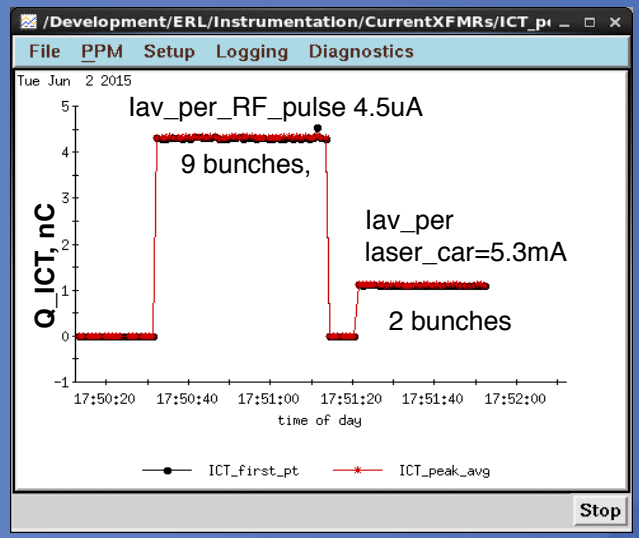
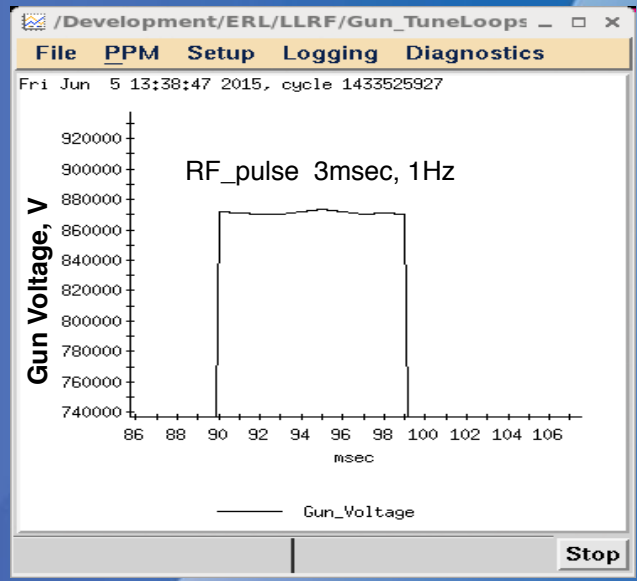
ERL2015 ERL2015 The 56th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs

Status and Commissioning Progress of the R&D ERL at BNL



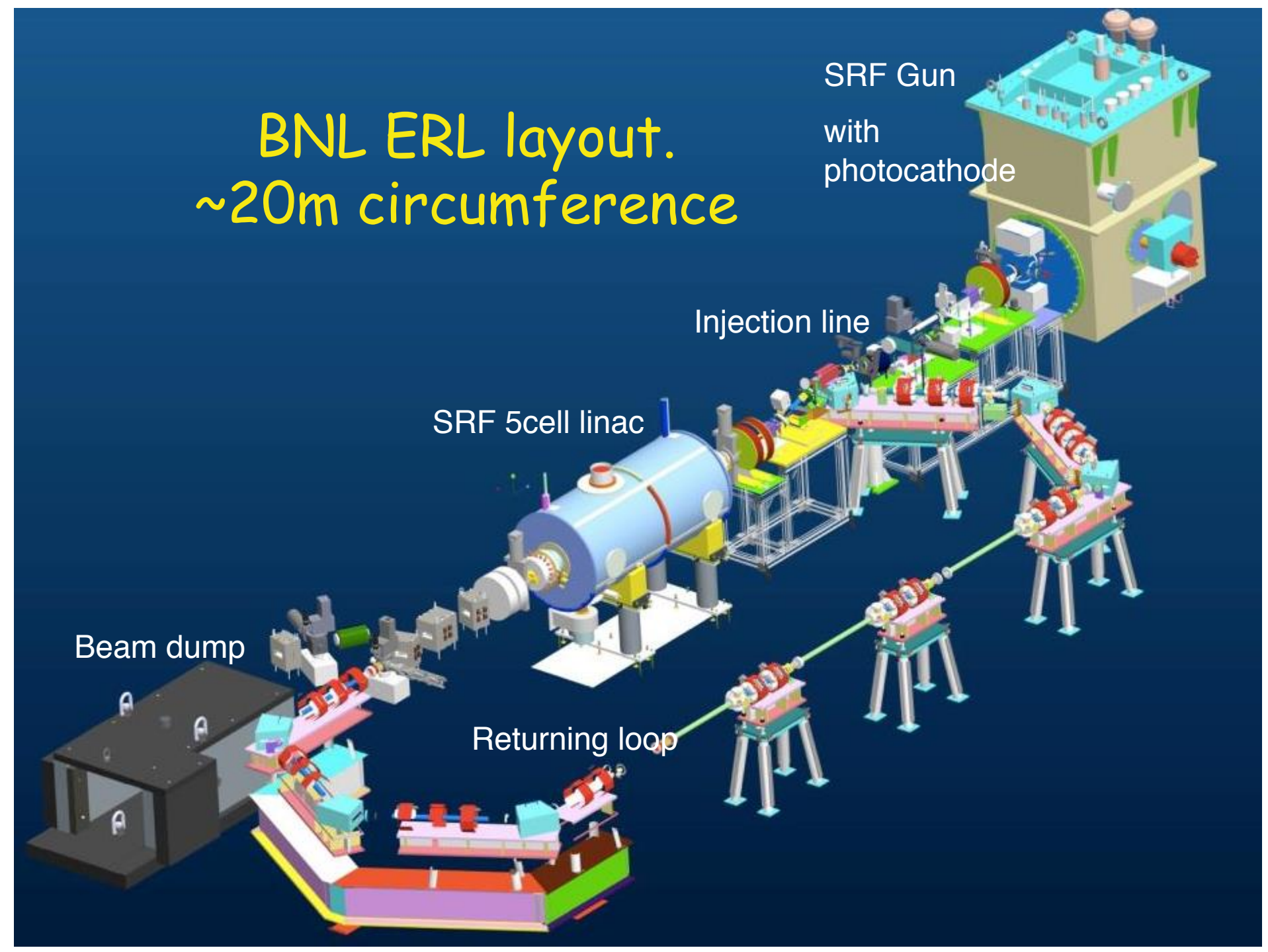


Dmitry Kayran, for BNL R&D ERL team

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science U.S. DEPARTMENT OF ENERGY

Stony Brook, NY, USA, June 7-12, 2015


BNL ERL layout.
~20m circumference
SRF Gun
with
photocathode
Injection line
SRF 5cell linac
Beam dump
Returning loop

R&D ERL: Installation and commissioning progress

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

Milestones :

- High power RF components installed and commissioned (2005-2007)
- SRF 5-cell installed and cold emission test completed (2009)
- 9.4MHz Laser system commissioned (2009)
- Digital LLRF system commissioning (2012)
- 2 K LHe cryogenic system/refrigerator commissioned (2012)
- SRF half-cell gun cold emission test w/o cathode (2013)
- Conditioning of the SRF gun with a copper cathode stalk (Jan 2014)
- Beam instrumentation installed, commissioning continues.

Mile stones: commissioning with beam

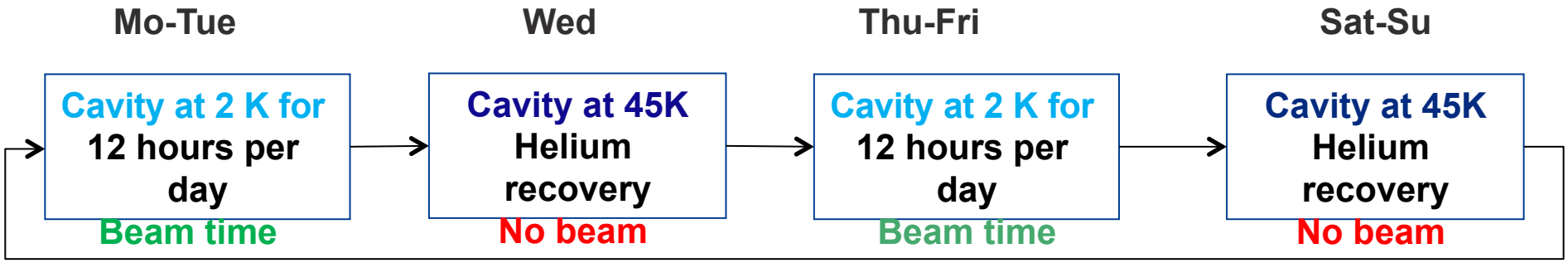
- First beam from the SRF gun with CsK2Sb photo cathode (Nov. 2014)
- DOE Approved to beam commissioning Gun to dump (Jan 2015)
- New cathode conditioned (Jan 2015)
- All ERL components installed, ARR for full ERL commissioning (May 2015)
- First good QE cathode (May 2015)
- High charge per bunch from the gun (achieved June 2015)

Future plans

- Gun into beam dump commissioning (Summer 2015)
- ERL beam test low current (Fall 2015)
- Laser system upgrade (Fall 2015)
- Gun to dump then ERL gradually increase current (until Feb 2017).
- Preparing for commissioning ERL components at RHIC IP2 for Low Energy RHIC electron cooler. (Feb 2017-March 2018)

ERL gun commissioning job flow

- 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

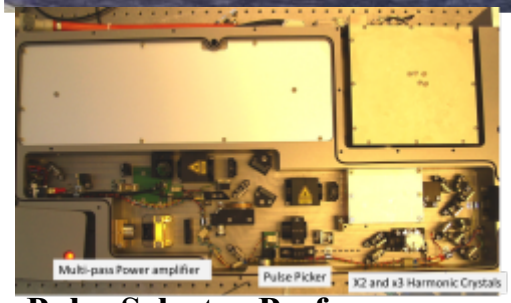
Monday : Cool down the gun to 2 K, Insert cathode, stay at 2 K for 16 hours; then, hold 4.5 K over night
Tuesday : Cool down the gun to 2 K, stay at 2 K for 16 hours; then, remove cathode warm it up to 40 K over night;
Wednesday, the gun with stay at 45K cathode is out;
Thursday Cool down the gun to 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%

Laser system

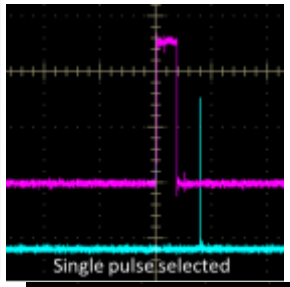
- **Lumera Laser:**

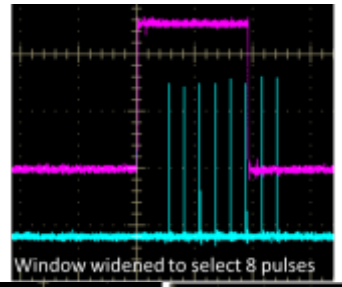
Specifications for the Laser System

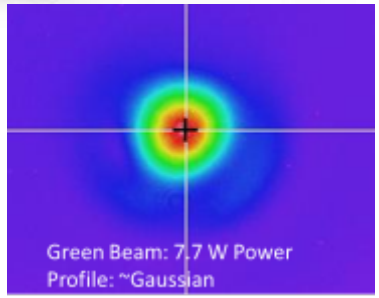
Ability to lock and follow master RF clock	
Master RF Repetition Rate	703.75 MHz
Laser PRF (Phase I for ERL)	Sub multiple of 703.75 MHz
Laser PRF (Phase II for RHIC II)	9.383 MHz
Frequency tunability	+/- 1 MHz
Synchronization deviation to master oscillator	<1 ps
Pulse Length	5-12 ps
Jitter in pulse length	0.1 ps
Final Output wavelength	355 nm
Optional output wavelength	532 nm
Beam Quality @ 355 nm	TEM_{00}; $M^2 \leq 1.5$
Optimized for a required power at 355 nm	>5 W
Average output power stability at 355 nm	< 1% rms
Amplitude noise	< 1% rms

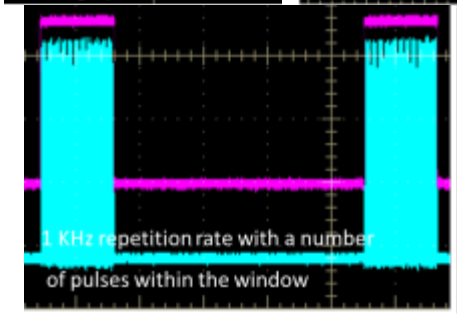


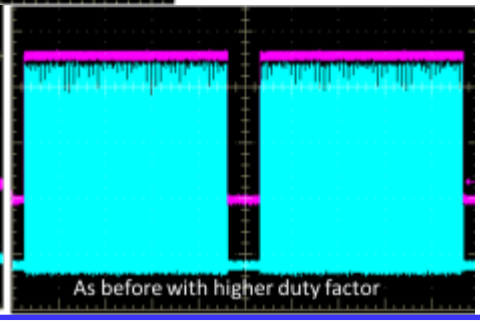
Pulse Selector Performance







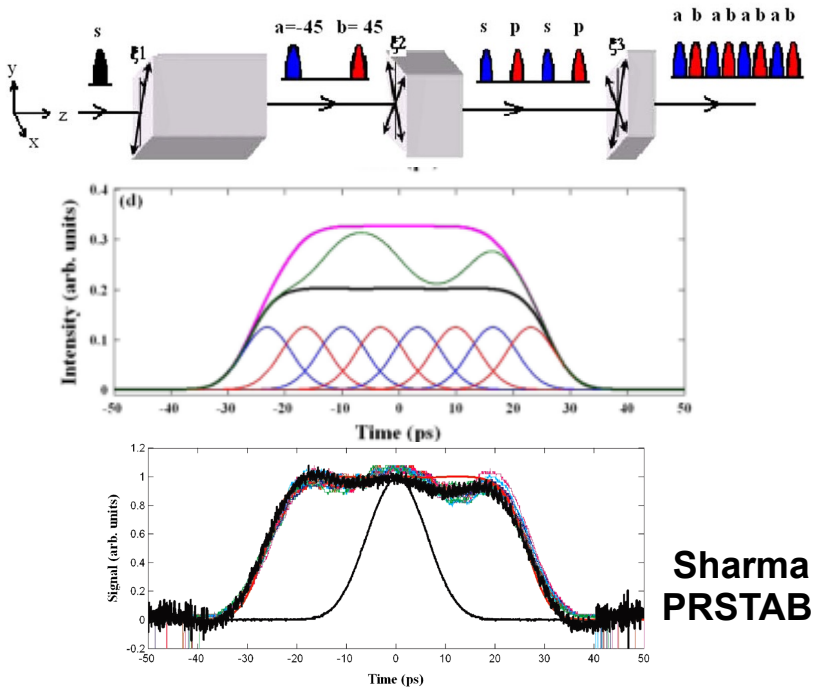




Commissioned and operational since 2009

Laser pulses manipulation

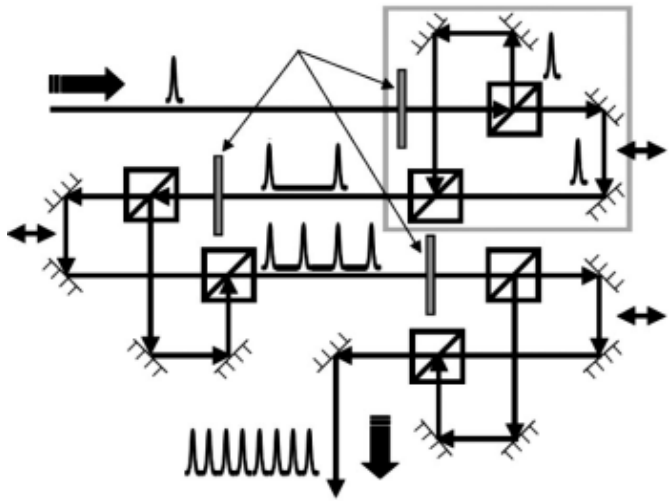
Birefringent Method



Sharma *et al* PRSTAB 2009

- No adjustable parameters
- Crystal length and quality issues

Interferometric Method



Tomizawa *et al* Quant Elec 2007

- Extremely sensitive to alignment
- Stability

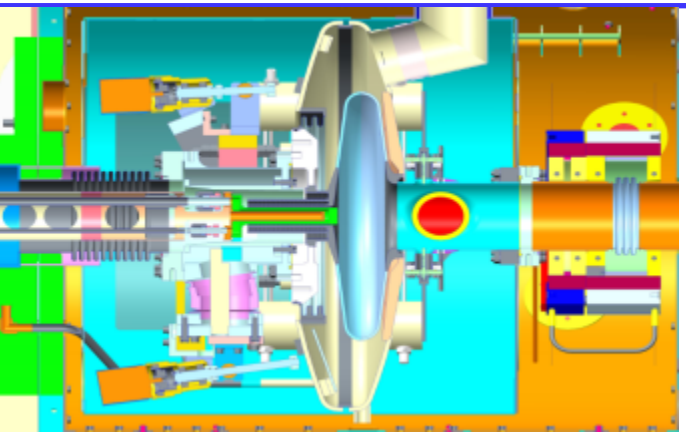
Used to increase pulse width by 4, 8 and pulse flat.

Tested with e-beam

Used to increase to increase rep. rate by 4. (to 4*9.38MHz)

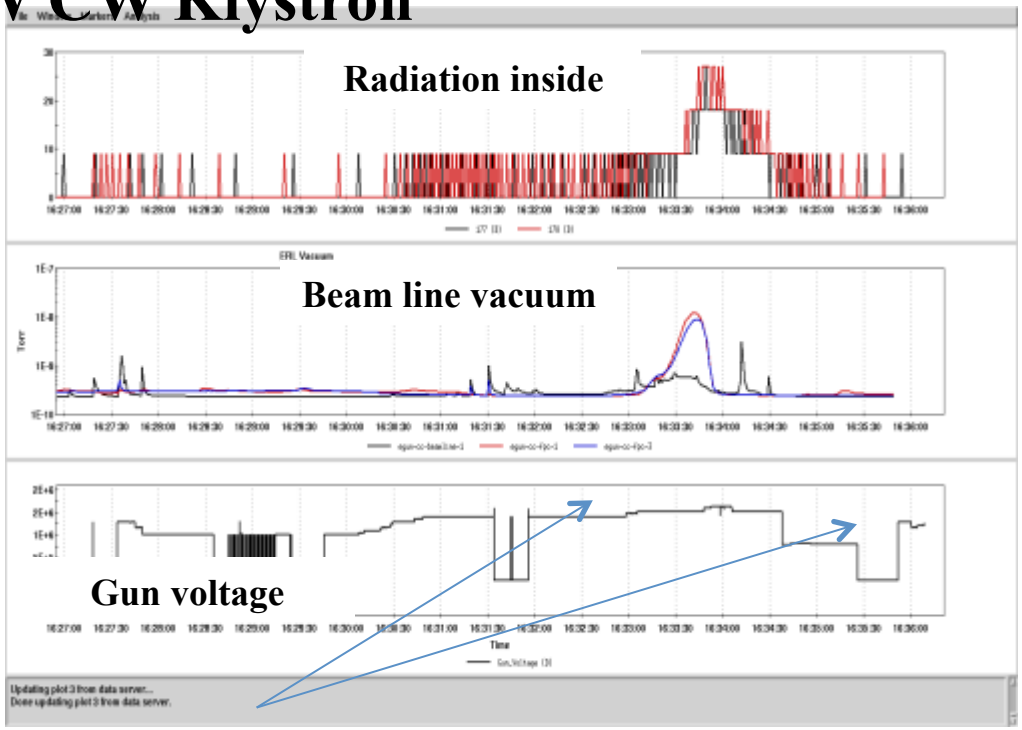
Ready to test with e-beam

704 MHz SRF Gun: 2 MV CW operation



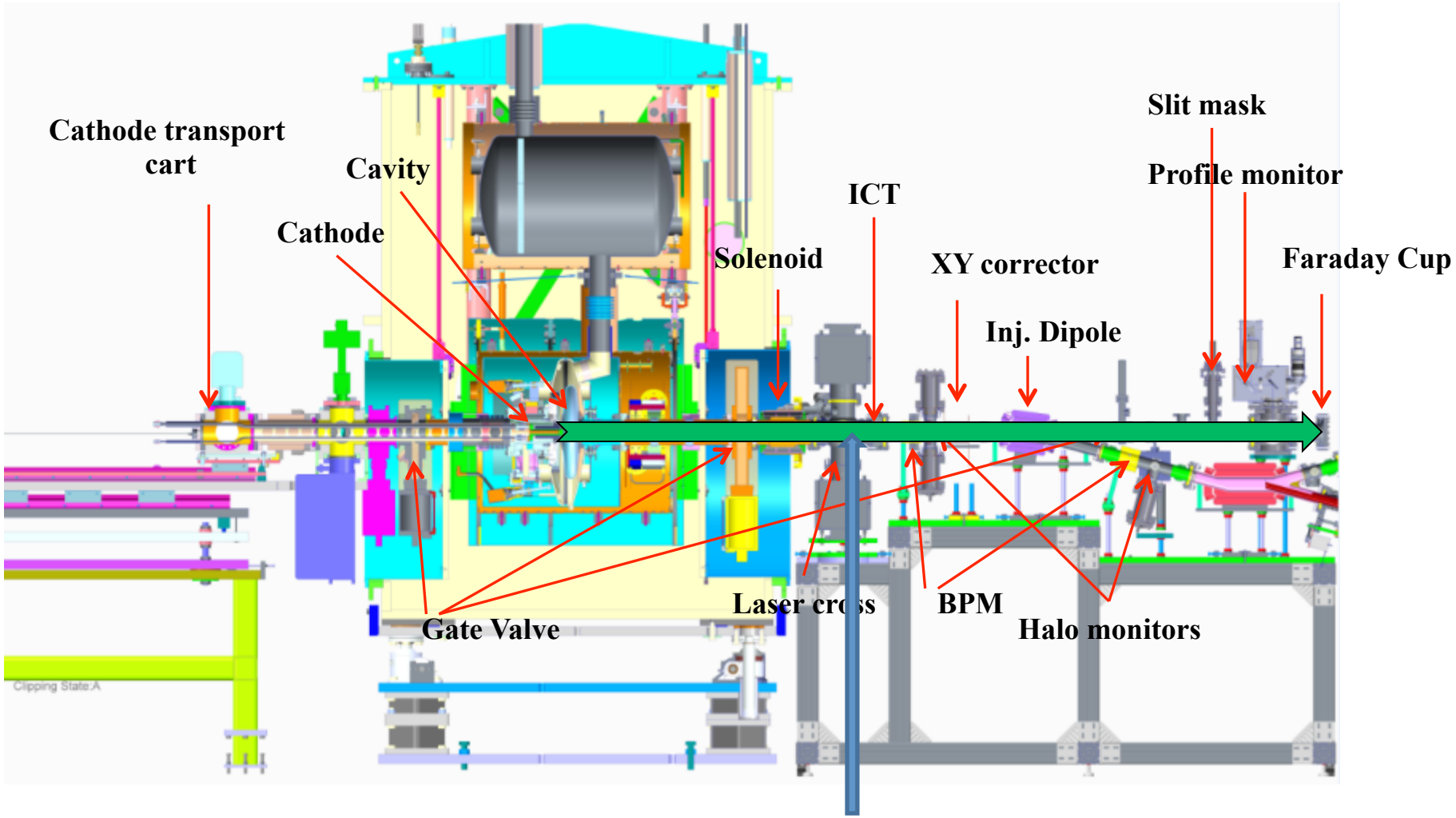
½ cell SRF gun

1MW CW Klystron

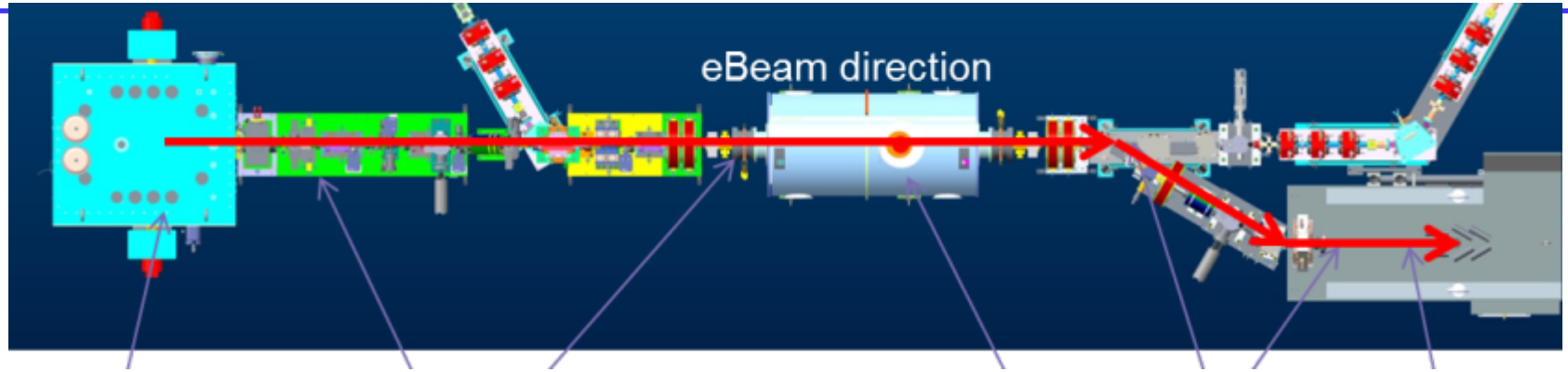


1-2 MV CW operation of 704 MHZ SRF gun at BNL

Gun to FC beam test setup



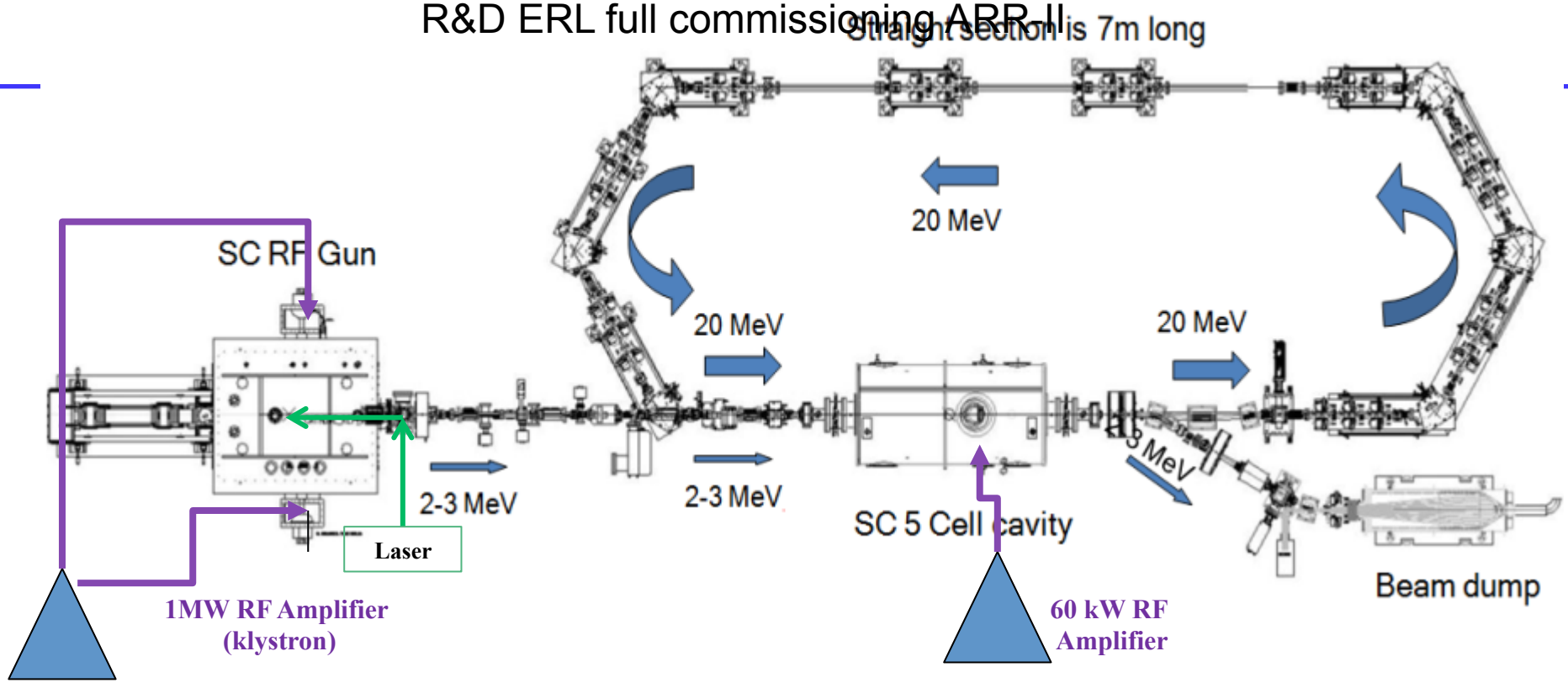
Goals of Gun to Dump commissioning stages (ARR stage I)



- Injection line commissioning (low current)
  - *transport beam through the ERL injection line (ZigZag)*
  - *calibrate beam loss monitors*
  - establish routine and fault dose rates external to the shielding
- Extraction and beam dump commissioning (low current)
  - *transport beam through 5cell cavity and the ERL extraction line to beam dump*
  - *calibrate beam loss monitors and DCCTs*
  - *establish close to 100% beam to dump transport line propagation*
  - *carry out beam measurements*
  - establish routine and fault dose rates external to the shielding
- High Intensity Studies (final stage)
  - *demonstrate stable gun operation at minimum 30 mA average current*
  - *conduct cathode life time studies*
  - *beam dump commissioning*
  - establish routine dose rates external to the shielding

Learning the machine performance during previous commissioning phases allows proceeding with smooth transition to loop commissioning.

R&D ERL full commissioning ARR-II



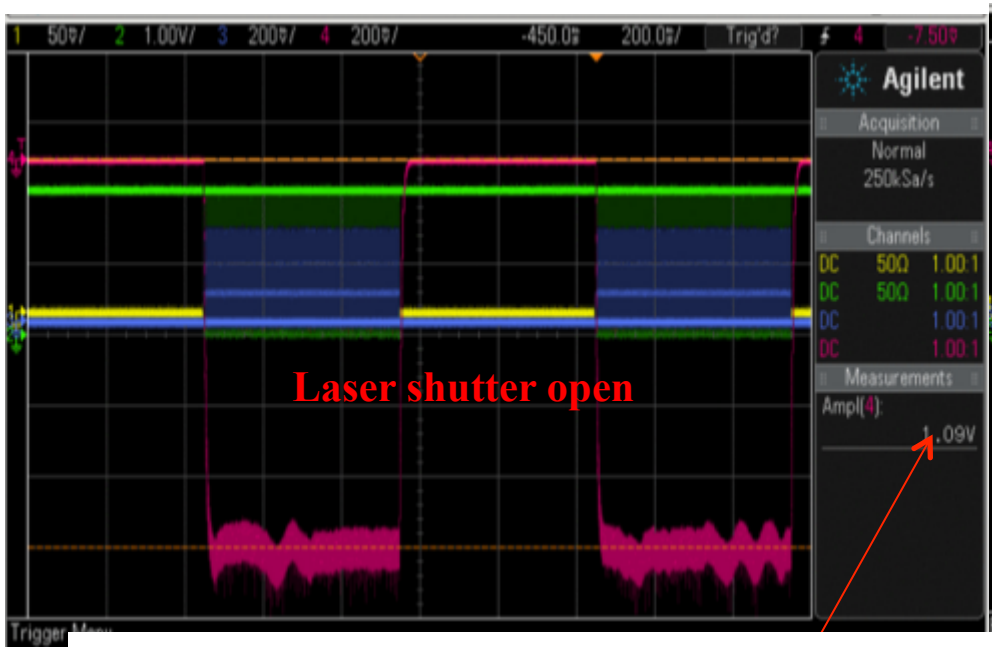
Beam Parameters

Commissioning goal:	
Injection energy:	2 MeV
Top energy:	20 MeV
Multi-Alkali photocathode :	QE>3e-3
Laser repetition rate:	9.4 MHz
Operating: single or/and train pulses	
Charge per bunch:	1 nC
Average current :	30 mA

ASE limits (controlled by design)

Max SRF Gun Energy	**<3.5 MeV**
Power source for SRF	**< 1.5 MW**
Max loop electron energy	**<25 MeV**
Maximum Reactive Power:	**< 10MW**
Power source for 5cell cavity	**< 60 kW**
Extraction Beam energy	**<3.5 MeV**
Extraction beam power	**< 1.5 MW**

First beam, old cathode Nov 2014.



Faraday cup signal (1MΩ termination)

Set up

- Laser: 6.1 Watt, green,

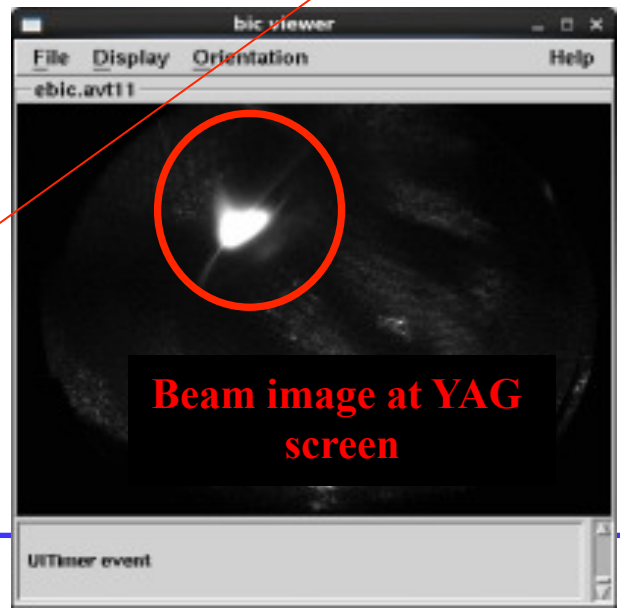
Pulse structure 7 µsec, every 500 µsec; 9.38MHz rep rate.

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

  bunch charge: 7.7 pC,

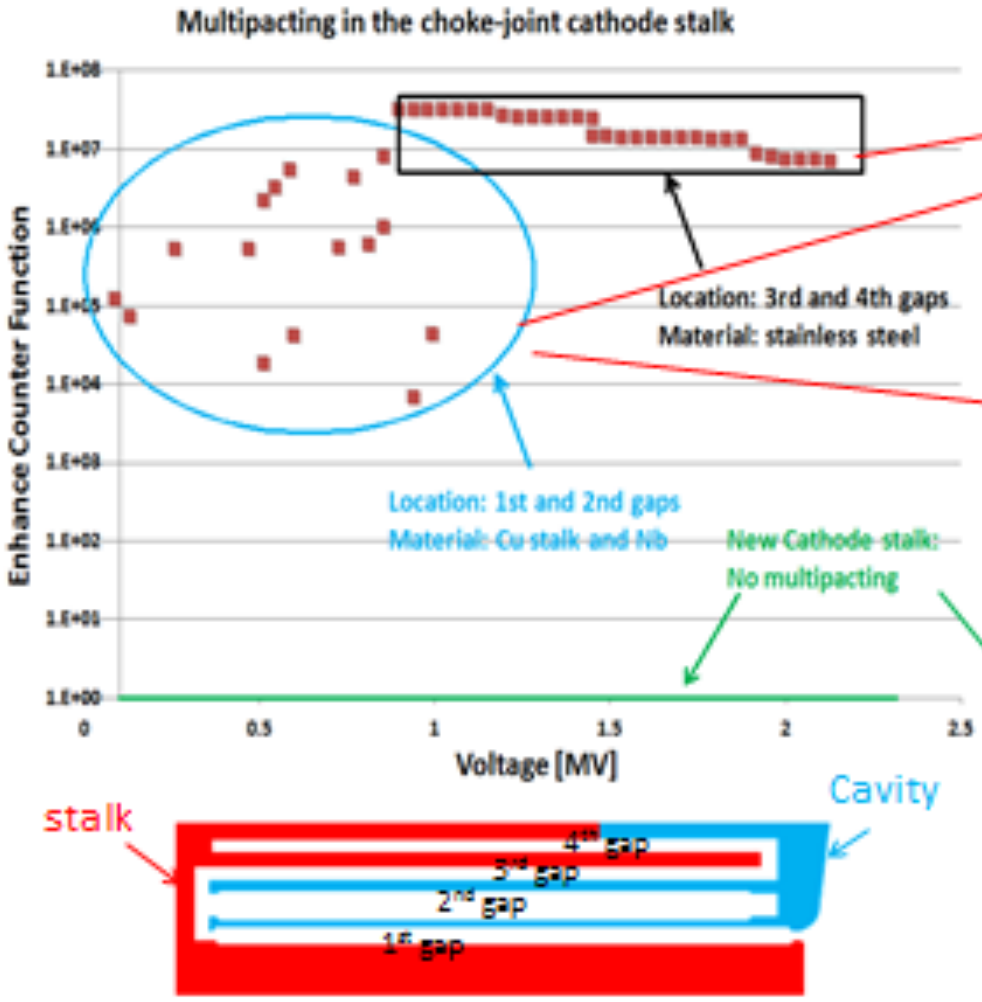
  Average per RF pulse

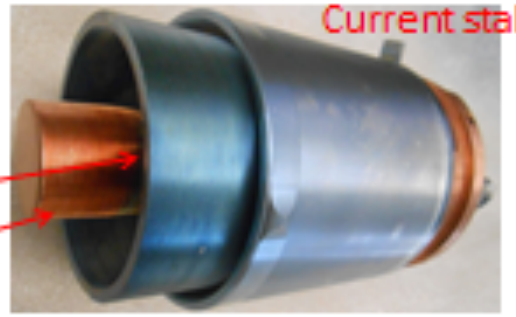
  photocurrent 1 µA, dark current 38 nA;
- Photocathode cold QE=2.7e-5 Very low!!!

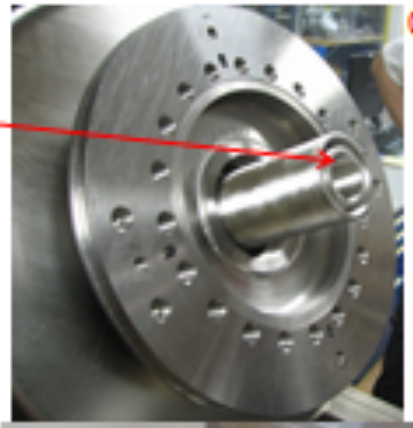


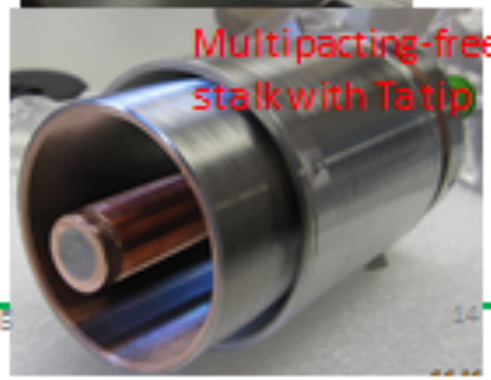
D. Kayran, ERL2015

New cathode stalk with Ta tip





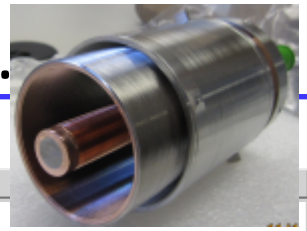




Wencan Xu C-AD Machine Advisory Committee Meeting 14

Courtesy Wencan Xu, more details on Tuesday, WG1+WG4 joint session.

Conditioning Gun with new cathode stalk.



File Window Markers Analysis

Radiation inside

dose (mRe 100 0

13:20 13:30 13:40 13:50 14:00 14:10 14:20 14:30 14:40 14:50 15:00 15:10 15:20 15:30 15:40 15:50 16:00 16:10 16:20 16:30 16:40 16:50 17:00 17:10 17:20

,177 ,178

ERL Vacuum

Vacuum signal

1E-8 1E-10

13:20 13:30 13:40 13:50 14:00 14:10 14:20 14:30 14:40 14:50 15:00 15:10 15:20 15:30 15:40 15:50 16:00 16:10 16:20 16:30 16:40 16:50 17:00 17:10 17:20

egun-cc-beamline-1 egun-cc-fpc-1 egun-cc-fpc-3

Klystron power

200000 0

13:20 13:30 13:40 13:50 14:00 14:10 14:20 14:30 14:40 14:50 15:00 15:10 15:20 15:30 15:40 15:50 16:00 16:10 16:20 16:30 16:40 16:50 17:00 17:10 17:20

Gun_Fwd_Klystron_Power (C) Gun_Ref_Load_Power (C)

Gun voltage

Conditioning~4 hours

1.0E+6 0.0E+0

13:20 13:30 13:40 13:50 14:00 14:10 14:20 14:30 14:40 14:50 15:00 15:10 15:20 15:30 15:40 15:50 16:00 16:10 16:20 16:30 16:40 16:50 17:00 17:10 17:20

Time

Gun_Voltage (C)

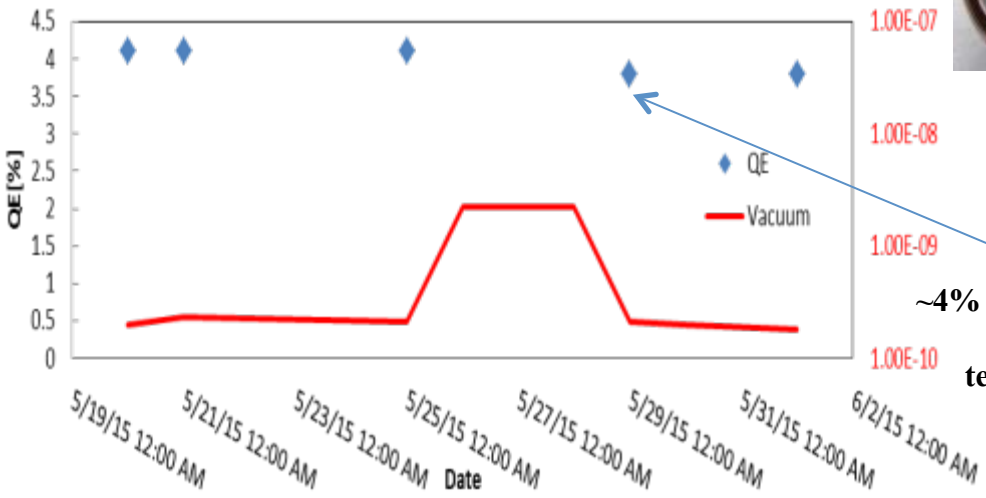
Done updating plot 4.

Auto update successfully disabled.

1.25MV CW
Good vacuum,
No radiation

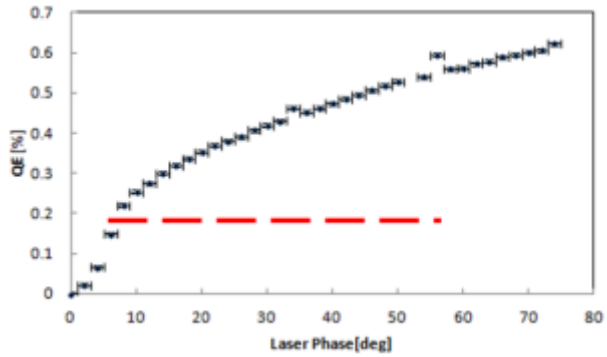
QE with new Ta cathode

ERL Cathode deposition system at BLD912



~4% QE measured at room temperature

- We tested 3.8% QE K_2CsSb cathode in the 704MHz SRF gun.
- The cathode survives well the gun and stalk RF conditioning.
- The cathode QE inside the gun (cold) is 1%. We didn't see any QE degradation after two days of high bunch charge operation. The vacuum at the gun exit is at 10^{-9} scale during gun operation.
- After extracting the cathode out of the gun, the QE is still at 3.8%.

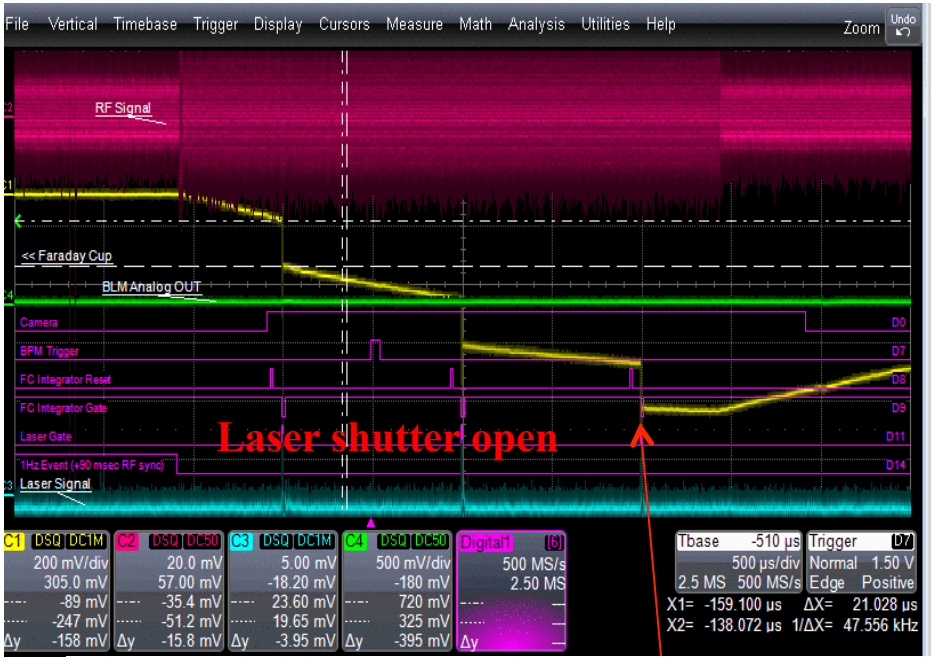


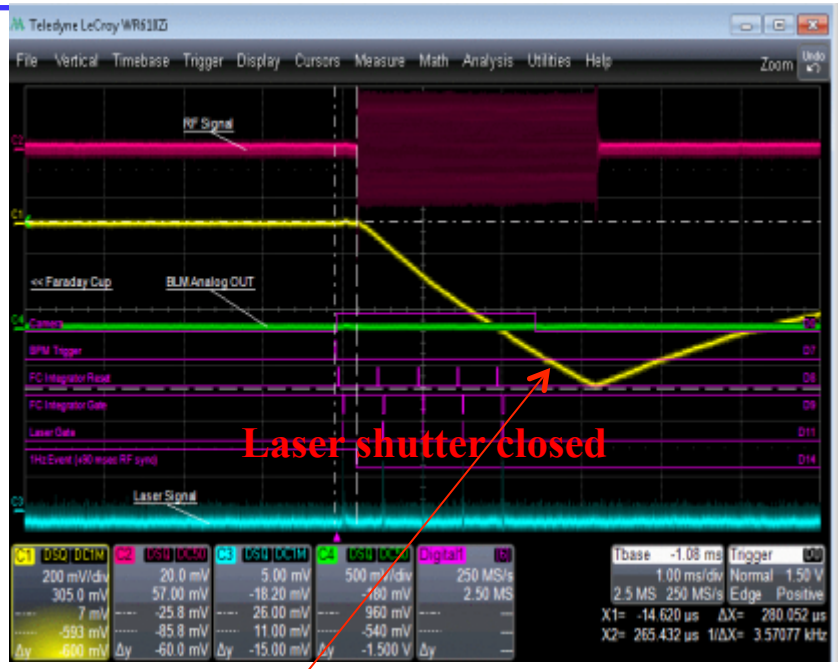
Peak current 1.65A, Gradient 10 MV/m

Schottky effect

Courtesy Erdong Weng, more details on Tuesday, WG1 right after lunch session.

Beam commissioning with new cathode June 2015.





Faraday cup signal (1MΩ termination)

Set up

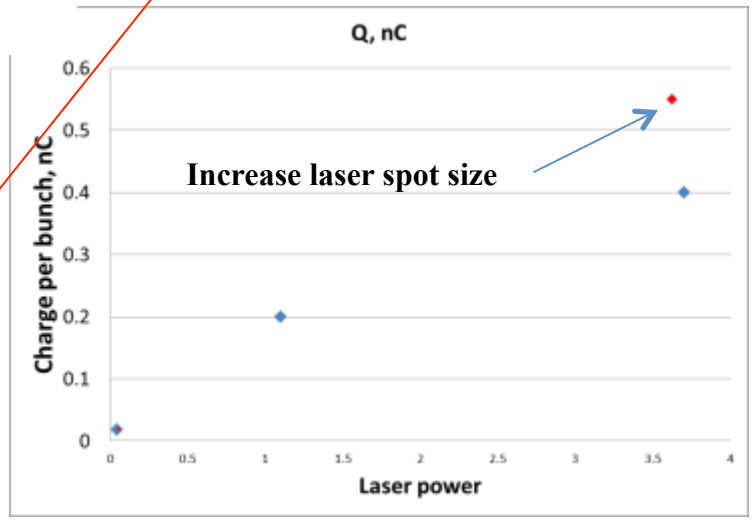
- **Laser: 0.044 mWatt, green,**

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

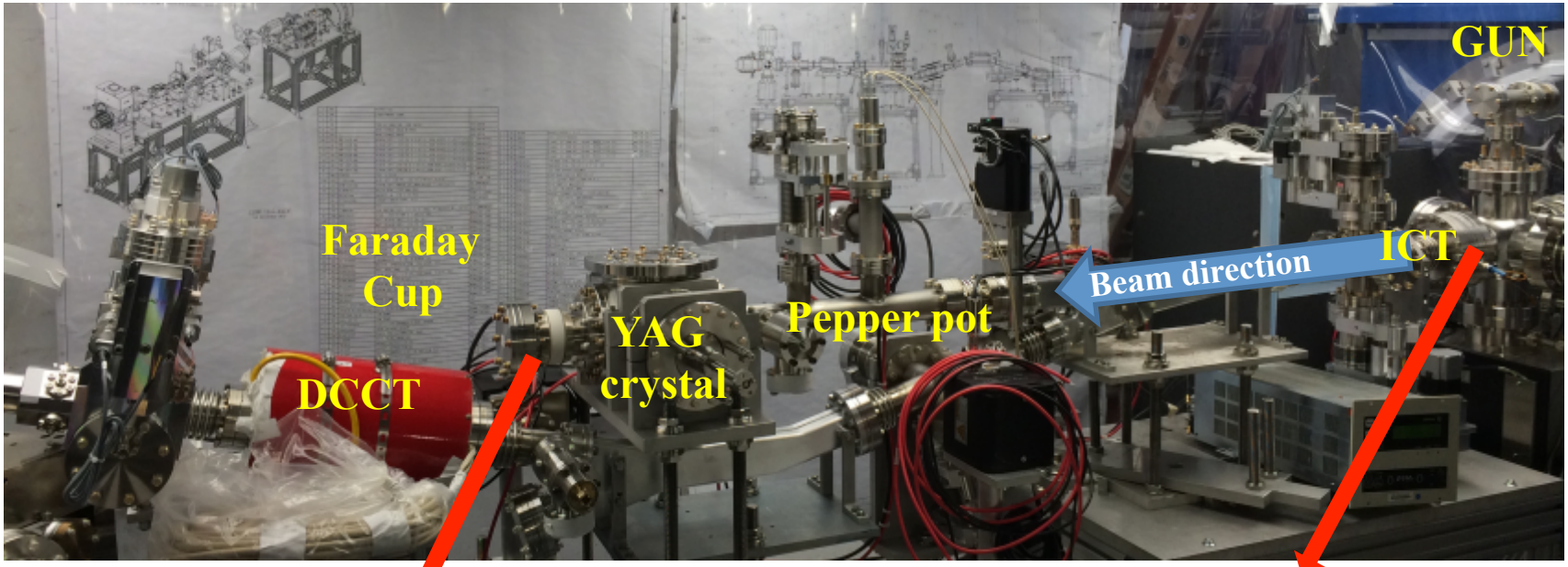
- **RF: 0.65 MV, 3 ms;**
- **eBeam:**

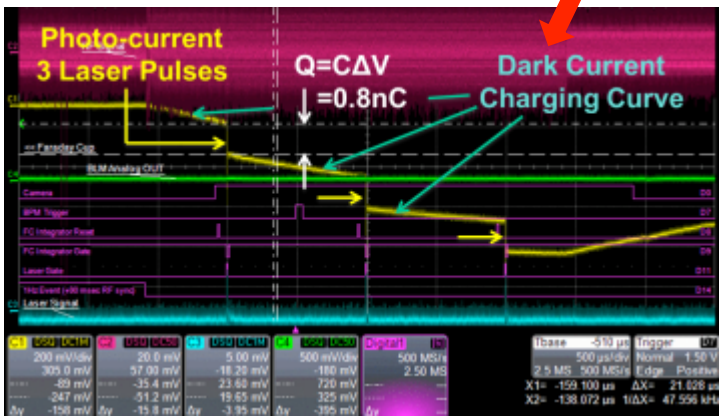
  charge per macro bunch 0.8nC/47bunches=17pC

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

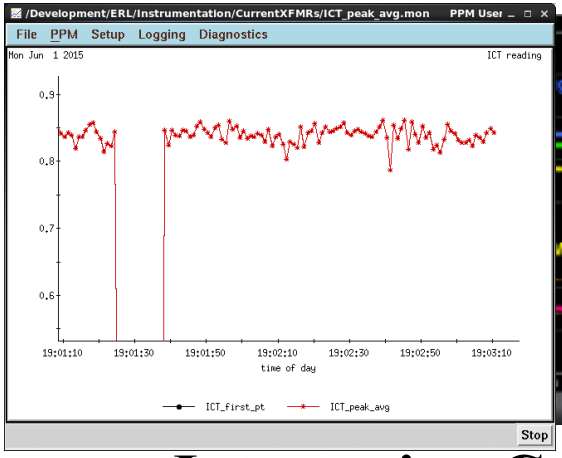


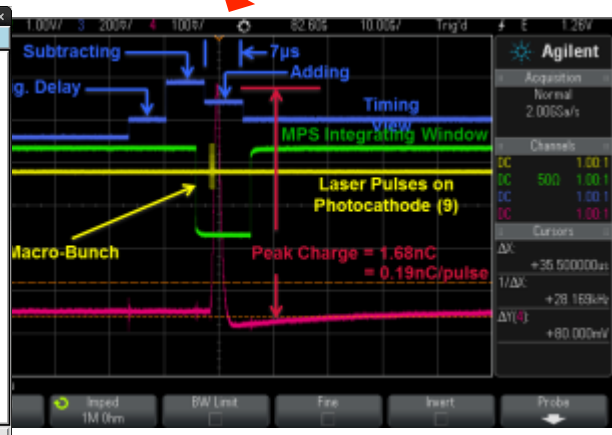
Beam charge measurements





Faraday cup

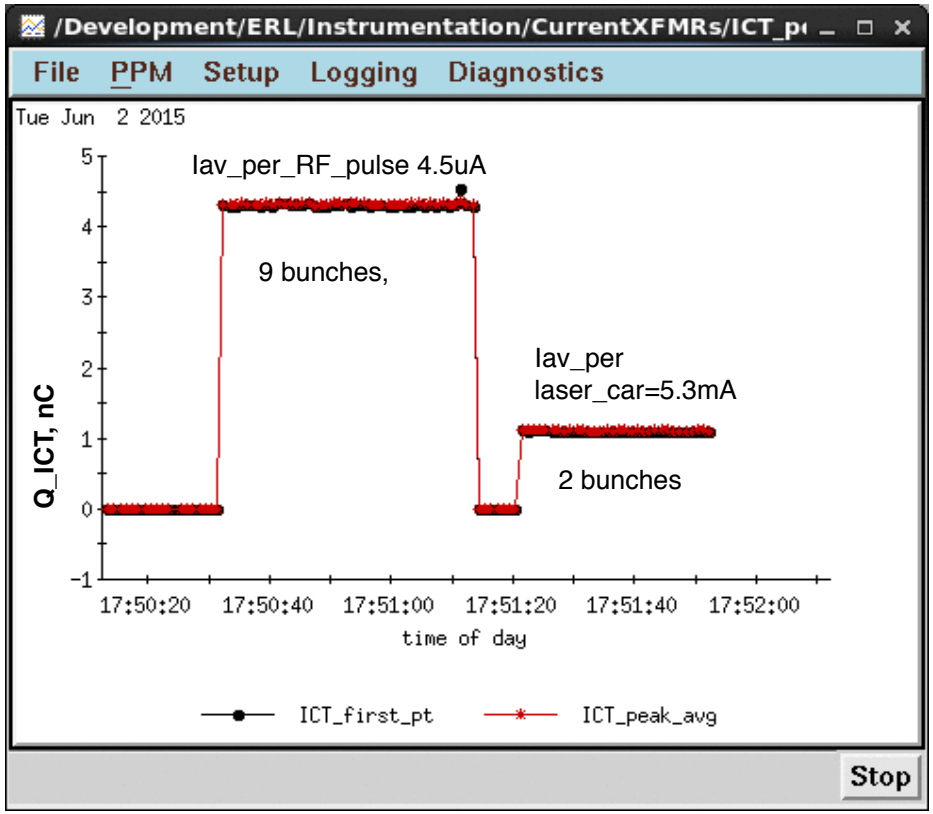




Integrating Current Transformer

FC vs ICT. ICT signal 0.85 nC , FC signal 0.8 nC

Charge per bunch 0.55nC

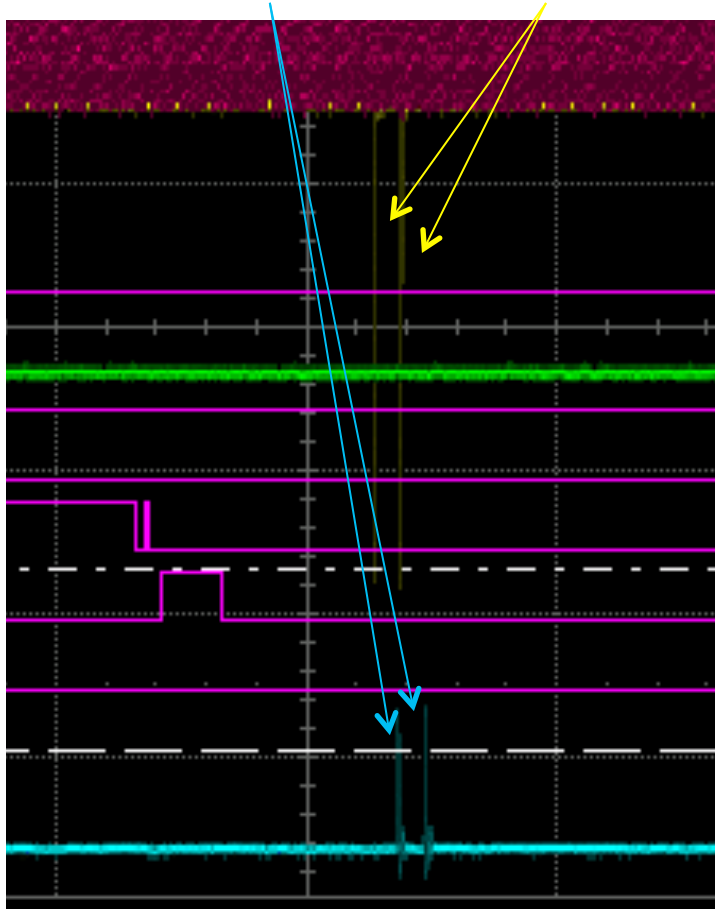


ICT signal for 9 pulses (4.4 nC> 4nC ICT saturation)

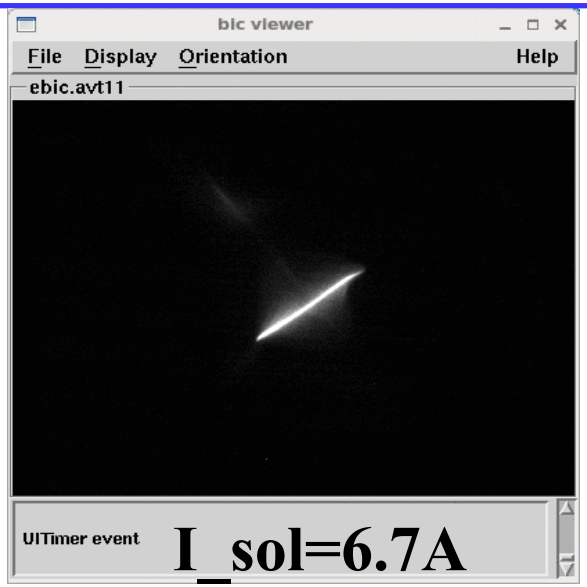
Reduce back to 2 laser pulses (1.1 nC) 0.55nC Each.

2 laser pulses, 0.39uJ each

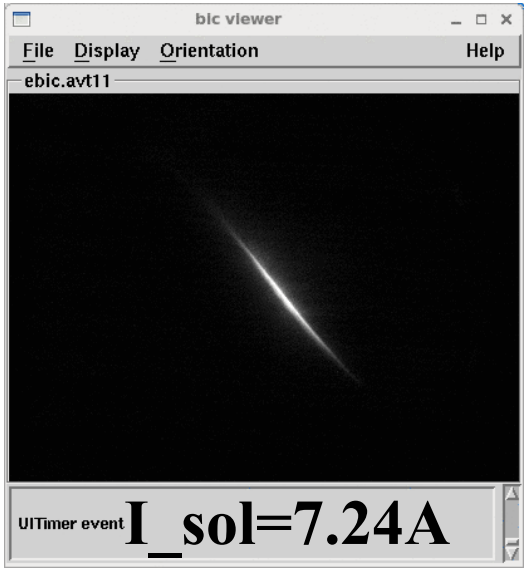
2 e-bunches at FC observed



Solenoid scan to measure gun astigmatism (preliminary)

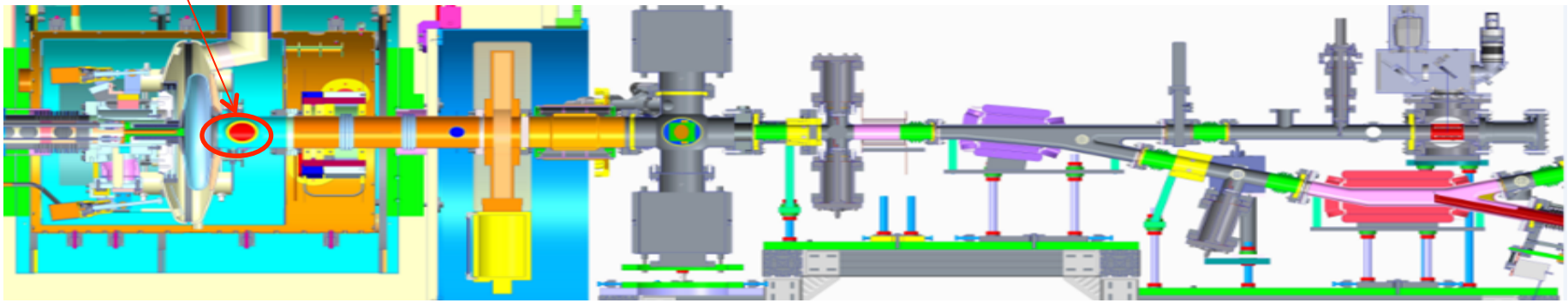


Ninja star shape



2 FPCs

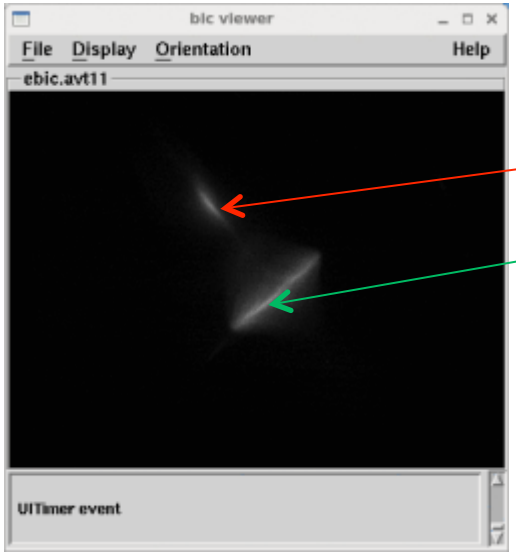
Axial symmetric system or not?



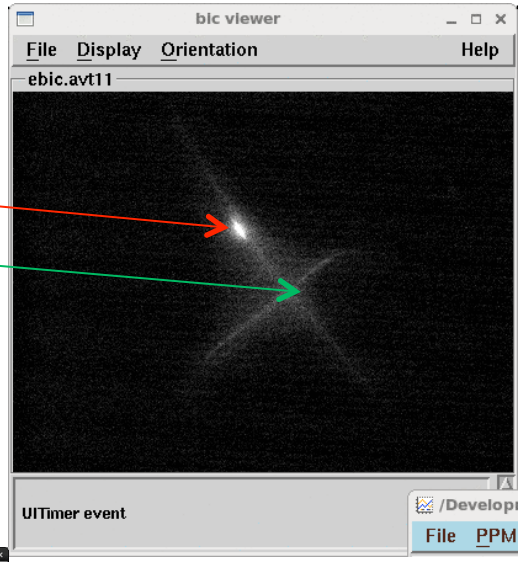
Preliminary result focus length 64cm!!!. Required more investigation.

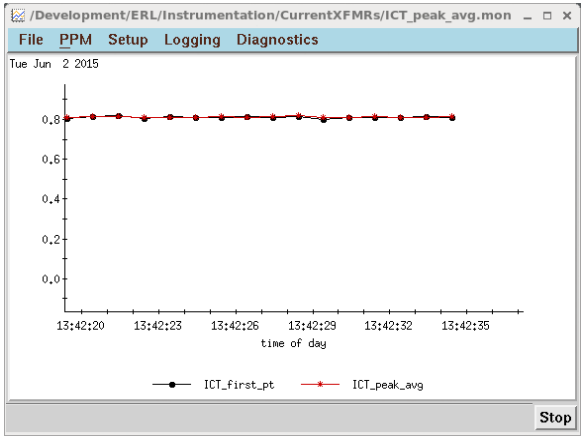
Courtesy V. Litvinenko

Dark current and photocurrent

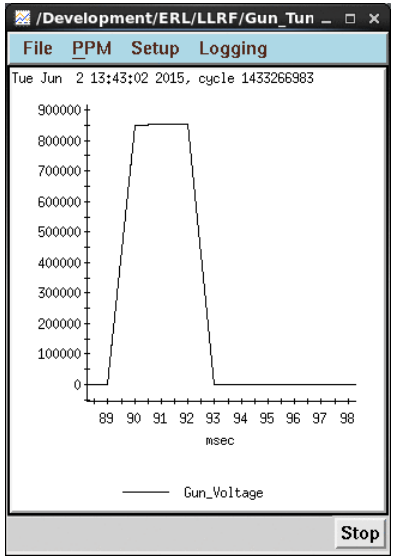


Dark current and photocurrent respond similar to solenoid and corrector change.



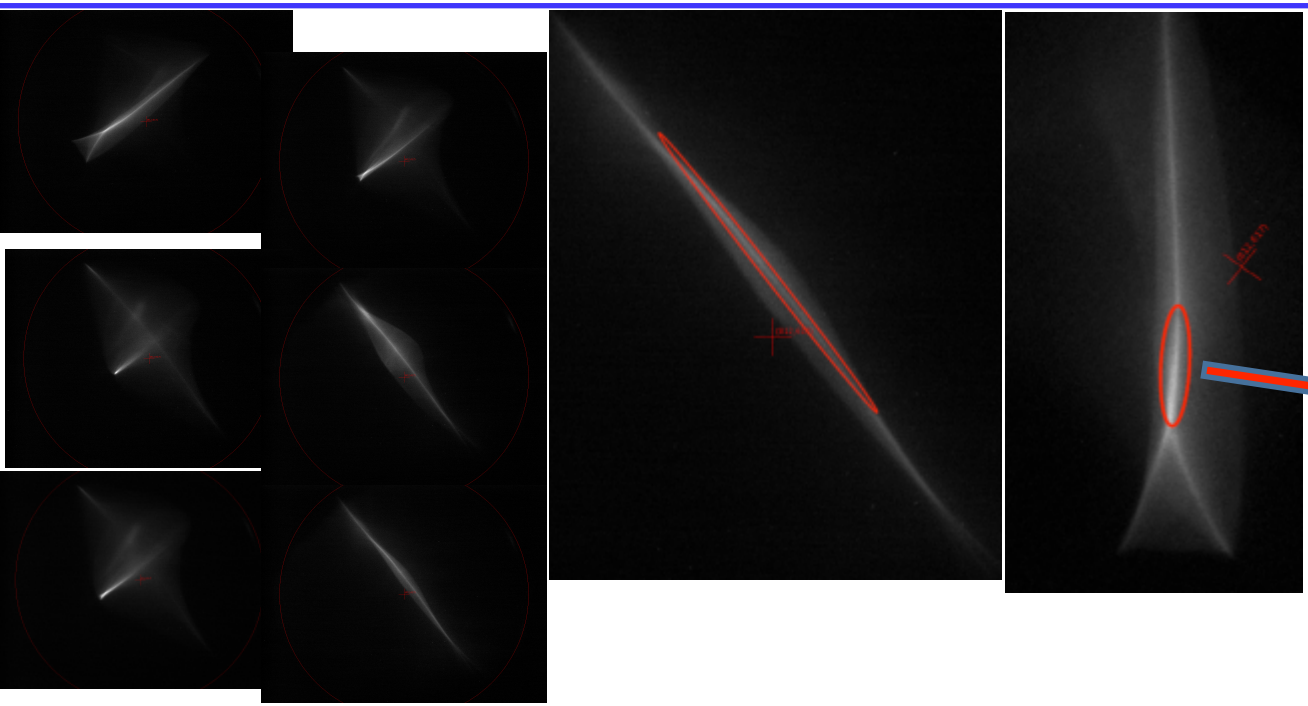


Photocurrent 0.8 nC /2 laser pulses



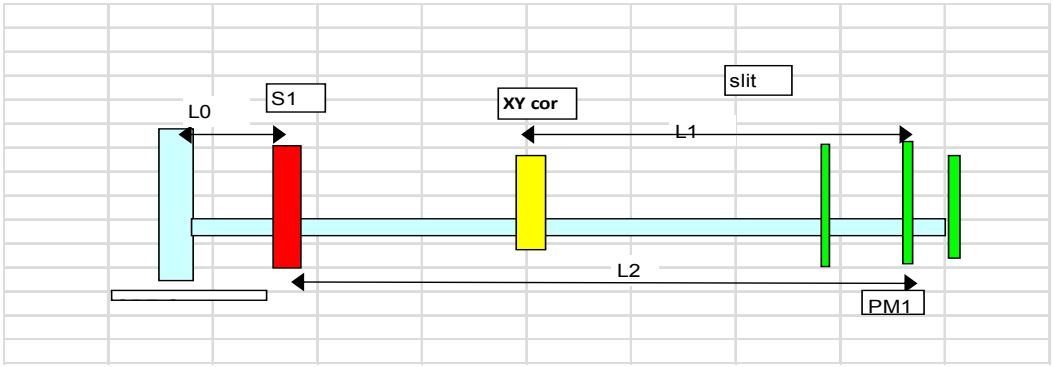
Dark current @ .85MV 4uA per 3 msec

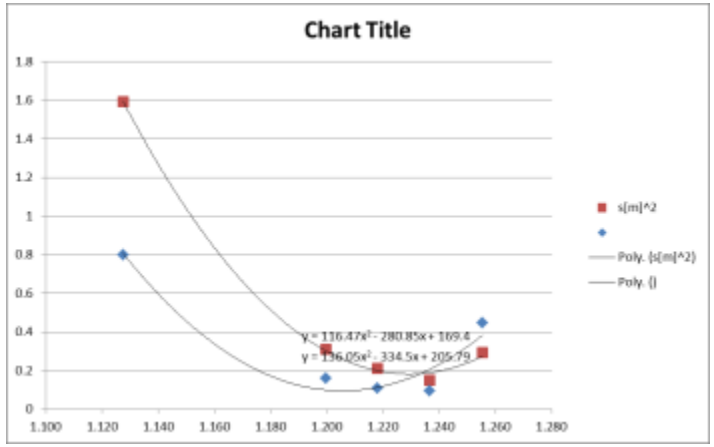
Try Solenoid scan, Q=133pC (preliminary)



Very Preliminary results

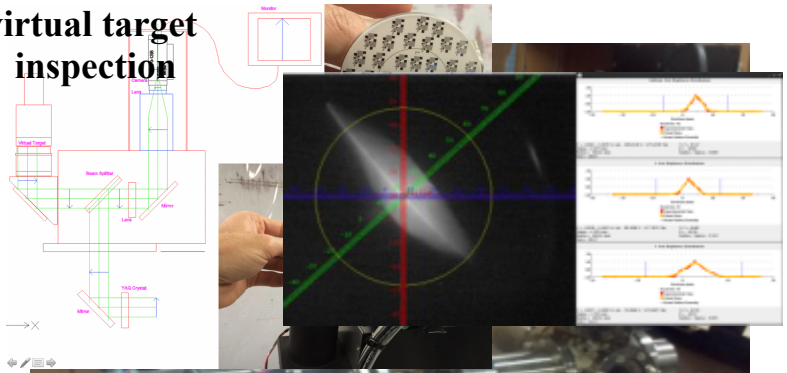
	Normalized emittance
full beam	12 mm mrad
20% core	0.25 mm mrad

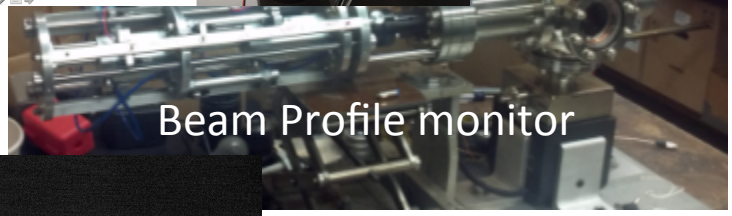


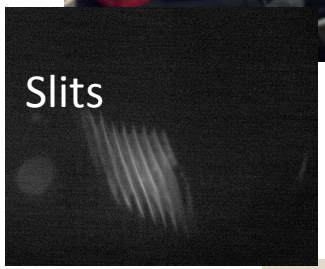


Beam instrumentation tested with beam

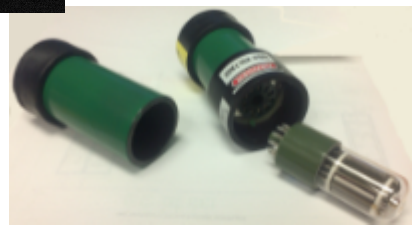
virtual target inspection



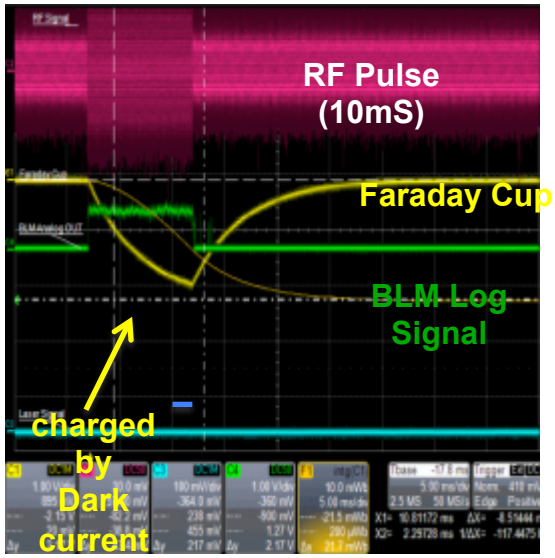




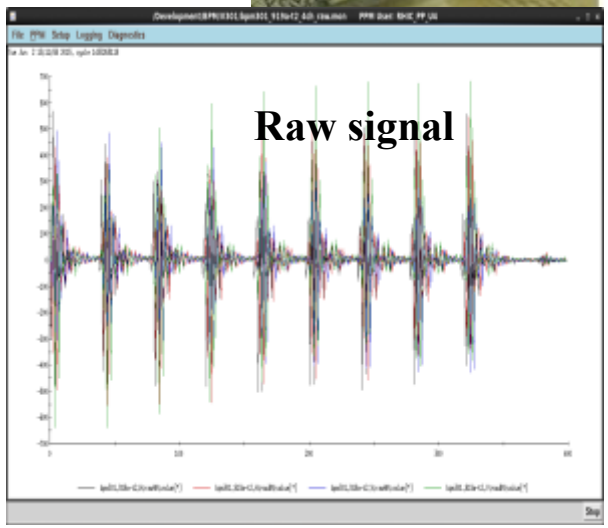
PMT Detectors

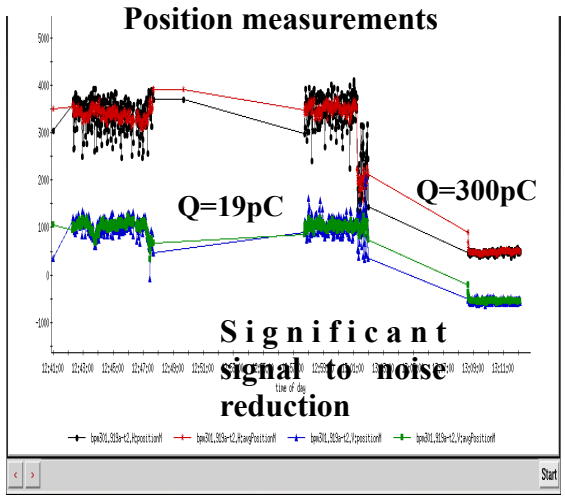


Faraday Cup



BPM



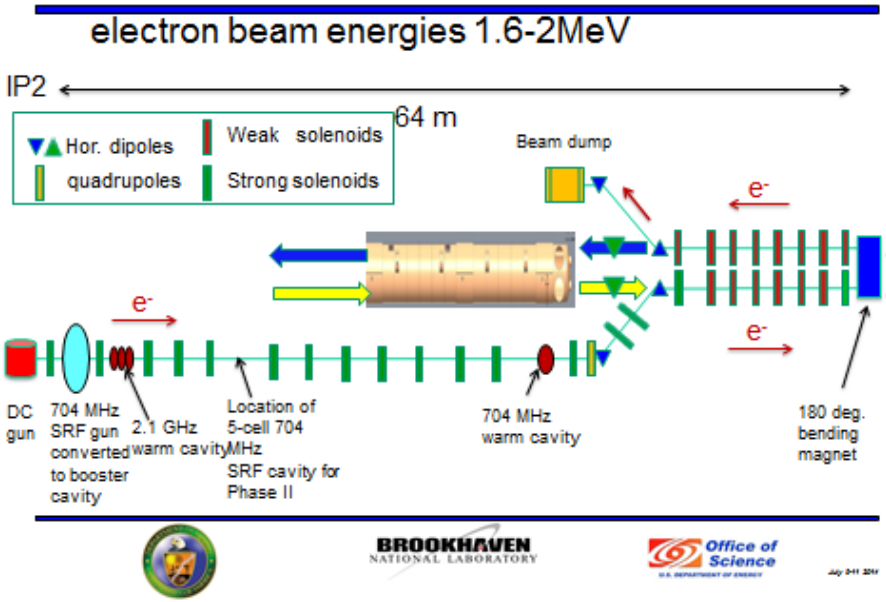


BNL ERL: designed parameters, progress

Parameter	Units	High current	High Charge	Measured
Energy max/inject	MeV	20/2.5	20/3.0	?/1.4 **Only gun measured**
Charge per bunch	nC	0.5	5	0.55
Average Current	mA	350	50	0.001
RMS Bunch length	psec	8-20	30	8.5; 22 **Laser pulse** **Very preliminary**
Normalized emittance	10^{-6} m	1.4	5	20% core: 0.25 Full rms: 12
RMS energy spread, dE/E	10^{-3}	3.5	10	?
Repetition rate	MHz	704	9.4	**Faraday Cup**
Beam dump power	kW	875	150	1e-3

ERL for LeRHIC

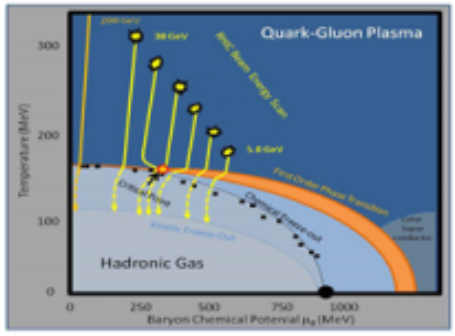
LEReC Phase-I: Gun-to-dump mode



Courtesy Jörg Kewisch, More details on Wednesday, WG5 after lunch session

Low Energy RHIC Physics program:
Search for QCD phase transition Critical Point

Center of mass energies: $\sqrt{s_{NN}}$ = 5, 6.3, 7.7, 8.8, 11.5, 14.6, 19.6, 27 GeV



- Energies in black have been measured in the 2010 & 2011 & 2014 RHIC runs
- Because of large emittance and IBS at low energies the integrated luminosity is small
- We need to cool the ions to improve luminosity

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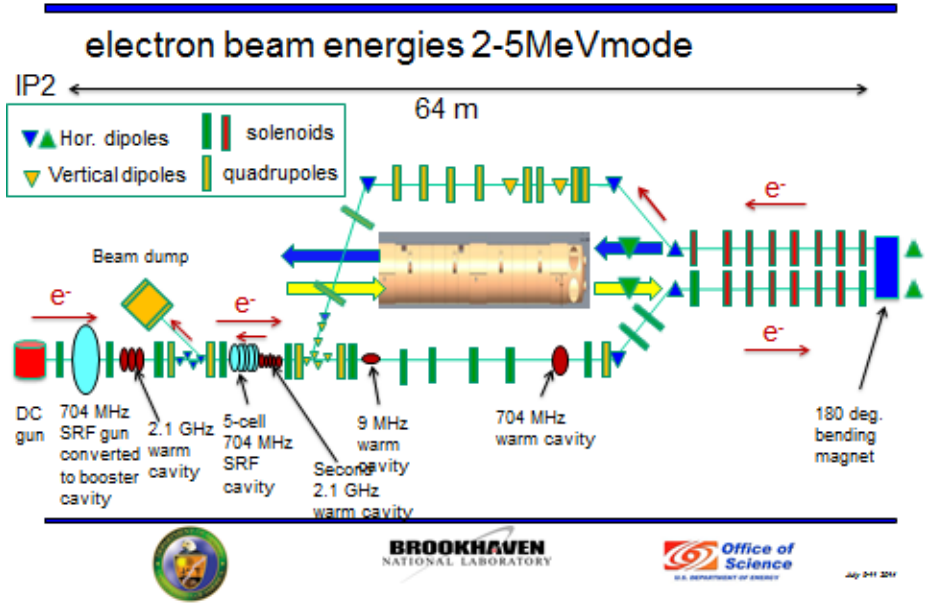
LEReC Phase-II : ERL mode



Summary

- An ampere class 20 MeV superconducting Energy Recovery Linac (ERL) is presently under commissioning at Brookhaven National Laboratory (BNL) for testing of concepts relevant for high-energy electron cooling and electron-ion colliders.
- Commissioning with beam started on July, 2014
- The first photo current from ERL SRF gun has been observed in Nov. 2014 (1 uA per 500msec RF pulse)
- 2 new "mulipactor free" Ta tip cathode stalks conditioned for CW March, 2015
- ERL returning loop components installation is completed in May, 2015
- QE with Ta cathode tip: room temperature 4% , in gun 1%. May, 2015.
- First test with new cathode June 1-2, 2015.
- Some beam parameters measured: energy, emittance, maximum bunch charge .55 nC achieved, max average current per 3msec RF pulse 4.5uA .
- Start commissioning beam instrumentation with beam.
- After ERL commissioning in BLDG912 the ERL will be relocated to RHIC IP2 to be used as low energy RHIC electron cooler.

This is just a beginning of a new adventure

To be continue…..

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, Harald Hahn, 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, Thomas Roser, 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 many others.

Thank you all