Electron cooling of hadrons at RHIC at IR2

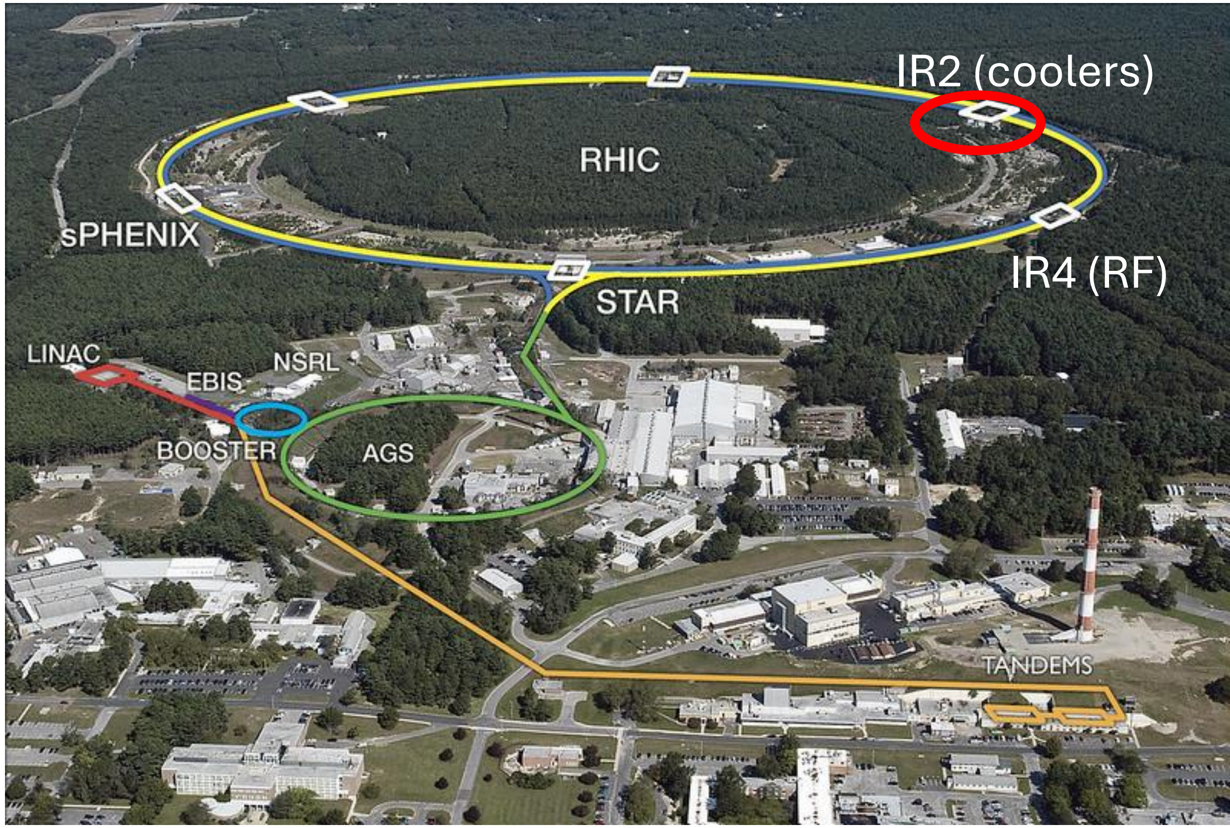
Dmitry Kayran

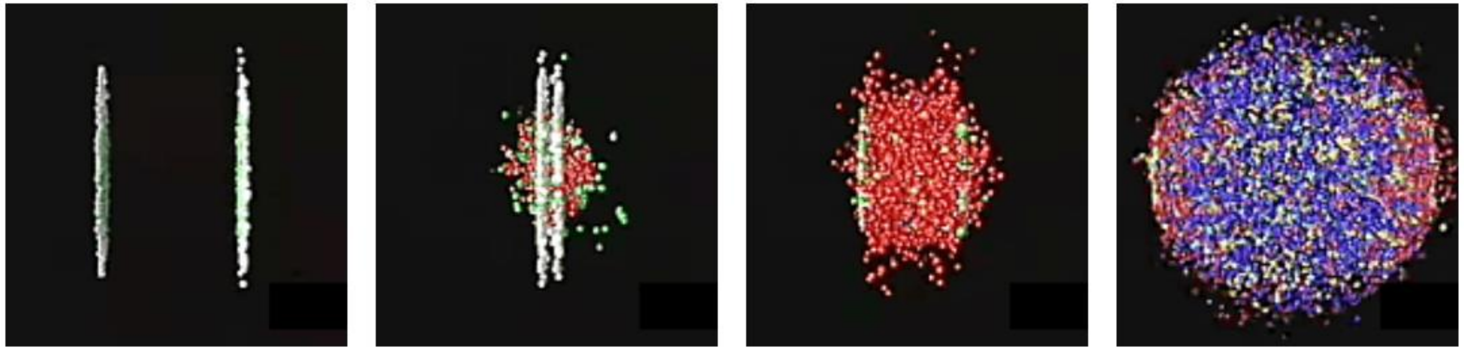
April 21, 2025

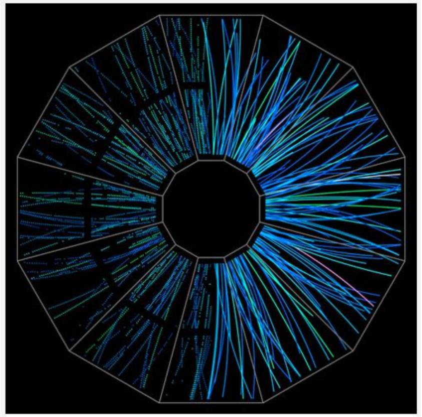
Relativist
Heavy Ions
Collider

Relativist Heavy Ions Collider (RHIC)

- RHIC is the first machine in the world capable of colliding heavy ions RHIC primarily uses ions of gold, one of the heaviest common elements, because its nucleus is densely packed
- RHIC collides two beams of hadrons head-on when they're traveling at nearly the speed of light.
- The beams travel in opposite directions around RHIC's 2.4-mile (3.8km), two-lane "racetrack." At six intersections, the lanes cross, leading to an intersection. When ions collide at such high speeds fascinating things happen.
- Currently Only two intersections are used for detectors

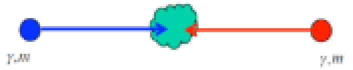



1. Ions about to collide*
2. Ion collision
3. Quarks, gluons freed
4. Plasma created



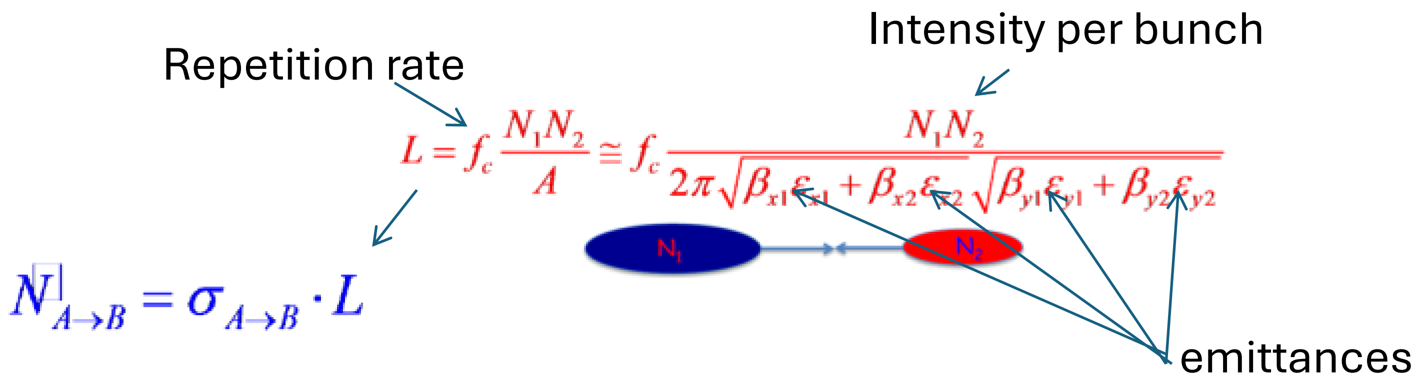
What do we need for colliders?

- In colliders: The minimum energy required to create a particle (or group of particle) with total mass M is: $E_{\min} = Mc^2$



  - High energy colliding particles=>high energy center mass=> massive particles production (cross section σ)
  - luminosity:

Numbers of events



Repetition rate

Intensity per bunch

$$L = f_c \frac{N_1 N_2}{A} \cong f_c \frac{N_1 N_2}{2\pi\sqrt{\beta_{x1}\varepsilon_{x1}+\beta_{x2}\varepsilon_{x2}}\sqrt{\beta_{y1}\varepsilon_{y1}+\beta_{y2}\varepsilon_{y2}}}$$

$$N_{A\to B} = \sigma_{A\to B}\cdot L$$

emittances

- We cannot control cross section of evens. We can control luminosity for some extend
- For more effective data collection we need peak and average luminosity be as high as possible
- For peak luminosity:
  - Minimize emittance,
  - Increase intensity and repetition rate (very often is limited by source and collective instabilities).
- For average luminosity: keeps bunches at store as long as possible (need a good lifetime)

Intro Beam Scattering is the most common beam heating mechanism in hadron machines: increase longitudinal emittances (loss particles from RF bucket) and may increase transverse emittance

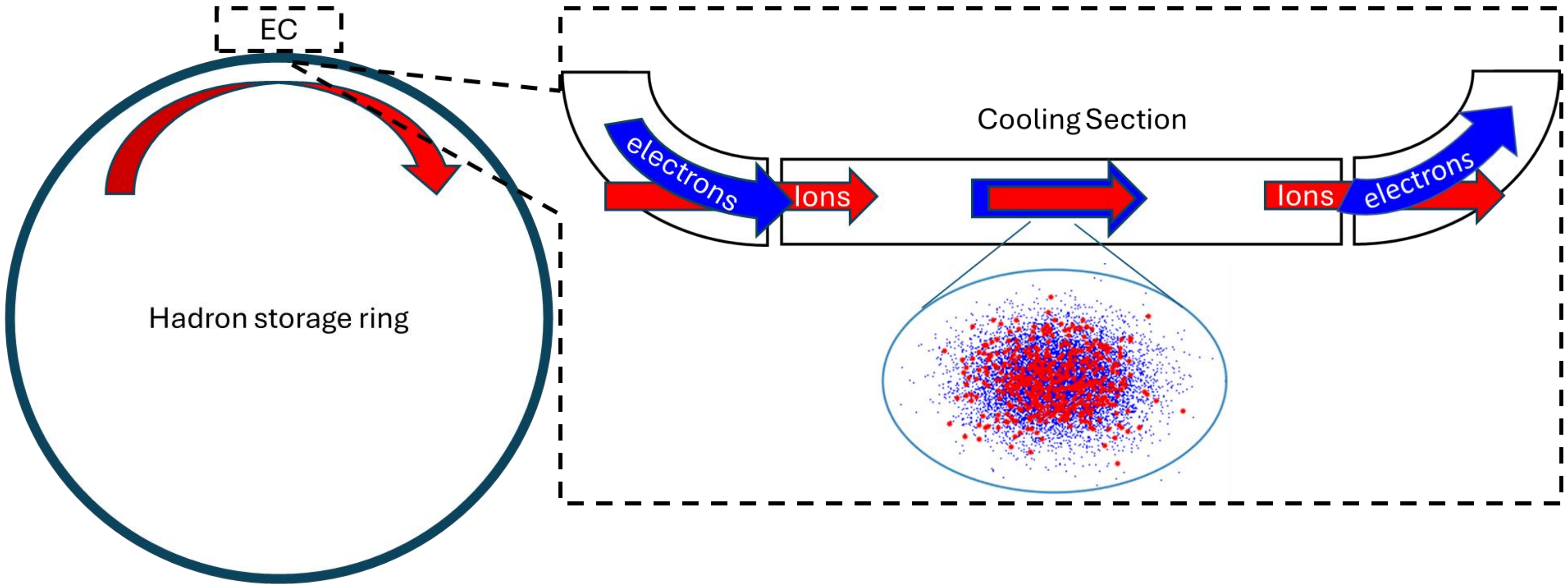
IBS (google it) :)

- IBS involves multiple small-angle Coulomb scattering events between particles within a beam
- These scatterings cause particles to change their momentum and energy, leading to a diffusion-like growth in the beam's dimensions in phase space
- IBS increases the beam emittance, which is a measure of the beam's size and divergence in phase space.
- The growth of emittance can degrade beam quality, reduce luminosity in colliders, and affect the performance of light sources and other applications.

Cooling would be very useful to overcome heating due to IBS

What is Electron Cooling?

- Mix a hadron bunch with an electron bunch traveling with the same velocity and let the two bunches travel together over some length. ➡ The velocity spread of hadrons will get reduced. Why?
- In the co-moving frame, the mixture of an ion bunch and an electron bunch looks like a mixture of two gases – a gas of ions and a gas of electrons
- Electrons are much lighter; hence, the gas of electrons is much colder than the gas of ions. ➡ Heat transfer ≡ Electron Cooling



$$m_e \ll m_i$$

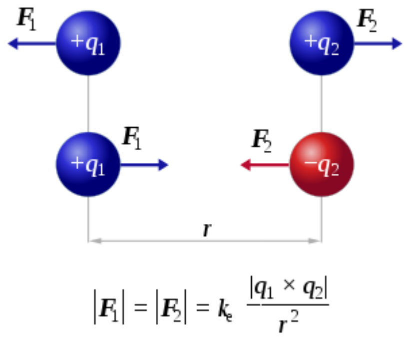
$$T = \frac{m\bar{v}^2}{3k_B}$$

$$T_e \ll T_i$$

Dynamical friction and Electron Cooling

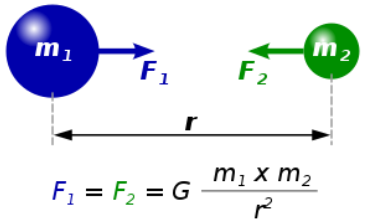
- In the co-moving frame, electron bunch looks like a “gas of electrons”
- An ion is much heavier than the electrons
- So, in the co-moving frame we have a massive object (an ion) moving through the cloud of much lighter particles
- The electric force and the gravitational force look very similar:

Coulomb’s law:

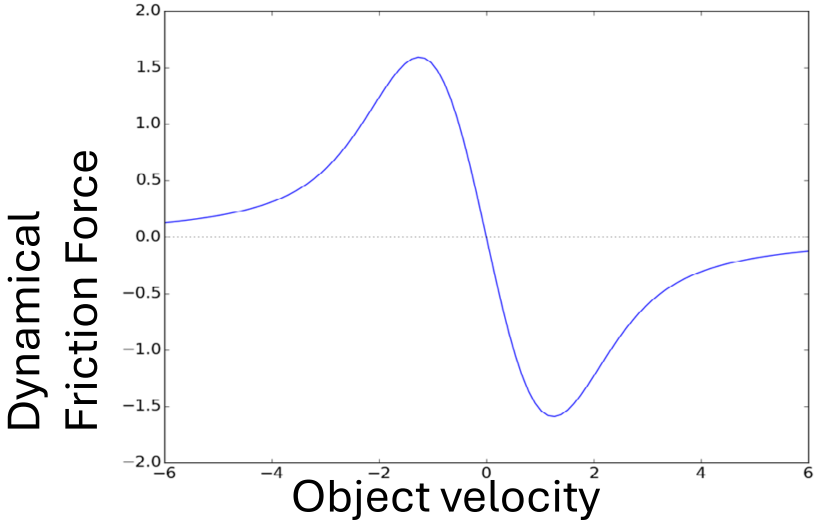


$$|F_1| = |F_2| = k_e \frac{|q_1 \times q_2|}{r^2}$$

Newton’s law:



$$F_1 = F_2 = G\,\frac{m_1 \; x \; m_2}{r^2}$$



- Then for the Electron cooling we will see the same effect of dynamical friction, which we see in astrophysics.
- Why it’s important? Because in order to describe electron cooling we would use friction force formulas what were

first established by Subrahmanyan Chandrasekha in 1943 “As a massive celestial object (a star, for example) is moving through a cloud of smaller lighter bodies (for instance, space dust) the gravitational pull from the “space dust cloud” slows down the star. This effect is called **Dynamical Friction**.”

Friction force in Electron Cooling

density of electron bunch

ion velocity

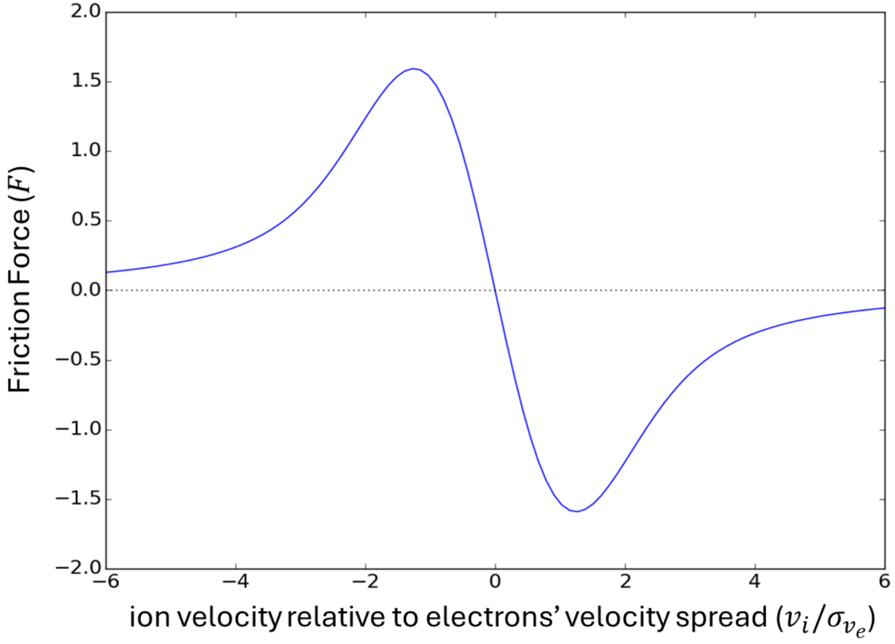
electron velocity

$$\boxed{\vec{F} = -\frac{4\pi n_e e^4 Z_i^2}{m_e}\int \Lambda_C \frac{\overrightarrow{v_i} - \overrightarrow{v_e}}{|\overrightarrow{v_i} - \overrightarrow{v_e}|^3} f_e(v_e) d^3 v_e}$$

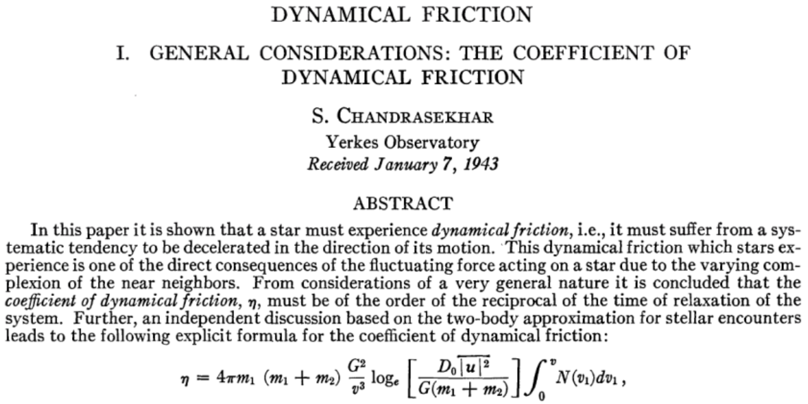
Coulomb logarithm $\Lambda_C = \ln\left(\frac{\rho_{max}}{\rho_{min}}\right)$

e-velocity distribution function

$$\rho_{min} = \frac{Ze^2}{m_e}\frac{1}{|\overrightarrow{v_i} - \overrightarrow{v_e}|^2}; \quad \rho_{max} = \max\left(\frac{\langle v_i\rangle}{\sqrt{4\pi n_e r_e c^2}}, \frac{\langle v_i\rangle}{L_{CS}\gamma\beta c}\right)$$



- 1943



DYNAMICAL FRICTION

I. GENERAL CONSIDERATIONS: THE COEFFICIENT OF DYNAMICAL FRICTION

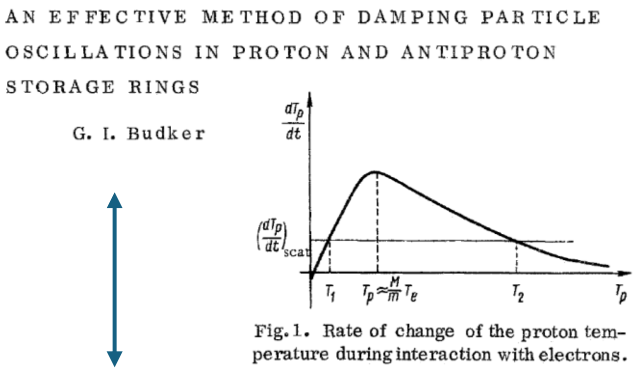
S. CHANDRASEKHAR
Yerkes Observatory
Received January 7, 1943

ABSTRACT

In this paper it is shown that a star must experience *dynamical friction*, i.e., it must suffer from a systematic tendency to be decelerated in the direction of its motion. This dynamical friction which stars experience is one of the direct consequences of the fluctuating force acting on a star due to the varying complexion of the near neighbors. From considerations of a very general nature it is concluded that the *coefficient of dynamical friction*, η, must be of the order of the reciprocal of the time of relaxation of the system. Further, an independent discussion based on the two-body approximation for stellar encounters leads to the following explicit formula for the coefficient of dynamical friction:

$$\eta = 4\pi m_1 (m_1 + m_2)\frac{G^2}{v^3}\log_e\left[\frac{D_0 \overline{|u|^2}}{G(m_1+m_2)}\right]\int_0^v N(v_1)dv_1 ,$$

- 1956; 1966



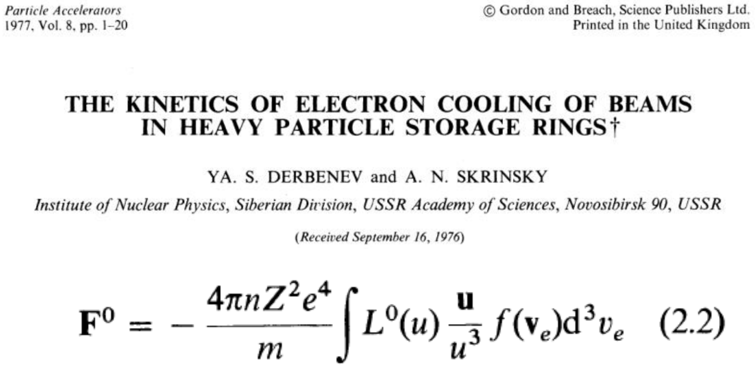
AN EFFECTIVE METHOD OF DAMPING PARTICLE OSCILLATIONS IN PROTON AND ANTIPROTON STORAGE RINGS

G. I. Budker

Fig. 1. Rate of change of the proton temperature during interaction with electrons.

S.T. Belyaev and G.I. Budker, Doklady Akad. Nauk SSSR, 107, 807 (1956).

- 1977



Particle Accelerators
1977, Vol. 8, pp. 1–20

© Gordon and Breach, Science Publishers Ltd.
Printed in the United Kingdom

THE KINETICS OF ELECTRON COOLING OF BEAMS IN HEAVY PARTICLE STORAGE RINGS†

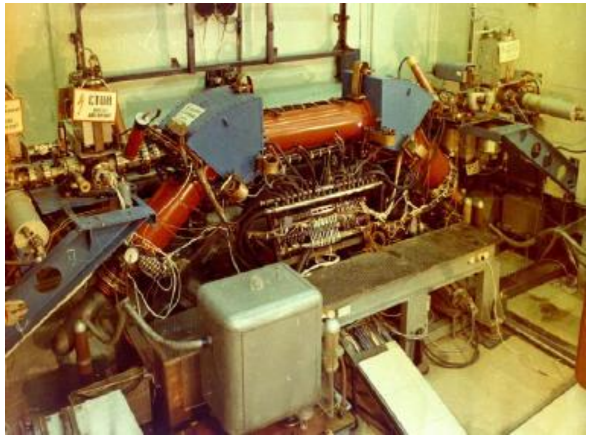
YA. S. DERBENEV and A. N. SKRINSKY

Institute of Nuclear Physics, Siberian Division, USSR Academy of Sciences, Novosibirsk 90, USSR

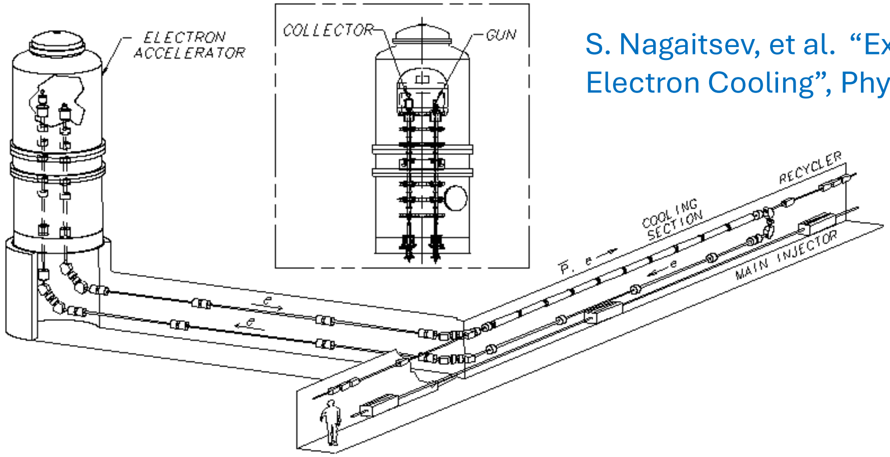
(*Received September 16, 1976*)

$$\mathbf{F}^0 = -\frac{4\pi n Z^2 e^4}{m}\int L^0(u)\frac{\mathbf{u}}{u^3} f(\mathbf{v}_e)\mathrm{d}^3 v_e \quad (2.2)$$

Electron Cooling



Experimental demonstration of electron cooling at NAP-M (Novosibirsk, 1974).



S. Nagaitsev, et al. “Experimental Demonstration of Relativistic Electron Cooling”, Phys. Rev. Lett. 96, 044801 (2006)

- **Electron Cooling is a well-established technique with 50 years of experimental experience.**

High Voltage DC coolers: (1974-): all DC electrostatic accelerators; all use magnetic field to confine electron beam (magnetized cooling). **FNAL cooler (2005-11):** Extension to relativistic energies (4MeV electrons), transport of electron beam without continuous magnetic field.

RF acceleration (High Energy approach): BNL LEReC electron cooler (2019-21): First RF-linac based electron cooler (concept directly extendable to higher energies). LEReC does not use any magnetization of electrons. LEReC was successfully used for RHIC operations in 2020-21 to cool ion bunches directly at collision energy.

A. V. Fedotov et al. “Experimental Demonstration of Hadron Beam Cooling Using Radio-Frequency Accelerated Electron Bunches”, Phys. Rev. Lett. 124, 084801 (2020)

LEReC Project

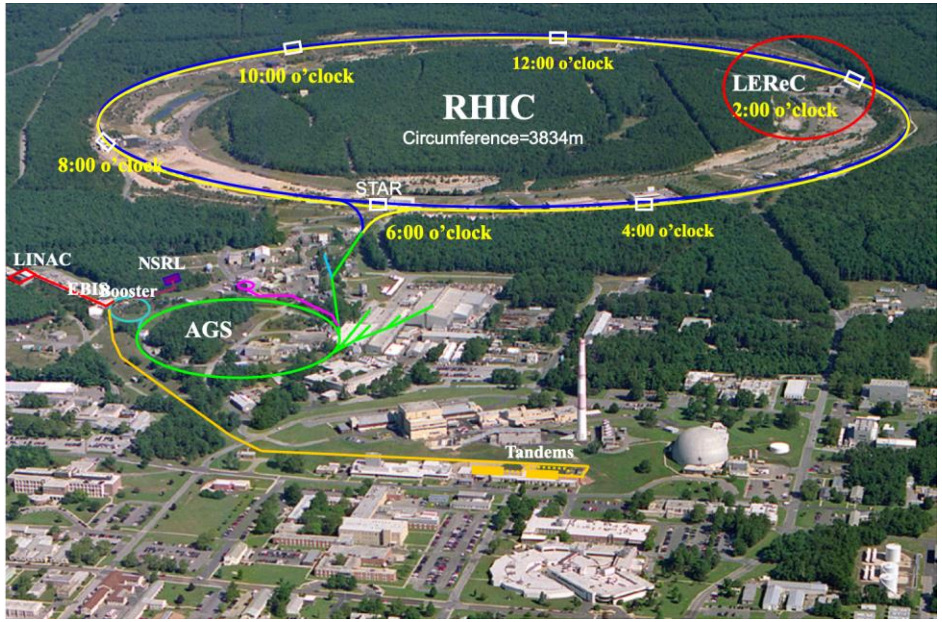
The Goal of the LEReC project is to provide luminosity improvement for RHIC operation at low energies to search for a QCD critical point: Beam Energy Scan Phase-II physics program

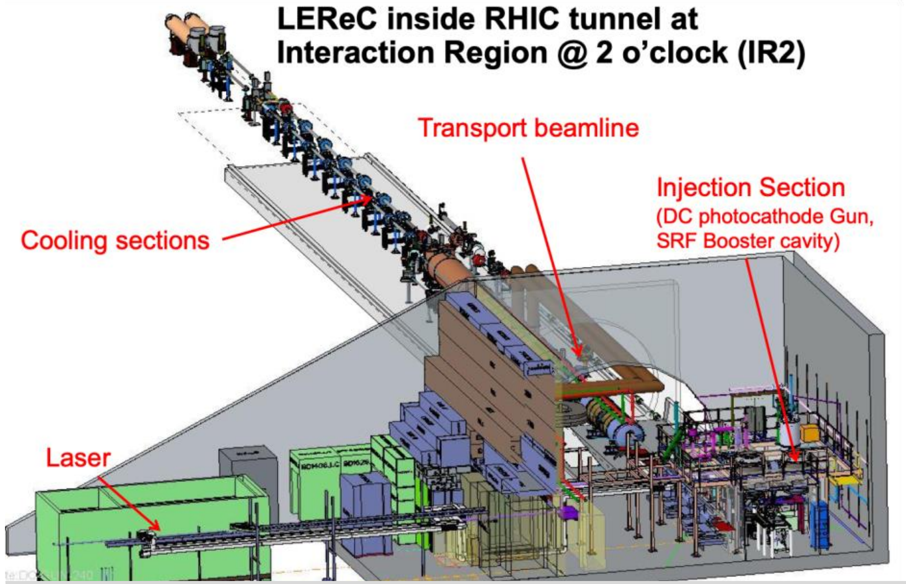
LEReC is first RF linac-based electron cooler (bunched beam cooling)

Required:

Building and commissioning of new state of the art electron accelerator

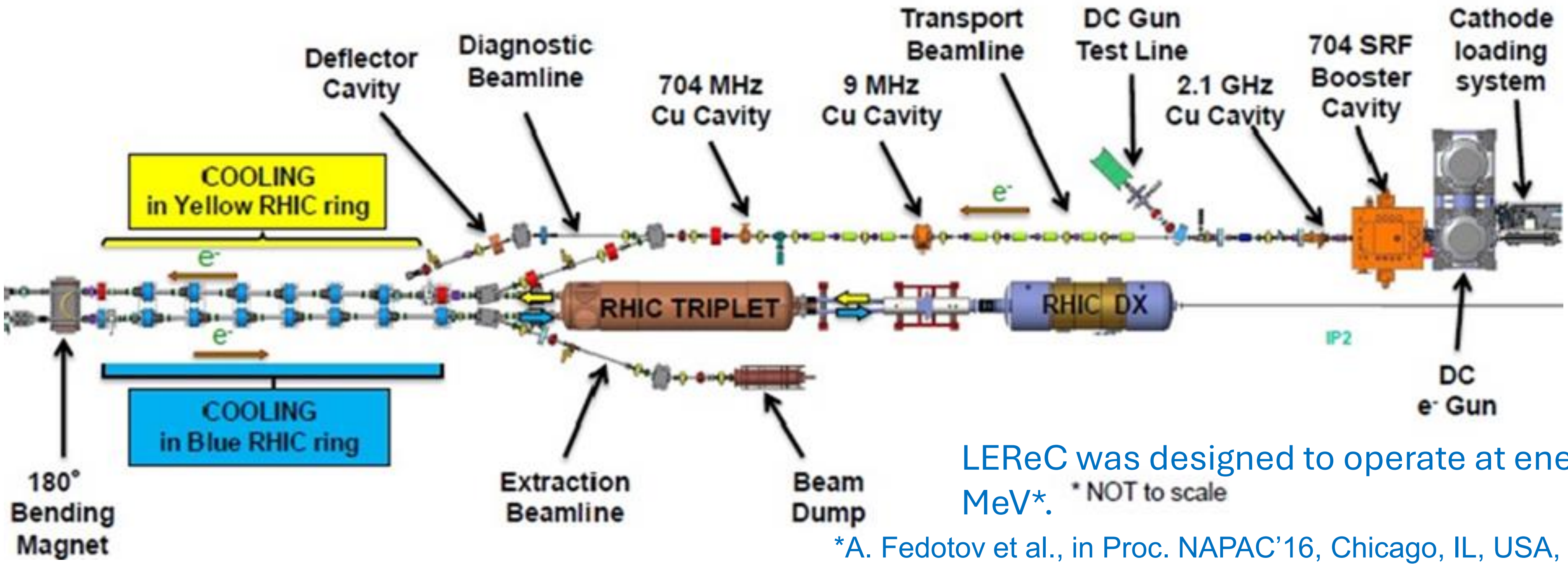
- ☐ **Produce electron beam with beam quality suitable for cooling**
- ☐ **RF acceleration and transport maintaining required beam quality**
- ☐ **Achieve required beam parameters in cooling sections**
- ☐ **Commissioning of bunched beam electron cooling**
- ☐ **Commissioning of electron cooling in a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




LEReC inside RHIC tunnel at Interaction Region @ 2 o'clock (IR2)

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

LEReC electron cooler



LEReC was designed to operate at energies up to 2.6 MeV*.

*A. Fedotov et al., in Proc. NAPAC’16, Chicago, IL, USA, Oct. 2016, pp. 867-869.

- **LEReC is a fully-operational electron cooler which:**
  - utilizes **RF-accelerated** electron bunches
  - uses non-magnetized electron beam (there is no magnetization at the cathode and there is no continuous solenoidal field in the cooling section)

- **LEReC approach was chosen for the EIC LEC (12.5 MeV electron kinetic energy).**

LEReC electron beam parameters

Two energies commissioned ✓

Electron beam requirement for cooling			
Kinetic energy, MeV	1.6	2	2.6
Cooling section length, m	20	20	20
Electron bunch (704MHz) charge, pC	130	170	200
Effective charge used for cooling	100	130	150
Bunches per macrobunch (9 MHz)	30	30	24-30
Charge in macrobunch, nC	4	5	5-6
RMS normalized emittance, um	< 2.5	< 2.5	< 2.5
Average current, mA	36	47	45-55
RMS energy spread	< 5e-4	< 5e-4	< 5e-4
RMS angular spread	<150 urad	<150 urad	<150 urad

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.

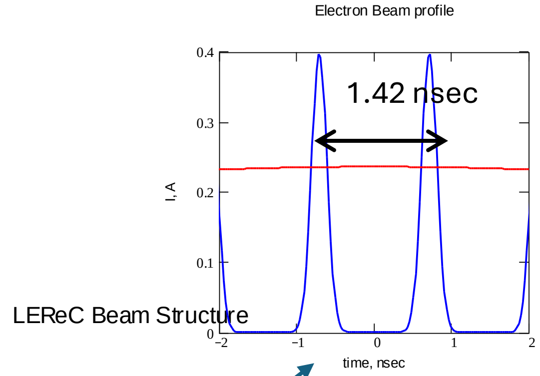
- Accelerate such bunches with RF and use RF gymnastics (several RF cavities) to achieve energy spread required for cooling.
- Deliver and maintain beam quality in both cooling sections.

- Electron bunch overlaps only small portion of ion bunch. All amplitudes are being cooled as a result of synchrotron oscillations.

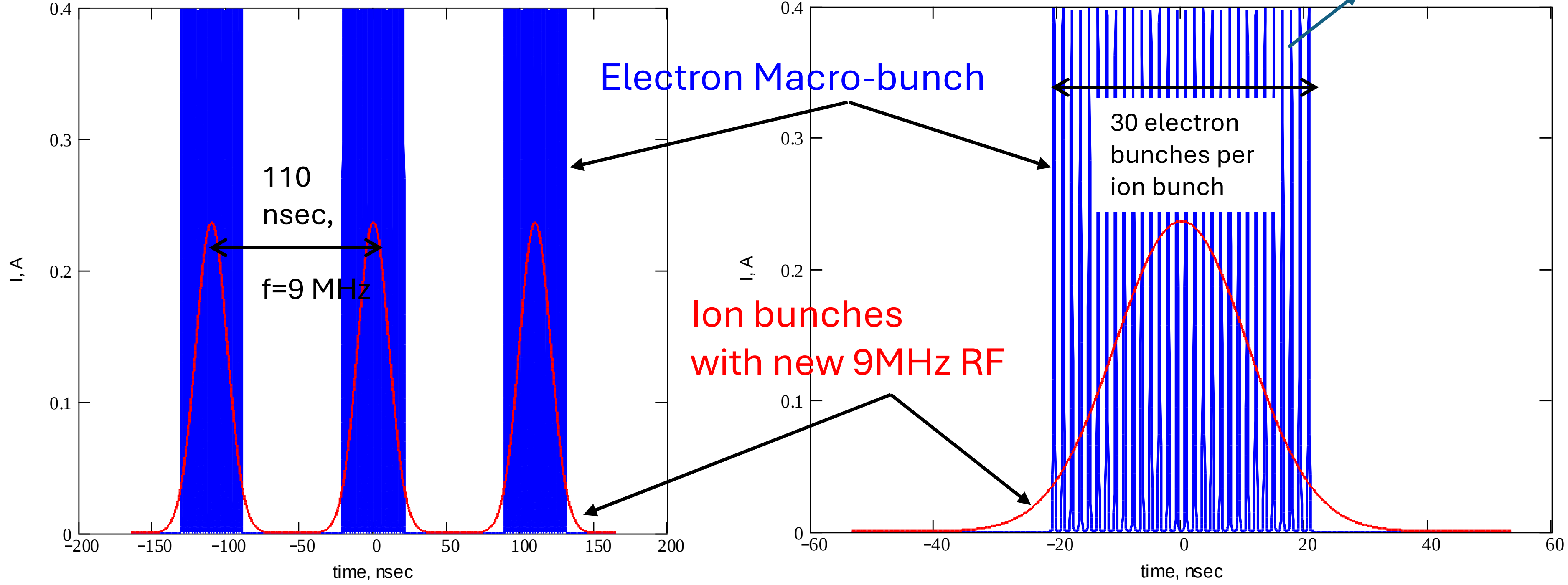
LEReC beam structure in cooling section

Ions structure:
120 bunches
f_rep=120x75.8347 kHz=9.1 MHz
N_ion=5e8, I_peak=0.24 A
Rms length=3 meters

Electrons:
f_SRF=704 MHz
Q_e=100 pC, I_peak=0.4 A
Rms length=3 cm

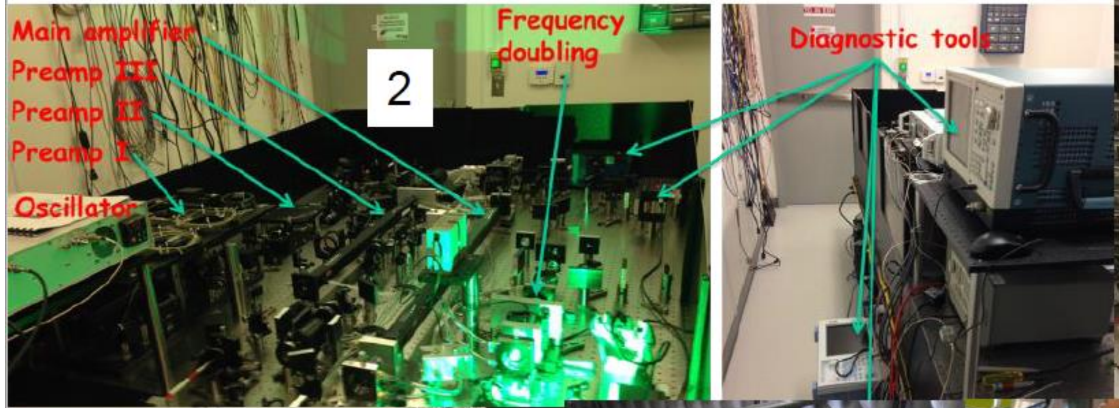


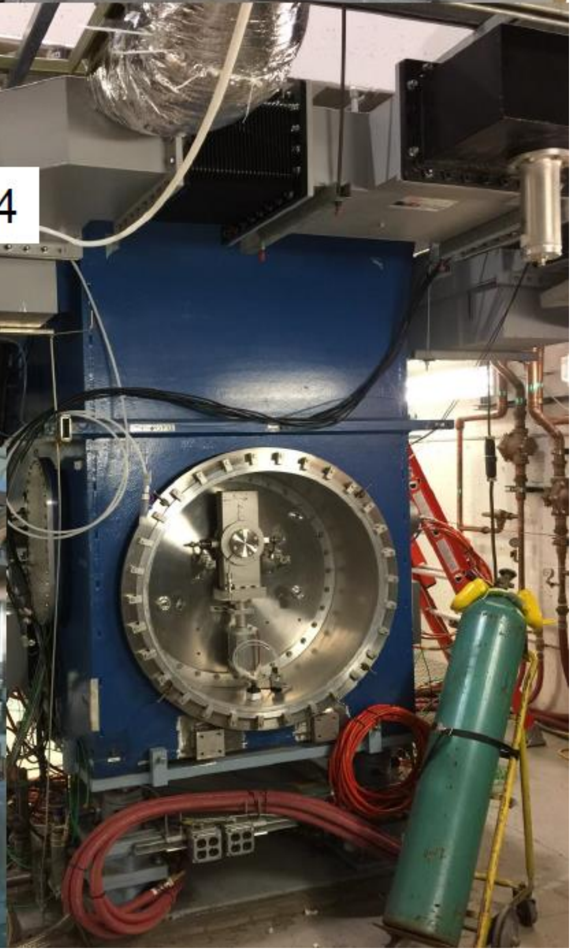
9 MHz bunch structure

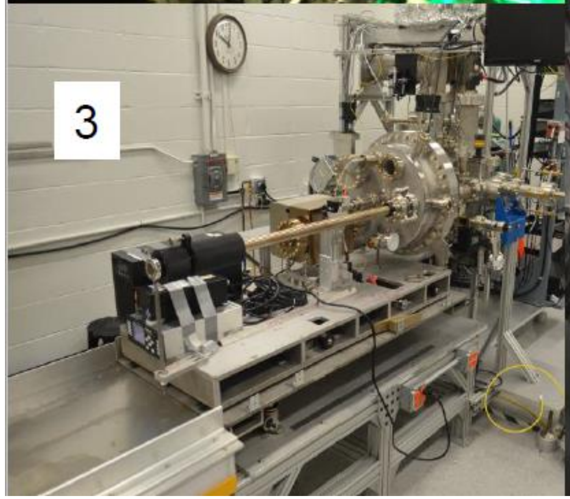


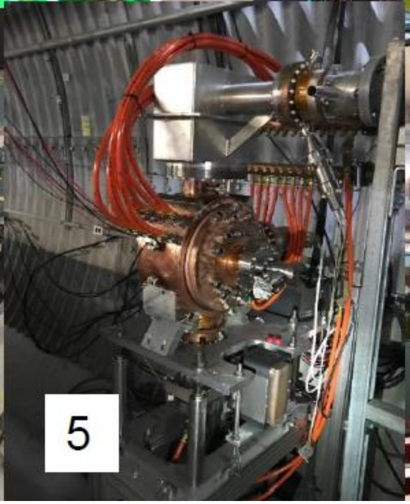
LEReC Critical Technical Systems

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

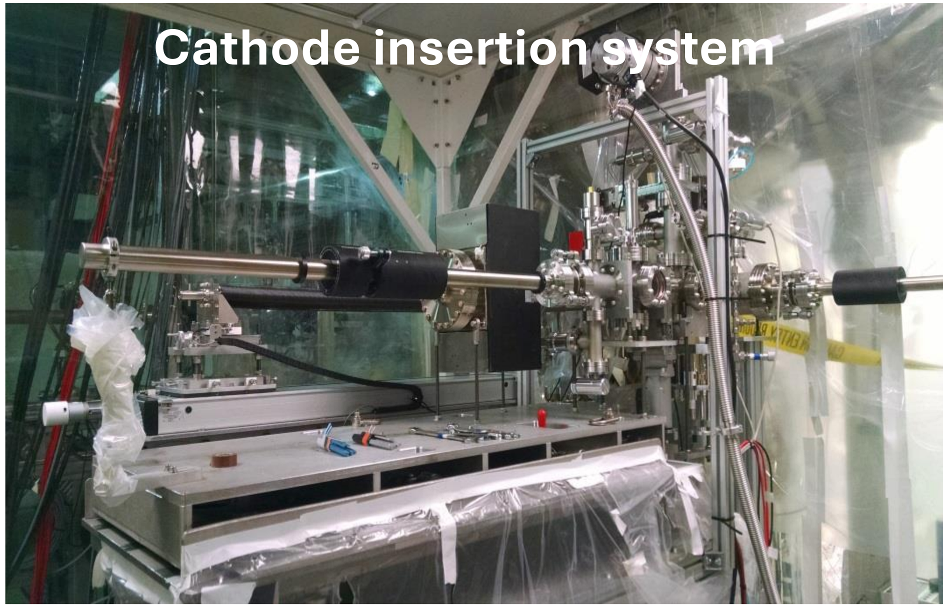






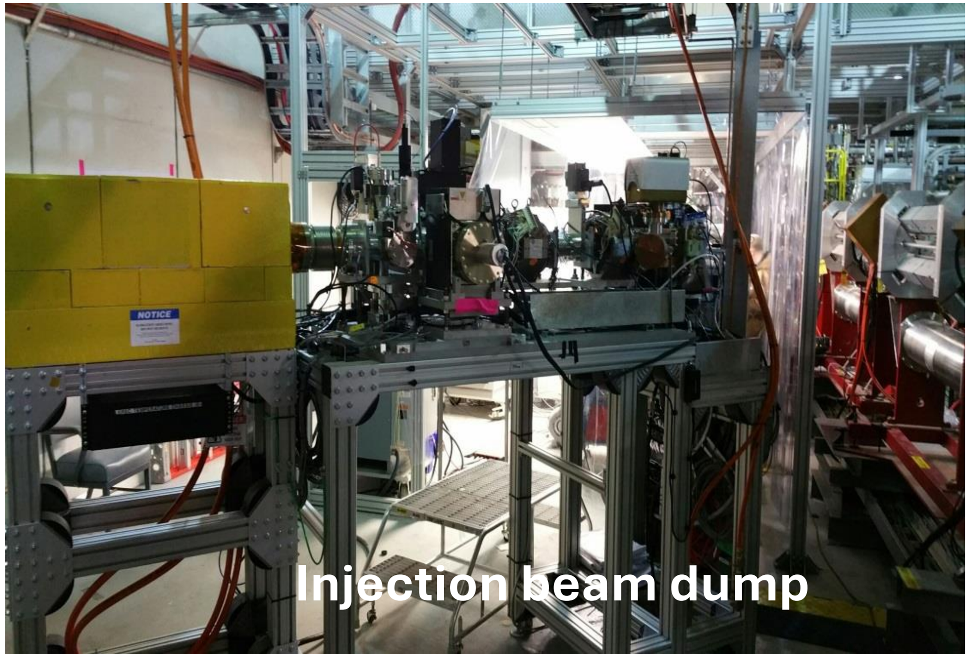


LEReC Gun test beamline (2017)


Cathode insertion system

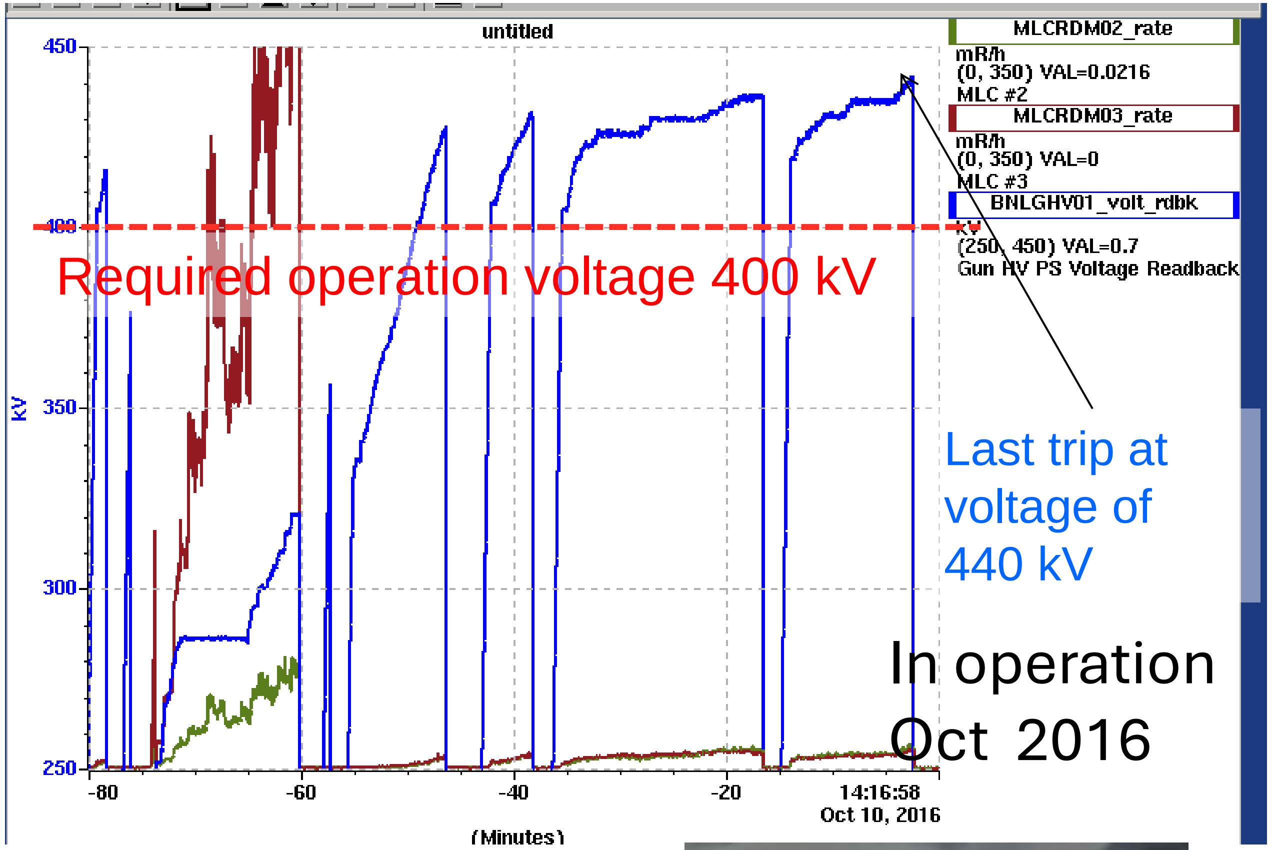

Gun transport section


Injection beamline


Injection beam dump

BNL DC gun performance during HV conditioning at Cornell

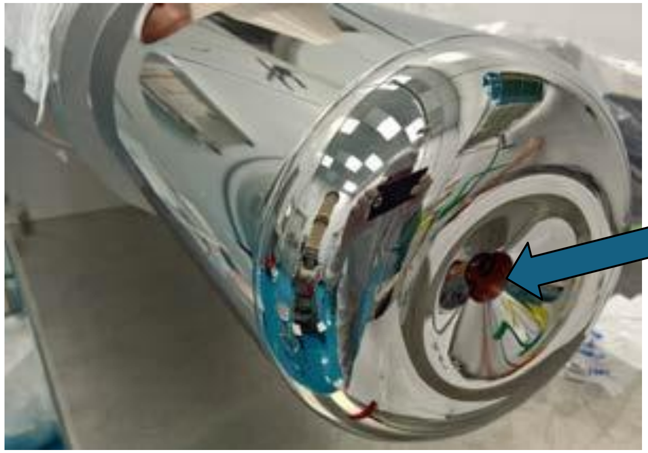
Designed, built and conditioned at Cornell University

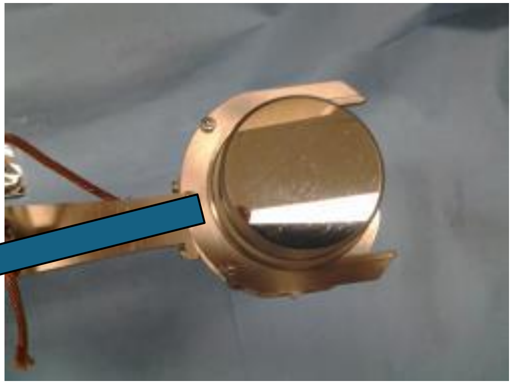


Required operation voltage 400 kV

Last trip at voltage of 440 kV

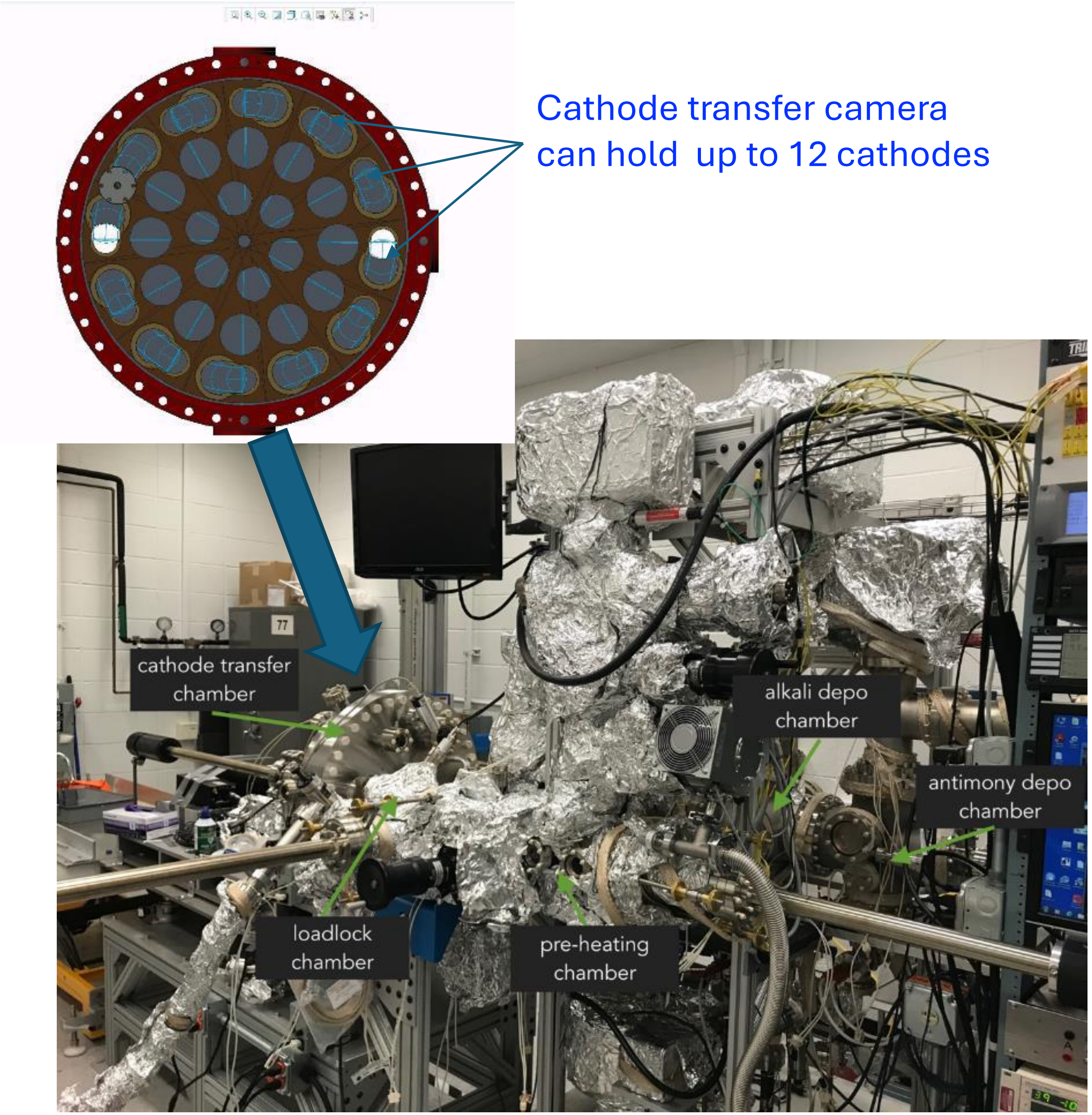
In operation Oct 2016





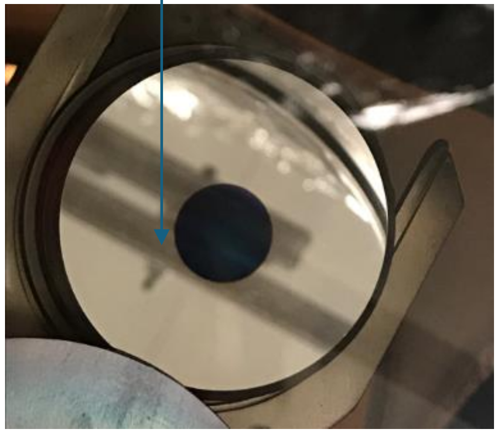
Molybdenum cathode plug

Photocathode production (in instrumentation building)

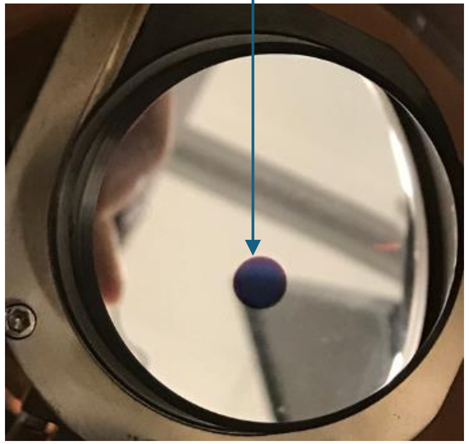


Cathode transfer camera can hold up to 12 cathodes

On center 12mm active area
Used 2017-18 commissioning



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



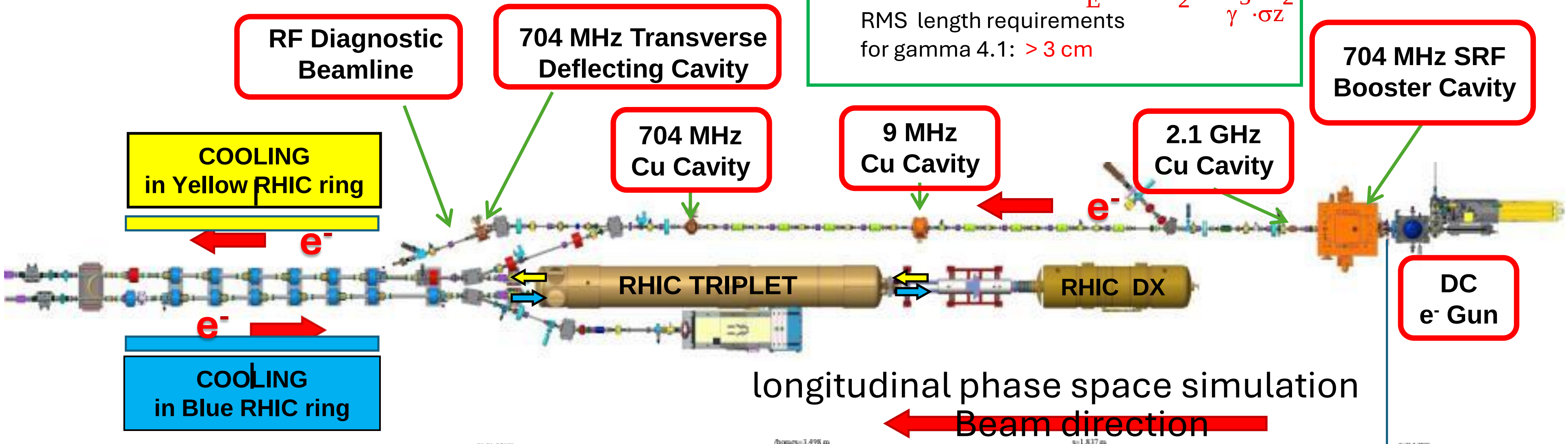
Longitudinal gymnastic

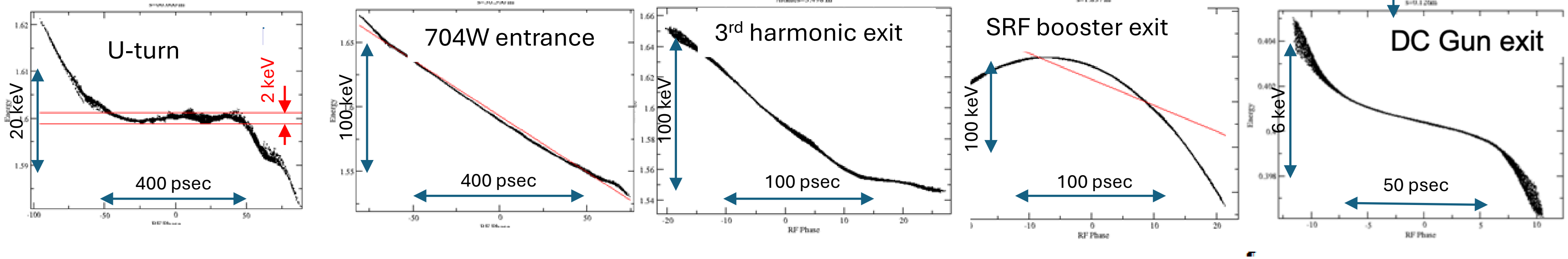
Energy spread due to longitudinal Space charge

Gaussian beam

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

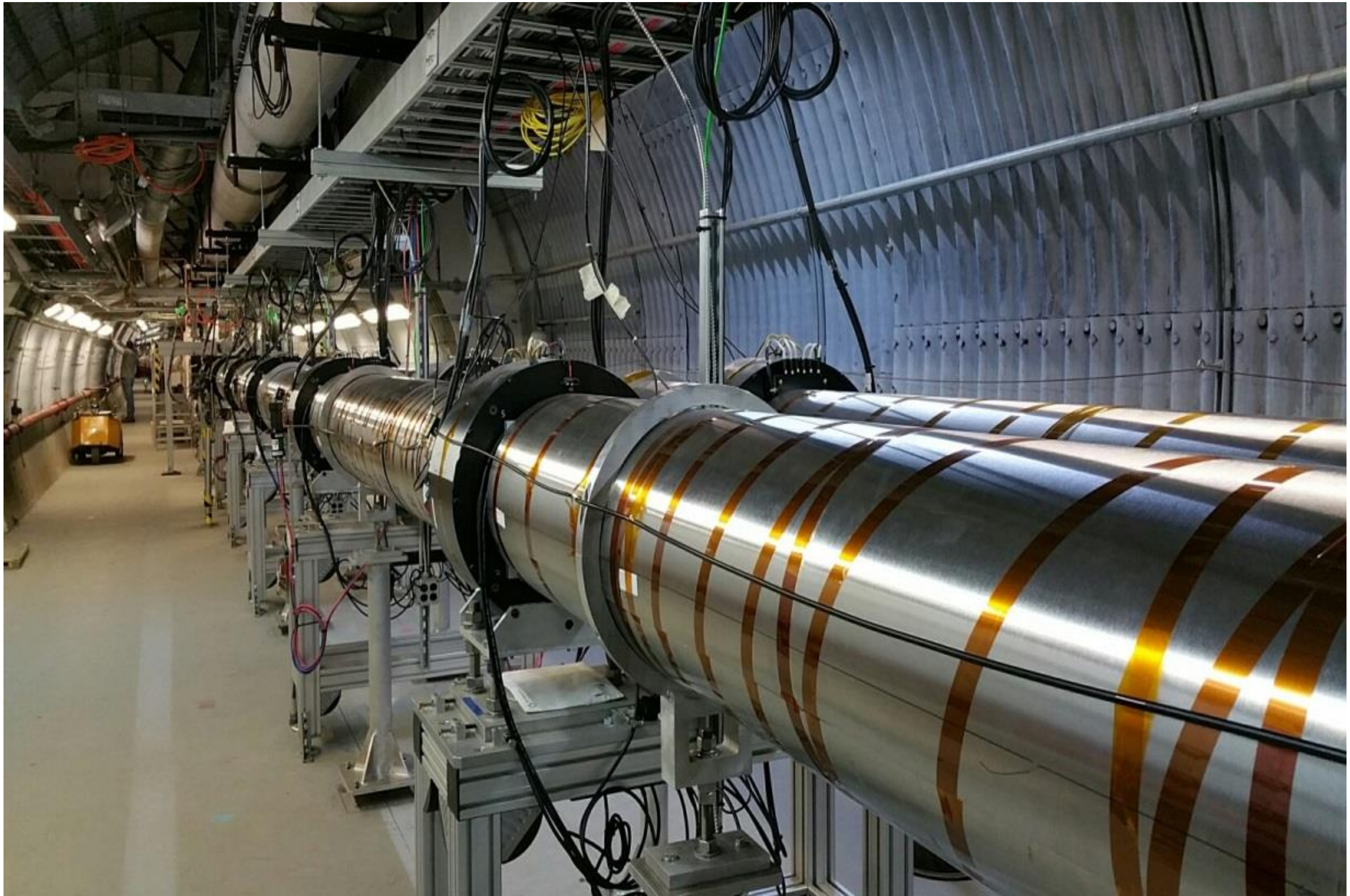
RMS length requirements for gamma 4.1: > 3 cm





- 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

LEReC cooling sections fully installed (2018)



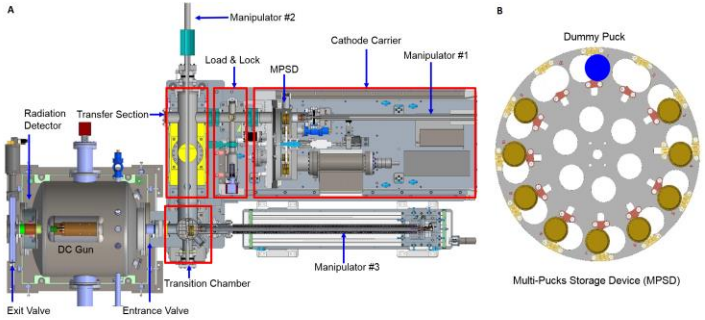
Attainment of “cold” electron beam suitable for cooling

- LEReC is based on the state-of-the-art accelerator physics and technology:

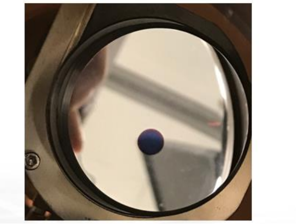
- Photocathodes: production and delivery system
- High power fiber laser and transport
- Laser beam shaping to produce electron bunches of required quality
- Operation of DC gun at high voltages (around 400kV) with high charge and high average current
- RF gymnastics using several RF cavities and stability control
- Energy stability and control
- Instrumentation and controls

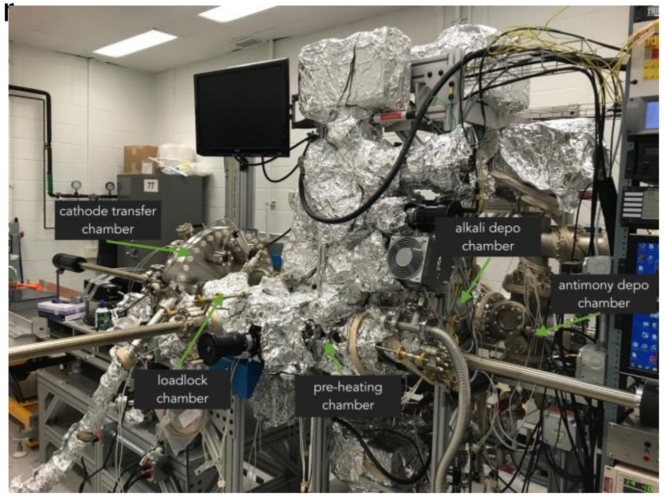
Gun performance

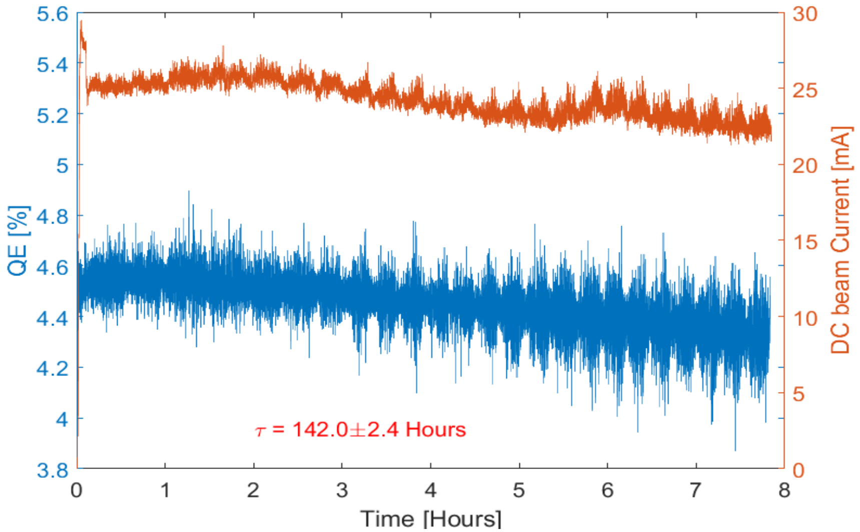
- To support 24/7 operations, cathode production and exchange systems were developed which include two cathode deposition systems, three multi-cathode (up to 12 cathodes) carriers, and a mechanism allowing for cathode exchange in RHIC tunnel in less than 1 hour.
- DC gun with high QE cathodes and stable laser provided reliable beam operation over a period of 7 months.



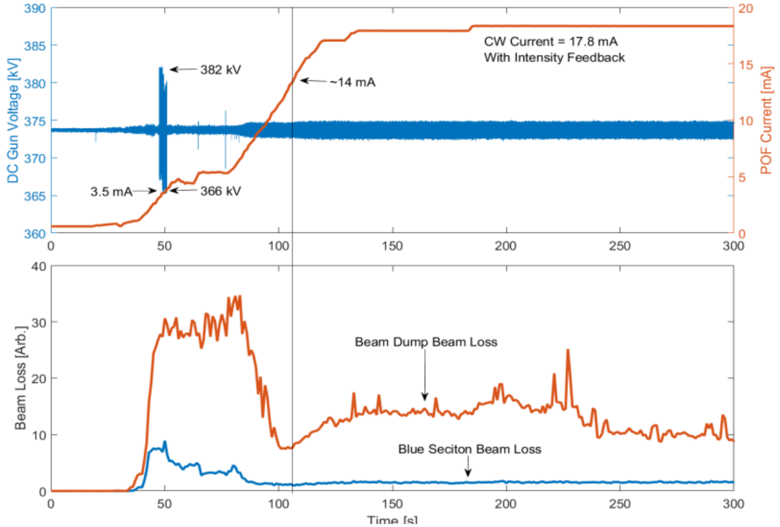
Off center 6mm active area





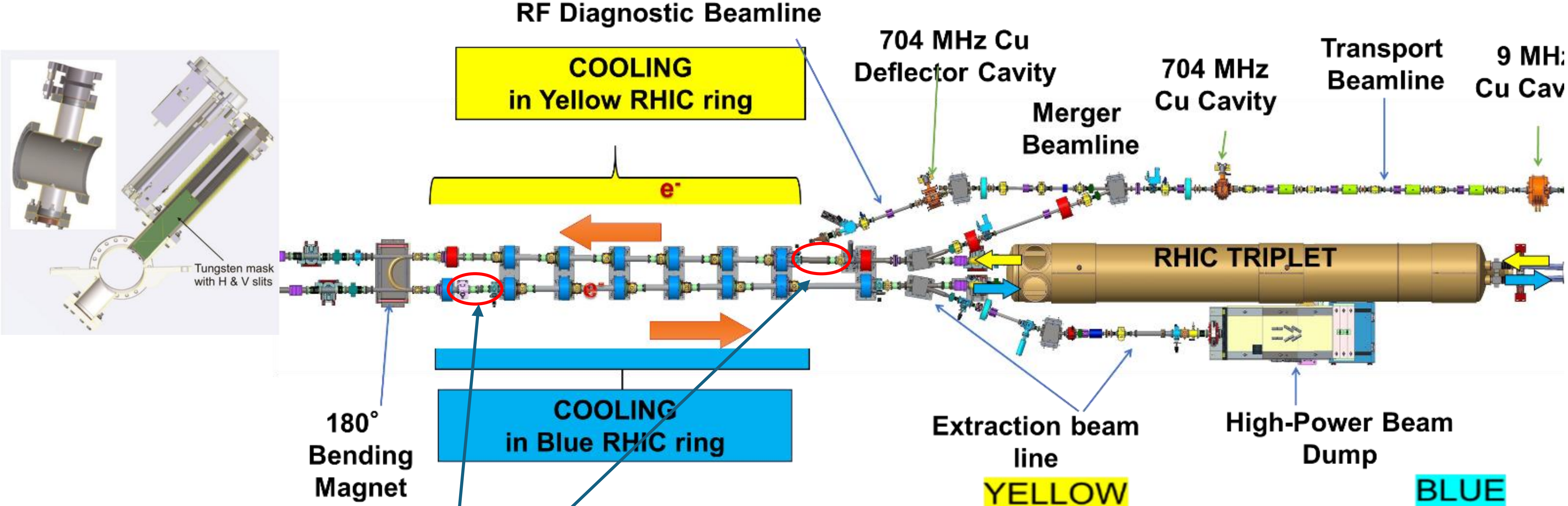


Beam current in CW operation (red line) over 8 hours, and QE (blue line) with a fitted cathode current lifetime of 142 h.



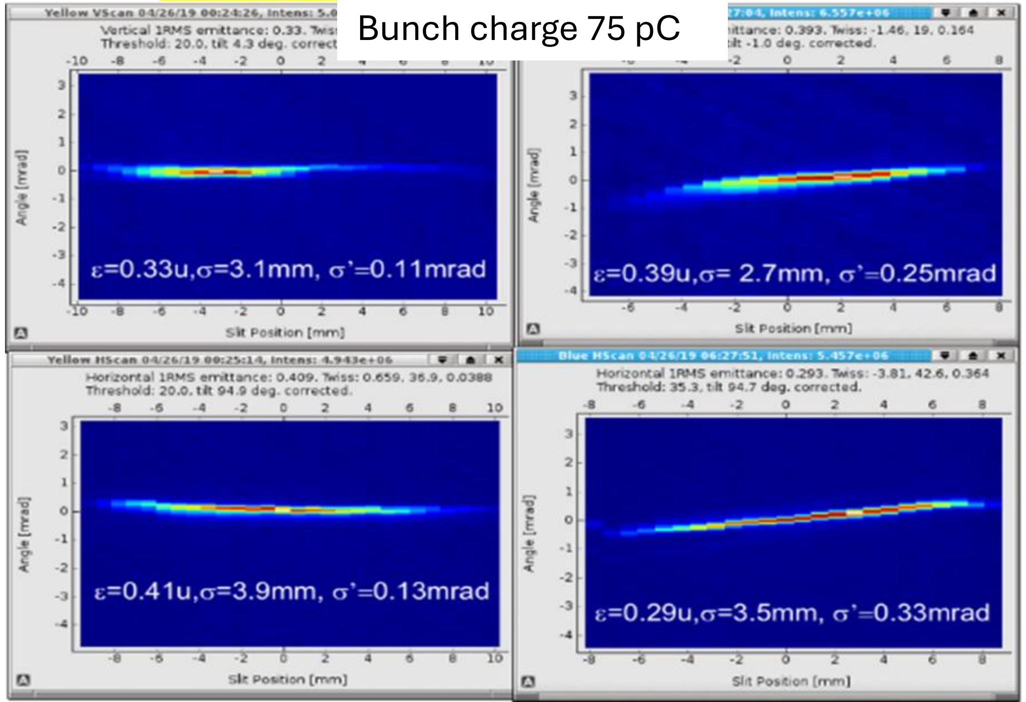
Typical CW beam current ramp-up for cooling optimization.

Transverse phase-space measurements of electron beam



YELLOW

BLUE



Bunch charge 75 pC

Movable slit and downstream beam profile monitors are installed at the beginning of each cooling section.

Achieved rms normalized emittances
in cooling sections < 2 µm
(requirement: 2.5 µm)

RF diagnostics line commissioning

Pulsed mode

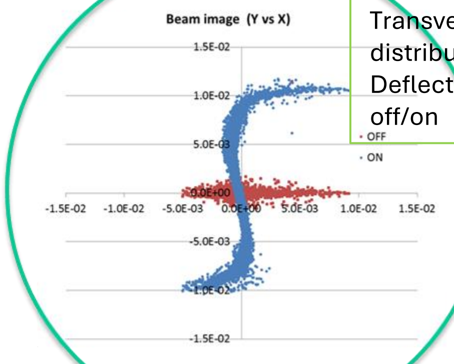
Calibrate RF deflection cavity with beam.

Commission RF diagnostic line beam instrumentation and MPS

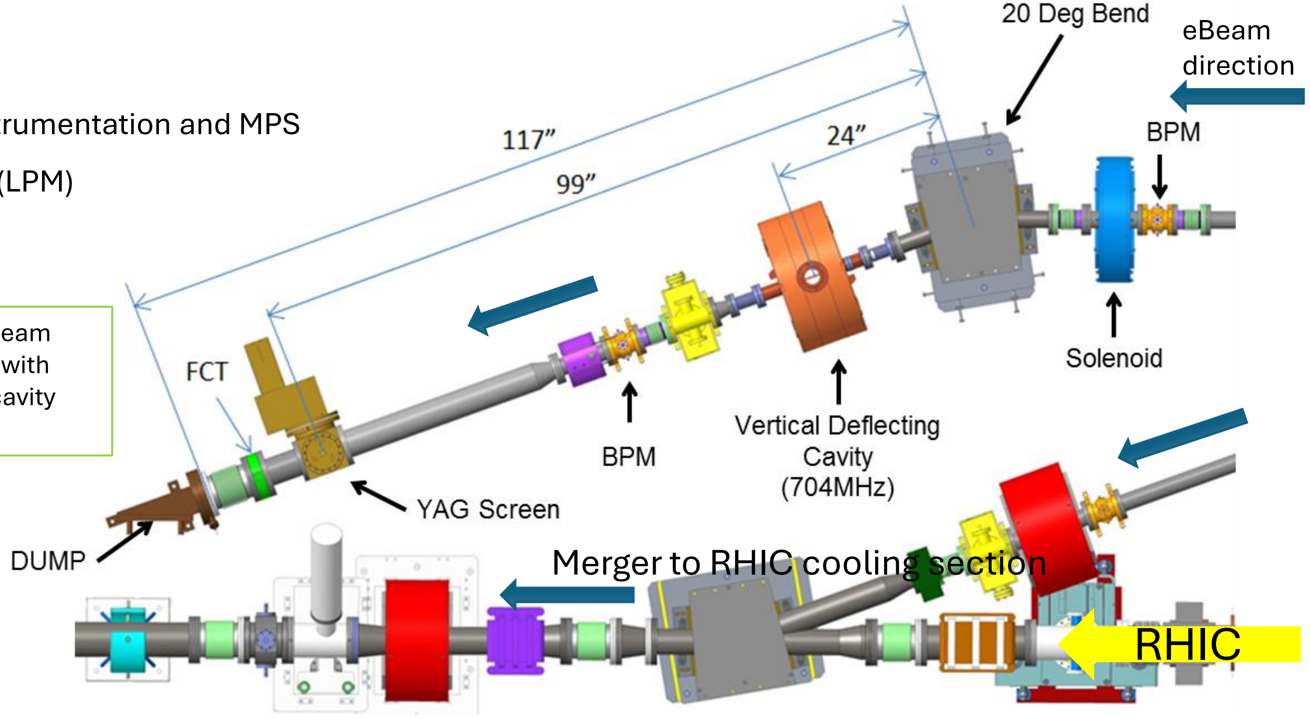
Commission longitudinal profile monitor (LPM)

Commission beam dump

Calibrate all RF cavities with the LPM



Transvers beam distribution with Deflection cavity off/on



Long trains mode

In long train mode (average power limited by diagnostic line beam dump, macro bunch train duration is longer than SRF booster response time):

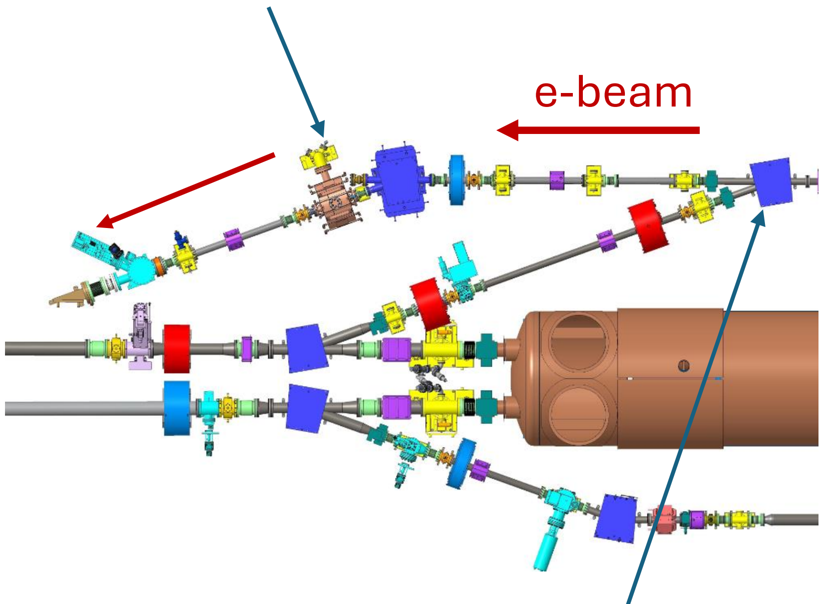
Commissioning SRF booster and other RF cavities feed forward system

Optimize beam longitudinal profile for close to CW operation.

Longitudinal phase-space measurement of electron beam

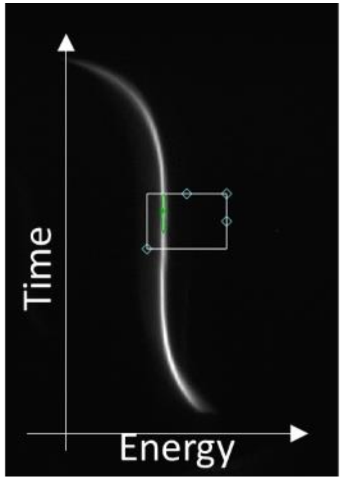
704MHz deflecting cavity

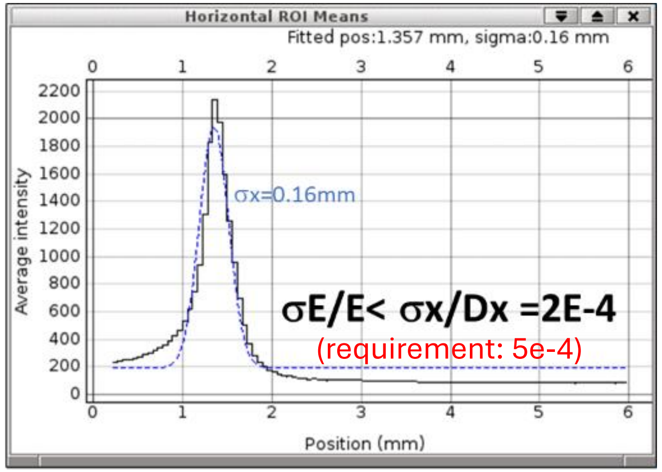
e-beam



- First dogleg merger dipole is off
- Beam goes to RF diagnostic line
- 20 degree dipole produces dispersion
- 704MHz RF deflecting cavity produces time dependent vertical kick

1 macro-bunch of electrons (total charge 3nC)



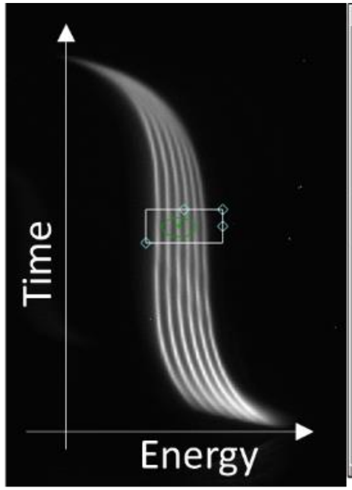


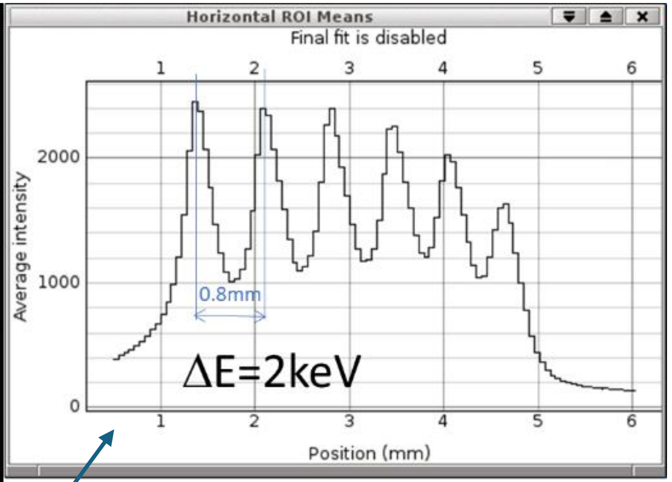
Fitted pos:1.357 mm, sigma:0.16 mm

σE/E< σx/Dx =2E-4

(requirement: 5e-4)

6 macro-bunches, 3 nC each.



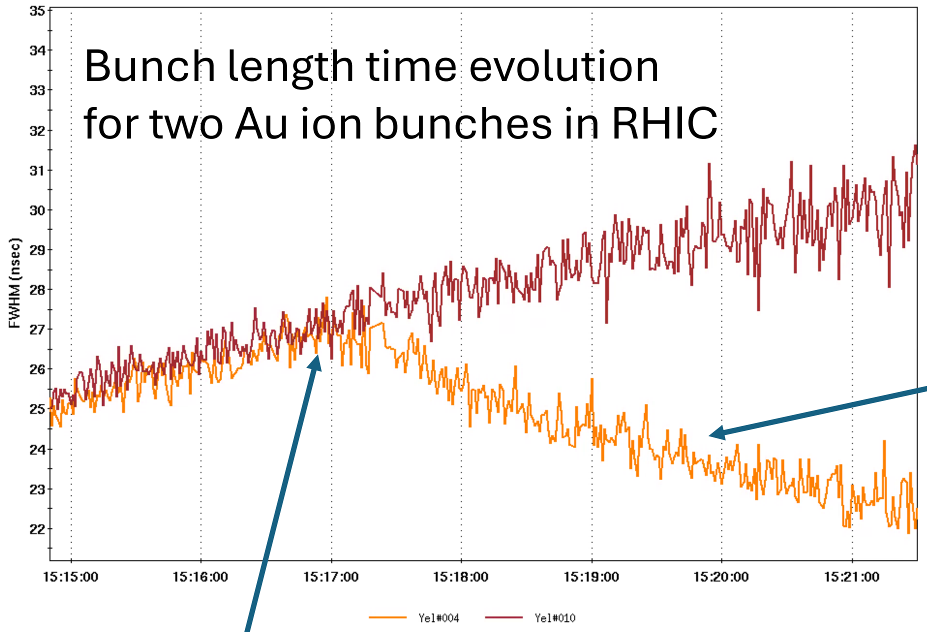


Final fit is disabled

ΔE=2keV

In pulsed mode, subsequent electron macro-bunches have lower energy due to beam loading in RF cavities.

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

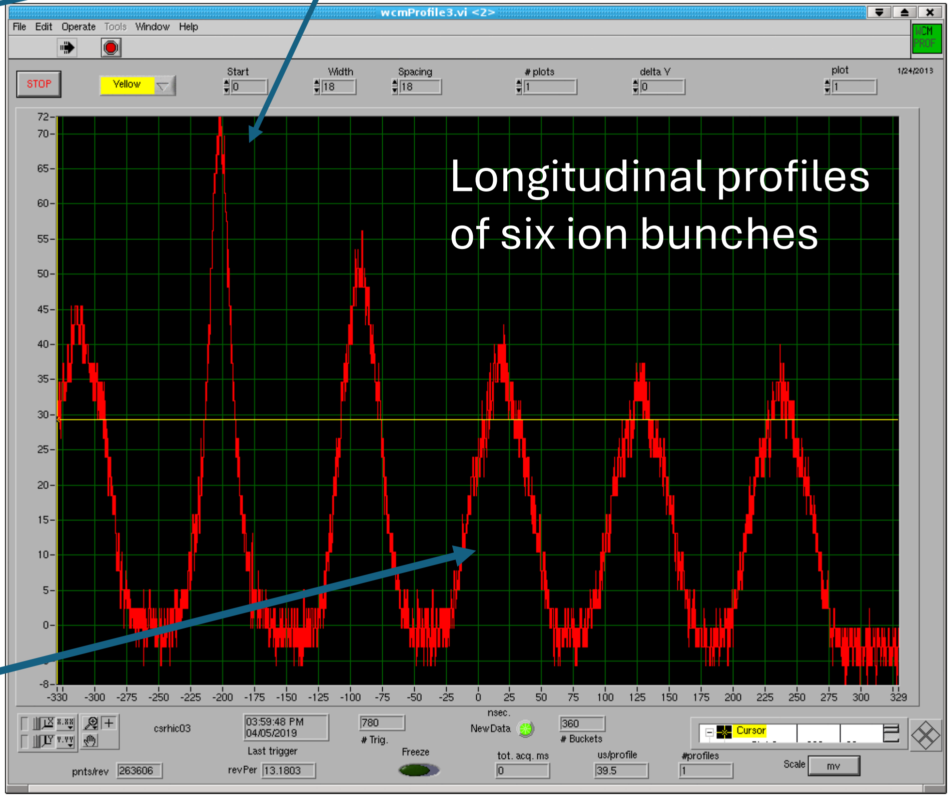


Bunch length time evolution for two Au ion bunches in RHIC

Ion bunch #4 which is not being cooled

Ion bunch #2 is being cooled

Energy of electrons and ions matched



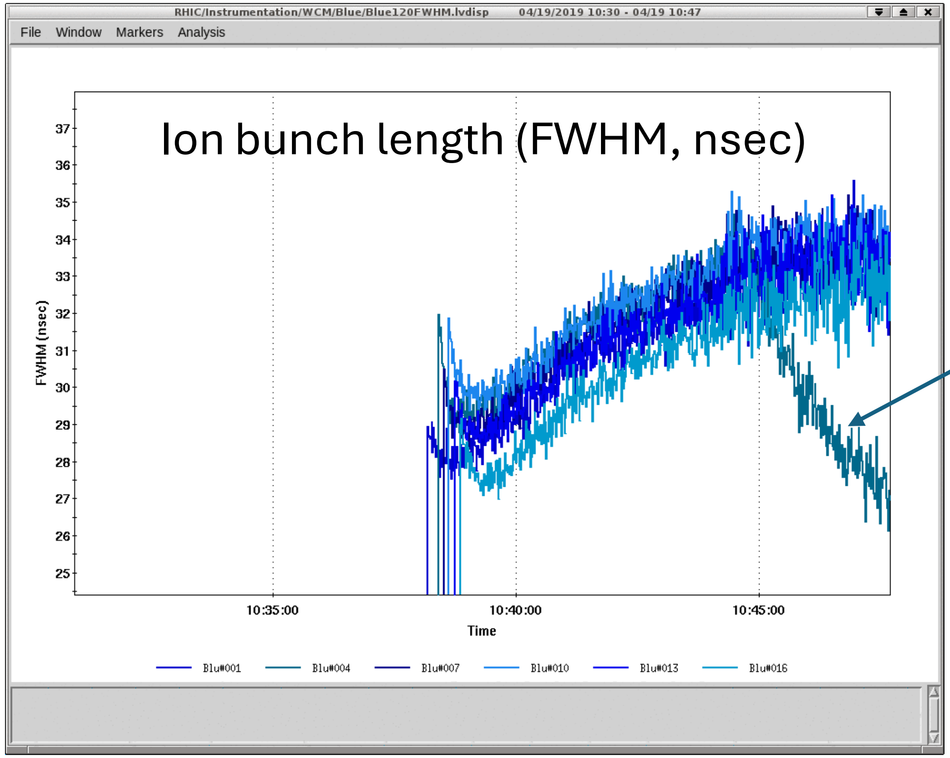
Longitudinal profiles of six ion bunches

Start 0
Width 18
Spacing 18
plots 1
delta Y 0
plot 1
Last trigger 03:59:48 PM 04/05/2019
Trig. 780
Buckets 360
pnts/rev 263606
revPer 13.1803
tot. acq. ms 0
us/profile 39.5
#profiles 1
Scale mv

In 76kHz mode, subsequent electron macro-bunches have lower energy due to beam loading in RF cavities (can match energy/cool effectively single ion bunch).

First cooling in Blue RHIC Ring (April 19, 2019)

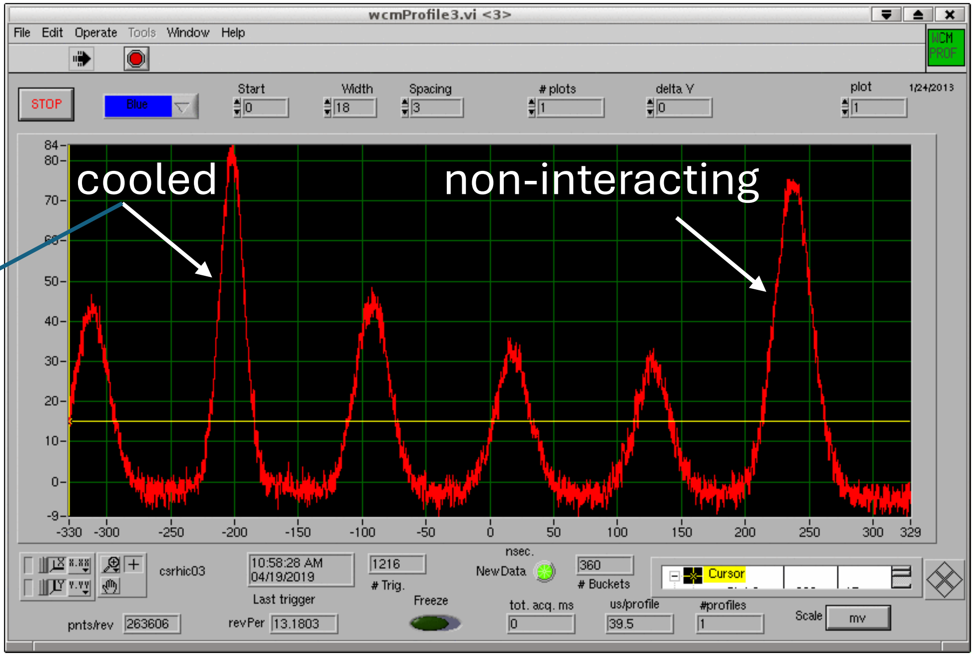
- After RHIC lattice for Au ions and good electron beam optics for Blue cooling section was established, cooling of ions in Blue RHIC Ring was achieved.



Ion bunch length (FWHM, nsec)

RHIC/Instrumentation/WCM/Blue/Blue120FWHM.lvdisp 04/19/2019 10:30 - 04/19 10:47

Longitudinal profiles of six ion bunches



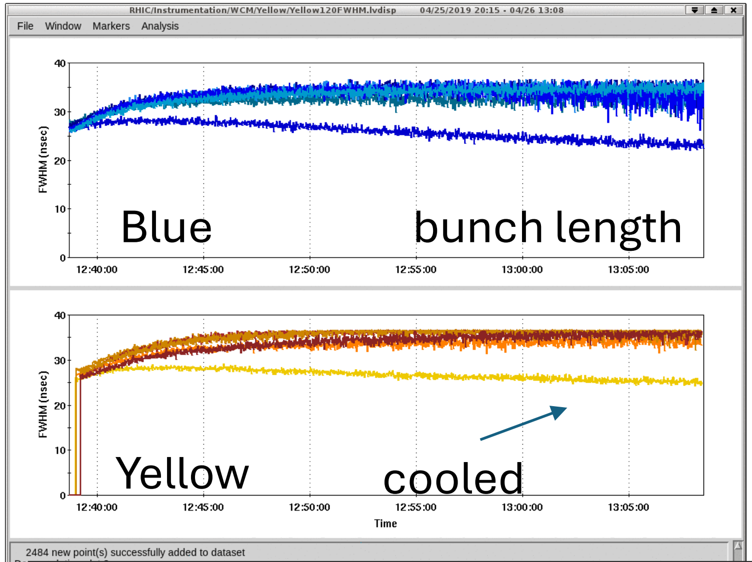
cooled

non-interacting

wcmProfile3.vi <3>

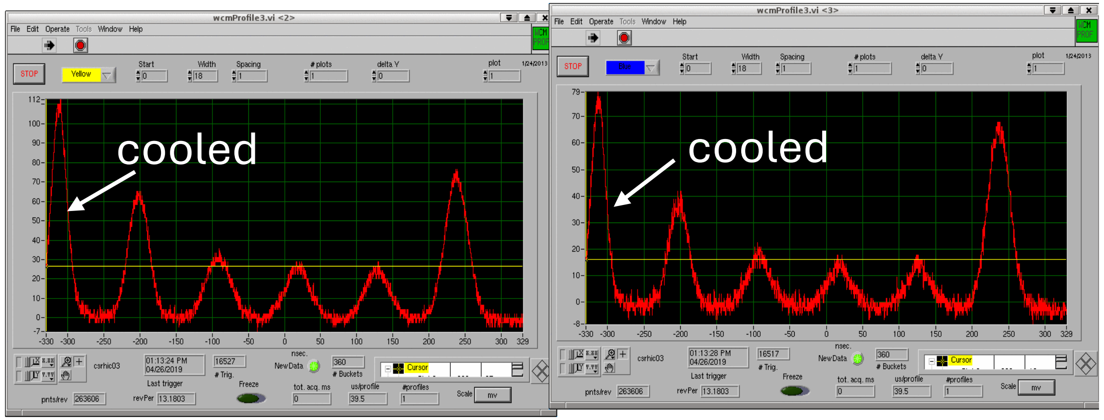
Start 0
Width 18
Spacing 3
plots 1
delta Y 0
plot 1
1/24/2013
csrhic03
Last trigger 10:58:28 AM 04/19/2019
Trig. 1216
Buckets 360
pnts/rev 263606
revPer 13.1803
tot. acq. ms 0
us/profile 39.5
#profiles 1
Scale mv

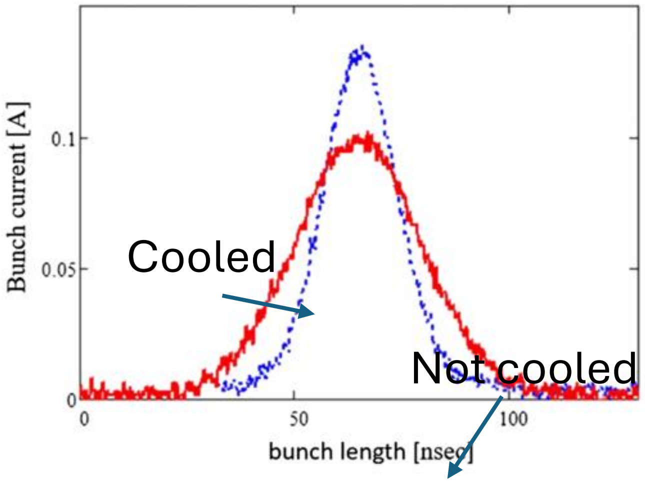
Simultaneous cooling in both Yellow and Blue RHIC rings using the same electron beam (76kHz mode, 6 ion bunches: bunch #1 is being cooled; bunch #6 does not see electrons)

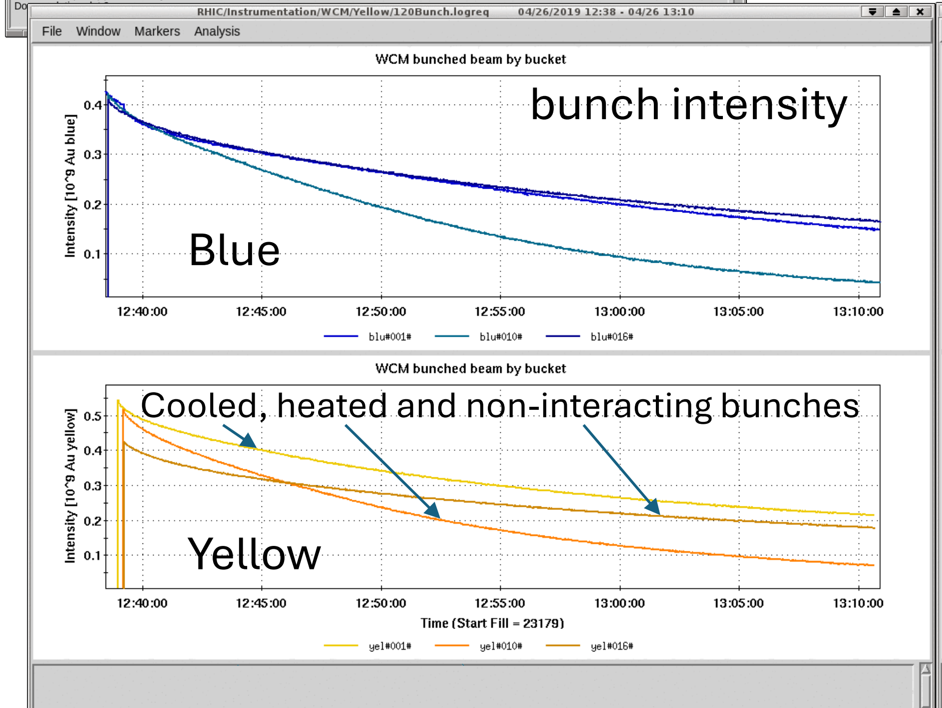


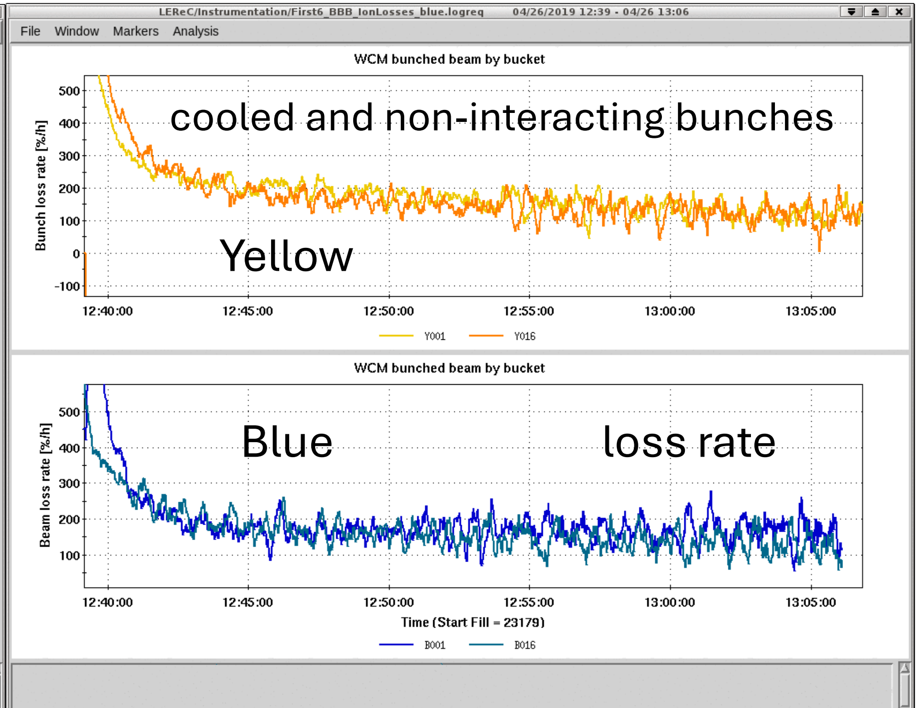
2484 new point(s) successfully added to dataset

Longitudinal bunch profiles



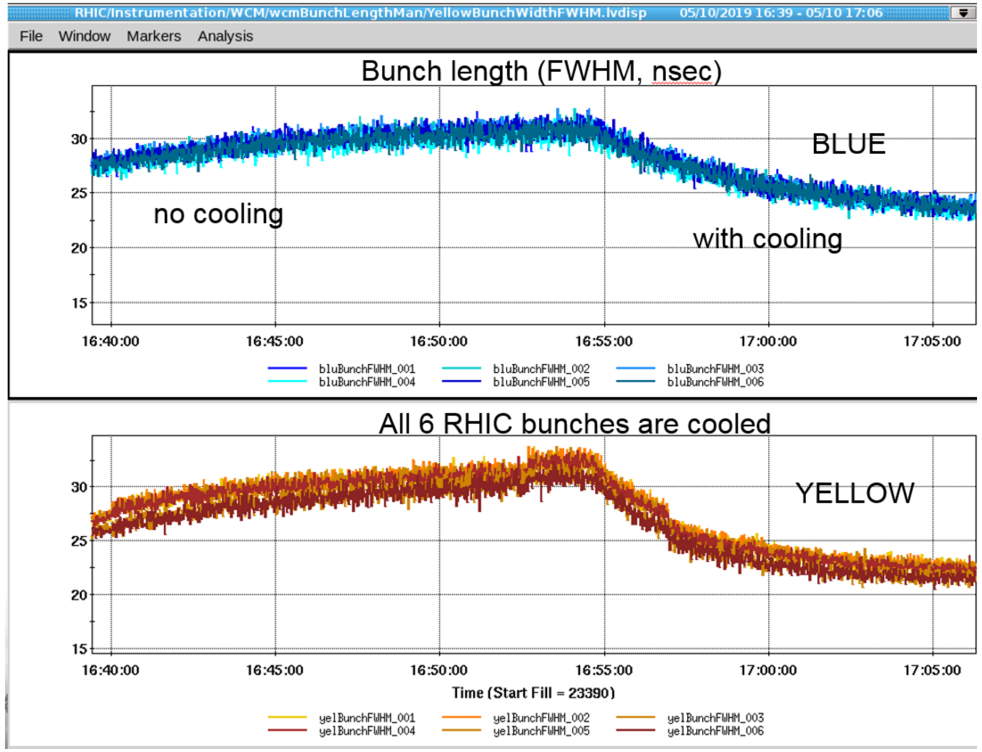


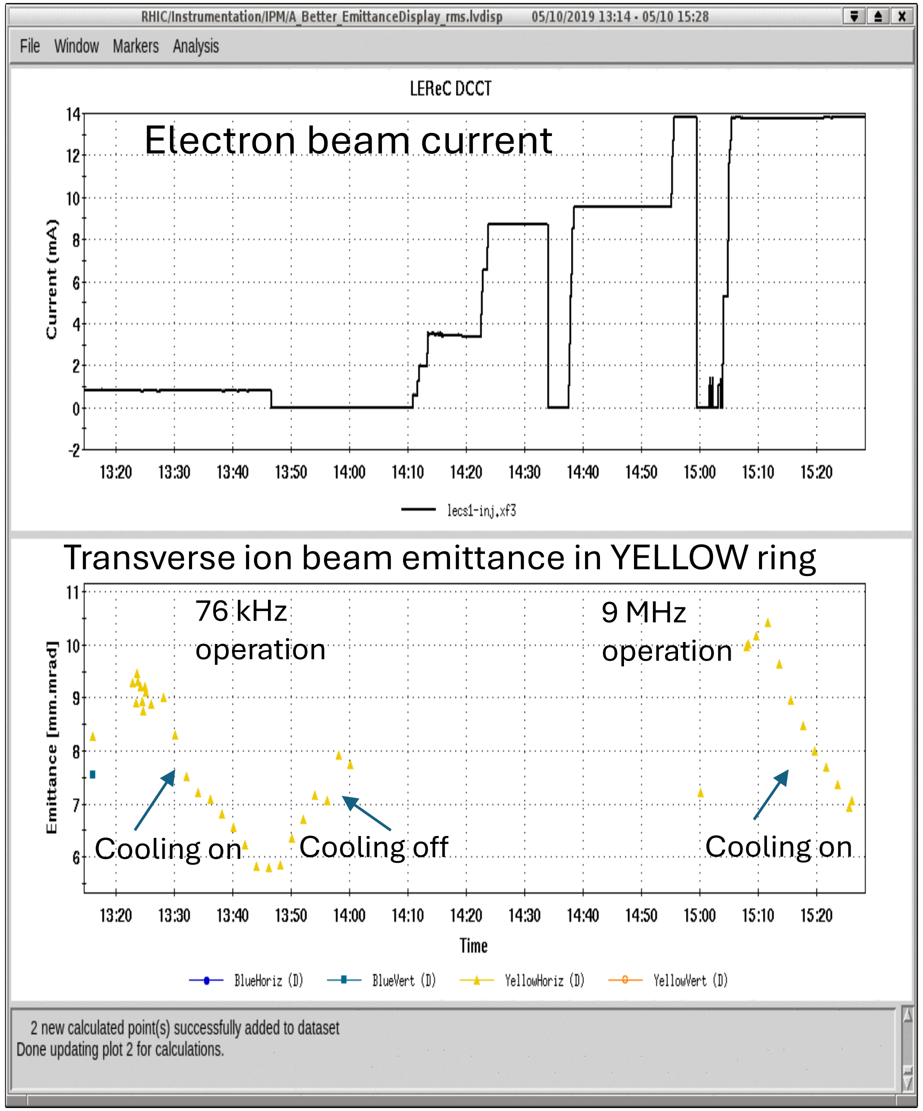




High-current CW electron beam operation and cooling of many ions bunches simultaneously

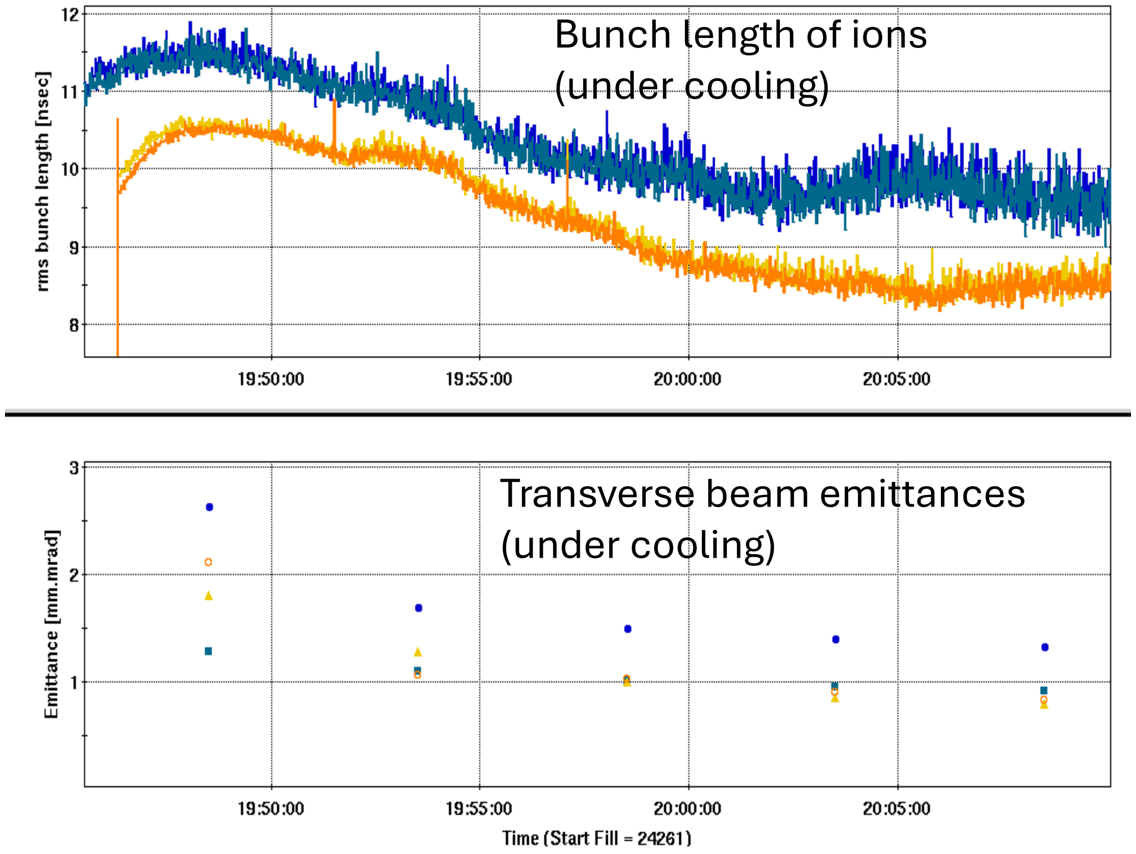
- To proceed from cooling single ion bunch using 76kHz electron beam to cooling of many ion bunches required establishing high-current 9MHz CW electron beam operation through both cooling sections all the way to the high-power beam dump.





2 new calculated point(s) successfully added to dataset
Done updating plot 2 for calculations.

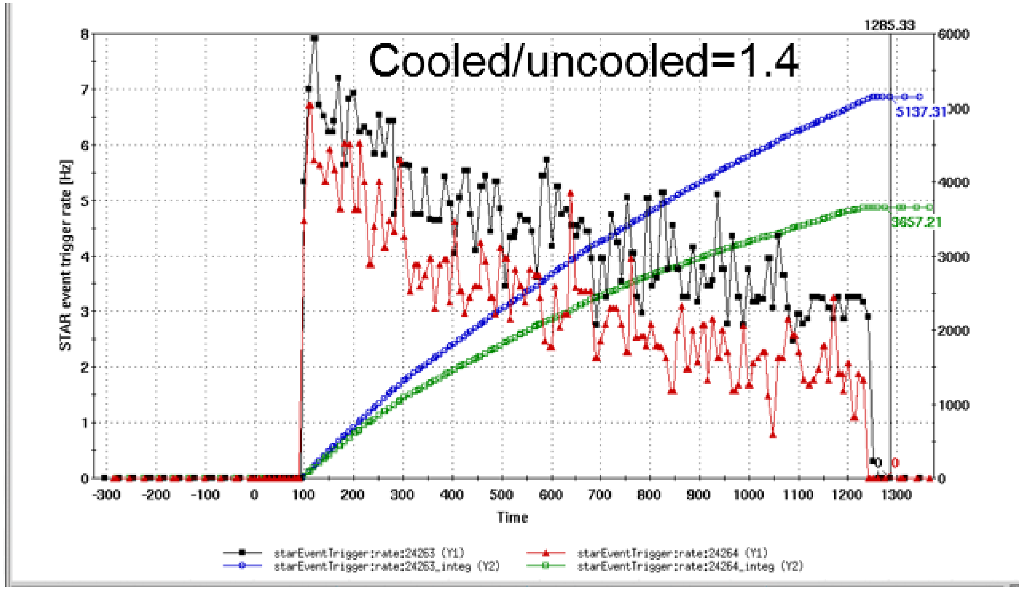
Cooling of hadron beams under collisions (RHIC store with 111x111 Au ion bunches) @ 3.85GeV/n using 1.6MeV high-current 9MHz CW electron beam *



6-D cooling of a 111x111 bunch RHIC store at 3.85 GeV (1.6 MeV electrons, 9 MHz CW current of 15mA).

Electron cooling in a collider:
Cooling of hadron beams in collisions

Both peak and integrated luminosity improvement in test stores with cooling.

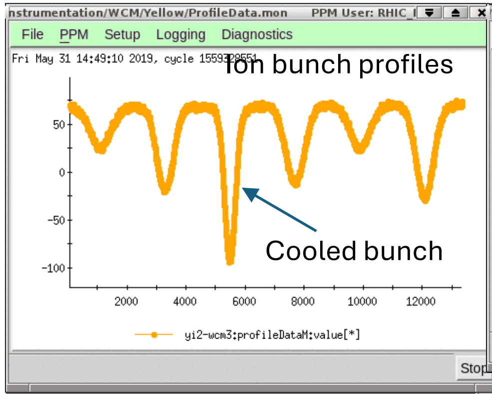


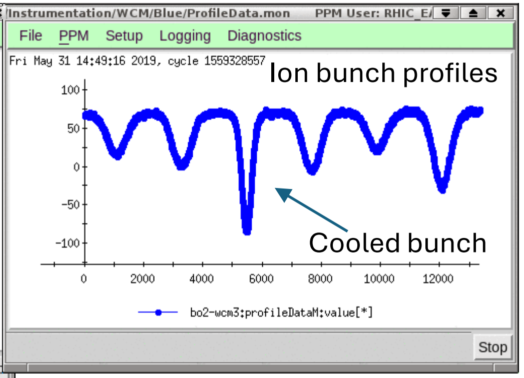
With introducing the beta* we were able to achieve factor of 2 gain in integrated luminosity.

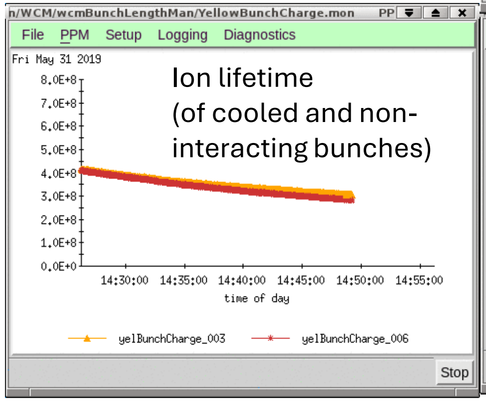
[*] **Experimental Demonstration of Hadron Beam Cooling Using Radio-Frequency Accelerated Electron Bunches.** Phys. Rev. Lett. **124**, 084801**(2020)**

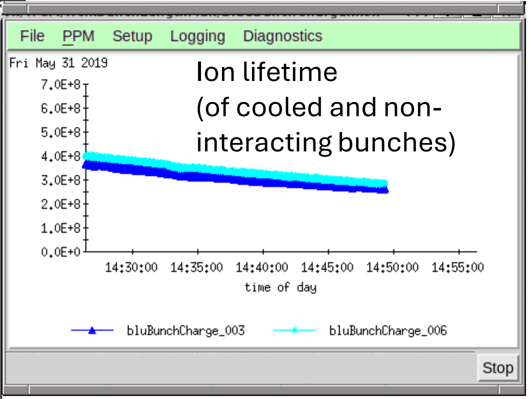
Benefits from electron cooling of hadron bunches

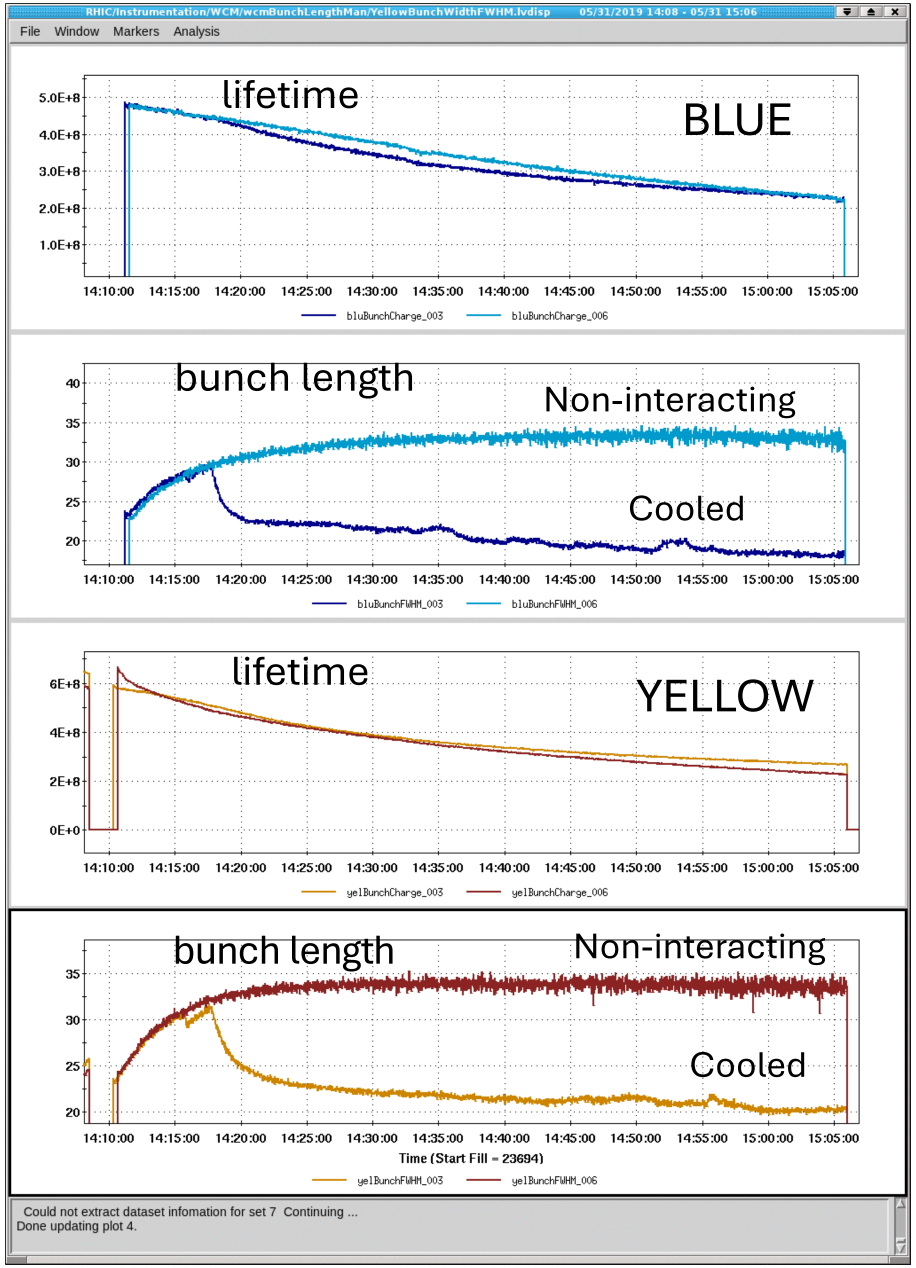
- Cooled bunch is kept shorter, more useful events within trigger window
- Minimize ion beam de-bunching and losses from the RF bucket
- Peak current significantly higher for cooled bunch
- Allows longer stores
- Transverse cooling can help with reduction of beta*







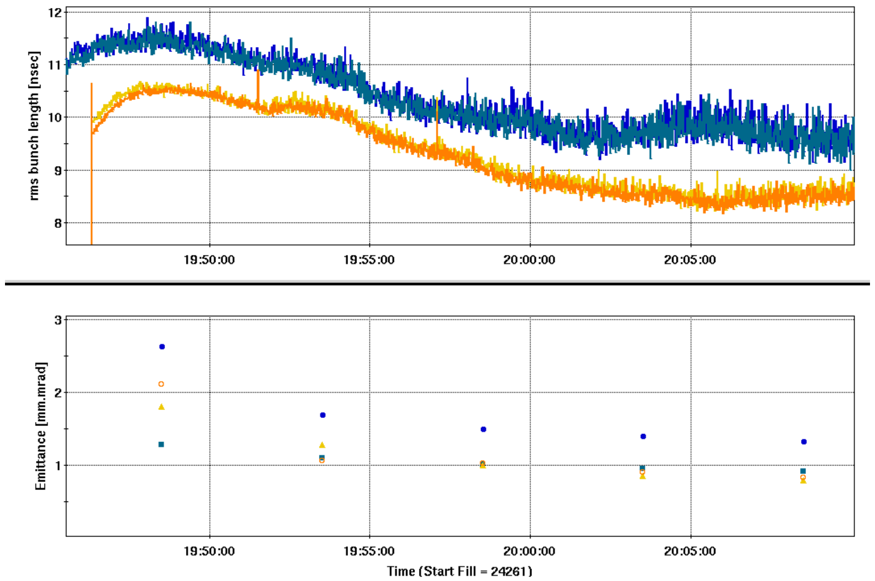




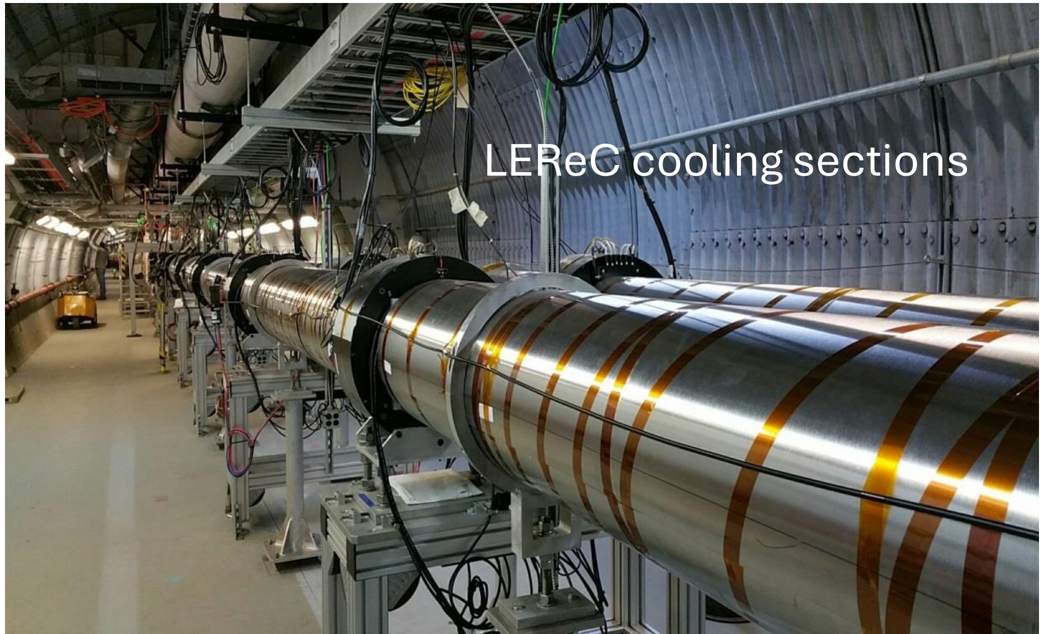
Could not extract dataset infomation for set 7 Continuing ...
Done updating plot 4.

LEReC summary

- World’s first electron cooling of hadron beams based on RF acceleration of electron bunches was successfully demonstrated. Such cooling approach is new (all previous coolers used DC beam) and opens the possibility of using this technique to high beam energies.
- Electron cooling using electron beam without any magnetization on the cathode or cooling section (“non-magnetized” cooling) was demonstrated.
- Cooling was commissioned at electron energy of 1.6MeV (ion energy 3.85GeV/n) and at 2MeV (ion energy of 4.6GeV/n)
- First electron cooling in a collider (cooling of ion beams in collisions with various effects impacting beam lifetime) was achieved by successfully cooling 111 ion bunches in both RHIC rings.

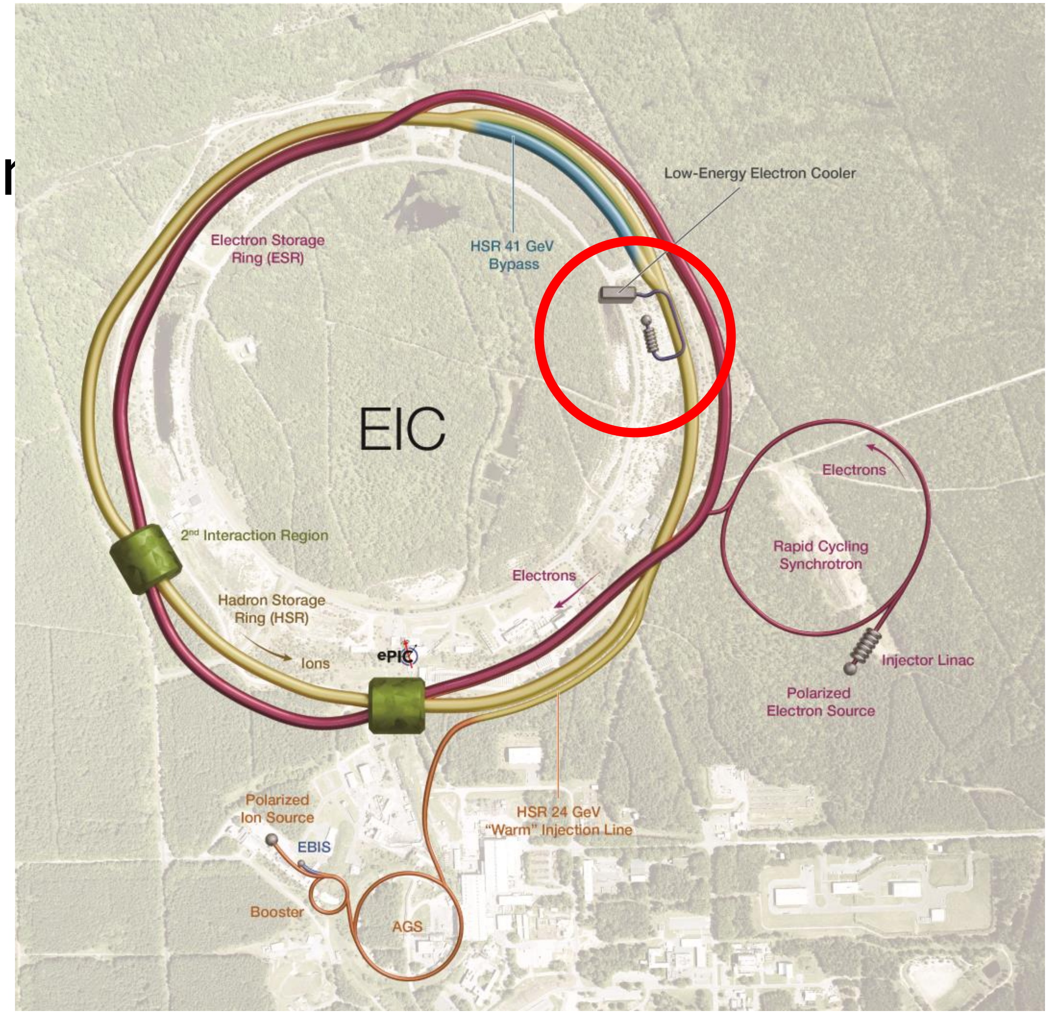


6-D cooling of a 111x111 bunch RHIC store at 3.85 GeV (1.6 MeV electrons, 9 MHz CW current of 15mA).
Top plot - reduction of bunch length. Bottom plot - reduction of transverse beam emittances (two RHIC rings, two planes).



What is next? Cooling protons for EIC

- Cooling requirements
- Cooler design concept and technical appr
- Cooler parameters and performance



EIC Parameters (CDR) and Cooling Goals

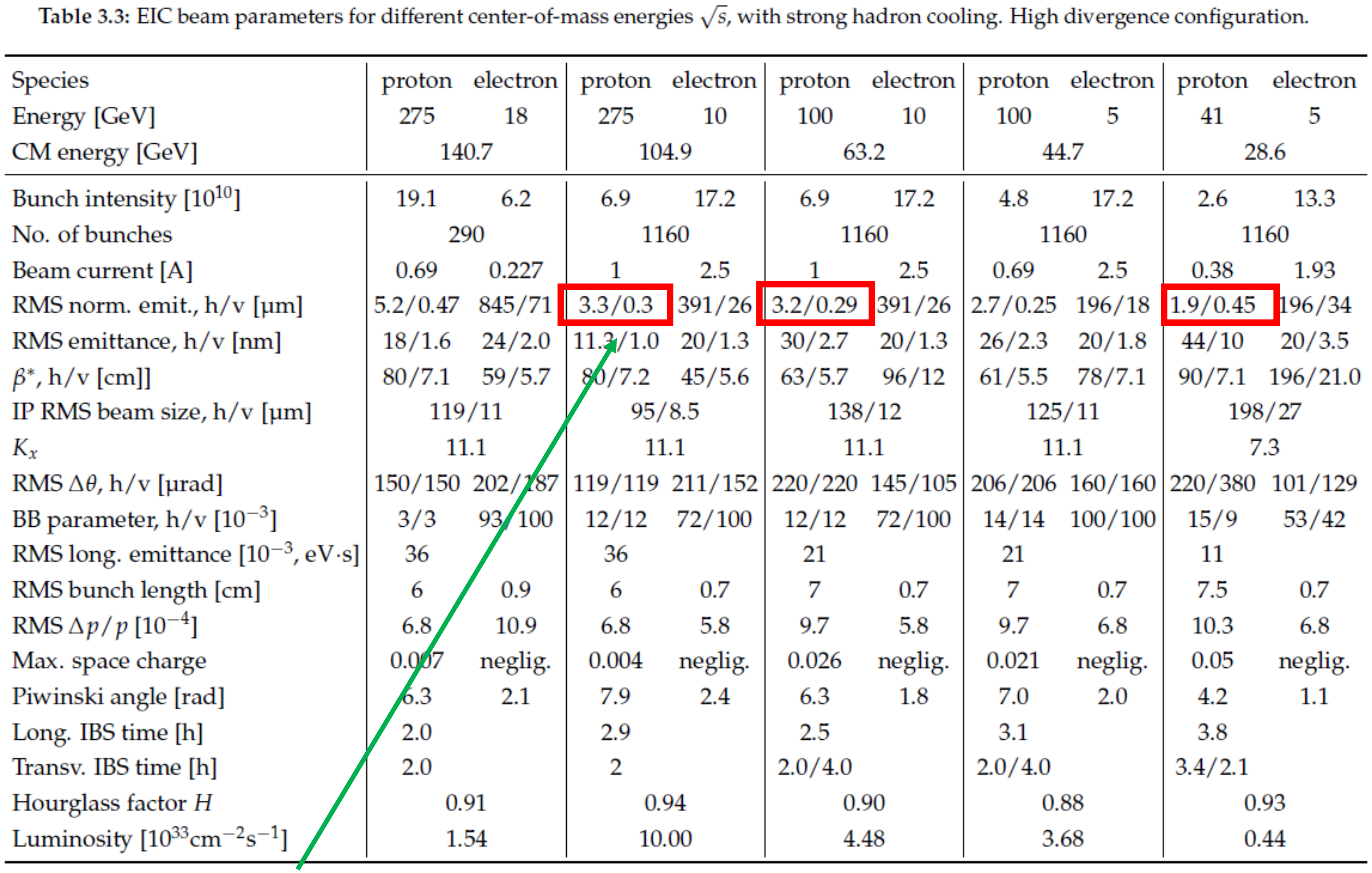
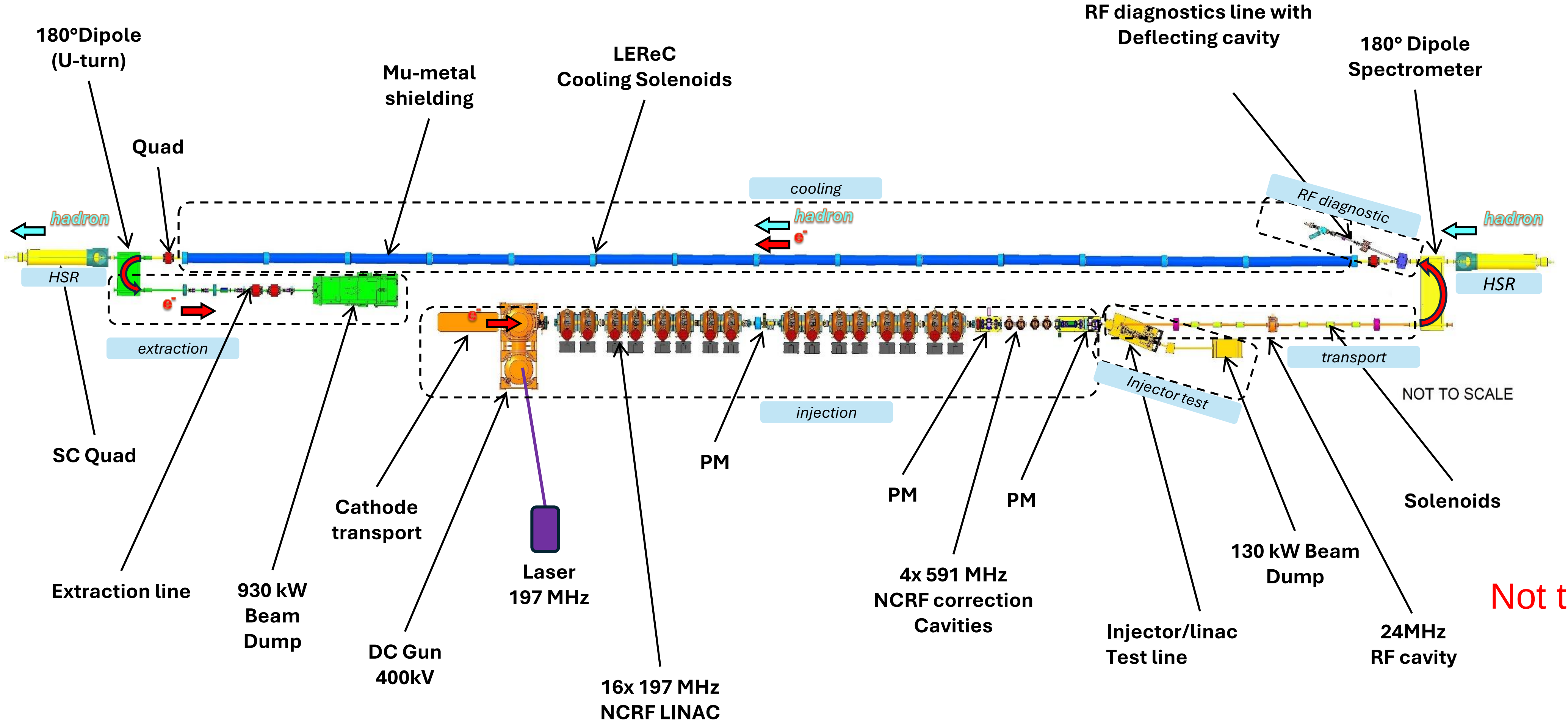


Table 3.3: EIC beam parameters for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling. High divergence configuration.

Species	proton	electron	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5	41	5
CM energy [GeV]	140.7		104.9		63.2		44.7		28.6	
Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam current [A]	0.69	0.227	1	2.5	1	2.5	0.69	2.5	0.38	1.93
RMS norm. emit., h/v [μm]	5.2/0.47	845/71	3.3/0.3	391/26	3.2/0.29	391/26	2.7/0.25	196/18	1.9/0.45	196/34
RMS emittance, h/v [nm]	18/1.6	24/2.0	11.3/1.0	20/1.3	30/2.7	20/1.3	26/2.3	20/1.8	44/10	20/3.5
β^*, h/v [cm]]	80/7.1	59/5.7	80/7.2	45/5.6	63/5.7	96/12	61/5.5	78/7.1	90/7.1	196/21.0
IP RMS beam size, h/v [μm]	119/11		95/8.5		138/12		125/11		198/27	
K_x	11.1		11.1		11.1		11.1		7.3	
RMS $\Delta\theta$, h/v [μrad]	150/150	202/187	119/119	211/152	220/220	145/105	206/206	160/160	220/380	101/129
BB parameter, h/v [10^{-3}]	3/3	93/100	12/12	72/100	12/12	72/100	14/14	100/100	15/9	53/42
RMS long. emittance [10^{-3}, eV·s]	36		36		21		21		11	
RMS bunch length [cm]	6	0.9	6	0.7	7	0.7	7	0.7	7.5	0.7
RMS $\Delta p/p$ [10^{-4}]	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8	10.3	6.8
Max. space charge	0.007	neglig.	0.004	neglig.	0.026	neglig.	0.021	neglig.	0.05	neglig.
Piwinski angle [rad]	6.3	2.1	7.9	2.4	6.3	1.8	7.0	2.0	4.2	1.1
Long. IBS time [h]	2.0		2.9		2.5		3.1		3.8	
Transv. IBS time [h]	2.0		2		2.0/4.0		2.0/4.0		3.4/2.1	
Hourglass factor H	0.91		0.94		0.90		0.88		0.93	
Luminosity [10^{33}cm^{-2}s^{-1}]	1.54		10.00		4.48		3.68		0.44	

The goal of LEC is to obtain initial proton beam parameters.

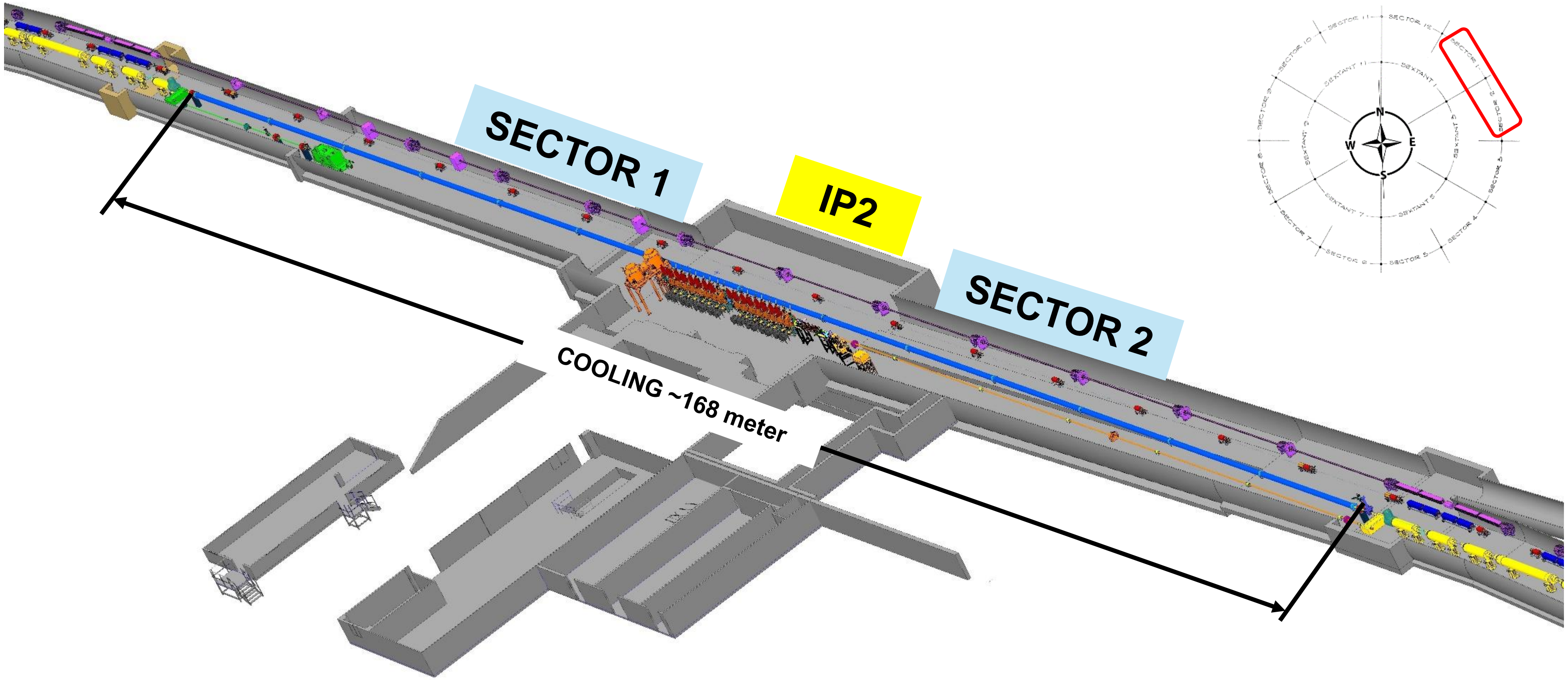
LEC schematic layout at IR2 @EIC

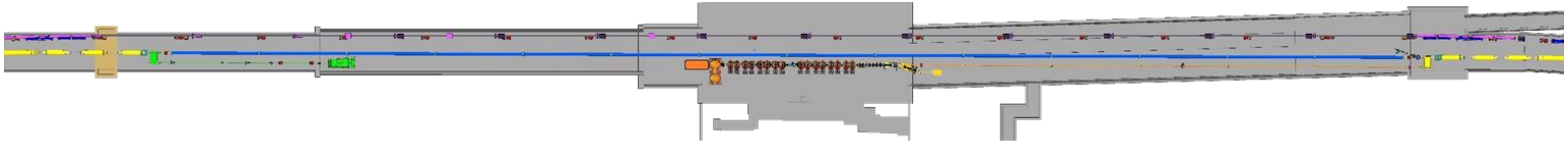


Not to scale

The LEC is scaled up version of LEReC: more RF cavities, longer cooling section, higher beam current.

LEC Layout at IR2





EIC Low Energy Cooler Parameters

	electrons	protons
gamma	25.4	25.4
RHIC RF frequency, MHz	197	24.6
Cooling section length, m	168	168
Cooling sections beta function, m	150	100-200
Hadrons Dy, Dy’, m, rad		<1, <0.02
Total charge per proton bunch, nC	3	45
Electrons kinetic energy, MeV	12.46	
Electron average current, mA	74	
Normalized emittance, rms, um	<1.5	2
rms bunch length, cm	4	100
rms dp/p	<5e-4	6e-4
Angles in cooling section, urad	20-30	20

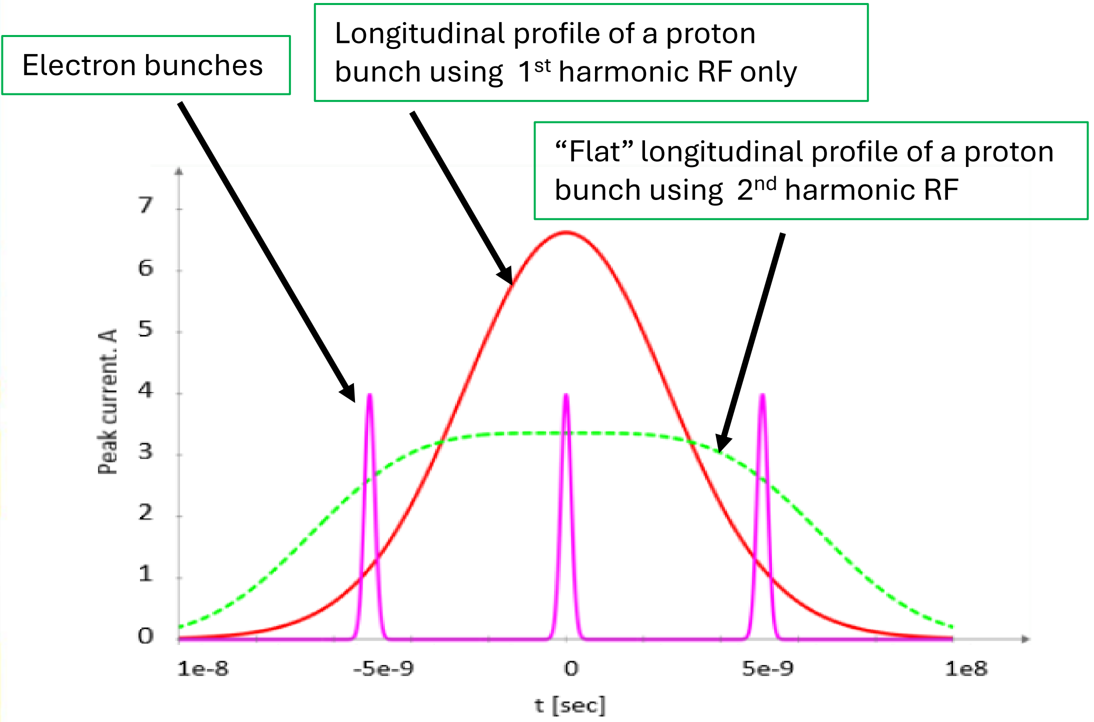
LEReC key parameters for reference

electrons
4-5
704 MHz (9 MHz)
20 m
30 m
3 nC
1.6-2 MeV
30 (60 mA in tests)
<2 um
5 cm
<5e-4
<150 urad

Beam Structure in Cooling Section

Protons bunch structure:
f_rep=24.6 MHz
N_p=2.8e11, I_peak=3 A (with 2nd harmonic)
Rms length=1m

Electrons bunch structure:
f_RF=197 MHz
Single bunch: Q_e=1 nC
Number of bunches in macro-bunch: 3
Rms length=0.04m


Electron bunches

Longitudinal profile of a proton bunch using 1st harmonic RF only

“Flat” longitudinal profile of a proton bunch using 2nd harmonic RF

Figure 3: Three electron bunches (magenta) spaced by 5.1ns placed on a single proton bunch (red: single RF harmonic; green: double RF harmonic).

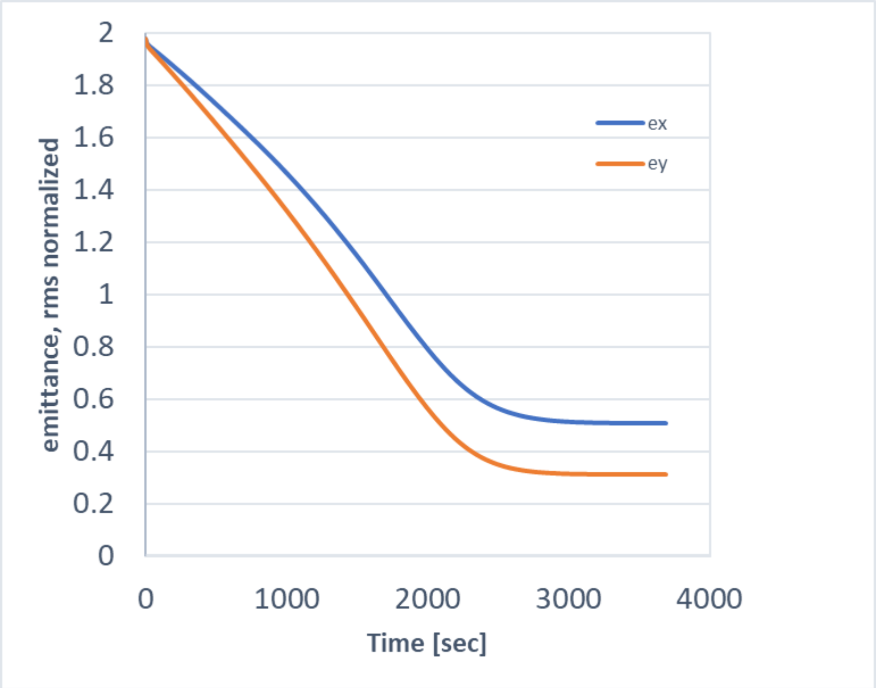
<u>Proton bunches during cooling:</u>
2nd harmonic RF alleviates space-charge effects reducing peak current of protons to about 3A , with the space-charge tune shifts of **$\Delta Q_{sc,x,y}$=0.07, 0.13** (with 2nd harmonic RF) at the end of cooling.

RHIC APEX studies, May 8, 2024:

1) Expected proton beam parameters with using quad pumping in AGS were established: peak current of 5.4A with single harmonic 28MHz RF. Double RF system will decrease peak current by about factor of 2.
2) Use of double RF system and making flattened bunch profiles was also demonstrated at proton injection energy in RHIC.

Cooling Performance

Average current of electrons: **I_{av}=74mA**
Electrons rms angles in the cooling section: **25 urad**
Effective cooling section length: **168 meters**



Cooling simulations of protons at γ=25, with decoupled transverse motion (**IBS+Cooling only,** using single harmonic RF). Longitudinal emittance is kept constant during cooling process. After cooling, normalized rms emittances of protons **ex, ey=0.5,0.3 um (**horizontal emittance can be increased further as needed.**)**

Non-magnetized cooling: very strong dependence on relative angles between electrons and ions.

$$\vec{F} = -\frac{4\pi Z^2 e^4 n_e L}{m} \frac{\vec{v}_i}{\beta^3 c^3 \boxed{((\gamma\vartheta)^2 + \sigma_p^2)}^{3/2}}$$

Requirement on electron angles:
for γ=25: σ_p<4e-4; θ<25 urad

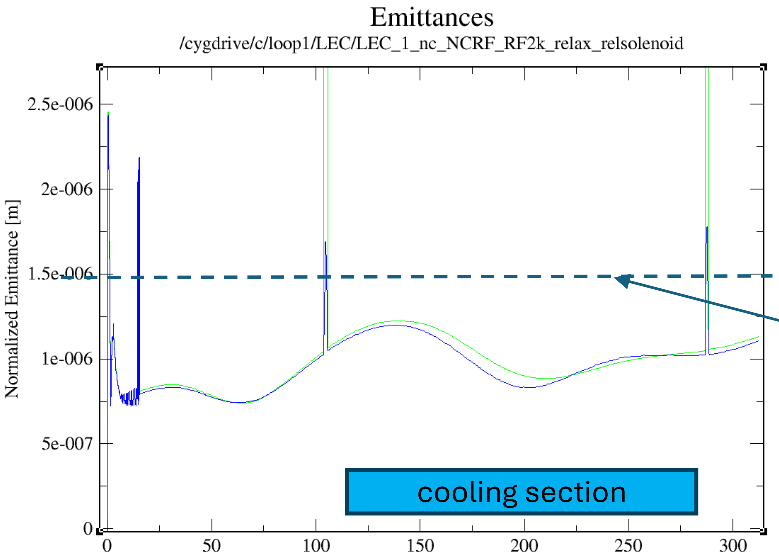
Contributions to the rms electrons angles **budget** in the cooling section:

- Electron beam emittance:	< 20 urad
- Electron beam space charge:	< 10 urad
- Focusing from proton beam:	< 10 urad
- Remnant magnetic fields (with shielding)	< 7 urad

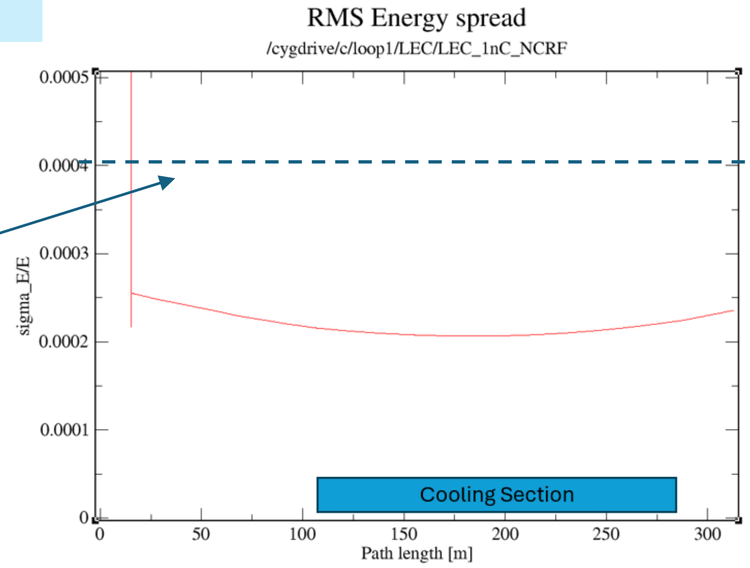
Total preliminary budget (added in quadrature): **25 urad**

Note:
For electron beam beta-function of 150m in cooling section, rms emittance of 1.5 um corresponds to 20urad divergence. Hence requirement on emittance in cooling section: <1.5um.

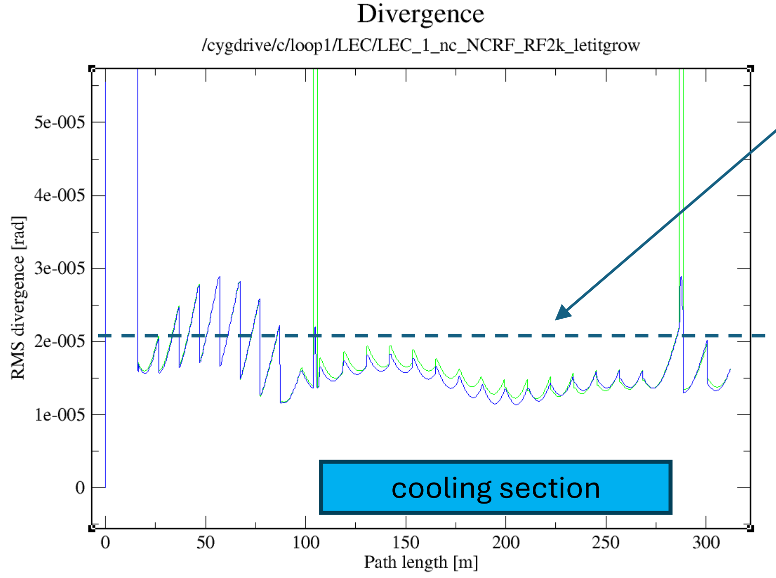
Start-to-End Electron Beam Simulations



See D. Kayran presentation



requirements



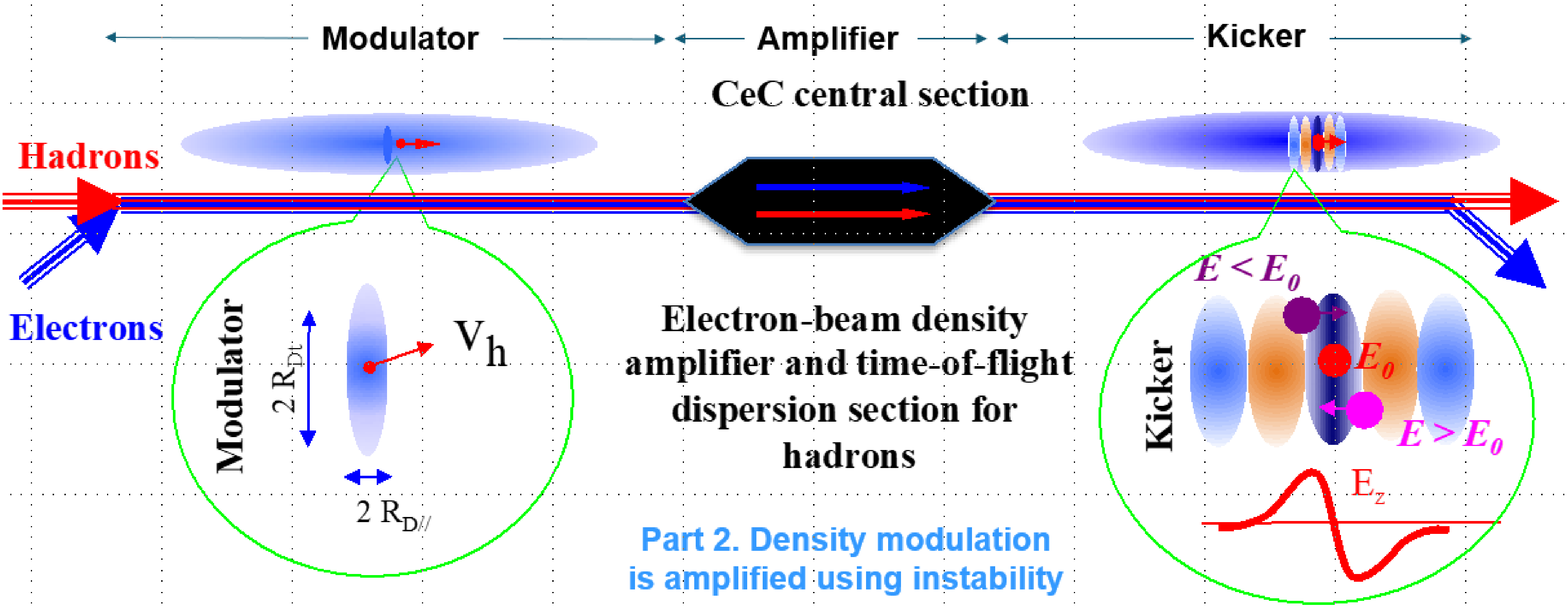
Simulations for 1 nC electron bunch charge:

Results:
Normalized rms emittances <1.5um
RMS energy spread <4e-4
Electron beam divergence in the cooling <20 urad.

Summary using eCooler for EIC

- Electron cooler at injection energy of protons at 24 GeV addresses challenges of achieving design luminosity and simplifies requirements on high-energy cooling at collisions.
- Present version of stand-alone Low-Energy Cooler (LEC) with single long cooling section significantly reduced risks compared to previous design.
- The LEC design parameters are challenging with required angular spread of electrons in cooling section about factor of 5 smaller than in LEReC and electron current about factor of 3 larger than used in routine long-term LEReC operations.

Coherent Electron Cooler Proof of Principal (CeC PoP) Experiment *



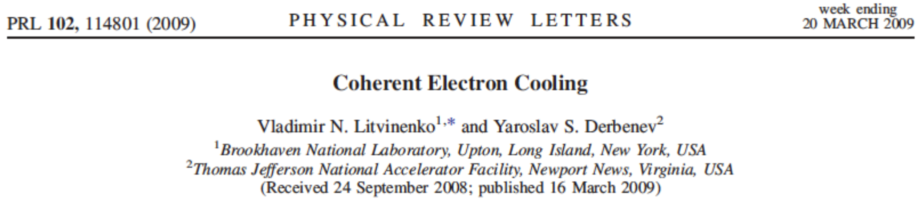
Electron-beam density amplifier and time-of-flight dispersion section for hadrons

Part 2. Density modulation is amplified using instability

Part1. Hadrons create density modulation in co-propagating electron beam

$$\boxed{\gamma_e = \gamma_h}$$

Part 3. Time-of-flight dependence on the hadron's energy results in energy correction, i.e. cooling.



PRL **102**, 114801 (2009) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2009

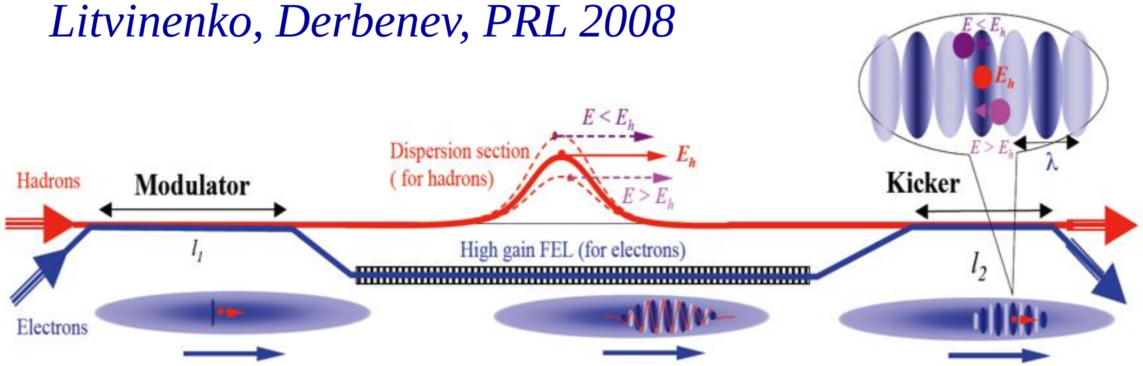
Coherent Electron Cooling

Vladimir N. Litvinenko[1,*] and Yaroslav S. Derbenev[2]
[1]*Brookhaven National Laboratory, Upton, Long Island, New York, USA*
[2]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia, USA*
(Received 24 September 2008; published 16 March 2009)

*) As presented by Yichao Jing at CAD- MAC review

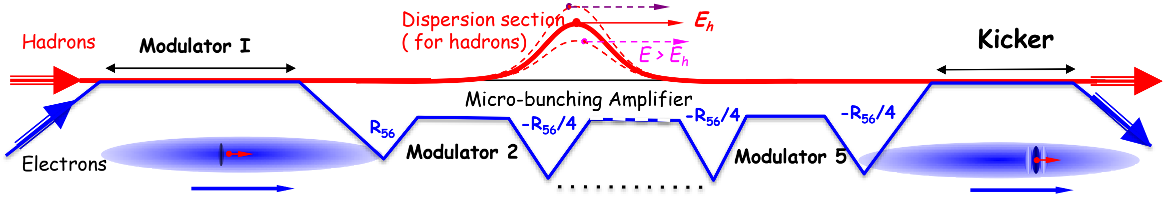
CeC schemes

Litvinenko, Derbenev, PRL 2008



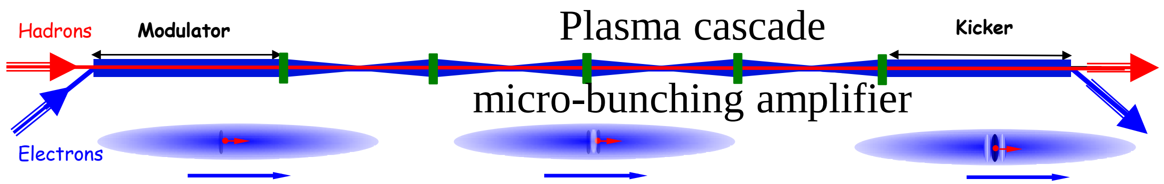
High gain FEL amplifier

Ratner, PRL 2013



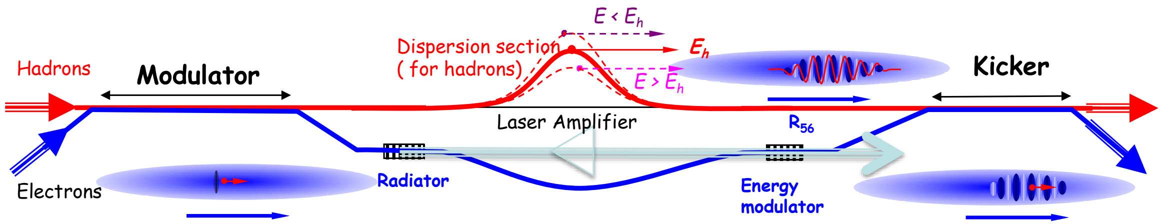
Multi- Chicane Microbunching amplifier

Litvinenko, Wang, Kayran, Jing, Ma, 2017



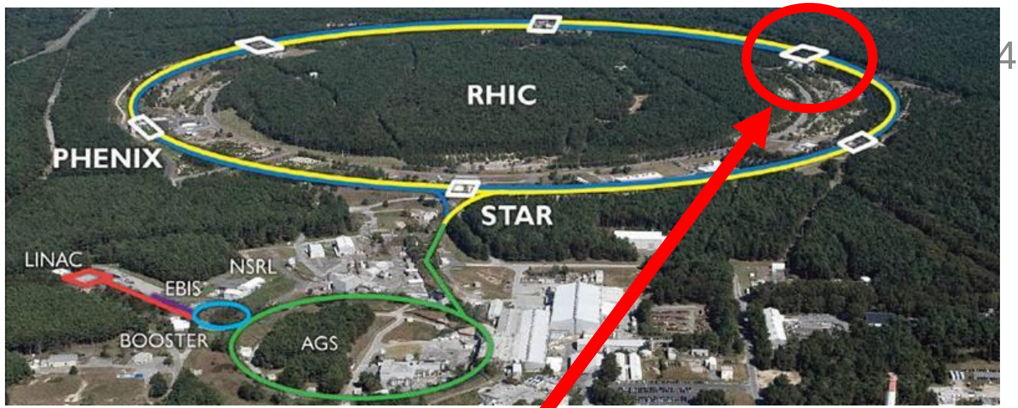
Plasma-Cascade Microbunching amplifier

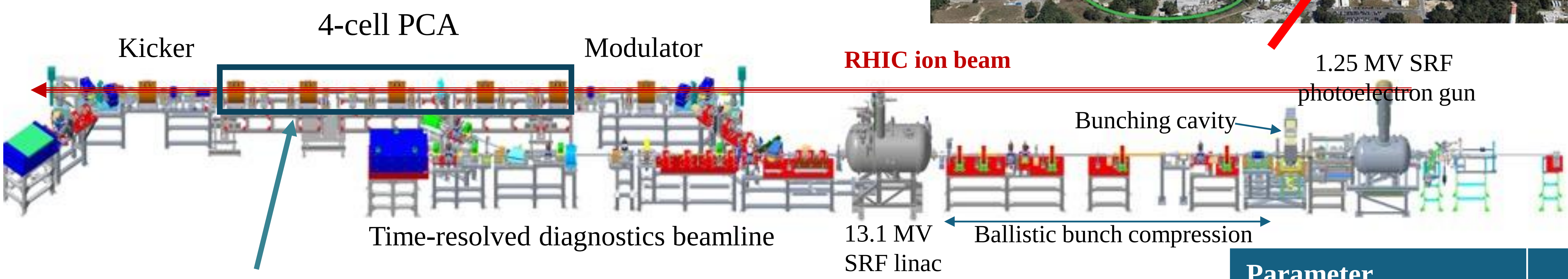
Litvinenko, Cool 13

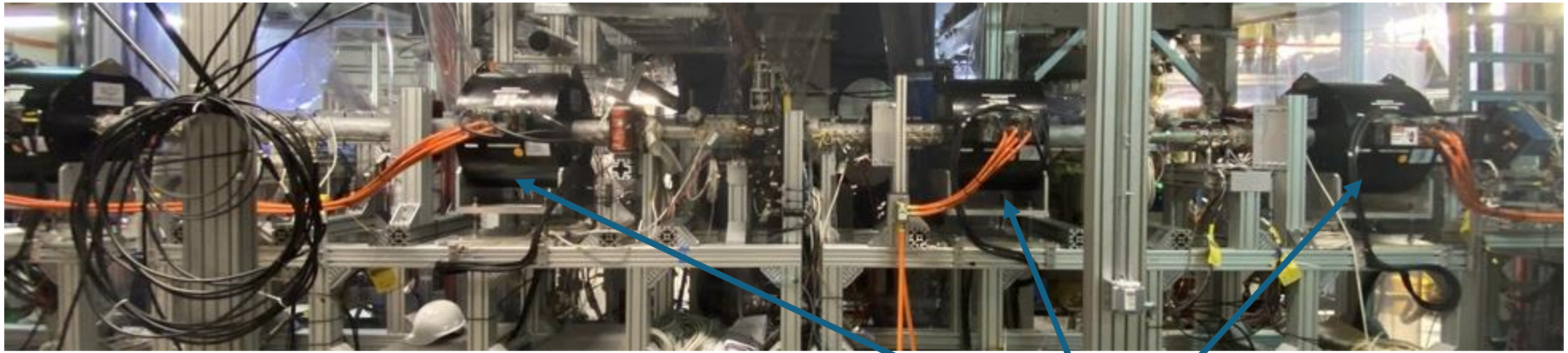


Hybrid laser-beam amplifier

CeC experiment at RHIC





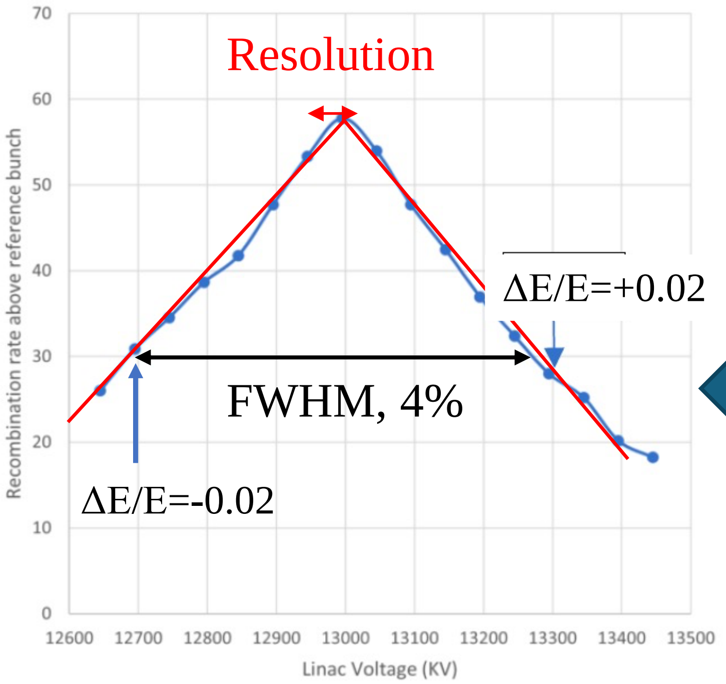


Solenoids for Plasma-Cascade Amplifier

Parameter	
Charge per bunch, nC	1.5
Peak current, A	50
Normalized emittance (slice), RMS, µm	1.5
Beam energy, Gamma	28.5
Beam energy, MeV	14.56
Energy spread (slice), RMS	$< 2\times10^{-4}$
Bunch rep-rate (CW), kHz	78

Recombination of electrons with Au ions: Run 21

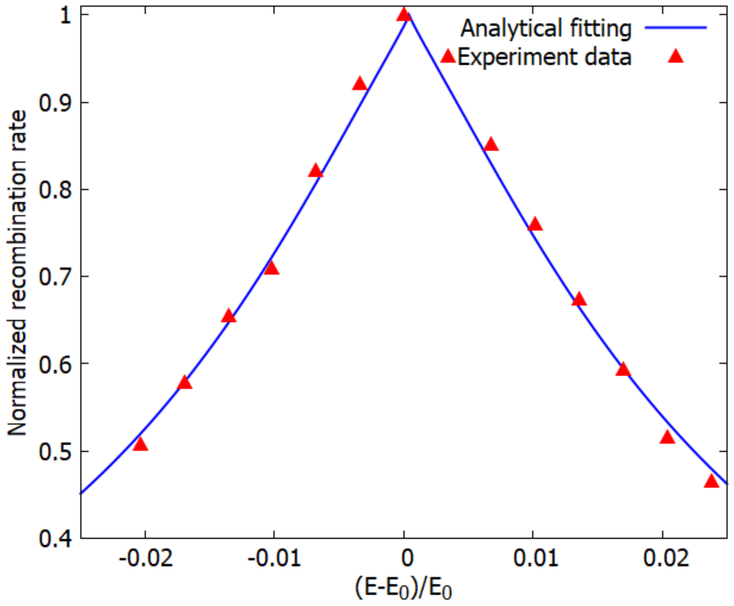
Experiment



Triangular shape of the measured dependence allows to define matching of the relativistic factors with accuracy ~ 0.2%, which is significantly smaller than 4% FWHM. This finding will reduce the range where we need to search for the CeC signature by 5-to-10 fold.

Recombination effect is very important for fine matching of energy both beams (ions and electrons)

Experiment vs Calculations



© G. Wang

$$\alpha_r = \frac{\int_{-\infty}^{\infty} d^3v_i d^3v_e\, f_e(v_e)\, f_I(v_i)\, |\vec{v}_e - \vec{v}_i|\, \sigma\left(|\vec{v}_e - \vec{v}_i|\right)}{\int_{-\infty}^{\infty} d^3v_i d^3v_e\, f_e(v_e)\, f_I(v_i)}$$

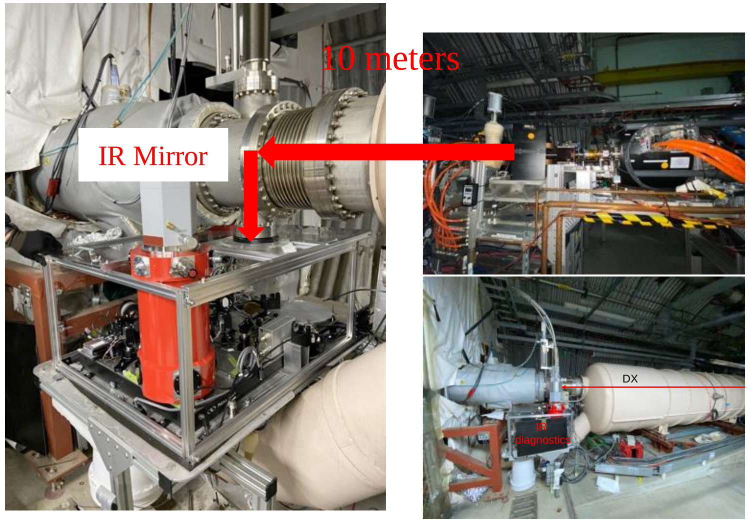
$$f_e(v_e) = \frac{1}{(2\pi)^{3/2}\beta_{e,\perp}^2\beta_{e,z}} \exp\left(-\frac{v_{e,x}^2 + v_{e,y}^2}{2\beta_{e,\perp}^2}\right) \exp\left(-\frac{(v_{e,z} - v_{z0})^2}{2\beta_{e,z}^2}\right)$$

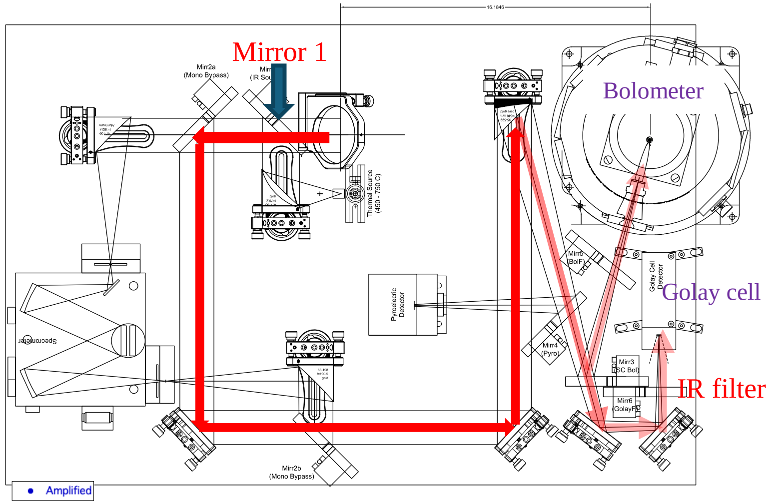
$$f_I(v_i) = \frac{1}{(2\pi)^{3/2}\beta_{i,\perp}^2\beta_{i,z}} \exp\left(-\frac{v_{i,x}^2 + v_{i,y}^2}{2\beta_{i,\perp}^2}\right) \exp\left(-\frac{v_{i,z}{}^2}{2\beta_{i,z}^2}\right)$$

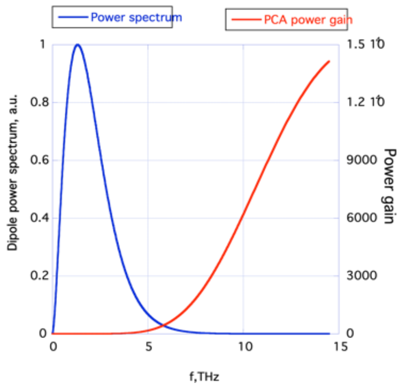
This results include convolution of the exact formula recombination cross-section (in the commoving frame) with distributions of two beams

How PCA gain is measured?

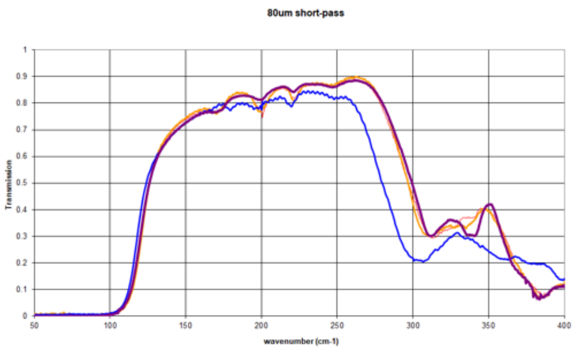
- We used IR radiation from the bending magnet at the exit of the CeC section. Critical frequency of synchrotron radiation from the bending magnet is 1.3 THz
- PCA gain peaks at 15 THz and there is no gain below 4 THz
- IR radiation is intercepted by 2” mirror 10 meters downstream
- For there measurements, the radiation was delivered to two most sensitive IR detectors: broad-band Golay cell or cryo-cooled Bolometer.
- IR filter with passband of 3.5-10 THz was used in front of the Golay cell to improve sensitivity at high frequencies
- Signal from Golay cell was detected by lock-in amplifier synched with the electron bunch pattern (typically 5 Hz, five 100 msec bunch trains per second). We used 3rd order modulation-demodulation (MDM) technique to remove background unrelated to IR radiation, by periodically blocking IR using Mirror 1.
- Signal from Bolometer was delivered in unsynchronous mode (140 kilo-samples per second) with respect to electron beam pattern. Analog signal was not available. We developed MatLab application for asynchronous detection of this digital pattern.
- PCA gain was evaluated by comparing radiated power in the PCA lattice (strong solenoids) with relaxed lattice (weak solenoids) using the same setting of the CeC accelerator and the electron beam

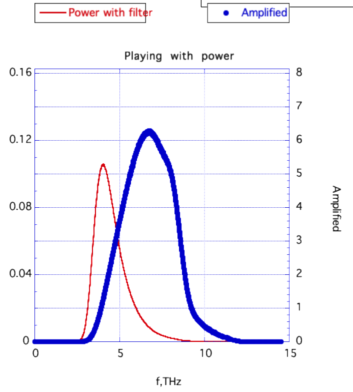






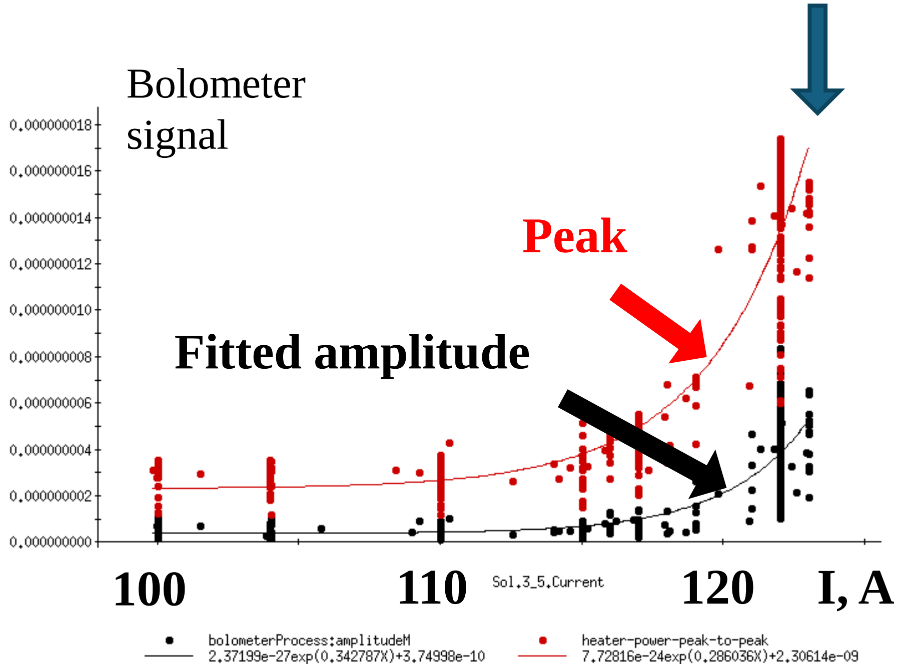
×



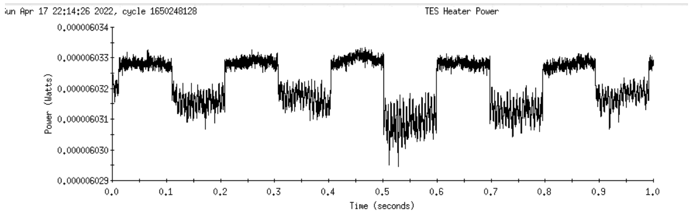


Comparing measurements with expectations

- ☐ Golay cell + IR filter measurements resulted in the average increase of IR power by factor 65 with PCA lattice
  - With 50% of electron bunch satisfying PCA condition (peak gain of 100 at 15 THz), expected increase of the measured IR power is 60
- ☐ Cryo-cooled bolometer measurements resulted in 100±20 average and 300±50 peak increase of IR power caused by PCA lattice
  - The bolometer manual specifies the sensitivity range from 6 THz to 60 THz, but absence of calibrated spectral response does not allow accurate comparison
  - Very crude estimation (using a step-function response in 6 to 60 THz) shows that with 50% of electron bunch satisfying PCA, expected increase of the measured IR power is 535
- ☐ Both results are in reasonable agreement with our expectations



Exponential growth of the IR signal at the bolometer as function of current in PCA solenoids: e-fold increase each 3 A (2.4%)



Summary CEC –POP experiment

- We developed techniques to observe/demonstrate some key features, namely the ion imprint (albeit weak), low beam noise, high gain amplification etc, in preparation for the CeC.
- Cooling demonstration was not achieved because the CeC accelerator suffers from lack of reliability: in terms of beam parameter jitter and poor repeatability of operation set-ups. It requires several significant improvements to generate stable electron beam required to demonstrate CeC.
- Recently development in the cooling simulations requires the electron beam to have good uniformity in both longitudinal and transverse directions. We developed a new laser pattern to tackle this problem. Experiments are ongoing.
- We are still targeting to demonstrate longitudinal Coherent electron Cooling before RHIC stops operations (in 2025).

Tour to the RHIC interaction region 2 IR2