

Development of a Polarized $^3\text{He}^{++}$ Ion Source for RHIC and an EIC

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in collaboration with

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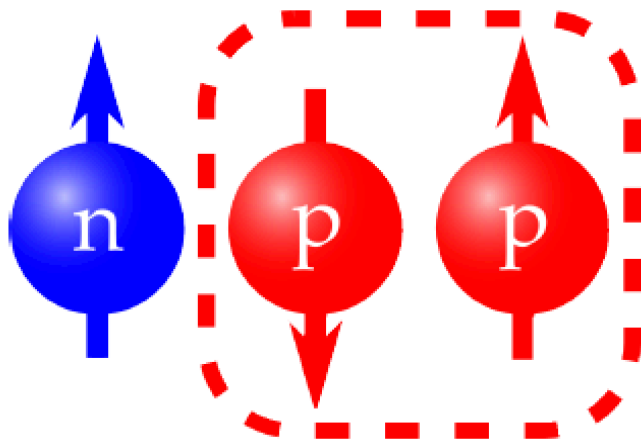
**Massachusetts
Institute of
Technology**



Nuclear Physics Accelerator R&D PI Meeting
October 20, 2017

Why a Polarized ^3He Ion Source?

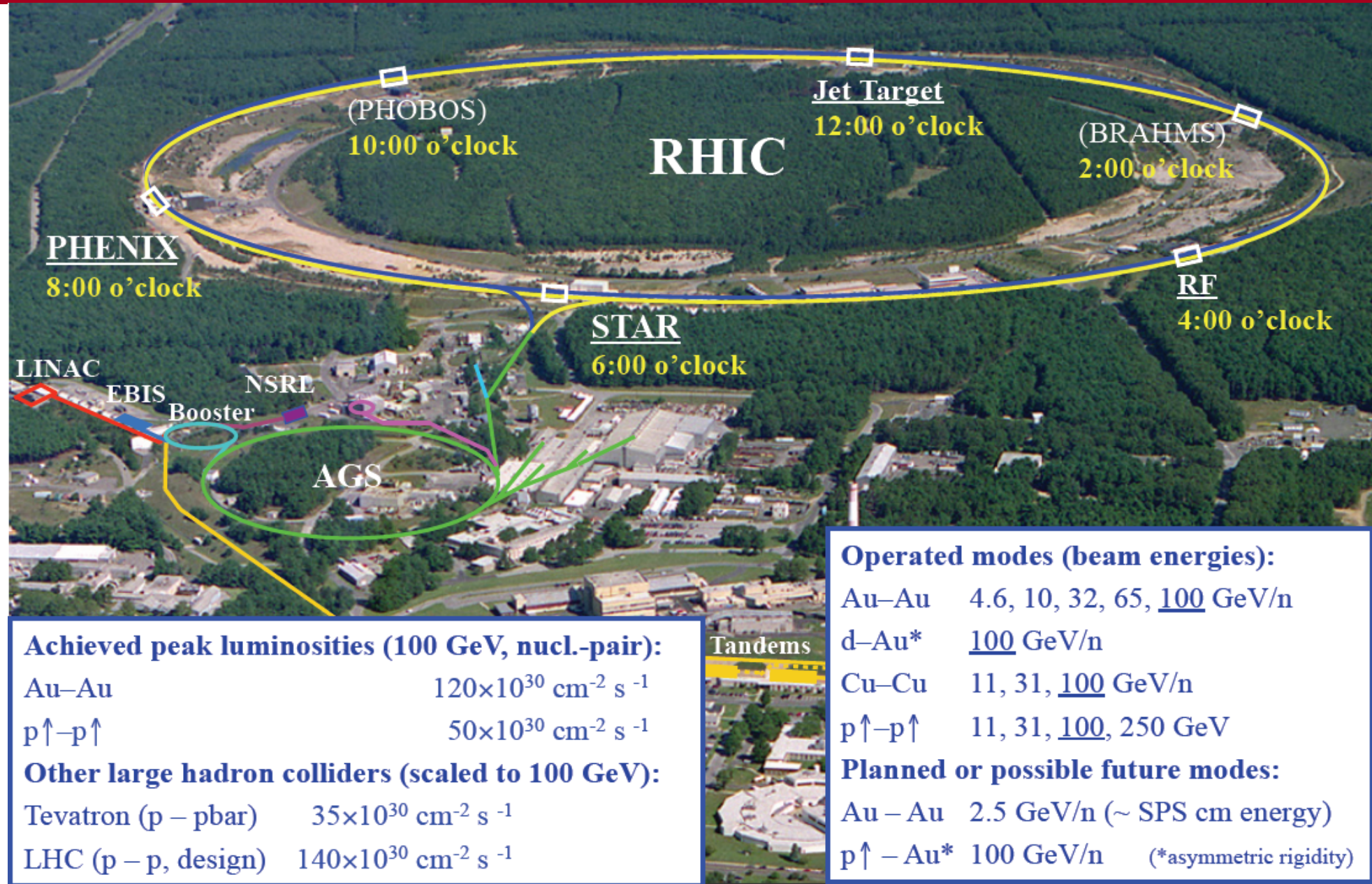
- Polarized DIS crucial for study of neutron spin structure
 - PPDFs; tests of QCD, Bjorken sum rule; higher energies



State	Probability
S	88.6%
S'	1.5%
D	8.4%

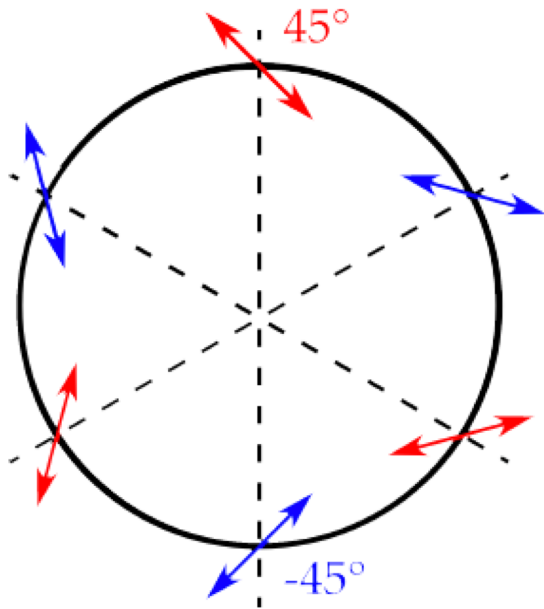
- S-state ^3He : nuclear spin carried by the neutron
- ^3He 's magnetic moment close to n, compatible with RHIC spin manipulation
- Polarized ^3He ions offer a “polarized neutron beam” for RHIC and a future EIC

RHIC: High-Luminosity Relativistic Heavy Ion Collider

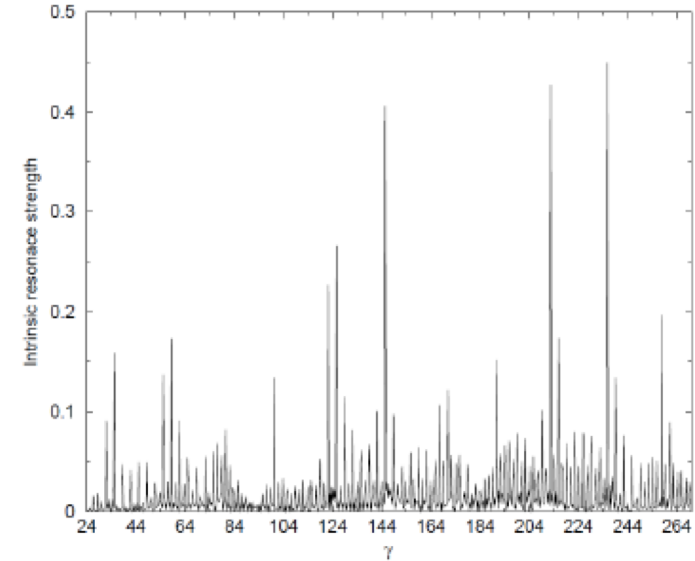


Polarized ^3He at RHIC

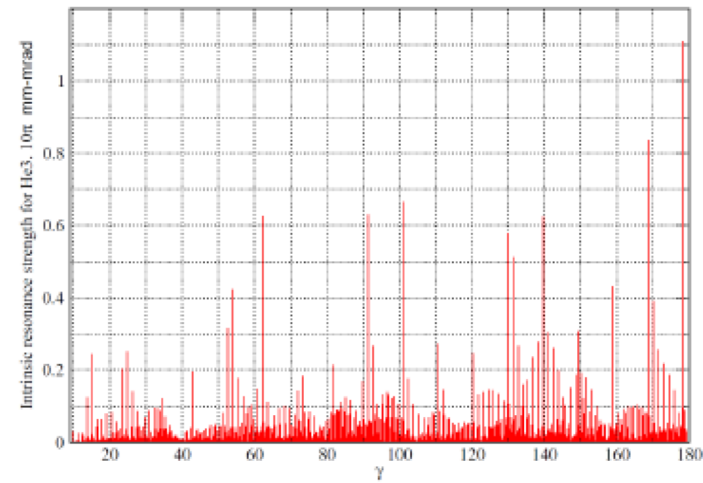
- ^3He 's anomalous g -factor is larger than p : more & stronger resonances
- Need 6 siberian snakes per ring¹



¹Bai, Courant *et al.*, BNL-96726-2012-CP, 2012.



p resonances



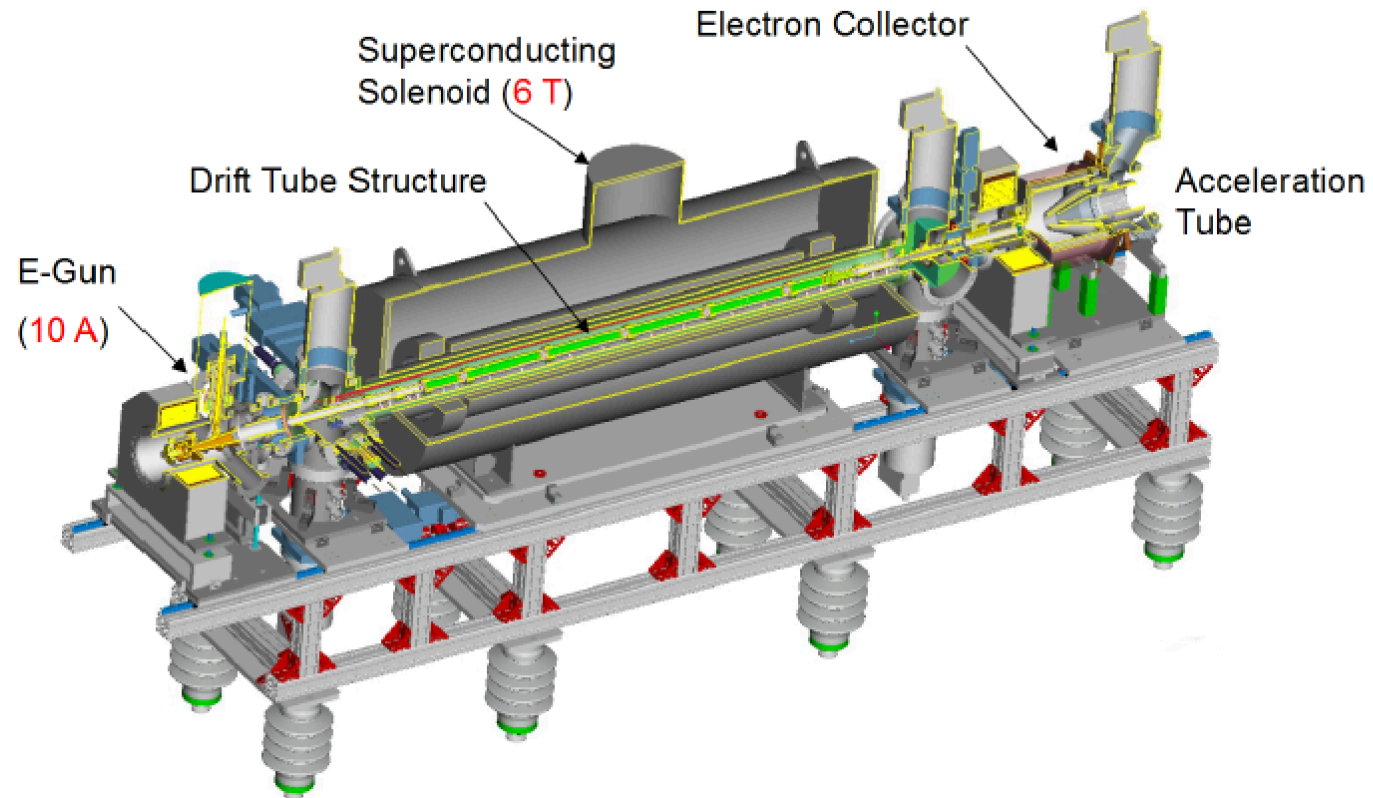
^3He resonances

Source Concept

- Proposed originally by Anatoli Zelenski and Jim Alessi in ICFA Newsletter (2003)
- Identified as high priority R&D for EIC by EICAC review in 2009 and Office of Nuclear Physics Community Review in 2017
- Concept developed by BNL-MIT collaboration
- Polarized ^3He using optical pumping and injection into EBIS at 5 T
- Maximum polarization >80%
- Intensity 5×10^{11} $^3\text{He}^{++}$ ions in $20 \mu\text{s}$ pulse (~ 10 mA peak current)
- Spin-flip in the beam transport line

RHIC's Electron Beam Ion Source (EBIS)

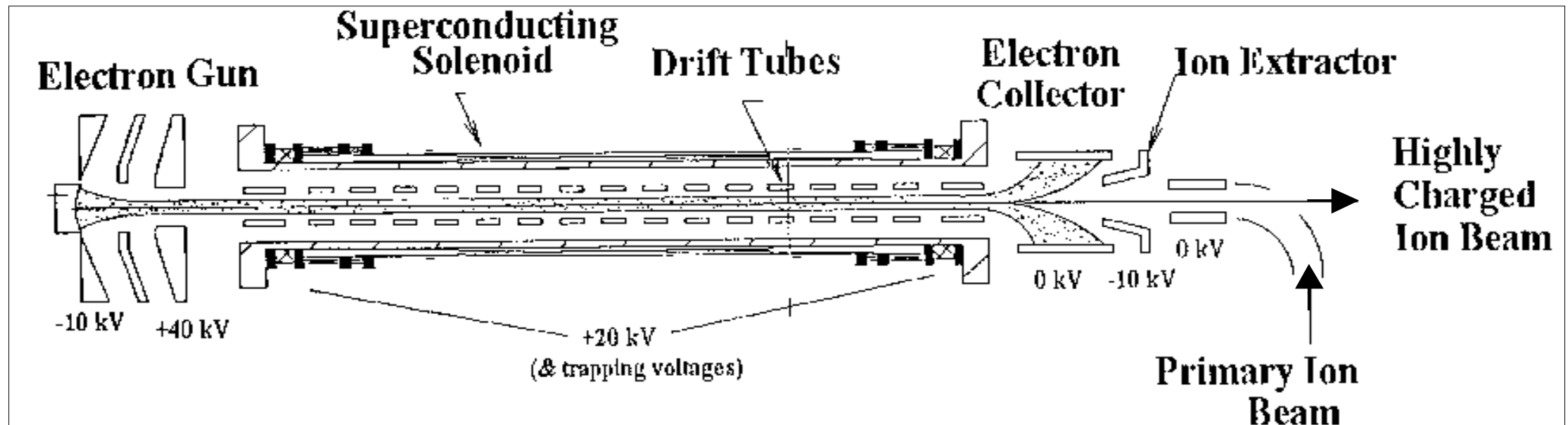
- 5 T Solenoid B Field; 1.5 m Ion Trap
- 20 keV electrons up to 10 A, 575 A/cm² Current Density
- **Any** species, switch between species in 1 sec



Principle of EBIS Operation

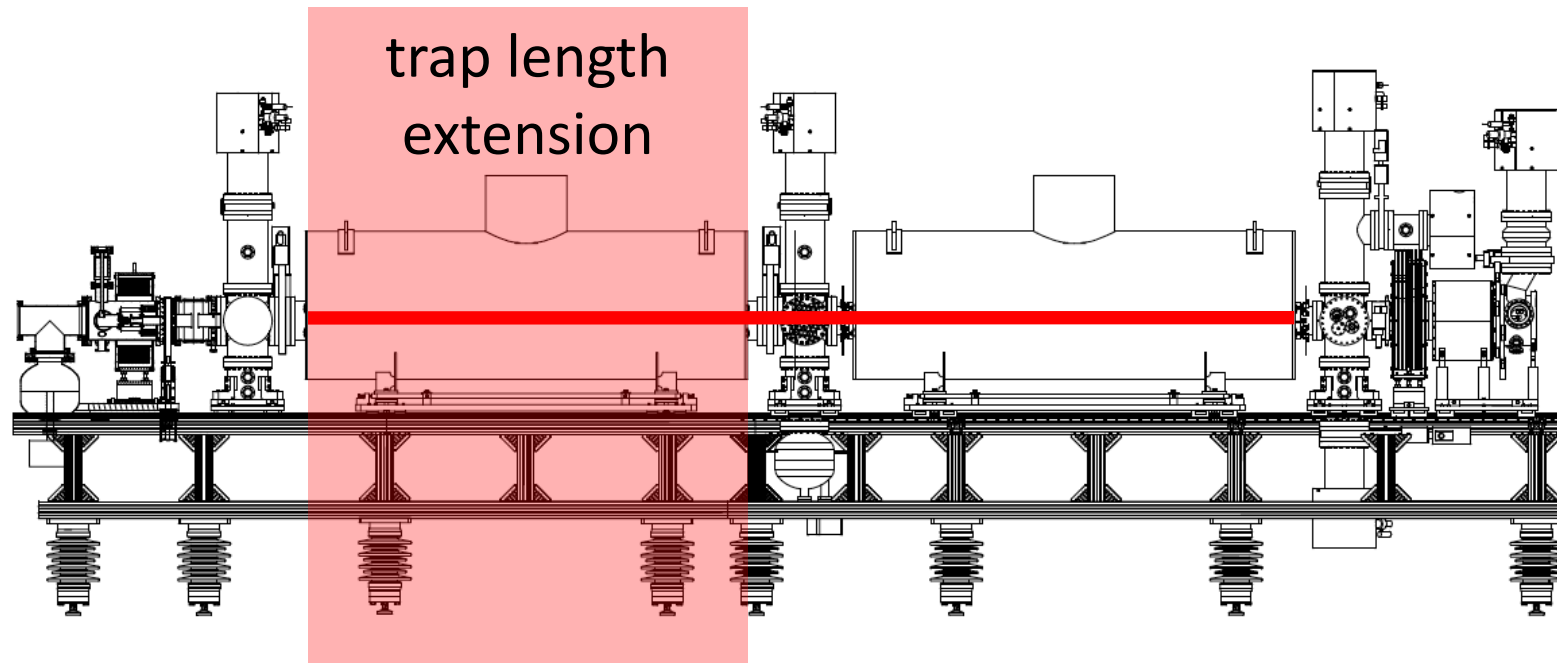
- Radial trapping of ions by the space charge of the electron beam
- Axial trapping by applied electrostatic potentials at ends of trap
- Ion output per pulse is proportional to the trap length and electron current
- Ion charge state increases with increasing confinement time
- Output current pulse is independent of species or charge state

$$C = \frac{I}{e} \times l \times \sqrt{\frac{m_e}{2E}}$$

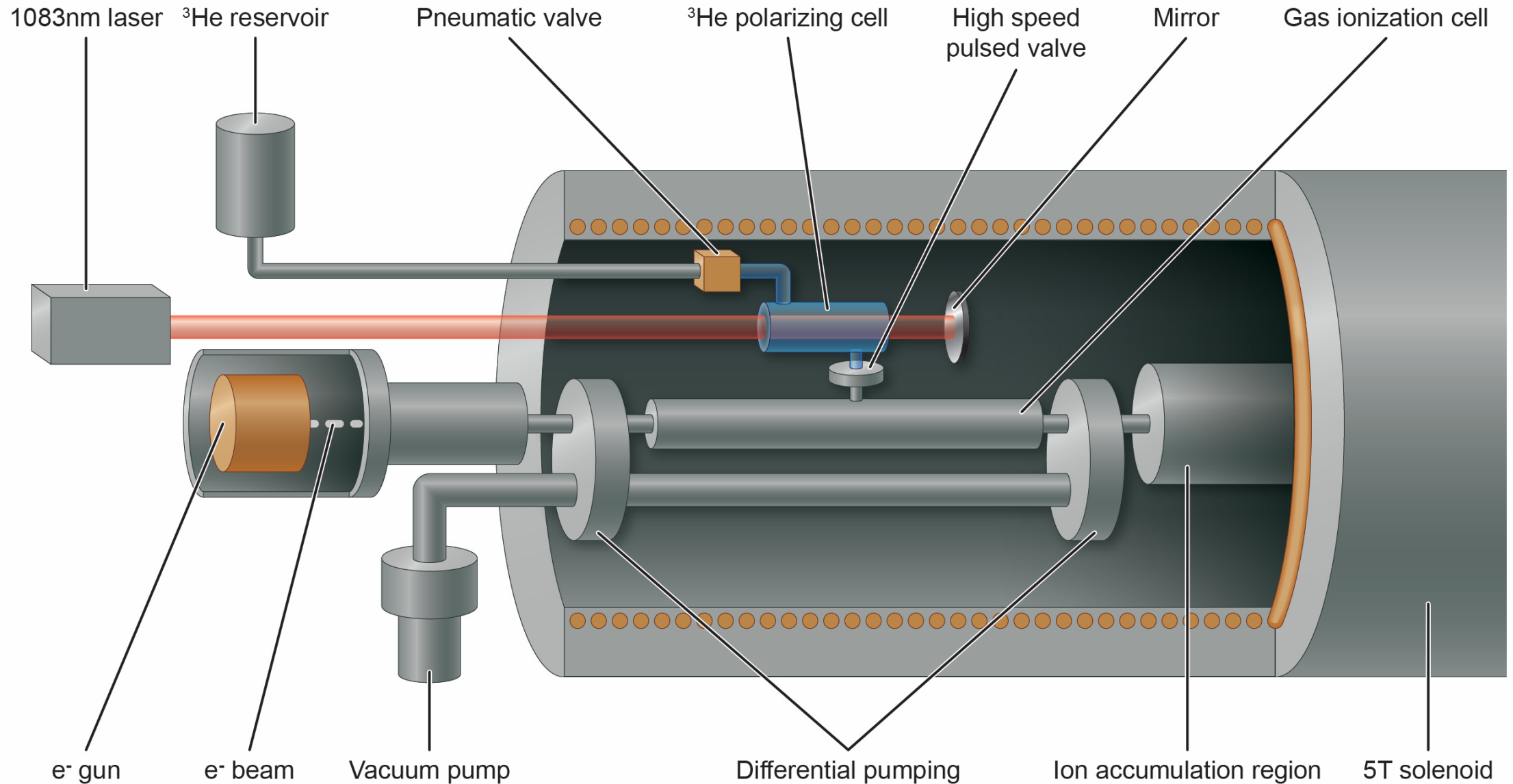


Extended EBIS Upgrade

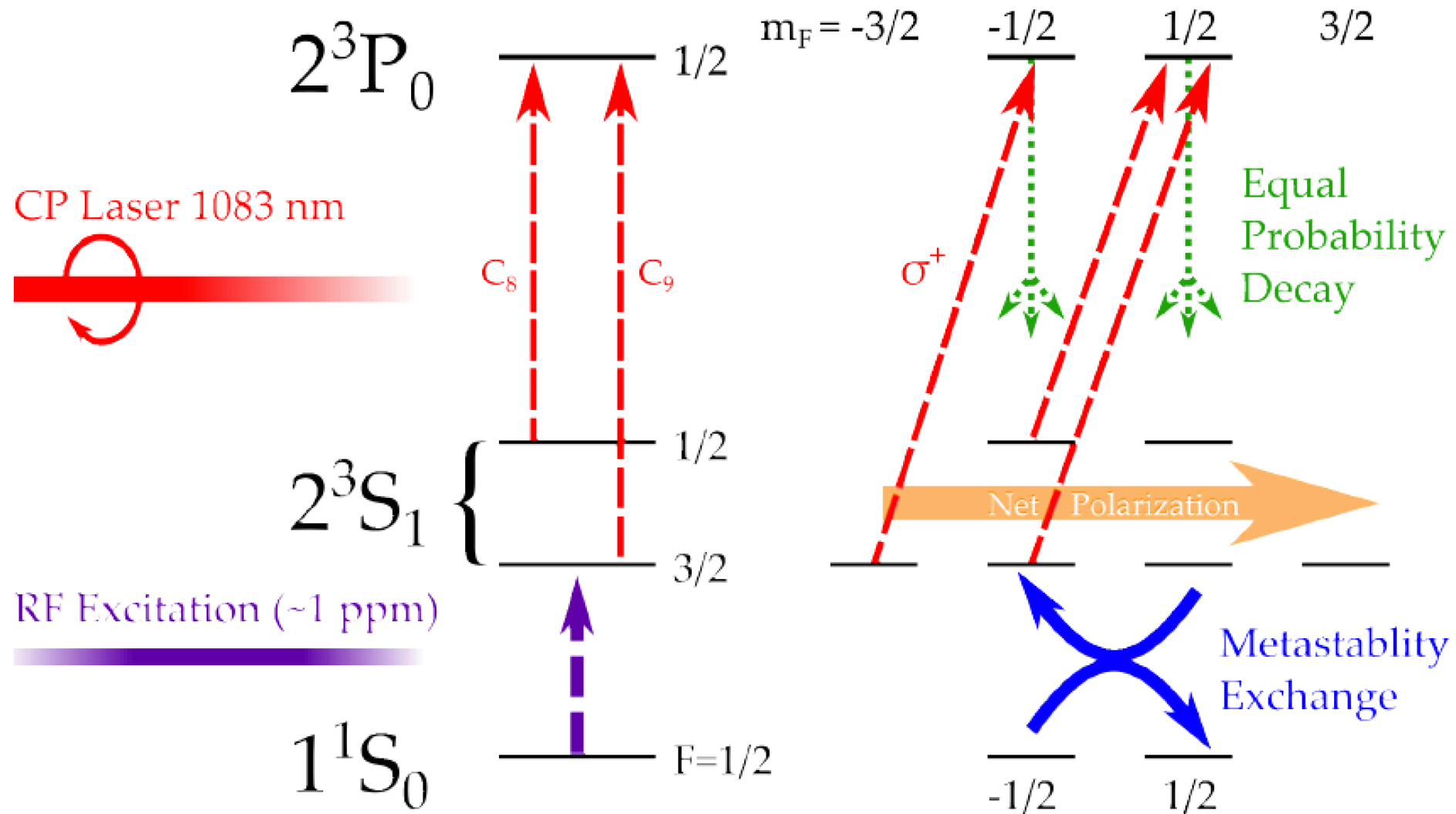
- Add a second 5 T superconducting solenoid for trap length extension: 40% increase in Au intensity
- Install ^3He polarization and injection system into the upstream solenoid
- Opportunity for various vacuum and other minor improvements



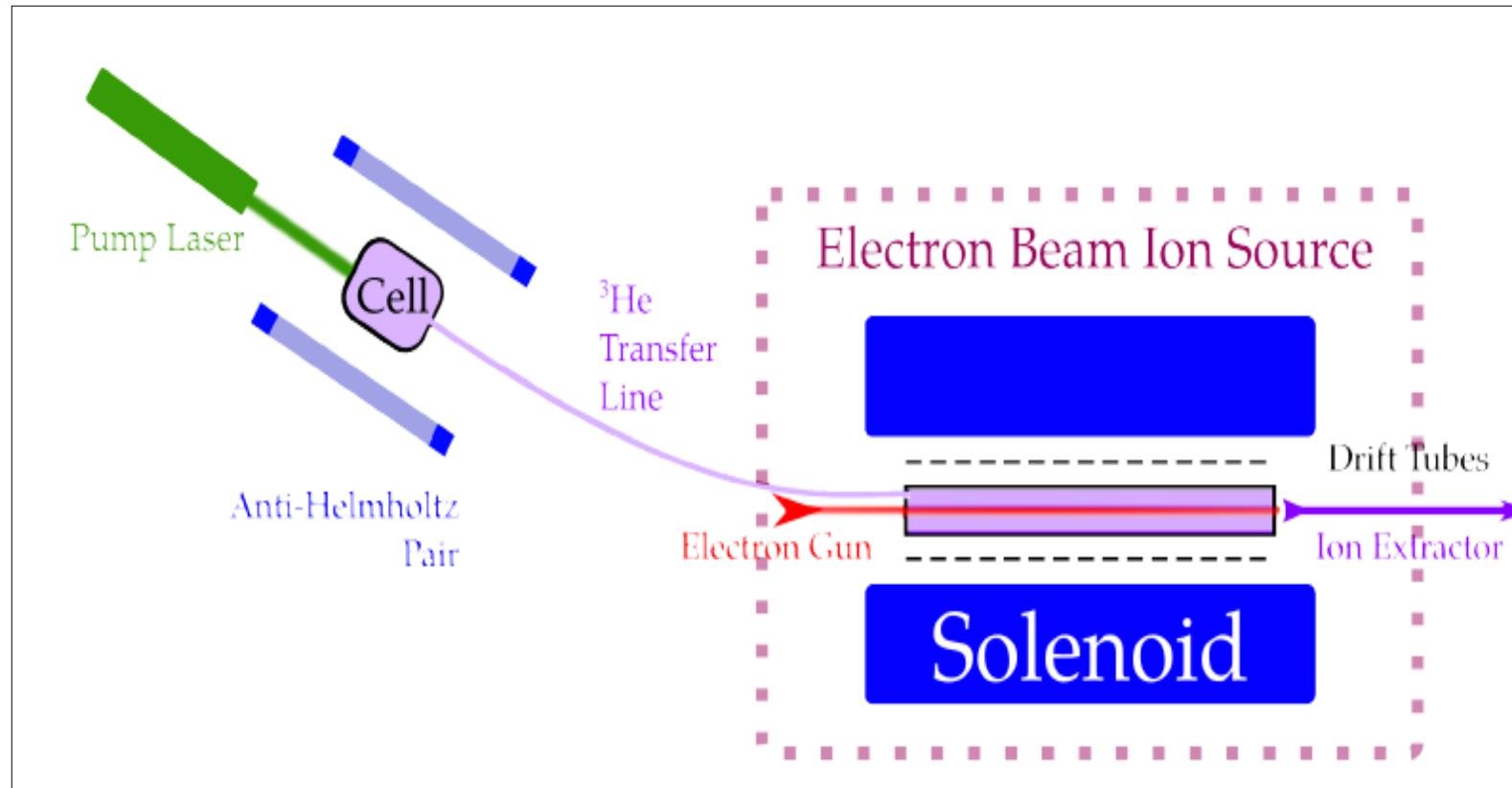
Polarized ^3He Ion Source



Metastability Exchange Optical Pumping



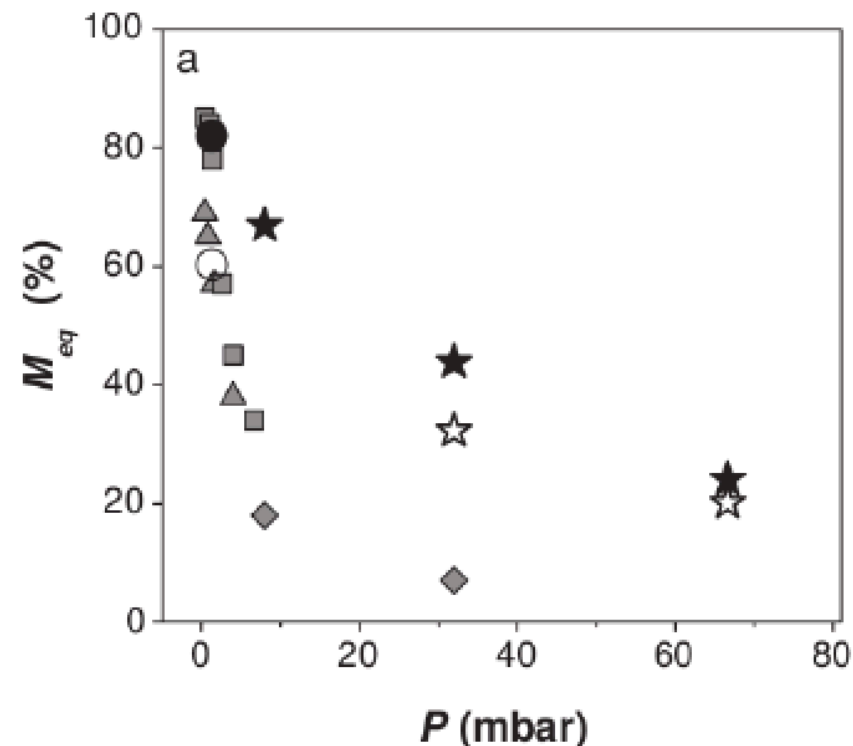
^3He Polarization in Low Field



- Polarize to $\sim 70\%$ at 1 mbar
- Path must be found through depolarizing gradients in stray field
- Path averaged relaxation time is 0.7 s at 0.01 mbar
- Polarizing in low field is feasible but not easy and the maximum polarization is compromised

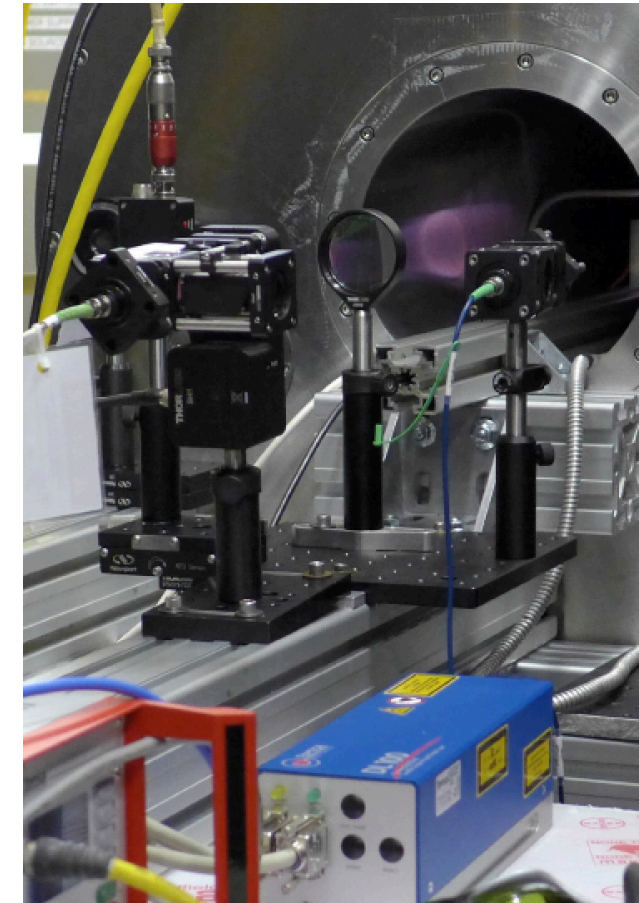
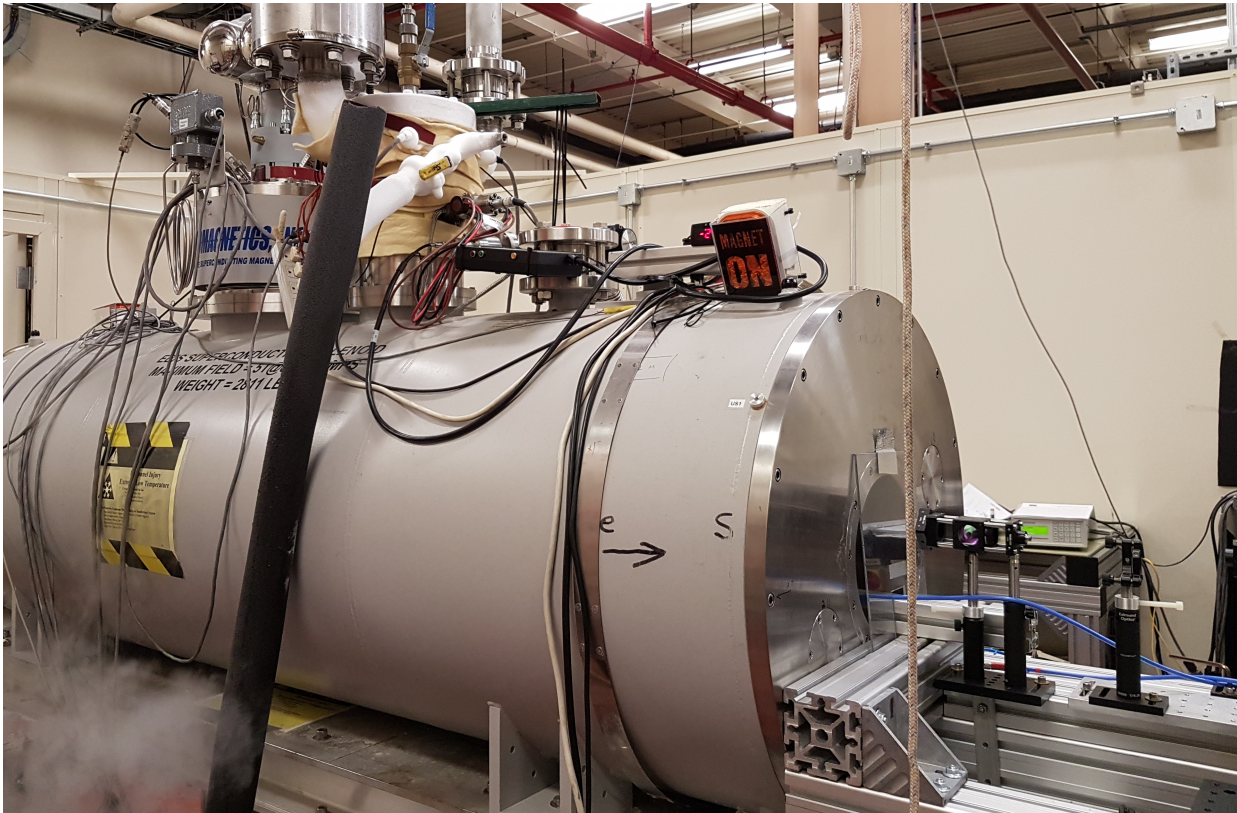
^3He Polarization in High Field

- European group (Paris, Krakow) researching high pressure MEOP, medical applications
- Pioneering achievements in pumping efficiency at high pressures leveraging fields above 1 T in last ten years
- M. Abboud, Europhys. Lett. 68, 2004
 - 1.5 T; 0.5, 2 W OP laser
 - 1.3, 8, 32, 67 mbar
 - Circles and stars are at 1.5 T, others at low field

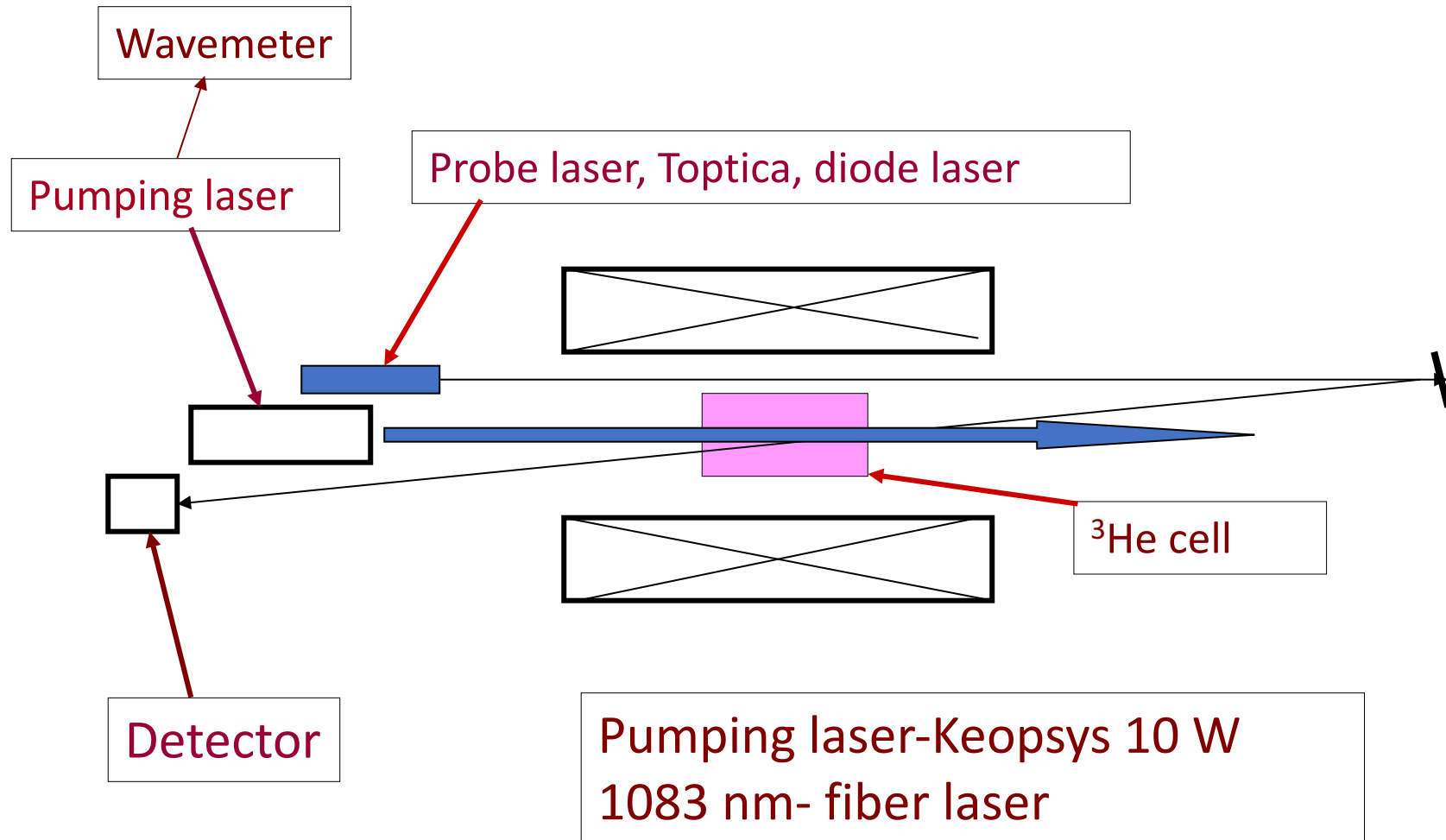


High Field MEOP System in EBIS Spare Solenoid

- ^3He polarization measured with low power probe laser
- Operated at magnetic fields of 1, 2, 3, and 4 T
- Tested sealed cells at 1 mbar: 5cm OD by 5cm long and 3 cm OD by 10 cm long
- Tested open cell system connected to ^3He purification system

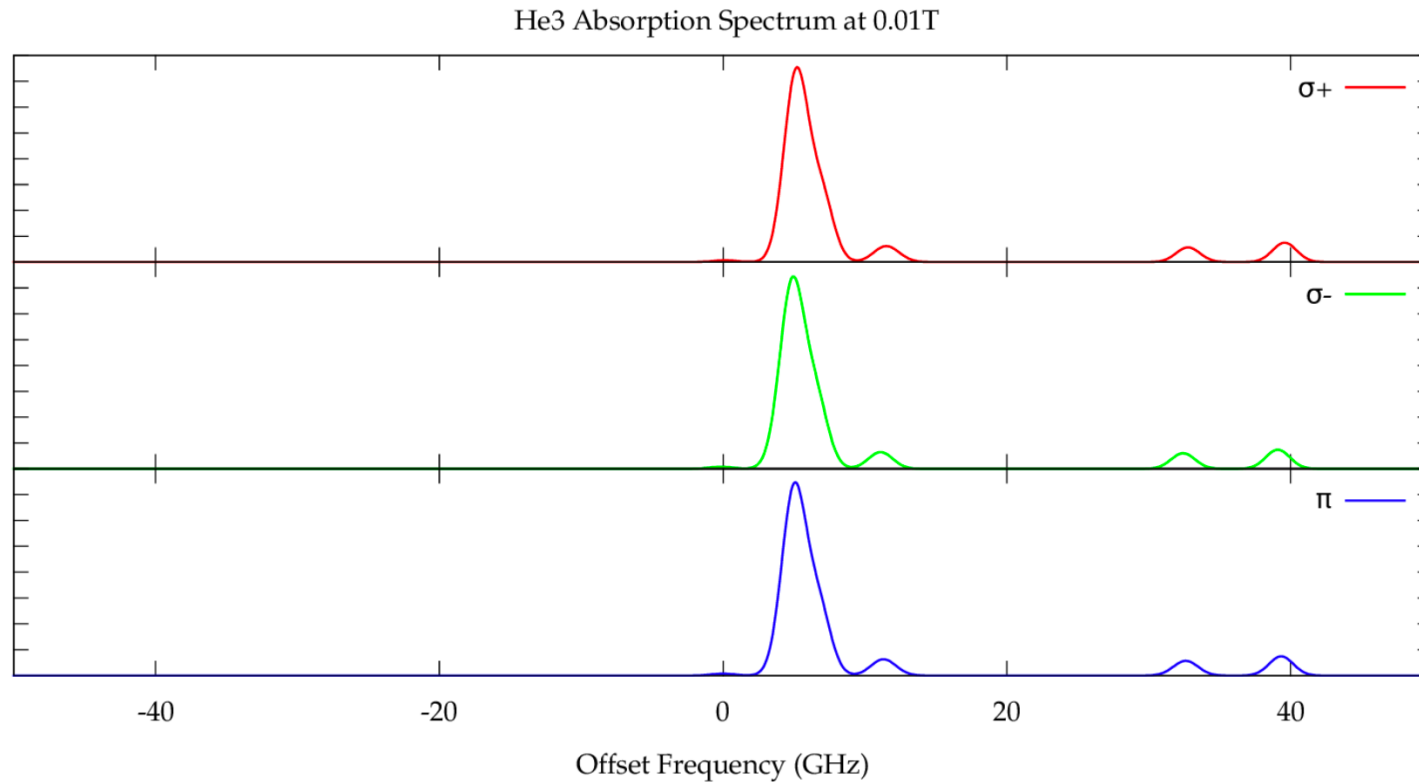


Optical Probe Polarimetry



Optical Probe Polarimetry

- High or low field, no calibration required
 - Sweep low power probe laser through two 2^3S-2^3P transitions to directly probe states^{7,8}

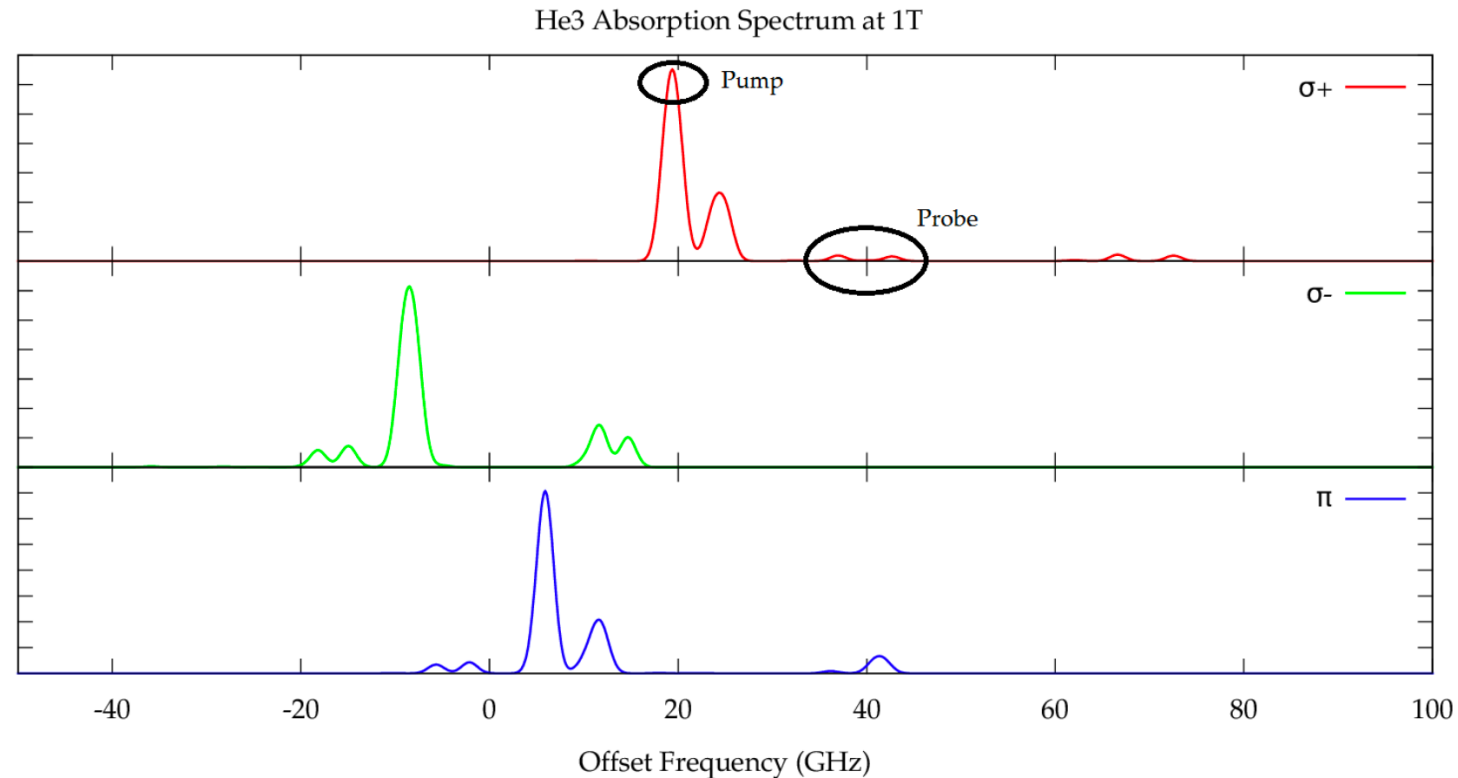


⁷Courtade *et al*, Eur. Phys. J. D 21 (2002).

⁸Suchanek *et al*, Eur. Phys. Special Topics 144 (2007).

Optical Probe Polarimetry

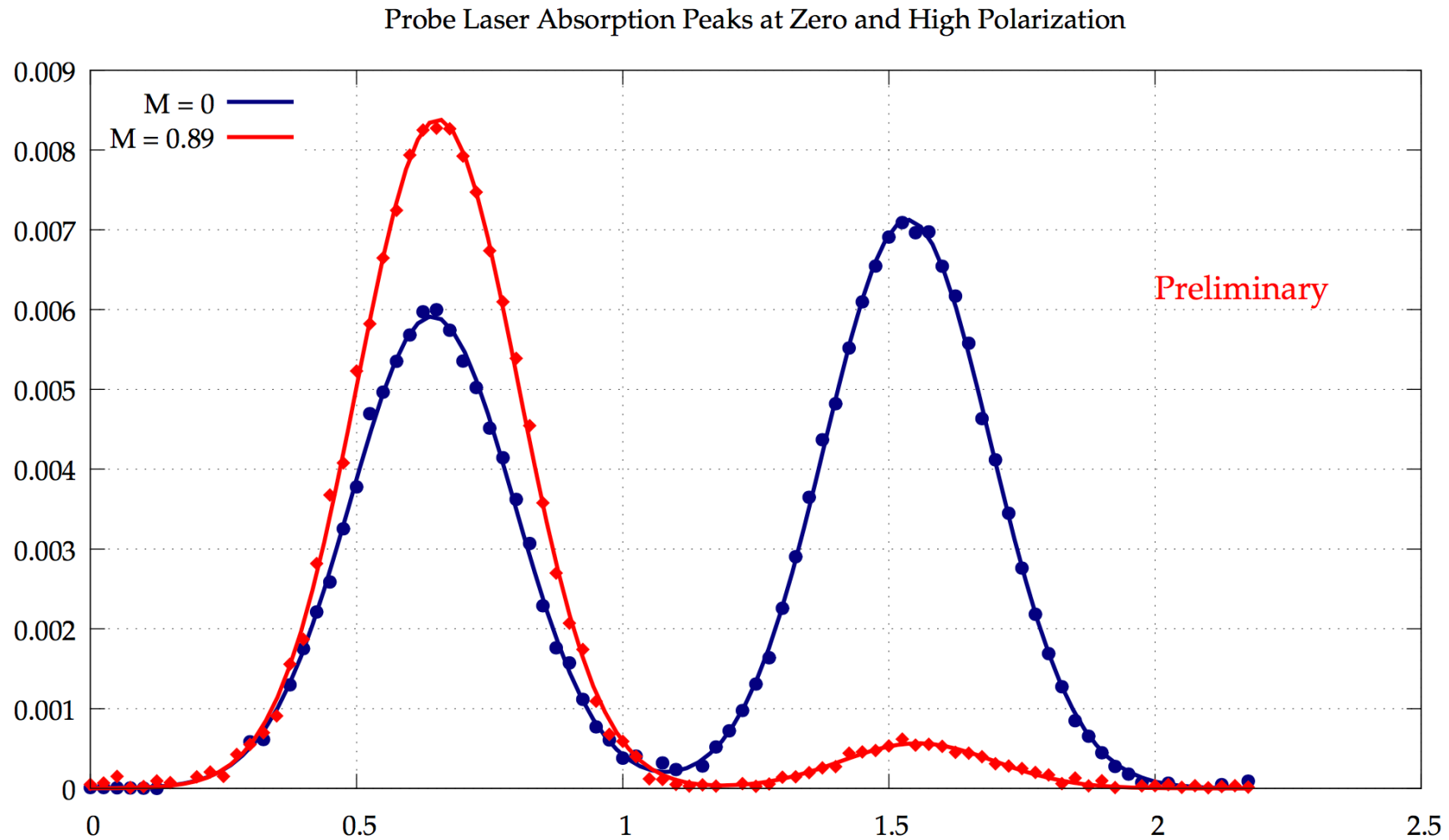
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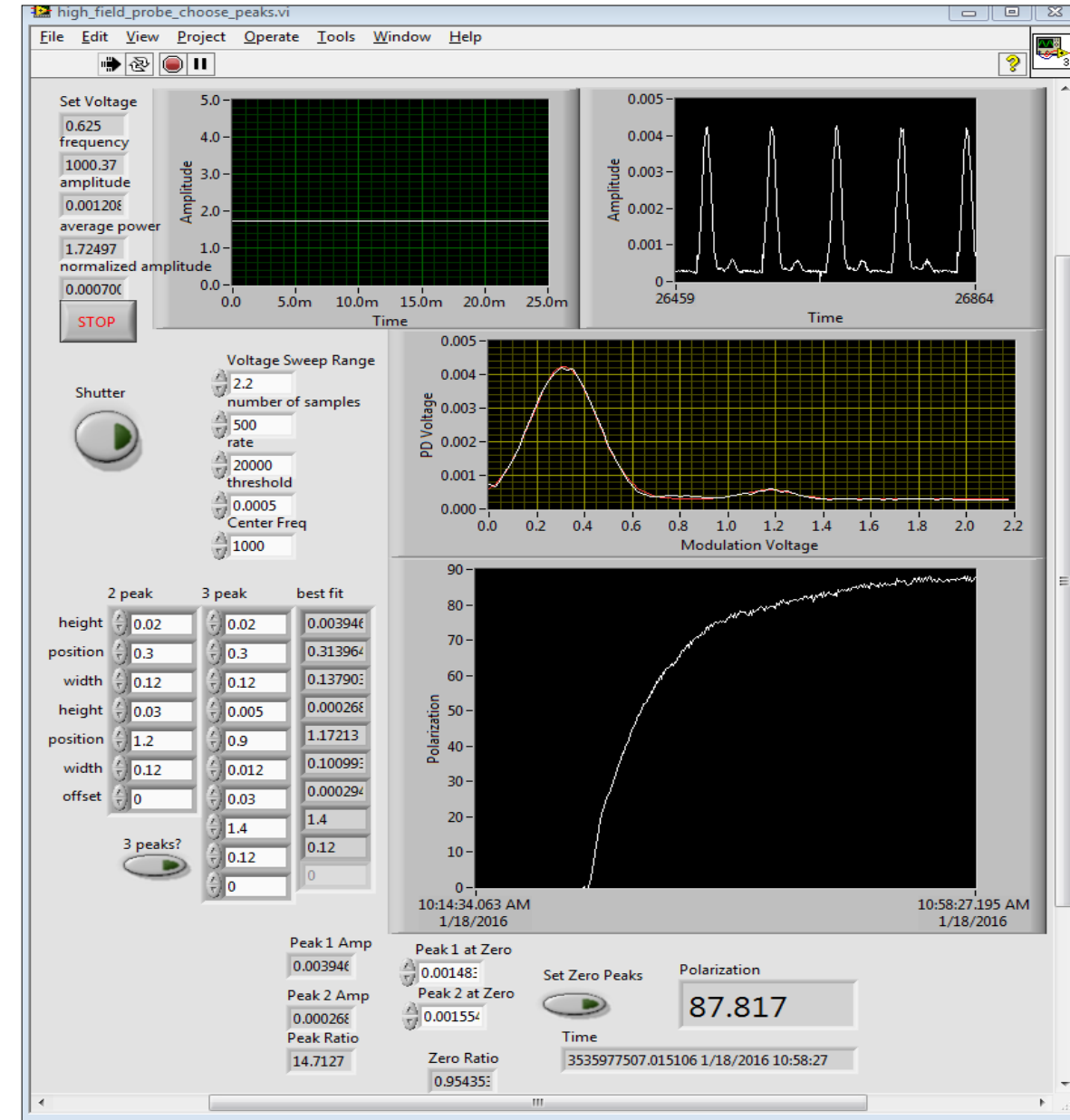
⁸Suchanek *et al*, Eur. Phys. Special Topics 144 (2007).

Measuring Optical Pumping

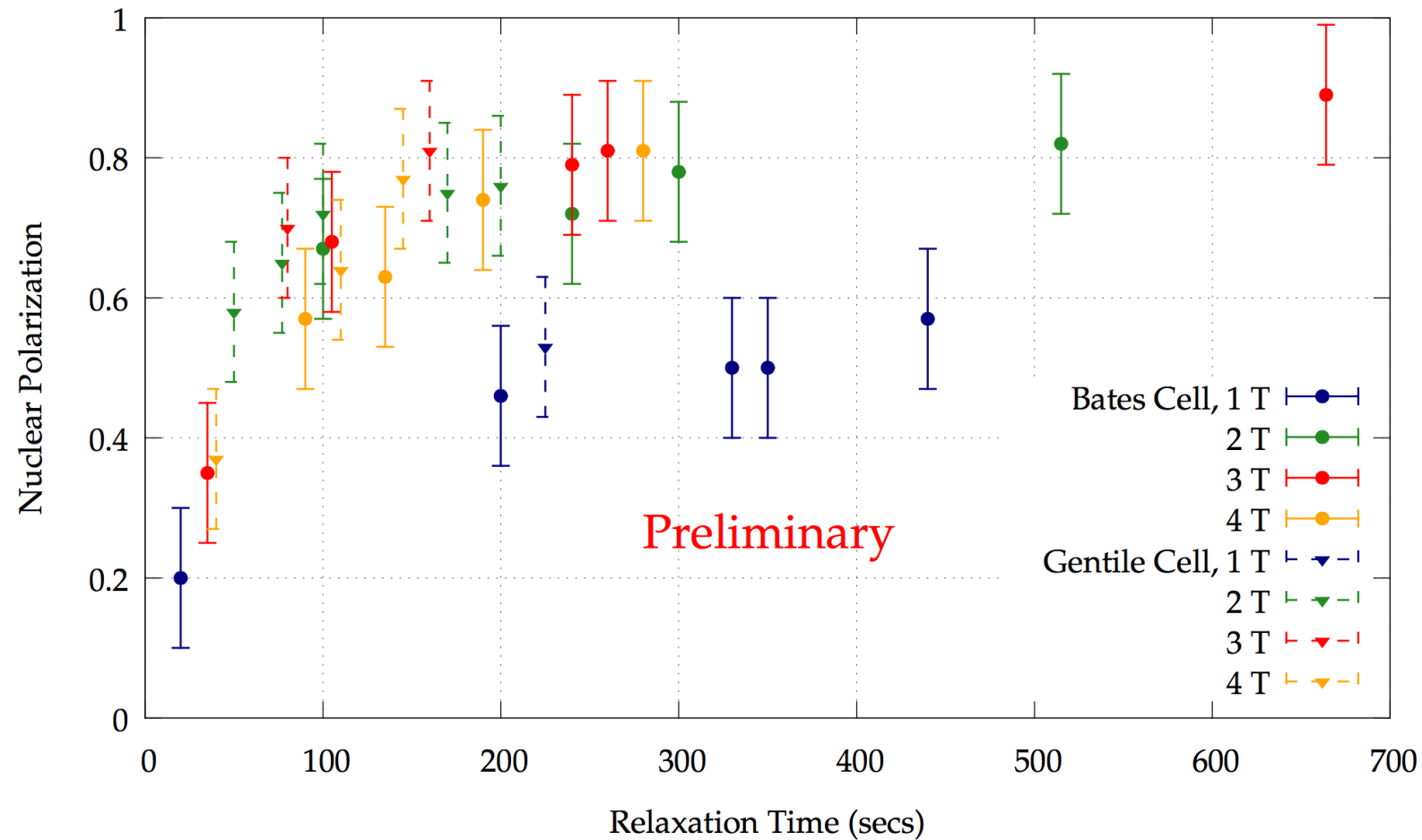


High Field MEOP Conclusions at BNL

- MEOP still works at magnetic fields over 1 T.
 - Zeeman splitting reduces electron-nucleus spin coupling for polarization but also inhibits relaxation channels.
- First results for MEOP at 3 & 4 T and 1 mbar are near 90%.
- The same ^3He cell that reached 70% polarization at 10 G, easily reached over 80% at high field.
- No gas transfer through large field gradients.
- Longitudinal relaxation due to field gradients is naturally slow at high field.

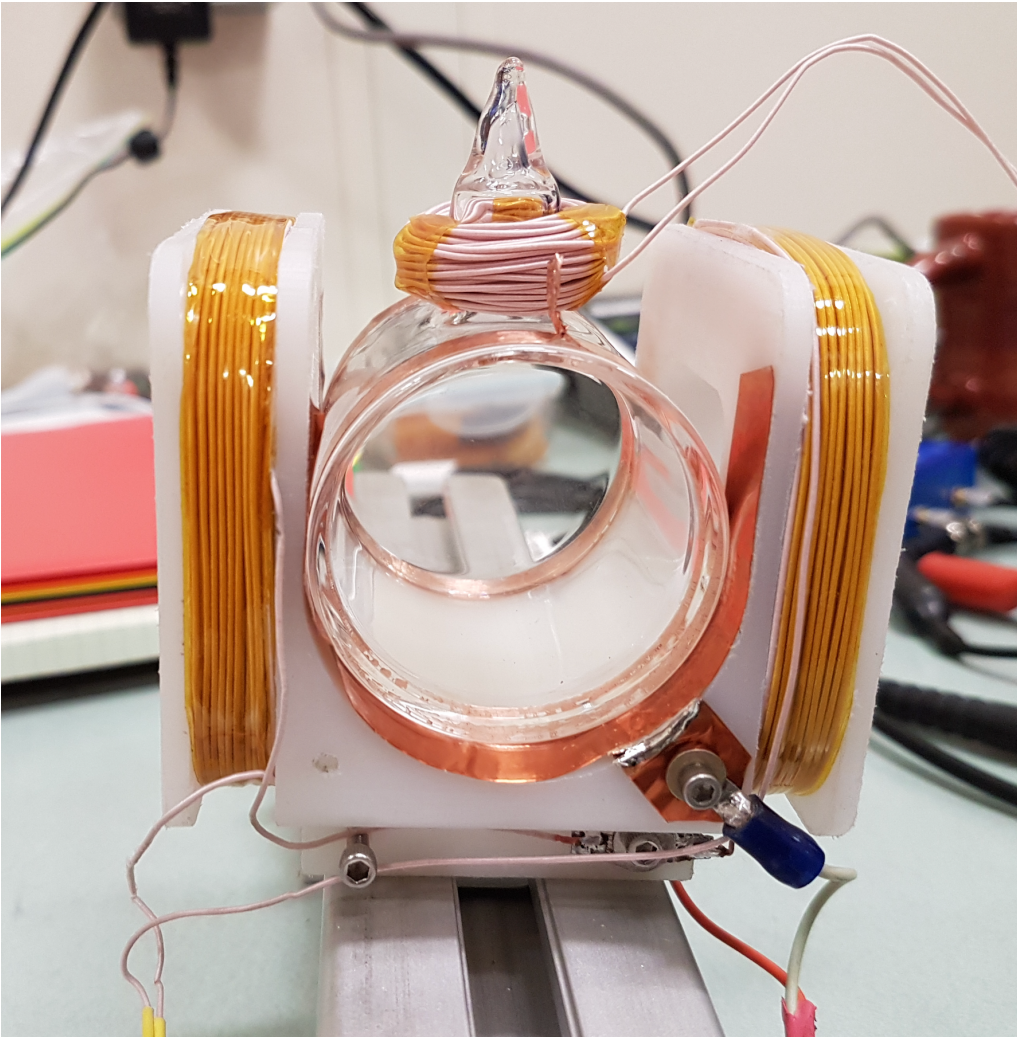


High Field Polarization Results



- Preliminary results found by J. Maxwell. Error bars set at 10% while being investigated.
- ^3He Polarizations were measured between 80-90% with sealed ^3He cells between 1-4 T.

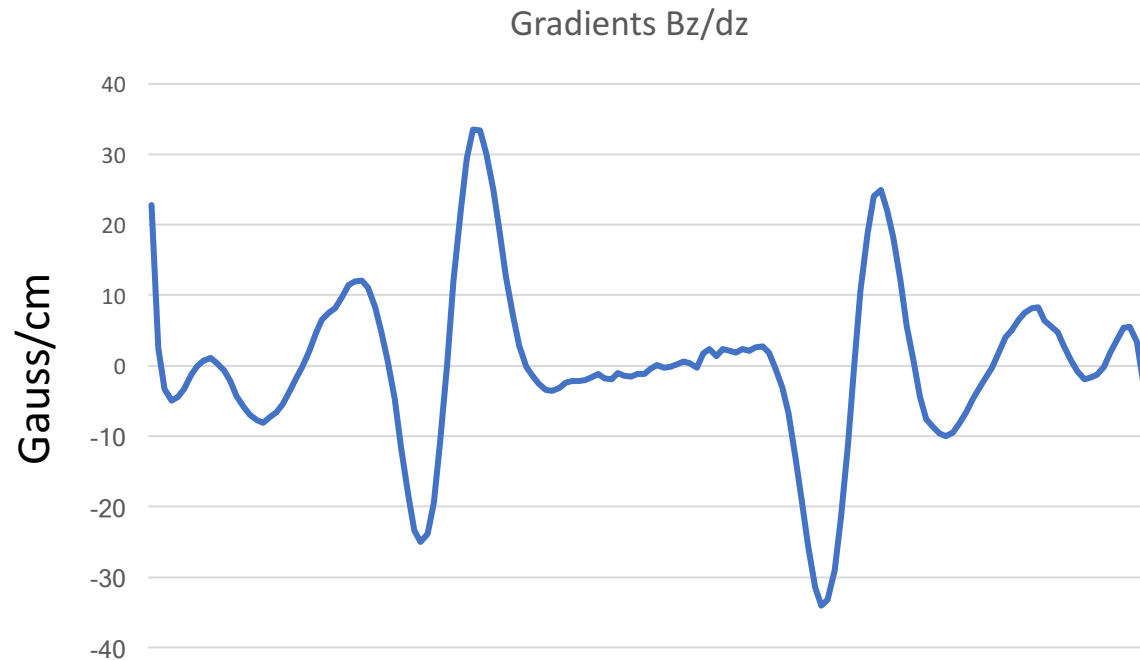
High Field NMR Polarimeter



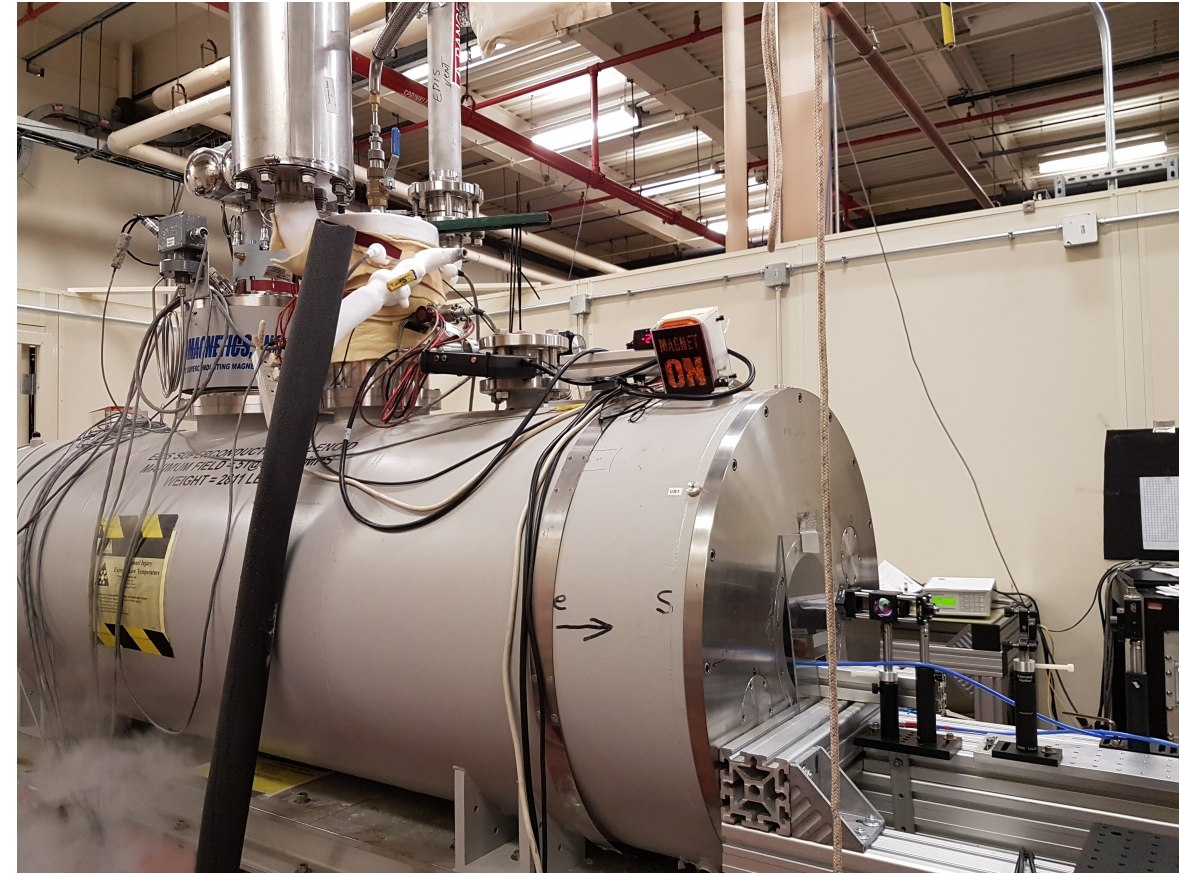
An NMR system is being developed to absolutely measure in a second, independent way the ^3He polarization.

Currently the field homogeneity of high field magnets at BNL is not uniform enough to see a clear resonant NMR signal.

Field Map of Spare EBIS Solenoid

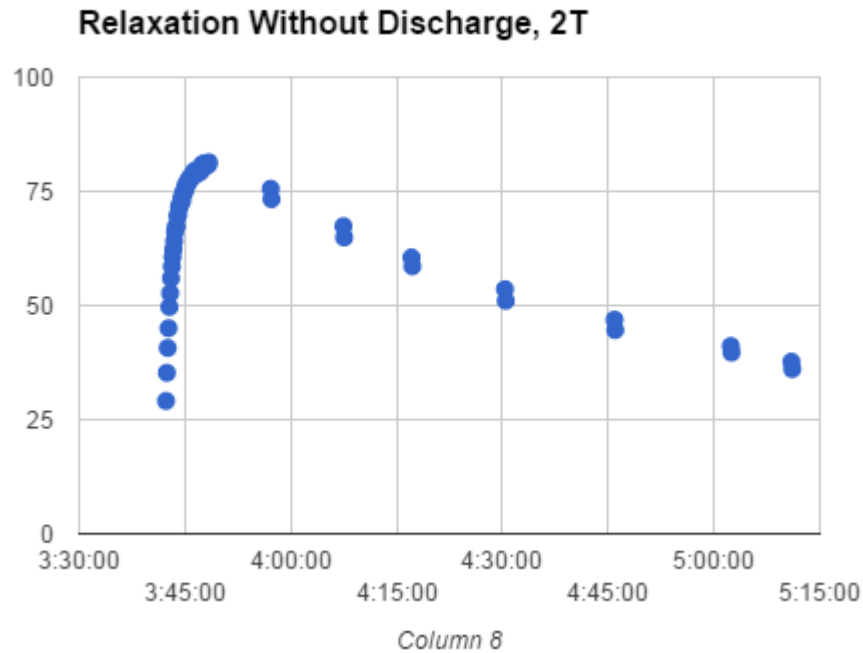


- In the multi-Tesla regime, field homogeneity needs to be 1-10 ppm to see a clear NMR signal.
- The EBIS solenoid was designed for an ion source and has 0.5% homogeneity (the measured homogeneity is 0.01%).



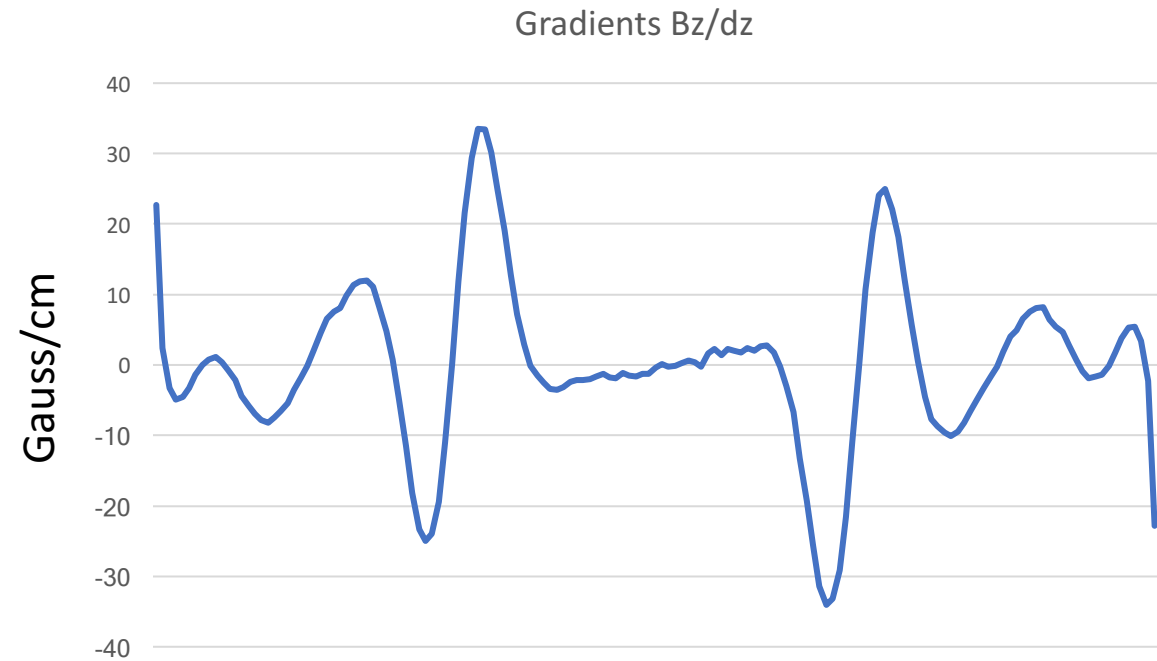
$$\frac{1}{T_2} \approx \frac{8R^4 |\vec{\nabla} \Omega_{1z}|^2}{175D}$$

T1 Relaxation in Spare EBIS Solenoid



T1 Relaxation measured at 2 T.

$T_1 \approx 5000 \text{ s}$



$$\frac{1}{T_1} \approx D \frac{|\vec{\nabla} \Omega_{1x}|^2 + |\vec{\nabla} \Omega_{1y}|^2}{\Omega_0^2}$$

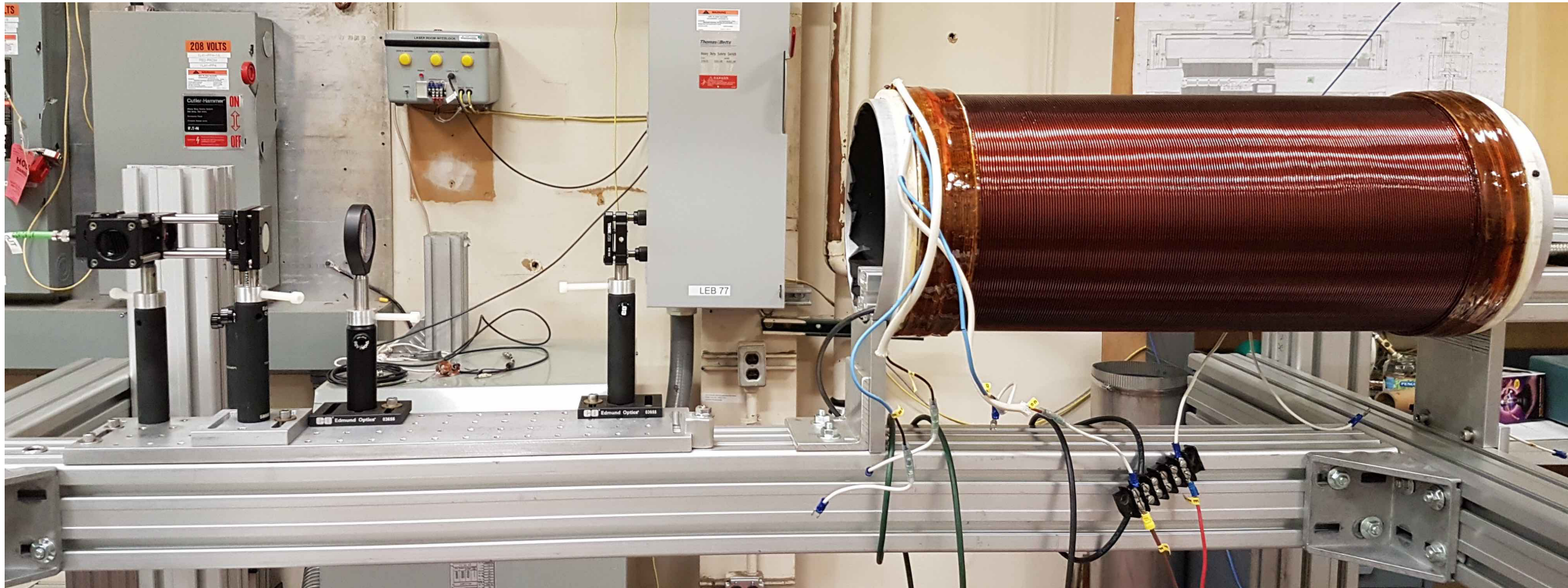
Assume dBx=dBy=dBz=5 G/cm (0.5 mT/cm)

$D = 1880 \text{ cm}^2/\text{s}/\text{mbar}$

$B_0 = 2\text{T}$

$T_1 \approx 4000 \text{ s}$

Low Field NMR Development

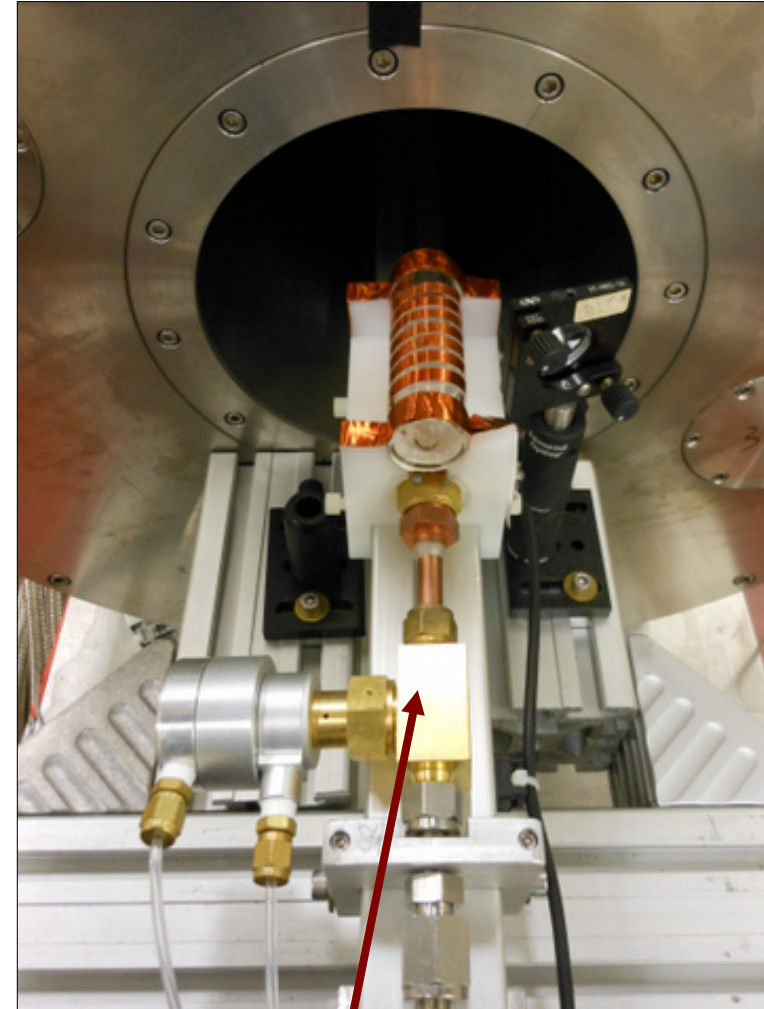


- At 5 Amps current, $B \approx 25$ Gauss.
- Field gradients at 2 Tesla were of order 10 Gauss/cm.
- After NMR is successful at low field, we will modify the system for high field and transport it to an high-homogeneity NMR magnet.

Open ^3He Cell and Gas Purification System

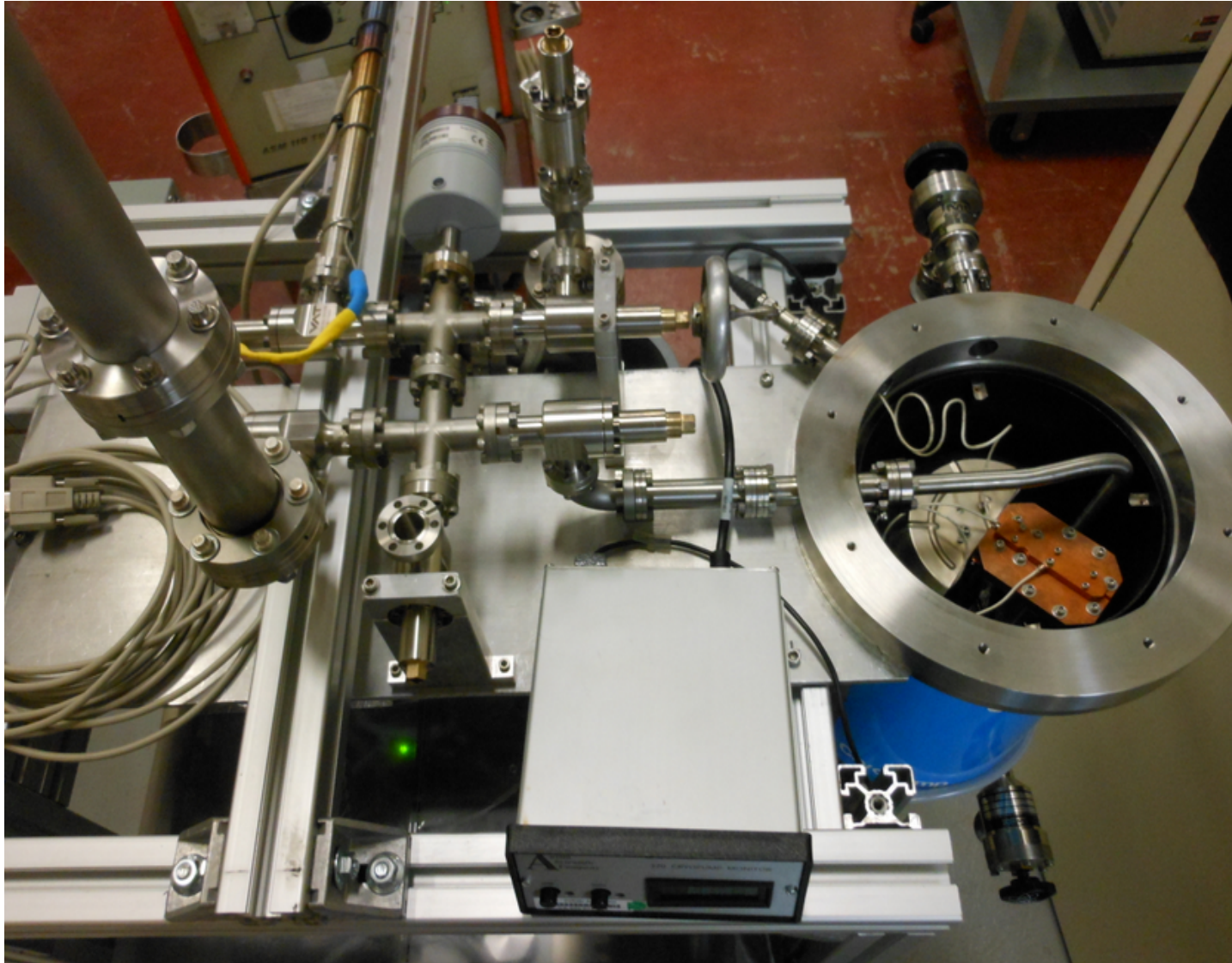


Open ^3He Cell and Gas Purification System

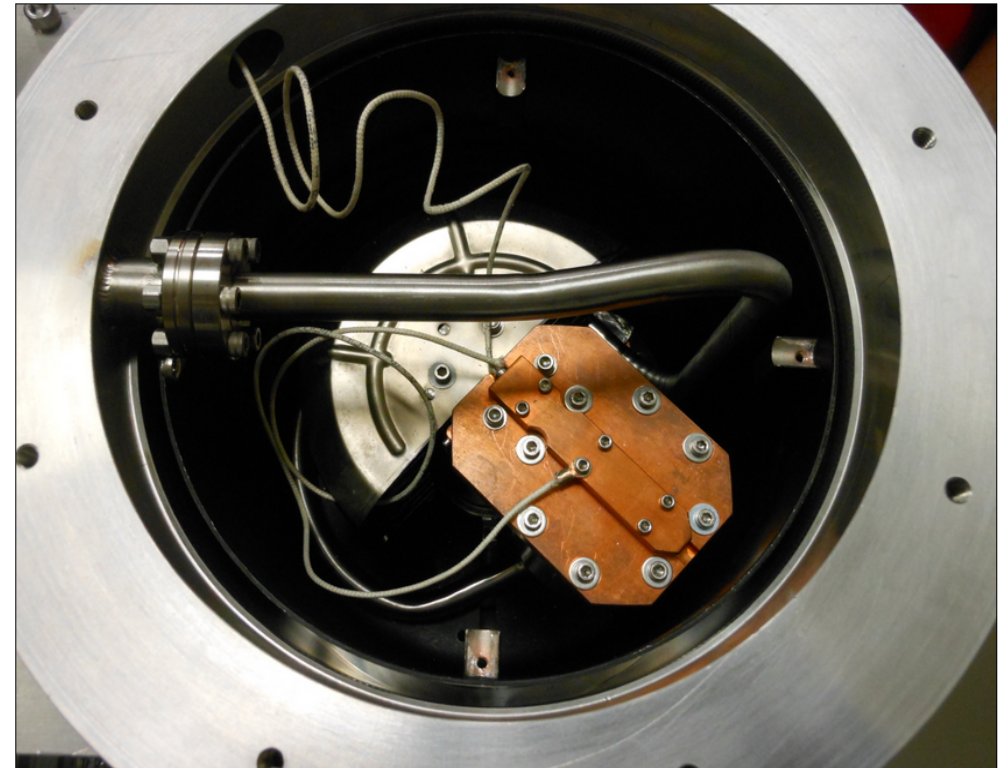


Non-magnetic brass pneumatic
remotely controlled Isolation Valve

Open ^3He Cell and Gas Purification System

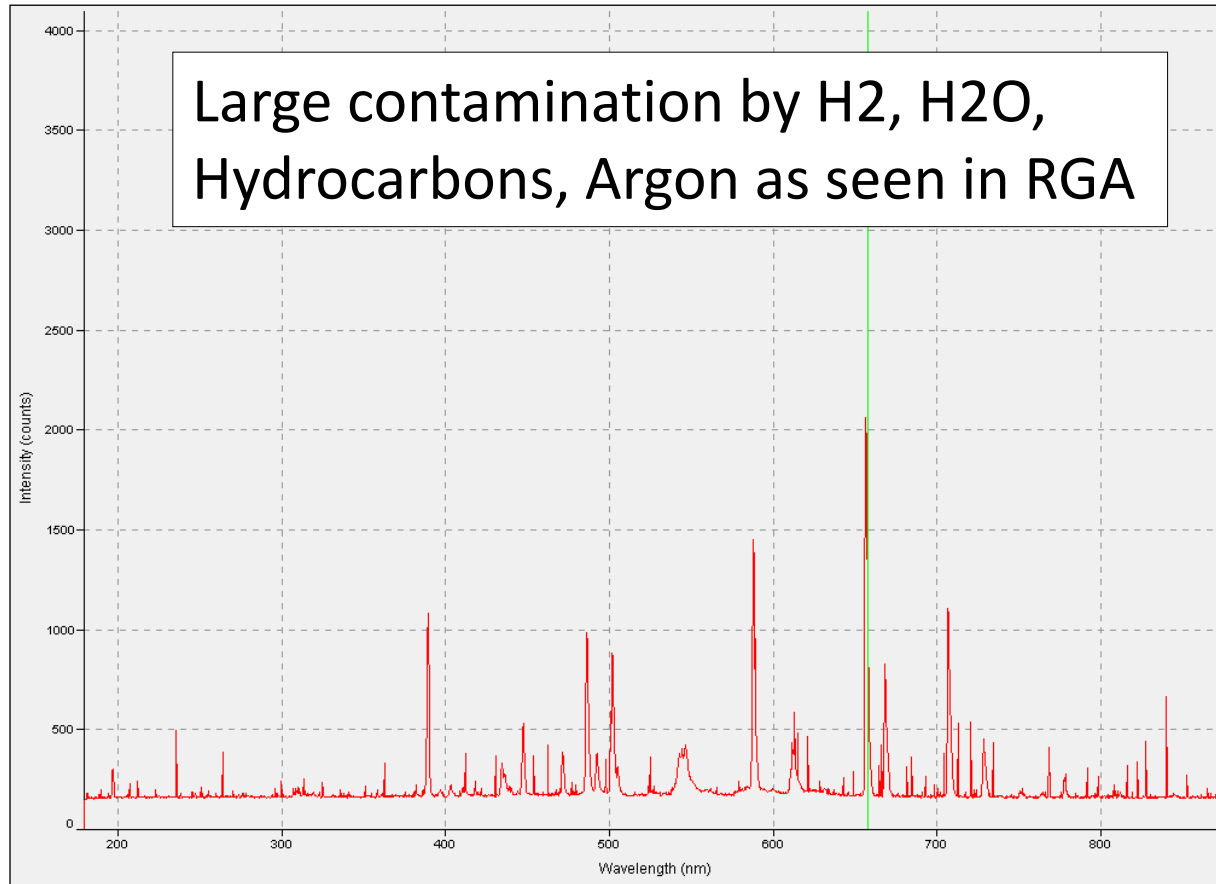


^3He cyro-purification system built in CTI-8 cryo-pump. Pumps everything except helium.

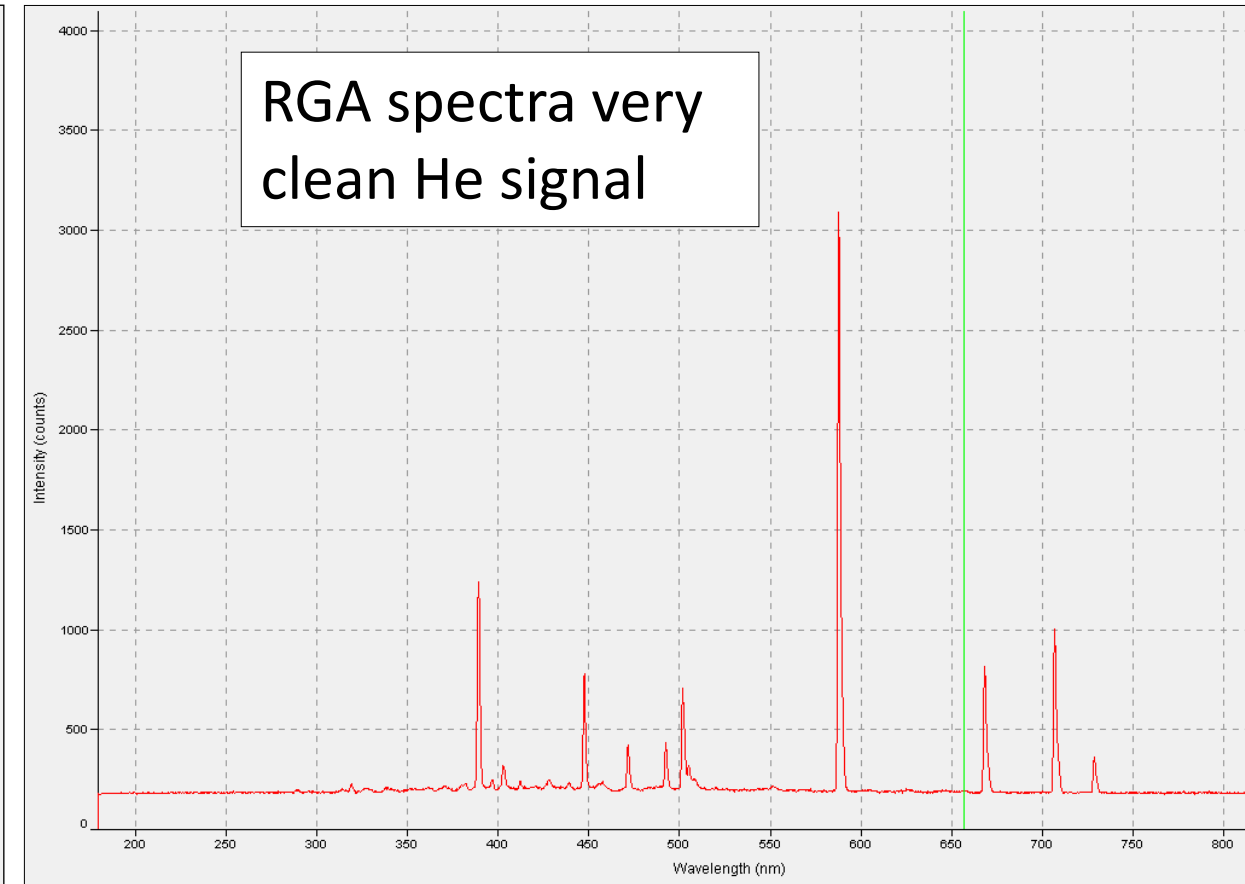


RGA Spectra in ^3He Open Cell

Before purification with cryo-pump

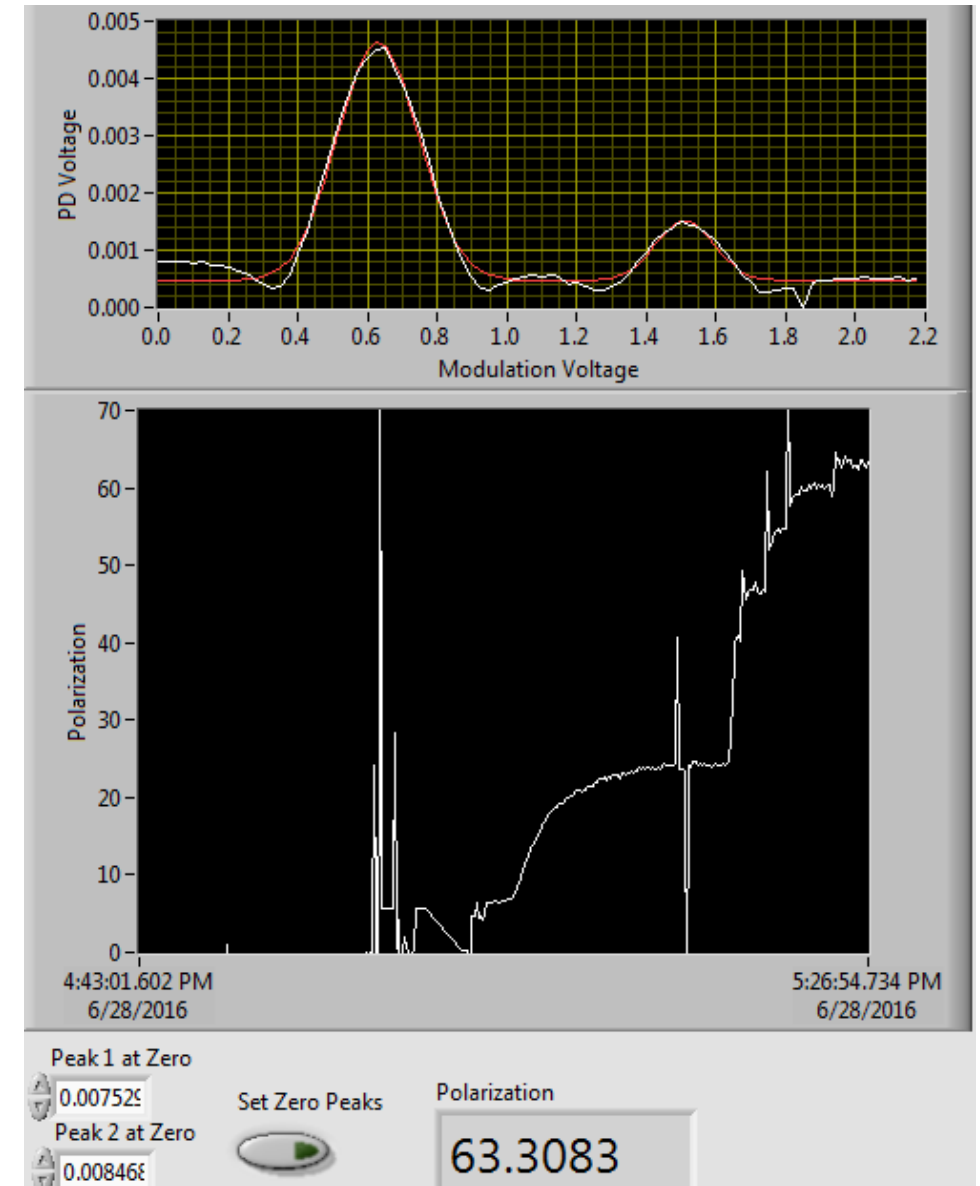


After purification with cryo-pump



^3He Open Cell Results

- ^3He pressure can be controlled with cryo-pump temperature.
- Polarizations have been measured up to 73% at 4.5 mbar.
- Relaxation time of 30 s measured in open cell. Relaxation rate is limited by metal surfaces in pneumatic valve.
- Valve construction and open cell design will be optimized to improve relaxation rate and maximum polarization.



RF Discharge at 2 T

- RF discharge parameters strongly affect maximum polarization.
- RF discharge power needs to be reduced as ^3He polarization increases.
- Optimization of the ^3He cell geometry and placement of RF electrodes should improve polarization.



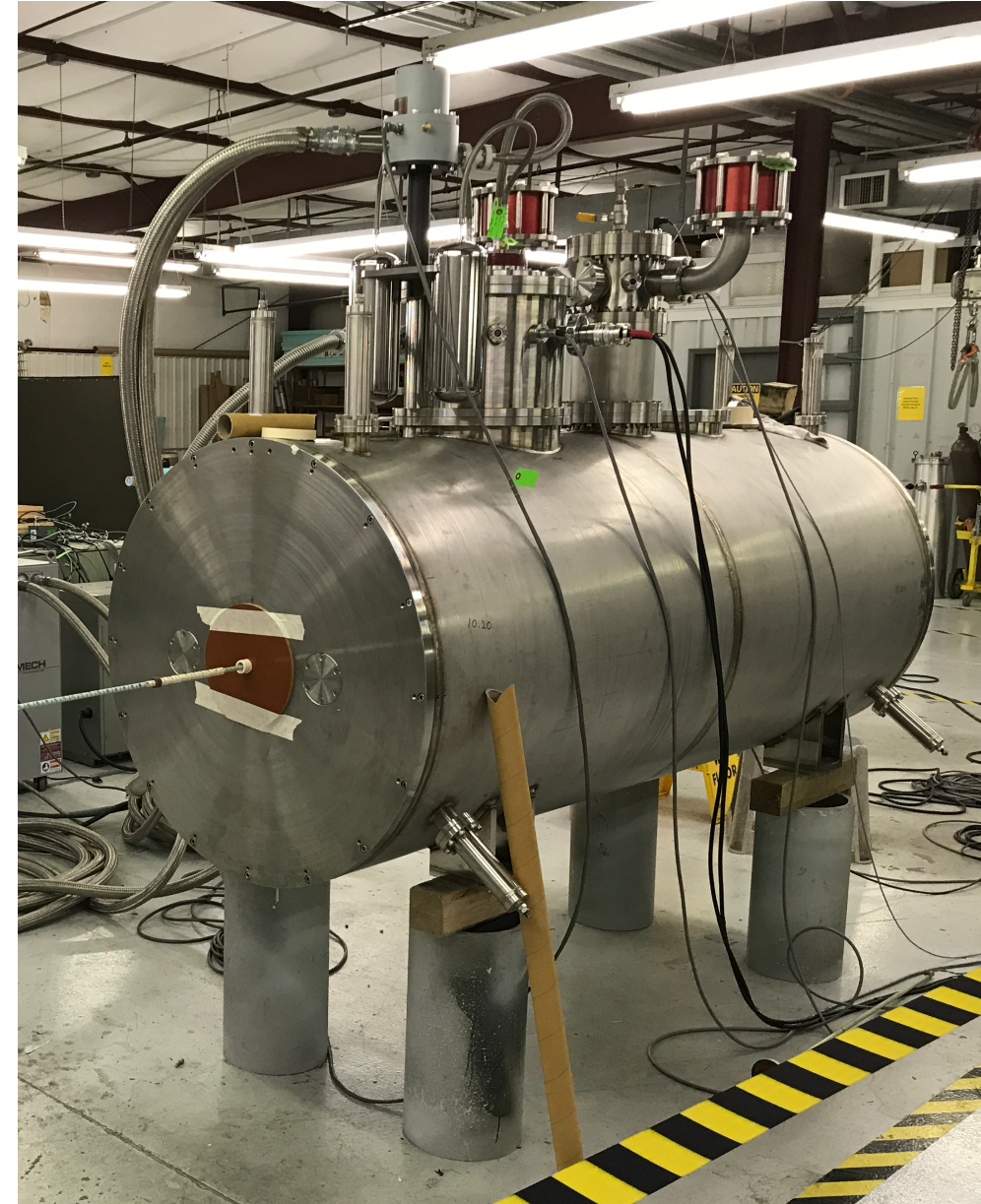
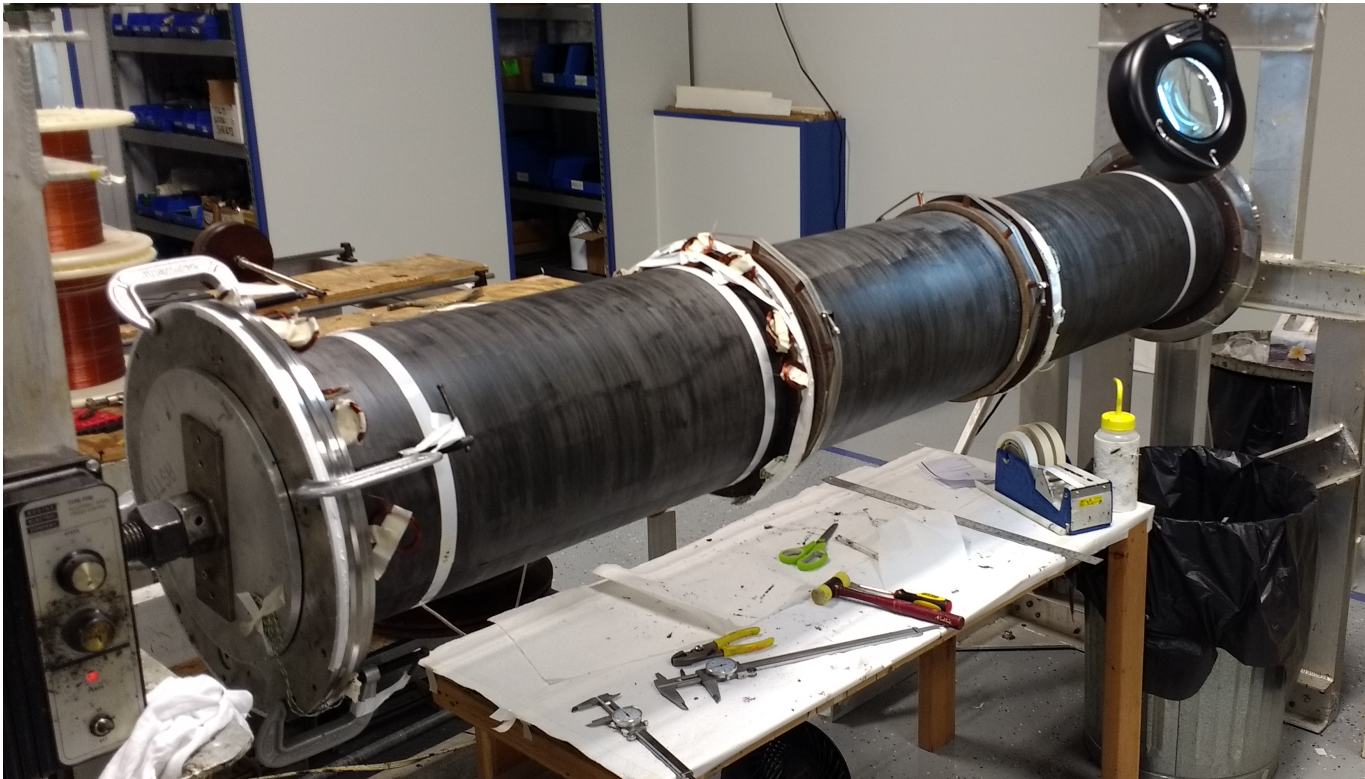
High Field MEOP Lab in March 2017



Extended EBIS upgrade is funded and EBIS spare solenoid was shipped to CryoMagnetics for reinforcement.

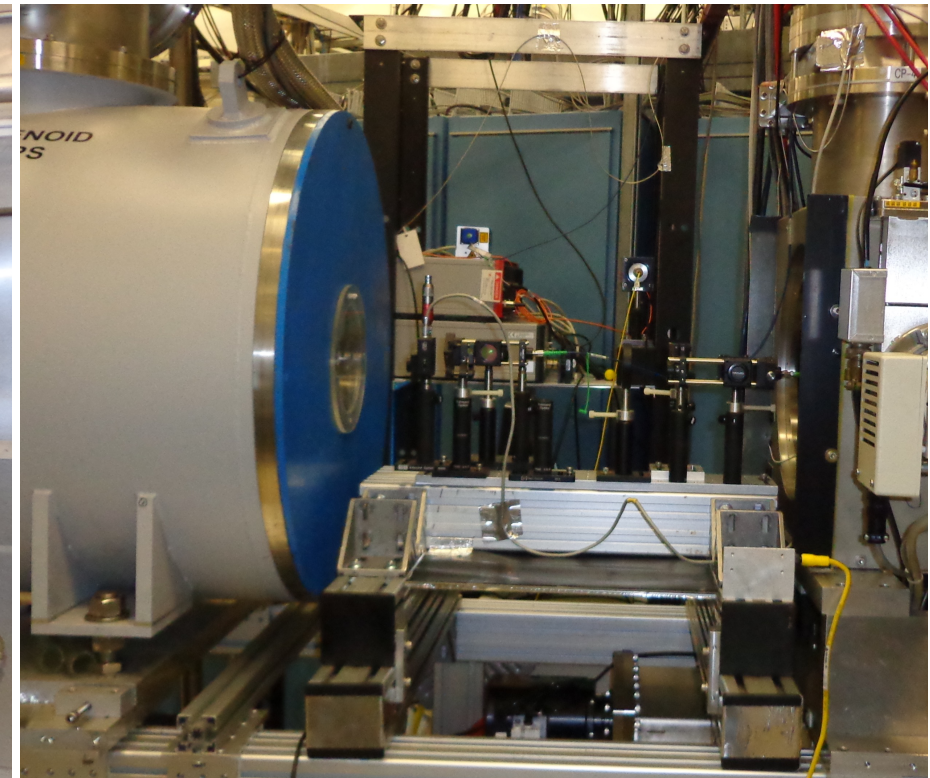
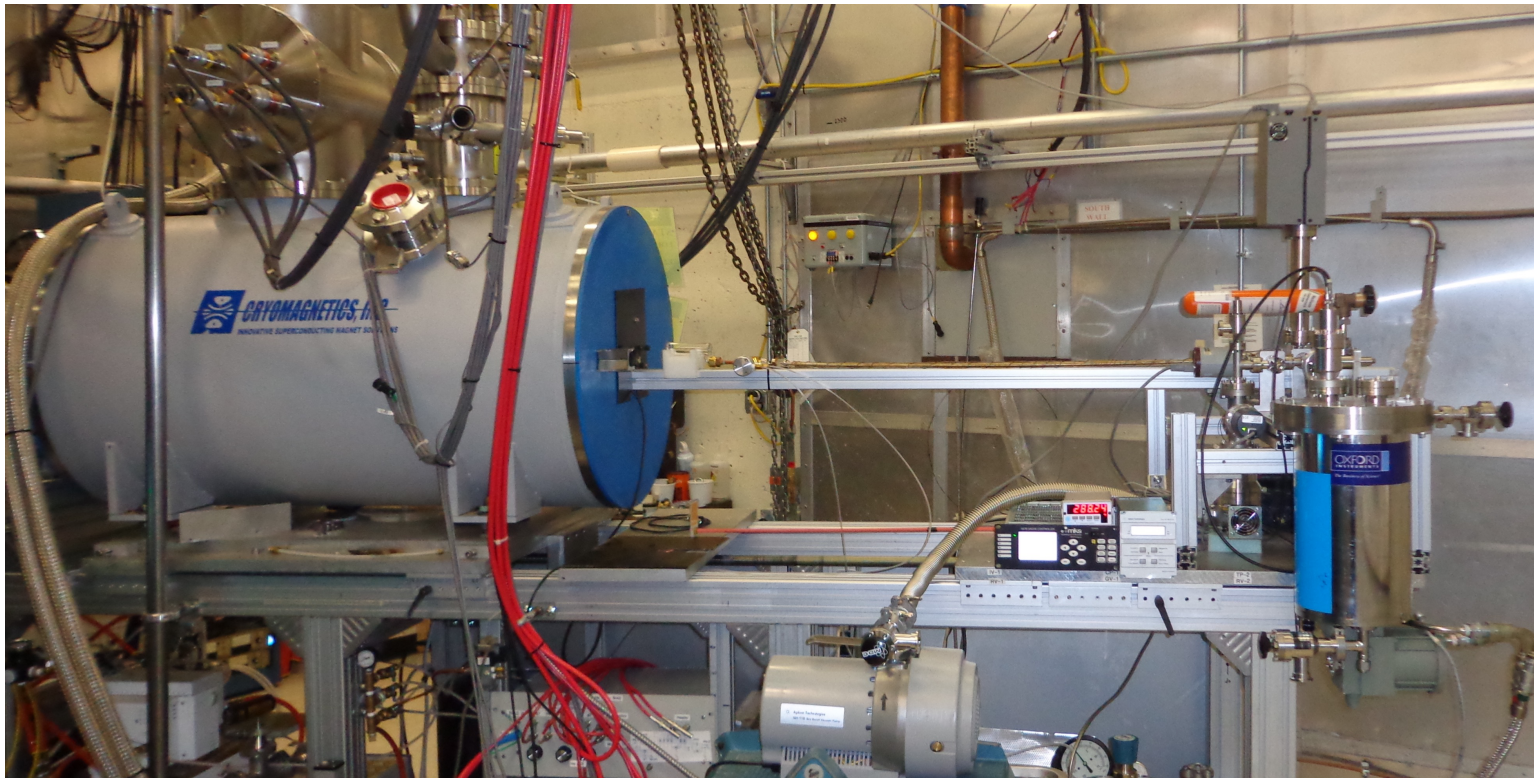
Extended EBIS 5 T Solenoids

- Rebuilt solenoid has completed the preliminary factory tests.
- The new solenoid should be ready for factory testing in November.
- Shipment of both magnet systems to BNL is scheduled for December.

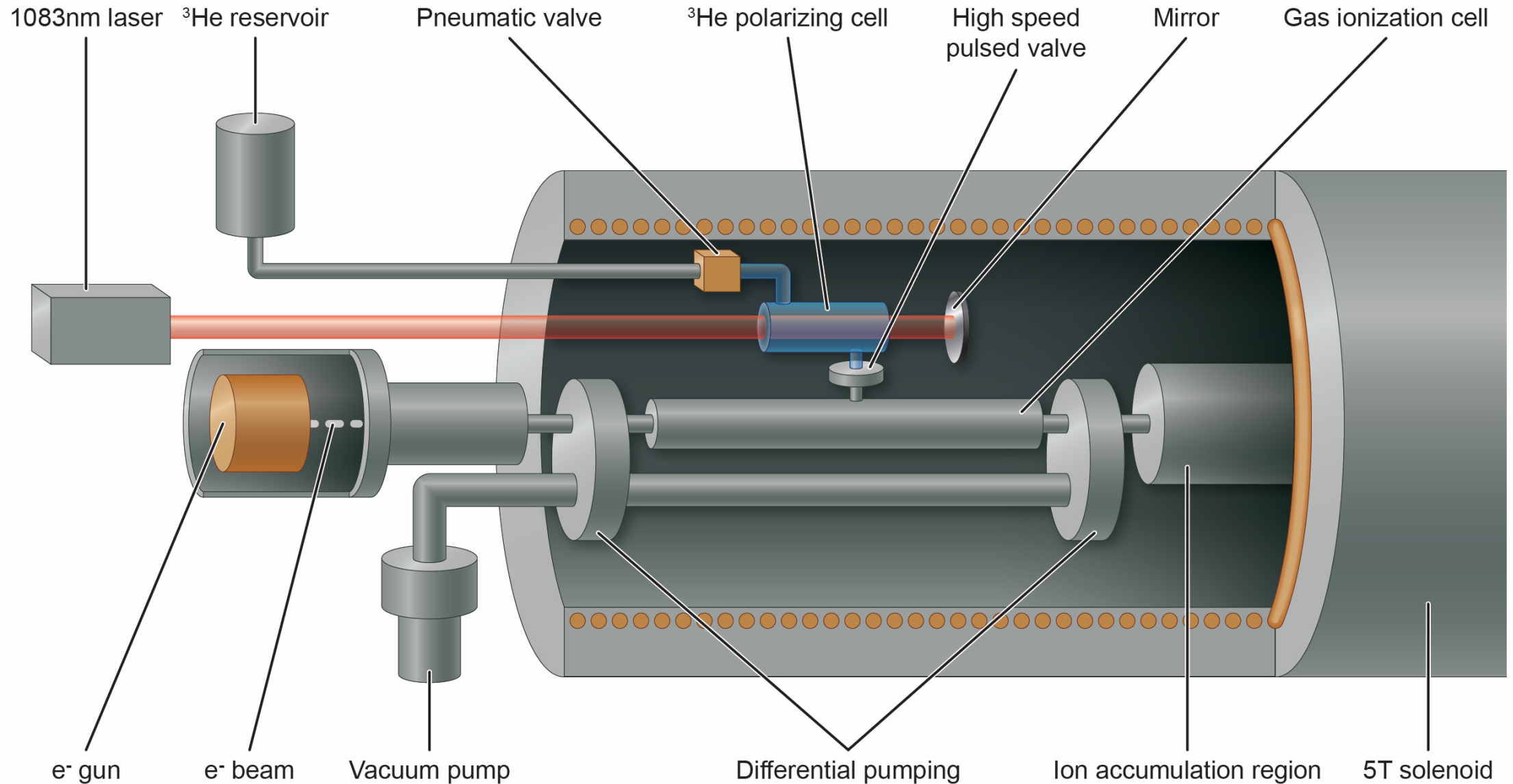


New High Field MEOP System

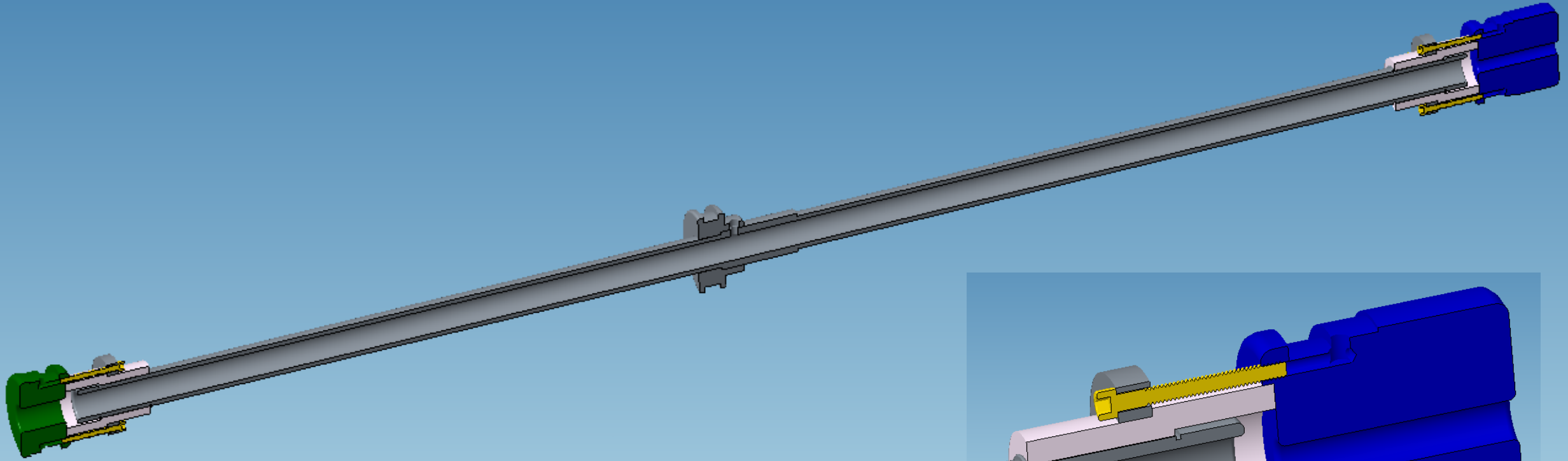
- No polarized proton runs are scheduled for 2018 RHIC program.
- OPPIS (RHIC's polarized proton source) was converted into our new high field MEOP system for polarizing ^3He .



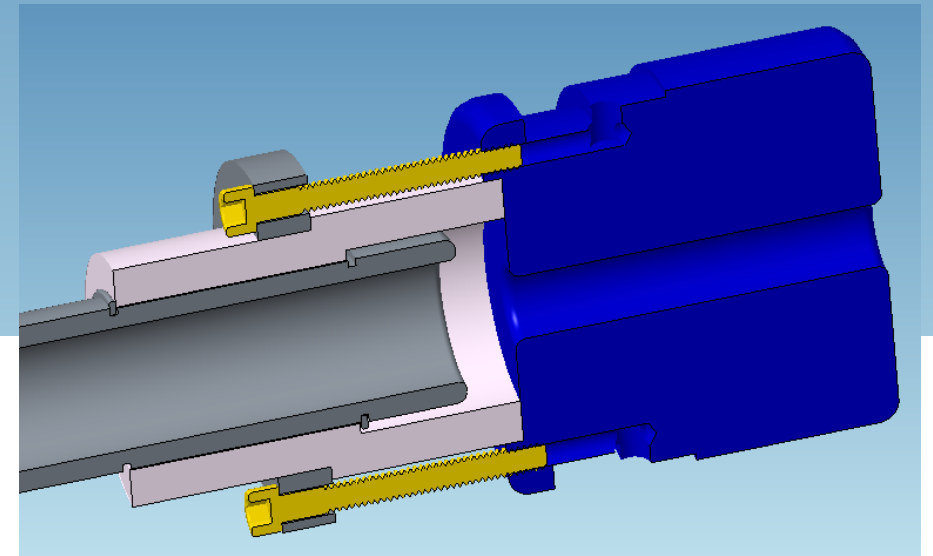
Polarized ^3He Ion Source



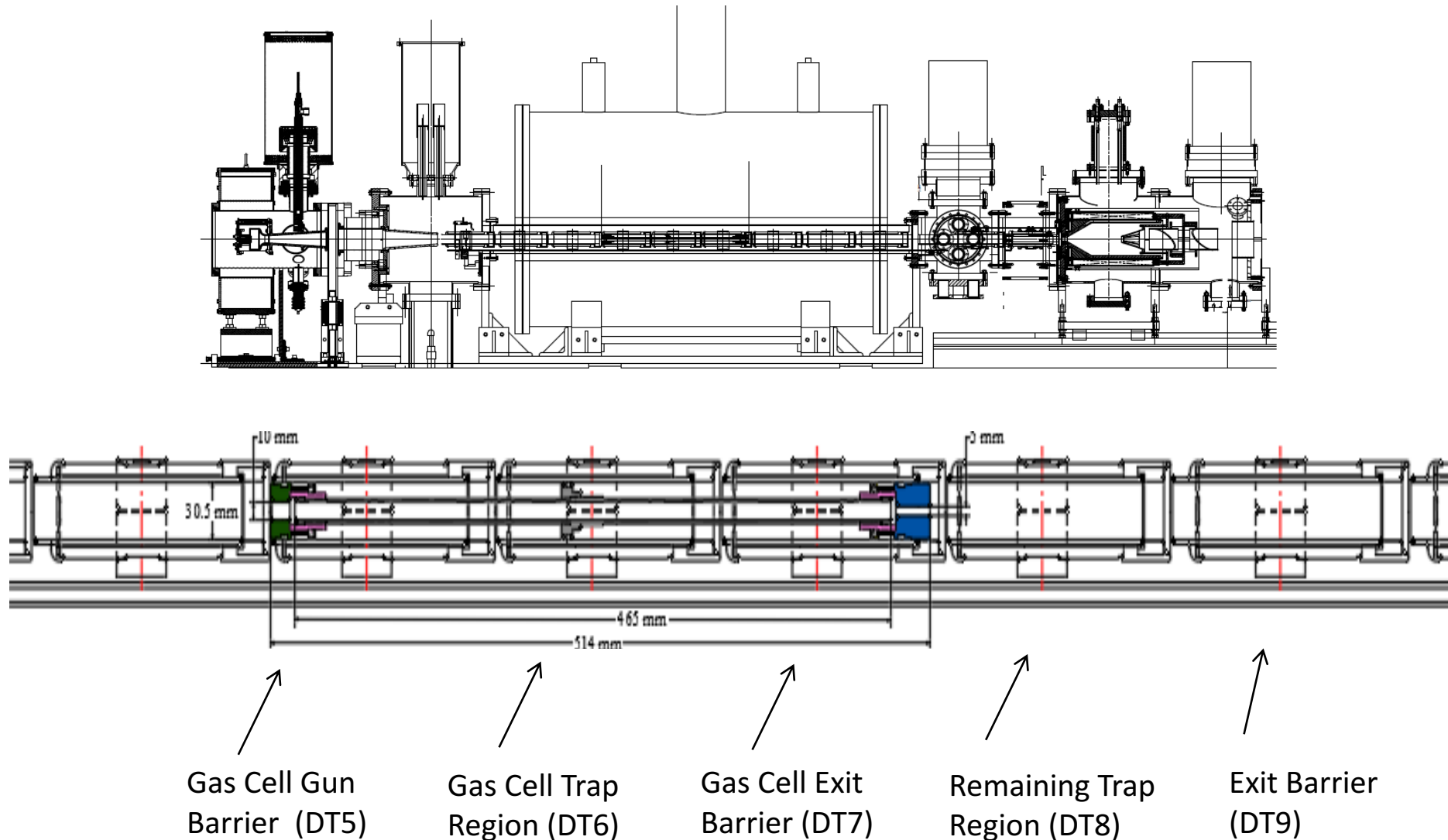
Gas Ionization Cell for Electron Beam Tests at the BNL TestEBIS



46 cm long, 1 cm diameter gas ionization cell
3 cm long, 0.5 cm diameter down stream barrier (blue)

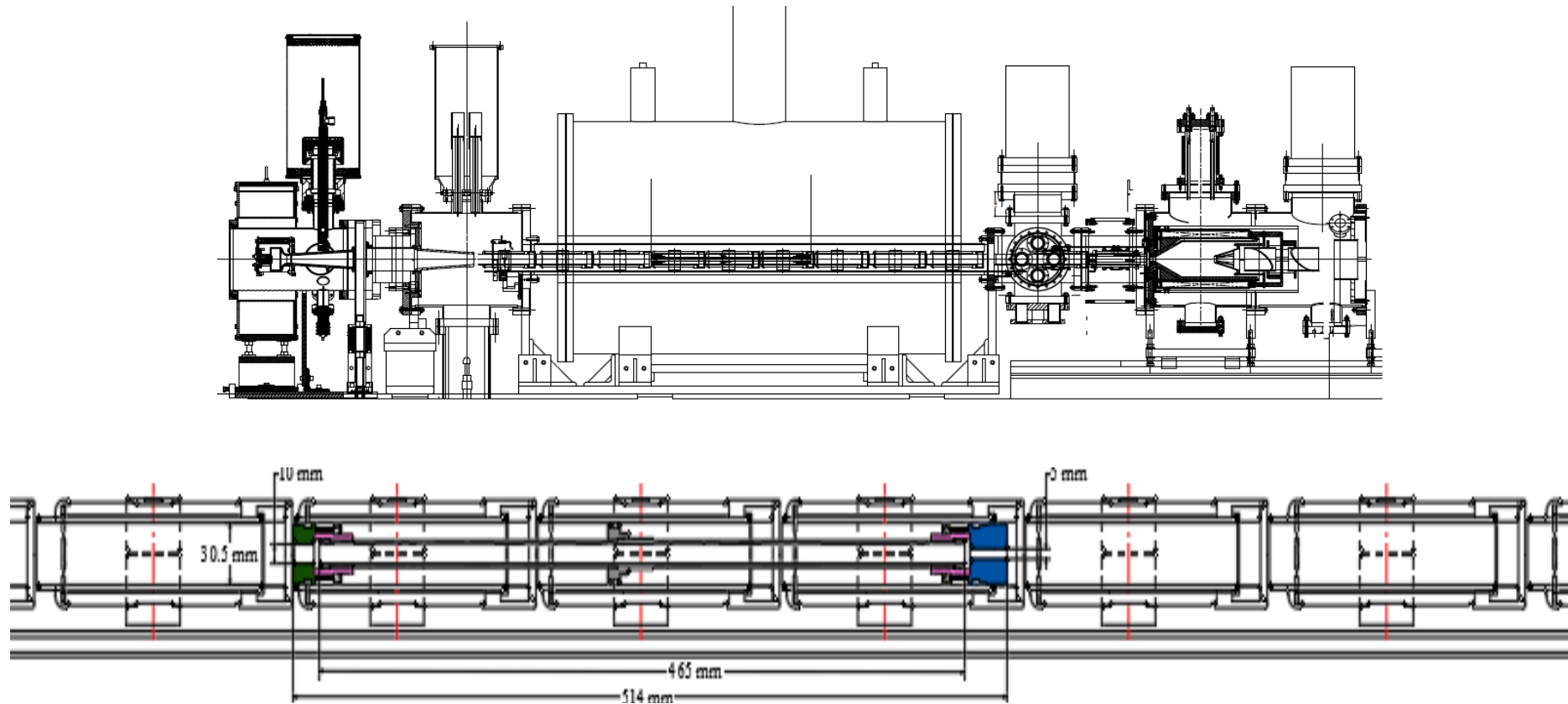


Gas Ionization Cell for Electron Beam Tests at the BNL TestEBIS



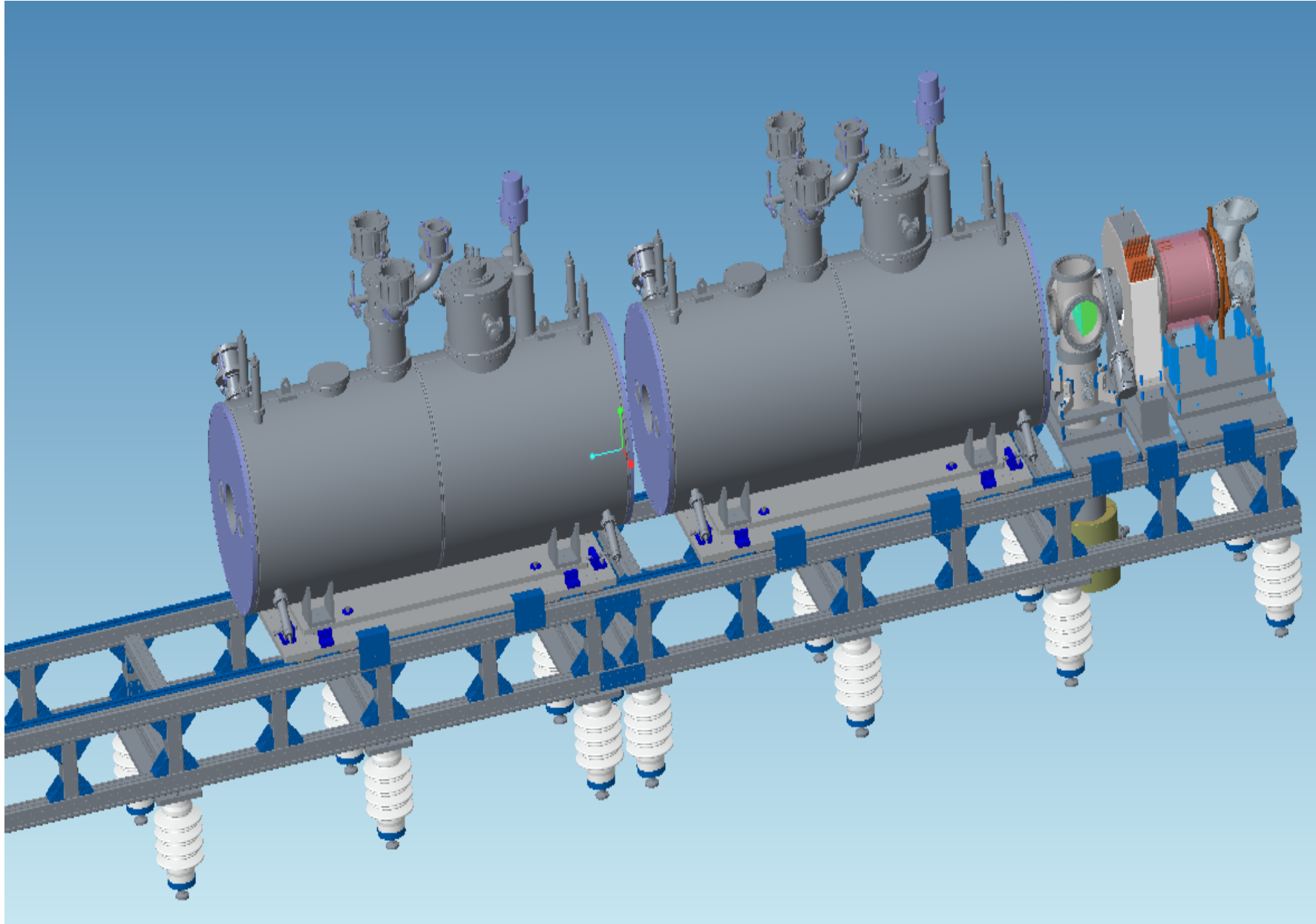
Voltage control via existing TestEBIS DT Leads (i.e., old structure not disturbed)

Gas Ionization Cell for Electron Beam Tests at the BNL TestEBIS



- Electron beams of 6 Amps were successfully propagated through the assembly.
- Ion extraction from residual gas was successfully performed.
- External ion injection tests are planned for November 2017.

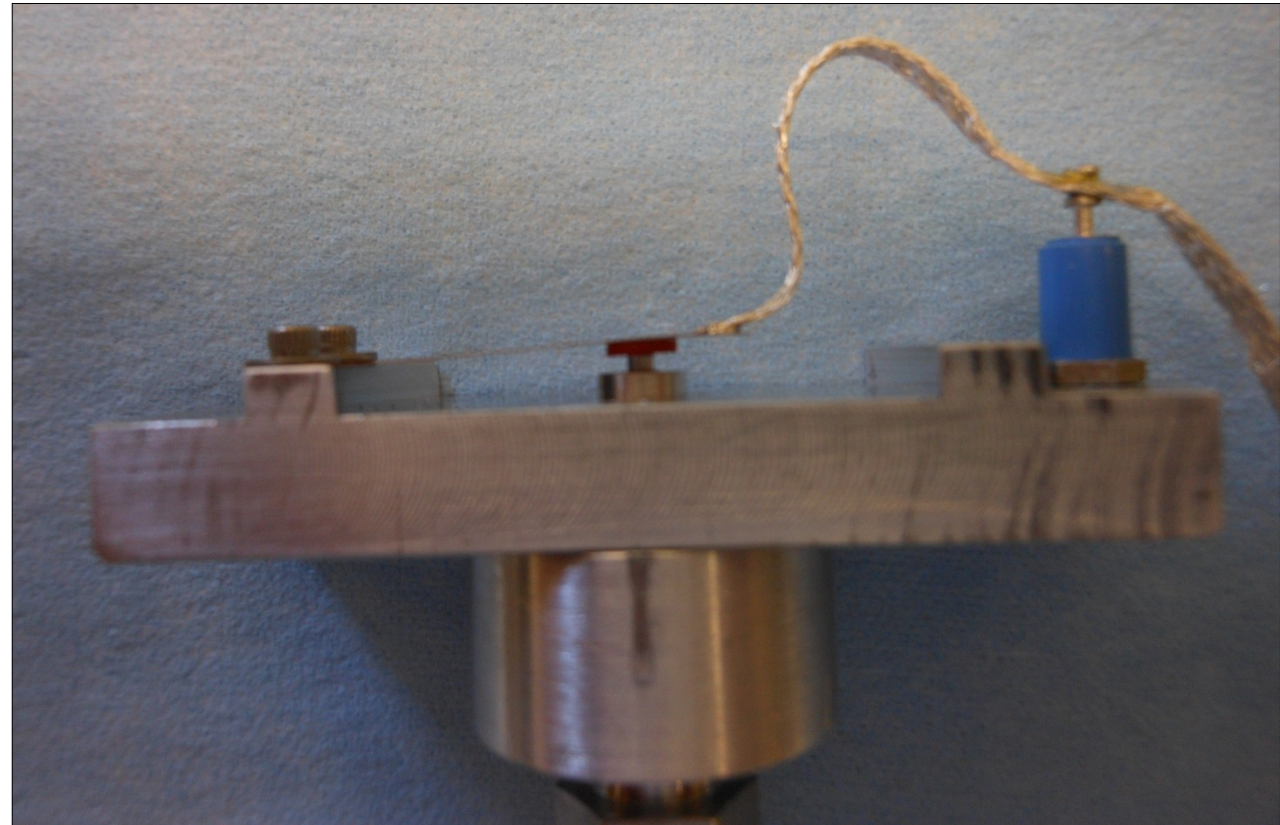
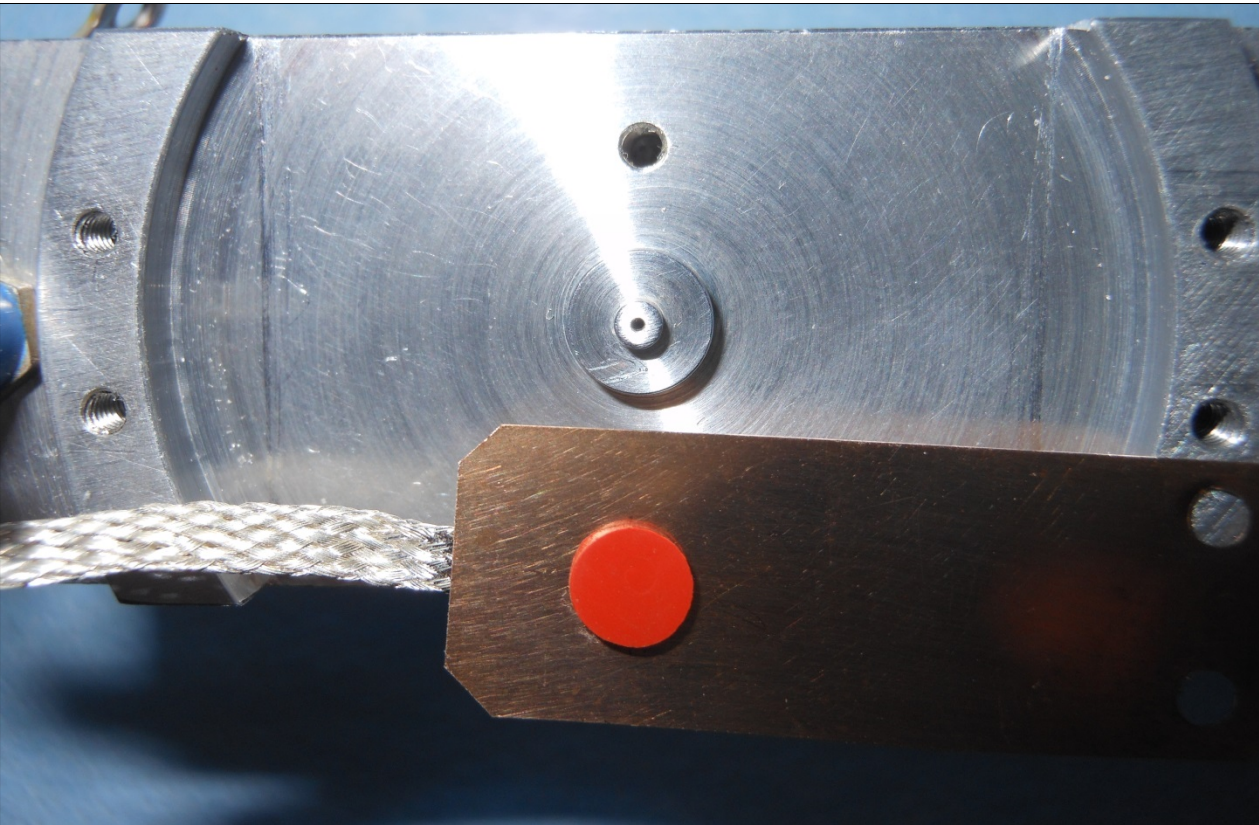
Extended EBIS 5 T Solenoids



High Speed Pulsed ^3He Valve

- Pulsed current causes valve to open by Lorentz Force to the conducting plate in high magnetic field.
- Valve design has successful long-term operation in OPPIS: $B=3\text{ T}$, $I=100\text{ A}$, $L=5\text{ cm}$, & $F=15\text{ N}$.

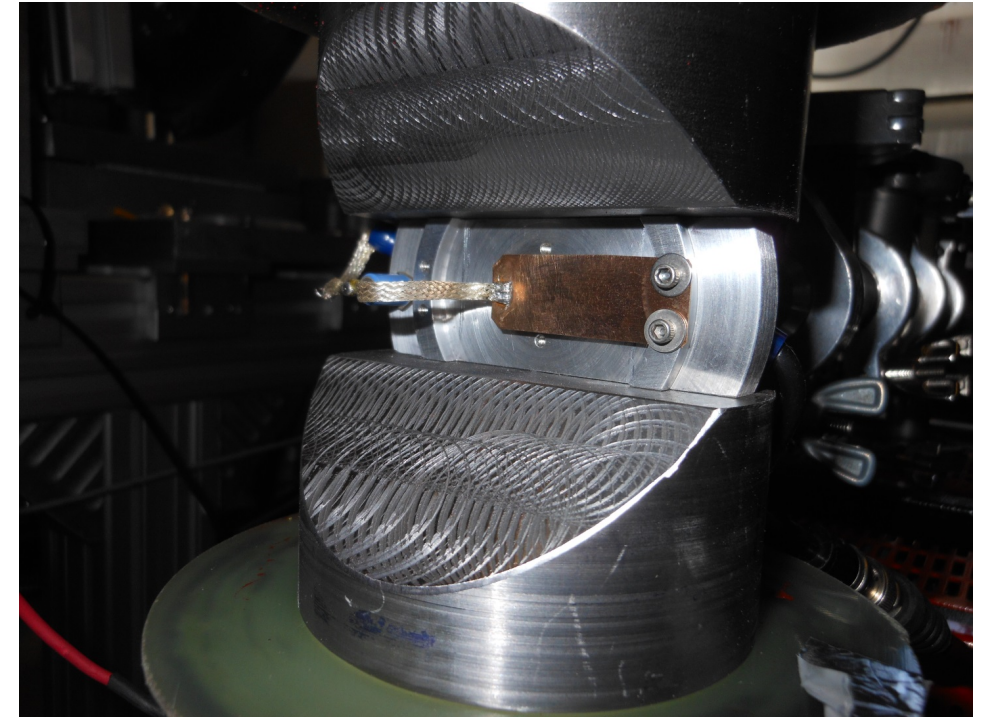
$$d\vec{F}_A = I d\vec{l} \times \vec{B}$$



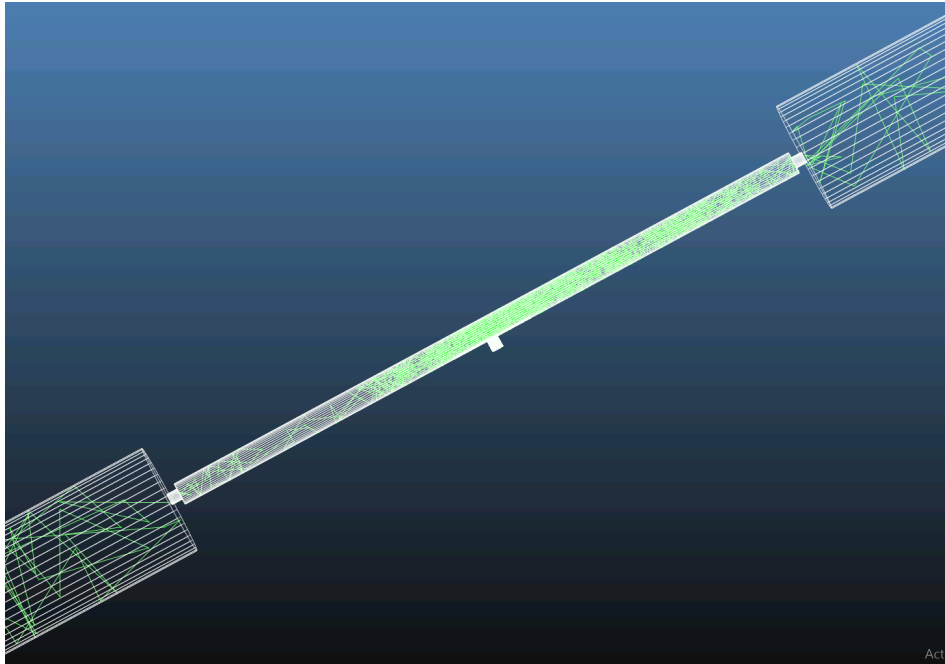
High Speed Pulsed ^3He Valve



Pulsed valve was tested with a dipole magnet and He leak checker.



MolFlow – Monte Carlo Simulator for High Vacuum



MolFlow is a Monte Carlo simulator of molecular flow of gases that tracks the trajectories of test particles and increments hits, momentum transfer, and reciprocal of orthogonal speed component on each geometric surfaces.

Surface Parameters:	sticky factor, opacity, gas desorption, temperature, velocity, wall sojourn time, and specular/diffuse reflection
Gas Parameters:	mass, temperature, radioactive decay
Time-Dependent:	sticky factor, opacity, gas desorption

Extended EBIS Parameters

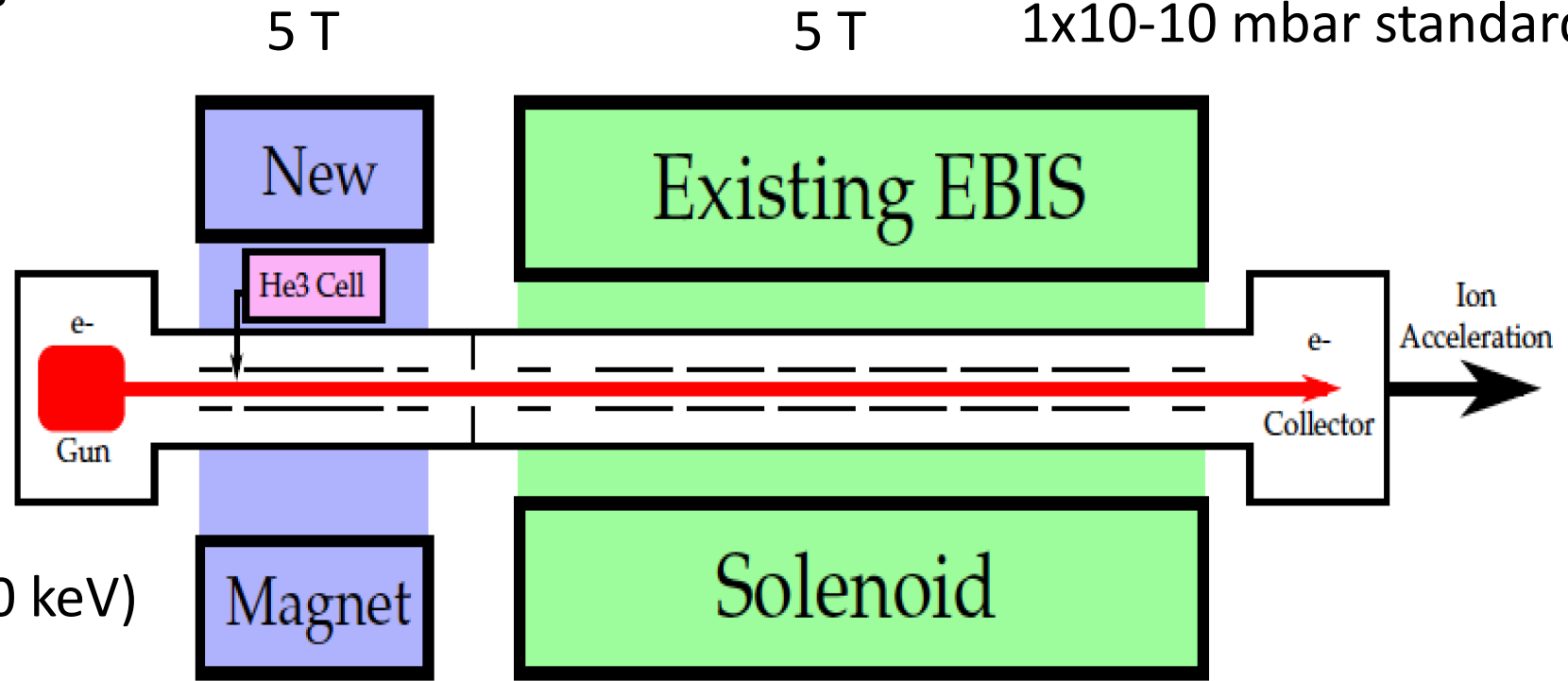
Maximum EBIS
pulse time = 200 ms

Pressure

1×10^{-6} mbar during gas injection

1×10^{-10} mbar standard operation

Electron Beam
1 mm diameter
10 Amp
10 keV (actual 20-30 keV)

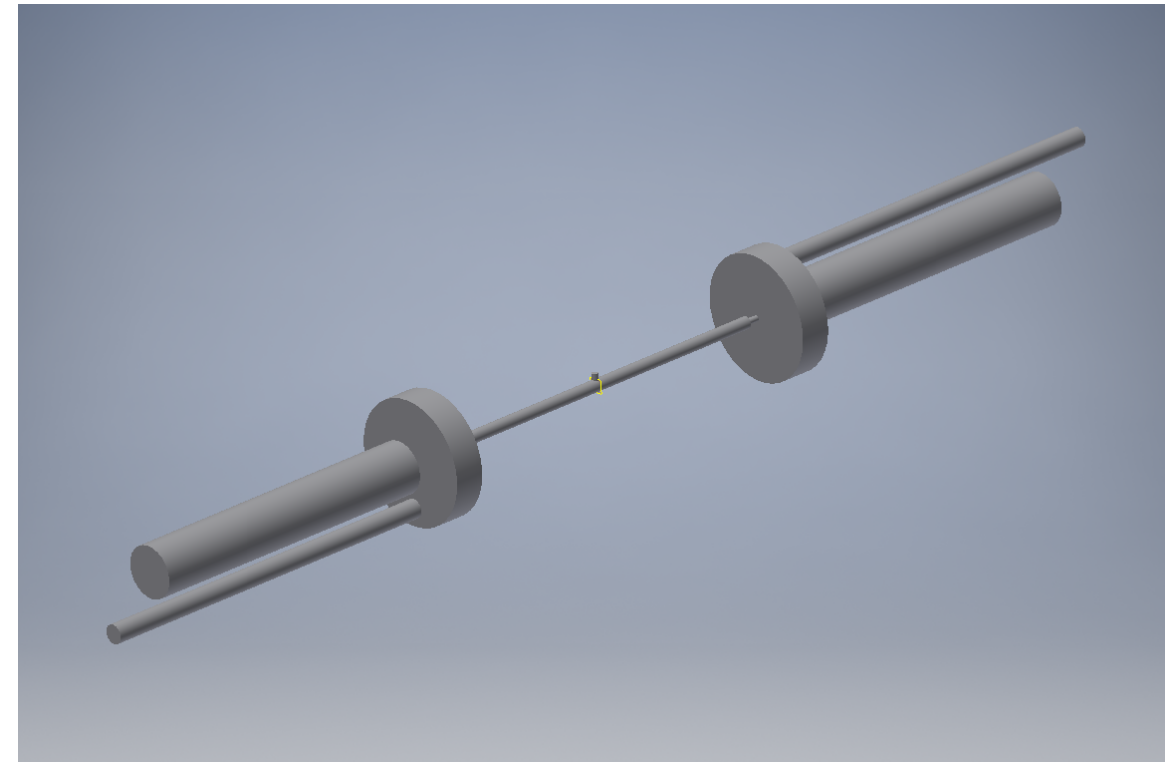
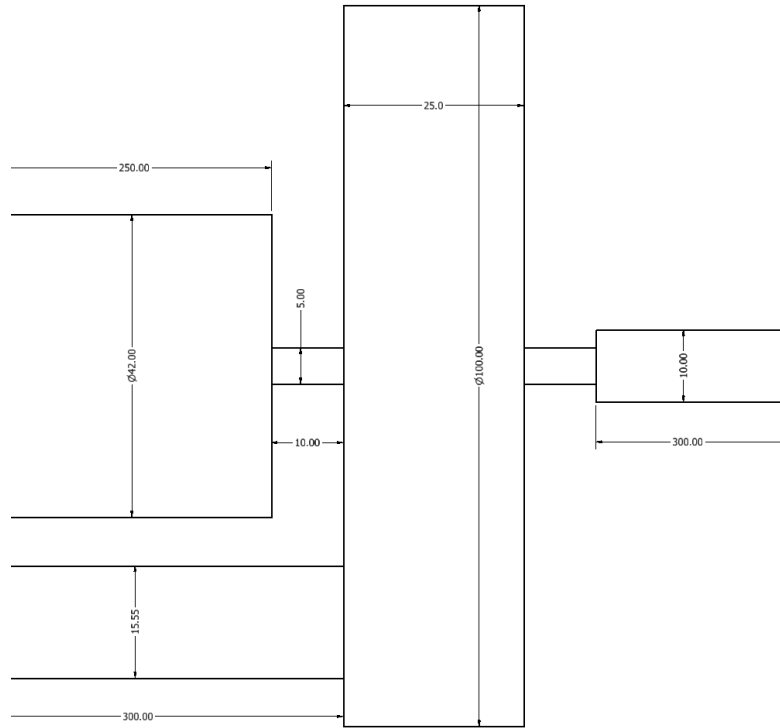
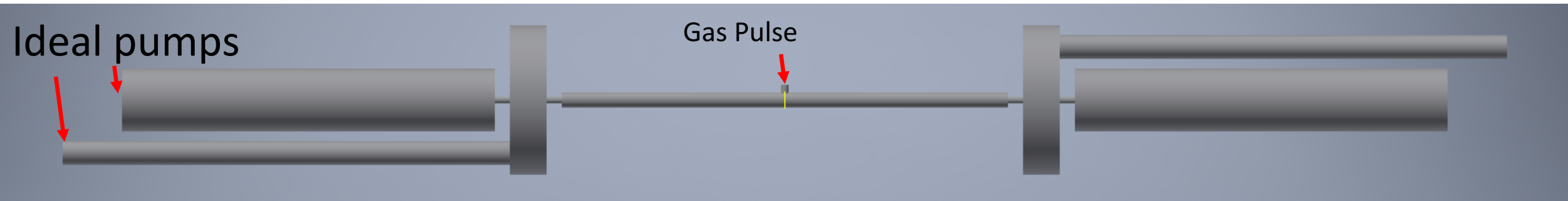


Charge Capacity = $\sim 10^{12}$ elementary charges

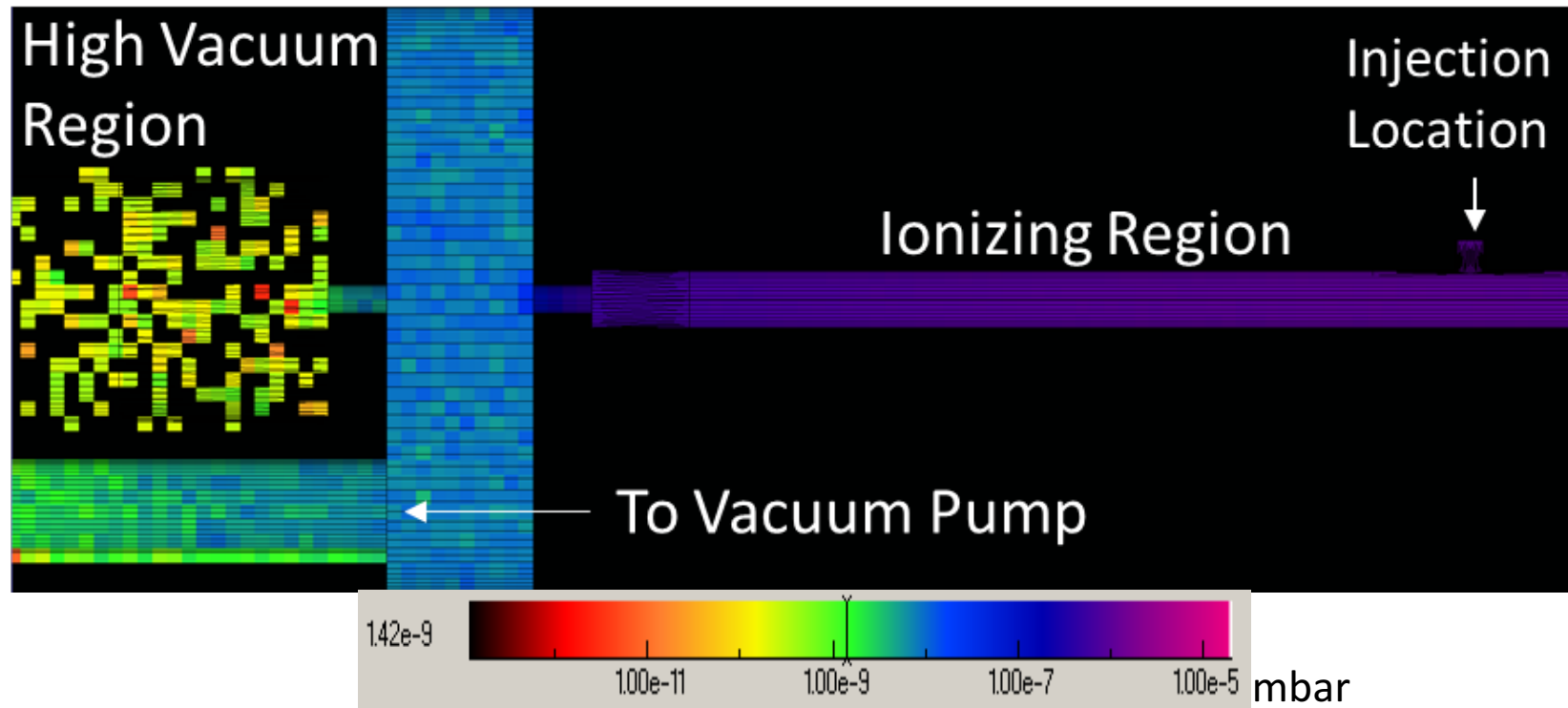
$^3\text{He}^{++}$ Capacity = $\sim 5 \times 10^{11}$ $^3\text{He}^{++}$ (1 m trap length)

$$C = \frac{I}{e} \times l \times \sqrt{\frac{m_e}{2E}}$$

Geometry of Gas Injection System



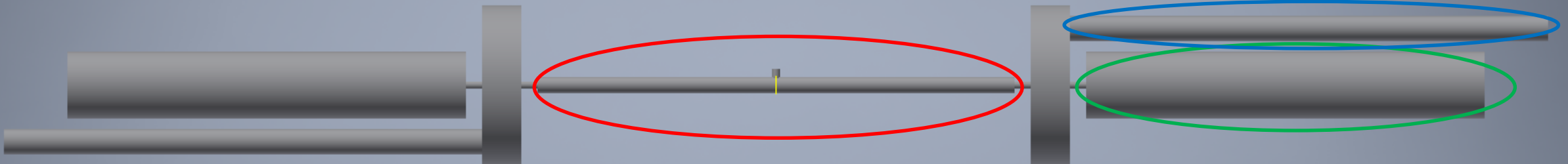
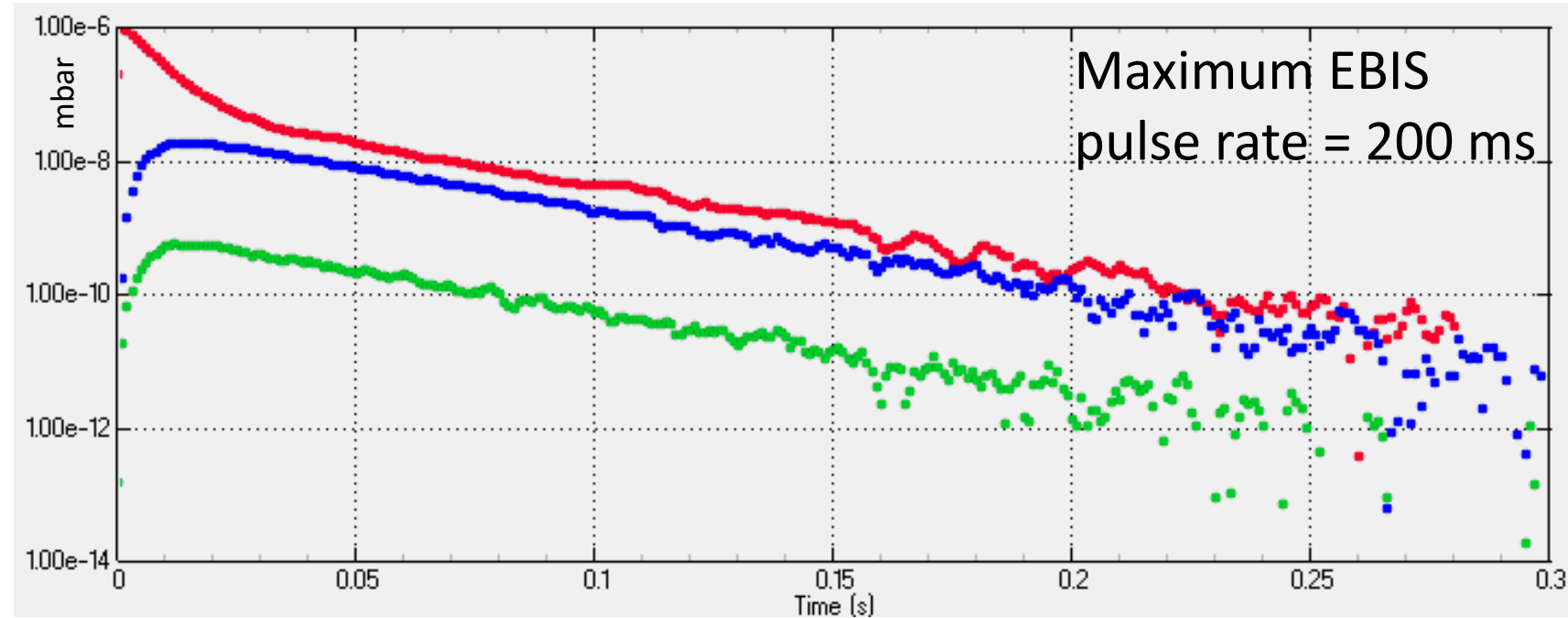
MolFlow Model of Gas Diffusion (2ms)



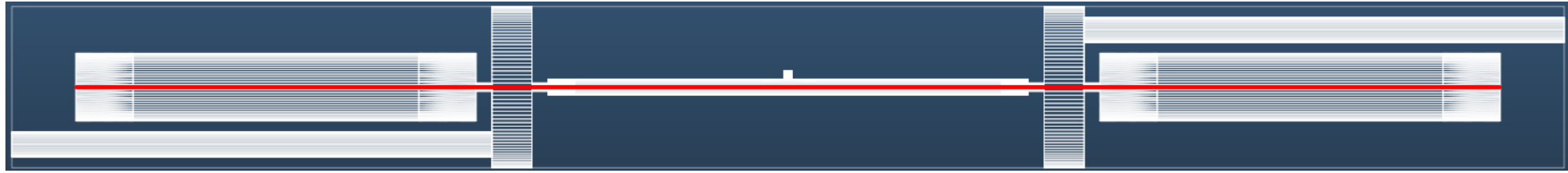
- Simulation is at 2 ms modeled in 5×10^{-5} s intervals
- Gas injection is $0.0005 \text{ mbar} \cdot \text{L/s}$ of ^3He for 5×10^{-5} s
- 1×10^{-6} mbar pressure when diffused in gas cell (23.6 cm^3)
- $\sim 5.8 \times 10^9$ ^3He molecules

Gas Diffusion and Pumping in Ionization Cell

- Simulation is 300 ms long with 1 ms intervals
- $0.00005 \text{ mbar}\cdot\text{L/s}$ for 1 ms
- $1\text{e-}6 \text{ mbar}$ when diffused in gas cell (23.6 cm^3)
- $\sim 5.8\text{e}9 \text{ }^3\text{He}$ molecules



Electron Beam Ionization of ^3He

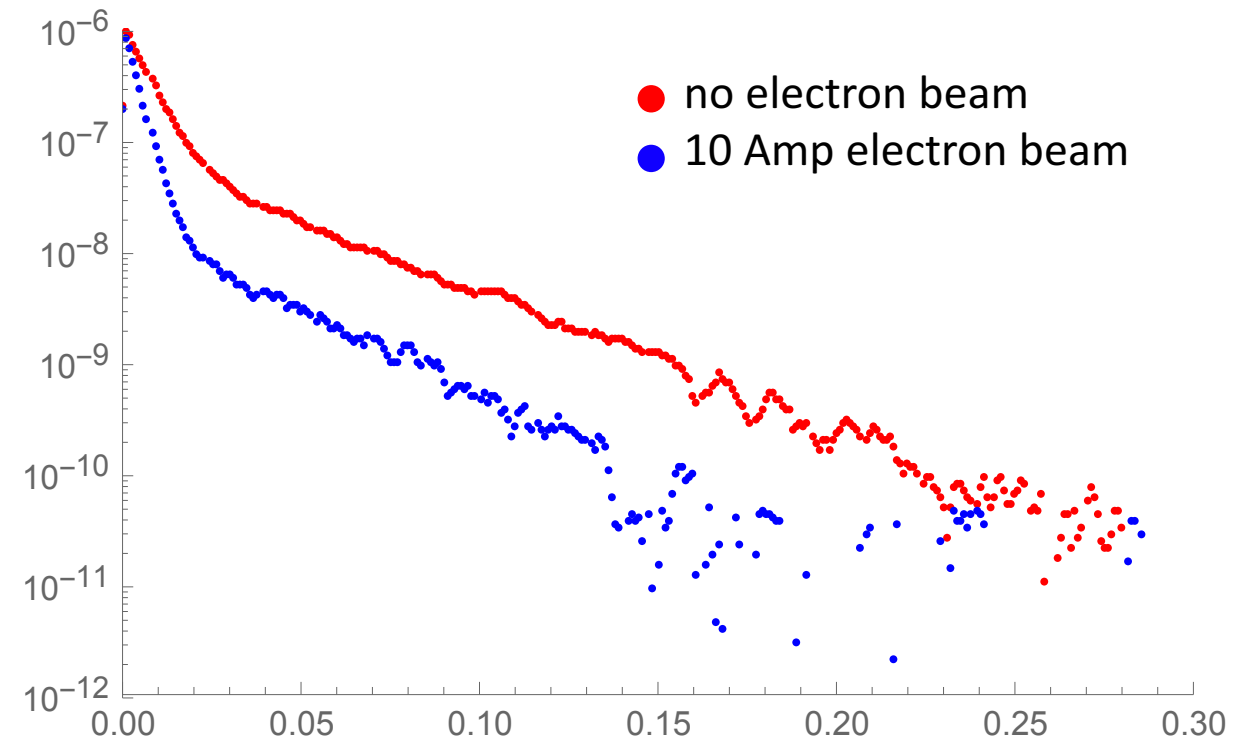


Electron Beam

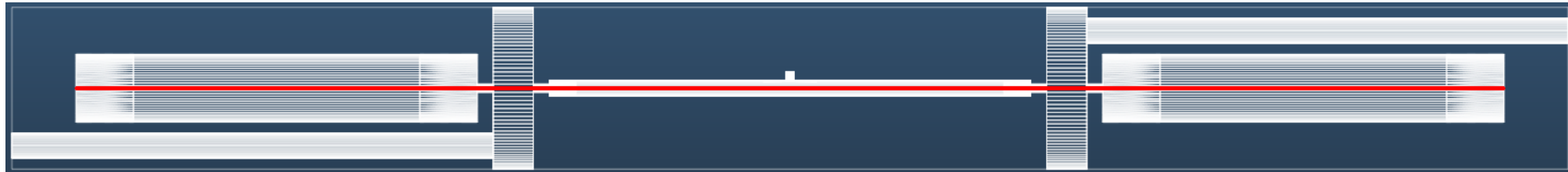
- 1 mm diameter
- 10 Amp
- 10 keV

1% probability that ^3He is ionized during traverse of electron beam

Treat electron beam as ideal pump with 99% transparency.



Electron Beam Ionization of ^3He



Charge Capacity = $\sim 10^{12}$ elementary charges

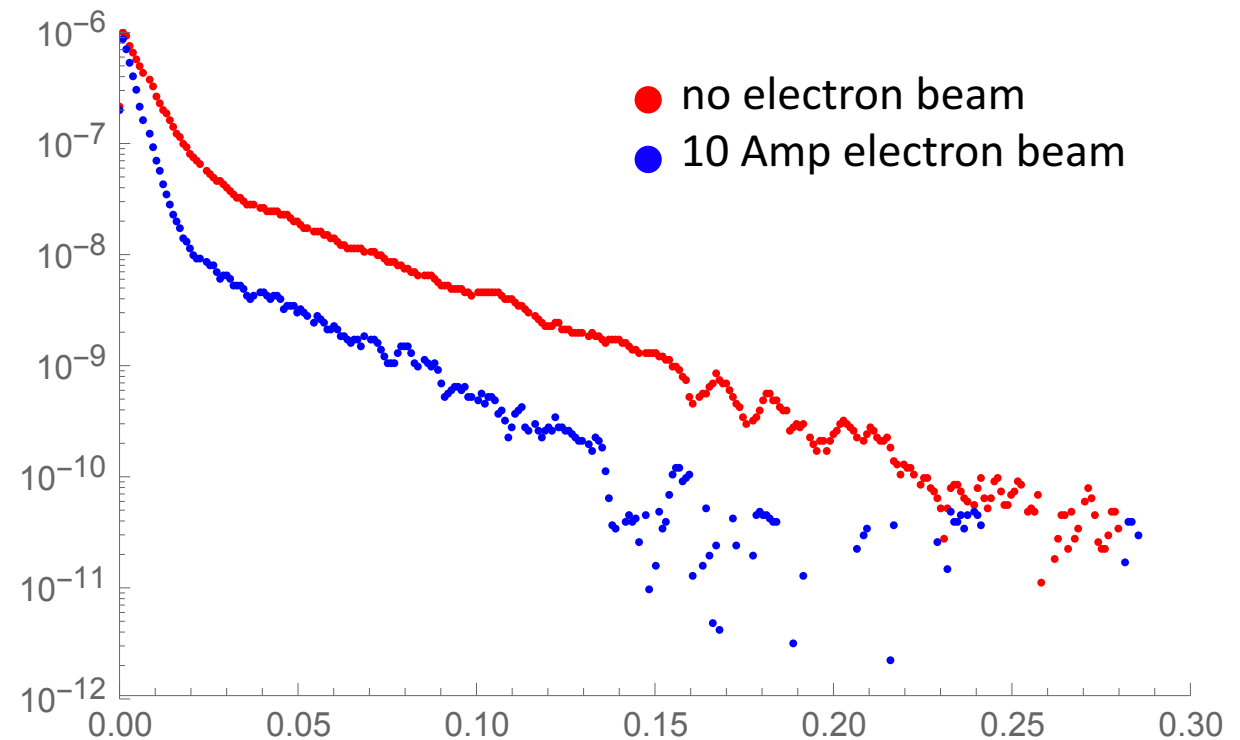
10 Amp electron beam

6.2×10^{11} injected ^3He atoms

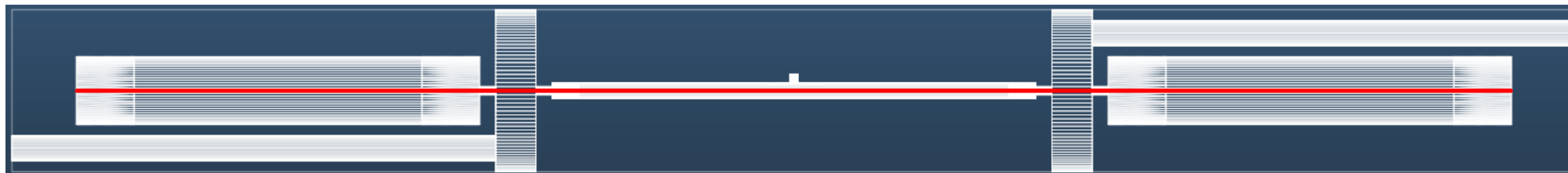
3.8×10^{11} ionized by electron beam

2.4×10^{11} pumped out

Most ^3He atoms are ionized!



Electron Beam Ionization of ^3He



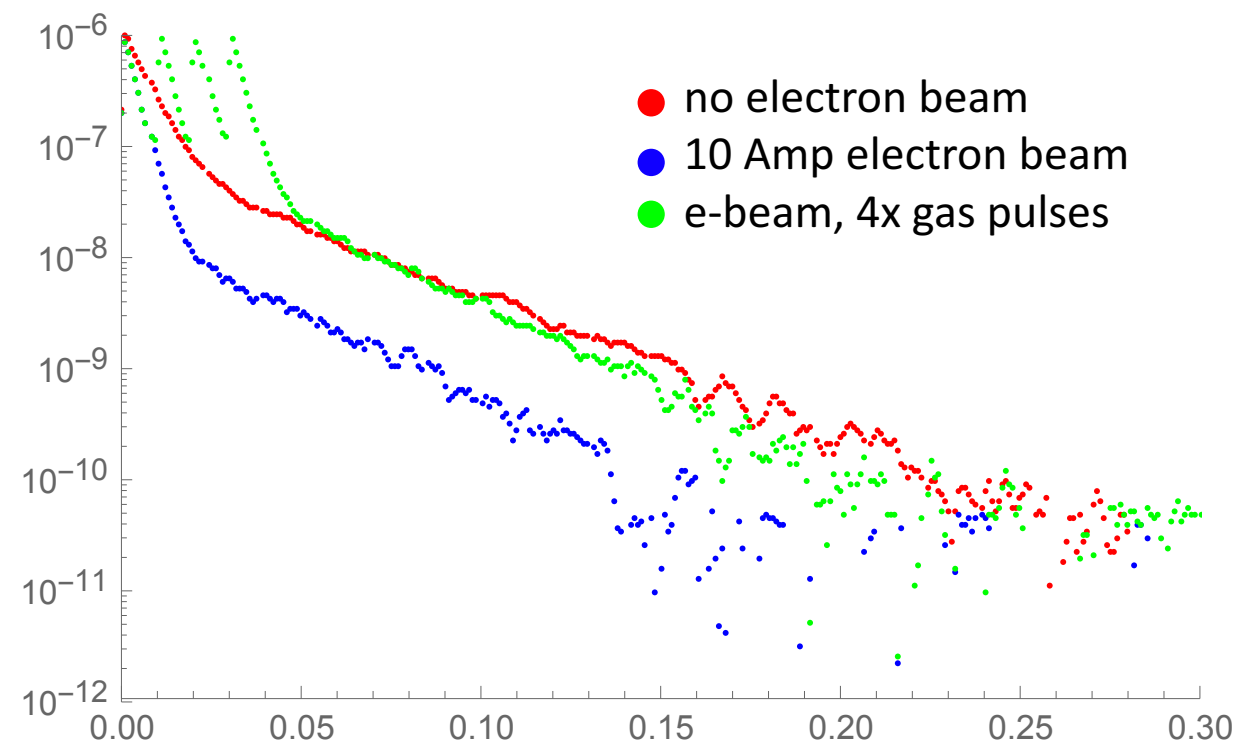
Charge Capacity = $\sim 10^{12}$ elementary charges

10 Amp electron beam

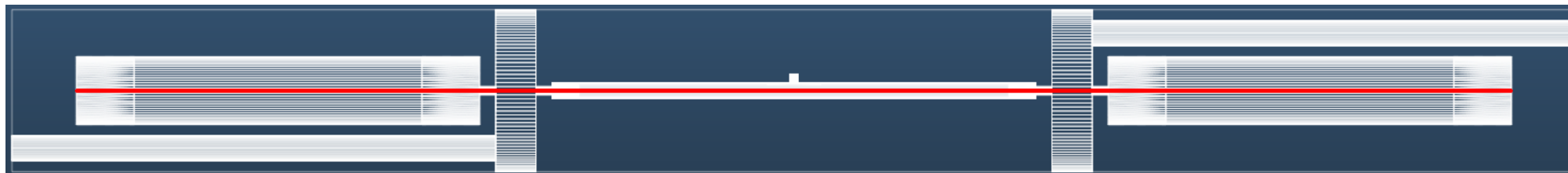
6.2×10^{11} injected ^3He atoms
 3.8×10^{11} ionized by electron beam
 2.4×10^{11} pumped out

10 Amp e-beam, 4x gas pulses

24.8×10^{11} injected ^3He atoms
 15.2×10^{11} ionized by electron beam
 9.6×10^{11} pumped out



Electron Beam Ionization of ^3He



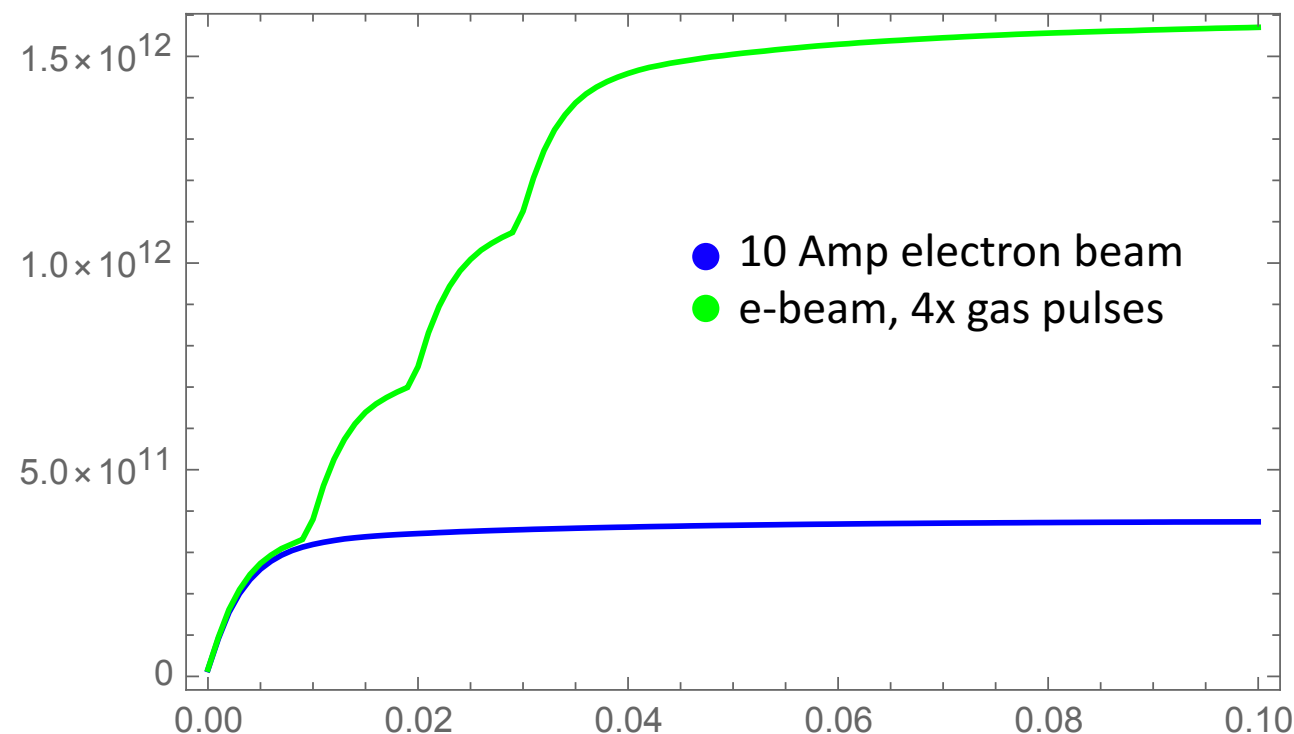
Charge Capacity = $\sim 10^{12}$ elementary charges

10 Amp electron beam

6.2×10^{11} injected ^3He atoms
 3.8×10^{11} ionized by electron beam
 2.4×10^{11} pumped out

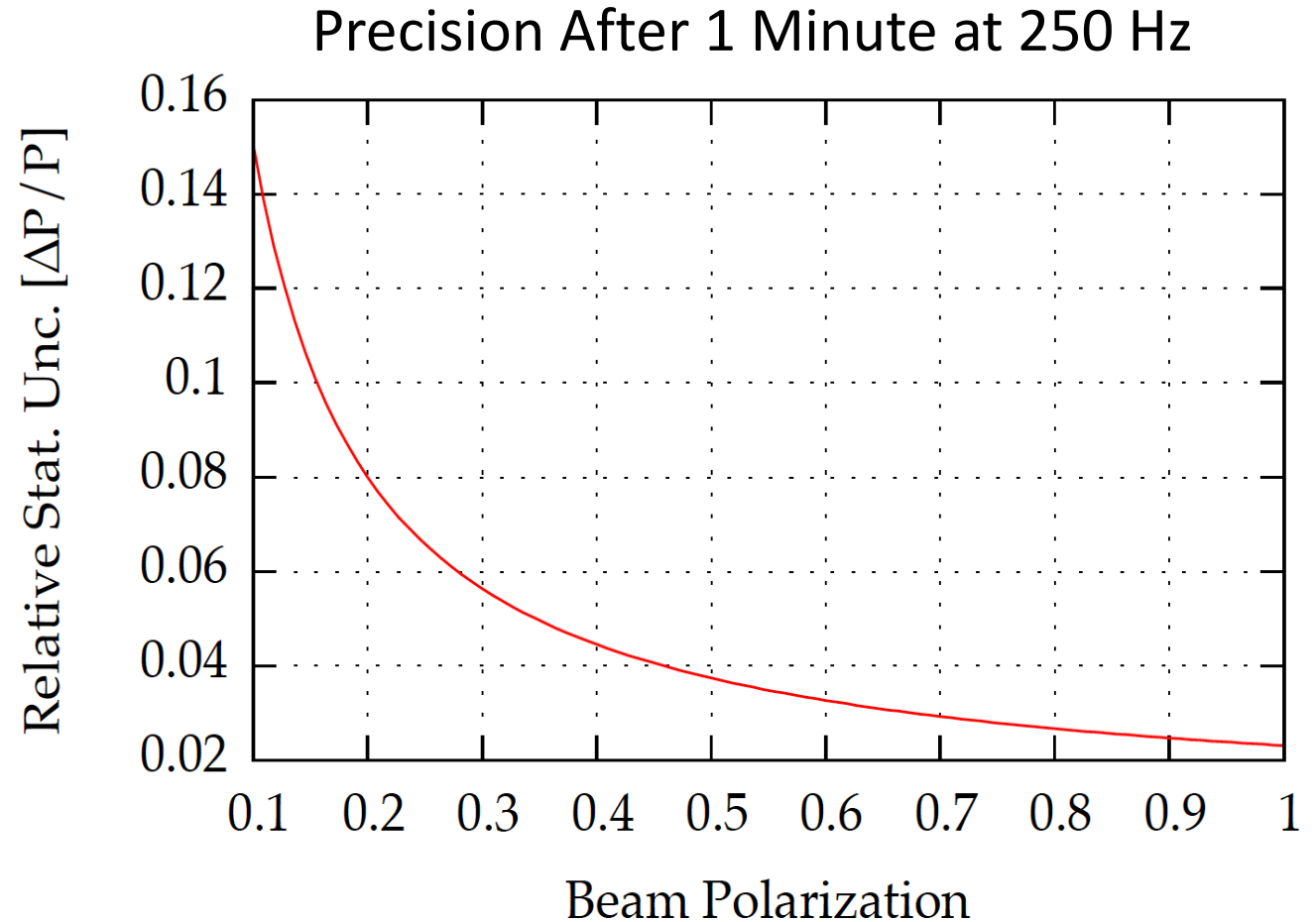
10 Amp e-beam, 4x gas pulses

24.8×10^{11} injected ^3He atoms
 15.2×10^{11} ionized by electron beam
 9.6×10^{11} pumped out



Feasibility Experiment

- Use extended EBIS and extract fully stripped polarized ${}^3\text{He}^{++}$ ions accelerated to 5.3 MeV
- Measure ${}^3\text{He} + {}^4\text{He} \rightarrow {}^3\text{He} + {}^4\text{He}$ elastic scattering
- Analyzing power has been measured to be 100% at 91°_{CM} at 5.3 MeV
- Process yields 2.66 MeV ${}^3\text{He}$ at 53.6°_{lab} and 2.64 MeV recoil ${}^4\text{He}$ at 44.5°_{lab}

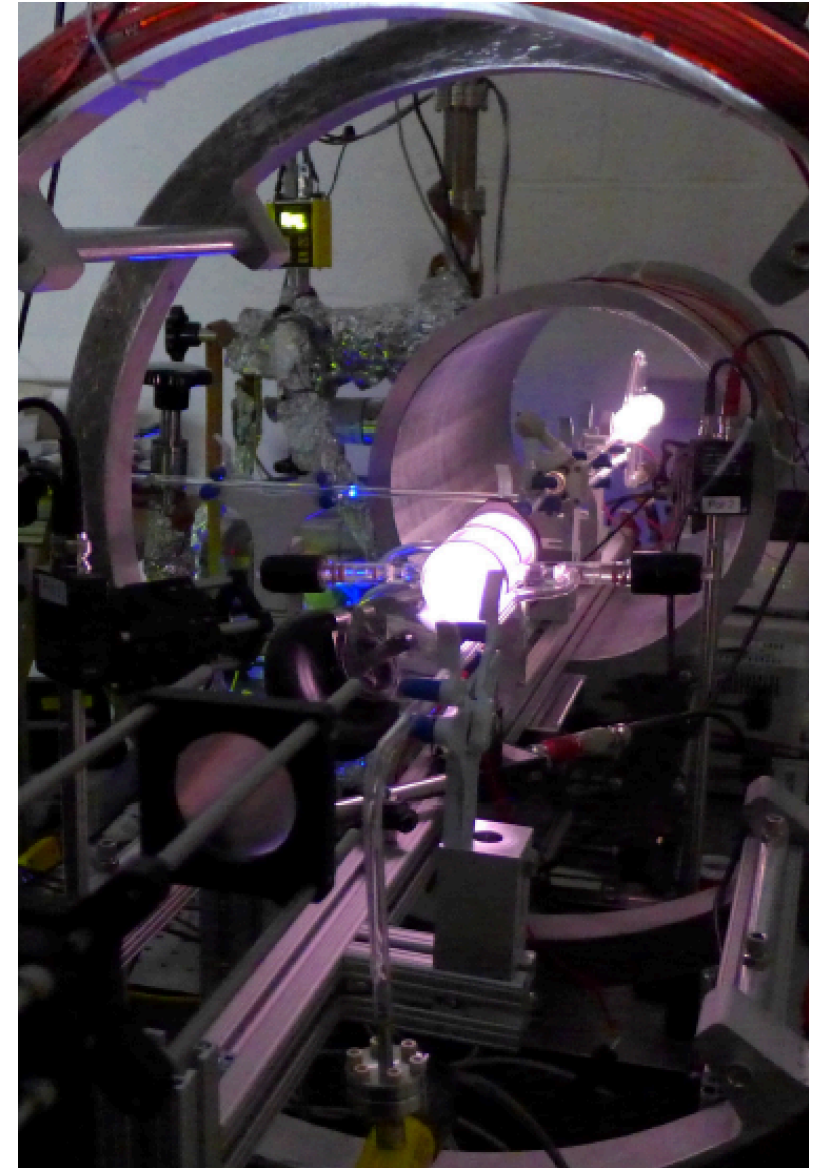


$$\Delta P = \sqrt{\frac{(P+1)(P+3)}{N}}$$

- Magnet, vacuum, laser setup
- 70% polarization achieved
- Allows flow of polarized gas between cells
- Observe polarization diffusion through region of depolarizing gradients⁷
- Test bed for polarization, transfer and data acquisition
- Discharge and optical probe polarimeter development⁸

⁷Maxwell, Epstein, Milner, NIM A (777), 2015.

⁸Maxwell, Epstein, Milner, NIM A (764), 2014.



Schedule

- **FY2016**
 - High field optical pumping measurements
 - Development of ^3He gas purification system
- **FY2017**
 - Superconducting magnets for trap length extension ordered
 - Development of valve system and vacuum system
- **FY2018**
 - Superconducting magnets for EBIS extension delivered
 - NMR calibration of high field optical pumping measurements
 - Design of RHIC ^3He polarimeter for feasibility experiment
- **FY2019**
 - Upgraded EBIS used for Gold run
 - Construction of RHIC ^3He polarimeter
- **FY2020**
 - Polarized $^3\text{He}^{++}$ beam of 2×10^{11} ions/pulse and 70% polarization in RHIC
 - Completion of feasibility experiment

Deliverables

	Date
MIT lab constructed	2011
MEOP technology low-field	2012
70% pol. low-field MEOP	2012
BNL lab constructed	2014
Spin transfer studies completed	2014
Pump-probe polarimeter	2014
80% pol high-field MEOP	2015
Extended EBIS design completed	2016
^3He cryo-purification system	2016
Gas ionization cell tests	2017
Prototype pulsed valve	2017
MolFlow model of gas injection	2017
Converted OPPIS into R&D facility	2017
Publications	2014, 2015
MIT Senior Thesis	2013

Expenditures by Fiscal Year

	FY10 + FY11	FY12 + FY13	FY14 + FY15	FY16 + FY17	Totals
a) Funds allocated	150,000	233,000	220,000	150,000	953,000
b) Actual costs to date	145,111	233,000			

Main Goals of FY2016

- High field optical pumping measurements
- Optimization of open ^3He polarization system
- Development of NMR to calibrate pump-probe polarimeter

Summary

- A polarized ^3He source was classified as high priority by the NP Community Review (Jones report).
- The R&D effort has enabled development of key state-of-the-art MEOP technology at BNL and MIT.
- High field optical pumping has been successfully developed, and a cyro-purification system was developed.
- Designs for a gas injection system are being developed and tested.
- The Extended EBIS upgrade is underway with 5 T magnets scheduled for delivery in December 2017.
- We are on a path to have polarized ^3He ions in RHIC early in the next decade.

Thank you for your attention

MIT-BNL Polarized ^3He Ion Source Collaboration

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Spare Slides

- Spare slides

History of Polarized ^3He Ion Sources

Source	Current	Polarization	Emittance	Beam Energy	Energy Spread	Ion
Birmingham	50 pA	55-65%	70 mm mrad.	29 keV	100 eV	$^3\text{He}^{++}$
Laval	100 nA	95%	25 mm mrad.	12 keV		$^3\text{He}^+$
Rice/Texas A&M	8 μA	11%	10mm mr $\text{MeV}^{1/2}$	16 keV	10-50 eV	$^3\text{He}^+$

- No new operational ^3He ion sources were built since 1984. A number of new ideas were proposed and tested (not successfully).
- Spin-exchange and metastability-exchange optical pumping techniques for ^3He polarization were greatly improved due to laser development and new applications.

Future Work with MolFlow

Model depolarization of ^3He during molecular flow in ionization cell.

- Reduce desorbed ^3He atoms by 70% → Only model polarized ^3He gas
- Radioactive Decay parameter → Relaxation in magnetic field gradients
- Sticky Factor on ionization cell walls → Wall Relaxation
- Take ratio with total number of ionized ^3He atoms to get depolarization

Depolarization Contributions

- Wall Bounces
 - 3 mm long, 0.1mm diameter leak: 1 torr to 10^{-7} torr
 - 1m long, 2mm diameter tube: $\approx 10^6$ bounces, ≈ 1 msec
 - Negligible depolarization with glass walls
- Magnetic field gradients from EBIS stray field
 - Hinder Polarization
 - Depolarization During Transport to EBIS
- Small Contributions During Ionization:
 - Charge Exchange: ${}^3\text{He}^+ + {}^3\text{He}^{++} \rightarrow {}^3\text{He}^{++} + {}^3\text{He}^+$
 - Recombination: $e^- + {}^3\text{He}^{++} \rightarrow {}^3\text{He}^+$
 - Spin Exchange from Beam

See MIT Senior Thesis of Charles S. Epstein:

***Development of a Polarized Helium-3 Ion Source for RHIC using the Electron Beam Ion Source* , June 2013, unpublished.**

Proposed Extended Trap EBIS

- This upgrade provides us an opportunity to incorporate features which will allow us to use the EBIS for optimal injection of polarized ^3He atoms.
- The design provides space in the bore to incorporate a polarizing cell at the beginning of the first coil.
- The design with a drift tube configuration in the first solenoid can be used as a “gas cell” region.
- This will benefit production of all gaseous beams – *e.g.* ^4He , Ne, Kr, Ar, Xe, O for NSRL.
- The design will have good vacuum separation between the two magnets, by means of differential pumping.
- The field dip will be minimized to preserve polarization.
- This upgrade is also an opportunity to improve the reliability and maintainability of the conventional EBIS section (improved access to components, improved HV holdoff).