Development of a Polarized $^3He^{++}$ Ion Source for the EIC

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BROOKHAVEN NATIONAL LABORATORY

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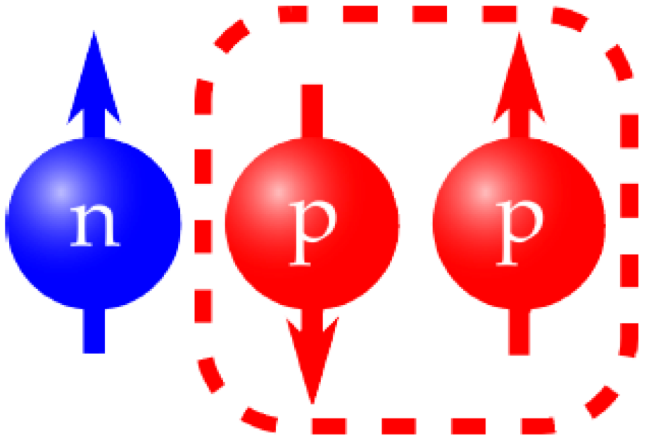
Why a Polarized ^{3}He Ion Source?

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

Source Concept

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.

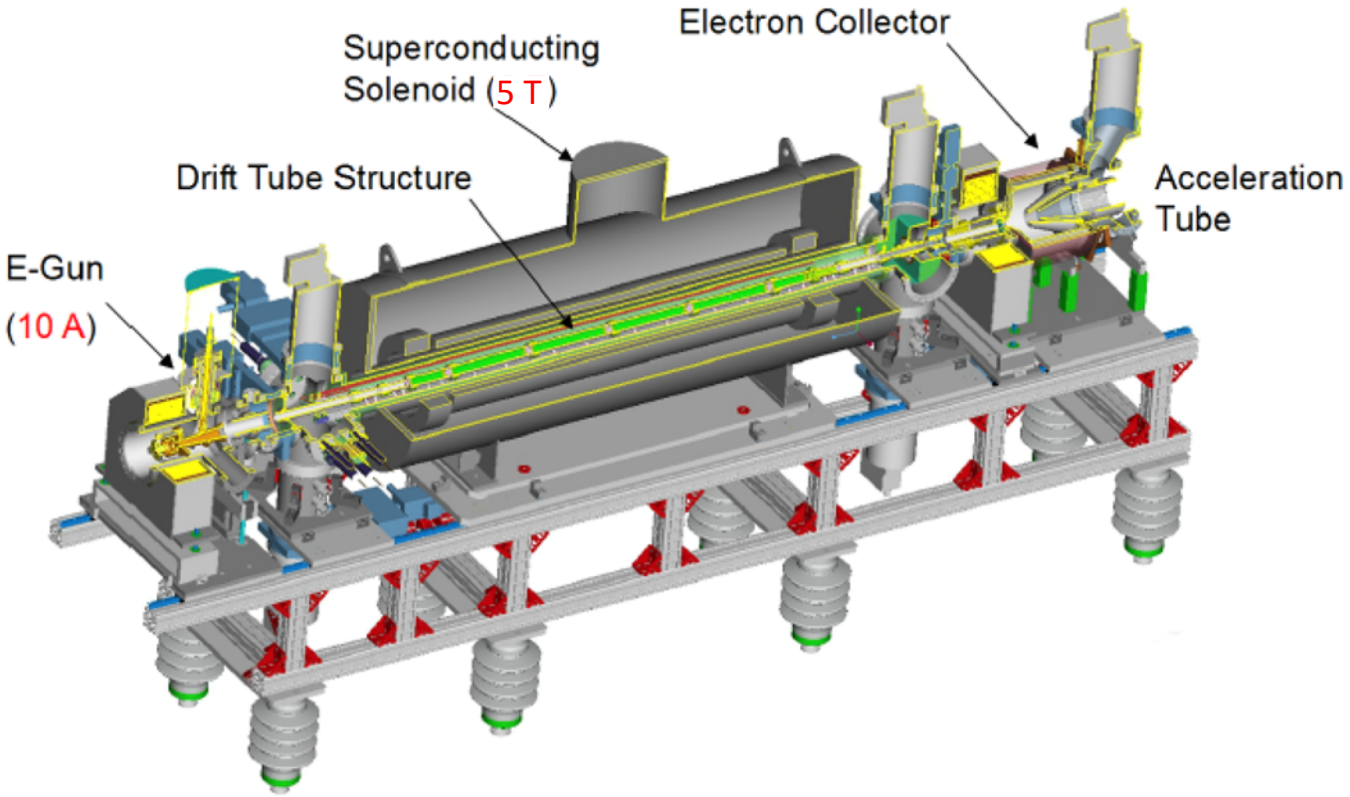
<u>Requirements</u>

- Polarized ^{3}He using optical pumping and injection into EBIS at 5 T
- Maximum polarization >70%
- Intensity 2.5×10^{11} ^{3}He++ ions in 20 μs pulse (~4 mA peak current)
- Spin-flip in the beam transport line

RHIC EBIS

- 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

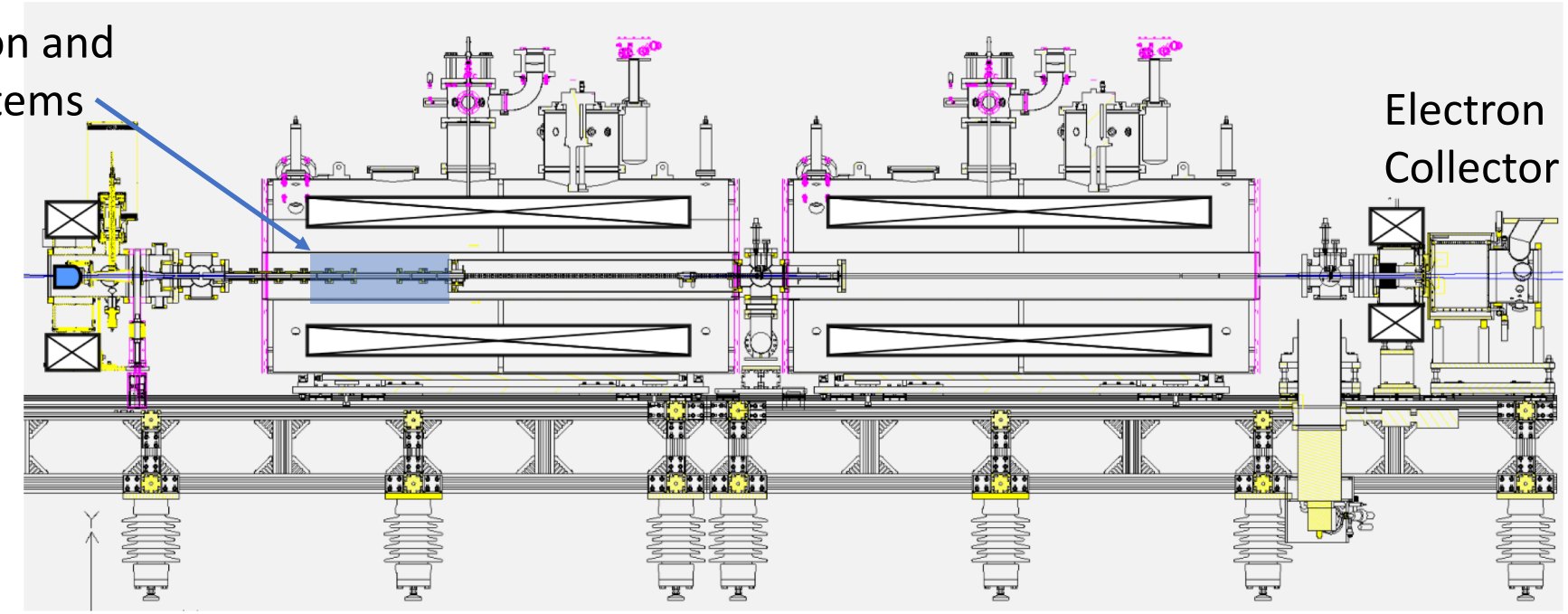
$$C = \frac{I}{e} \times l \times \sqrt{\frac{m_e}{2E}}$$



- 5T solenoid B Field; 1.5 m ion trap
- 20 keV electrons up to 10 A
- 5 Hz maximum repetition rate

Extended EBIS Upgrade

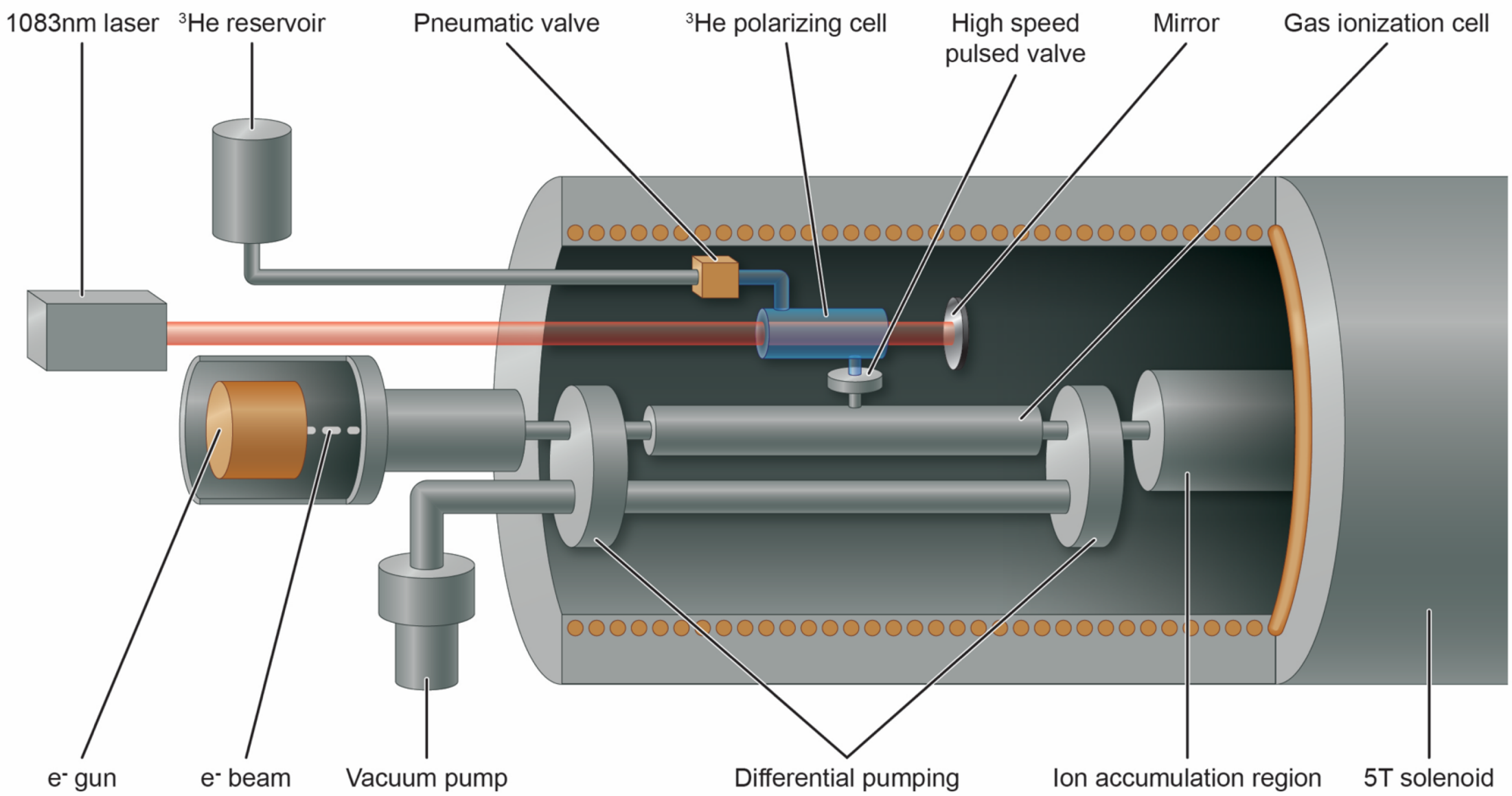
- Add a second 5 T superconducting solenoid for trap length extension: 40% increase in Au intensity
- Install ^{3}He polarization and injection system into the upstream solenoid
- Opportunity for various vacuum and other minor improvements



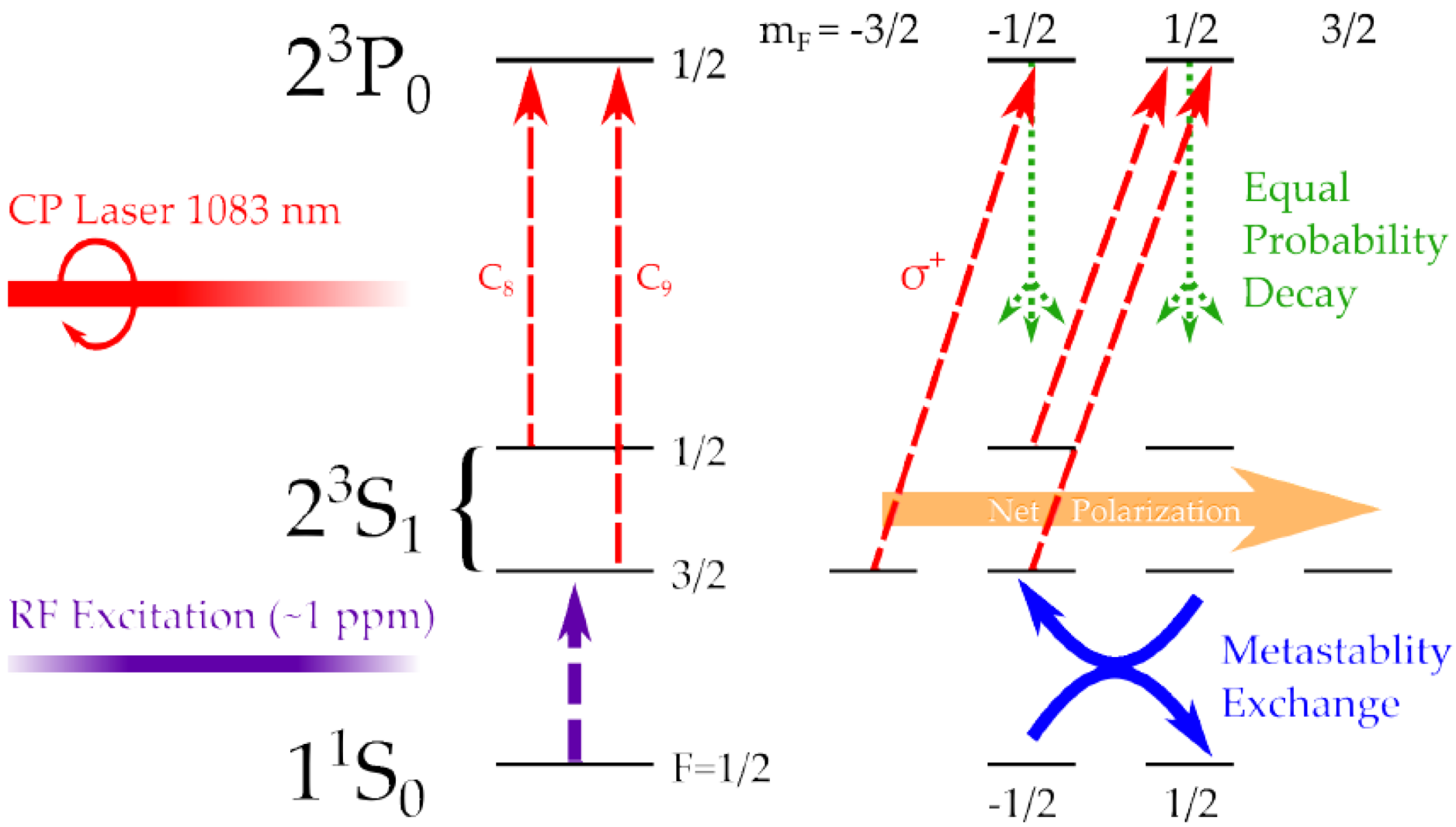
Extended EBIS Superconducting Solenoids

- 5.0 Tesla field, about 1.0 Tesla at field minimum in solenoid separation (~30 cm)
- Electron beam successfully propagated through both solenoids in May 2019.

Polarized ^{3}He Ion Source

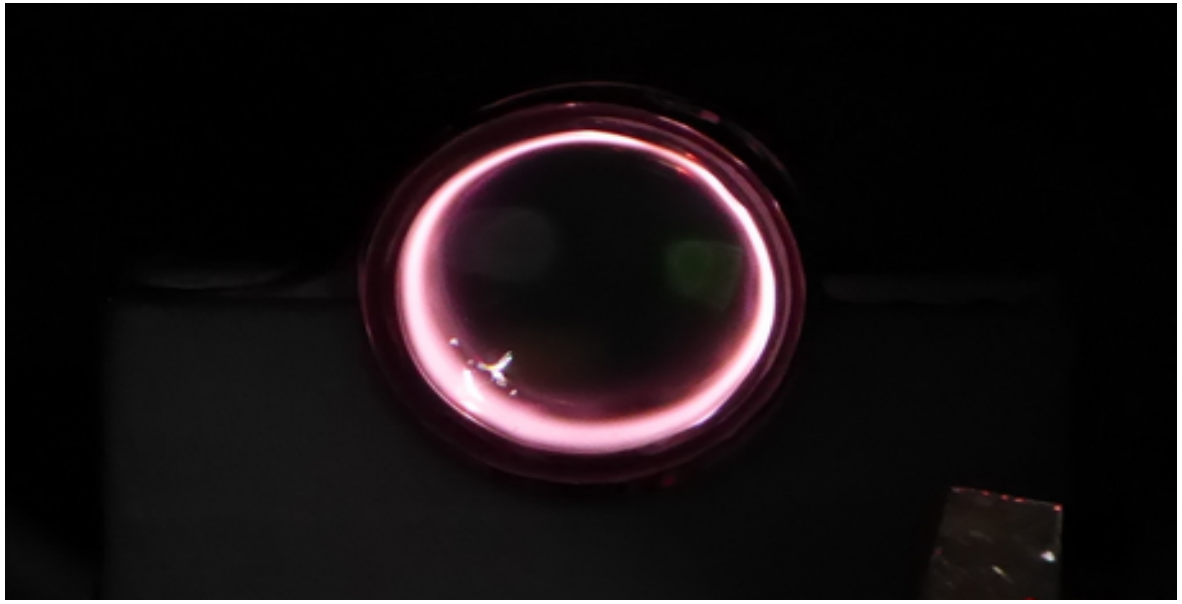


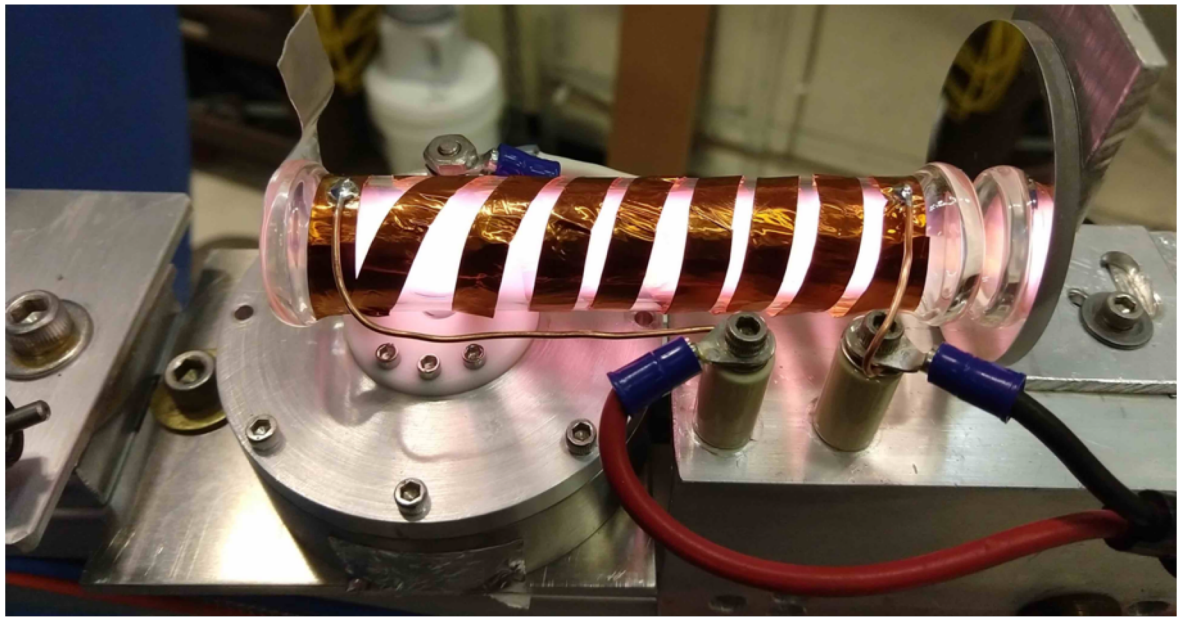
Metastability Exchange Optical Pumping



RF Discharge at Multi-Tesla Fields

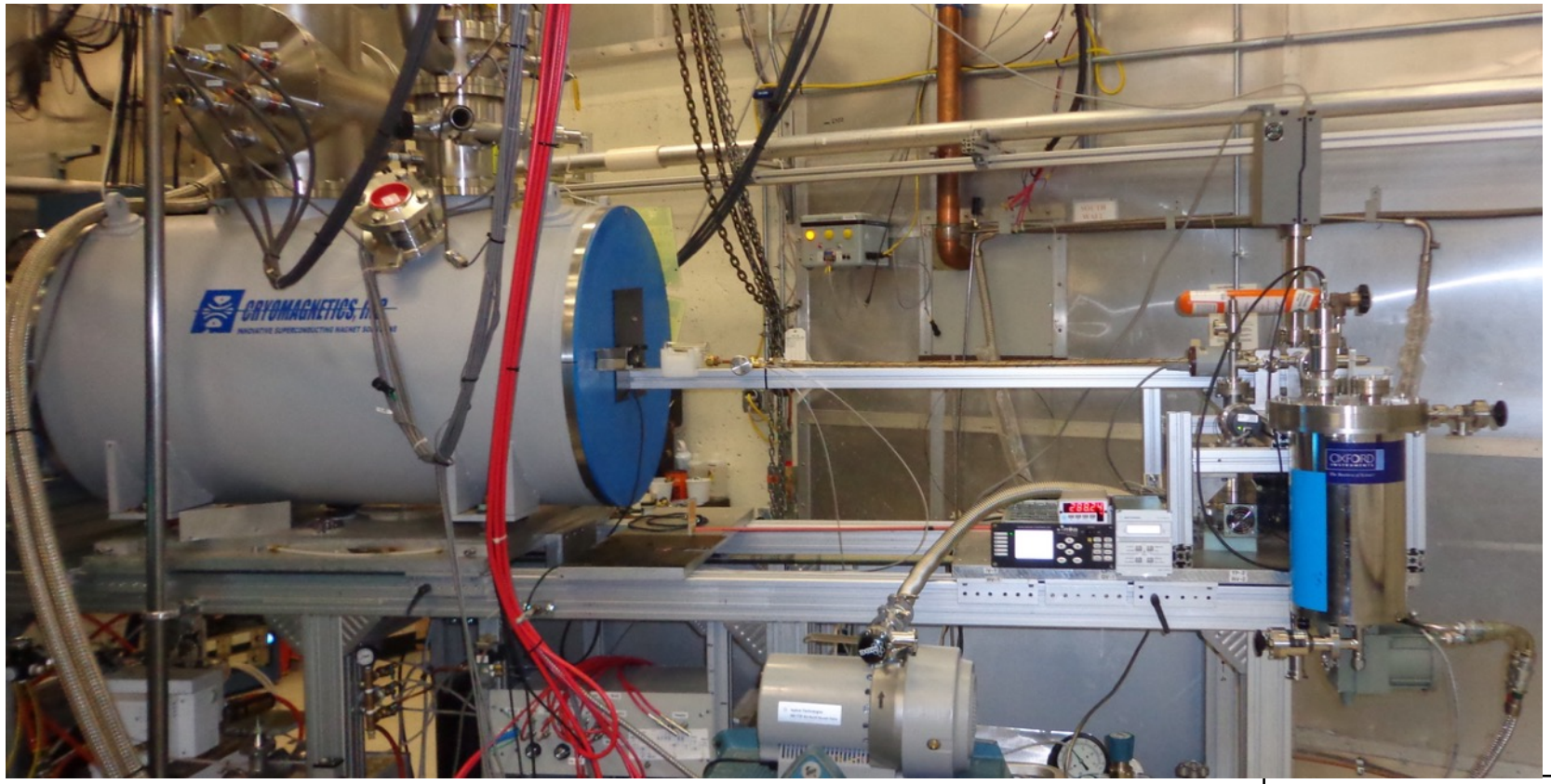
- RF discharge parameters strongly affect maximum polarization.
- RF discharge power needs to be reduced as ^{3}He polarization increases.
- Optimization of the ^{3}He cell geometry and placement of RF electrodes should improve polarization.

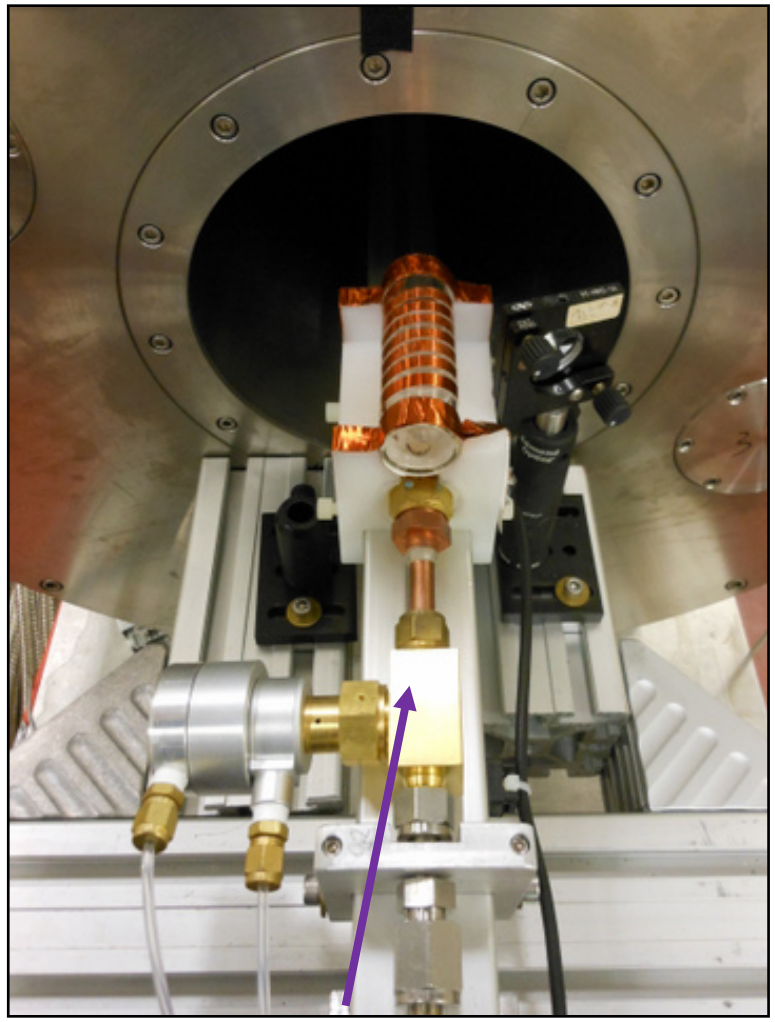




Open ^{3}He Cell and Gas Purification System

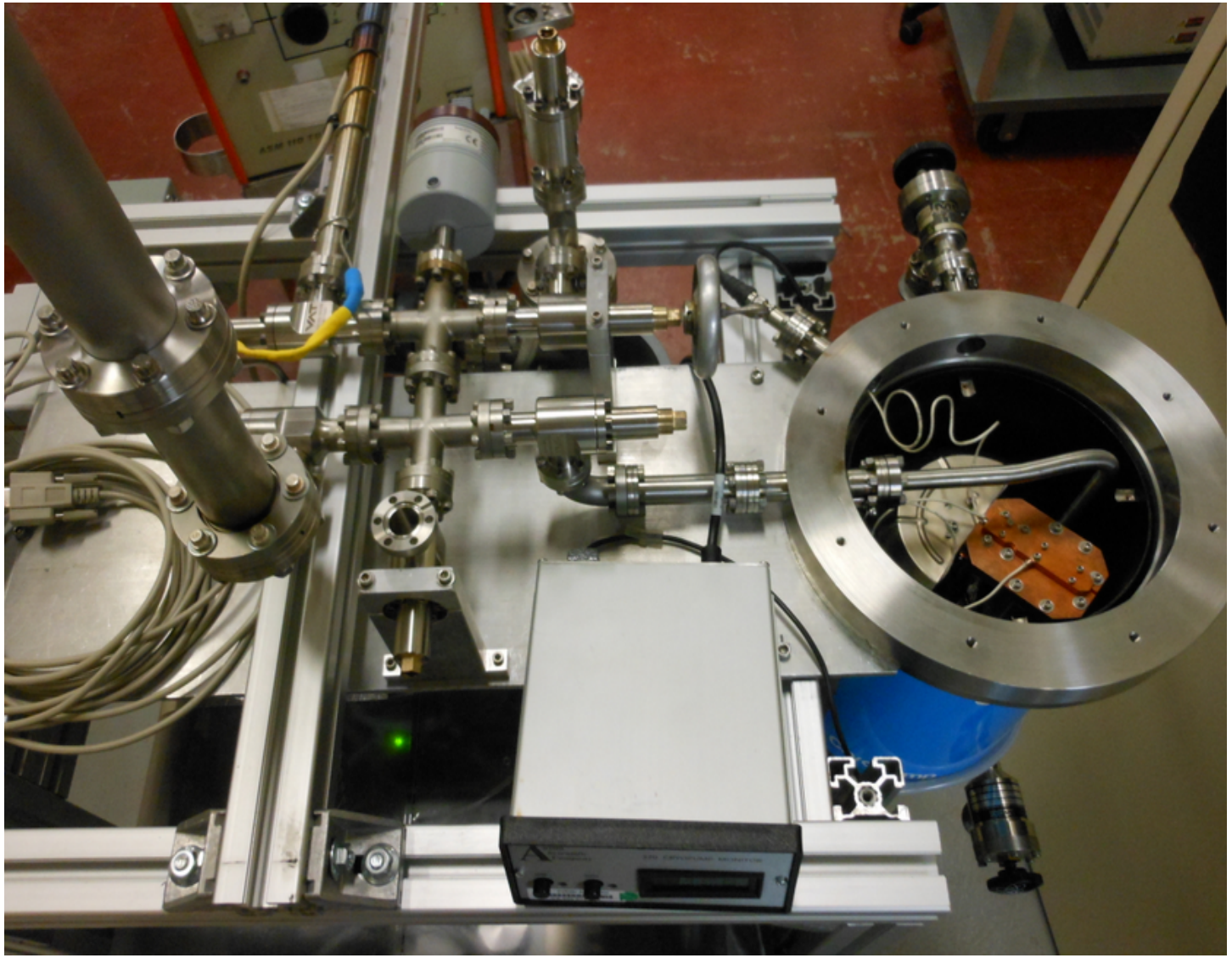
OPPIS (RHIC's polarized proton source) was converted into a high field MEOP system for polarizing ^{3}He.



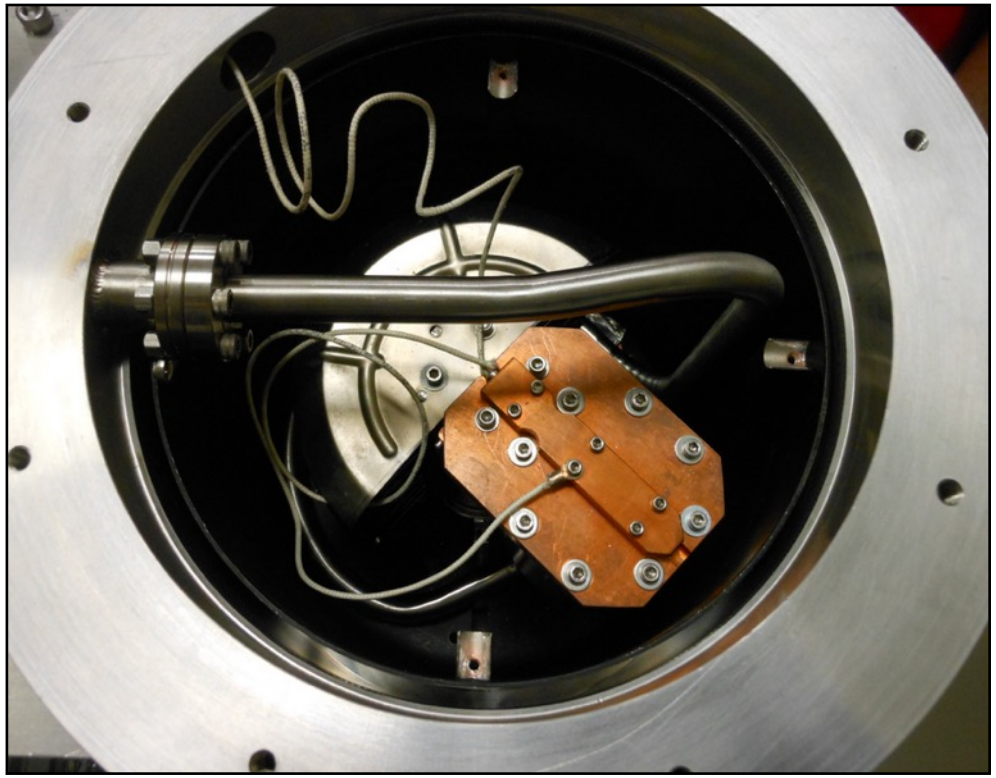


Non-magnetic brass pneumatic remotely controlled Isolation Valve

Open ^{3}He Cell and Gas Purification System

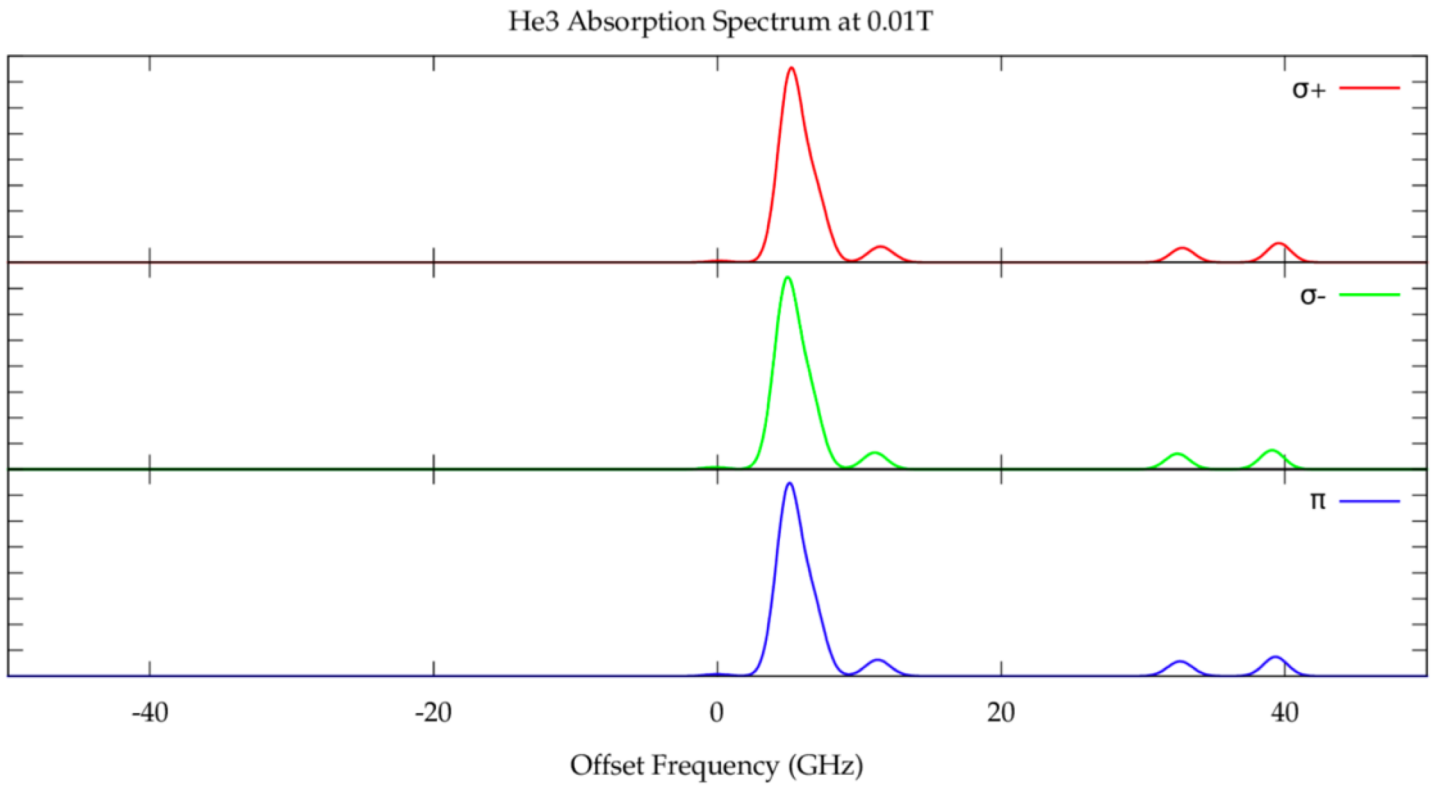


^{3}He cyro-purification and storage system was built from a modified cryo-pump. Pumps everything except helium!



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]



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

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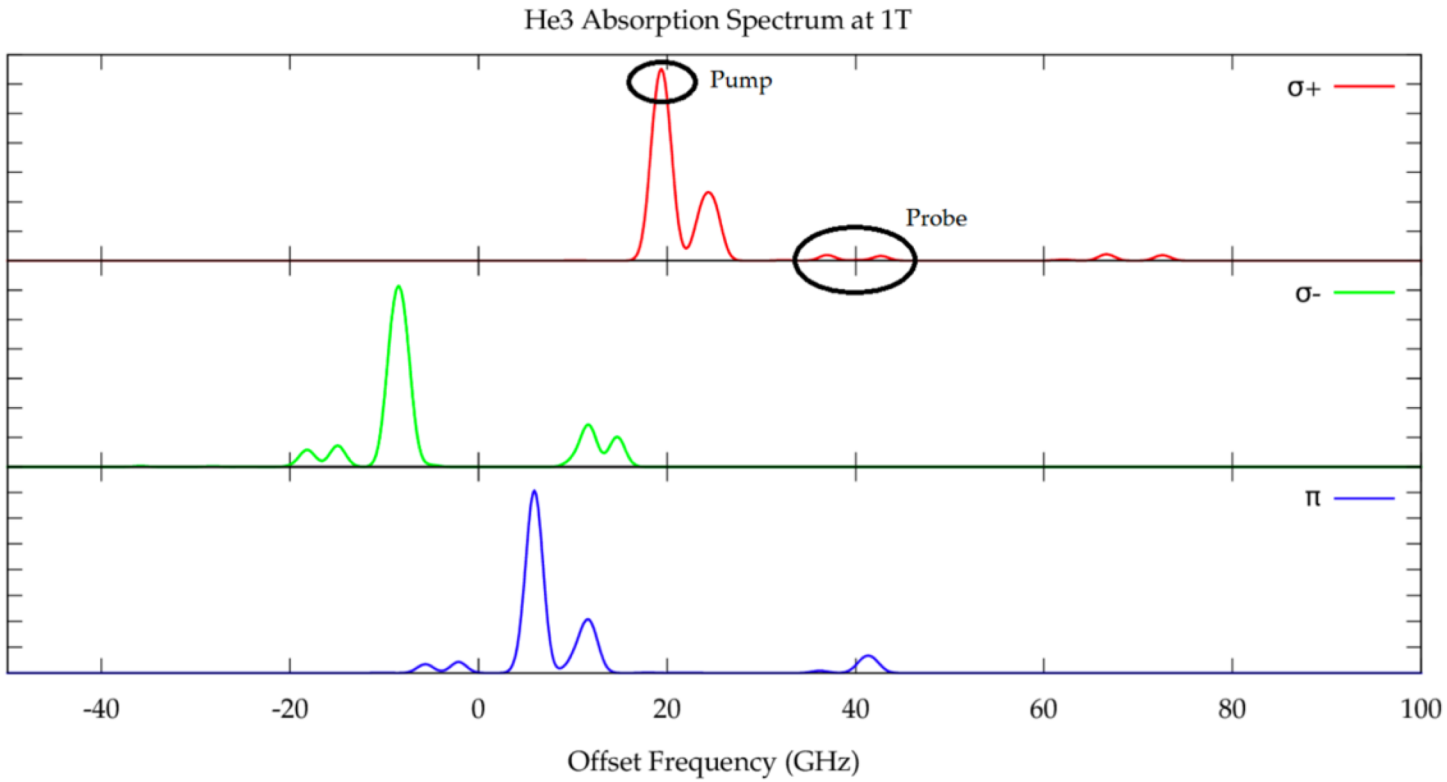

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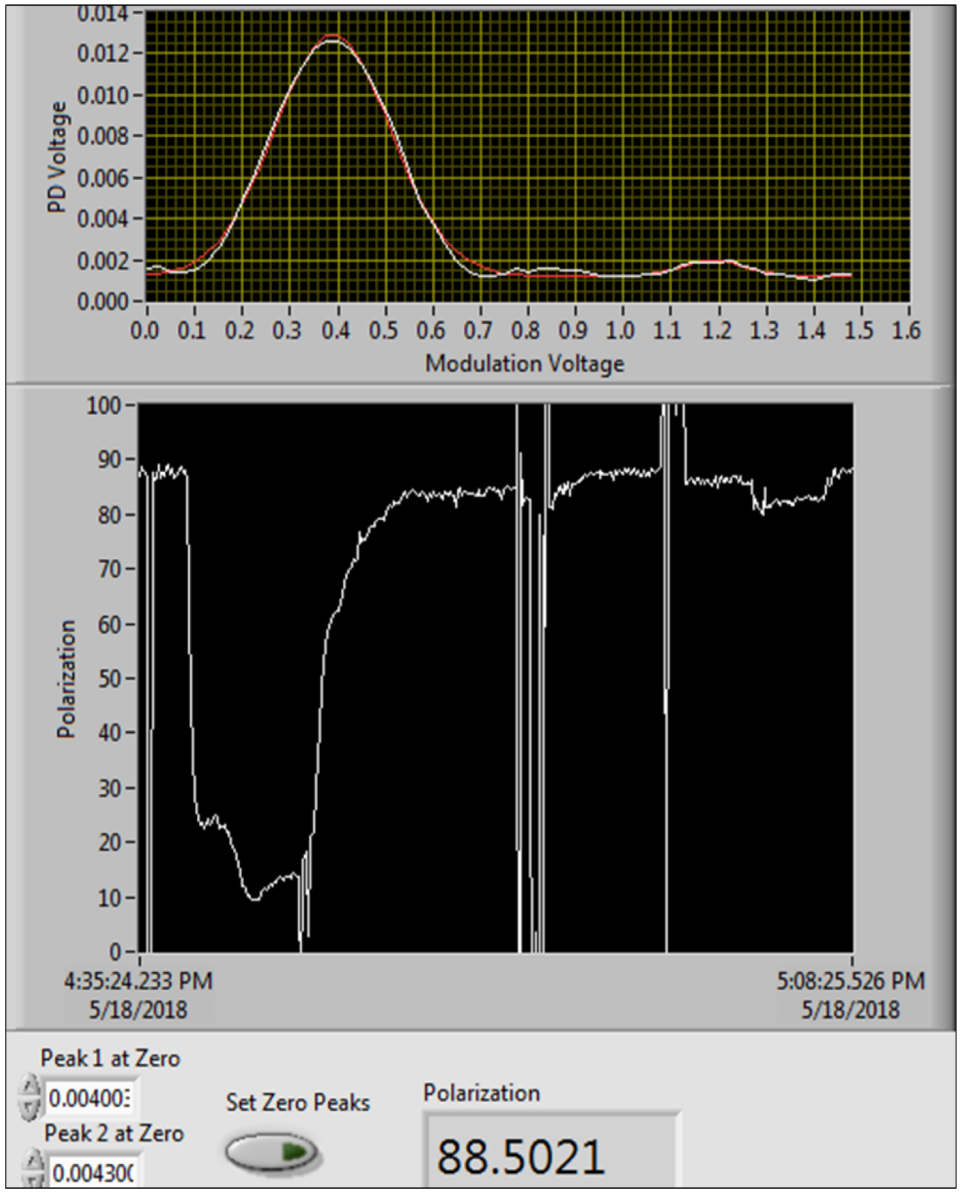
^{3}He Open Cell Results

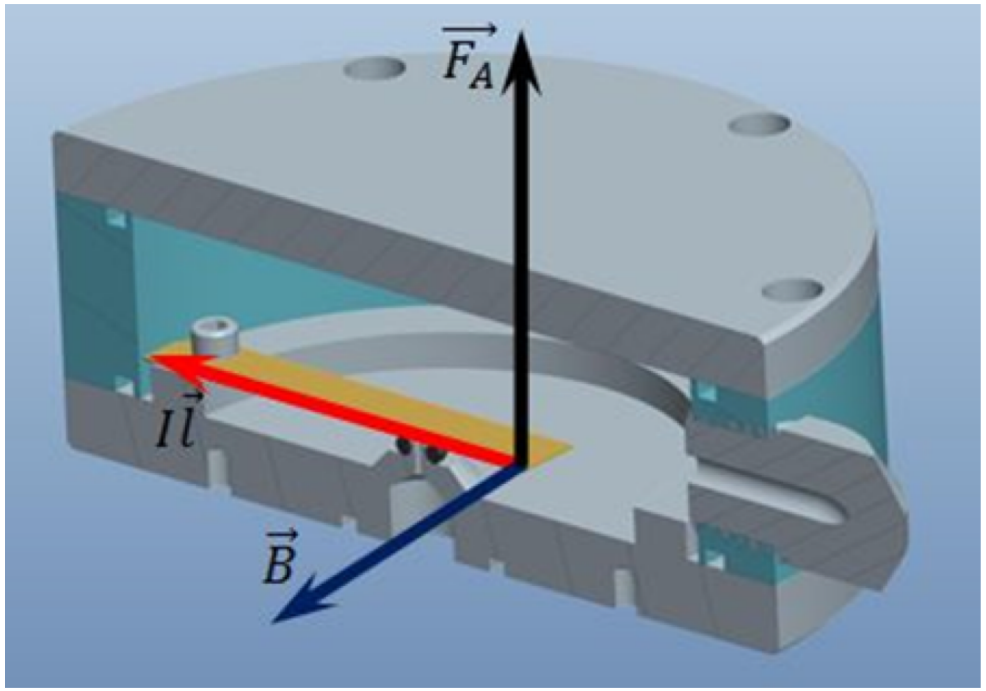
- ^{3}He pressure can be controlled with the cryo-pump temperature.
- Polarizations have been measured >80% at 2 torr and higher pressures have similar results.
- Relaxation time of 30 s measured in open cell. Relaxation rate is limited by metal surfaces of the fill valve and gas contamination.
- Valve construction and open cell design will be optimized to improve relaxation rate and maximum polarization.

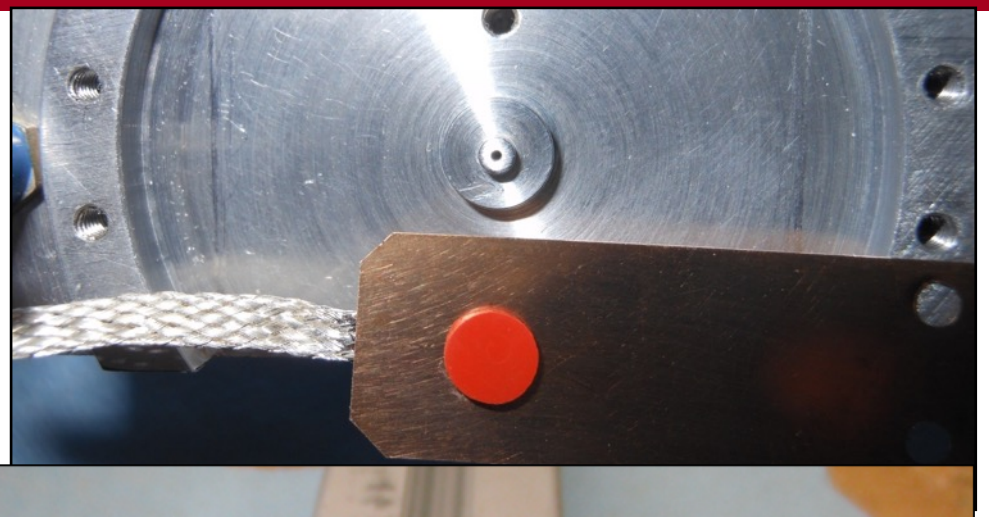


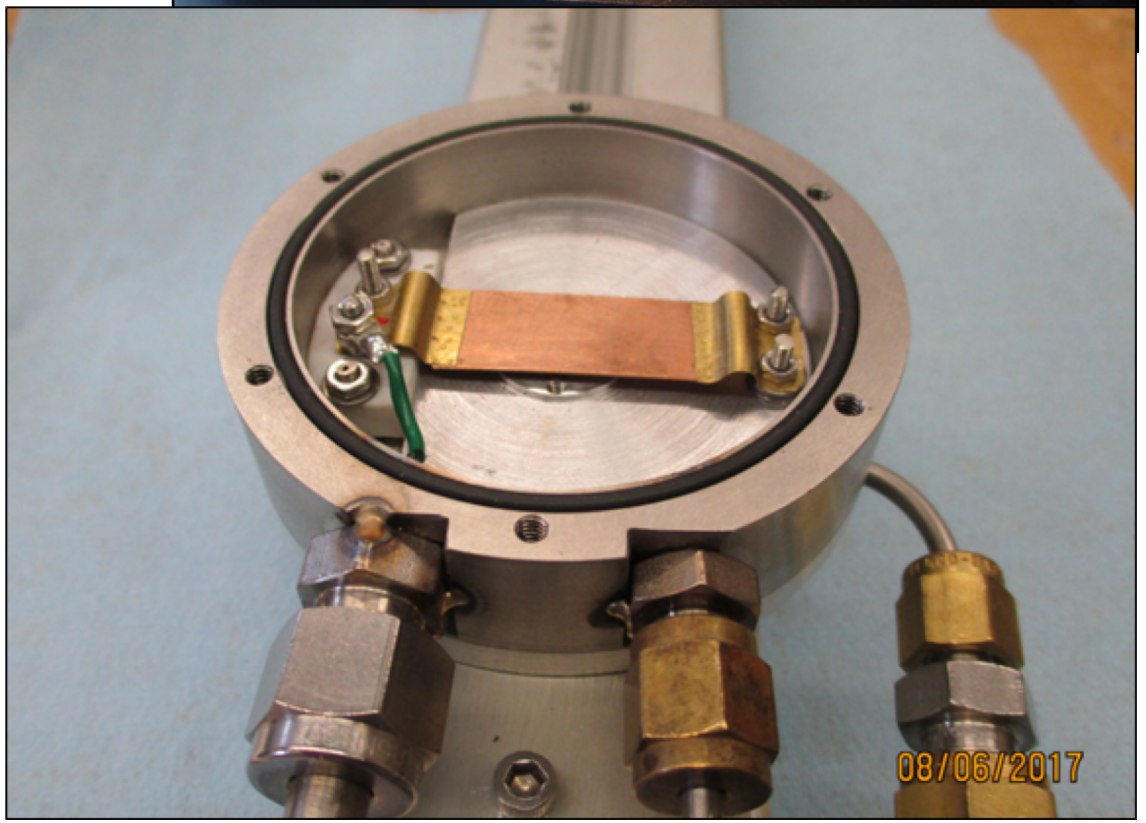
High Speed Pulsed ^{3}He Valve

- 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 T, I=100 A, L=5 cm, F=15 N, τ=100μs.

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

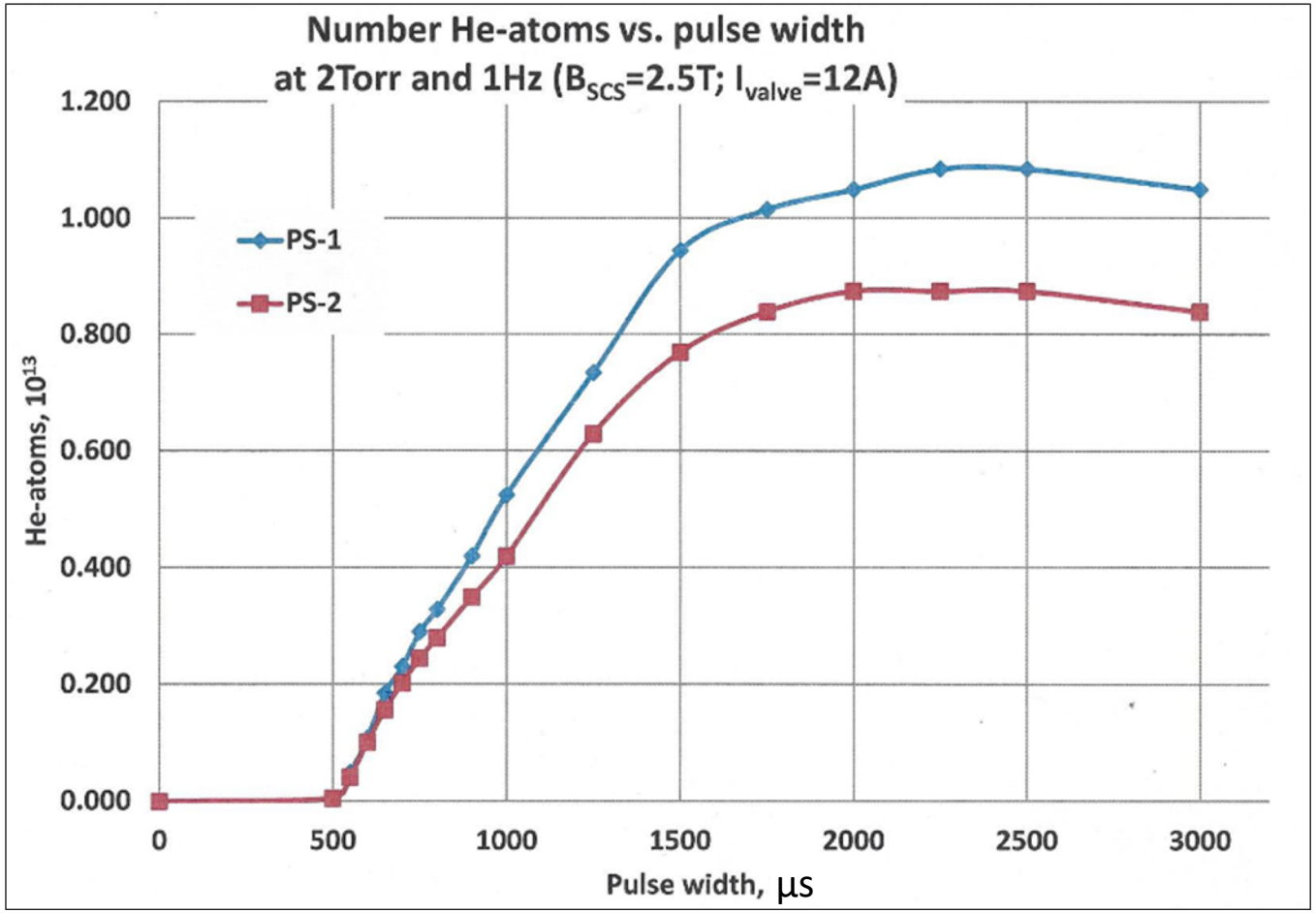






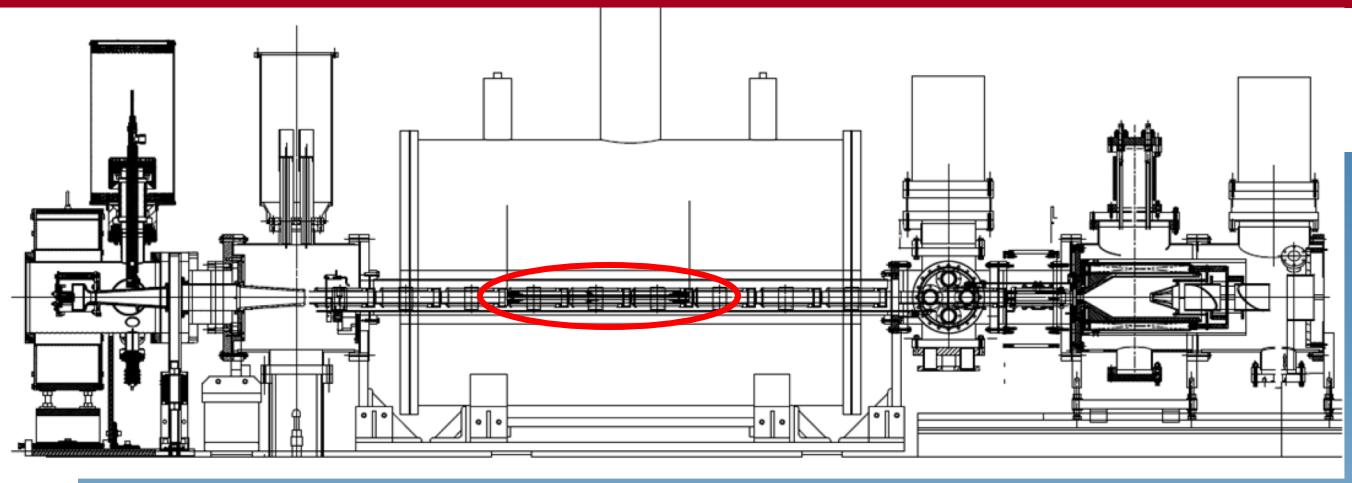
High Speed Pulsed ^{3}He Valve

- Test of high speed pulsed valve in a 2.5 T field in the OPPIS solenoid.
- B = 2.5 T, I = 12 A, ^{3}He reservoir pressure = 2 Torr



*Actual valve open time may be longer than the electric current pulse width.

Gas Ionization Cell for Electron Beam Tests in the BNL TestEBIS



- 46 cm long, 1 cm diameter gas ionization cell
- 3 cm long, 0.5 cm diameter down stream barrier (blue)
- Electron beams of 6 Amps were successfully propagated through the assembly.

Vacuum Simulations of EBIS with MolFlow

Timing & Trap Capacity

Maximum EBIS pulse time = 200 ms

Charge Capacity = ~10^{12} elementary charges

$^{3}He^{++}$ Capacity = ~ $2.5x10^{11}$ $^{3}He^{++}$

Electron Beam

1 mm diameter

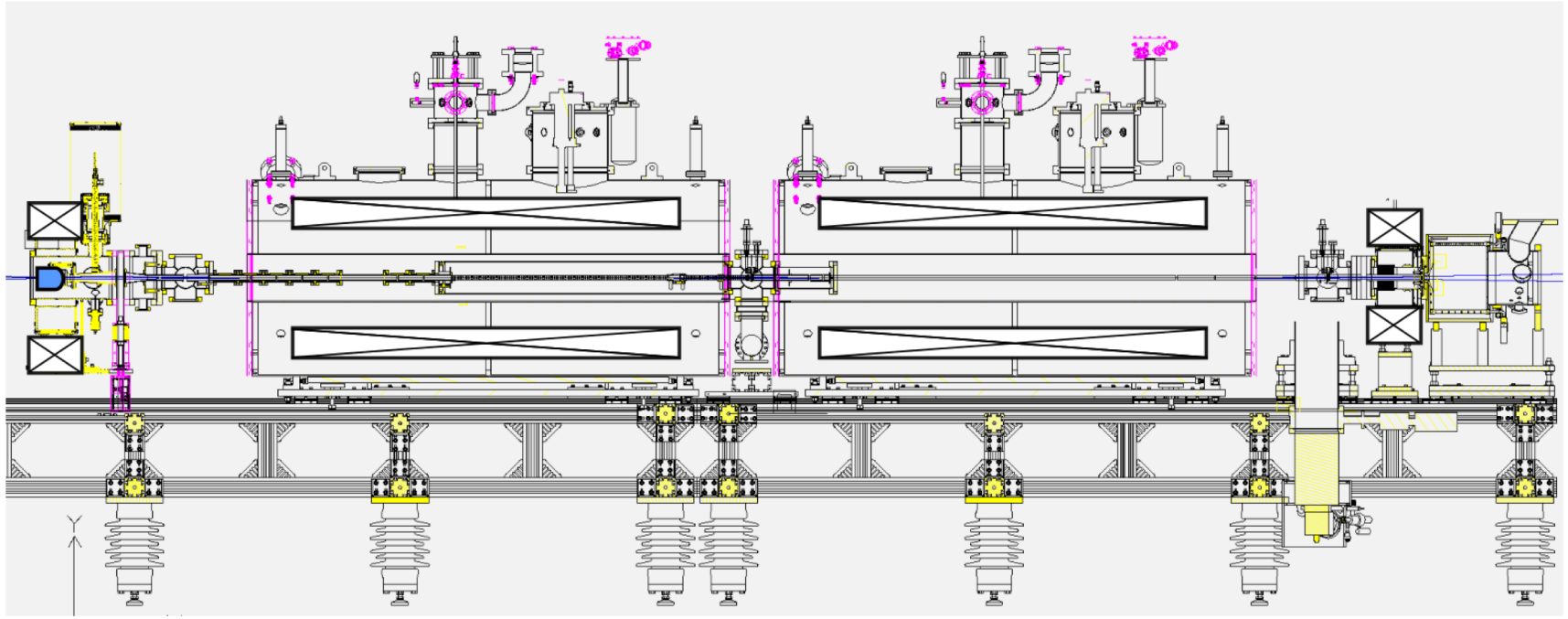
10 Amp

25 keV

Pressure

$1x10^{-6}$ mbar during gas injection

$1x10^{-10}$ mbar standard operation



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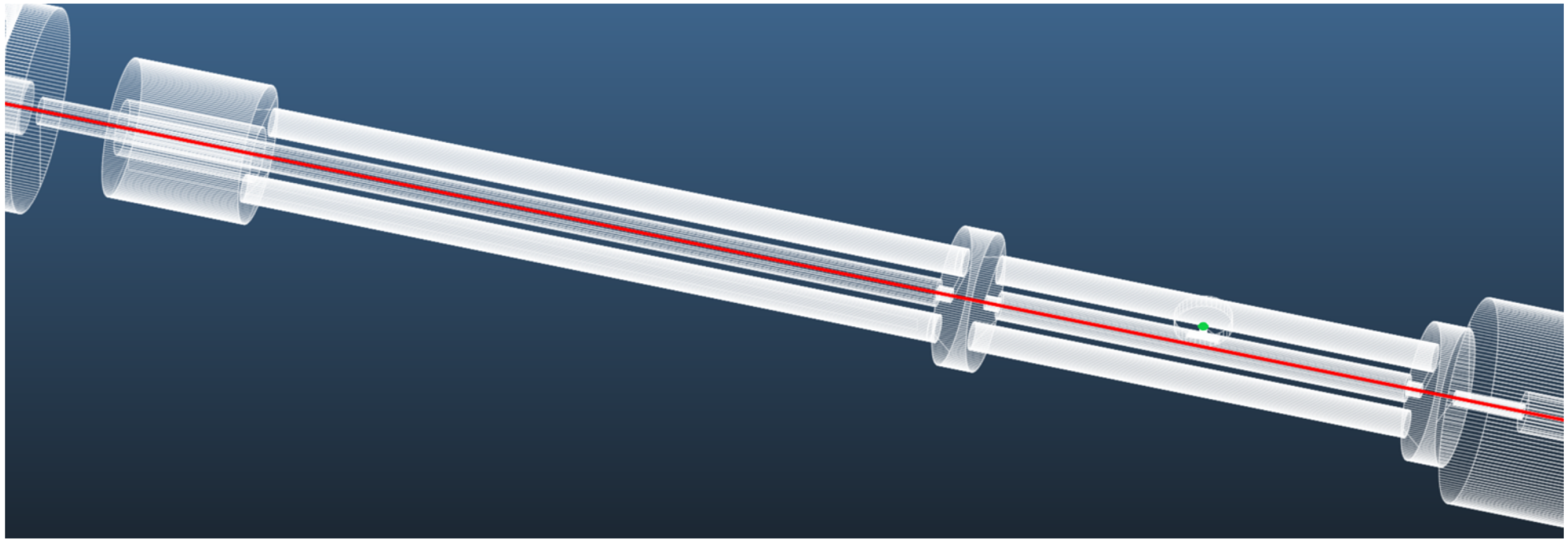
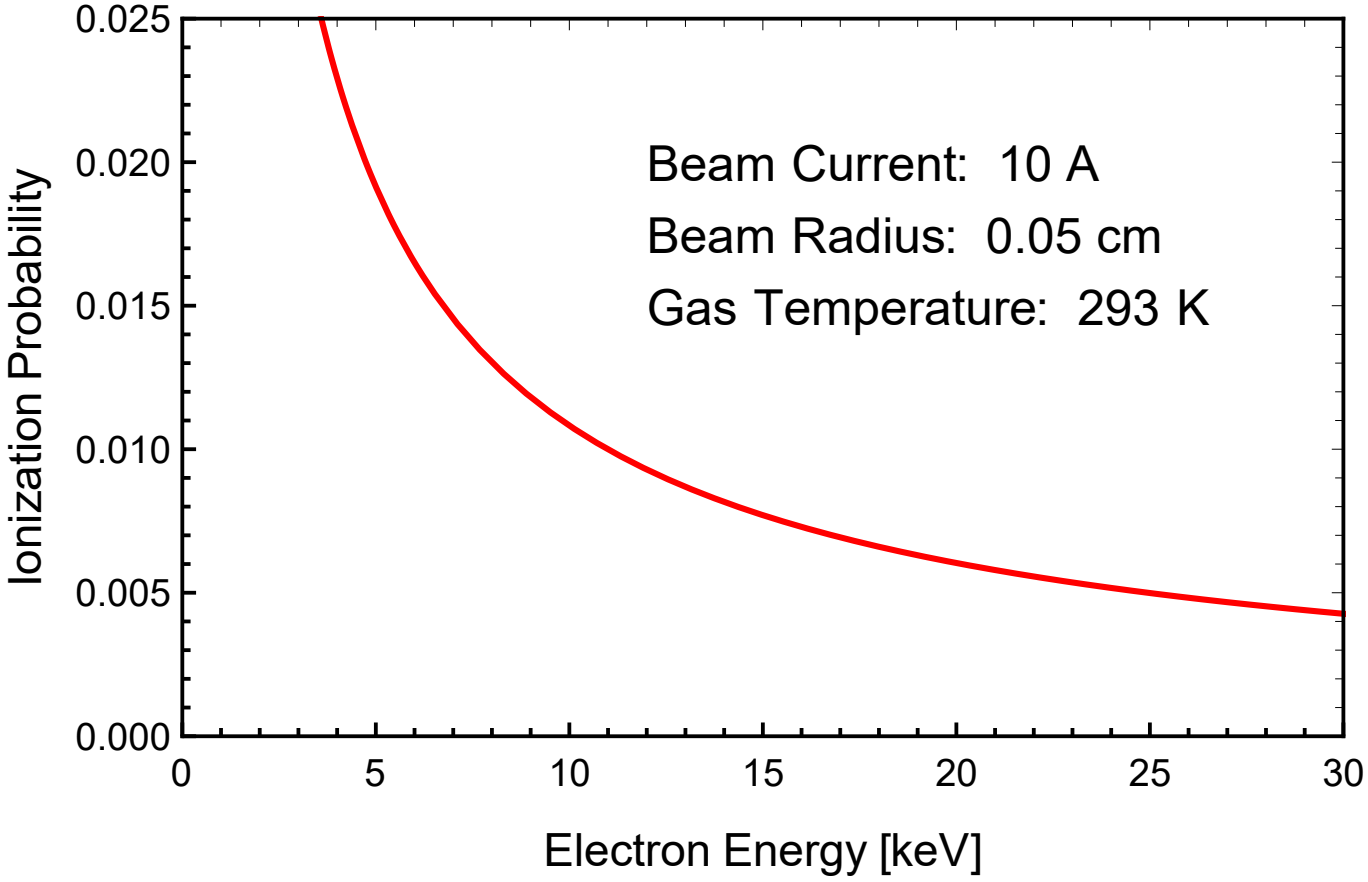


Electron Beam Ionization of ^{3}He



$$S = \frac{16 I \sigma}{3\pi^2 e r_e v_{gas}}$$

- For an e-beam of 25 keV there is a ≈0.5% probability that ^{3}He is ionized during traverse of the e-beam.
- Therefore, treat the e-beam as an ideal pump with 99.5% transparency.

Electron Beam Ionization of ^{3}He

Proportion of ^{3}He ionized after 20 ms

Length:	10 cm	20 cm	30 cm	50 cm
1 cm (0.5 cm ends)	0.142	0.263	0.372	0.537
1 cm (1 cm ends)	0.0556	0.132	0.224	0.411
2 cm (0.5 cm ends)	0.123	0.184	0.218	0.257
2 cm (1 cm ends)	0.0382	0.0695	0.0997	0.155
2 cm (2 cm ends)	0.0176	0.0355	0.0557	0.101
3 cm (0.5 cm ends)	0.097	0.121	0.131	0.141
3 cm (1 cm ends)	0.0349	0.0576	0.0747	0.0988
3 cm (2 cm ends)	0.0158	0.0278	0.039	0.06

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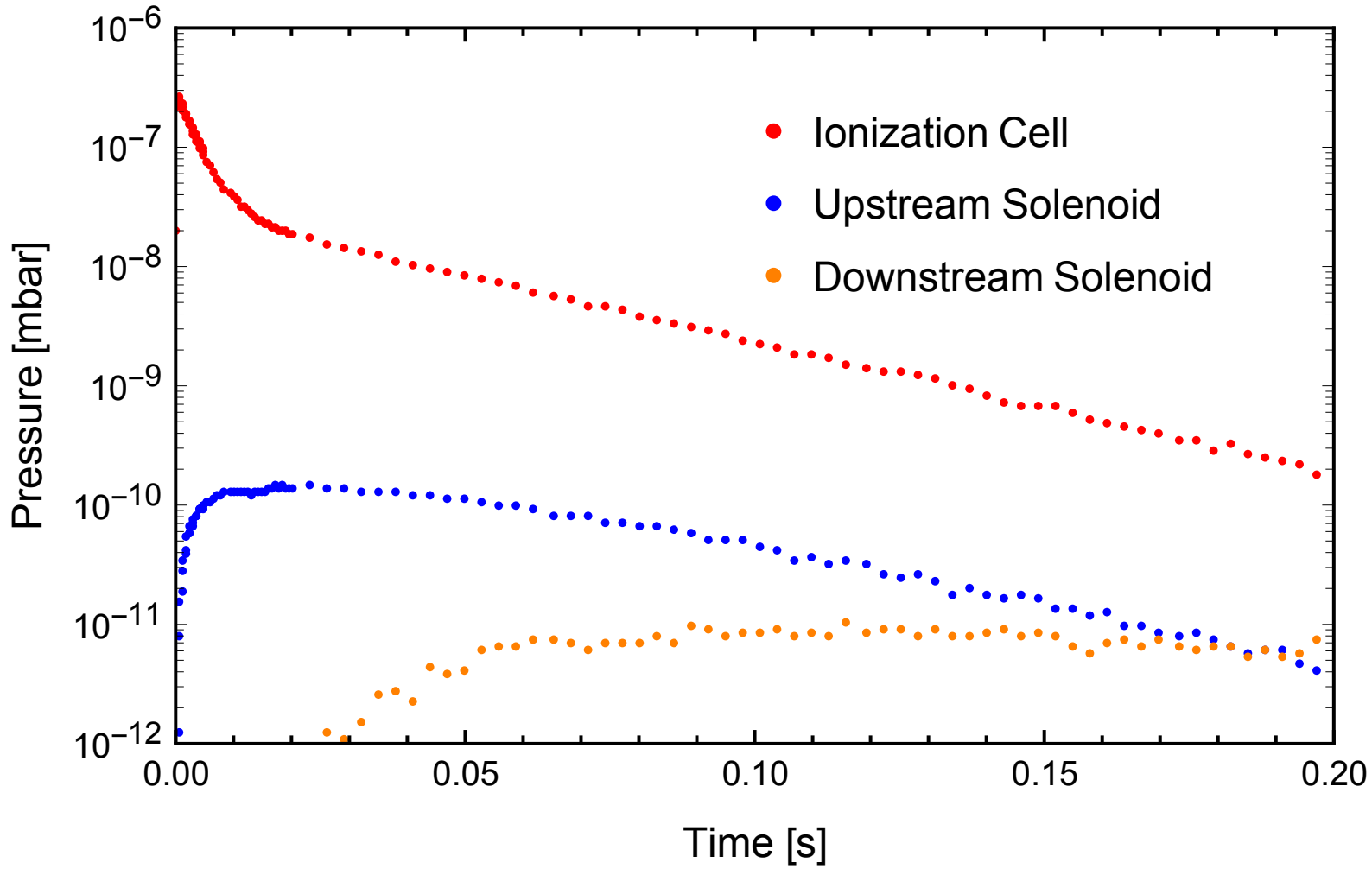
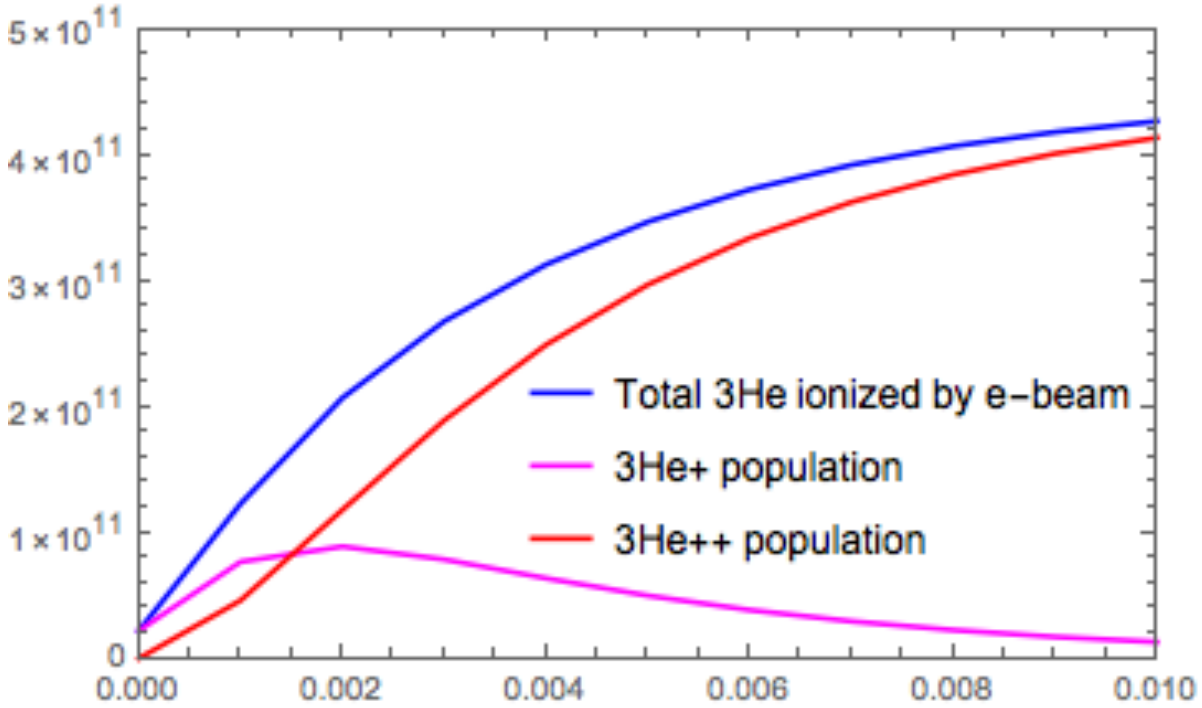
Gas Diffusion and Pumping in Ionization Cell

- 6.18 x 10^{11} ^{3}He atoms injected
- 10 A, 25 keV e-beam
- Ionization Cell
  - 30 cm long
  - 2 cm diameter
  - 1 cm constrictions



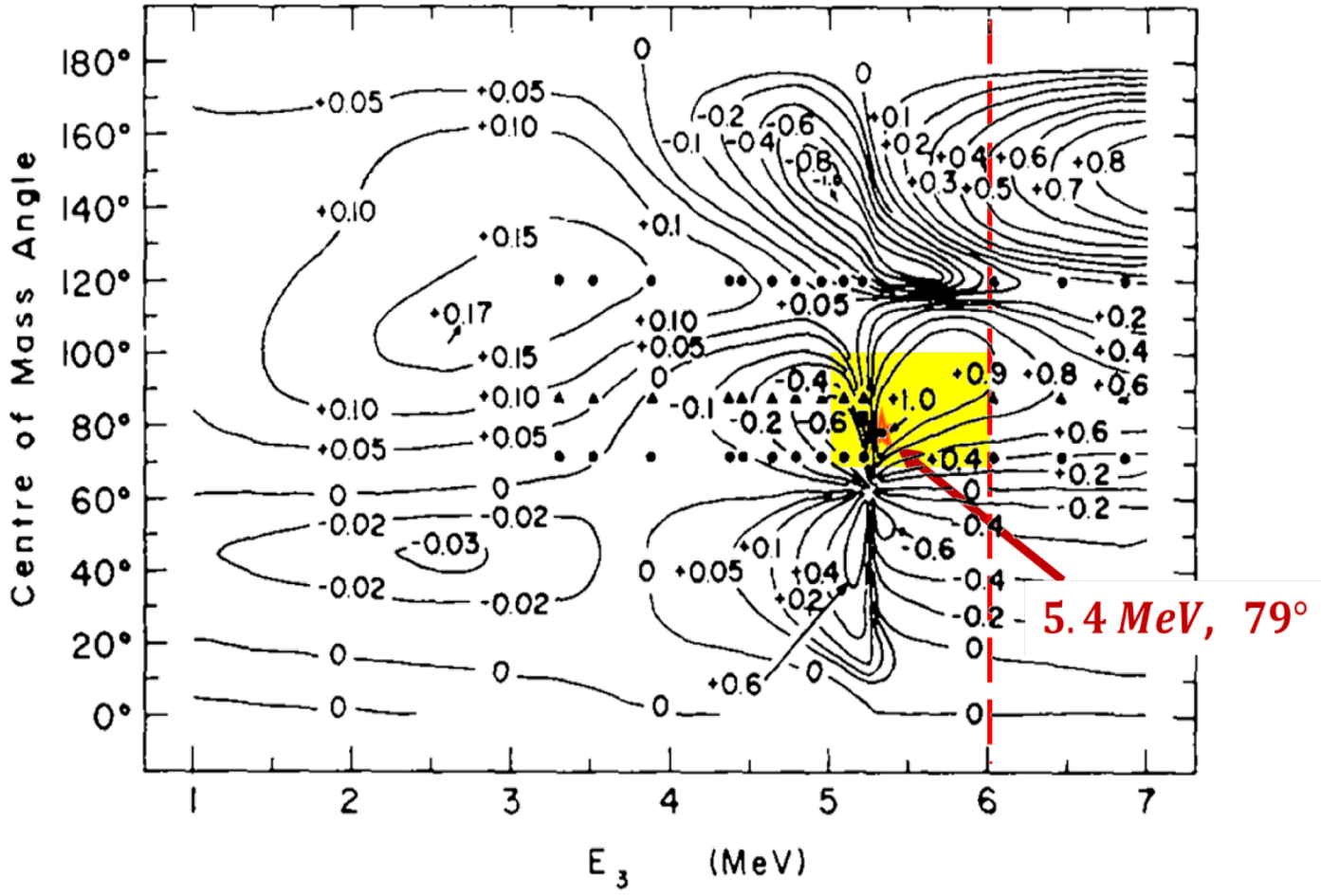
Electron Beam Ionization of ^{3}He



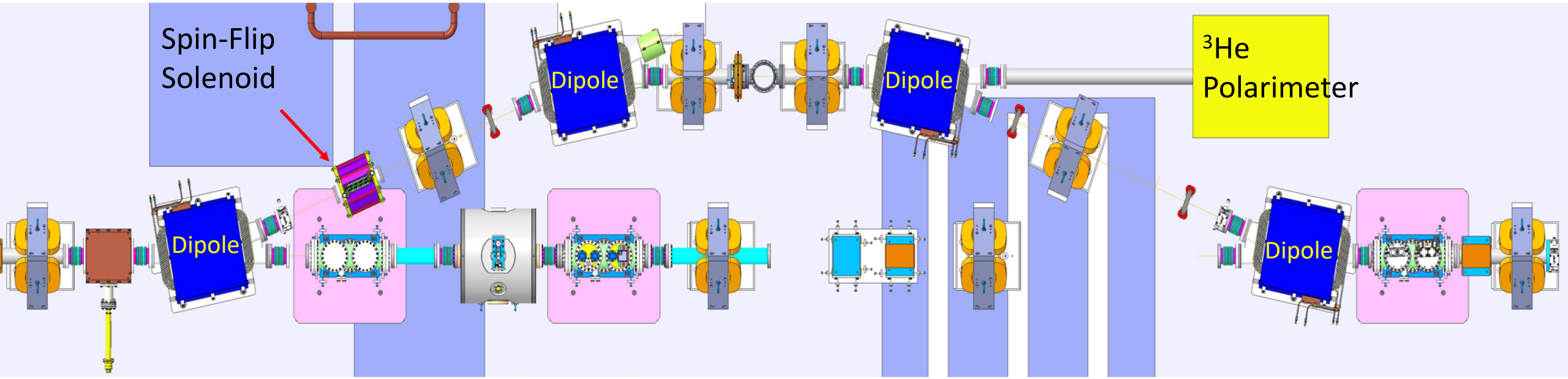
Step sequence	Time
^{3}He gas injection	0.5 ms
Diffusion into ionization cell	2 ms
Injected gas pressure falls 50%	3 ms
Ionization of ^{3}He to ^{3}He$^+$	~10 ms per gas injection
Time constant for ^{3}He$^+ \rightarrow {}^3$He^{++} conversion	1 ms
Pump down to 10^{-9} torr	100-150 ms
5 Hz EBIS pulse repetition rate	200 ms
Switching time between species	1 second

Feasibility Experiment

- Use extended EBIS and extract fully stripped polarized $^{3}He^{++}$ ions accelerated to 6 MeV
- Measure $^{3}He + {}^{4}He \rightarrow {}^{3}He + {}^{4}He$ elastic scattering
- Analyzing power has been measured to be 100% somewhere between 79^{o}_{CM} & 91^{o}_{CM} at ~5.4 MeV
- Process yields 2.66 MeV ^{3}He at 53.6^{o}_{lab} and 2.64 MeV recoil ^{4}He at 44.5^{o}_{lab}



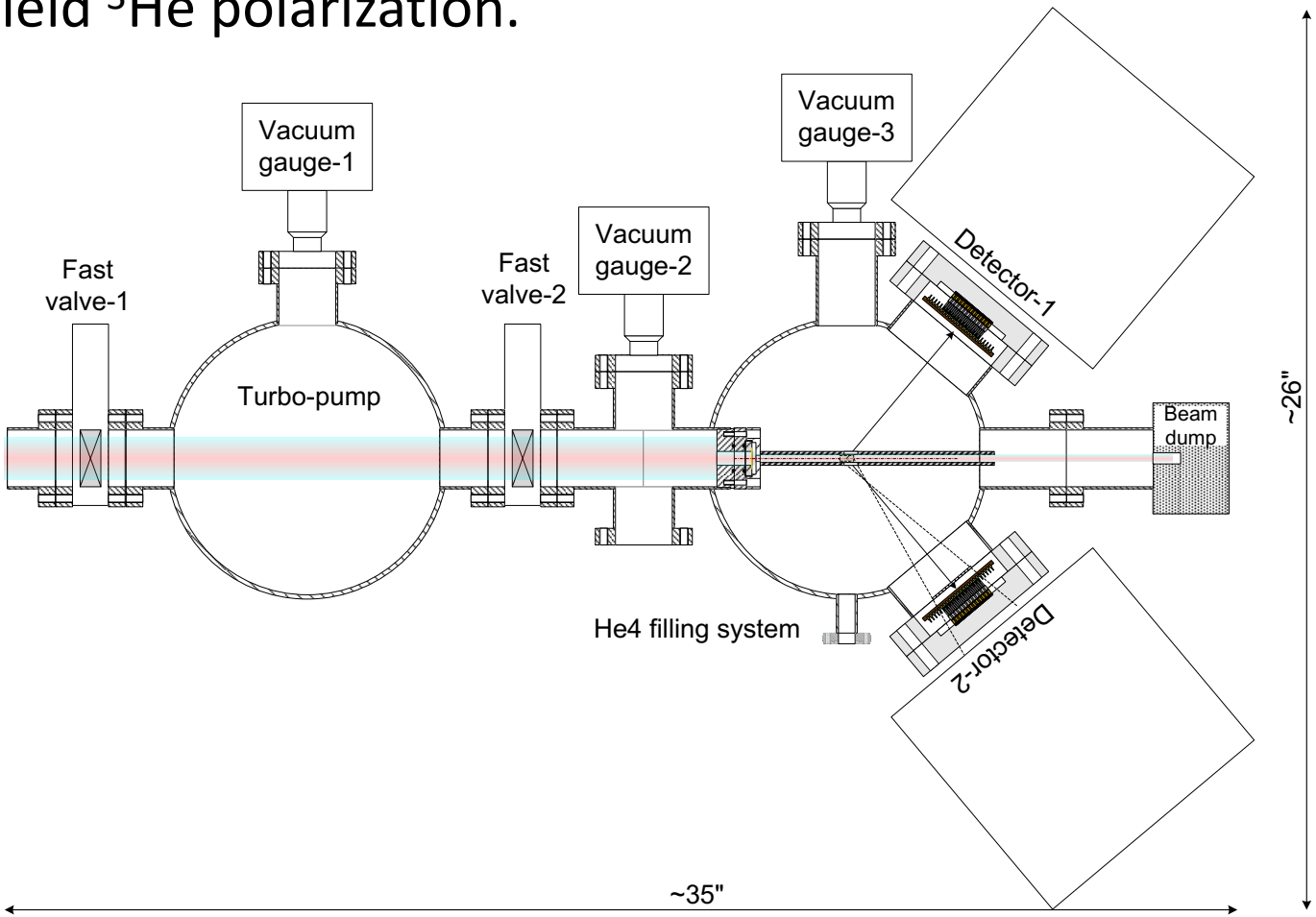
$^3He^{++}$ Spin Rotator and 6 MeV Polarimeter

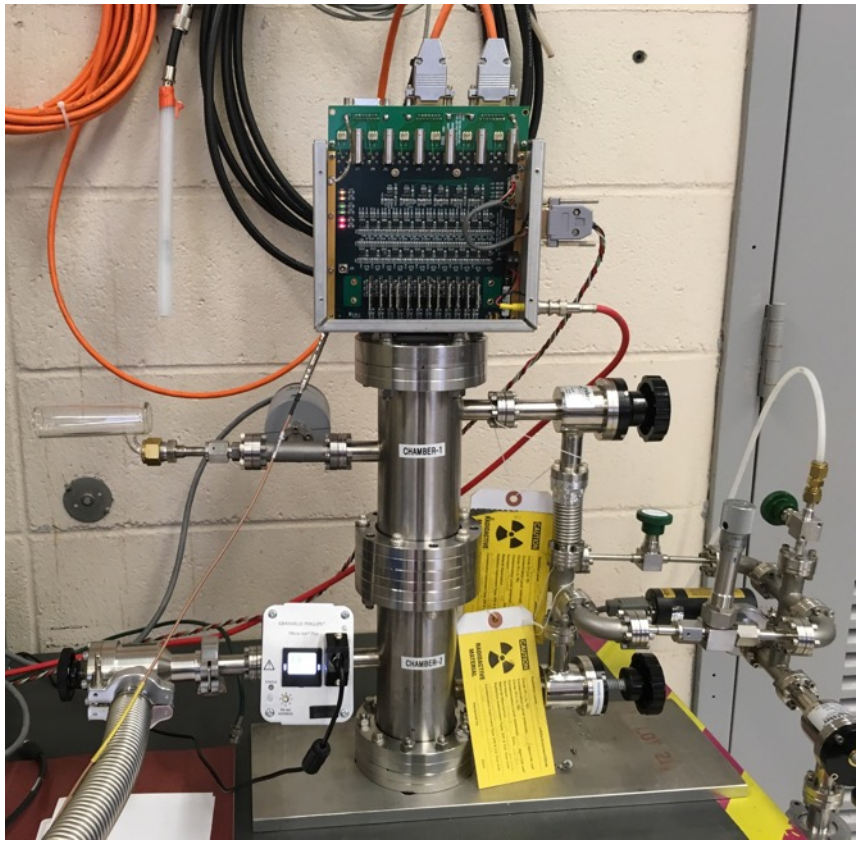


- 1st dipole magnet rotates ^{3}He spin into the horizontal transverse plane.
- Spin-flip solenoid selectively rotates ^{3}He spin into the vertical transverse plane (spin-up or spin-down).
- 2nd, 3rd, & 4th dipole magnets direct the ^{3}He beam into either the 6 MeV polarimeter or back into the transport line to RHIC.

6 MeV $^{3}He^{++}$ Polarimeter Design

- Measure 2.66 MeV ^{3}He at 53.6°$_{lab}$ and 2.64 MeV recoil ^{4}He at 44.5°$_{lab}$ after $^{3}He + {}^{4}He \rightarrow {}^{3}He + {}^{4}He$ elastic scattering.
- Asymmetry of detector signals for opposite spin states will yield ^{3}He polarization.





^{3}He polarimeter test setup to measure null signal asymmetry.

Summary

- Extended EBIS upgrade is ongoing and electrons were propagated through two 5 T solenoids.
- ^{3}He was successfully polarized to >80% in a 3 T field.
- An optical probe polarimeter to measure ^{3}He polarization was developed.
- A prototype high-speed pulsed valve has been tested.
- Gas injection & ionization simulations show promising results.
- The ^{3}He spin-rotator is being designed and equipment purchased.
- The 6 MeV ^{3}He polarimeter has been designed and the concept was tested with an alpha source.

Now all the parts need to be put together. We plan for partial installation in the summer of 2020 and complete installation followed by polarization measurements in the summer of 2021.

Thank you for your attention

MIT-BNL Polarized ^{3}He Ion Source Collaboration

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