APEX Phase-II Commissioning Results at the Lawrence Berkeley National Laboratory

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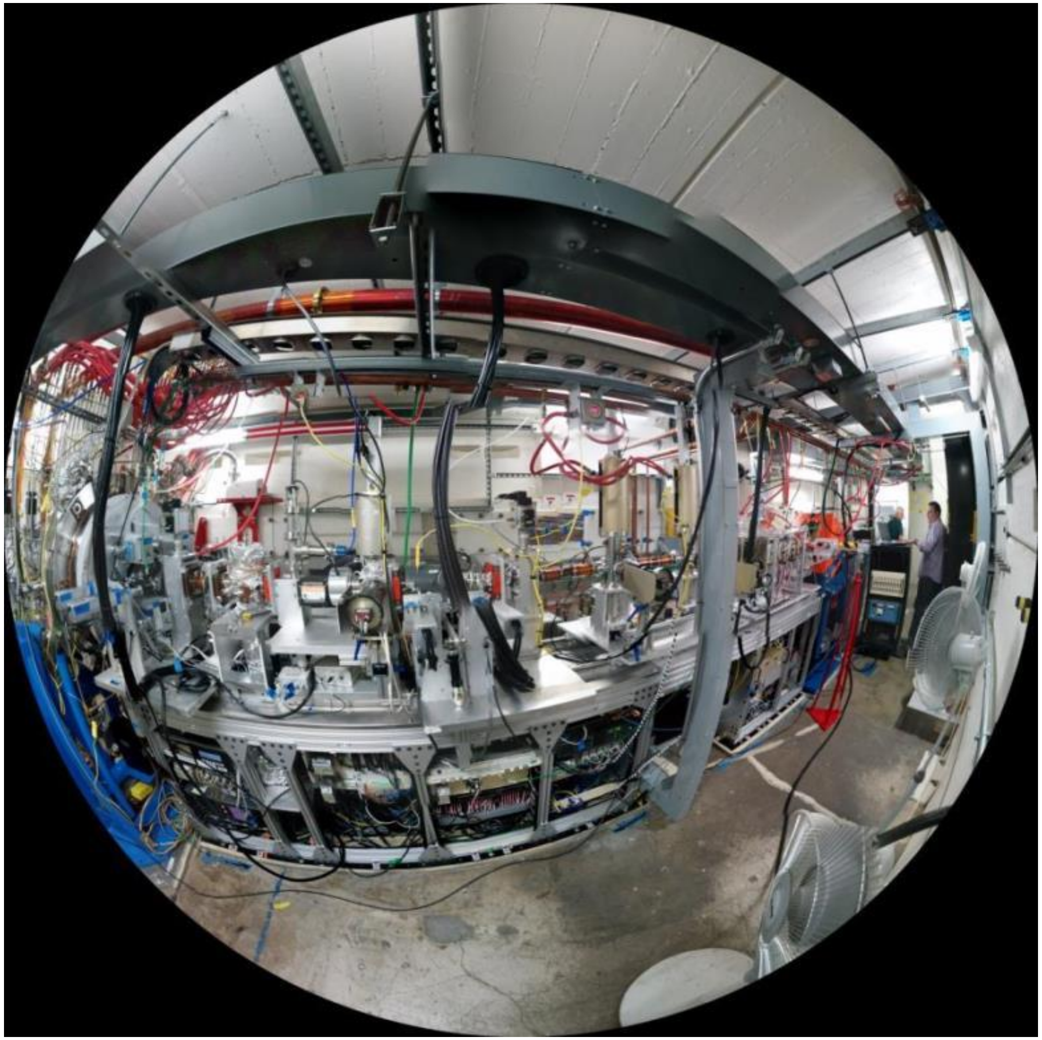
for the APEX Commissioning Team

IPAC16, Busan, South Korea
May 10, 2016

Outline

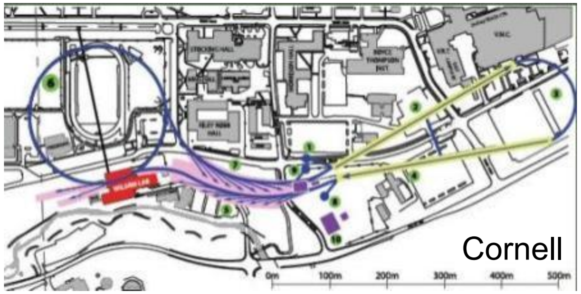
- **Science Demand**
- **The VHF-Gun and APEX**
- **APEX Performance and Recent Results**
- **Conclusions**



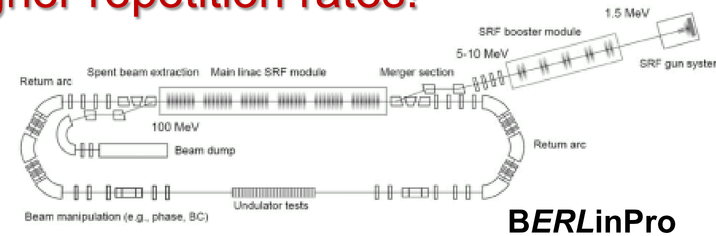
Science Driven Proposals/Projects!

All operating 4th generation light sources are low repetition rate (< 120 Hz)

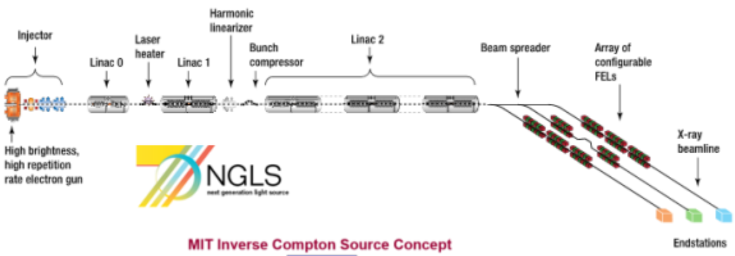
But science is driving towards much higher repetition rates!



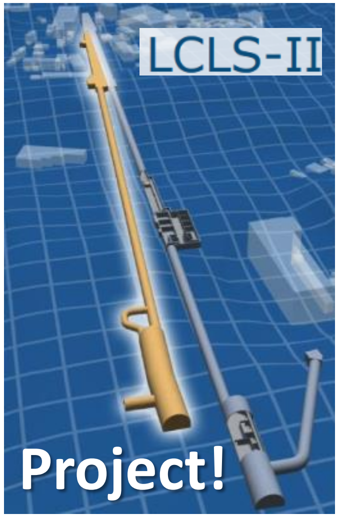
Proposed X-ray ERLs require the same beam quality at GHz repetition rates.



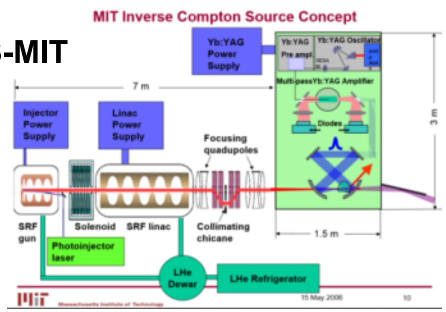
BERLinPro

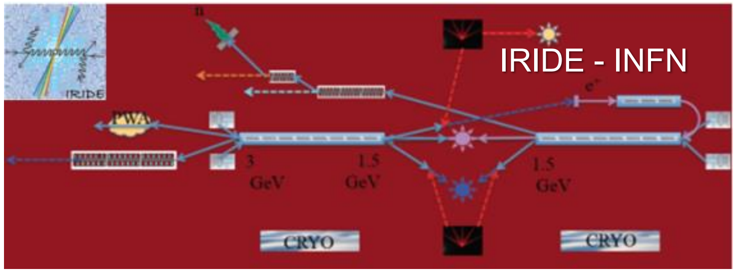


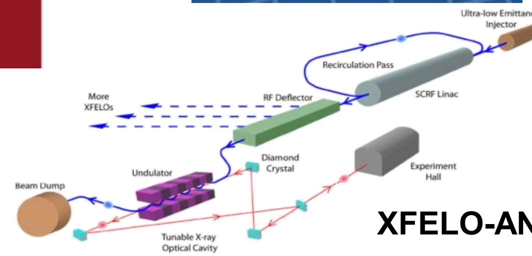
And proposed high repetition rate X-ray FELs, FEL oscillators and inverse Compton sources all require the similar beam quality at MHz repetition rates.



ICS-MIT







XFELO-ANL

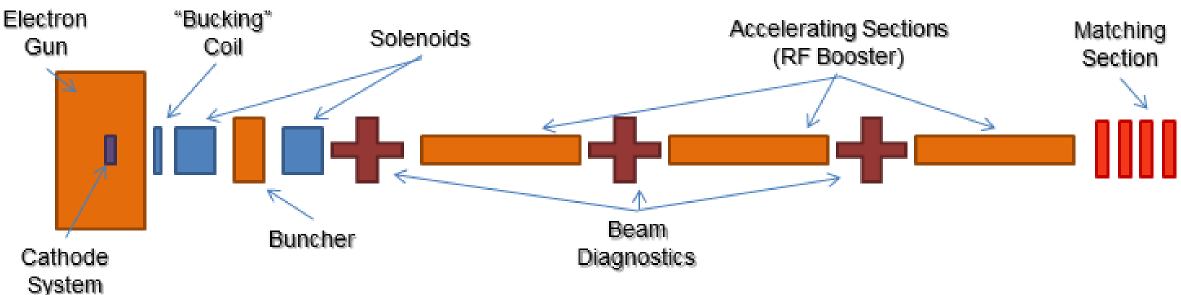
High repetition rate wakefield accelerators, UED, UEM, …

High-repetition rates high-brightness electron injectors are now required

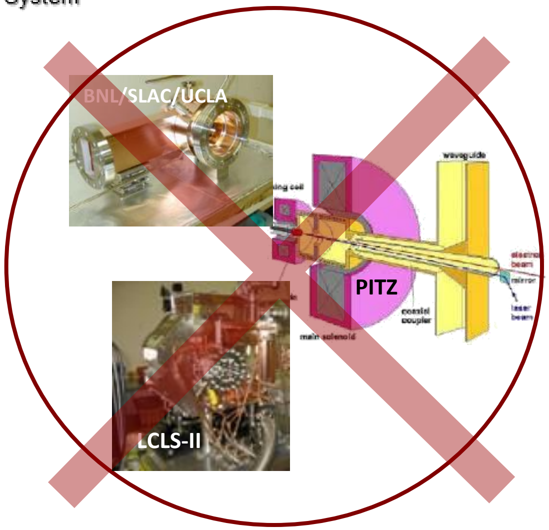
High Rep. Rate Technological Implications on the Injector

APeX @ Berkeley Lab

The ultimate performance in terms of brightness in linac-based facilities is set at the injector



- **High-repetition rates impose superconductive accelerating cavities in the RF booster to avoid unrealistic thermal losses.**



Successful low-repetition rate gun schemes

- **High-repetition rates require high QE photo-cathodes for realistic laser power requirements. Such cathodes are very reactive and susceptible to damage. Demanding vacuum requirements.**

- **Successful high-brightness low-repetition rate schemes such as NC high frequency (> 1.3 GHz) RF guns cannot run at repetition rates >~ 10 kHz (excessive thermal load).**

A high-repetition rate high-brightness gun needs to be developed!

Requirements for a High Rep. Rate x-ray FEL Gun/Injector

APeX @ Berkeley Lab

A high repetition rate FEL requires the electron source to simultaneously allow for:

Repetition rate	Up to ~ 1 MHz	
Charge per bunch	~ 10 – 300 pC	Different modes of operation
Normalized emittance	~ 0.2 – 0.6 μm	Lower value for lower charge
Beam energy at the gun exit	>~ 500 keV	For controlling space charge
Cathode electric field at photoemission	>~ 10 MV/m	Space charge limit; maximum brightness limit
Bunch length and shape control	From < 1 to ~ 60 ps	Space charge control; different modes of operation
Cathode/gun area magnetic field compatibility		Emittance compensation; (exotic modes)
Dark current at nominal gun energy	< ~ 1 μA	SRF quencing; rad. damage
Operational vacuum pressure	~10^{-10} –10^{-9} Torr	High QE cathode lifetime
Loadlock cathode vacuum system		"Quick" cathode exchange
Reliability	High (>~98%)	Required for an user facility

F. Sannibale, D. Filippetto, C. Papadopoulos, JMO **58**, 1419 (2011)

Available Gun Technologies in 2006

APeX @ Berkeley Lab

High frequency (> 1 GHz) normal-conducting RF

Super-conducting RF

DC gun

Not usable

R&D required

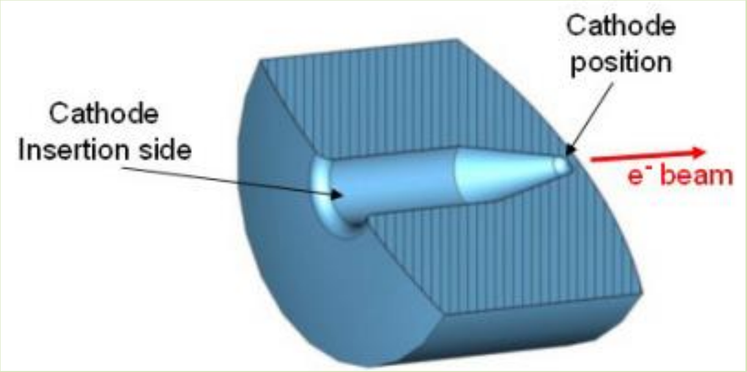
LBNL new concept electron gun: the VHF-Gun

CBP Tech Note 366

VHF-band Photoinjector

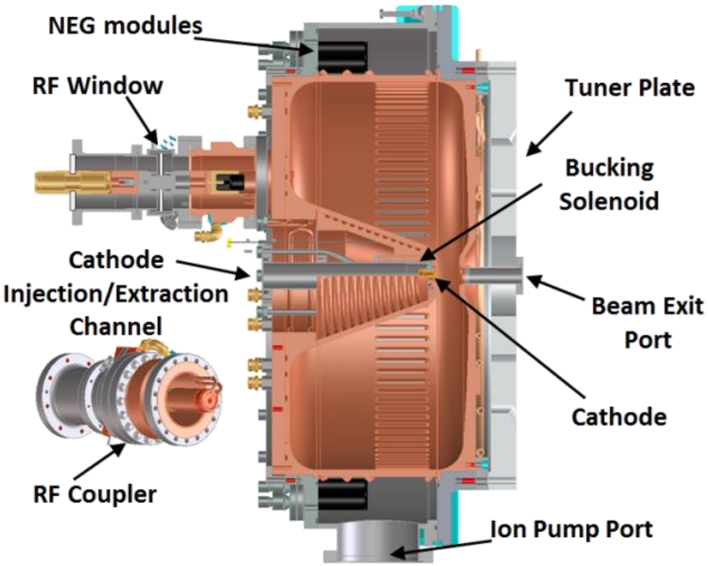
J. Staples, F. Sannibale, S. Virostek
Lawrence Berkeley National Laboratory

26 October 2006



The LBNL VHF RF Gun

The Berkeley normal-conducting scheme satisfies all next generation FEL requirements simultaneously.



J. Staples, F. Sannibale, S. Virostek, CBP Tech Note 366, Oct. 2006

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

R. P. Wells, et al., Review of Scientific Instruments, 87, 023302 (2016)

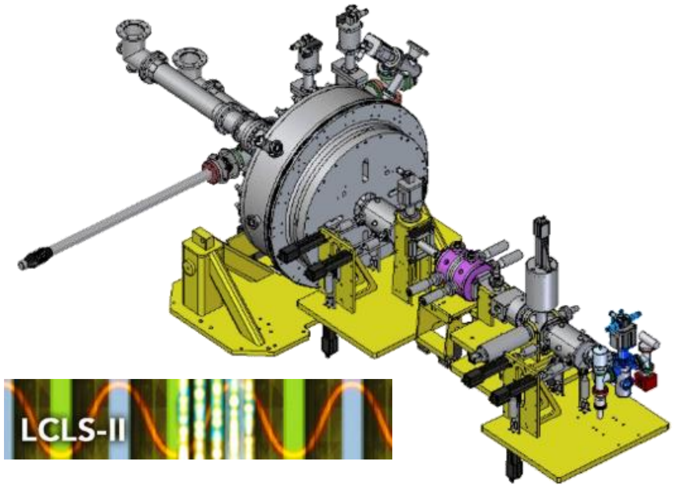
Frequency	186 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19.47 MV/m
Q_0	30400
Shunt impedance	6.5 MΩ
RF Power @ Q_0	87.5 kW
Stored energy	2.3 J
Peak surface field	24.1 MV/m
Peak wall power density	25.0 W/cm^2
Accelerating gap	4 cm
Diameter/Length	69.4/35.0 cm
Operating pressure	~ 10^{-10}-10^{-9} Torr

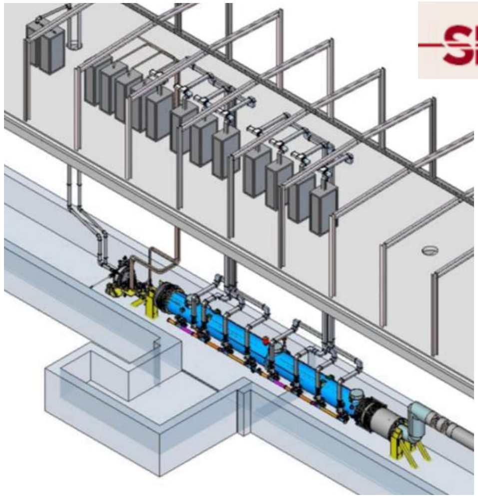
- At the VHF frequency, the cavity structure is large enough to withstand the heat load and operate in CW mode at the required gradients.
- Also, the long λ_{RF} allows for large apertures and thus for high vacuum conductivity.
- Based on mature and reliable normal-conducting RF and mechanical technologies.
- 186 MHz compatible with 1.3 and 1.5 GHz super-conducting linac technologies.

The LCLS-II Injector is Based on the APEX VHF-Gun

APEX @ Berkeley Lab

The injector of the LCLS-II FEL at SLAC includes a VHF-Gun.
LBNL is responsible for the construction of the gun and of the downstream low-energy beamline (Fabrication initiated).



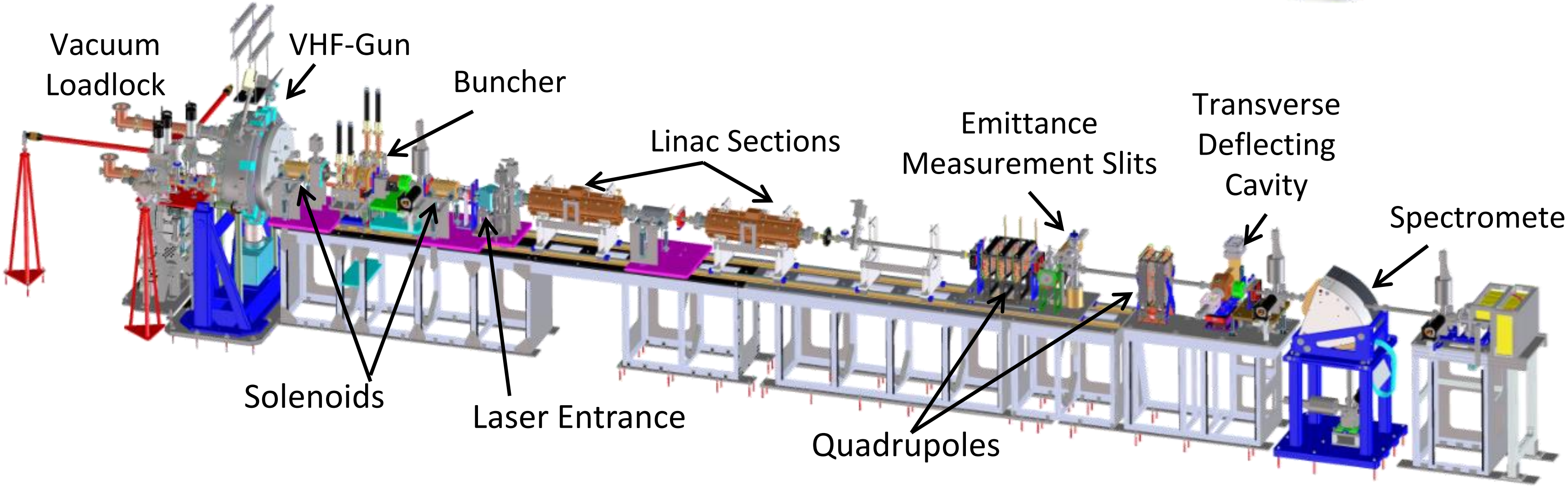


SLAC

The high-energy high-gradient gun (respectively ~ 2 and 3 times higher than in the present best DC gun) allows for a more relaxed thermal emittance cathode requirement, and for a simple injector layout: VHF Gun, NC buncher, solenoids and <u>standard</u> LCLS-II linac cryomodule.
Simulations indicates that all LCLS-II requirements are met with margin

APEX, the Advanced Photoinjector Experiment

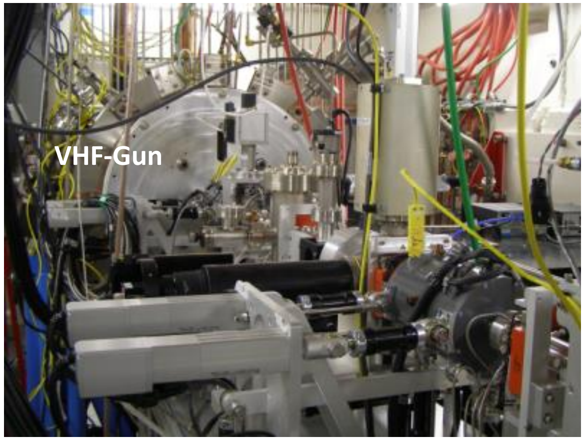
APeX @ Berkeley Lab

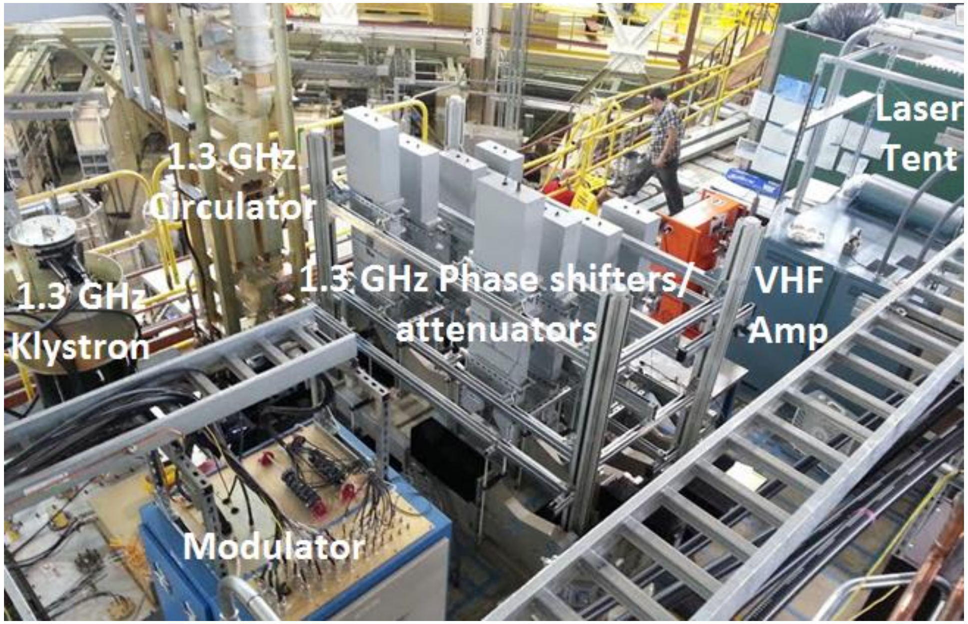


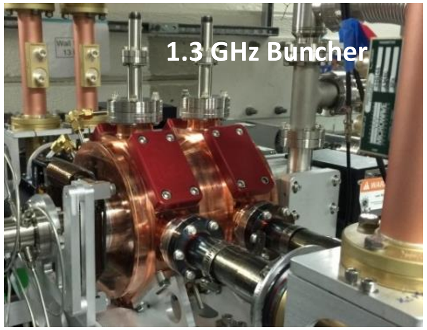
Main Goals:

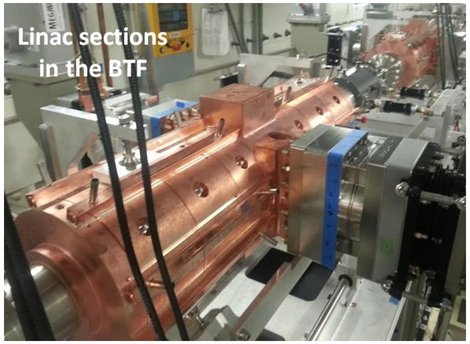
- **Demonstrate the *RF and Vacuum Performance of the VHF-Gun.***
- **Characterize and *identify high QE photocathodes* capable to operate at the challenging regime imposed by MHz-class FELs (LCLS-II).**
- ***Dark current* characterization, define removal techniques.**
- **Demonstrate FEL-quality *bunch compression* and *high-brightness* capability of an injector based on the VHF-Gun.**

The APEX Phase-II: More Photos










APEX Phase-II Fully Installed in the BTF

APEX Experimental Results: Milestones for LCLS-II

Demonstrate capability of the VHF-Gun to run in CW mode at the required cathode fields and energy (750 keV)
F. Sannibale, *et al.*, PRST-AB **15**, 103501 (2012)

> 840 keV measured

Identify a cathode and demonstrate its capability to operate with sufficient lifetime (τ > 4 days - LCLS-II) at the required charge/bunch, rep. rate, and thermal emittance (<1 μm/mm required, ~0.7 μm/mm measured with Cs_2Te)
Filippetto, Qian, Sannibale, Appl. Phys. Letters **107**, 042104 (2015).

τ ~ 17 days Measured with Cs_2Te

Characterize and reduce dark current from the gun at the required level (< 400 nA @ 750 keV – LCLS-II)
R. Huang, *et al.*, PRST-AB **18**, 013401 (2015)

~ 0.1 nA measured

Demonstrate the capability of APEX to operate with emittance and compression compatible with LCLS-II requirements.
On March 8 and 9, 2016 a review of experts confirmed that all formal LCLS-II beam parameter requirements were demonstrated.

All parameters demonstrated

Last LCLS-II Milestone Details

APeX @ Berkeley Lab

Quantity	Required	Measured	Demonstrated
Charge per bunch [pC]	> ~ 20	20-25	☺
Normalized emittance [μm]	< ~ 0.25	~ 0.20*	☺
Bunch peak current [A]	> ~ 5	5 - 9	☺
Energy Spread (H.O. whole beam) [keV]	< ~ 15	< 9**	☺

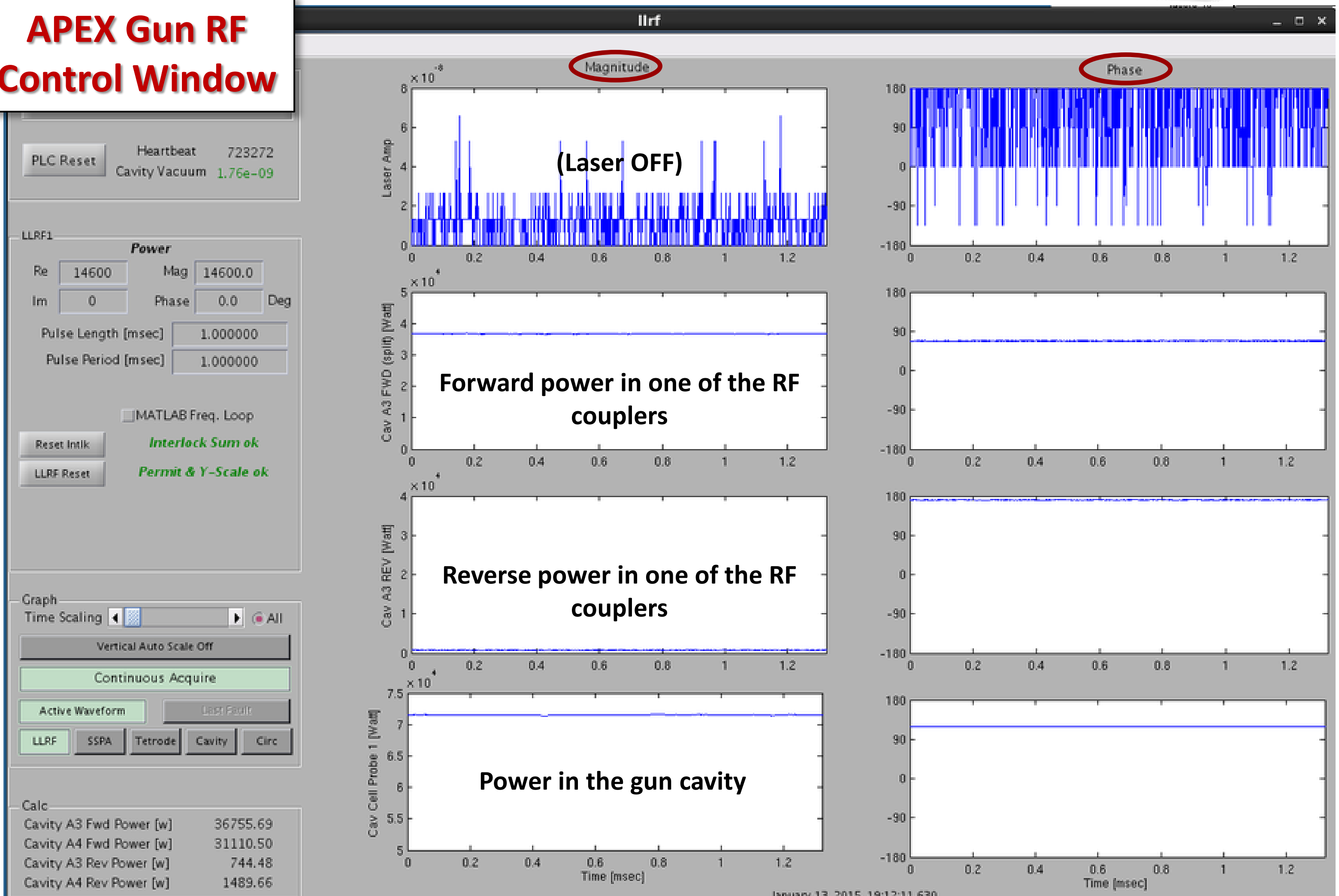
* After accounting for space charge contribution

** Value affected by space charge. Much smaller values at LCLS-II injector energies.

Tests at higher charge per bunch (100 pC) for LCLS-II and full characterization of multi-alkali antimonides cathode starting in June.

VHF-Gun Successful CW operation

APEX Gun RF Control Window

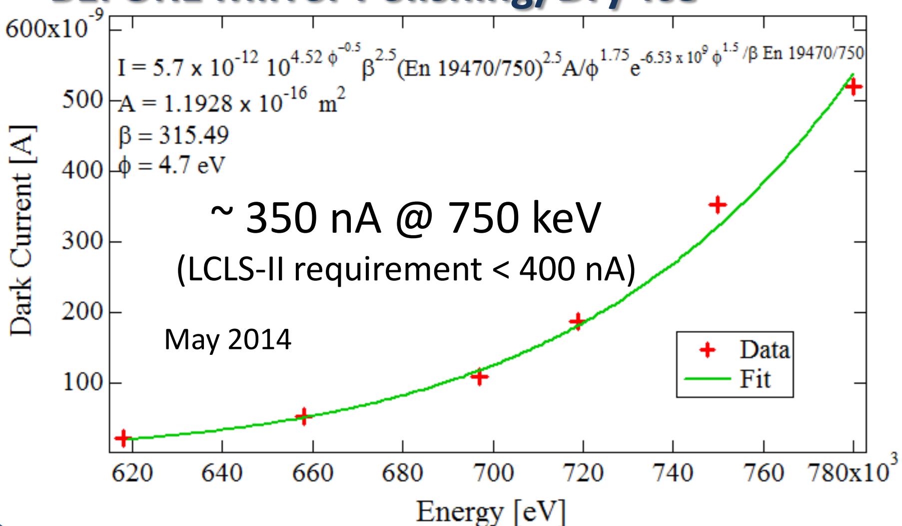


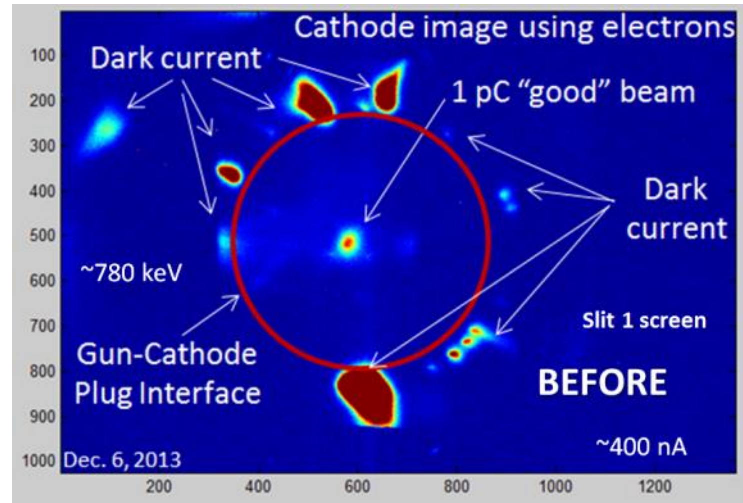
Since November 2011, several thousand hours of CW operation at the nominal field and beyond.

Exceptional Gun Dark Current Reduction

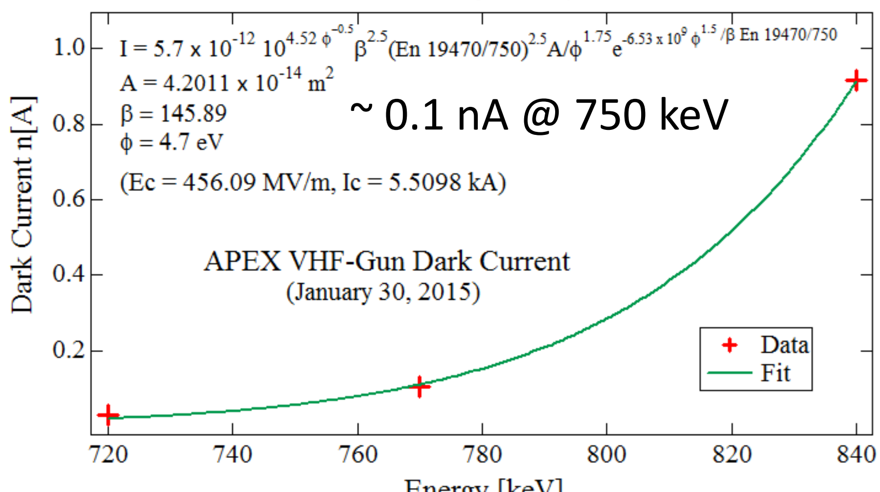
APEX @ Berkeley Lab

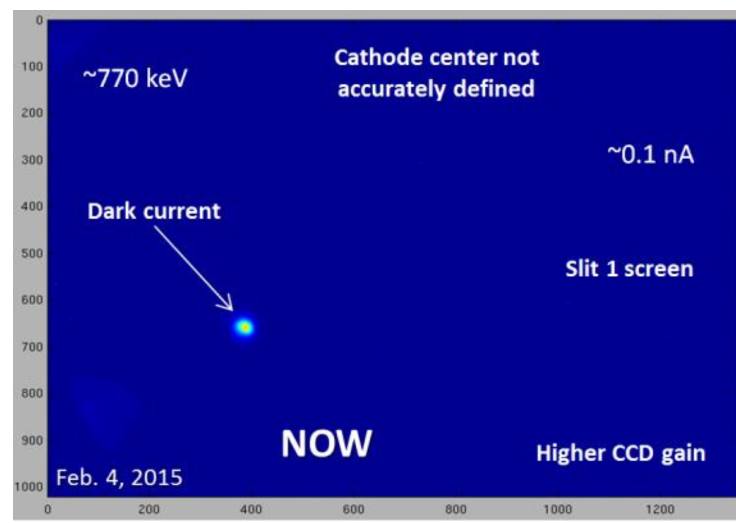
BEFORE Mirror Polishing/Dry-Ice





AFTER Mirror Polishing/Dry-Ice



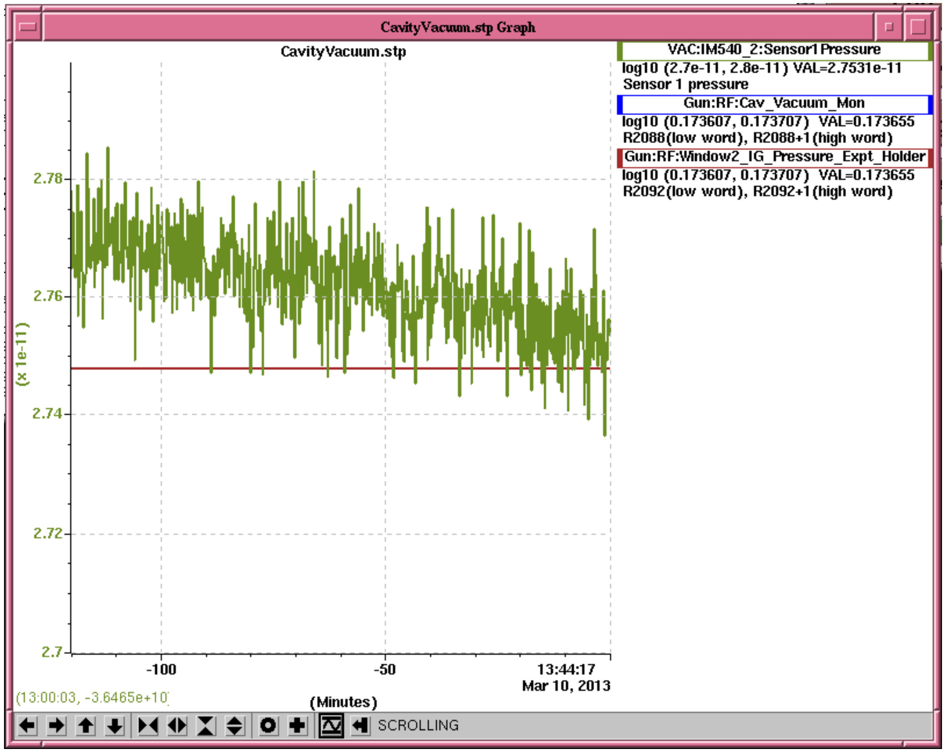


More than 3-orders of magnitude reduction!

VHF-Gun Demonstrates Vacuum Requirements

@ Berkeley Lab

- 20 NEG pumps activated
- 2.5 days of RF baking at ~180-200 °C



Pressures in the gun without RF:

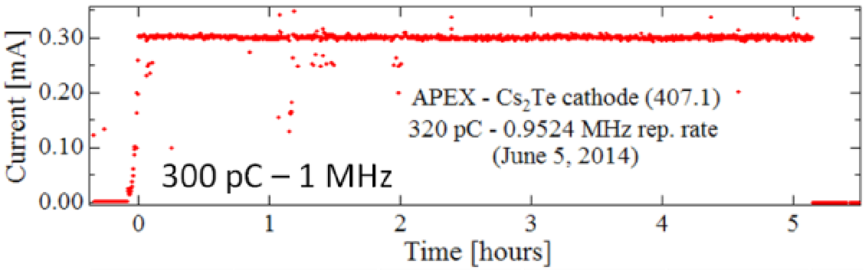
- Extractor gauge: **2 x 10^{-11} Torr** (2.7 10^{-11} mBar) (this gauge has the proper sensitivity)

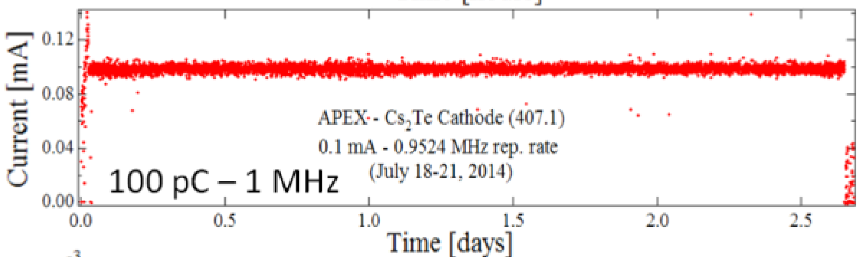
RGA measurement indicated partial pressures of H_2O, CO, CO_2 two-orders of magnitude smaller.

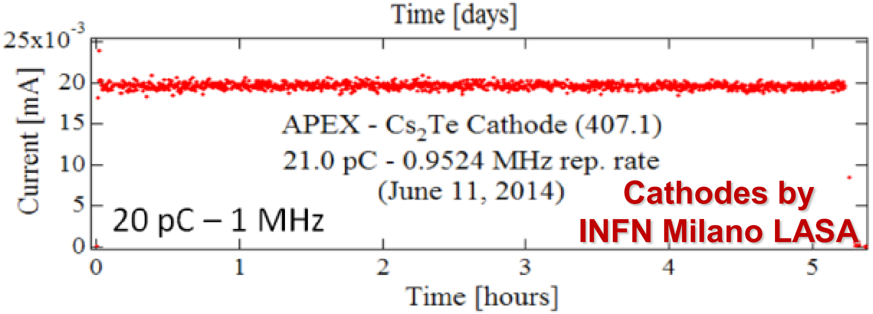
With RF at the nominal power the pressure rises to ~ 3 x 10^{-10} Torr

Cs_2Te Cathodes Satisfies with Margin LCLS-II Needs

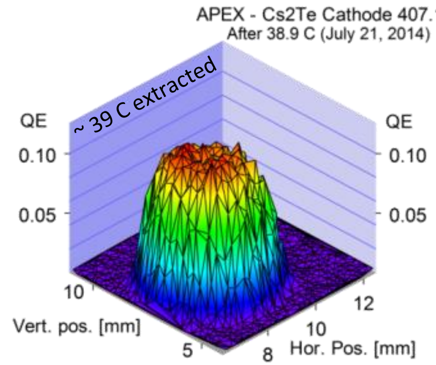
APeX @ Berkeley Lab



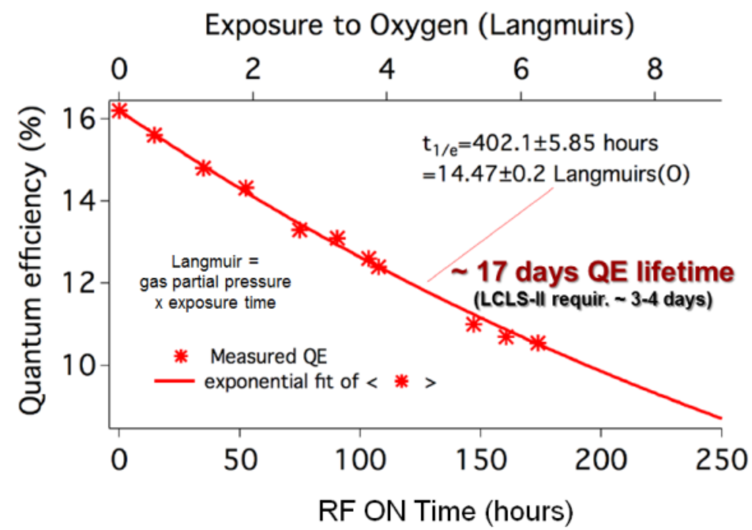




Cathodes by INFN Milano LASA



No signs of either ion back-bombardment or of laser induced QE depletion after ~ 39 C extracted



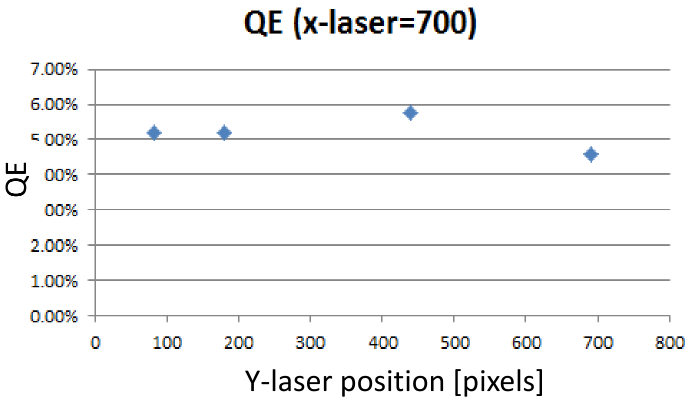
The major QE degradation mechanism for Cs_2Te is oxidation.
(A. di Bona, et al. JAP 80,1996).

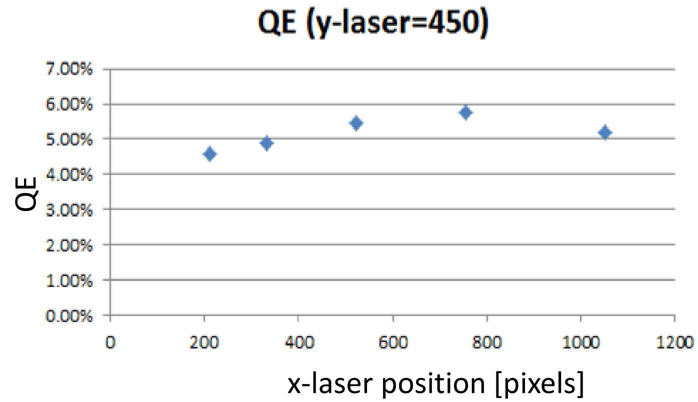
In LCLS-II cathodes will be replaced when the QE drops to 0.5%.
Using the results for Cs_2Te, a cathode will last for ~ 2 months.

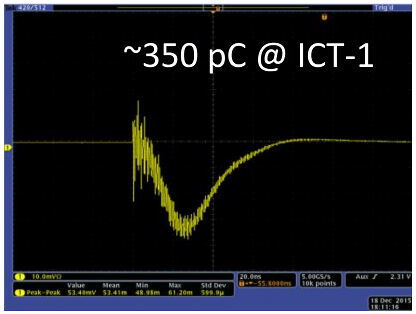
Filippetto, Qian, Sannibale, Appl. Phys. Letters **107**, 042104 (2015).

High QE CsK_2Sb Cathodes Used for Recent Beam Tests

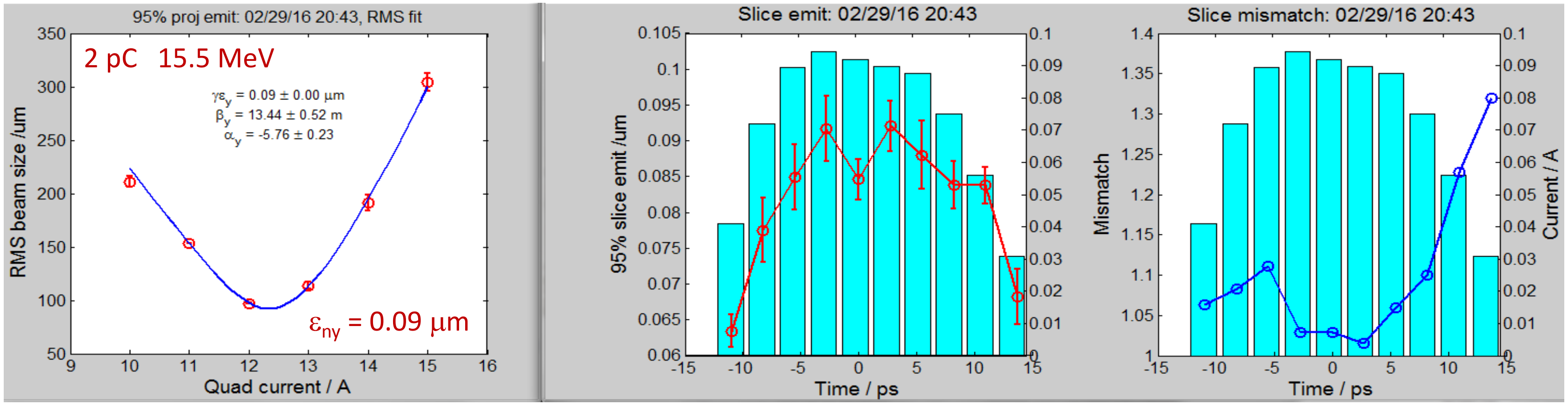
CsK_2Sb cathodes by H. Padmore's group at LBNL







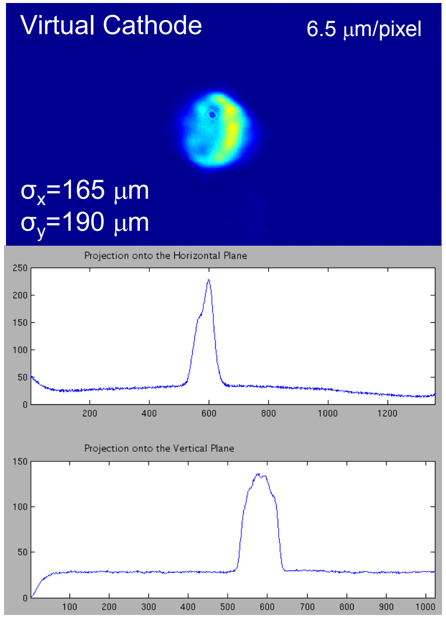
QE >~ 5% at 532 nm (~ 5.5 % in the preparation chamber 12/16/2015)



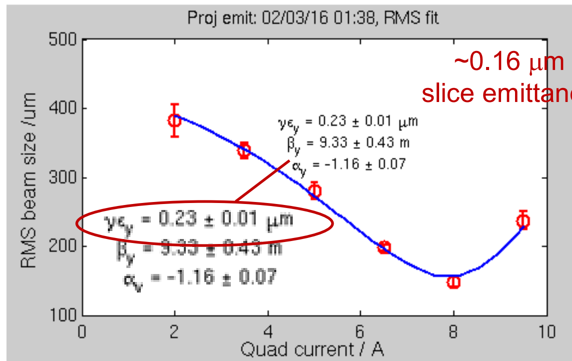
Measured thermal emittance of ~ 0.5-0.6 μm/mm rms.
Full characterization will be done in the next several months.

Example of Slice Emittance Measurement (Feb. 2, 2016)

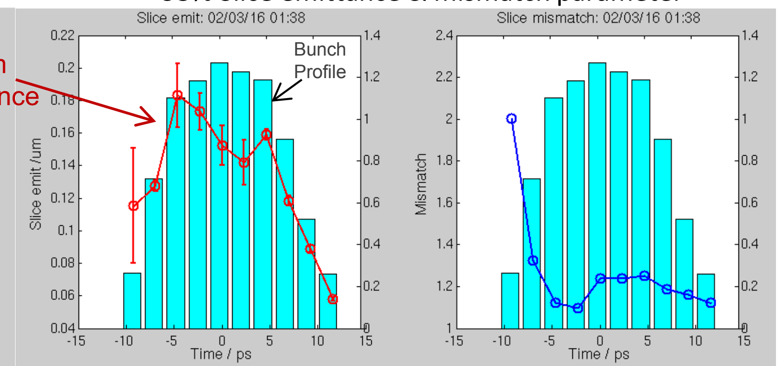
APeX @ Berkeley Lab

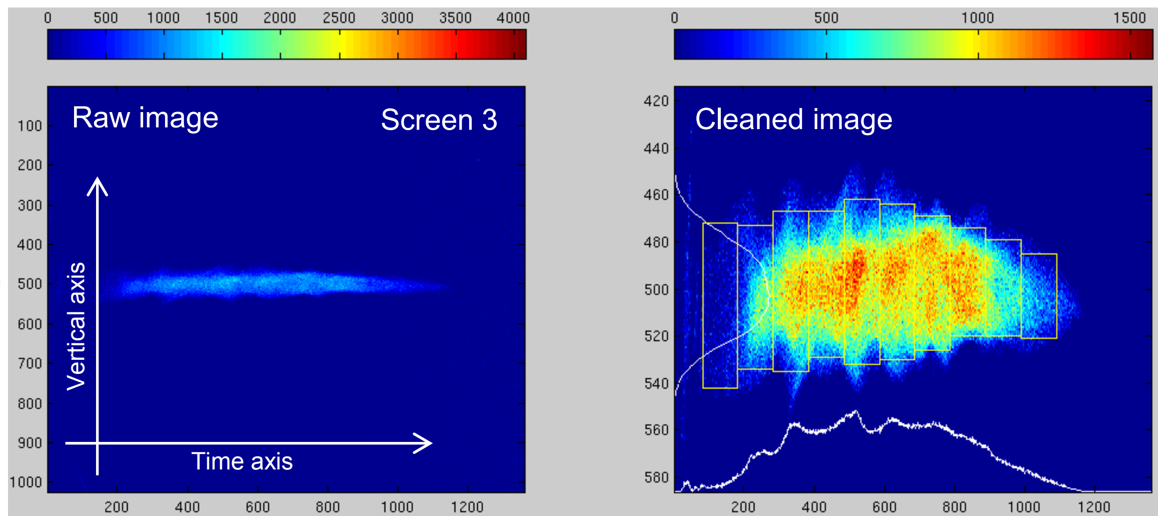


20 pC, 15.4 MeV, 95% Projected emittance



95% Slice emittance & mismatch parameter

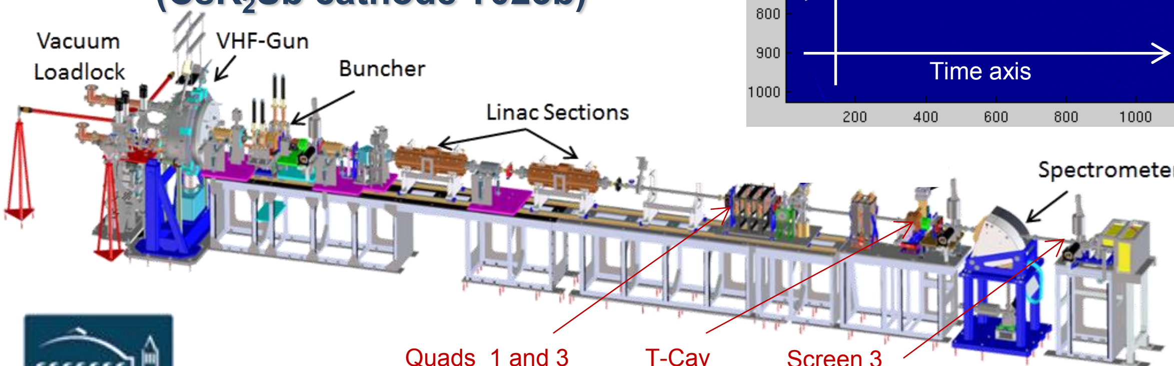




20 pC, 15.7 MeV, 14 ps laser pulse

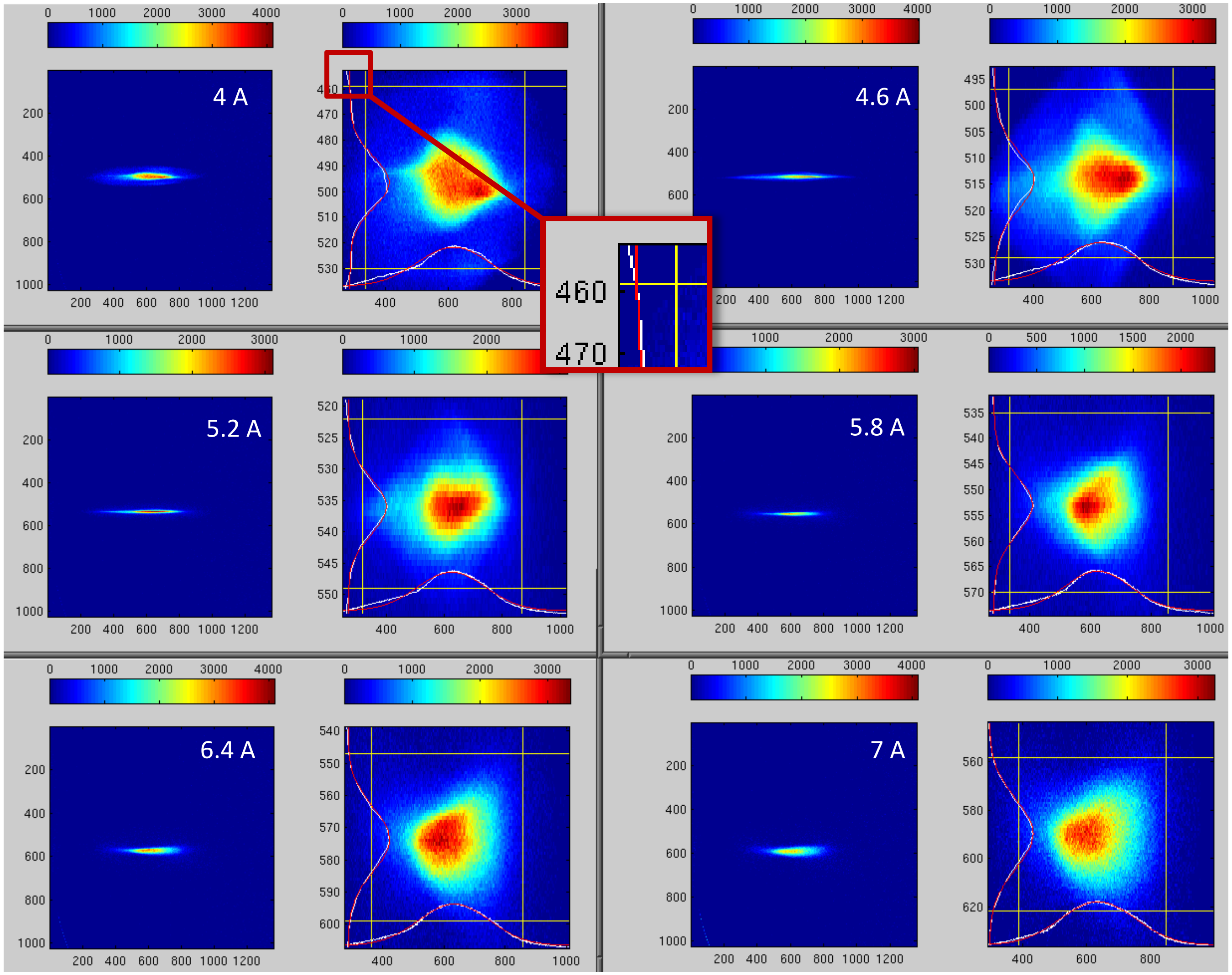
T-Cav DAC 8000, no Buncher

(CsK_2Sb cathode T023b)

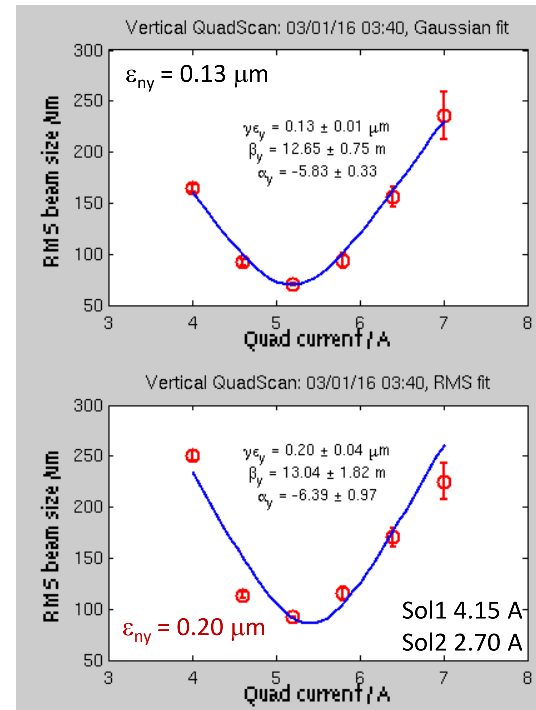


Measured ~0.16 μm slice emit. and ~1 A peak current.

Example of Projected Emittance Measurement



20 pC, ~6.5 A peak
~15.7 MeV
Quad 3 scan
95% projec. emittance



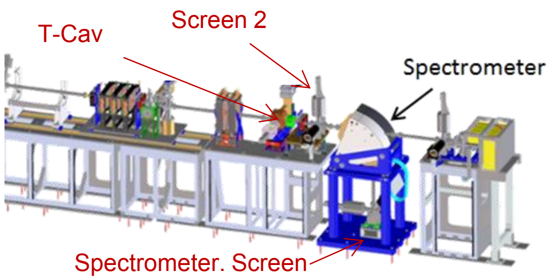
Halo makes values from rms emittance analysis larger than from Gaussian (core)

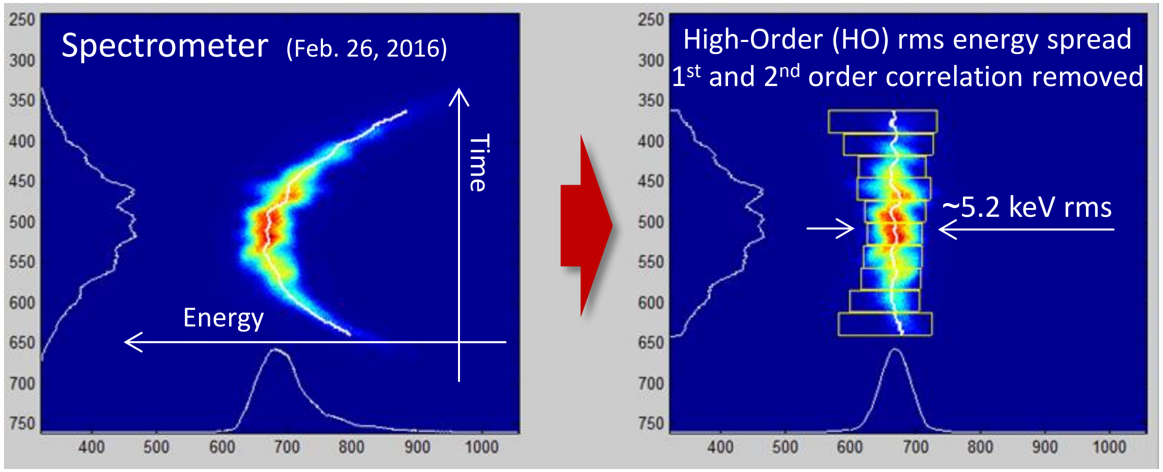
Example of Long. Phase Space Measurement

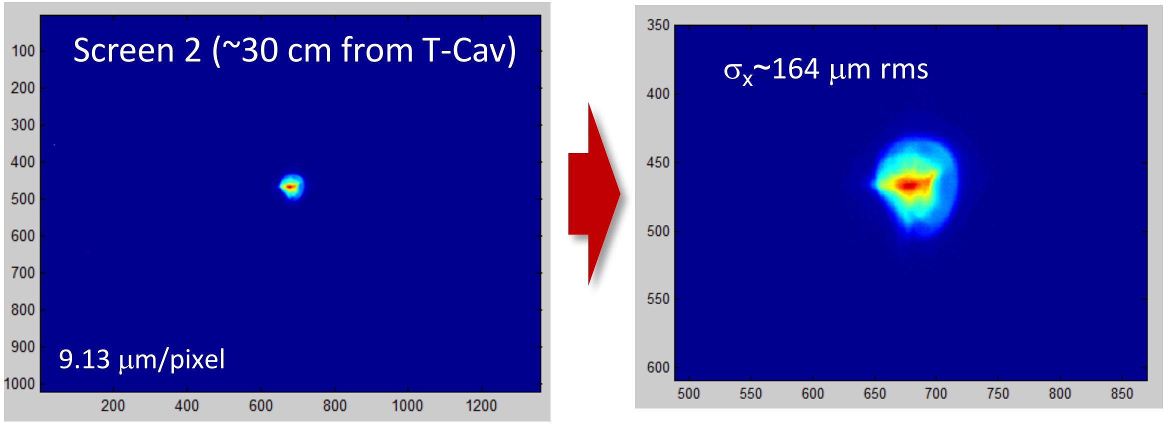
APeX @ Berkeley Lab

22 pC, 15.7 MeV

~3.2 A peak current







T-Cav induced energy spread @ 18k DAC (2.2 keV/100 μm σ_x) ~ 3.6 keV rms

HO energy spread < $(5.2^2 - 3.6^2)^{1/2}$ keV < 3.7 keV rms (space charge affected) (spectrometer resolution not deconvolved)

Few "Hiccups" on the Way…

August 1, 2014. RF Coaxial Failure. One of the two 4" copper coaxial waveguide that feed the power to the gun overheated because of a sustained reflection inducing the rupture of one of the RF windows.

- The gun was contaminated and had to be opened for cleaning.

September, 2015. Charge build-up on one of the RF windows. Direct line of sight between the cavity internal wall and the RF window ceramic allowed for field emitted electrons inside the cavity to build up on the ceramic generating flash arc and ultimately ceramic puncture.

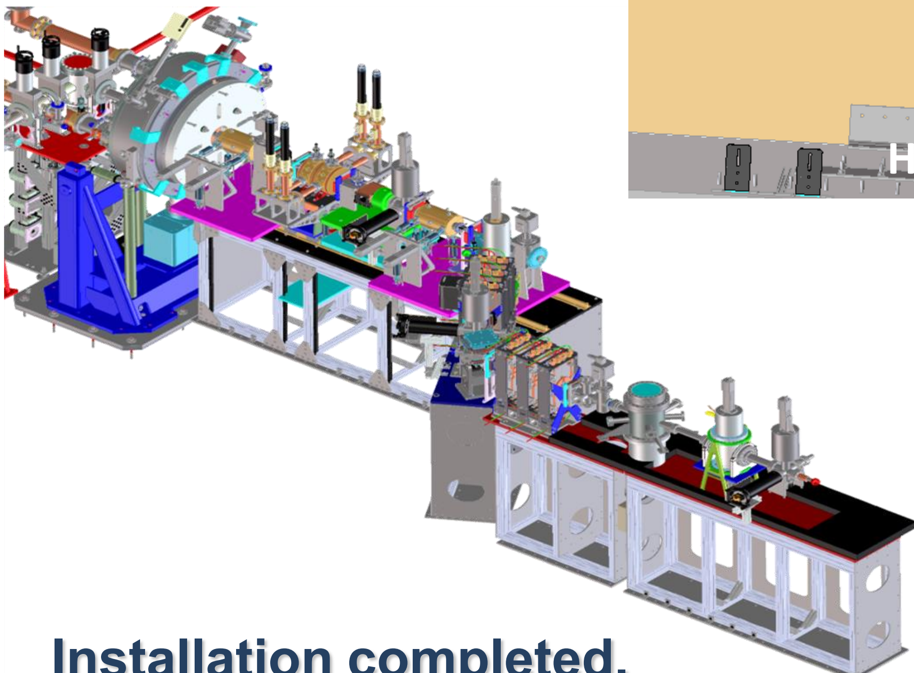
- RF window area redesigned to avoid direct line of sight.
- Parts fabricated and installed to the gun.
- RF conditioning to full power underway.

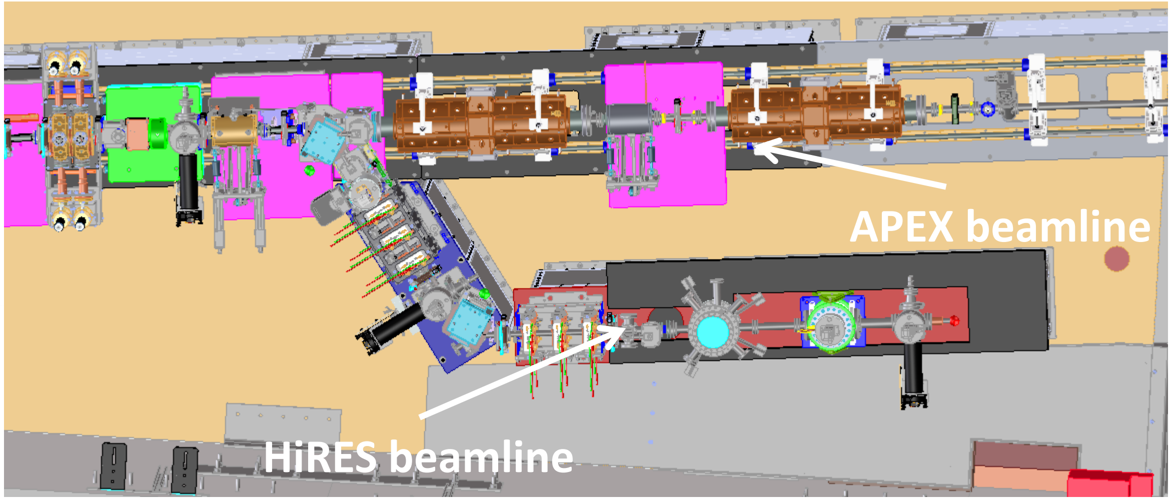
…

HiRES, MHz-Class Repetition Rate UED at APEX

APEX @ Berkeley Lab

DOE Early Career Award to Daniele Filippetto





MHz repetition rate

source properties → Science enabled

source properties	Science enabled
ultra-small pulses	atomic scale snapshots
high average flux	integrated measurements of weakly scattering processes
	matched to droplet injectors for biological sample replacement.
ultra-low charge pulses, high flux	weakly pumped systems
	unperturbed samples
	radiation sensitive materials

Installation completed. First beam delivered in March and experiments coming soon!

Conclusions

- **APEX the prototype injector based on the LBNL VHF-Gun has successfully demonstrated all major parameters, including formal requirements for LCLS-II.**
- **The LCLS-II injector is based on a close version of VHF-Gun that is being fabricated by LBNL.**
- **In the next several months additional tests for LCLS-II will be performed at APEX, including higher charges per bunch beam tests, and reliability tests for the new RF window configuration.**
- **HiRES, the high repetition rate UED beamline at APEX, has delivered its first beam and will initiate experiments in the next few months.**

The APEX Team!

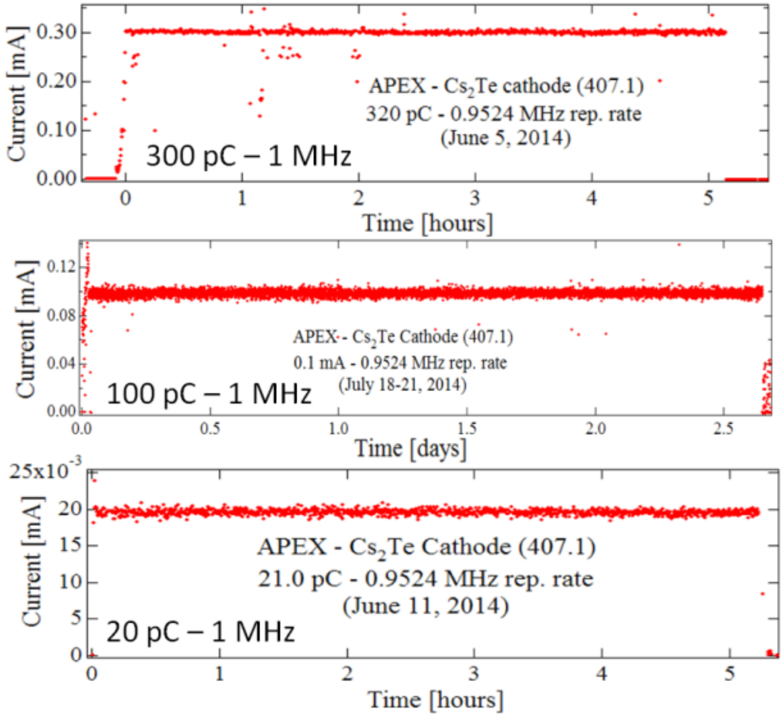
K. Baptiste, C. Cork, J. Corlett, M. Decool, S. De Santis, M. Dickinson, L. Doolittle, J. Doyle, J. Feng, D. Filippetto, D. Gibson, S. Giermann, G. Harris, G. Huang, M. Johnson, M. Kirkpatrick, T. Kramasz, S. Kwiatkowski, D. Leitner, R. Lellinger, R. Li, C. Mitchell, V. Moroz, J. Nasiatka, W. E. Norum, H. Padmore, G. Portmann, H. Qian, H. Rasool, F. Sannibale, J. Schmerge, D. Syversrud, T. Vecchione, M. Vinco, S. Virostek, R. Wells, F. Zhou, M. Zolotorev.

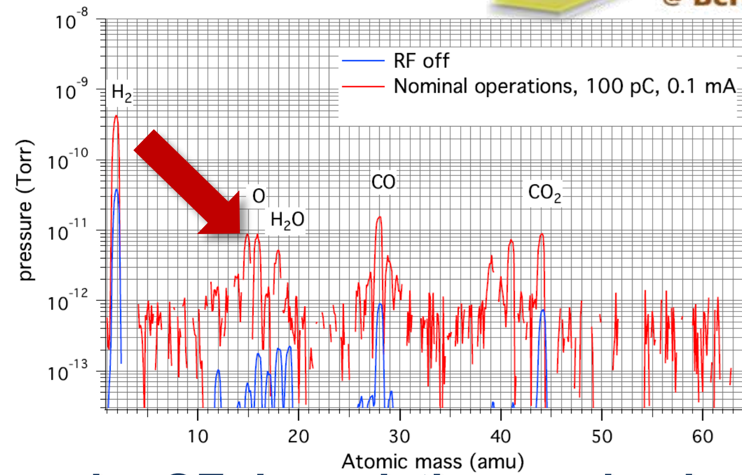
Large part of people is part time on APEX

Backup Viewgraphs

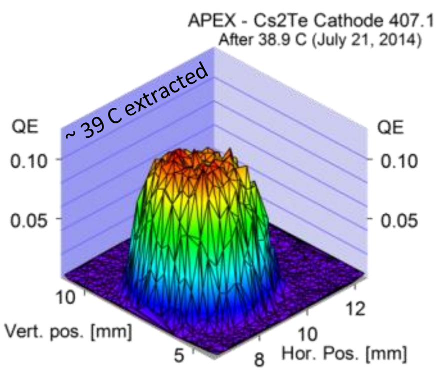
Phase 0-I: Cs_2Te Satisfies with Margin LCLS-II Needs

APeX @ Berkeley Lab



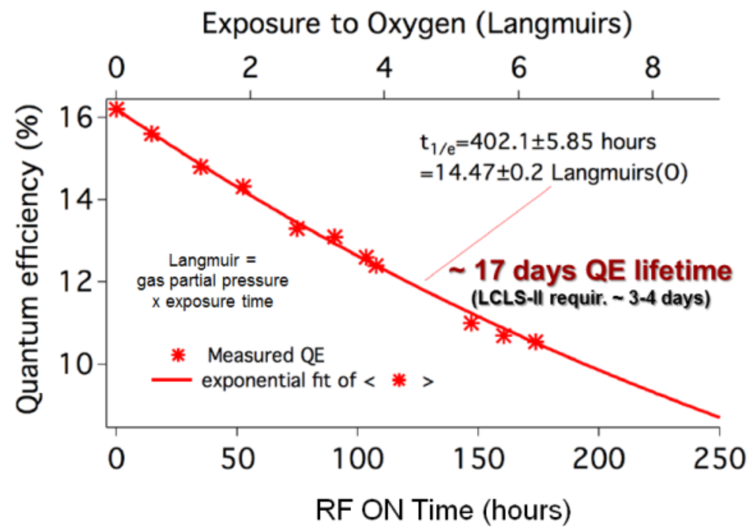


The major QE degradation mechanism for Cs_2Te is oxidation. (A. di Bona, et al. JAP 80,1996).



Cathodes by INFN Milano LASA

No signs of either ion back-bombardment or of laser induced QE depletion after ~ 39 C extracted

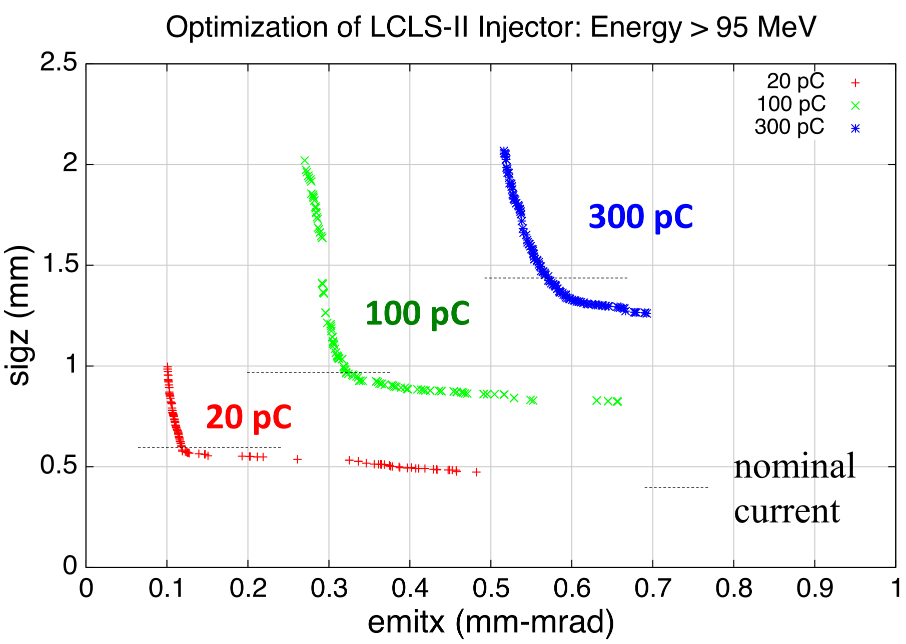


In LCLS-II cathodes will be replaced when the QE drops to 0.5%.
Using the results for Cs_2Te, a cathode will last for ~ 2 months.

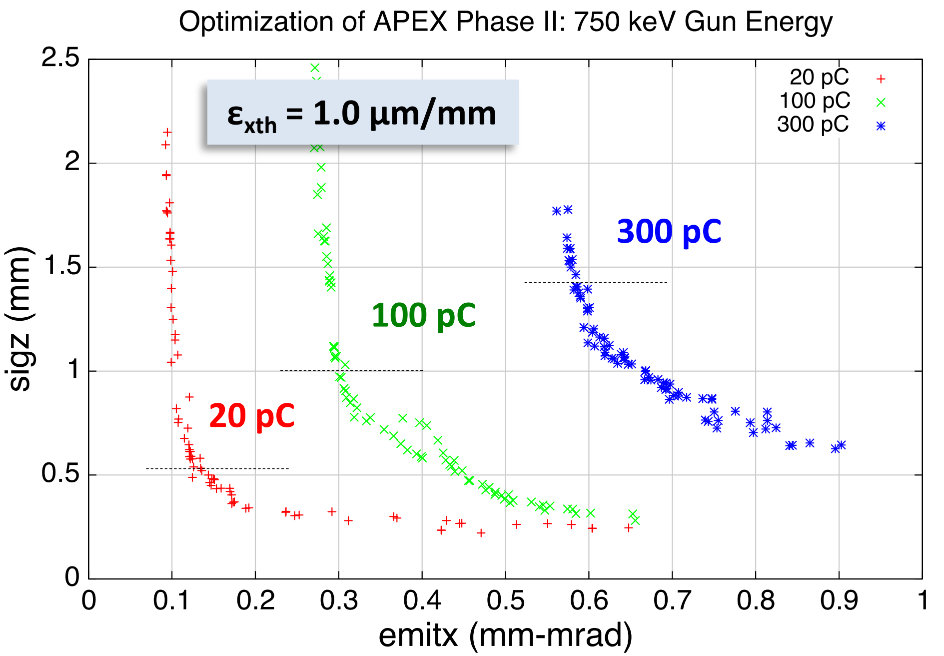
Simulations Shows that the APEX Can Perform at the Required Level.

@ Berkeley Lab

LCLS-II Injector



APEX Phase-II Injector

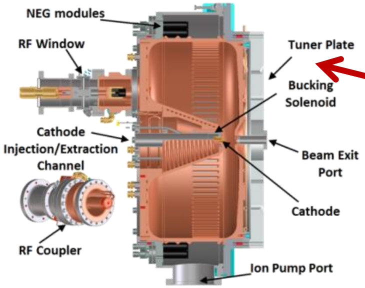


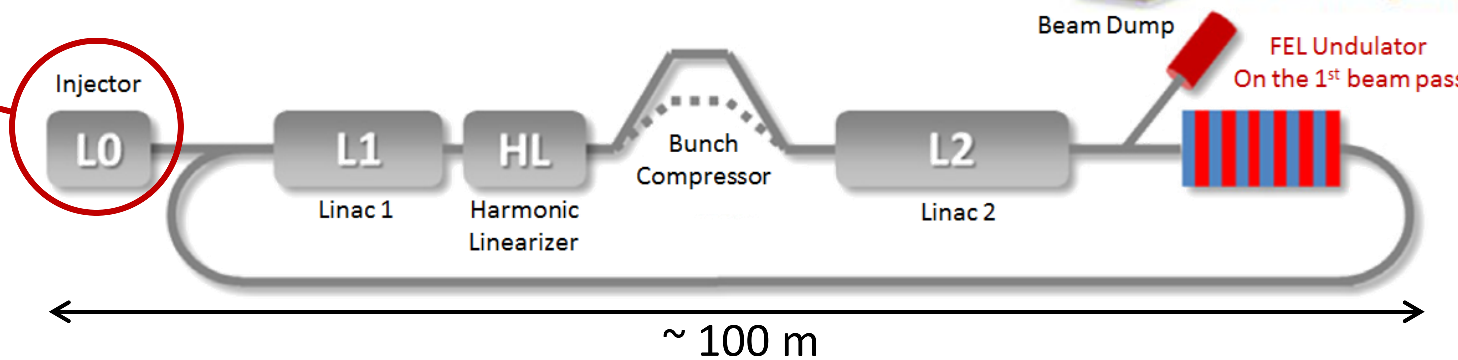
Simulation results are shown using 10K particles – this overestimates emittance in the 100 and 300 pC cases.

APEX goal is to experimentally demonstrate a level of performance sufficient to retire the risk that the VHF-Gun would not be able to deliver the beam quality required for LCLS-II

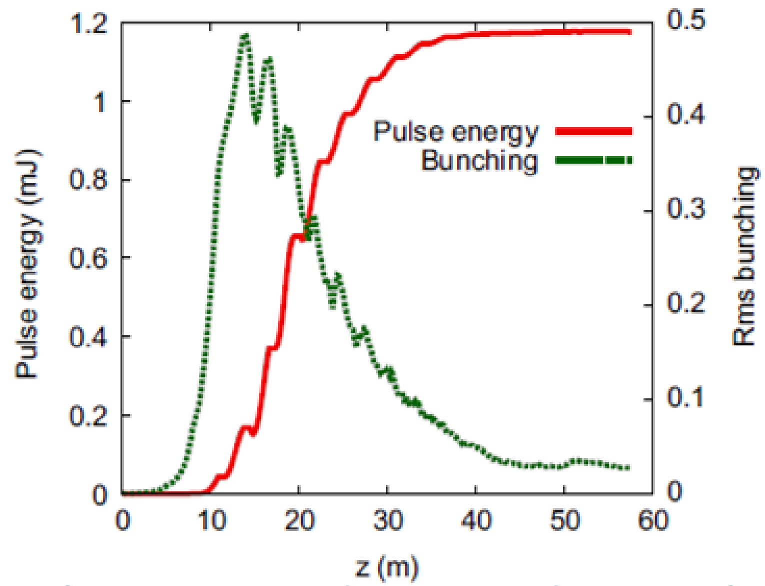
30 kW 13.5 nm EUV FEL with Energy Recovery

APeX @ Berkeley Lab





Energy at undulator	600 MeV
Bunch charge	300 pC
Inj. peak current	45 A
Inj. rms emittance	0.6 μm
Und. peak current	550 A
u-Period λ_u	18 mm
u-Parameter K (max.)	1
u-Length L_u	26 m
Gain length L_g	~0.5 m
Avg. beta functions $\beta_x = \beta_y$	5.3 m
FEL efficiency η	0.5%

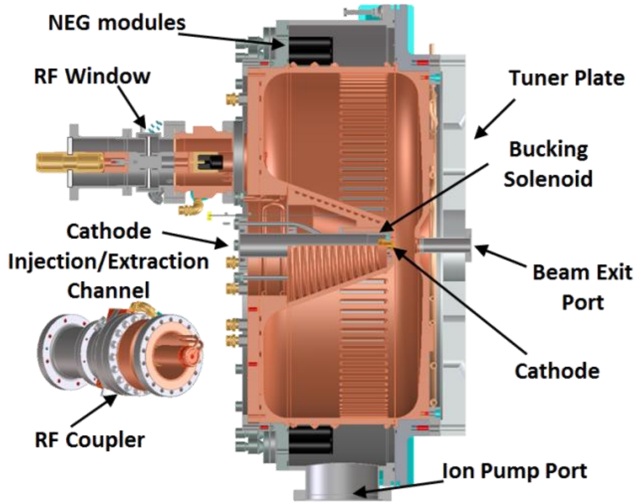


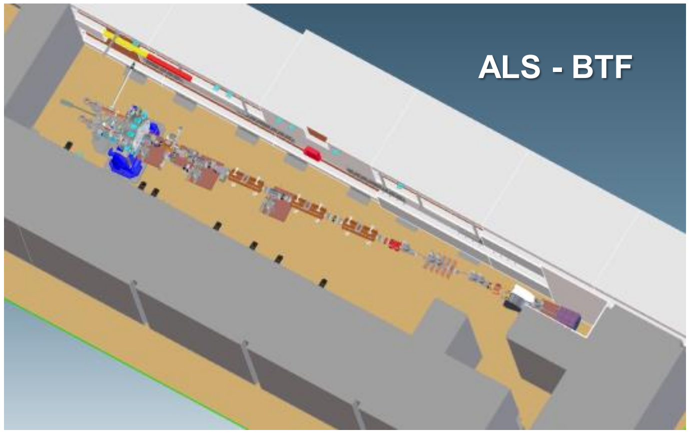
For ~ 30 kW EUV, as presently required by the semiconductor industry, the facility has to operate at ~25 MHz repetition rate (~7.5 mA average current)

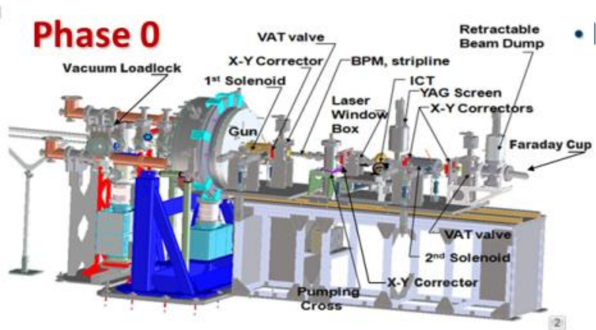
M. Venturini, G. Penn, *A non-conventional ERL configuration for high-power EUV FELs*, NIMA 795, 219 (2015)

The Three Phases of the APEX Project

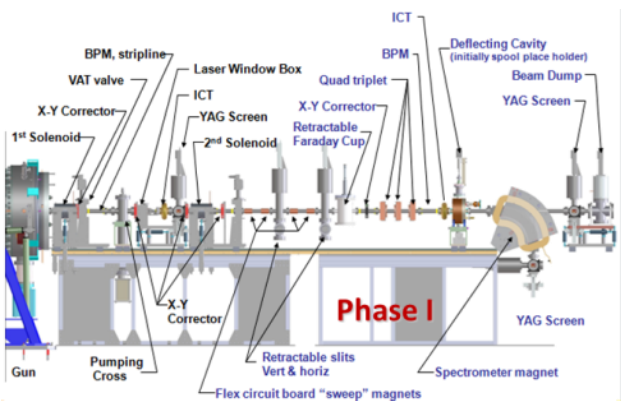
APEX @ Berkeley Lab



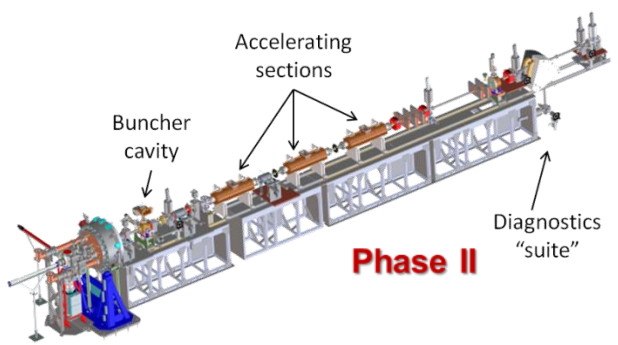




VHF Gun performance demo. Photocathode tests. (Completed)



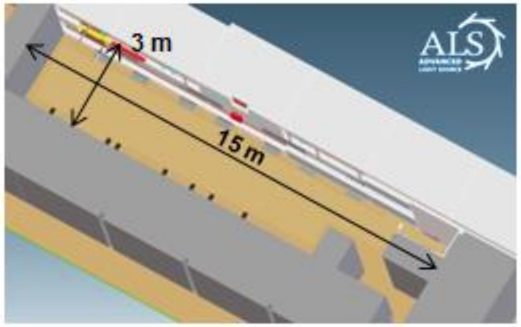
Beam characterization at the gun energy. Cathode tests. (Completed)



Full performance demonstration at relativistic energy. (Installation completed – in operation)

APEX: the Advanced Photoinjector EXperiment

APEX @ Berkeley Lab



Located in the Beam Test Facility (BTF) at the ALS.

ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

LDRD in 2009

DOE-BES 2009-15

LCLS-II 2015-16

Main Goals:

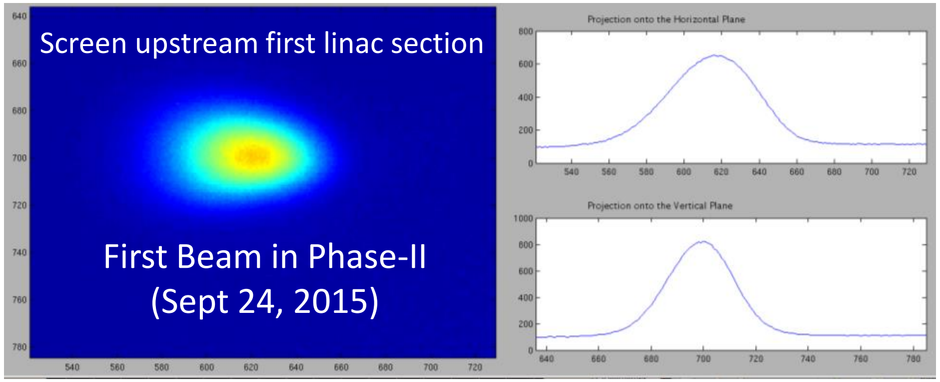
- **Demonstrate the *RF and Vacuum Performance of the VHF-Gun.***
- **Characterize and *identify high QE photocathodes* capable to operate at the challenging regime imposed by MHz-class FELs (LCLS-II).**
- ***Dark current* characterization, define removal techniques.**
- **Demonstrate FEL-quality *bunch compression* and *high-brightness* capability of an injector based on the VHF-Gun.**

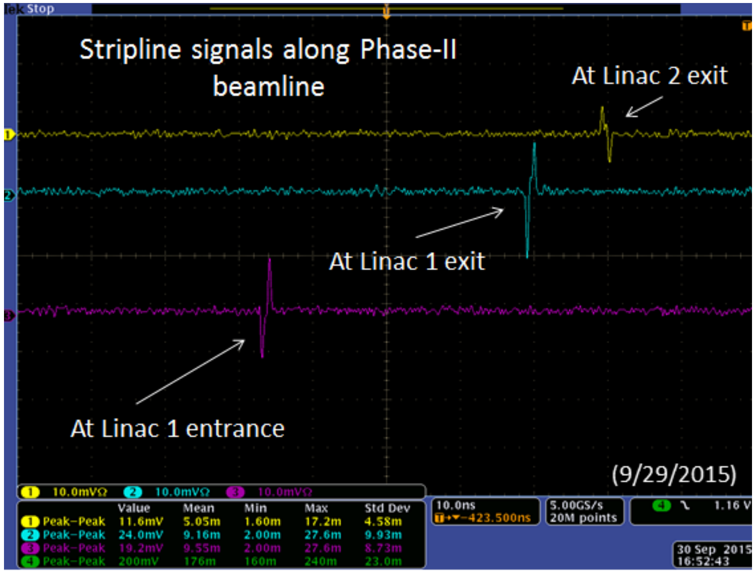
Additional Goals:

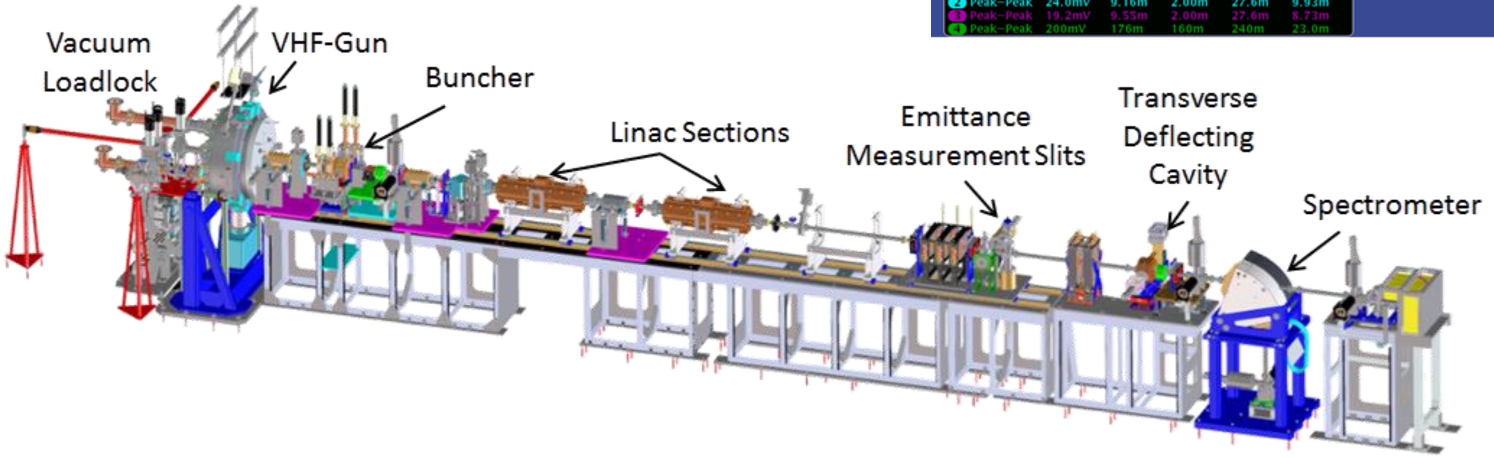
Identify (and possible procure funds) additional possible applications that could exploit APEX capability.

APEX Phase II Commissioning Progress: First Beam

On September 24, Phase-II installation was completed and the first beam (~ 1 pC) was generated and progressively transported through the linac in the following days.





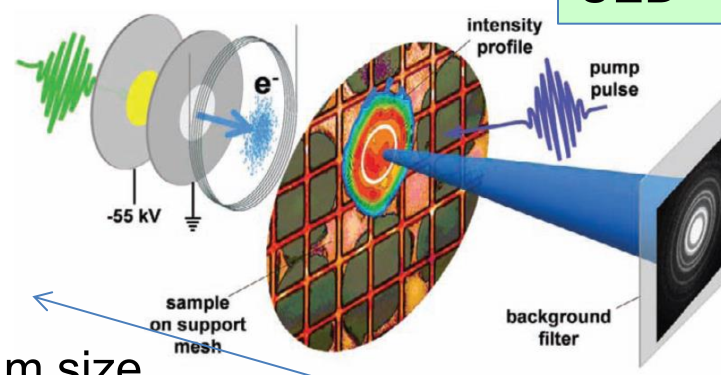


Ultra-Fast Diffraction: Photons vs. Electrons

X-FEL

Km size

UED



m size

Thomson

$$\sigma_T = \frac{8\pi}{3} r_e^2 = 6.65 \cdot 10^{-25}\ cm^2$$

Rutherford

$$\sigma_{el} = \frac{h^2 Z^{4/3} c^2}{\pi E_0^2 \beta^2} = 8.57 \cdot 10^{-20}\ cm^2$$

- Probing with electrons can be better for surfaces, thin films, gas phase
- Damage in biological samples 400-1000 times less
  - Elastic/inelastic scattering ratio 3 times higher than for X-ray
  - Energy deposited per inelastic scattering event:
    20 eV for 500 KeV electron vs. 8 KeV for 1.2 Å x-ray

Courtesy of Daniele Filippetto