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U.S. DEPARTMENT OF ENERGY

Low-energy Electron Cooling Experiments

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on behalf of CAD Beam Cooling group

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Outline

- EIC Low-Energy Cooler (LEC) and APEX studies
- LEReC cooling studies
- LEReC/LEC high-current R&D
- Readiness of experiments

Motivation for Low-Energy Cooler experiments

1. EIC Low-Energy Cooler (LEC) studies:

To guide LEC design, dedicated experiments are performed to establish proton beam conditions to be used for EIC at injection energy of protons.

2. Cooling studies using LEReC:

Cooling experiments are performed using LEReC accelerator to explore effects of electron beam on hadrons under cooling (such as recombination, "heating" of ions due to various effects, effects on lifetime of ions) and to address questions relevant to the design of electron cooler for EIC.

3. High-current experiments using LEReC:

EIC LEC requires stable long-term operation of electron source at around 75mA current. LEReC Gun is being used for such high-current studies.

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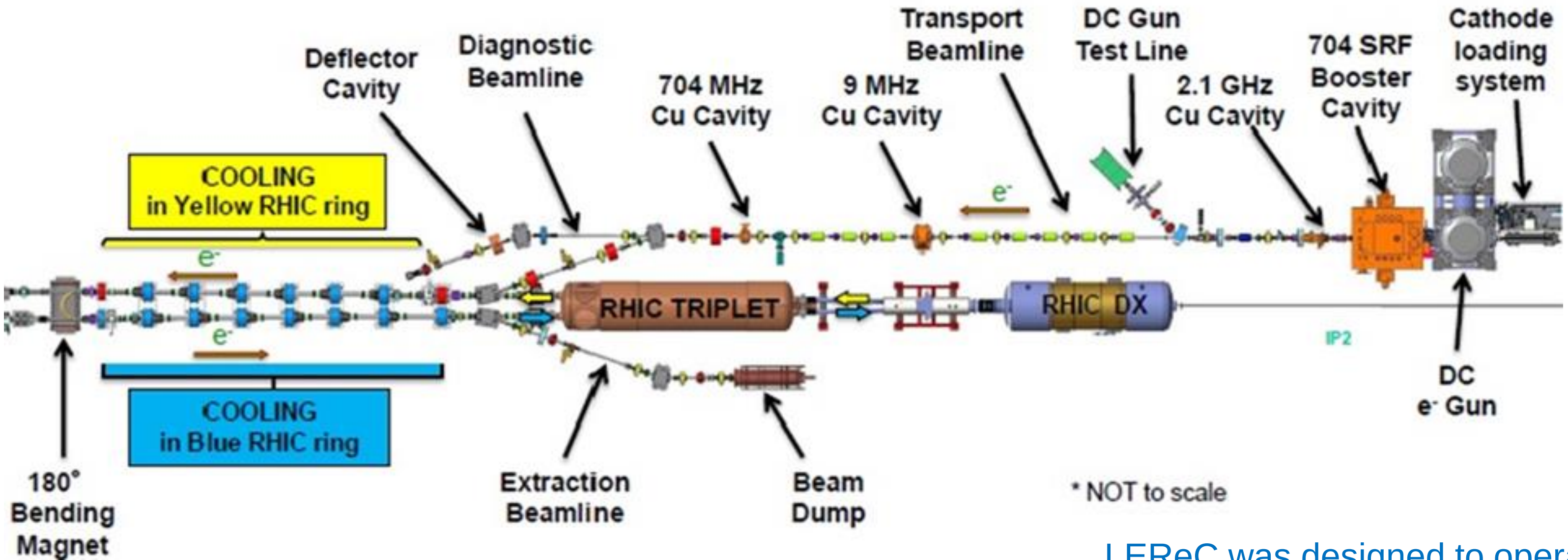
Operational Electron Cooler LEReC @ RHIC



LEReC was designed to operate at electron energies up to 2.6 MeV (using single-cell SRF accelerating cavity).

- **LEReC is a fully-operational electron cooler which utilizes RF-accelerated electron bunches.**
- **LEReC approach was chosen for the EIC LEC (12.5 MeV electron kinetic energy).**

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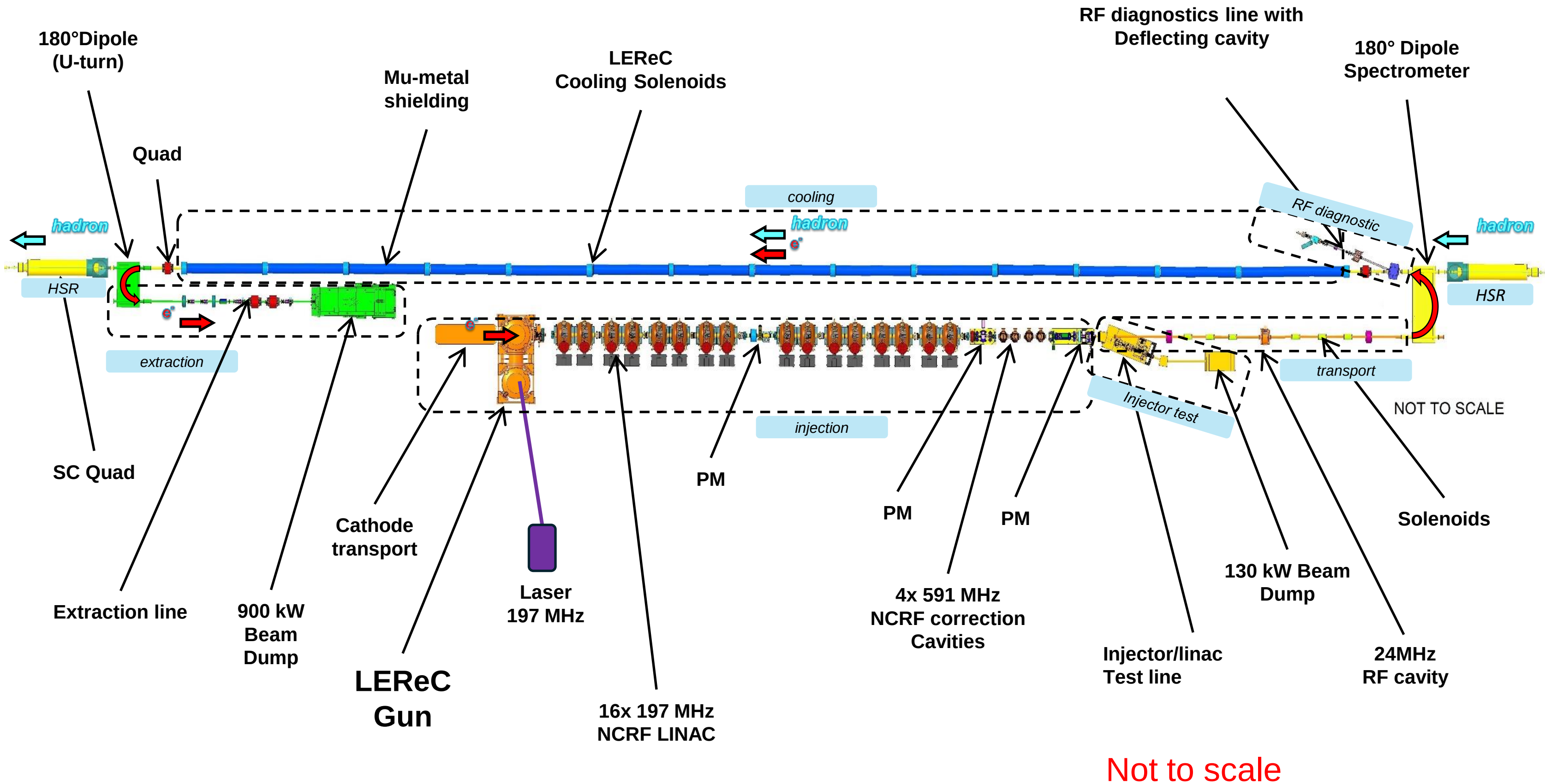
EIC Low-Energy Cooler (LEC) layout @IR2



EIC LEC is LEReC scaled to higher energy (12.5 MeV electron kinetic energy).

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EIC LEC beam structure in cooling section

Protons bunch structure:
f_rep=24.6 MHz
N_p=2.8e11, I_peak=3 A
(with 2^{nd} 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

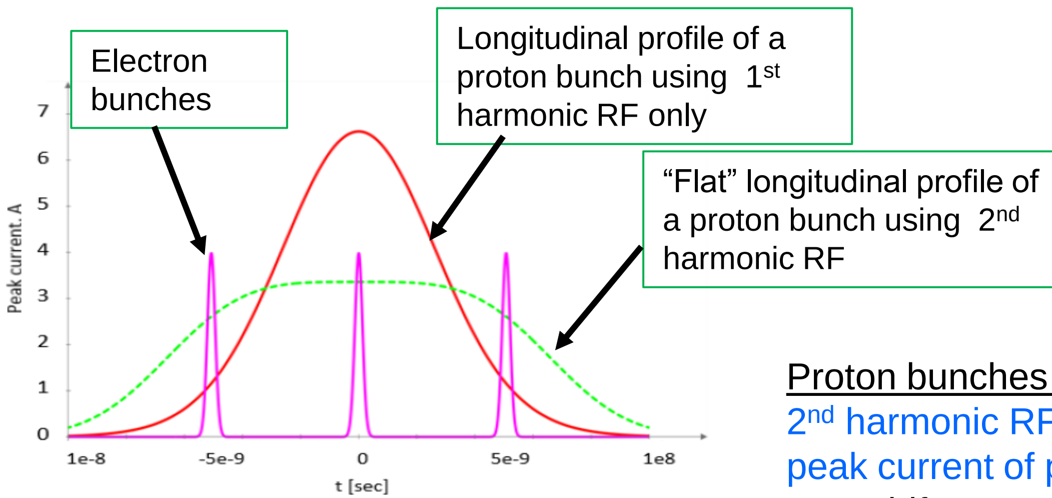

Figure 3: Three electron bunches (magenta) spaced by 5.1ns placed on a single proton bunch (red: single RF harmonic; green: double RF harmonic).

Proton bunches during cooling:
2^{nd} harmonic RF alleviates space-charge effects reducing peak current of protons to about 3A so the space charge tune shifts are $\Delta Q_{sc,x,y}$**=0.07, 0.13**

Use of **double RF system and making flattened bunch profiles** was recently demonstrated at proton injection energy in RHIC (**APEX May 8, 2024**).

Experiments for EIC LEC

Completed in 2024:

1) APEX 24-07: **Injection studies for the EIC** (A. Fedotov et al.) – **completed**
2) APEX 24-06: **Injection studies for the EIC with dual RF system** (D. Kayran et al.) – **completed**

Planned for Run-25:

3) APEX 22-05: **Emittance growth of ion beam** due to interaction with bunched electron beam (S. Seletskiy et al.) – in process
4) APEX 22-06: **Ion beam lifetime** in the presence of the electron beam (S. Seletskiy et al.): - to be performed

Withdrawn:

APEX 22-07: **Dispersive cooling** (A. Fedotov et al.) – not directly relevant for LEC, and limited performance range with present 28MHz RF.

APEX 24-15: **Recombination rate for proton beam** (G. Wang et al.)- due to ASE limitation on the proton bunch intensity for CeC experiment.

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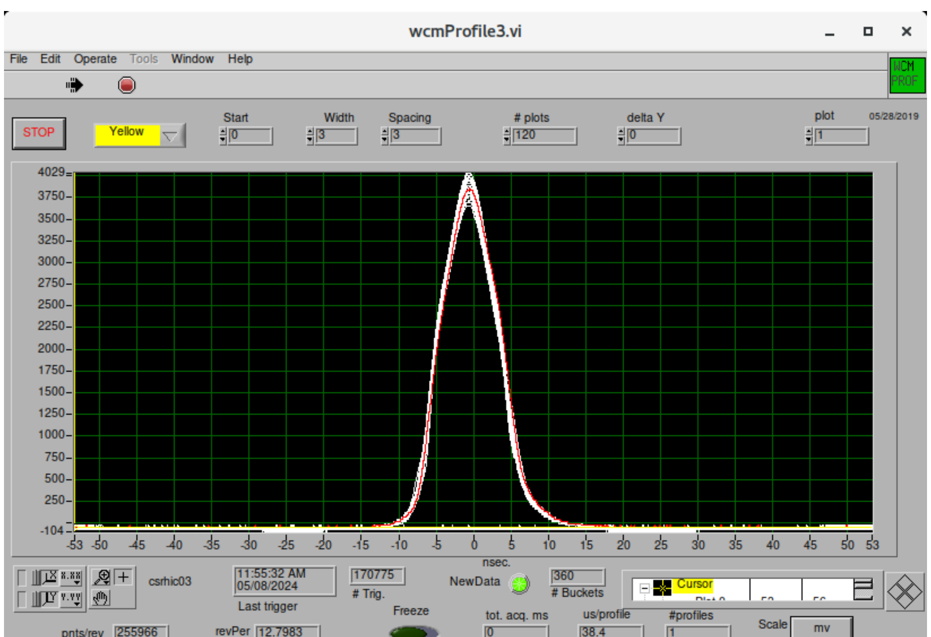
Recently completed experiments

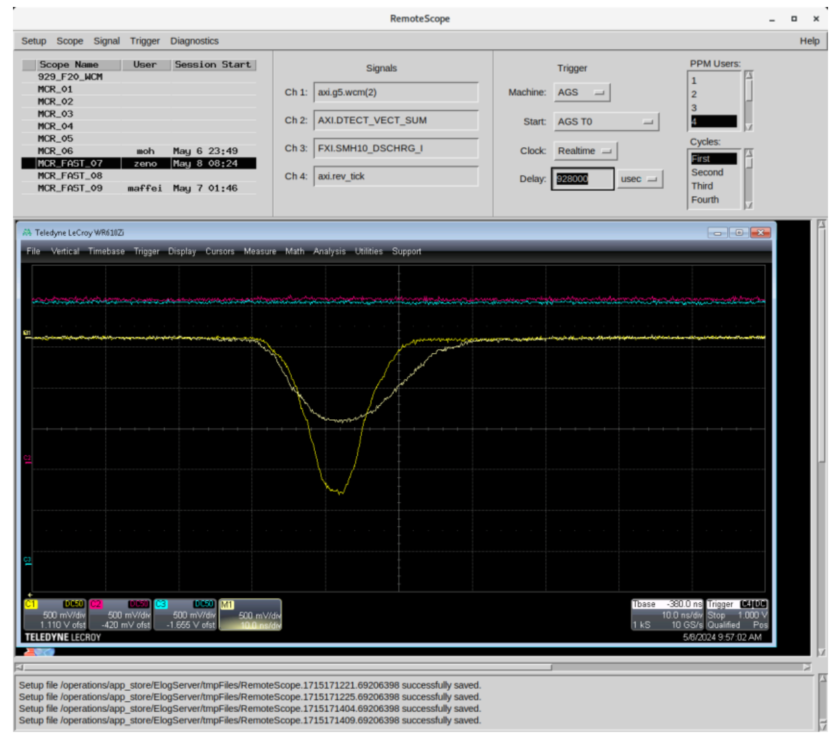
APEX #24-07 (A. Fedotov et al.), May 2024

In the EIC, high-intensity protons will be injected in modified 28MHz RF system, while presently in RHIC they are injected in 9MHz RF.

The goal of this experiment: Explore and establish proper beam parameters of high intensity protons at injection **with 28MHz RF system**

Two settings of quad pumping in AGS were tried:
Stable conditions in 28MHz RF were established.
Resulting beam parameters measured.





Summary of APEX #24-07

Experiment:

Explored injection into 28MHz RF with Quad Pumping in AGS, measured beam parameters:

Case 1: S_{95}=1.1eVs, Erms,s=0.06, sigma_s=0.7m, sigma_p=1.1e-3

Case 2: S_{95}=1.1eVs, Erms,s=0.06, sigma_s=1.0m, sigma_p=7.4e-4

Case 2 is better for cooling of protons at EIC injection energy - will use it as a baseline. It is also better than Case 1 since it corresponds to smaller peak current of 5.4A for the EIC bunch intensity. Double RF with flattened bunch profile should help to reduce peak current further (see APEX #24-06).

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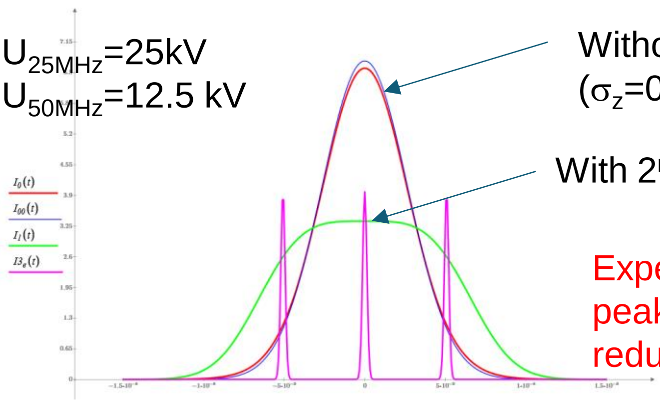
APEX #24-06 (D. Kayran et al.), May 2024

In the EIC, high-intensity protons will be injected in modified 28MHz (24.6 MHz) RF system just above transition energy. To allow strong cooling of vertical emittance and maintain good proton beam lifetime, requires reducing peak current of proton bunches. Such peak current reduction can be achieved by using higher frequency RF used in counter phase, which flattens longitudinal profile of proton bunch. However, above transition energy and especially very close to transition energy, this can lead to various beam instabilities. The goal of this experiment is to explore parameters of high intensity bunch at injection with dual RF system and study beam stability.

$\gamma_t := 22.344 \quad \gamma_r := 24$

$$\frac{1}{\gamma_r^2} - \frac{1}{\gamma_t^2} = -2.669 \cdot 10^{-4}$$

U_{25MHz}=25kV
U_{50MHz}=12.5 kV



Without 2^{nd} harmonic (σ_z=0.8m)

With 2^{nd} harmonic

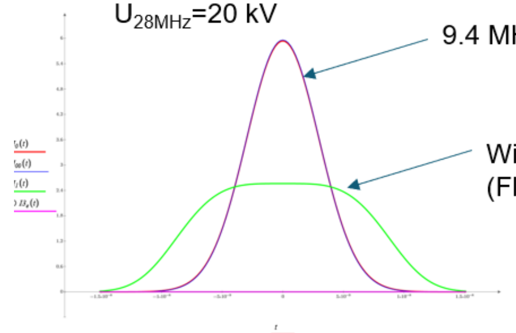
Expected protons peak current reduction 2 folds.

Proton bunch and electron bunches longitudinal profiles during cooling at the injection energy

The closest to EIC configuration: main RF 28MHz and 2^{nd} harmonic 56 SRF cavity for flattening profile. However, it was not possible to use 56 SRF system for APEX.

9 MHz system with 28MHz as a 3^{rd} harmonic was used instead:

$U_{9.4MHz}$=60kV
U_{28MHz}=20 kV

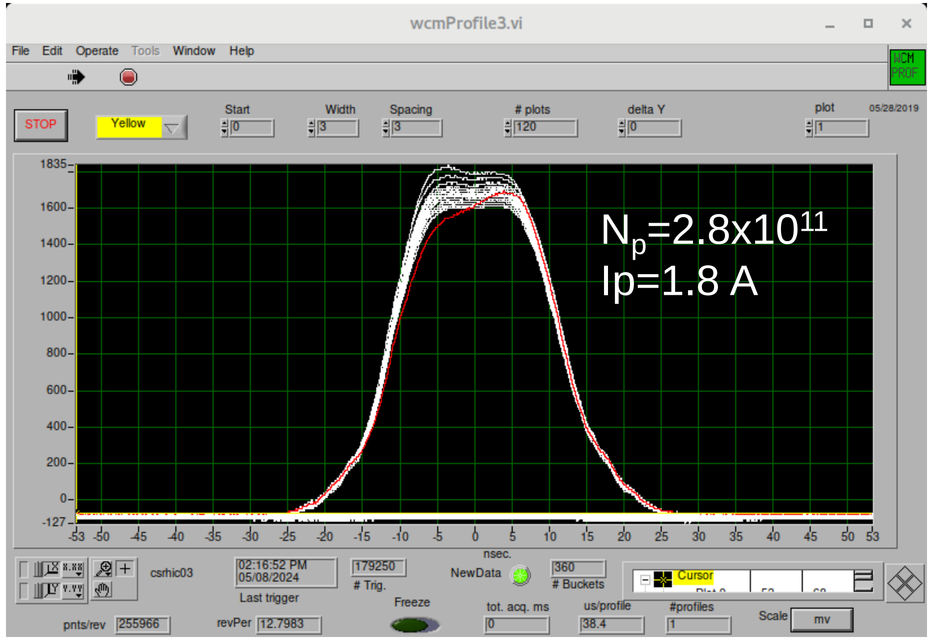


9.4 MHz only (Gaussian)

With 3^{rd} harmonic (Flat top)

Example: Expected longitudinal bunch profiles

Summary of APEX #24-06



Established setup with dual RF system in the YELLOW ring at the injection energy (above transition energy) and reduced operational peak current by about factor of 2.

Demonstrated that highest required intensity proton bunch ($2.8x10^{11}$) can be injected and can be kept stable in the dual RF system above transition energy (flat longitudinal profile).

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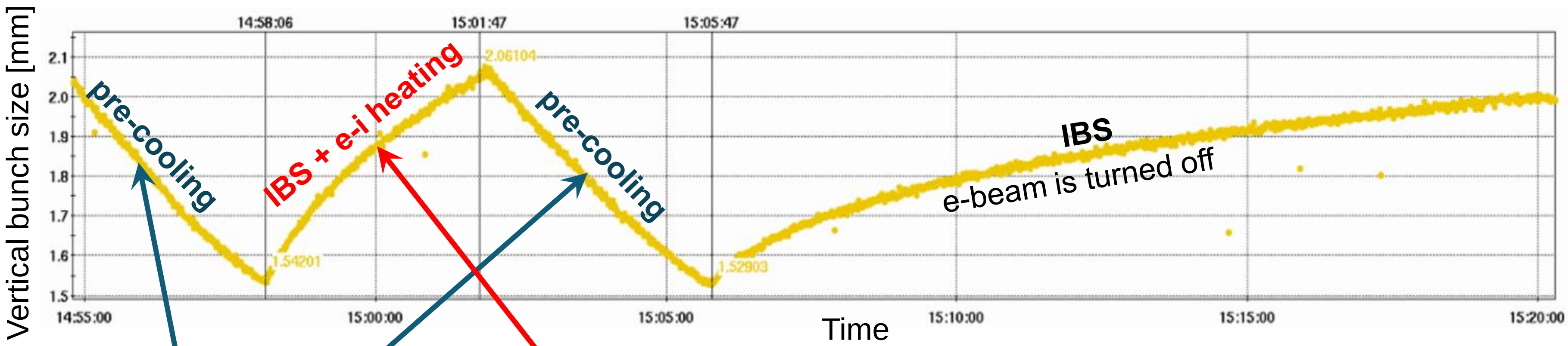
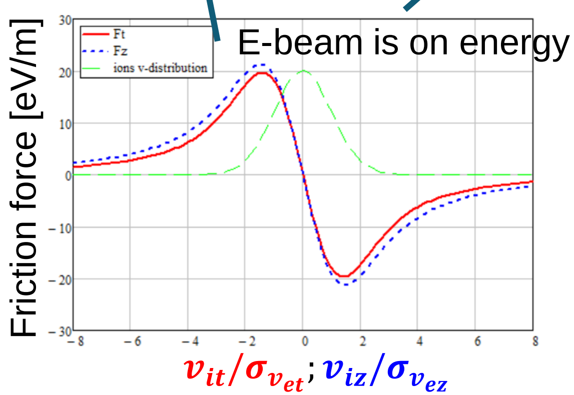
Ongoing Studies

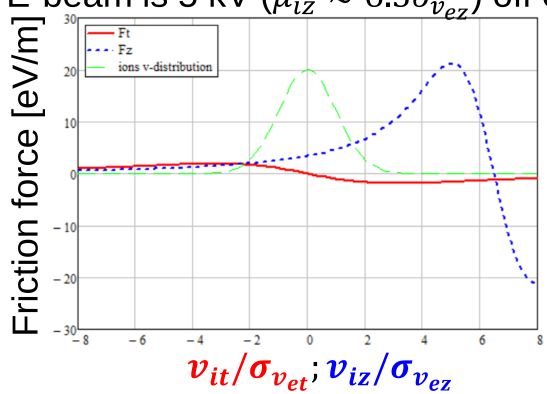
APEX 22-05: (S. Seletskiy et al.) **Electron-ion heating experiment**

In LEReC, in the presence of e-beam, we observed a much faster growth of the transverse size of the i-bunch than the IBS driven size growth. We called this additional growth of the emittance "**the electron-ion heating**"





E-beam is 5 kV ($\mu_{iz} \approx 6.3\sigma_{v_{ez}}$) off energy



For measurements of the "heating effect", to suppress cooling while keeping the electron beam, the electron beam energy was detuned by a few kV.

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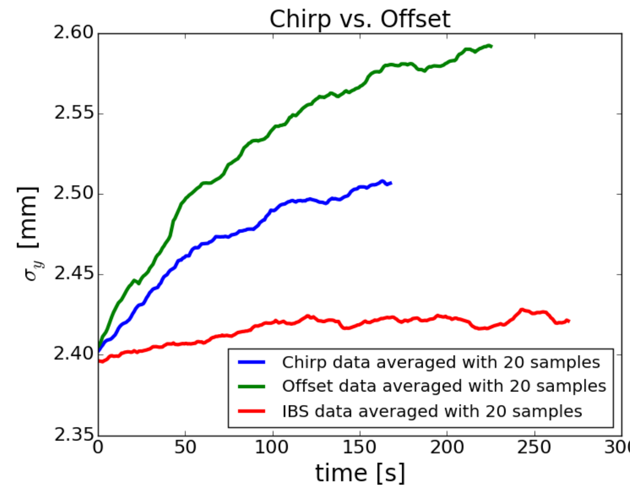
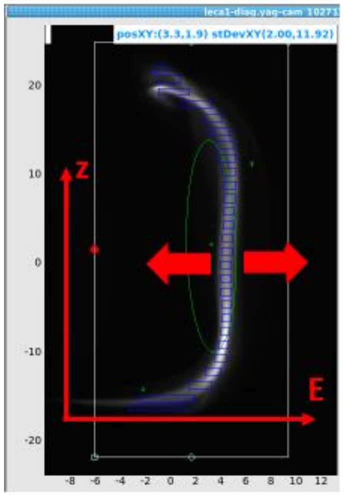
Example from 2022 heating studies



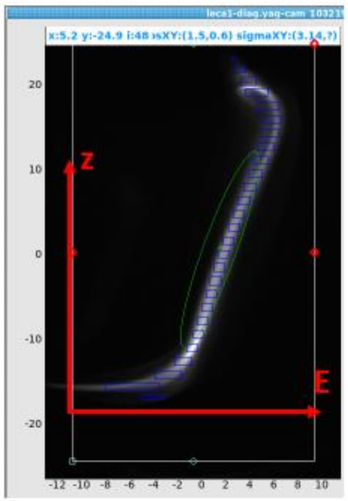
A substantial enough offset in electron beam energy creates a mechanism of longitudinal heating. This heating can be partially redistributed to transverse direction through coupling

To check whether we **"create"** transverse heating by offsetting beam energy we performed measurements with chirped e-bunch.

offset



chirp



Results:
Substantial part of emittance growth can be explained by the energy offset.

Remaining task:
Study "heating" with cooling suppressed by angular spread, no energy offset or energy chirp.

Time request for Run-2025:

1) Heating with large energy spread (6 hrs)
2) Heating with large trajectory angles (6 hrs)
   Plus extra time for switching to/from 3.85GeV.

Additional needed time for setup:
RHIC setup for Au at 3.85GeV: 10 hrs
Cooling setup: 4 hrs

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APEX 22-06: (S. Seletskiy et al.) **Ion lifetime in presence of electron beam**

- **Operational electron cooling at LEReC was associated with elevated ions losses.**
- Such an effect on ion beam lifetime was observed in several electron coolers and is not fully understood.
- Part of the elevated losses is caused by recombination, but also there are additional, not recombination-related losses.
- During the commissioning in 2019 we had set-ups for which the lifetime of a cooled ion bunch was comparable or even larger than the lifetime of ion bunch not interacting with the electron beam.
- Studies of the elevated ion losses in the presence of the electron beam are critical for creating a feasible design of the EIC coolers (of any type).

The plan is to:

- Reestablish a setup with a positive effect on ion beam lifetime.
- Explore the dependence of ion losses on:
  - Electron beam average size, current, density
  - RHIC tunes (working point around 0.1 and working point around 0.23)

Time request for Run-2025:

1. Optimizing lifetime of cooled ions (with active cooling) (6 hrs)
2. Explore lifetime dependence on e-beam densities (6 hrs)
3. Repeat measurements 1-2 at a different working point (8 hrs)

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RHIC setup for APEX #22-05 and 22-06

3.85 GeV/nucleon Au

N_i/bunch ≈ (2-4) · 10^8

Fill pattern (Yellow ring only):

- For heating studies fill one out of three 28 MHz buckets (28-56 bunches)
- For initial cooling setup it is enough to fill only 6 consecutive (1 filled, 2 empty, 1 filled etc…) buckets

Establishing a good lifetime

i-beam trajectory in the Yellow CS has to be aligned through LEReC BPMs

Diagnostics: WCM, IPM (with 30 sec readings), H-Jet (if available)

- **Meeting with MCR/OC for these experiments was held (01/15/25).**

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LEReC cooling experiments readiness

Cooling studies:

Pre-APEX setup:

1. Cooling studies using LEReC require setting up Au ions at $\gamma = 4.1$

Establishing Au ions at 3.85GeV in RHIC takes about one shift (**about 10 hours**)

2. Setup of LEReC electron accelerator

Setup of electron accelerator is done parasitically to RHIC operations, does not require APEX time.

3. Setup of cooling of Au ions

Once LEReC accelerator and Au at 3.85GeV setups are available, **about 4 hours** of dedicated APEX time will be required to setup electron/ion beams in common sections and reestablish cooling.

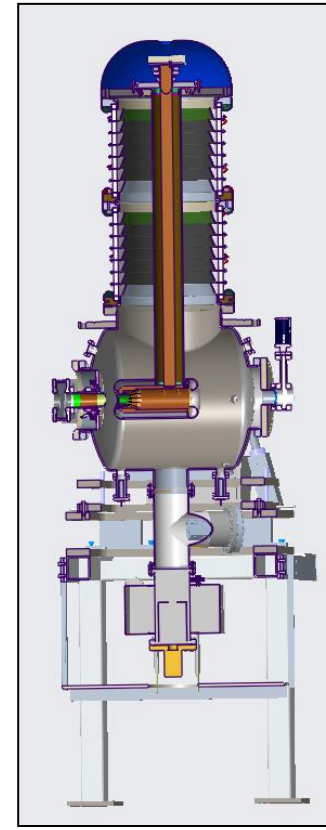
After steps 1-3 are accomplished, LEReC is ready for dedicated APEX cooling studies.

APEX 22-05 (12 hrs total): ready to start once steps 1-3 are done.
APEX 22-05 (20 hrs total): ready to start once steps 1-3 are done.

Note 1: LEReC is electron accelerator with high-power laser system and many RF cavities. During summer of 2023, heat and humidity strongly affected laser and RF systems availability, requiring reestablishing LEReC operation many times and affecting readiness.

Note 2: LEReC accelerator readiness depends on timely availability of systems experts if problems occur.

High-current studies

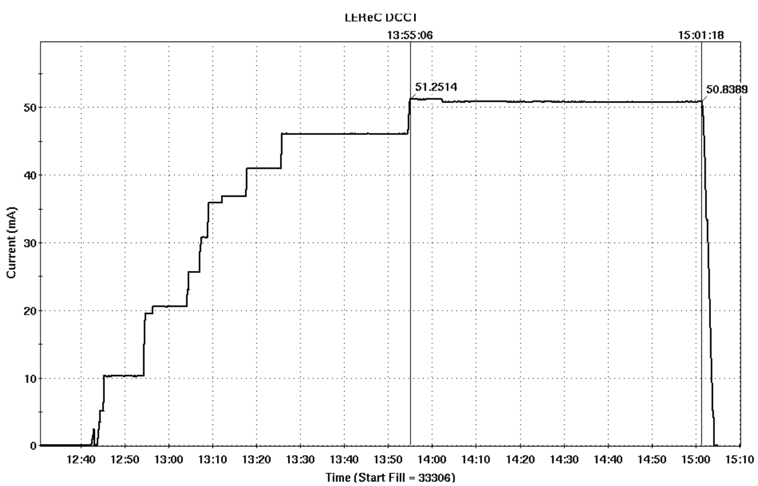


- **High current source is required for EIC LEC:**
  - **The LEC requires stable operation at around 75mA current.**

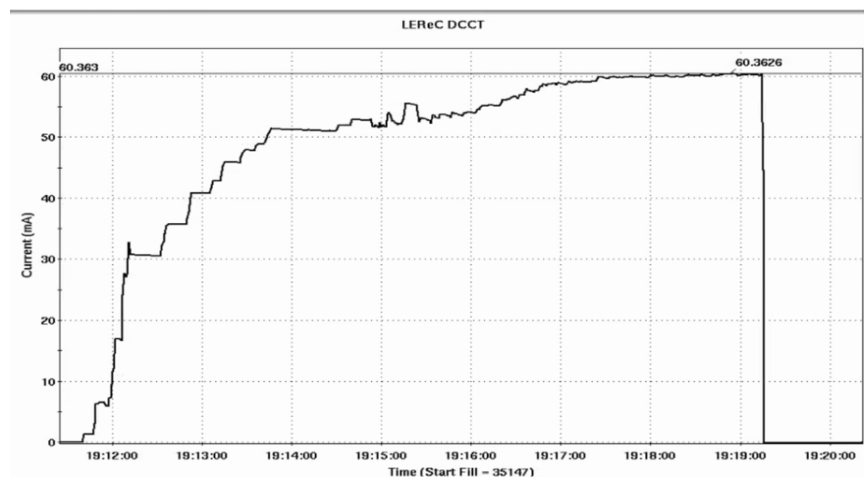
- **High-current source R&D:**
  - Explore LEReC Gun operation **with high-current up to 80mA.**
  - Explore Gun and HVPS **long-term stability** at high currents.
  - Explore Gun **voltage limitations**
  - Explore operation with active cathode on center vs cathode off center.
  - Explore large cathode area vs small active area. Explore various laser spot sizes on the cathode.
  - Explore cathode QE at various laser powers with and without cathode stalk cooling.
  - Test multi-alkali photocathodes using different growth methods.

LEReC DC gun tests (to injection beam dump):

Stable operation at **50mA** in tests (April 2022)



60mA (October 2024):



LEReC high-current experiments readiness (II)

High-current experiments:

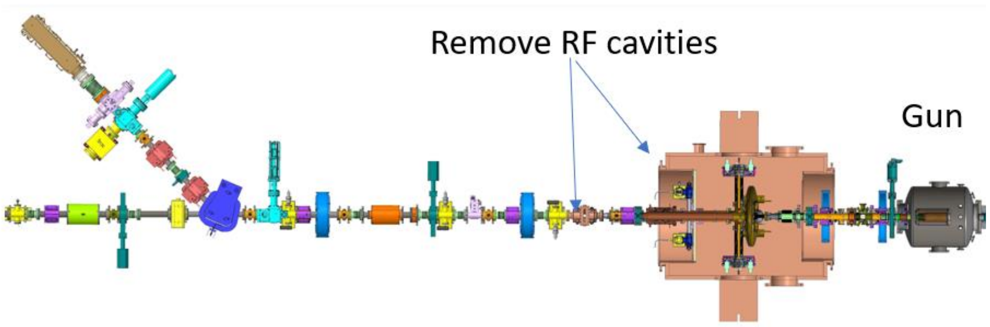
- Does not require RHIC ions, but injection dump is limited to 25kW.
- Running to high-power beam dump (150kW) requires dedicated time without RHIC beam. One has to establish high-current electron beam transport over 100 meters with many RF cavities and through RHIC common sections.
- There is a possibility to relocate high-power beam dump next to the Gun in IR2 after RHIC 2025 run.

Plan for 2025:

Explore Gun operation at high currents **above 30mA** to **high-power beam dump** (100 meters of beam line and RHIC common sections). So far, in nominal LEReC configuration, operated up to 30mA to high-power beam dump. **We will explore reduced energy setup (1MeV) to reduce required power from SRF cavity amplifiers.**

After 2025 RHIC run (TBD):

Moving High-Power beam dump closer to the Gun and removing RF cavities.



Summary

- Intensive program of the cooling studies and high-current R&D is underway. Several studies were successfully completed.
- Ongoing cooling studies include ion heating, effects on ions lifetime and high-current R&D.
- For cooling studies using LEReC, RHIC setup with Au ions at 3.85GeV will need to be established prior to APEX time.
- LEReC accelerator will be set up for the studies.
- Meeting on APEX studies with MCR/OCs was held and recommendations were followed up.

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