ERL High-Current Technology

Dmitry Kayran
for BNL ERL team

Collider-Accelerator Department,
Brookhaven National Laboratory

COOL'15 Workshop, Newport News, VA,
September 29, 2015

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

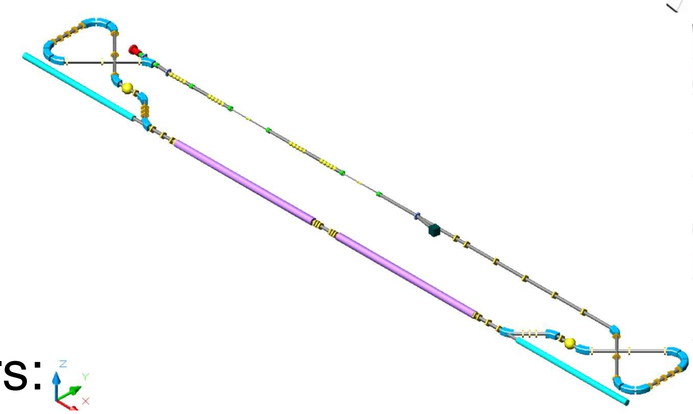
Office of Science
U.S. DEPARTMENT OF ENERGY

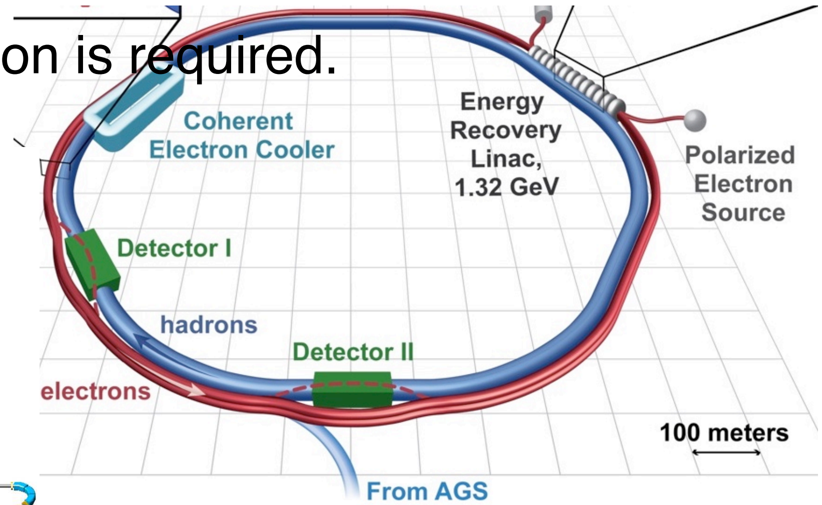
Overview

- Motivation
- Specific issues
- R&D ERL at BNL design
- Status and plans

Motivation.

- High luminosity Electron Ion Collider projects (eRHIC, MEIC or other) fully depends on very intense electron cooling at high energy.
- Electron coolers with very good cooling rate is needed.
- Electrostatic coolers are limited by 5-10 MeV.
- Bunched beam, RF linac based acceleration is required.





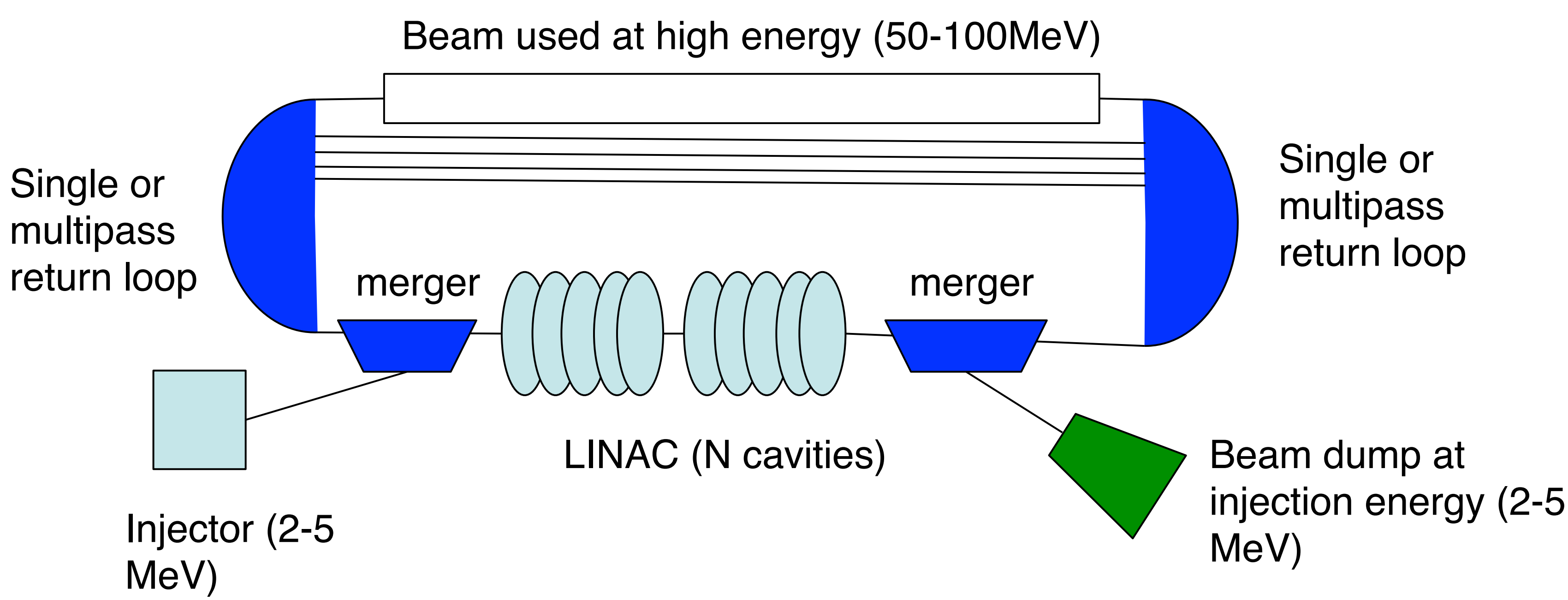
Typical parameters:

	MEIC	eRHIC/Mag	eRHIC/CEC.
Energy:	20-55 MeV	14-55,136MeV	136MeV
Average current:	200 mA	150-300, 400mA	50mA
Max. power	11MW	54MW	7MW

High energy, very high current and good quality beam accelerator required

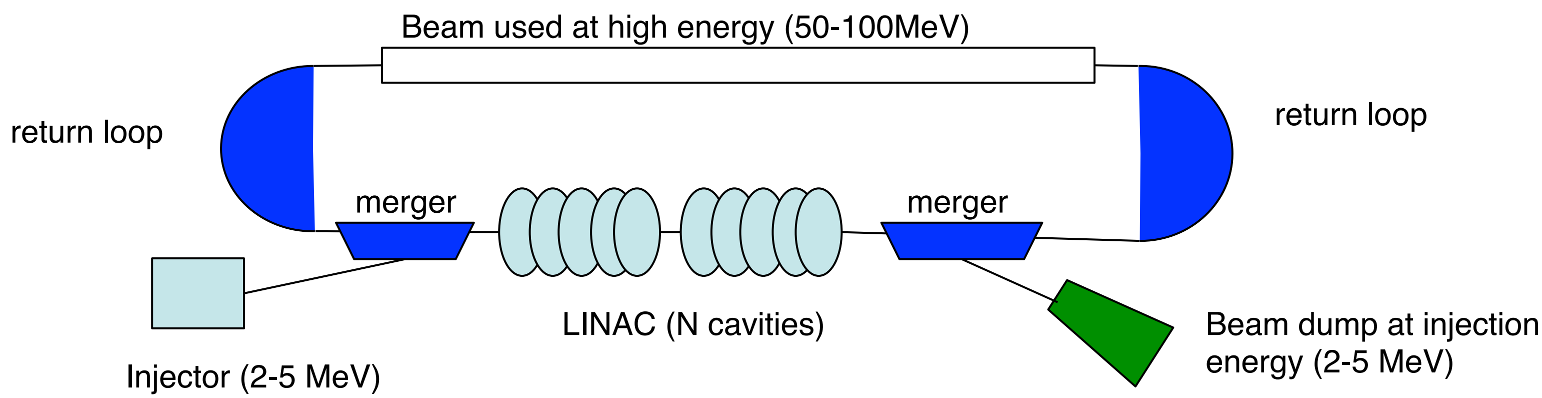
Why ERLs?

- Energy-Recovery-Linacs provides Linac Quality Beams with Storage Ring Beam Currents
- Reduce RF power consumption
- Reduced beam dump energy and power
- More recirc. passes => fewer cavities. Merge different energy could be the challenging.

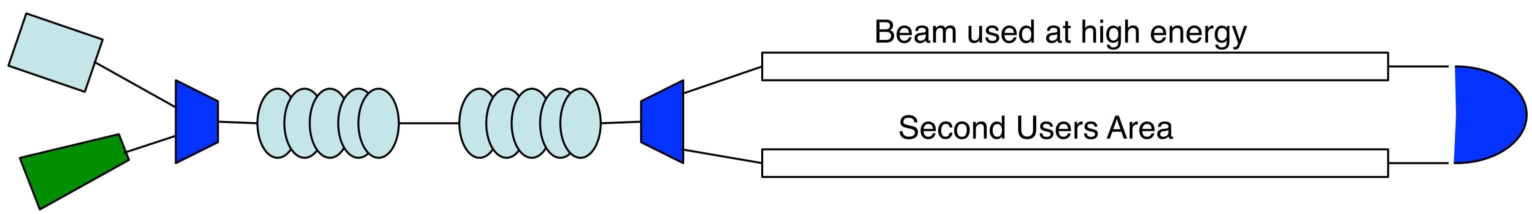


ERLs

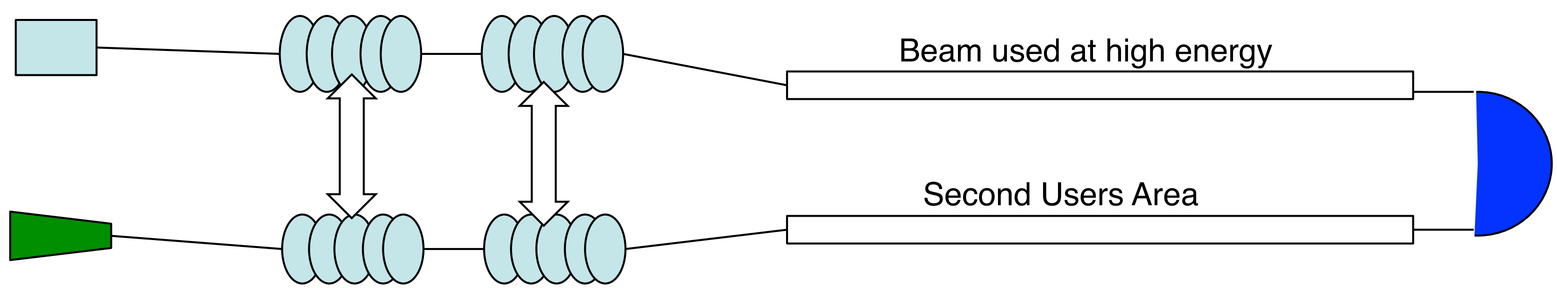
- High rep. rate. Match to RF frequency. Merger different energy.



- Same energy optics. Timing carefully to avoid bunch colliding



- No merger. Linac beam quality. Double cavity quantity for the same maximum energy

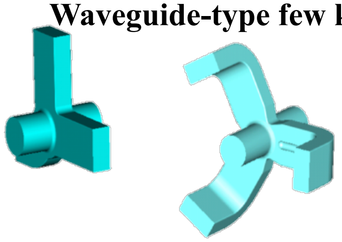


ERL design consideration

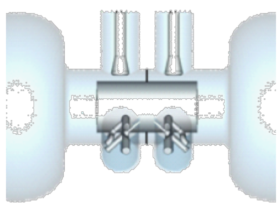
- Beam Break Up; Limit the average beam current in an ERL. For single cavity and single pass the threshold current.[1)]
- Low RF frequency and optics with low m12 should help
- HOM dumpers required
- Monopole mode HOM dumper power:

$$I_{\rm th} = -\frac{2pc}{q\frac{\omega}{c}\left(\frac{R_d}{Q}\right)Qm_{12}^{*}\sin(\omega T_r)}.$$

Waveguide-type few kW



Antenna absorbers up to 1kW



$$P \sim k * I^2$$

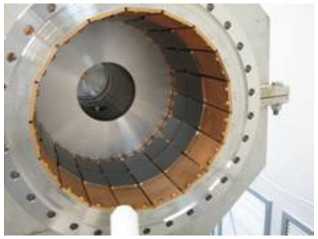
loss factor k~ Q

For new design 422 MHz cavities

k=1.4-1.9V/pC

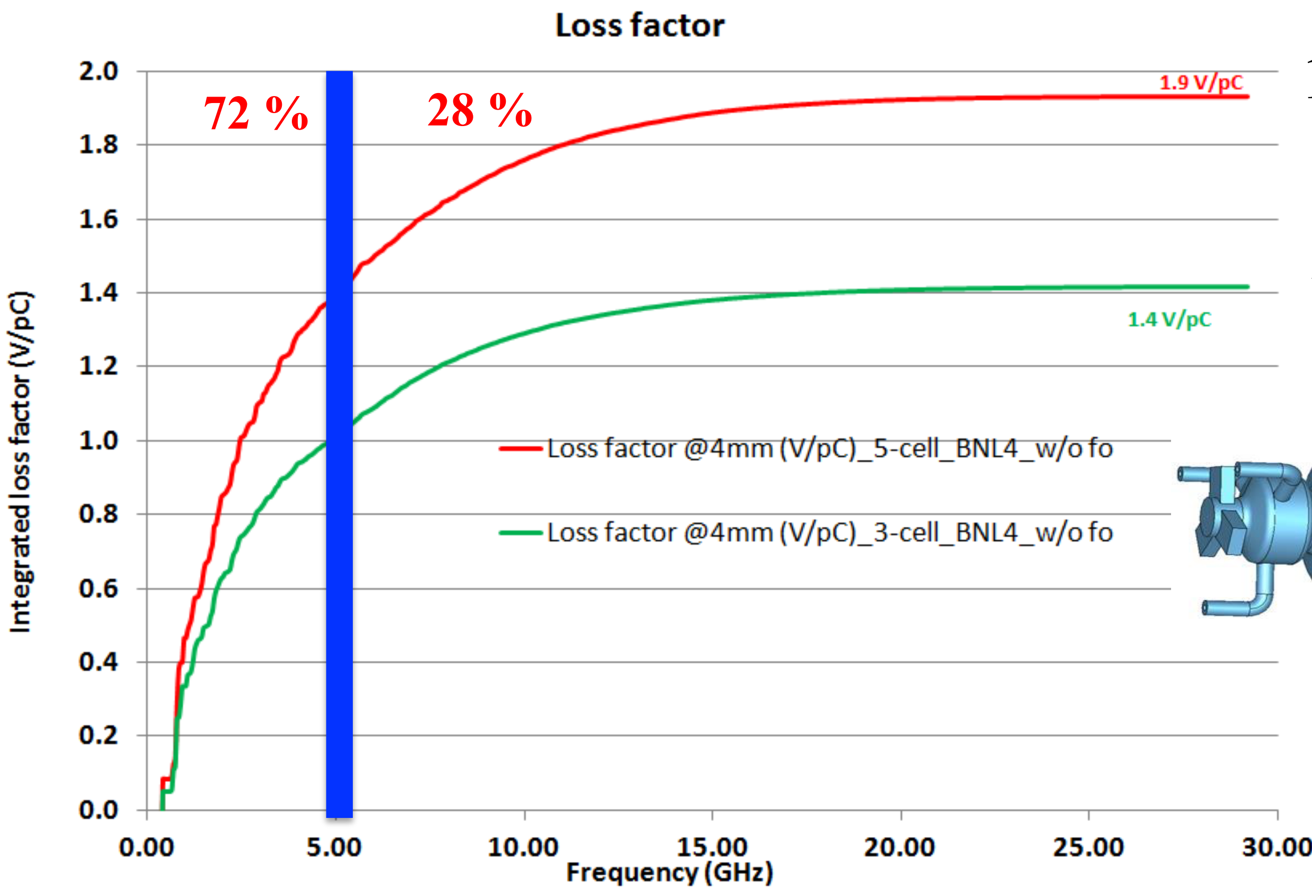
- **Emittance preservation at low energy injection**
- **Larger aperture pipes , strong optics, small dispersion for large longitudinal and transvers acceptance.**

warm pipe absorbers~10kW



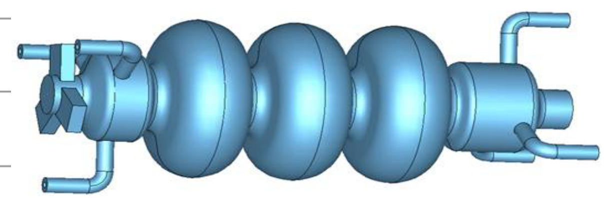
[1.]Pozedev E., PRST-AB 8, 074401(2005).

Loss factor in HOM. Example BNL 422MHz cavity



1.9 V/pC (5cell)

1.4 V/pC (3cells)



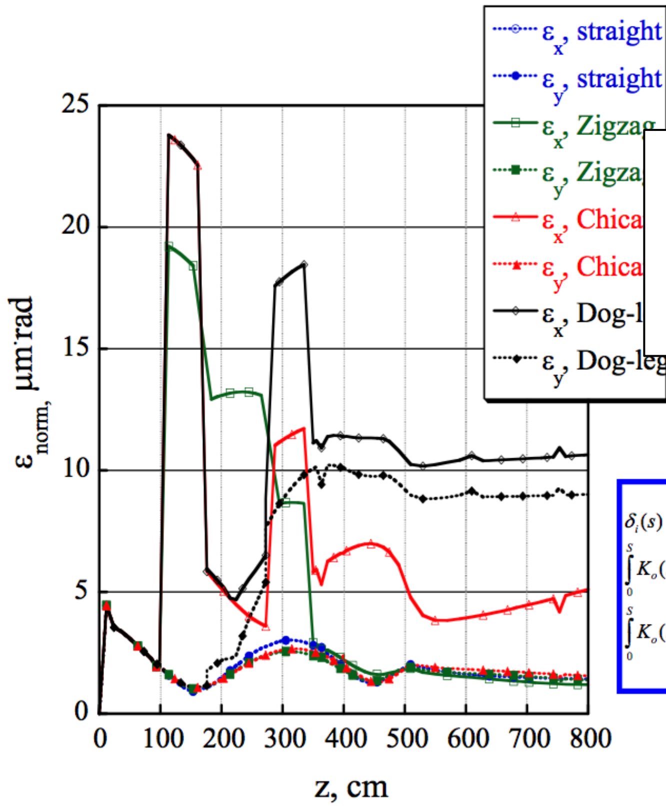
Fewer cells smaller loss factor per cavity.
Required more cavities and more space.

Electron beam bunch length: RMS 4 mm
Frequency range: 0.5 to 30 GHz

Courtesy Wencan Xu

Looking for good merger at low energy:

Result of three different injection systems comparison

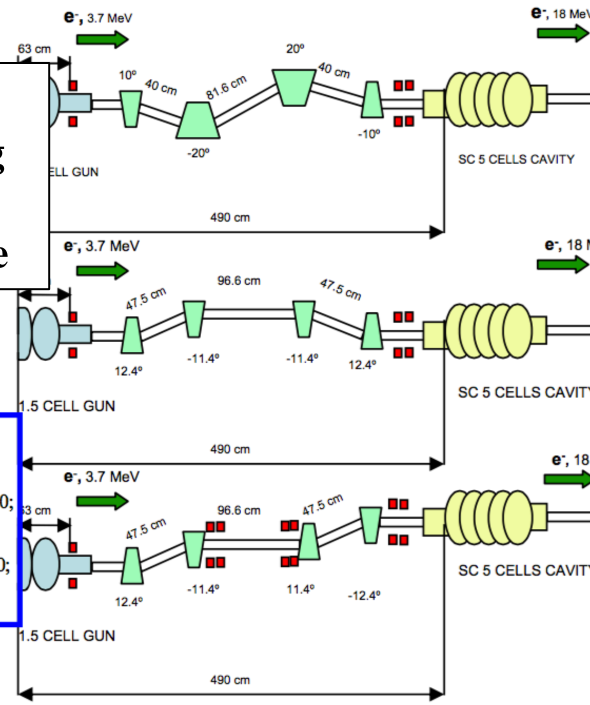


For the same inj. parameters, Zigzag merger better preserves emittance

$$\delta_i(s) = \delta_{i0} + s\cdot g(\zeta_i) \Rightarrow \text{4 "Achromat" conditions}$$

$$\int_0^s K_o(s')\cdot m_{11}(s')ds' = 0; \qquad \int_0^s K_o(s')\cdot s\cdot m_{11}(s')ds' = 0;$$

$$\int_0^s K_o(s')\cdot m_{12}(s')ds' = 0; \qquad \int_0^s K_o(s')\cdot s\cdot m_{12}(s')ds' = 0;$$



Evolution of horizontal and vertical normalized emittances in the four systems: the axially symmetric system (non shown), the Zigzag, the chicane and the Dog-leg.*

A Methode of Emittance Preservation in ERL merger System, D.Kayran, V.N. Litvinenko proceedings FEL2005

R&D ERL at BNL

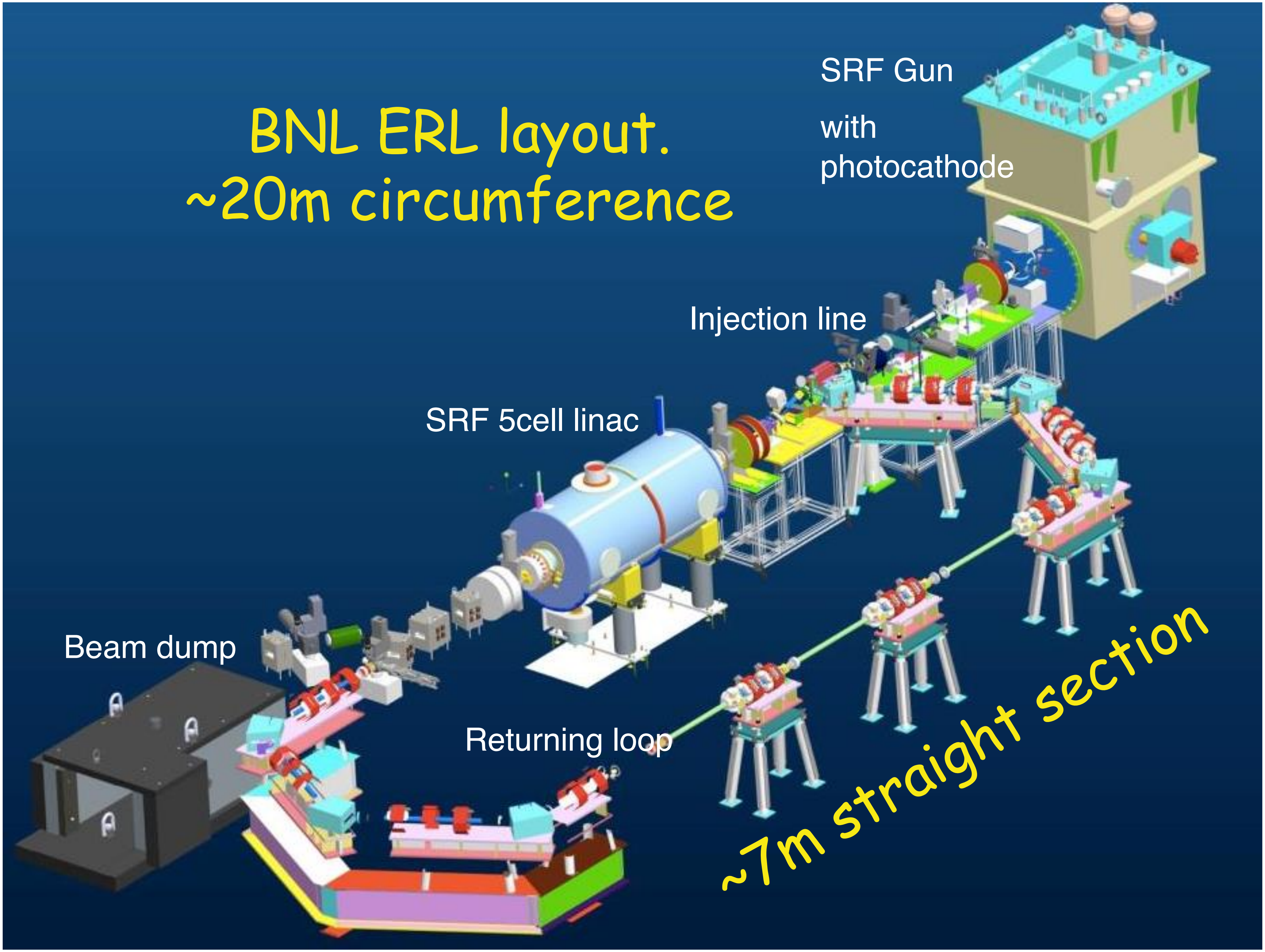
In order to address issues related to high current operation ERL R&D ERL has been built and now under commissioning at BNL

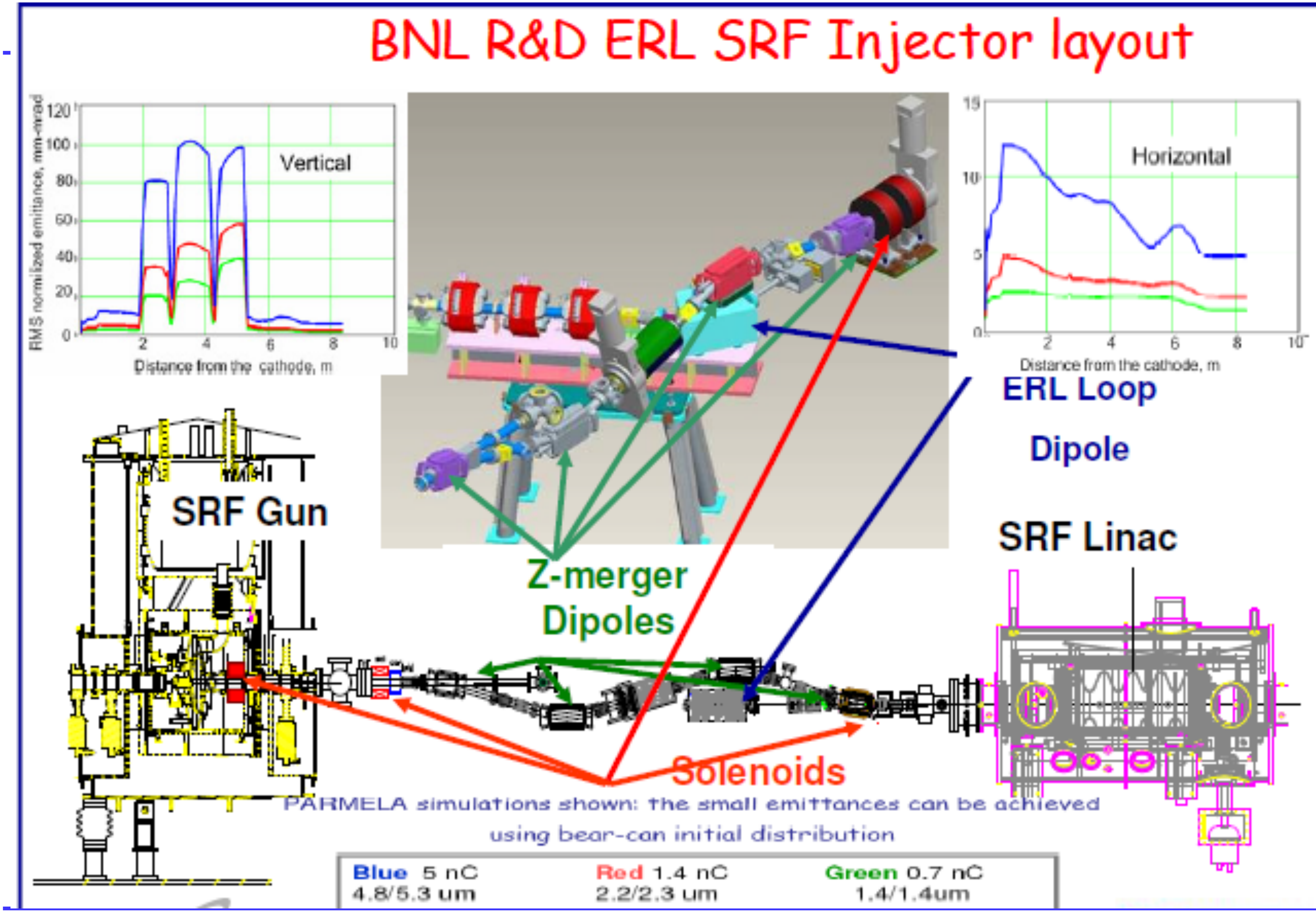
R&D ERL serves as a test-bed for future RHIC projects

Test concepts relevant for electron-ion colliders and high-energy electron cooling (coherent and conventional)

- High average current
- SRF injector
- BBU
- e-dump
- Stability criteria for CW beam current
- Halo/losses control

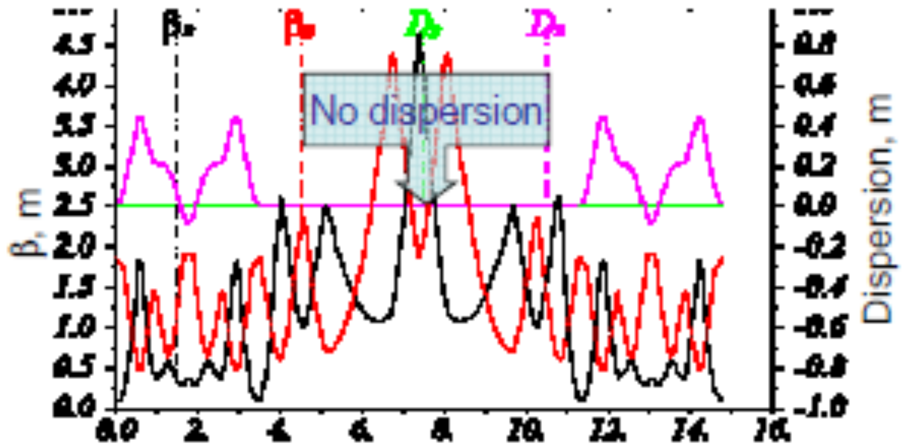
- Specifically for e-cooler
  - High charge per bunch
  - Conservation of beam parameter in merger at low energy (Z-bend test will give an answer)
  - Ion bunch much longer then electron one (could use 703.75 MHz train of e-bunches, will split laser beam to 2, 4 or 8)


BNL ERL layout.
~20m circumference
SRF Gun
with
photocathode
Injection line
SRF 5cell linac
Beam dump
Returning loop
~7m straight section

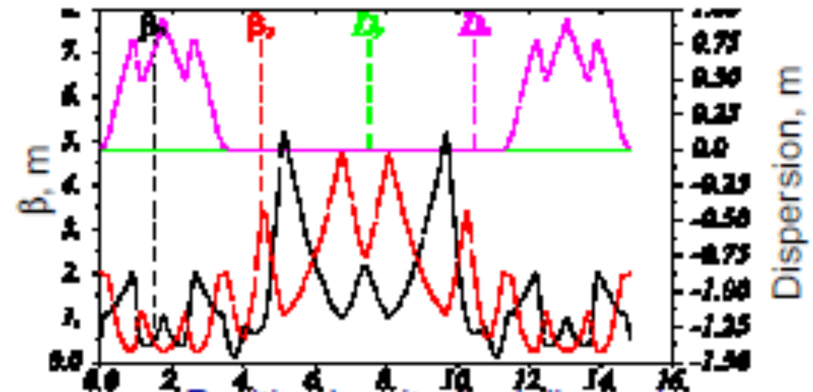

BNL R&D ERL SRF Injector layout
Vertical
RMS normalized emittance, mm-mrad
Distance from the cathode, m
Horizontal
Distance from the cathode, m
ERL Loop
Dipole
SRF Gun
SRF Linac
Z-merger
Dipoles
Solenoids
PARMELA simulations shown: the small emittances can be achieved
using bear-can initial distribution
Blue 5 nC
4.8/5.3 um
Red 1.4 nC
2.2/2.3 um
Green 0.7 nC
1.4/1.4um

ERL loop lattice is very flexible

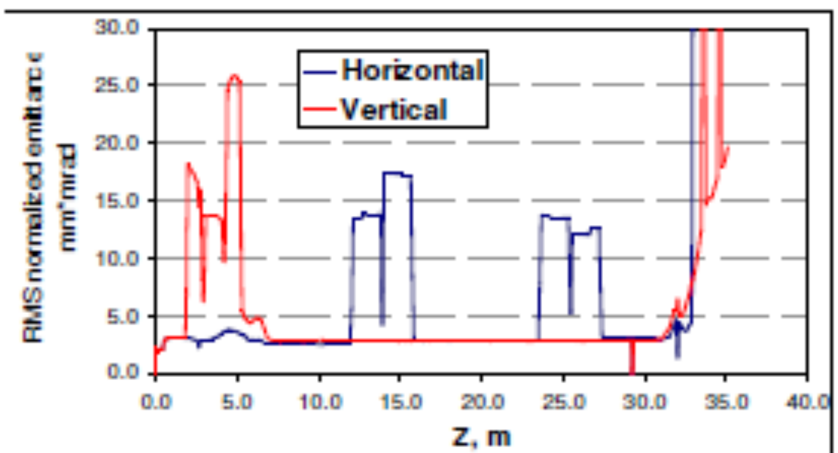
Lattice β and D functions of the ERL for the different cases longitudinal dispersions (Ds=M56):



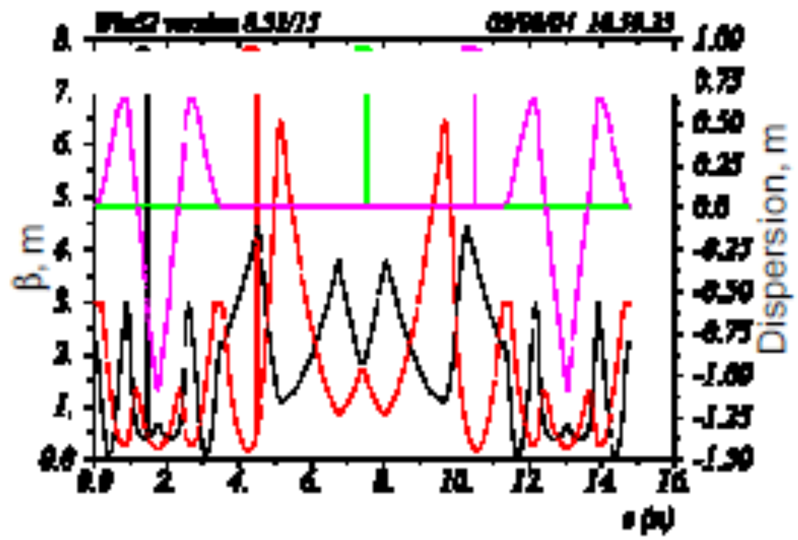
Zero longitudinal dispersion



Positive longitudinal dispersion

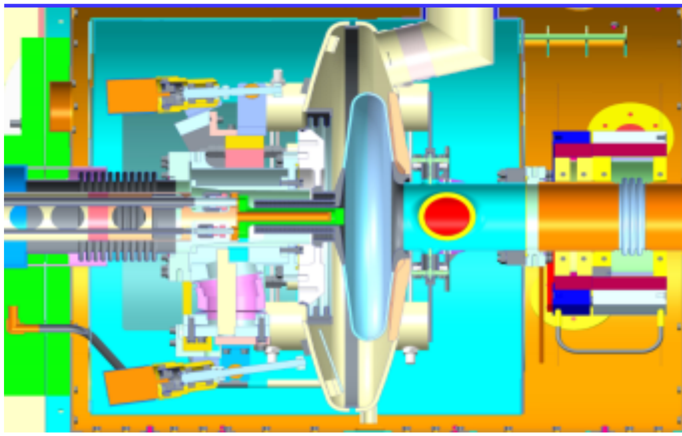


Transverse normalized emittances from cathode to dump Q=0.7 nC (PARMELA simulation)



Negative longitudinal dispersion

704 MHz SRF Gun: 2 MV CW operation

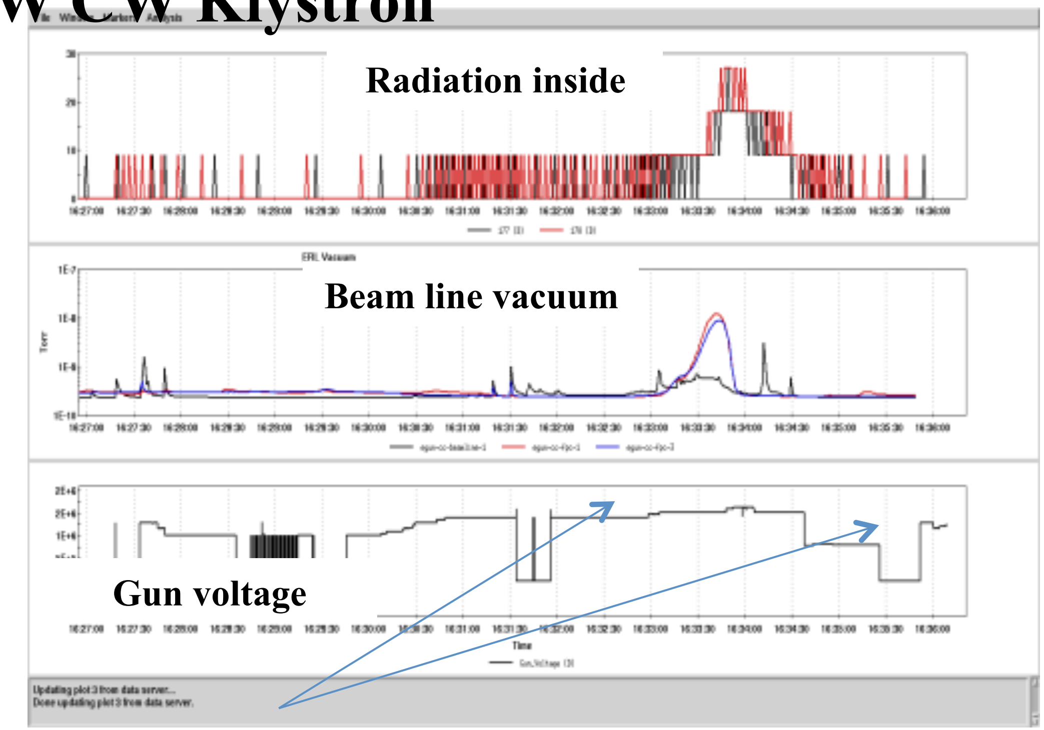


½ cell SRF gun

1MW CW Klystron

Dummy load

SRF gun before installation into the crymodule. March 2011



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

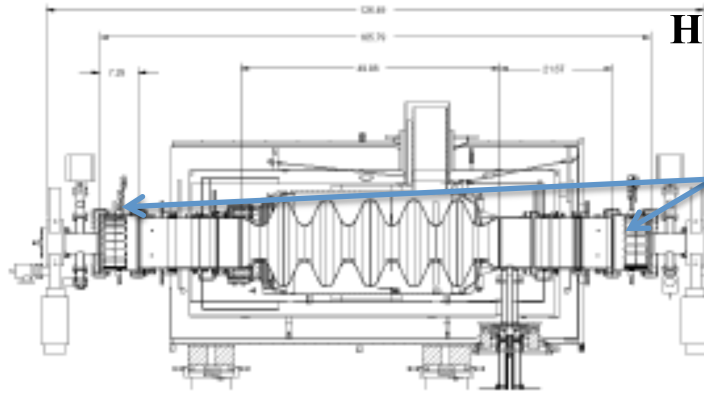
BNL 5 Cell SRF Linac

F = 703.75 MHz, δE = 20 MeV

$Q_0 \sim 10^{10}$, $Q_{HOM} \sim 10^3$

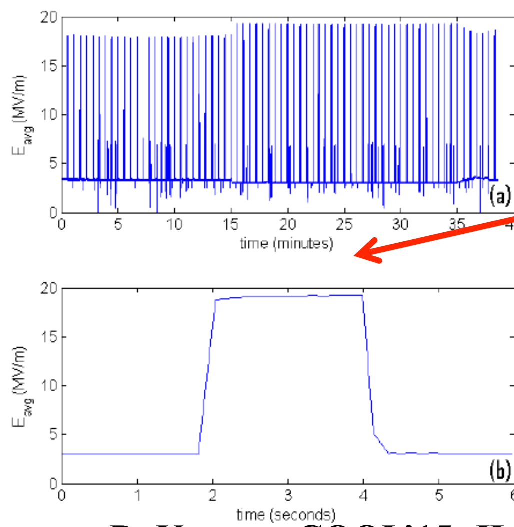
5 Cell SRF Cavity inside the cryomodule in ERL cave

In cry module horizontal test results 2010.



HOM absorbers

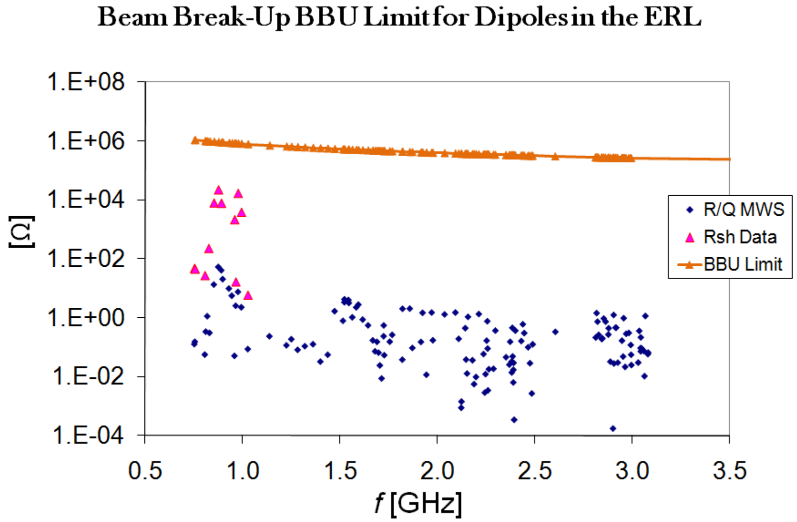
- The 5-cell cavity was specifically designed for high current, high bunch charge applications such as eRHIC and high energy electron cooling.
- The loss factor of the cavity was minimized.
- The number of cells was limited to 5 to avoid HOM trapping.
- Additionally, HOM power is effectively evacuated from the cavity via an enlarged beam pipe piece 24 cm diameter.
- The simulated BBU threshold is of the order of 20 A



We find that by adopting a duty cycle of ~1:15 (on:off), we can safely turn the cavity up to an accelerating gradient of 18 MV/m We demonstrated continuous running for 30 minutes with a pulse length of 2 seconds, and an off time of 30 seconds. During the "off" phase, the gradient is held at 3 MV/m. The longest pulse achieved before quenching was 5 seconds..

D. Kayran, COOL'15, JLAB

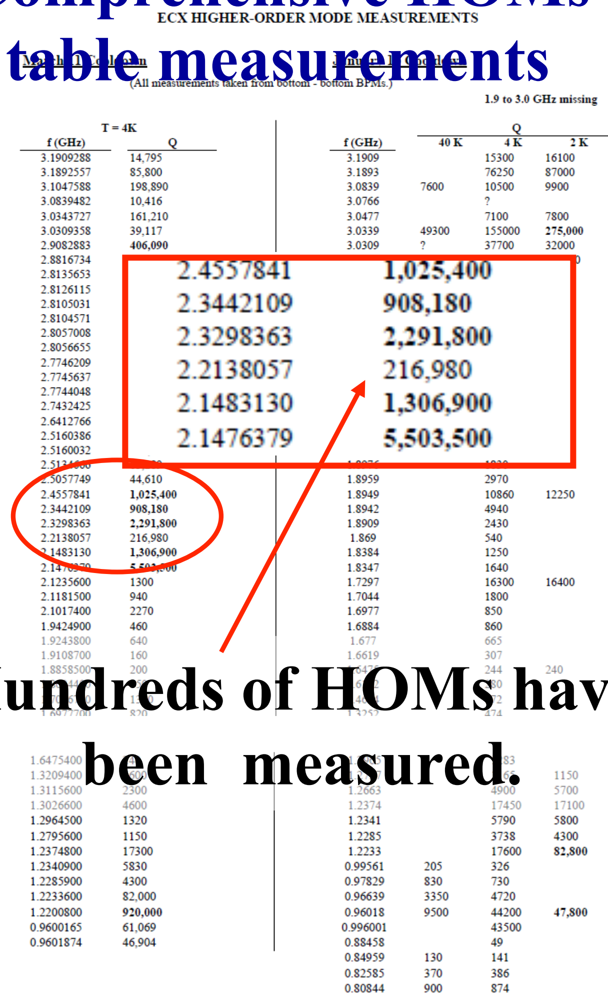
5cell cavities HOM’s studies



Data				Simulations					
f_{2-12} [MHz]	f_{6-6} [MHz]	Q_{NC}	Q_{SC}	f [MHz]	R/Q_{1cm} $\times 10^3$ [Ω]	R/Q [Ω]	Q_{ext} [Ω]	Q_{FRT} [Ω]	$R_{\perp}$ [Ω]
770				752	3.2	0.13	174	382	49
780				755	3.6	0.14	18	322	46
808	808.4	900	874	806	1.4	0.05	611	586	28
826	825.9	370	386	825	20.8	0.70	174	335	233
850	849.6	130	141	852	432.1	13.6	89	605	8,225
878				875	1777.8	52.9	18	433	22,921
894				890	1593.3	45.6	15	176	8,020
959	960.2	9,500	47,800	958	2.0	0.1	2,820	44,391	2,216
966	966.4	3,350	4,720	964	103.9	2.6	927	6,683	17
978	978.3	630	730	976	317.6	7.6	379	2,288	17,392
998	995.6	205	326	993	98.9	2.3	9	1,735	3,969
				1026	4.0	0.1	9	67	6

First two bands dipole modes

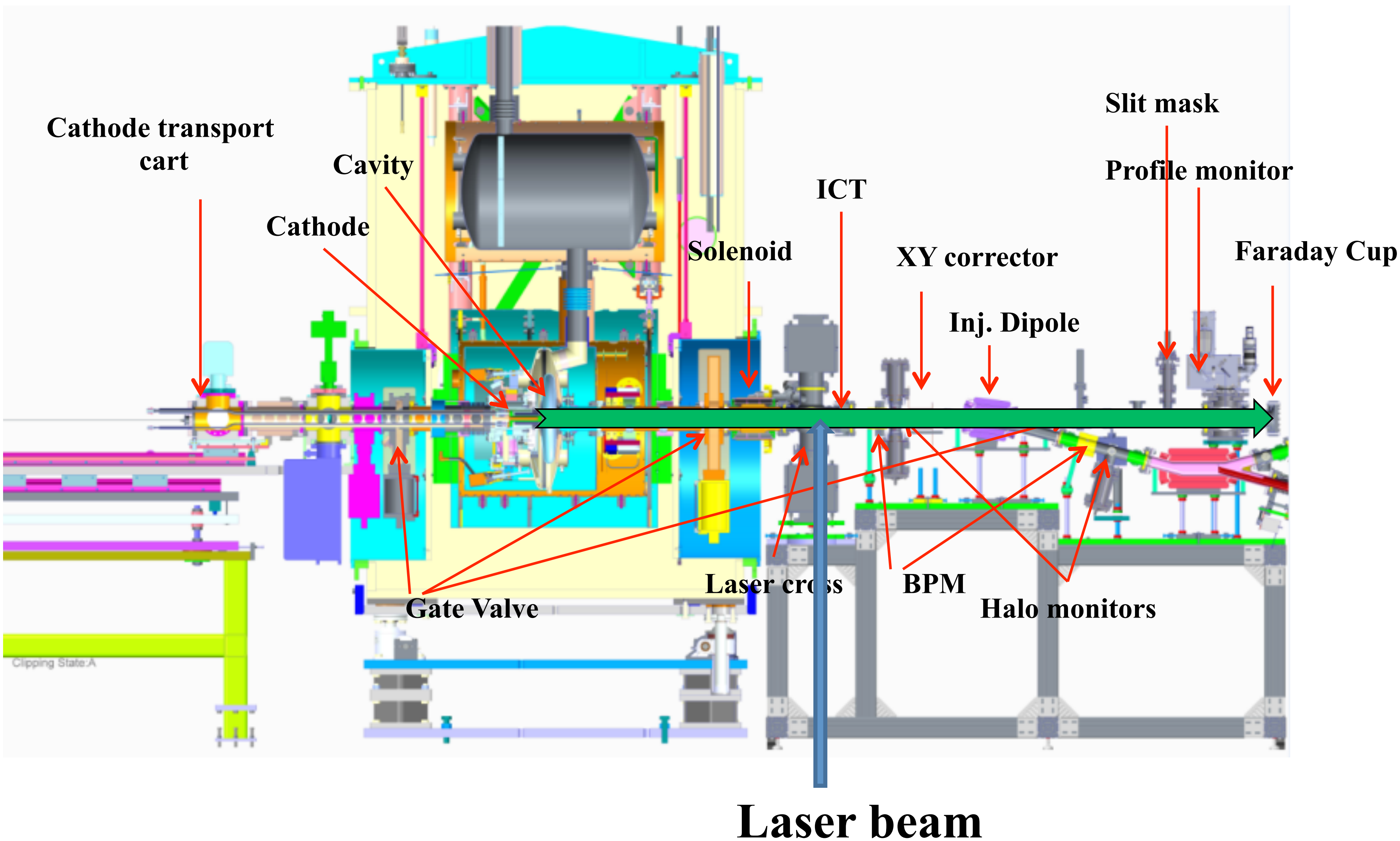
Comprehensive HOMs table measurements



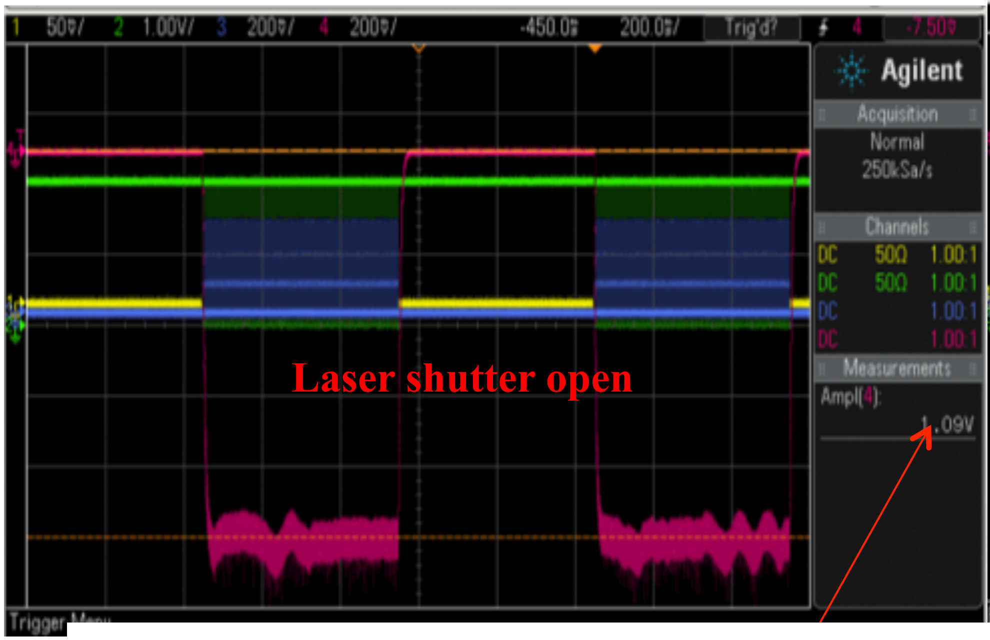
Hundreds of HOMs have been measured.

D. Kayran, COOL’15, JLAB

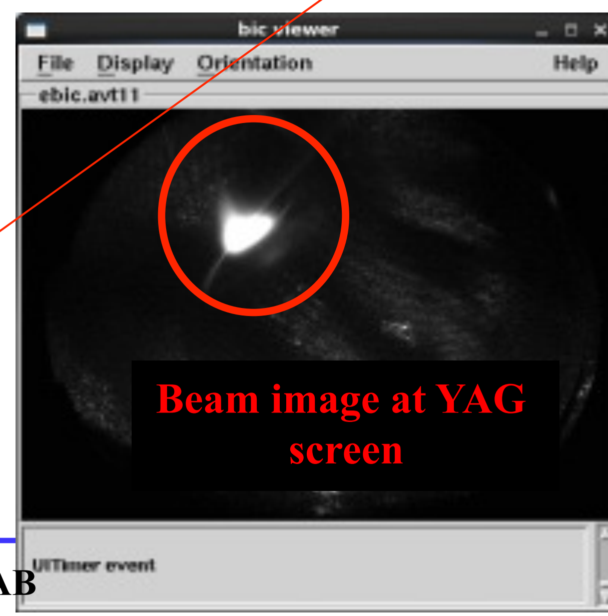
Gun to FC beam test start June 2014



First beam, old cathode Nov 2014.



Faraday cup signal (1MΩ termination)



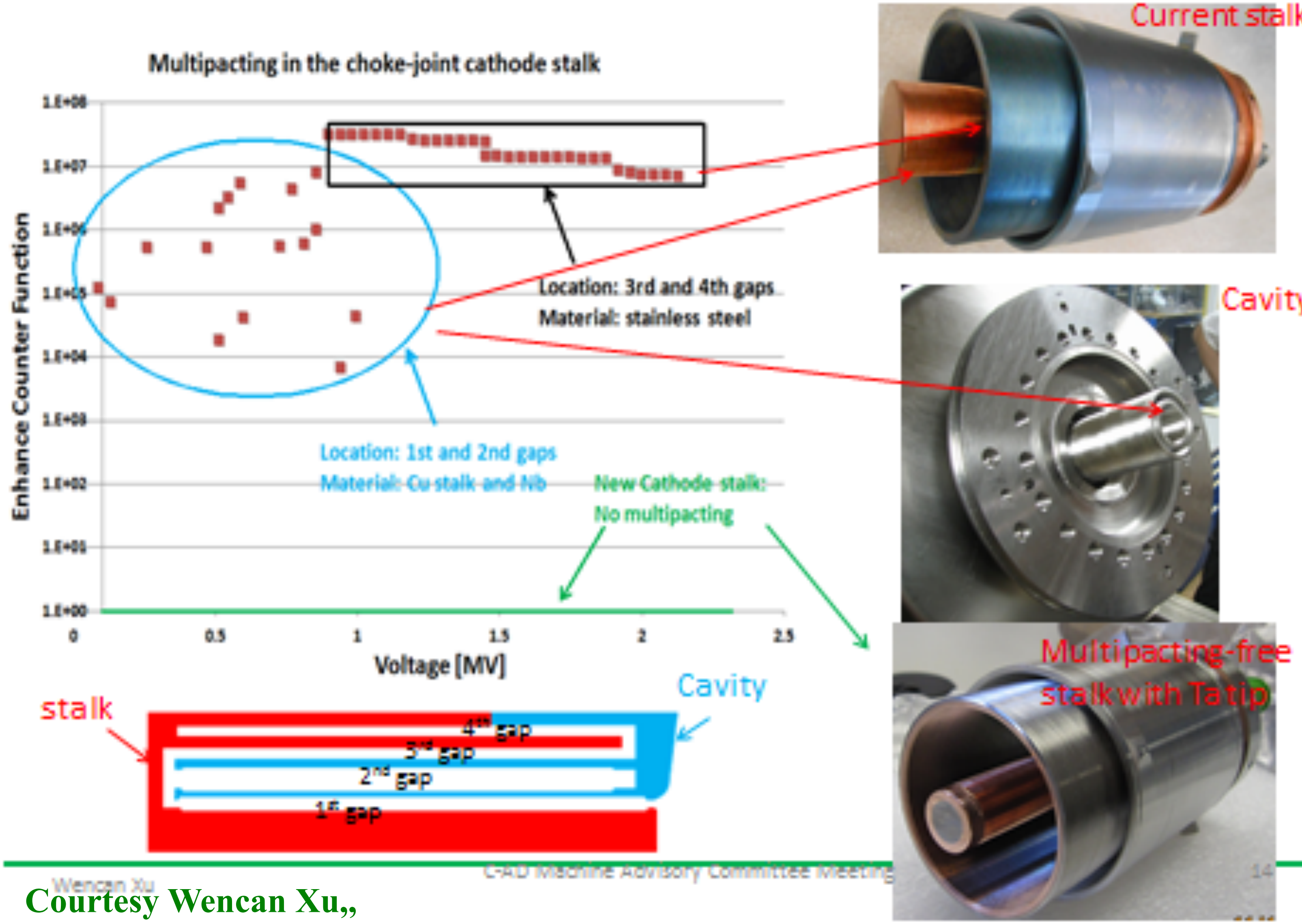
Set up

- Laser: 6.1 Watt, green,

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

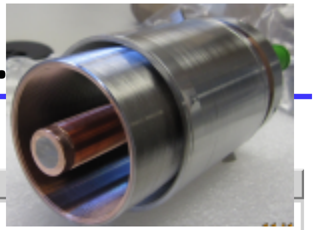
- RF: 1.2 MV, 500 ms;
- Beam:
  - bunch charge: 7.7 pC,
  - Average per RF pulse
    - photocurrent 1 μA, dark current 38 nA;
- Photocathode cold QE=2.7e-5 Very low!!!

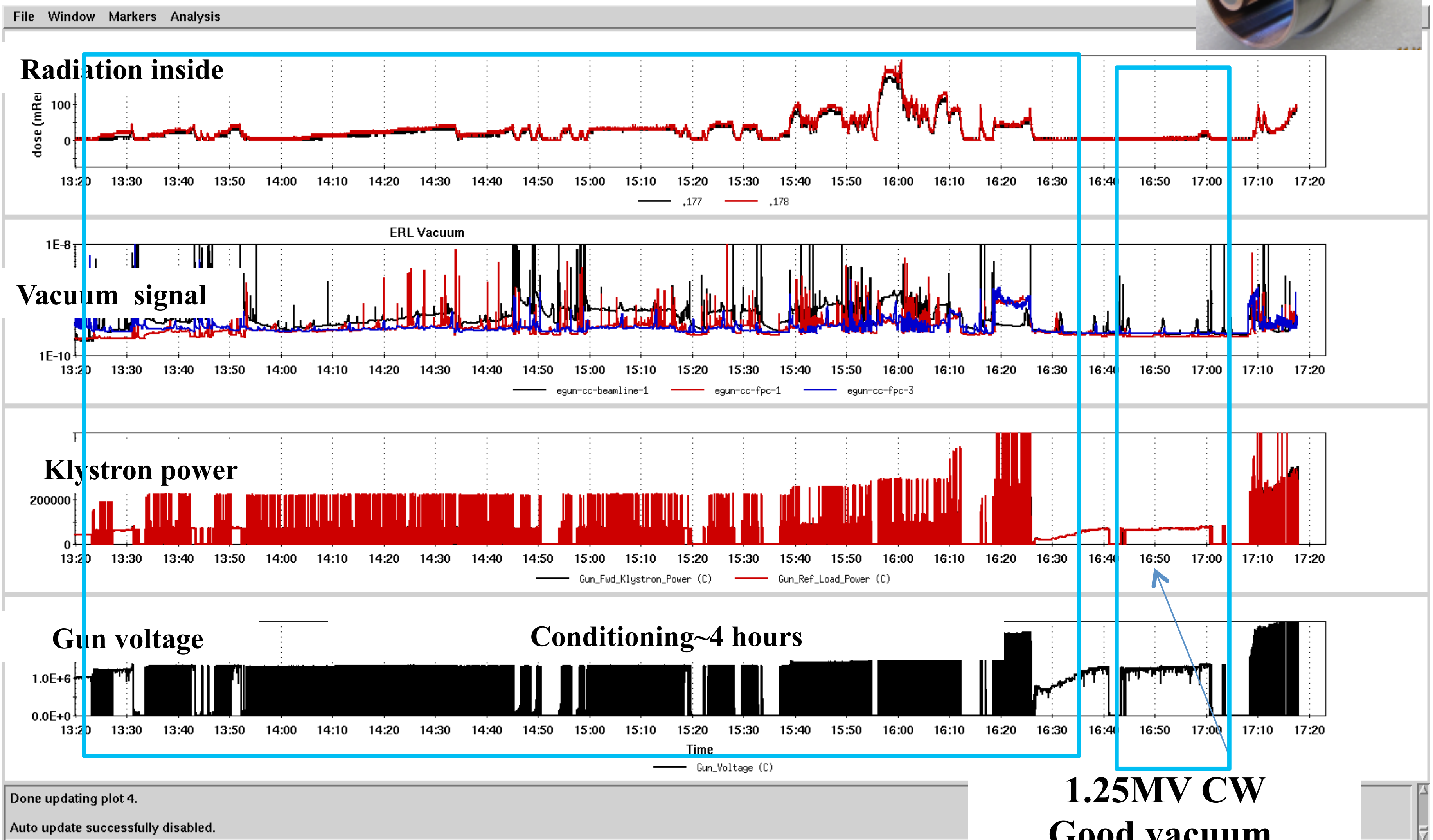
New cathode stalk with Ta tip



Courtesy Wencan Xu,,

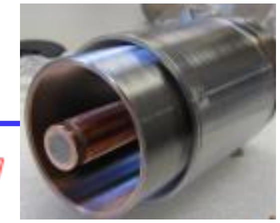
Conditioning Gun with new cathode stalk.



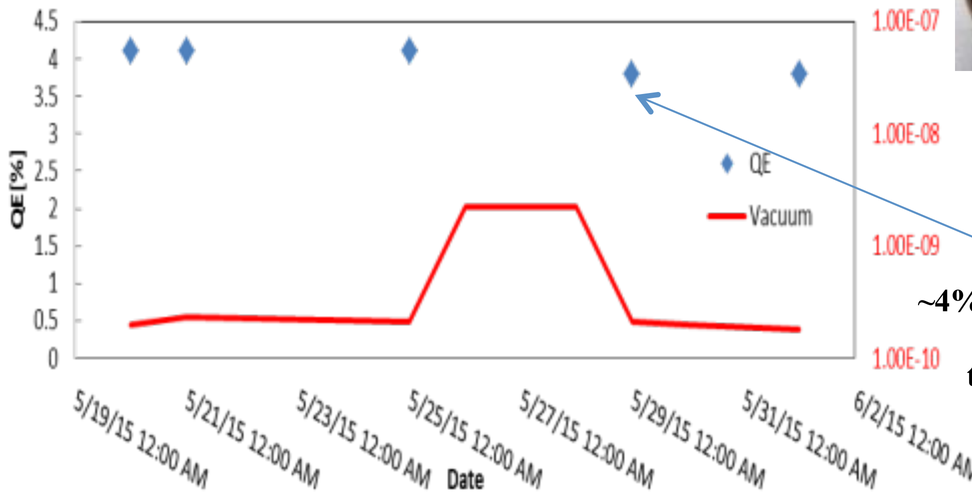


1.25MV CW
Good vacuum,
No radiation

QE with new Ta cathode

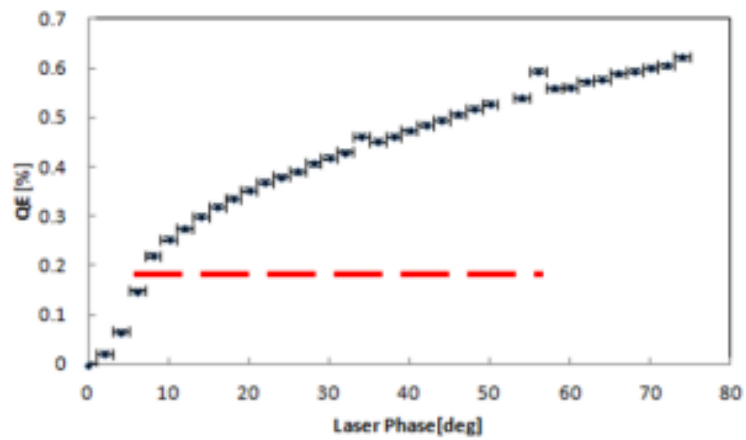


ERL Cathode deposition system at BLD912



~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%.

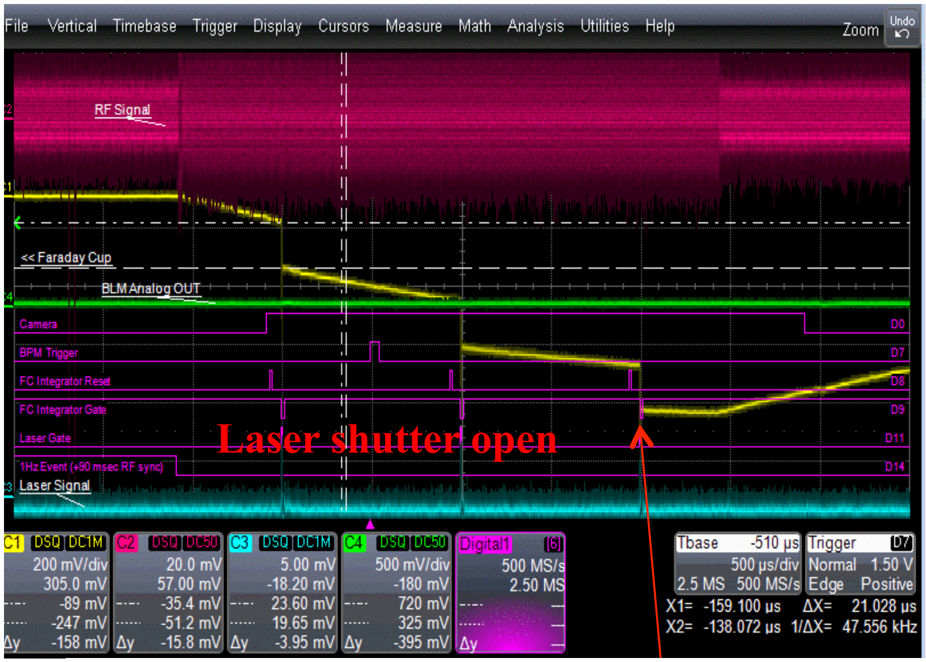


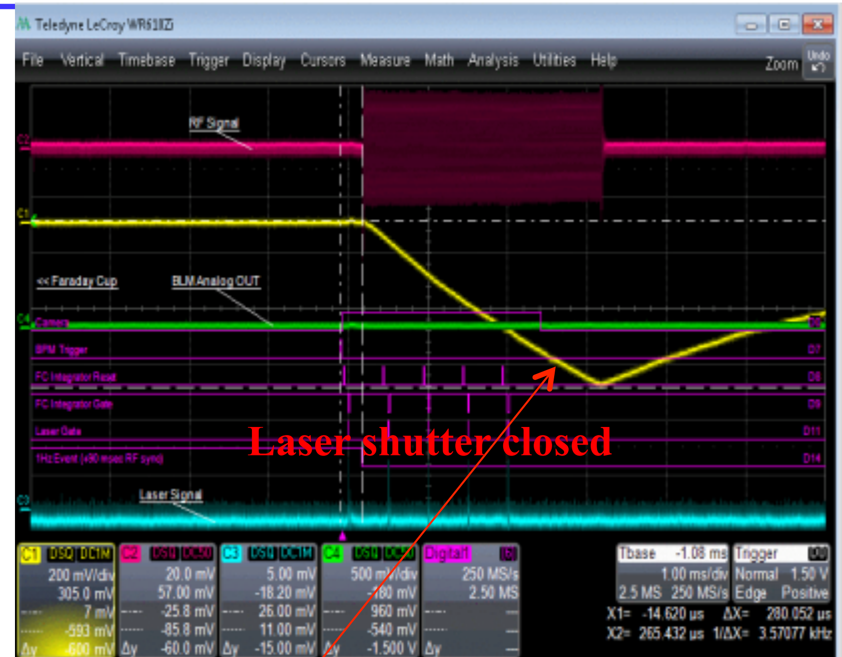
Peak current 1.65A, Gradient 10 MV/m

Courtesy Erdong Wang

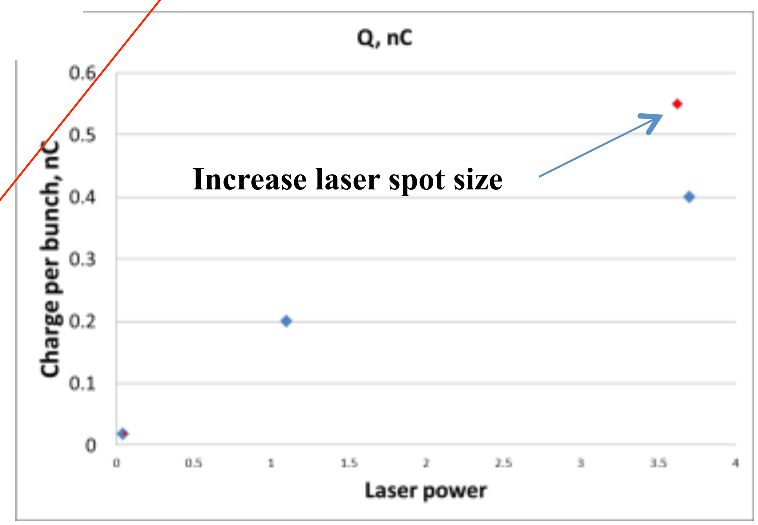
At high voltage QE enhanced Schottky effect

Beam commissioning with new cathode June 2015.





Faraday cup signal (1MΩ termination)



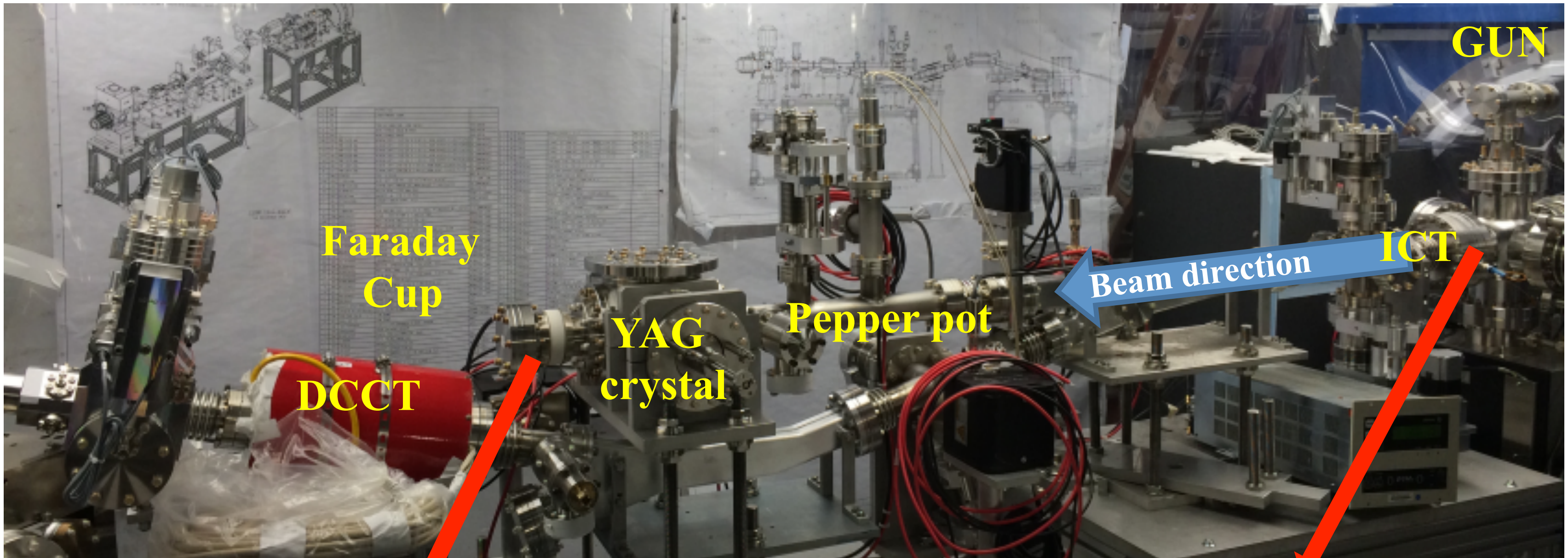
Set up

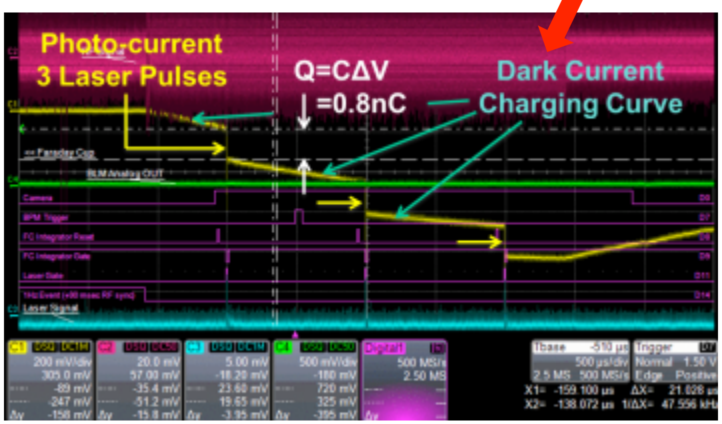
- Laser: 0.044 mWatt, green,

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

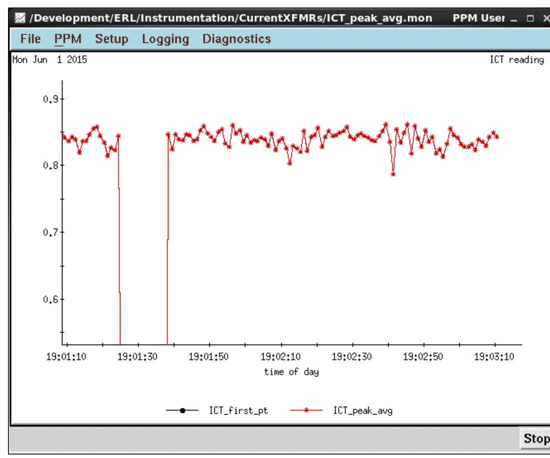
- RF: 0.65 MV, 3 ms;
- eBeam:
  - charge per macro bunch 0.8nC/47bunches=17pC
  - dark current 4 µ A;
- Photocathode cold QE=1e-2 very Good!!!

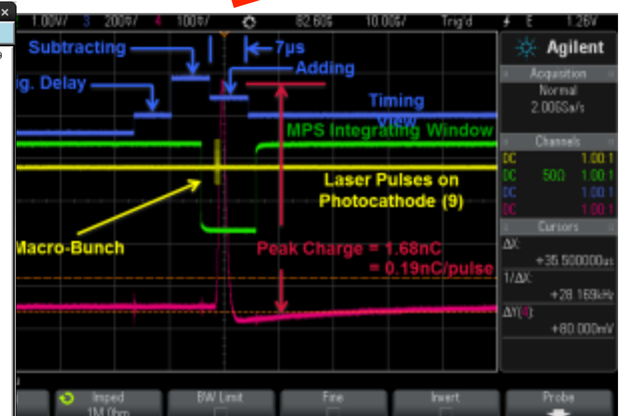
Beam charge measurements





Faraday cup

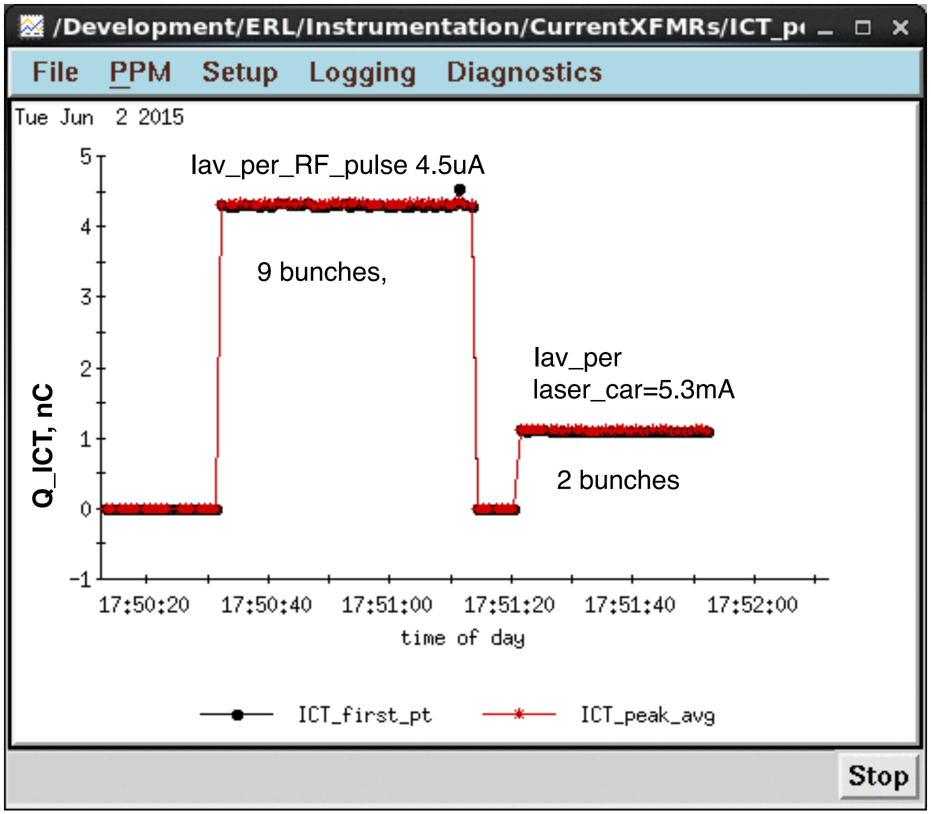




Integrating Current Transformer

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

Charge per bunch 0.55nC



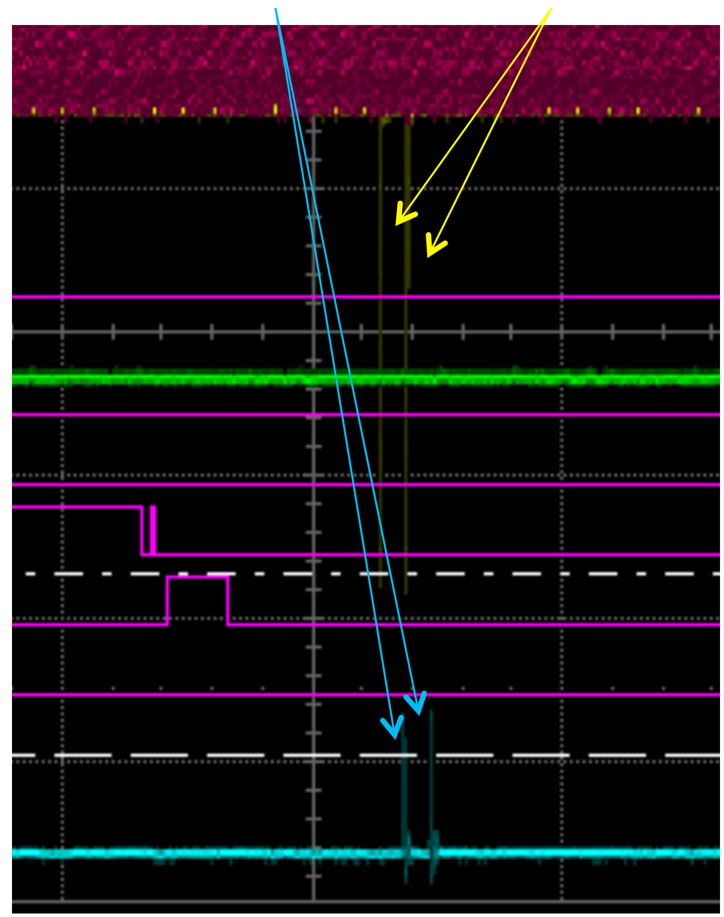
ICT signal for 9 pulses (4.4 nC> 4nC ICT saturation)

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

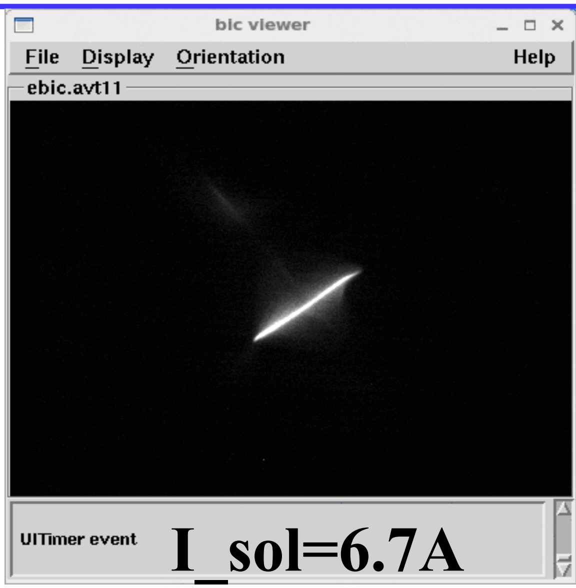
Charge is enough to generate 386mA at 704MHz

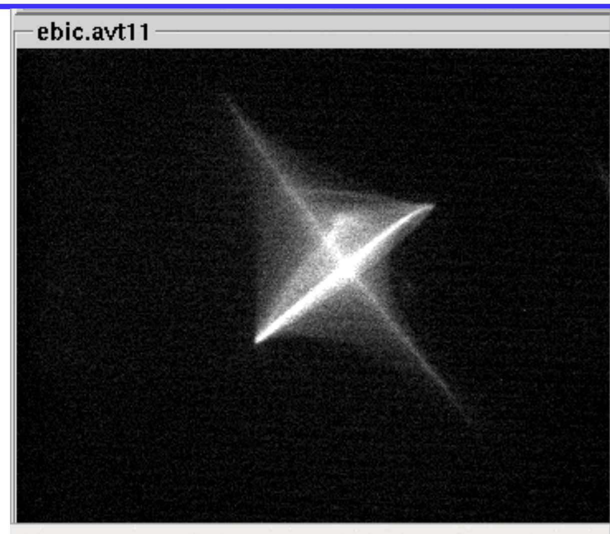
2 laser pulses, 0.39uJ each

2 e-bunches at FC observed

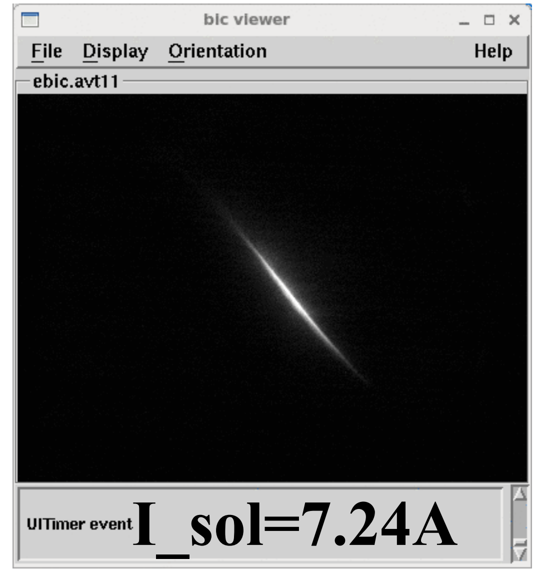


Solenoid scan to measure gun astigmatism (preliminary)



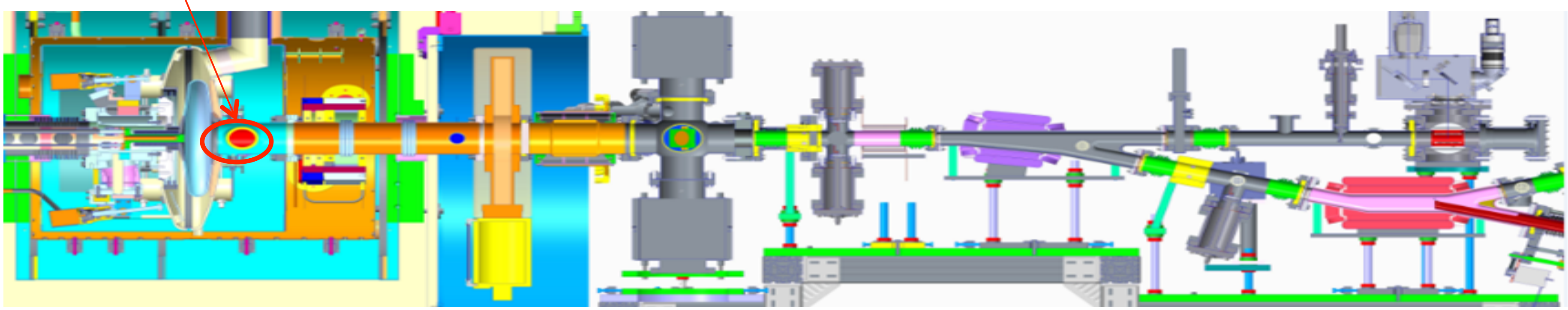


Ninja star shape



2 FPCs

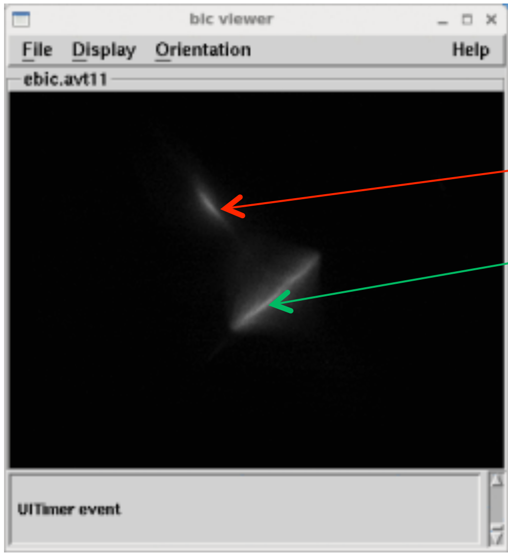
Axial symmetric system or not?



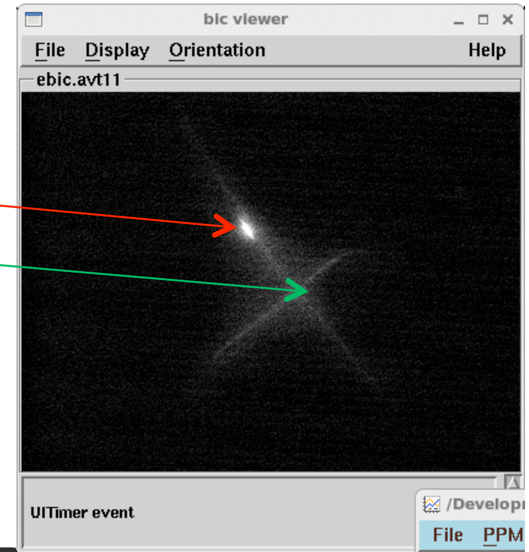
Preliminary result focus length 64cm!!!. Required more investigation.

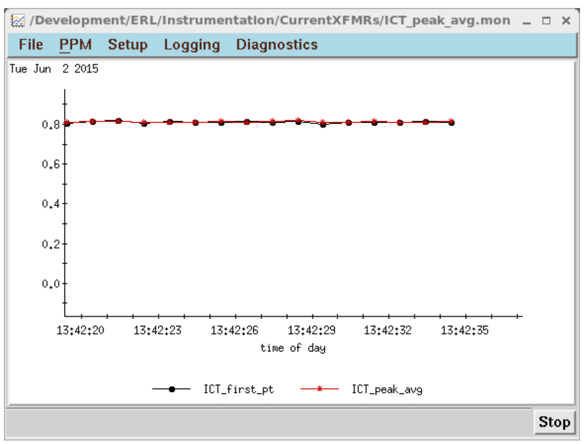
Courtesy V. Litvinenko

Dark current and photocurrent

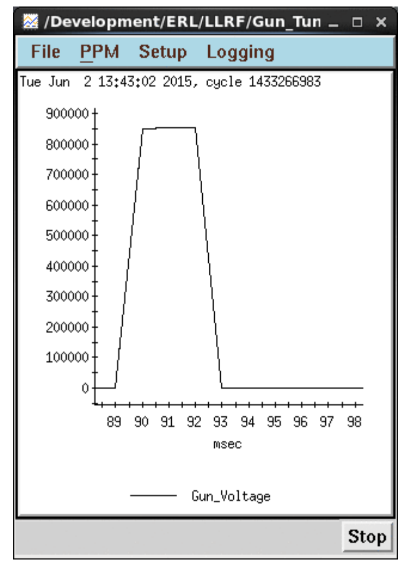


Dark current and photocurrent respond similar to solenoid and corrector change.



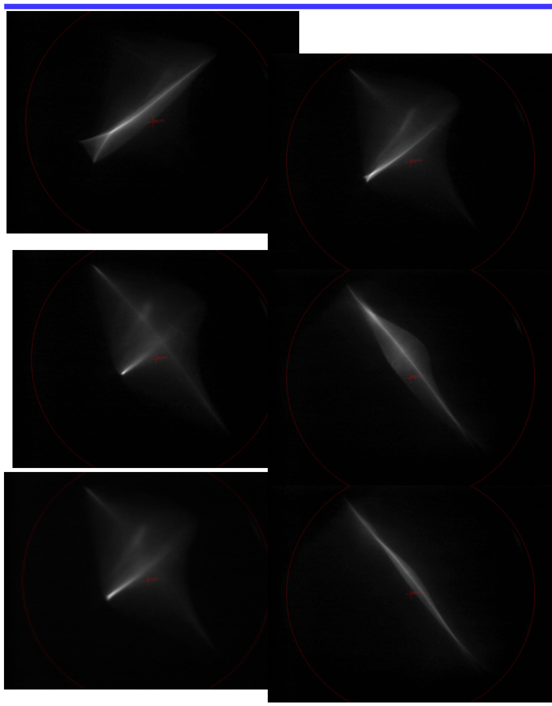


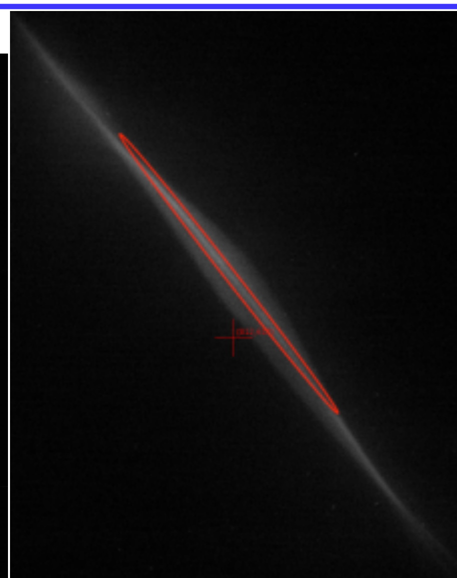
Photocurrent 0.8 nC /2 laser pulses

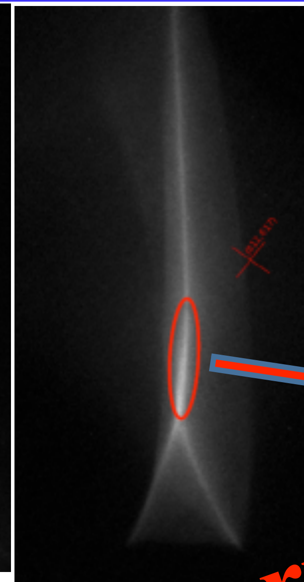


Dark current @ .85MV 4uA per 3 msec

Try Solenoid scan, Q=133pC (preliminary)

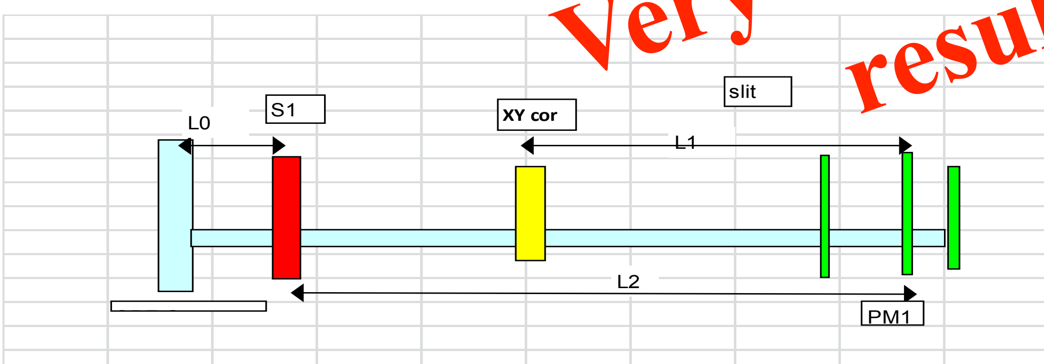


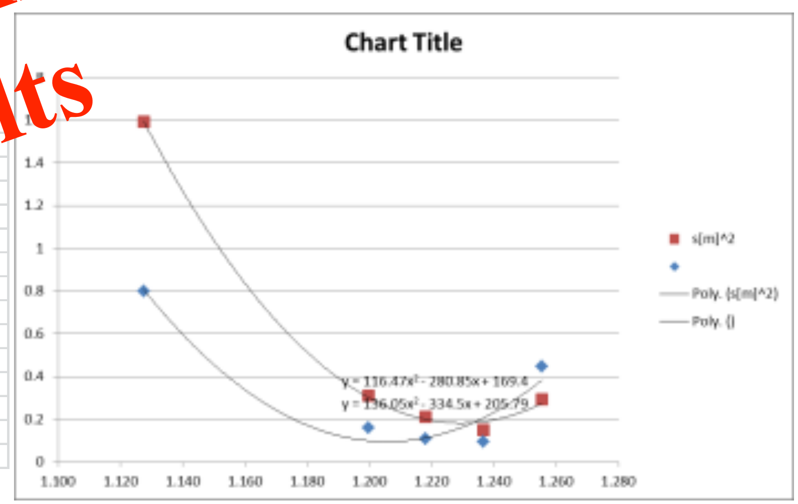




	Normalized emittance
full beam	5 mm mrad
20% core	0.25 mm mrad

Very Preliminary results



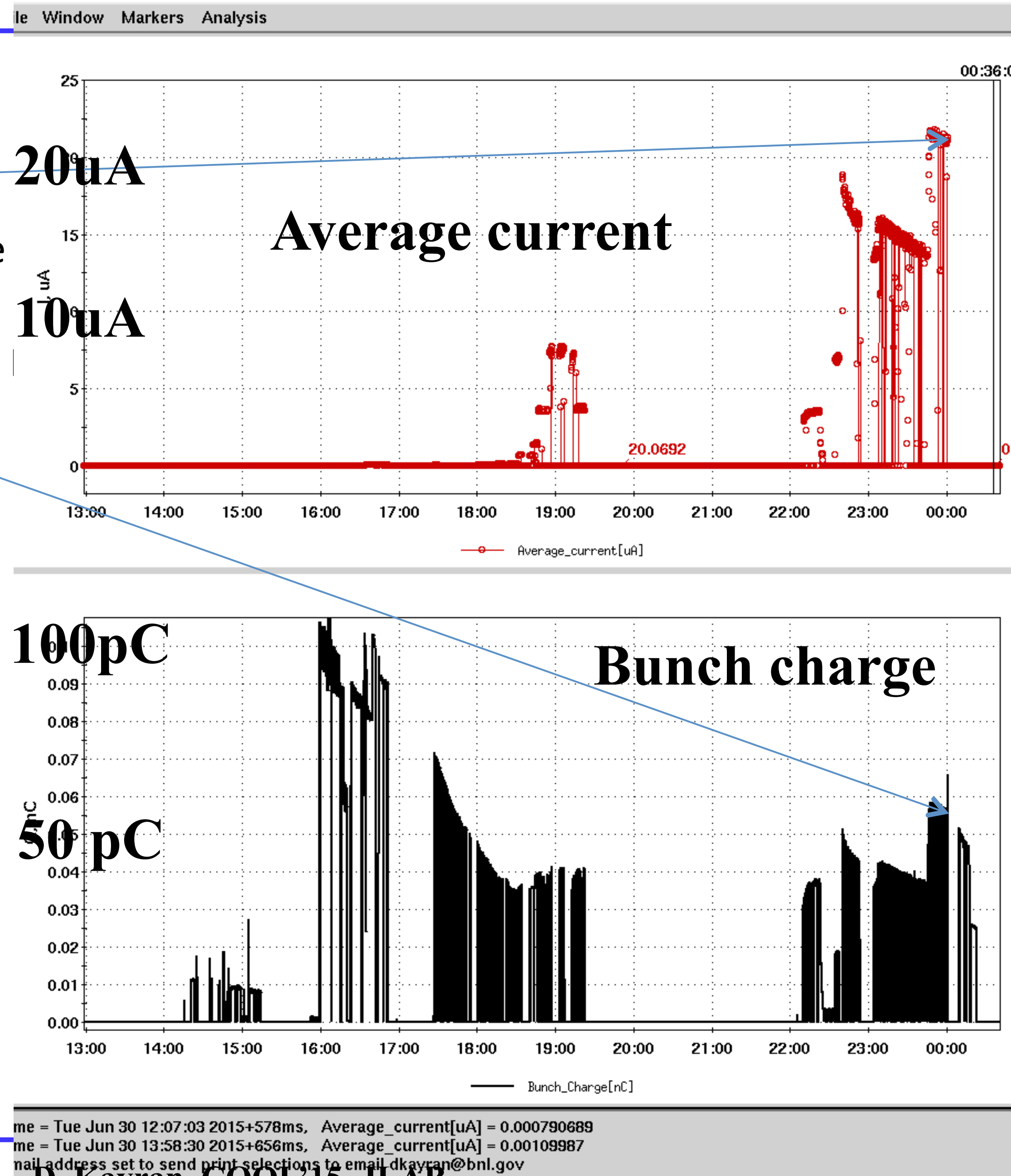


June 29

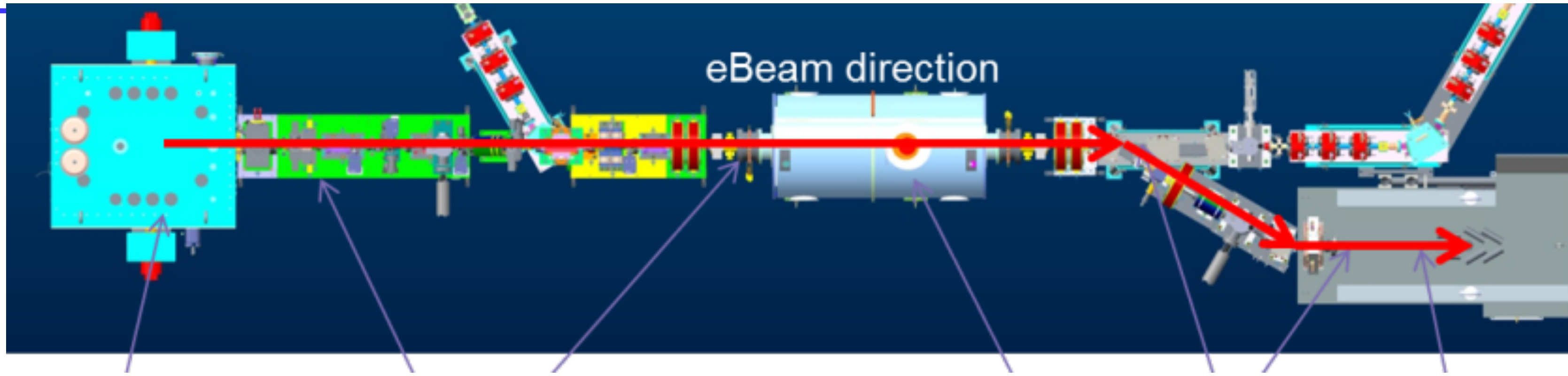
- Maximum average current from the gun 20 uA.
- Confirmed charge per laser pulse 49 pC.
- We were limited by 5msec 10 Hz operation . Average current in 5 msec RF pulse I=400uA

Beam for conducting fault studies.

Radiation Safety Requerement.



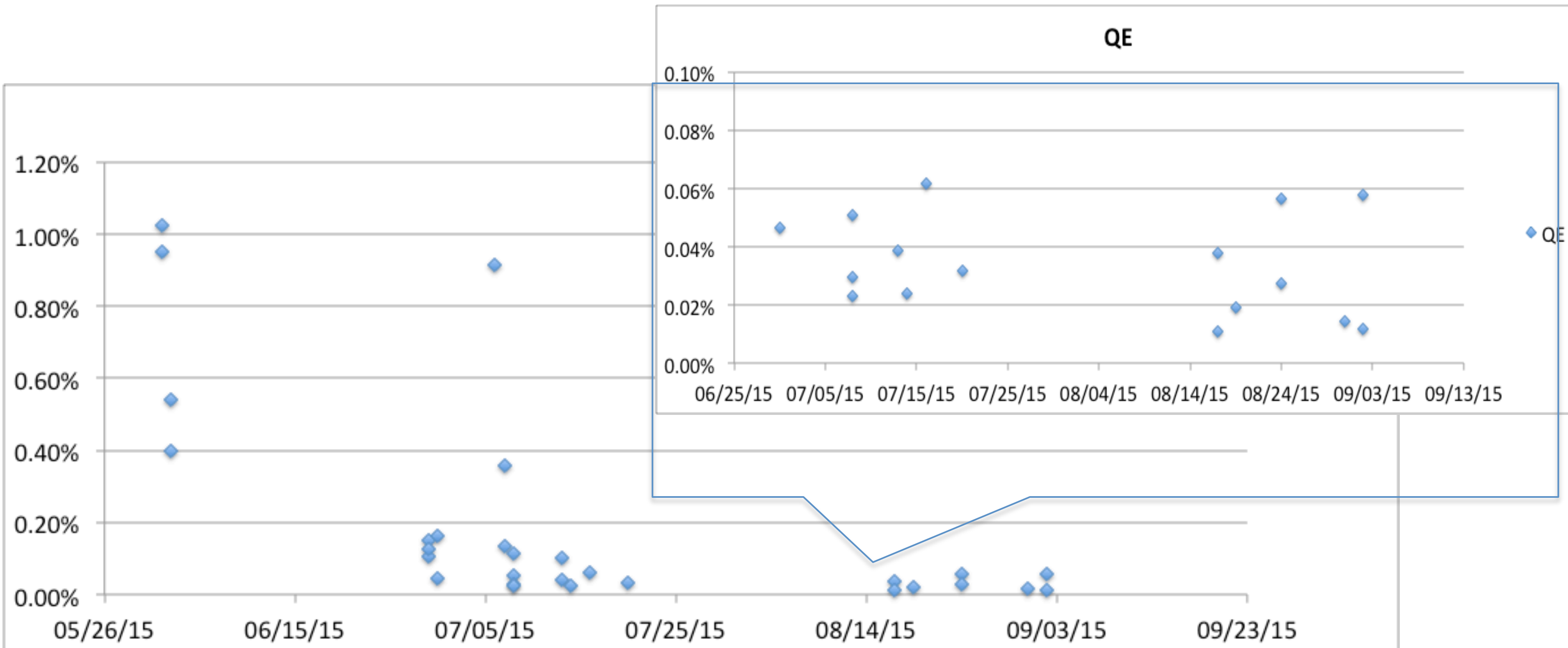
Goals of Gun to Dump commissioning stages (ARR stage I)



- 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.

QE changes



Due to limitation of leq. He supply. Cathode stalk retracted after each beam test and inserted before next beam test.

After first week of testing QE drops from from 1% to 0.4% (June 1-5)

Then it's recovered by cathode tip warming up (July 5).

By moving laser spot slightly around better QE area could be found (QE=3-6 e-4)

BNL R&D ERL: designed parameters, progress

Parameter	Units	High current	High Charge	Measured
Energy max/inject	MeV	20/2.5	20/3.0	?/1.2 (pulsed)
Charge per bunch	nC	0.5	5	0.55
Average Current	mA	350	50	0.020/ 0.4 in RF pulse
RMS Bunch length	psec	8-20	30	8.5; 22
Normalized emittance	10^{-6} m	1.4	5	20% core: 0.25 Full rms:5
RMS energy spread, dE/E	10^{-3}	3.5	10	?
Repetition rate	MHz	704	9.4	9.4
Beam dump power	kW	875	150	8e-3

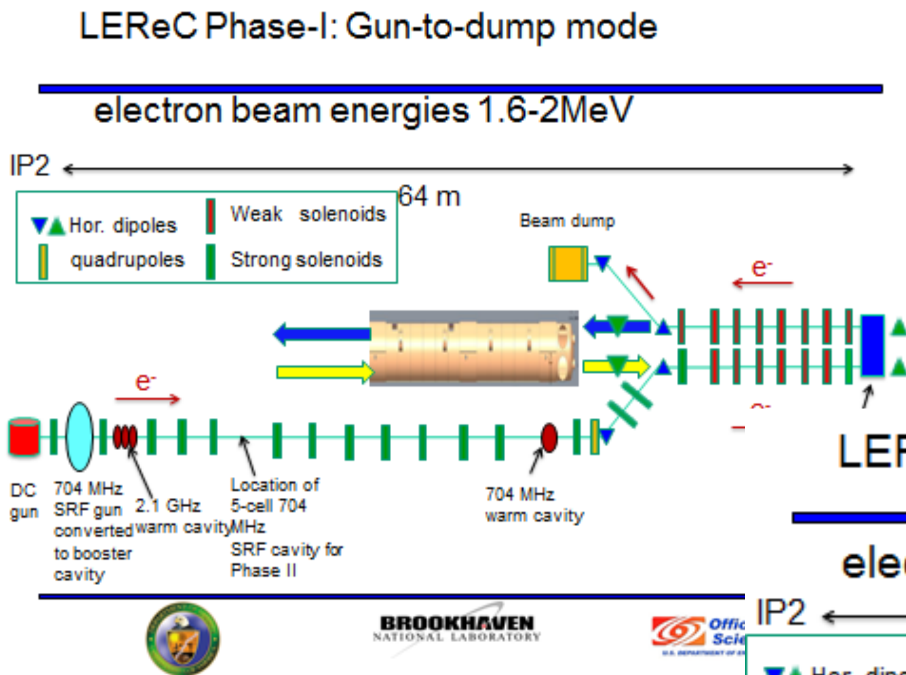
Only gun measured

Laser pulse

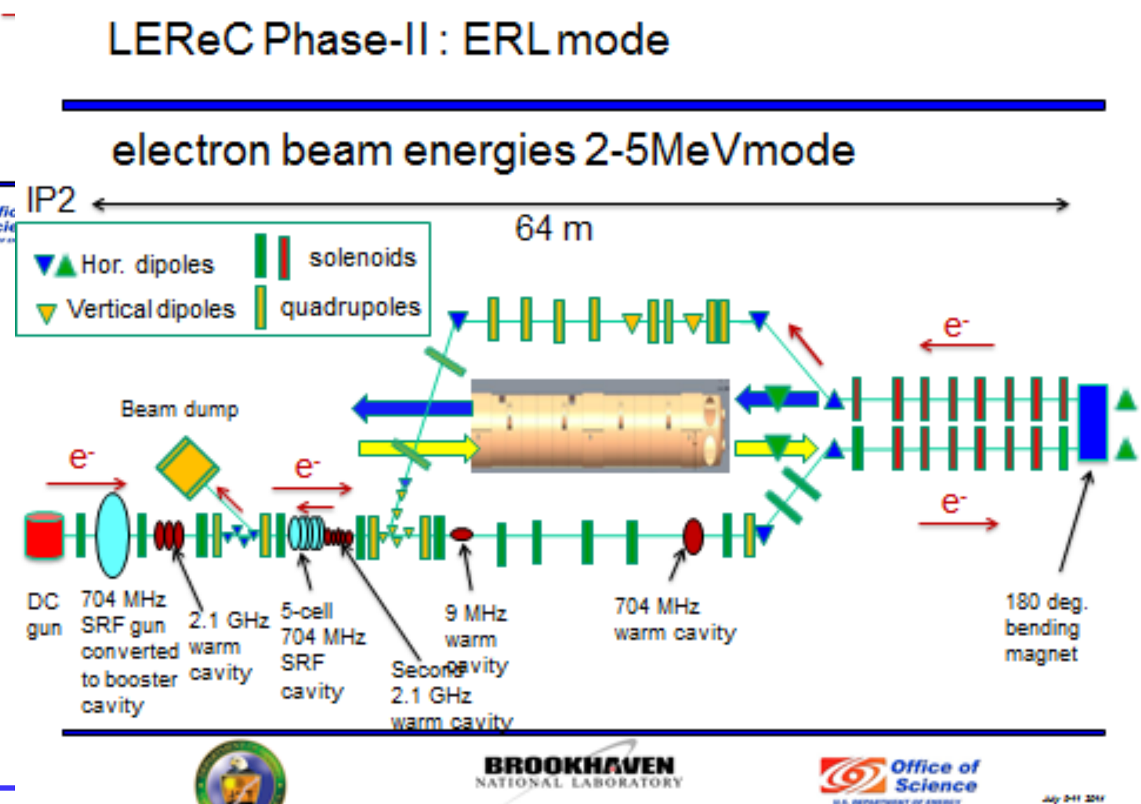
Very preliminary

Faraday Cup

ERL for LEReC



After completed tests at R&D ERL. ERL components will be relocated to use in LEReC



Courtesy Jörg Kewisch. ERL'15

D. Kayran, COOL'15, JLAB

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 cold QE 1%. May, 2015.
- SRF GUN with new cathode starts June 1-2, 2015. Maximum Q=0.55nC, maximum average current 20uA.
- 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.

Acknowledgment for providing material

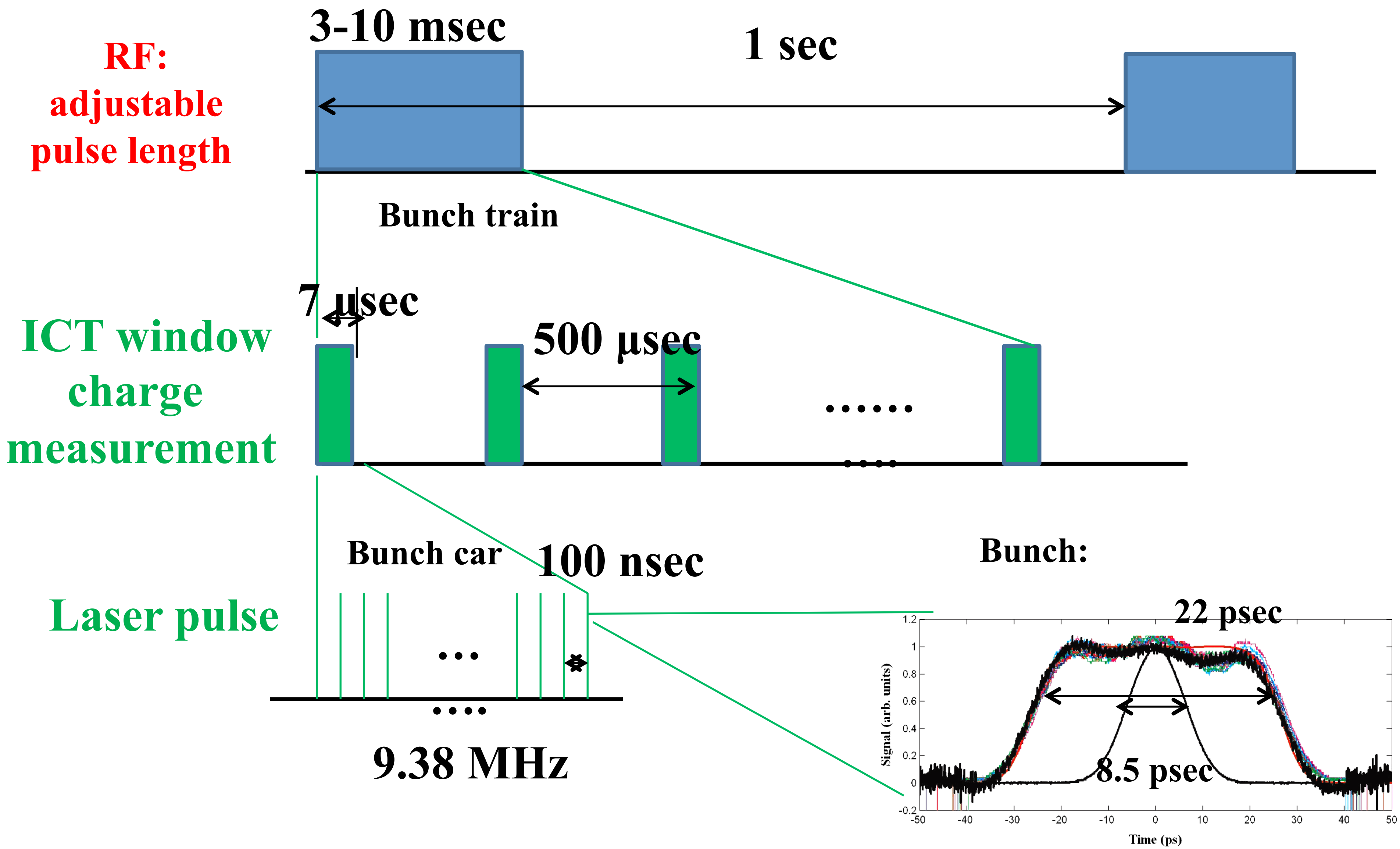
Ilan Ben-Zvi, Jörg Kewisch, Toby Allen Miller, Vadim Ptitsyn,
Brian Sheehy, Erdong Wang, Wencan Xu and R&D ERL team.

Thank you
for your attention!

- Back up

- Our current laser system:
  - without laser splitting can run 10 MHz
  - with laser pulse splitting it can run 40MHz.

Laser pulses matching RF pulse structure and ICT for start up test

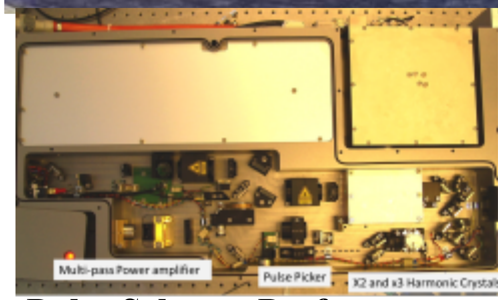


Laser system

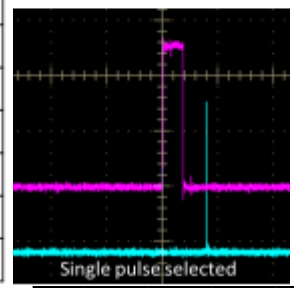
- **Lumera Laser:**

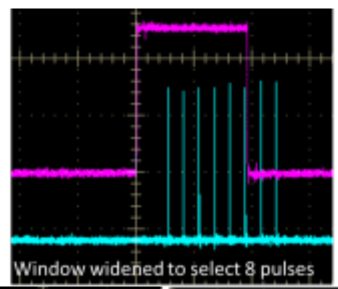
Specifications for the Laser System

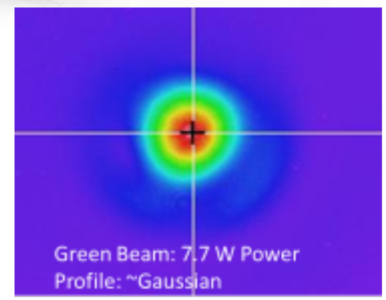
Ability to lock and follow master RF clock	
Master RF Repetition Rate	703.75 MHz
Laser PRF (Phase I for ERL)	Sub multiple of 703.75 MHz
Laser PRF (Phase II for RHIC II)	9.383 MHz
Frequency tunability	+/- 1 MHz
Synchronization deviation to master oscillator	<1 ps
Pulse Length	5-12 ps
Jitter in pulse length	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



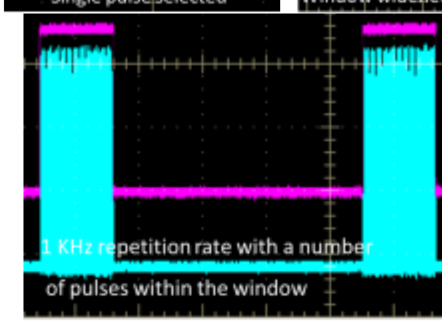
Pulse Selector Performance

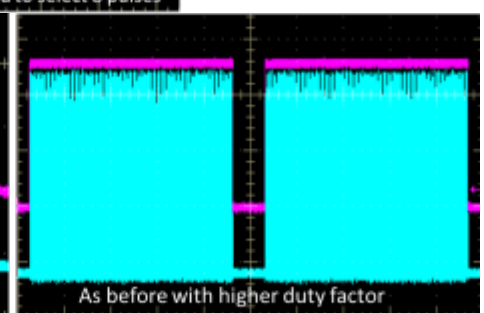






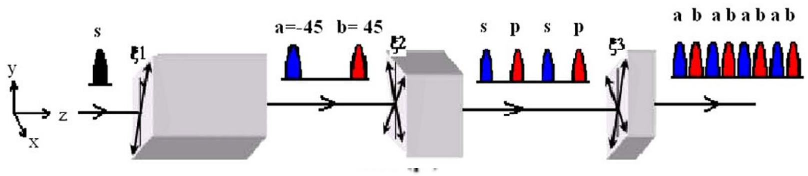
Commissioned and operational since 2009

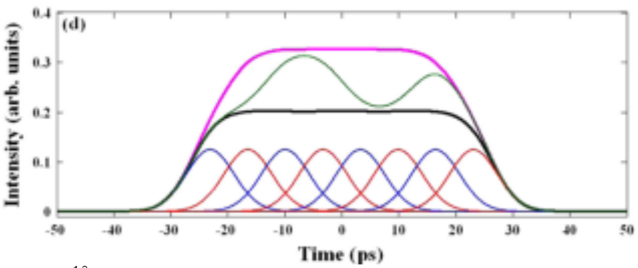


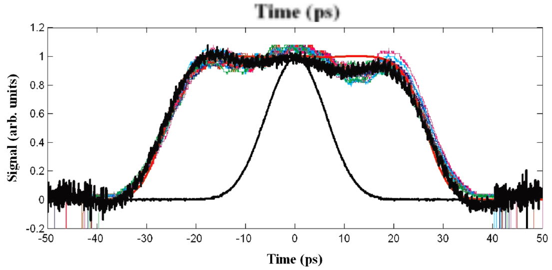


Laser pulses manipulation

Birefringent Method



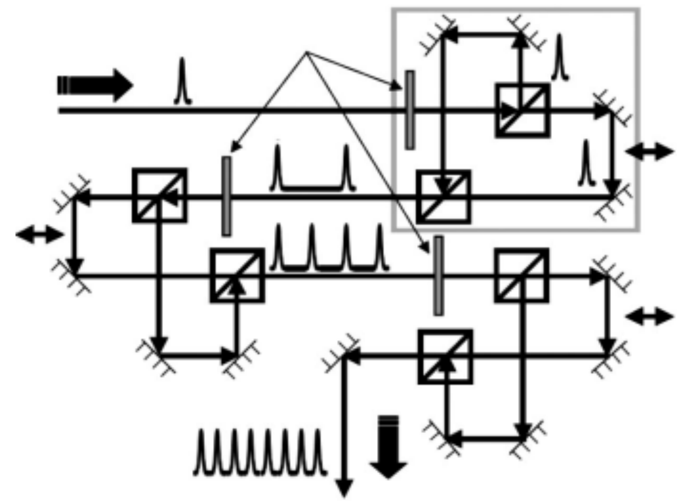




Sharma *et al*
PRSTAB 2009

- 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