Beam Commissioning Experience at Low Energy RHIC Electron Cooler (LEReC)

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Outline

- LEReC overview
- Beam requirements
- Stages of commissioning
- Critical components
- Beam quality measurements
- High current operation
- Cooling demonstration
- Summary

LEReC Project

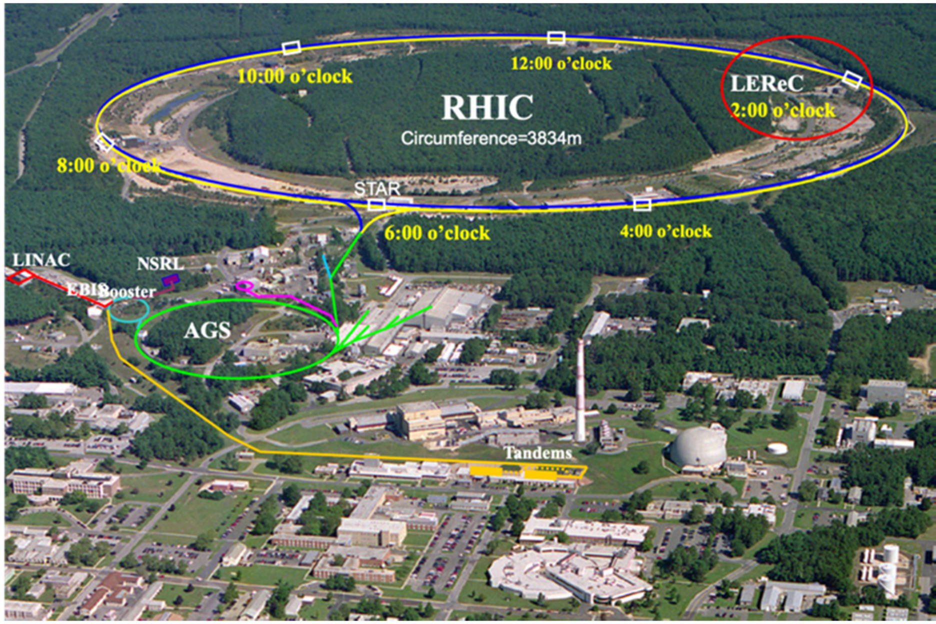
The Goal of the LEReC project is to provide luminosity improvement for RHIC operation at low energies to search for a QCD critical point: Beam Energy Scan Phase-II physics program

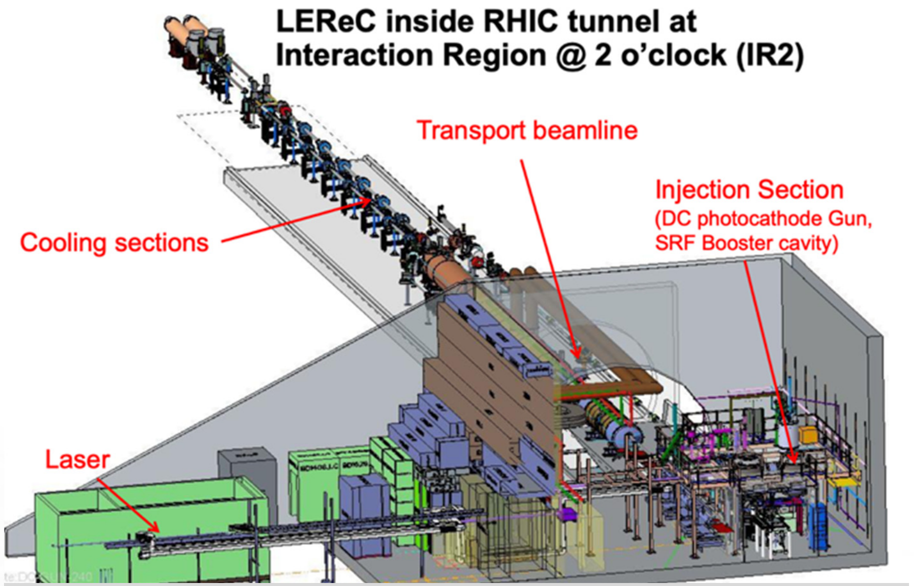
LEReC is first RF linac-based electron cooler (bunched beam cooling)

Required:

Building and commissioning of new state of the art electron accelerator

- ❑ **Produce electron beam with beam quality suitable for cooling**
- ❑ **RF acceleration and transport maintaining required beam quality**
- ❑ **Achieve required beam parameters in cooling sections**
- ❑ **Commissioning of bunched beam electron cooling**
- ❑ **Commissioning of electron cooling in a collider**





Laser, RF amplifiers, Magnets power supplies,
Beam instrumentation racks are located outside of the RHIC tunnel

Original plan: LEReC to provide cooling at KE=1.5-5 MeV*

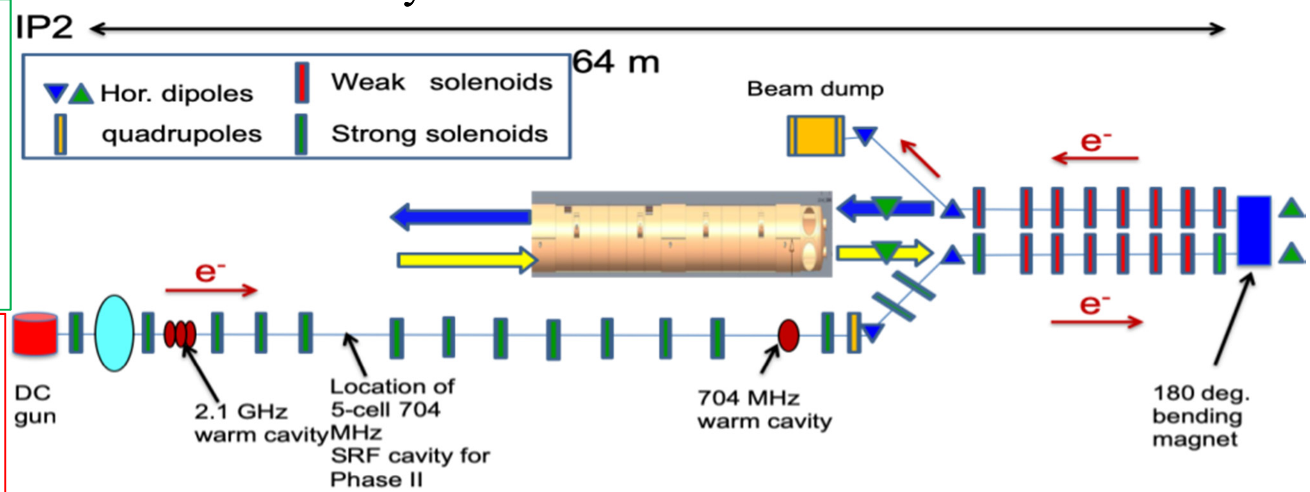
And reuse components from BNL ERL

Phase I (NO ERL):
Provide 1.6-2.6 MeV beam:
DC Gun and 2MeV SRF booster and RF correction

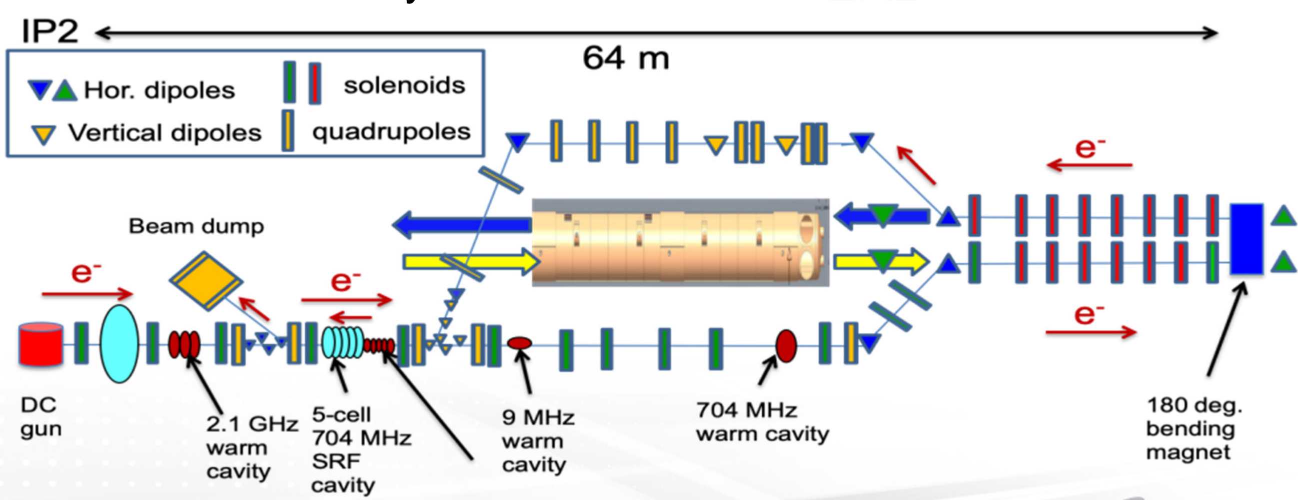
Phase II (ERL):
Provide upto 5 MeV beam:
DC Gun, 2 MeV SRF booster, RF correction and additional cavity in ERL mode

Abandoned due to limited time, additional components and not so obvious benefits for RHIC physics program at this energy

Layout for Phase I   No ERL



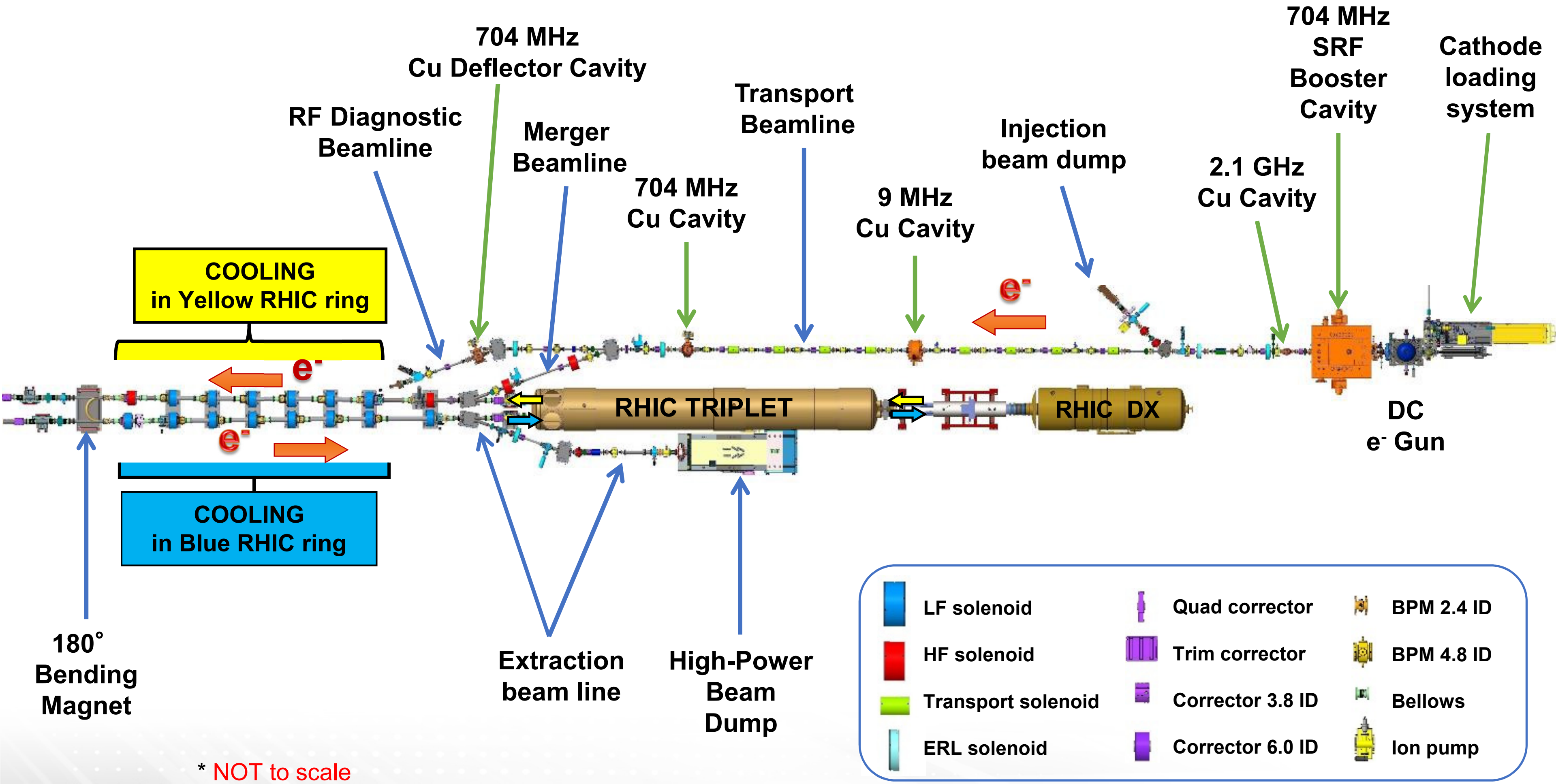
Layout for Phase II   ERL



*) J. Kewisch *et al.*, "ERL for low energy electron cooling at RHIC (LEReC)", ERL2015, Stony Brook, USA, 2015

LEReC Accelerator Layout

(100 meters of beamlines with the DC Gun, high-power fiber laser, 5 RF systems, including one SRF, many magnets and beam instrumentation)



* NOT to scale

LEReC electron beam parameters

D. Kayran *et al.*, “Commissioning of the electron accelerator LEReC for bunched beam cooling”, NAPAC2019, Lancing, MI, 2019.

Electron beam base parameters for cooling				Measured*
Kinetic energy, MeV	1.6	2	2.6	1.6, 2.0
Pulse duration at the cathode, psec	40	40	40	40
Bunch duration in cool. sect, psec	400	400	20	400
Electron bunch (704MHz) charge, pC	130	170	200	50-200
Bunches per macrobunch (9 MHz)	30	30	24-30	30
Charge in macrobunch, nC	4	5	5-6	1-6
RMS normalized emittance, um	< 2.5	< 2.5	< 2.5	1.6-2
Average current, mA	36	47	45-55	14-30
RMS energy spread	< 5e-4	< 5e-4	< 5e-4	<2e-4
RMS angular spread in cooling section	<150 urad	<150 urad	<150 urad	100-200 urad

Commissioned during 2019 RUN

*) not at the same time

Bunched beam electron cooling for LEReC

Approach:

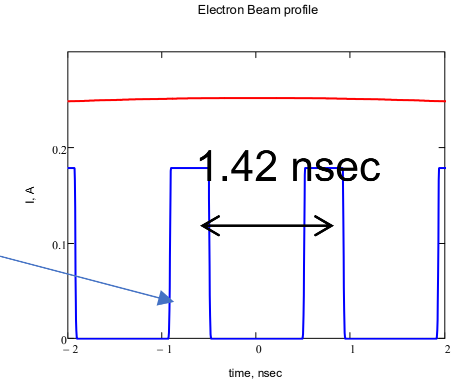
- Produce electron bunches suitable for cooling by illuminating a multi-alkali photocathode inside the Gun with green light using high-power laser (high-brightness in 3D: both emittance and energy spread).
- The 704 MHz fiber laser produces required modulations to overlap ion bunches at 9 MHz frequency with laser pulse temporal profile shaping using crystal stacking.
- Accelerate such bunches with RF and use RF gymnastics (several RF cavities) to achieve energy spread required for cooling.
- Deliver and maintain beam quality in both cooling sections.
- Electron bunch overlaps only small portion of ion bunch. All amplitudes are being cooled as a result of synchrotron oscillations.

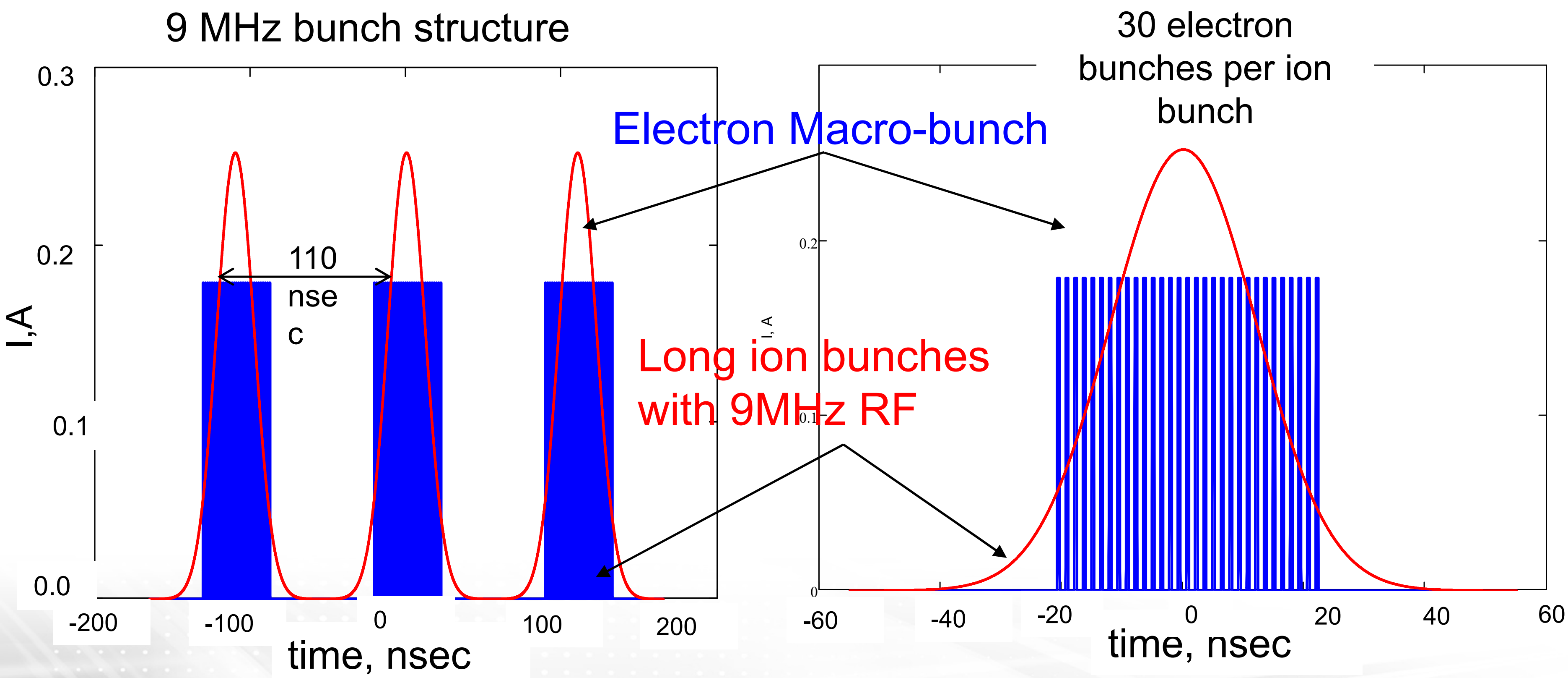
LEReC beam structure used in cooling section

N_ion=6e8

Ions structure:
120 bunches
f_rep=120x75.8347 kHz=9.1 MHz
N_ion=6e8, I_peak=0.25 A
Rms length=12 nsec

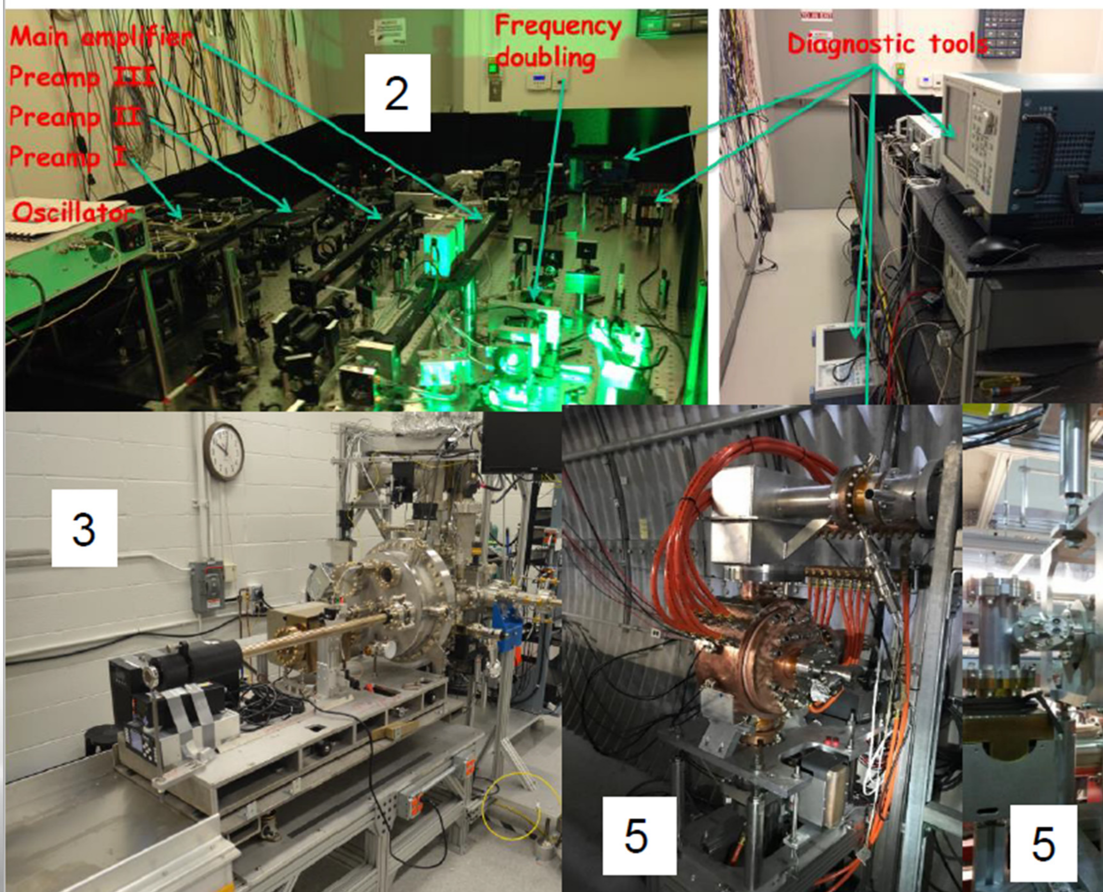
Electron bunches:
f_SRF=703.5 MHz
Q_e=75 pC, I_peak=0.18 A
FWHM=400 psec

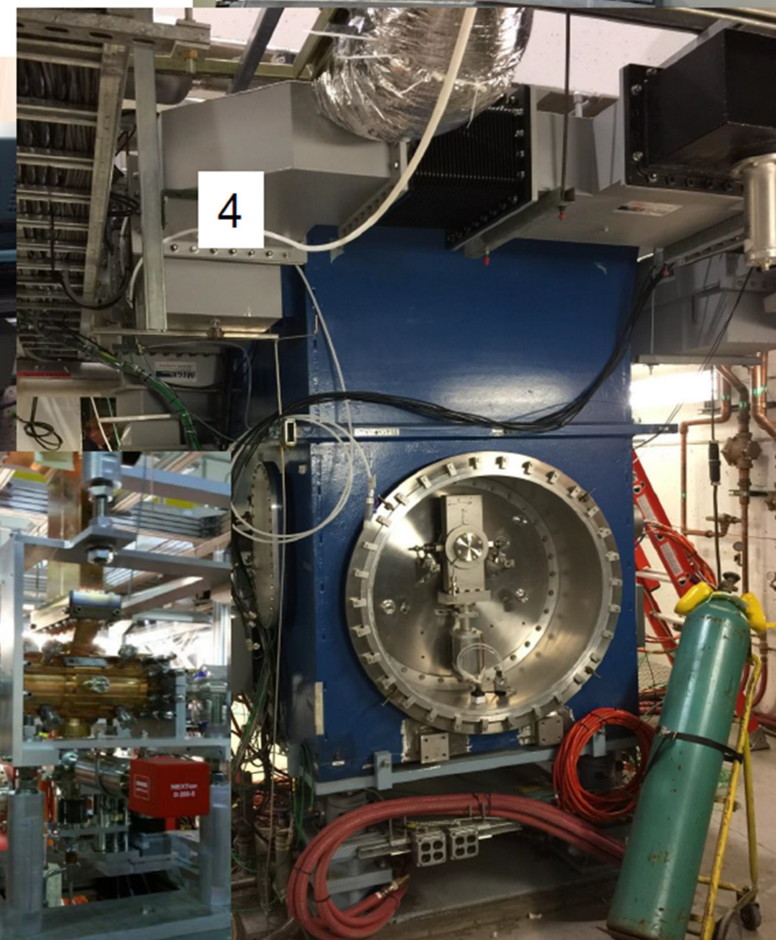




LEReC Critical Technical Systems

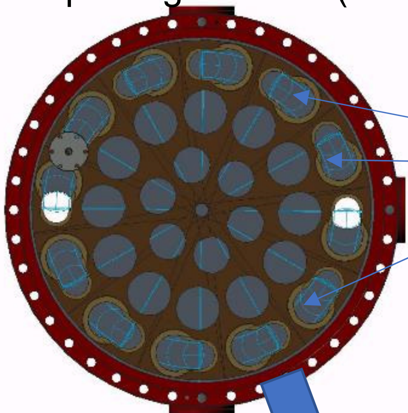
1. DC photocathode electron gun and HV PS
2. High-power fiber laser system and transport
3. Cathode production deposition and delivery systems
4. SRF Booster cavity
5. 2.1 GHz and 704 MHz warm RF cavities



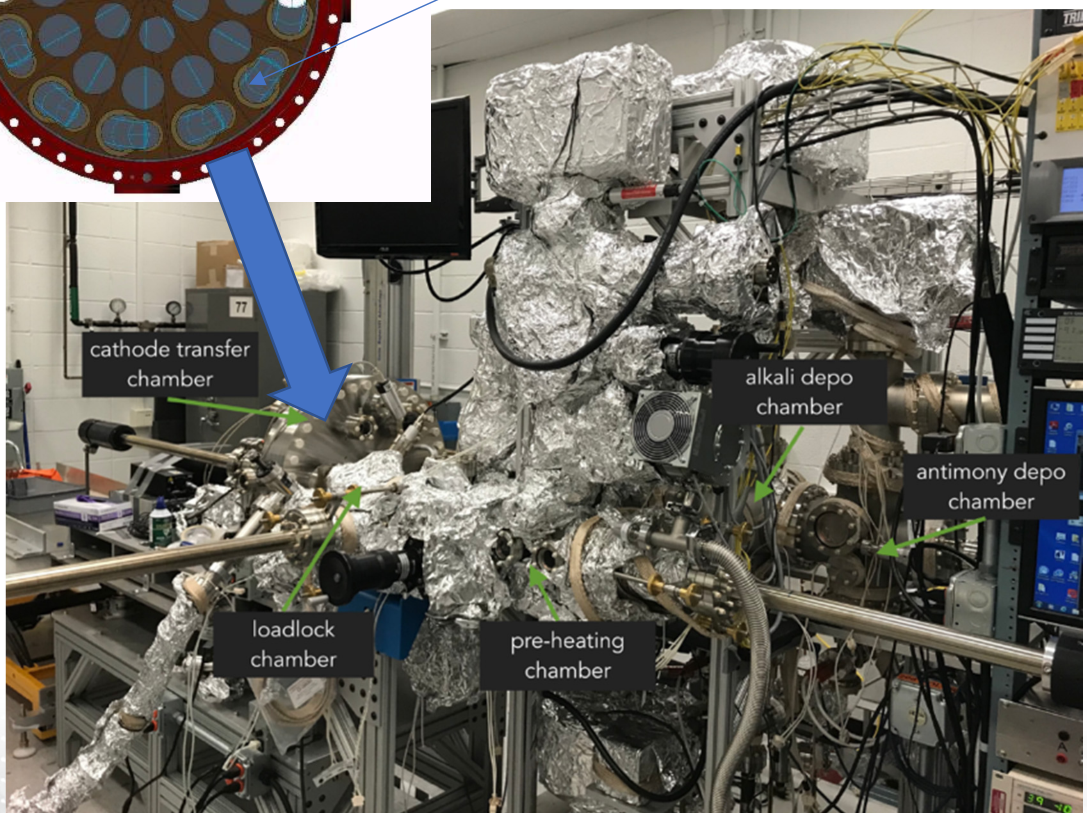


Photocathode production (in instrumentation building)

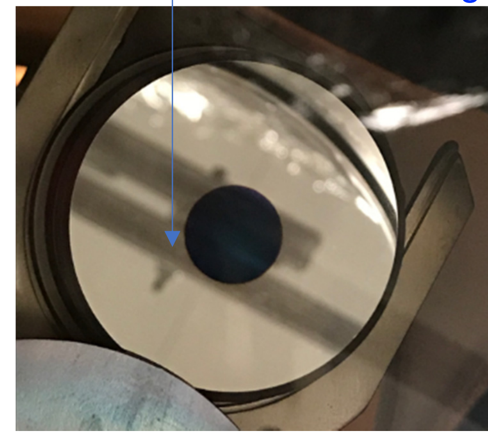
- In order to reduce down time due to cathode exchange we built three 12-cathodes transport systems
- It require one long access (1 shift) to swap systems and short access for replacing cathode (1 hour)



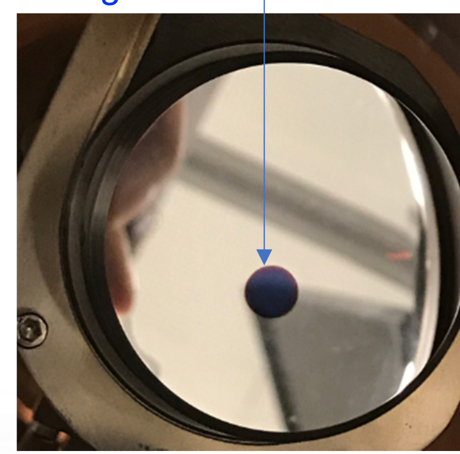
Cathode transfer camera can hold up to 12 cathodes



On center 12mm active area
Used 2017-18 commissioning



Off center 6mm active area
Used end of 2018 and during 2019



More about LEReC photocathodes, talk by *Mengjia Gaowei* "**Cathode performance for high current operation in LEReC" on Wednesday WECOXBS02**

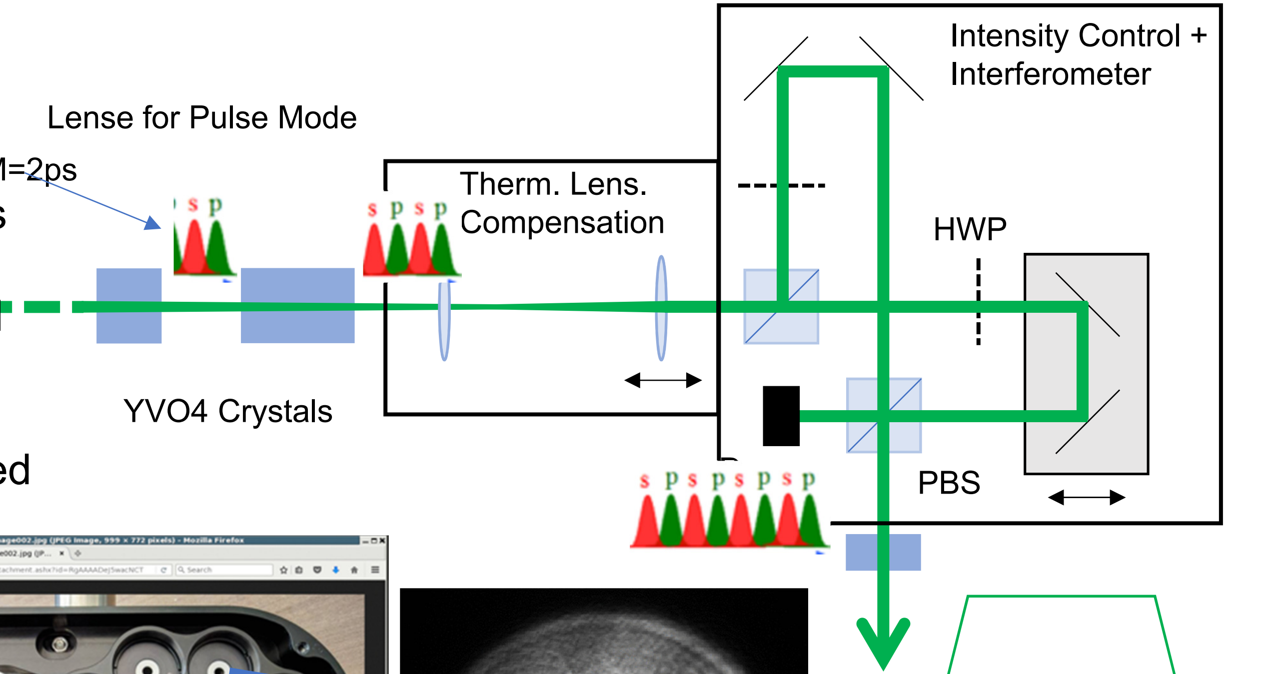
Laser: Temporal Shaping and Intensity Control

During 1st year of operation laser spot profile at the cathode was strongly dependent on average laser power due to thermal lensing effect

After reduce numbers of crystal from 5 to 4 and replace the longest crystal to the interferometer

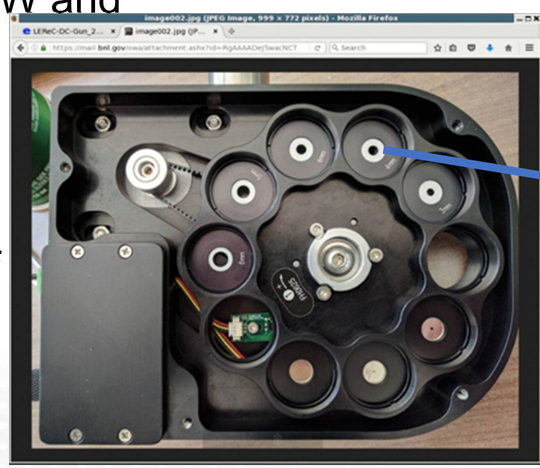
Experiments show Thermal lens is fully compensated and independent of Intensity Control settings

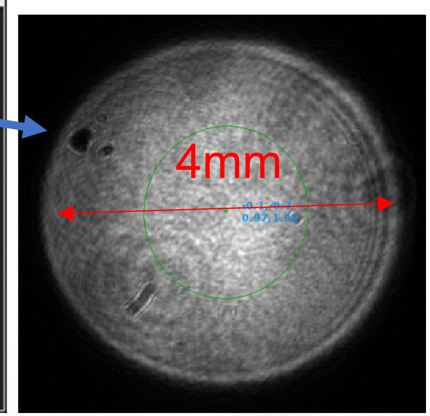
Compensation stage setting fixed for given laser mode (CW and pulsed/76kHz)



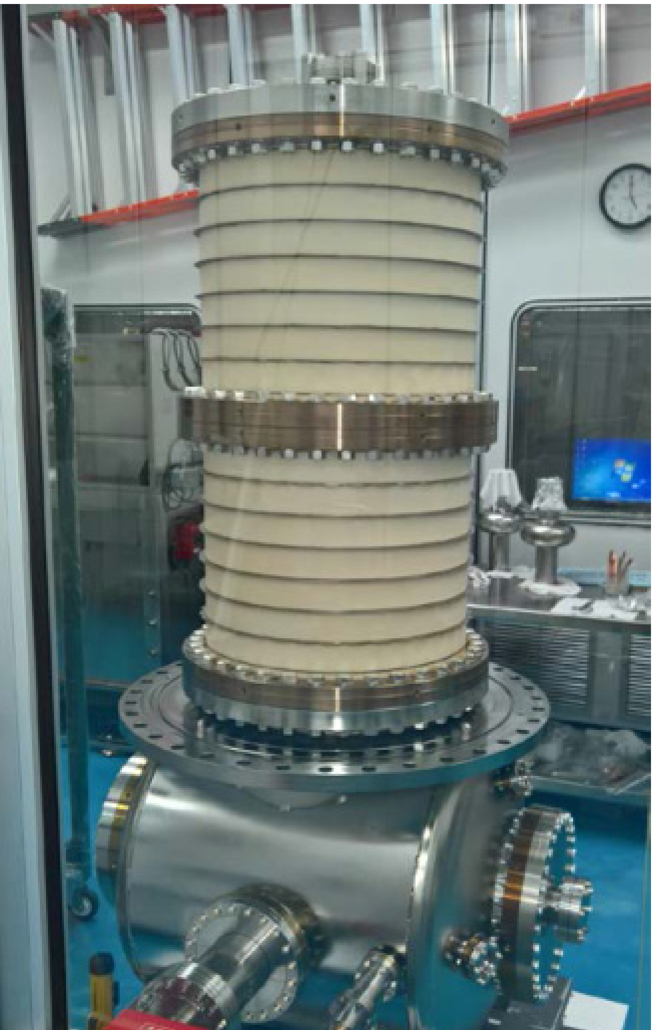
16 Stacked sub-pulses=40ps long close to flat top pulse

To control laser spot size
Filter wheel with set of irises
Is installed at the gun table 1:1 image of iris to the cathode

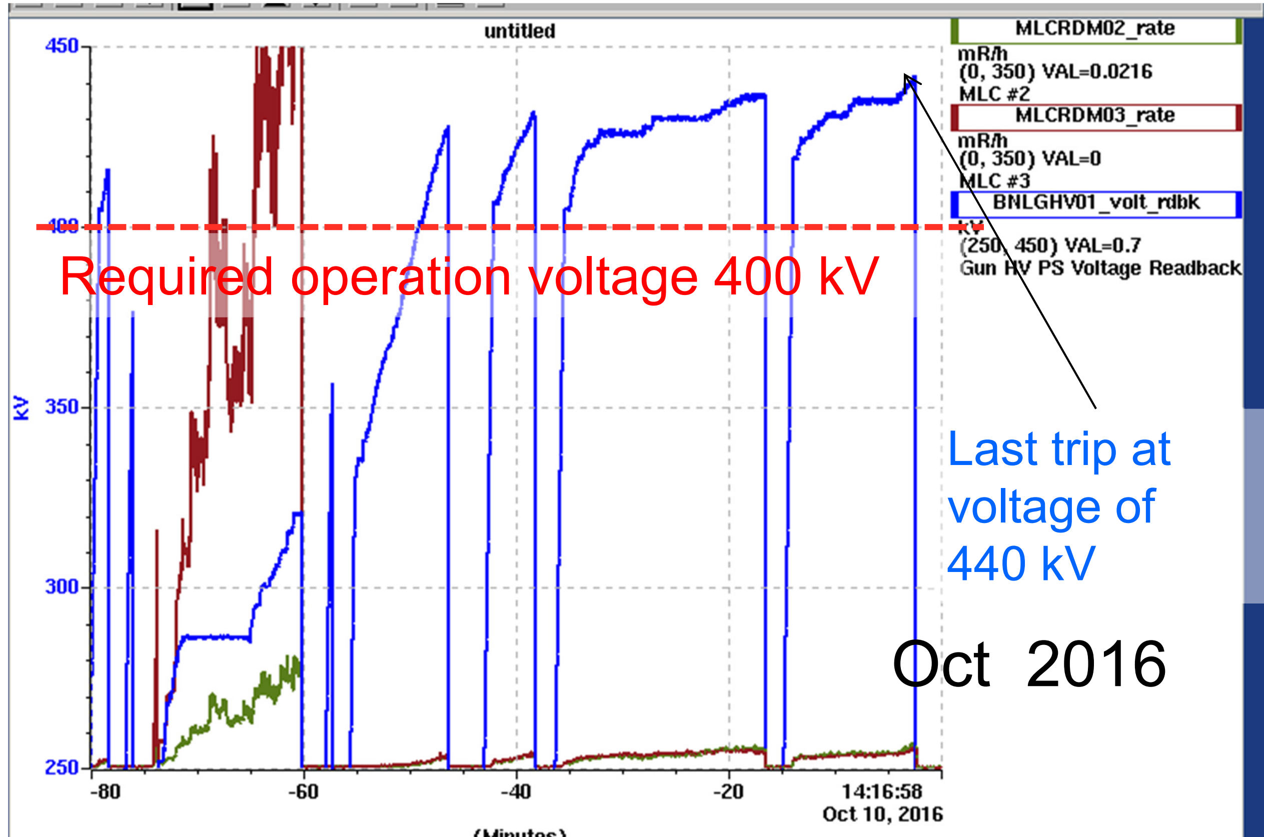




BNL DC gun performance during HV conditioning at Cornell



Designed, built and 1st time conditioned at Cornell University



Molybdenum cathode plug

More about LEReC Gun performance see poster by *Xiaofeng Gu* “**Experience With LEReC High Current DC Gun**” **on Wednesday WEPNEC22**

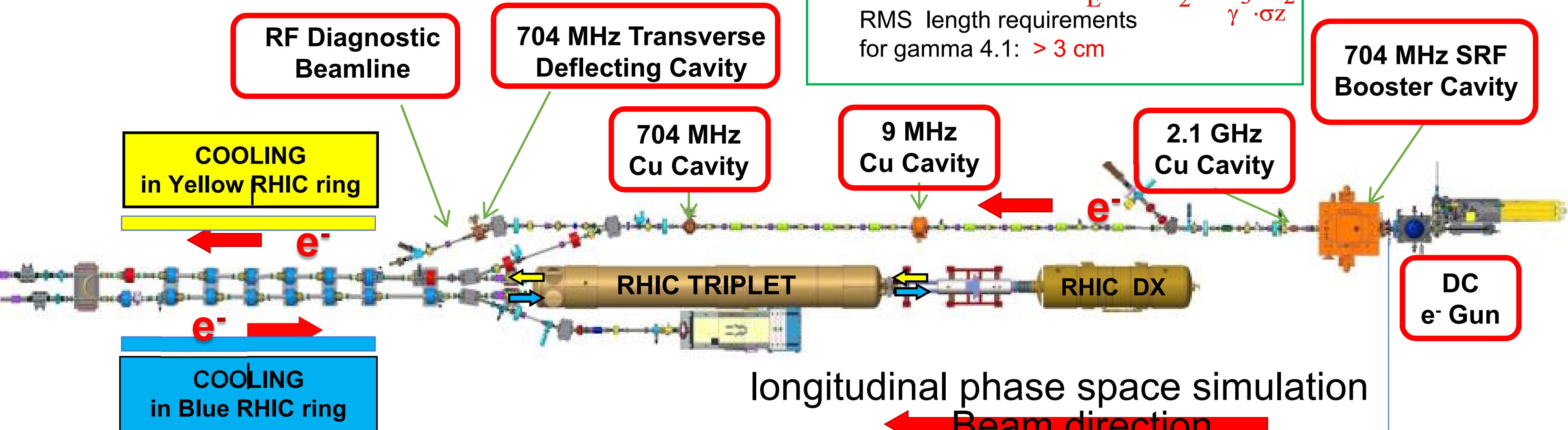
Longitudinal gymnastic

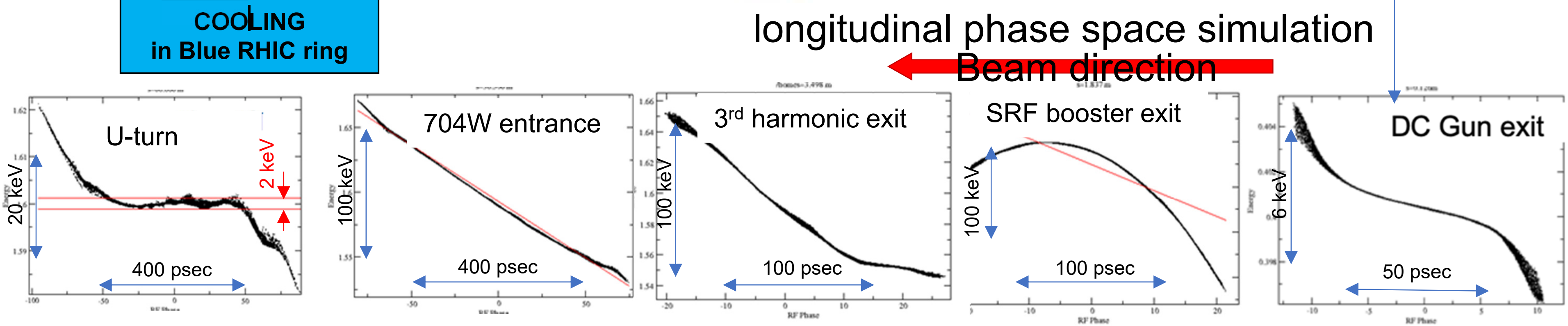
Energy spread due to longitudinal Space charge

Gaussian beam

$$\frac{\sigma\_E}{E} := \frac{re\cdot Nq}{2}\cdot\frac{Lcool}{\gamma^{3}\cdot\sigma z^{2}}$$

RMS length requirements for gamma 4.1: > 3 cm





- 704 MHz SRF Booster Cavity = Acceleration, Energy Chirp for Ballistic Bunch Stretch *
- 2.1 GHz Cu Cavity = RF Curvature Correction
- 704 MHz Cu Cavity =Removal of Energy Chirp
- 9 MHz Cu Cavity = Macrobunch Linear Transient Beam Loading Compensation
- 704 MHz Transverse Deflecting Cavity =Longitudinal Phase Space, Vertical Deflection to Provide Head to Tail Streak

*) J. Kewisch *et al.*, "Beam optics for the RHIC low energy electron cooler (LEReC)", NAPAC2016, Chicago, IL, 2016

Ramp up from pulsed operation to high current

- At nominal charge setup RF and beam optics using beam in pulsed mode with few macro bunches to achieve required beam quality and beam transport efficiency.
- Check if no significant changes in beam quality for lower charge per bunch, then increase average current.

Our original plan was to keep charge per bunch constant and increase numbers of macro bunches to reach required beam current:

The big advantage of this approach no need for optics adjustment.

Due to DC gun beam loading and slow voltage PS regulation loop response strong loss were observed in non zero dispersion section (next slide).

Resulting of changing approach during commissioning for CW operation:

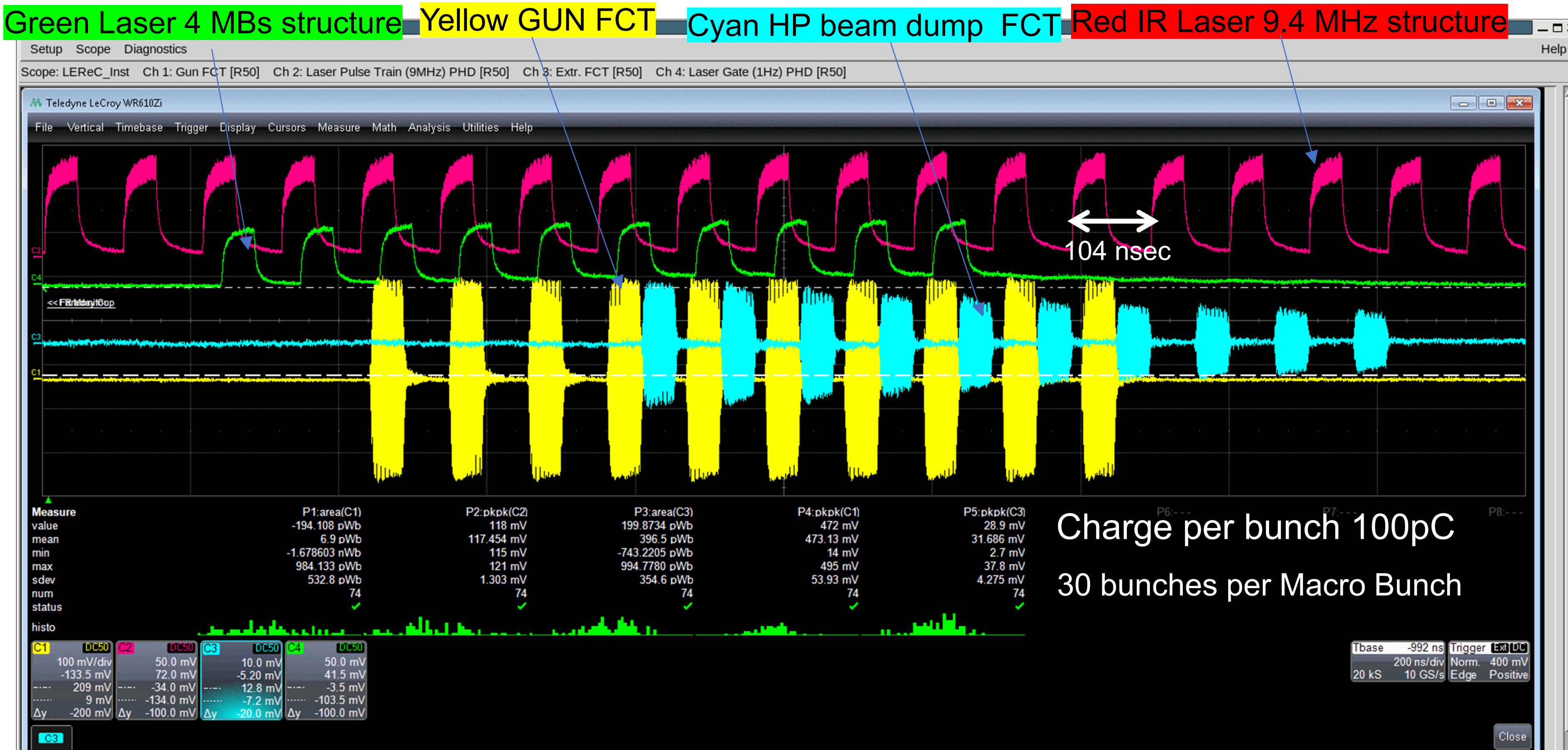
Reduce laser intensity to minimum

Switch laser mode to CW (9 MHz)

Slow increase laser power until required current is reached

Magnets adjustment as necessary by monitoring beam position, beam losses, beam line vacuum and temperature

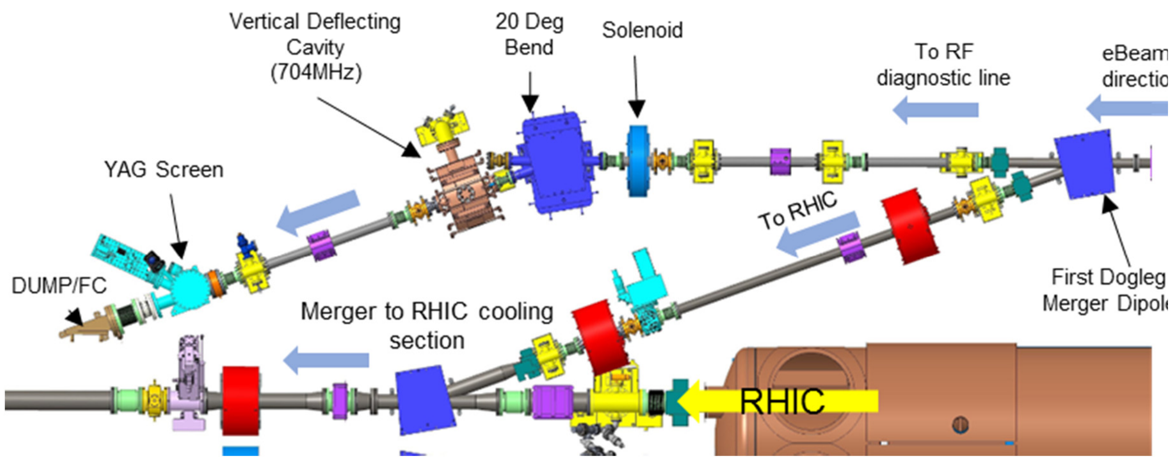
Beam loading effect observed at HP Beam Dump FCT



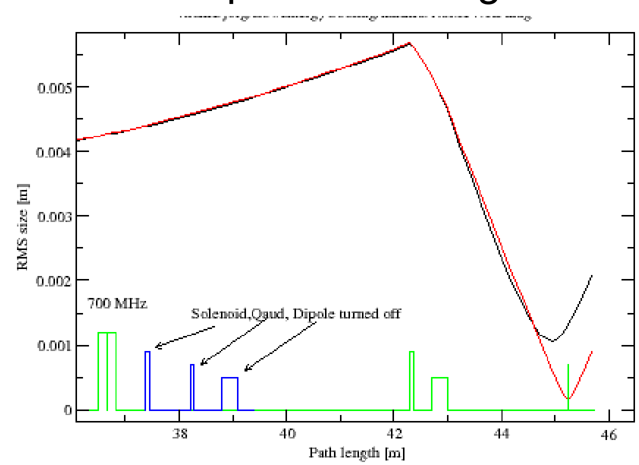
Due to beam loading effect to RF cavities later bunches get less acceleration and some particles have been lost most likely in the merger section with largest dispersion

Beam quality measurements

RF diagnostic line for RF system fine tuning

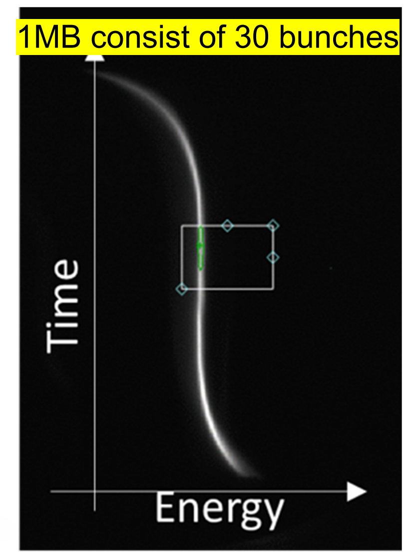


RMS envelopes in RF diagnostic line



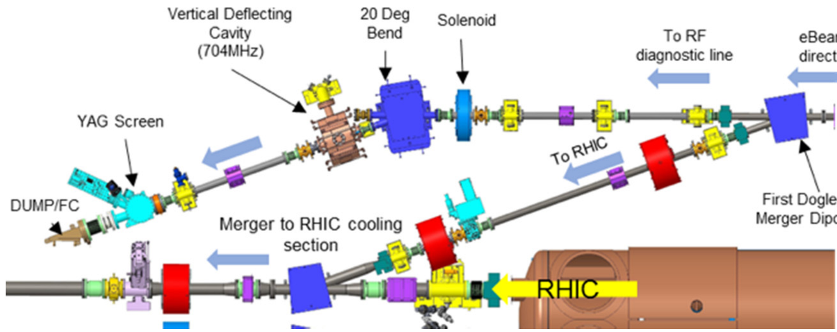
If first dogleg merger dipole is turned off the electron beam is transported to the RF diagnostic line to measure longitudinal phase space profiles.

- 20 degrees dipole to generate a dispersion of 800 mm,
- solenoid provides small beta function at the YAG screen location,
- 704 MHz deflecting cavity to provide vertical time-dependent kicks.
- Then we adjust phase and voltage of 9MHz cavity to compensate bunc2bunch RF cavity beam loading effect



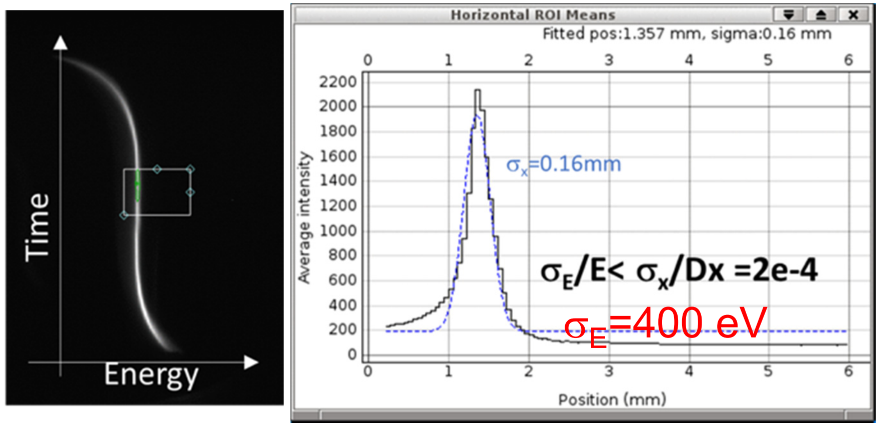
Beam profile at RF diagnostic line YAG

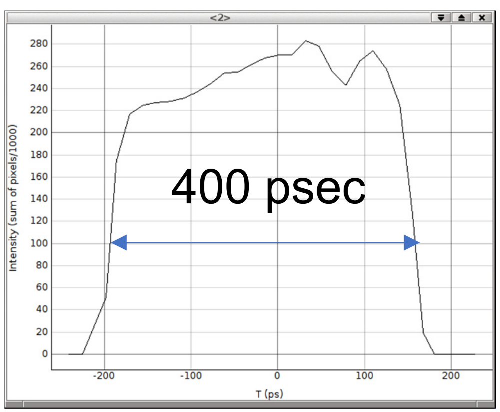
Longitudinal phase space measurement in RF diagnostic line



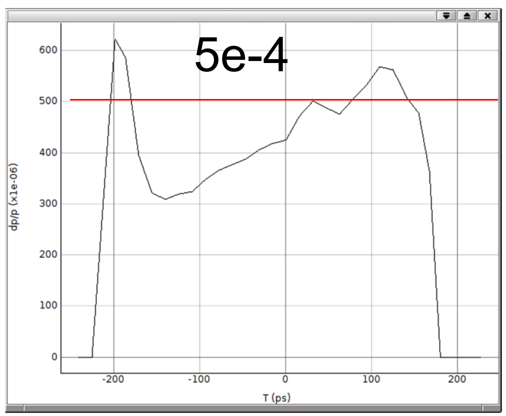
Measurements at RF diagnostic YAG profile monitor for a bunch charge of 100 pC, FWHM of 400 psec.

1 macrobunch, 3 nC



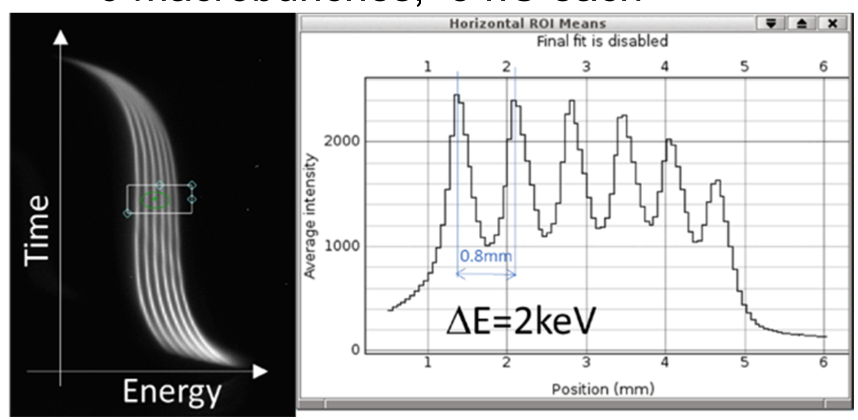


Longitudinal profile



RMS sliced energy spread

6 macrobunches, 3 nC each

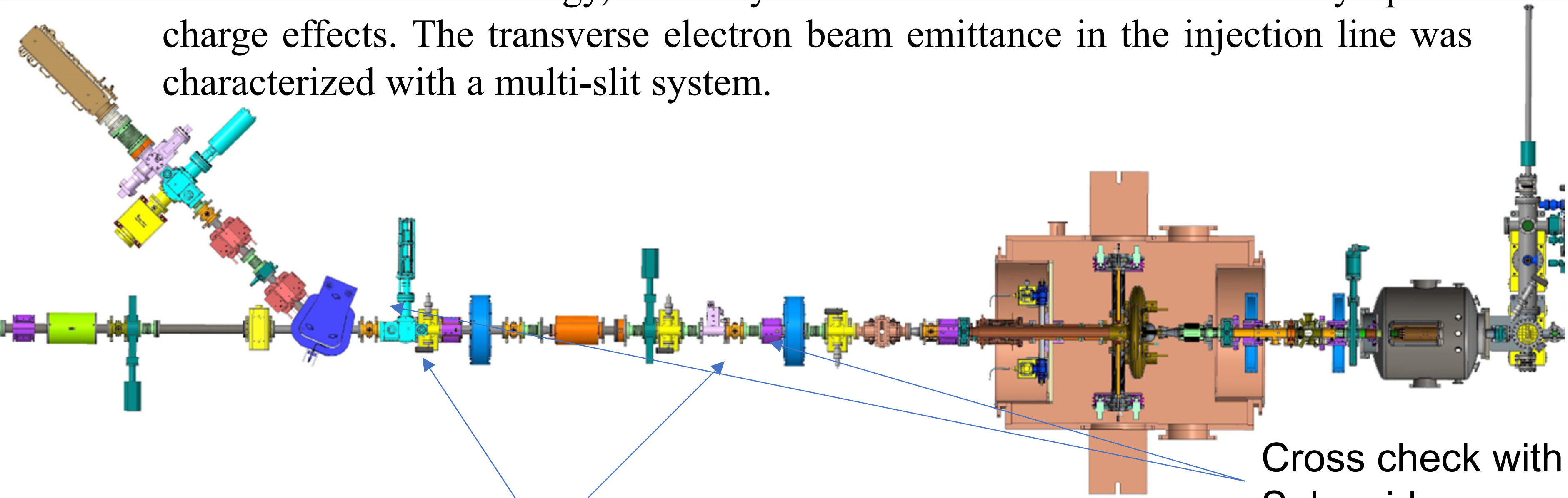


In pulsed mode due to beam loading effect followed bunches have lower energy

Later we used this MB2MB energy difference as an energy probe for study simultaneously cooling performance at different energy

Transverse beam quality measurements

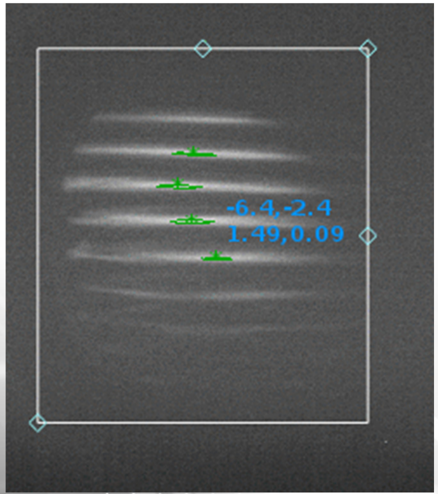
Due to low beam energy, beam dynamics in LEReC is dominated by space-charge effects. The transverse electron beam emittance in the injection line was characterized with a multi-slit system.

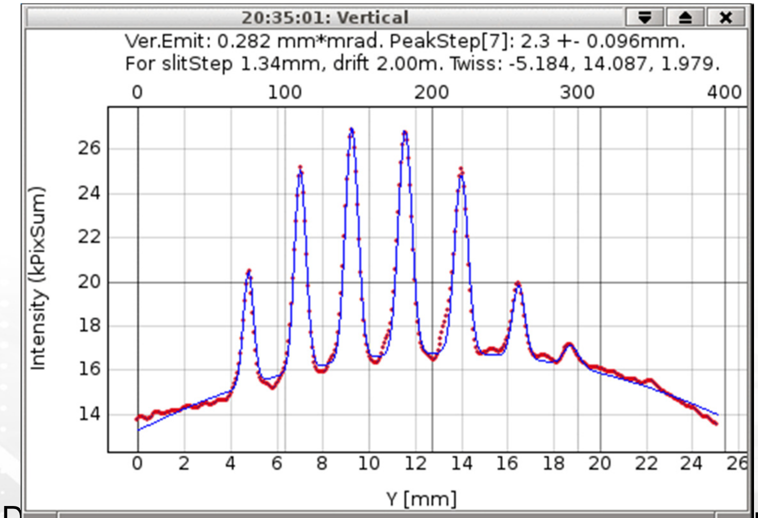


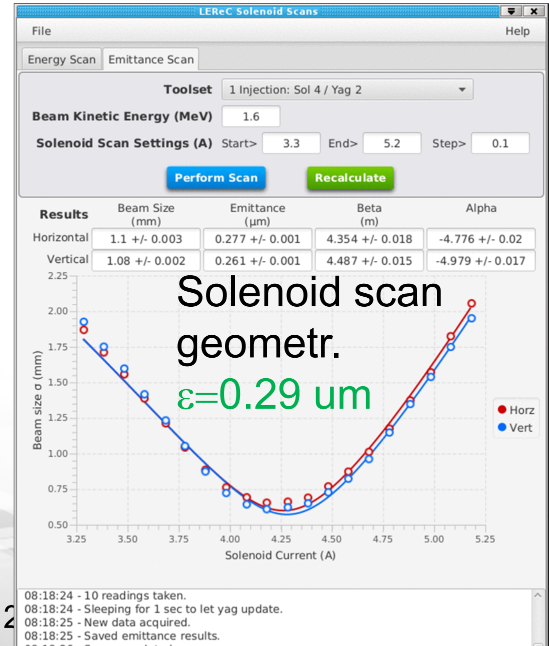
Cross check with Solenoid scan

Multi slits emittance measurements geometr.

ε=0.28 um



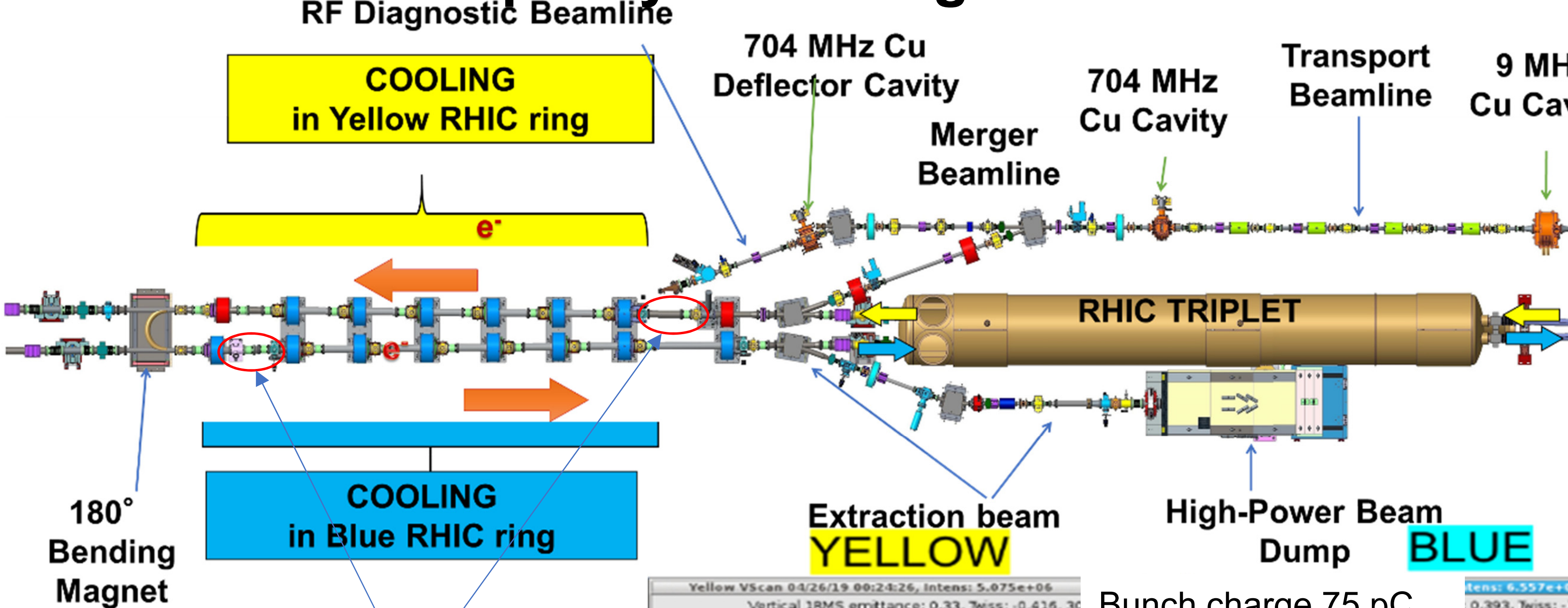




Solenoid scan geometr.

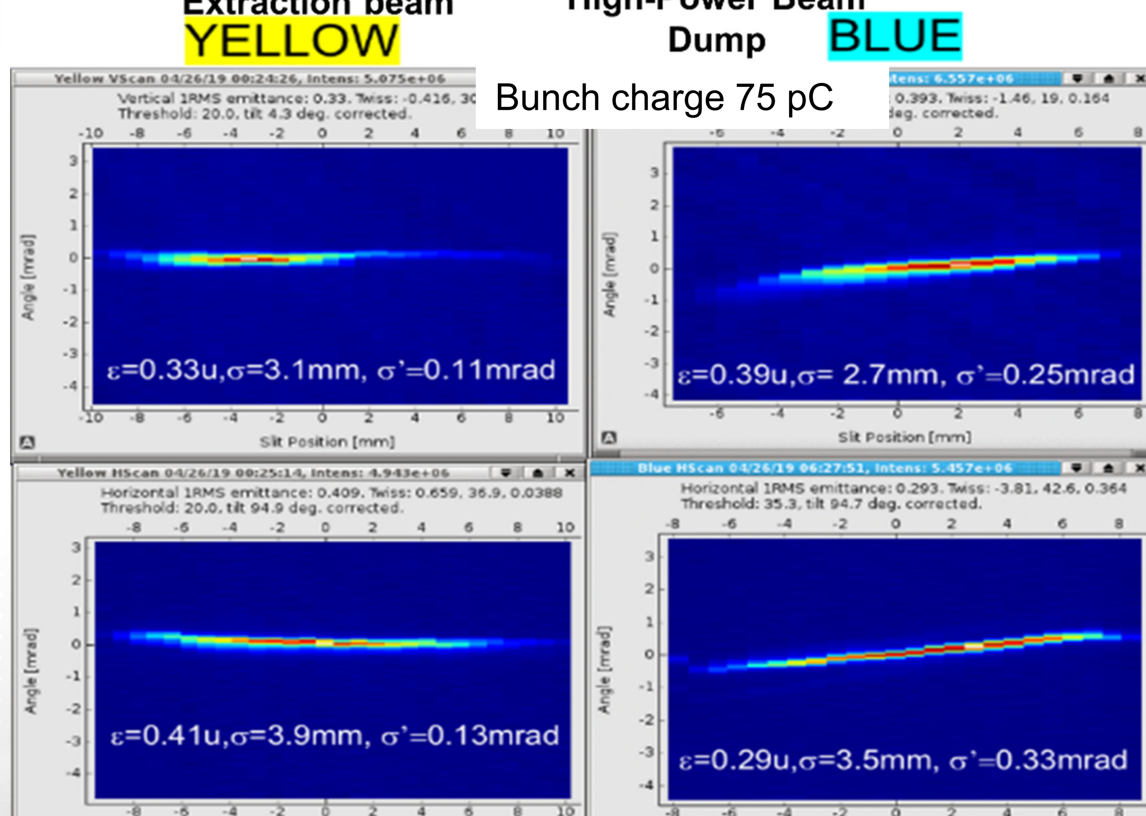
ε=0.29 um

Transverse beam quality in cooling sections without ions



Cut-away model of the emittance slit scanner and cut-away view of the chamber

Movable slits + downstream beam profile monitors are installed at the beginning of each of cooling section



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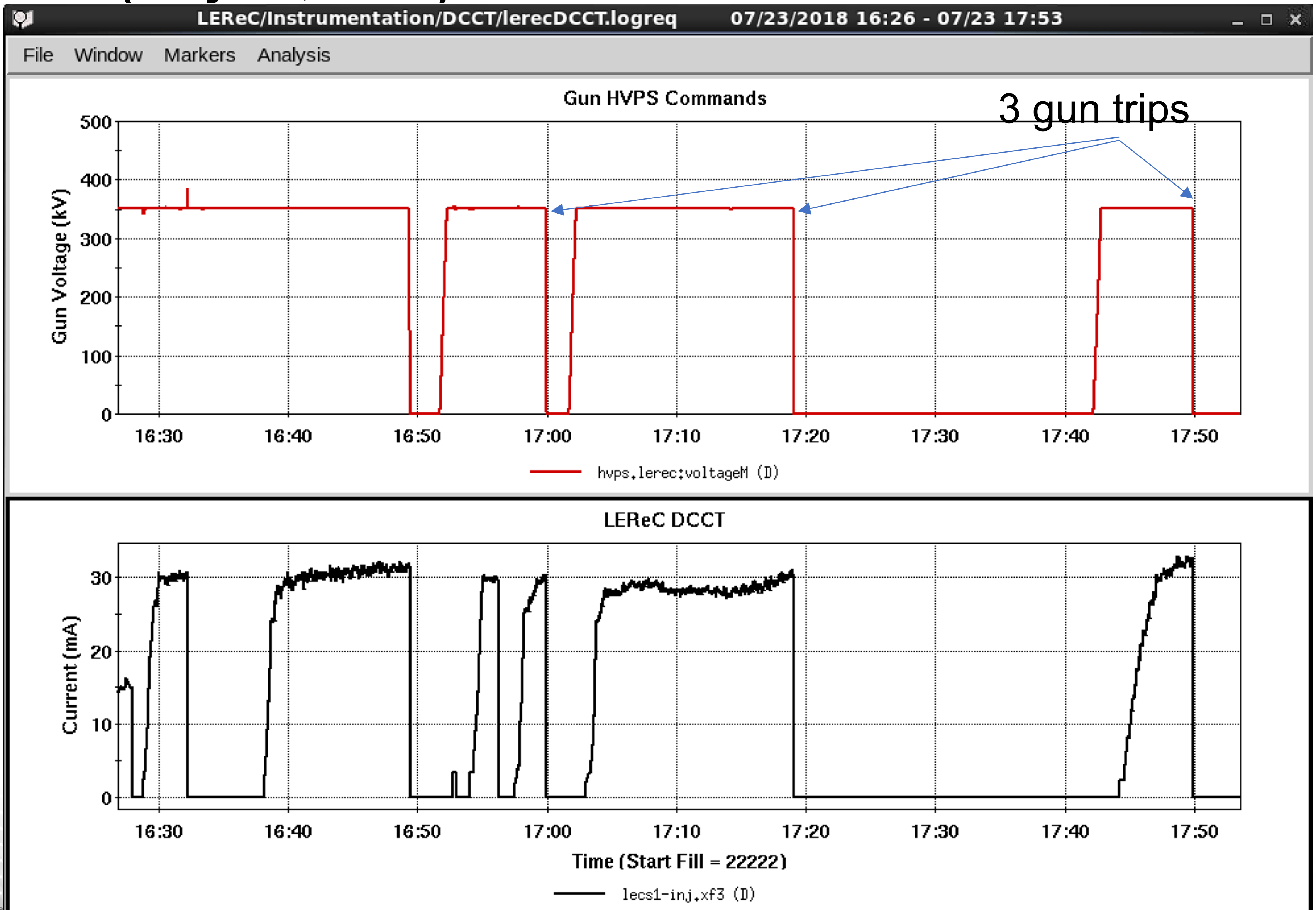
High current operation

Typical run of 30 mA with large cathode and laser on the center (July 23, 2018)

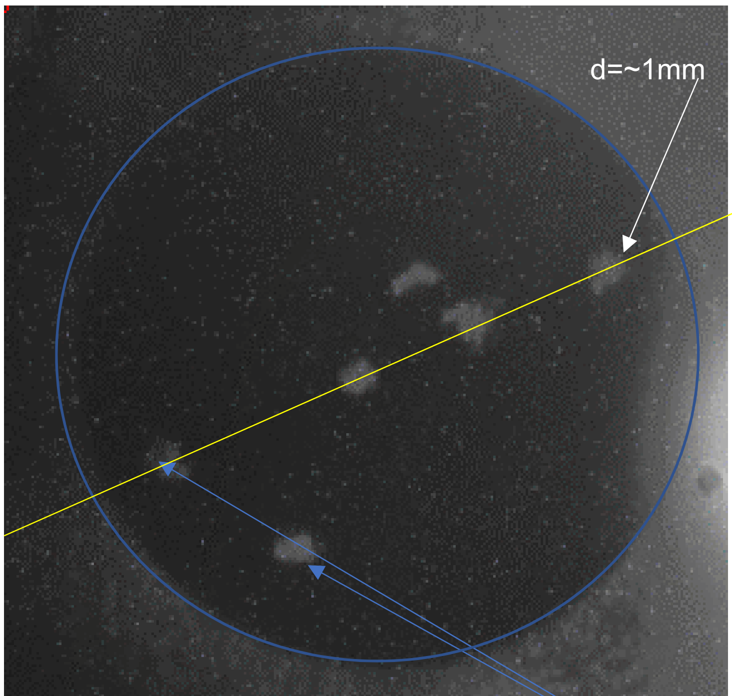


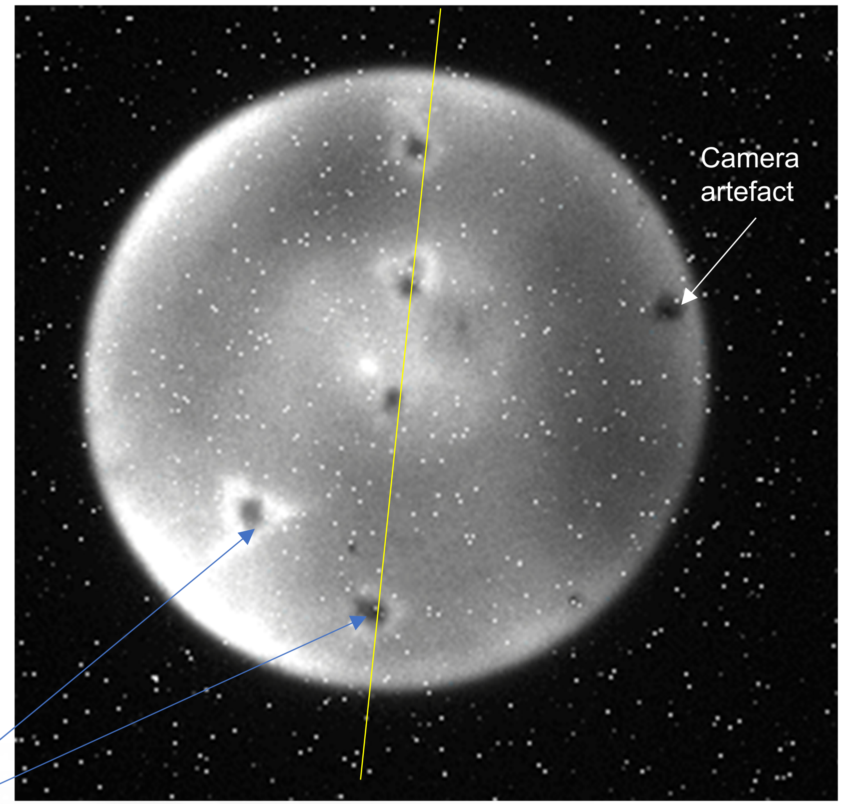
Cathode image after several Gun trips at CW 30mA

July 24, 2018

Cathode image camera
(large cathode active area, diameter 12mm)

LED lamp induced electron beam image at beam profile monitor YAG (one shot QE map)
E-beam is rotated by Gun Solenoid and flipped due to YAG profile camera oriantation



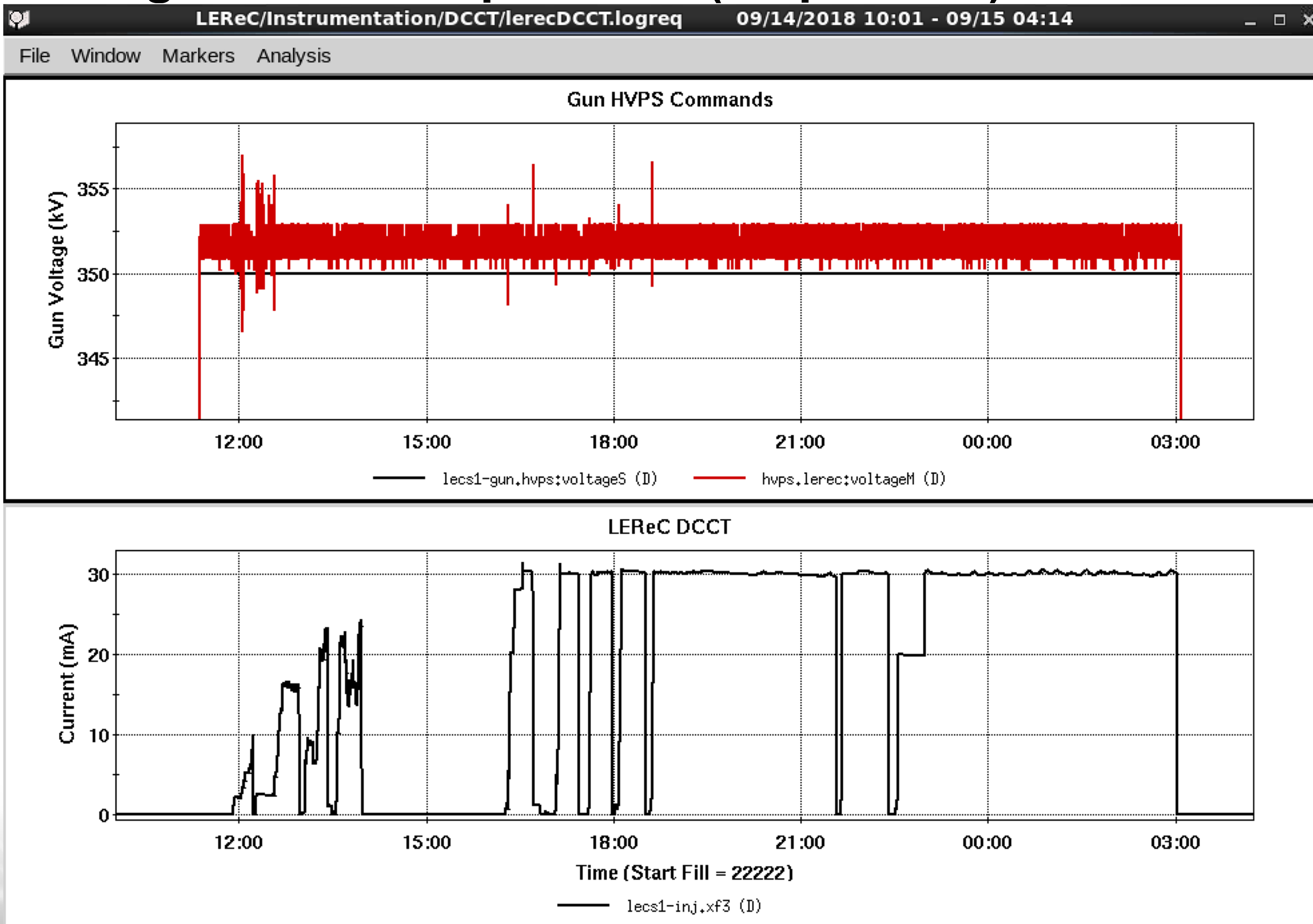


YAG image is flipped, solenoid I=7A rotates image 69 deg

No QE at the center of damaged spots and higher QE around the damaged spots

More about LEReC photocathodes, talk by *Mengjia Gaowei* “**Cathode performance for high current operation in LEReC” on Wednesday WECOXBS02**

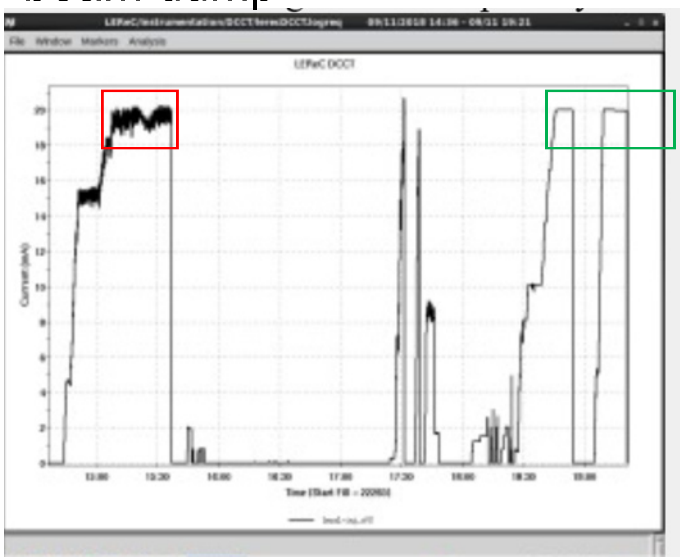
NO single Gun trips with small off center active cathode during 30 mA CW operation (Sept 14-15)



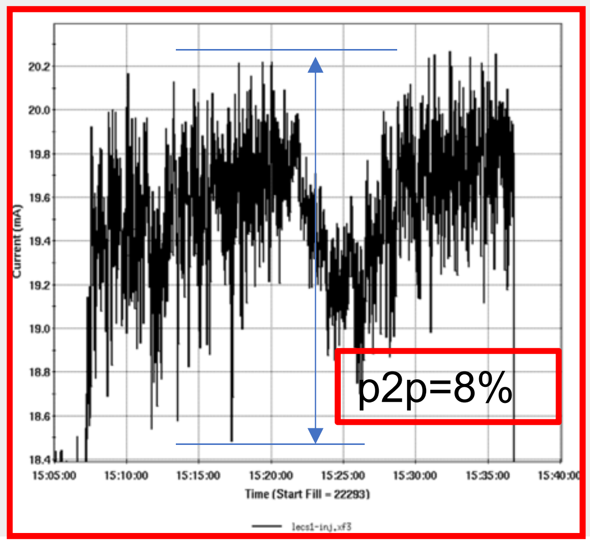
Beam Intensity Stabilization

Successfull implementation and commissioning of Laser and e-Beam based Intensity feedback

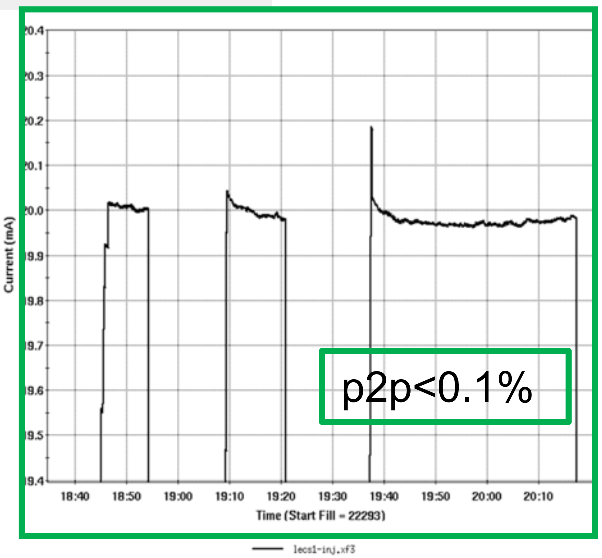
20 mA average current to HP beam dump



Intensity feed back off



Intensity feed back ON



2 stages stabilization:

1. Fast feed back to reduce noise level
2. slow to compensate cathode QE changes

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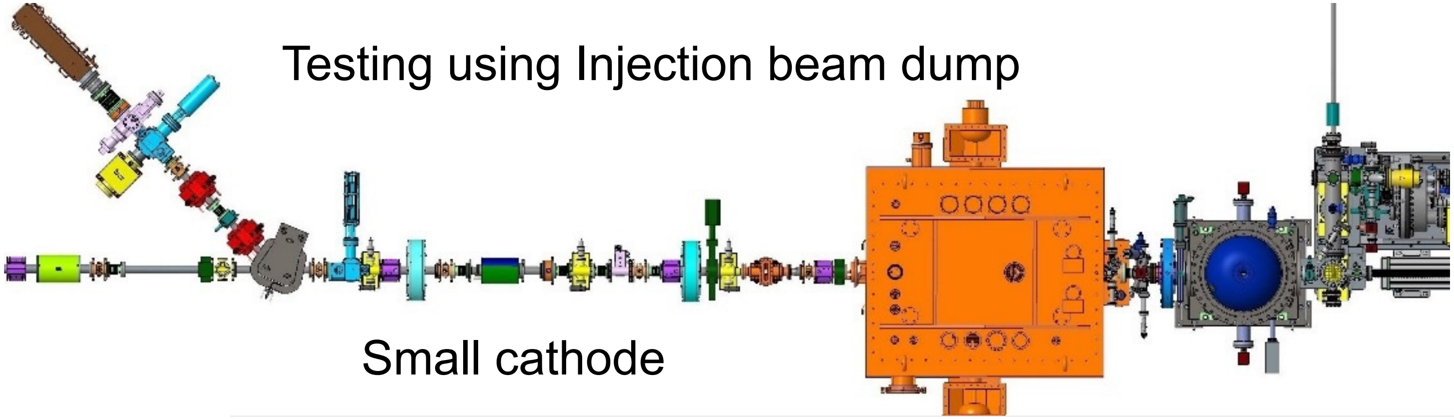
High current 9MHz CW operation to injection beam dump

Run 2018: stable 30 mA beams to the injection beam dump using reduced SRF booster voltage.

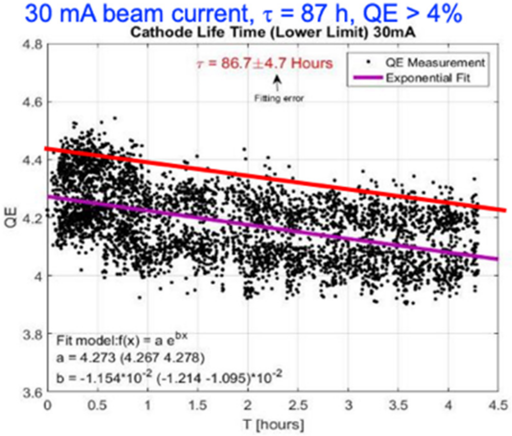
Testing using Injection beam dump

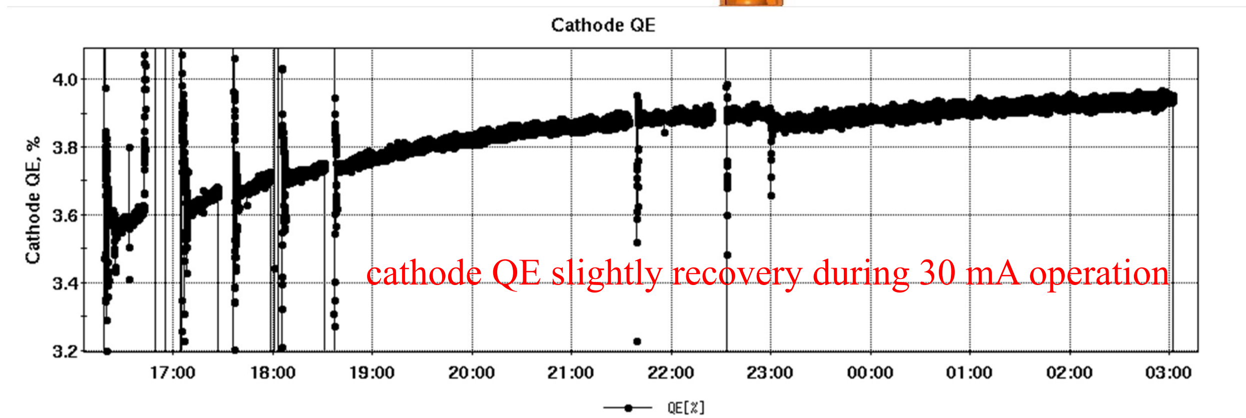


Large cathode

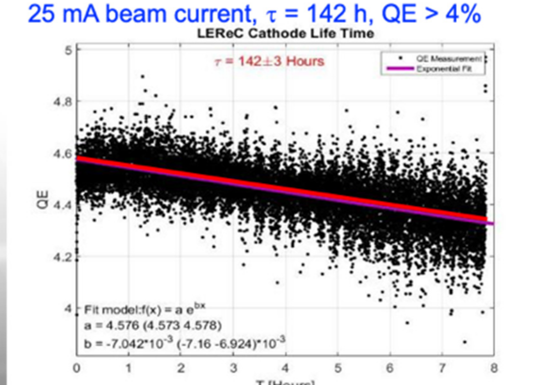
Small cathode

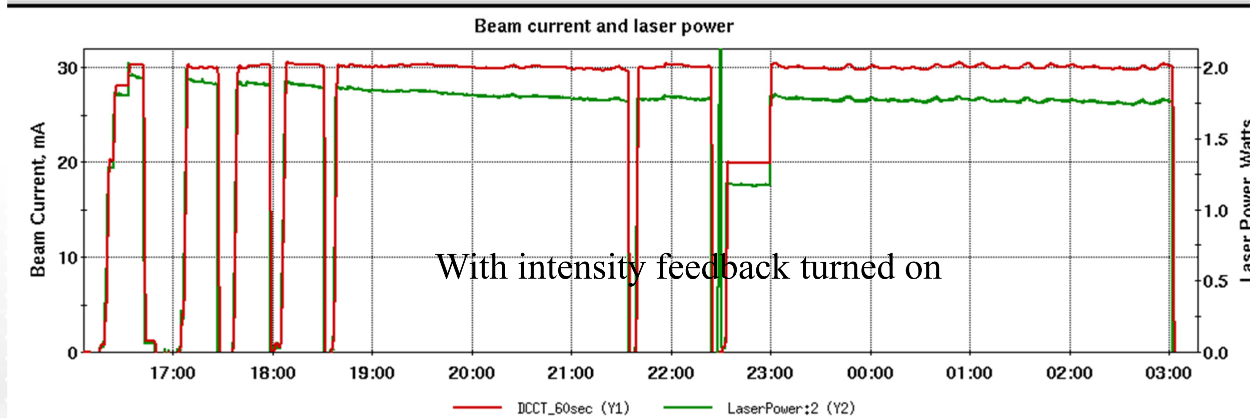
30 mA beam current, τ = 87 h, QE > 4%





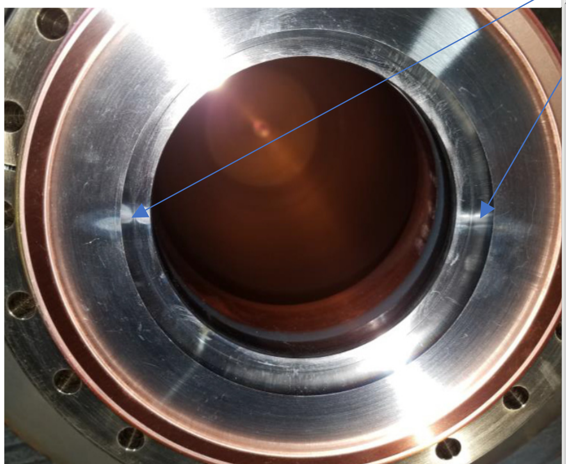
25 mA beam current, τ = 142 h, QE > 4%

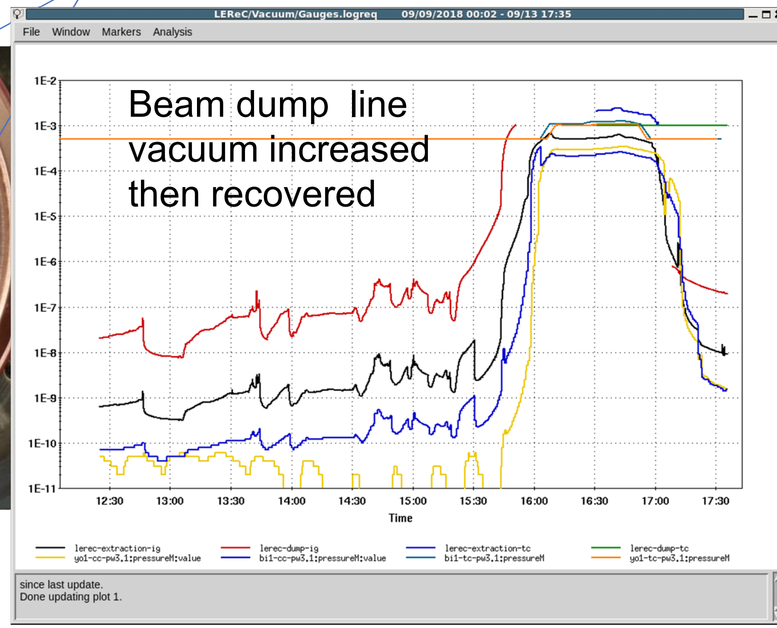


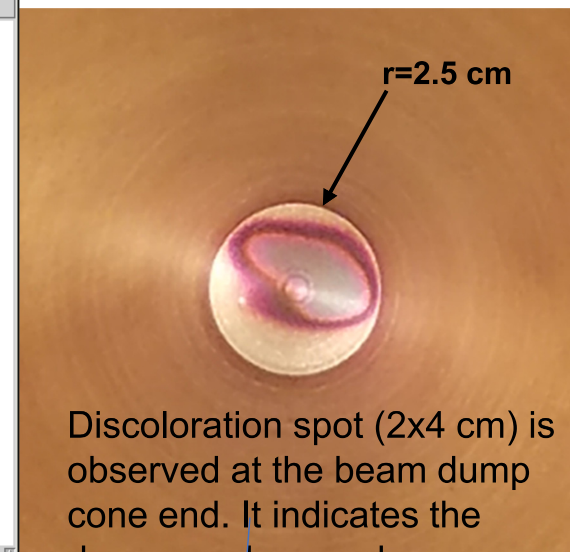


CW operation impact to High Power Beam Dump (2018)

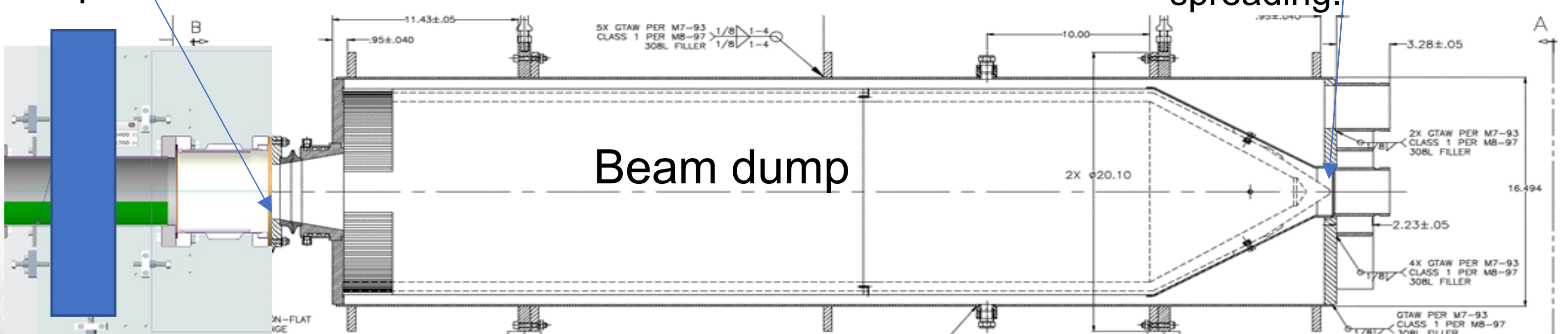
During the summer of 2018, we experienced some difficulties to operate at high current in the final high-power beam dump due to worsening beamline vacuum resulting from beam-induced thermal cycling of the flange in front of the dump. After opening the high-power beam dump at the end of the run 2018 we observed overheating marks at the entrance flange and at the cone tip of the high-power beam dump







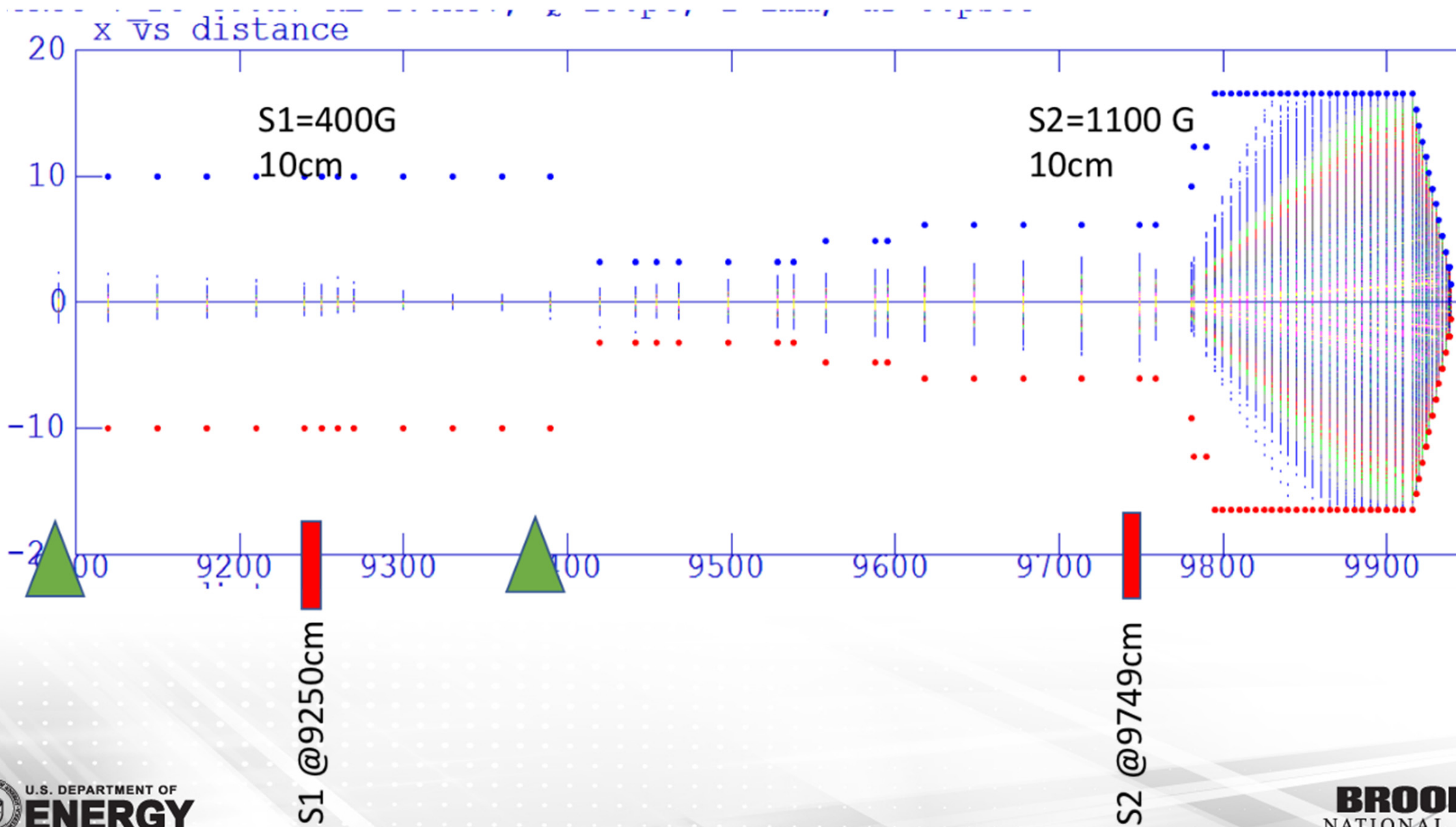
Discoloration spot (2x4 cm) is observed at the beam dump cone end. It indicates the dump needs more beam spreading.



Beam dump line improvements:

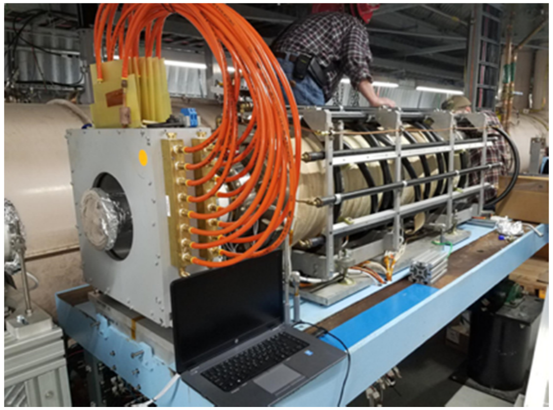
- The beam dump flange has been replaced to larger aperture one
- Quadrupole is replaced by strong field solenoid to provide more uniform spreading in both direction

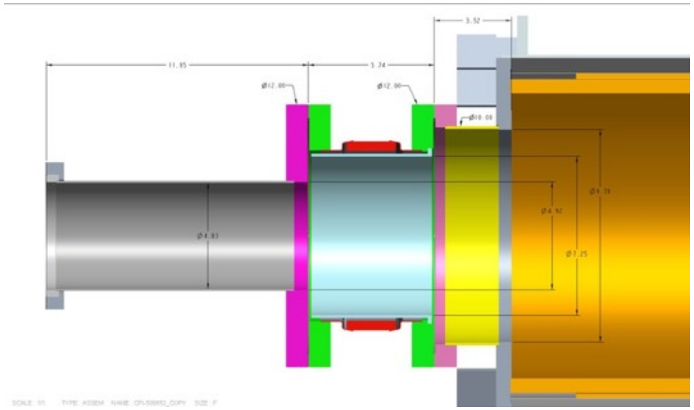
Particles trajectory spreader by over focusing solenoid in beam dump line



Beam Dump Inspections

2018: Opened Dump Aperture, added high field solenoid magnet.





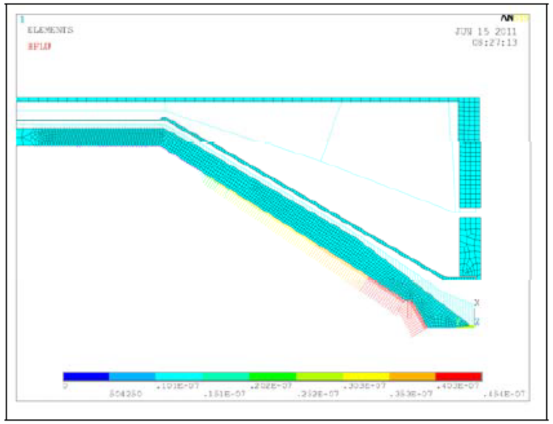


Figure 4: Heat Flux

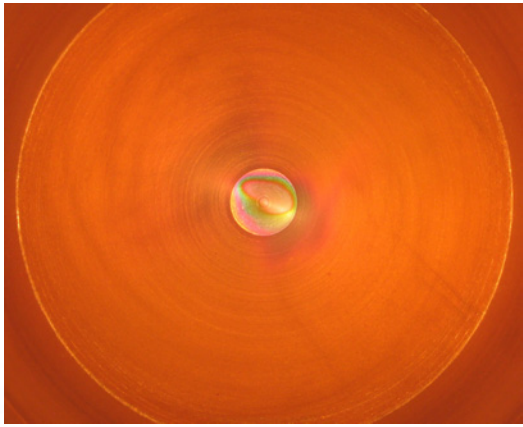
Beam Dump Inspections:

- 2018 HP Dump

Beam dump marks as a result of a high power beam operation during the 2018 run. Beam current 20 mA, kinetic energy 1.6 MeV: end of the cone.

No new marks have been developed after operation of 20-25 mA average current at energy 1.6-2 MeV during the 2019 run.

2019 HP Dump



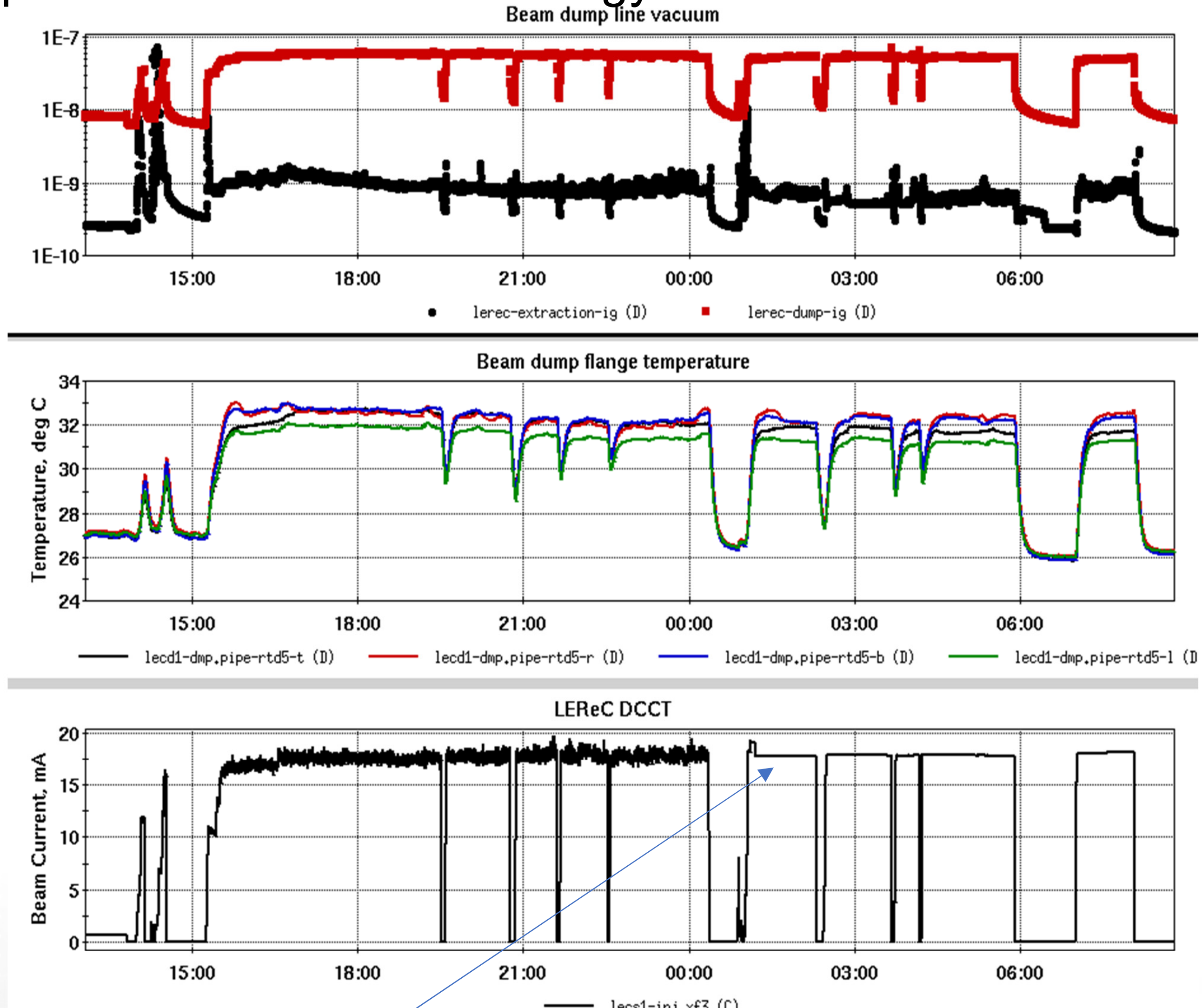
High current 9MHz CW operation full LEReC

operation to the final high-power beam dump at the end of run 2019 with average beam current up to 18 mA and kinetic energy 2 MeV.

At the top plot, vacuum in the extraction line and near the beam dump,

at the middle plot beam dump entrance flange different sides temperatures,

at the bottom plot beam current measured by DCCT.



Intensity feedback was turned on at 01:00 am then beam fast intensity fluctuation has been reduced from 5×10^{-2} to 5×10^{-4} peak-to-peak.

Cooling of ions at RHIC

LEReC: First observation of electron cooling using bunched electron beam (April 5, 2019)

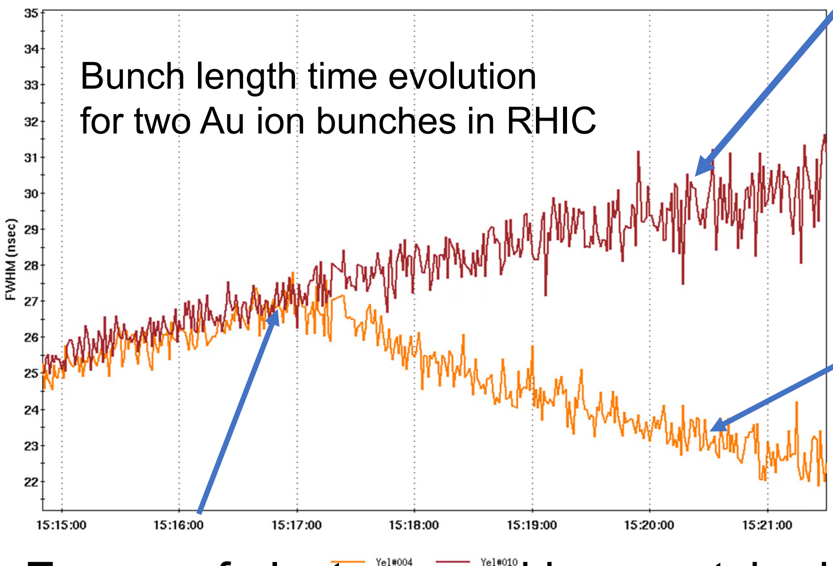
Spring of 2019, a new RF timing system, including a 76 kHz mode of operation, was commissioned. The 76 kHz corresponds to the RHIC revolution frequency at gamma of 4.1.

Cooling commissioning started with the 76 kHz mode of operation, which reduces average beam current and average power by a factor of 120, while providing beam quality and interaction frequency sufficient to cool one ion bunch in each of the RHIC rings

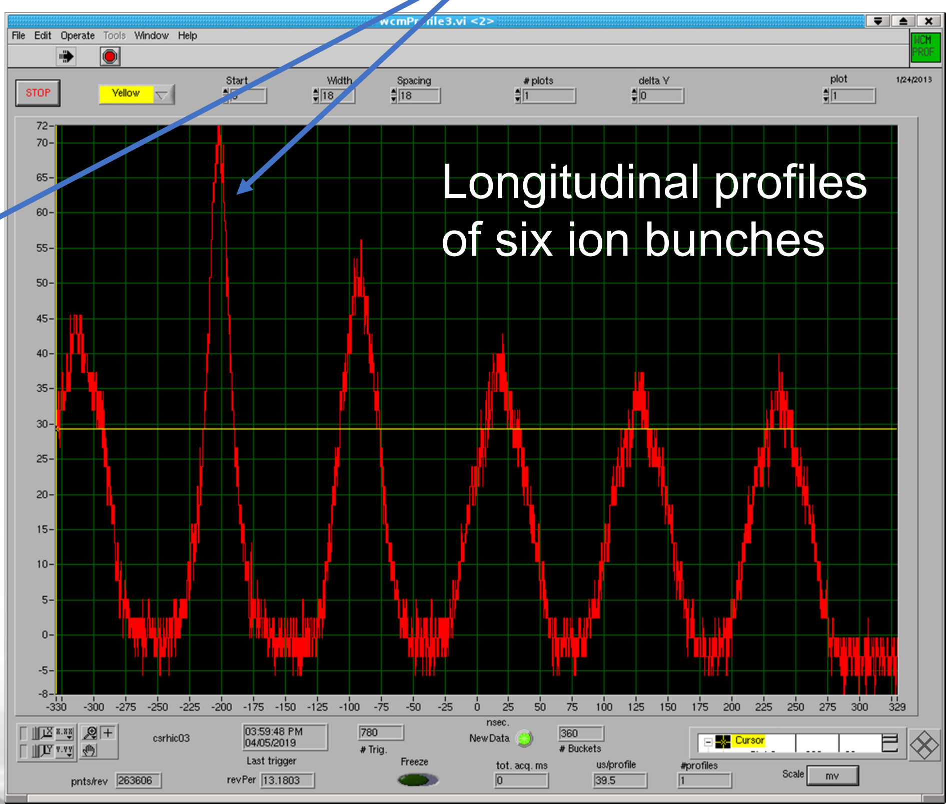
*) A. Fedotov *et al.*, “First electron cooling of hadron beams using a bunched electron beam”, NAPAC 2019, Lansing, MI 2019

Ion bunch #4 which is not being cooled

Ion bunch #2 is being cooled



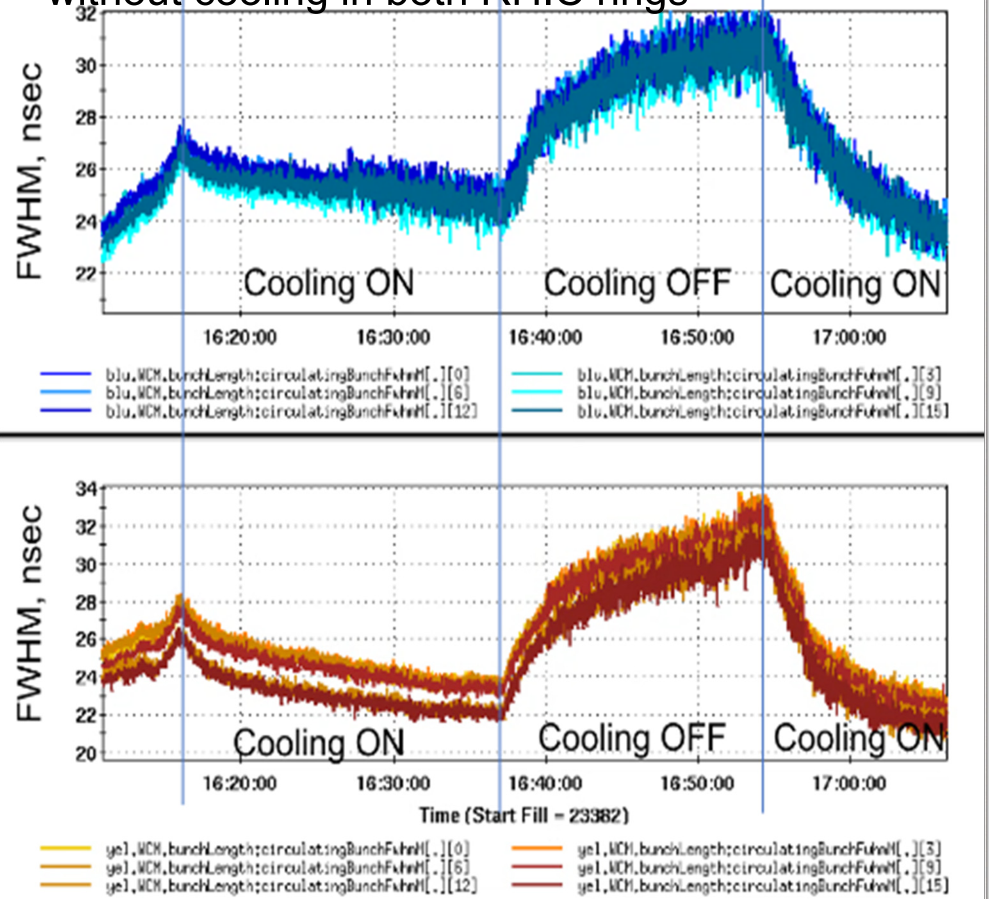
Energy of electrons and ions matched

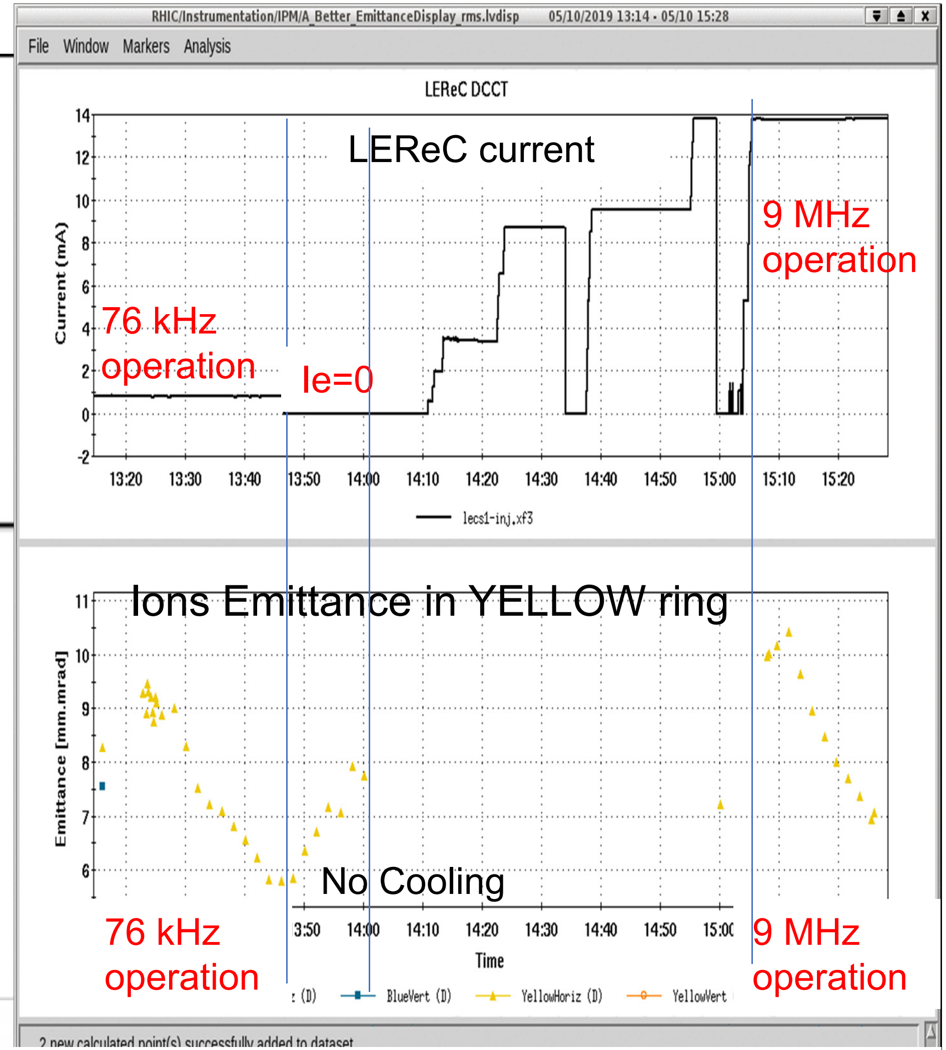


*) S. Seletskiy *et al.*, “Precise beam energy matching for the experimental demonstration of ion cooling with a bunched electron beam.” NAPAC 2019, Lansing, MI 2019

CW operation at 14 mA and simultaneous cooling in Yellow and Blue RHIC rings, 6 bunches in each .

Ion bunch length changes with and without cooling in both RHIC rings

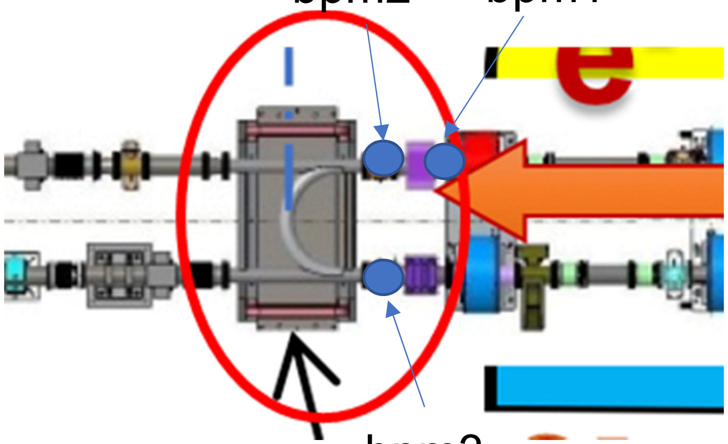




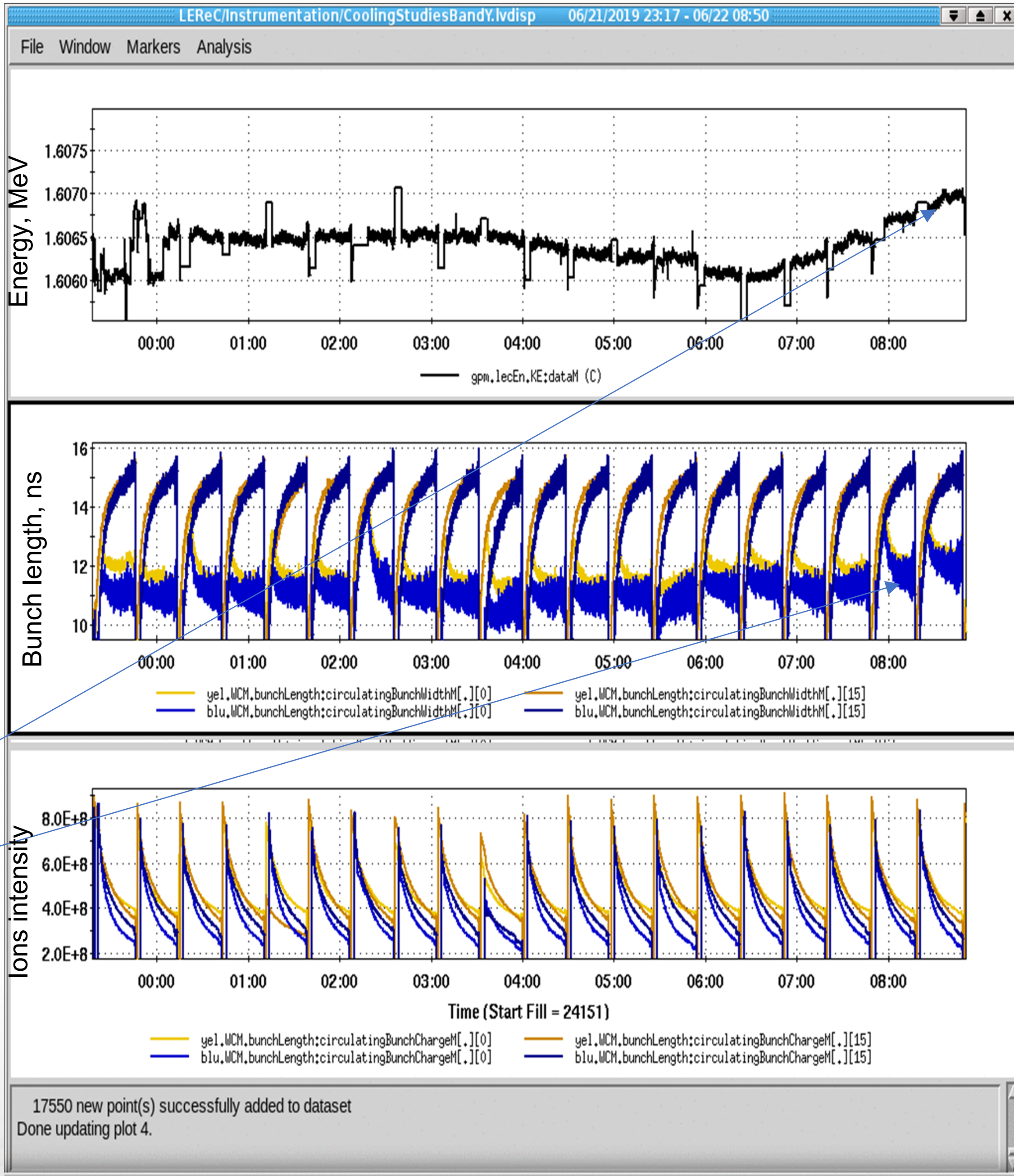
Cooling in CW is not much different then in 76 kHz indicates that beam quality is satisfied LEReC requirement

Long Term Energy Stability in Cooling Section

Based on 3 BPMs system (2 upstream and 1 downstream of mirror magnet) and field of 180 degrees magnet measurements



*) S. Seletskiy et al., "Absolute Energy Measurement of LEReC Electron Beam", NAPAC16, Chicago, USA, 2016



Overnight 9 hours physics stores with one bunch per ring cooled.
Due to temperature changing in the morning LEReC energy is changed then the longitudinal cooling is slightly weaker.
Energy slow feedback could help with this. Plan to commissioning for run 2020.

U.S. DEPARTMENT OF ENERGY

LEReC timeline

May 2015:	LEReC project approved by DOE for construction
December 2016:	DC gun installed and successfully conditioned in RHIC tunnel
February 2017:	Gun Test beamline installed in RHIC
April-Aug., 2017:	First Gun tests with beam
July-Dec., 2017:	Installation of full LEReC accelerator
Jan.-Feb., 2018:	Systems commissioning (RF, SRF, Cryogenics, Instrumentation, Controls, etc.)
March-Sept. 2018:	Commissioning of full LEReC accelerator with e-beam
Sept 2018:	Achieved e-beam quality suitable for cooling
Oct.-Dec., 2018:	Scheduled upgrades and modifications (NO beam testing)
Jan.-Feb., 2019:	Restart operation with electron beam.
March 2019:	Start commissioning with Au ion beams.
	Matched RHIC/LEReC beams energies and trajectories in cooling sections
Apr 2019:	First cooling in one ring then in both RHIC rings using 76 kHz bunch
May 2019:	Simultaneous cooling of many ion bunches using 9MHz CW e-beam
June 2019:	Cooling optimization at 1.6MeV, cooling of beams in collisions (3.85GeV/n ions)
July 2019:	Cooling commissioned at higher electron energy of 2MeV (4.6GeV/n ions)

Summary and Plans

- LEReC is the first electron cooler based on the RF acceleration of electron beam.
- LEReC demonstrated beam parameters required for cooling of ions
- Beam quality suitable for cooling is preserved through acceleration and 100 m of beam line in pulsed and CW modes of operation
- It allowed to cool Ion bunches in both RHIC rings simultaneously using the same LEReC beam at two different energies (gamma 4 and 5)
- **The next step,** optimize LEReC cooling efficiency and effects on ion beam lifetime to maximize collision rates during the next RHIC low-energy run in 2020.
- With a bunched beam electron cooling technique now experimentally demonstrated, its application to high-energy cooling can open new possibilities by producing high-quality hadron beams

Acknowledgement

LEReC success would not be possible without team effort and expertise of many people from various groups of the Collider-Accelerator and other Departments of the BNL.

As well as FNAL, ANL, JLAB and Cornell University.

Thank you!

LEReC team

https://www.bnl.gov/newsroom/news.php?a=215585