



EBIS Status and Performance Ramp-Up Plan

Sergey Kondrashev

December 19, 2023



Outline

- Motivation for upgraded EBIS, Extended EBIS design and main features
- Extended EBIS key components
- Extended EBIS commissioning at accelerator location
- Issues and challenges found during first seven months of operation
- Performance ramp up approach and timeline
- $^3\text{He}^{2+}$ polarized ion source development
- Summary

Motivation for Upgraded EBIS, Extended EBIS Design and Main Features

Motivation for an Upgraded EBIS at BNL

RhicEBIS was commissioned in 2009 and since then has provided ions for the RHIC and NSRL programs. An upgrade, Extended EBIS (EEBIS), has been developed to provide increased capabilities:

- Provide increased intensities of Au^{32+} and other species for the Relativistic Heavy Ion Collider (RHIC)
- Provide polarized ${}^3\text{He}^{2+}$ for a future electron-ion collider (EIC) with near term feasibility studies in the injectors and RHIC
- Provide H^+ from the EBIS, reducing or eliminating the need to use the TVDG or 200 MeV Linac to provide protons to NSRL
- Maintain Rapid switching of Ion Beams for quasi-simultaneous beam delivery to RHIC and the NASA Space Research Laboratory (NSRL) at BNL

Production of Polarized ${}^3\text{He}^{2+}$ in an EBIS

Polarized ${}^3\text{He}$ ions offer a “polarized neutron beam” for RHIC and a future EIC. Polarized ${}^3\text{He}^{2+}$ ion source development is made in a collaboration between BNL and MIT. The use of an EBIS offers the following advantages:

- ${}^3\text{He}$ gas can be polarized efficiently within the uniform 5 Tesla axial magnetic field of the EBIS solenoid.
- EBIS can maintain high polarization throughout the ionization and confinement process
- EBIS can produce a high ratio of ${}^3\text{He}^{2+} / {}^3\text{He}^{+}$
- ${}^3\text{He}^{2+}$ can be transported to ion rings without depolarization

Identified as high priority R&D for EIC by EICAC review in 2009, Office of Nuclear Physics Community Review in 2017, and the 2018 assessment of the US National Academy of Sciences.

The Extended EBIS Three trap System: (gas injection trap, short trap, long trap)

Two identical unshielded 5T warm bore superconducting solenoids are used for “Extended” EBIS

The upstream solenoid contains the new features for the efficient gas injection and eventual polarized ^3He ion production:

- **gas injection / ionization cell at pressures up to 5×10^{-6} mbar (2cm diameter, 40cm long)**
- “External drift tube” construction with differential pumping stages and custom pump out manifold to provide space for gas reservoir / high field polarization cell
- An innovative pulsed valve operating on the Lorentz force mounted to the gas ionization cell drift tube via a compact insulator
- Future installation: High field ^3He polarization cell and purification system (tested in a separate solenoid)

The upstream solenoid also contains the “**short trap**”, a **95 cm long** ionization region to provide additional intensity of highly charged ions over the single solenoid RhicEBIS system.

The downstream solenoid contains the “**long trap**”, a **178 cm long** ionization region with good vacuum separation from the upstream module and electron collector.

Extended EBIS Operating Modes

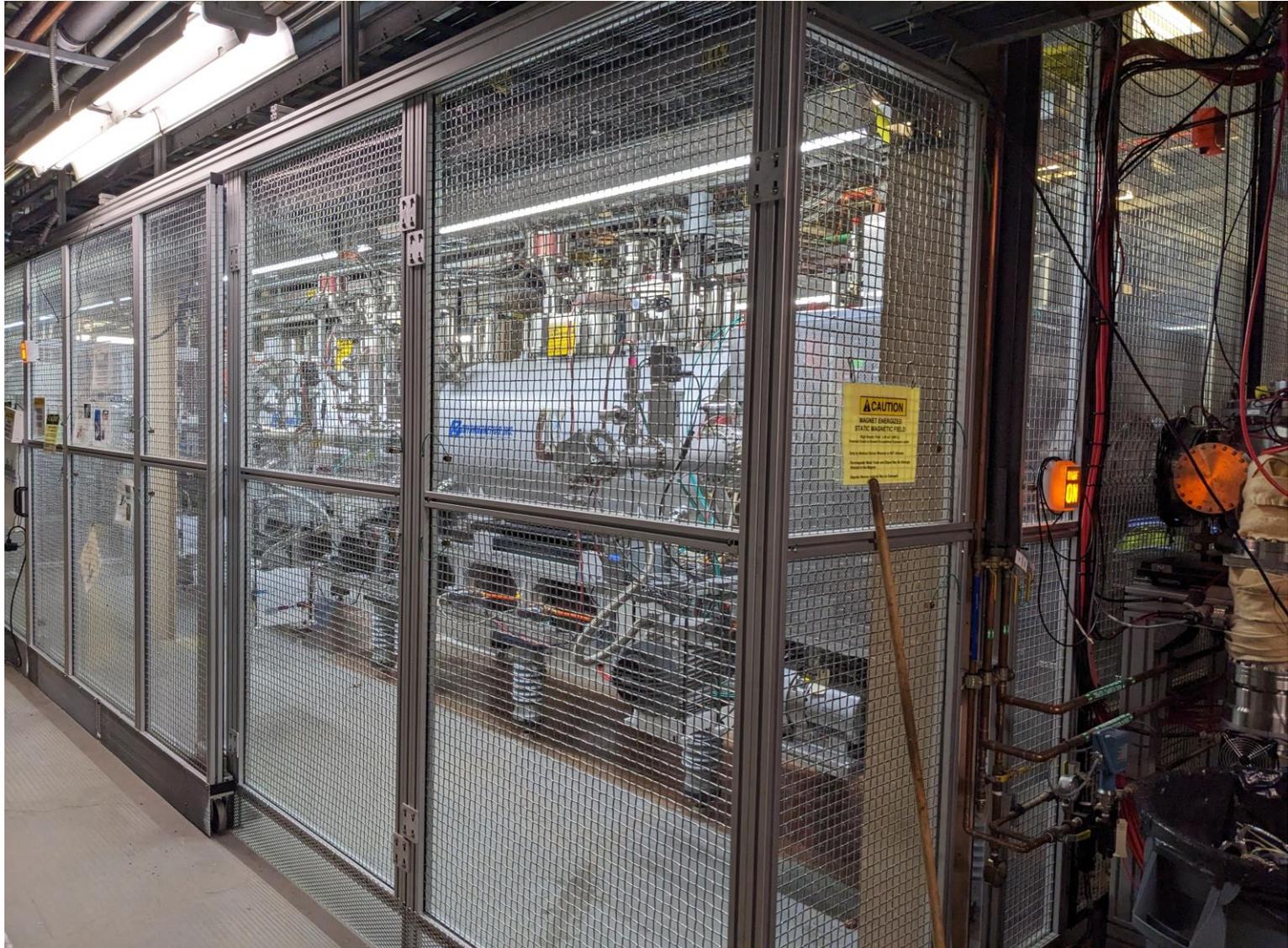
RHIC Au³²⁺: External Ion injection --- Combined Long and Short Trap

NSRL High charge state ions: External Ion Injection --- Long Trap
(Very good vacuum conditions for very high charge state ions)

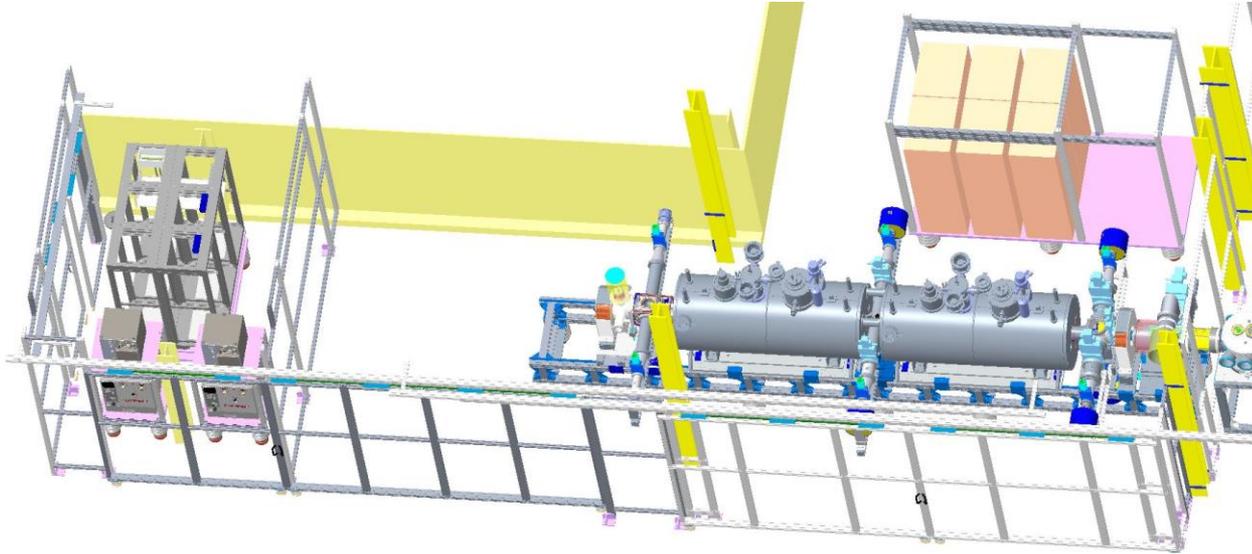
Light Ions: He, H Internal gas injection

Polarized ³He: Internal gas injection; ³He²⁺ extraction from Long Trap

EEBIS Inside HV Cage



Extended EBIS Installation at Accelerator with High Voltage Enclosure



Left: Solid state electron collector power supply (not installed yet because delayed delivery to BNL)

Middle: Extended EBIS with two Superconducting Solenoids

Right: Existing Ion injection and LEBT beamlines

Collector supply partition and EBIS shielded connections allows EBIS experts to enter the EBIS and power supply cage during electron beam aided source alignment and other operations not needing platform high voltage. (The entire cage is off limits during HV pulsing for ion injection from the laser ion source (LION) and ion extraction for beam propagation to the accelerator)

Expected Extended EBIS Intensities Based on RhicEBIS Performance

The extended EBIS uses the same electron beam launching and collection system as RhicEBIS. The upgrade to provide polarized ${}^3\text{He}^{2+}$ ions to RHIC and the future EIC results in increased intensities for other ion species as well:

- Higher intensity of light ions can be produced from light gases using a highly efficient gas injection system rather than previous RhicEBIS ion injection method.
- Ion intensities of externally injected heavy ions benefit from the additional trap capacity provided by the short trap in the first solenoid.

Intensity Estimates for EBIS upgrade (at Extended EBIS exit)

$\text{He}^{2+} \sim 2.5 - 5 \times 10^{11}$ ions/pulse

$\text{H}^+ \sim 5 - 10 \times 10^{11}$ ions/ pulse

$\text{Au}^{32+} \sim 2.6 \times 10^9$ ions/pulse (1.4-1.5 times the RhicEBIS output)

Extended EBIS Additional Features

High-capacity ZAO NEGs + Turbo Pumping:

Provide high pumping speed where needed. Pulsed Hydrogen pumping speed measurement system developed to monitor NEG status.

Alignment during EBIS electron beam propagation:

HV cage is partitioned and HV connections are protected such that EBIS experts can enter the HV cage for initial mechanical magnetic alignment

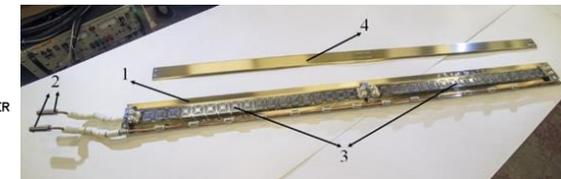
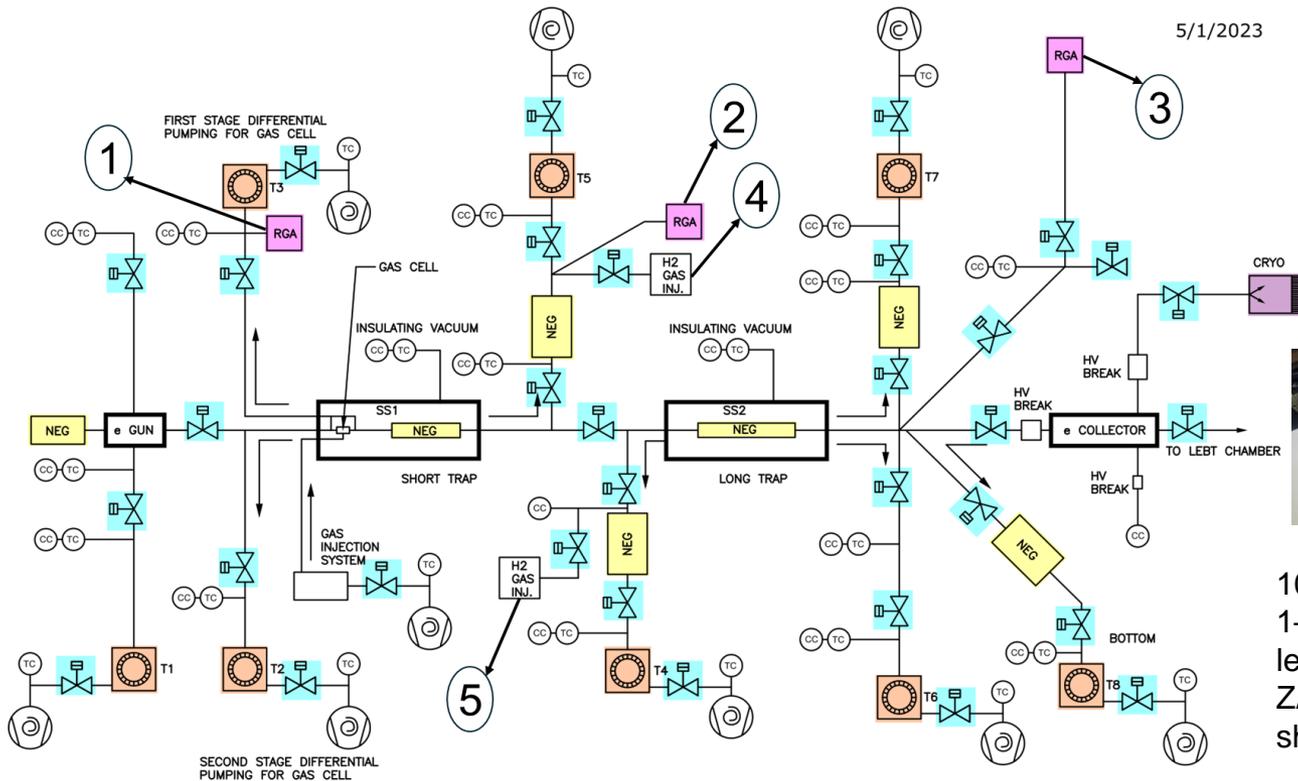
New Electron Gun Cathode:

3M lower temperature oxide cathodes - improved beam quality, domestically available, important for BNL and our other colleagues at ANL and FRIB

New Solid State Electron Collector Supply:

Expect less down time with faster reset time, collector voltage can be varied during a single species beam time as well as optimized for each species

Extended EBIS Vacuum System



1000 l/s ZAO NEG custom linear unit:
 1—mounting cradle, 2—electrical leads to provide heating current, 3—ZAO NEG linear modules, 4—heat shielding top plate.

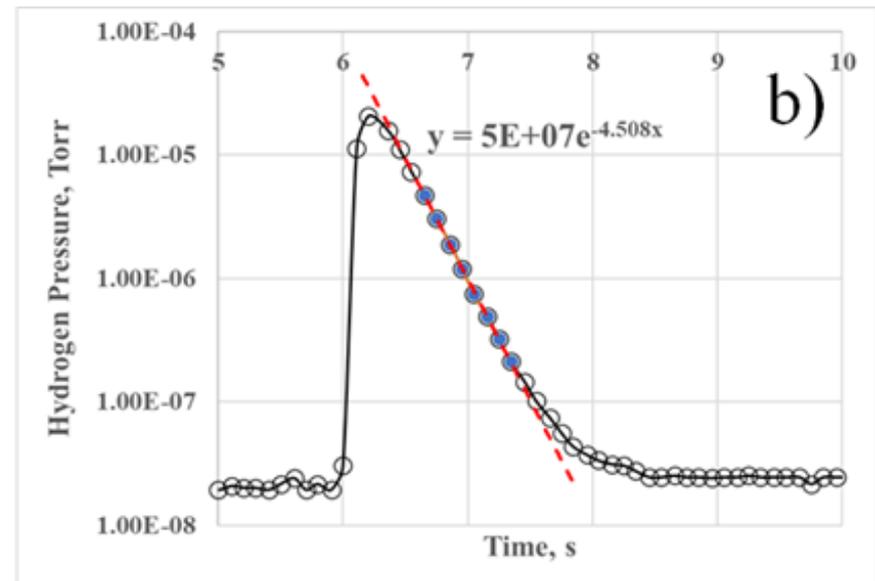
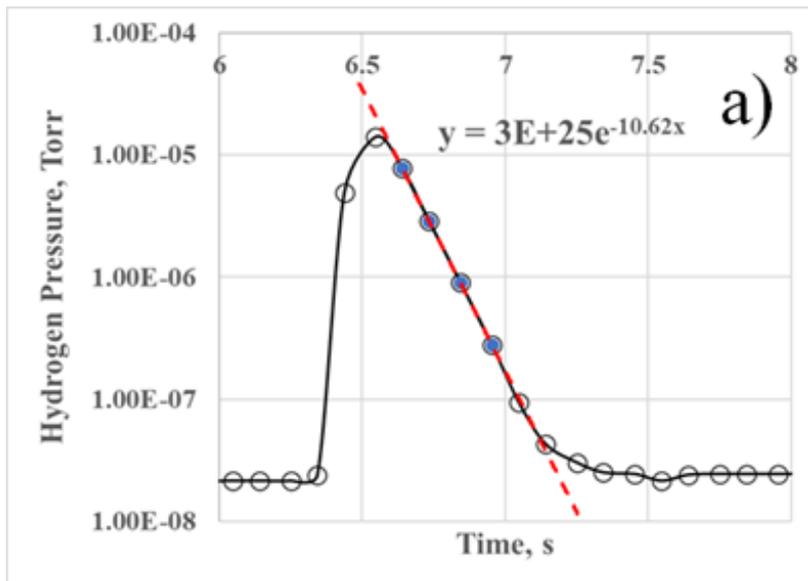
- Cryopumps use is avoided in the ionization regions of the EEBIS vacuum system because of their required frequent maintenance and limited capabilities concerning helium pumping
- Two custom linear ZAO NEG units with 1000 l/s and 1500 l/s pumping speed for hydrogen which are placed inside the short and long ion trap vacuum chambers
- Four standard SAES Getter UHV 1400 wafer ZAO NEG modules with 1360 l/s pumping speed for hydrogen are placed within the vacuum chamber connecting arms
- In situ effective pumping speed measurements to monitor NEG activation and saturation time evolution

In situ Effective Pumping Speed Measurement System to Monitor NEG Activation and Saturation

If a finite pulse of gas is injected into vacuum chamber, the pressure inside the chamber will rise and then decrease exponentially according to following equation:

$$P(t) = P(t = 0) \cdot e^{-\frac{S}{V} \cdot t} \quad (1)$$

where $P(t)$ is the pressure at the detector location (RGA in our case) at time t , $t = 0$ is the time at the end of gas injection pulse, S is the pumping speed at the detector location, and V is the effective volume of vacuum chamber.



By using hydrogen one can prevent influence of measurements on ZAO NEG pumping speed.

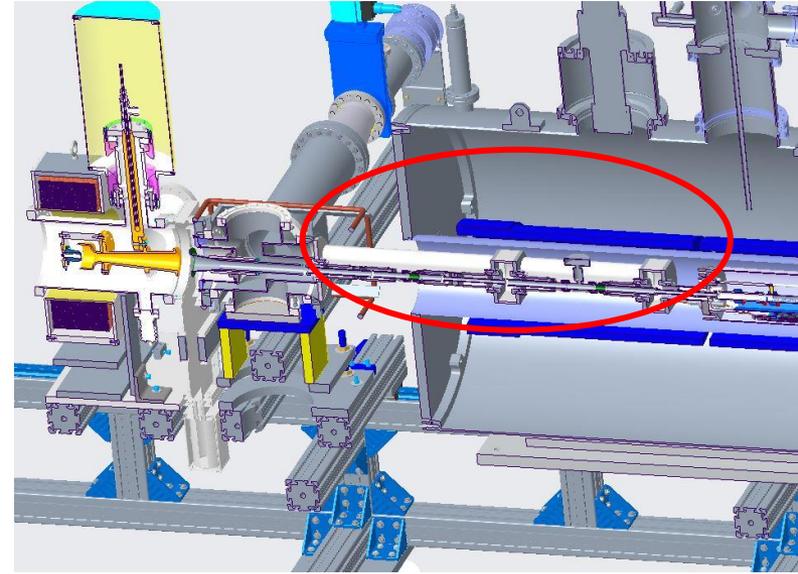
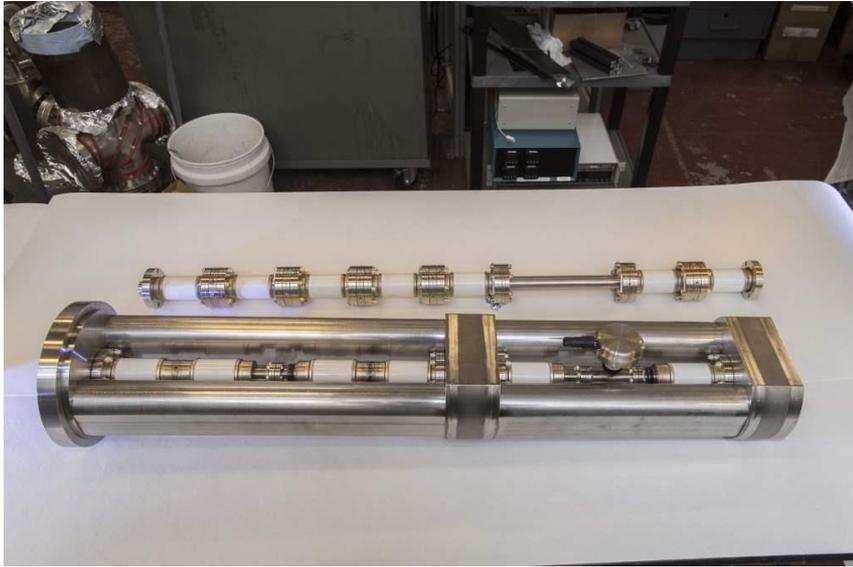
NEG Status Monitoring

Results of effective pumping speed measurements with hydrogen for long trap (LT) with different gate valves open/close configurations: 5 individual measurements for each configuration and average values (all in s^{-1}), all values without brackets were measured right after EEBIS bakeout and consequent activation of all ZAO NEGs, all values within brackets were measured about one month after all ZAO NEGs were activated and exposed to vacuum leak which was later eliminated prior to EEBIS bakeout.

Gate valves (GV) config	1 and 16 GV closed	6 and 16 GV closed	6, 8 and 16 GV closed	6, 8, 12 and 16 GV closed	6, 8, 10, 12 and 16 GV closed	6, 8, 10, 11, 12 and 16 GV closed	6, 8, 9, 10, 11, 12 and 16 GV closed	6, 8, 9, 10, 11, 12, 15 and 16 closed
Measur. 1	11.7	11.2 (4.31)	11.2	11.2 (2.29)	11.0 (1.67)	9.4	4.5	4.5 (1.17)
Measur. 2	11.5	11.5 (4.28)	11.1	11.1 (2.29)	10.5 (1.68)	9.7	4.5	4.5 (1.16)
Measur. 3	11.5	11.0 (4.26)	11.1	11.0 (2.22)	10.5 (1.7)	9.3	4.5	4.5 (1.16)
Measur. 4	11.4	11.0 (4.36)	11.0	11.1 (2.32)	10.8 (1.67)	9.5	4.5	4.5 (1.16)
Measur. 5	11.7	10.9 (4.38)	11.0	11.0 (2.3)	10.9 (1.68)	9.5	4.5	4.5 (1.17)
Average	11.6	11.1 (4.32)	11.1	11.1 (2.28)	10.7 (1.68)	9.5	4.5	4.5 (1.16)

Extended EBIS Key Components

Gas Cell with Pump out Manifold and External Drift Tube Connections

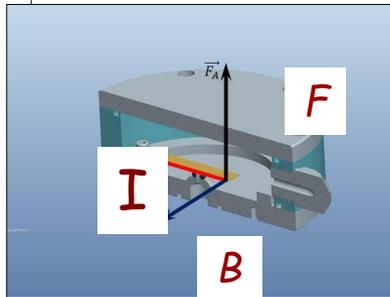


Fast Pulsing Gas Valve

"Electro-magnetic", $[I \times B]$ valve operation principle

Lorentz (Laplace) force moves the flexible conducting plate in the high ($\sim 3-5$ T) magnetic field.

For $I=10$ A, $L=5$ cm, $F=2.5$ N. Current pulse duration $\sim 100-500$ μ s



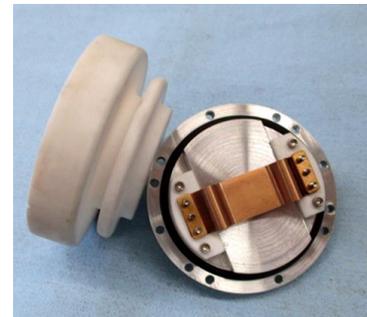
$$d\vec{F}_A = I [d\vec{l} \vec{B}]$$



Prototype of the pulsed (isolated valve) for the gas injection to the extended EBIS.



Pulsed valve for Un-polarized gas Injection to the EBIS



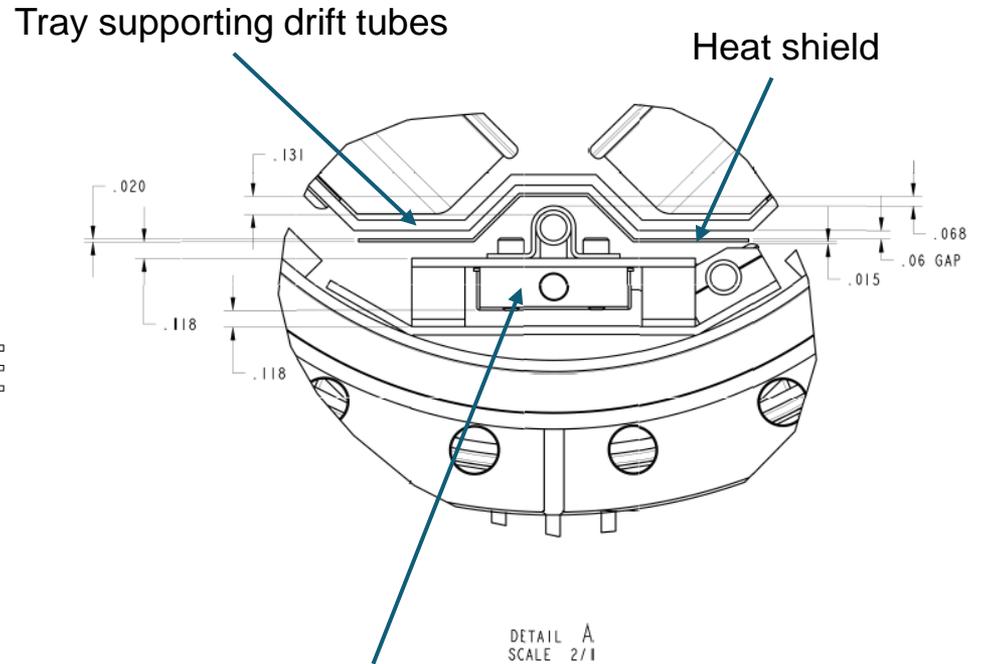
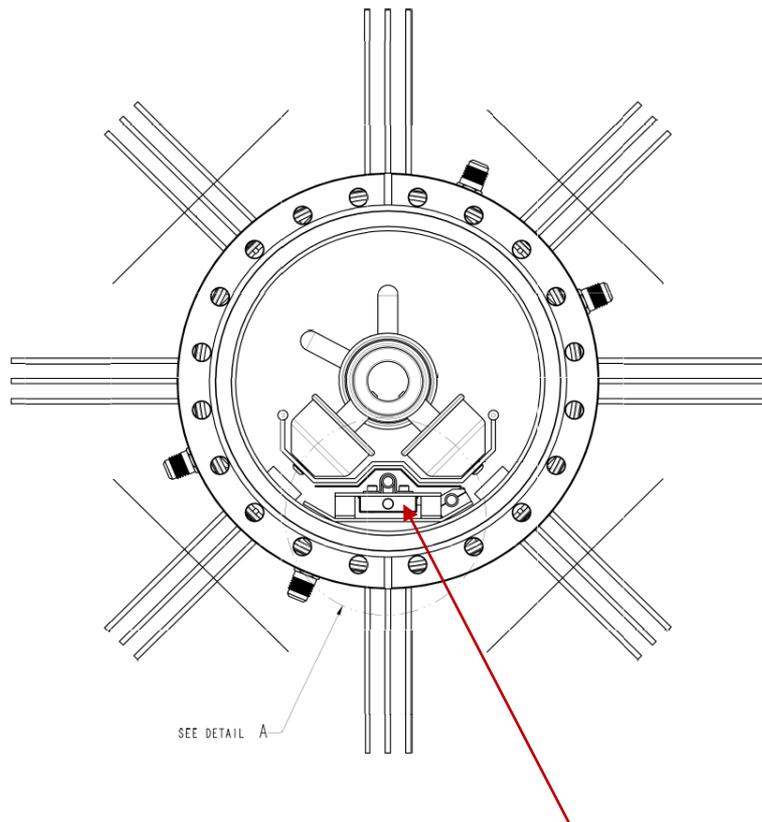
Valve demonstrated robust and reliable operation at Extended EBIS for more than 6 months.

Custom Linear NEG Pumping Unit

Upstream “Short Trap” Drift Tubes (right foreground)
Two module ZAO high-capacity custom linear NEG pumping unit
(left foreground)



Design of ZAO NEG Linear Pumping System



ZAO NEG linear pumping system

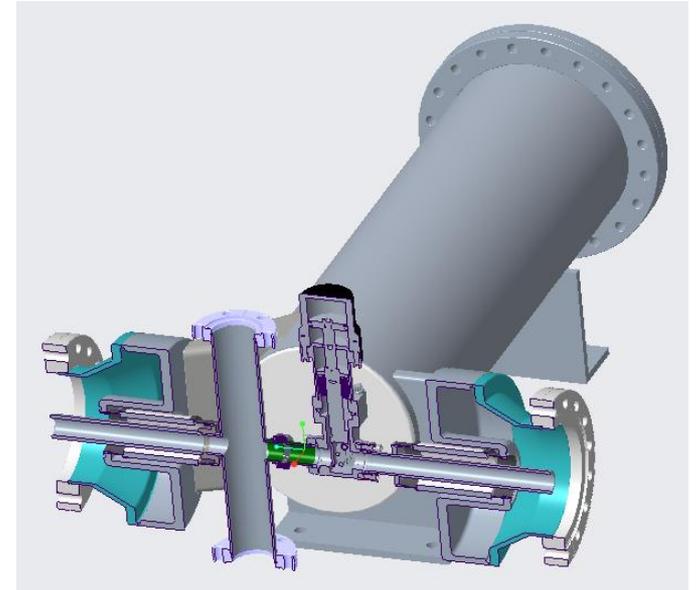
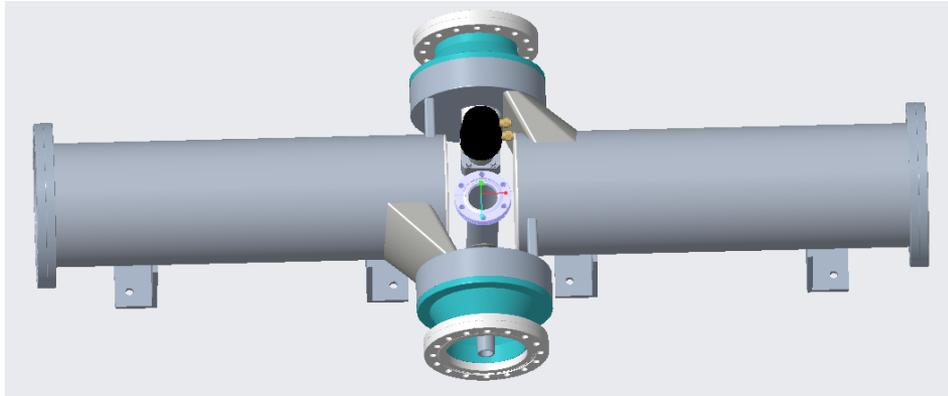
ZAO NEG linear pumping system is located under the drift tubes support tray

Downstream Drift Tubes and Custom Linear NEG Module



Center Vacuum Chamber

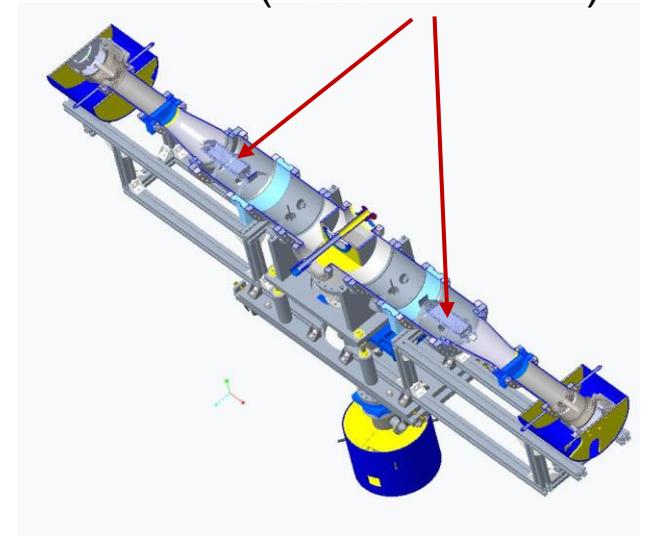
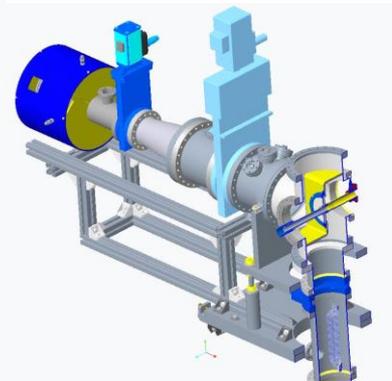
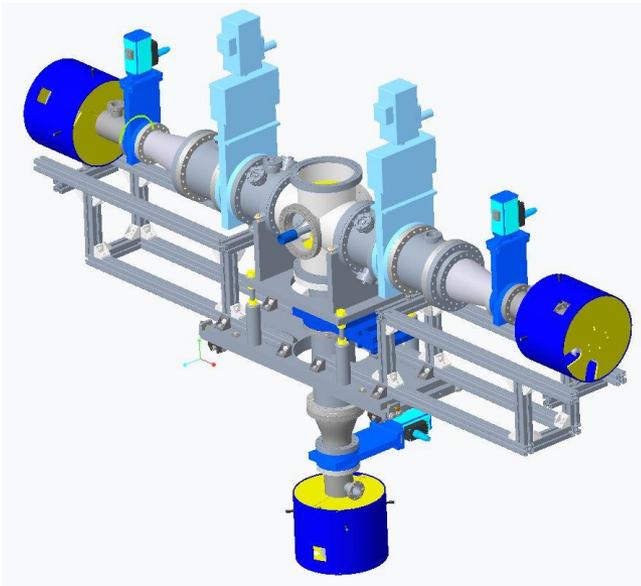
Includes gate valve for isolating upstream and downstream vacuum chambers
Differential pumping ports for upstream and downstream regions



Location: axial gap between the two superconducting solenoids.

Vacuum Chamber with Differential Pumping Baffles between Downstream Ionization Trap and the Electron collector.

ZAO NEG Modules
(1360 l/s for H₂)



Horizontal arms pump Long Trap ionization region.
Lower Vertical arm pumps collector transition region.

Extended EBIS Commissioning at the Accelerator Location

Extended EBIS Commissioning Stages

EEBIS startup went very quickly with 4He^{2+} beam being delivered to NSRL within 3 weeks of the initial electron beam propagation at the accelerator location.

Very high charge state ions were delayed until a bakeout could be fit into the the busy NSRL schedule...but were produced immediately after vacuum improvement once leak was eliminated and bakeout by the vacuum group was made.

Gas injection is working with He for NSRL.

Gas is ionized in the gas trap and transferred to the LONG trap for fast extraction by the Behlke HV electronics.

Singly charged ion injection from LION into the EBIS long trap is working with both the Au rotating target for RHIC operations and the various targets Si, Fe, Bi, Ta, Ti, etc. in the xy target system.

The Behlke fast HV electronics is not yet installed for the short trap, so the short trap is not currently in use for ion capture or high charge state ion extraction. (The installation will be completed in December 2023 during NSRL shutdown with following ion beam tuning).

Commissioning Milestones (March-August 2023)

- March 23 Initial Electron Beam off cathode 200-300mA 0.2Hz
- March 24 1A electron beam to collector after reversing Gun solenoid leads
(limited by drift tube power supply)
- March 27-28 Magnetic Mechanical Alignment using electron beam
3A, 30ms e-beams no transverse magnetic steering used
6A, 0.4ms e-beam with some steering correction
- March 29-30 First ions from Long Trap residual gas: 8nC, 3A e-beam, 5ms conf.
Helium Gas injection and RGA monitoring systems installed
- March 31 Ion output vs Conf time for Gas, Short and Long Traps (Pressure probe)
Helium gas injection tests (3.5nC Helium ions from gas trap)
HV platform pulsing test to 500V (for ion beam transport to RFQ)
- April 1-2 Partial 150C bore vacuum system bakeout and NEG pumps 550C activation
- April 3-4 Three Behlke Switch Fast Capture and Extraction system debugged
4He Gas injection, He+ transfer to Long Trap, Ion extraction demonstrated
11nC total charge, at least 50% helium ions
- April 8 He²⁺ propagation through RFQ and HEBT to FC96
April 10 He²⁺ set up in Booster from internal gas injection in EEBIS

- April 11 Behlke switch configured for 1+ ion capture by EBIS from LION
- April 17 PPM control feature added for CAEN transverse magnetic steering
- April 22 First NSRL operations with EEBIS ion beams He⁺, He²⁺, O⁵⁺, Si⁹⁺, C⁵⁺ beams from Extended EBIS were setup for use with NSRL GCR testing.
- April 24 Ti¹³⁺ setup in booster for NSRL
- April 27 Fe¹⁵⁺ setup in booster for NSRL
(This allowed Tandem to start RHIC operations with Au)
- May NSRL operations
- May 26 – June 12 Flange leak in collector transition found and eliminated
EBIS High Temperature Bake by Vacuum Group
NEG Activation**
- June 13 Pulsed H₂ NEG pumping speed measurements completed
Cathode replaced (after vacuum accident) and activated
- June 14-17 Superconducting solenoid problems: multiple quenches and recovery
- June 17-18 EEBIS Electron beam restart after vacuum improvement by baking, etc.
(4.1A ebeam)

- June 19 -20 Si11+, Nb23+, Ta38+ and Au32+ were produced now. The EBIS vacuum is improved greatly after the bake and NEG activation.
- July 1 8A electron beam (1P/sc)
- July 8 Au32+ 12P/sc (5.2A ebeam, 35uVs at FC96)
- July 27 Au32+ improved distribution (lower gas and short trap drift tube potentials), 12P/sc intensity doesn't change with rep. rate
Stable with most NSRL beams for few hours.
- Aug 6 Au32+ 12P/sc, 5Hz runs for more than 5 hours with moderate pressure raise (4.5A ebeam, 20uVs at FC96) – the longest demonstrated 12P/sc, 5Hz run so far
- Aug 27 Au32+ Low voltage drift tube distribution with increased cathode bias.
8.3A electron beam achieved
FC96 = 45 uVs with 6.5A ebeam not fully optimized

EEBIS Operation Status at the Accelerator

- 1) Electron Beams up to 8.3A for Au³²⁺ production
- 2) He gas injection, ion transfer to the long trap and 4He²⁺ extraction for NSRL operations
- 3) External ion injection of 1+ ions from Laser Ion Source (LION) into the EBIS long trap with subsequent high charge state extraction to the RFQ, LINAC and Booster.
- 4) Two user operation on the same super cycle:
NSRL (Various very high charge state ions) + RHIC Au³²⁺
- 5) 12P/sc Au³²⁺ operation has had some difficulties due to prolonged ExB discharges on drift tubes in the gas injection region. The voltages have been reduced and the electron beam energy has been maintained by operating with a higher cathode bias voltage. (This new distribution has been demonstrated on Sunday Aug 27, 2023 and should allow operations to continue without physical rework of the “problem” drift tubes).
- 6) Matching of NSRL distributions to the modified Au³²⁺ distribution was done to provide better stability for NSRL beams as well.

Species Developed and Supplied for NSRL Operation

4He²⁺, C⁵⁺, O⁷⁺, Si¹¹⁺, Ti¹⁷⁺, Ti¹⁸⁺, Fe²⁰⁺, Nb²³⁺, Ag²⁹⁺, Tb³⁵⁺, Ta³⁸⁺, Au³²⁺, Bi⁴³⁺

+	æ Nov 02 08:57	cp	mcr (tape)	NSRL species changed to Fe20 (LaserXY,EU6) from Si11 (LaserXY,EU8)
+	æ Nov 02 09:03	cp	mcr (tape)	NSRL species changed to p (Tandem, EBIS: Fe(LaserXY,EU6)) from Fe20 (LaserXY,EU6)
+	æ Nov 02 09:52	cp	nsrl (tape)	NSRL species changed to Si11 (LaserXY,EU8) from Proton (Tandem, EBIS: Fe(LaserXY,EU6))
+	æ Nov 02 09:59	cp	nsrl (tape)	NSRL species changed to He (GasInj,EU6) from Si11 (LaserXY,EU8)
+	æ Nov 02 10:03	cp	nsrl (tape)	NSRL species changed to O7 (LaserXY,EU8) from He (GasInj,EU6)
+	æ Nov 02 10:07	cp	nsrl (tape)	NSRL species changed to Fe20 (LaserXY,EU6) from O7 (LaserXY,EU8)
+	æ Nov 02 10:10	cp	nsrl (tape)	NSRL species changed to p (Tandem, EBIS: Fe(LaserXY,EU6)) from Fe20 (LaserXY,EU6)
+	æ Nov 02 10:29	cp	nsrl (tape)	NSRL species changed to Si11 (LaserXY,EU8) from Proton (Tandem, EBIS: Fe(LaserXY,EU6))
+	æ Nov 02 10:34	cp	nsrl (tape)	NSRL species changed to He (GasInj,EU6) from Si11 (LaserXY,EU8)
+	æ Nov 02 10:39	cp	nsrl (tape)	NSRL species changed to O7 (LaserXY,EU8) from He (GasInj,EU6)
+	æ Nov 02 10:42	cp	nsrl (tape)	NSRL species changed to Fe20 (LaserXY,EU6) from O7 (LaserXY,EU8)
+	æ Nov 02 10:44	cp	nsrl (tape)	NSRL species changed to p (Tandem, EBIS: Fe(LaserXY,EU6)) from Fe20 (LaserXY,EU6)
+	æ Nov 02 12:10	cp	nsrl (tape)	NSRL species changed to He (GasInj,EU8) from Proton (Tandem, EBIS: Fe(LaserXY,EU6))
+	æ Nov 02 12:38	cp	mcr (tape)	Default NSRL archives have been created (He,GasInj,User8)
+	æ Nov 02 12:42	cp	nsrl (tape)	NSRL species changed to p (Tandem, EBIS: He(GasInj,EU8)) from He (GasInj,EU8)
+	æ Nov 02 12:51	cp	nsrl (tape)	NSRL species changed to Si11 (LaserXY,EU6) from Proton (Tandem, EBIS: He(GasInj,EU8))
+	æ Nov 02 12:56	cp	nsrl (tape)	NSRL species changed to He (GasInj,EU8) from Si11 (LaserXY,EU6)
+	æ Nov 02 13:00	cp	nsrl (tape)	NSRL species changed to O7 (LaserXY,EU6) from He (GasInj,EU8)
+	æ Nov 02 13:04	cp	nsrl (tape)	NSRL species changed to Fe20 (LaserXY,EU8) from O7 (LaserXY,EU6)
+	æ Nov 02 13:06	cp	nsrl (tape)	NSRL species changed to p (Tandem, EBIS: Fe(LaserXY,EU8)) from Fe20 (LaserXY,EU8)
+	æ Nov 02 13:35	cp	nsrl (tape)	NSRL species changed to Fe20 (LaserXY,EU6) from Proton (Tandem, EBIS: Fe(LaserXY,EU8))
+	æ Nov 02 13:39	cp	nsrl (tape)	NSRL species changed to p (Tandem, EBIS: Fe(LaserXY,EU6)) from Fe20 (LaserXY,EU6)
+	æ Nov 02 14:04	cp	nsrl (tape)	NSRL species changed to Si11 (LaserXY,EU8) from Proton (Tandem, EBIS: Fe(LaserXY,EU6))
+	æ Nov 02 14:08	cp	nsrl (tape)	NSRL species changed to He (GasInj,EU6) from Si11 (LaserXY,EU8)
+	æ Nov 02 14:18	cp	nsrl (tape)	NSRL species changed to O7 (LaserXY,EU8) from He (GasInj,EU6)
+	æ Nov 02 14:22	cp	nsrl (tape)	NSRL species changed to Fe20 (LaserXY,EU6) from O7 (LaserXY,EU8)
+	æ Nov 02 14:24	cp	nsrl (tape)	NSRL species changed to p (Tandem, EBIS: Fe(LaserXY,EU6)) from Fe20 (LaserXY,EU6)
+	æ Nov 02 14:43	cp	nsrl (tape)	NSRL species changed to Si11 (LaserXY,EU8) from Proton (Tandem, EBIS: Fe(LaserXY,EU6))
+	æ Nov 02 15:08	cp	nsrl (tape)	NSRL species changed to He (GasInj,EU6) from Si11 (LaserXY,EU8)
+	æ Nov 02 15:13	cp	nsrl (tape)	NSRL species changed to O7 (LaserXY,EU8) from He (GasInj,EU6)
+	æ Nov 02 15:17	cp	nsrl (tape)	NSRL species changed to Fe20 (LaserXY,EU6) from O7 (LaserXY,EU8)
+	æ Nov 02 15:18	cp	nsrl (tape)	NSRL species changed to p (Tandem, EBIS: Fe(LaserXY,EU6)) from Fe20 (LaserXY,EU6)

NSRL GCR testing

No any other type of ion source can provide such degree of flexibility, except EBIS

Issues and Challenges Found During First Seven Months of Operation

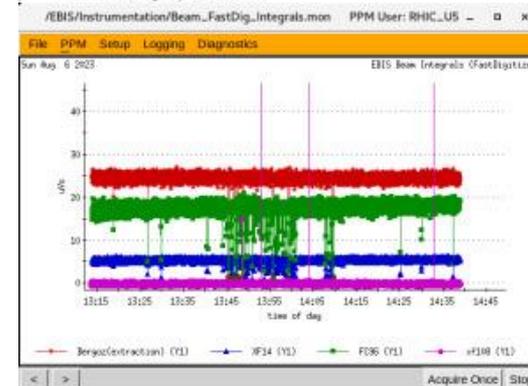
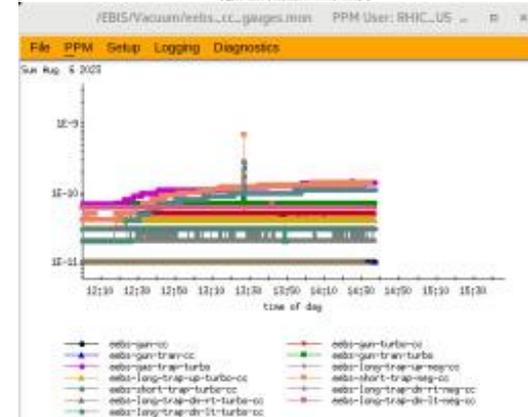
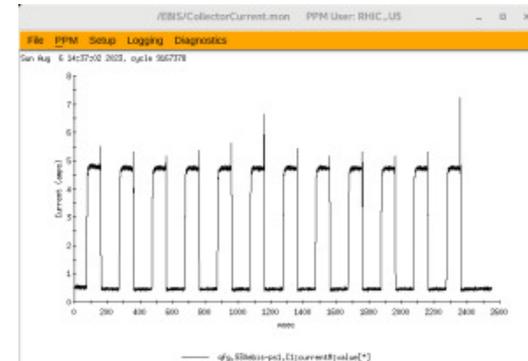
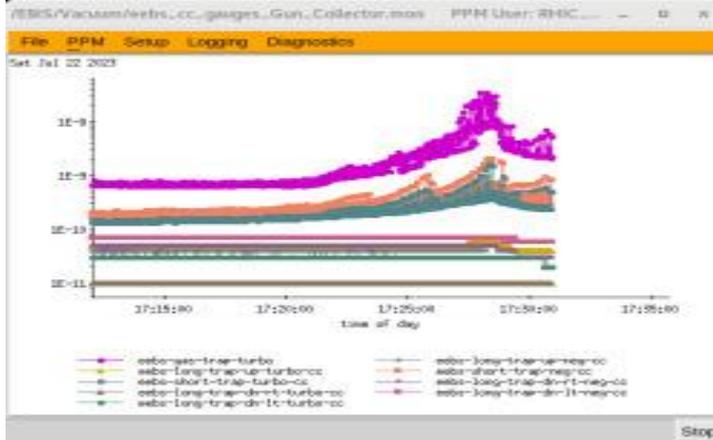
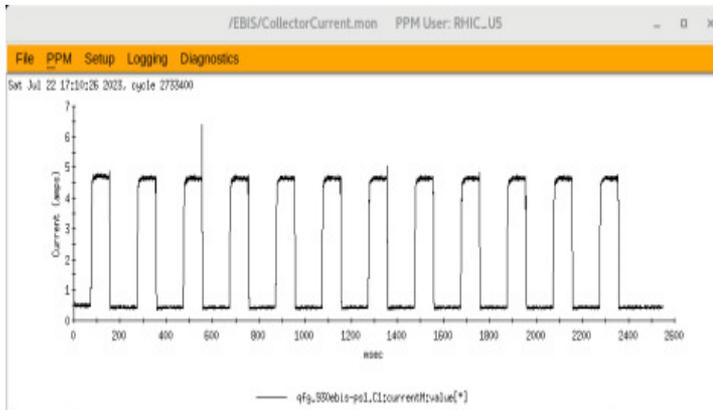
Issues and Challenges Found during First Seven Months of Extended EBIS Operation

- ExB discharges in gas trap region cause pressure rise and limit Au³²⁺ ion beam intensity and period of operation at 5 Hz and 12 ion pulses for super cycle (6.6 s) (it was found in July 2023)
- Life-time of new oxide cathode is shorter than initially expected, probably, in the range of 4-5 months (it was found in October 2023).

ExB Discharges in Gas Trap Region

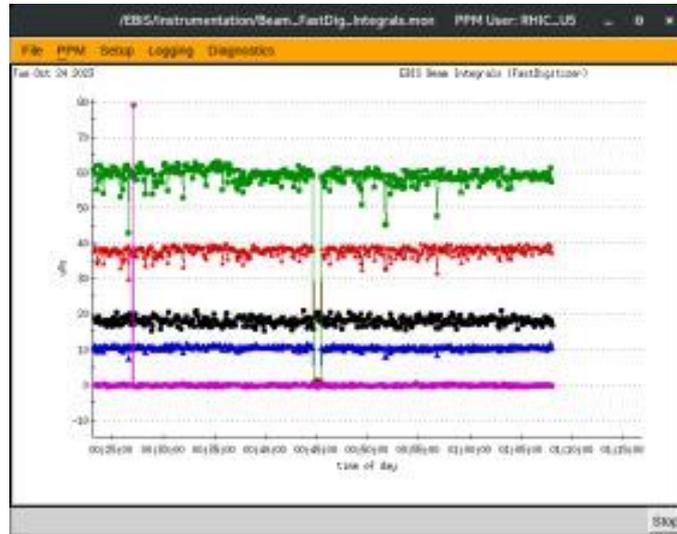
Lower DT potentials in those traps

High DT potentials in gas and short traps

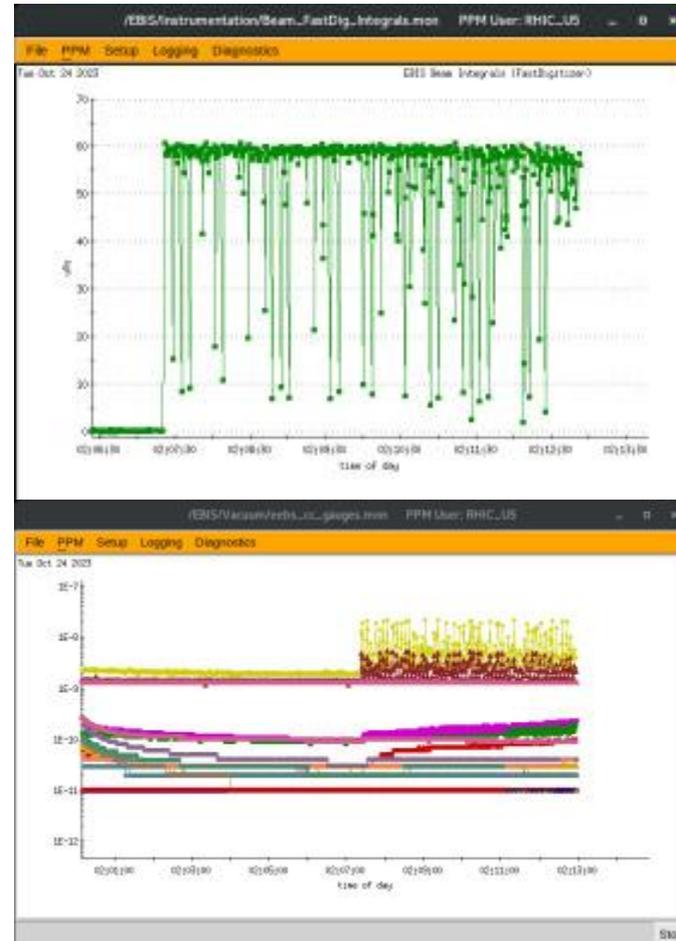


Challenge of 12 Au³²⁺ Pulses at 5 Hz

1 Au pulse

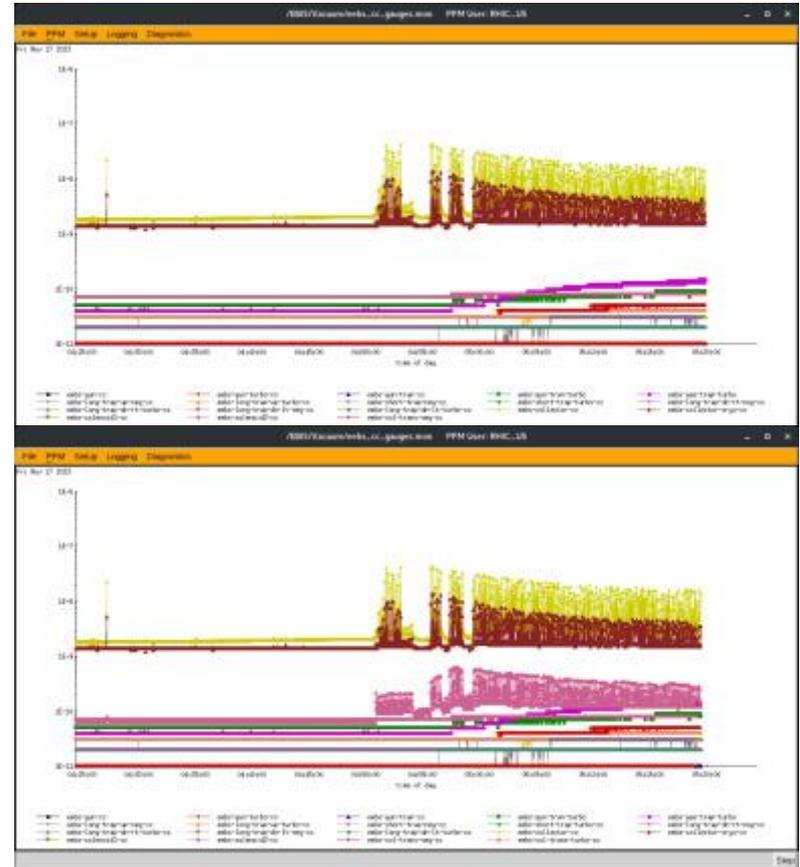
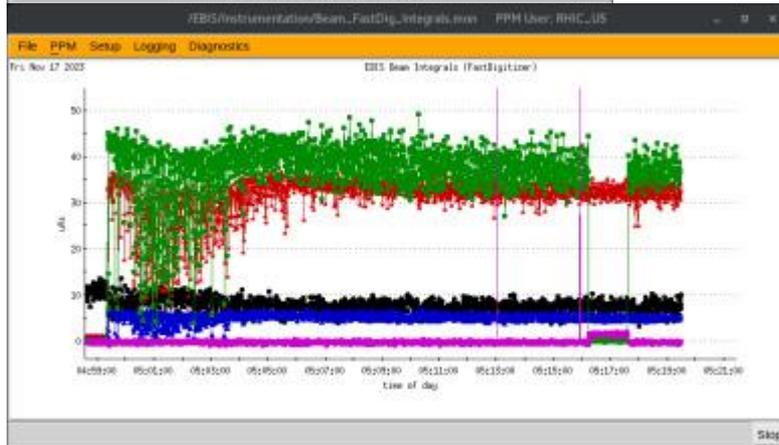
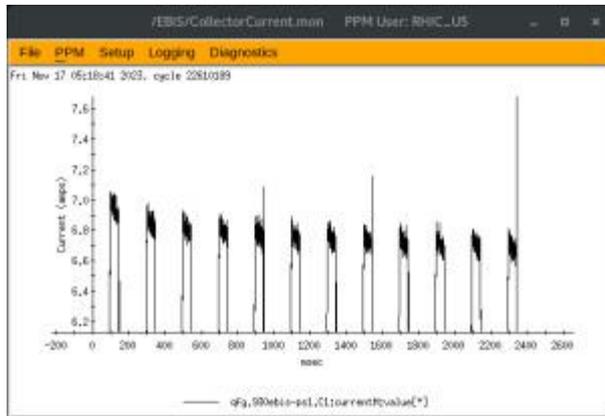


12 Au pulses



The Best (So Far) Run of 12 Au32+ P/SC at 5 Hz

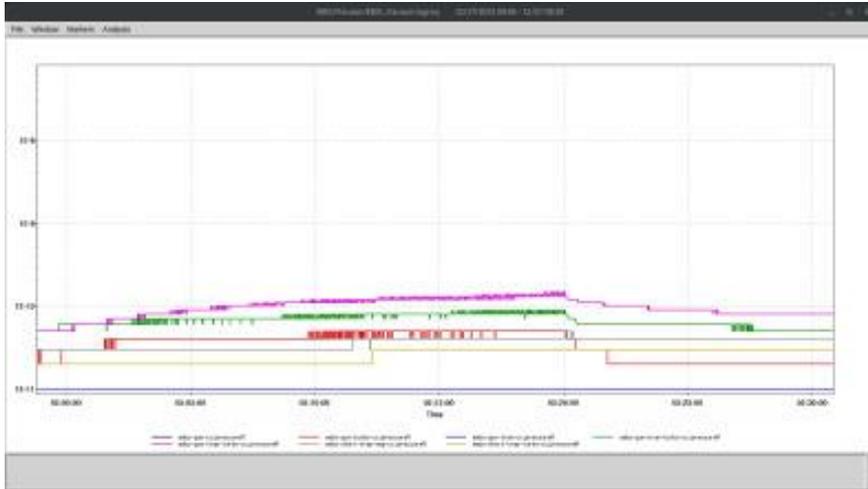
6.5A e-beam, 33-40 μVs at FC96 (1.5-2.0 μVs at XF108), 20 min run (Nov 17, 2023)



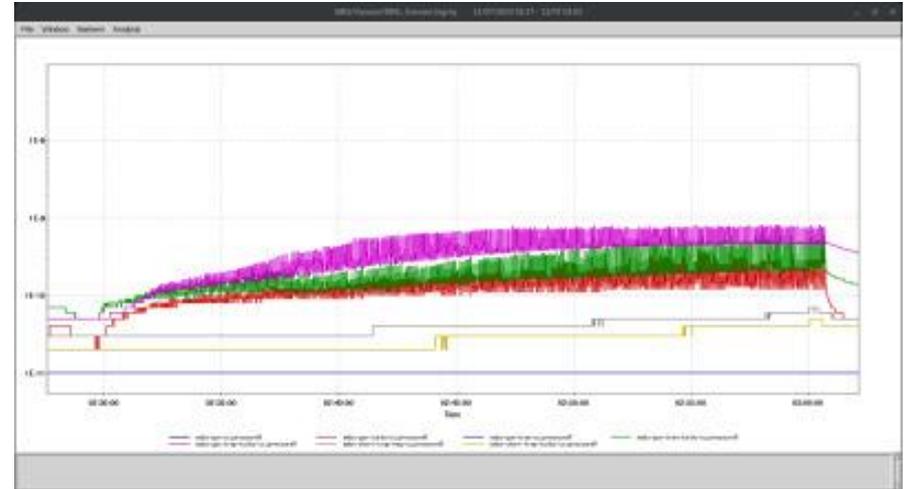
- Good Au32+ output for RHIC EBIS (within few years of decommissioning) was $\sim 3.5\text{-}4.2 \mu\text{Vs}$ at XF108
- Au32+ output for EEBIS is about factor 2 lower so far

Similar DT Potentials, Only Different Magnetic Coils

Nov 17, 2023



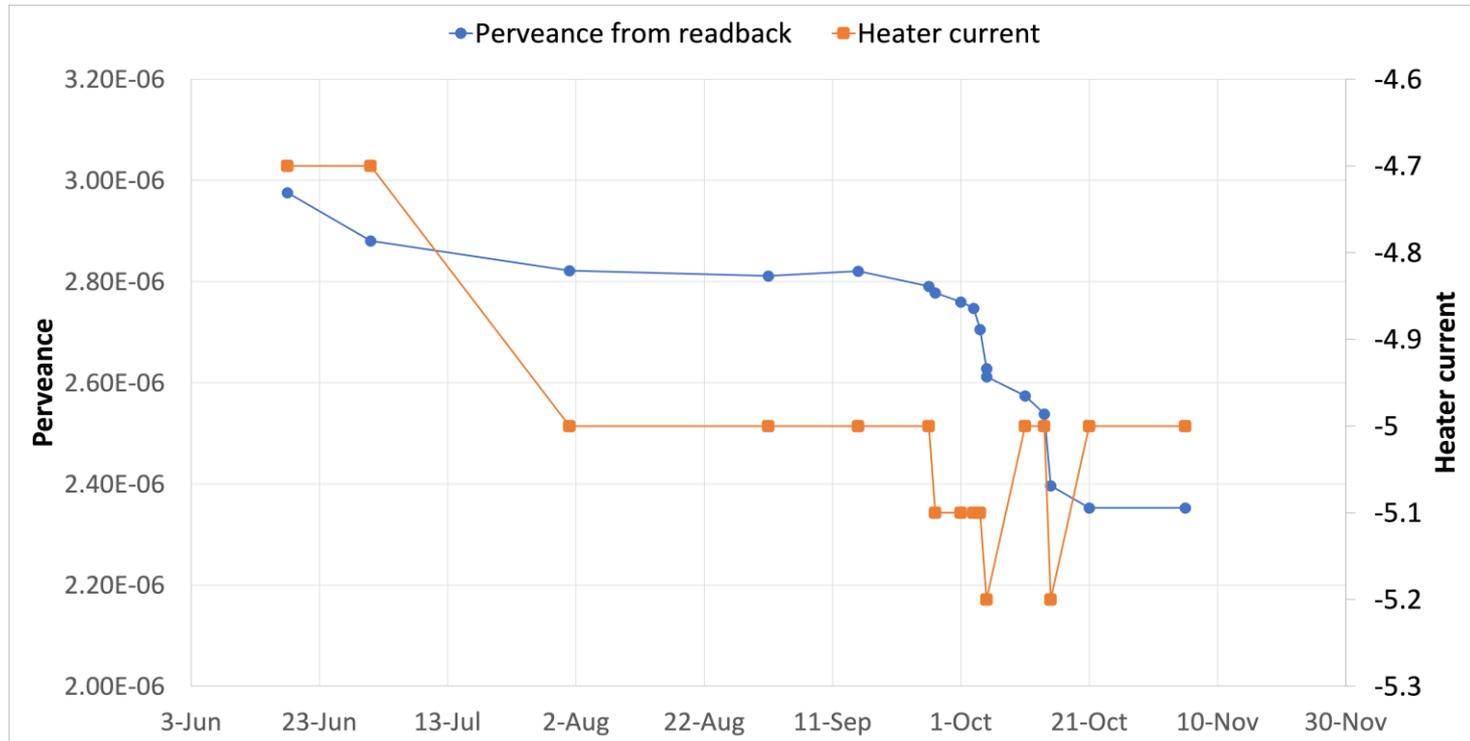
Nov 7, 2023



The same horizontal and vertical scales for both plots.

Oxide E-gun Cathode Life-Time Issue

E-gun perveance timeline



- Cathode was installed on May 30, 2023, activated on June 13, 2023
- Initial e-gun perveance was measured $\sim 3 \mu\text{Pv}$, $\sim 2.4 \mu\text{Pv}$ (Nov 05, 2023)
- Cathode life-time 4-5 months
- Most likely, Oct-Nov 2023 Au32+ tunes were affected by cathode degradation.

12P/SC 5Hz Au Performance Ramp Up Approach

- There is a limitation of 12P/SC 5Hz Au³²⁺ performance related to ExB discharges in gas trap
- Opening and refurbishing of gas trap would need about 2 months of EEBIS downtime
- Probably it is good to combine above task with polarized 3He installation as we will need to take out of solenoid gas and short trap vacuum chambers anyway at that time
- Installation of short trap Behlke HV electronics should allow us to ramp up Au³²⁺ (and other species) intensity up to 40-50% (one can expect about **3.0 μ Vs** at XF108 (it was **3.6-4.2 μ Vs** in the “golden era” of RHIC EBIS operation)
- If RHIC require higher Au³²⁺ intensity this year, than opening and refurbishing gas trap **is a must!**
- **2 months time slot** should be allocated for that within NSRL operation timeline prior to RHIC Au operation will start.

Next Steps

December 2023:

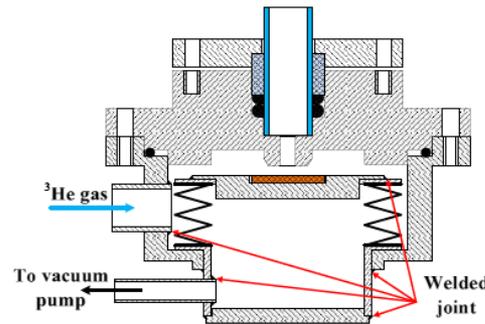
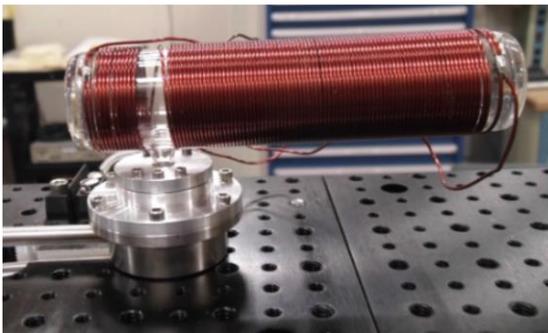
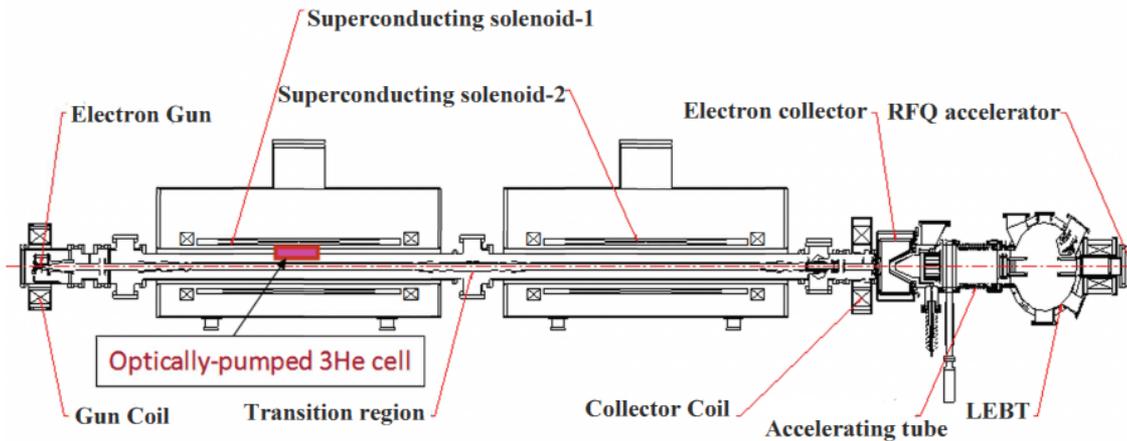
- **Unpolarized 4He^{2+} ion beam will be used to test the chicane beam line and polarimeter**
- **Pumping speed measurements**
- **Replacement of e-gun cathode**
- **Installation of the Short Trap HV extraction system**
- **Combined short and long trap operation for increased Au^{32+} intensity (as soon as feasible).**

Future upgrades will include:

- installation of the new electron collector power supply – 2 months slot is required (when ???), would be good to combine with refurbishing of gas trap section
- a high field 3He polarization setup in the bore of the first superconducting solenoid, a second gas injection valve and gas handling system, and a gas manifold for remote automatic gas switching – Oct – Nov 2024
- refurbishing of gas trap section to eliminate ExB discharges – Oct – Nov 2024.

${}^3\text{He}^{2+}$ Polarized Ion Source Development

Developments Towards $^3\text{He}^{2+}$ Polarized Ion Source (BNL-MIT Collaboration)



Left: "Open" ^3He gas cell (30 mm in diameter) with the isolation (filling) valve attached

Right: A new custom built pneumatic (bellows based) isolation valve

Top: Cryogenic ^3He purification and filling system

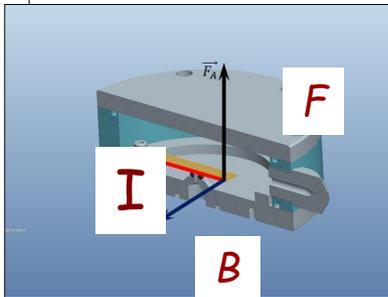
Bottom: Vessel filled with charcoal granules is attached to the cold head of the cryopump

Fast Pulsing Gas Valve

“Electro-magnetic”, $[I \times B]$ valve operation principle

Lorentz (Laplace) force moves the flexible conducting plate in the high ($\sim 3-5$ T) magnetic field.

For $I=10$ A, $L=5$ cm, $F=2.5$ N. Current pulse duration $\sim 100-500$ μ s



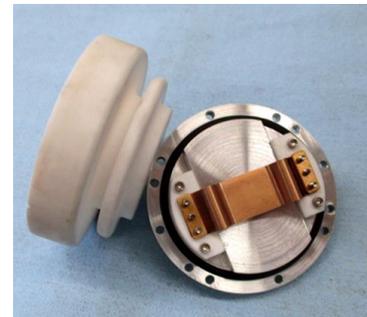
$$d\vec{F}_A = I [d\vec{l} \times \vec{B}]$$



Prototype of the pulsed (isolated valve) for the gas injection to the extended EBIS.

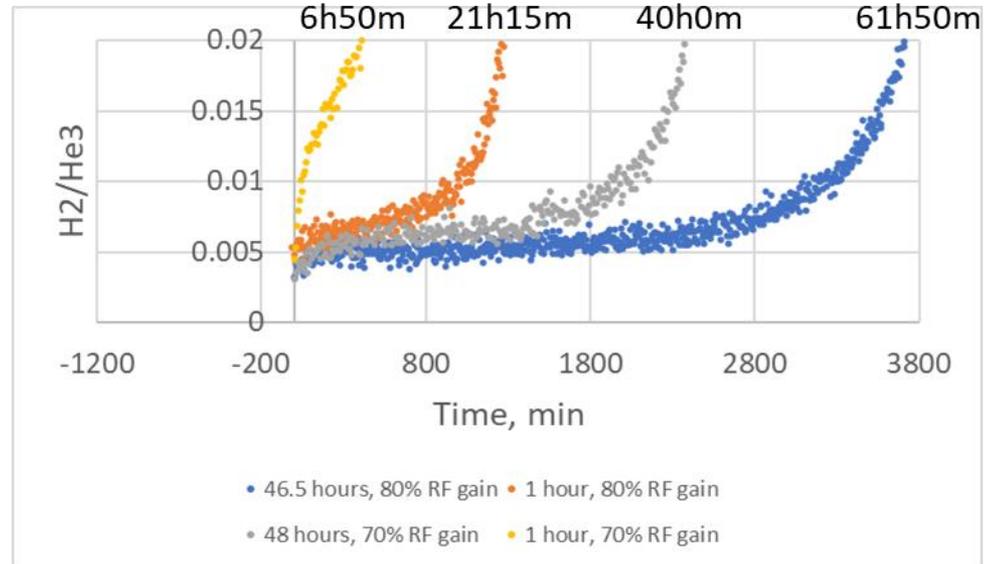
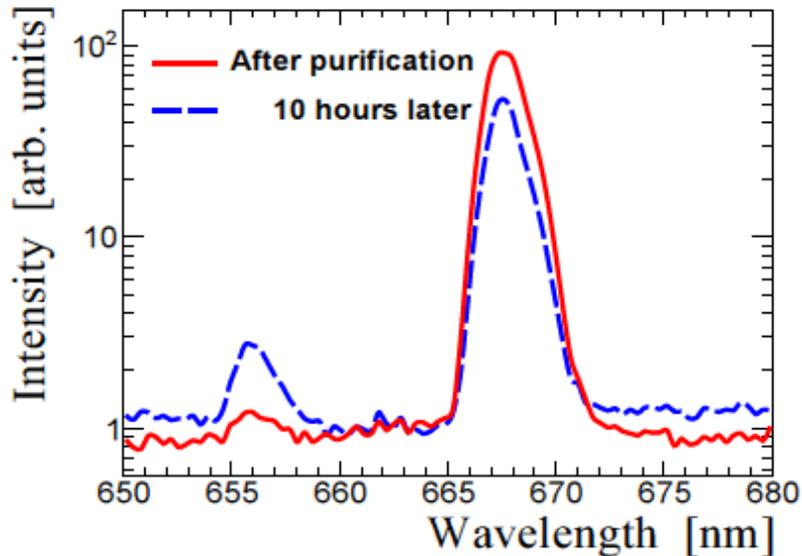


Pulsed valve for Un-polarized gas Injection to the EBIS



This valve is now in operation at Extended EBIS for about 7 months to generate 4He^{2+} unpolarized beam for NSRL.

Recent Progress with 3He Purification System

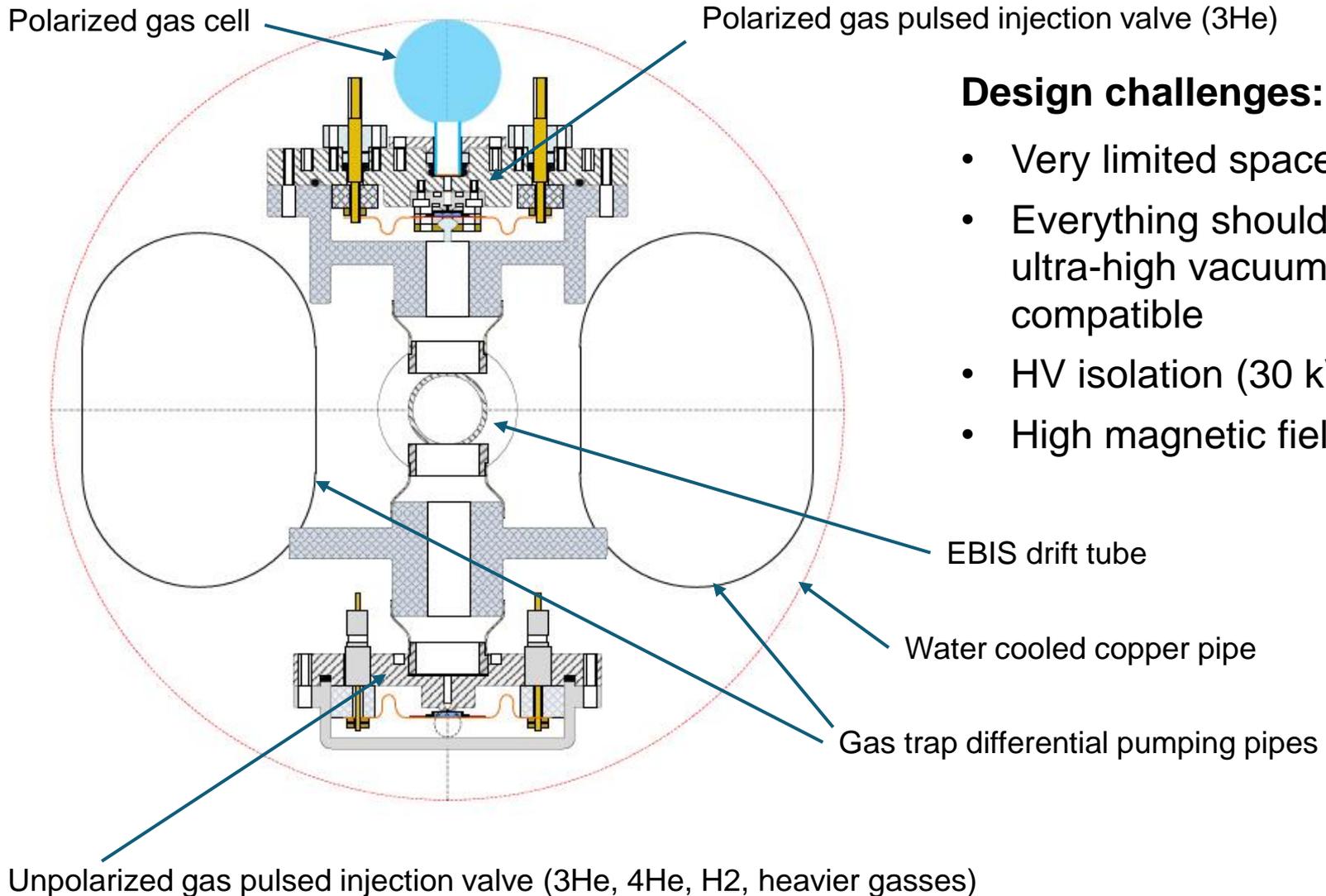


3He contamination monitoring: The hydrogen Balmer-alpha line intensity at 656 nm is strongly reduced, < 0.4% (red solid line), relative to the 668 nm 3He line after the cryogenic purification cycle (cooling to 10 K) and increased to ~3% (dashed blue line) after 10 hours of RF discharge with the isolation valve closed.

Dependence of 3He purity life-time on RF discharge power and duration of purification time (< 2% criteria for ratio of hydrogen to helium line intensities was used as upper limit for purity degree of 3He for reaching about 80% polarization.

A. Zelenski, G. Atoian, E. Beebe, S. Ikeda, T. Kanesue, S. Kondrashev, J. Maxwell, R. Milner, M. Musgrave, M. Okamura, A.A. Poblaguev, D. Raparia, J. Ritter, A. Sukhanov, S. Trabocchi, Optically pumped polarized 3He⁺⁺ ion source development for RHIC/EIC, Nuclear Inst. and Methods in Physics Research, A(2023), doi: <https://doi.org/10.1016/j.nima.2023.168494>.

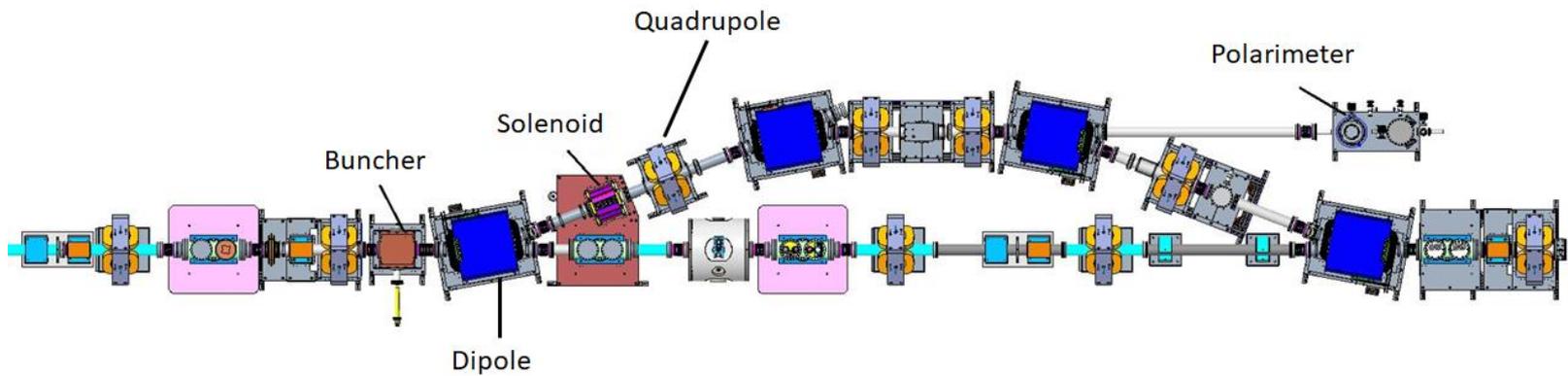
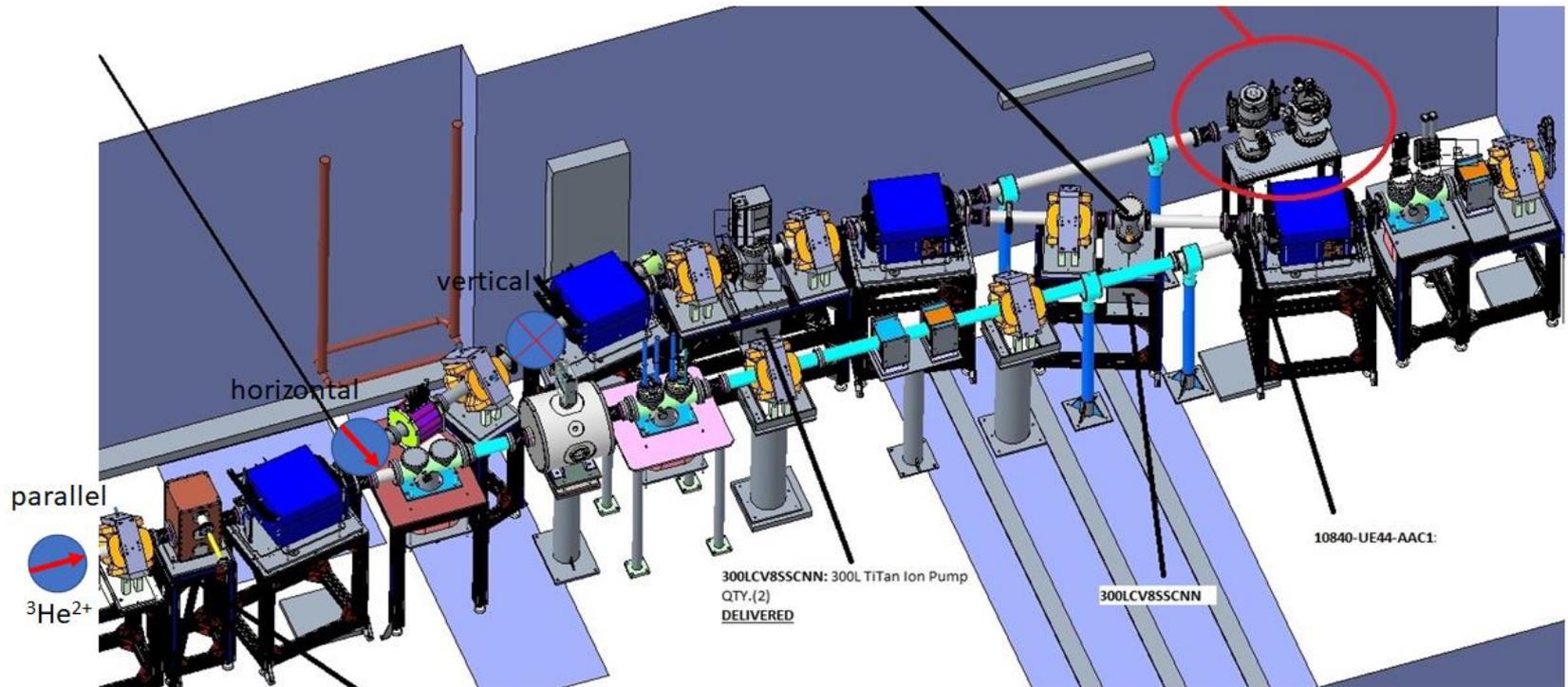
Polarized and Unpolarized Gas Injection into Extended EBIS



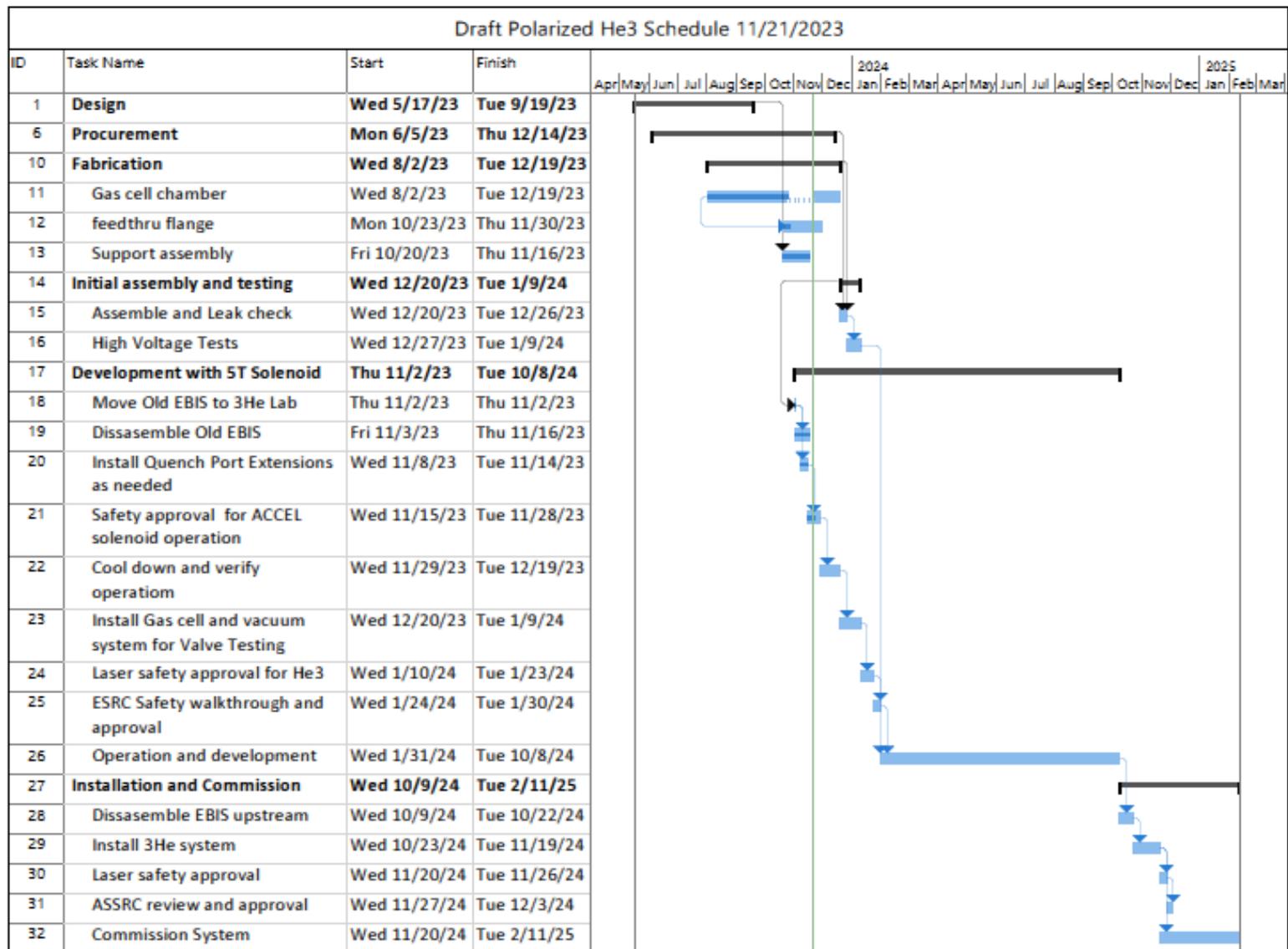
Design challenges:

- Very limited space
- Everything should be ultra-high vacuum compatible
- HV isolation (30 kV)
- High magnetic field (5 T)

Chicane Ion Beam Line for Spin Rotation



Polarized 3He Development and Installation Schedule



Future Main Tasks and Timeline

- 1) Replacement of e-gun cathode – Dec 2023
- 2) Testing of chicane beam line with unpolarized 4He ion beam - Dec 2023
- 3) Testing and optimization of 3He polarization in 5T magnetic field and preparation for its installation into EEBIS – Jan – Oct 2024
- 4) Installation of 3He polarization section into EEBIS – Oct – Nov 2024
- 5) Commissioning of 3He polarized ion beam – Dec 2024
- 6) Optimization of 3He polarization and intensity – Jan 2025
- 7) Refurbishing of gas trap section to eliminate ExB discharges – Oct – Nov 2024
- 8) Installation of new collector power supply – Oct – Nov 2024

NSRL plan to run continuously from January 8 till June 30, 2024.
Detailed RHIC 2024 schedule is not known yet.

Depending on RHIC and NSRL priorities, tasks 4) – 8) can be postponed till RHIC shutdown to reduce EEBIS downtime for RHIC and NSRL.

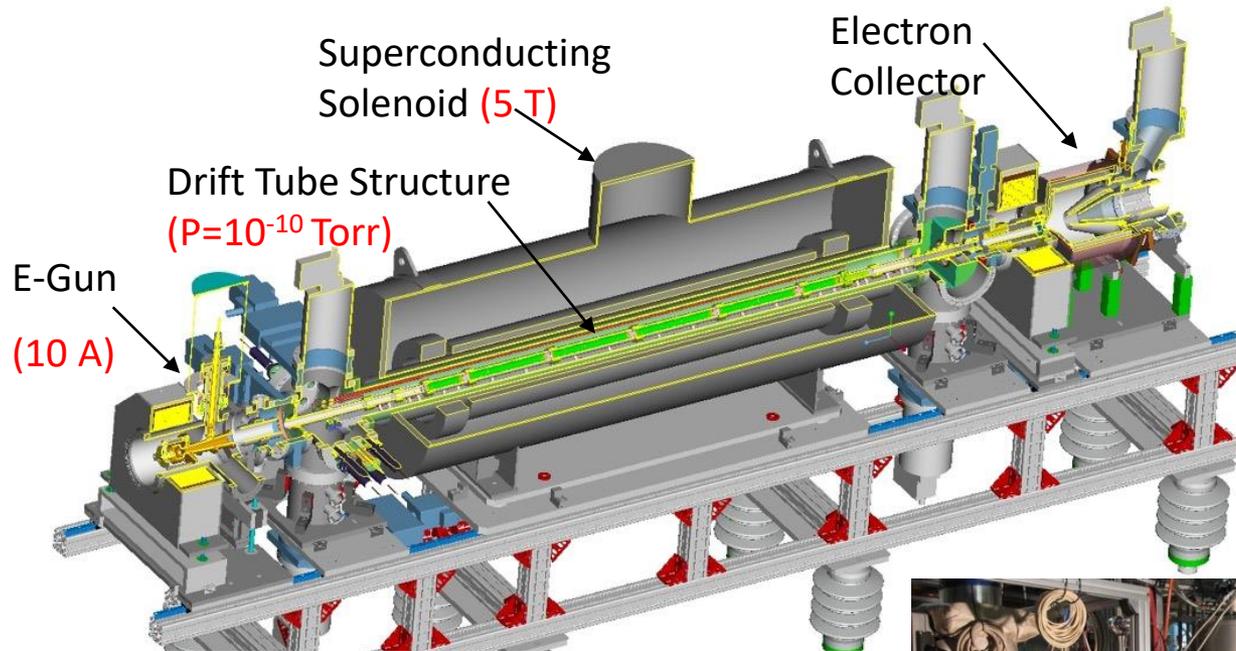
Summary

- Design of Extended EBIS is based on success of its predecessor, RHIC EBIS, but has multiple new features that make it a new, more advanced ion source.
- Extended EBIS was installed at the accelerator location in December 2022 - March 2023.
- Extended EBIS was commissioned and became operational quite fast (within 1 month only).
- Extended EBIS provided **4He²⁺, C⁵⁺, O⁷⁺, Si¹¹⁺, Ti¹⁷⁺, Ti¹⁸⁺, Fe²⁰⁺, Nb²³⁺, Ag²⁹⁺, Tb³⁵⁺, Ta³⁸⁺, Au³²⁺, Bi⁴³⁺** ion beams with required intensity for NSRL operation starting from April 22, 2023 till NSRL end-year shutdown break on December 1, 2023 (total operation period more than 7 months so far).
- It was found that ExB discharges in gas trap region limit performance of EEBIS with 12 pulses per super cycle at 5Hz rep-rate Au³²⁺ operation
- It was found that life-time of new oxide cathode is shorter than initially expected, but still adequate for Extended EBIS operation.
- Elimination strategy for ExB discharge limitation will be defined by RHIC operation priorities and will take into account RHIC and NSRL next year operational schedules.

RhicEBIS

Existing development and operation

RhicEBIS Source Assembly



Parameter		RHIC EBIS
Max. electron current	$I_{el} =$	10 A
Electron energy	$E_{el} =$	20 keV
Electron density in trap	$j_{el} =$	575 A/cm ²
Length of ion trap	$L_{trap} =$	1.5 m
Ion trap capacity	$Q_{el} =$	1.1×10^{12}
Ion yield (charges)	$Q_{ion} =$	5.5×10^{11} (10 A)
Yield of ions Au ³²⁺	$N_{Au^{32+}} =$	3.1×10^9 [1.9×10^9]



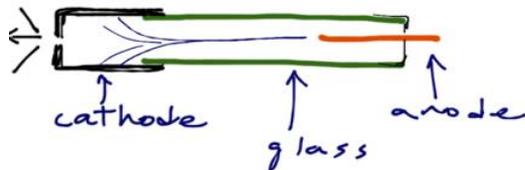
$$N = \kappa * I_e * L_{trap} * E_e^{-0.5}$$

External 1+ ion production to feed the EBIS trap

Slow injection (accumulation mode)

HCIS

Hollow cathode ion source



EBIS is a “charge breeder” of the injected 1+ ions

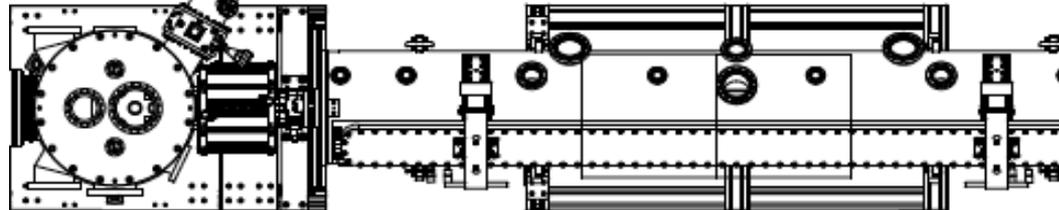


1+ Ions
into EBIS

Cu source

U source, then Au

RFQ



Extended EBIS in Test Lab

