C-AD R&D Strategy and Plans

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C-AD Machine Advisory Committee Meeting
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C-AD Accelerator R&D and expertise

Collider-Accelerator Department (C-AD) has unique world's expertise and leadership in several areas:

1. **Ion beam sources:**
   World records in high-current intense ion sources
   Highest intensity polarized ion source

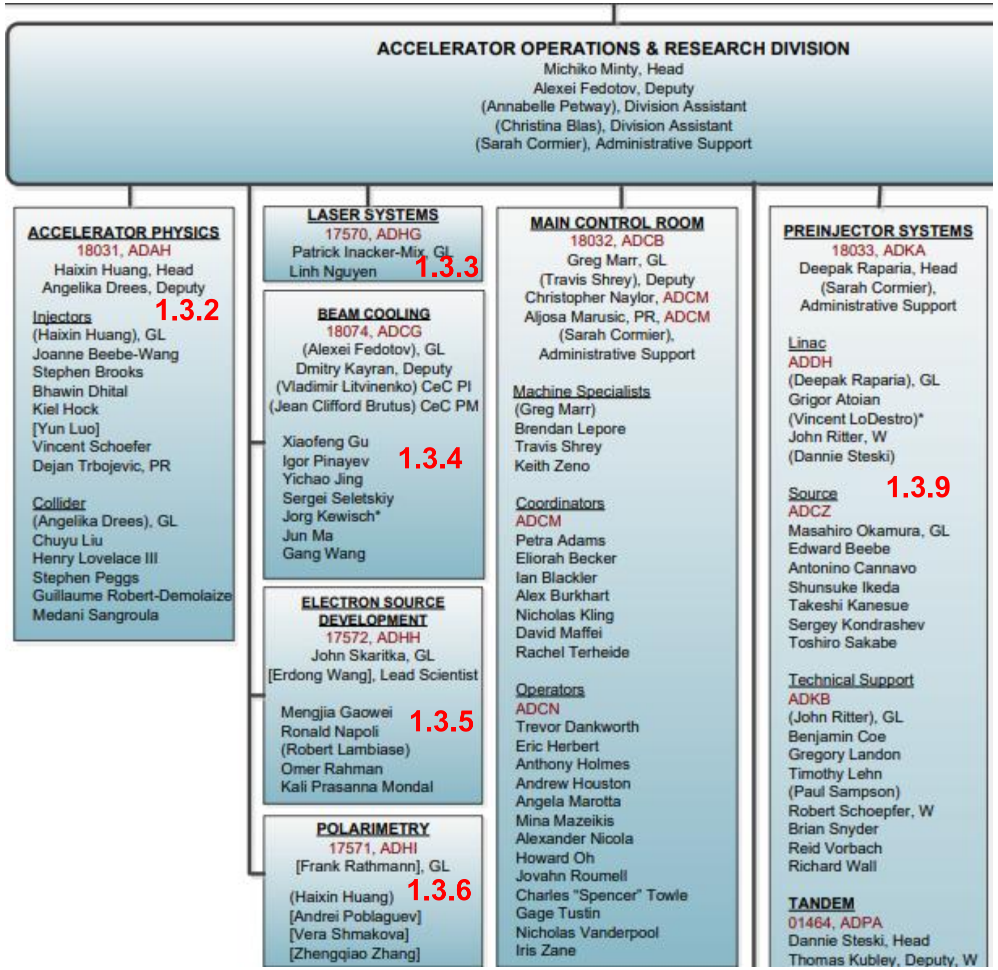
2. **Electron beam sources:**
   High-charge polarized electron beam source
   High-intensity high-brightness electron sources
   State-of-the-art laser systems

3. **Polarized ion beams:**
   The only polarized hadron collider; polarization control through a chain of several accelerators

4. **Beam Cooling:**
   World's first application of bunched beam stochastic cooling in a collider
   World's first RF-based electron cooler using bunched electron beam
   World's first electron cooler without use of electron beam magnetization
   World's first application of electron cooling in a collider, to cool beams in collisions

C-AD Accelerator R&D (present)

Accelerator R&D is distributed across several C-AD groups (OBS 1.3.2-1.3.6 and 1.3.9):



Ion beam sources (OBS 1.3.9):

- High-intensity H^- source
- Polarized proton source (OPPIS)
- Laser Ion Source (LION)
- Electron Beam Ion Source (EBIS)
- Polarized He-3 production

Electron beam sources (OBS 1.3.3 and 1.3.5):

- Polarized electron beam source
- High intensity electron sources (LEReC DC guns, CeC SRF gun)
- Photocathodes and laser systems

Polarized ion beams (OBS 1.3.2 and 1.3.6):

- AGS spin resonance correction with skew quadrupoles
- Machine Learning for AGS polarization increase
- Polarimetry in AGS/RHIC/EIC (jets, pC), He-3

Beam Cooling (OBS 1.3.4):

- Coherent Electron Cooling (CeC)
- RF-based electron cooler LEReC
- Low-Energy Cooler for EIC, High-Energy Cooling

Advanced accelerator R&D (external funding):

- Machine Learning in accelerators (FOA funding)
- Extreme low-emittance ion sources (LDRD funding)
- Permanent magnets for Fixed Field Alternating Synchrotron (LDRD)
- Ion sources (LDRD, FOA funding)
- Electron sources (ECA funding)

C-AD R&D Strategy

Strategy:

- **Maintain leadership and expertise in key areas and**

  align mid-term R&D with EIC needs and future EIC performance and capabilities.
- **Pursue advanced accelerator R&D (external funding using FOA and LDRDs)**
- **Actively pursue AI/ML applications at various C-AD accelerators to optimize beam controls, automate machine tuning and data analysis, improving reliability and operations.**

Our goal is to use mid-term R&D in a coherent strategy to maintain leadership in technology which we need **for the EIC**,

for future EIC capabilities and upgrades, and

possibly the next generation of NP facilities

with focus on:

1) Ions sources
2) Electron sources
3) Polarizations and Polarimetry
4) Beam cooling

Focused mid-term R&D efforts

Focused mid-term R&D efforts:

- **Ions sources:**

 - To fully establish EIC requirements, including polarized He-3 source development

 - Develop future EIC capabilities

- **Electron sources:**

 - Development of polarized and high-current cathodes for the EIC

 - Development of high-current electron Gun suitable for the EIC

- **Polarization and polarimetry:**

 - Maximizing polarization through Injectors chain of accelerators

 - Development of robust polarimetry at various stages of acceleration

- **High-Energy Cooling (HEC):**

 - Development of HEC system for the EIC to maximize luminosity and fully optimize the EIC potential

Mid-term R&D presentations

- **Ion sources:**

Polarized He3 source development: **J. Ritter**

Next-Generation High-Current Ion Sources: Demonstration with Niobium: **M. Okamura**

Polarized deuteron ion source: **D. Steski**

- **Electron sources:**

High-current Gun developments: LEReC and Stony Brook R&D guns: **in this presentation**

Cathodes R&D: **M. Gaowei**

- **Polarization and polarimetry:**

Polarization development: **K. Hock**

Polarimetry : **F. Rathmann**

- **Beam Cooling:**

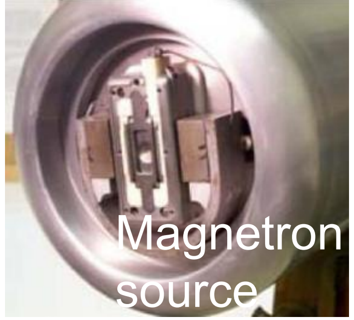
Development of high-energy cooling systems: **S. Seletskiy**

Ion sources R&D

Ion sources - highlights

Magnetron H^- source

- Hydrogen plasma interacts with Cs-Mo surface
- Highest H^- peak current (135 mA)



Optically Pumped Polarized Ion Source (OPPIS)

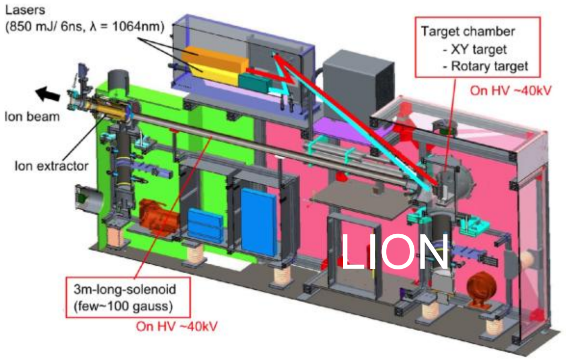
- Polarized electrons from optically pumped Rb are used to generate polarized H^- ions
- Highest intensity (1 mA) polarized (85%) H^- source

Electron Beam Ion Source (EBIS)

- ~10 A e-beam inside 5 T solenoid used to stepwise ionize heavy ions, Au^{32+} after about 40 ms
- World’s highest intensity EBIS

Laser Ion Source (LION)

- Development of high-current laser source for wide range of ions

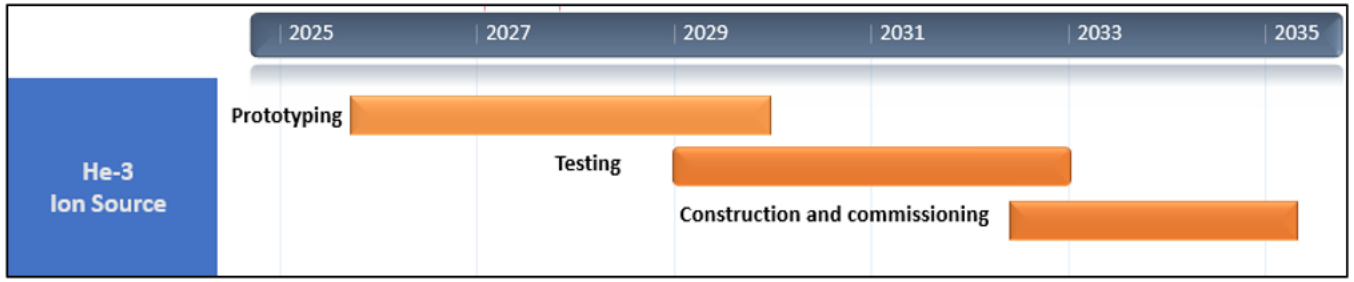


Ion sources – future mid-term R&D plans

1. Polarized ^{3}He ion source, **J. Ritter presentation**
2. Polarized deuteron ion source (FOA), **D. Steski presentation**
3. Development of high-current highly charged Laser Ion Source (FOA), **M. Okamura presentation**

He-3 source R&D plans (J. Ritter):

Next steps (for prototyping stage)
- install He-3 gas cell in EBIS (summer 2026)
- commission He-3 gas cell (end of CY26)
- iterate He-3 cell design until >85% polarization is reached



Electron Sources R&D

Electron sources - highlights

Active photocathode development

- Bi-alkali antimonide cathodes with high QE
- Polarized cathodes

DC photo-electron gun for LEReC

- 350-400 kV operation
- Demonstrated 60mA (EIC requirement 75mA)

DC photo-electron inverted gun at Stony Brook (SB)

- R&D Gun under construction at Stony Brook University

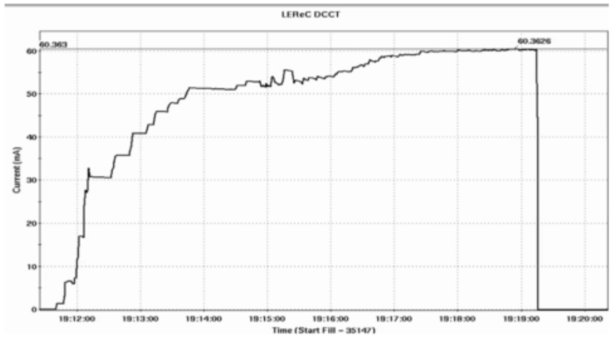
SRF photo-electron gun for CeC

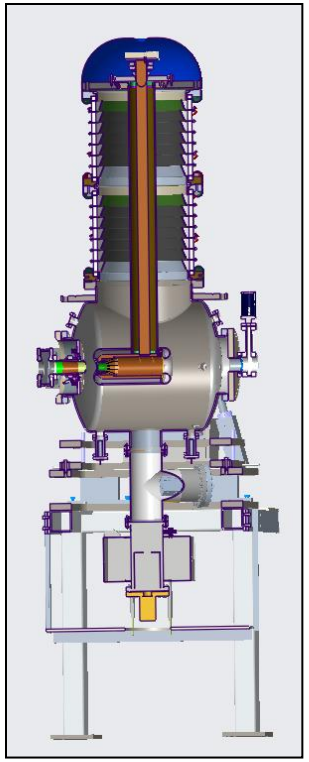
- High brightness: 0.3 um emittance for 0.5nC charge
- High bunch charges: up to 10 nC

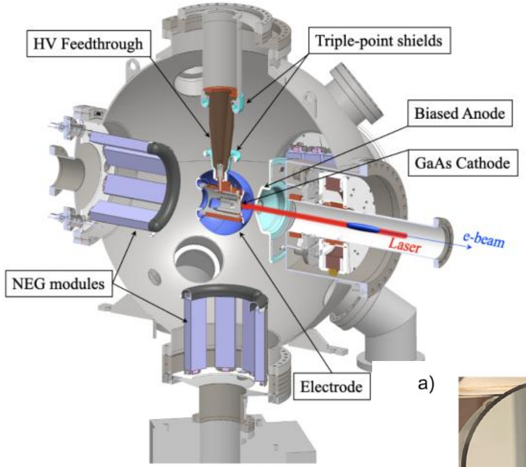
Laser systems

- State of the art laser systems for LEReC, CeC and SB guns.

60mA (October 2024):







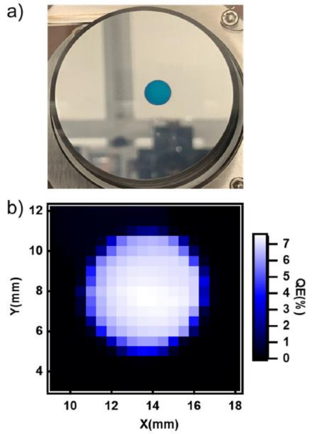
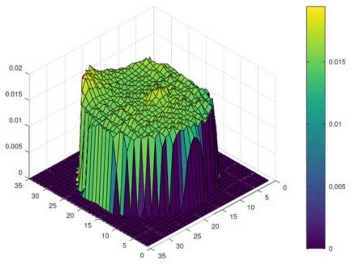
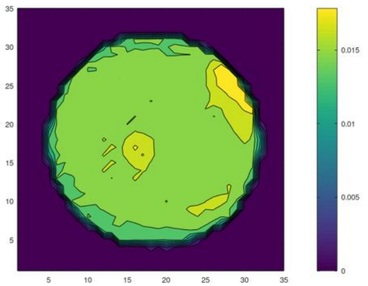
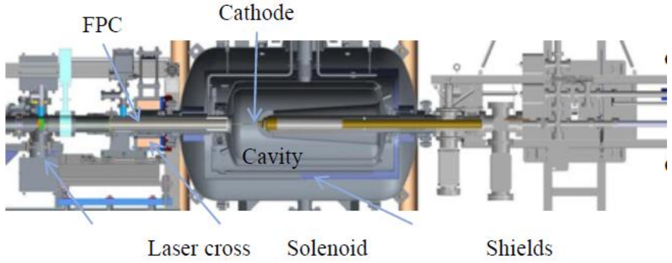


Figure 4: a) The sequentially deposited K2CsSb cathode with off-centered design on the on the LEReC puck; b) 2D QE map indication the cathode uniformity.







Quarter-wave SRF 4K Nb gun cavity tuned to operation frequency
Room temperature CsK2Sb high QE photocathode inside adjustable stalk
Photocathode QE lifetime – one to two months
Nominal accelerating voltage: 1.25 MV, maximum 1.5 MV

Brookhaven National Laboratory

Electron sources – future R&D plans

1. Development and support of high-current e-gun systems for EIC, **see next 3 slides**
   - LEReC Gun R&D
   - Stony Brook University R&D gun

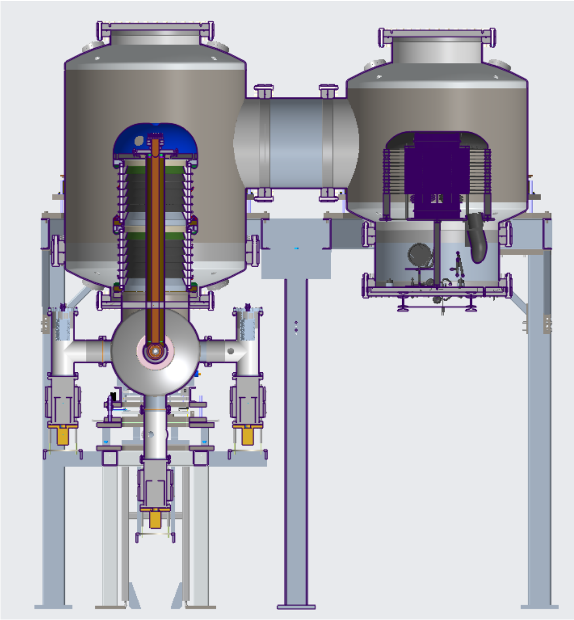
Plans:

2026-2027: High-current tests with LEReC and Stony Brook guns

2028: Determine which Gun and HVPS is best suited for the EIC hadron cooler.

2. Advanced cathodes R&D, **see Mengjia Gaowei presentation**

EIC Electron Cooler gun choices

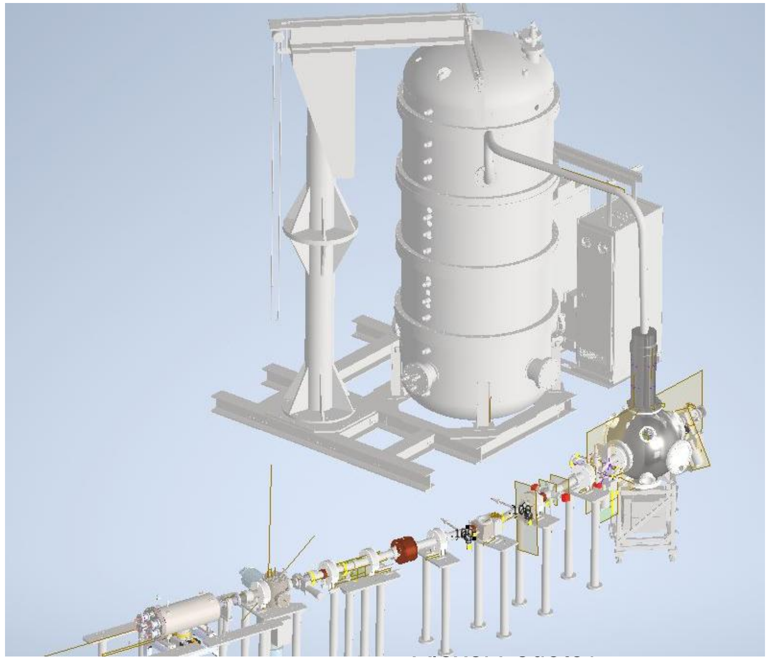


<u>EIC DOE Review, January 2025:</u>
"The requirements for the DC electron gun for the LEC are beyond the current state-of-the-art performance presently demonstrated by DC gun and high-QE (quantum efficiency) semiconductor cathode technology. A significant R&D effort is necessary to demonstrate the required performance. The project has at least two options to consider: pursuit of a new gun being developed at Stony Brook University, and potential improvements to the existing LEReC gun. **The project is encouraged to consider investigating both options in parallel until the required performance has been demonstrated.**"

LEReC Gun:

Existing LEReC Gun (400kV) and HVPS (600kV).

Need to demonstrate stable operation at required current (75mA) for the EIC.



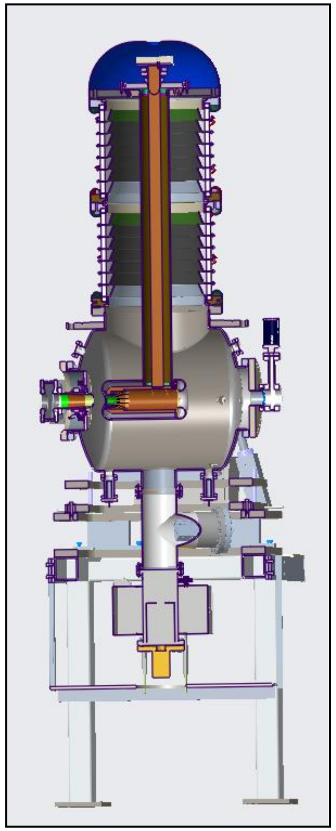
R&D Gun at Stony Brook (under development):

Gun (500kV) and HVPS (600kV): designed to operate at 100mA. Active cathode cooling. Tests with beam to start in late 2026.

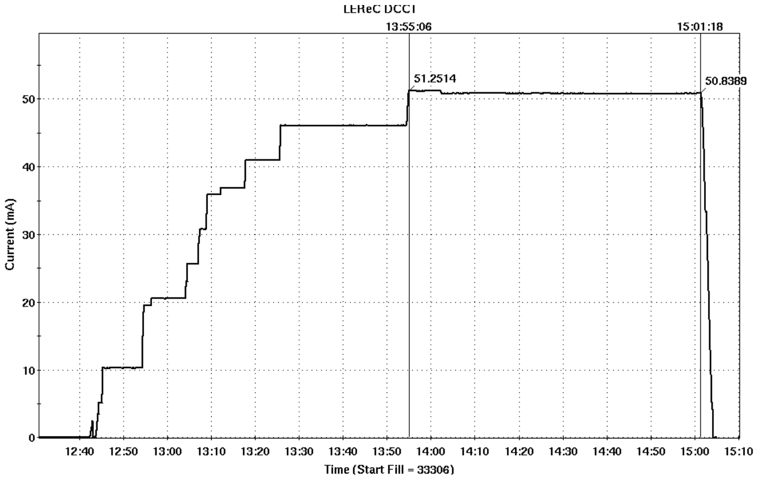
LEReC Gun high-current tests and plans

- **High current source is required for EIC LEC**:
  - The LEC requires stable operation at **75mA current @350-375kV**.

- **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.

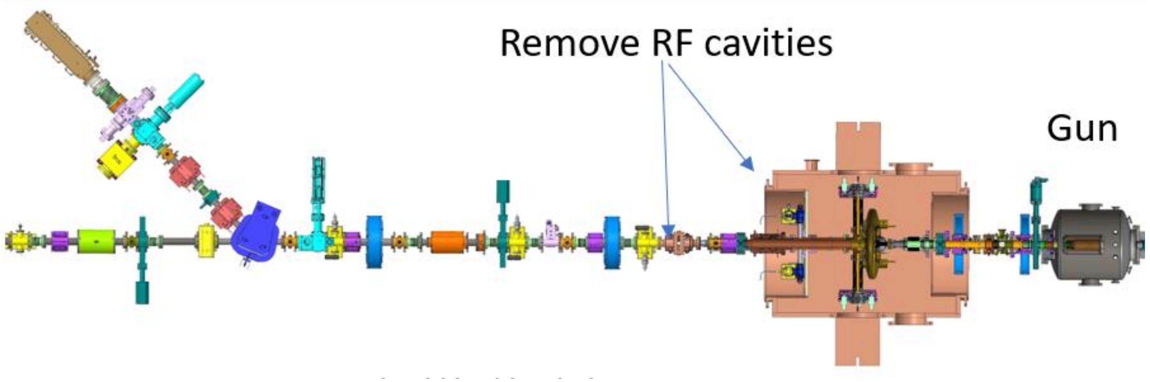


LEReC DC gun tests (to injection beam dump):
Stable operation at **50mA** @320kV (April 2022)

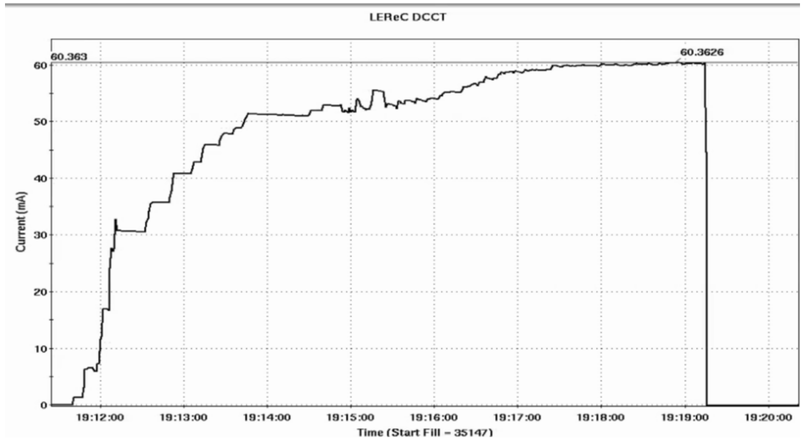


After 2025 RHIC run (2026-2027):

Gun (400kV) to low-power dump tests (P=32kW; V=400kV, I=80mA).
Remove two RF cavities in LEReC injection line (as part of RHIC R&R project). Install spool vacuum pipe with several devices in place.
Details on these tests plan are being developed in coordination with RHIC Removal project, Safety, Access Controls and other groups.



60mA @300kV (October 2024):

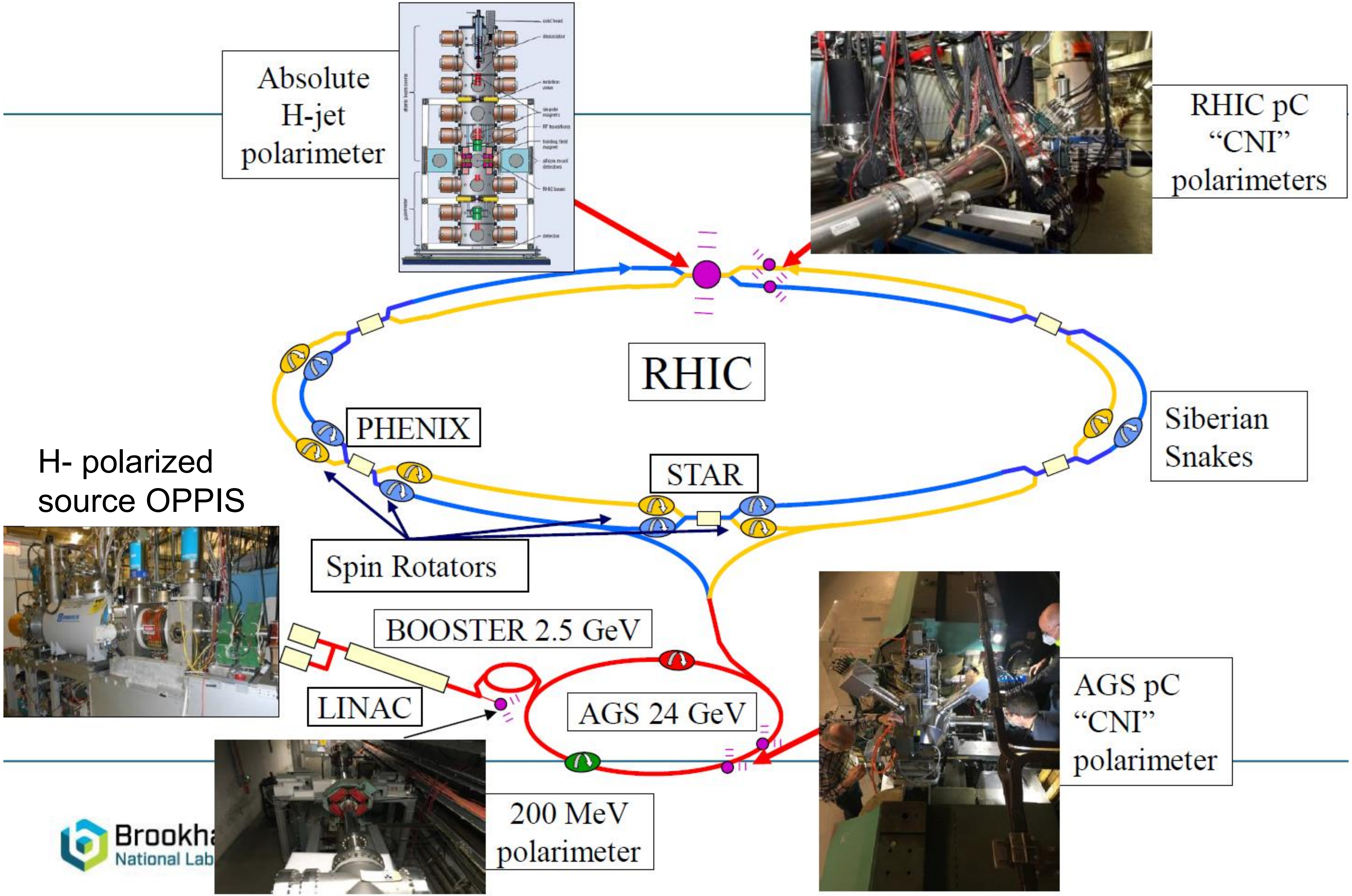


Stony Brook R&D gun plans

	Schedule	Current status
HVPS	Fall 2025	Testing at the vendor
Gun	Fall 2025	Machining and parts in assembly
Beamline upgrade	Mar. 2026	Procurement
Laser	Nov. 2025	Installation onsite, then move to SBU
Photocathode	Feb. 2026	Installation onsite, then move to SBU
HV components (cable, resistor)	Aug. 2025	Vendor fabrication
Beam dump	Mar. 2025	Tested
Low Current test	Fall 2026	
High Current tests	2027	

Polarization and Polarimetry R&D

Polarization devices through accelerator chain



Polarization and Polarimetry – future R&D plans

Polarization development and improvements:

- Polarized protons: simulations and development in the injectors to overcome both intrinsic and imperfection resonances. (**2026-2030, in backup slides**)

- Polarized He-3 simulations and development in the injectors.

Plan (2027-2030): Develop He-3 polarization in injector complex

see K. Hock presentation for He-3 polarization development plans

Polarimetry:

- Development of simulation tools for polarized atomic beams

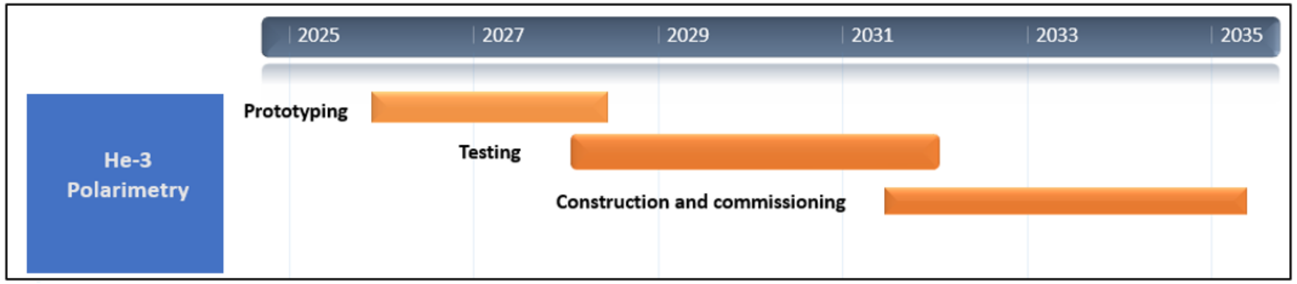
- RHIC H-jet refurbishment and upgrades for EIC needs

- Design of new AGS polarimeter for absolute polarization measurements

see F. Rathmann presentation for Polarimetry details and plans

He-3 atomic beam polarimeter in the AGS

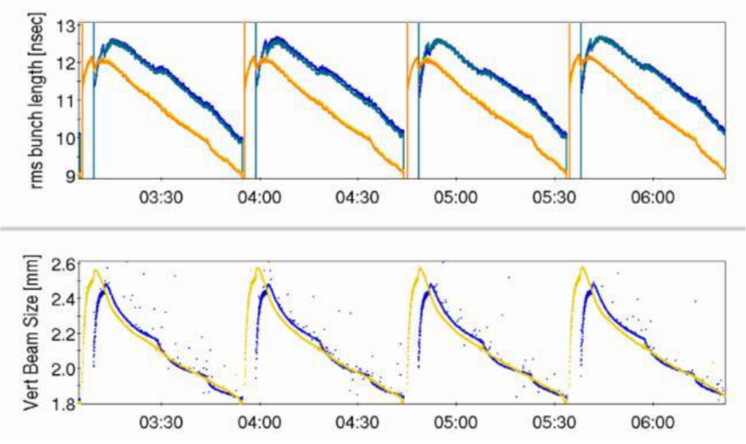
- in (ongoing) collaboration with MIT/BATES and BNL, develop an absolute He-3 beam polarimeter for the EIC based on a polarized He-3 atomic beam source
- install and test in the AGS



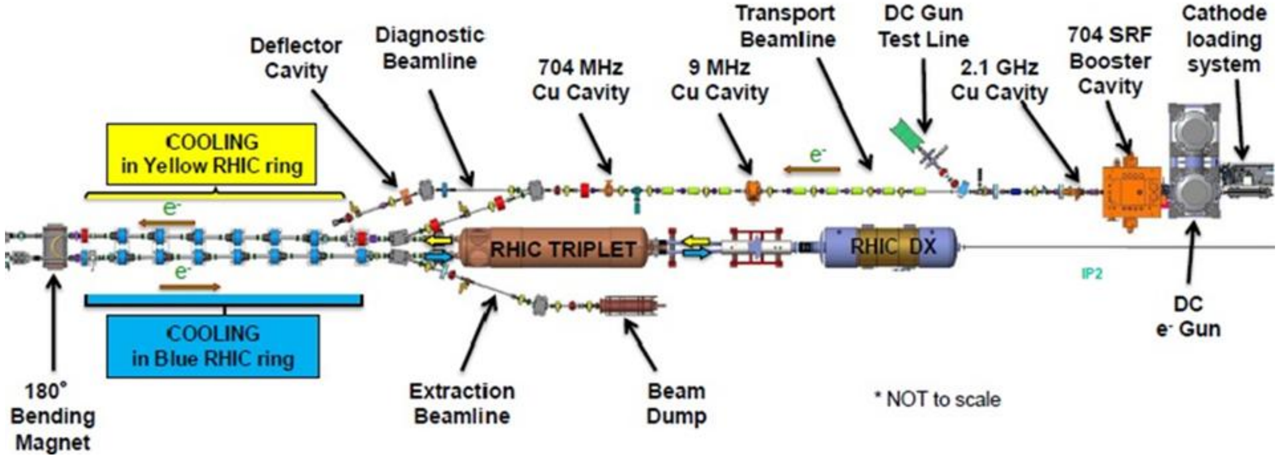
Beam Cooling R&D

RF-based Electron cooling at RHIC and EIC

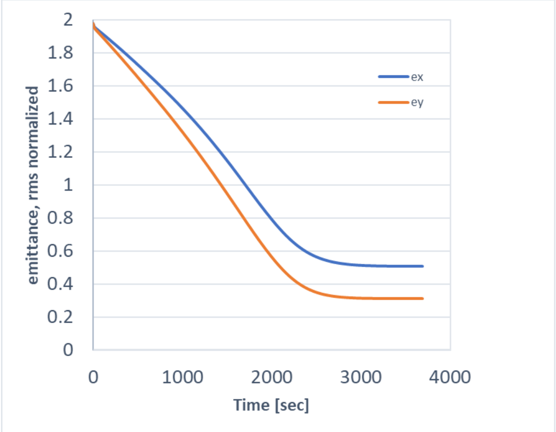
- **LEReC @RHIC** is a fully-operational electron cooler which utilizes RF-accelerated electron bunches (2 MeV electron kinetic energy).



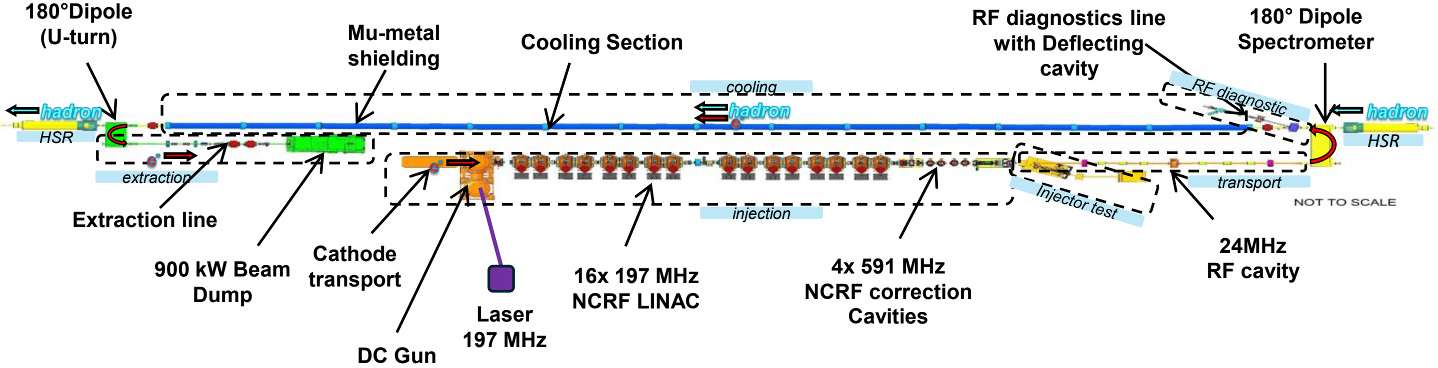
Operational 3D cooling of Au ions during RHIC Run 2021



- LEReC approach was chosen for the **Low-Energy Cooler @EIC** (12.5 MeV electron kinetic energy).



Cooling simulations of protons at γ=25



Alexei Fedotov

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.

Previously, the HEC system for the EIC was based on a novel method of micro-bunched Coherent Electron Cooling (CeC). While in recent years CeC R&D studies have made significant progress, there are crucial unresolved issues related with extremely tight tolerances on timing electron and hadron beams in the cooler and cooling diagnostic, for EIC parameters.

Several approaches using well-established technique of **Electron Cooling (EC)** are presently being explored at 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.

Beam Cooling – future R&D plans

High-Energy Cooling (HEC) accelerator physics and accelerator design R&D, in order to develop a feasible and efficient scheme for the HEC (for future EIC upgrade):

1. **2026:** Conceptual Design Report for Ring-based High-Energy Cooler
2. **2027-2028:** Conceptual Design of ERL-based Recirculator Cooler, **see S. Seletskiy presentation**
3. Evaluate risks and costs
4. Hold review to choose a most reliable and cost-effective approach for the HEC.

Response to Recommendations: High Energy Cooling

Last December we presented High-Energy Cooling design based on the storage Ring Electron Cooler HEC.

High Energy Cooling R&D:

R15: Consider engaging external partners (e.g. university faculty, graduate students) to accelerate the work on HEC options.

We followed up on R15 with close collaboration with Cornell University (Jonathan Unger, graduate student).

Results: finalized Dynamic Aperture studies, performed detailed study of effects of nonlinearities and magnet errors. We are getting close to producing CDR for this approach (S. Seletskiy et al.: BNL-228463-2025-TECH, July 2025).

For the ERL-based HEC, collaboration with JLAB (**see S. Seletskiy presentation**).

R16: Begin work towards an integrated assessment of beam dynamics in EIC hadron cooling (i.e. start-to-end simulation) for the HEC options.

On R16, once proper design of the HEC is chosen the plan is to have such integrated beam dynamics studies.

Response to Recommendations: CeC

Coherent Electron Cooling (CeC):

R7: Overcome the lack of reliability: both in terms of beam parameter jitter and poor repeatability of operation set-ups.

In the past, CeC worked in the regime where it was difficult to establish required electron beam parameters with high peak current, which required constant tuning of accelerator. Also, last year setup strongly depended on laser configuration which required proper stacking of several laser pulses.

For 2025, CeC switched to a new lower energy setup where much smaller peak current of electron beam is required and it is easier to achieve required electron beam parameters. Requirements on laser were also simplified without the need of laser pulse stacking.

This year, CeC was able to achieve required electron beam parameters many times routinely with required stability.

CeC experiment started to use dedicated APEX time on December 3 and 17. Additional dedicated time (several days) at the end of Physics run in January is under consideration.

R8: Develop a Plan B to continue the CeC development after the RHIC shutdown.

There is no Plan B to continue CeC development.

After the end of RHIC operations, RHIC Cryo will be off. CeC accelerator which requires cryo will be taken apart.

Machine learning in Accelerator

AI/Machine Learning in accelerators

AI/Machine Learning (ML) is being actively applied for various accelerators at the C-AD to optimize beam controls, automate machine tuning and data analysis.

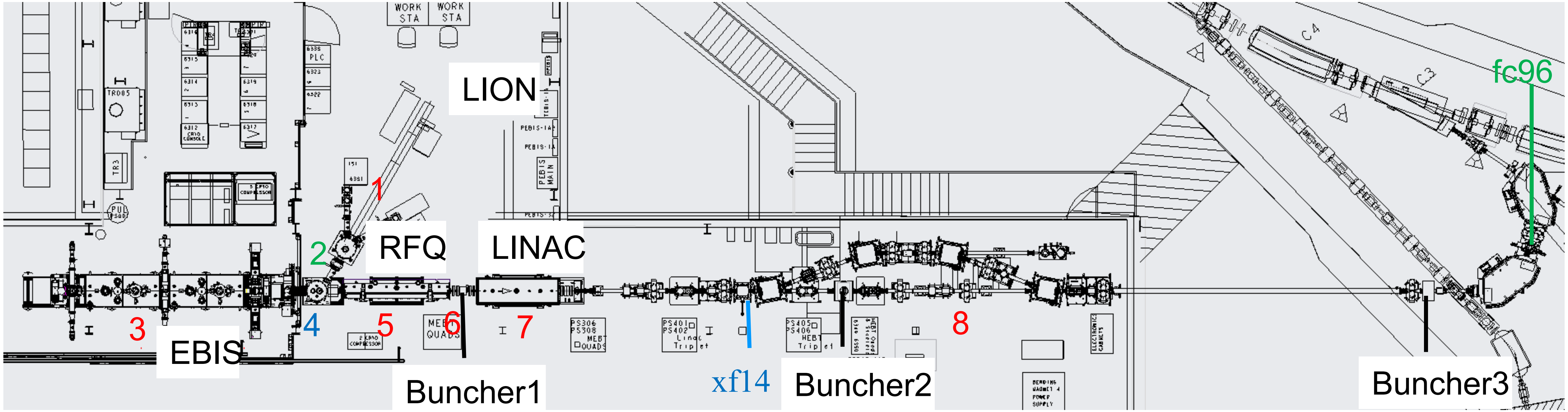
Developed AI/ML tools will be used for EIC operations and optimizations.

Examples:

- Electron Beam Ion Source (EBIS) intensity improvement
- Polarization improvement in the injector chain of accelerators
- Beam Cooling optimization

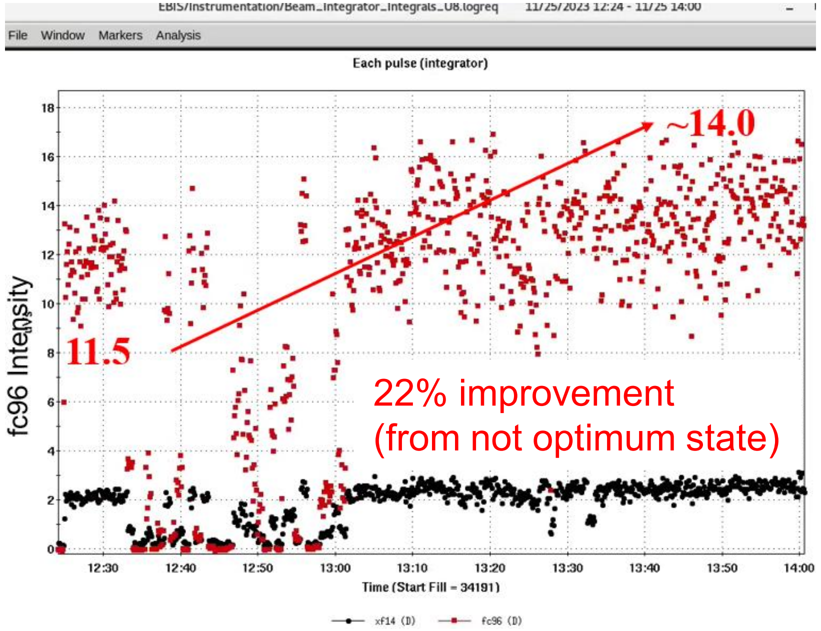
see K. Brown presentation for details

ML: EBIS Intensity Optimization using GPTune (FOA funding)



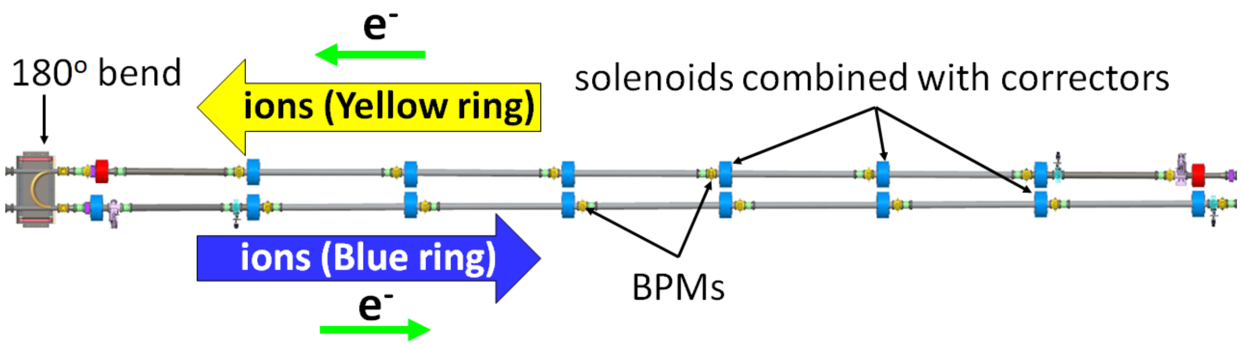
1. LION
2. EBIS Injection Line (fc96)
3. EBIS
4. EBIS Extraction line (xf14)
5. RFQ
6. MEBT
7. Linac
8. HEBT

		Injection [xf14]	Extraction [fc96]
1	IonLens20-40kV	-	-
2	DeflPlatBias	-	-
3	16PoleX	-	-
4	16PoleY	-	-
5	Gridded_Lens	-	-
6	Horiz_Bend_Defl	-	-
7	Inter_Vert_Defl	-	-
8	Inter_Vert_Defl_Lower	-	-
9	Horiz_Sphere_Bend	-	
10	RFQ_Horiz_Bend		-
11	LEBT_Solenoid		-
	Total Variables	9	10



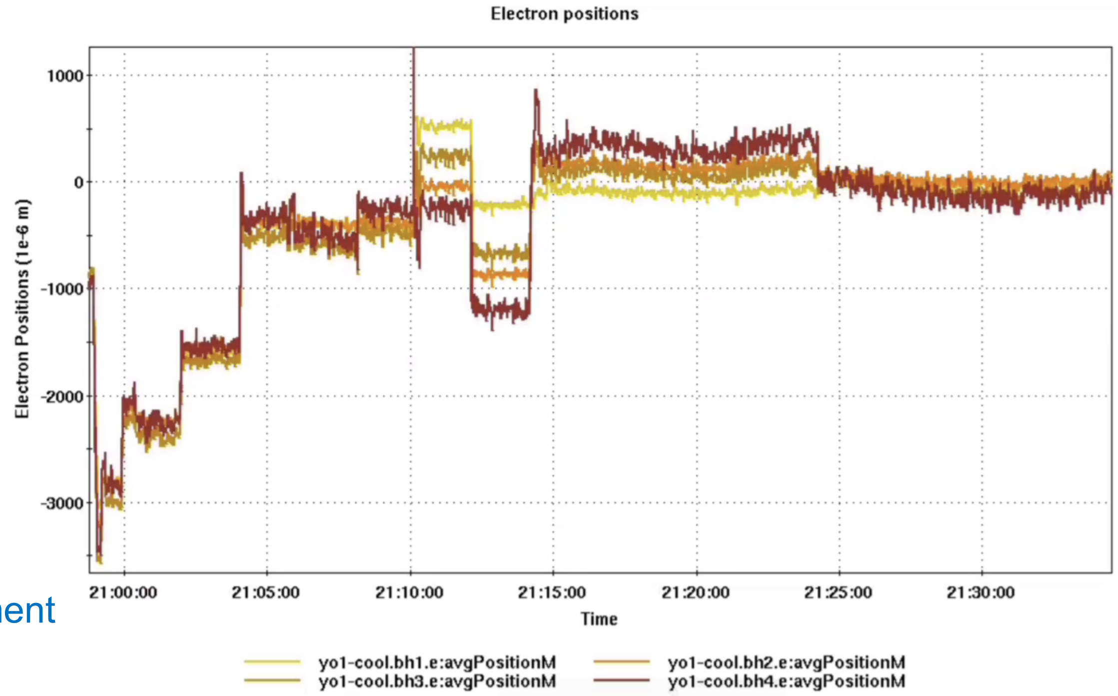
ML: Beam Cooling applications at LEReC

- LEReC was used as a testing ground for machine learning (ML) algorithms, which in the future may become useful for optimizing performance of the coolers.
- The objective of the test was to optimize the cooling rate by improving the e-beam trajectory (as measured by BPMs in the cooling section).



Results:

- The algorithm based on Bayesian Optimization method worked successfully and returned optimum for cooling e-beam trajectory.



Y. Gao, W. Lin, et al., "Bayesian optimization experiment for trajectory alignment at the low energy RHIC electron cooling system", PRAB 25, 014601 (2022).

Advance Accelerator R&D

Advanced Accelerator R&D

In addition to focused mid-term R&D efforts, we actively pursue advanced accelerator R&D (external funding using FOA, ECA and BNL LDRDs):

- Extreme low-emittance ion sources (LDRD), **S. Brooks presentation**
- Permanent magnets for Fixed Field Alternating Synchrotron (LDRD), **D. Trbojevic presentation**
- Lithium-Beam driver for Boron Neutron Capture Therapy (LDRD), **M. Okamura presentation**
- Production and acceleration of molecular ion beams (LDRD), **S. Ikeda presentation**
- Monoenergetic neutron beam (LDRD), **X. Jiang presentation**
- Advanced cathodes R&D (ECA), **M. Gaowei presentation**
- Laser-driven Nb source (LDRD), **A. Cannavo**
- Development of CW Laser Ion Source (LDRD), **S. Kondrashev**
- High-Voltage R&D for pEDM (LDRD), **H. Huang**

Summary

- C-AD has unique world's expertise and leadership in several areas which are essential for future EIC needs and broader NP community:

  Ion beam sources

  Electron beam sources

  Polarized ion beams

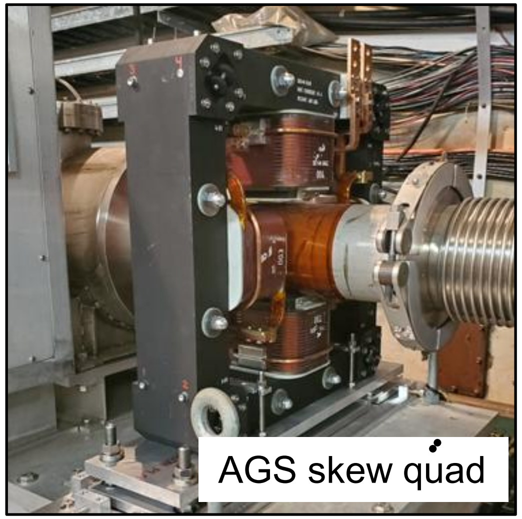
  Beam Cooling

- Mid-term R&D is focused on these key areas to maintain leadership in technology which we need for the EIC, for future EIC capabilities and upgrades, and possibly the next generation of NP facilities.
- In addition to focused mid-term R&D efforts, we actively pursue advanced accelerator R&D (external funding using FOA and LDRDs):
- AI/Machine Learning (ML) is being actively applied for various accelerators at the C-AD to optimize beam controls, automate machine tuning and data analysis. Developed AI/ML tools will be used for EIC operations and optimizations.

Backup slides

Polarized Beam Developments – protons

- re-survey and align AGS magnets (summer 2026)
- improve modeling of AGS lattice at lower energies; beam test with skew quads (Dec 2026)
- upgrade AGS Booster and AGS BPMs (by Feb 2028)
- optimize operations with skew quads over entire AGS energy range (Dec 2028)
- optimize skew quads settings for polarization (Dec 2029)
- test raising AGS injection energy from Gγ=4.5 to Gγ=5.5 (Dec 2030)



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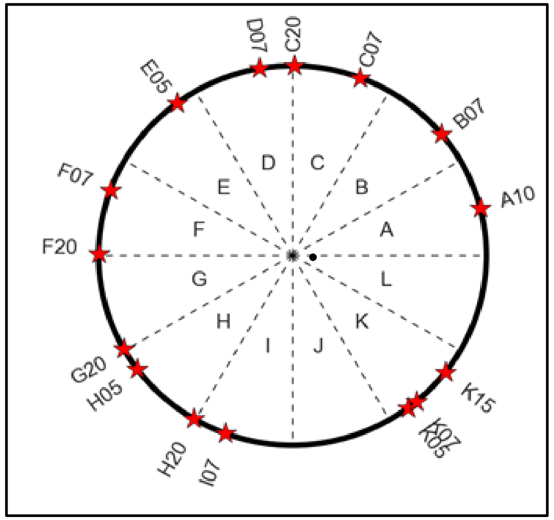
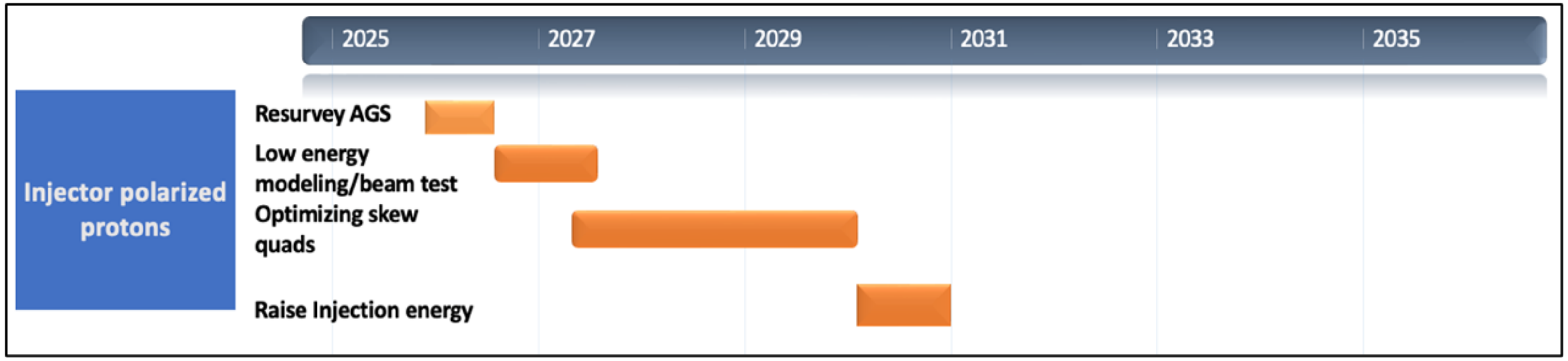
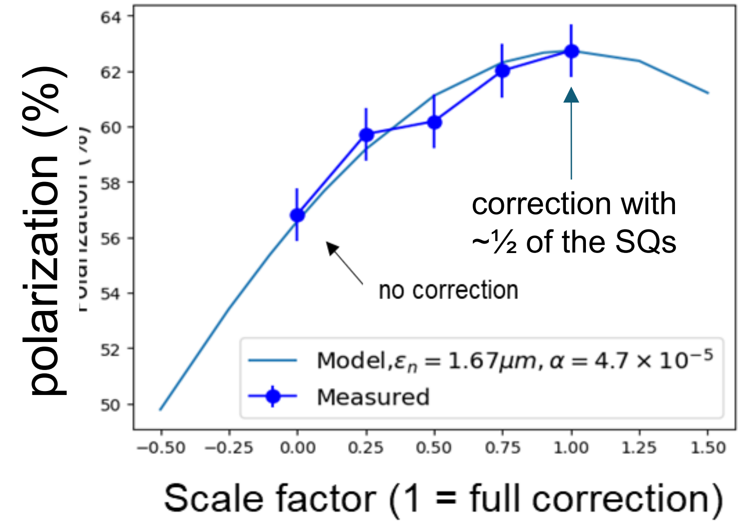
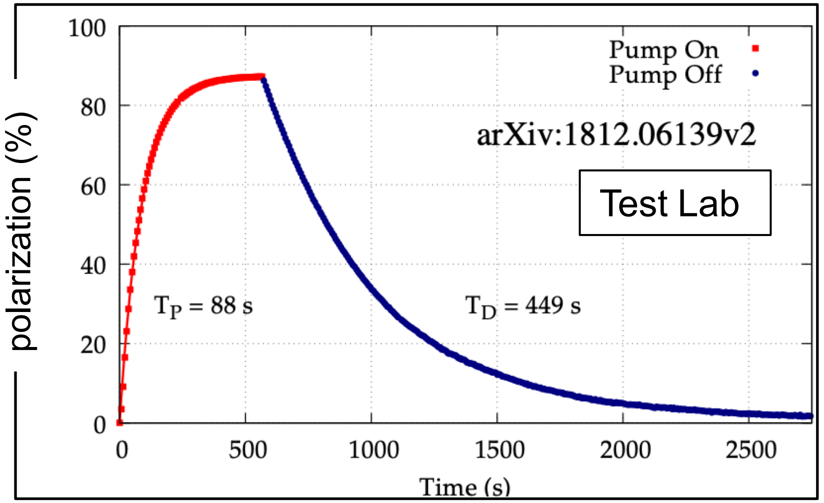






Polarized He-3 Ion Source Developments*

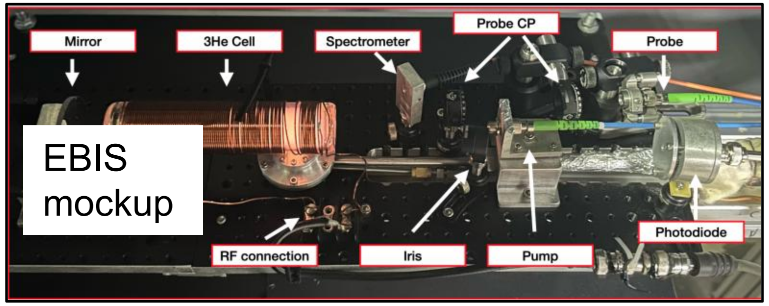
*Developments in collaboration with MIT/BATES



EIC He-3 requirement: 13e10/bunch with 72% polarization

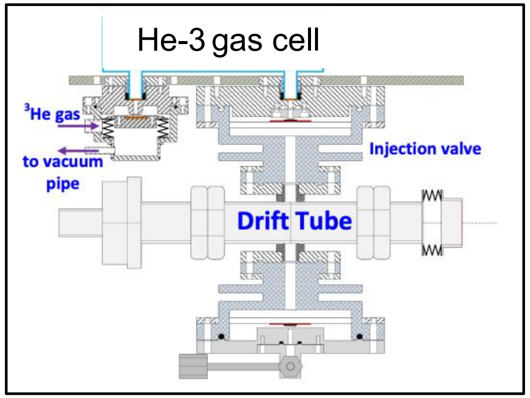
Achievements to date

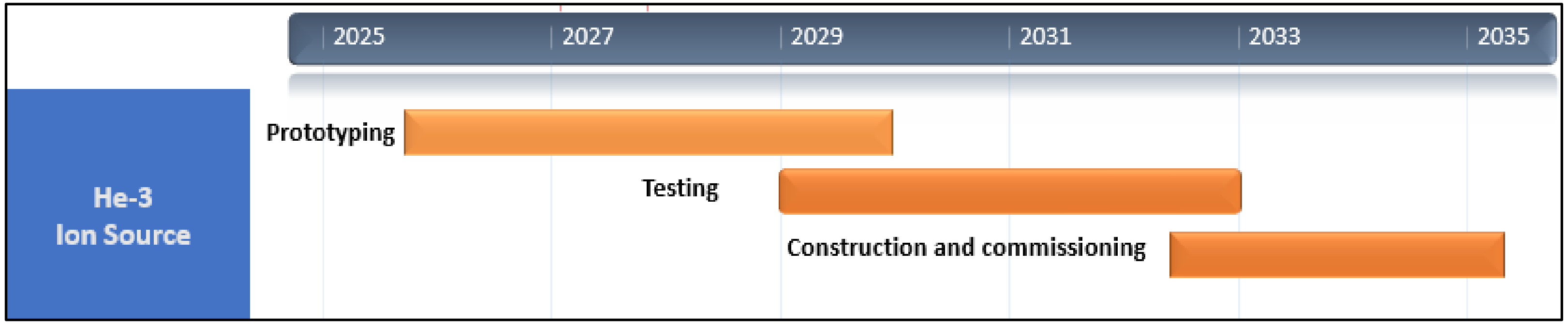
- ~ 90% polarization in test lab
- ~ 60% in electron beam ion source (EBIS) mockup



Next steps (for prototyping stage)

- install He-3 gas cell in EBIS (summer 2026)
- commission He-3 gas cell (end of CY26)
- iterate He-3 cell design until >85% polarization is reached

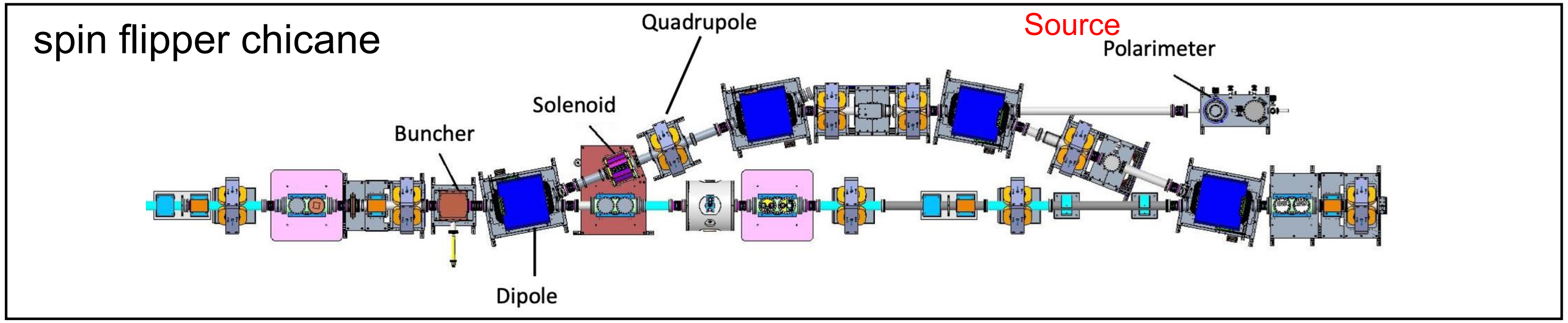




He-3 Polarimetry Developments

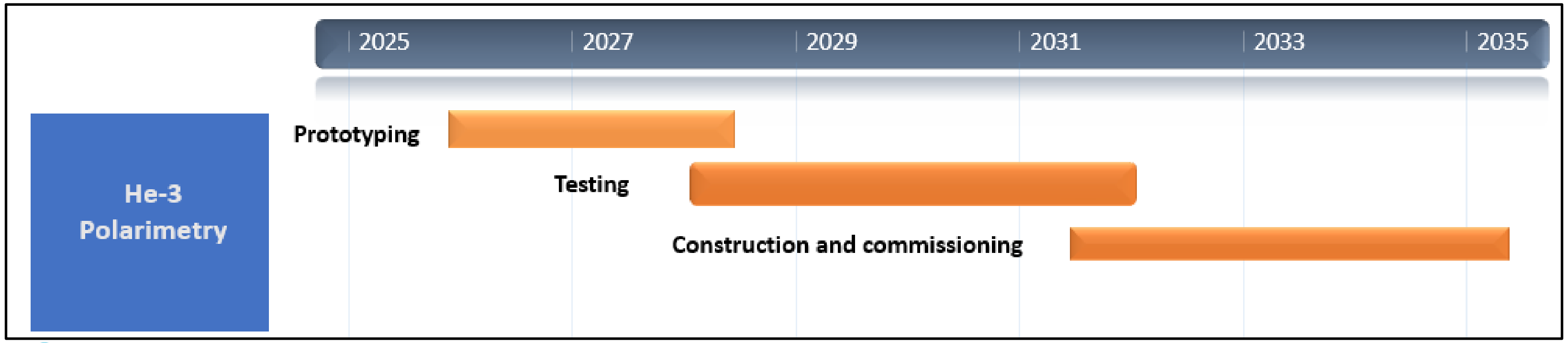
Source polarimeter (6 MeV absolute measurements)

- commission (by end of CY26)
- optimize He-3 beam parameters (pulse length, pulse peak current and polarization) to optimize for <1% statistical error
- commission spin flipper chicane



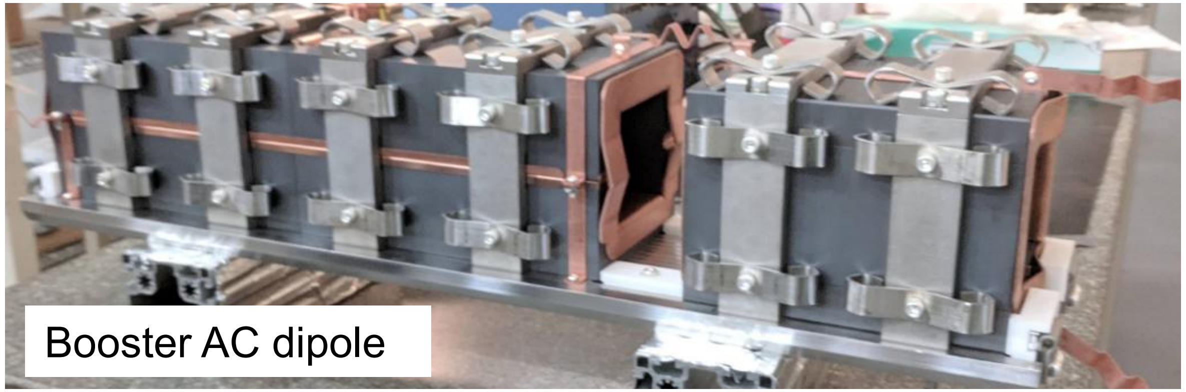
He-3 atomic beam polarimeter in the AGS

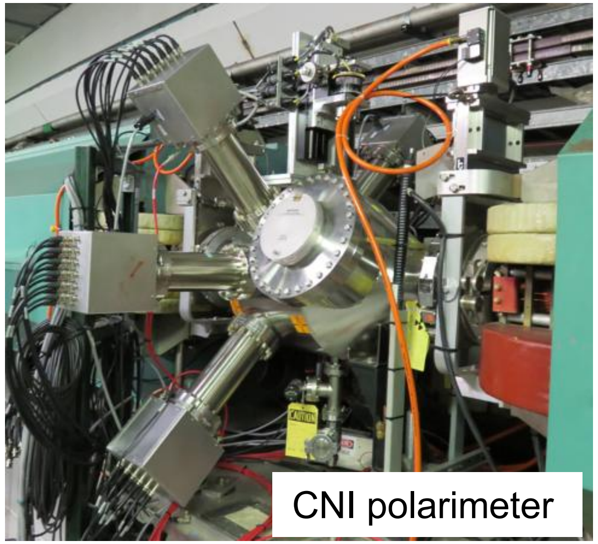
- in (ongoing) collaboration with MIT/BATES and BNL, develop an absolute He-3 beam polarimeter for the EIC based on a polarized He-3 atomic beam source
- install and test in the AGS

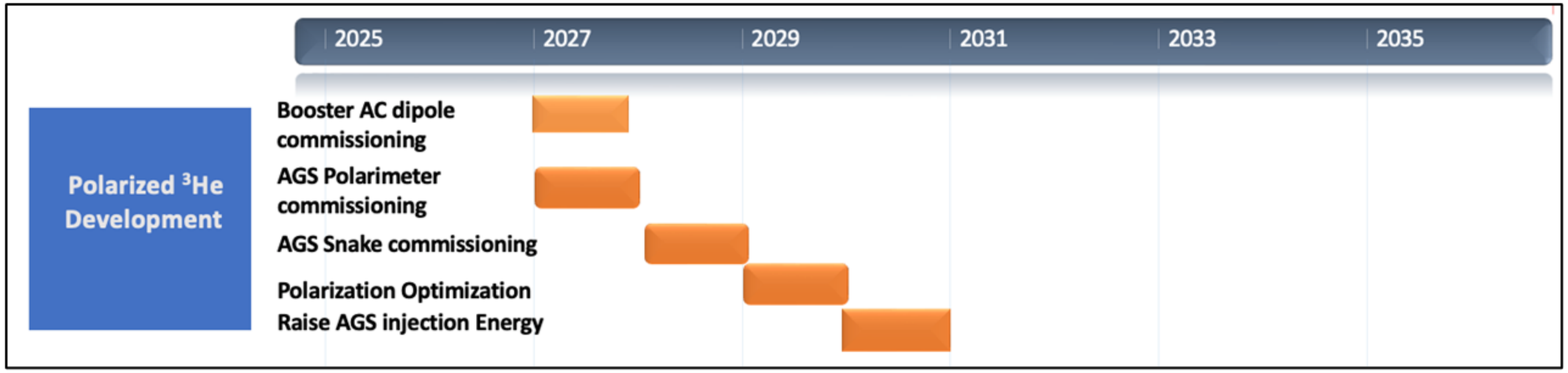


Polarized Beam Developments – He-3

- commission Booster AC dipole to overcome intrinsic resonances
- commission AGS CNI polarimeter (Dec 2027)
- commission AGS partial snakes (Dec 2028)
- optimize polarization transmission efficiency via betatron tunes (Dec 2029)
- test raising AGS injection energy (Dec 2030)


Booster AC dipole


CNI polarimeter



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.

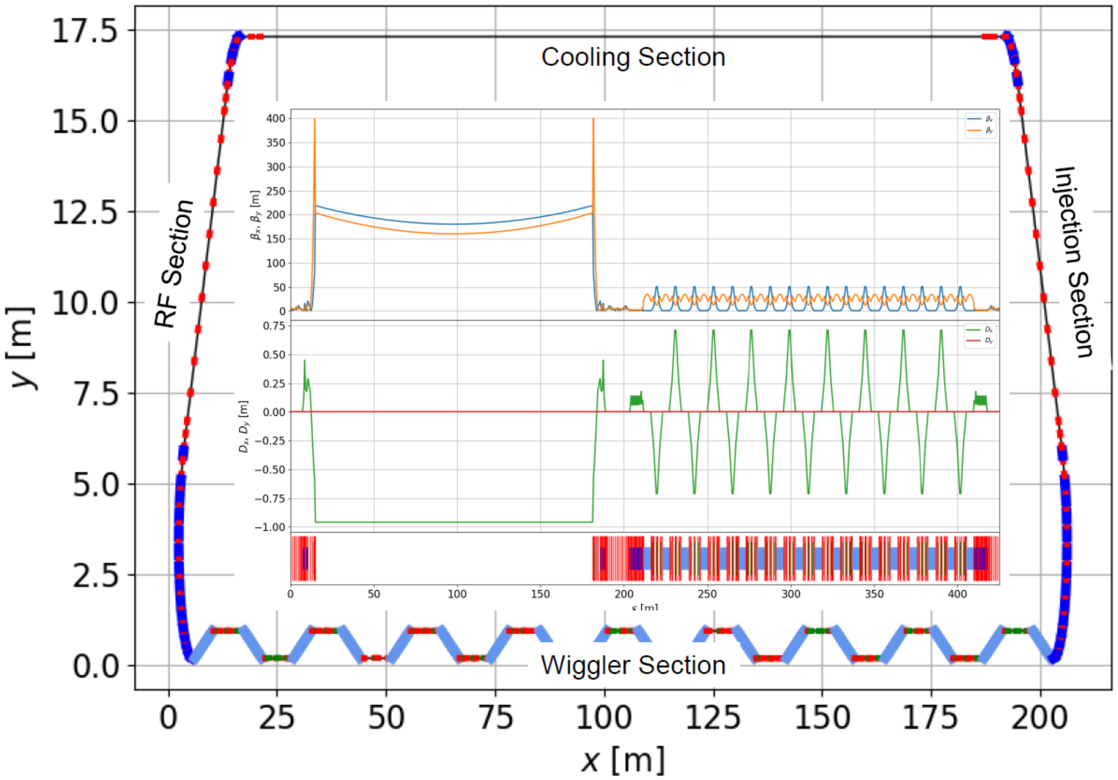


Table 1: The REC parameters (electron storage ring)

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

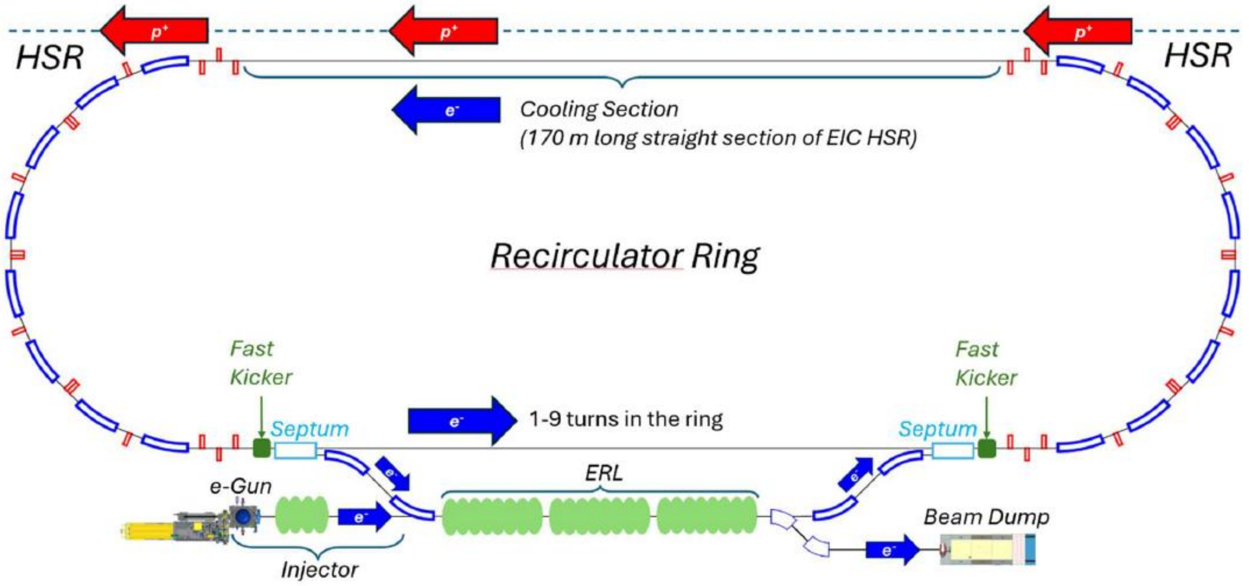


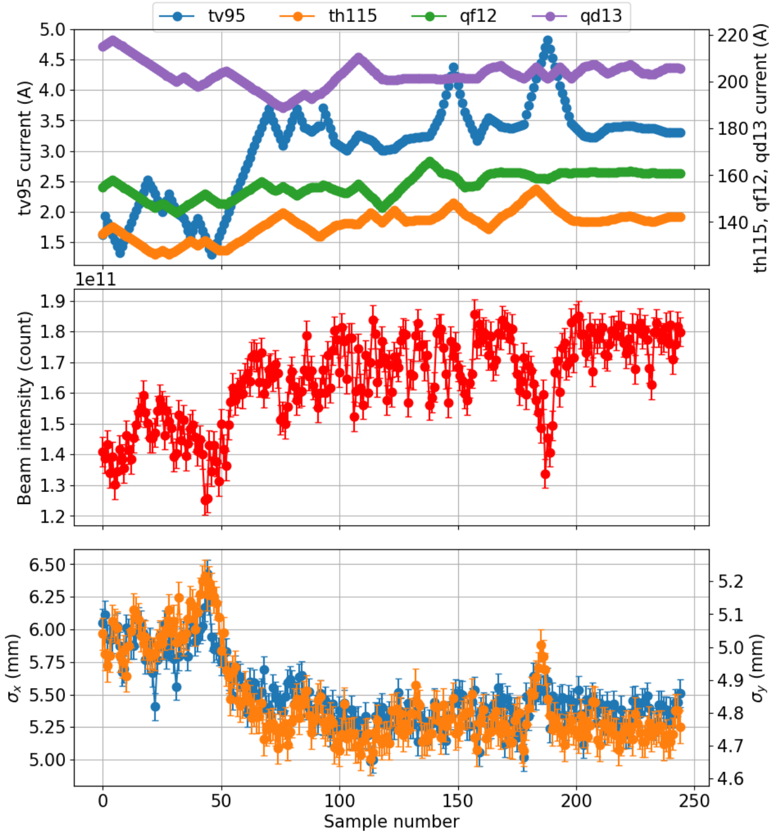
Table 2: Tentative ERLEC parameters

Proton energy, GeV	275	100	41
Electron energy, MeV	150	55	22
Number of electrons per bunch	3×10^{10}	1.25×10^{10}	4×10^{9}
Charge of electron macro-bunch, nC	4.8	2	0.64
Repetition rate in cooling section, MHz	98.5	98.5	98.5
Average repetition rate in injector and ERL, MHz	10.9	19.7	98.5
Number of turns in storage ring	9	5	1
Average current in injector and ERL, mA	53	40	63
Normalized emittance (x, y), μm·rad	2.0, 2.0	1.5, 1.5	1.5, 1.5
Relative momentum spread (rms)	3×10^{-4}	3×10^{-4}	3×10^{-4}
Bunch length (rms), cm	2.5	2.5	2.5
Horizontal cooling time, hours	1.8	1.9	2.0
Vertical cooling time, hours	3.6	3.9	1.8
Longitudinal cooling time, hours	2.9	1.6	1.0

ML: Tools for beam polarization increase (FOA funding)

Collaborators: Georg Hoffstaetter (Cornell) + Kevin Brown (BNL), BNL, Cornell, JLAB, SLAC, RPI
Goal: higher and more stable proton polarization from AGS.
Strategy: (1) Emittance reduction, (2) More accurate timing of tune jumps, (3) Reduction of resonance driving terms
Methods: Gaussian Process (GP), Bayesian Optimization (BO), physics informed learning, and digital twins.

Example:
Bayesian optimization of the Booster injection process.
Top plot: power supply currents of two correctors and two quadrupoles in the Linac-to-Booster line.
Middle plot: beam intensity after Booster injection and acceleration.
Bottom plot: Beam size measurements in the Booster-to-AGS line during Bayesian optimization.



Results: This Bayesian Optimization is now available as a control system application to operators.

The goal is to use ML for automatically optimizing and maintaining beam emittances in Booster and AGS which should help with polarization preservation in injectors.