Development of a Polarized ^{3}He Beam Source

for RHIC with EBIS

J. Maxwell

for the
BNL–MIT Polarized He3 Ion Source Collaboration

Massachusetts Institute of Technology

Laboratory for Nuclear Science

PSTP 2013, Charlottesville, VA
September 12th, 2013

Outline

1. Source Design
   - Electron Beam Ion Source
   - MEOP ^{3}He Polarization
   - Depolarization Effects
2. Gas Transfer Test Design
   - Magnetic Shielding
   - Test Polarization System
   - Transfer Path
3. Current Progress
   - New Discharge Polarimeter
   - MIT Lab Setup

Outline

Why a Polarized Helium 3 Source?

- Polarized DIS crucial for study of nucleon spin structure
  - Measurements of PPDFs; tests of QCD, Bjorken sum rule; exploration at higher energies
- Targets have proton and neutron surrogates (H, D, ^{3}He)
- Polarized neutron beam for polarized DIS needed as an Electron Ion Collider becomes new focus
  - Deuterium has small magnetic moment: tough
  - ^{3}He has a magnetic moment close to the free neutron, will work with RHIC spin manipulation
- Polarized ^{3}He ions offer a polarized neutron beam for RHIC and a future eRHIC
- Workshop on Opportunities for Polarized He-3 in RHIC and EIC (2011)

History of ^{3}He Ion Sources

- Rice University, 1969: MEOP for $^3He^+$
  - 16 keV, 8 particle μA at 11% polarization
- Univ. of Birmingham, 1973: Lamb Shift for $^3He^{++}$
  - 29 keV, 50 particle μA at 65% polarization
- Laval University, 1980: Stern-Gerlach for $^3He^+$
  - 12 keV, 100 particle nA at 95% polarization

Our Proposal[1]

- RHIC's **Electron Beam Ion Source** Preinjector
  - Proven in recent RHIC runs, NASA Space Radiation Lab
- Metastability Exchange Optical Pumping
- Doubly ionize $^3He^{++}$ for injection

[1] A. Zelenski, J. Alessi, ICFA Newsletter (2003).

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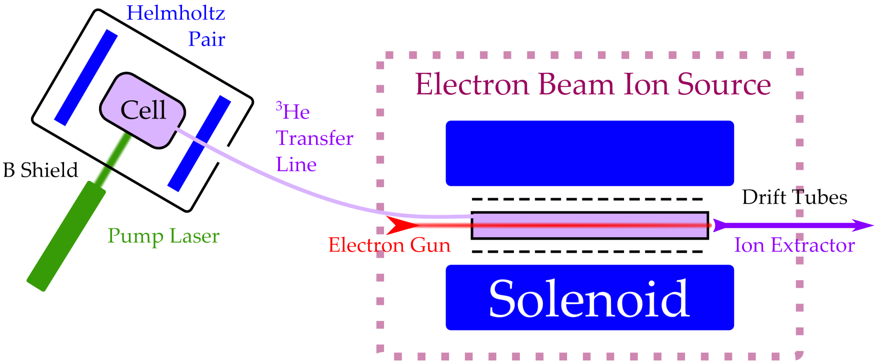
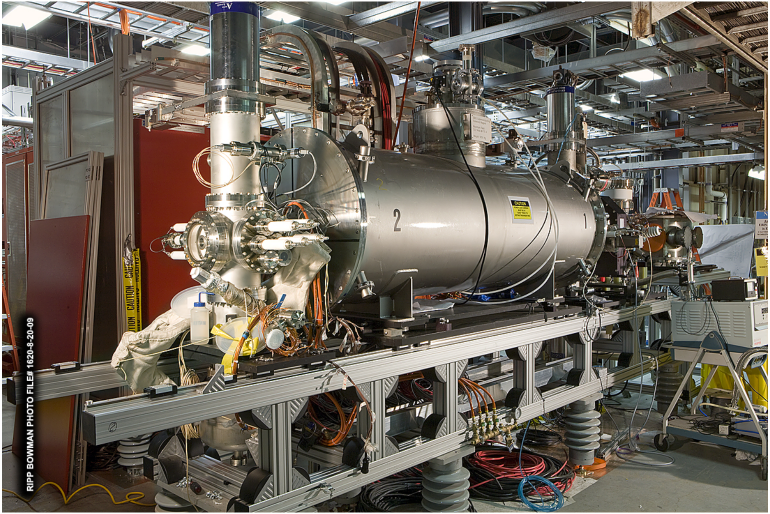
Source Design Goals

- Polarize to ∼70% at 30 G & 1 torr with 10 W laser
- Transfer $\sim 10^{-14}$ ^{3}He/s to EBIS at 5 T & 10^{-7} torr
- Deliver 1.5×10^{11} $^3\text{He}^{++}$ ions per 20 μsec pulse

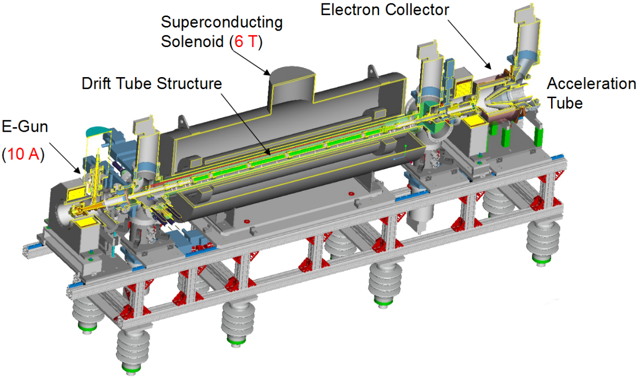


RHIC's Electron Beam Ion Source



RHIC's Electron Beam Ion Source

- 5 T Solenoid B Field; 1.5 m Ion Trap
- 20 keV electrons up to 10 A, 575 A/cm^2 Current Density
- **Any** species, switch between species in 1 sec



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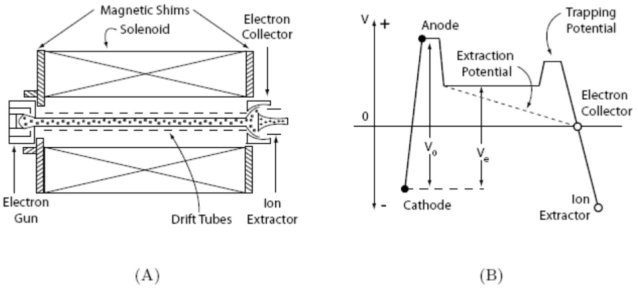
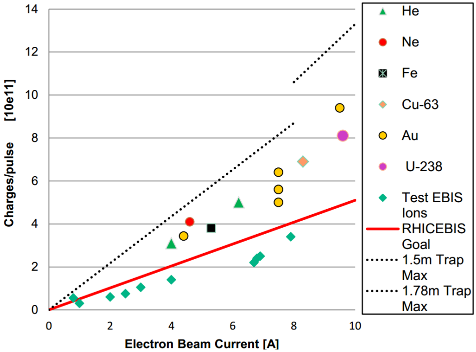


Figure 4. (A) A schematic of the EBIS course. (B) The electric potential along the axis of the source.

RHIC's EBIS Performance

- EBIS has provided He^{2+}, Ne^{5+}, Ar^{10+}, Fe^{20+}, and Ti^{18+} for NASA's SRL
- For RHIC run supplied U^{39+}, and both Au^{32+} and Cu^{11+} with rapid switching[2]
- Capable of $^3He \Rightarrow {}^3He^{++}$ at nearly 100%



[2]Alessi, Beebe, Pikin: BNL-94248-2011-CP and BNL-98867-2013-CP

^{3}He Polarization

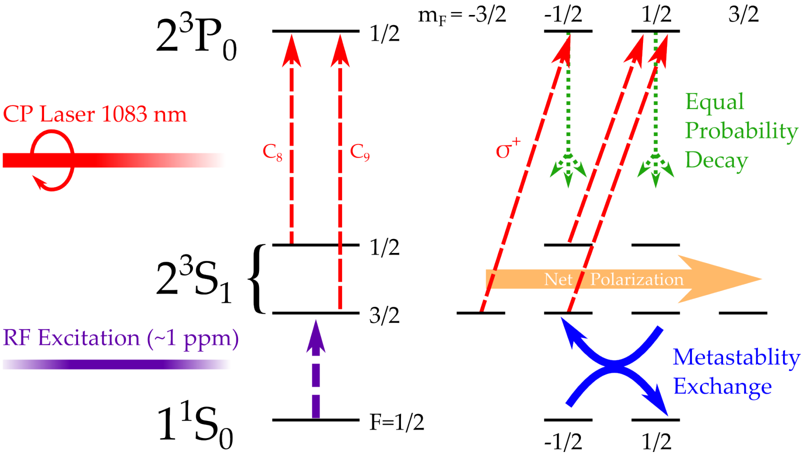
- EBIS has done much of the work for us!
- Need polarized ^{3}He; pure sample for injection
- Revisit MEOP technique[3] with modern lasers

Metastability Exchange Optical Pumping

- Mature technique: polarized targets, medical imaging[4]
- Laser technological advances give 10 W @ 1083 nm easily
- Polarize at $\approx$ 1 torr, $\approx$ 30 G (Higher possible)
- Pure ^{3}He sample, faster than SEOP

[3] Colegrove *et al*, Phys. Rev. 132 (1963).
[4] Kauczor et al. JMRI, 7 (1997).

MEOP Mechanism



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: $^3He^+ + ^3He^{++} \rightarrow \ ^3He^{++} + ^3He^+$
  - Recombination: $e^- + ^3He^{++} \rightarrow \ ^3He^+$
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Depolarization from Field Gradients

From Schearer[5], we have:

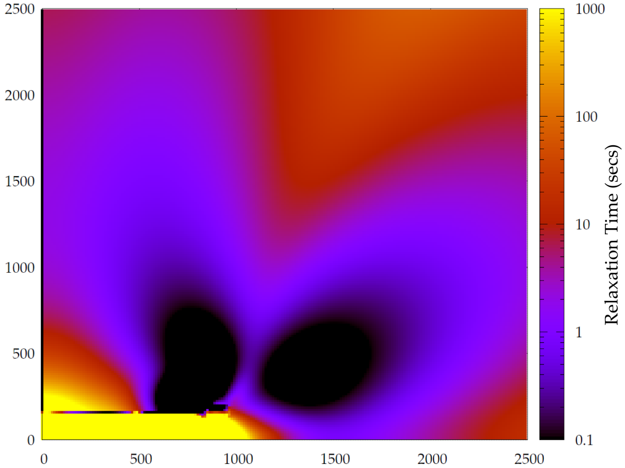
$$\frac{1}{\tau} = \frac{2}{3}\frac{|\Delta B_t|^2}{|B_l|^2}\langle v^2\rangle\frac{\tau_c}{\omega_0^2\tau_c^2 + 1}$$

- Transverse gradient ΔB_t
- Holding field B_l
- Velocity v
- Average time between collisions τ_c
- Resonant frequency ω_0

We can map regions of stray field which should be problematic, but a full-scale test of the source with test solenoid is planned.

[5] Schearer, Walters, Phys. Rev. 139(5A) (1965).

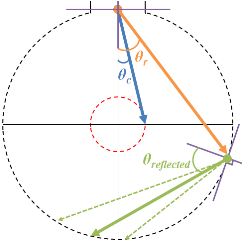
Relaxation Time in EBIS B field

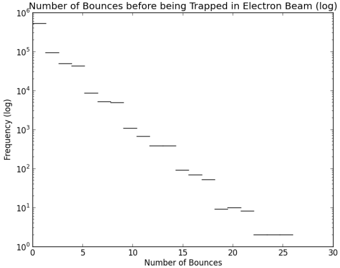


- Avoiding dark spots will minimize spin relaxation

Depolarization After Entering EBIS

- Simulation by E. Mace
- Number of Bounces before:
  - Trapped
  - Absorbed in wall
  - Exit cylinder
- No particles bounces more than 35 times
- Expect 10^3 bounces before depolarization





Polarimetry

- Gas Polarization Measurements
  - RF discharge polarimeter[6]: Low P, Low B
  - Probe laser absorption polarimeter[7]: Wide range of P, B
  - NMR: calibration with water cell
- After Extraction (10-20 keV)
  - Lamb-shift polarimeter[8]
- After RFQ and Linac ($\sim$ 6 MeV)
  - ^{3}He–C Foil[9], calibration using:
  - ^{3}He–^{4}He polarized elastic scattering[10]

[6] Pavlovic, Laloe, J. Phys, (Paris), 1970.
[7] Courtade *et al*, Eur. Phys. J. D 21 (2002).
[8] Pliss, Soroko, Nuc. Inst. Meth. (1976).
[9] Wissink *et al* Phys Rev C (1992).
[10] Plattner, Bacher, Phys. Letters (1971).

Outline

Polarization and Relaxation Test

- What polarization relaxation do we expect during transfer from pumping cell, through stray field, to EBIS?
- Perform gas transfer to test solenoid following same route
  - **But**: Polarization measurement at 10^{-7} torr is difficult

Polarization Relaxation in Transfer at 1 torr

- Pumping cell and test cell at same pressure, gas exchange via diffusion (worse depolarization than molecular flow)
- Estimate polarization in test cell from discharge polarimetry in pumping cell, observing rates of relaxation
- Secondary polarization measurement in test cell with optical probe and electrical discharge

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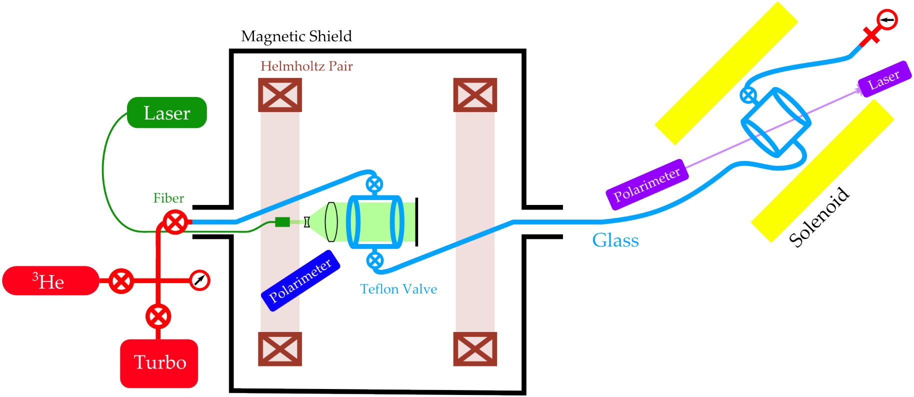
Testing Depolarization in Transfer to EBIS



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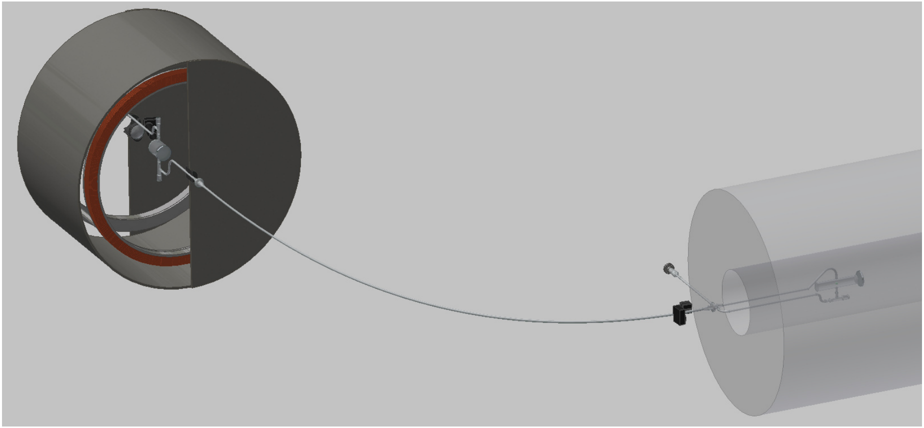


^{3}He Depolarization Transfer Test Setup

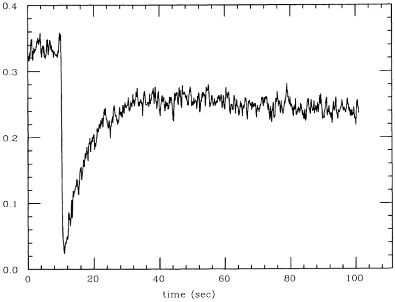
- Allows simple test of quantities we need to study
  - Polarization performance in shielded pumping cell
  - Relaxation in transfer into and inside solenoid
- Works if diffusion time is shorter than relaxation time

Relaxation rate measurements from pumping cell:

- Discharge off, pumping off
- Discharge on, pumping off
- Polarization destroyed with transverse field →

Direct measurements:

- Discharge on in test cell, optical probe laser



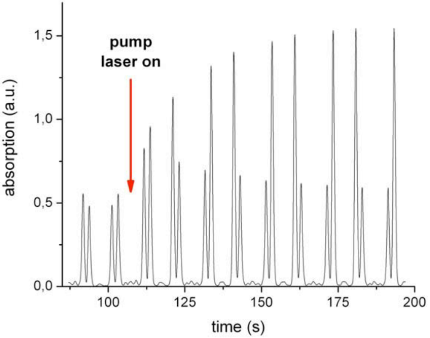
C.E. Jones et al. ^{3}*He(e,e') Quasielastic Asymmetry*, Phys. Rev. C, 47 (1993).

Optical Probe Polarimetry

Possible secondary polarization measurement for solenoid cell.

- Optical absorption technique[11,12] good at high field

- Sweep probe laser through two 2^3S-2^3P transitions
- For common spin temperature $1/\beta$ between metastable and ground state atoms: $P = \frac{e^\beta - 1}{e^\beta + 1}$
- β can be deduced from ratio of absorption signals



G. Collier

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

[12] Suchanek *et al*, Eur. Phys. Special Topics 144 (2007).

Optical Probe Polarimetry

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- Optical absorption technique[11,12] good at high field

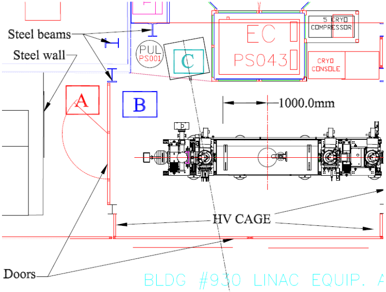
Technique Benefits

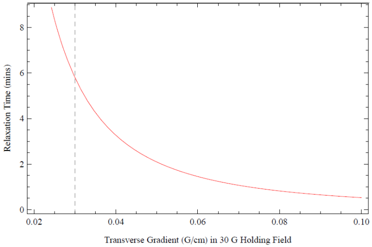
- No calibration required
- Can be performed at high, static B field
- High accuracy, signal-to-noise

[11] Courtade *et al*, Eur. Phys. J. D 21 (2002).
[12] Suchanek *et al*, Eur. Phys. Special Topics 144 (2007).

Polarizing in Stray Field

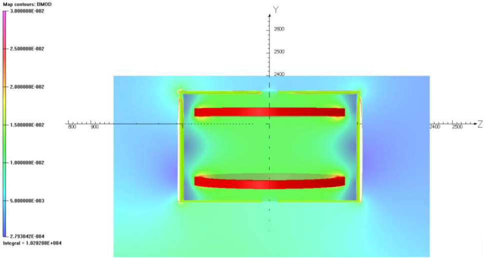
- Potential sites for our polarizer reside within the solenoid's 10 G line
- Stray field gradients unsuitable for longer time scales needed to polarize
- In region of polarizing cell, correction necessary: correcting coil, or shield and additional magnet
- Aim for better than 0.03 G/cm in our 30 G holding field

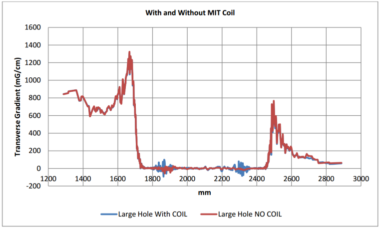




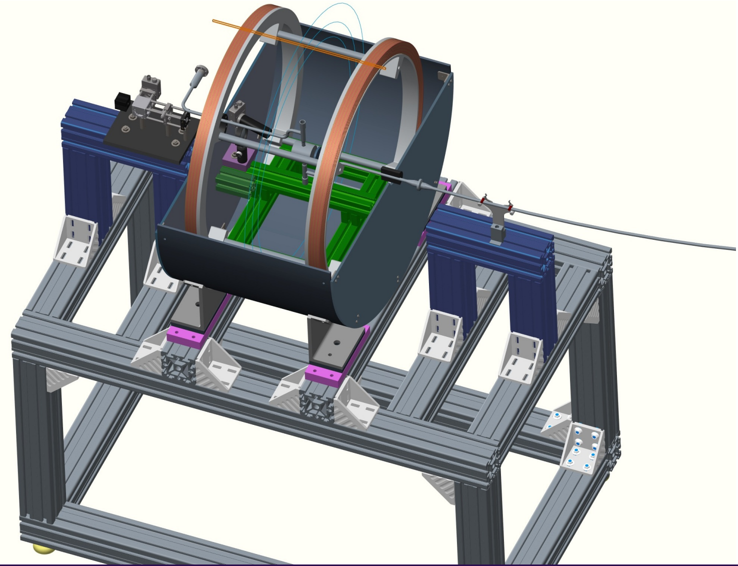
Magnetic Shielding for Pumping Cell

- Soft steel magnetic shield designed by Brookhaven collaborators (Gu, Pikin)
- Simulated in Opera
- Settled on $1/4$ inch thick soft steel cylindrical shell
- 3 cm clearance around Helmholtz coils
- Better than 10^{-4} field uniformity in cell region
- Tested several extensions to reduce gradients as transfer line exits shielding



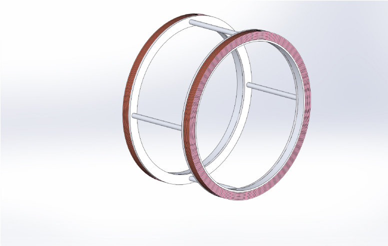


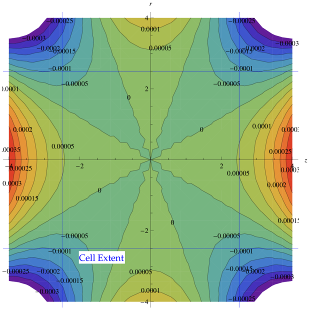
Magnetic Shield and Test Stand Design (Farrell)



Helmholtz Pair Magnet

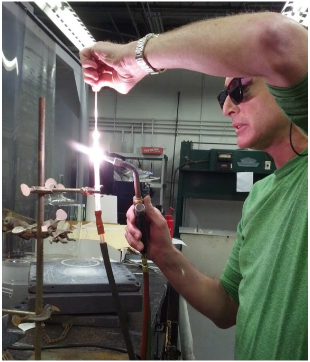
- Weak magnetic field needed
- Uniformity better than 10^{-4} to ensure long relaxation time in pumping cell
- Open access for discharge polarimeter, flexibility
- 30 G, 30 cm Helmholtz pair chosen

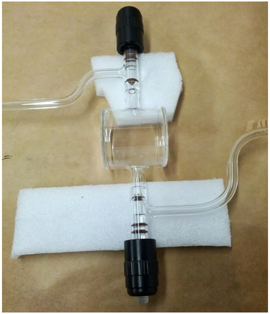




Glass Design

- Pumping cell inside shielding
- Test cell inside 5 T solenoid, longer path for absorption probe polarimeter
- $100\,\text{cm}^3 \gg$ transfer line 4 mm ID

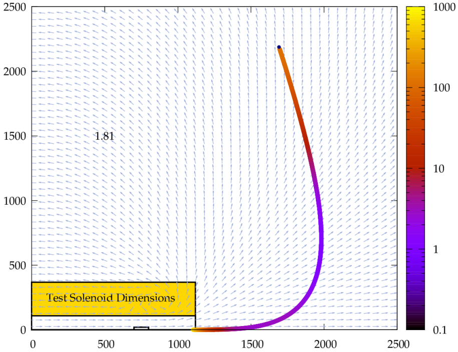




Transfer Path Relaxation Studies

- Investigating possible paths into EBIS with solenoid field map, calculating relaxation time at each point

- Algorithm compromises between relaxation time and transfer length to pick next step in path
- Average inverse relaxation times to qualify path
- Two transfer lines to be made for upcoming test
  - "Best" case, avoiding depolarization
  - Real case, following EBIS feed-throughs



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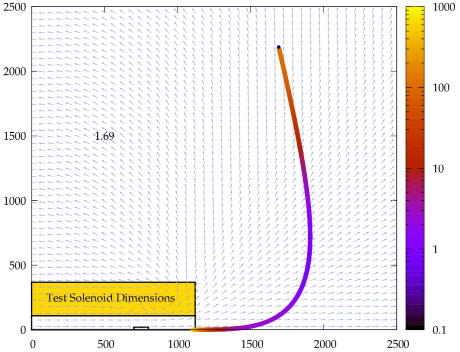

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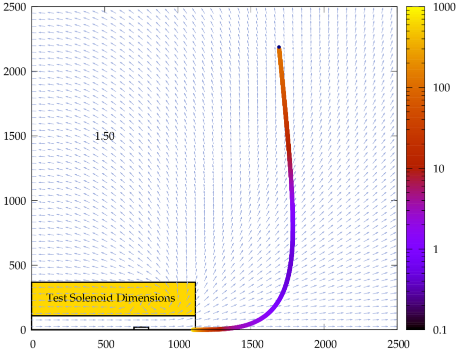

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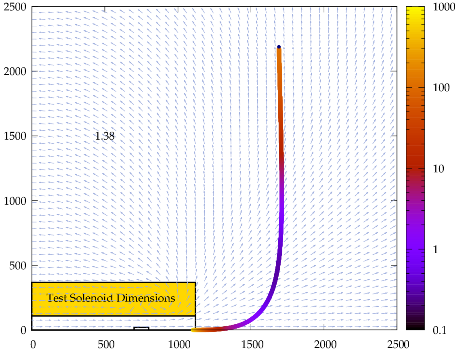

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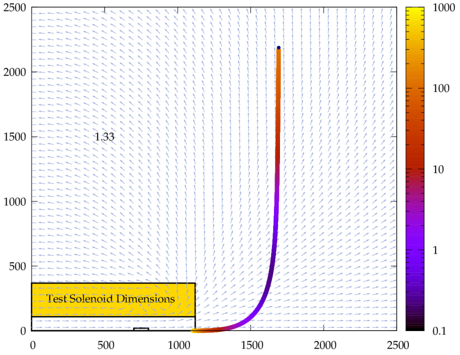

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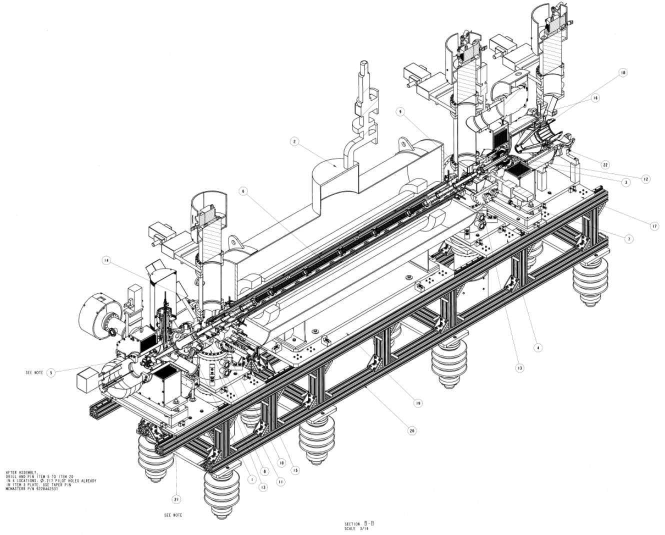
Constraints on Path into EBIS



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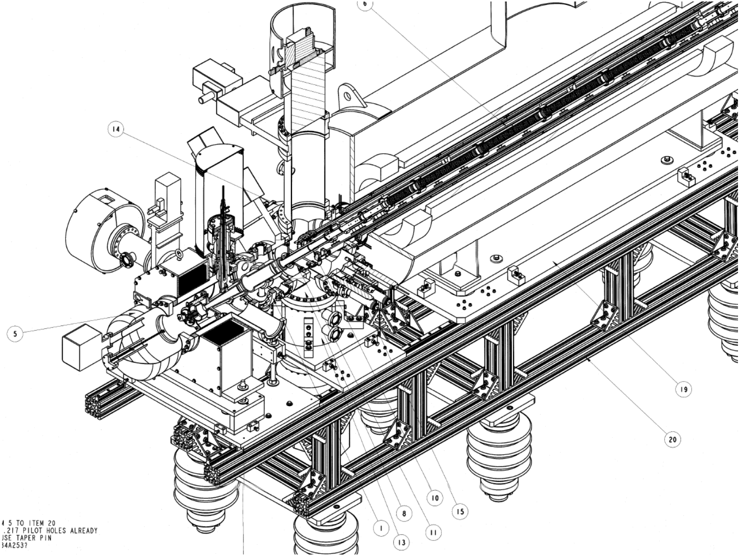

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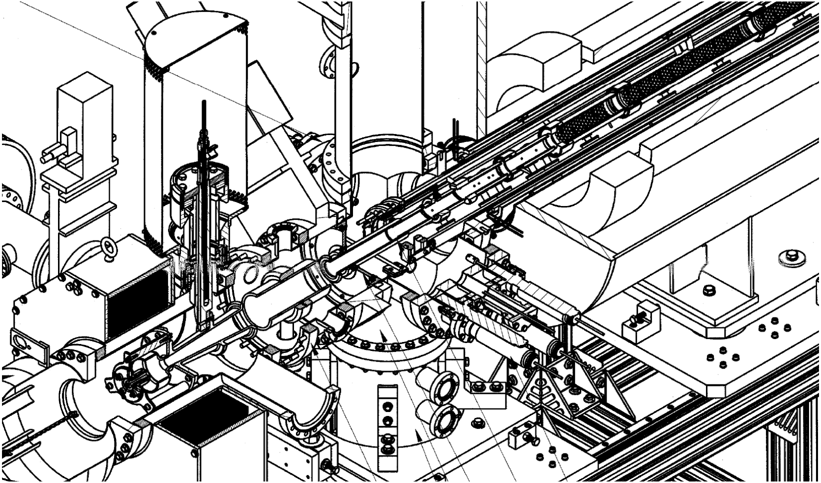

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Liquid Crystal Based Discharge Polarimeter

- Nuclear polarization proportional to circular polarization of 668 nm discharge light[13]
  - Historically measured via light intensity with linear polarizer, rotating 1/4 wave plate. For angle off axis θ_m:

$$M_c = \frac{1}{2\cos\theta_m}\frac{\text{AC amplitide}}{\text{DC offset}}$$

- Advent of nematic liquid crystals offer variable wave plates for light polarimetry[14] with msec switching times
  - Obviates need for noisy motor and lock-in amplifier
  - Directly observe 1/4, 3/4 wave plate intensities

$$M_c = \frac{1}{\cos\theta_m}\frac{I_{3/4} - I_{1/4}}{I_{3/4} + I_{1/4}}$$

[13] Lorenzon *et al*, Phys Rev A (1993).
[14] Bueno, J. Opt. A, 2000.

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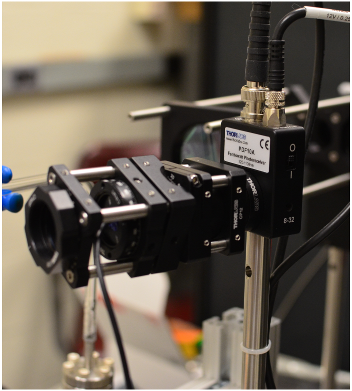
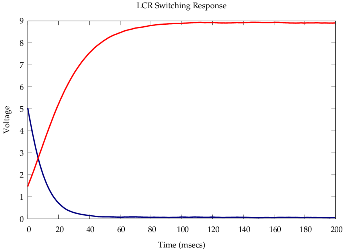
Polarimeter Design from Off-the-shelf Parts

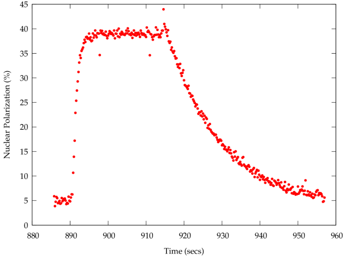
- LCR with voltage controller (2 kHz)
- Linear polarizer
- Bandpass filters (10 W of laser light to avoid)
- Rotation mounts for alignment
- Photodiode
  - Extreme sensitivity for discharge light after loss to filters
  - Femtowatt photoreceiver eventually selected
  - Si based photodiode with very high gain and low noise, sacrificing bandwidth (20 Hz)



Polarimeter Performance

- Must subtract small offsets due to ambient light, laser light (sub 1%)
- Time resolution of measurement dependent on LCR switching time
    - Typically 110 msec to switch down to 1/4 wave
    - 60 msec to switch to up to 3/4 wave
- Measures several times a second
- "Warm-up" time, after which voltage calibration should be redone
- Working to tighten error, which is mostly from electronic noise





MIT ^{3}He Lab Equipment Tests

- Keopsys 10 W, 1083 nm fiber laser
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    - 30 G at 16.5 A
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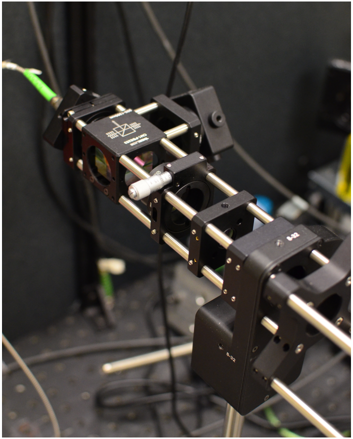

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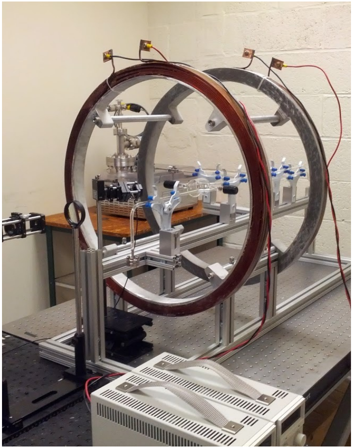

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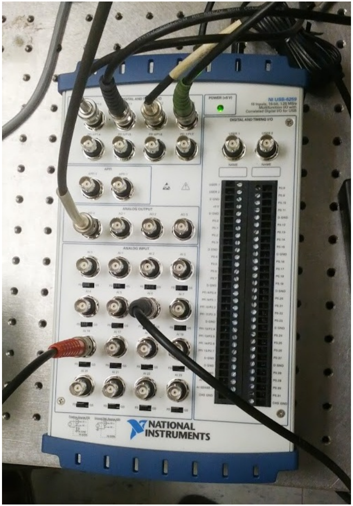

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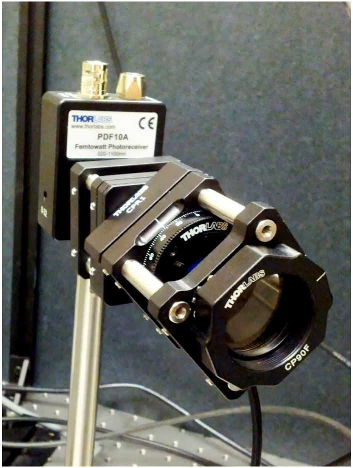

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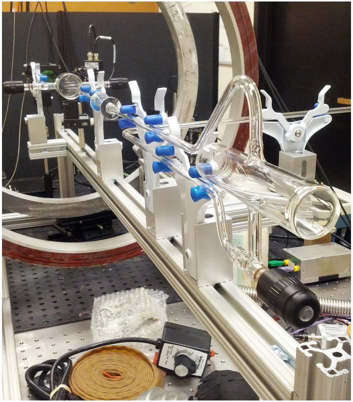

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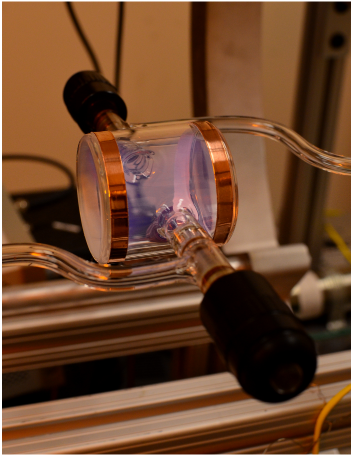

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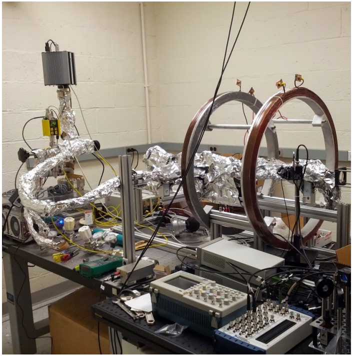
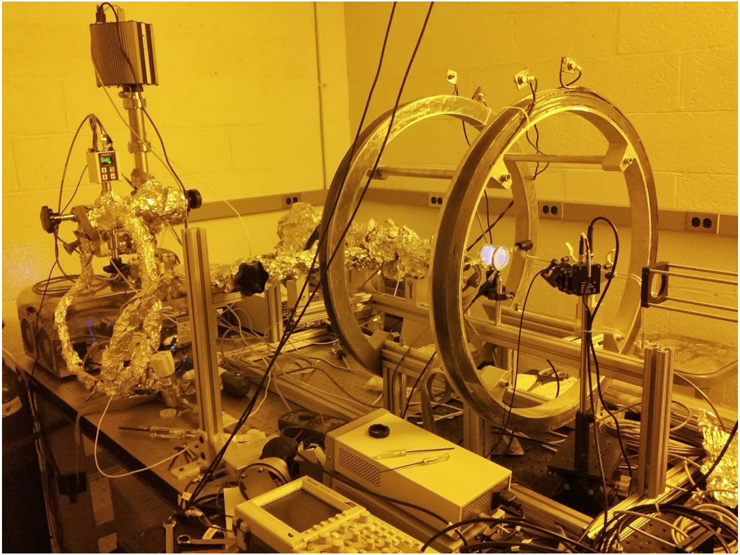
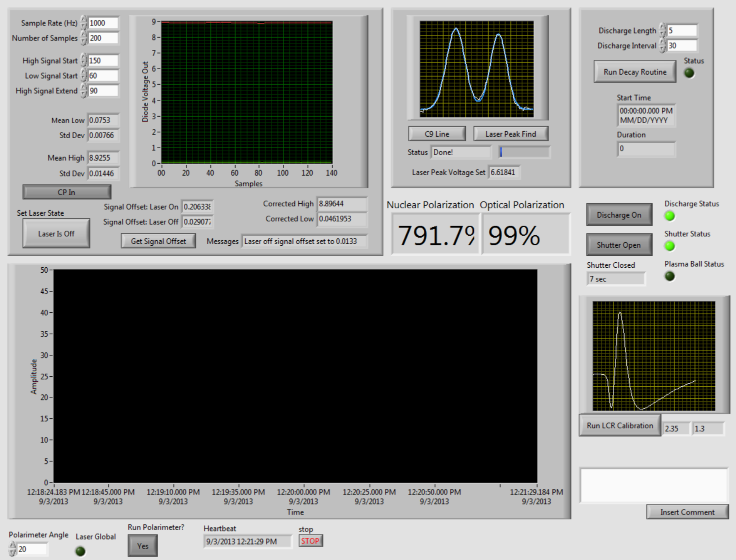


MIT ^{3}He Lab



DAQ Software



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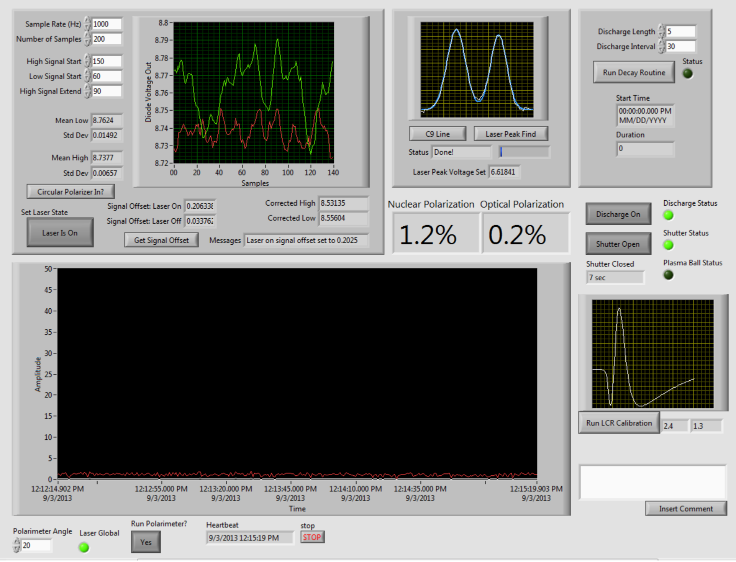
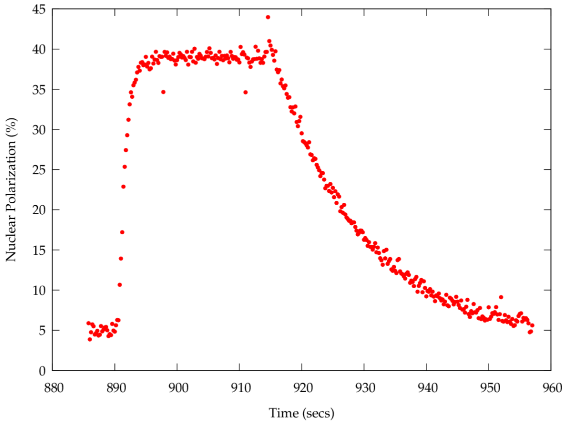


First Polarization Results



- New sealed cell, no getters, moderate bake-out
- 2 s build-up, 20 s relaxation time (discharge on)

Looking forward

- Polarizing in the lab: plenty of power, we now need purity.
- Plan to move polarizer to Brookhaven in the next couple months to start depolarization tests.
- Spare EBIS solenoid undergoing minor refurbishment, will become available in this timeframe.
- Hope to finish initial depolarization in transfer tests by end of year.
- Next: Transfer into and ionization in EBIS.
  - Polarization measurement after extraction: Lamb-shift? He3–He4 elastic scattering?

BNL–MIT Pol He3 Source Collaboration:

- Brookhaven National Laboratory
  - J. Alessi, E. Beebe, J. Farrell, A. Pikin, J. Ritter, A. Zelenski
- MIT Laboratory for Nuclear Science
  - C. Epstein, E. Mace, J. Maxwell, R. Milner
  - P. Binns, P. Goodwin, E. Ihloff, B. O'Rourke, C. Vidal

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- MIT Department of Physics

Thanks for your attention!