Recent Results From The APEX Project at LBNL

Fernando Sannibale

NA-PAC 2013, Pasadena, CA USA
October 2, 2013

The APEX Team!

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

Large part of people is part time on APEX

Outline

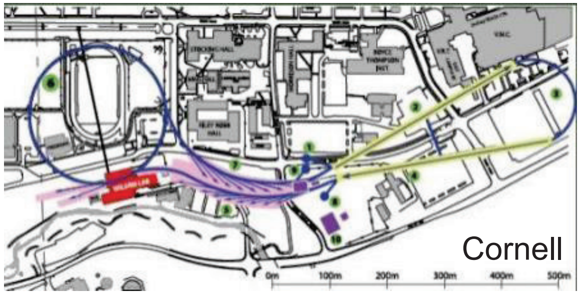
- Why do we need high-brightness, high-repetition rate electron injectors?
- The VHF Gun, the LBNL response to that need.
- The APEX project at LBNL, a bench test for the VHF Gun.
- Status and recent results of APEX.
- APEX Future Plans.

Science Driven Proposals!

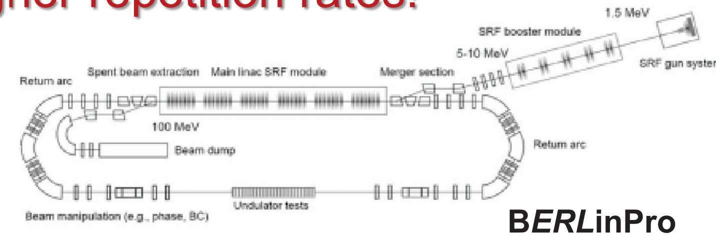
APeX @ Berkeley Lab

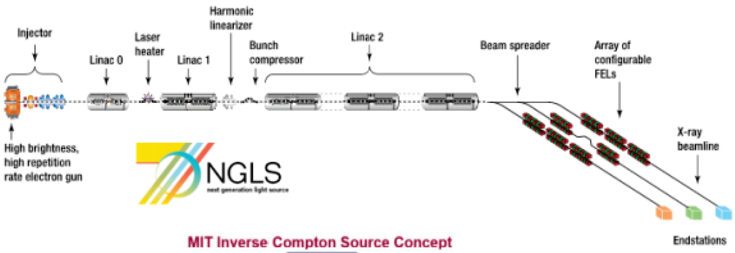
All operating 4[th] generation light sources are low repetition rate (< 120 Hz)

But science is driving towards much higher repetition rates!

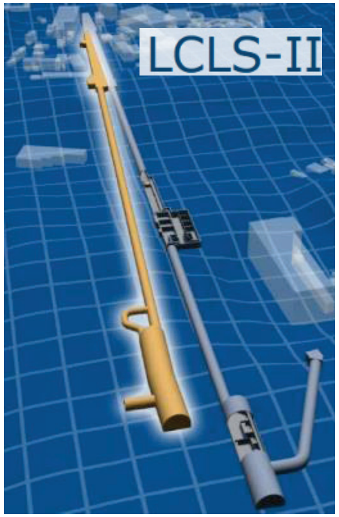


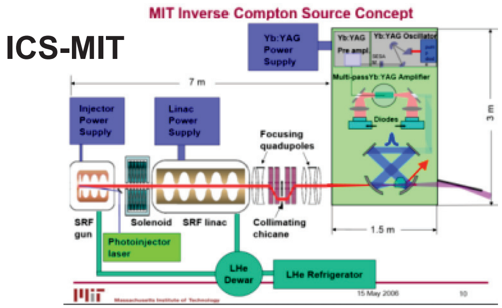
Proposed X-ray ERLs require the same beam quality at GHz repetition rates.

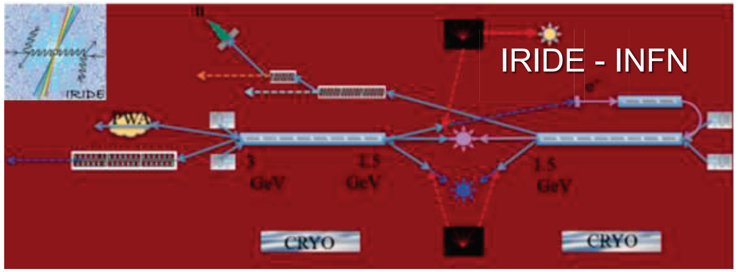


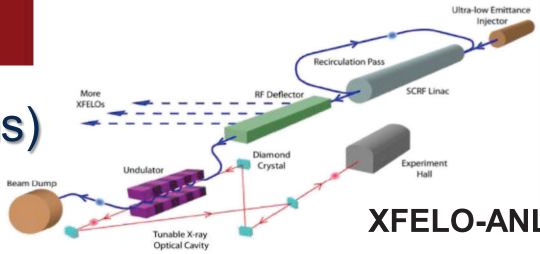


And proposed high repetition rate X-ray FELs, FEL oscillators and inverse Compton sources all require the similar beam quality at MHz repetition rates.









High repetition rate wakefield accelerators (drive and main beams)

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

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:

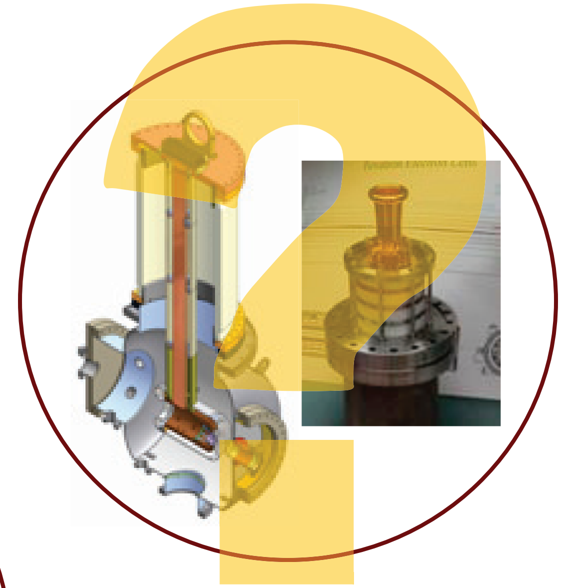
Repetition rate	Up to ~ 1 MHz	
Charge per bunch	~ 10 – 300 pC	Different modes of operation
Normalized emittance	~ 0.2 – 0.6 μm	Lower value for lower charge
Beam energy at the gun exit	>~ 500 keV	For controlling space charge
Cathode electric field at photoemission	>~ 10 MV/m	Space charge limit; maximum brightness limit
Bunch length and shape control	From < 1 to ~ 50 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 (>~95%)	Required for an user facility

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

Available Technologies

High frequency (> 1 GHz) normal-conducting RF

Super-conducting RF



DC gun

Not usable

R&D required

No ready to go solution was available!

The LBNL Electron Gun Concept

CBP Tech Note 366

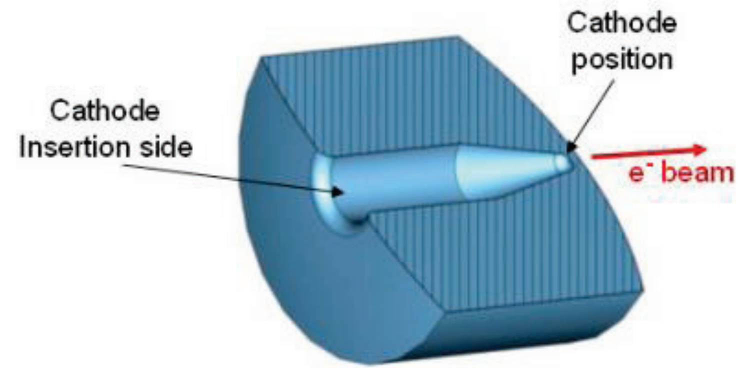
VHF-band Photoinjector

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

26 October 2006

Introduction

New generation accelerator-based x-ray light sources require high quality electron beams. Parameters such as transverse emittance (projected or "sliced"), energy spread and bunch length for beams in the nC charge range, need to be pushed beyond their present limits for the successful operation of light sources such as Energy Recovery Linacs (ERL) and Free Electron Lasers (FEL). At the same time, the demand for a high average brightness is also driving towards technologies capable of very high repetition rate operation. The overall performance is greatly determined at the accelerator injector and in particular, at the electron gun.

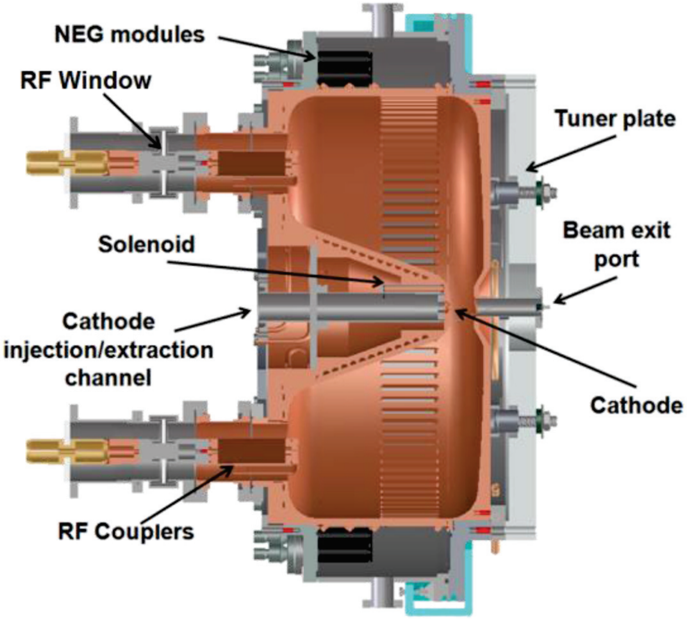


Originally it was a "spoke cavity" that became gradually a quarter wave structure and finally a "reentrant nose" cavity.

The initial frequency was 65 MHz and…

The LBNL VHF RF Gun

The Berkeley normal-conducting scheme satisfies all the LBNL FEL requirements simultaneously.



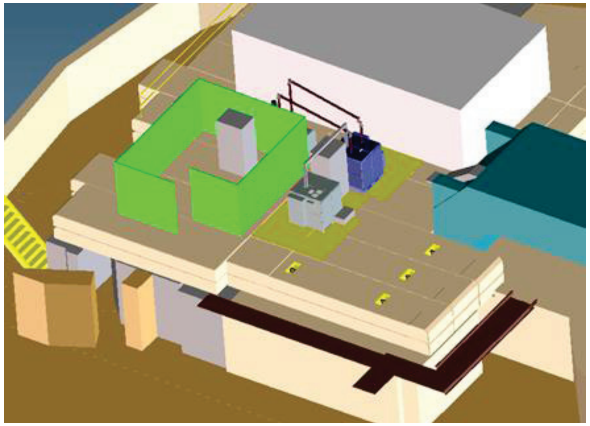
J. Staples, F. Sannibale, S. Virostek, CBP Tech Note 366, Oct. 2006

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

Frequency	186 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 @ 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

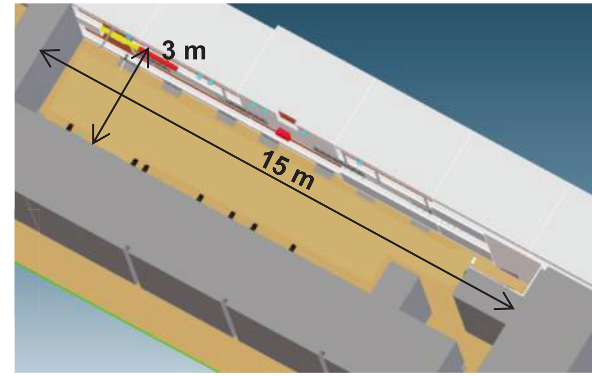
- At the VHF frequency, the cavity structure is large enough to withstand the heat load and operate in CW mode at the required gradients.
- Also, the long λ_{RF} allows for large apertures and thus for high vacuum conductivity.
- Based on mature and reliable normal-conducting RF and mechanical technologies.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

APEX: the Advanced Photoinjector EXperiment



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

BES **LDRD**



Main Goals:

Demonstrate the *bunch compression* and *high-brightness* capability of an injector based on the LBNL VHF Gun.

***Cathode physics*: selection of the best cathode for NGLS-like FEL.**

Additional Goals:

***Diagnostics*: demonstrate diagnostics systems for NGLS-like FEL.**

***Dark current* characterization, removal techniques.**

Injector *jitter and noise* characterization.

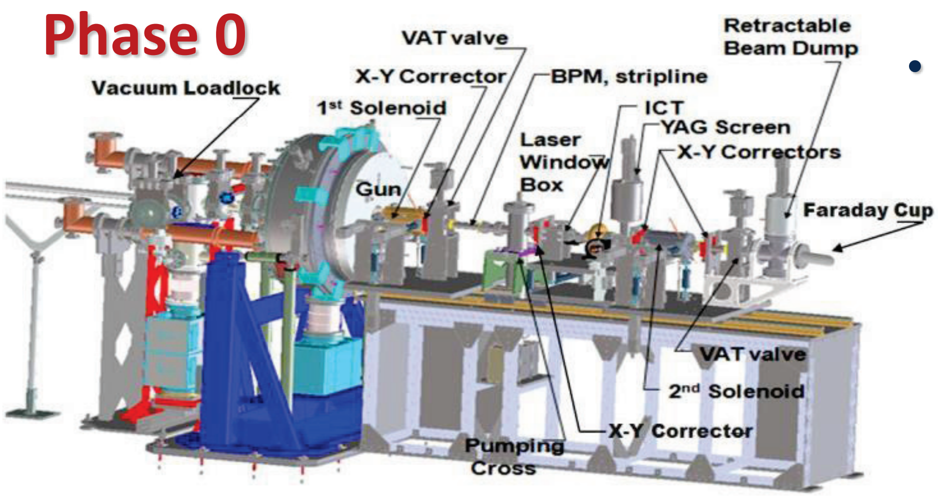
Development of a *fast equipment protection system*

…

Low energy *collimation* schemes.

***New undulator technology* test, … (funds?).**

APEX: Phases 0 & I



Phase 0 scope:

- Demonstration of the RF performance at full repetition rate.
- Vacuum performance demonstration.
- Dark current characterization.
- High QE cathode physics (QE and lifetime measurements)

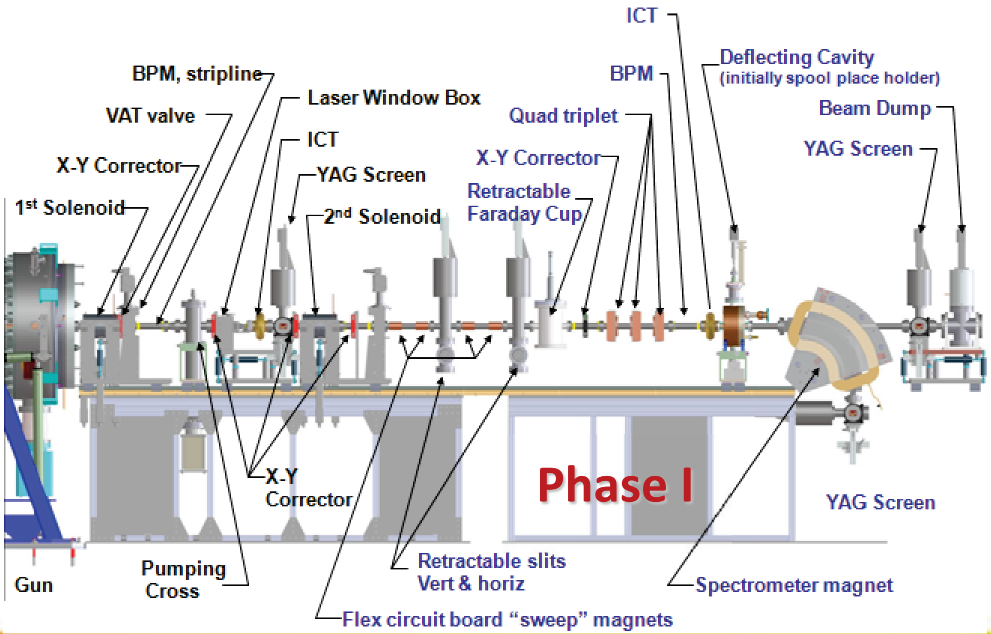
Funded.
Under commissioning

Phase I scope:

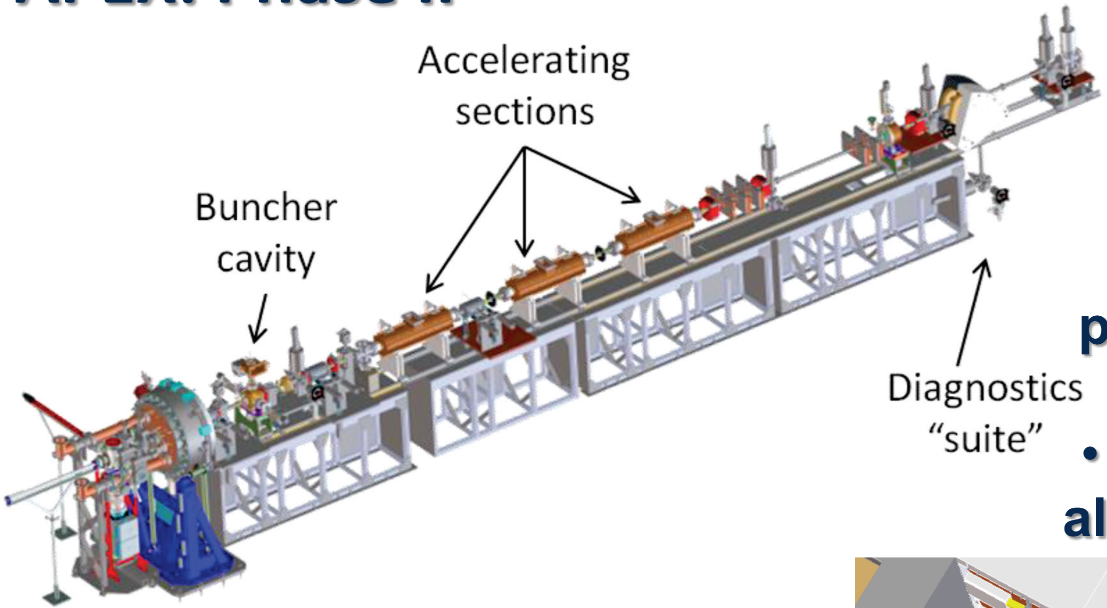
(Phase 0 + extended diagnostics)

- High QE cathode physics (Intrinsic emittance measurements)
- Diagnostics systems tests.
- Low energy beam characterization and comparison with simulations

If funding profile confirmed
Initial operation in early 2014

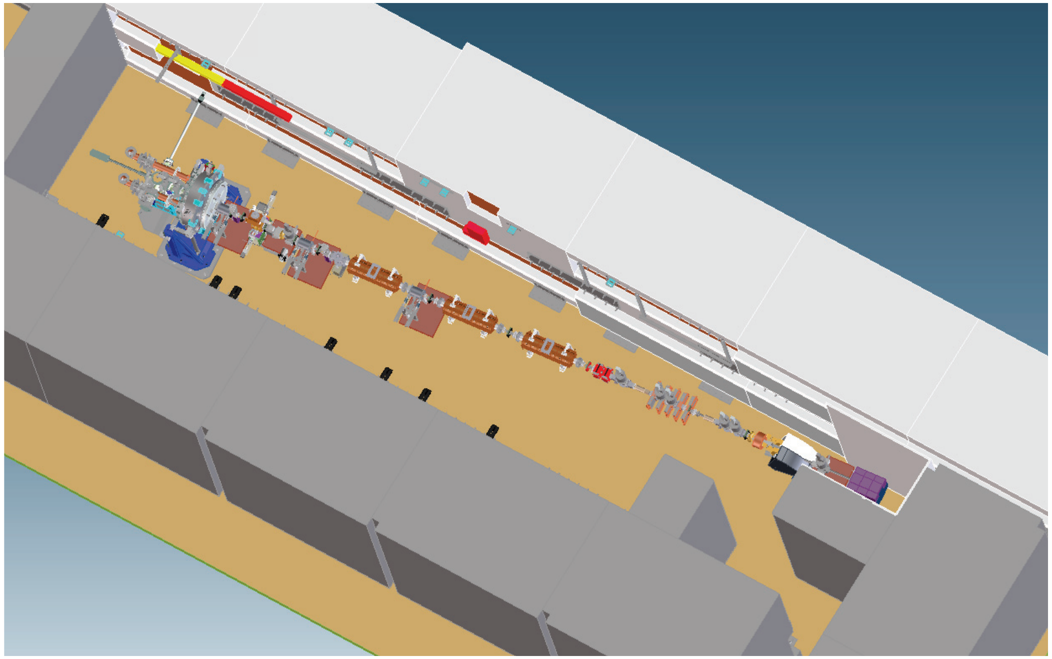


APEX: Phase II



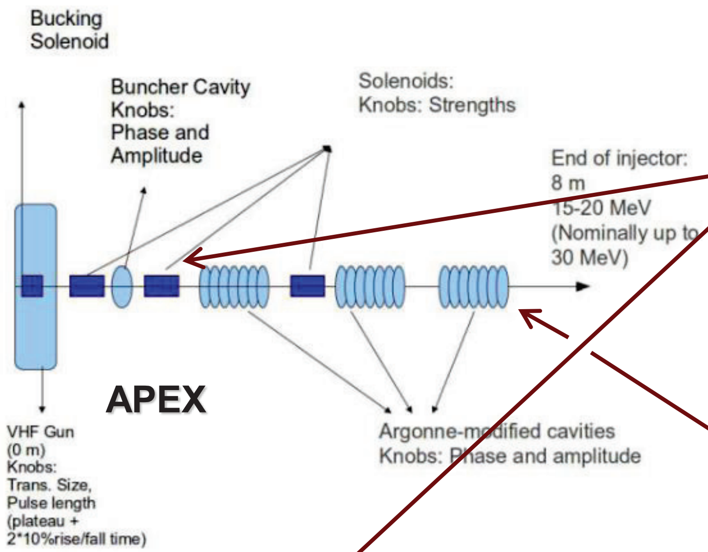
Phase II scope:

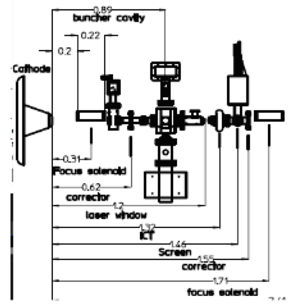
- **Demonstration of the *brightness* and *compression* performance at ~ 30 MeV at low repetition rate.**
- **Reduced space charge forces allow for reliable measurements.**



If funding profile confirmed operation in early of 2015

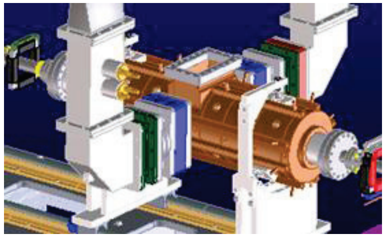
APEX: a Cost Effective Test Bench for Critical Issues in High Rep. Rate Injectors

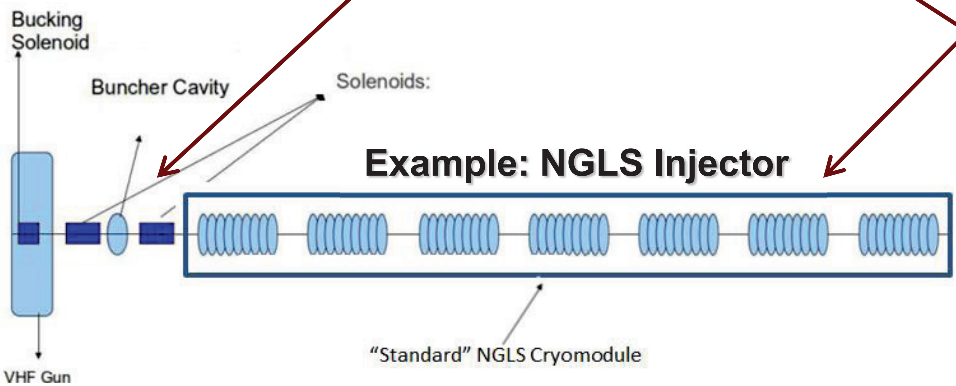




Up to the first accelerating cavity layouts and components are identical.

Modified* ANL-AWA acc. cavities very similar to typical 1.3 GHz SRF cavity (same frequency, multicell, standing wave, similar beam pipe sizes, ...).
*Optimized for multipole minimization.





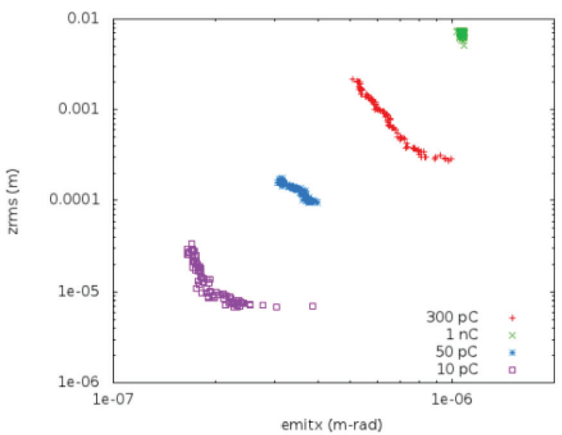
APEX is a cost-effective "representative" of a typical high repetition rate injector. All relevant beam dynamics issues represented and ready to be investigated.

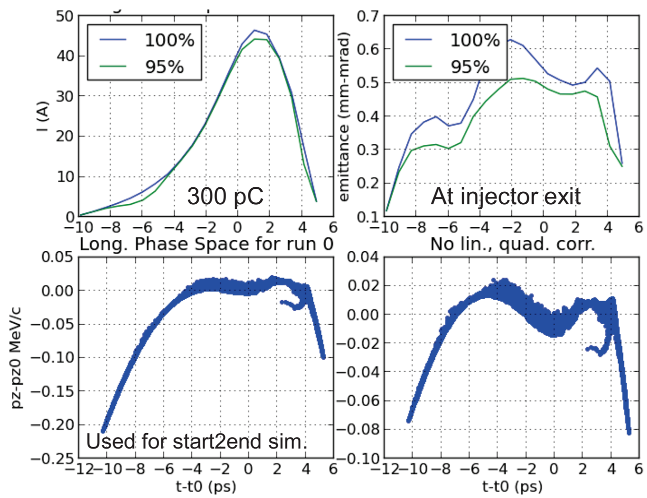
Large beam apertures and μs bunch distance make long range wakes non important (see FLASH), and hence the reduced repetition rate in APEX is appropriate.

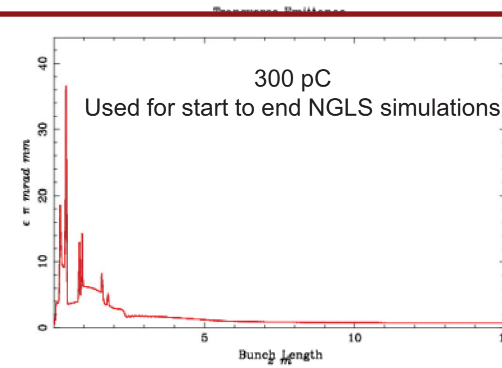
Beam Dynamics Simulations

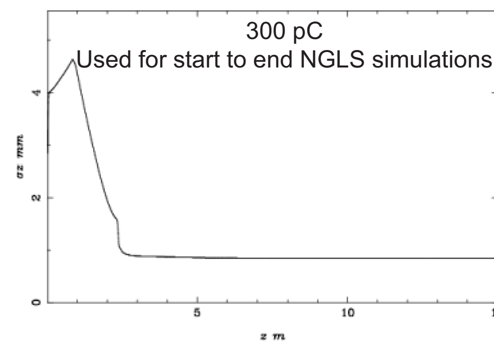
Extensive simulations and studies (inclusive of start to end simulations including linac and FELs) are showing that the task can be accomplished.

NGLS-Injector example.









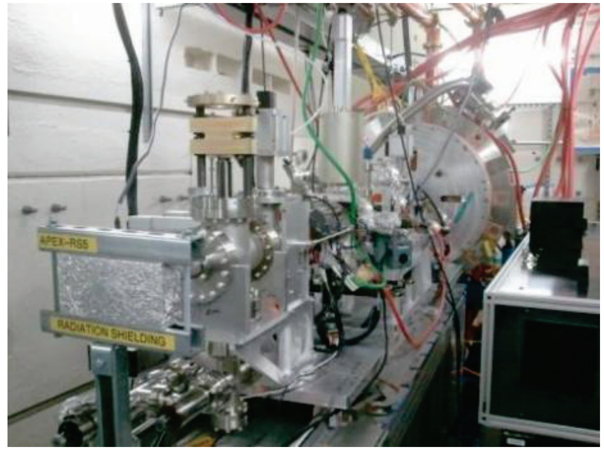
- **Multi-Objective Genetic Algorithms optimization, trading for example, between final emittance and bunch length, "regularity" of the longitudinal phase space, distribution symmetry, …**

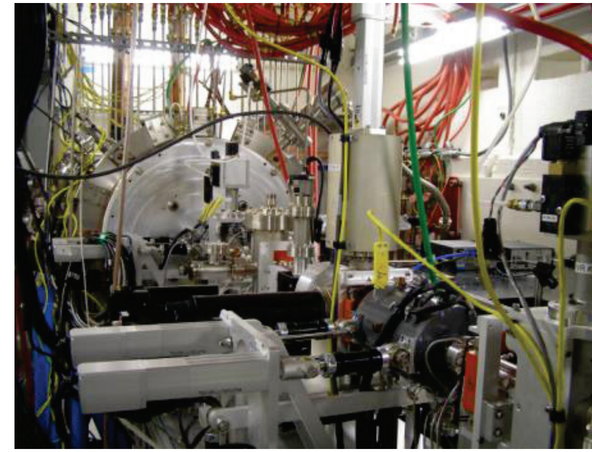
C. Papadopoulos

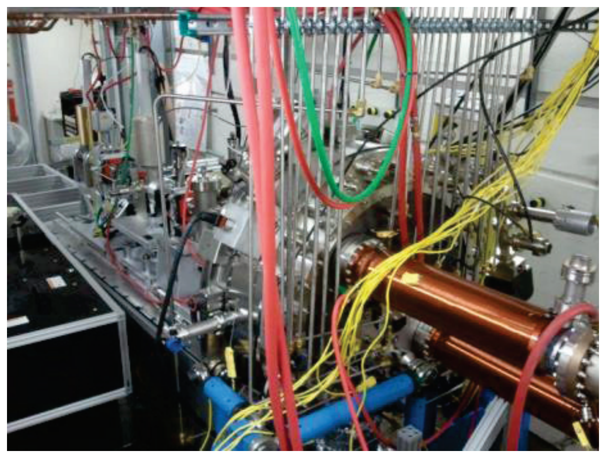
The same simulations show the interdependence of the transverse and longitudinal "knobs", and the need of a "6D" injector tuning" (Simultaneous compression and emittance compensation).

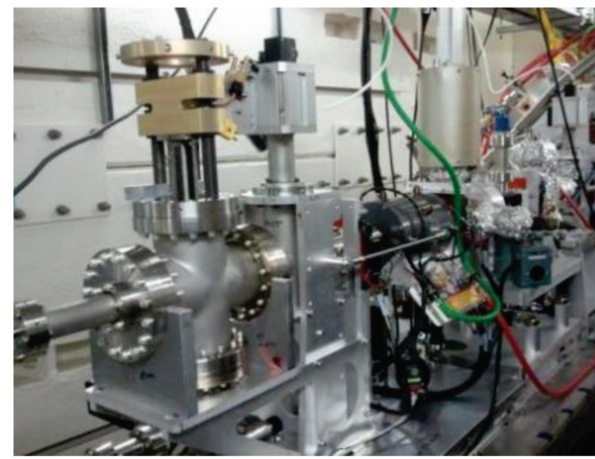
It is important for such a performance to be demonstrated experimentally.

Phase 0 Beamline Installed



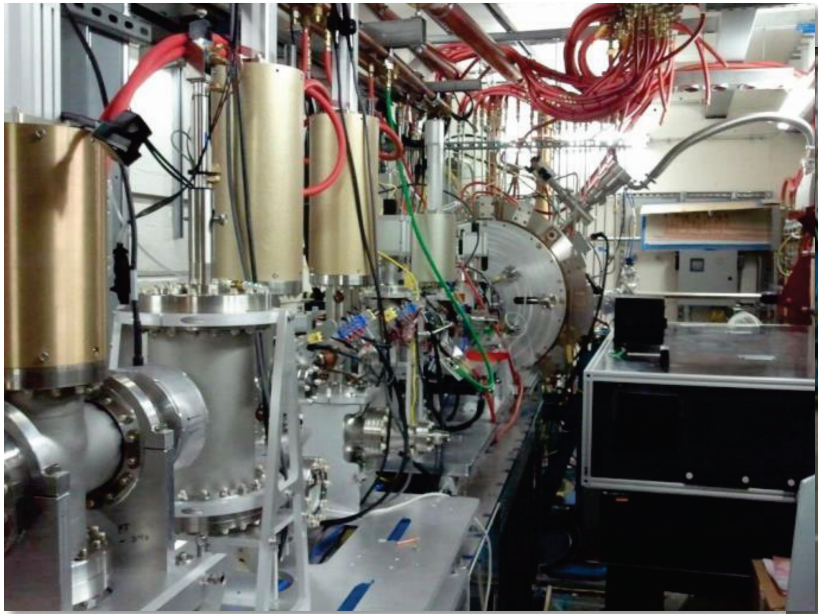






APEX Phase I Installation in Progress

- Phase I supports installed and aligned.
- 2-slit emittance measurement system installed (based on Cornell scheme)
- Spectrometer system under installation
- Transverse deflecting cavity under fabrication (based on Cornell system)



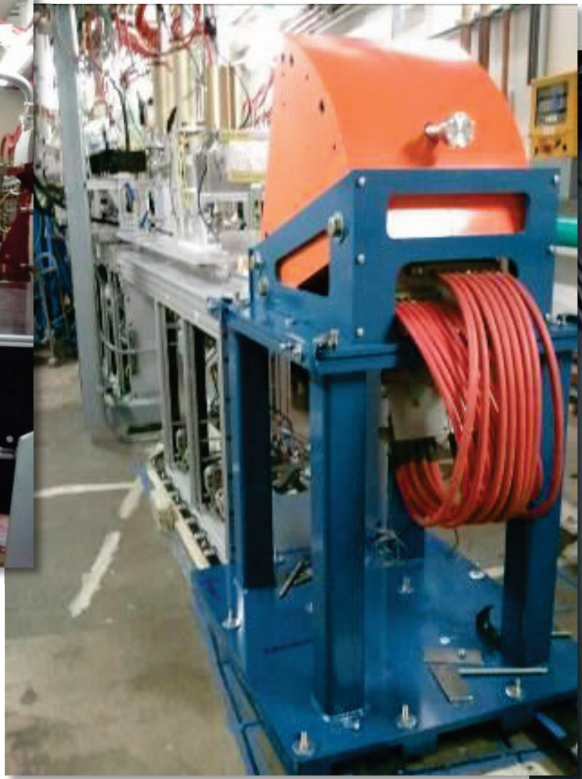
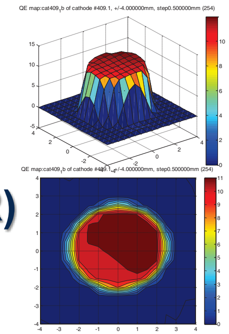
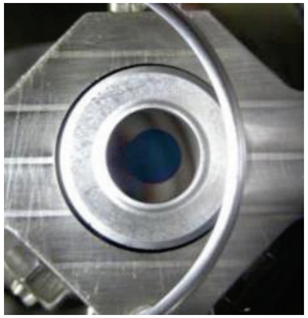


Photo-Cathodes for APEX

PEA Semiconductor: Cesium Telluride Cs_2Te (In collaboration with INFN-LASA)

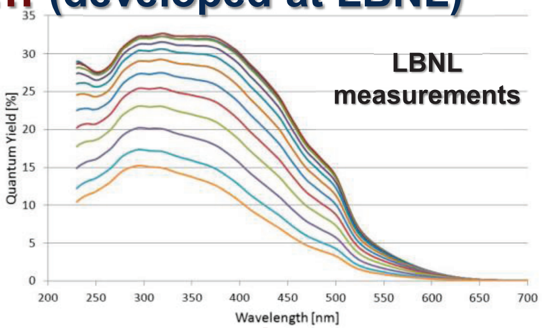
- <~ps pulse capability
- relatively robust and un-reactive (operates at ~ 10^{-9} Torr)
- successfully tested in NC RF and SRF guns
- high QE > 1%
- photo-emits in the UV (~250 nm) ($3^{rd}/4^{th}$ harm. conversion from IR)
- for 1 MHz reprate, 1 nC, ~ 10 W 1060nm required





First 3 cathodes successfully developed at INFN/LASA and delivered to LBNL.

PEA Semiconductor: Alkali Antimonides CsK_2Sb, … (developed at LBNL)



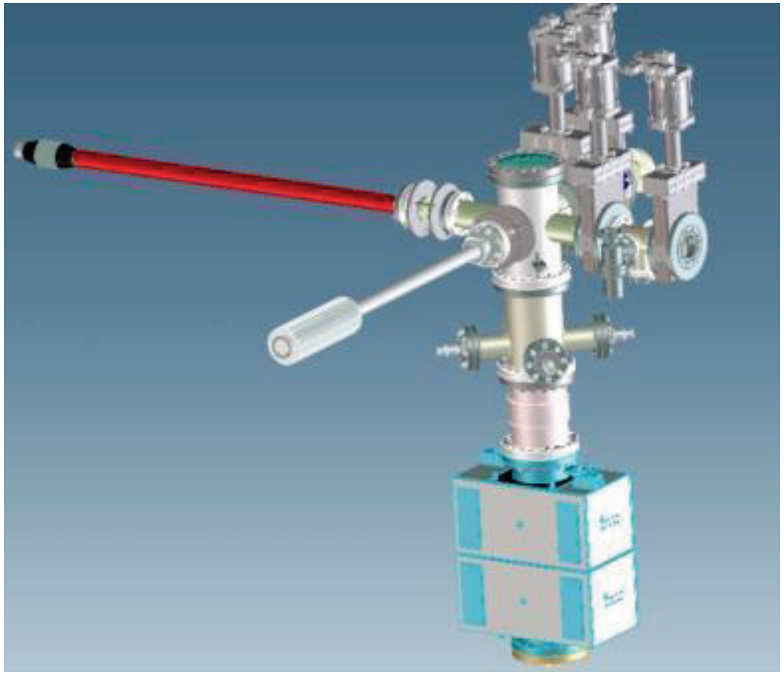
- <~ps pulse capability
- reactive; requires ~ 10^{-10} Torr pressure
- high QE > 1%
- requires visible light (eg. 2^{nd} harm. Nd:YVO4 = 532nm)
- for nC, 1 MHz reprate, ~ 1 W of IR required

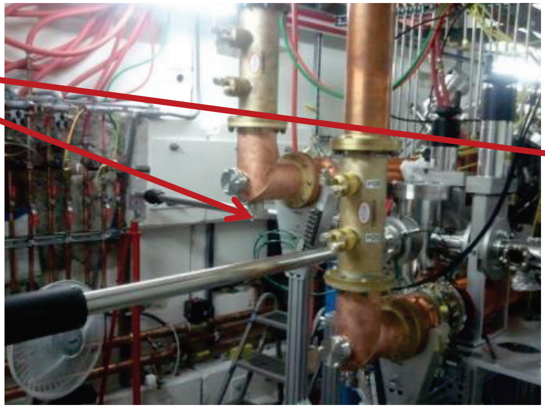
Cathodes development at LBNL (H. Padmore's group).
Promising lifetime and intrinsic emittance results (Cornell and LBNL).
Preparation& transfer chamber completed (1^{st} high QE cathode generated).

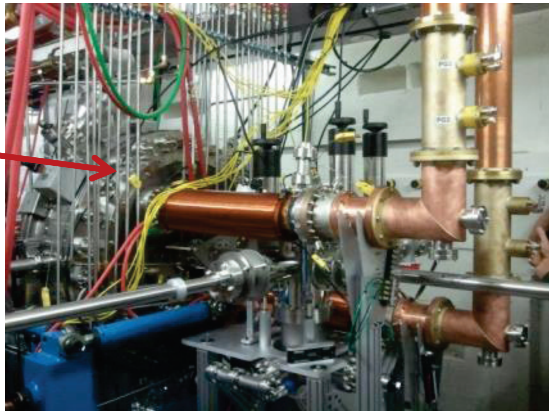
Other cathodes under consideration for future tests on APEX.

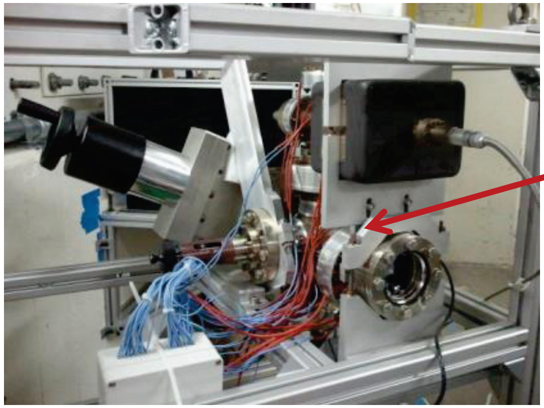
Vacuum Load Lock System

Installation completed.
Baking to start.





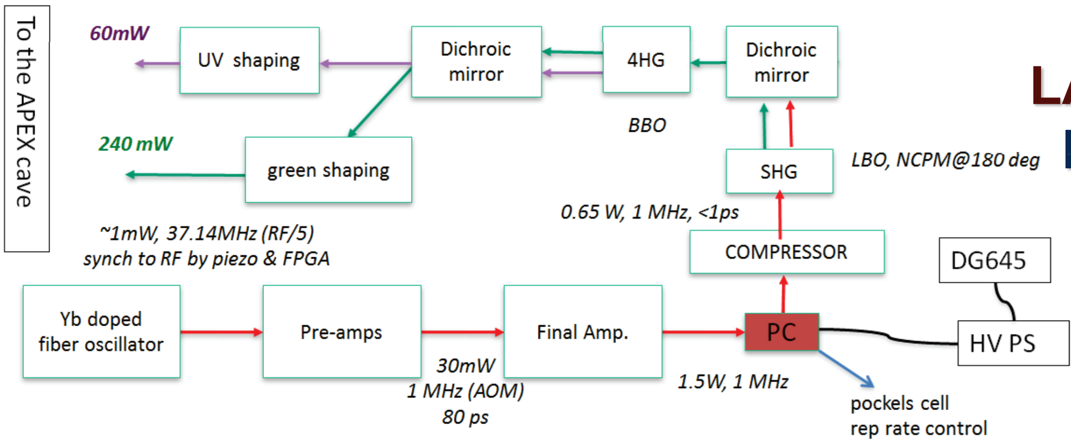




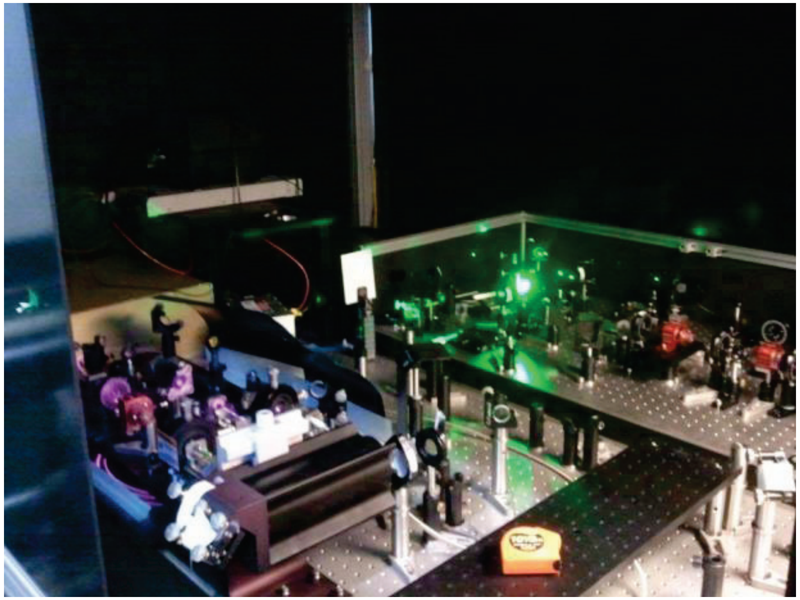
Vacuum "suitcase" compatible with airplane transportation (NEG pump)

Collaboration with INFN – LASA
Adapted version of the INFN/PITZ/FLASH load-lock system

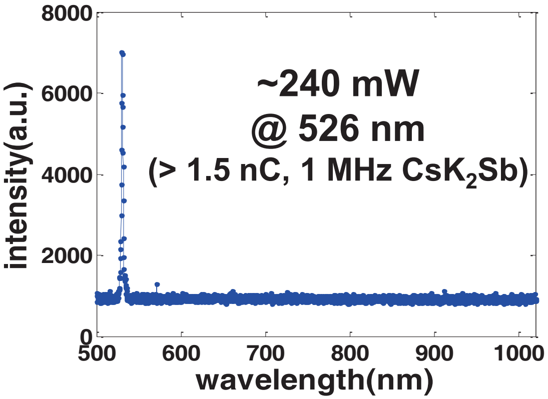
Photo-Cathode Laser

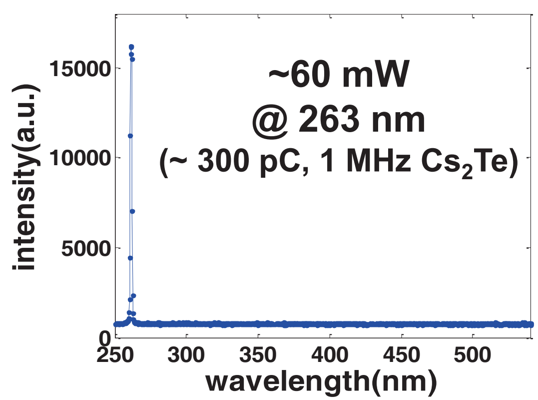


LASER 1: 1 MHz reprate Yb fiber laser from a LLNL/UCB/LBNL collaboration.



Present: 0.7 W at ~1052 nm.
Margin for improvement.



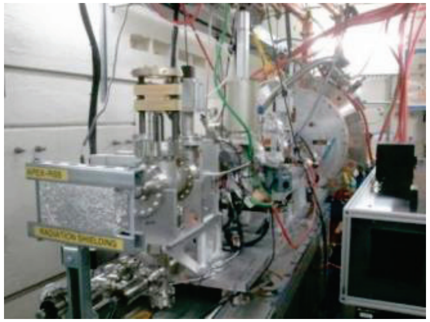


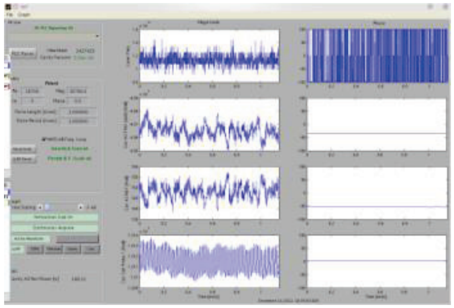
D. Filippetto, J. Feng

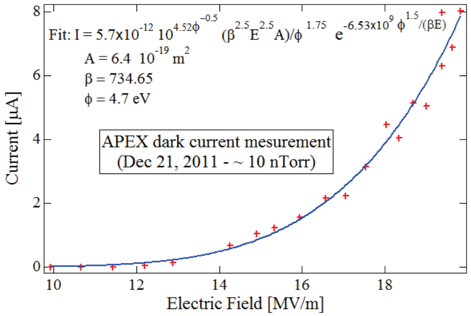
LASER 2: Commercial 1 MHz 2 W Calmar 1052 nm being installed.

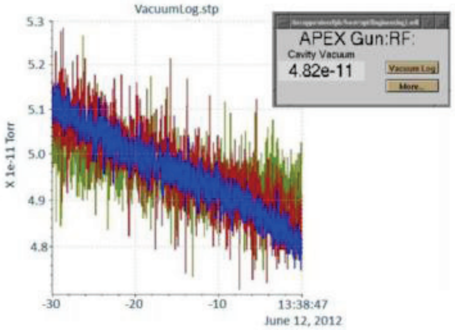
APEX VHF Gun Commissioning

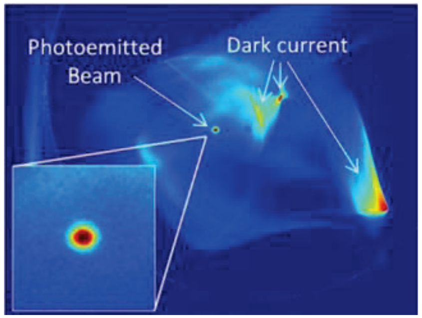
- **Gun and Phase 0 beamline built and installed.**
- **Gun reliably operated in CW at nominal RF power.**
- **Dark current characterized: < ~ 1 μA (acceptable level)**
- **Required vacuum performance demonstrated.**
- **First photo-emitted electron beam with low QE cathode generated.**
- **Photo-emitted electron beam nominal energy demonstrated.**

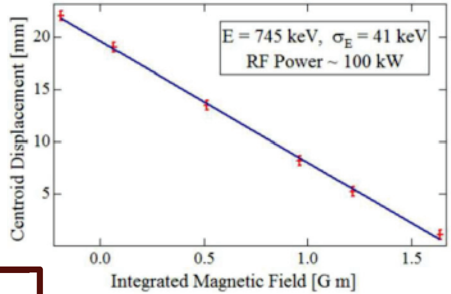








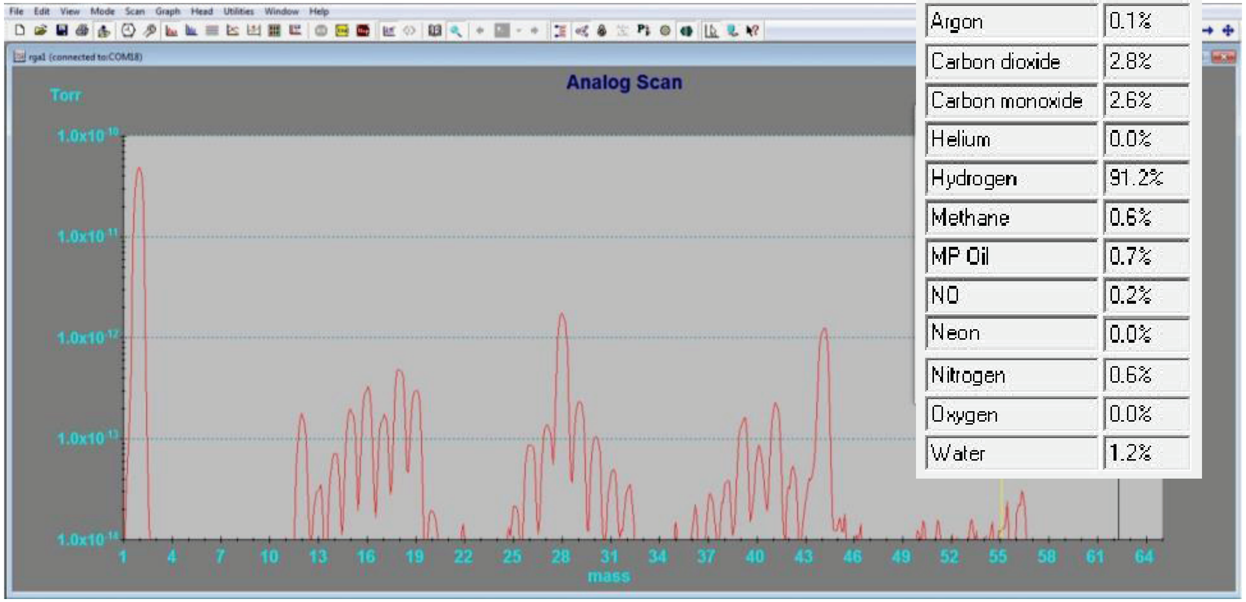




Gun technology fully demonstrated!

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

APEX Gun RGAs (RF OFF vs. RF ON)

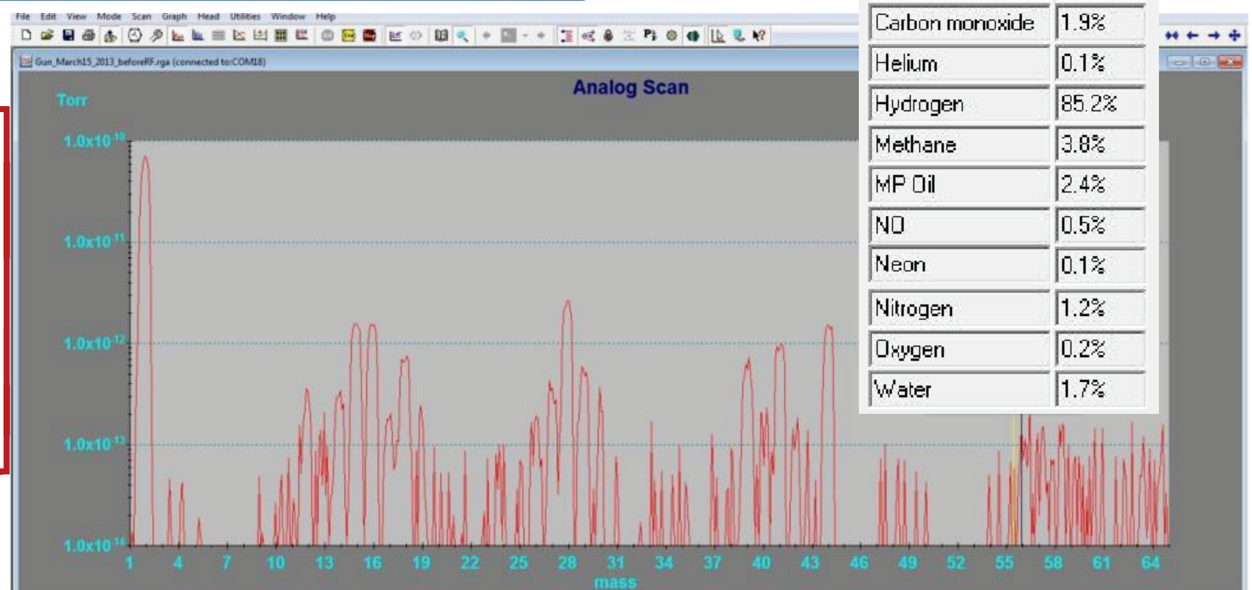


Argon	0.1%
Carbon dioxide	2.8%
Carbon monoxide	2.6%
Helium	0.0%
Hydrogen	91.2%
Methane	0.6%
MP Oil	0.7%
NO	0.2%
Neon	0.0%
Nitrogen	0.6%
Oxygen	0.0%
Water	1.2%

RF OFF:

P_{TOT} ~ 3 10^{-11} Torr.

Largely H_2 and H_2O, CO and CO_2 at percent level



Argon	0.6%
Carbon dioxide	2.2%
Carbon monoxide	1.9%
Helium	0.1%
Hydrogen	85.2%
Methane	3.8%
MP Oil	2.4%
NO	0.5%
Neon	0.1%
Nitrogen	1.2%
Oxygen	0.2%
Water	1.7%

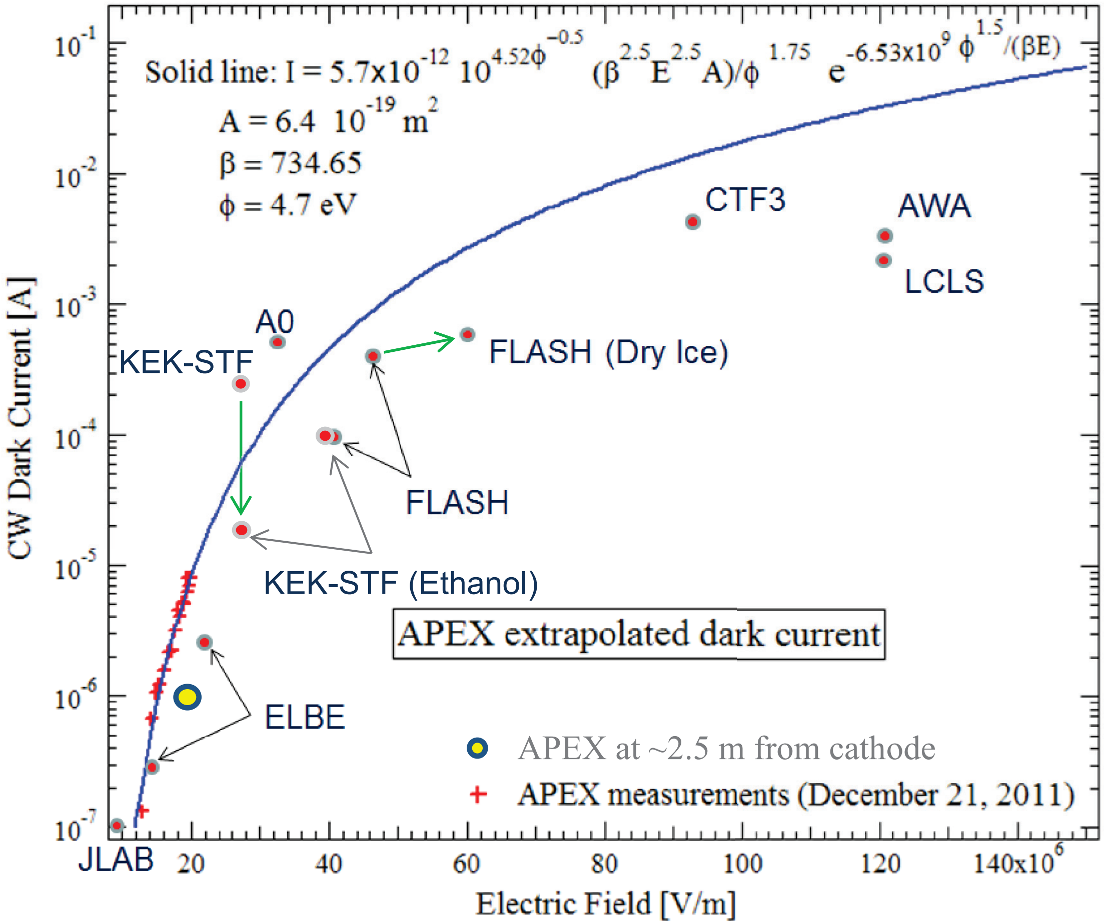
RF ON:

(nom. power 98% duty Cycle)

P_{TOT} ~ 9 10^{-10} Torr

H_2O, CO and CO_2 still at percent level. Few percent of hydrocarbons pop out.

Dark Current Gun Comparison



- **Measured values in general in line with data from others guns in operation.**

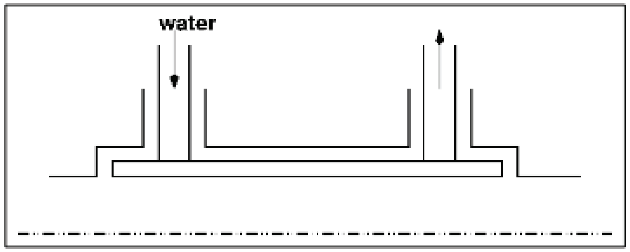
Potentially improvable by using "dry-ice" or "ethanol rinsing" cleaning of the cathode area.

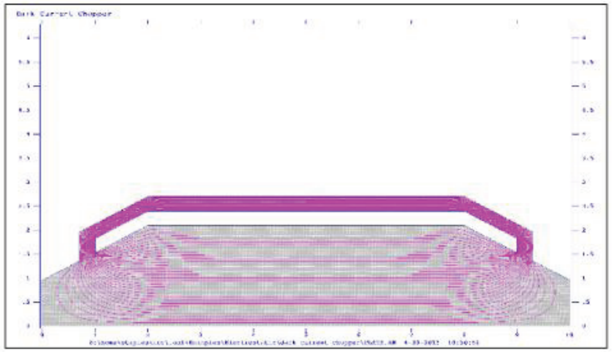
REMARK: APEX data collected right downstream the gun (~ 25 cm from cathode). Most of other data were collected few meters downstream the beamlines.

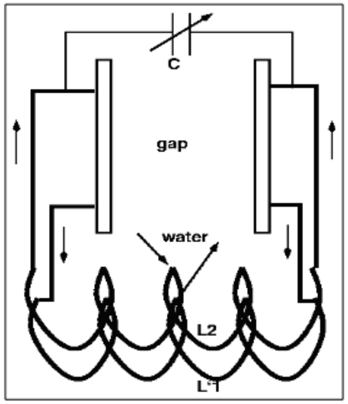
Active Dark Current Removal

Simulations showed that the measured dark current is borderline acceptable when transported along the NGLS linac.

So in addition to study cleaning techniques we started to investigate options to actively remove some of the dark current generated at the gun.



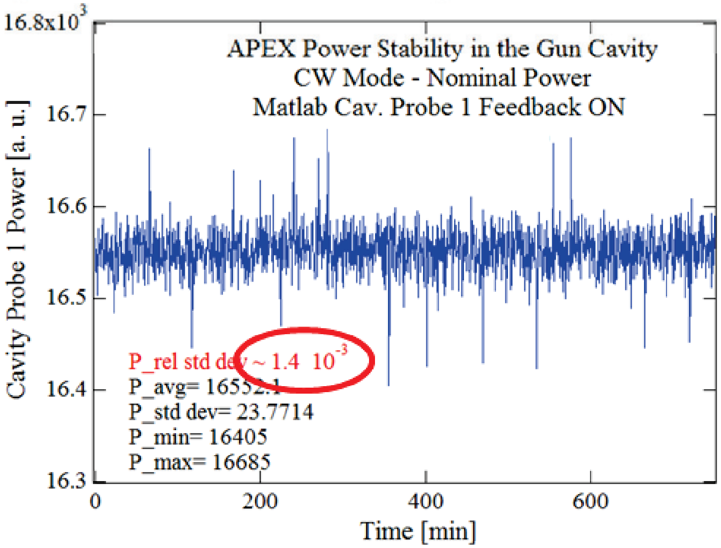


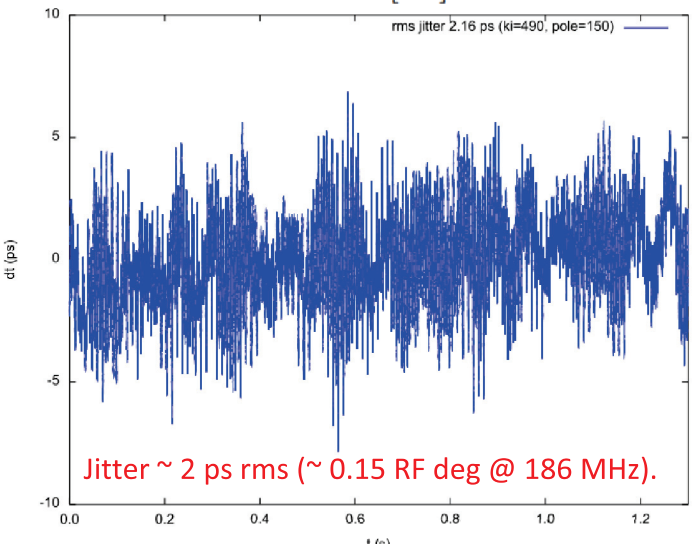


High impedance electrode structures driven by 1 MHz sinusoidal excitation. Synchronized with the photoemitted beam at "zero crossing" (J. Staples).

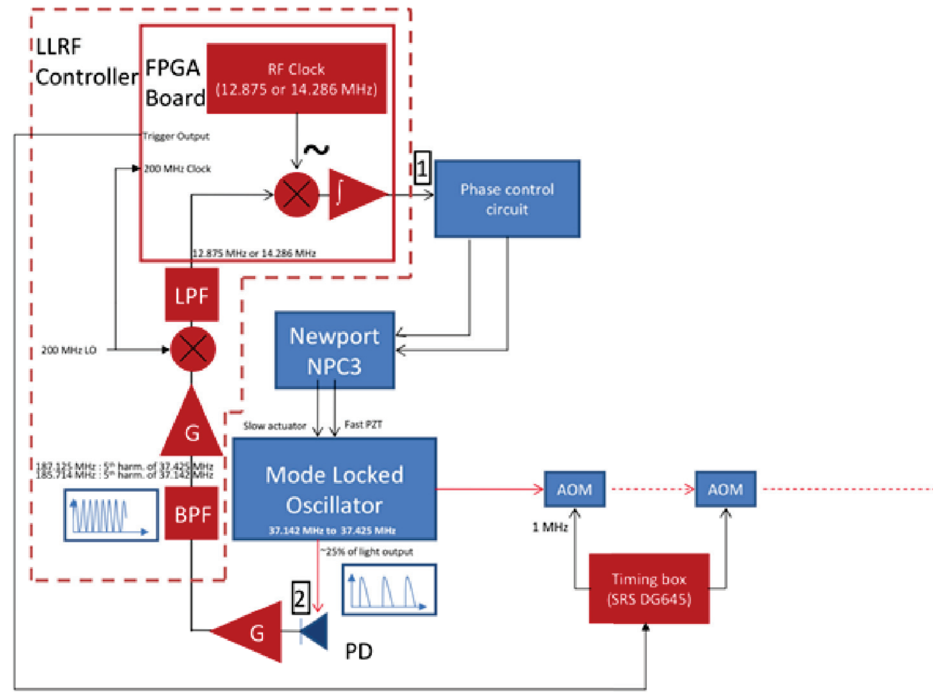
Several options available.
Simulations show a factor ~ 10 dark current reduction.

System Stability Characterization



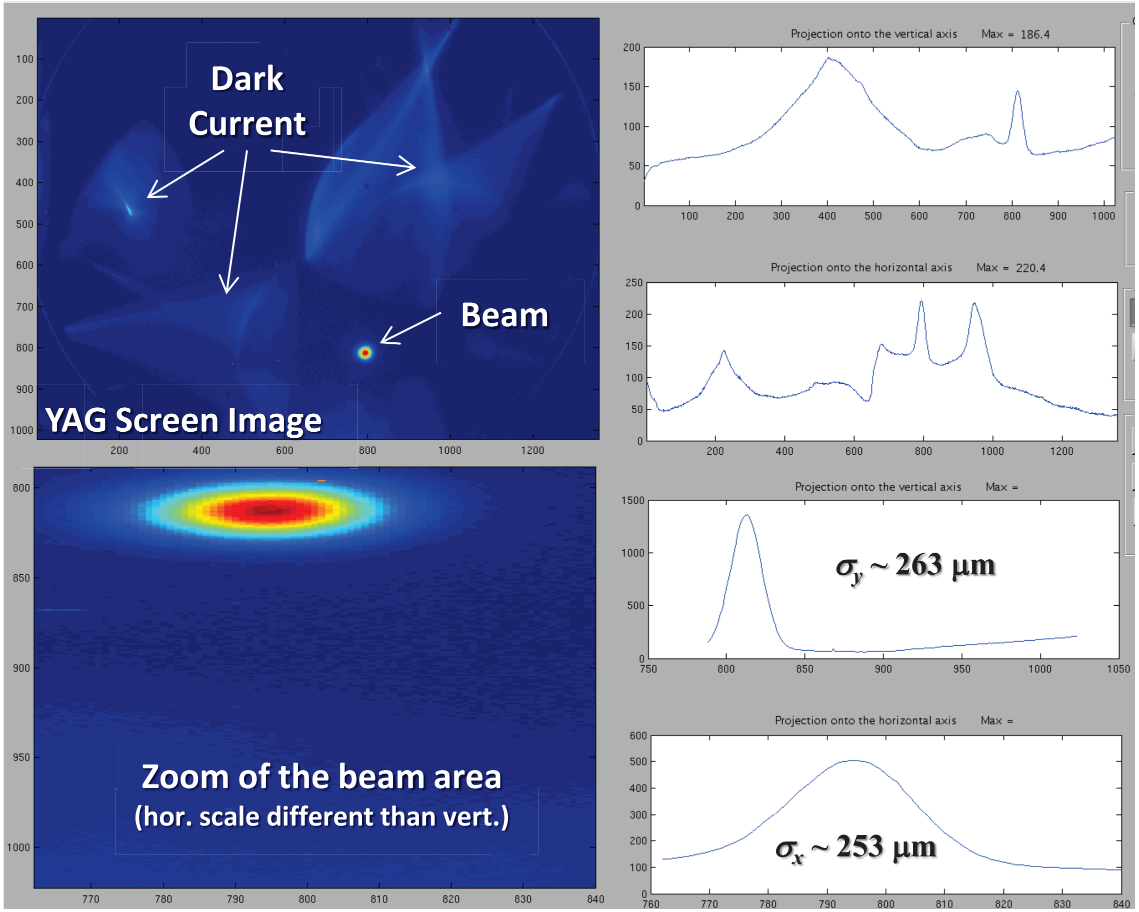


Cavity power stability controlled with high-level MatLab loop reading the cavity power through the LLRF system and setting the input power to the RF driver.

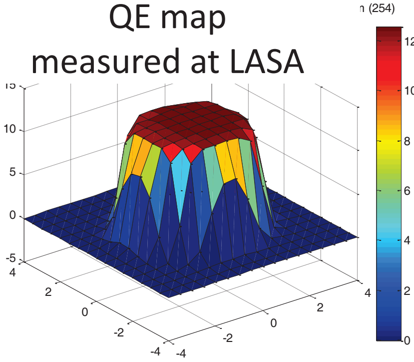


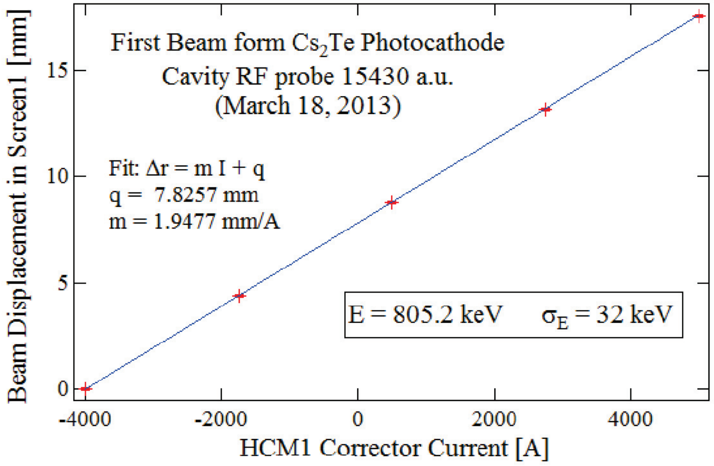
2 ps rms is more than enough for present APEX operation.
To be improved by upgrading the piezo/picomotor mirror actuator.

March 18, 2013: First Beam from Cs_2Te Photocathode



Cathode 417.1: Cs_2Te, Te = 10nm,
(deposited at INFN-LASA on March 30, 2011)



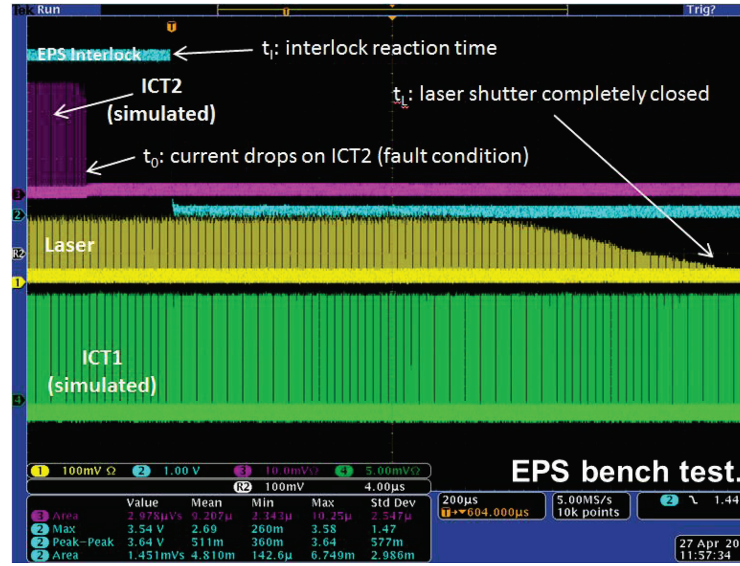


Several hundreds of pC at 100 Hz repetition rate

First Tests at 1 MHz with Cs_2Te (April 29, 2013)

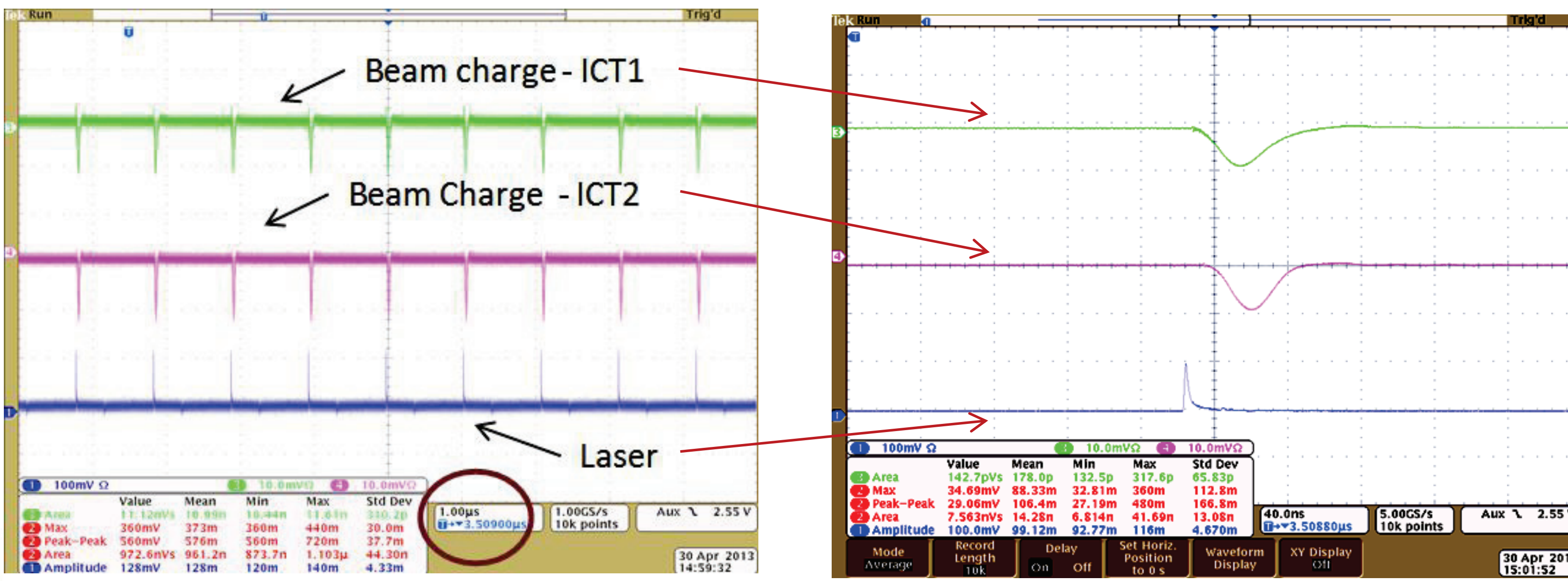
APeX @ Berkeley Lab

Operation @ 1 MHz ~ 300 pC/bunch requires an EPS system for protecting the chamber from accidental misteering of the beam



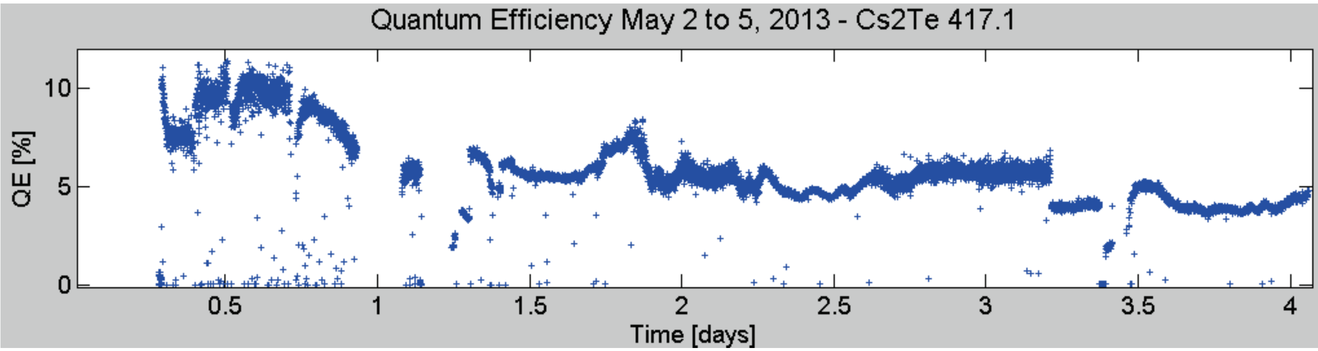
Total response time: ~1.75 ms (~2 ms required)

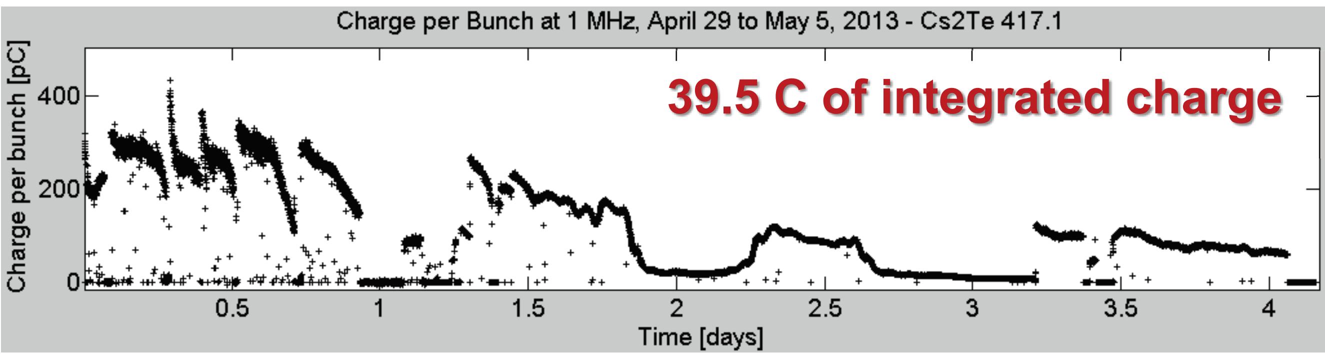
LLRF-FPGA based (Eric Norum)

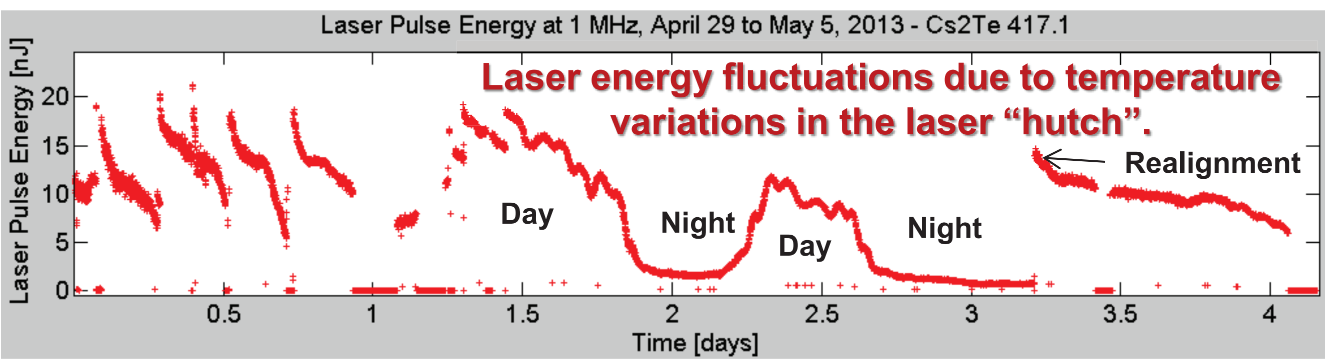


4 Days of Almost-Continuous MHz Tests with Cs_2Te.

APEX @ Berkeley Lab







Laser action items:

- feedbacks (pointing & energy).
- laser area temperature control.
- replace present laser by a commercial more stable & powerful unit ("borrowed" from H. Padmore).

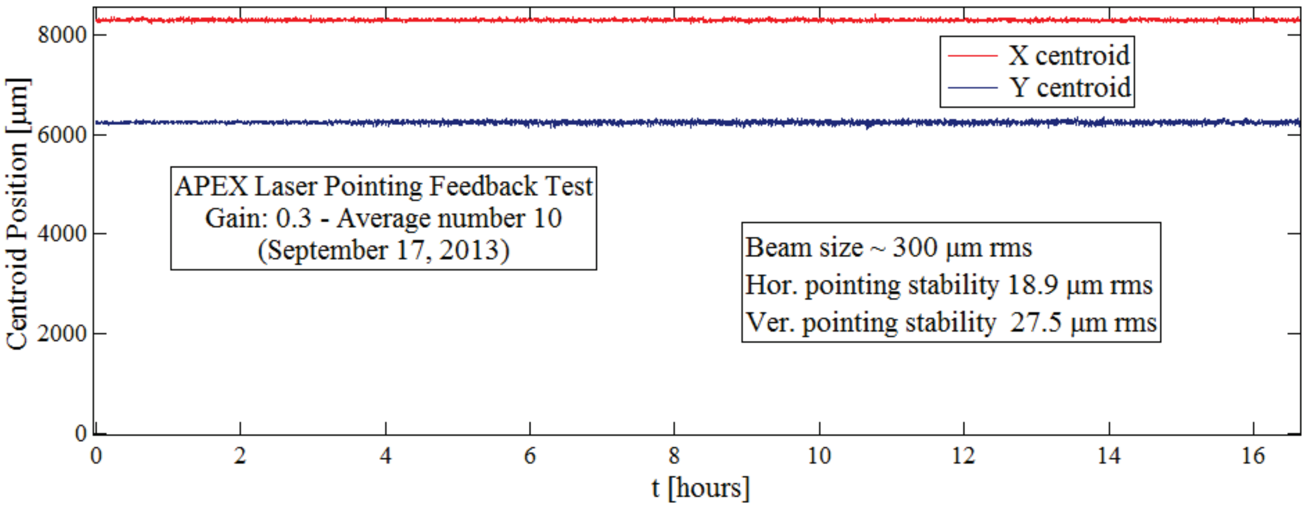
39.5 C equivalent to ~ 3 months of FLASH operation.

QE dropped from ~ 10 to ~ 4 %

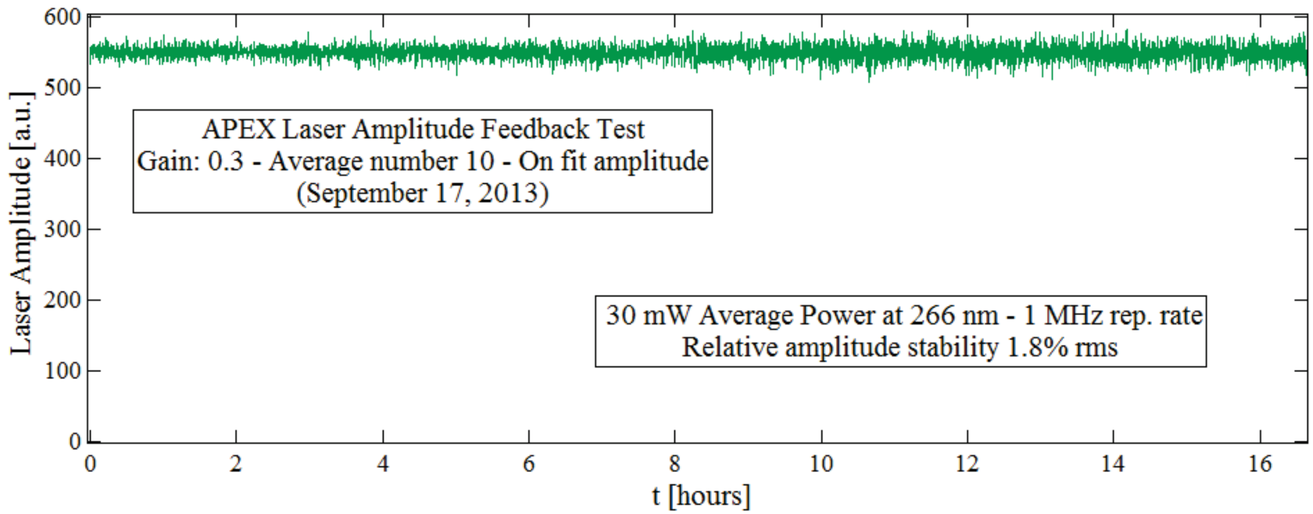
Best FLASH cathode QE dropped from 10 to 1% in 6 months.

First indication that Cs_2Te could be effectively used for an NGLS-like machine.

Laser Pointing and Amplitude Feedback Test



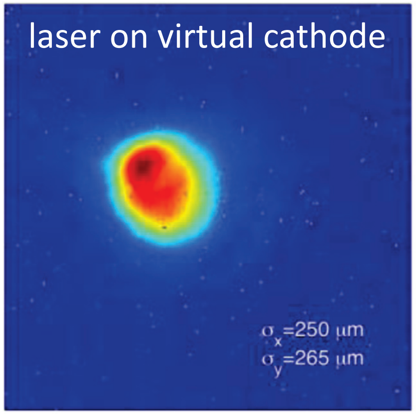
MatLab level feedback reads from virtual cathode and uses remotely controlled mirror and attenuator



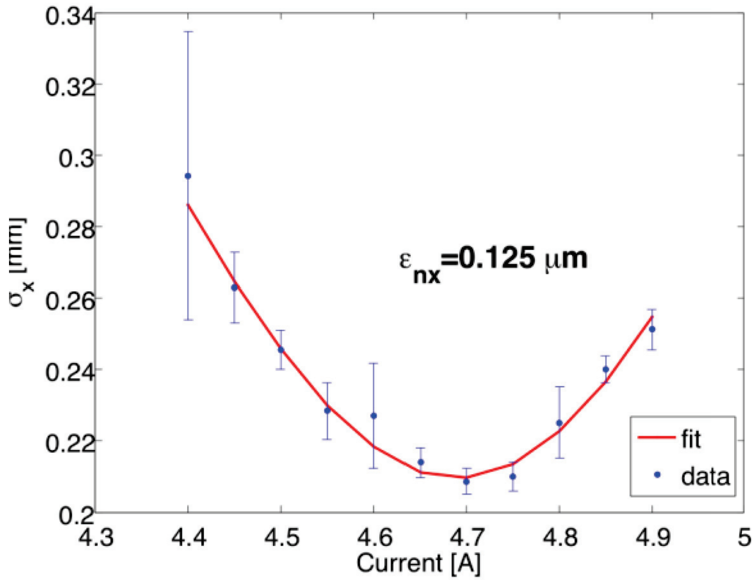
Ready for more controlled high current test!

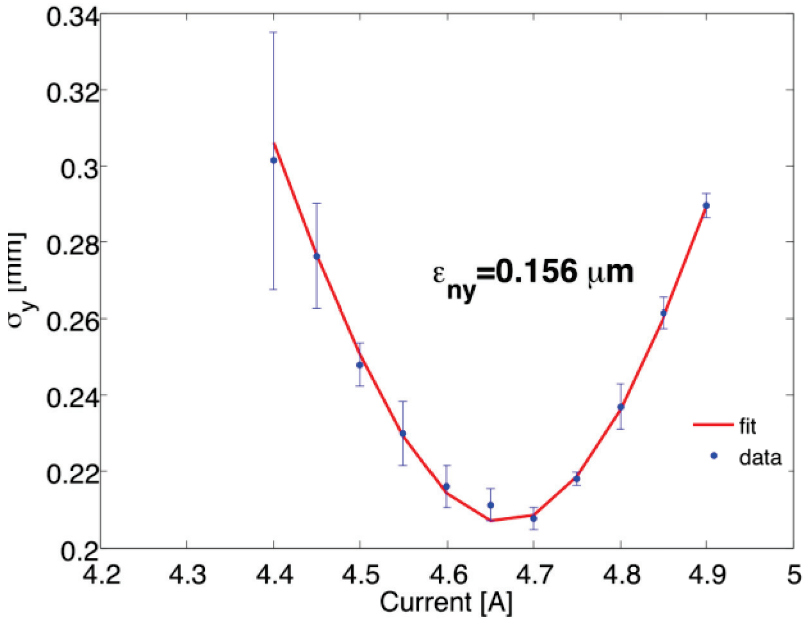
First Cs_2Te Cathode "Thermal" Emittance Measurement

900 fC bunch charge
20 Hz repetition rate
~ 800 keV beam energy
Solenoid 1 scan



Thermal emittance: 0.54 ± 0.05 µm/mm$_{RMS}$
(Consistent with values measured in other labs.)





D. Filippetto (September 11, 2013)

Future APEX Milestones and Activities

Cathodes:

- Complete the characterization of Cs_2Te cathodes
- Test CsK_2Sb and other cathodes

Beam Dynamics:

- Characterization of the beam at the gun energy and comparison with simulations (Phase I).
- Demonstration of the brightness performance of an injector based on the VHF gun (Phase II). In particular, simultaneously demonstrate:
  - Emittance compensation to the values and charge required by future light sources such as the NGLS.
  - Longitudinal compression, while minimizing density asymmetries (tails) and high-order correlations in the longitudinal phase space.

The VHF is Getting Popular

APeX @ Berkeley Lab