Beam commissioning results from the R&D ERL at BNL

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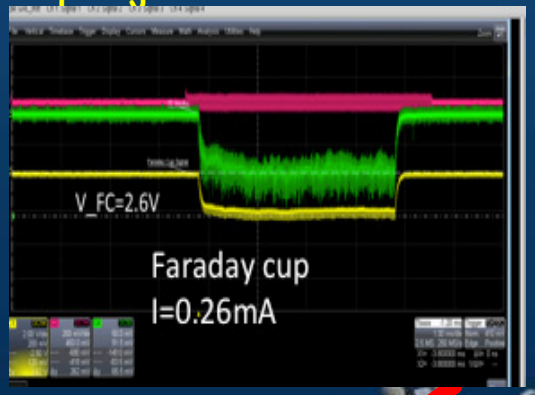
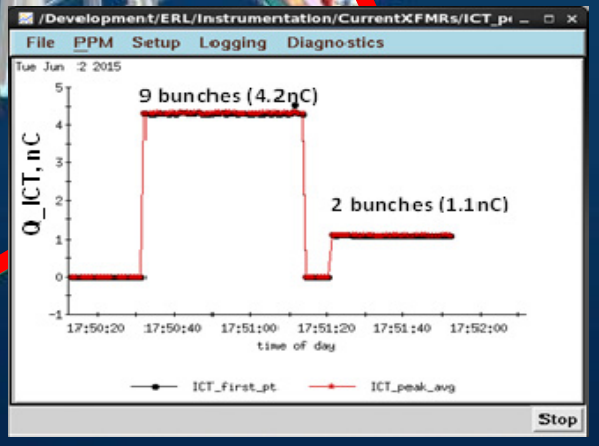
BNL R&D ERL

- ✓ ERL construction was completed: May 2015
- ✓ Q=0.55nC, I=.26mA per 4 msec reached: June-July, 2015
- ✓ R&D ERL has been built to serve as the test bed for future projects at CAD.
- ✓ Many ERL components will be used for RHIC upgrade project: LEReC.





SRF Gun with photocathode

Injection line

SRF 5cell linac

Faraday cup
I=0.26mA

Beam dump

Returning loop

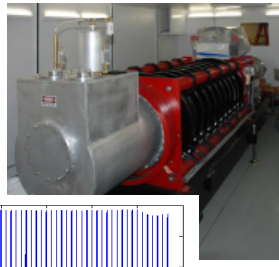
~20m circumference

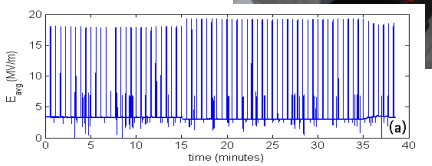
R&D ERL: Installation and commissioning time line

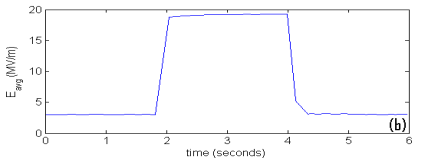
Strategy: Start commission of key components when systems installed and recourses are available.

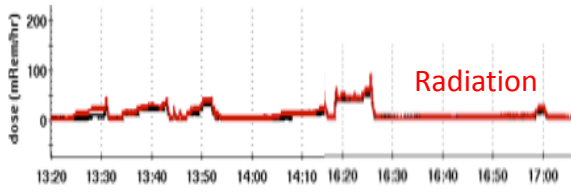
(no beam)

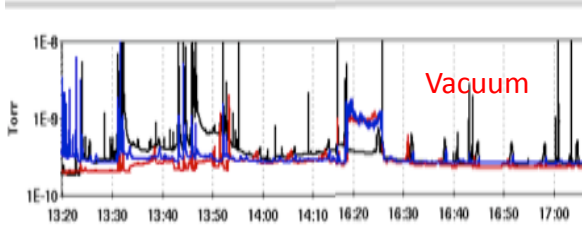
- ✓ High power RF components installed and commissioned (2005-2007
  - ✓ 1MW Klystron, 50kW RF PA, waveguides, controls, circulator, dummy load
- ✓ SRF 5-cell installed and cold emission test completed (2009)
  - ✓ Eacc=18MV, 2 sec CW every 10 sec.
- ✓ 9.4MHz Laser system commissioned (2009)
- ✓ Digital LLRF system commissioned (2012)
- ✓ 2 K LHe cryogenic system/refrigerator commissioned (2012)
- ✓ SRF half-cell gun cold emission test w/o cathode (2013)
  - ✓ Eacc=2MV
- ✓ Conditioning of the SRF gun with a cathode stalk (Jan 2014)
  - ✓ Eacc=1.25MV
- ✓ Gun test beam line components installation completed
- ✓ Low power gun beam test approved (May 2014)

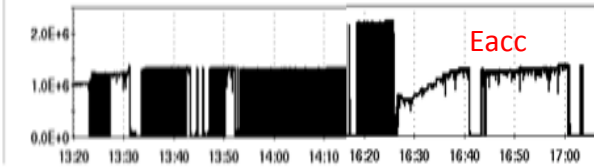




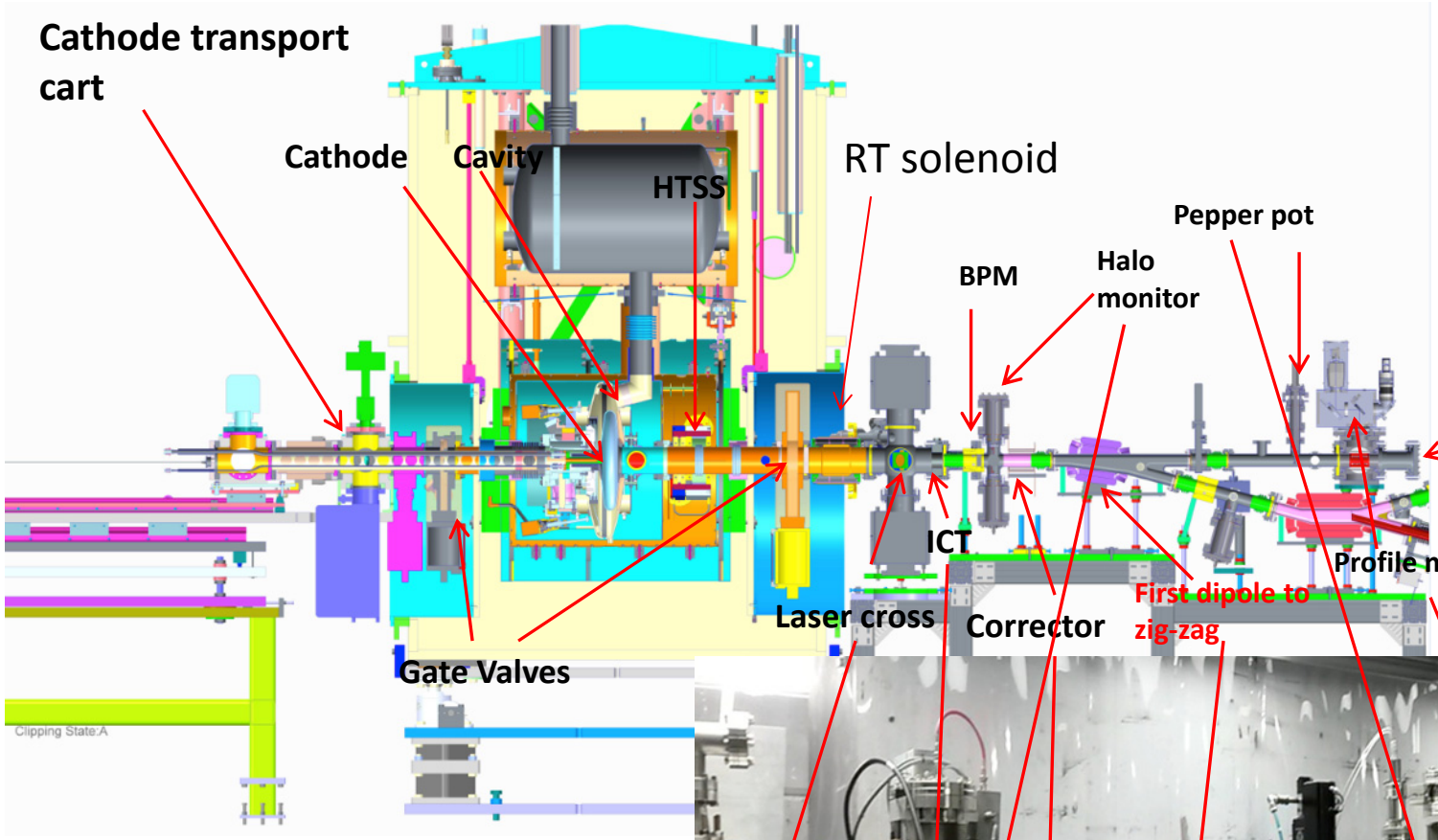




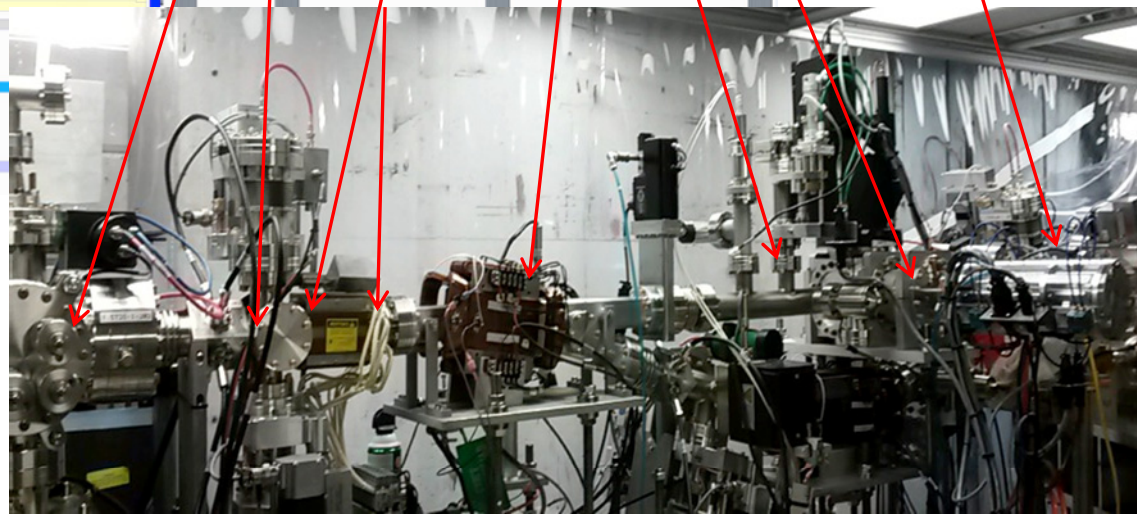




First beam commissioning (June-Nov. 2014)



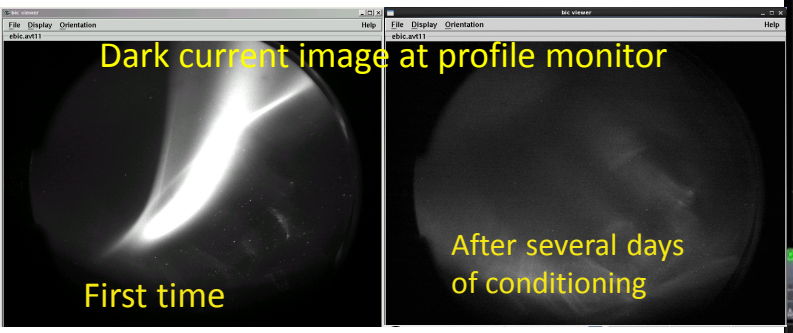
RT solenoid wrapped around the v.pipe in situ due to problems with running HTS one.



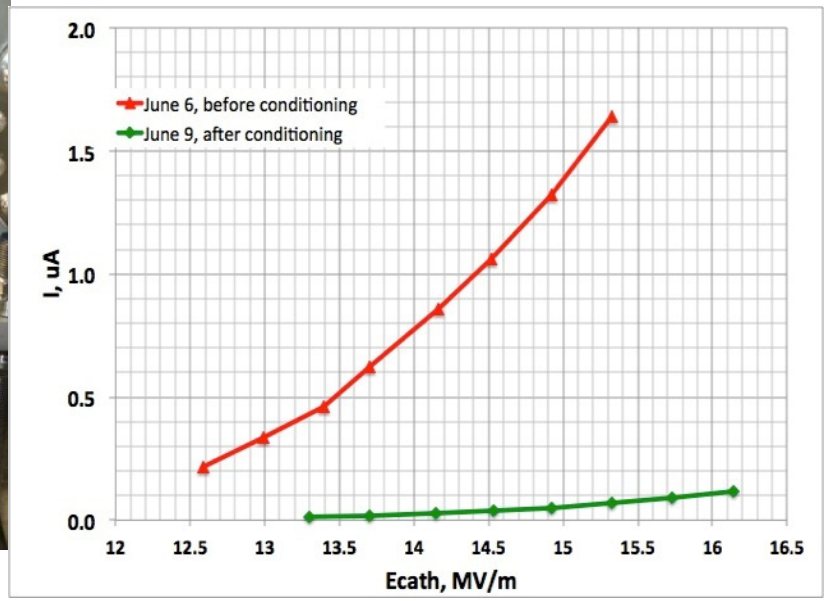
First Injection line dipole stays off during gun beam tests. Straight line is used to check QE at the beginning and the end of every regular shift, and energy measurements.

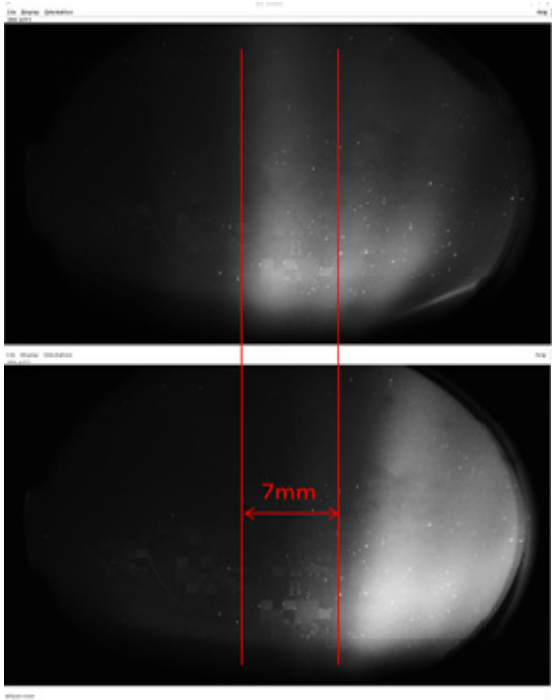
First attempt to run SRF gun with cathode (June 2014)

✓ Cathode dark current measured.



FC current measurements
RF duration 40 msec, Eacc=1.2 MV
FC signal R=1 MOhm termination:
green -225mV peak,
integral yellow 28 mVsec
Charge per pulse Q=28 nC, I_{dark}=700 nA



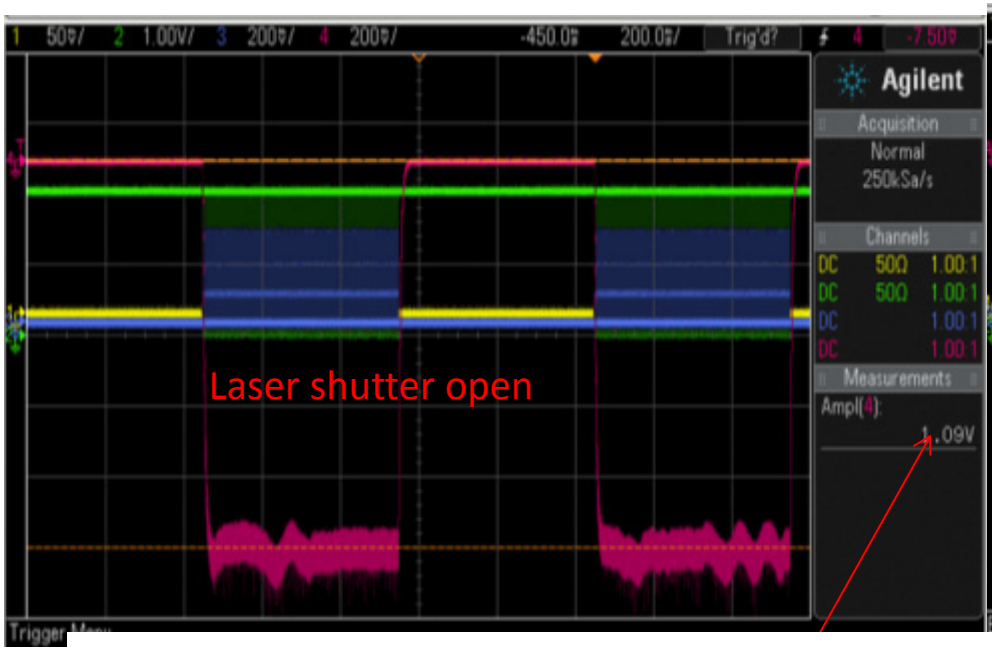


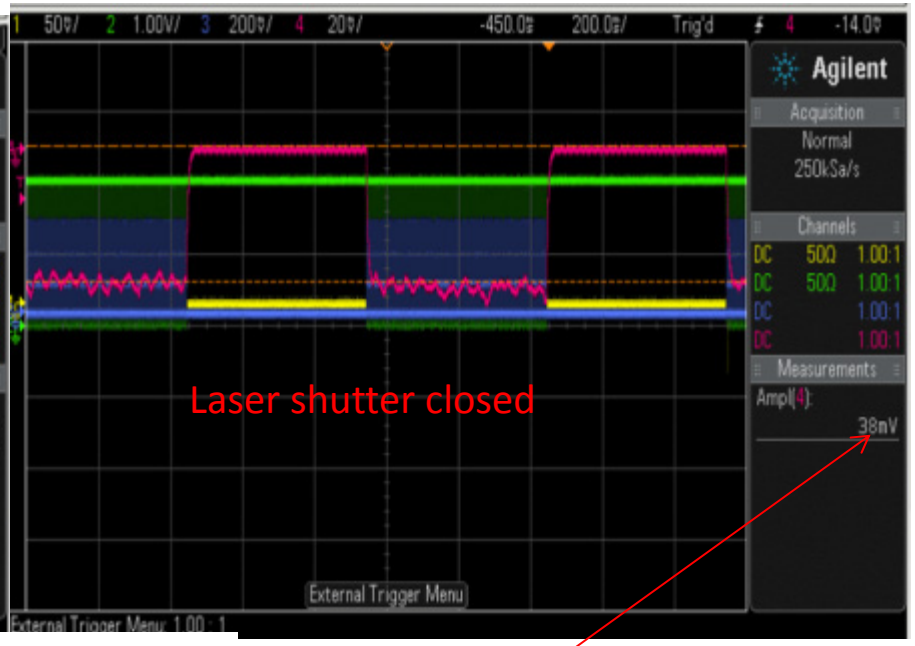
Energy measurements.
Corrector top 0.5 A, bottom 1 A.
7mm shift due to 0.5 A corrector change corresponds to beam energy of 1.2 MeV.

Dark current measured before (red) and after (green) conditioning June 2014. Drops ~25 times after conditioning.

D. Kayran

First beam, old cathode Nov 2014.





Faraday cup signal (1MΩ termination)

Set up

- Laser: 6.1 Watt, green,

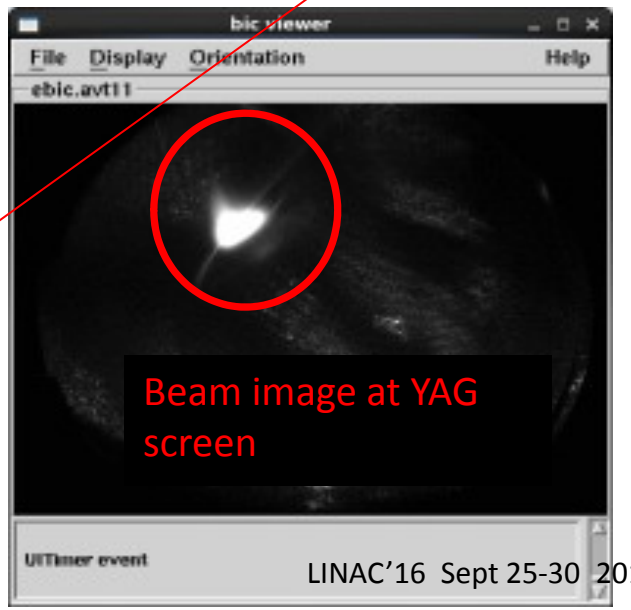
Pulse structure 7 μsec, every 500 μsec; 9.38MHz rep rate.

- RF: 1.2 MV, 500 ms, 1Hz;
- Beam:

  bunch charge: 7.7 pC,

  Average per RF pulse

  photocurrent 1 μA. dark current 38 nA;
- Photocathode cold QE=2.7e-5 Very low!!!

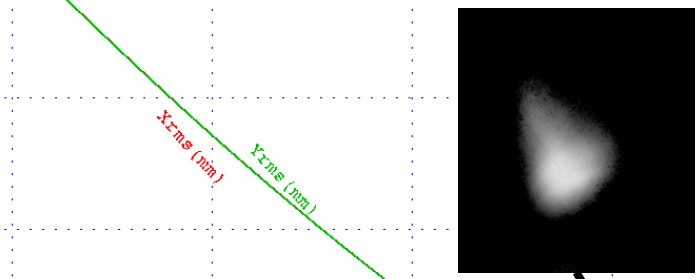


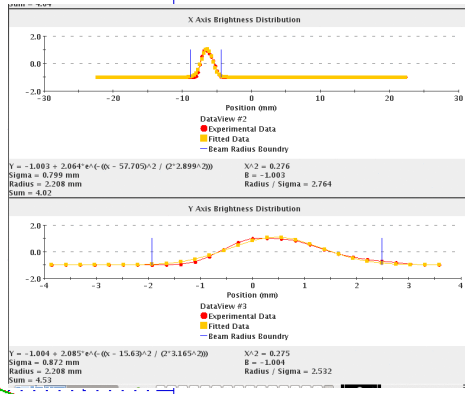
First beam test results meas. vs sim

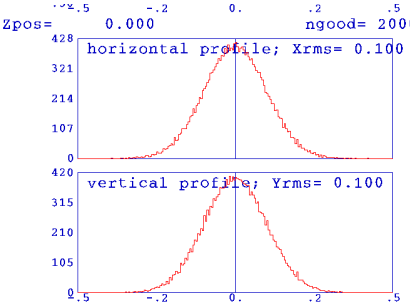
Measurements

σx=0.8 mm

σy=0.9 mm





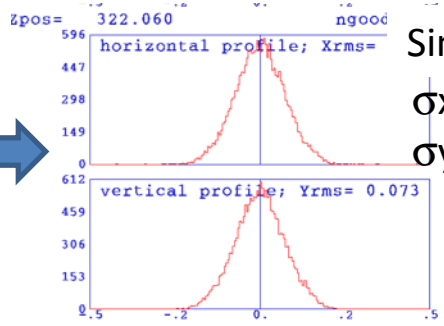


E=1.2 MeV

Q=10 pC

σ_laser=1 mm

Simulations



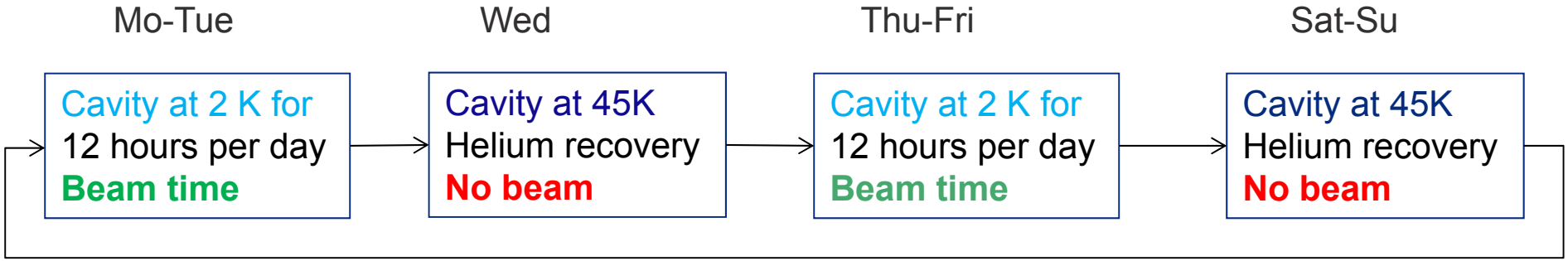
Simulations:

σx=0.74mm

σy=0.73mm

ERL beam commissioning job flow (cryogenic limited)

- ERL Cryogenic system is capable of providing 2K cold operation time of the SRF gun up to 16 hours in low power load mode.
- Then 8 hours hold at 4.5 K.
- After that it requires 1-2 days for helium recovery
- We can run the gun maximum four days per week



Optimum schedule

Monday : Cool down the gun to 2 K, Insert cathode, stay at 2 K for 16 hours; then, hold 4.5 K over night

Tuesday : Cool down the gun to 2 K, stay at 2 K for 16 hours; then, remove cathode warm it up to 40 K over night;

Wednesday, the gun with stay at 45K cathode is out;

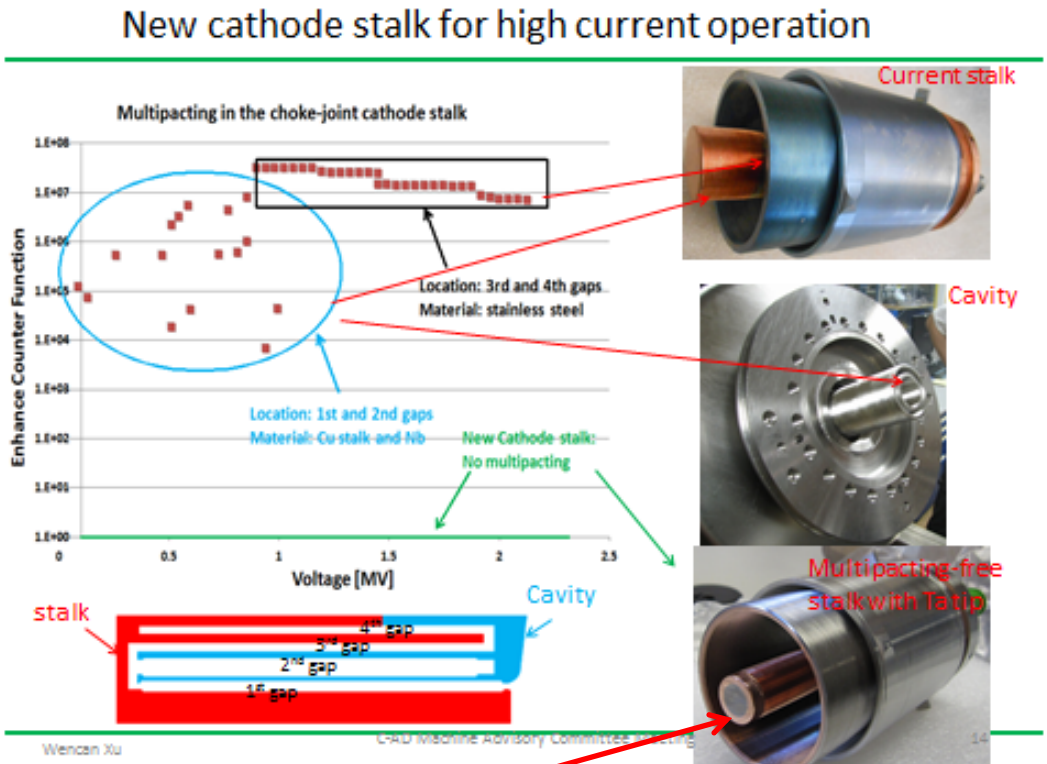
Thursday Cool down the gun to 2 K, Insert cathode, stay at 2 K for 16 hours; then, hold 4.5 K over night.

Friday, Cool down the gun to 2 K, stay at 2 K for 16 hours; then, remove cathode warm it up to 40 K over night

Saturday, Sunday, the gun with stay at 45K cathode is out

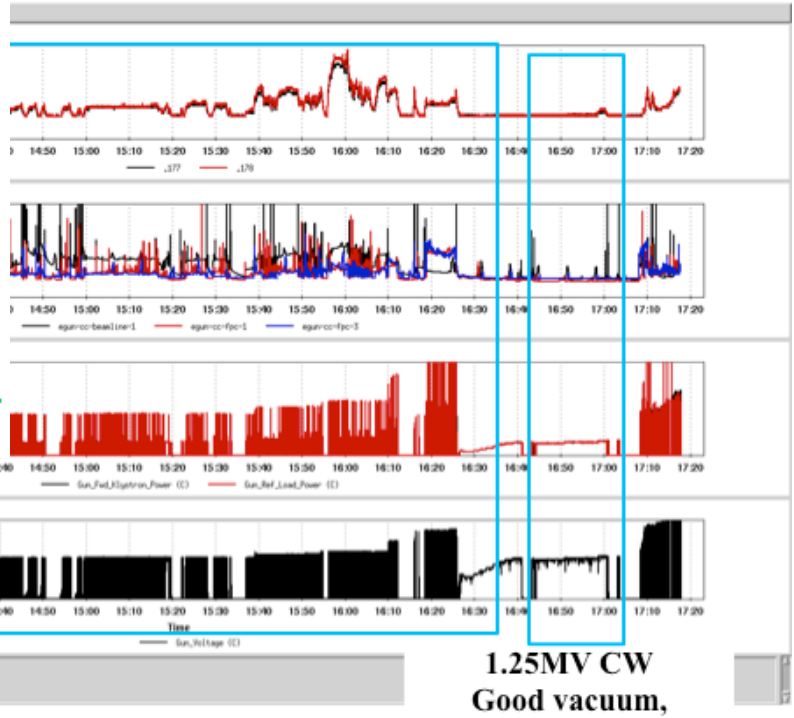
Beam time / Cryogenic time about 38%

New “multipacting-free” cathode stalk has been designed and fabricated with Ta tip*.



Ta Substrate

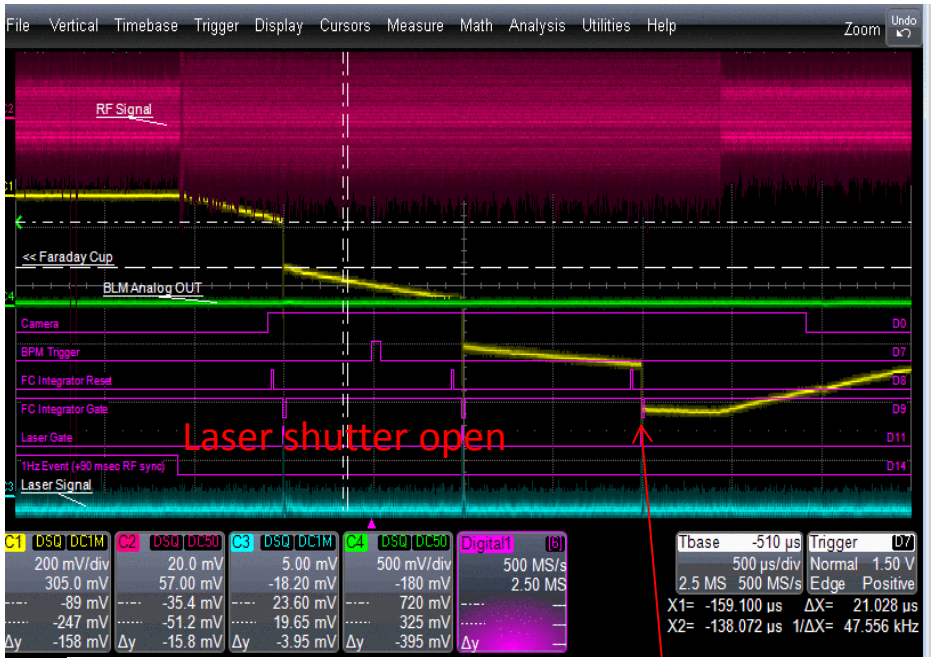
; Gun with new cathode stalk.

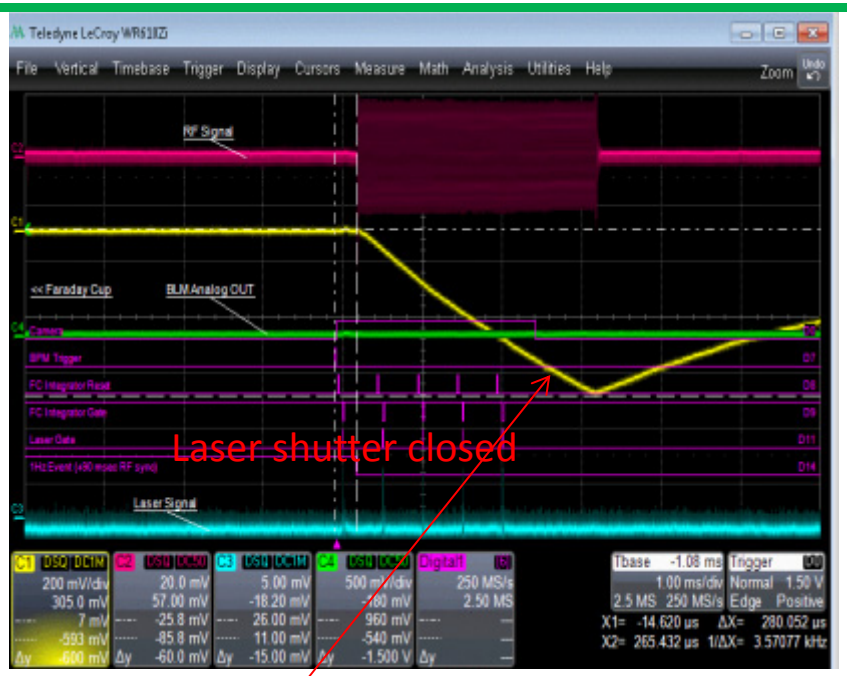


1.25MV CW
Good vacuum,
No radiation

*Wencan Xu et al., “Multipacting-free quarter-wavelength choke joint design for BNL SRF gun”, In Proc. of IPAC’2015, pp 1935-1937 (2015).

Beam commissioning with new cathode June 2015.





Faraday cup signal (1MΩ termination)

Set up

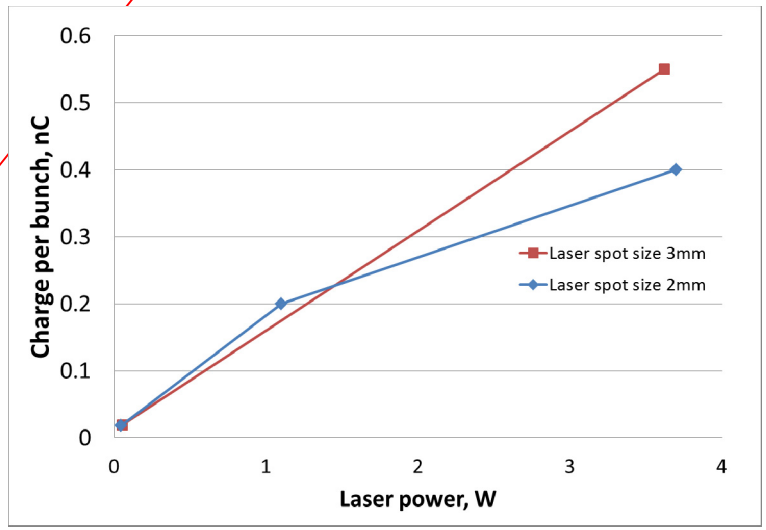
- Laser: 0.044 mWatt, green,

Pulse structure 5 μsec, every 500 μsec; 9.38MHz rep rate.

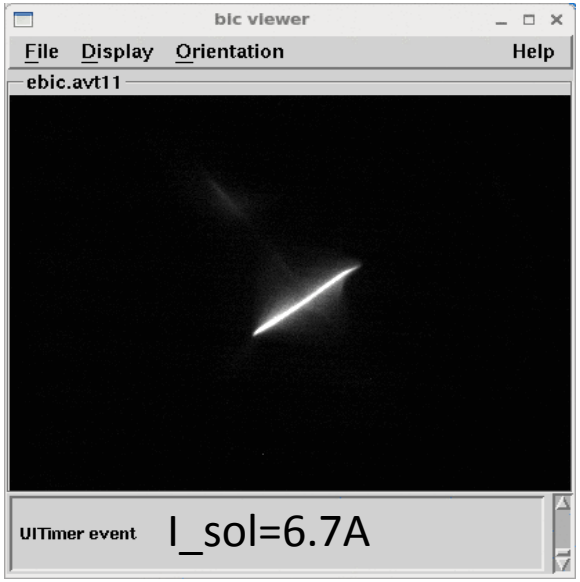
- RF: 0.65 MV, 3 ms;
- eBeam:

  charge per macro bunch 0.8nC/47bunches=17pC

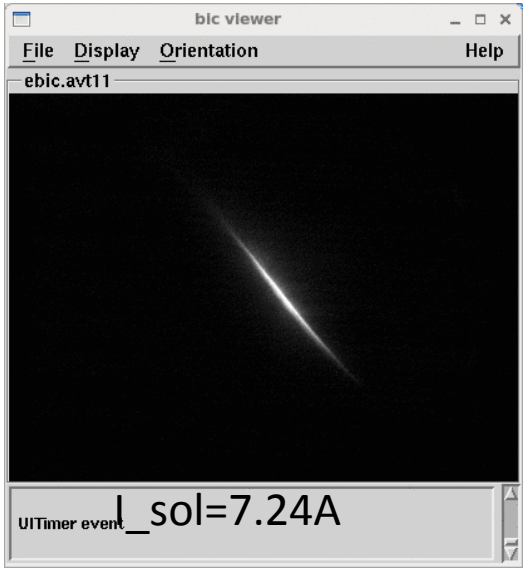
  dark current 4 μ A;
- Initial photocathode cold QE=1e-2 very Good!!!



Solenoid scan to measure gun astigmatism (preliminary)



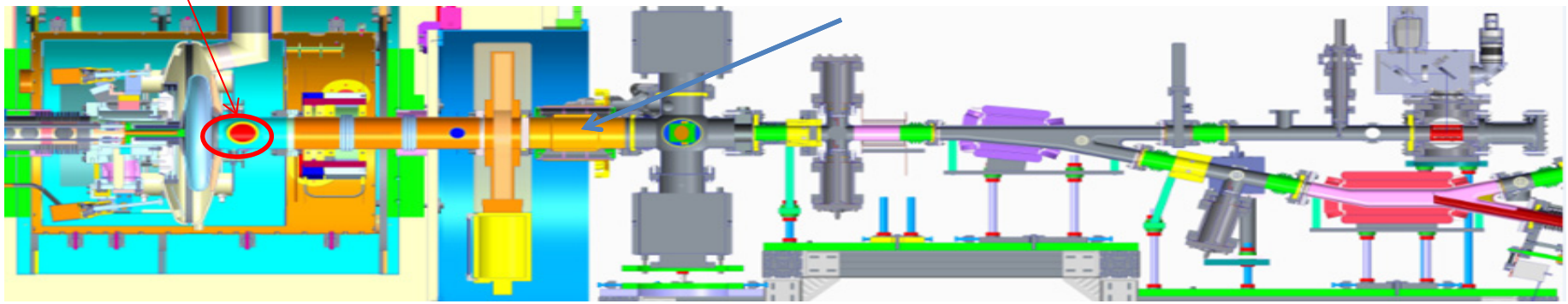
Ninja star shape



2 FPCs

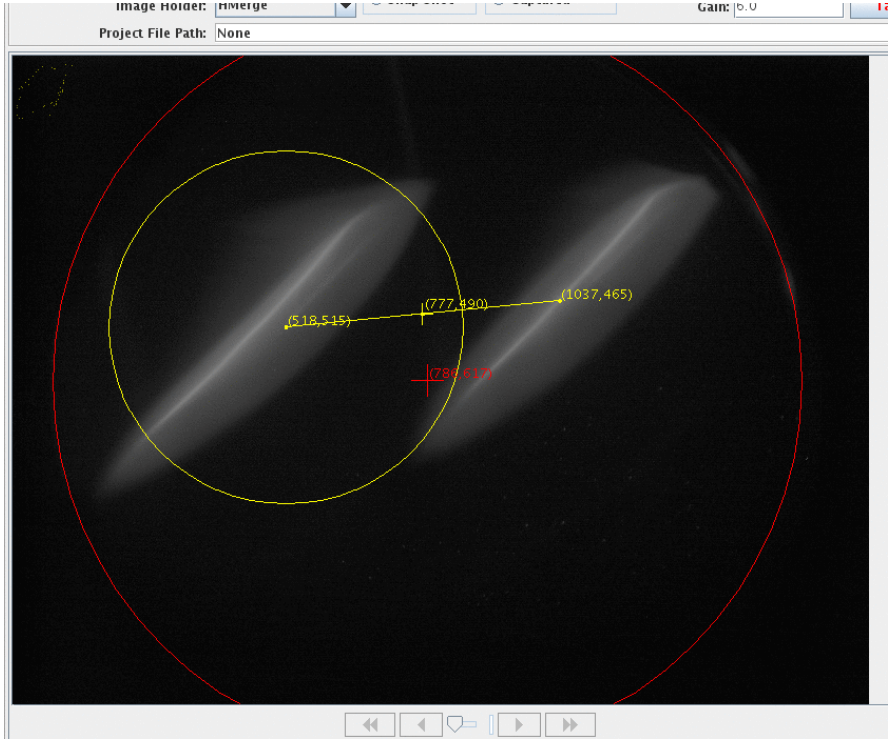
Axial symmetric system or not?

In situ built solenoid around vacuum pipe.

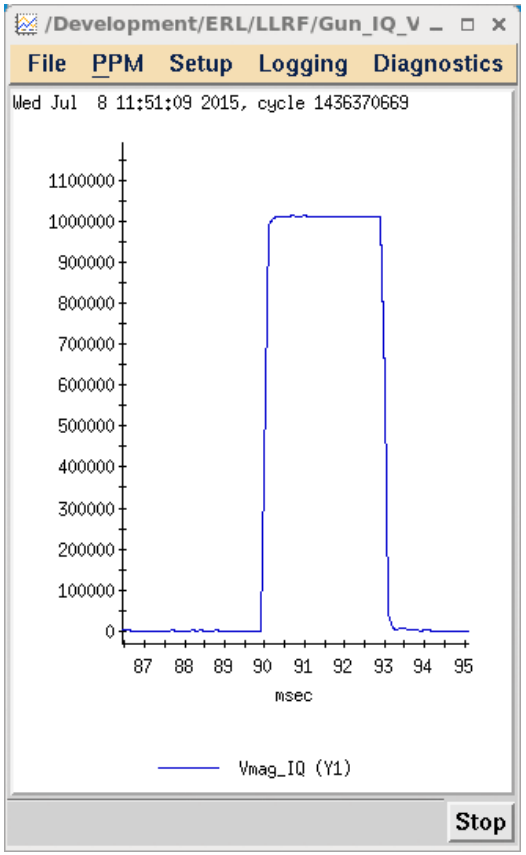


Such asymmetry could be generated by quadruple with focus length 64cm!!!. Located at FPC or solenoid imperfection. Required father investigation.

Energy measurements using correctors and profile monitor

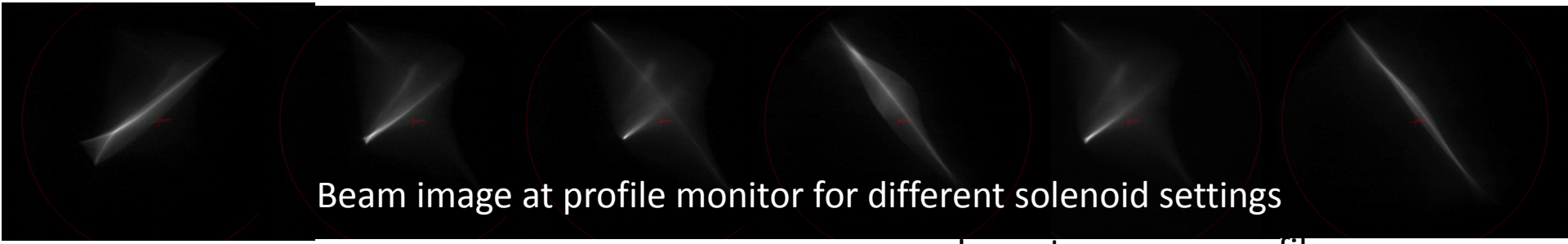


RF voltage setting 1.02 MV

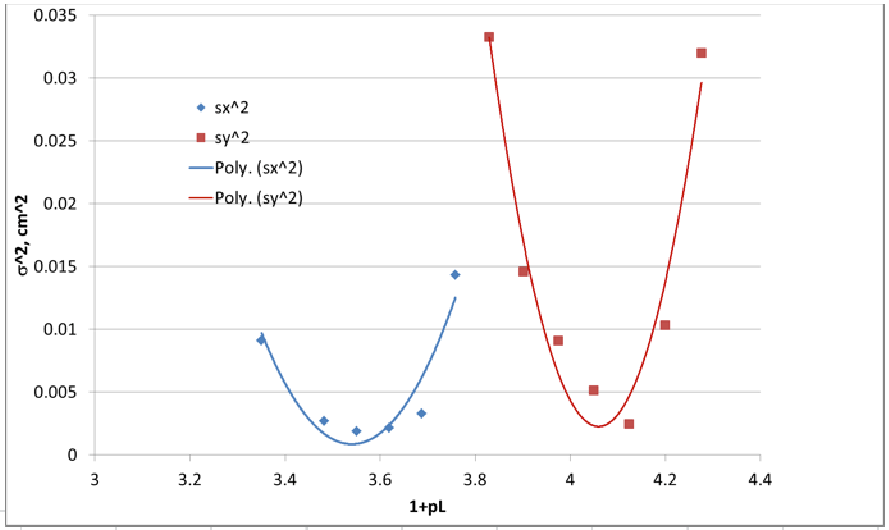


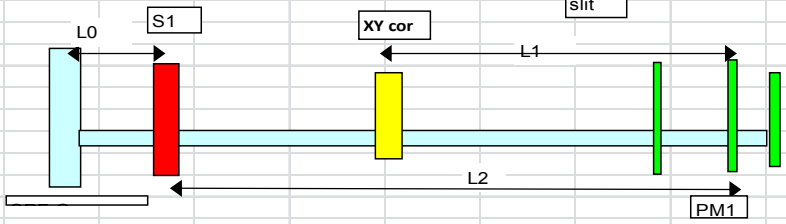
Beam shift at straight line profile monitor
15.5 mm
corrector changes dI=1.4A
Corresponds to beam energy KE=1MeV

Try Solenoid scan, Q=130pC

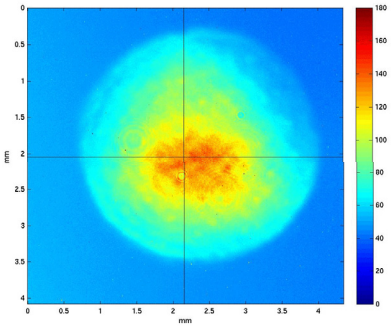


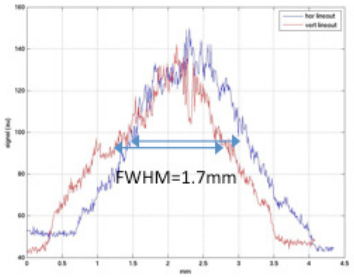
Beam image at profile monitor for different solenoid settings





Laser transveres profile





Power on cathode 3.49 W at 9.38 MHz, or 372nJouls per laser pulse, FWHM=1.7mm

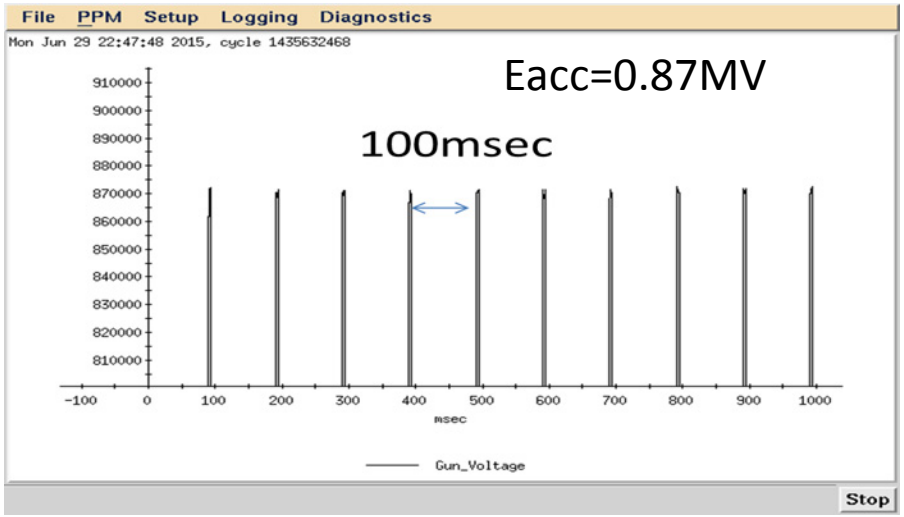
$$x_{rms}^2 =< x^2 >= A\left(\frac{1}{f^2}\right) - 2AB\left(\frac{1}{f}\right) + (C + AB^2)$$

$$\varepsilon = \frac{\sqrt{AC}}{d^2}$$

Vertical normalized emittance 3.5 um

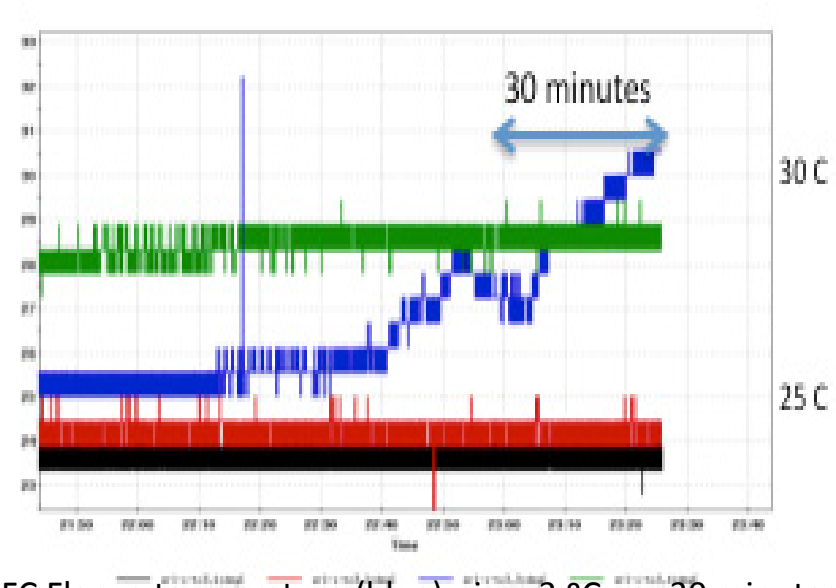
Horizontal normalized emittance 2.6 um

10 Watts e-Beam for fault studies.



RF pulses structure 5 msec every 100msec

One single: RF pulse duration 5msec (magenta), laser pulses 4msec (green) and faraday cup signal 4 msec (yellow) 10 kOhm termination.

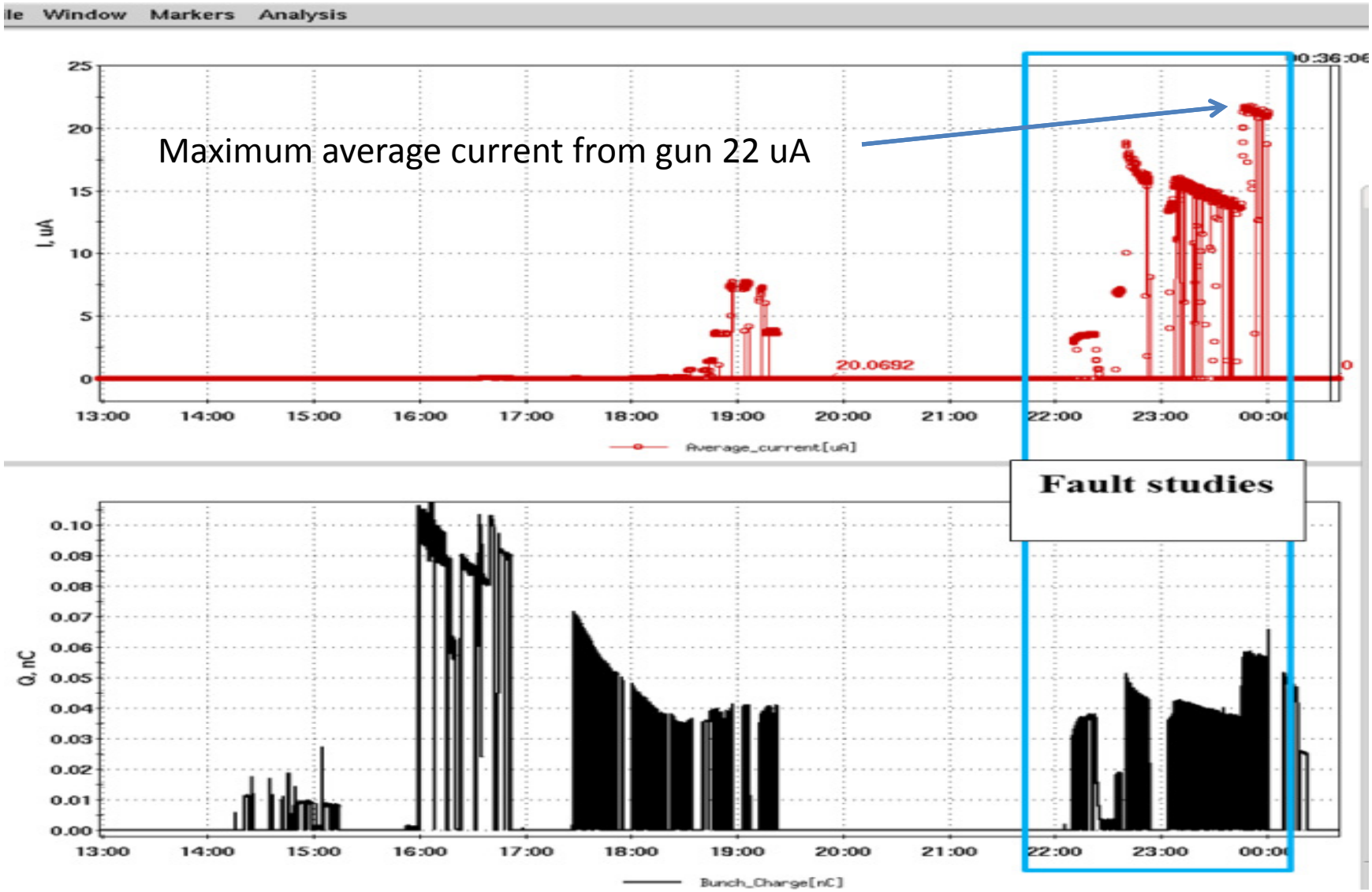


FC Flange temperature (blue) rises 3 ºC per 30 minutes.

260 uA in 4 msec pulse at FC has been measured. With duty cycle 4% corresponds to 10.4 uA average current at beam dump. Beam with average power in order to 10 Watts has been provided for radiation survey to FC.

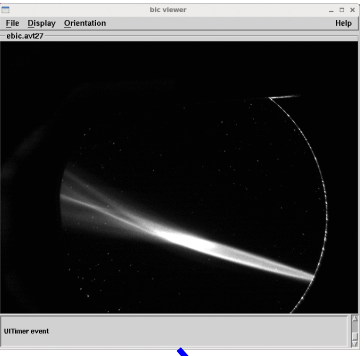
After these studies and completion of ARR DOE approval for full power gun-to-dump test commissioning has been received in July 2015.

Average current and charge from Gun

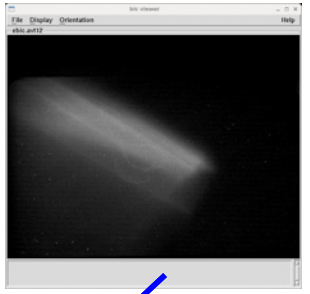


Average current and charge from the gun during fault studies measured by ICT and pulse counter .

Gun to Dump test: first propagation

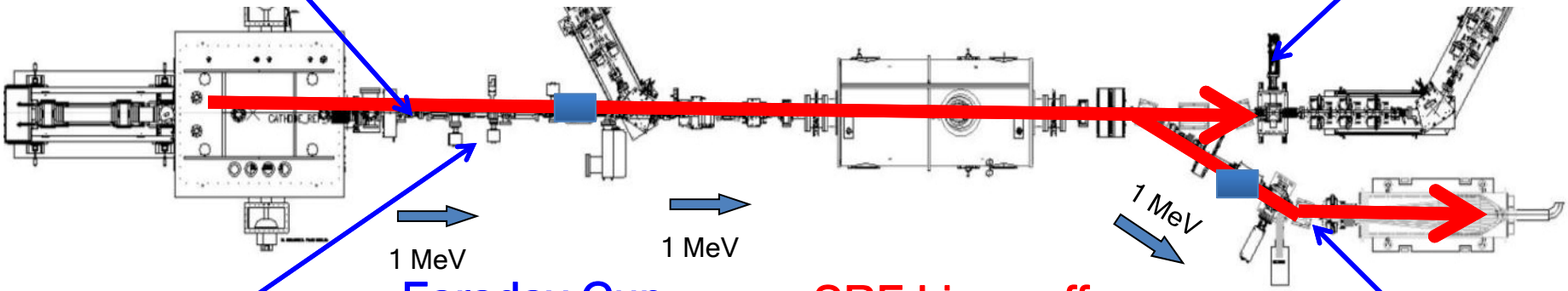


Beam propagates from the gun through injection line, linac extraction line to beam dump



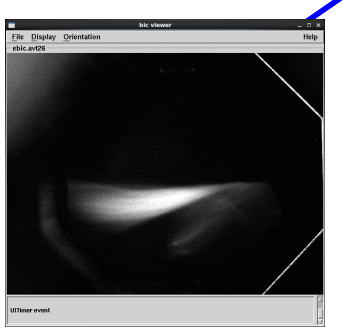
SRF Gun

Beam profile monitor

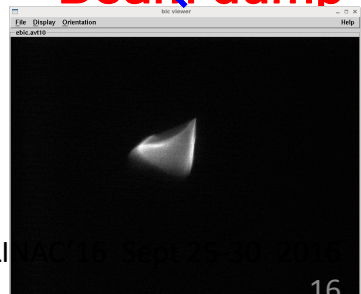


Faraday Cup

SRF Linac off

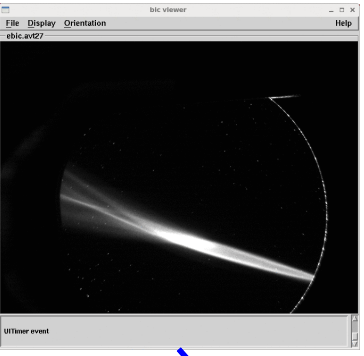


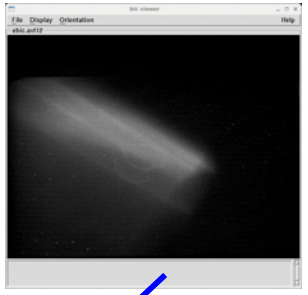
Beam dump



Gun to Dump test: first propagation

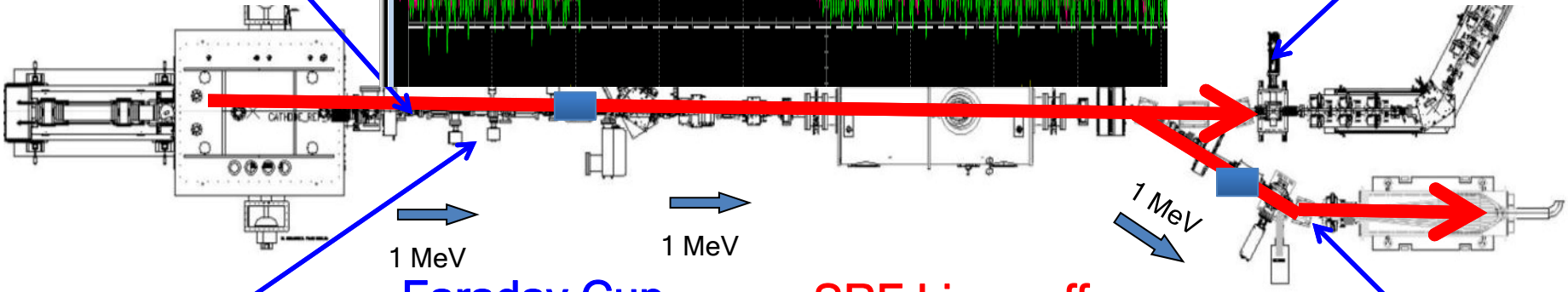
Beam current measured by injection line DCCT (magenta) and by extraction line DCCT (green). 90% transport efficiency has been achieved.





SRF Gun

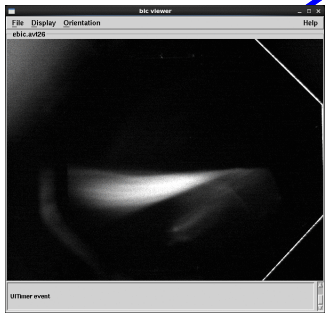
Beam profile monitor

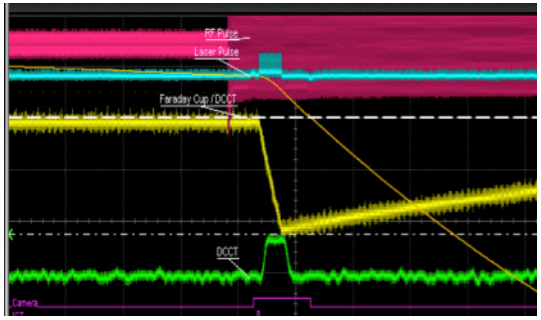


Faraday Cup

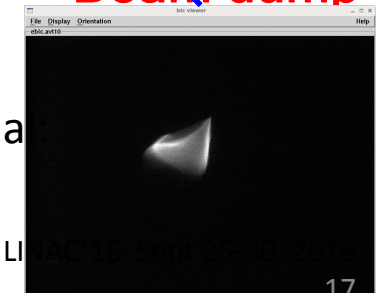
SRF Linac off

Beam dump

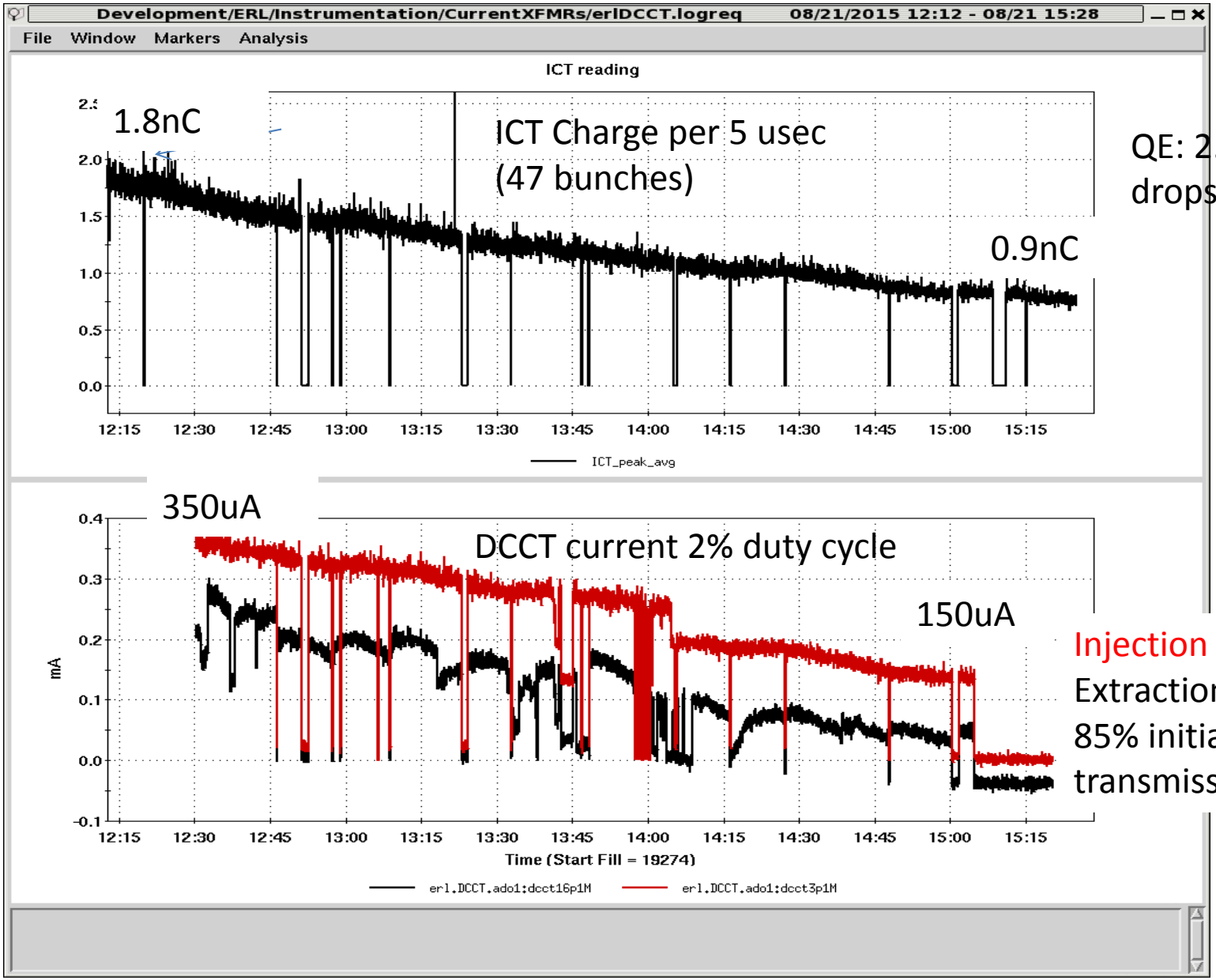




Magenta: RF pulse 20 msec;
Cyan: Laser pulses
Green: DCCT injection line signal
Yellow: Beam dump signal.



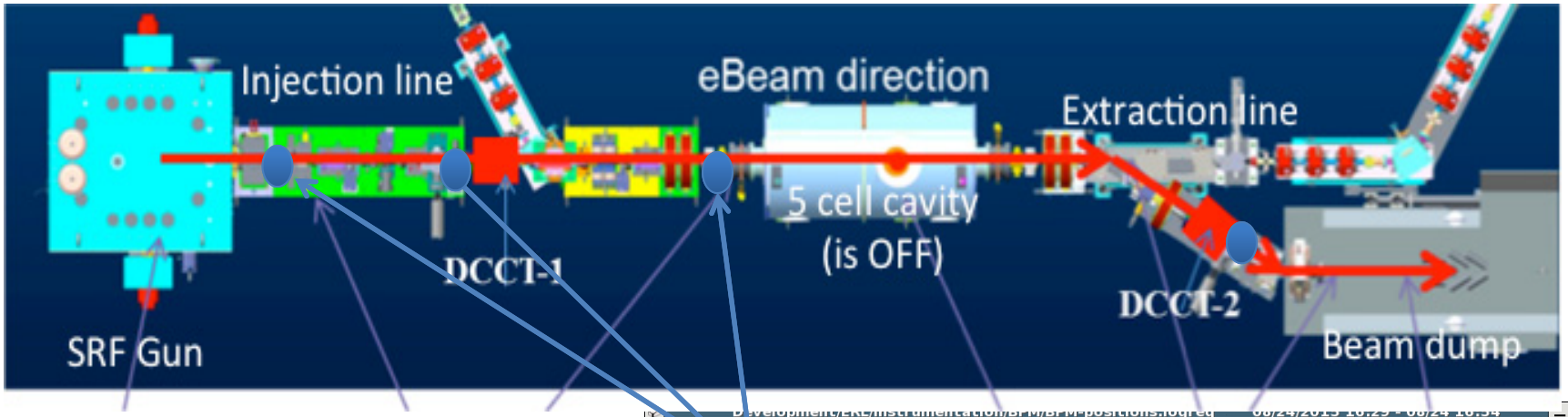
Typical cathode QE redaction during beam tests



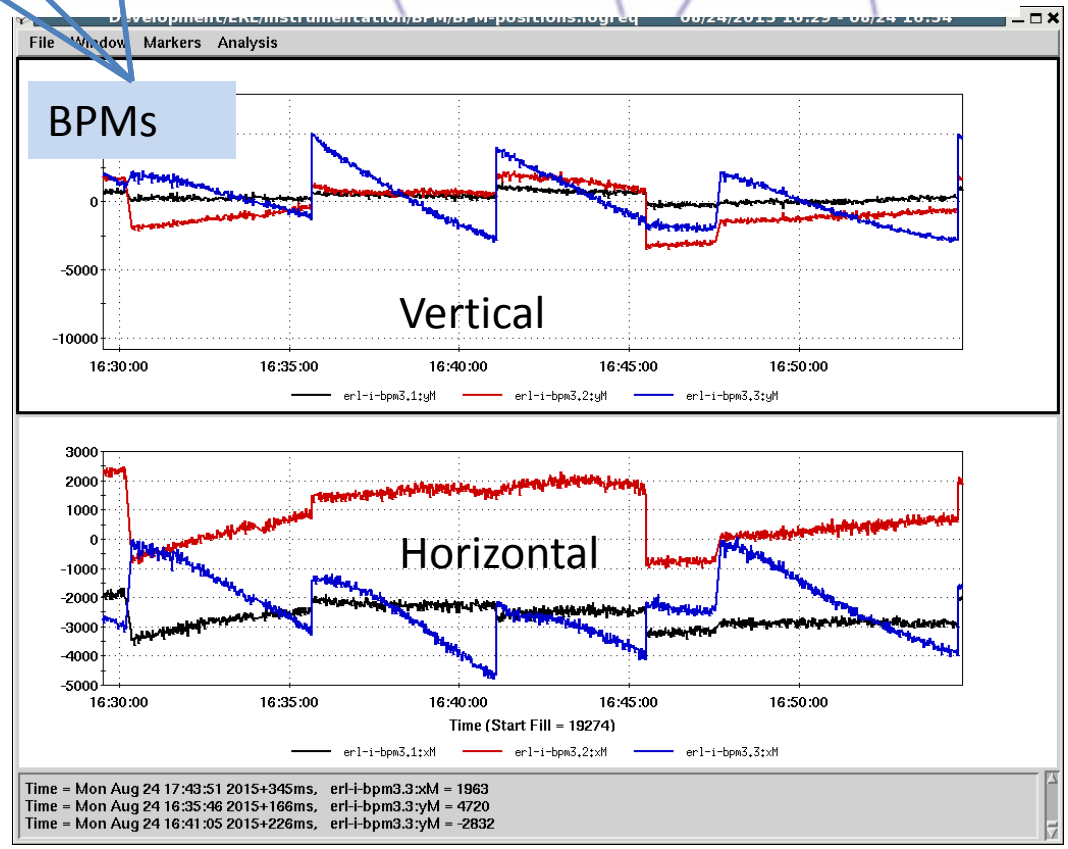
QE: 2.2e-4->1.1e-4 drops in 3 hours

Injection red
Extraction black
85% initial inj./ext. transmission

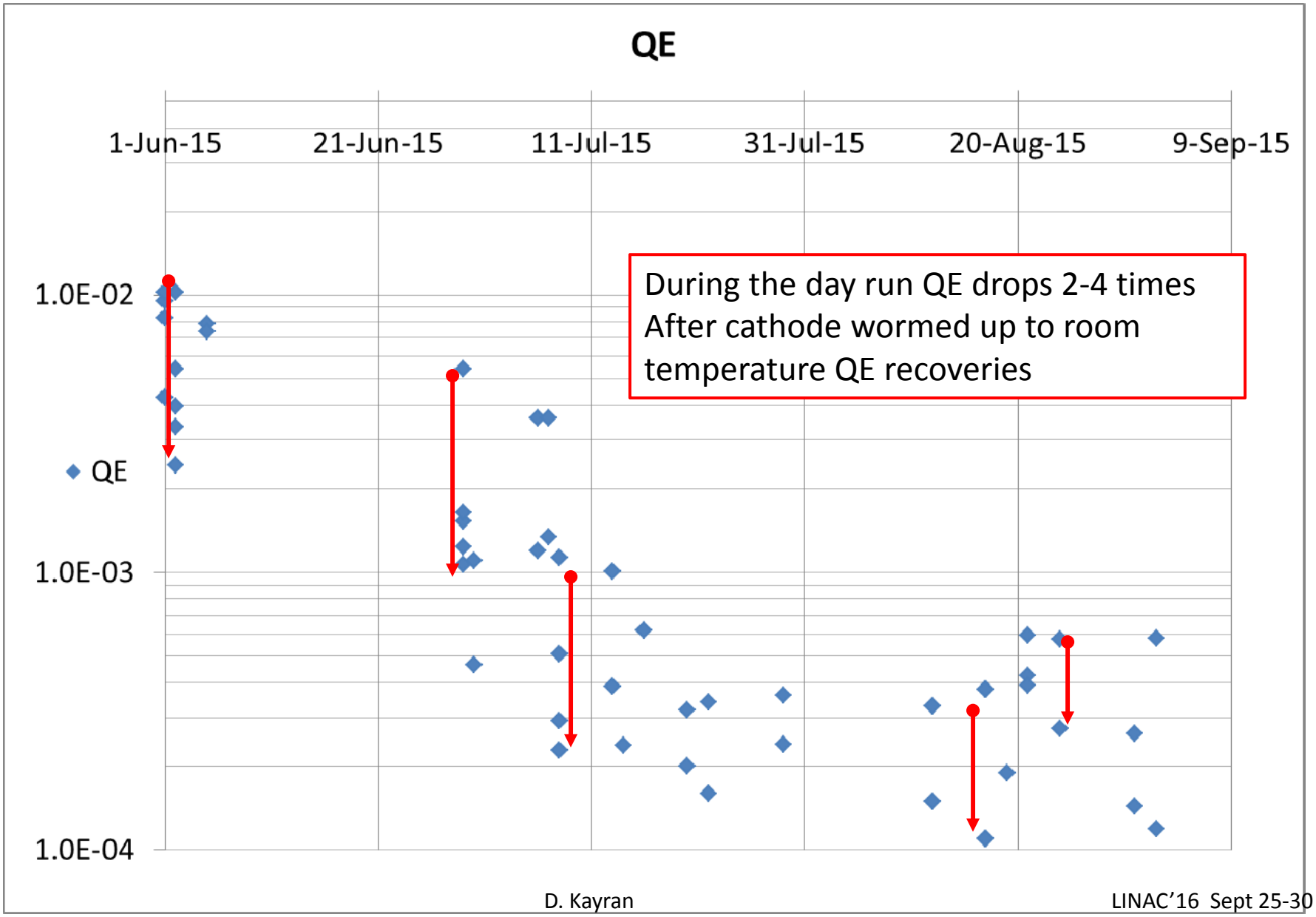
BPMs signal drifts and jumps



During commission significant jumps of trajectory.
It's very difficult to tune machine.
We suspect that ICT, DCCTs ceramic breaks are slow charged by halo or/and dark current and then sudden discharge.
The shielding for each ceramic break location has been designed it will be implemented where these elements are used in LEReC



Cathode QE measurements in the SRF gun during beam tests



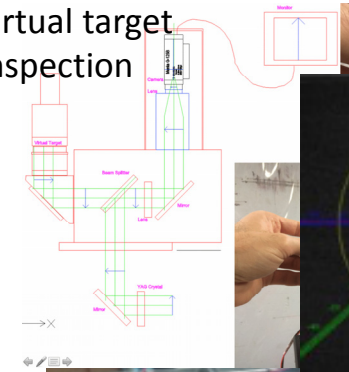
Beam parameters measured

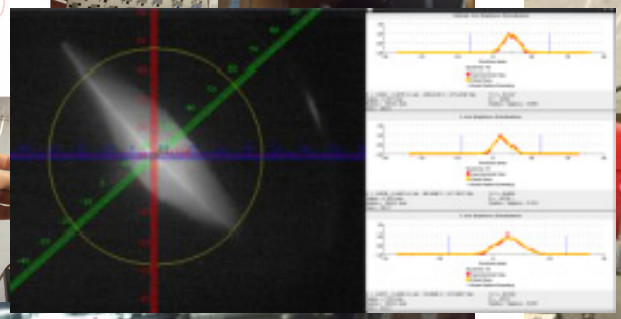
Parameter	Measured*
Kinetic Energy	1.2 MeV
Charge per bunch	0.55 nC
Cathode QE in the gun	1%
Current during RF pulse	350 uA
Average current	20 uA
Laser Rep. Rate	9.38 MHz
Average Laser power at the cathode	3.5 W
Laser Bunch Length	8.5, 22 psec
Norm. emittance x/y	2.5/3.5** um
Average dump power	10W @ FC

*Listed parameters have been achieved in different modes of operation
**Preliminary results

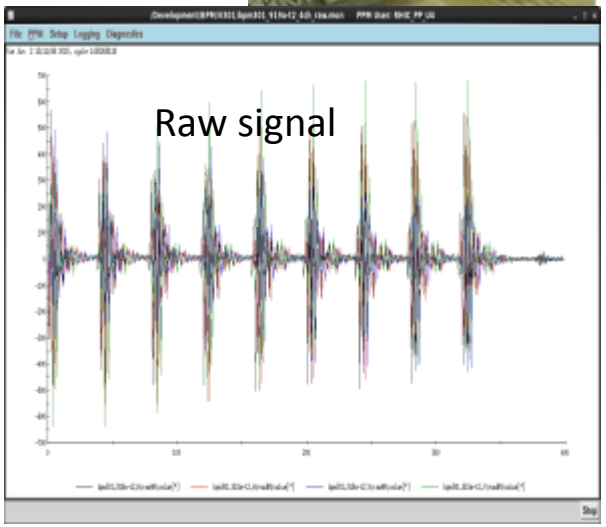
Beam instrumentation tested with beam

virtual target inspection





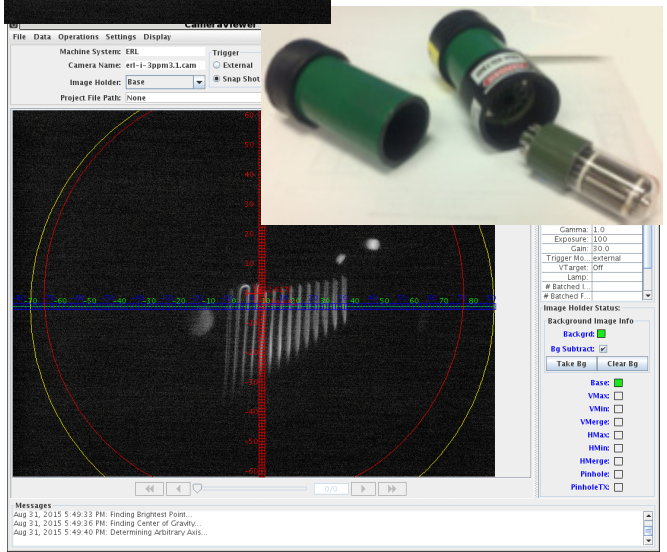
BPM

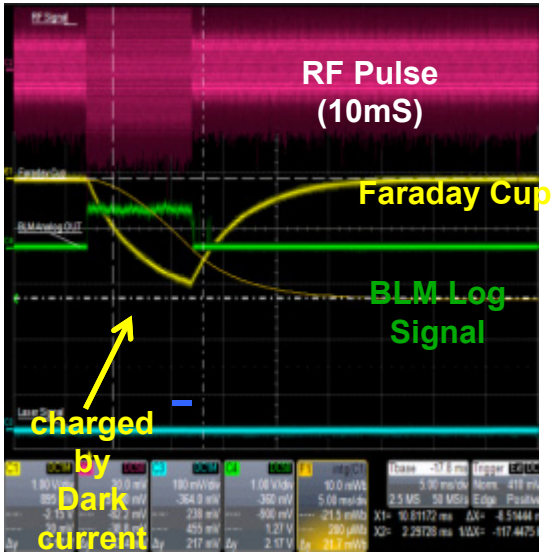


Beam Profile monitor

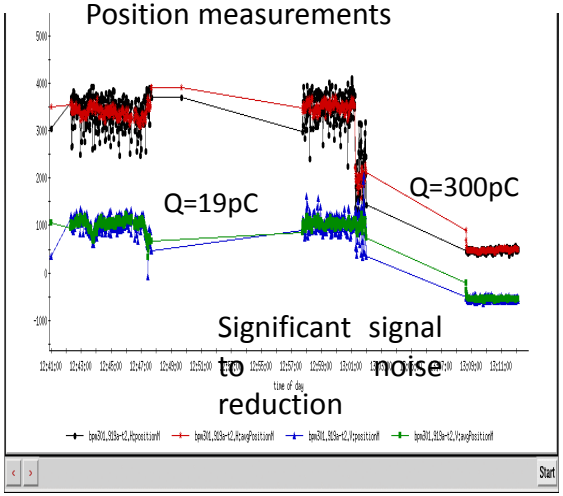
Faraday Cup

PMT Detectors





Position measurements



Summary and plans

- All ERL components have been installed by May 2015.
- The first test with “multipacting-free” Ta tip cathode took place in June, 2015.
- The highest charge from SRF gun .55 nC has been achieved (initial QE=1%.)
- The max average current from this gun 22 uA has been demonstrated with 260uA in 4msec.
- The bunch is very asymmetric most likely due to solenoid imperfection. HTs solenoid fix is needed.
- Beam has been propagated from the gun to beam dump with SRF linac off.
- 90% injection to extraction current transparency routinely has been achieved.
- Cathode with QE 4e-4 level allowed us to commissioning ERL systems with bunch charge 30-50 pC.
- Ceramic break charge discharge requires shielding installation
- During first 3 months of beam commissioning we were able to test and cross calibrate most of the beam diagnostics which will be used for the next project LEReC.
- LEReC will use SRF gun as a booster cavity without cathode inserted. The 704 half cell gun as a booster cavity will be installed for LEReC commissioning in summer of 2017
- Future beam tests are planned to resume when LEReC cinstallation is completed in RHIC IP2 at the end of 2017.

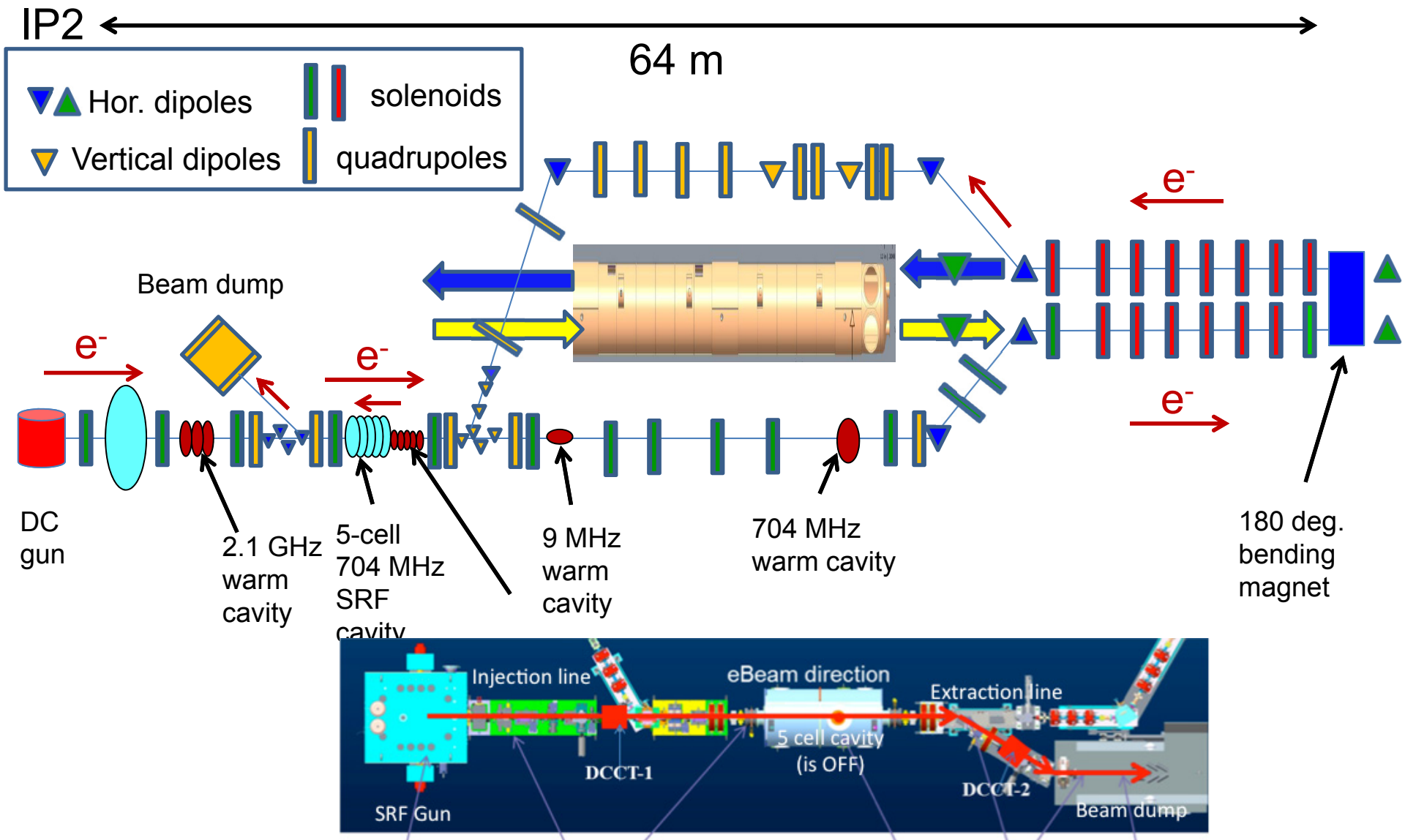
Acknowledgment for BNL R&D ERL team

Zeynep Altinbas, Dana Beavis, Sergey Belomestnykh, Ilan Ben-Zvi, Paul Bergh, Suresh Denarine, Jesse Fite, David Gassner, Lee Hammons, Robert Lambiase, Edward Lessard, Ramesh C. Gupta,Chung Ho, James Jamilkowski, Stephen Jao, Prerana Kankiya, Robert Kellermann, Nikolaos Laloudakis, Vladimir Litvinenko, George Mahler, Leonard Masi, Gary McIntyre, Wuzheng Meng, Robert Michnoff, Toby Allen Miller, John Morris, Igor Pinayev, David Phillips, Vadim Ptitsyn, Triveni Rao, Pablo Rosas, Scott Seberg, Thomas Seda, Brian Sheehy, Loralie Smart. Kevin Smith, Victor Soria, Andrew Steszyn, Roberto Than, Erdong Wang, Andreas Warkentien, Daniel Weiss, Huamu Xie, Wencan Xu, Alex Zaltsman
and money others.

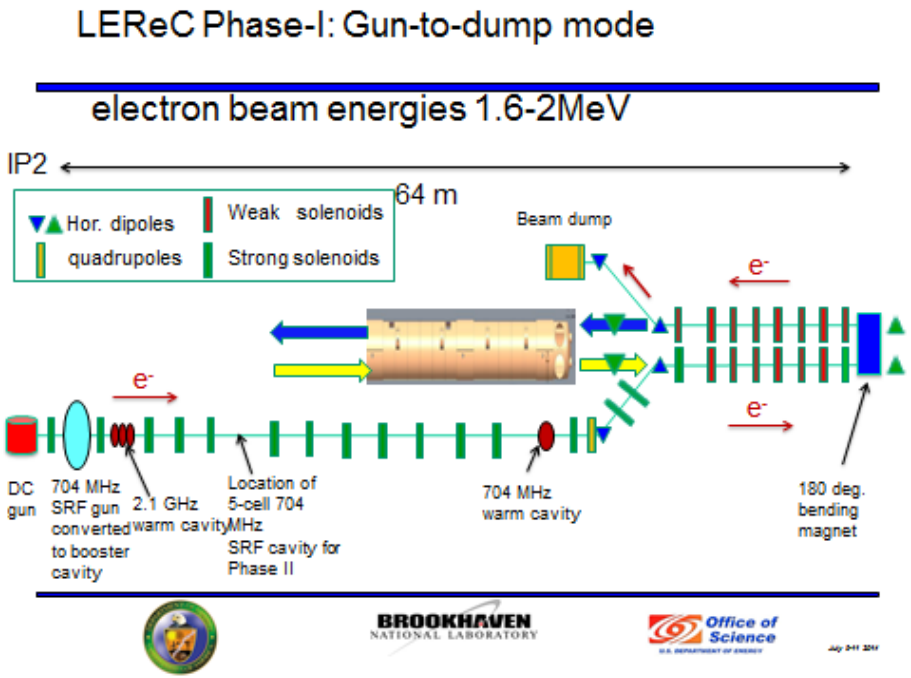
Thank you all!

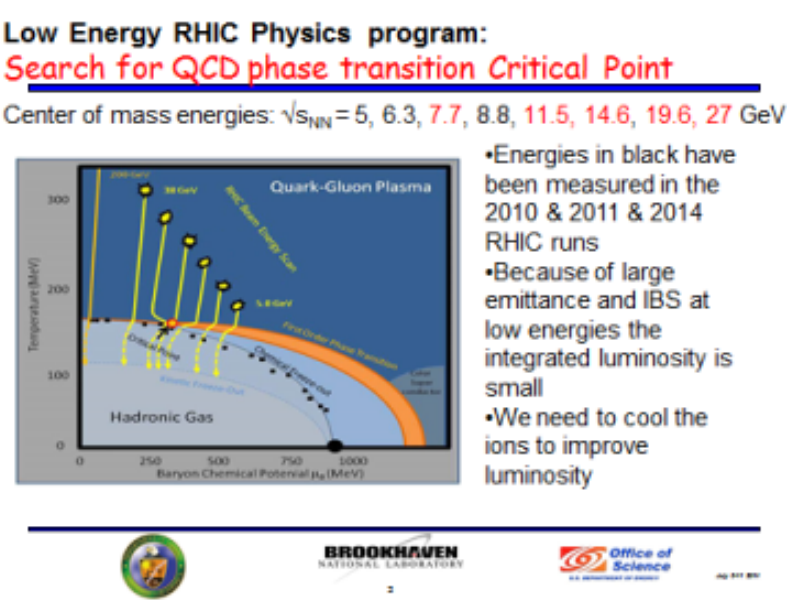
- Back up slides

ERL transformation to LEReC



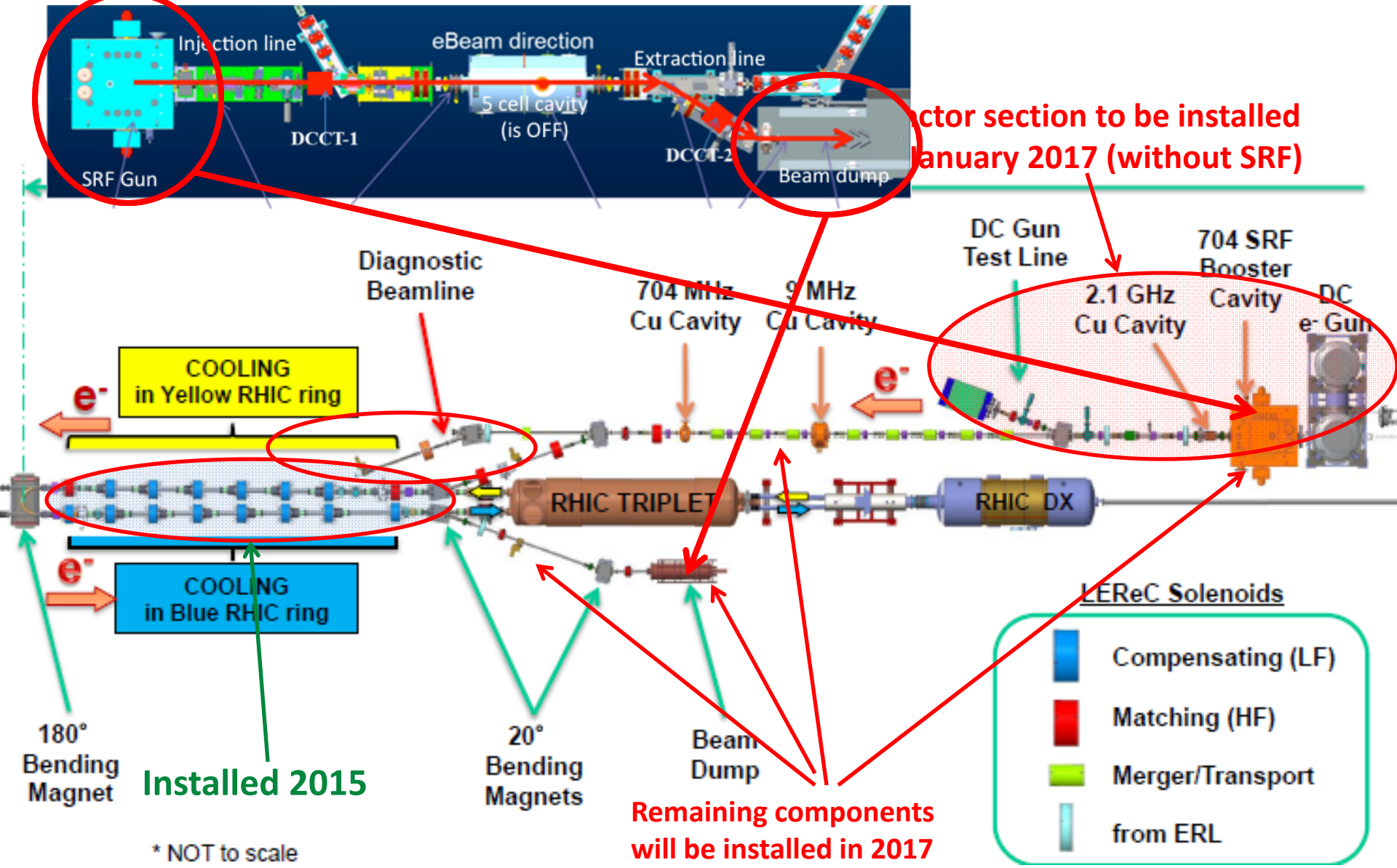
LEReC upgrate



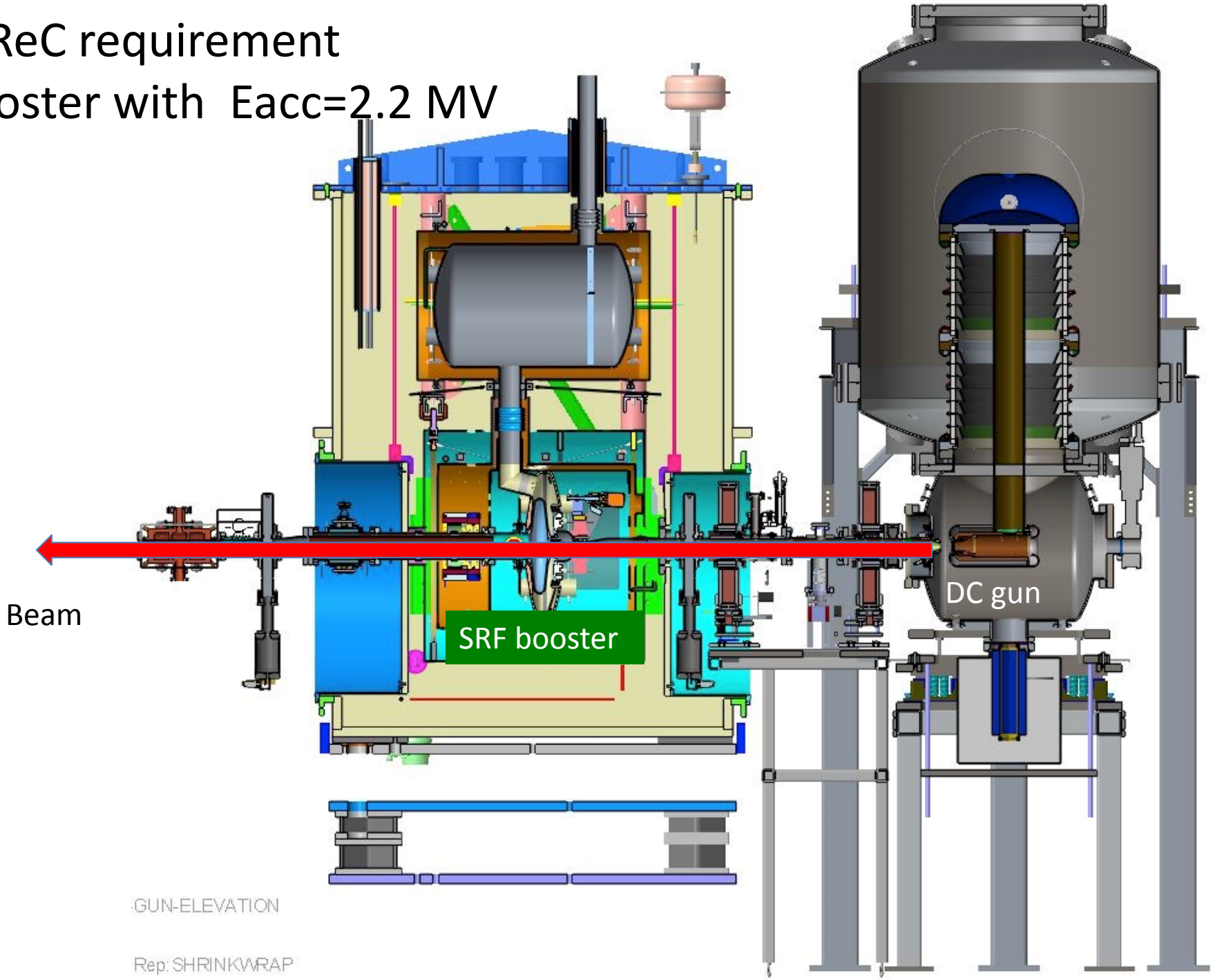


LEReC will use SRF gun as a booster cavity without cathode inserted. The booster needs to operate CW at 2.2 MV of voltage. In 2013 this cavity has been commissioning for such operation. However after beam tests it was discovered that the cavity can run only at 1.6 MV of voltage. Cavity was opened and copper marks have been observed at niobium part of chock join. Presumably cavity has been contaminated during severe cathode stalk RF conditioning. This gun as a booster cavity needs to be install for LEReC commissioning in summer of 2017. In summer of 2016 cavity has been sent for cleaning and testing.

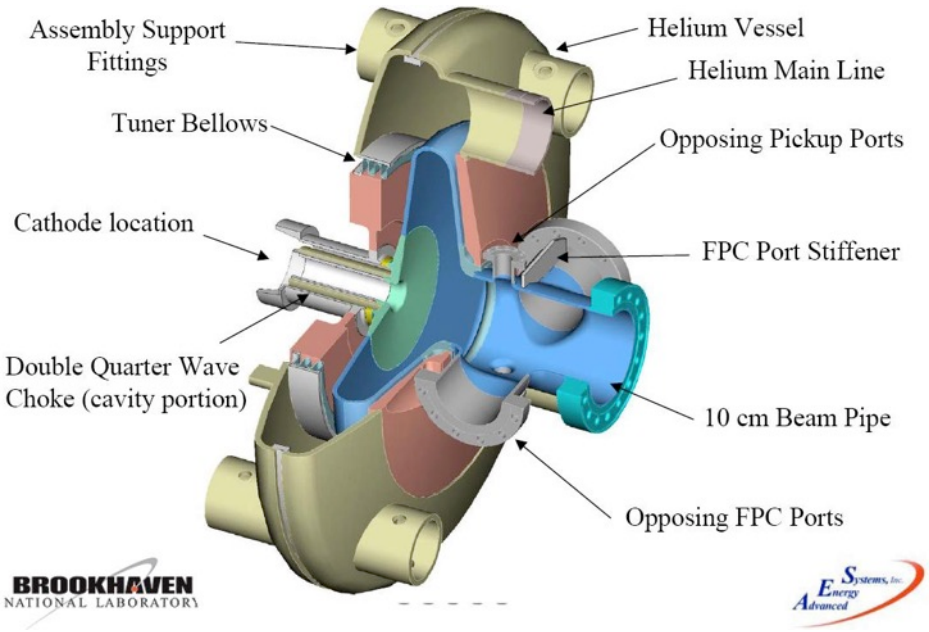
ERL components moved to LEReC location



LEReC requirement booster with Eacc=2.2 MV

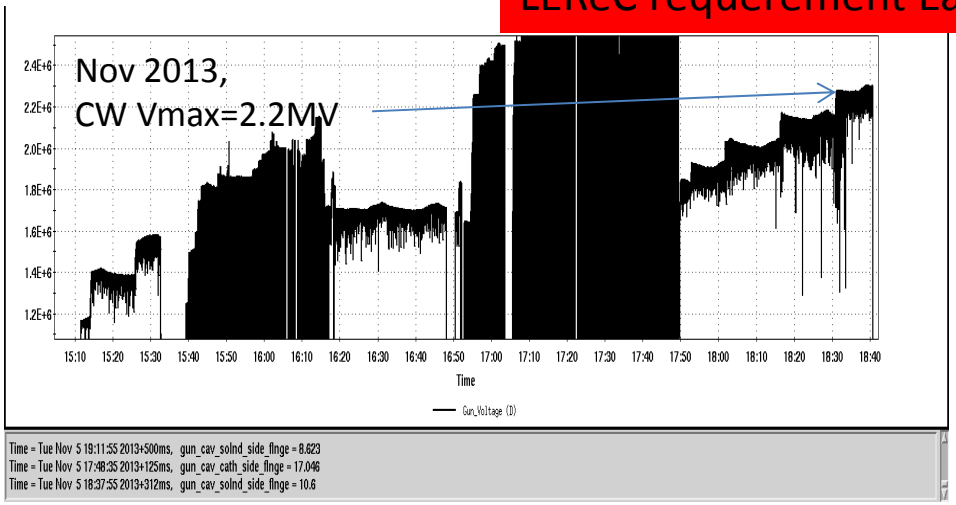


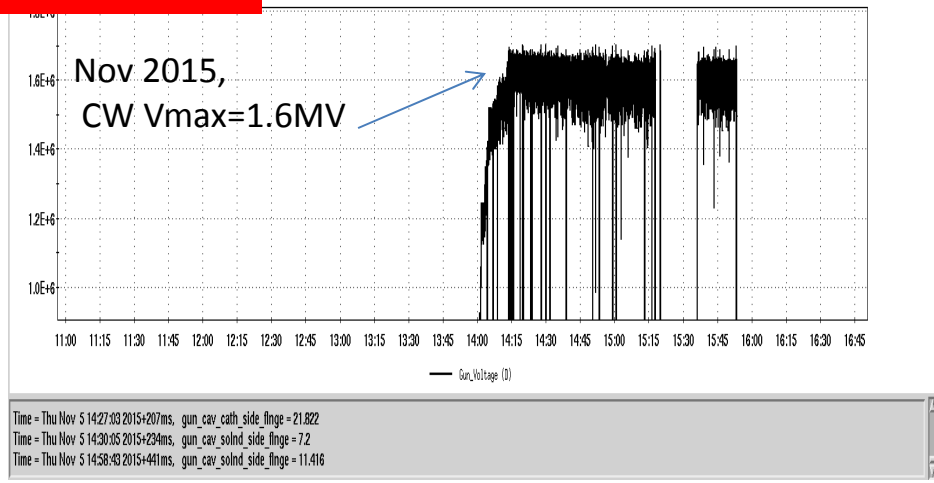
SRF Gun Cavity Parameters



RF frequency	703.6 MHz
Cavity active length	8.5 cm (0.4 cell)
Maximum energy gain	1.8 MeV
Maximum field at the cathode	26.7 MV/m
E_{acc} at 2 MV	23.5 MV/m
R/Q_{acc}	96.2 Ohm
Geometry factor	112.7 Ohm
Cavity operating temperature	2 K
Q_{ext}	4.5E5
Frequency tuning range	1 MHz
Required RF power	54 kW
Installed RF power	65 kW

LEReC requerement Eacc=2.2 MV

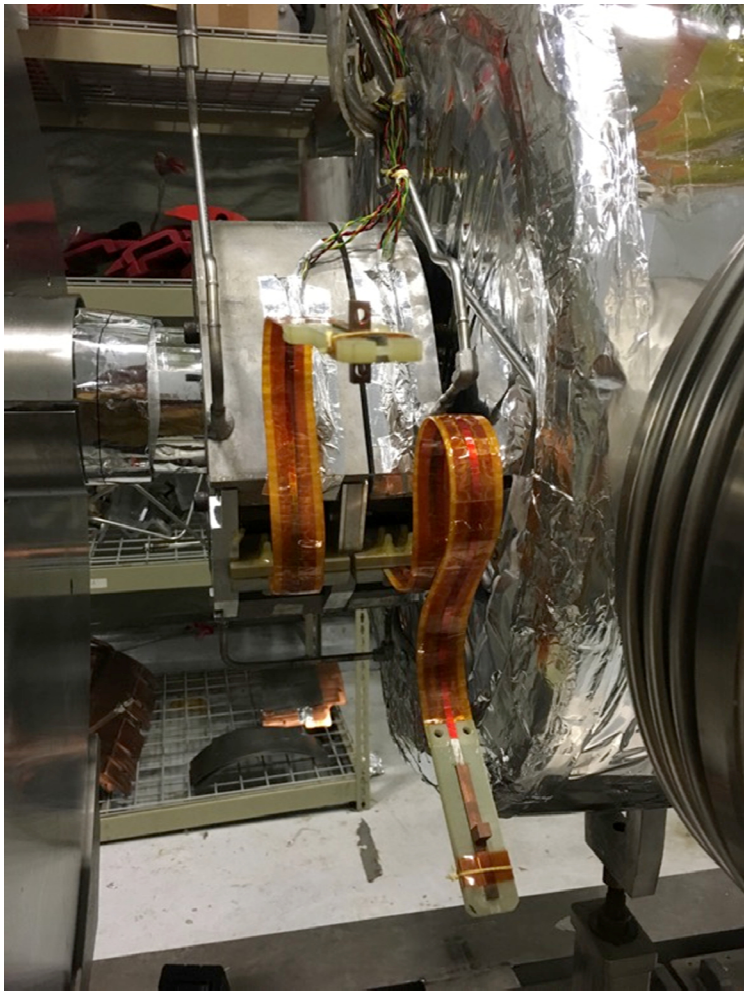


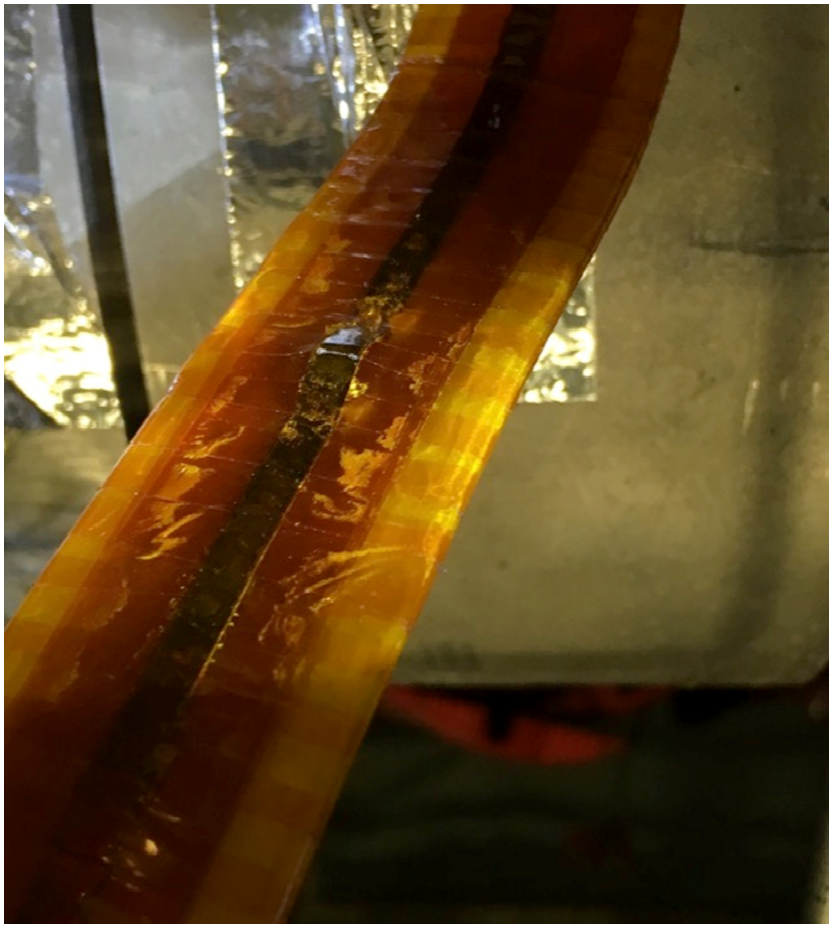


Copper rings marks

Cavity was opened and copper marks have been observed at niobium part of chock join. Presumably cavity has been contaminated during severe cathode stalk RF conditioning. This gun as a booster cavity needs to be install for LEReC commissioning in summer of 2017.

HTS solenoid lead damaged





From one side both HTS leads can be seen to be a uniform red color.

Main lead from other side it's different matter. Besides being discolored in spots, it's lifted up at one point. O