

15th International Workshop on

COOL25

**Beam Cooling and
Related Topics**



Brookhaven
National Laboratory



U.S. DEPARTMENT
of **ENERGY**

Hadron Beam Cooling Concept and Cooler Design Status for the EIC

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COOL25 Workshop, Stony Brook

27-31 October 2025



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Outline

Hadron Cooling in the EIC

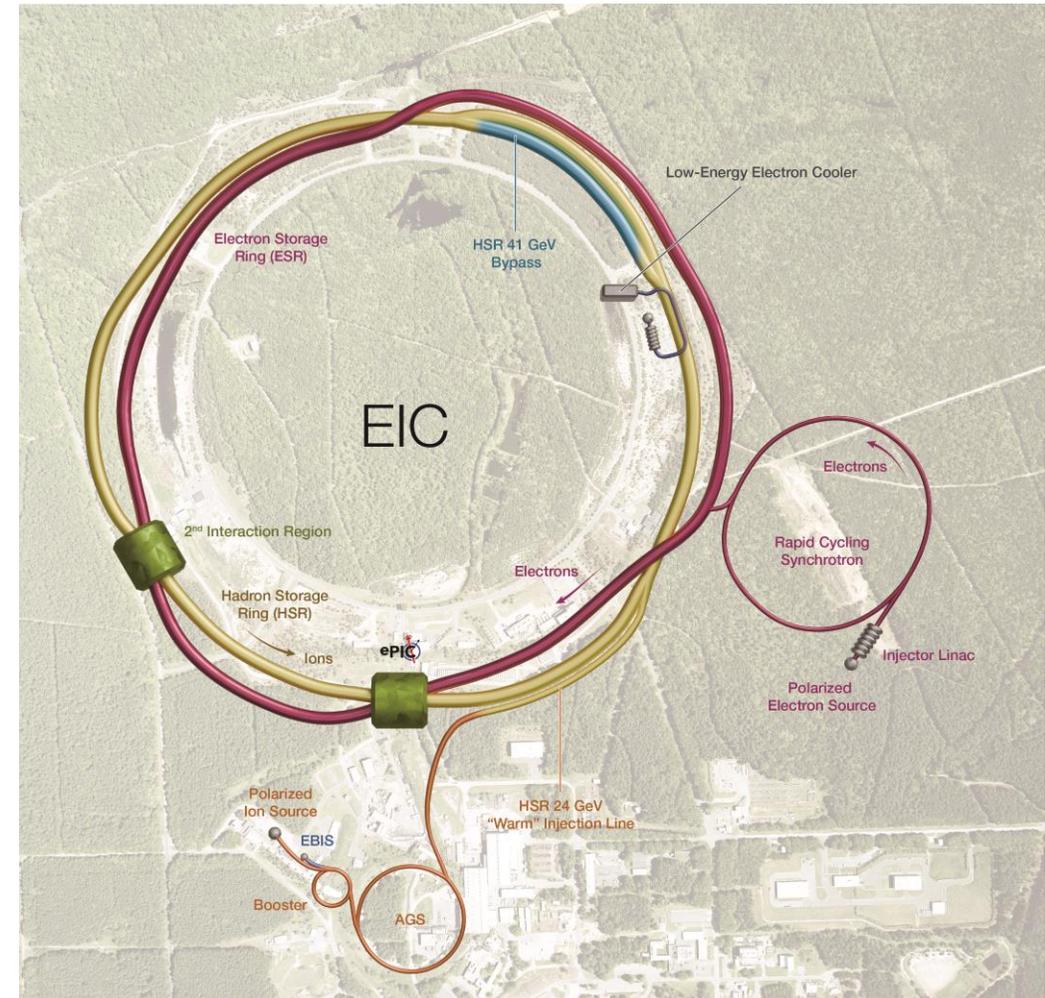
High-energy cooling for the EIC

Low-Energy Cooler (LEC) design status

LEC parameters and performance

Technical challenges

Summary



Hadron Cooling in the EIC

- Protons and ions will be precooled at 24 GeV using **Electron Cooling**.
- Heavy ions at collision energies will be cooled using **Stochastic Cooling**.
- Currently, no hadron cooling of proton is implemented at collision energies. However, it may be added in the future to increase the EIC average luminosity during store.

Cooling Requirements for EIC

Low-Energy Cooling (LEC):

The goal of cooling at proton injection energy is to obtain initial proton parameters by **cooling the vertical emittance from $\sim 2 \text{ } \mu\text{m}$ to $0.3 \text{ } \mu\text{m}$** (rms normalized).

Cooling at injection energy of protons (24 GeV) requires a 13 MeV electron beam.

High-Energy Cooling (HEC) of protons:

High-Energy Cooling (HEC) system capable of fully counteracting emittance growth at collision energies (41, 100, and 275 GeV) would greatly improve luminosity in the EIC.

Cooling techniques for the EIC

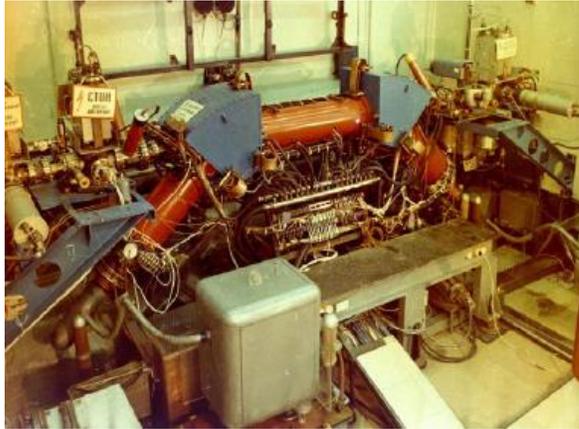
Present EIC concept:

- **Electron Cooling (13MeV electrons):**
Cooling of protons at injection energy of 24 GeV, [talks by A. Fedotov \(TUA1\), D. Kayran \(THB3\)](#)
- **Stochastic cooling:**
Cooling of heavy ions at collision energies, [see talk by M. Blaskiewicz \(TUB3\)](#)

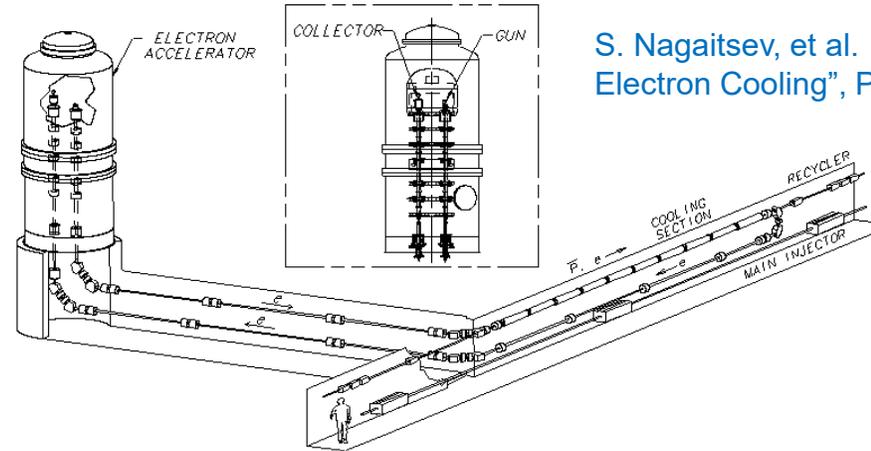
Possible future EIC upgrades:

- **Coherent electron Cooling (CeC)** based schemes (at collision energies) – detailed study for EIC was performed, [see talks by E. Wang \(TUA2\), W. Bergan \(TUA3\), K. Dietrick \(THB1\)](#)
- **Electron Cooling** (at collision energies) – under study, [see talks by S. Seletskiy \(TUB1\), D. Kayran \(TUB2\), J. Kewisch \(THB2\)](#)

Electron Cooling Technique



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 LReC electron cooler (2019-25): First RF-linac based electron cooler (concept directly extendable to higher energies). LReC does not use any magnetization of electrons. LReC 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)

Electron Cooling at high energy

Cooling rate $\lambda \propto \frac{r_e^2 m_e c Z^2 \Lambda_c}{A_i m_p} \cdot \frac{1}{\gamma^2} \cdot \frac{N_e}{\varepsilon_{xn} \varepsilon_{yn} \sigma_z \sigma_\delta} \cdot \frac{L_{CS}}{C_{ring}}$

Can one use **Electron Cooling** technique at very high energies in the EIC?

Reduction in a cooling rate with energy can be compensated by:

- Increasing the 6-D phase space density of the electron bunch
- Increasing the length of the cooling section
- Precooling an ion bunch, because ions with a small velocity spread are cooled faster

As **Electron Cooling** is a well-established technique, what is needed is to design accelerator which can provide electron beam parameters required for cooling.

High-energy Electron Cooling for EIC

Several approaches based on conventional **Electron Cooling**, were considered in the past:

1. Induction Linac based Ring cooler (FNAL):

V. Lebedev, S. Nagaitsev et al., "CDR: A ring-based electron cooling for EIC", JINST 16 T01003 (2021).

2. Dual-ring electron accelerator (JLAB):

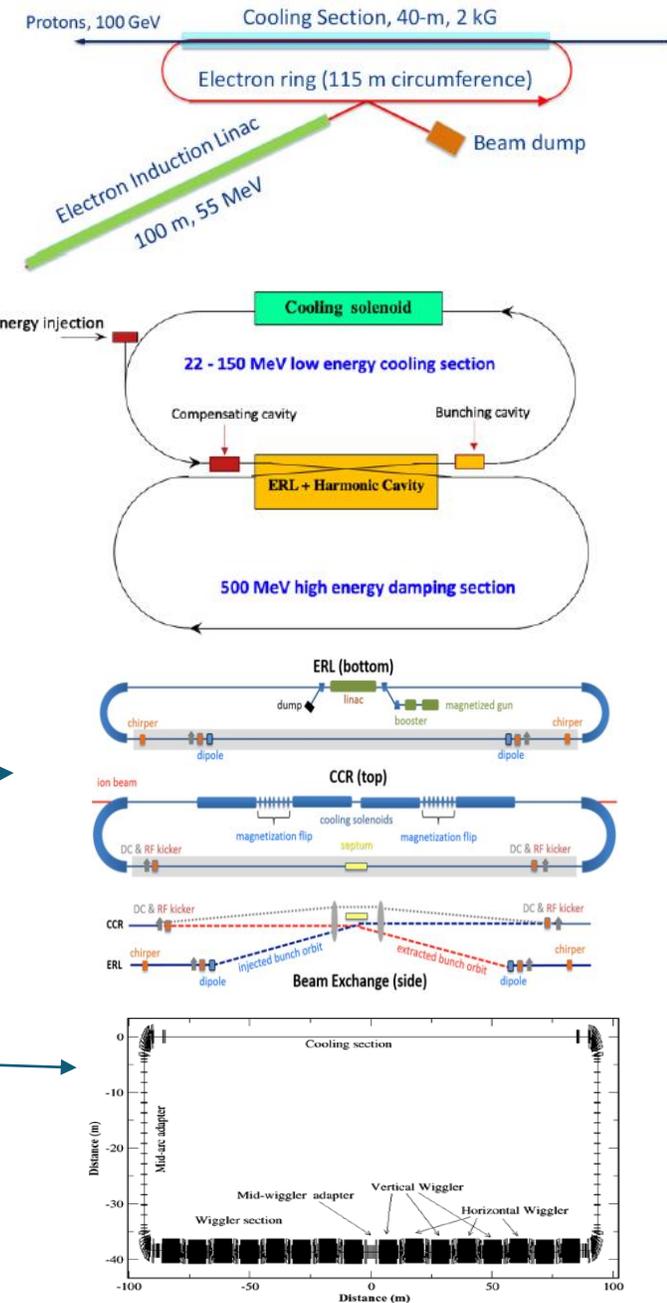
B. Dhital et al., "Beam dynamics study in a dual energy storage ring for ion beam cooling", Proc. IPAC21, TUXA07 (2021).

3. ERL-based Circulator Ring (JLAB):

S. Benson et al., ERL19, LINAC20 presentations

4. Storage Ring electron cooler (BNL):

H. Zhao, J. Kewisch et al., "Ring-based electron cooler for high energy beam cooling", PRAB 24, 043501 (2021)



High-energy Cooling for future EIC upgrades

Robust High-Energy Cooling (HEC) system capable of fully counteracting emittance growth at collision energies would greatly improve luminosity in the EIC.

Several approaches using well-established technique of **Electron Cooling (EC)** are presently being explored at BNL CAD for HEC application:

- Design of storage **Ring Electron Cooler** where electron bunches which provide cooling of protons are being cooled themselves via synchrotron radiation in wiggler magnets.
- Design of **ERL-based Recirculator** where electron bunches are supplied by high-brightness electron source.

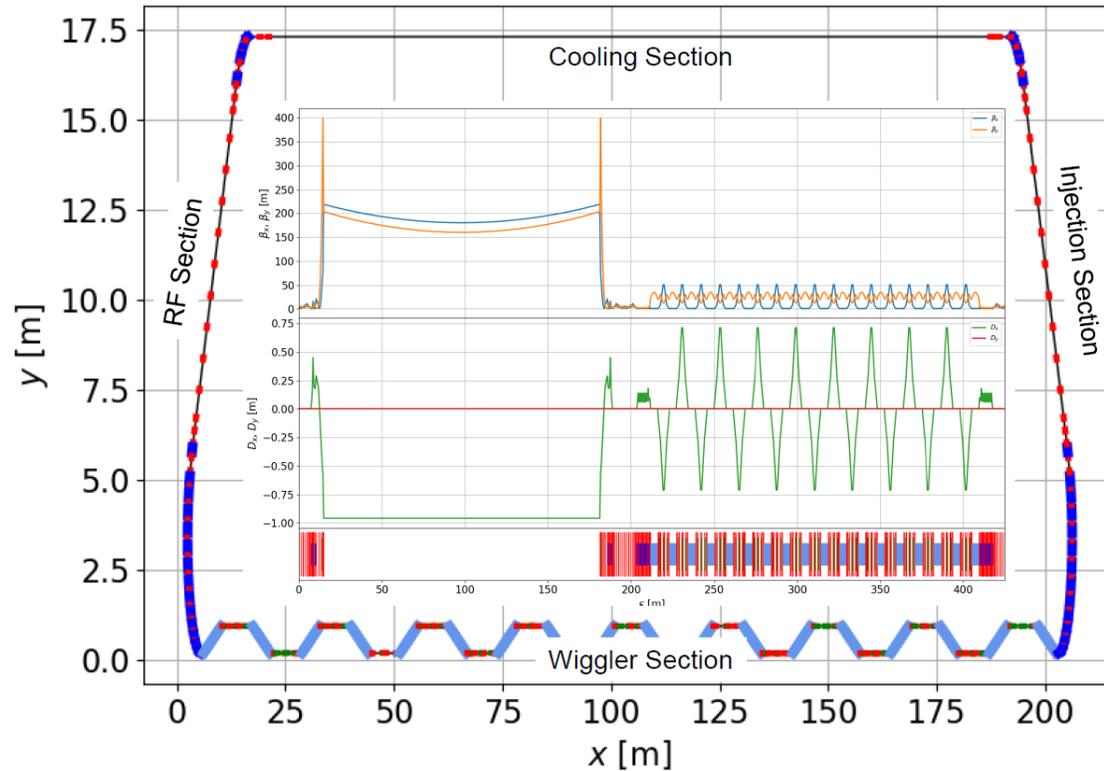
High-energy Ring Electron Cooler

The Ring Electron Cooler (REC) is a **non-magnetized, bunched electron cooler based on an electron storage ring**, which utilizes damping wigglers to provide radiation damping for the electrons.

See presentations:
S. Seletskiy (TUB1), J. Kewisch (THB2)

Table 1: The REC parameters (electron storage ring)

relativistic γ	293
ring circumference [m]	426
cooling section length [m]	170
horizontal dispersion in the CS [m]	1
number of damping wigglers	18
damping wiggler length [m]	4.2
damping wiggler field [T]	2.4
wiggler gap [cm]	2
wiggler period [cm]	20
momentum compaction	$-1.5 \cdot 10^{-3}$
main RF frequency [MHz]	98.6
main RF voltage [kV]	50
2nd harmonic RF voltage [kV]	25
number of bunches	140
number of particles per bunch	$1.3 \cdot 10^{11}$
charge per bunch [nC]	21
peak current [A] (flat top e-bunch)	17.5
average current [A]	2
geometric emittance (x, y) [nm]	7.8, 7.8
CS β -function (x, y) [m]	180, 160
rms relative momentum spread	$9.8 \cdot 10^{-4}$
FWHM bunch length (flat top e-bunch) [cm]	34
space charge tune shift (x, y)	0.14, 0.14
p-e focusing tune shift (x, y)	0.04, 0.09
radiation damping rate (x, y, z) [s^{-1}]	31, 31, 62
BBS rate (x, y, z) [s^{-1}]	0.8, -0.3, 12
IBS rate (x, y, z) [s^{-1}]	31, 31, 48

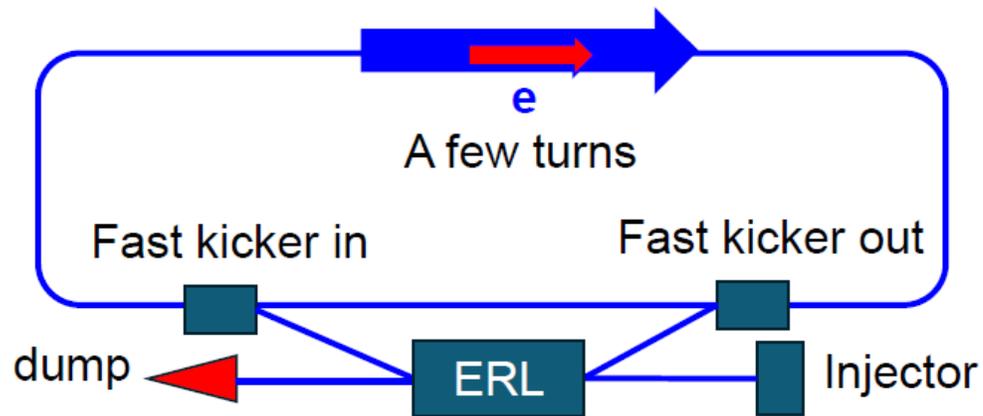


High-energy Recirculator Cooler

- Electron bunches are accelerated in the ERL
- Recirculated in the ring for just a few turns (1-9) to reduce current required from injector
- Decelerated and sent to a beam dump
- Non-magnetized electron beam is used

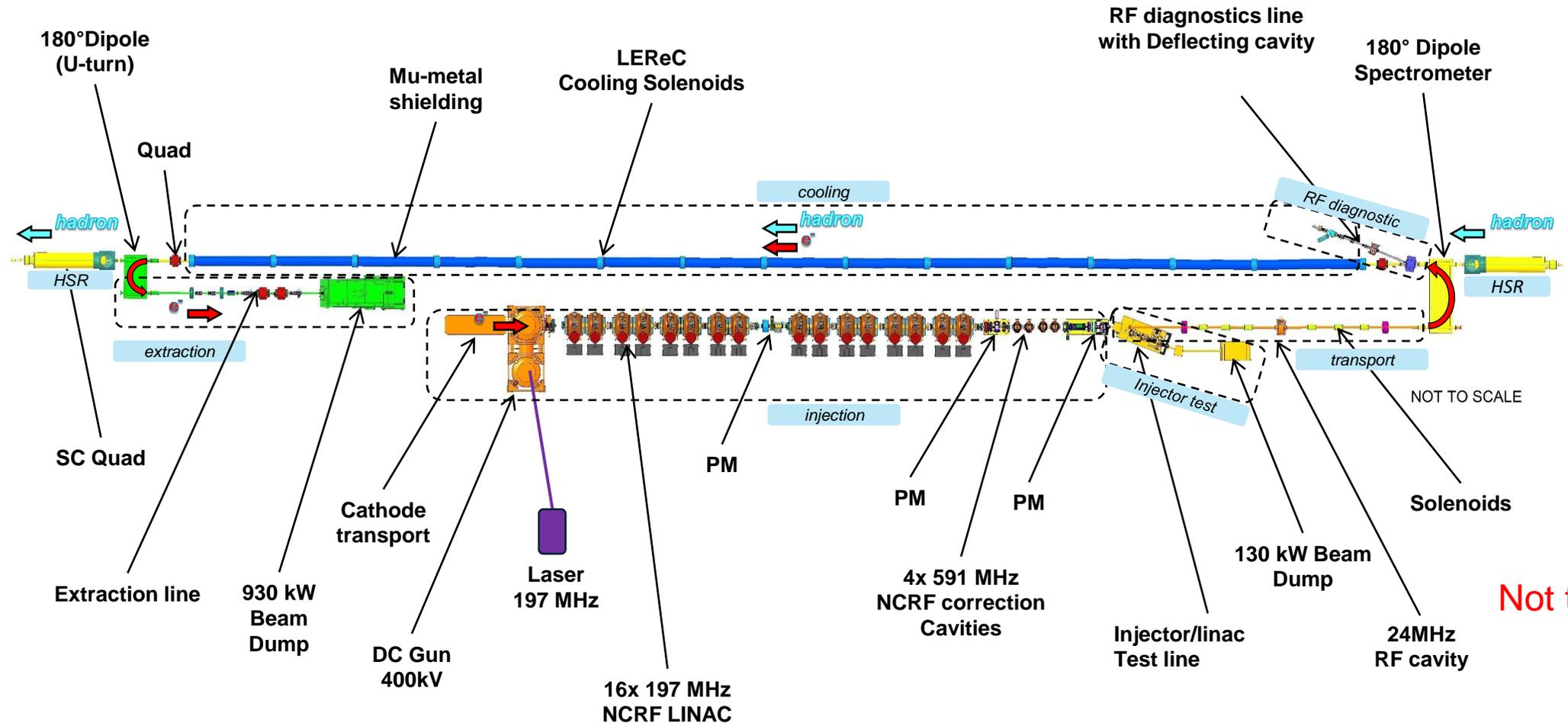
See presentation:
D. Kayran (TUB2)

Recirculator parameters



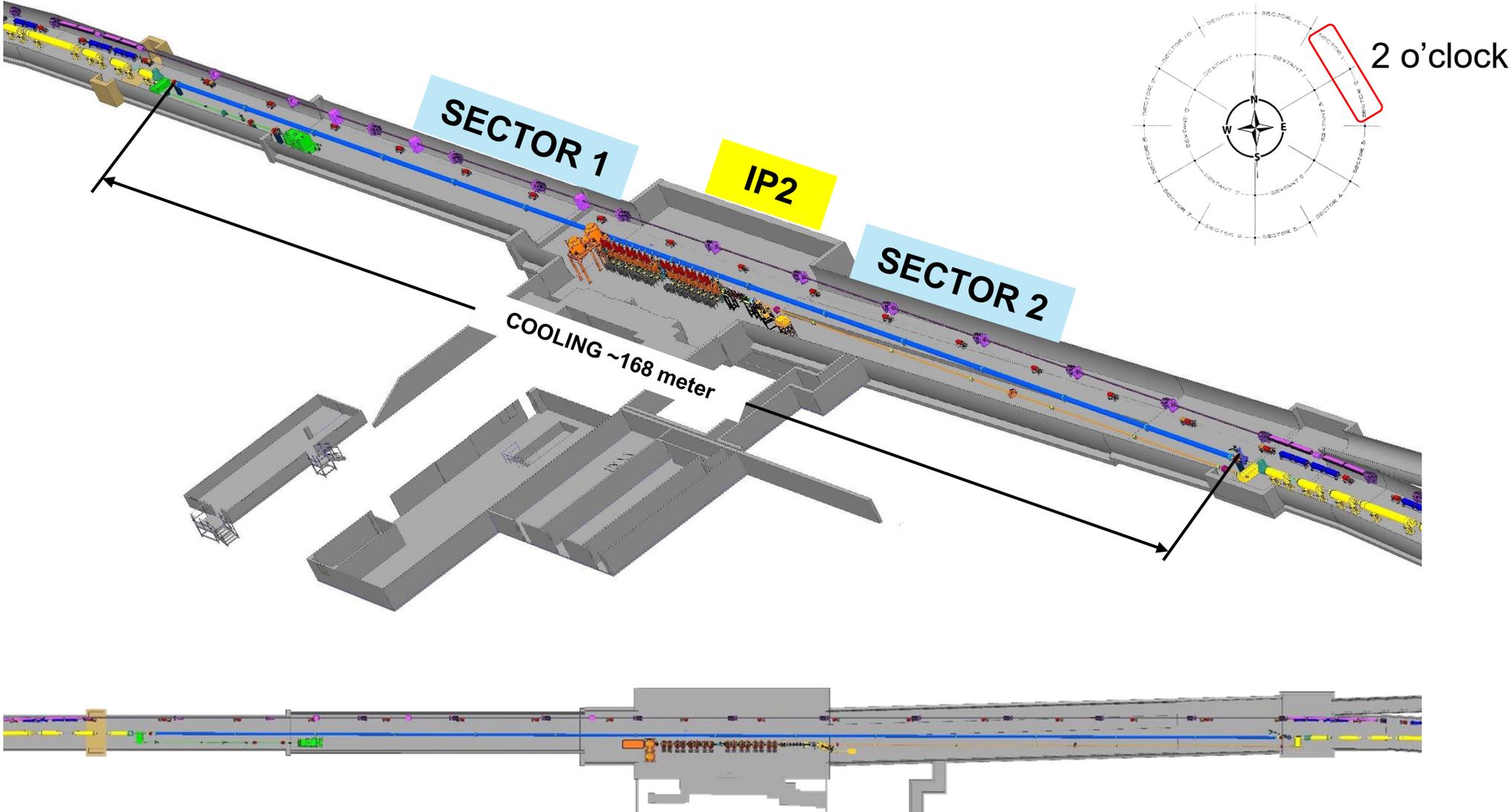
Proton Energy , GeV	275	100	41
N_e	3.00E+10	1.25E+10	4.00E+09
Q_e , nC	5	2	0.64
Rms bunch length, cm	2.5	2.5	2.5
Peak Current, A	24	10	3
Repetition rate, MHz	98	98	98
$\langle I \rangle$ in cooling section, mA	490	196	63
Number of recirculations	9	4	1
$\langle I \rangle$ from gun, mA	54	49	63
Rms energy Spread in CS	3.00E-04	3.00E-04	3.00E-04
RMS Normilized Emittance, m	2.00E-06	1.50E-06	1.50E-06
Cooling Time (τ_x), hrs	1.8	1.9	2
Cooling Time (τ_y), hrs	3.6	3.9	1.8
Cooling Time (τ_z), hrs	2.9	1.6	1

Low-Energy Cooler (LEC) for the EIC



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

Low-Energy Cooler (LEC) Layout



Low Energy Cooler Parameters

LEReC key parameters for reference

	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 D_y , D_y' , 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, μm	<1.5	2
rms bunch length, cm	4	100
rms dp/p	<5e-4	6e-4
Angles in cooling section, μrad	20-30	20

electrons

4-5

704 MHz (9 MHz)

20 m

30 m

3 nC

1.6-2 MeV

30 (60 mA in tests)

<2 μm

5 cm

<5e-4

<150 μrad

Beam Structure in Cooling Section

Protons bunch structure:

f_rep=24.6 MHz
N_p=2.8e11, I_peak=2.7 A (with 2nd harmonic RF)
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

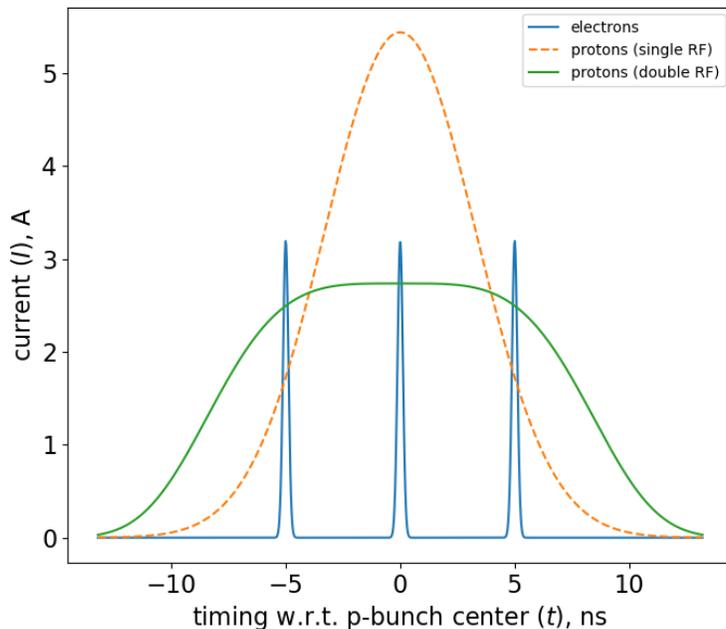


Fig. Three electron bunches (blue color) spaced by 5.1 ns placed on a single proton bunch (orange dashed line: single RF harmonic; green solid line: double RF harmonic).

Proton bunches during cooling:

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:](#)

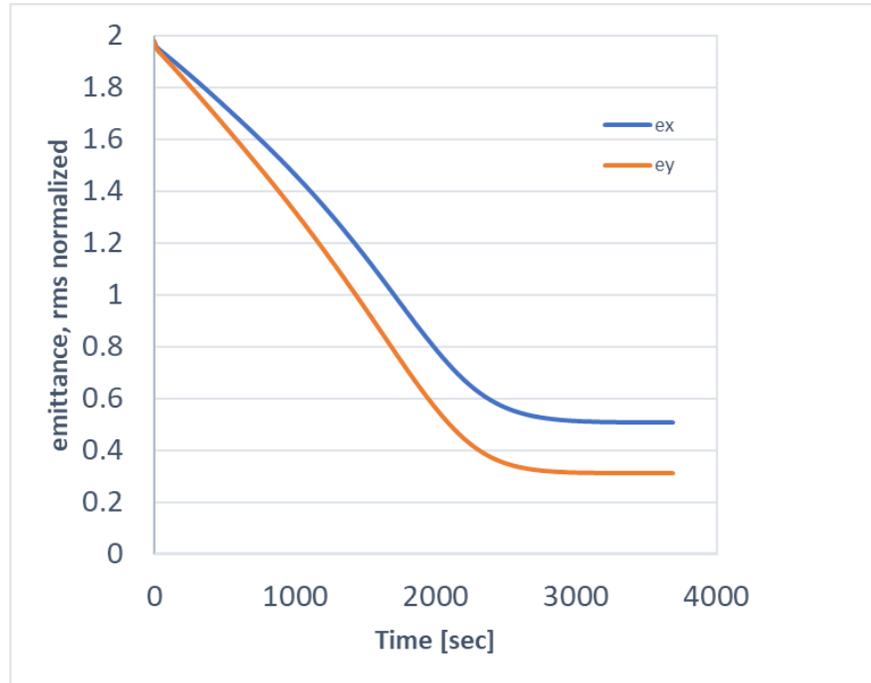
- 1) Expected proton beam parameters with using quad pumping in AGS were established: peak current of 5.4A with single harmonic 28MHz RF. Double RF system will decrease peak current by about factor of 2.
- 2) Use of double RF system and making flattened bunch profiles was also demonstrated at proton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

Cooling Performance

Average current of electrons: $I_{av}=74\text{mA}$

Electrons rms angles in the cooling section: **25 urad**

Effective cooling section length: **168 meters**



Cooling simulations of protons at $\gamma=25$, 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.

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

Requirement on electron angles:
for $\gamma=25$: $\sigma_p < 4e-4$; $\theta < 25$ 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.

$$\theta = \sqrt{\frac{\epsilon_{xn}}{\gamma\beta_x}}$$

LEReC experience and LEC challenges

LEReC experience:

1) Stable 24/7 running of high-current electron accelerator and stable cooling was provided over many weeks of RHIC collider. 2) Reliable operation was ensured by implementation of laser position feedbacks, intensity feedback, energy feedback, automatic cooling section orbit correction and feedback. 3) Robust photocathodes (K_2CsSb) with initial Quantum Efficiency of around 8%. 4) Pulsed beam diagnostics worked very well; did not find need for high-power beam diagnostics.

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.

Based on LEReC operational experience, the following areas require special attention:

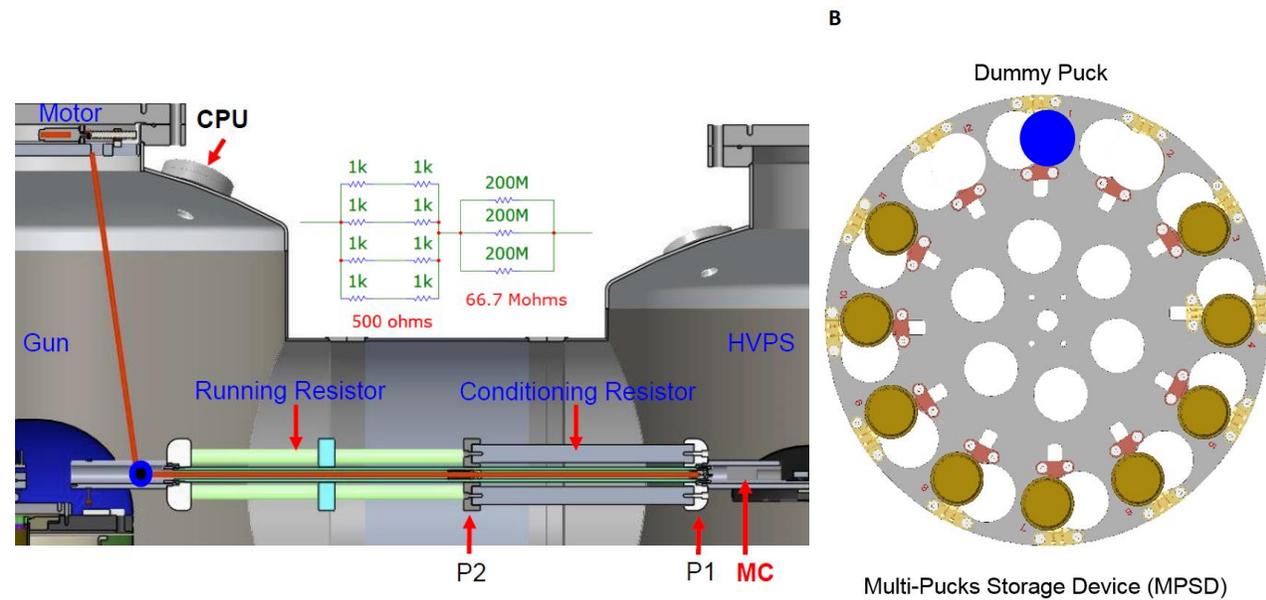
1. Long-term stable Gun operation at required current of 75mA.
2. Achievement and control of electron angles in cooling section at the level of 25 urad.
3. High-power beam dump, 930kW at 12.5MeV

LEC source requirements and LEReC gun experience

LEReC gun was built by Cornell University and upgraded at BNL.

- BNL developed cathode growth, cathode exchange and cathode transfer system.
- Upgraded Gun with conditioning/operation Resistor remote switch to support long term operation.

	LEReC operation	LEC requirements
Gun Voltage [kV]	375	350-375
Bunch charge [nC]	36x0.06	3 x 1
Macro Bunch Charge [nC]	2.2	3
Rep. rate [MHz]	9.3	24.6
Average current [mA]	20	74
Cathode peak current [A]	2.5-3	2-3
Cathode Laser power [W]	0.5-5	9
Cathode initial QE[%]	8	8
Lifetime [weeks]	>2	> 2

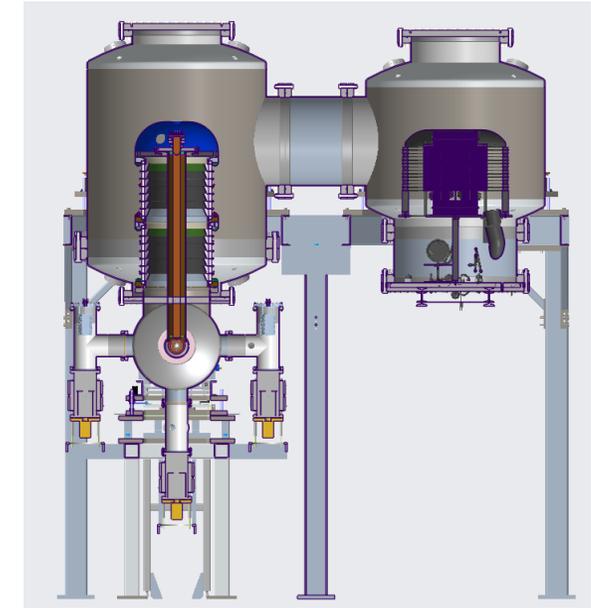


X. Gu et,al Phys. Rev. Accel. Beams **23**, 013401

LEC gun choices

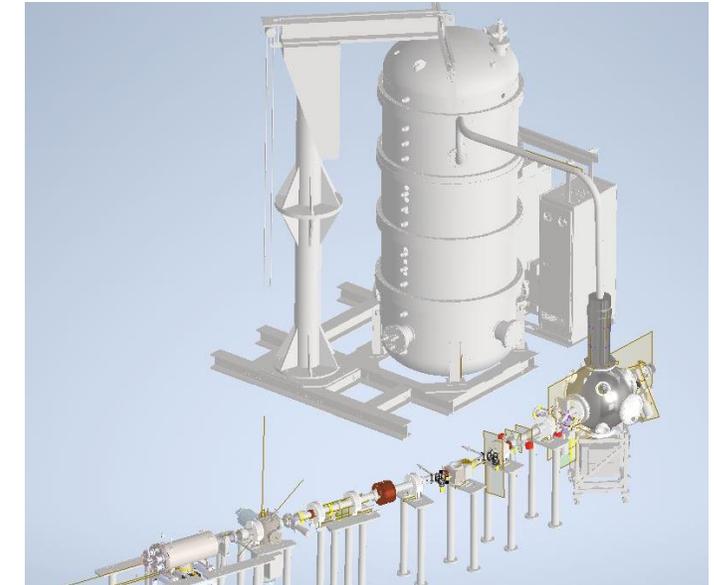
LEReC Gun (built by Cornell):

Existing LEReC Gun and HVPS (600kV). Need to demonstrate stable operation at require current (75mA) for the EIC. Present HVPS operation is limited to about 80mA current.



R&D Gun at Stony Brook (under development):

Active cathode cooling. HVPS (600kV) and Gun are designed to operate at 100mA. Tests with beam to start in late 2026.

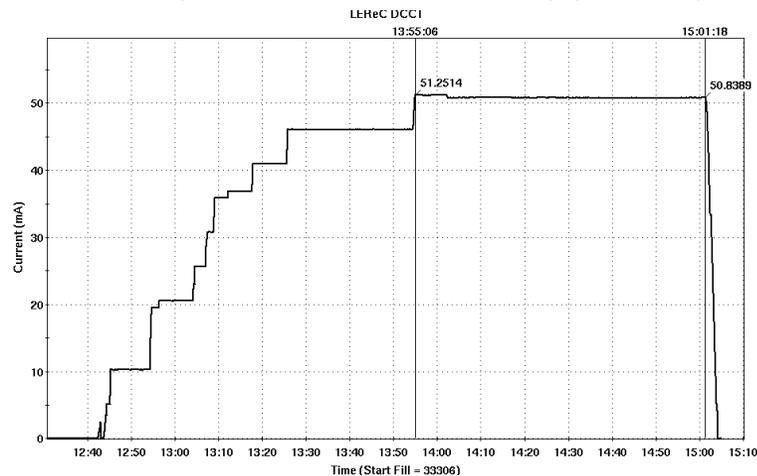


E. Wang et al., Phys. Rev. Accel. Beams **25**, 033401

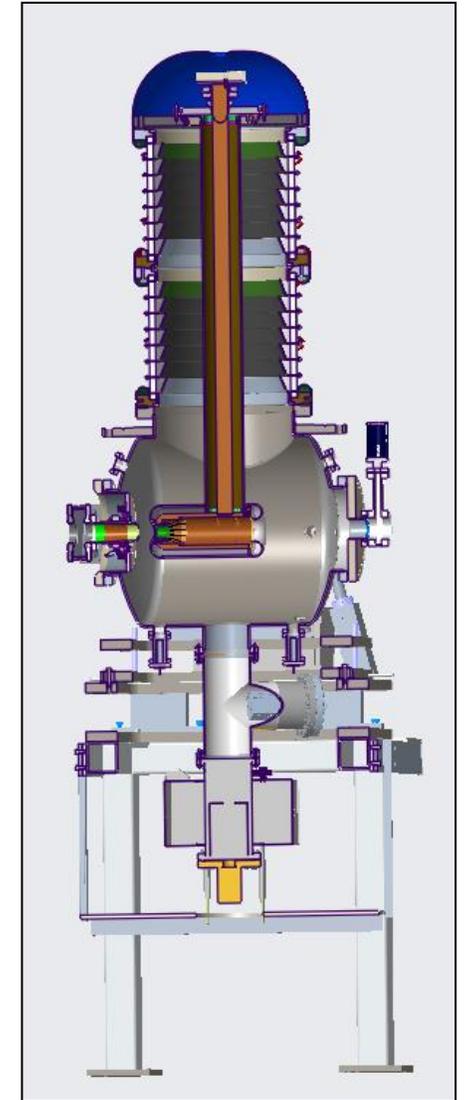
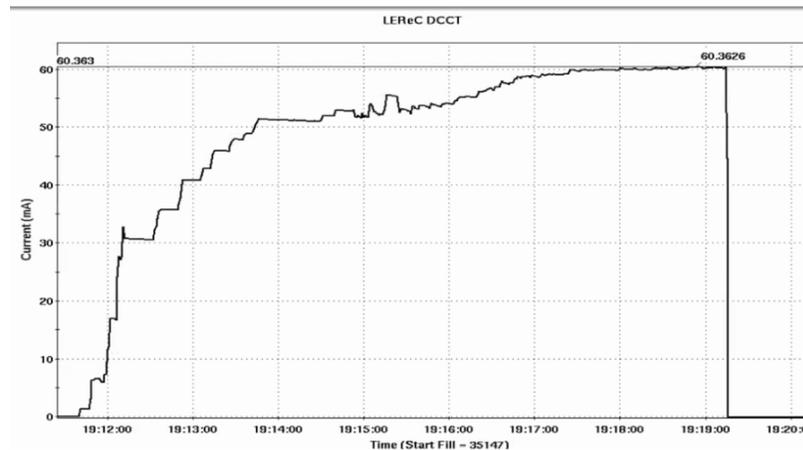
LEReC high-current studies

- High current source is required for EIC LEC:
 - The LEC requires stable operation at around 75mA current.
- High-current source R&D:
 - Explore LEReC Gun operation with high-current up to 80mA.
 - Explore Gun and HVPS long-term stability at high currents.
 - Explore operation with active cathode on center vs cathode off center.
 - Explore large cathode area vs small active area.
 - Explore cathode QE at various laser powers with and without cathode stalk cooling.
 - Test multi-alkali photocathodes using different growth methods.

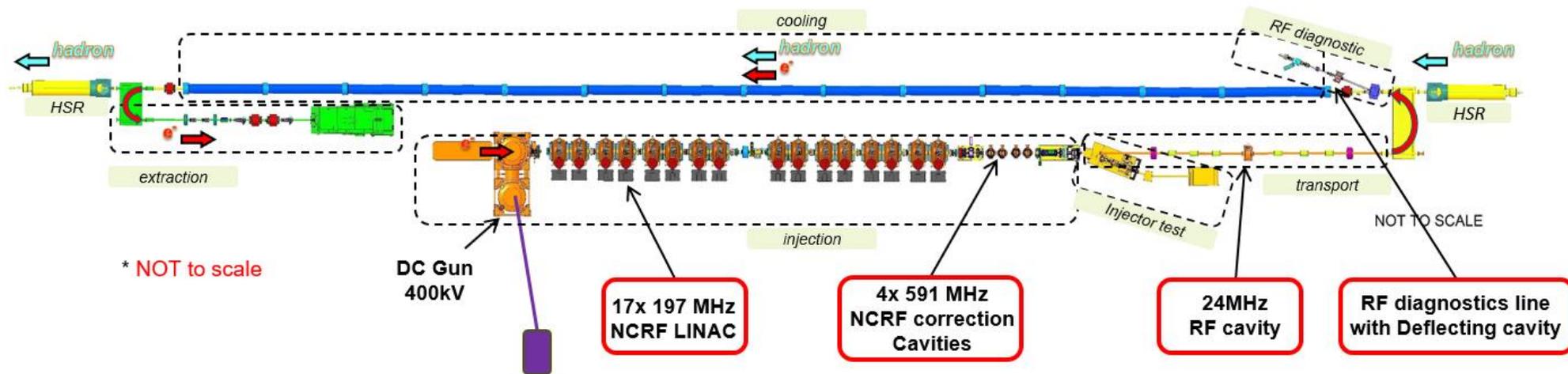
Stable operation at 50mA in tests (April 2022)



60mA (October 2024):



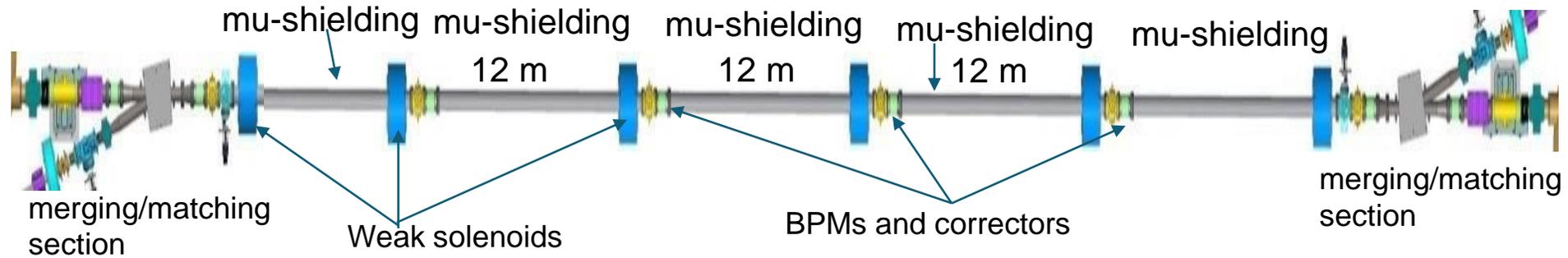
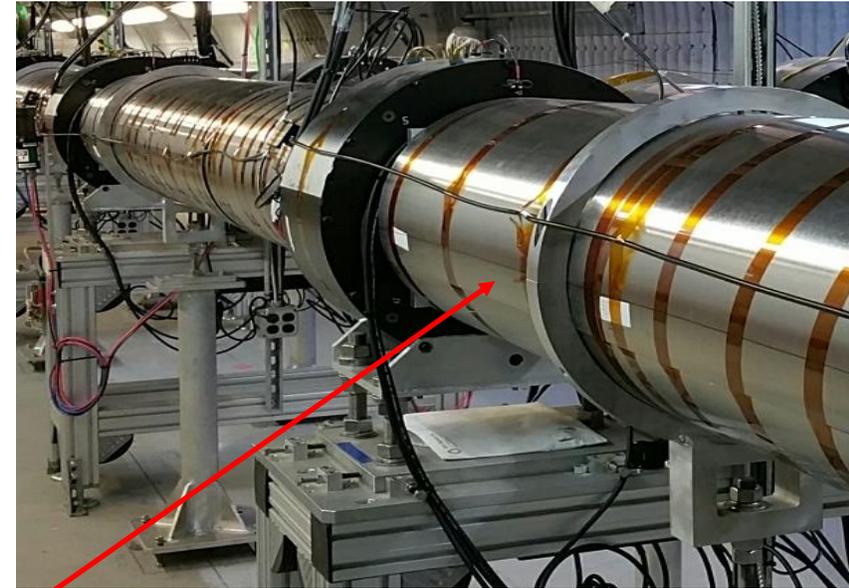
LEC RF systems



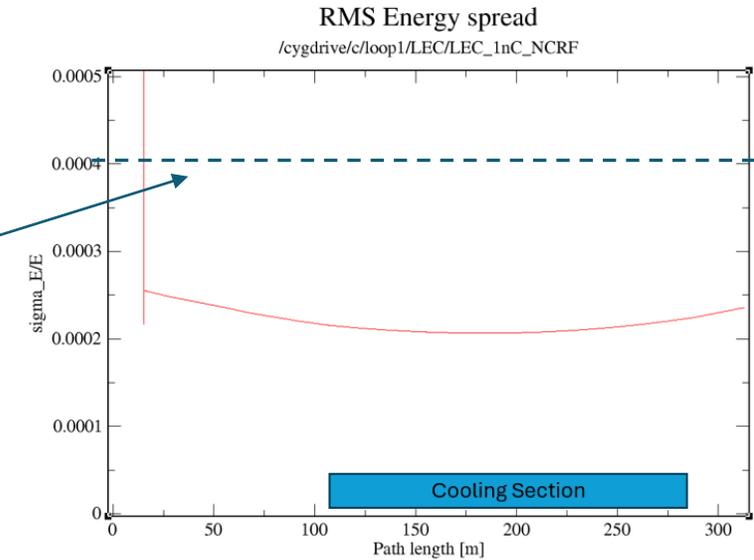
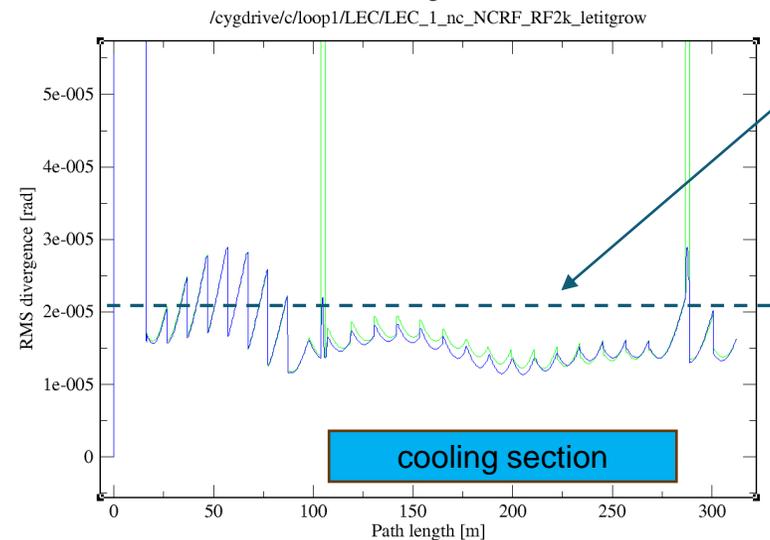
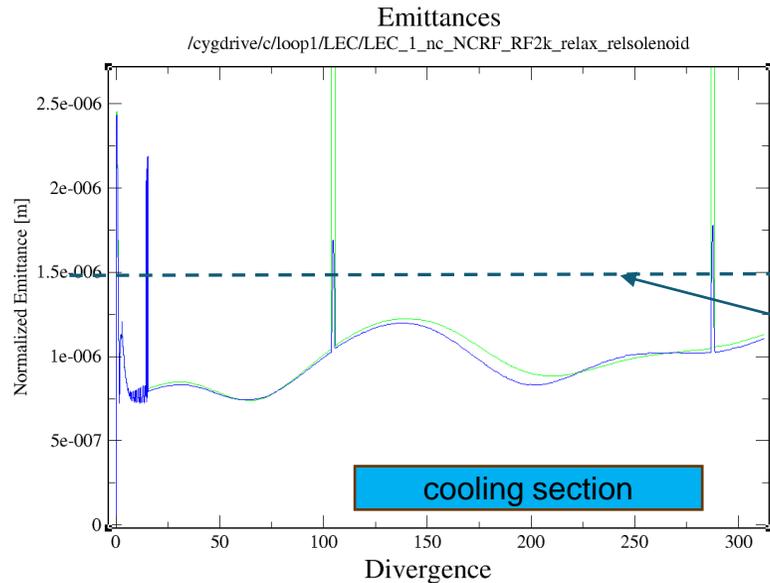
	197 MHz*	591 MHz	24 MHz	591 Deflecting
Frequency [MHz]	197.0508	591.1524	24.6314	591.1524
Tuning range [MHz]	±0.12	-0.5~+1.0	±0.15	
Total Voltage [MV]	13.6	1.5	0.01	0.12
# of Cavities	17	4	2	1
Voltage per cavity [kV]	800	400	5	120
R/Q cir. [Ω]	170	96	15	750
Q0	48000	34000	160	13500
FPC Qext	24000	34000	160	13500

LEC Cooling Sections

- Requirements on residual transverse magnetic field between correctors in the cooling region **is 1 $\mu\text{T}\cdot\text{m}$** , which is similar to LEReC requirements.
- Assuming 12 m long sections, the transverse magnetic fields should be shielded to **1 mG** level in each section.
- Shielding of the residual magnetic field to such level can be achieved using concentric cylindrical layers of high-permeability alloy in the cooling sections, similar to LEReC.



LEC Electron Beam Dynamics



requirements

Simulations for 1 nC electron bunch charge:

Results:

Normalized rms emittances $< 1.5 \mu\text{m}$

RMS energy spread $< 4 \times 10^{-4}$

Electron beam divergence in the cooling $< 20 \mu\text{rad}$.

See D. Kayran presentation (THB3)

Summary

- Protons and ions will be precooled at 24 GeV using **Electron Cooling**.
- Heavy ions at collision energies will be cooled using **Stochastic Cooling**.
- Low-energy Electron Cooler (LEC) at injection energy of protons at 24 GeV addresses challenges of achieving design luminosity in the EIC and simplifies requirements for potential future high-energy cooling at collisions.
- The LEC is RF-based 13MeV electron cooler designed to cool protons and ions at 24GeV.
- The LEC design is in progress.