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U.S. DEPARTMENT OF ENERGY

EBIS Development at BNL For Polarized $^{3}He^{2+}$

E. Beebe

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

E. Beebe[1], G. Atoian[1], B. Coe[1], S. Ikeda[1], T. Kanesue[1], S. Kondrashev[1], R. Milner[2], M. Musgrave[2], M. Okamura[1], D. Raparia[1], T. Rodowicz[1], J. Ritter[1], B. Schoepfer[1],S. Trabocchi[1], A. Zelenski[1]

[1]*Brookhaven National Laboratory, Upton, NY 11973, USA*

[2]*MIT, Cambridge, MA, USA*

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

- The ratio of $^{3}He^{2+}$ to $^{3}He^{1+}$ would be very low. (with $^{3}He^{2+}$ intensities well below requirements)
- Polarization would be reduced as ^{3}He 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 ^{3}He gas would be very high.

The Extended EBIS solution

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 109 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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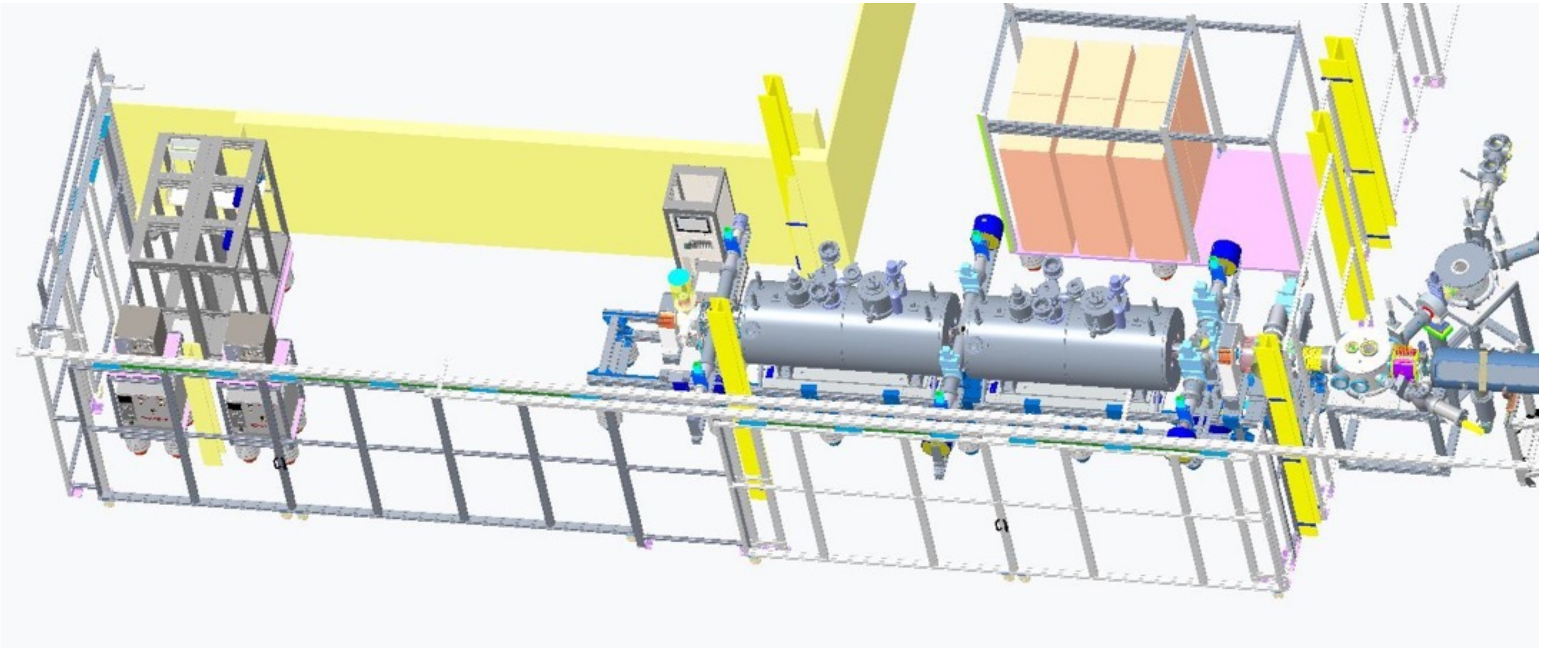
Extended EBIS Installation at Accelerator with High Voltage enclosure



Left: Solid State Electron collector supply
Middle: Extended EBIS with two Superconducting Solenoids
Right: Existing Ion injection and LEBT beamlines

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 then the EIC leads also to increases in other ion intensities.

- 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 will benefit from the additional trap capacity provided by the short trap in the first solenoid.

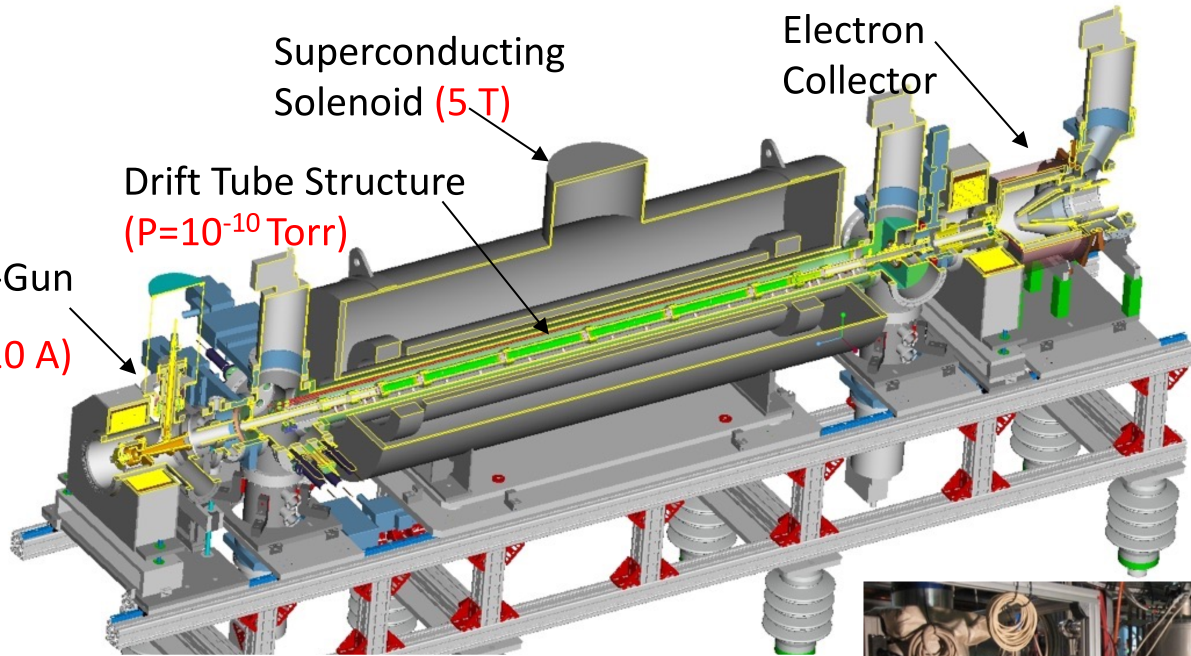
Intensity Estimates for EBIS upgrade (at Extended EBIS exit)

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

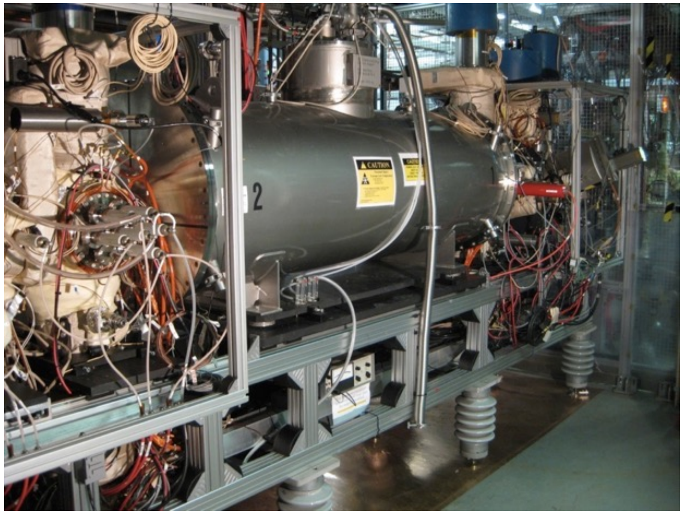
H^{+} ~5 – 10 x 10^{11} ions/ pulse

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]



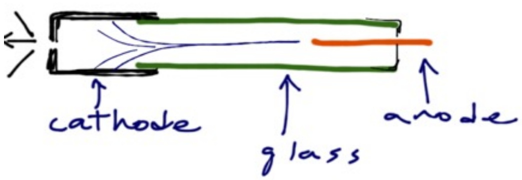
$$N = \kappa * I_e * L_{trap} * E_e^{-0.5}$$

External 1+ ion production to feed the EBIS trap

Slow injection (accumulation mode)

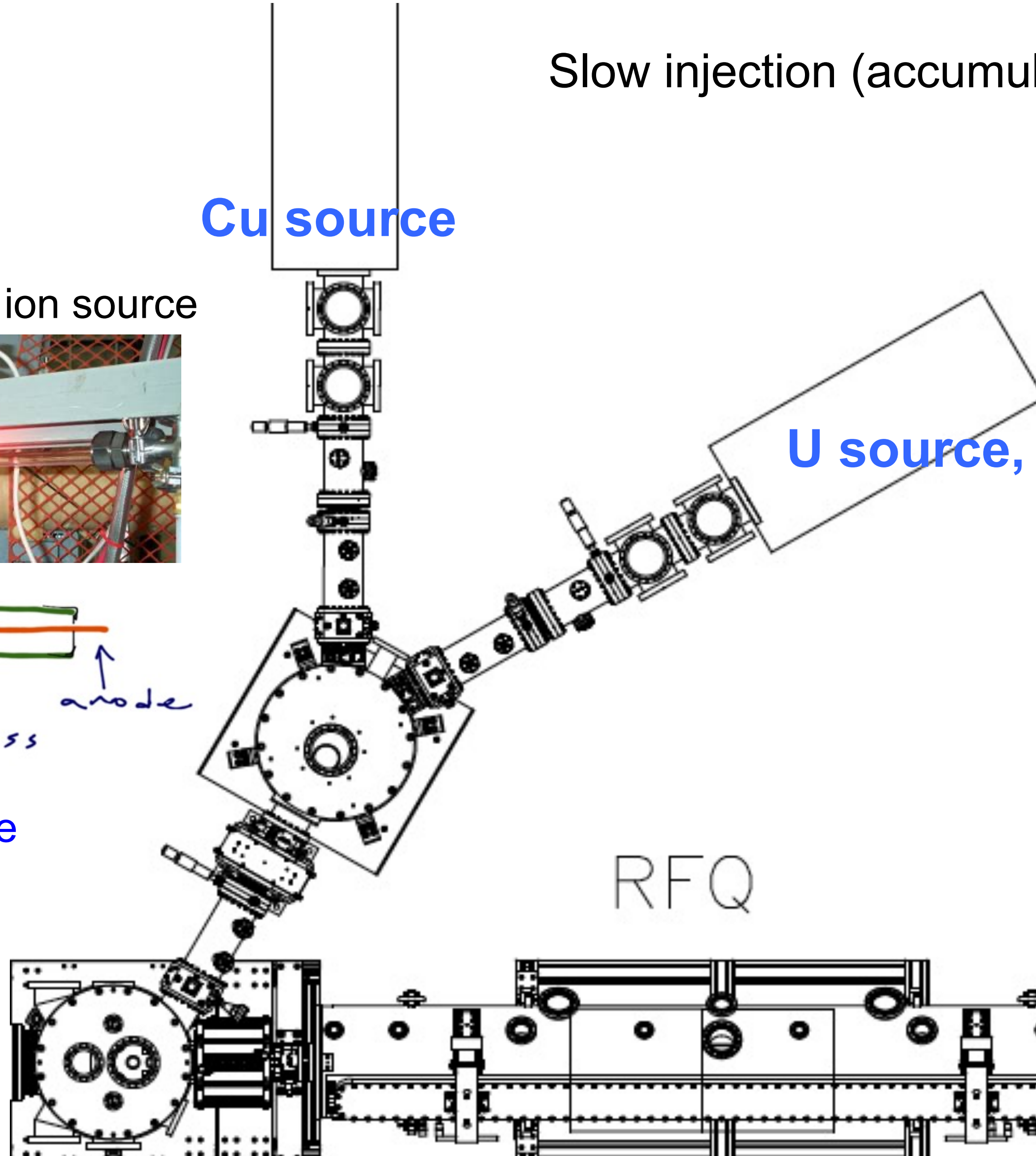
HCIS

Hollow cathode ion source



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

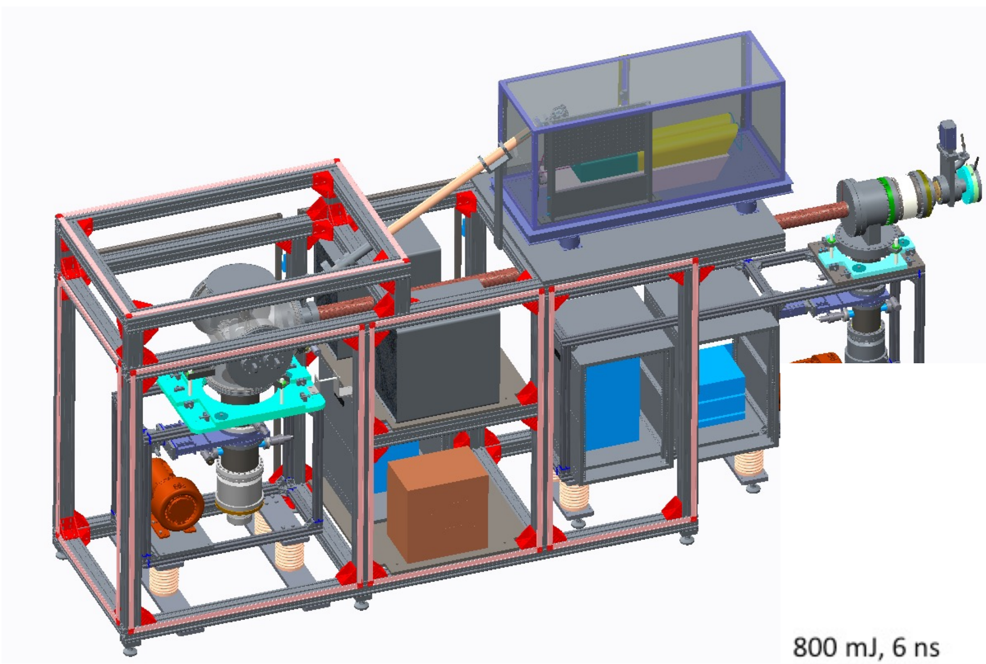
1+ Ions into EBIS

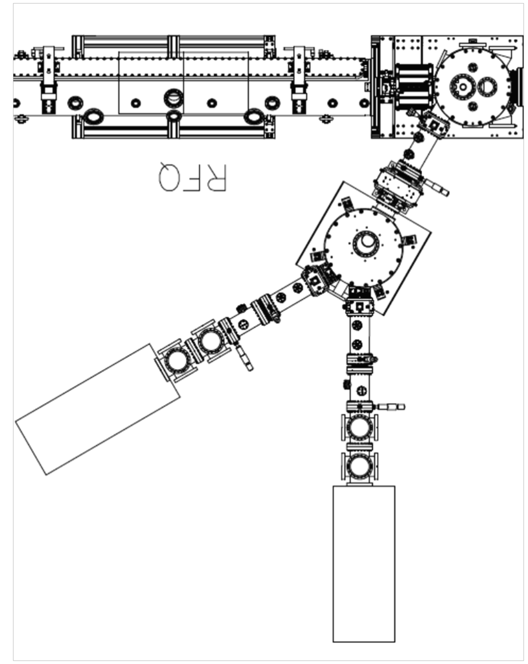


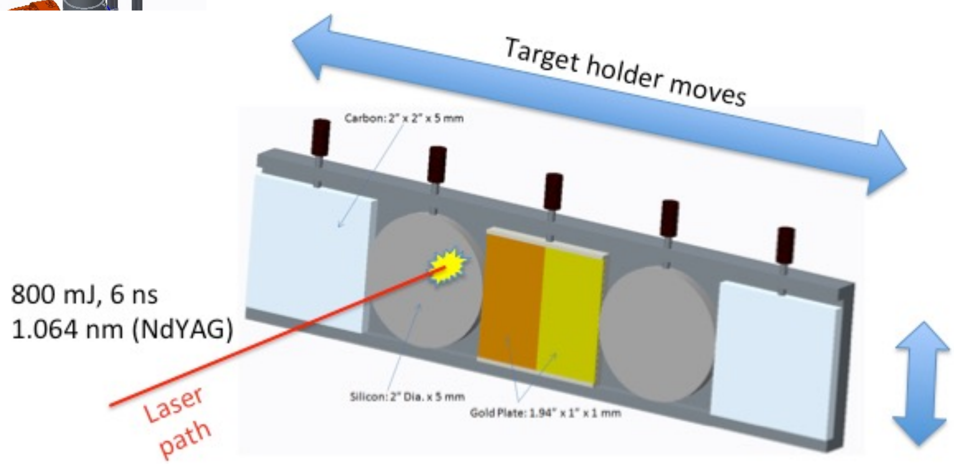
Versatile 1+ ion injection into EBIS by Laser Ion Source (LION)

3rd injection line added for LION
improved flexibility (multiple species)

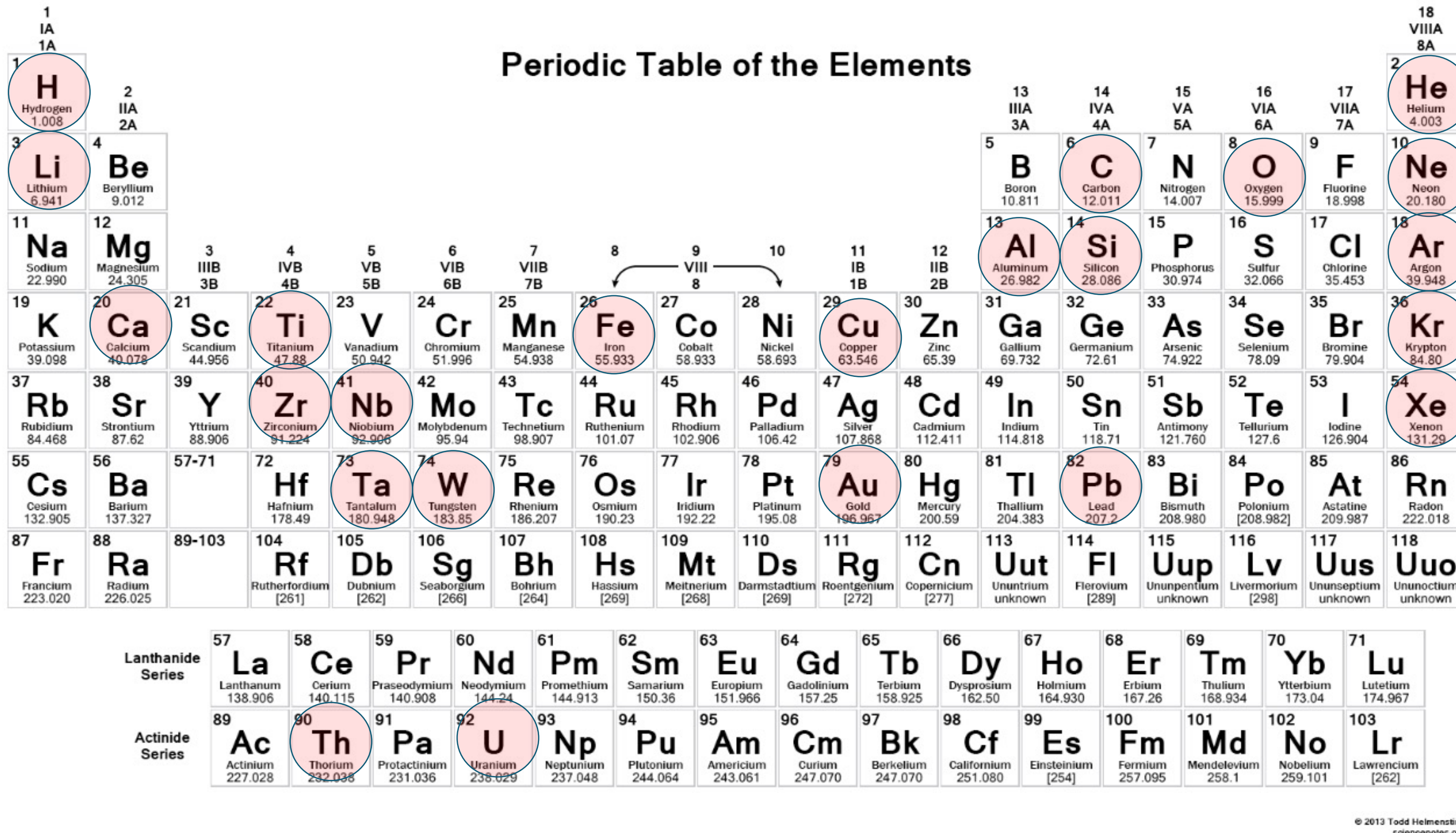
- low gas load
- Fast injection into EBIS







Examples of ions produced by RHIC EBIS



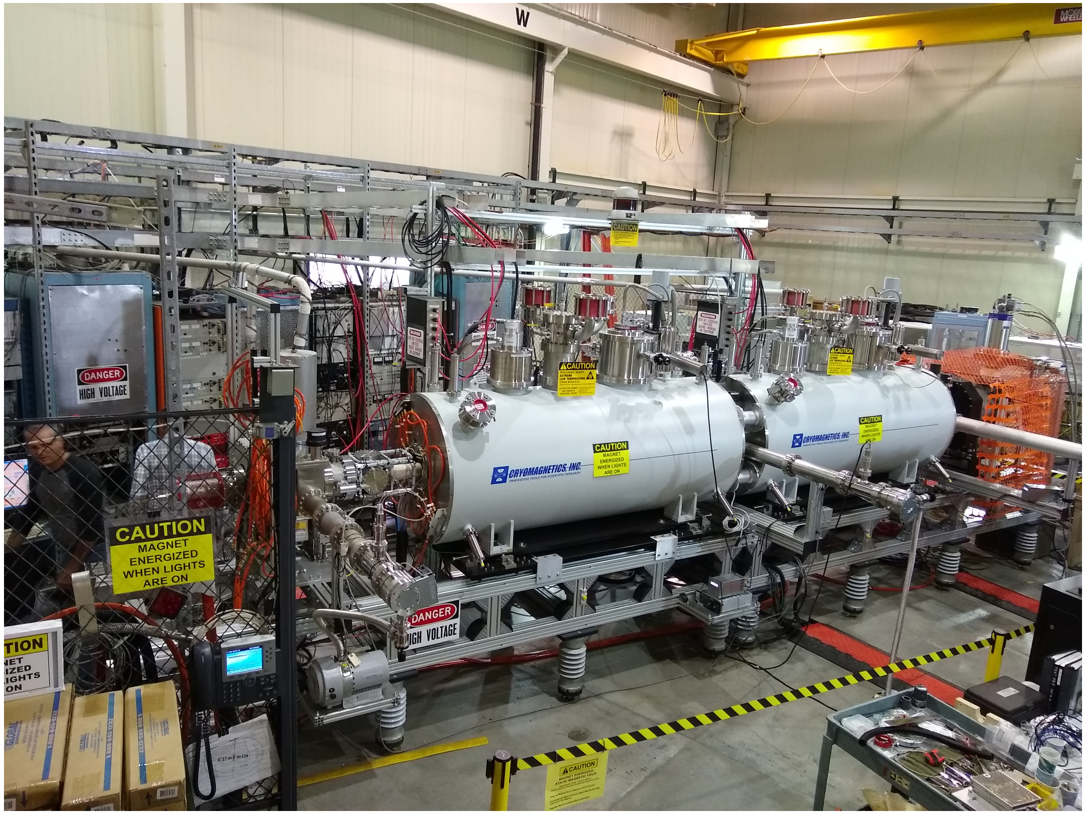
D^{+}, $^{3}He^{1+,2+}$, $^{4}He^{1+,2+}$, Li^{3+}, $C^{5+,6+}$, O^{7+}, Ne^{5+}, Al^{5+}, $Si^{11+,12+}$, Ar^{11+}, Ca^{14+}, Ti^{18+}, $Fe^{20+,24+}$, Cu^{11+}, Kr^{18+}, $^{90}Zr^{15+}$, $^{96}Zr^{16+}$, Nb^{16+}, Xe^{27+}, Ta^{38+}, $^{184}W^{31+}$, Au^{32+}, Pb^{34+}, $^{232}Th^{39+}$, U^{39+}

1 second switching between species (2, or more), alternating

<30 second switching among almost any 10, if loaded into external sources

Extended EBIS Component Development

Extended EBIS in Test Lab



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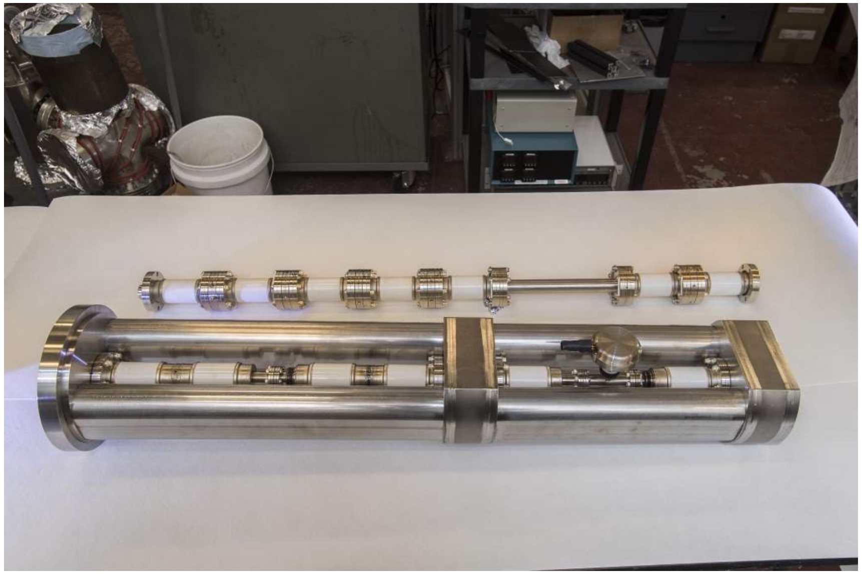
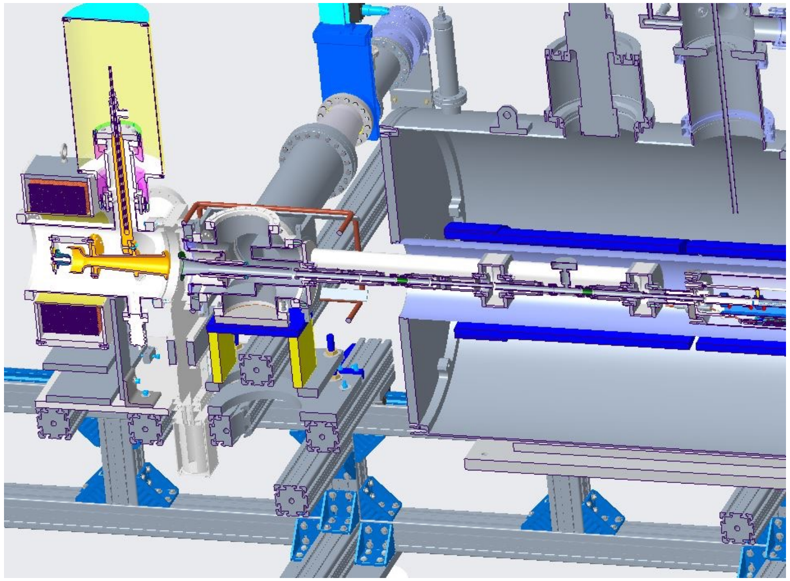
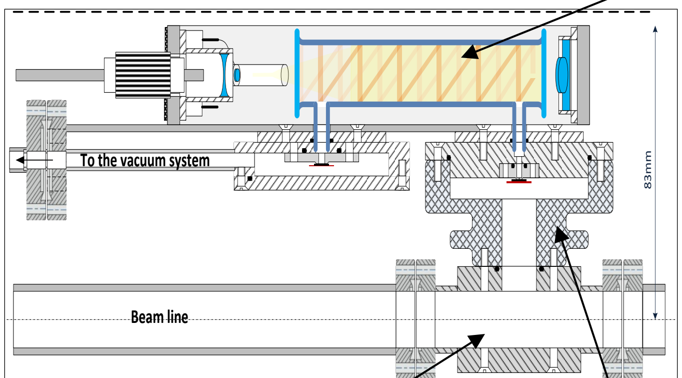
Gas Cell

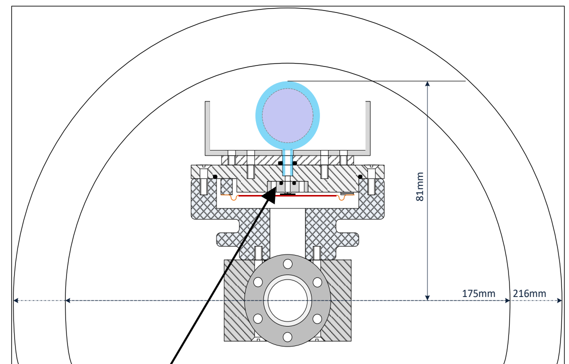




3He –optically-pumped cell in the high magnetic field

3He-cell





Drift tube -40 kV

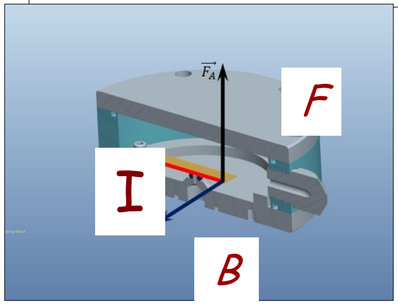
Insulator

Pulsed valve

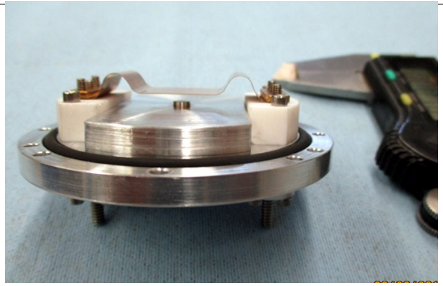
Long, small diameter drift tube works like a 3He storage cell, which reduces gas load to the EBIS vacuum system and increases polarization due to ionization localization in the high magnetic field region.

“Electro-magnetic”, [IxB] valve operation principle

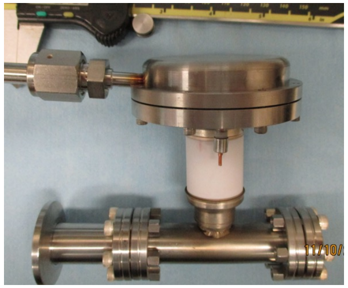
Lorentz (Laplace) force moves the flexible conducting plate in the high (~ 3-5 T) magnetic field.
For I=10 A, L=5 cm, F=2.5 N. Current pulse duration ~100-500 us



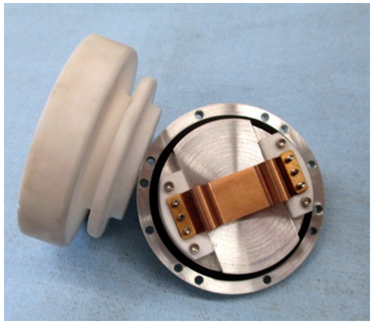
$$d\overrightarrow{F_A} = I[d\vec{l}\,\vec{B}]$$



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 Drift Tubes (right foreground)
Two module Zao high capacity NEG pump unit (left foreground)

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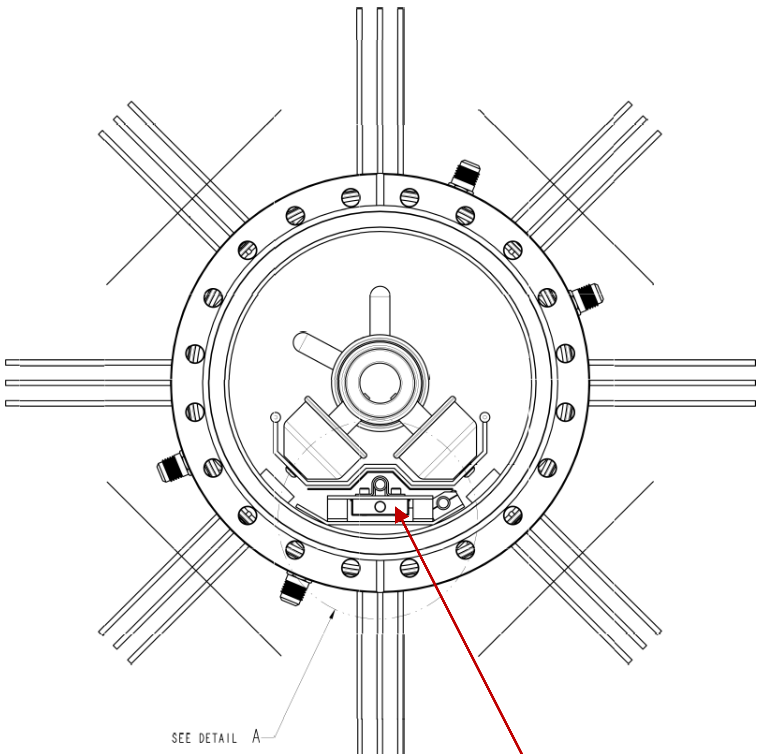
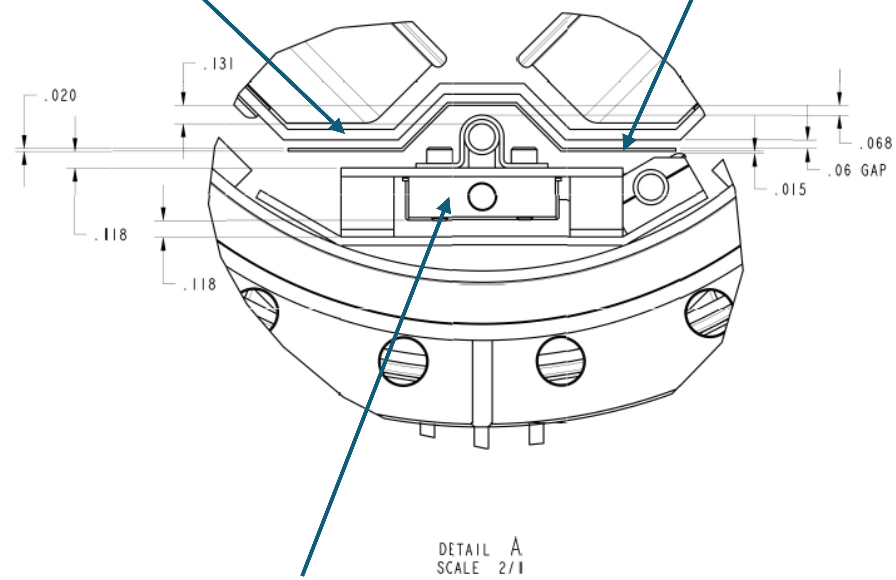
Design of ZAO NEG Linear Pumping System





ZAO NEG linear pumping system will be placed under tray supporting drift tubes

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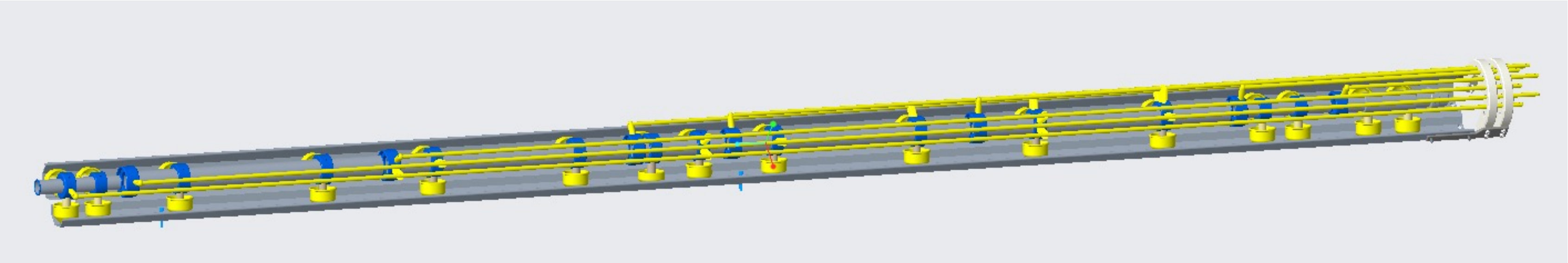
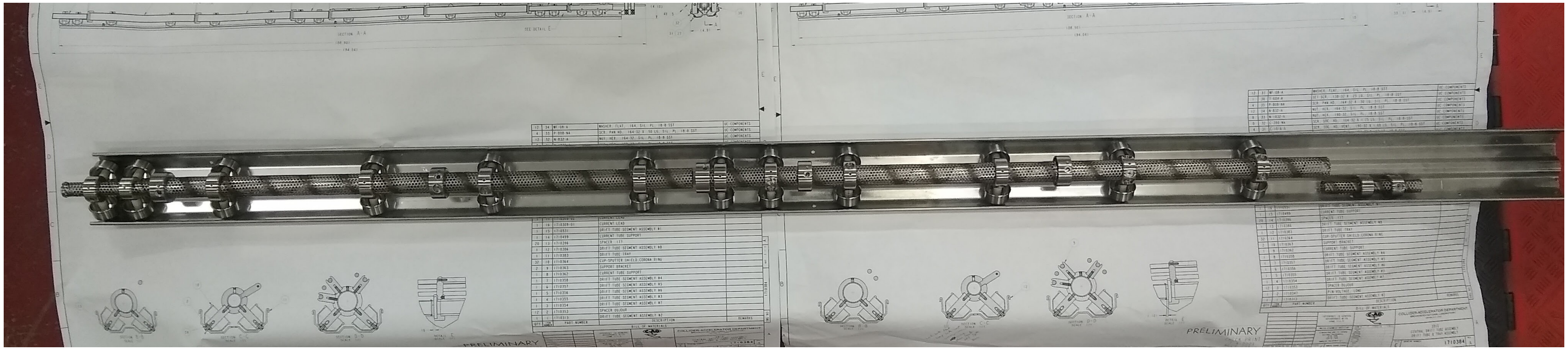
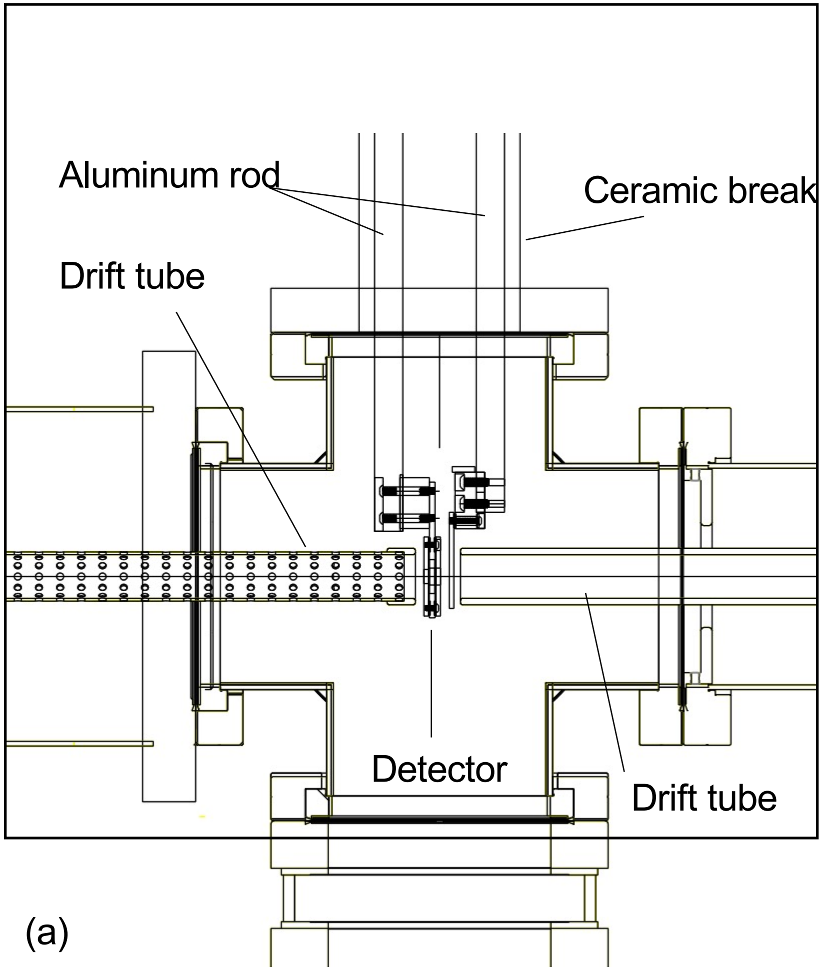
Downstream Drift Tubes

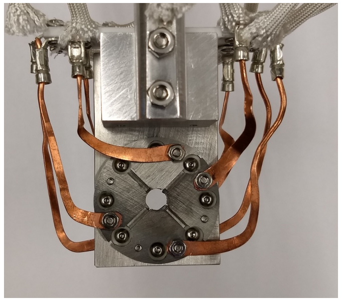




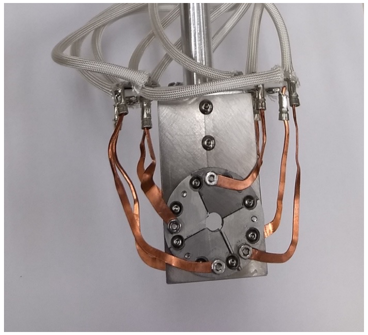
Quadrant electron beam detectors



(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.

Electron and Ion beam tests

Testing of electron beam propagation, gas injection and ion extraction was made with the main components of the extended ebis installed in the upstream solenoid, and temporary but functioning drift tubes in the downstream solenoid.

Electron beams up to 8A were propagated.

The magnetic system was aligned mechanically by using a low current electron beam (<1A). Coils producing transverse magnetic fields were used to make adjustment to the electron beam trajectories to keep losses essentially zero for beams up to 8A.

In particular, the gas injection cell with Lorentz pulsed valve and pump out manifold were tested, using Helium, Argon and Hydrogen gas. The results were excellent. Very little gas was seen to migrate in the down stream solenoid regions, but ions were created and transported easily.

Ions were created in the gas region using 3A electron beams, and then transported to both the short and long trap. Subsequently, the ions were and extracted to a Faraday cup after the collector. The upstream trap performed very well and the downstream trap was somewhat hampered by poor vacuum. (only the upstream NEG pump was installed and activated, and the differential pumping was not installed before the electron collector.

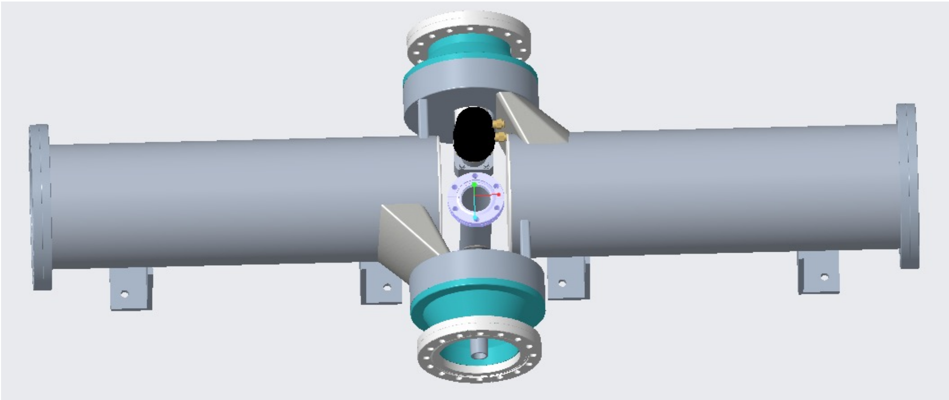
In January 2022, we will start the last phase of testing with the complete vacuum system installed.

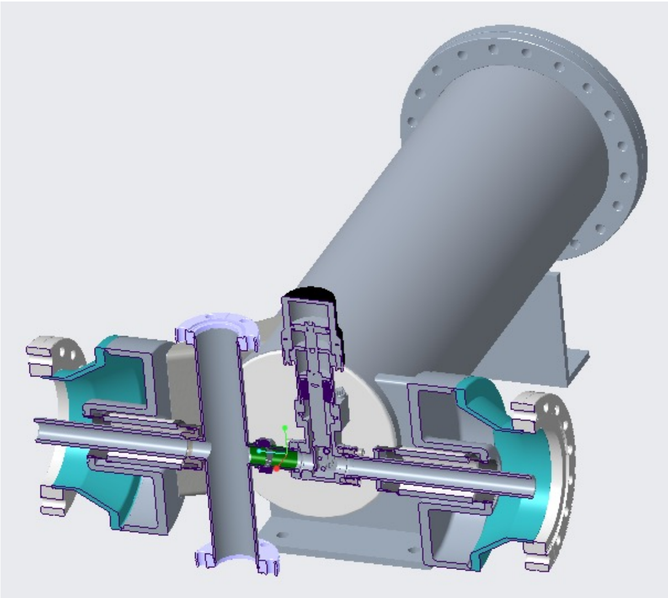
Center Vacuum Chamber (to be installed for operation in January)

Includes port for doublesided quadrant detectors

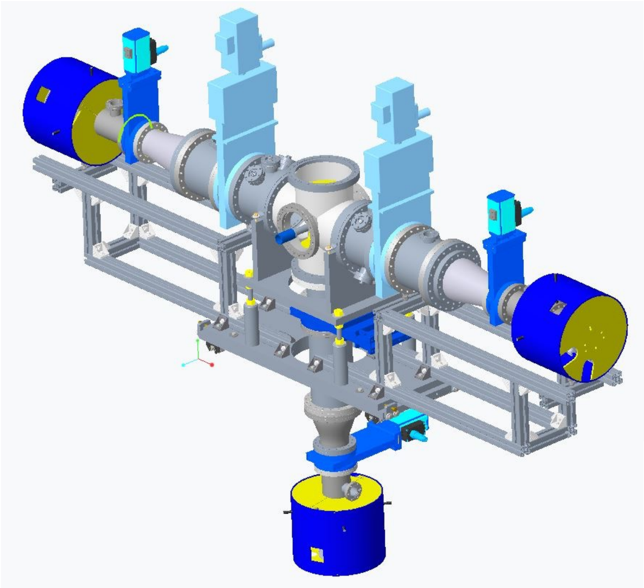
Includes gate valve for isolating upstream and downstream vacuum chambers

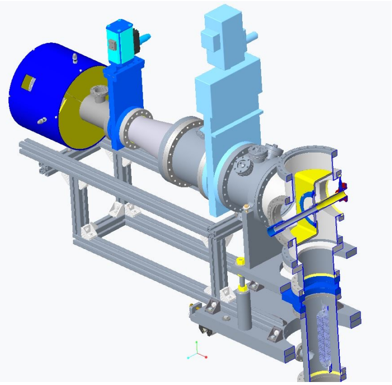
Differential pumping ports for upstream and downstream regions

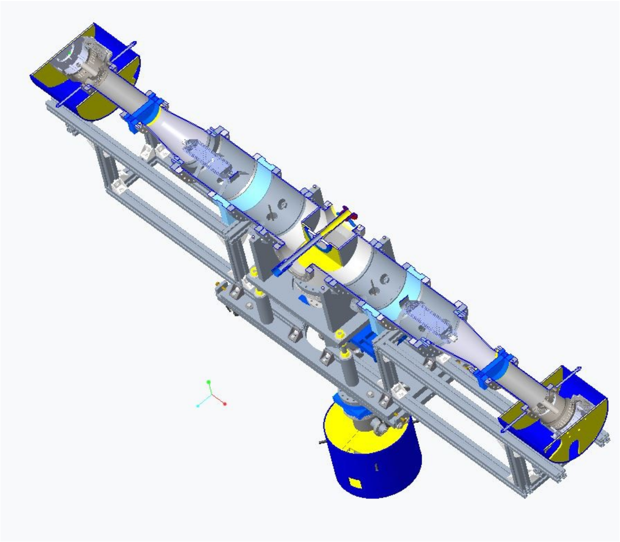




Vacuum chamber with differential pumping baffles between downstream ionization trap and the electron collector. (Manufactured --- soon to be installed)







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All vacuum components are now available for final assembly.

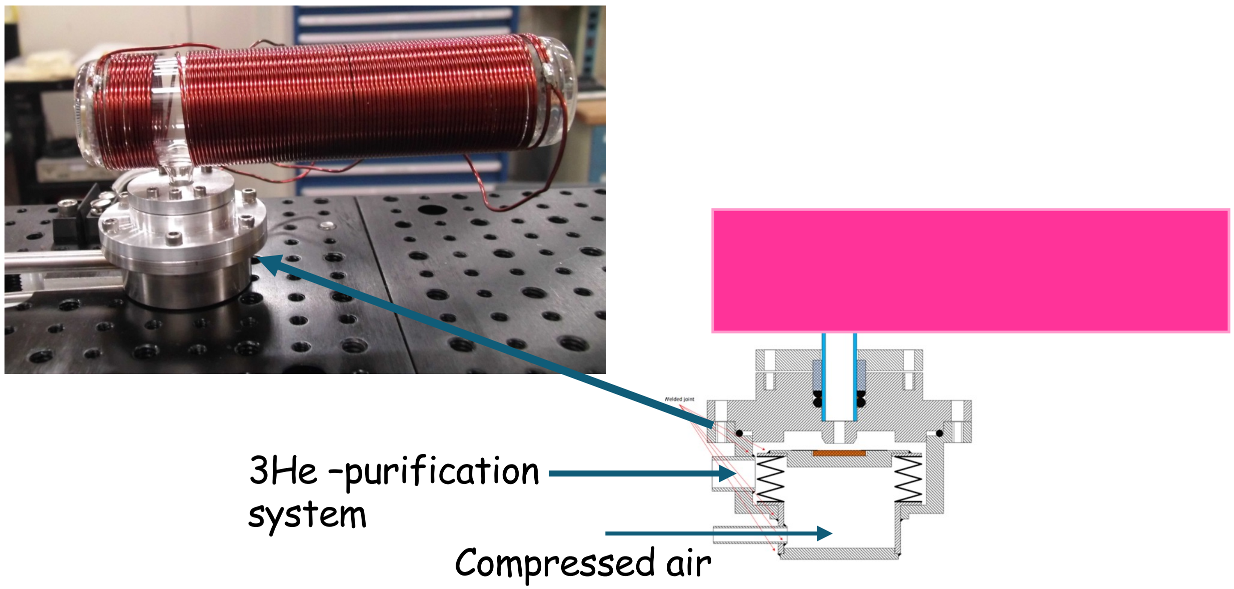
Extended EBIS Source testing will recommence in January

Schedule

July 2021:	Tests of gas injection into Ext-EBIS
Sept 2021:	Test of He, Ar, H-ion extraction from Ext-EBIS
Oct - Dec 2021:	Final assembly of Ext-EBIS vacuum system
Jan - June 2022:	Final test of Ext- EBIS in the test Lab
June - Oct 2022:	Installation of Ext- EBIS at the Accelerator
Nov - Dec 2022:	Commissioning of Ext-EBIS
Jan - June 2023:	Operation of Ext-EBIS
July - Sept 2023:	Installation of He-3
Oct - Dec 2023:	Test for He-3

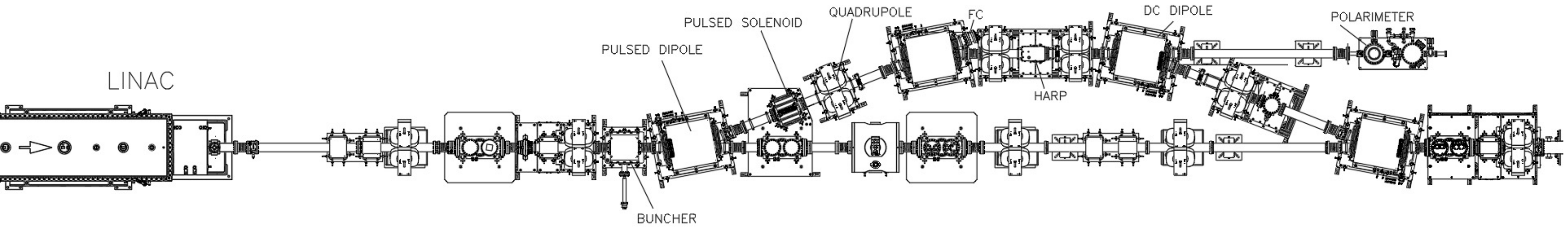
Recent Developments towards 3He Polarization and 3He2+ transport and Measurement

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



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

Progress:
-Buncher Cavity fabricated and tested
-Solenoid fabricated
-DC Dipoles, Faraday cup and Harp installed
-Stands fabricated
-Vacuum Chambers fabricated
-Pulsed Dipoles fabricated

Status of Optically-pumped $3He^{++}$ cell development at EBIS

Optical pumping studies of He- in high magnetic field is in progress.

Cryogenic He-3 gas delivery system provided required gas purity.

He-3 cell and laser system for the optical pumping is near completed.

Pneumatic gas filling valve was successfully tested.

Pulsed electromagnetic valve developed for the polarized gas injection to the EBIS.

Polarized He-3 cell development for installation to the extended EBIS is in progress.

3He Spin-rotator and absolute polarimeter (based on 3He3-4He elastic scattering) development is in progress.

Hiring process is beginning to replace two physicists from MIT that have left the research team.

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Summary

- The Extended EBIS magnetic system, electron optics, high efficiency gas injection system, and nearly final 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 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 H2 gas. This most critical test went very well. Ions were easily formed and transported to downstream traps and then extracted to a Faraday cup after the electron collector.
- A custom, high-capacity linear NEG pump was installed int the short trap and activated for the ion extraction tests. The NEG performed as expected.
- All remaining parts for the final vacuum tests, especially the differential pumping sections are now available for assembly.
- Tests with electron beams, gas injection and ion extraction with the final vacuum configuration are expected to start in Mid to late January.