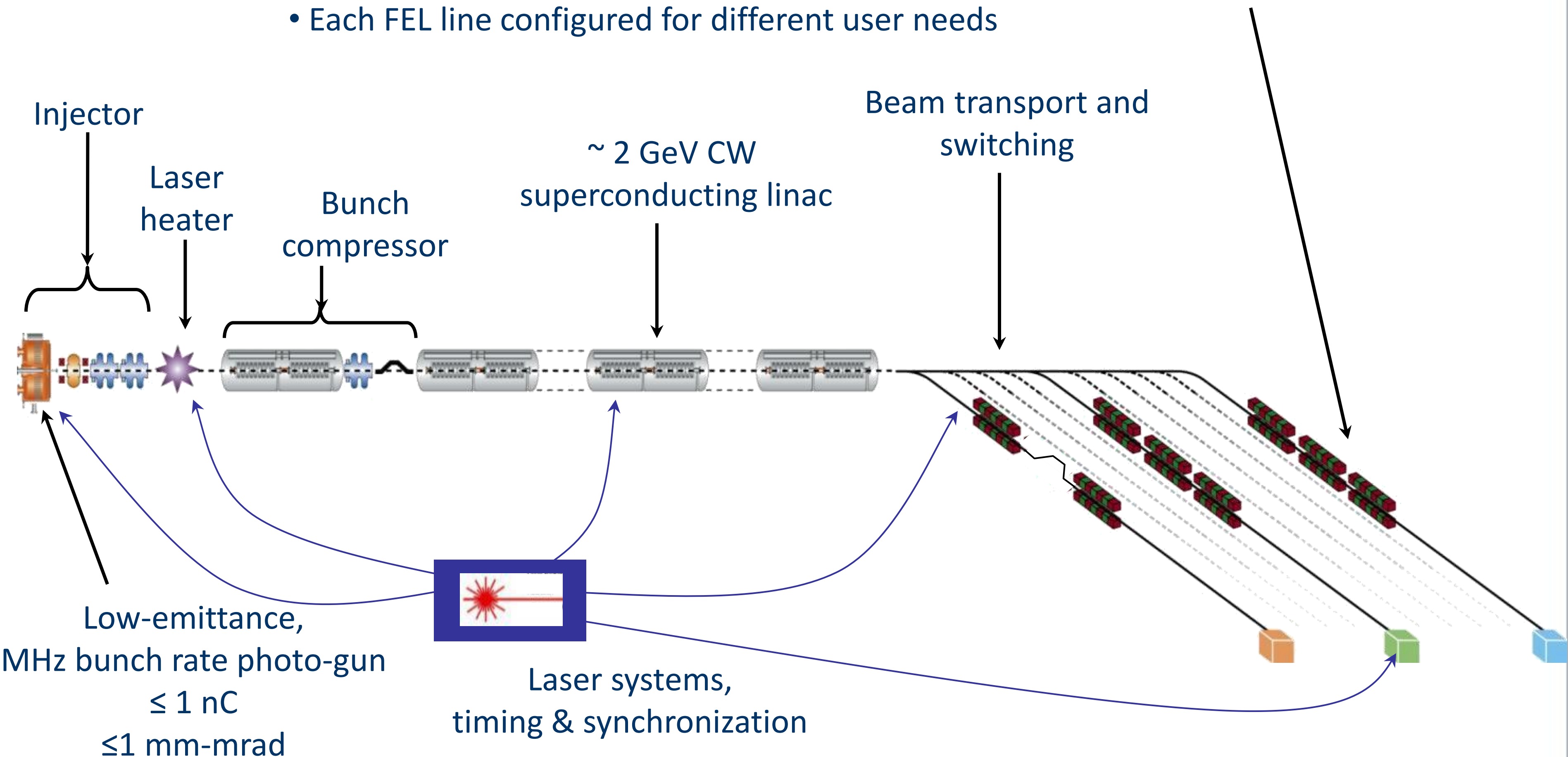
APEX
INITIAL COMMISSIONING RESULTS

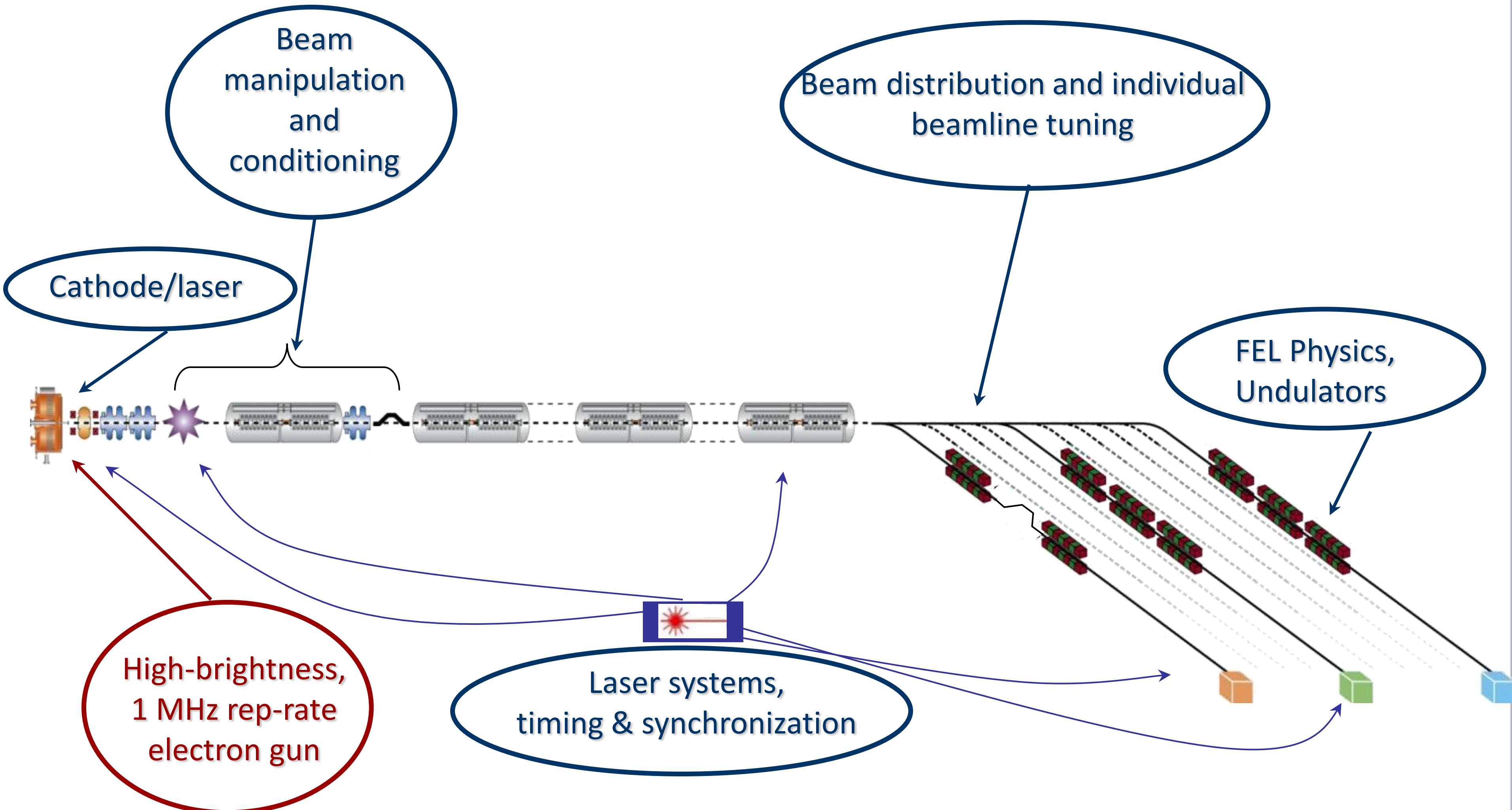
D. Filippetto on behalf of APEX team

The NGLS proposal at LBNL

- Array of (ultimately 10) configurable FEL, up to 20 X-ray beamlines
- 100-1000 kHz pulse rate
- Independent control of the pulse characteristics.
- Each FEL line configured for different user needs



The NGLS R&D activities



Injector Requirements

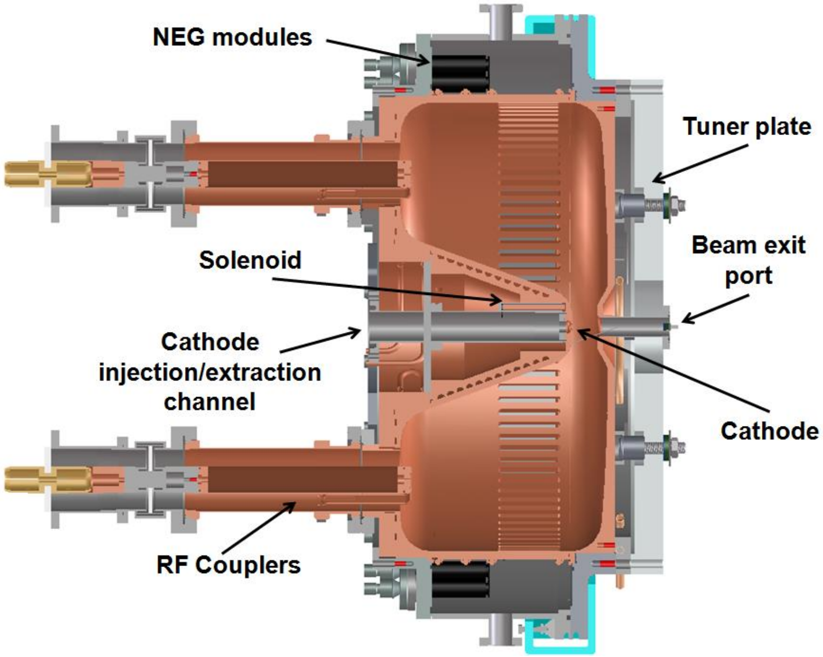
To achieve the NGLS goals, the electron source should simultaneously allow for:

- sub-µm beam emittance,
- beam charge control (from pC to ~ 1 nC)
- bunch length control (1-100 ps) for different modes of operation
- compatibility with significant magnetic fields in the cathode and gun regions (emittance compensation)

- MHz repetition rate
- electric field at the cathode > 10 MV/m (space charge limit)
- 10^{-9} - 10^{-11} Torr operation vacuum pressure (high QE photo-cathodes),
- "easy" installation and conditioning of different kind of cathodes,
- Reliability

The LBNL VHF Gun

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



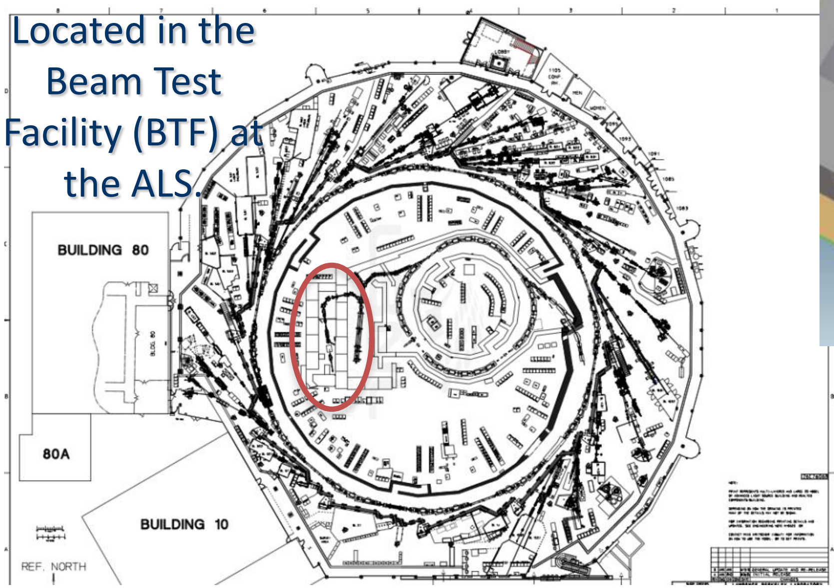
J. Staples, F. Sannibale, S. Virostek, CBP Tech Note 366, Oct. 2006
K. Baptiste, et al, NIM A 599, 9 (2009)

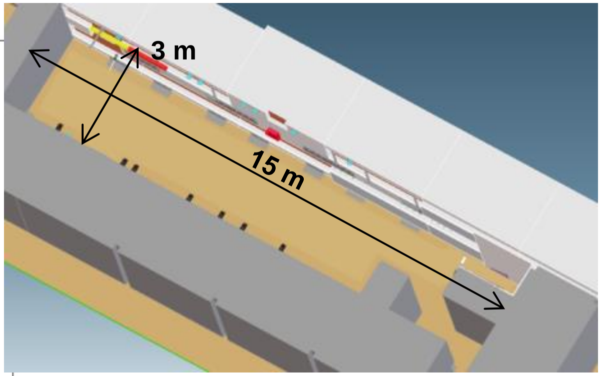
Frequency	186 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19.47 MV/m
Q_0 (ideal copper)	30887
Shunt impedance	6.5 MΩ
RF Power	100 kW
Stored energy	2.3 J
Peak surface field	24.1 MV/m
Peak wall power density	25.0 W/cm^2
Accelerating gap	4 cm
Diameter/Length	69.4/35.0 cm
Operating pressure	~ 10^{-11} Torr

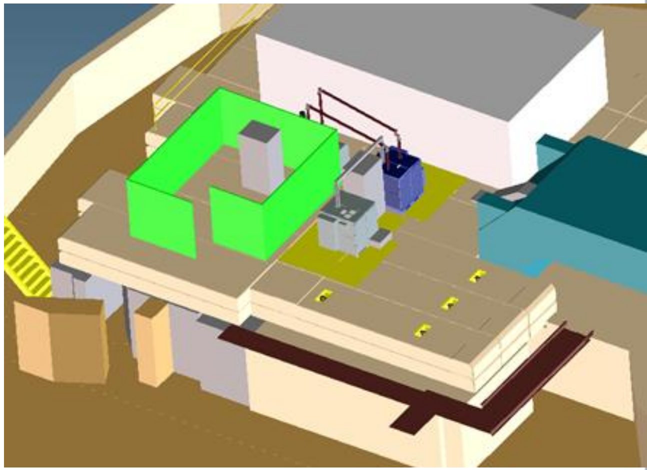
- At the VHF frequency, the cavity structure is large enough to withstand the heat load and operate in CW mode at the required gradients.
- Also, the long λ_{RF} allows for large apertures and thus for high vacuum conductance
- Based on mature and reliable normal-conducting RF and mechanical technologies.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

APEX @ ALS

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







Main Goals:

- **Demonstrate the high-brightness @ high-repetition rate**
- ***Cathode physics*: selection of the best cathode for NGLS.**
- ***Diagnostics*: demonstrate diagnostics systems for NGLS.**
- **Dark current characterization**

additional plans: (depending on funds)

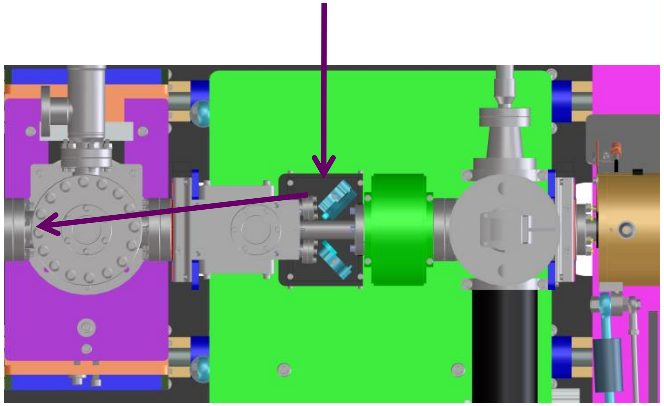
- *Low energy collimation schemes*
- *Electron diffraction*
- *…*

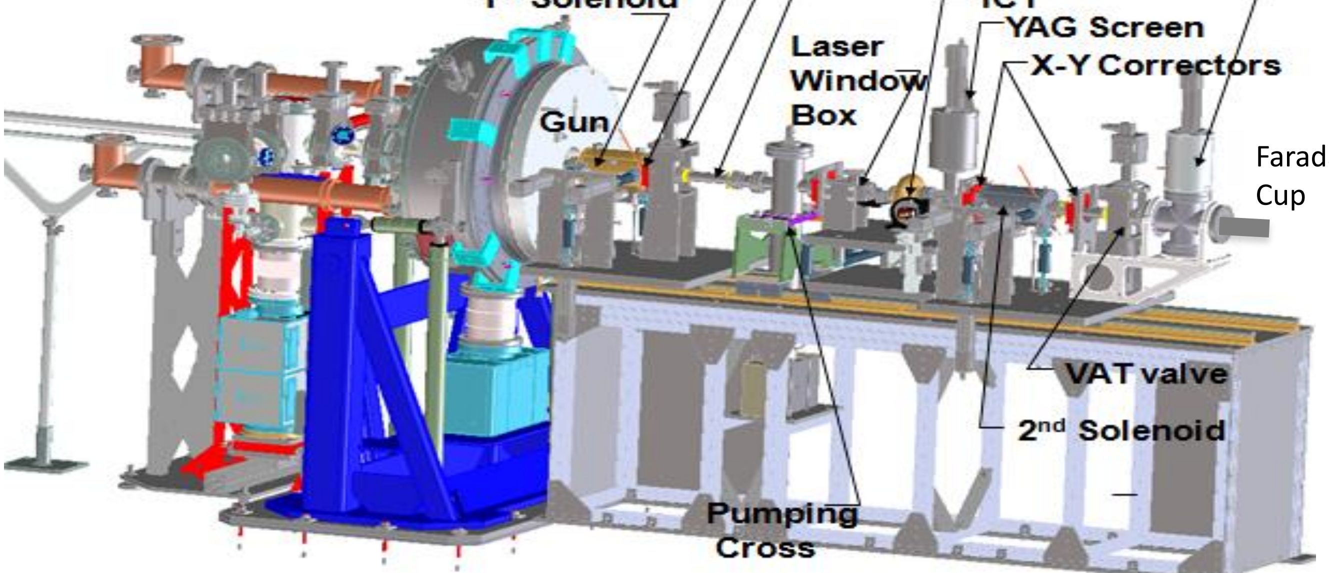
APEX: PHASE 0

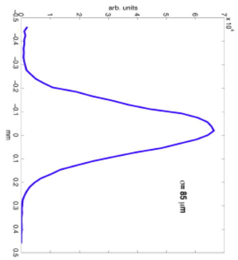
Phase 0 scope:

- **Demonstration of the RF performance at full repetition rate.**
- **Vacuum performance demonstration.**
- **Dark current characterization.**
- **High QE cathode physics (QE, lifetime, intrinsic emittance)**

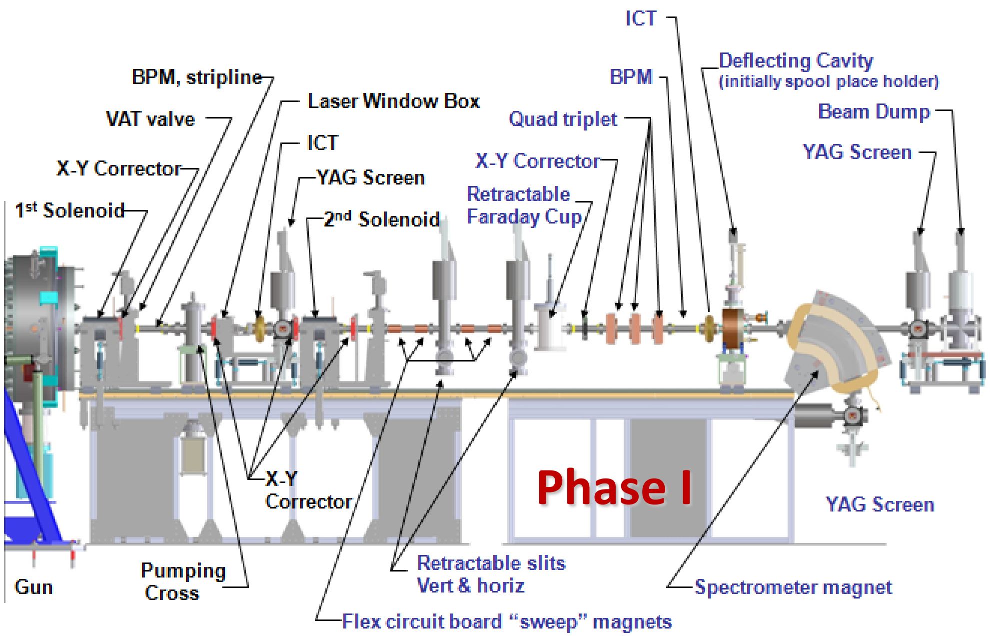
FUNDED, under commissioning







APEX: PHASE I & PHASE II



Phase I scope:

(Phase 0 + extended diagnostics)

- High current emittance
- Diagnostics systems tests
- Low energy beam characterization

If funding confirmed operation in summer 2013

Phase II scope:

- Demonstration of the brightness performance at ~ 30 MeV at low repetition rate* (*BTF shielding limited)

If funding confirmed operation in mid 2014

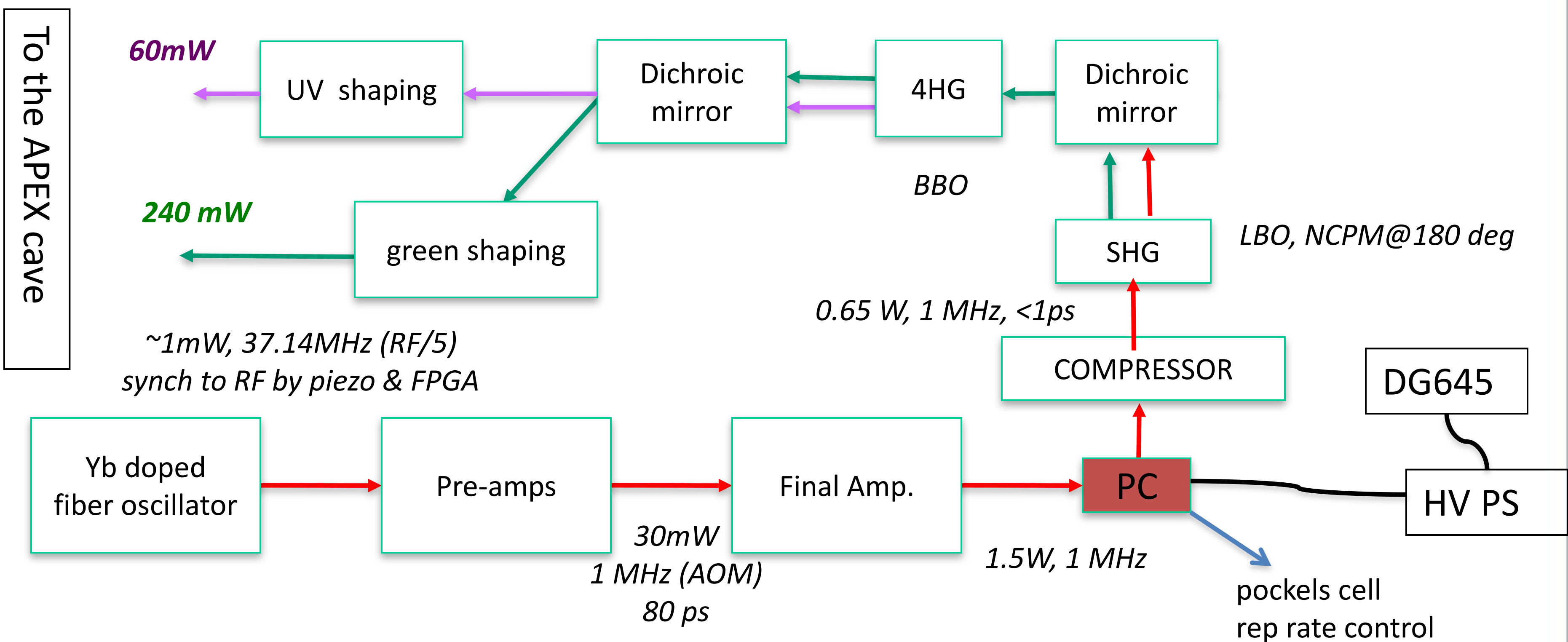
The Laser System

•repetition rate control (1-10^4Hz/1MHz)

•Two separate transport lines for UV and green

•Longitudinal pulse shaping

LLNL/UCB/LBNL collaboration

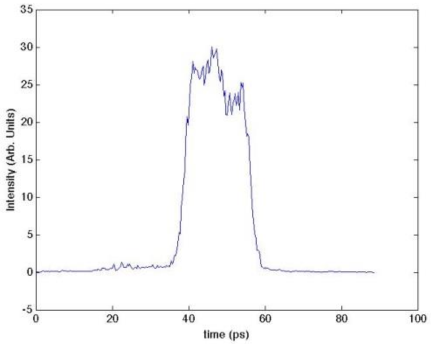


Working on the 350 and 213 nm …

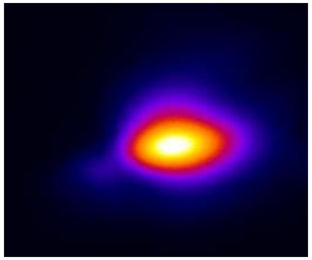
The Laser System

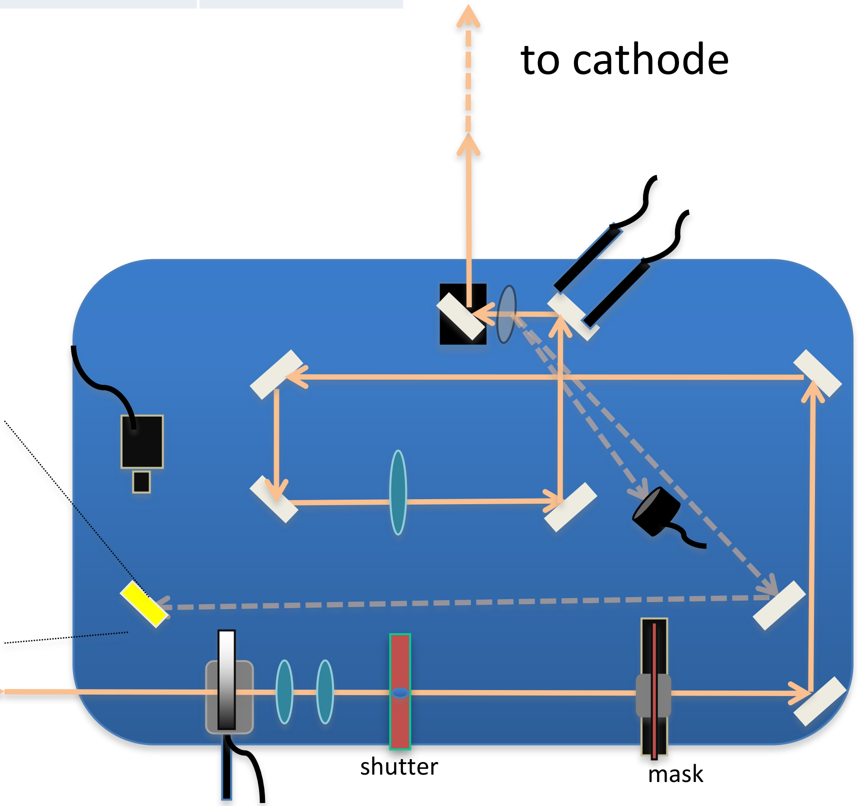
	IR	green	UV
bunch length (ps, FWHM)	0.6	0.6-60	
beam size (µm ,RMS)	N/A	700-50	
energy/pulse (nJ)	700	150	40
rel. energy fluctuations RMS	<1%	2%	5%

Flat top pulse generation via pulse stacking



C. Pogue, MOPD54





APEX COLLABORATIONS

- **LLNL/UCB**. Photocathode laser.
- **ANL-AWA**. Linac accelerating sections.
- **Cornell University**. Beam diagnostics and RF components.
- **INFN-Milano LASA**. Cs_2Te cathodes.
- **BNL**. Diamond amplifier cathodes.

…

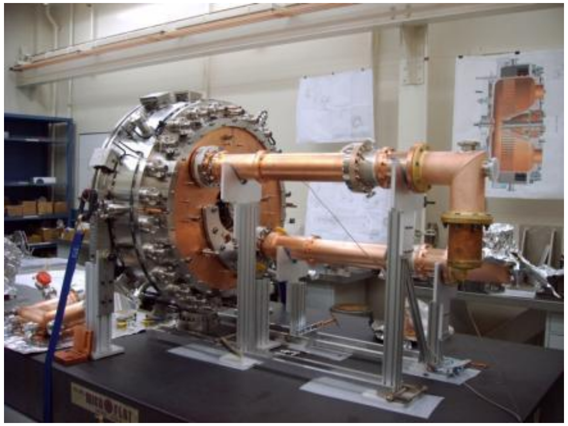
Also help from: SLAC (LCLS, SSRL), DESY-PITZ, …

…

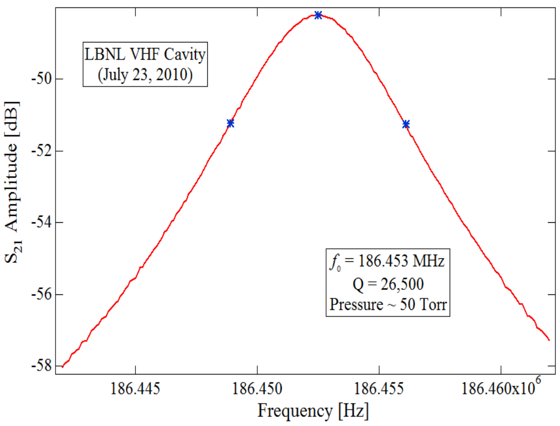
STTR with QPeak

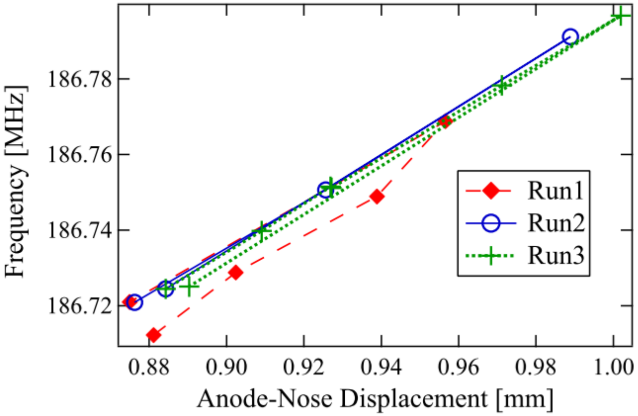
GUN FABRICATION COMPLETED (~90% at LBNL Shops)

R. Wells, R. Kraft



Successful low power RF test



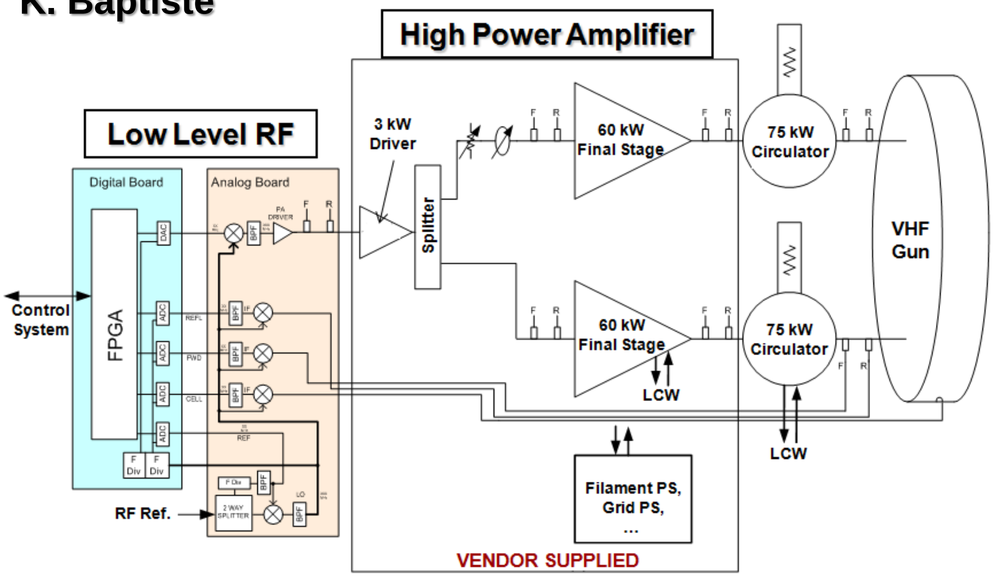


Tuning mechanism principle tested.

THE GUN 186 MHz CW SOURCE

- The 120 kW CW 186 MHz RF amplifier required to operate the VHF gun has been manufactured by ETM Electromatic.

K. Baptiste



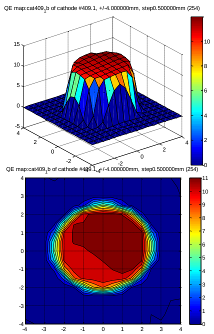
- Acceptance test completed at LBNL. Fully operational.

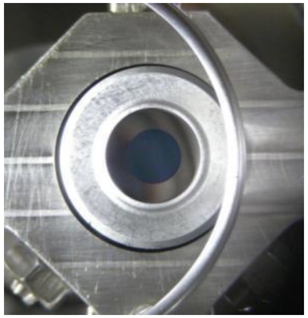
PHOTO-CATHODES FOR APEX

APeX @ Berkeley Lab

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 (~260 nm) (4^{th} harm. conversion from IR)
- for 1 MHz reprate, 1 nC, ~ tents of W 1060nm required

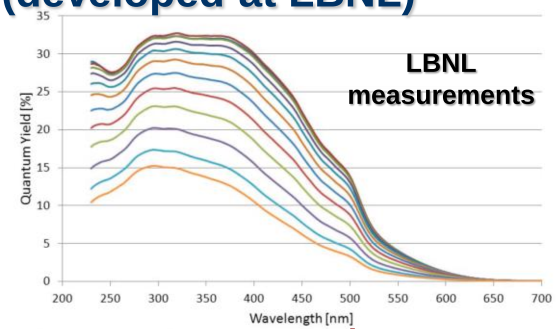




First 3 cathodes successfully developed at INFN/LASA and delivered to LBNL.

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

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

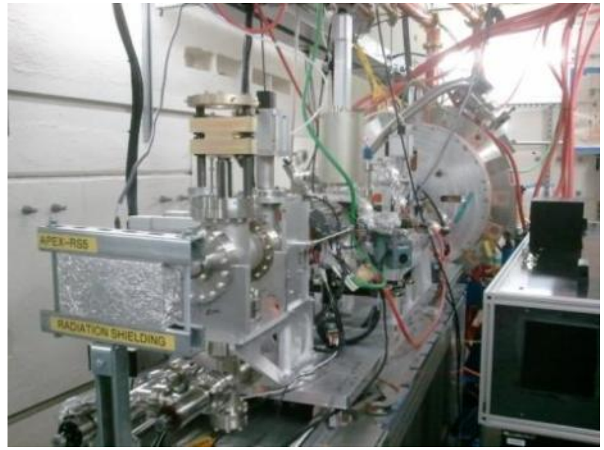


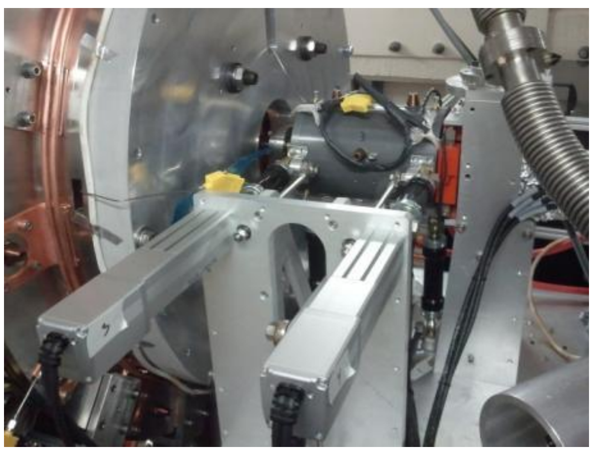
Cathodes under development at LBNL (H. Padmore's group).
Promising lifetime and intrinsic emittance results (Cornell and LBNL).
Transfer chamber from preparation chamber to VHF gun in fabrication.

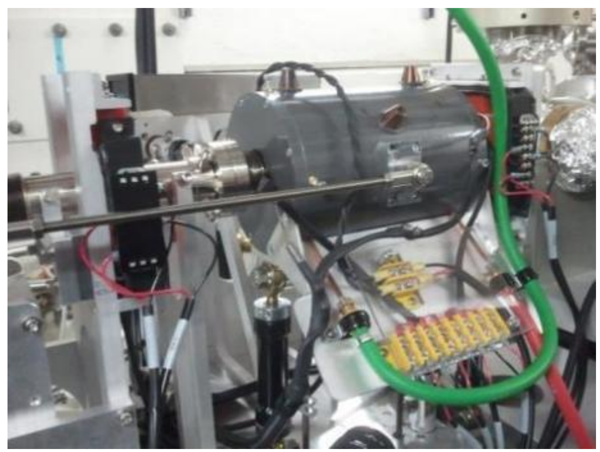
Try other cathode materials (diamond amplifier,…)

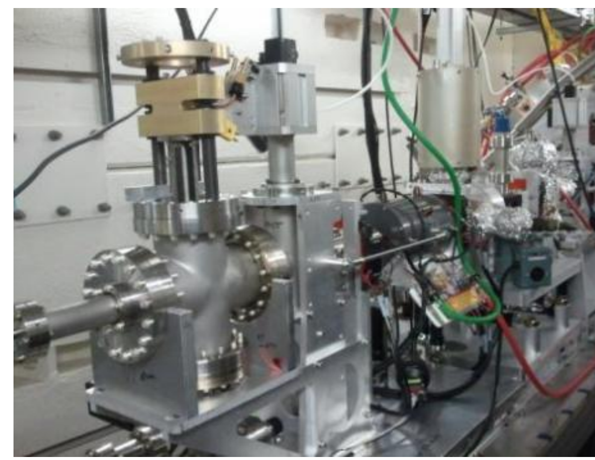
PHASE 0 BEAMLINE INSTALLED

APeX @ Berkeley Lab







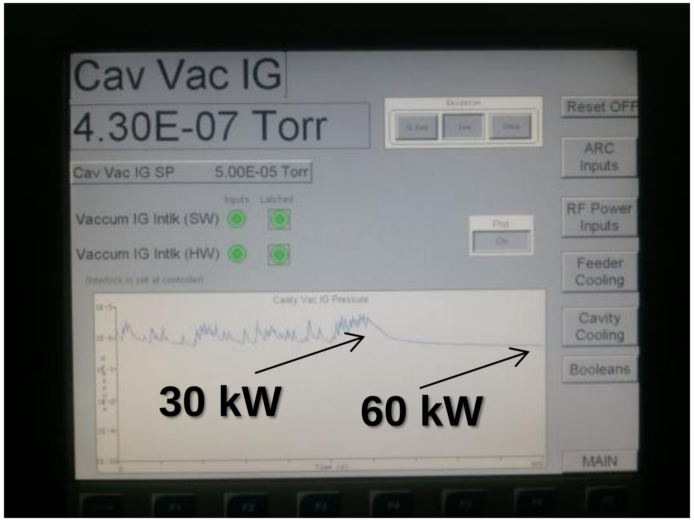


Beamline installation completed.

THE EXPERIMENTAL PART STARTS!

APeX @ Berkeley Lab

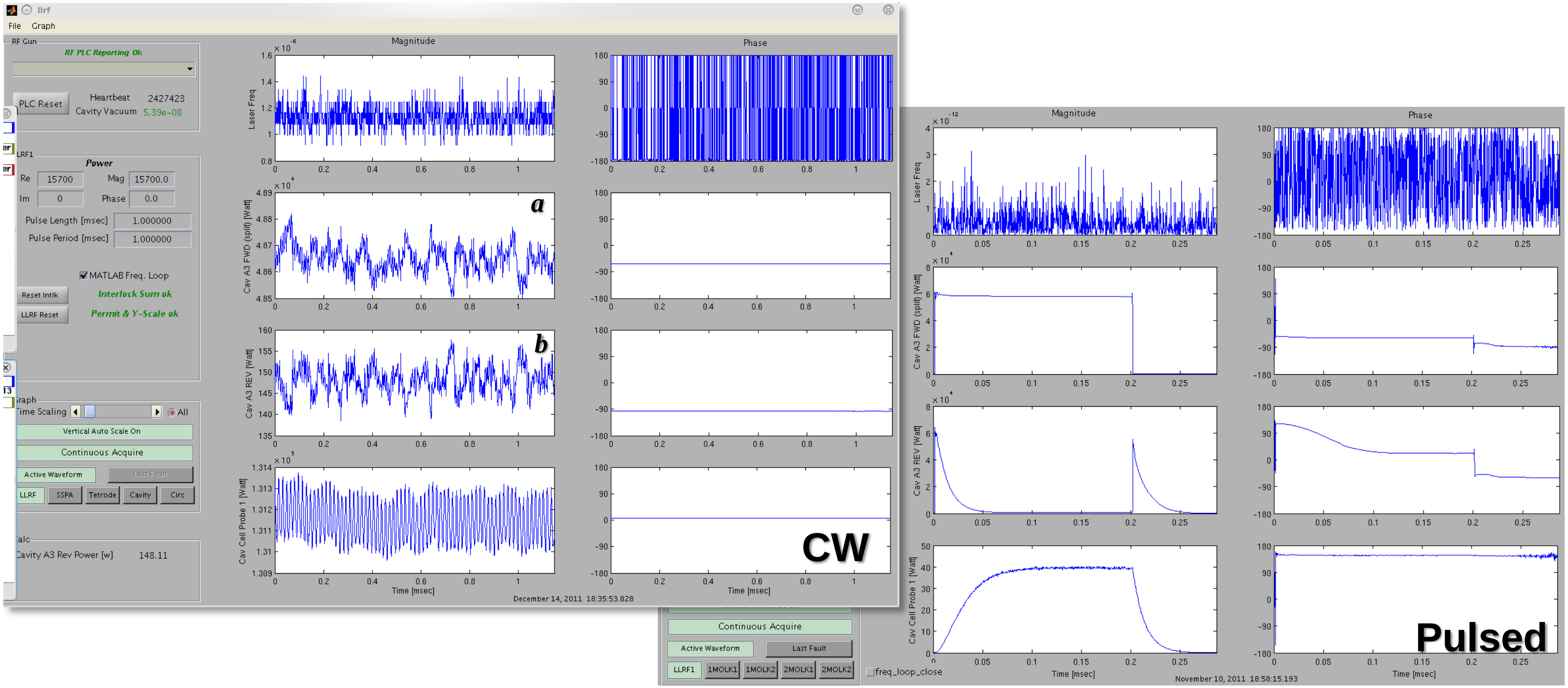
Sept. 22, 2011



The two Toshiba RF windows were conditioned at the full power of 60 kW (in less than twenty hours). Good system cross-check.

RF CONDITIONING

Gun RF conditioning started on November 7, 2011



On Dec. 15, 2011 after < 120 integrated hours of conditioning, more than 12,5 hours run without faults were achieved in CW mode at nominal power (100 kW). Results reconfirmed the day after (> 24 hours no fault).

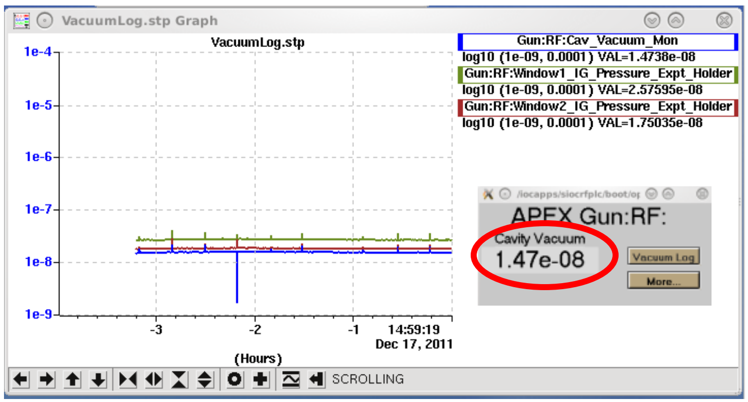
RF conditioning completed!

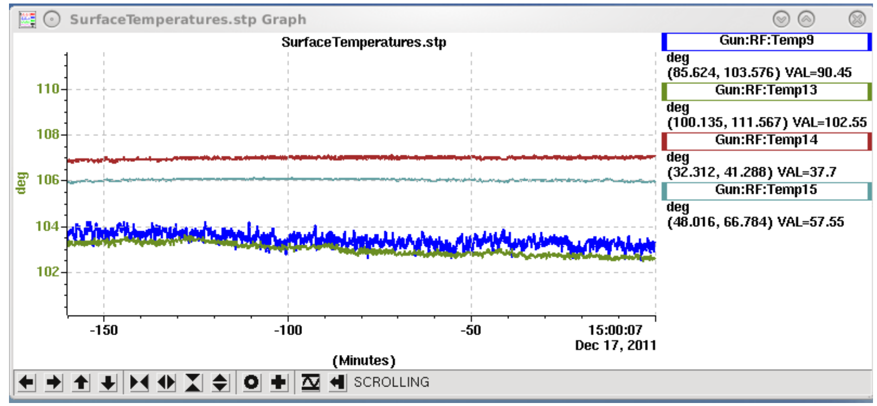
GUN OPERATION

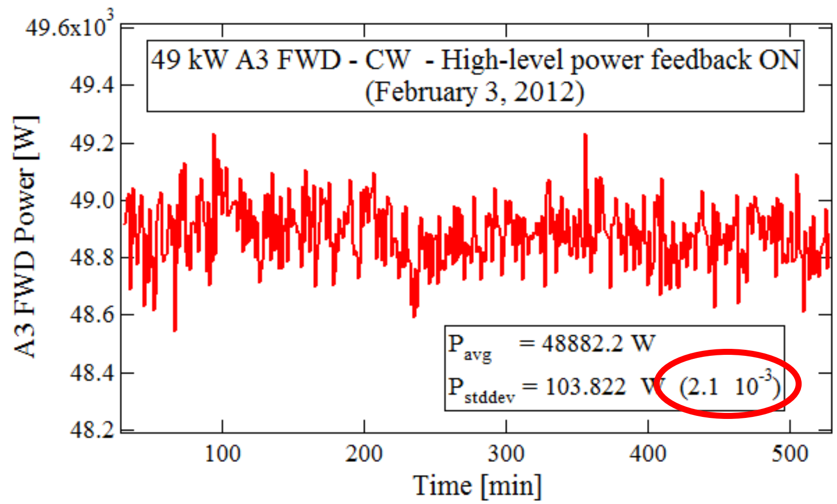
@ Berkeley Lab

Gun RF conditioning example: December 17, 2011 (17 hours run)

CW mode, ~100 kW RF Power, 100% of nominal power





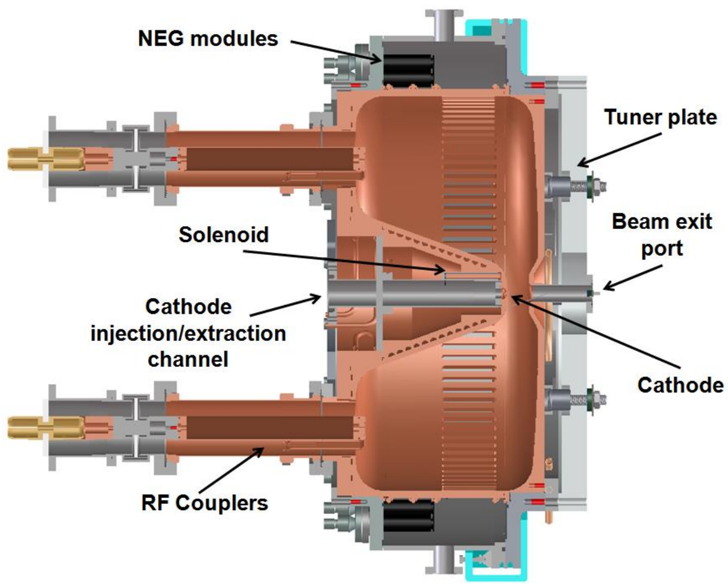


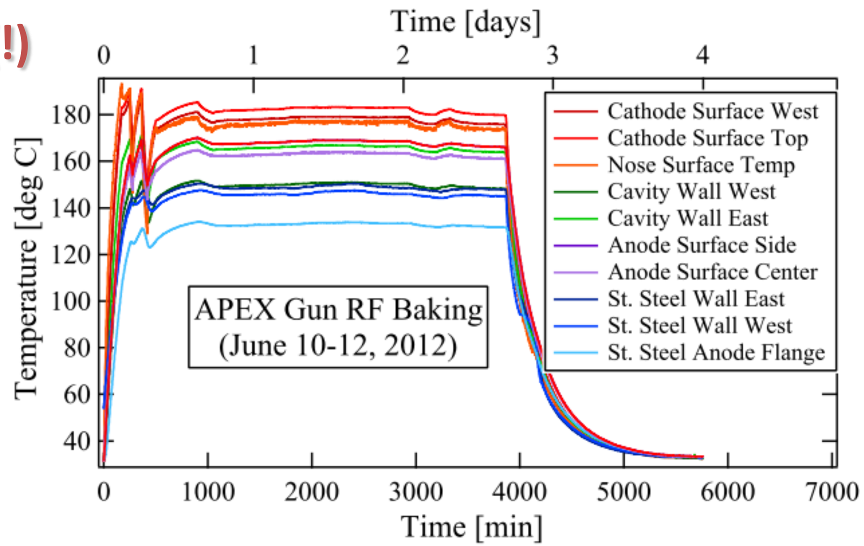
High-level (Matlab) feedback reading/writing EPICS PVs.

Stability can be probably improved by implementing the feedback in the LLRF.

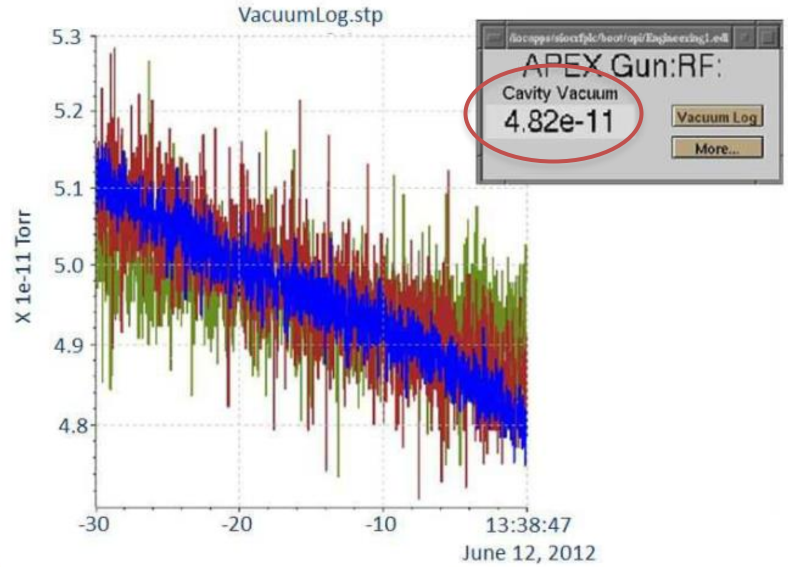
"RF BAKING"

RF power in the gun with no water cooling (!)
2-4 kW average RF power.

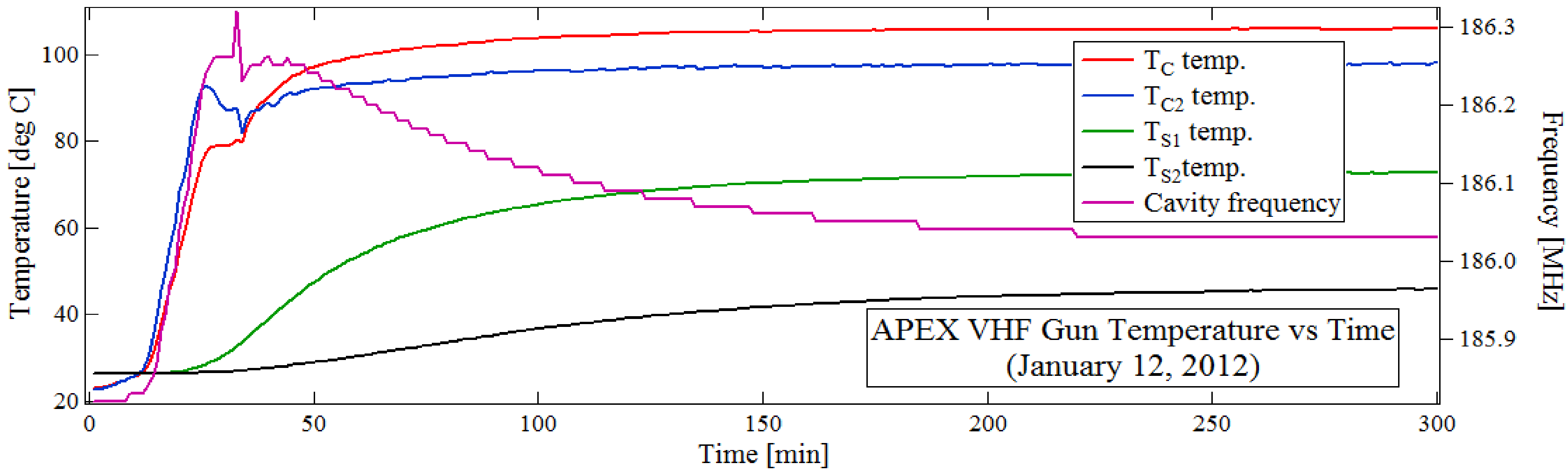




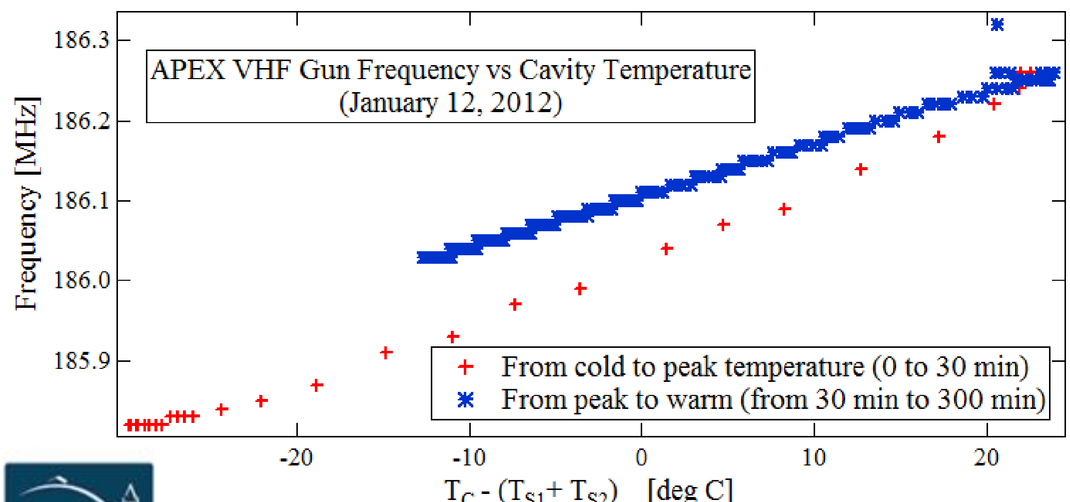
Only 1 NEG out of 20 activated after the 2.5 days RF baking.
The 400 l/s ion pump on.
Very promising!

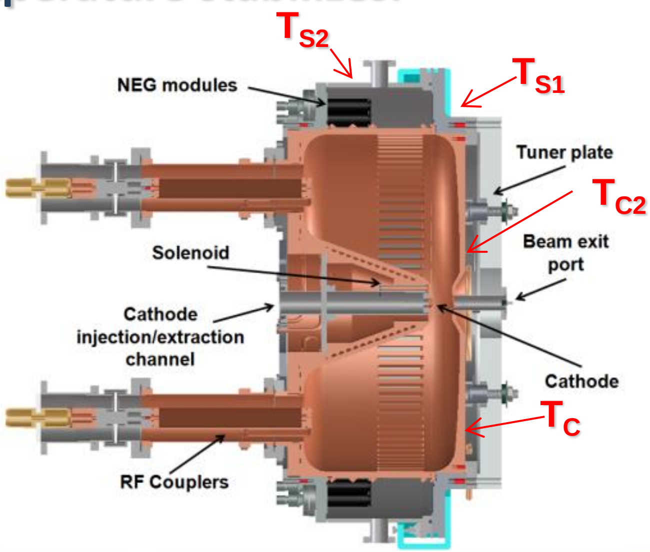


FREQUENCY VS TEMPERATURE



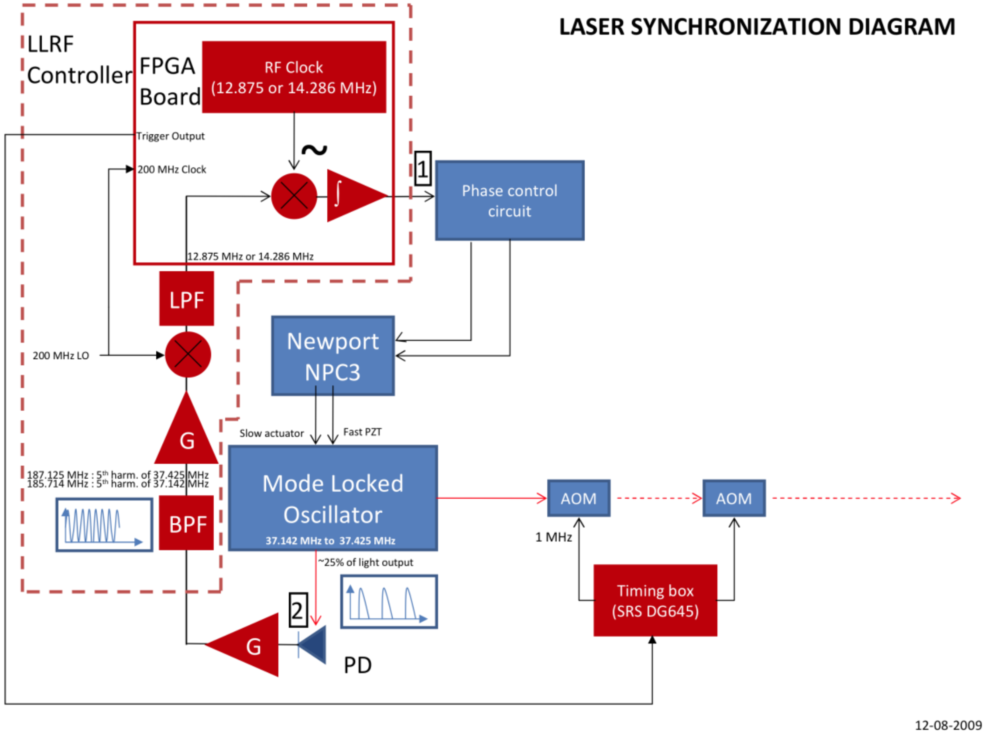
We have two "regimes": cold cavity in the first ~ 30 min where the copper is going to temperature; warm when the copper temperature stabilizes.

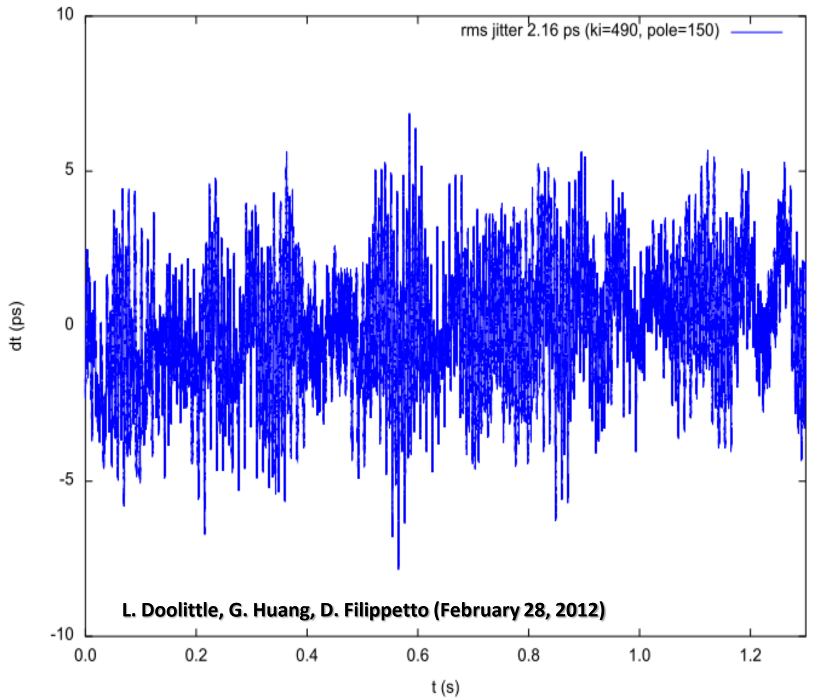




LASER-RF SYNCHRONIZATION

The LLRF system controls the synchronization between the laser oscillator frequency and the VHF gun RF.



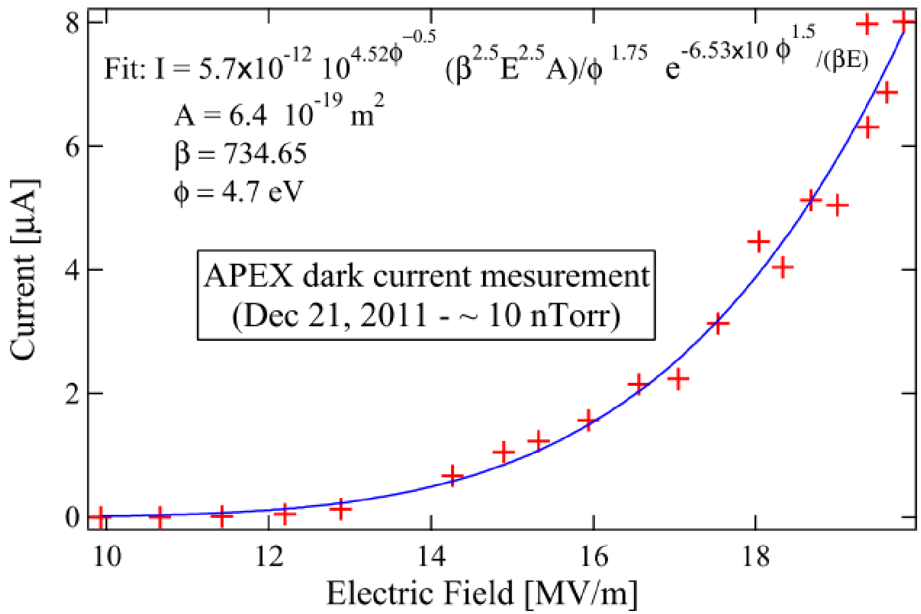


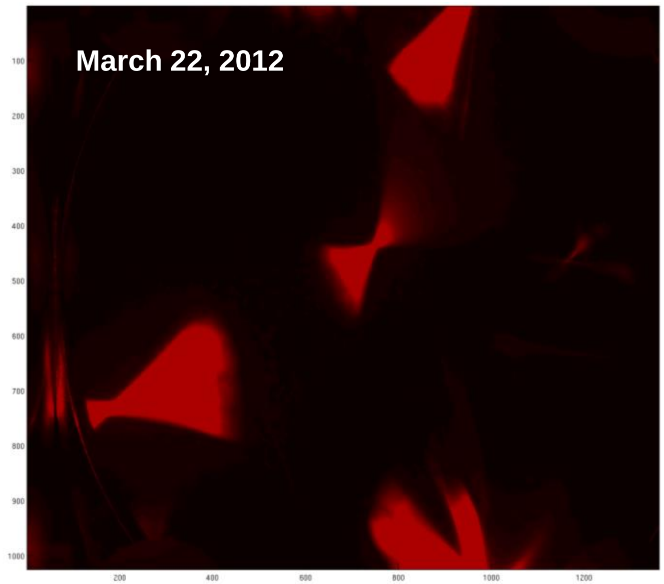
Jitter ~ 2 ps rms (~ 0.15 RF deg @ 186 MHz).
More than enough for present APEX operation.
To be improved by upgrading the piezo/picomotor mirror actuator.

DARK CURRENT

Measurement performed in CW mode by a coaxial Faraday cup right downstream the beam pipe exit.

New measurements with the Faraday cup at the end of Phase 0 beamline indicated less than a µA of dark current at the nominal operation field (collimated out by the vacuum chamber).





- **The dark current image on a YAG screen reveals several "butterflies" indicating the presence of "hot" tips on the temporary "dummy" plug.**

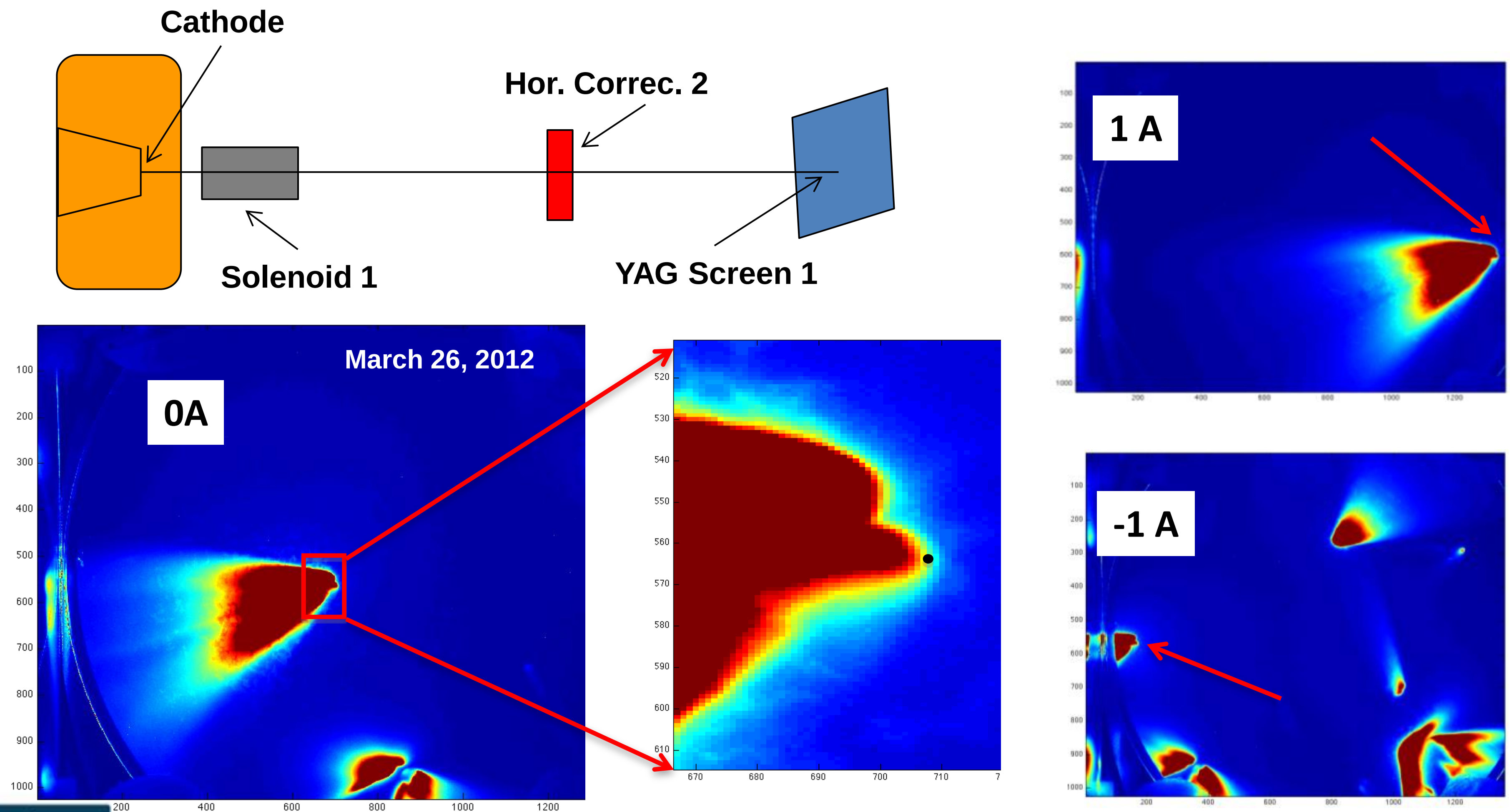
No evidence of field emission in the plug/gun contact area.

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

May get better with installation of real cathodes with better polished plugs.

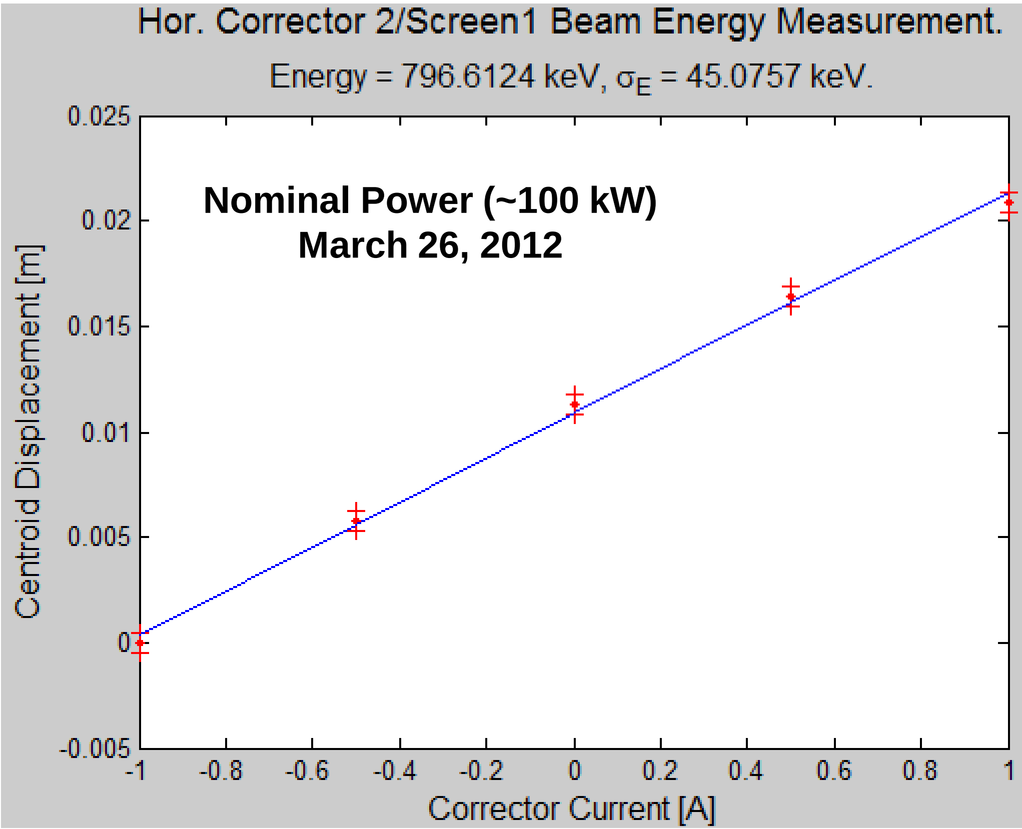
ENERGY MEASUREMENT BY DARK CURRENT

Solenoid 1 ON to focus dark current on screen.
Corrector 2 current varied for the measurement.



ENERGY MEASUREMENT BY DARK CURRENT

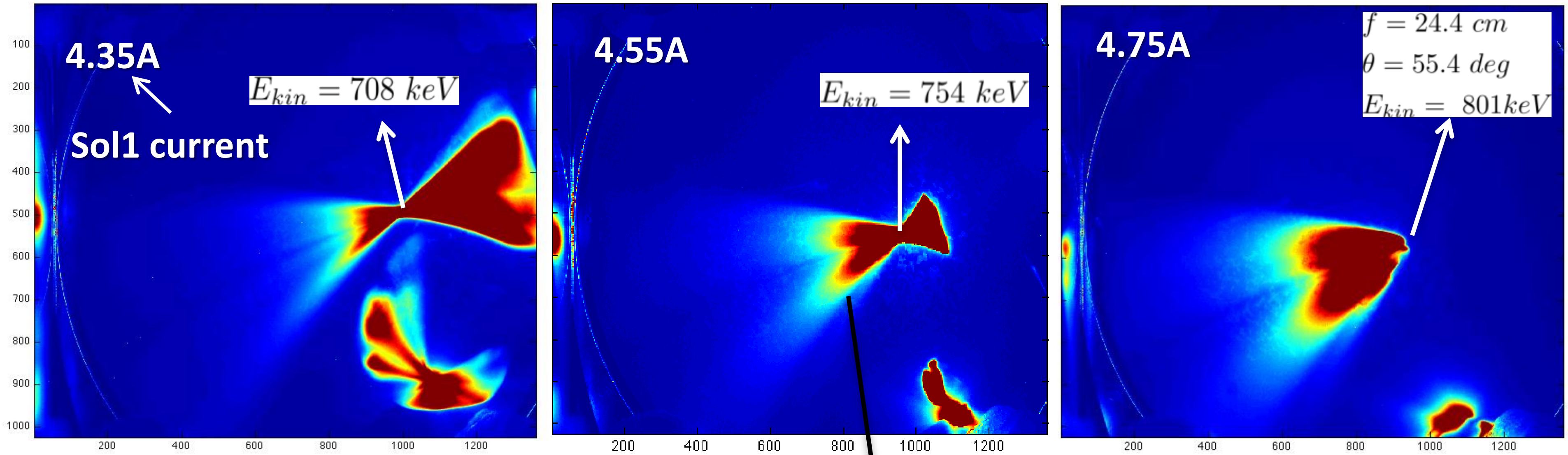
The fit slope is proportional to the particle momentum



$$\boxed{\begin{aligned} E &= 797\ \mathrm{keV} \\ \sigma_E &= 45\ \mathrm{keV} \end{aligned}}$$

Nominal Electron beam energy: 750 keV

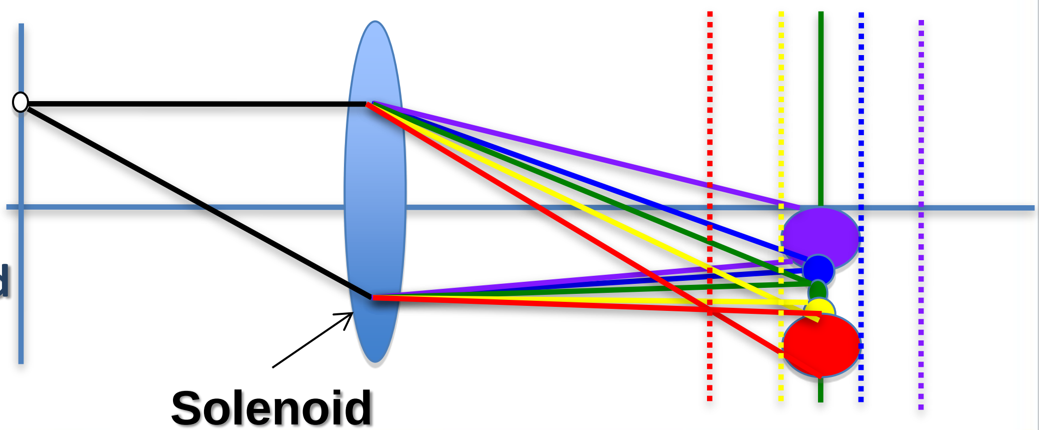
THE (DARK CURRENT) BUTTERFLIES



$$\frac{1}{f} = \left(\frac{q_e}{2mc\beta\gamma}\right)^2 \int B^2 ds$$

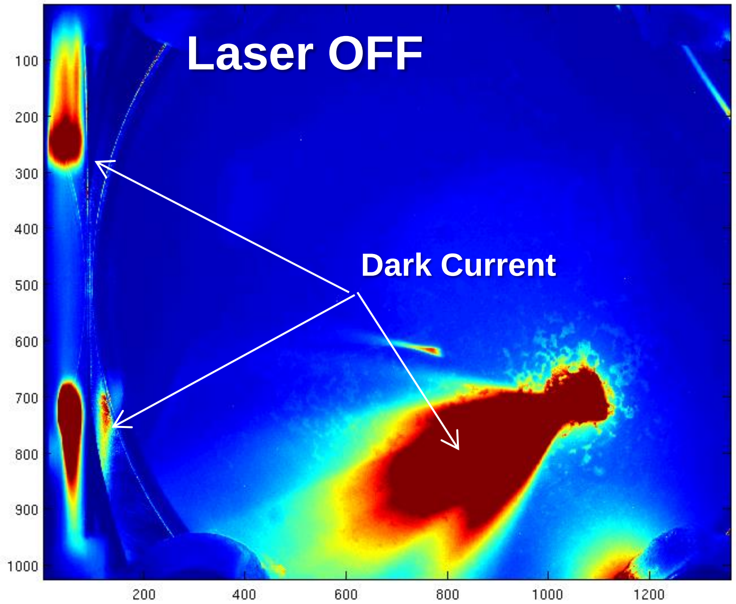
solenoid chromatic aberrations of off-axis source point imaging with energy spread

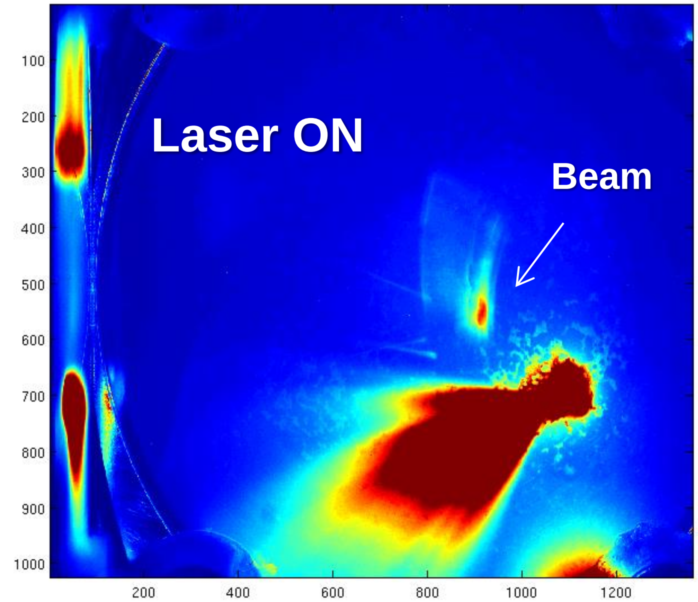
The focal length to have an image on the screen is fixed by the system geometry (distances).
Only a particular energy for a given B field creates an image of the point source on the screen.



FIRST PHOTO-EMITTED BEAM

On March 30, 2012 we synchronized the laser to the gun RF and measure the first photo-emitted beam at 1MHz by the dummy cathode plug presently installed in the gun.



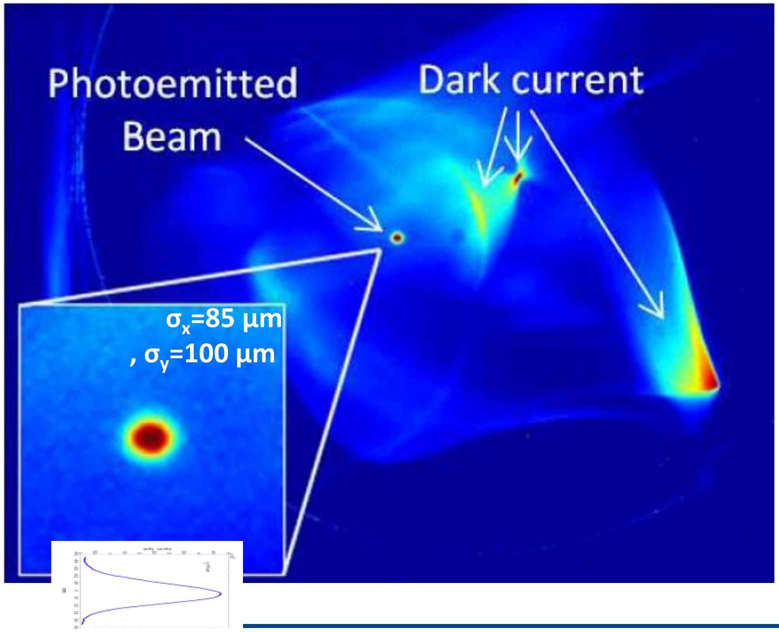


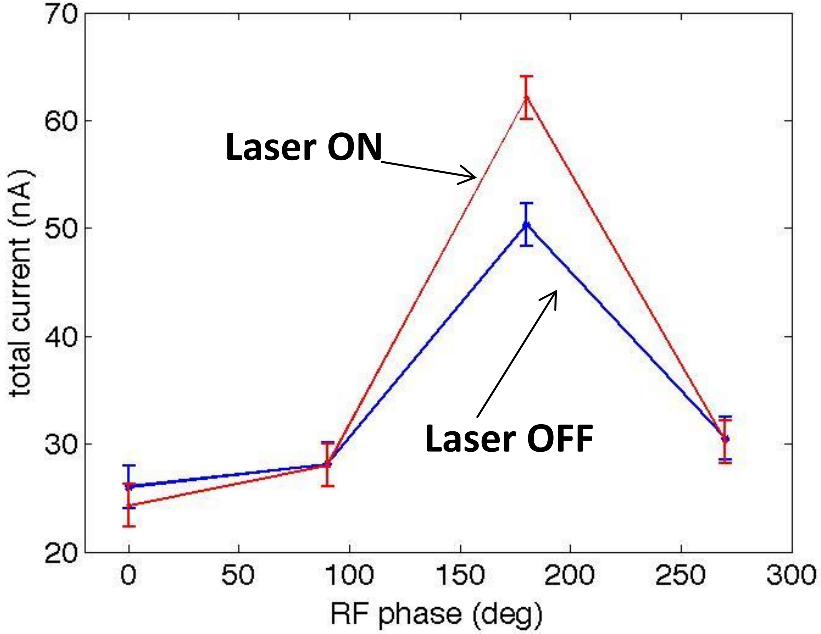
Laser average power at the cathode: ~ 30 mW at ~ 266 nm.
Cathode: Molybdenum plug, QE ~ 10^{-6}
Expected charge per bunch : ~ 6 fC (!!!)
Expected average current at 1 MHz: ~ 6 nA (dark current ~ 100 nA)

Full cross-check of the photo-gun functionality!

PHOTO-EMITTED BEAM CURRENT

Photoemitted average current measured by a lockin amplifier with the MHz laser trigger as reference and the Faraday cup signal in input.



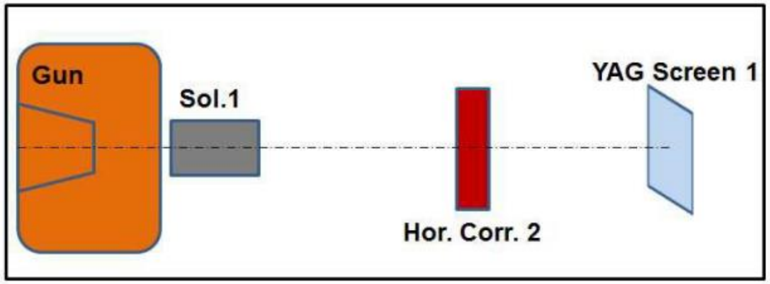


Laser average power at the cathode: ~ 30 mW at ~ 266 nm.
Cathode: Molybdenum plug, QE ~ 10^{-6}
Expected charge per bunch : ~ 6 fC
Expected average current at 1 MHz: ~ 6 nA (dark current ~ 100 nA)

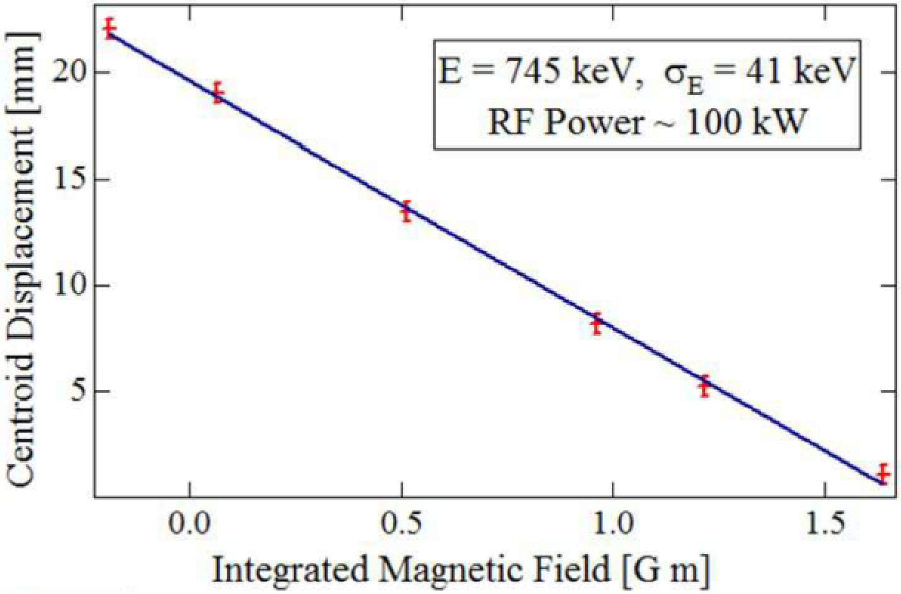
Measured ~ 10 nA, consistently with expectations!

ENERGY MEASUREMENT OF PHOTEMITTED BEAM

Nominal RF Power. Solenoid 1 ON to focus beam on screen.
Horizontal Corrector 2 current scanned for the measurement.



The fit slope is proportional to the particle momentum



$$\boxed{\begin{aligned} E &= 745\ \text{keV} \\ \sigma_E &= 41\ \text{keV} \end{aligned}}$$

Expected value at nominal power: 750 keV

Conclusions

- Reliable operation at full CW power (20MV/m)
- Vacuum levels on the 10^{-11} Torr level achieved with RF baking
- Dark current measurements within the expectations
- Measured 1MHz photo-beam at (very) low charge
- Installation of the load lock system is ongoing
- Ready for cathode tests!!

APEX people

APEX @ Berkeley Lab

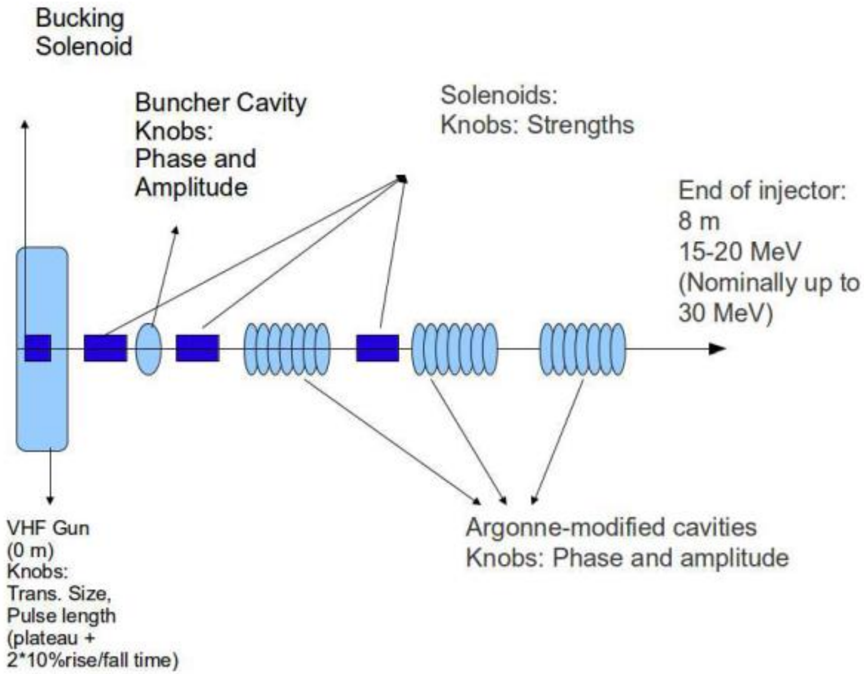
K. Baptiste, J. Byrd, M. Chin, J. Corlett, C. Cork, S. De Santis, L. Doolittle, J. Doyle, J. Feng, D. Filippetto, G. Huang, H. Huang, T. Kramasz, S. Kwiatkowski, V. Moroz,
W. E. Norum, H. Padmore, C. Papadopoulos,
C. Pogue, G. Portmann, J. Qiang,
F. Sannibale, J. Staples, T. Vecchione, M. Venturini,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

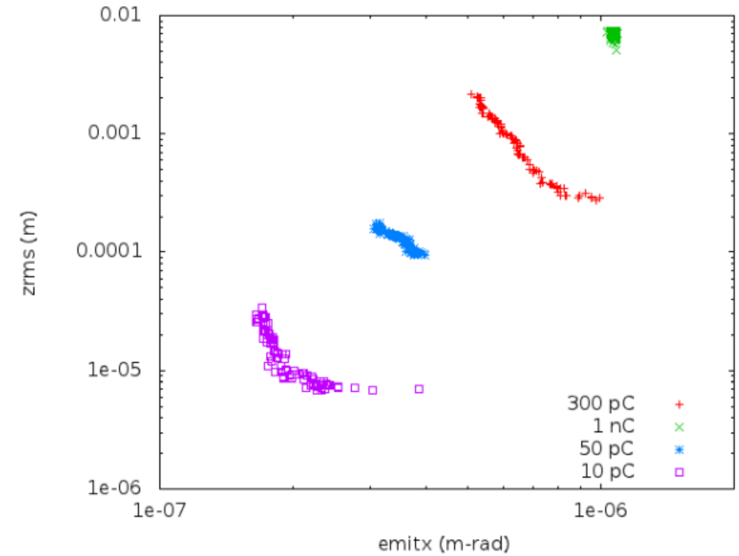
… a new *carrier track (research scientist)* position is now open for APEX/NGLS
for more information go to http://jobs.lbl.gov/open-positions.html

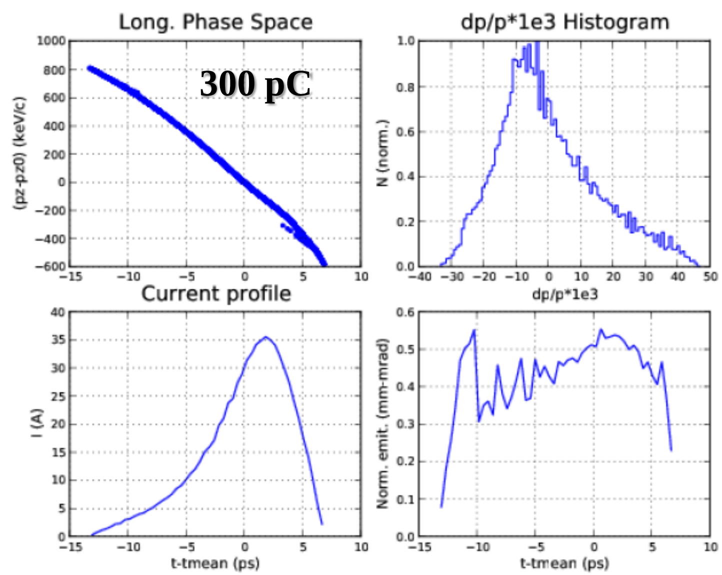
リスニングのおかげで

BACK UP SLIDES

Phase II BEAM DYNAMICS



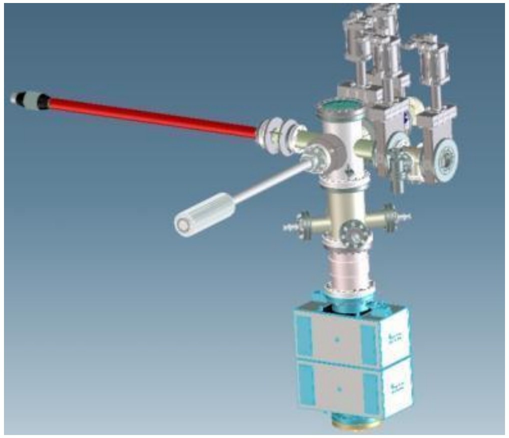


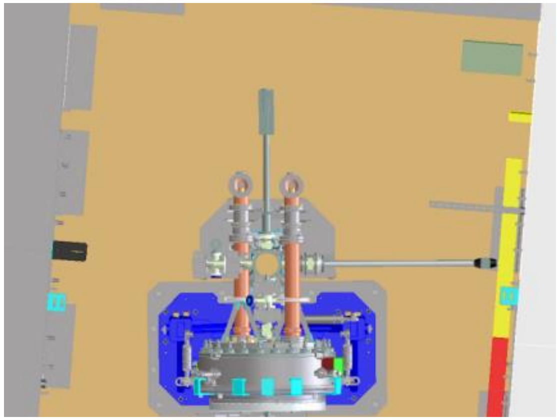


- **Multi-Objective Genetic Algorithms optimization, trading for example, between final emittance and bunch length.**

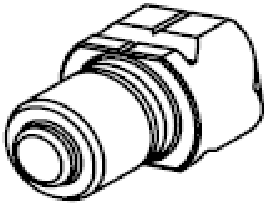
C. Papadopoulos

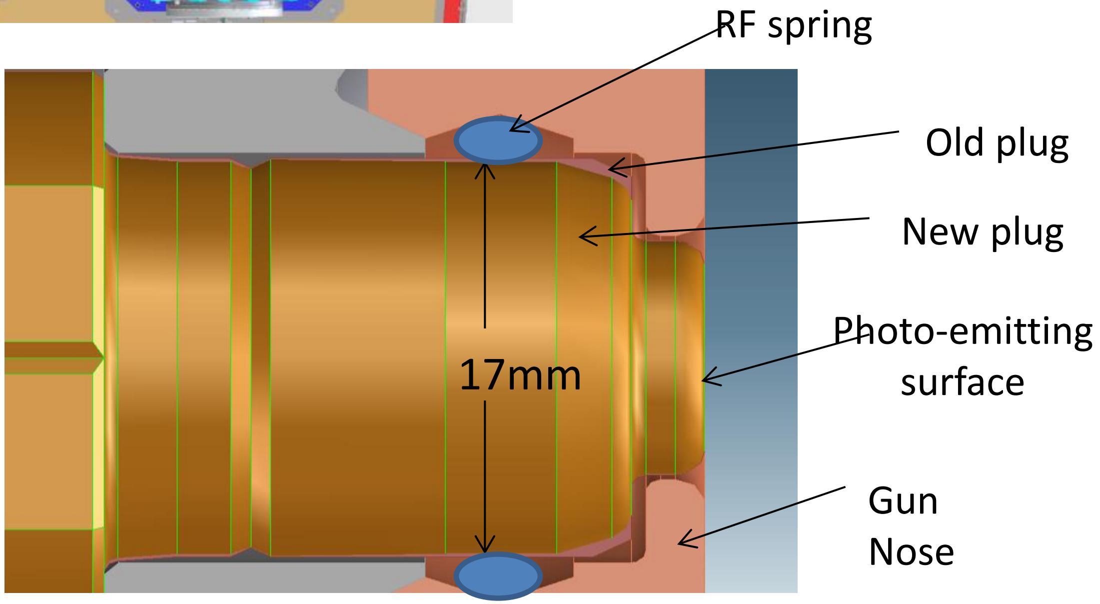
VACUUM LOAD LOCK SYSTEM





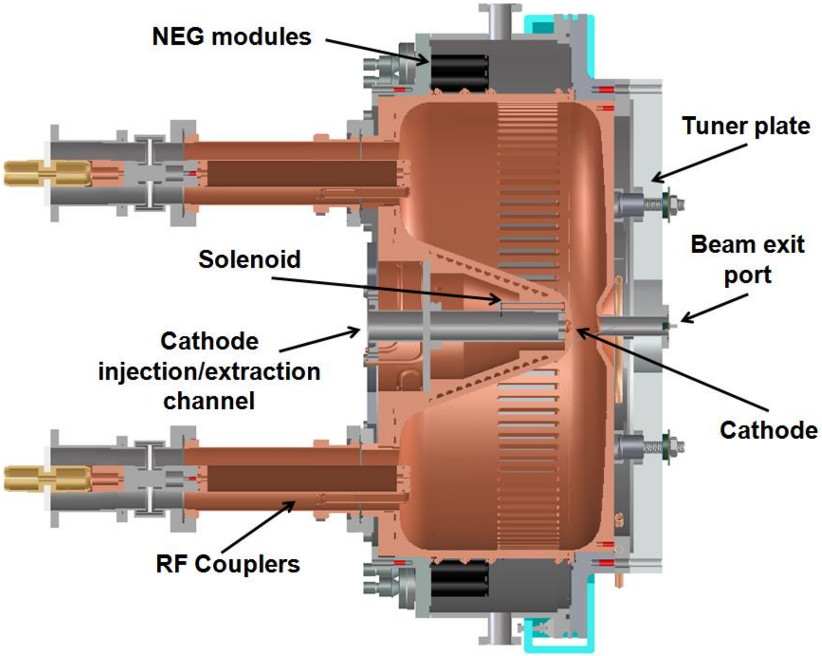
Adapted version of the INFN/PITZ/DESY load-lock system

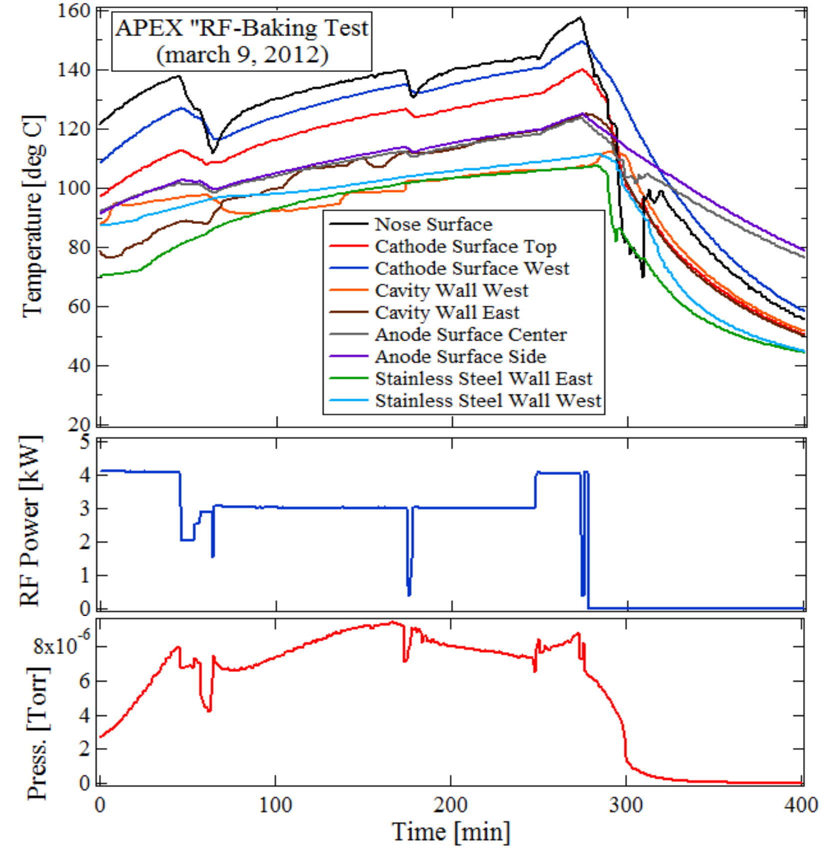




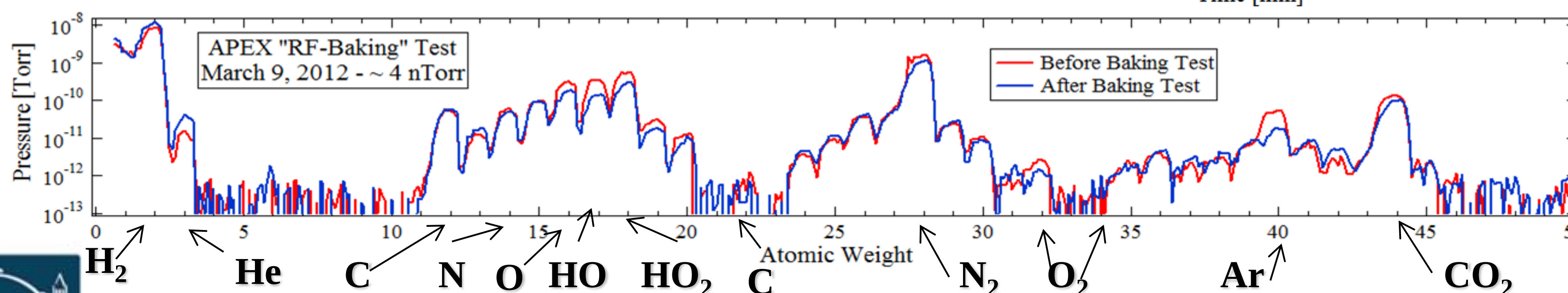
Any photocathode deposited on a same geometry plug can be potentially tested at the VHF gun

"RF BAKING"

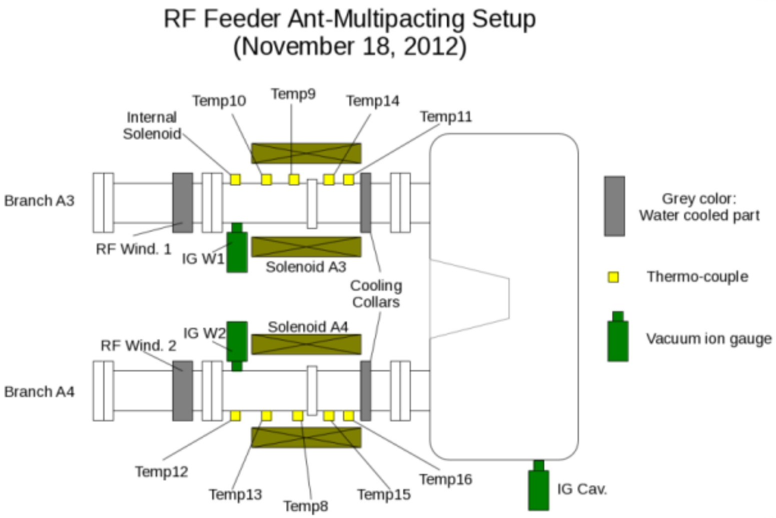


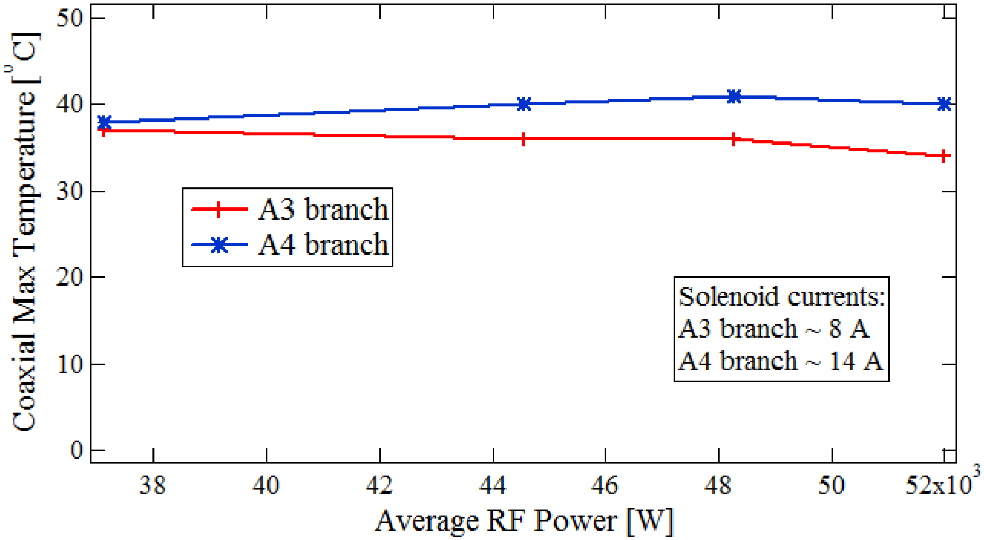


Baking the gun with no water cooling (!) and 2-4 kW average RF power.



MULTIPACTING IN COAXIAL LINE





The solenoid cure worked!

RF SYSTEMS

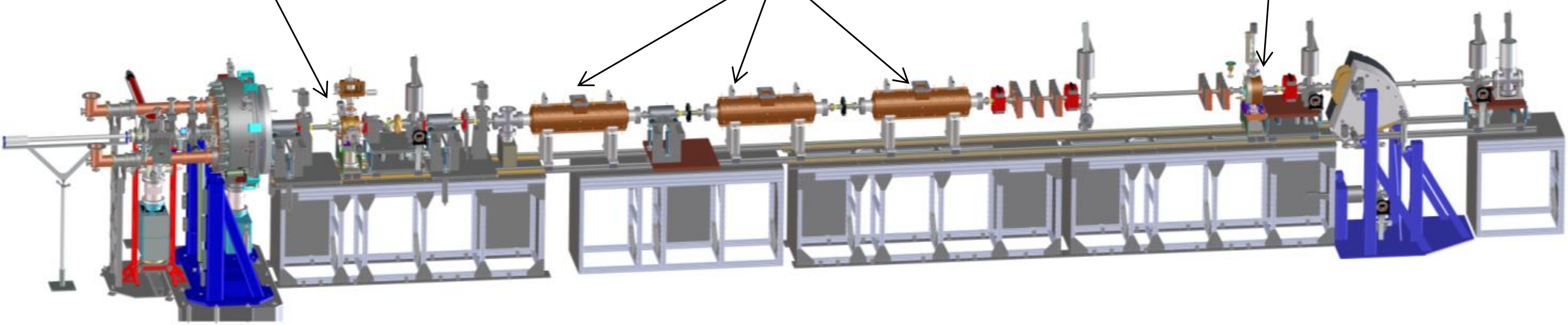
Single* RF source: 1.3 GHz, 25 MW pulsed at 10 Hz with 10 μs pulse.
(*real estate and funding limited)

RF Distribution System

Buncher cavity:
LBNL design

LINAC: 3 accel. sections.
AWA/ANL type

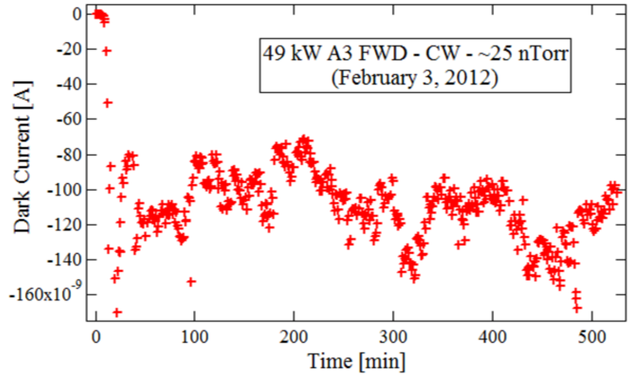
Deflecting cavity:
Modified Cornell Type

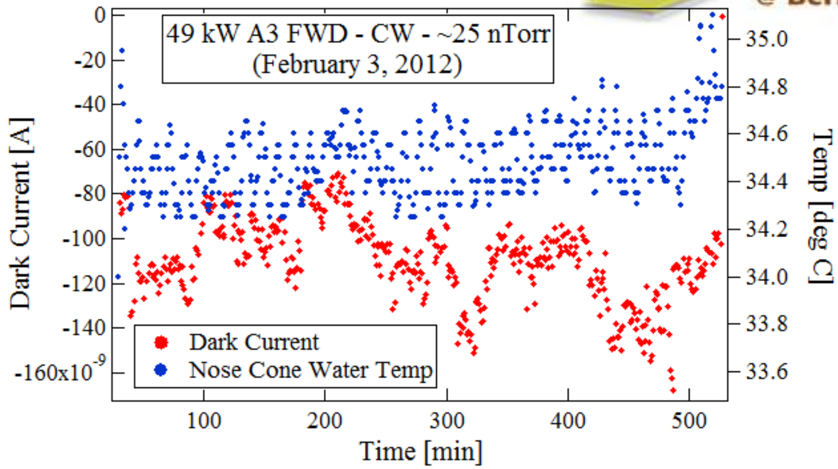


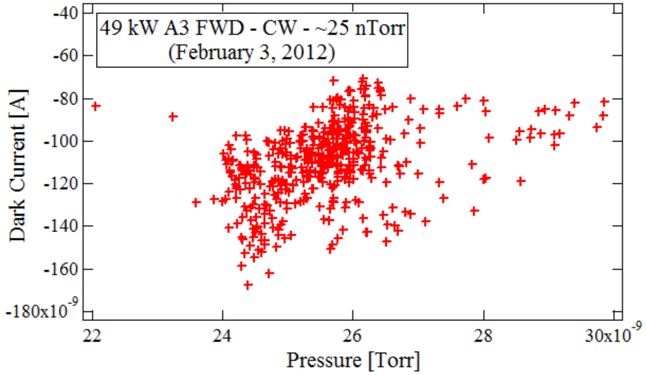
S. Kwiatkowski

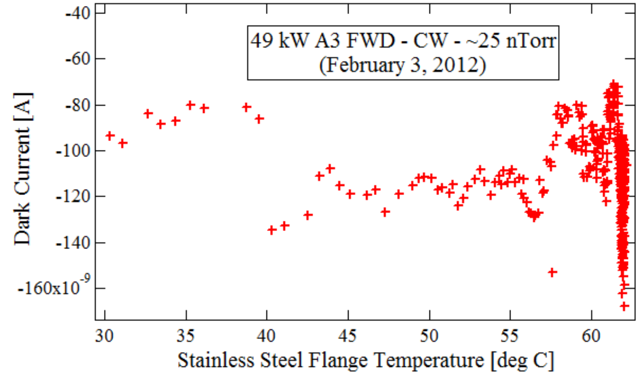
MORE ON DARK CURRENT

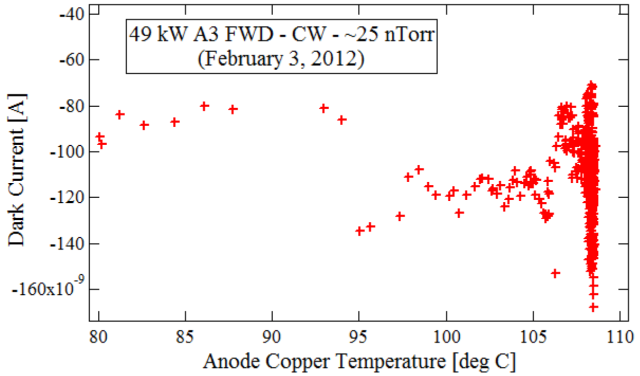
@ Berkeley Lab

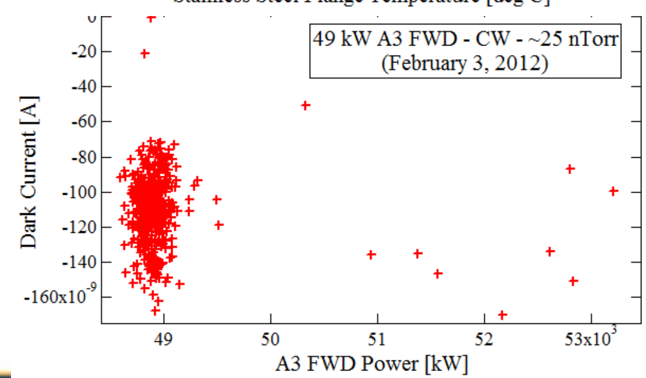












RGA MEASUREMENTS – RF ON and OFF

Measurements performed with a Dycor 2000 RGA system.
1 NEG pump activated, 1 ion pump, 2 turbo pumps. No gun baking.