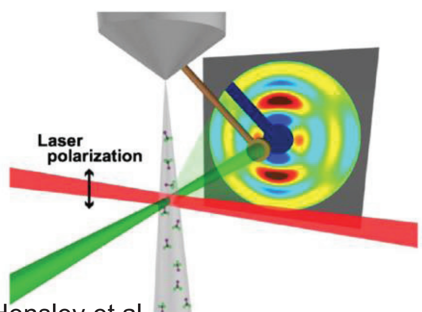


- ***Focus on ultrafast, reversible processes in material science***
  - Faster integrated measurements
  - Higher SNR in shorter time, weakly scattering targets
- ***Gas phase/hydrated samples***
  - 3D imaging of complex aligned molecules
  - Rep. rate matches with droplet injectors
    sample waist minimized (biology)

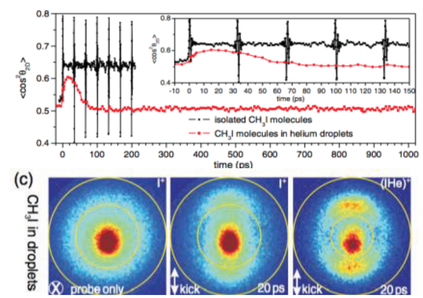


- ***May enable new science, as "tickle and probe"***
  - Weakly pumped systems. Non need to wait for relaxation time. Fully exploit the repetition rate. Lasers could be microfocused on sample via fibers.

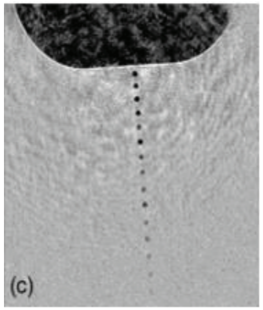
Superfluids and Ultracold chemistry



C.J. Hensley et al
Phys. Rev. Lett. **109**, 133202 (2012)



D. Pentlehner et al., PRL **109**, 133202 (2012)



D.P. DePonte et al.,
J. Phys. D: Appl. Phys. **41**, 195505 (2008)

Conclusions

- The VHF gun has ran for almost 3 years now, demonstrating high reliability
- The Cs_2Te cathodes allow mA operations with very good lifetime.
- Phase-II will be focused on emittance and current measurements and will prove the Brightness
- The blending of electron high flux and high peak B. enables high resolution measurements with UED.

The APEX team

K. Baptiste, M. Chin, J. Corlett, C. Cork, S. De Santis, L. Doolittle, J. Doyle, D. Filippetto, G. Harris, G. Huang, H. Huang, R. Huang, T. Kramasz, S. Kwiatkowski, R. Lellinger, C. Mitchell, V. Moroz, W. E. Norum, C. Papadopoulos, G. Portmann, H. Qian, F. Sannibale, J. Staples, M. Vinco, S. Virostek, W. Wan, R. Wells,
M. Zolotorev,