Extended EBIS (EEBIS) Status and Commissioning Plan

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Polarized 3He2+ source development is made in a collaboration between BNL and MIT

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Motivation for a New EBIS at Brookhaven National Laboratory (BNL)

RhicEBIS was commissioned in 2009 and since then has provided ions for the RHIC and NSRL programs. An upgrade is underway to provide increased capabilities.

- Provide increased intensities of Au^{32+} and other species for the Relativistic Heavy Ion Collider (RHIC)
- Provide (polarized) $^{3}He^{2+}$ for a future electron-ion collider (EIC) with near term feasibility studies at RHIC
- Provide H+ from the EBIS, reducing or eliminating the need to use the TVDG or 200Mev 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 $^3He^{2+}$ in an EBIS

Polarized 3He ions offer a “polarized neutron beam for RHIC and a future EIC. The use of an EBIS offers the following advantages:

- 3He 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 is capable of producing a high ratio of $^3He^{2+}$ / $^3He^{+}$
- $^3He^{2+}$ can be transported 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.

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What was the limitation of RhicEBIS considering $^3He^{2+}$ production?

RhicEBIS was developed primarily as a charge state multiplier using external injection of 1+ ions from external sources.

A simple gas injection system was incorporated using an external gas reservoir and a piezoelectric pulsed valve feeding a long capillary gas injection line into large diameter drift tubes.

This allowed production of modest amounts of highly charged ions. Higher intensities could be produced if lower charge state was required. By "flooding" the EBIS with neutral Helium gas from the typical $3x10^{-10}$mb operating pressure to about 10^{-7}mb high intensities ion intensities could be extracted. The consequence for a polarized $^3He^{2+}$ program were:

- The ratio of $^3He^{2+}$ to $^3He^{1+}$ would be very low. (with $^3He^{2+}$ intensities well below requirements)
- Polarization would be reduced as ^3He gas diffused throughout the EBIS before ionization
- Flooding of the EBIS with Helium is problematic for rapid switching to high ion charge states required by NSRL and the consumption rate of polarized ^3He gas would be very high.

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The Extended EBIS

Two identical unshielded superconducting solenoids are used in the "Extended" EBIS design.

The upstream solenoid contains most of the new features for the polarized 3He ion production:

- **gas injection / ionization cell operating at pressures up to 5x10^{-6} mb (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

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Extended EBIS Operating Modes:

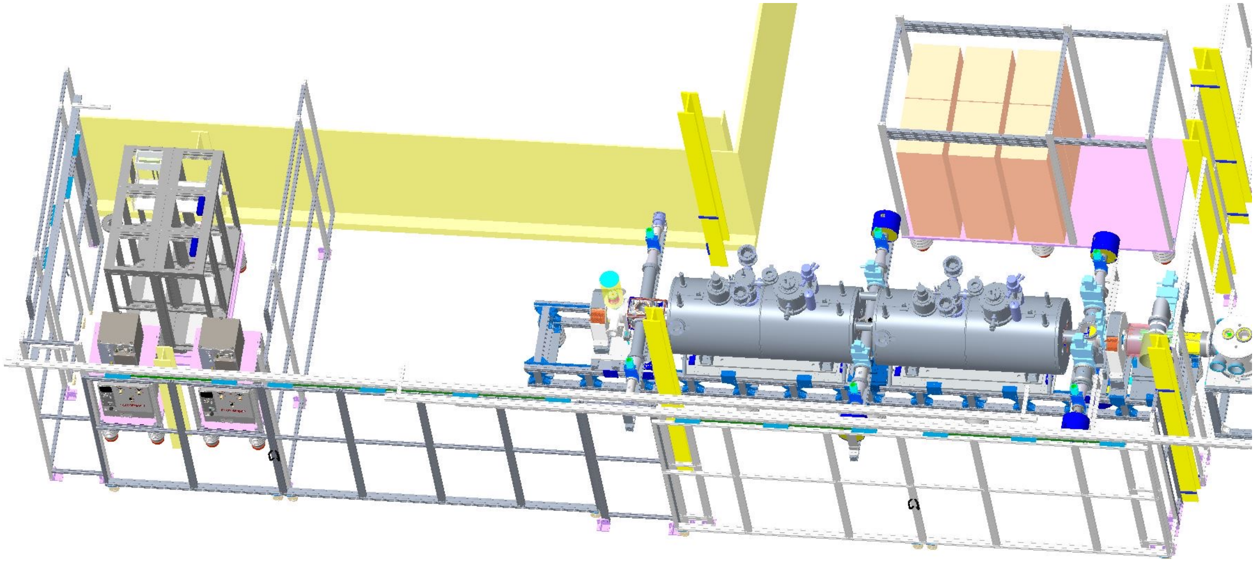
RHIC Au^{32+}: External Ion injection --- Combined Long and short trap

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

^3He: Internal gas injection; $^3He^{2+}$ extraction from Long Trap

Extended EBIS Installation at Accelerator with High Voltage enclosure



Left: Solid State Electron collector supply
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)

RhicEBIS

Existing development and operation

Expected Extended EBIS intensities based on RhicEBIS performance

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

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

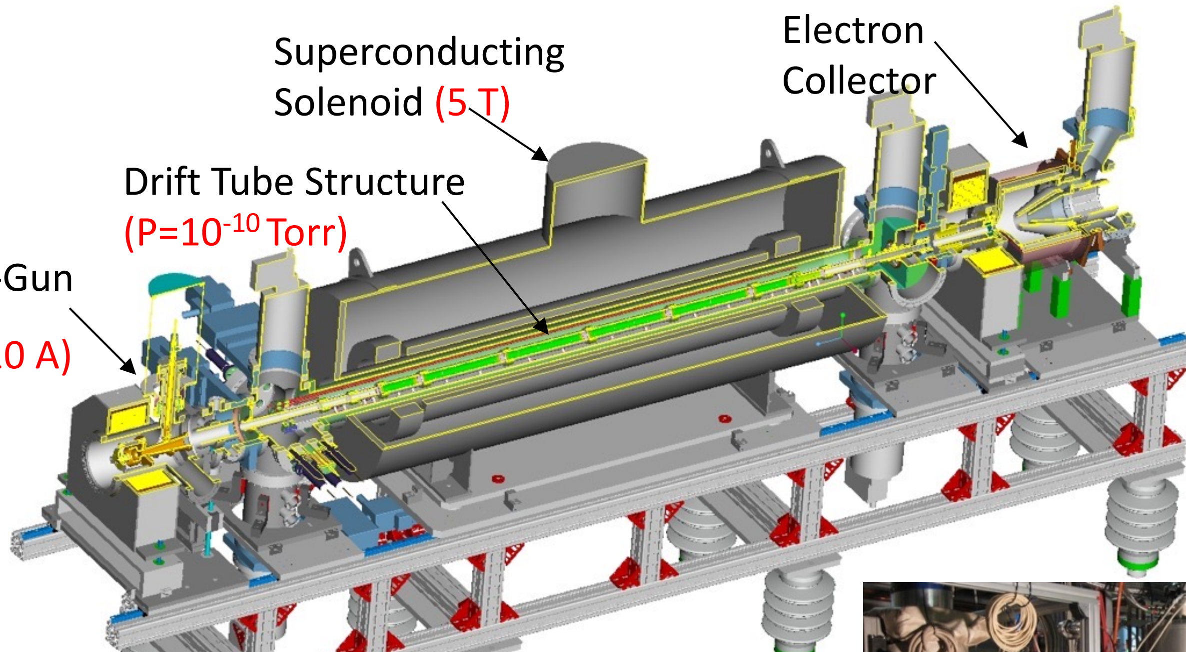
Intensity Estimates for EBIS upgrade (at Extended EBIS exit)

He^{2+} ~ 2.5 - 5 x 10^{11} ions/pulse

H^{+} ~5 – 10 x 10^{11} ions/ pulse

Au^{32+} ~2.6x10^{9} ions/pulse (1.4-1.5 times the RhicEBIS output)

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}=	1.1x10^{12}
Ion yield (charges)	Q_{ion}=	5.5x10^{11} (10 A)
Yield of ions Au^{32+}	$N_{Au}{}^{32+}$=	3.1x10^9 [1.9x10^9]

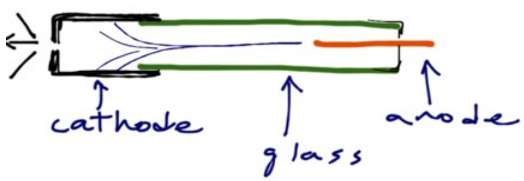
$$N = \kappa * I_e * L_{trap} * E_e^{-0.5}$$

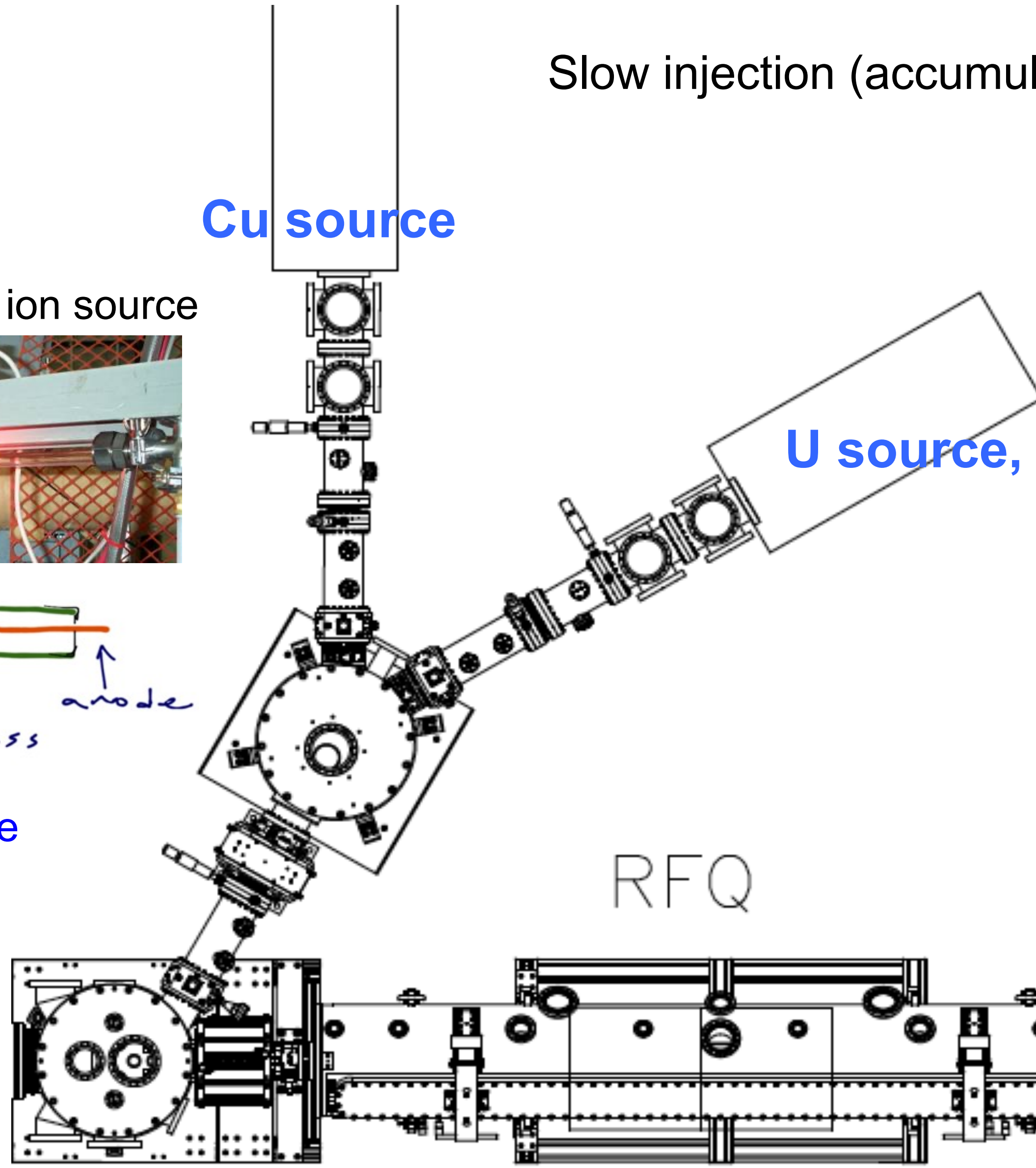
External 1+ ion production to feed the EBIS trap

Slow injection (accumulation mode)

HCIS

Hollow cathode ion source



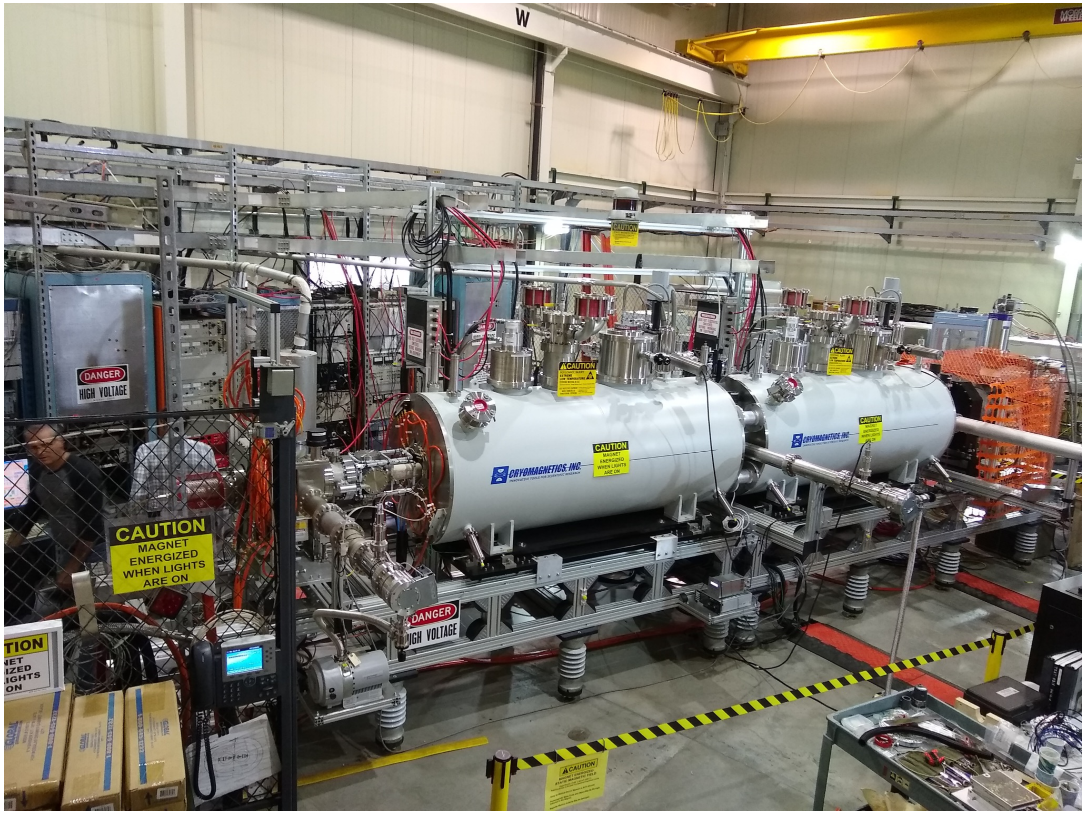


EBIS is a "charge breeder" of the injected 1+ ions

1+ Ions into EBIS

Extended EBIS Component Development

Extended EBIS in Test Lab



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Extended EBIS Features

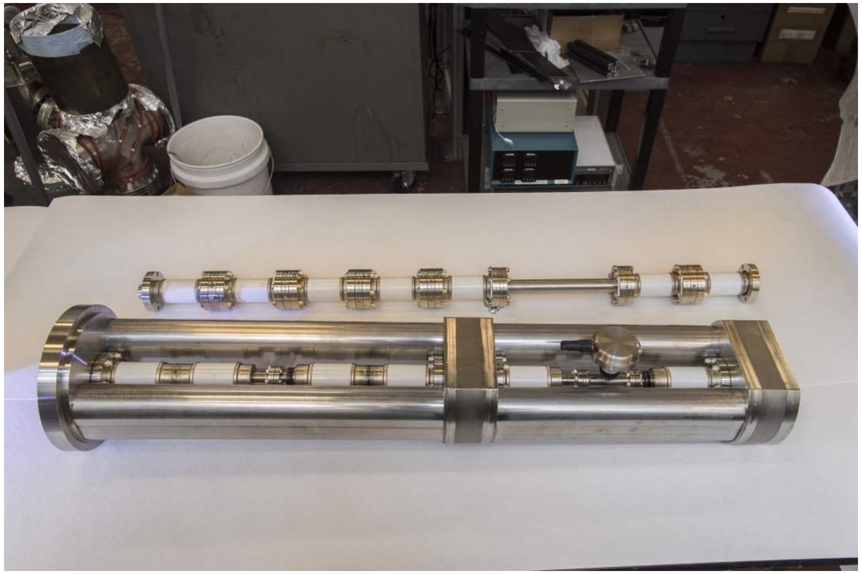
High-capacity NEGs + Turbo Pumping:
Provide high pumping speed where needed.   Pulsed Hydrogen pumping speed measurement system developed to monitor NEG status.

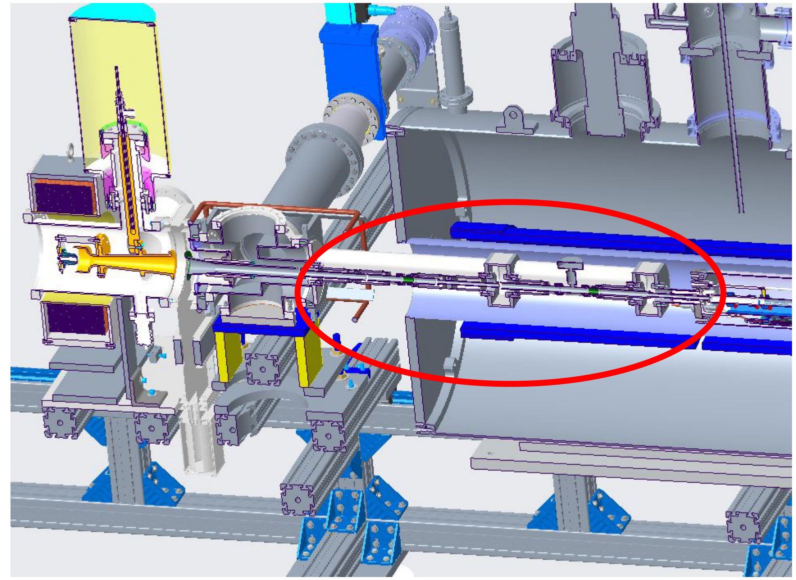
Alignment during EBIS electron beam propagation:
HV cage is partitioned and HV connections are protected such that EBIS experts can enter the HV cage for initial mechanical magnetic alignment

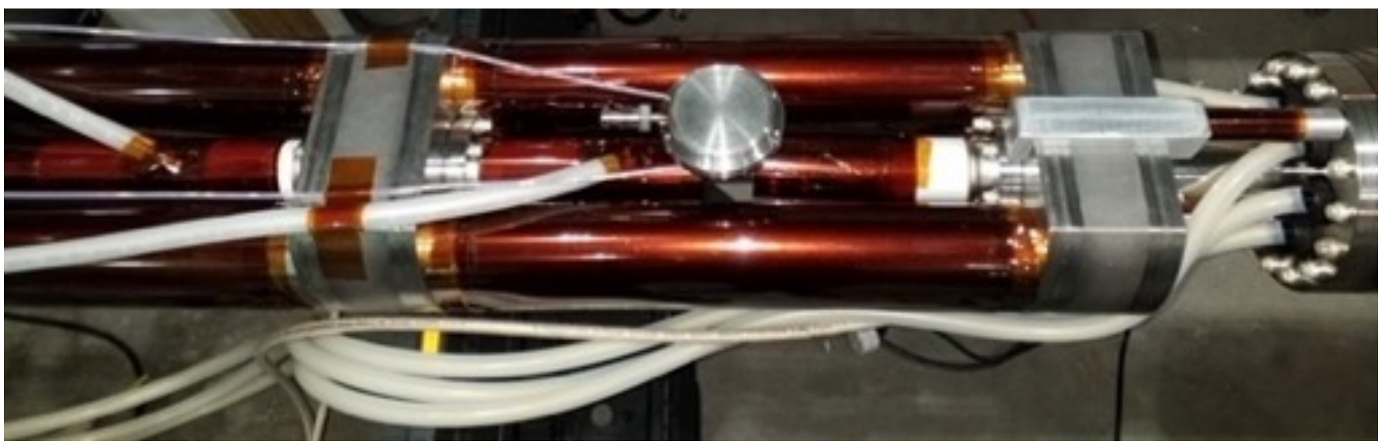
New Electron Gun Cathode:
3M lower temperature oxide cathodes. improved reliability and lifetime, improved beam quality, domestically available, important for BNL and our other colleagues at ANL and FRIB

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

Gas Cell with pump out manifold and external drift tube connections







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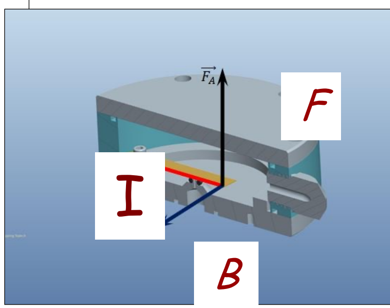
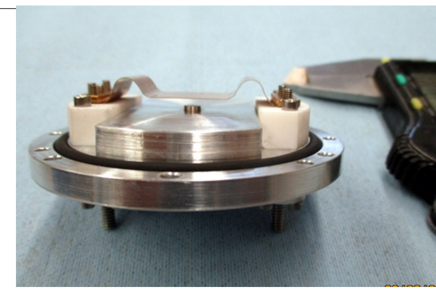
Fast Pulsing Gas Valve

"Electro-magnetic", [IxB] valve operation principle

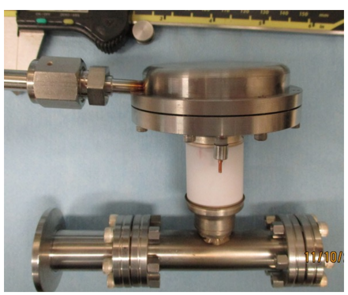
Lorentz (Laplace) force moves the flexible conducting plate in the high (~ 3-5 T) magnetic field.
For I=10 A, L=5 cm, F=2.5 N. Current pulse duration ~100-500 us



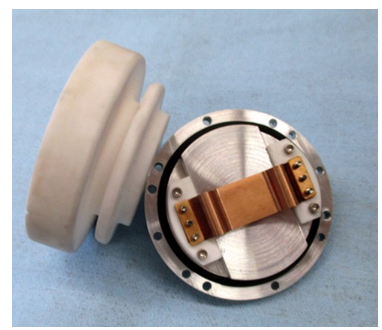
$$d\overrightarrow{F_A} = I[d\vec{l}\,\vec{B}]$$



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

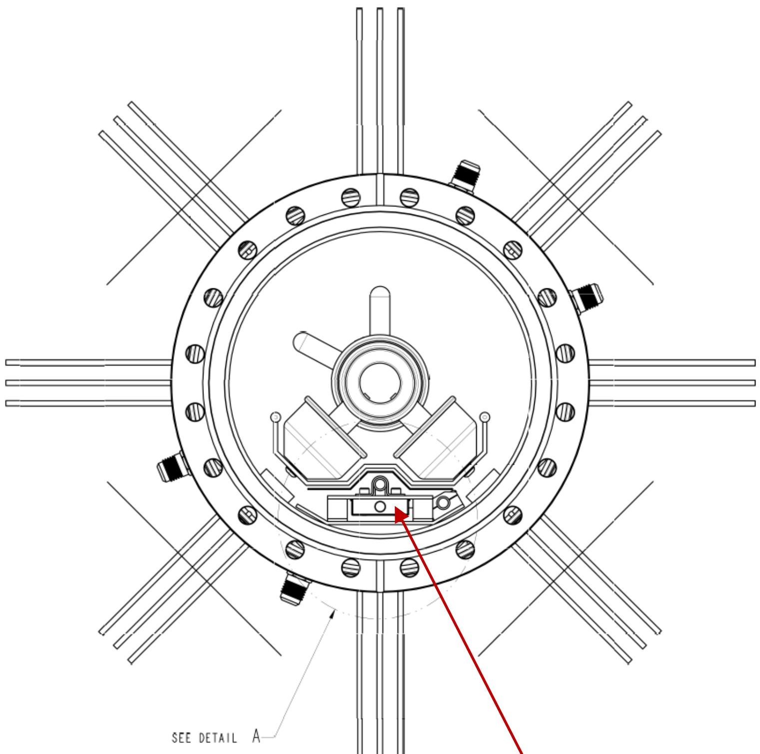


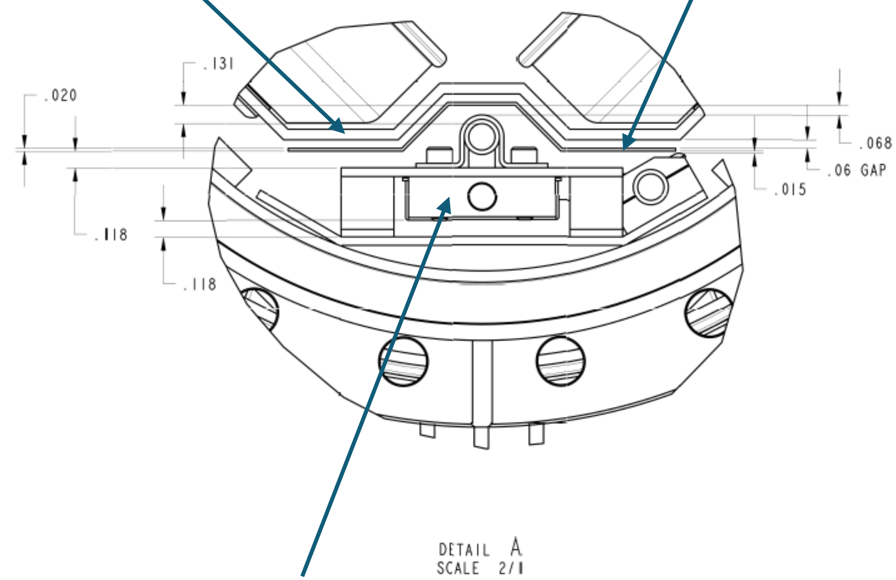
Pulsed valve for
Un-polarized gas
Injection to the EBIS



Upstream “Short Trap” Drift Tubes (right foreground)
Two module Zao high capacity NEG pump unit (left foreground)

Design of ZAO NEG Linear Pumping System





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

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Downstream Drift Tubes and Custom Linear NEG Module
(Installed for May 2022)

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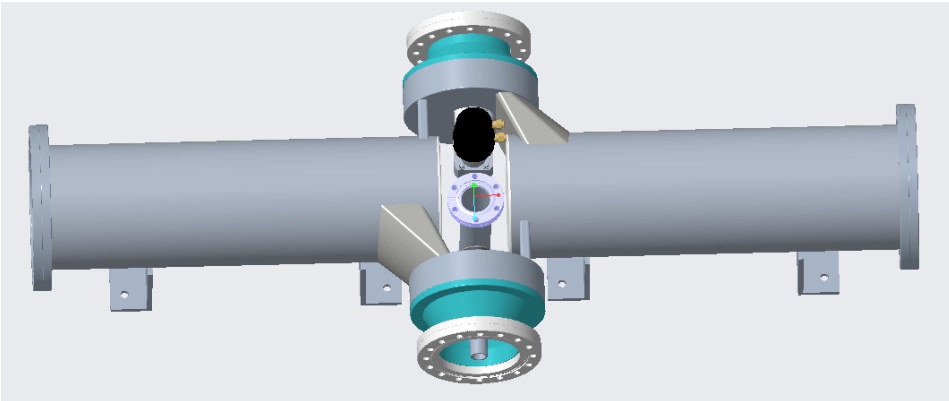
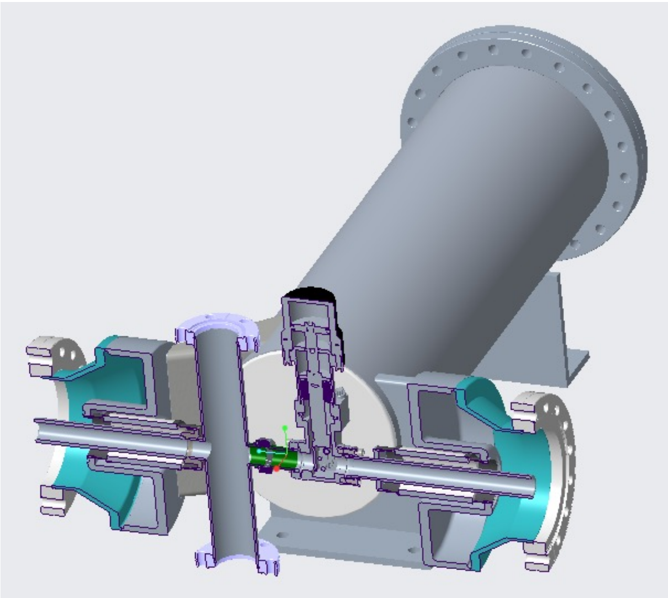
Center Vacuum Chamber

Includes port for double sided quadrant detectors

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.

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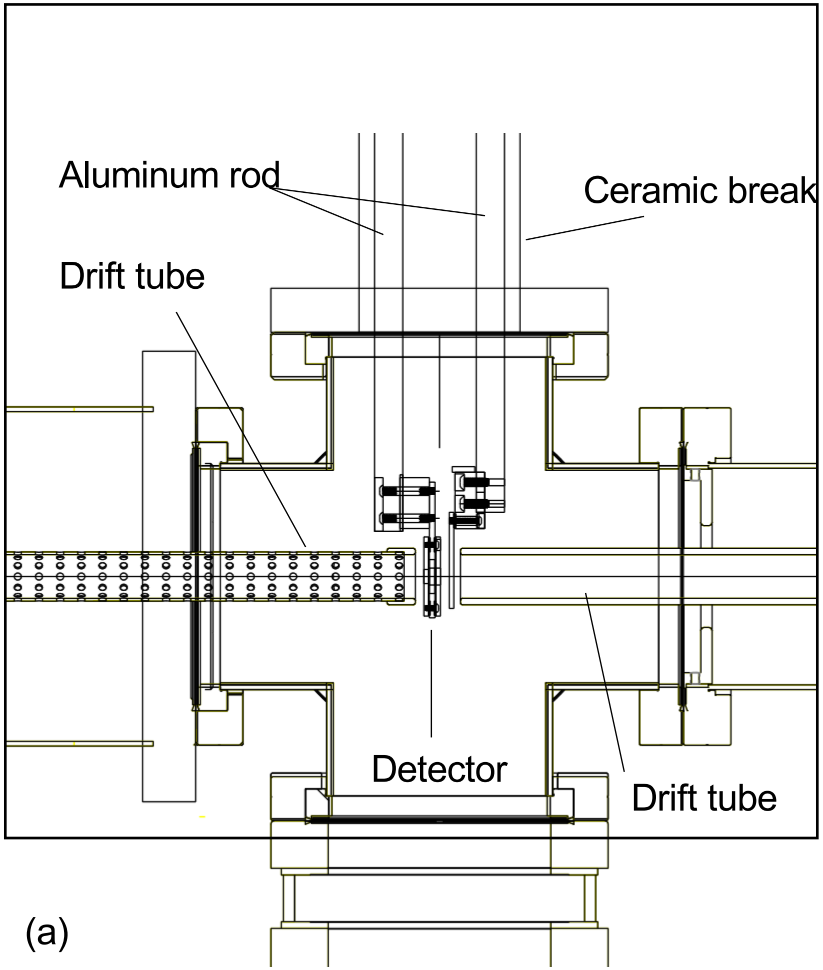
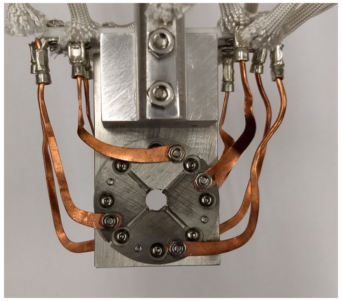
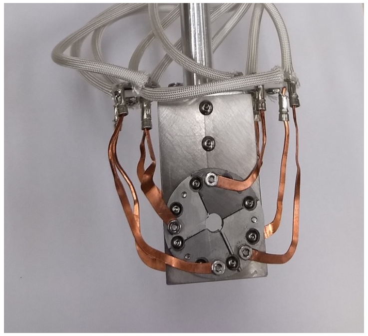
Quadrant electron beam detectors



(a)



(b)

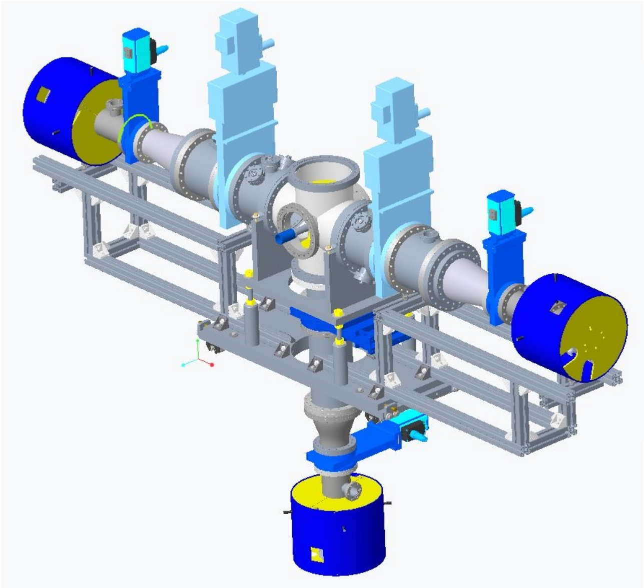


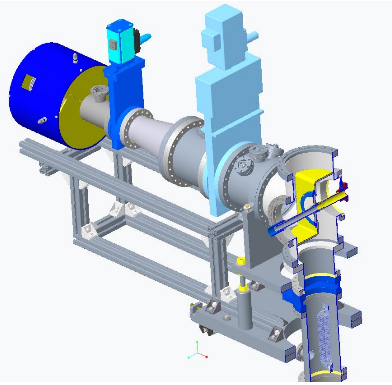
(c)

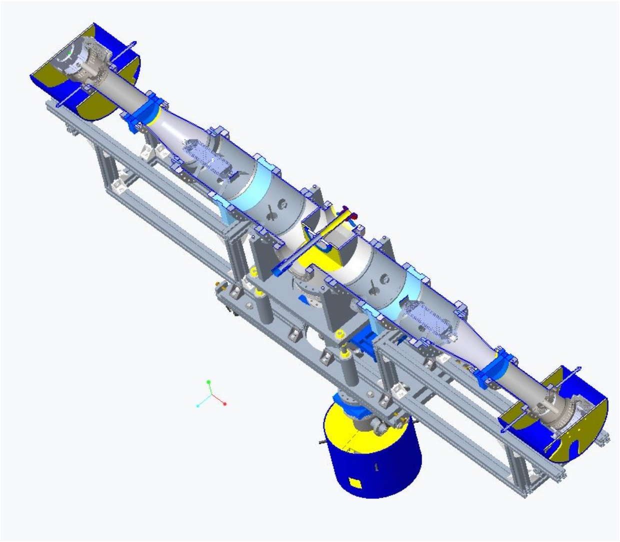
Independent quadrant detectors were installed in a temporary central chamber between the two superconducting solenoids. They are useful during electron beam alignment procedures and used to detect primary electrons as well as electrons reflected or backscattered from the electron collector.

Used in tests through Sept 2021
(To be modified and re-installed in new Center Vacuum Chamber for future investigations).

Vacuum chamber with differential pumping baffles between downstream ionization trap and the electron collector.







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

Electron Beam Results in the Test Lab

May 2022: Complete drift electrode and vacuum system installed.

1) High efficiency gas injection system
2) Upstream short trap (custom NEG not yet activated)
3) differential pumping system and gate valve between solenoids
4) downstream long trap (custom NEG not yet activated)
5) differential pumping system before electron collector

Electron beam results quickly exceeded results of the previous testing phase ending in Sept 2021, by using techniques developed in the earlier tests:

1) initial electron beam propagation using transverse coils
2) magnetic system alignment procedure
    a) low current electron beam (<1A)
    b) no transverse magnetic steering
    c) move all solenoids to eliminate e-beam losses on DTs

Good Magnetic alignment obtained; transverse coils used above ~4A e-beam

Electron Beam Results:

8.8A, 1ms pulsed electron beam (Anode power supply voltage limit)
4A, 120ms electron beam
5.2A, 50ms electron beam

June-September 2022: Ion production tests using gas injection

Gas Injection and Ion Extraction

Sept 2021 Gas injection and Ion extraction results:

1) High efficiency gas injection system
2) Upstream short trap (custom NEG activated)
3) Temporary but functioning drift tubes in the downstream solenoid.

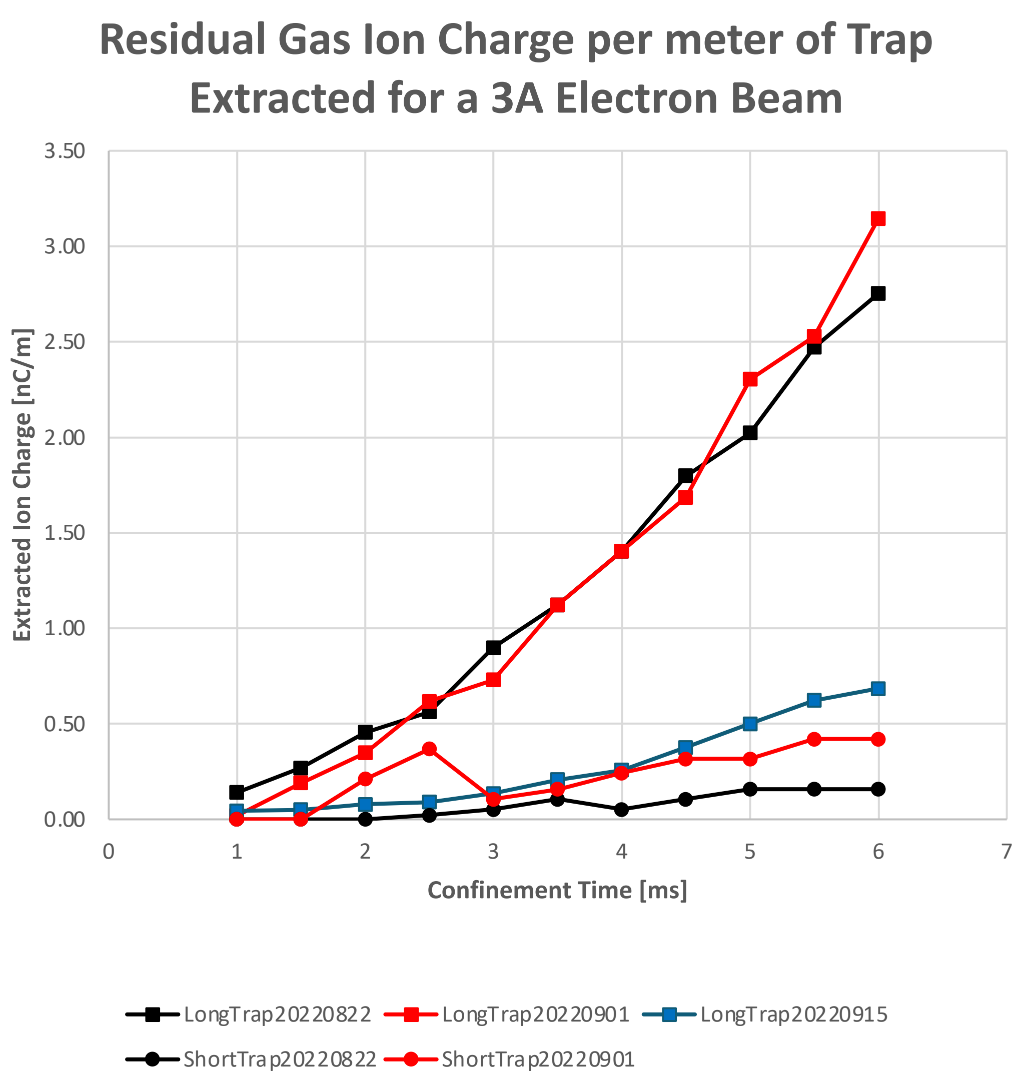
Gas injection cell, Lorentz pulsed valve, and pump out manifold were tested:

1) Helium, Argon and Hydrogen gas.
2) 3A electron beam
3) Verified low gas to migration to down stream regions
4) Ions were created in gas region and transported to traps.
5) Ions extracted to Faraday Cup after electron collector

The upstream short trap performed very well.

Downstream Long Trap trap performance matched short trap performance once several vacuum leaks were eliminated.

Long Trap Vacuum improved by leak elimination



The base pressure in the trap is indicated by the extracted ion charge of residual gas produced by the electron beam from residual gas. Initial measurements showed a base pressure about 50x higher in the long trap than the short trap.

The elimination of this "final" Long Trap region leak resulted in a vacuum improvement of a factor of 6x.

This confirmed that there was not a high voltage induced vacuum problem in the long trap.

29Jul_01Aug 2022:
Three pressure gauge leaks eliminated

11Aug2022:
Col Trans ceramic break leak sealed with CevaSeal

12Aug2022: Gun Trans flange leak eliminated

31Aug2022: Custom Linear NEG Activation

15Sep2022: Right angle valve leak eliminated

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Extended EBIS Performance Goals Have Been Met

1) Verification of Extended EBIS electron beam in a two superconducting solenoid system. Electron beams up to 8.8A

2) Testing of a Highly efficient gas injection system including a fast pulsed Lorentz valve

3) Verification of ion transfer from gas cell to adjacent short trap and distal long trap.

4) Ion extraction from short and long traps with ion pulse merging

5) Helium gas injection with ion extraction rates up to 5Hz

6) Magnetic Alignment and Beam steering techniques developed to assure timely re-establishment of operation after Extended EBIS move to accelerator

7) Development of pumping systems compatible with gas injection in addition to ion injection

Extended EBIS Installation at the Accelerator Location

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Upstream Section being placed installed
(October 12, 2022)

Infrastructure

Infrastructure upgrades to the Extended EBIS installation site began just after July 4, 2022, after the end of NSRL operations. The site includes the previous RhicEBIS area plus an adjacent space previously cleared to accommodate the longer Extended EBIS and a new solid state electron collector power supply. Decommissioning of the RhicEBIS was the first task, as it was necessary to remove the ion source to be able to access other equipment and install a new overhead trays and power distribution system for the installation of Extended EBIS.

- Aug. 1, 2022: RhicEBIS removed from installation area.
- Collector Power supply removed and 200kVA Isolation/Rectifier Transformer removed.
- 200kVA 480VAC Isolation Transformer installed for powering new solid state collector supply.
- Sep. 16, 2022: Extended EBIS Beam Tests completed in EBIS Test Laboratory
- Sep. 26, 2022: Pumping Speed vacuum characterization on Extended EBIS
- Superconducting magnetic fields ramped down and Extended EBIS disassembled for move to accelerator site.
- Oct 11, 2022: Extended EBIS moved to accelerator installation location
- Nov 2022 Extended EBIS vacuum system reassembled, mechanically aligned, under vacuums
- Dec2022 Electrical Infrastructure complete (except final collector supply installation)
- Rack power supply, controls and vacuum controls in progress
- Solid state collector supply installation is expected during January 2023. This may be delayed, depending on the ongoing acceptance testing. Contingency plan is to re-install the old collector power supply, but that also would take considerable manpower and require at least a month to accomplish.

Commissioning Plan

Operation of the Extended EBIS will begin at the accelerator location at the end of January 2023, after installation and testing of the electron collector supply. Early commissioning will verify that all systems are re-established and working as demonstrated in the Test Lab with an emphasis on preparing EBIS ions for Galactic Cosmic Ray simulation experiments at NSRL in mid March. During the first run, we plan to produce He^{2+} from internal gas injection with other ions produced from external ion injection as in the RhicEBIS setup.

- Establish low current pulsed electron beam (I_e~100mA, T~500μs) using transverse magnetic steering.
- Mechanical Alignment of source in the new environment using the electron beam to reduce the need for transverse magnetic steering.
- High current electron beam propagation (I_e~5-8A, T~100ms)
- Verify gas injection with 4He gas with ion transfer to the long trap.
- Demonstrate EBIS platform high voltage pulsing
- Re-establish external ion injection from Laser Ion Source (LION) into the Long Trap using fast capture with the existing Behlke Switch hardware.
- Demonstrate Fast extraction from the Long Trap.
- Accelerate Extended EBIS ions through RFQ and LINAC. Verify and optimize charge state and intensity using the Faraday Cup and Current transformer after the Big Bend dipole system
- Ion Delivery to NSRL
- Phase in short trap Behlke Switch system for combined short and long trap capture and extraction for eventual RHIC Au32+ production.

Extended EBIS Installation Continues
(December 8, 2022)

Initial Operation after Installation

Initial installation at the accelerator will include a highly efficient gas injection system for light ions and an extended trap region for increased Au32+ production.

Polarized 3He2+ will not be available from Extended EBIS until the polarized upgrade is made, but **tests of unpolarized 3He and perhaps H+ could be made during the first year of operation depending on schedule.**

Future upgrades will include a high field 3He polarization setup in the bore of the first superconducting solenoid, a second gas injection valve and gas handing system, and a gas manifold for remote automatic gas switching.

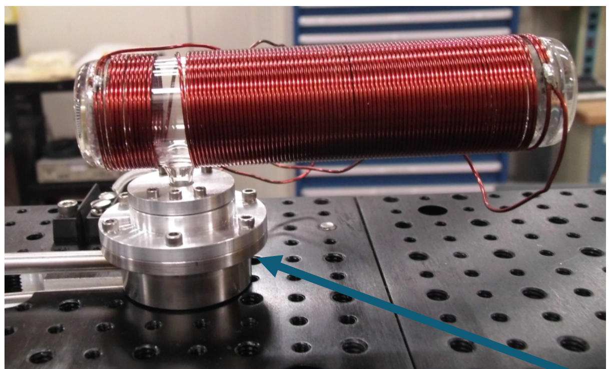
Summary

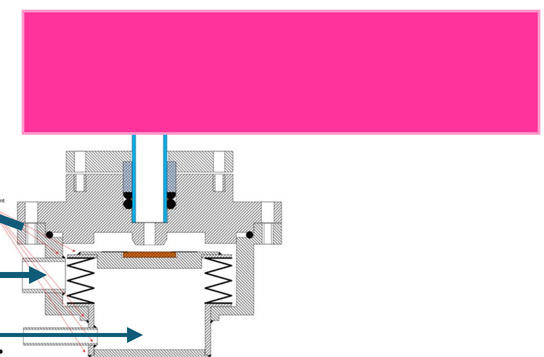
- The Extended EBIS magnetic system, electron optics, and high efficiency gas injection system, and complete vacuum system have been installed and operated in the test EBIS laboratory
- Electron beams up to ~1A were used to align the magnetic system and electron beams up to 8.8A were propagated to the electron collector with very little loss with the aid of transverse magnetic steering coils.
- The high efficiency gas injection system with a custom precision gas pulsed gas valve was tested with He, Ar and H_2 gas. Ions were formed within the electron beam in the gas trap and were captured downstream in the Short and Long traps. Ions were extracted to a Faraday cup located downstream of the electron collector after an adjustable confinement period.
- Custom, high-capacity linear NEG pump were installed in the both the short and long traps and activated for the ion extraction tests. The NEGs performed as expected.
- The Extended EBIS is now installed at the accelerator location with electron beam operation expected in February 2023 and Ion beams in March 2023.

Recent Developments towards 3He Polarization and 3He2+ transport and Measurement

(Additional Material)

“Open” cell with inductive RF power input and new pneumatic 3He-filling valve.





3He –purification system

Compressed air

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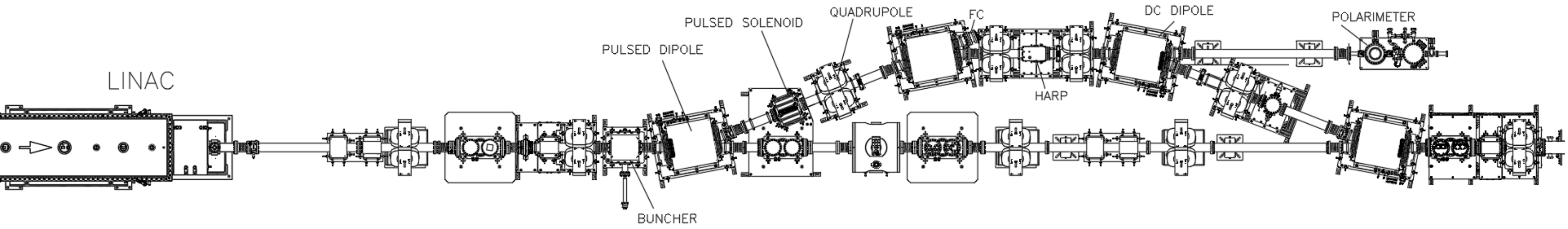
3He++ spin rotator and polarimeter in the EBIS HEBT line at 6.0 MeV beam energy

3He-4He-scattering



The development of the 3He polarizing apparatuses, the spin-rotator, and the nuclear polarimeter at the 3He++ ion beam energy 6.0 MeV (in the high-energy beam transport line after the EBIS drift-tube Linac). Completion in 2022

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