Lessons learned from BNL R&D ERL test facility

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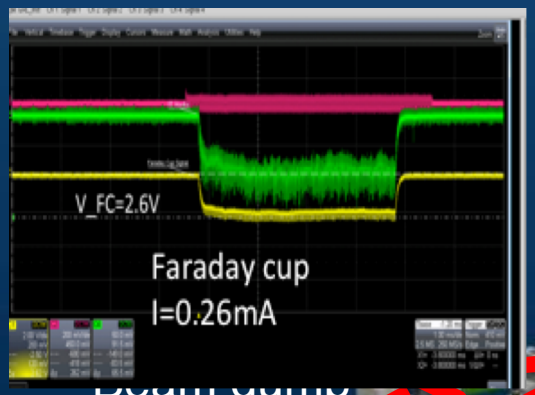
BNL R&D ERL

- ✓ ERL construction was completed: May 2015
- ✓ SRF gun 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 now moved to be used for RHIC upgrade project: LEReC



SRF Gun with photocathode

Injection line

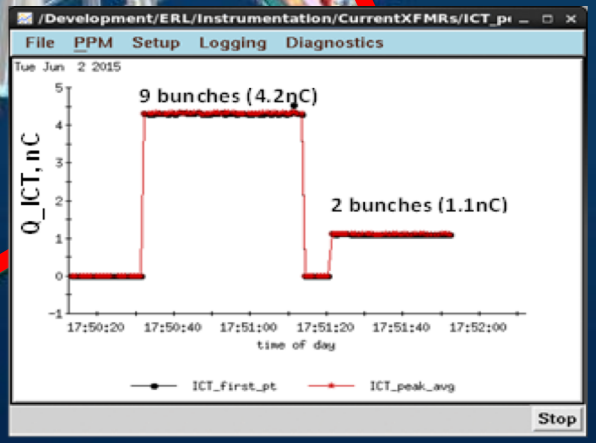
SRF 5cell linac

Faraday cup
I=0.26mA

Beam dump

Returning loop

~20m circumference



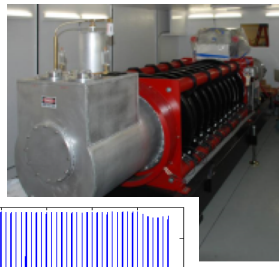
*more about LEReC on Wednesday afternoon

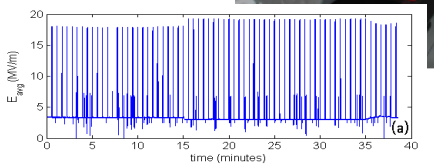
R&D ERL: Installation and commissioning time line

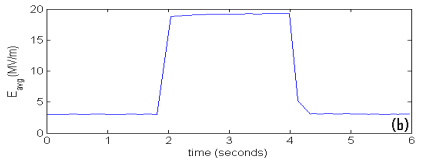
Strategy: Start commission of key components when systems installed and recourses are available.

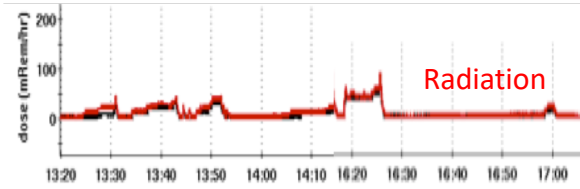
(no beam)

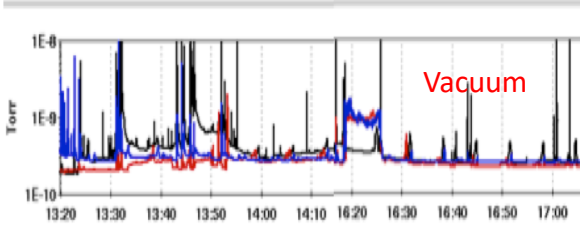
- ✓ High power RF components installed and commissioned (2005-2007
  - ✓ 1MW Klystron, 50kW RF PA, waveguides, controls, circulator, dummy load
- ✓ SRF 5-cell installed and cold emission test completed (2009)
  - ✓ Eacc=18MV, 2 sec CW every 10 sec.
- ✓ 9.4MHz Laser system commissioned (2009)
- ✓ Digital 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)
- ✓ Dark current measurement June 2014
- ✓ First photoelectrons Nov 2014

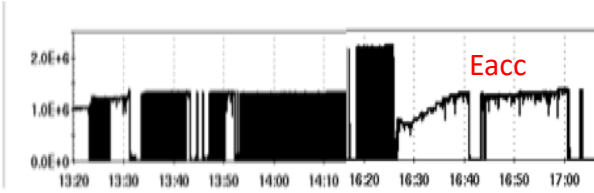




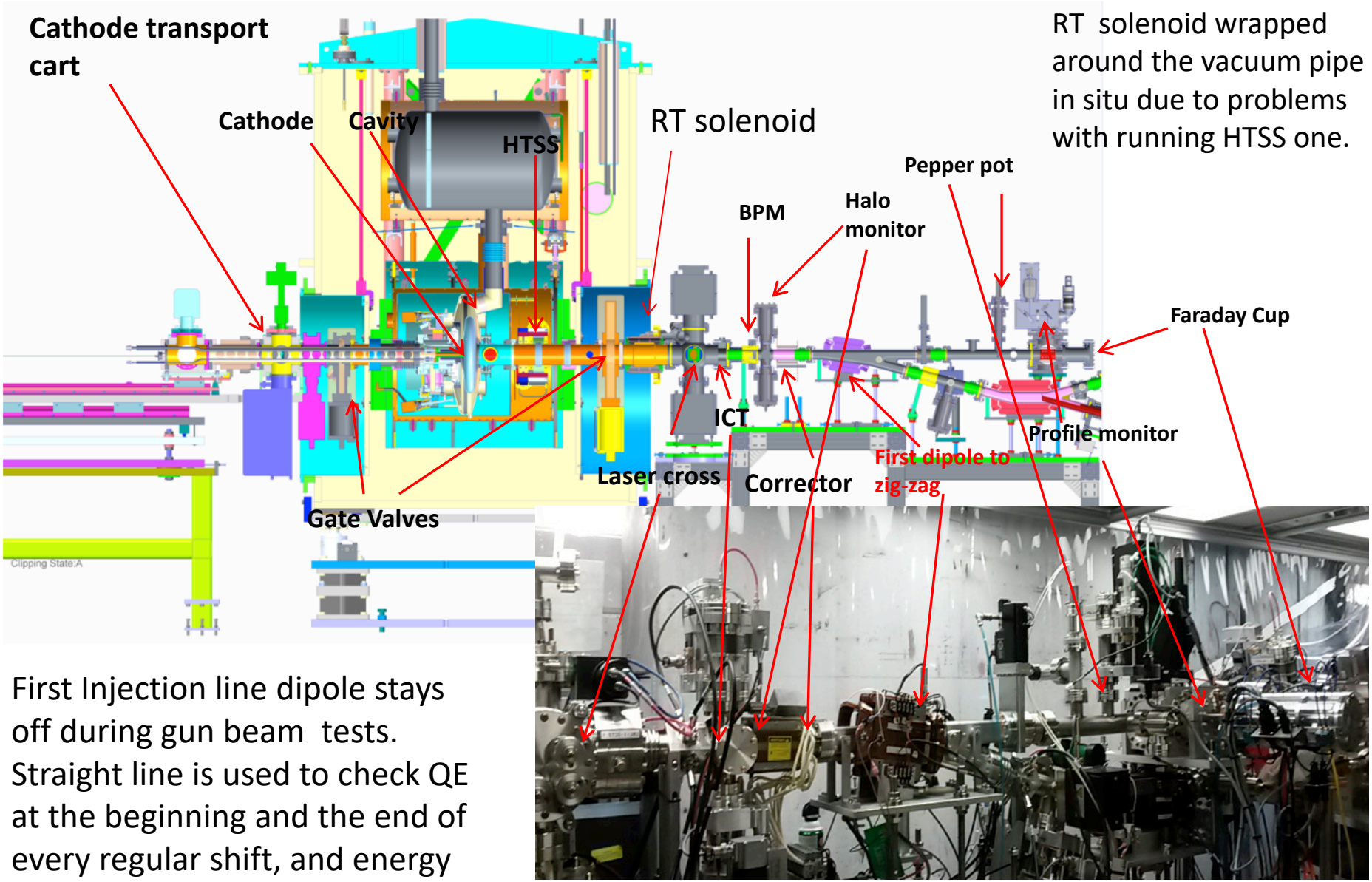








First beam commissioning (June-Nov. 2014)



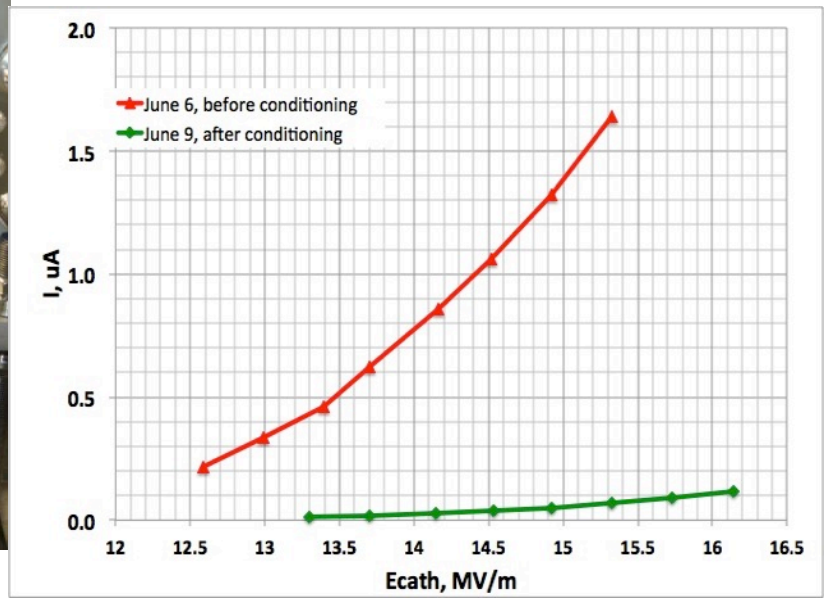
RT solenoid wrapped around the vacuum pipe in situ due to problems with running HTSS one.

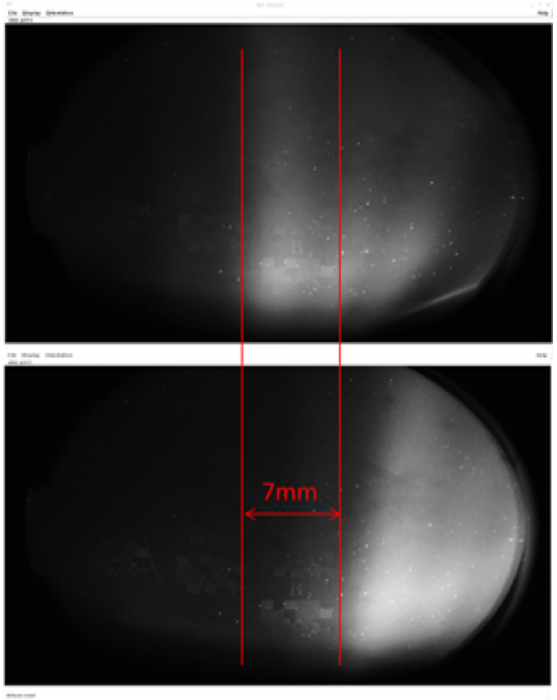
First Injection line dipole stays off during gun beam tests. Straight line is used to check QE at the beginning and the end of every regular shift, and energy measurements.

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

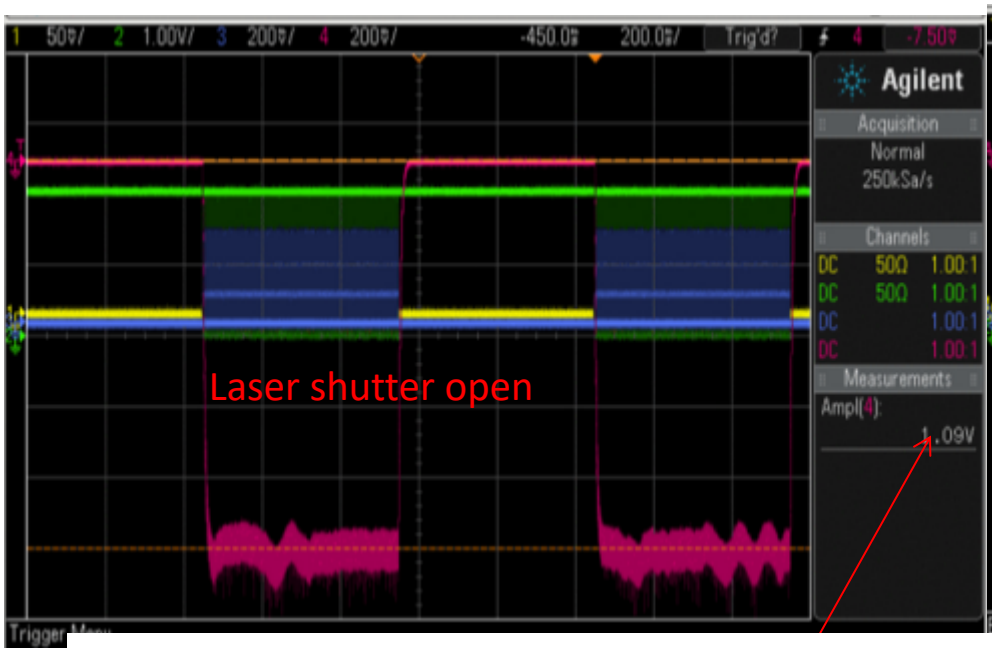


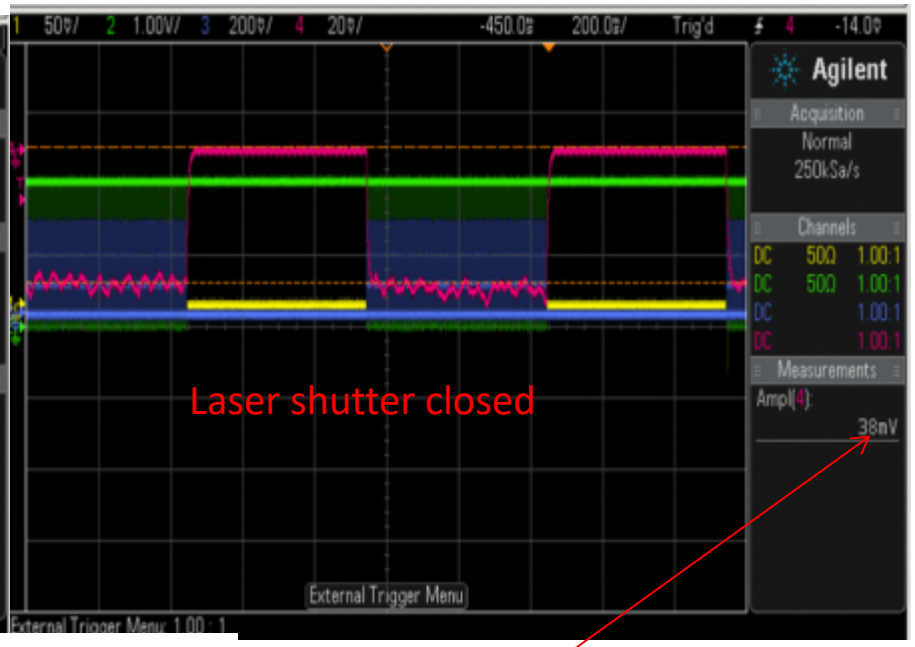


Energy measurements.
Corrector top 0.5 A, bottom 1 A.
7mm shift due to 0.5 A corrector change corresponds to beam energy of 1.2 MeV.

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

First beam, old cathode Nov 2014.





Faraday cup signal (1MΩ termination)

Set up

- Laser: 6.1 Watt, green,

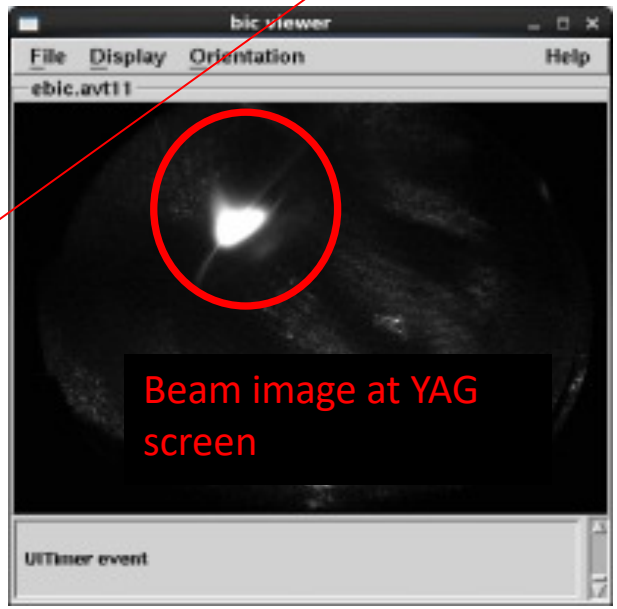
Pulse structure 7 µsec, every 500 µsec; 9.38MHz rep rate.

- 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!!!

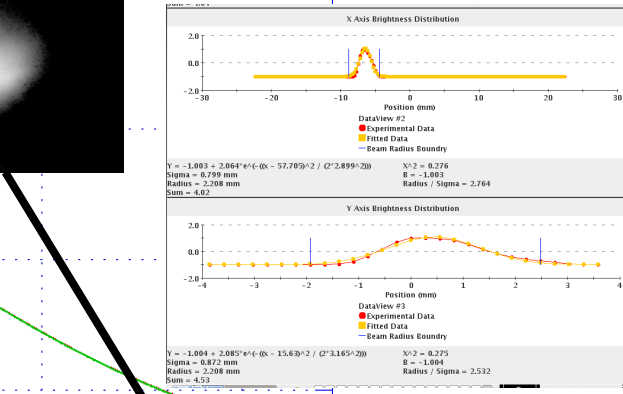


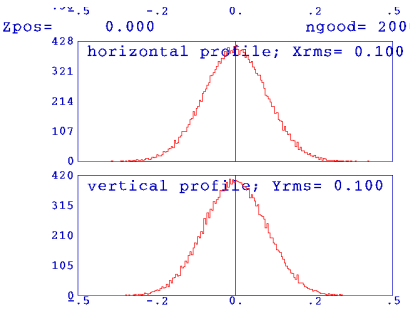
First beam test results meas. vs simulation

Measurements

σx=0.8 mm

σy=0.9 mm



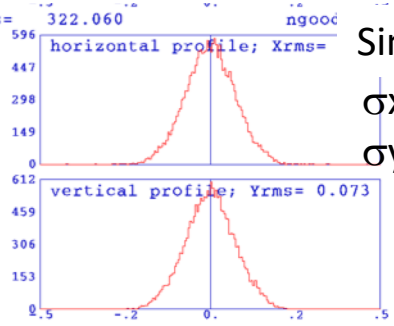


E=1.2 MeV

Q=10 pC

σ_laser=1 mm

Simulations

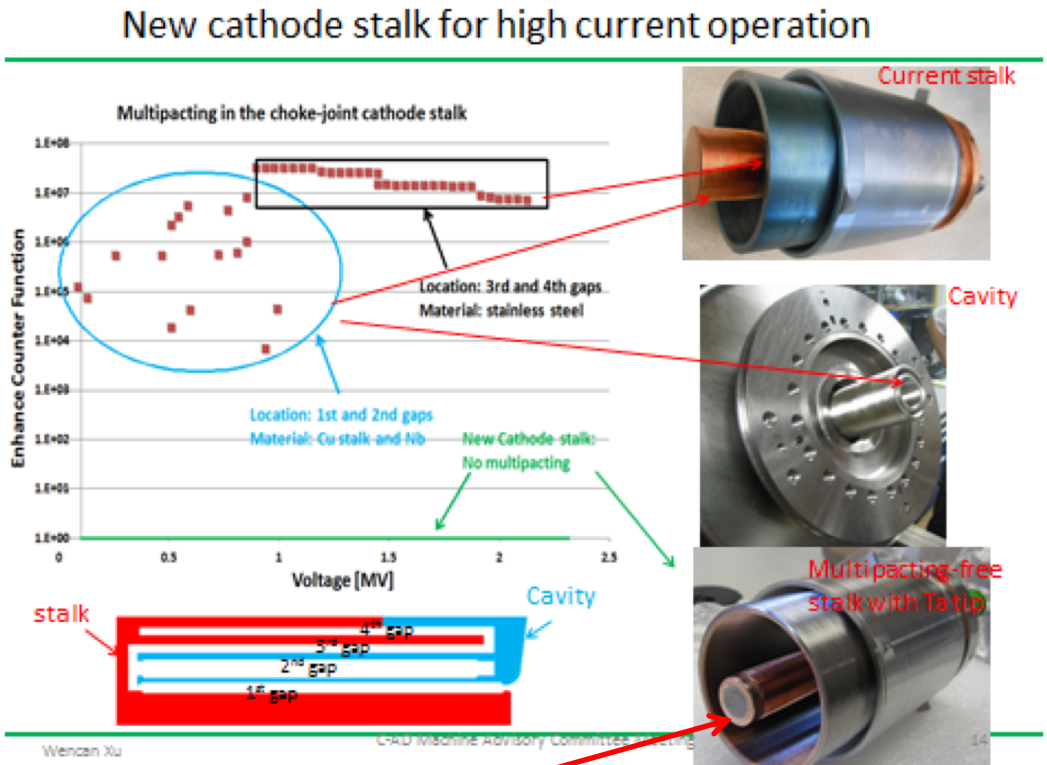


Simulations:

σx=0.74mm

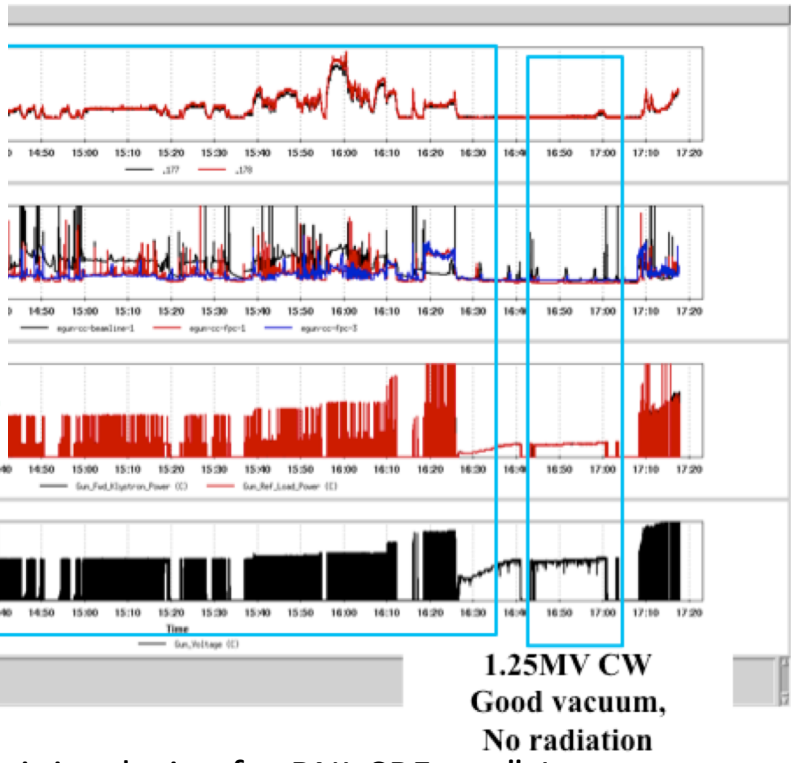
σy=0.73mm

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



Ta Substrate

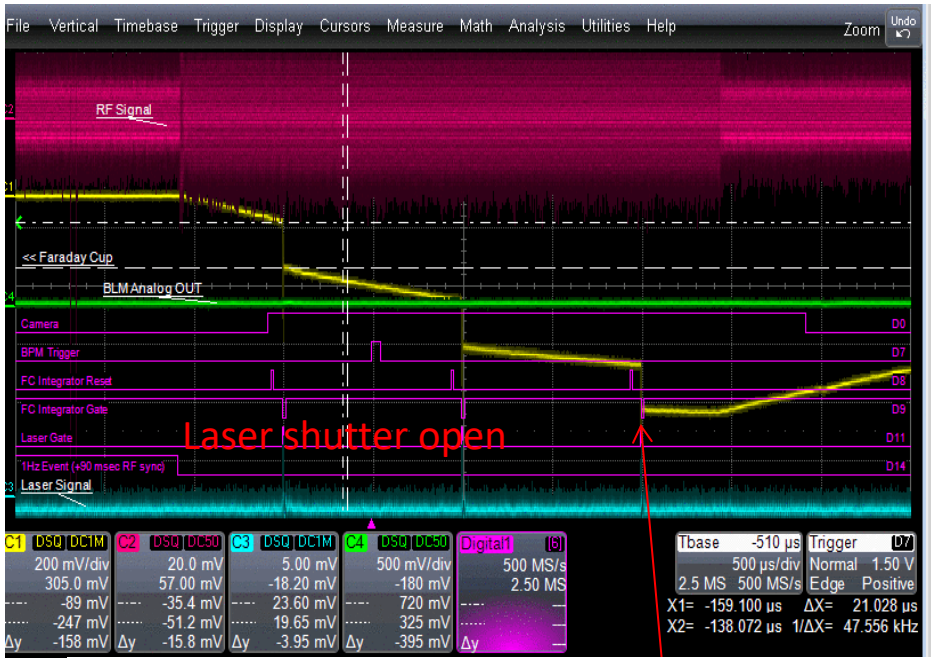
; Gun with new cathode stalk.

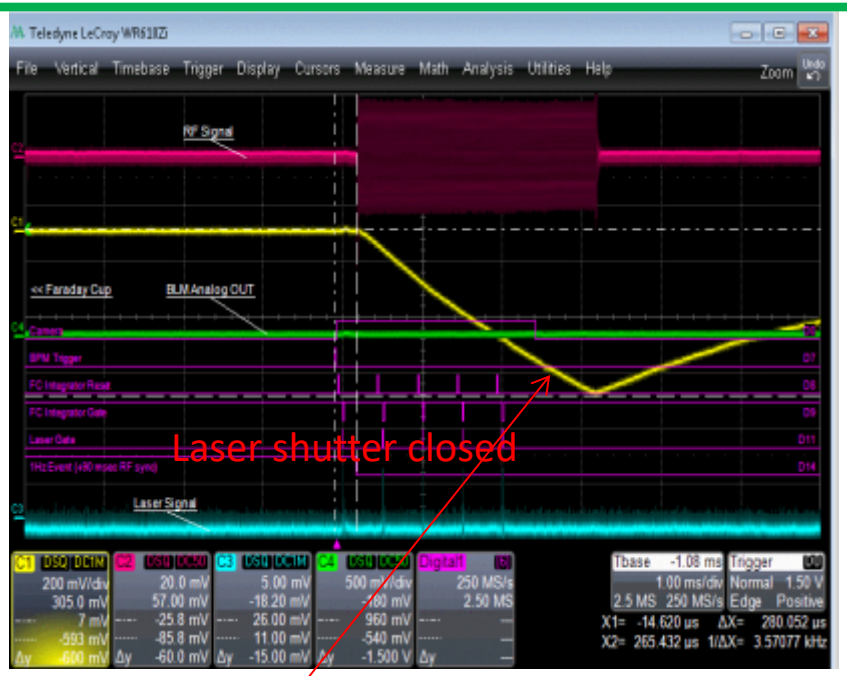


1.25MV CW
Good vacuum,
No radiation

*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

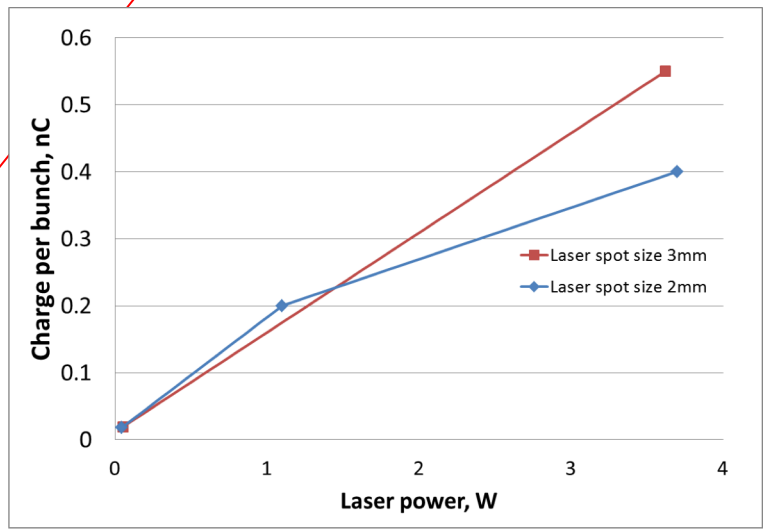
- Laser: 0.044 mWatt, green,

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

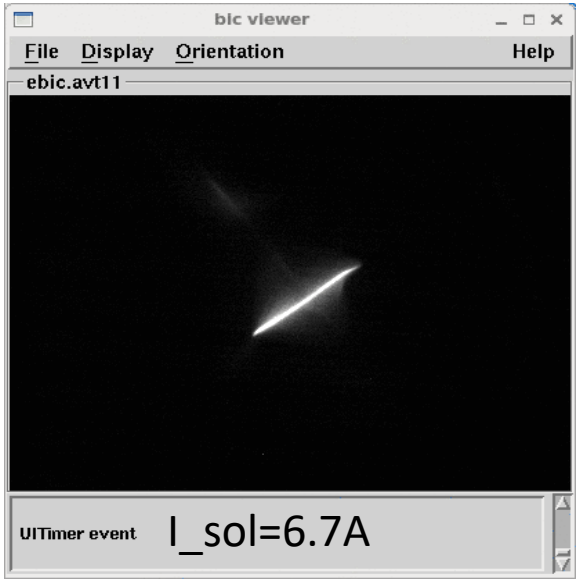
- RF: 0.65 MV, 3 ms;
- eBeam:

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

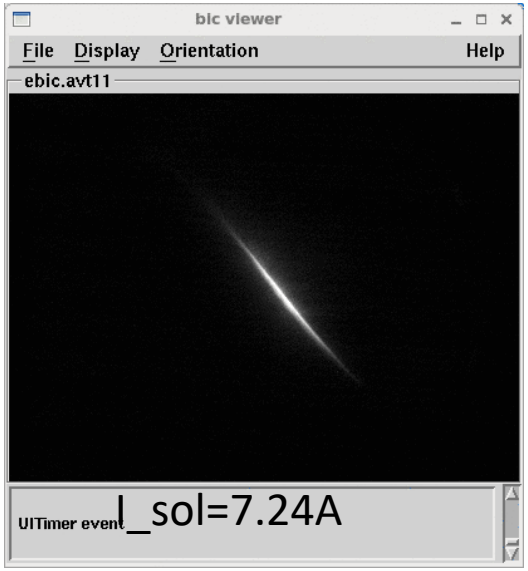
  dark current 4 μ A;
- Initial photocathode cold QE=1e-2 very Good!!!



Solenoid scan to measure gun astigmatism (preliminary)



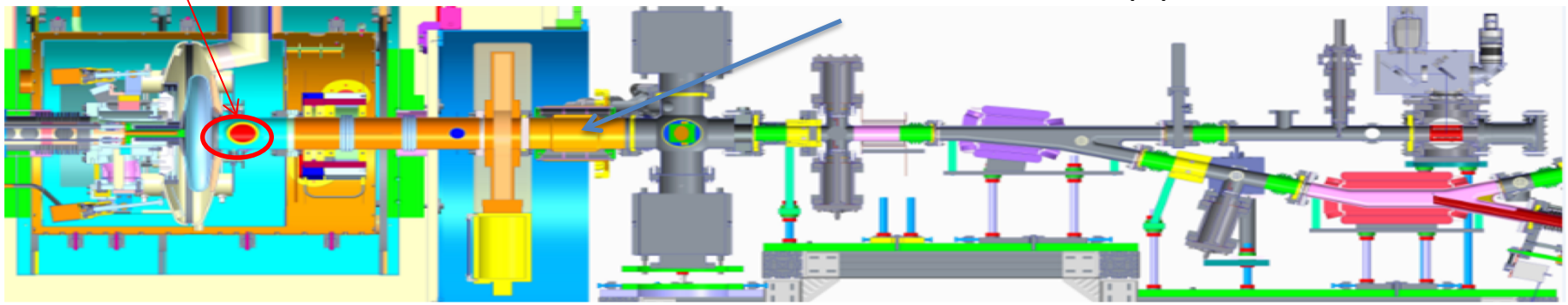
Ninja star shape



2 FPCs

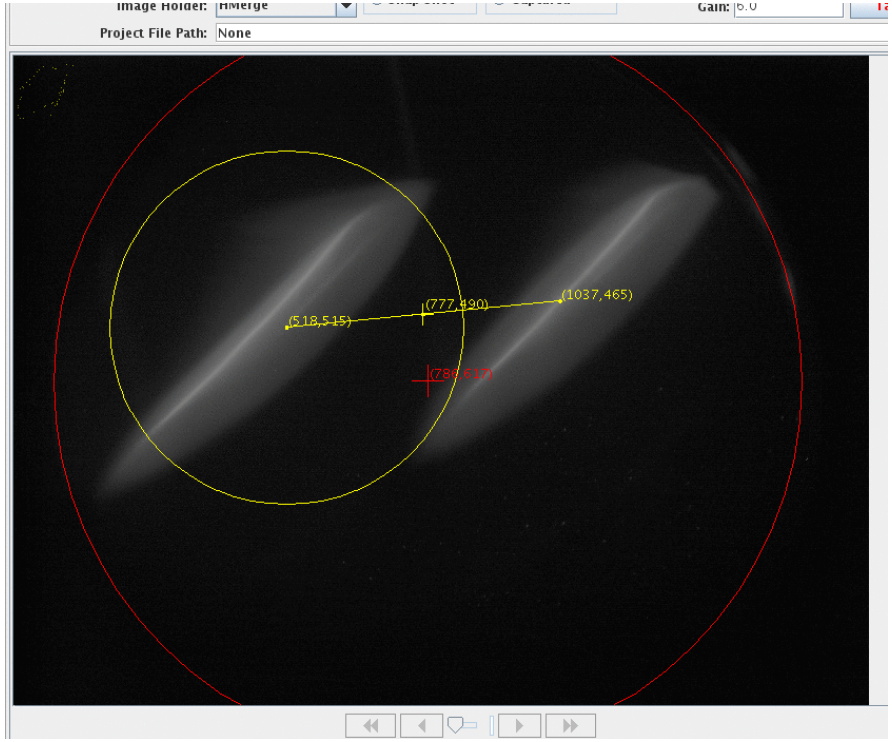
Axial symmetric system or not?

In situ built solenoid around vacuum pipe.

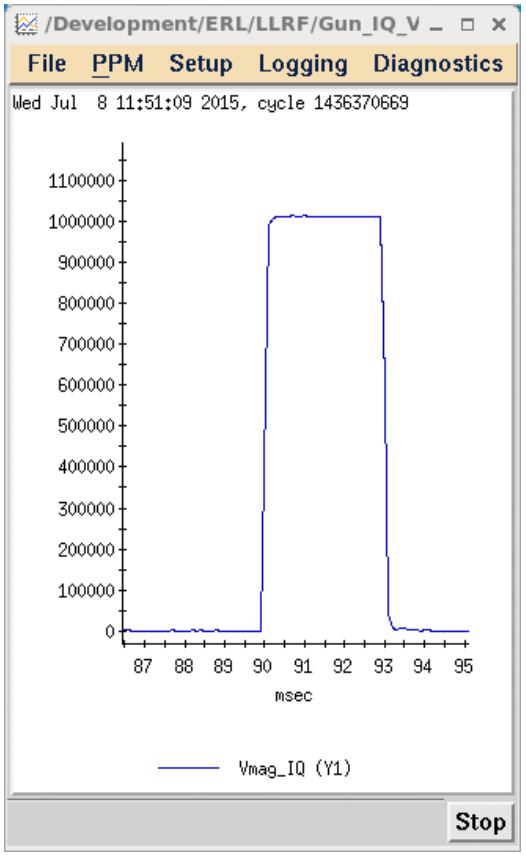


Such asymmetry could be generated by quadruple with focus length 64cm!!!. Located at FPC or solenoid imperfection.

Energy measurements using correctors and profile monitor



RF voltage setting 1.02 MV

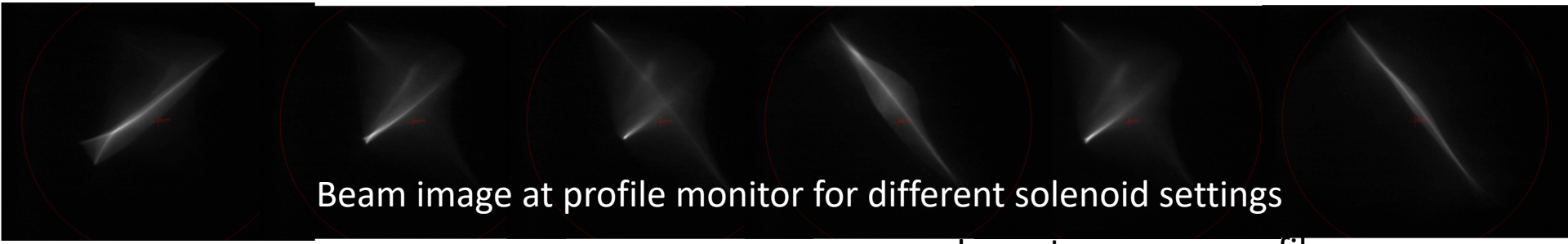


Beam shift at straight line profile monitor 15.5 mm

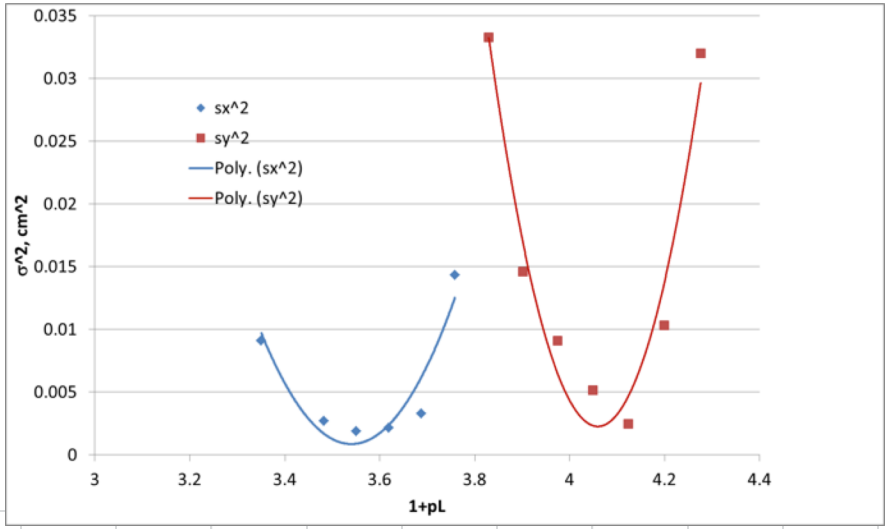
corrector changes dI=1.4A

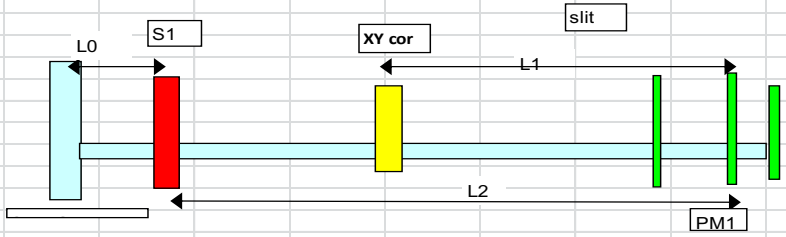
Corresponds to beam energy KE=1MeV

Try Solenoid scan, Q=130pC

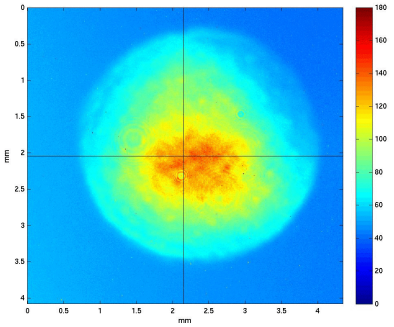


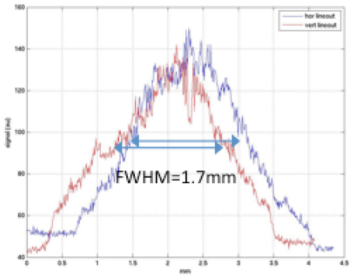
Beam image at profile monitor for different solenoid settings





Laser transveres profile





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

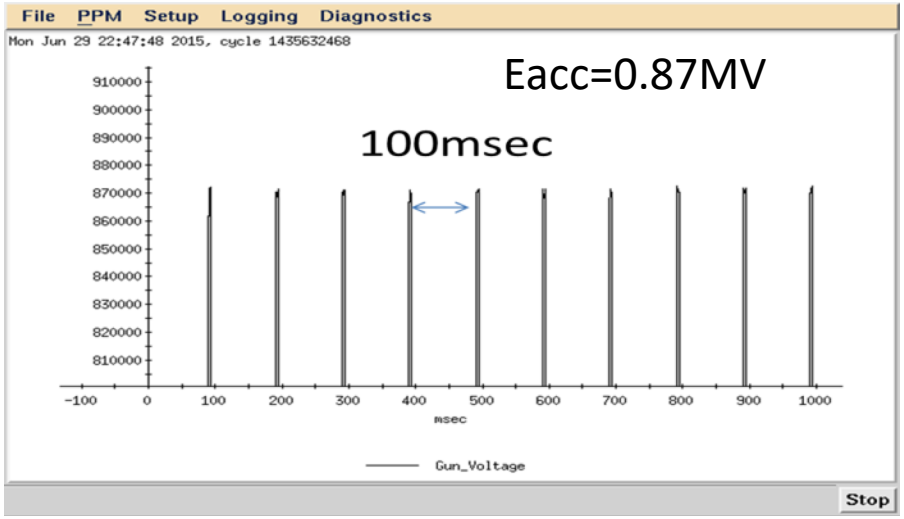
$$x_{rms}^2 =< x^2 >= A\left(\frac{1}{f^2}\right) - 2AB\left(\frac{1}{f}\right) + (C + AB^2)$$

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

Vertical normalized emittance 3.5 um

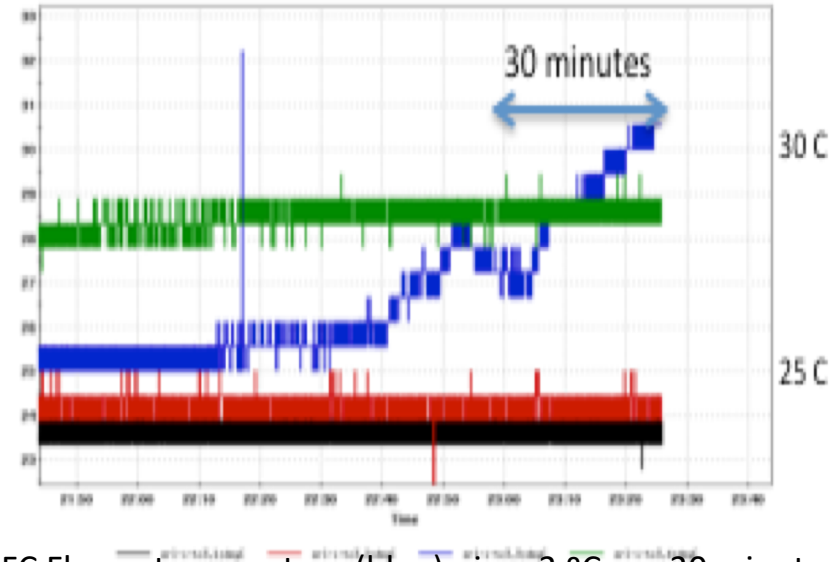
Horizontal normalized emittance 2.6 um

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.

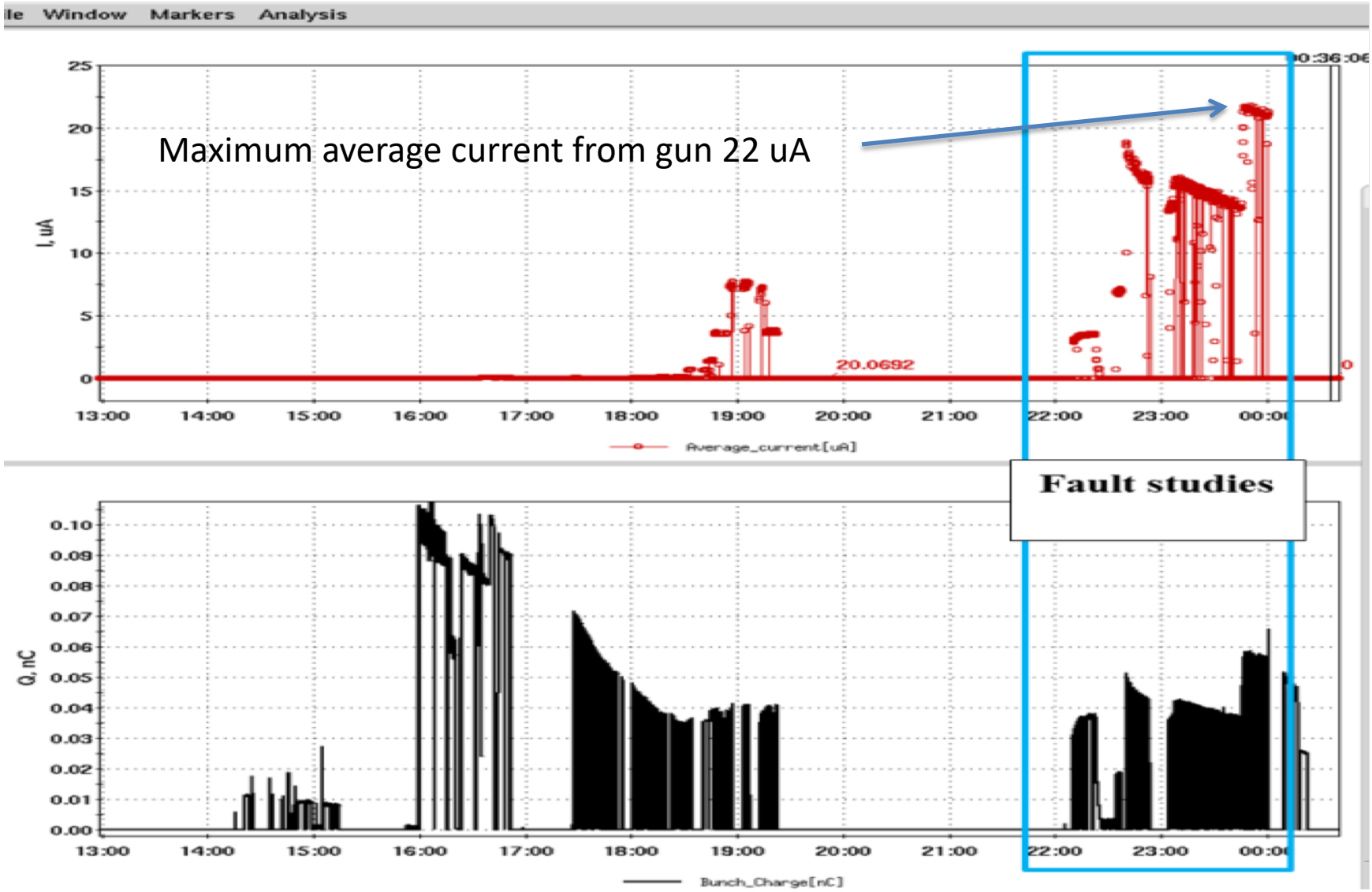


FC Flange temperature (blue) rises 3 ºC per 30 minutes.

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.

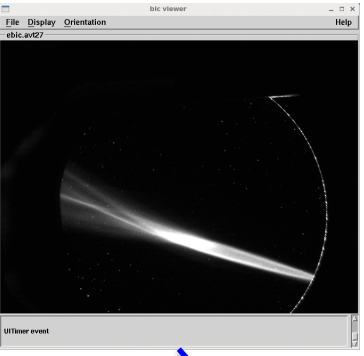
Average current and charge from Gun

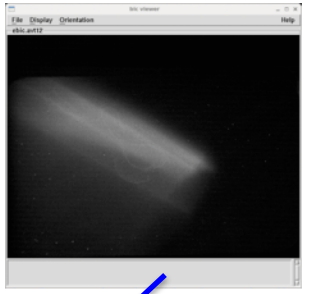


Average current and charge from the gun during fault studies measured by ICT and pulse counter.

Gun to Dump test: first propagation

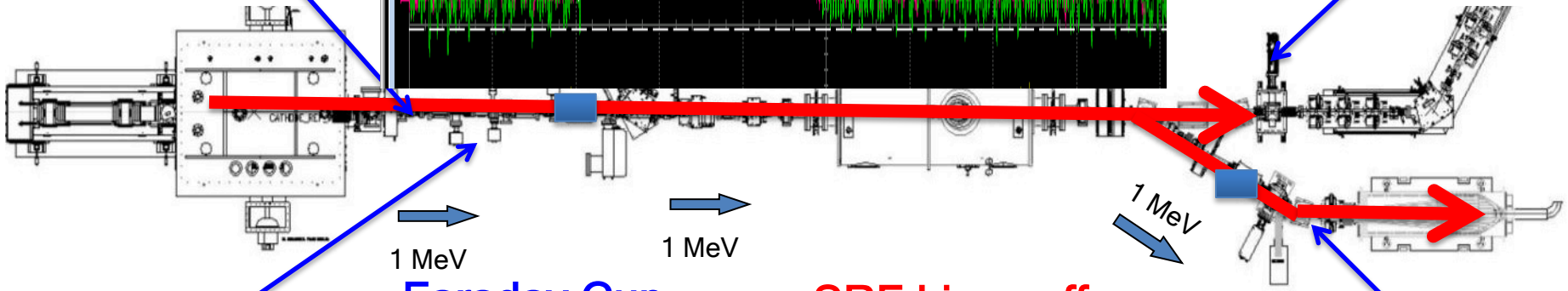
Beam current measured by injection line DCCT (magenta) and by extraction line DCCT (green). 90% transport efficiency has been achieved.





SRF Gun

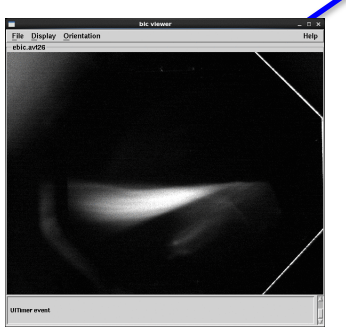
Beam profile monitor

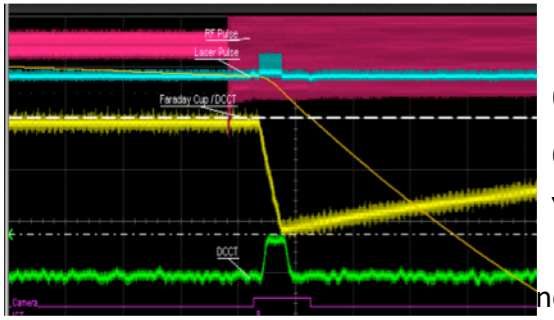


Faraday Cup

SRF Linac off

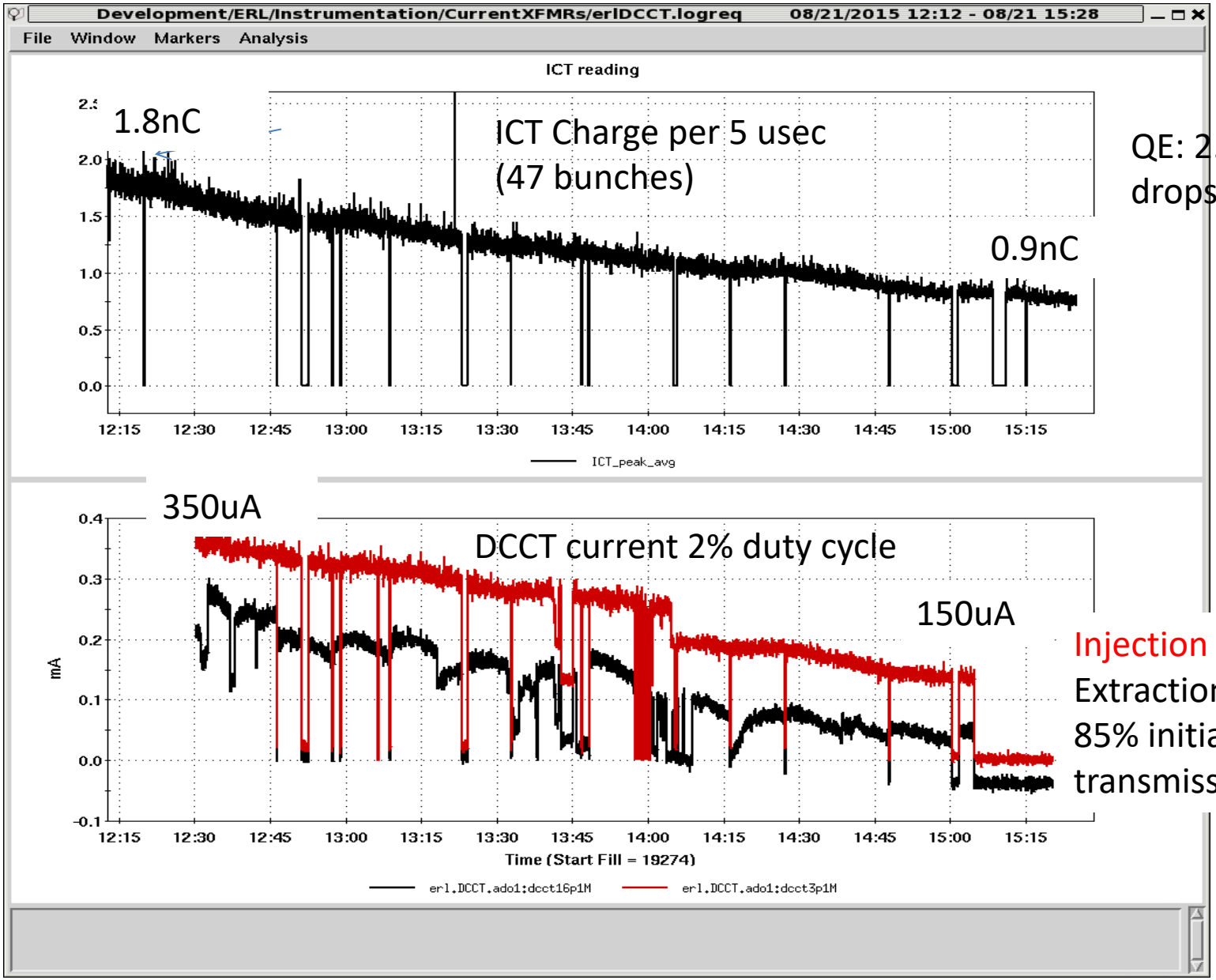
Beam dump





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

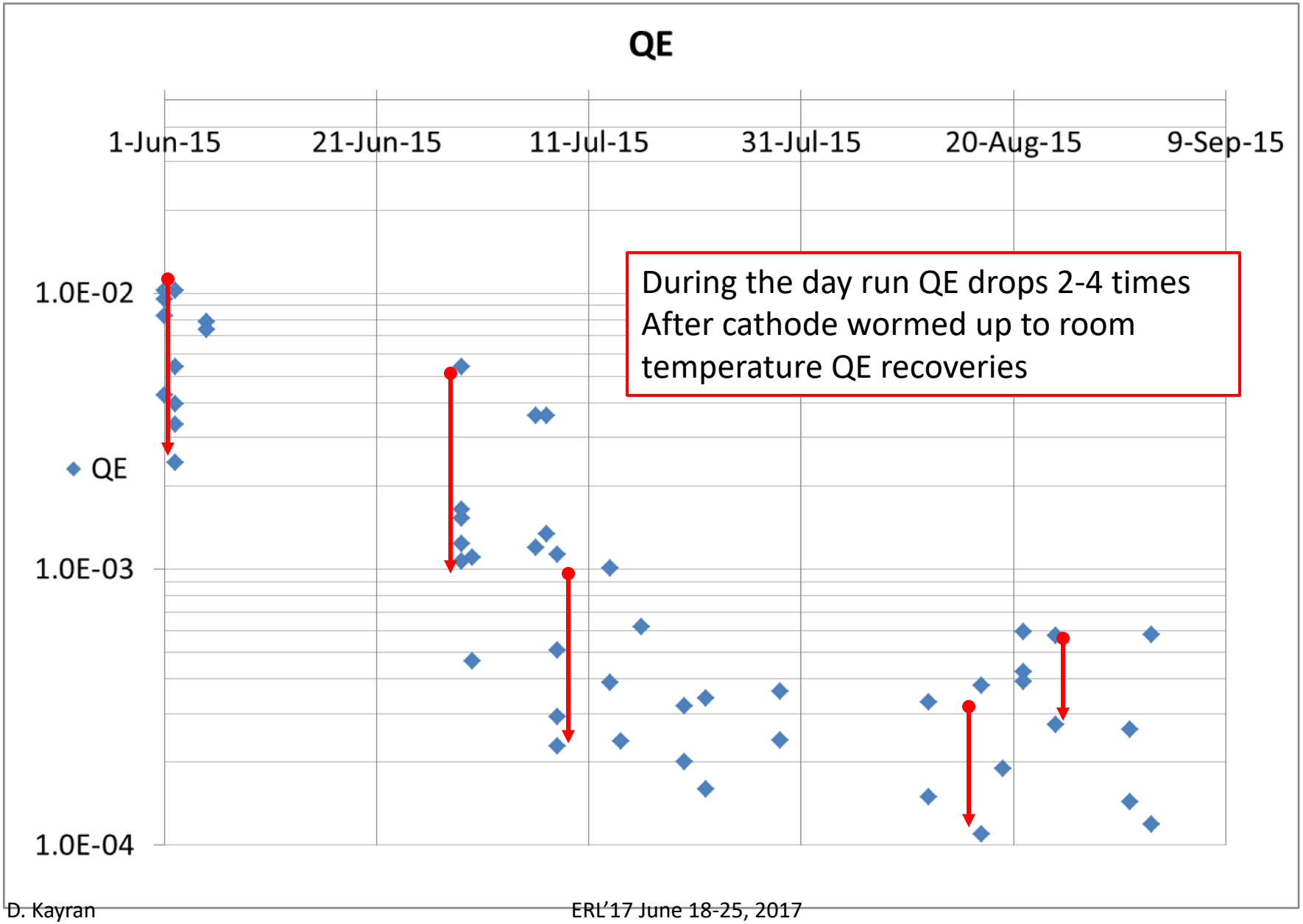
Typical cathode QE redaction during beam tests



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

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

Cathode QE measurements in the SRF gun during beam tests

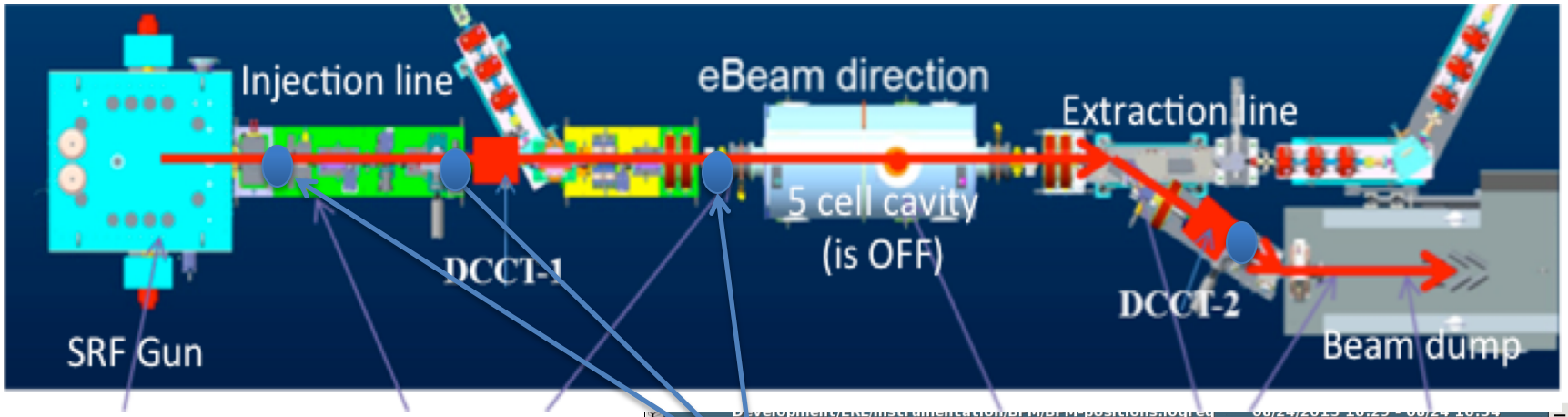


Beam parameters measured

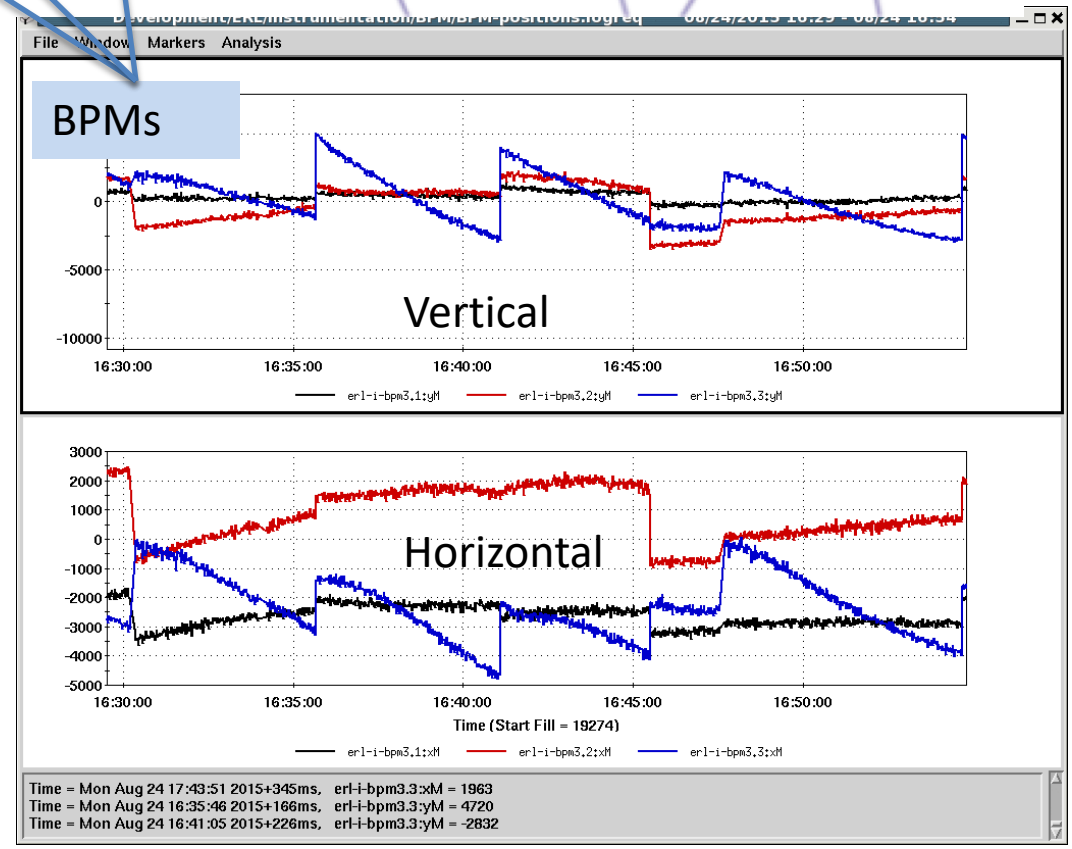
Parameter	Measured*
Kinetic Energy	1.2 MeV
Charge per bunch	0.55 nC
Cathode QE in the gun	1%
Current during RF pulse	350 uA
Average current (in second)	20 uA
Laser Rep. Rate	9.38 MHz
Average Laser power at the cathode	3.5 W
Laser Bunch Length	8.5, 22 psec
Norm. emittance x/y	2.5/3.5 um
Average dump power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

*Listed parameters have been achieved in different modes of operation

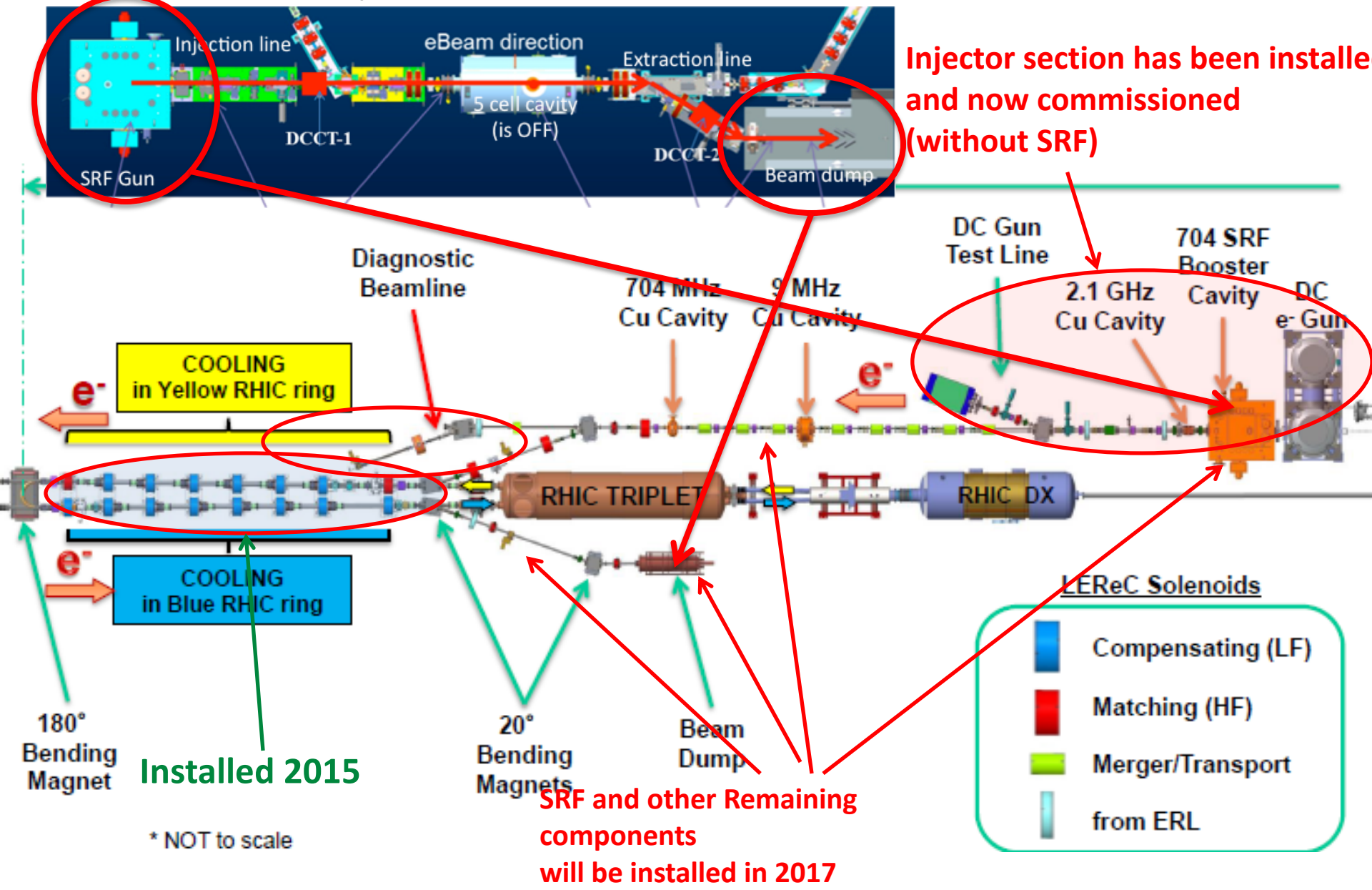
BPMs signal drifts and jumps



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 implemented and installed din LEReC Injection line.
No such problems observed anymore during LEReC DC gun commissioning

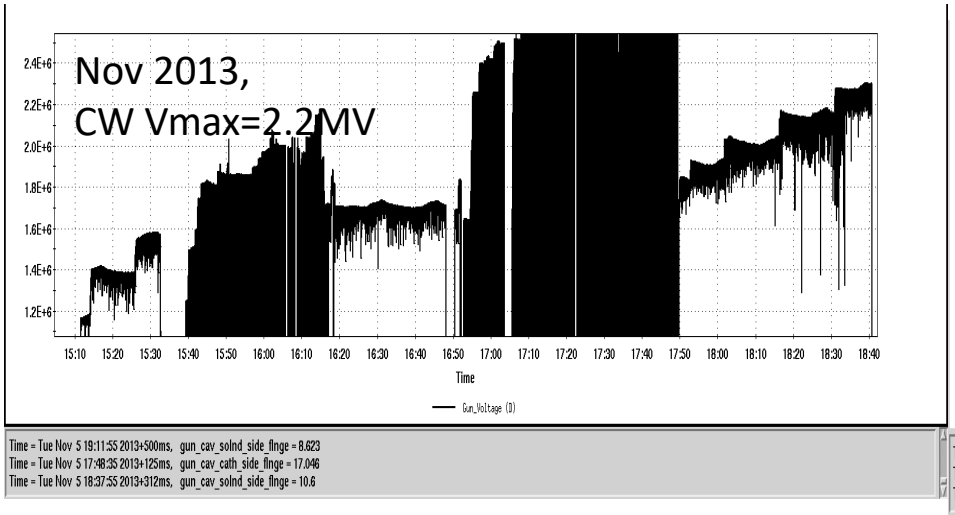


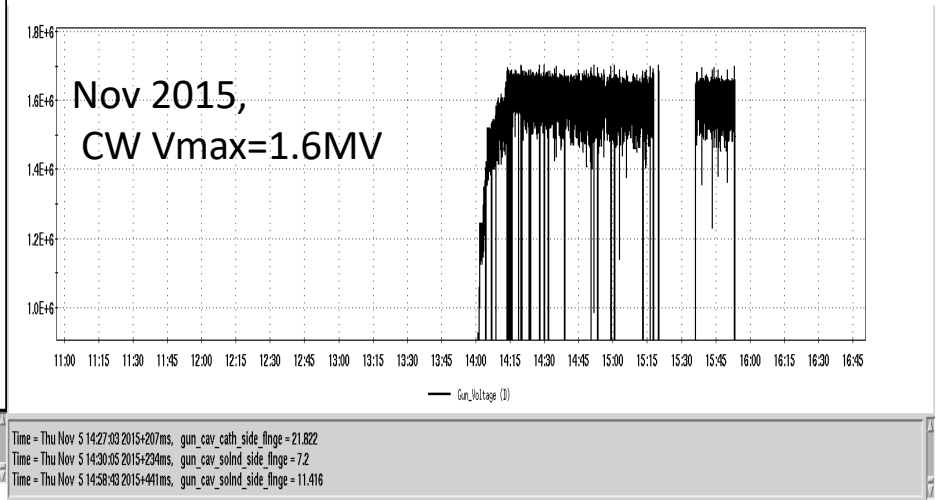
ERL components moved to LEReC location (RHIC IR2)



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.
- This gun as a booster cavity needs to be install for LEReC commissioning in summer of 2017.
- Cavity with cryostate has been removed from ERL beam line in De 2015.
- In summer of 2016 cavity has been sent for cleaning, modification (Argon) and testing (JLAB).
- Cavity now is reinstalled in ERL block house for HP conditioning before moving to LEReC this fall.
- RE-Commisioning with beam starts Spring 2018.





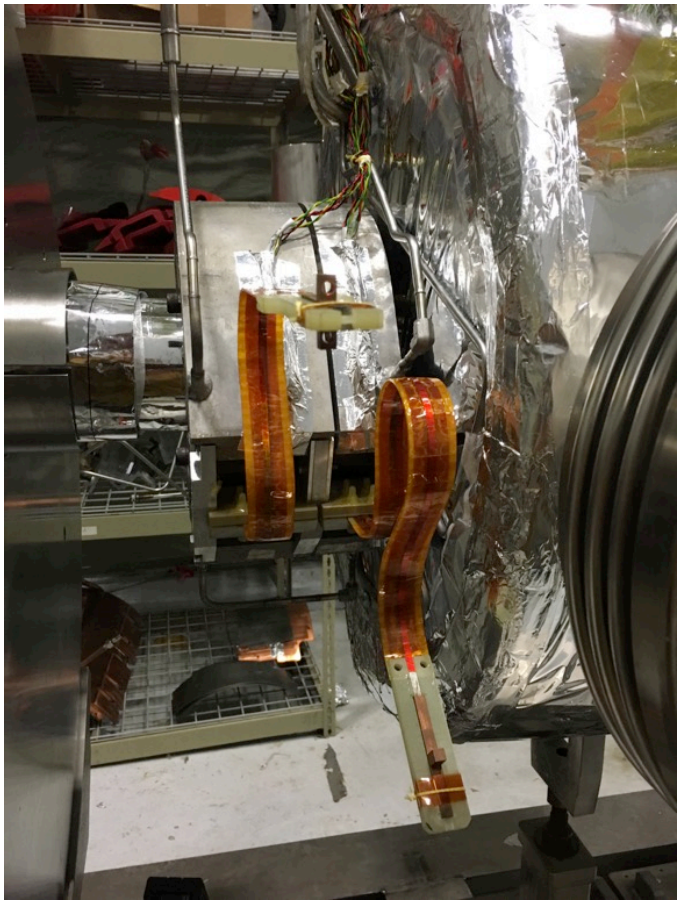
Copper rings marks

When cavity has been opened and copper marks have been observed at niobium part of chock join. Presumably cavity has been contaminated during severe cathode stalk RF conditioning.

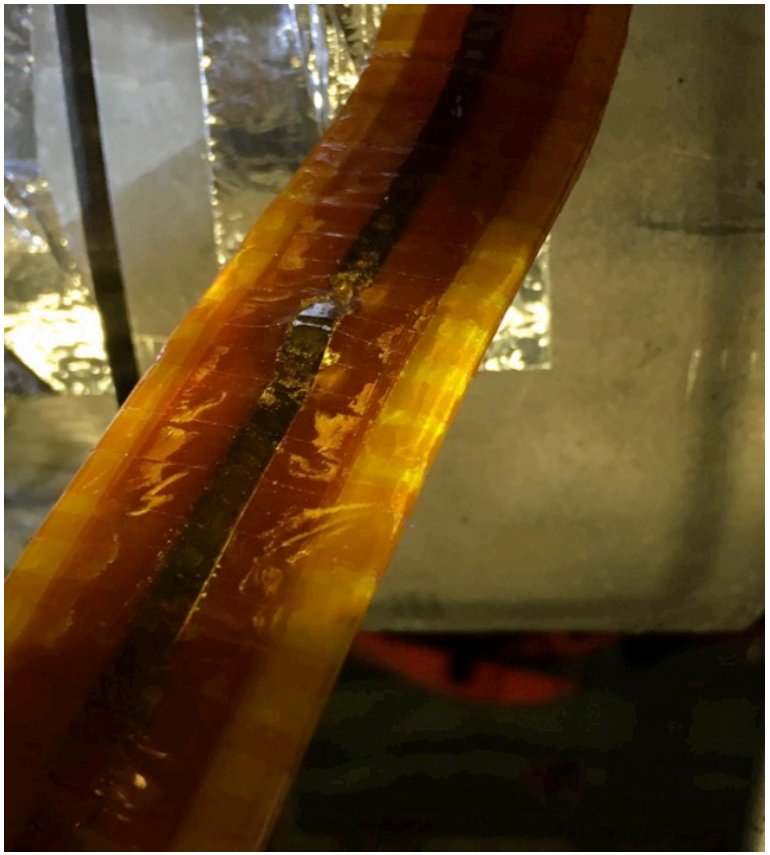
HTS solenoid lead damaged.

After opening gun cryostat we also discovered that main coil lead of HTS solenoid has been damaged.

It explains why we were not able to use this solenoid during beam studies.



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.

Summary and plans

- The first SRF gun 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 during these tests 22 uA has been demonstrated (with 260 uA in 4 msec pulses 10 Hz rep. rate)
- Beam has been delivered 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, 10 MHz.
- Beam instrumentation (BPMs, ICTs, FCs, BLM, PM etc)) has been tested/cross calibrated during beam ERL Gun beam tests. All this diagnostic has been reinstalled and now successfully used for LEReC project (Wednesday talk).
- Several operation limited factors have been discovered.
- LEReC demands to use of SRF gun as a booster cavity without cathode inserted. It required significant gun modification and longer turn around time. All ERL beam tests have been postponed on Dec 2015.
- Half cell SRF booster cavity has been removed, modified and will be installed for LEReC commissioning in fall of 2017
- Future beam tests are planned to resume when LEReC installation is completed in RHIC IP2 at the beginning of 2018.

As a result of BNL ERL R&D program SRF test faculty infrastructure has been developed at BNL.

- BNL SRF vertical test facility with clean room oven processing commissioned
- Well shielded ERL block house has received all necessary permits to run HP test
- It's fully equipped with cryogenics lines and cryo-refrigeration system
- It has 1 MW CW klystron and 50 kW solid state transmitter operational with all controls and diagnostics available from control room.
- HP couplers, 704MHZ 5cell SRF linac and 704 MHz half cell have been tested during ERL commissioning (2009-2015)
- Test and conditioning of the LEReC Booster 704 MHz cavity (used to be ERL Gun) (June-July 2017)
- After these tests the Block House will formally transform to High Power SRF –RF test facility

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