Development of a Polarized ^{3}He Beam Source

for RHIC with EBIS

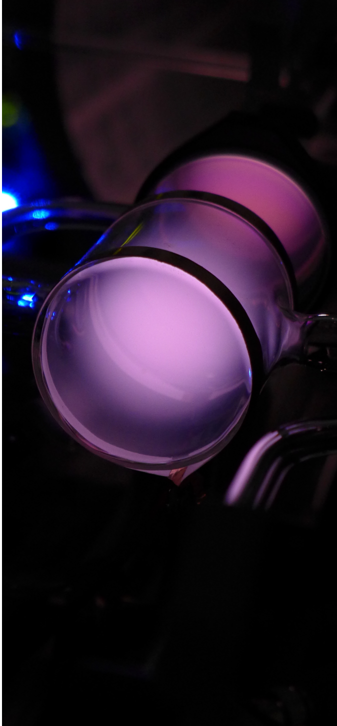
J. Maxwell

for the
BNL–MIT Polarized He3 Ion Source Collaboration

International Workshop on Polarized
Sources, Targets & Polarimetry
September 16th, 2015

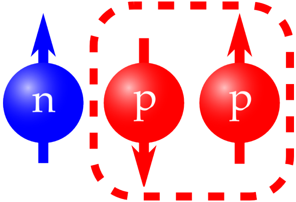
Outline

1. Source Design
    - Electron Beam Ion Source
    - MEOP ^{3}He Polarization
    - Depolarization Effects
2. Polarization and Relaxation Tests
    - MIT Lab
    - Stray Field Tests
    - High Field Tests
3. Next Steps



Why a Polarized Helium 3 Source?

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

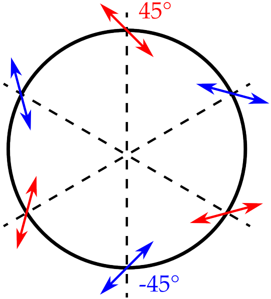


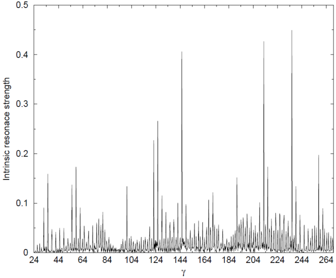
State	Probability
S	88.6%
S'	1.5%
D	8.4%

- 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

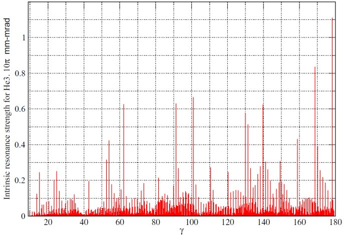
Polarized ^{3}He at RHIC

- ^{3}He's anomalous g-factor is larger than p: more & stronger resonances
- Need 6 siberian snakes per ring[1]





p resonances



^{3}He resonances

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

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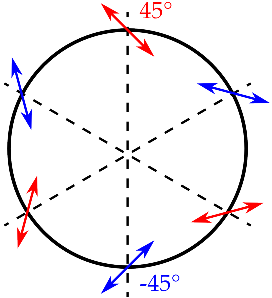
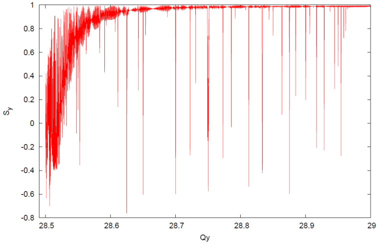
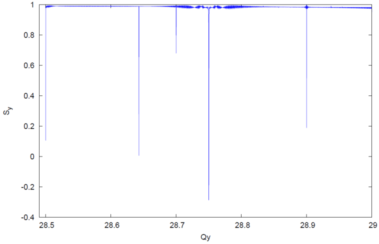




2 snakes



6 snakes

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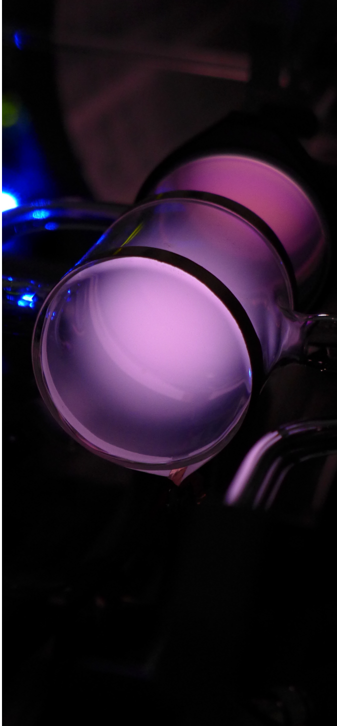

History of ^{3}He Ion Sources

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

Our Proposal[2]

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

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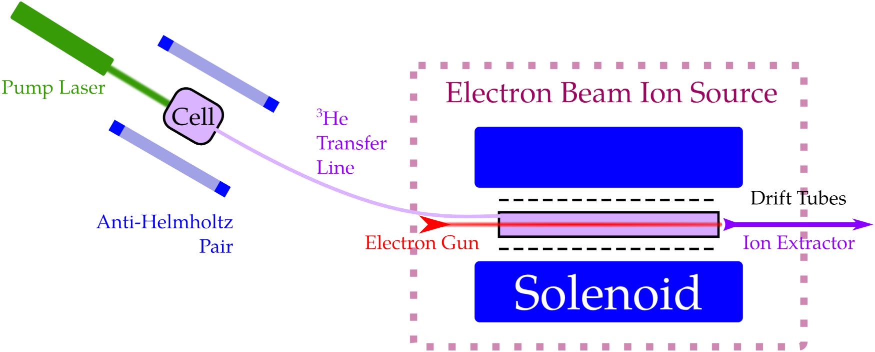
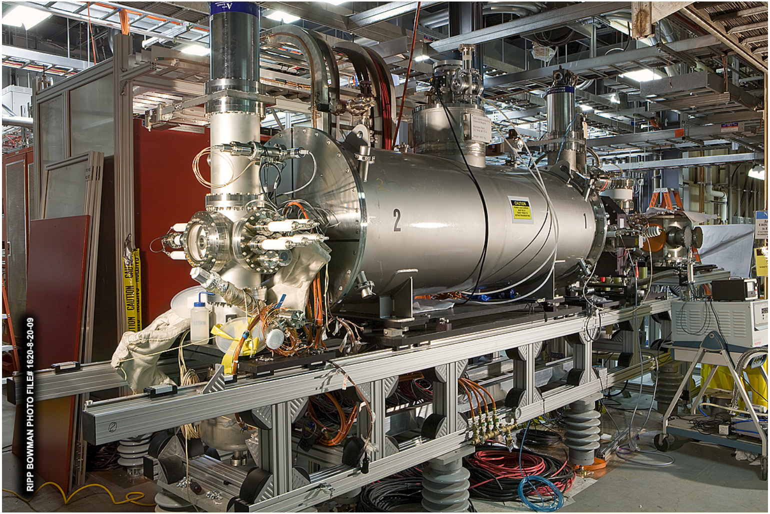
Source Design Goals

- Polarize to ∼70% at 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} $^3\mathrm{He}^{++}$ ions per 20 μsec pulse

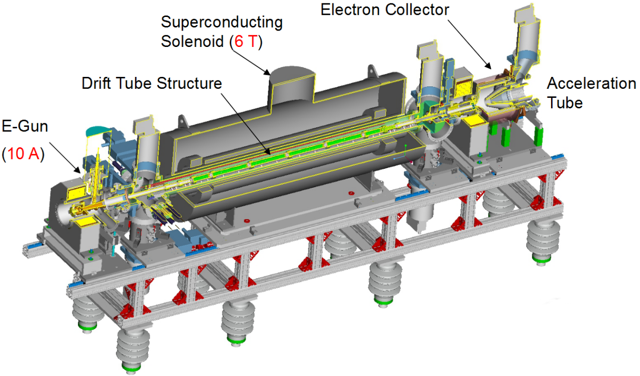


RHIC's Electron Beam Ion Source



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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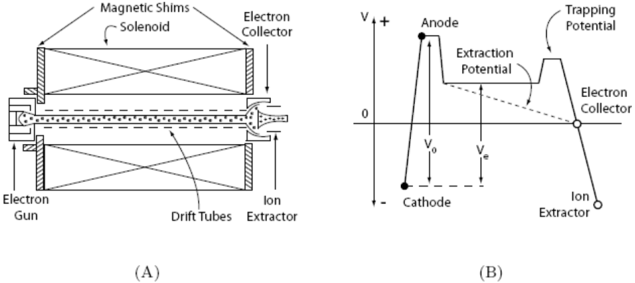
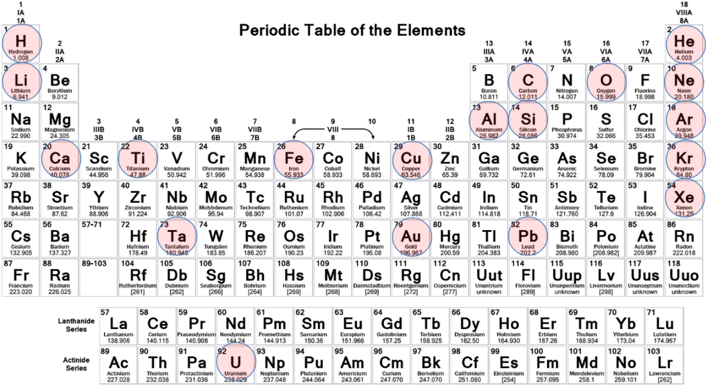


(A) (B)

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

EBIS Beams Run to Date



D, ^{3}He^{2+}, ^{4}He1$^{+,2+}$, Li^{3+}, C^{5+}, O^{7+}, Ne^{5+}, Al^{5+}, Si^{11+}, Ar^{11+}, Ca^{14+}, Ti^{18+}, Fe^{20+}, Cu^{1+}, Kr^{18+}, Xe^{27+}, Ta^{38+}, Au^{32+}, Pb^{34+}, U^{39+}. Capable of ^{3}He $\Rightarrow$ ^{3}He^{++} at nearly 100%

^{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 or higher
- Pure ^{3}He sample, faster than SEOP

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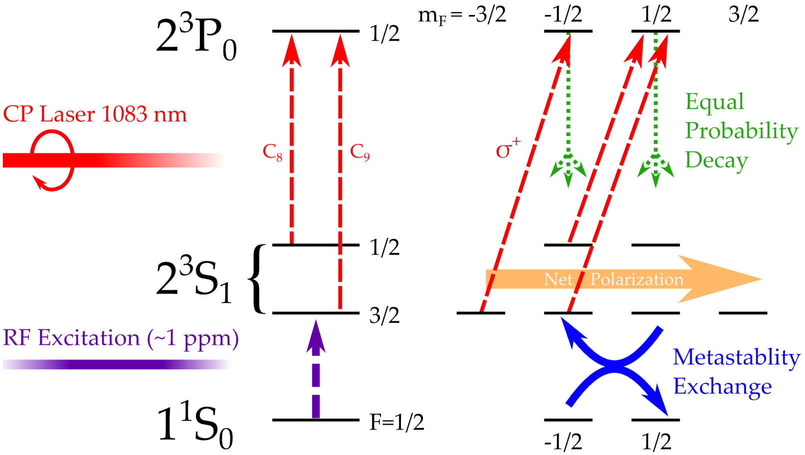
[3] Colegrove *et al*, Phys. Rev. 132 (1963).

[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: $^3\text{He}^{+} + {}^3\text{He}^{++} \rightarrow {}^3\text{He}^{++} + {}^3\text{He}^{+}$
  - Recombination: $e^{-} + {}^3\text{He}^{++} \rightarrow {}^3\text{He}^{+}$
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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.

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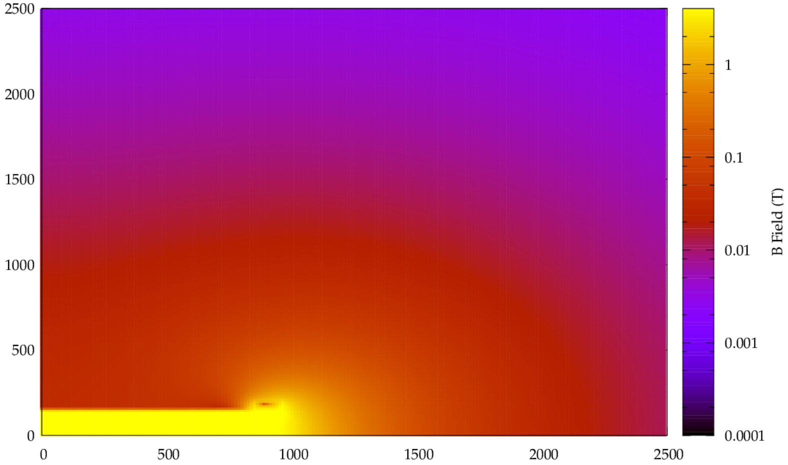
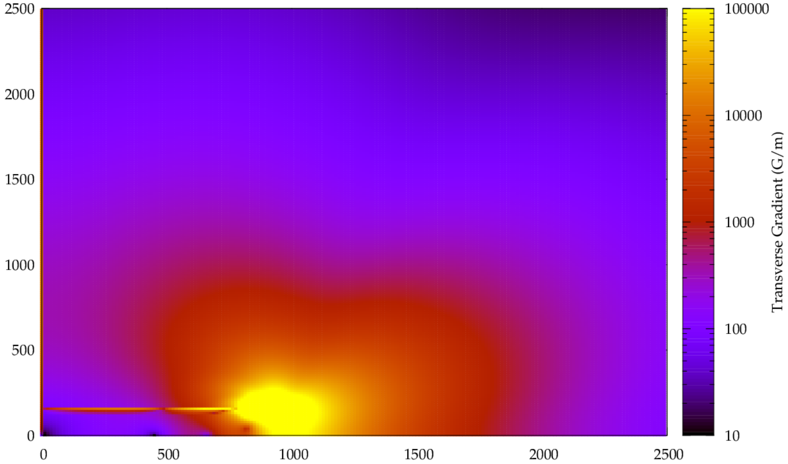
[5] Schearer, Walters, Phys. Rev. 139(5A) (1965).

Calculating Relaxation Time in EBIS B field



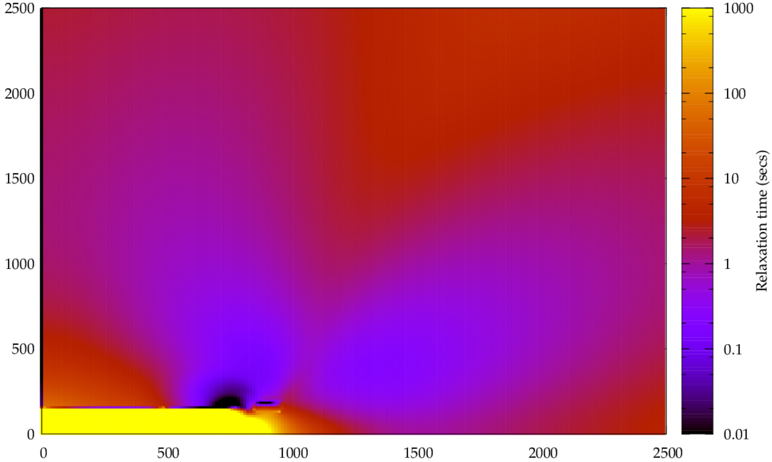
Map in mm of Field Magnitude

Calculating Relaxation Time in EBIS B field



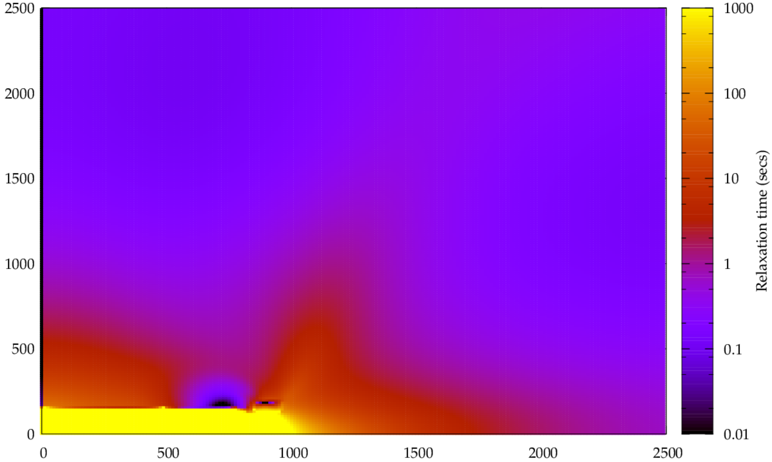
Map in mm of Transverse Field Gradient

Calculating Relaxation Time in EBIS B field



Map in mm Relaxation Time (1 torr)

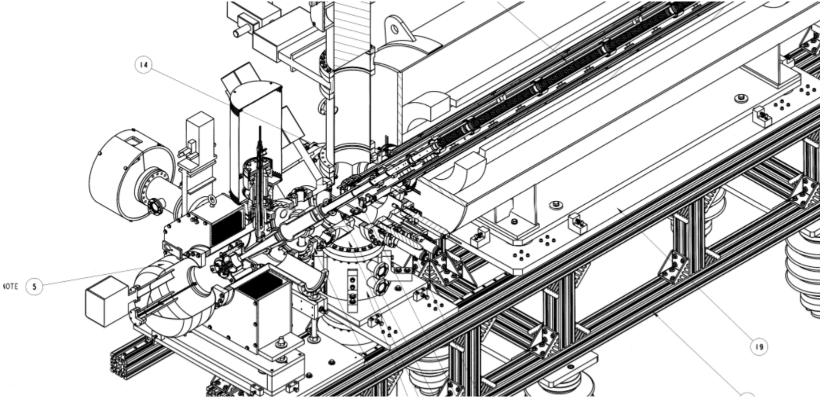
Calculating Relaxation Time in EBIS B field



Map in mm Relaxation Time ($< 10^{-2}$ torr)

Two Source Design Options: Low or High Field?

- Two design possibilities present themselves:
    - Polarize at 30 G in EBIS stray field using field correction, then transfer into EBIS
    - Polarize in EBIS, or nearby, extending field region



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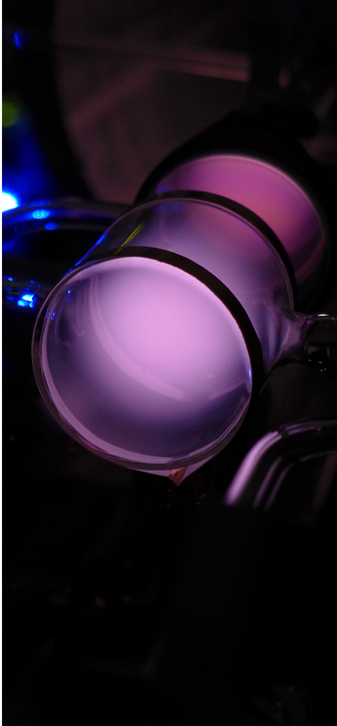
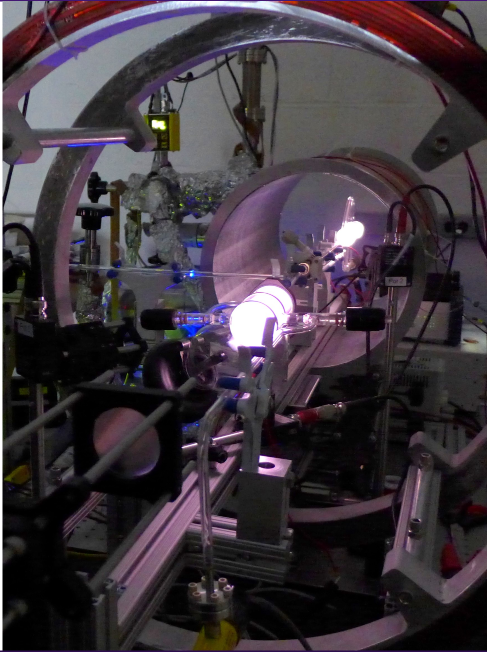


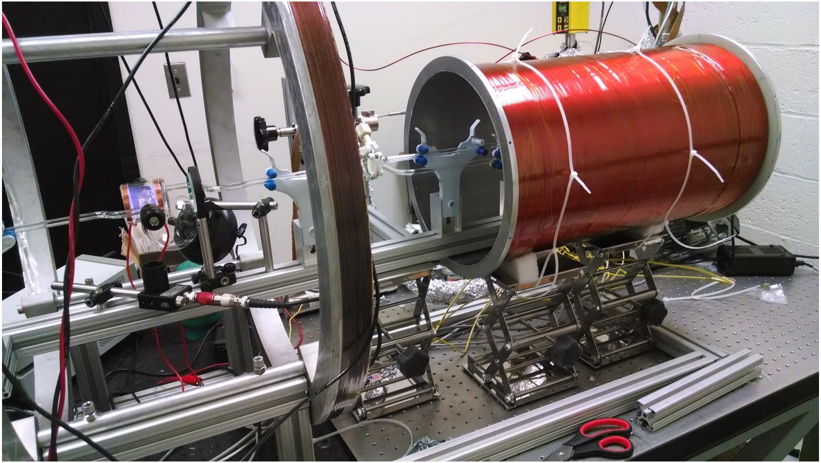
MIT Test Lab

- Magnet, vacuum, laser setup
- 70% polarization achieved
- Allows flow of polarized gas between cells
- Observe polarization diffusion through region of depolarizing gradients[6]
- Test bed for polarization, transfer and data acquisition
- Discharge and optical probe polarimeter development[7]

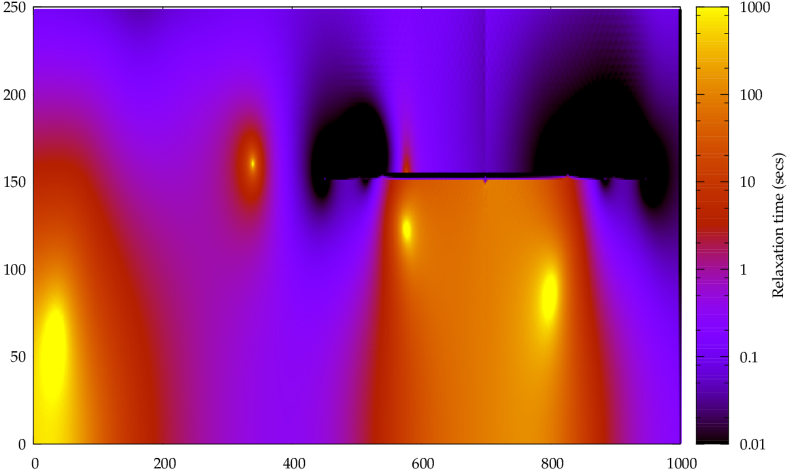


[6] Maxwell, Epstein, Milner, NIM A (777), 2015.
[7] Maxwell, Epstein, Milner, NIM A (764), 2014.

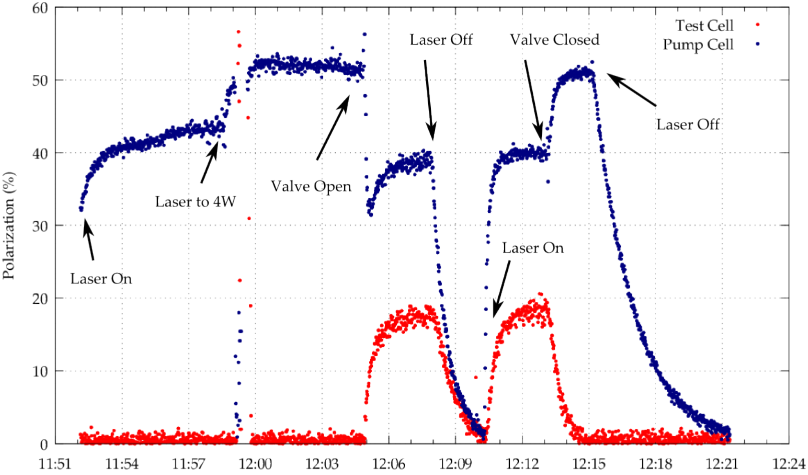
Transferring between B Fields via Diffusion



Relaxation Time Map, Helmholtz and Solenoid

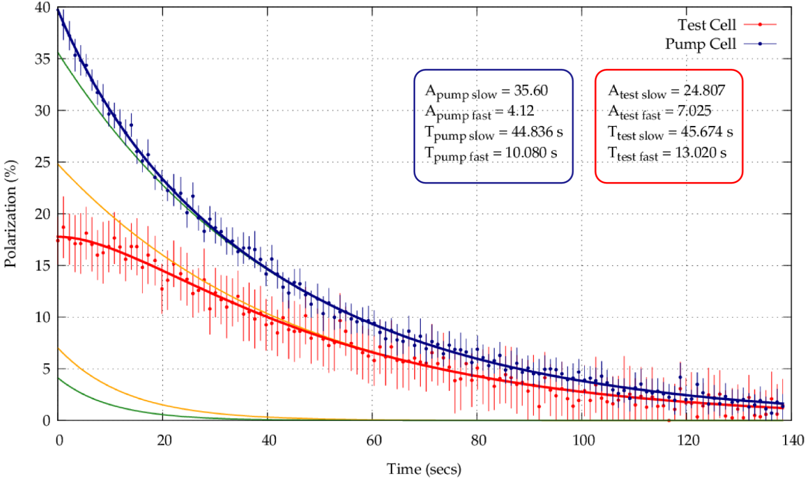


Polarization Transfer via Diffusion



Polarization measured via discharge light in each cell

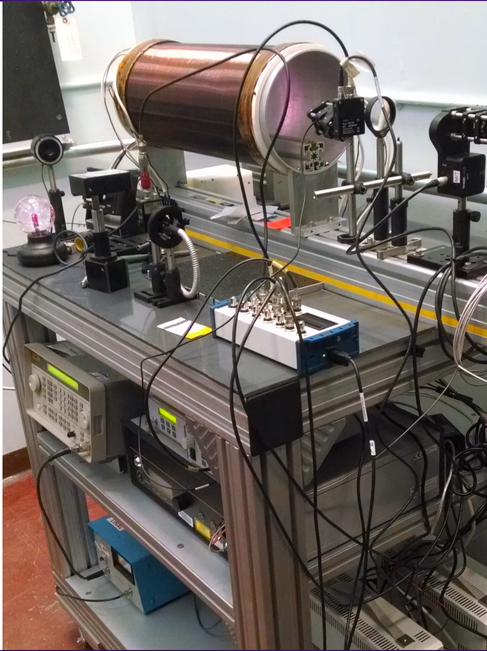
Relaxation in Both Cells



Fits roughly match relaxation & diffusion model of 2 cells, line

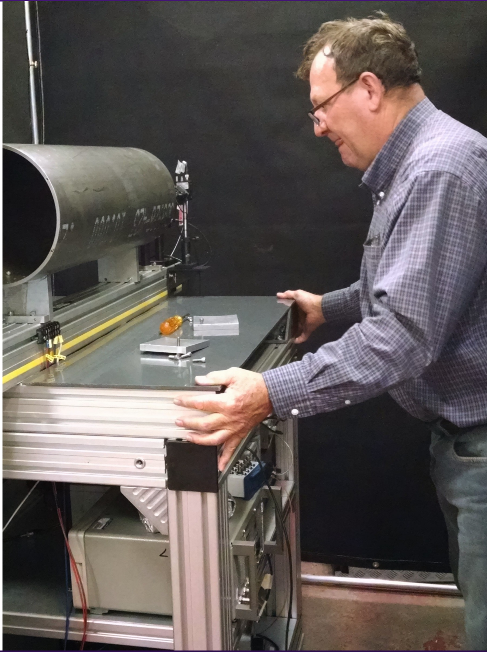
BNL Test Polarizer

- Polarizer on movable stand
- EBIS 5 T spare solenoid
- Allows polarization at any location in the stray field
- Initial polarization tests with NO field correction
- 30 G solenoid allows small increase of B_l
- Tested at two locations on axis of solenoid, one off axis



Stray Field Results

- Spare solenoid at 1 T
- Polarizing sealed cell, which attained 50% in 30 G solenoid
- At location of interest in stray field:
  - Only stray field, 17% with ∼0.5 A pump
  - Only stray field, 28% with ∼10 A pump
  - 6 second relaxation, matches calculation nicely
  - Adding 30 G holding field improves as expected



Low Field Conclusions Thus Far

- Transfer of polarized gas at 1 torr matches calculations
- Polarization and relaxation in the EBIS stray field with no magnetic shielding also agree
- Trusting these calculations, a path into EBIS through the stray field exists in which the path averaged relaxation time is around 0.7 sec (0.01 torr)

Low Field Source with MEOP and EBIS is feasible

- But not necessarily easy or optimal
- Battle must be fought with the stray field both to polarize and to transfer, compromising the achieved polarization, however little

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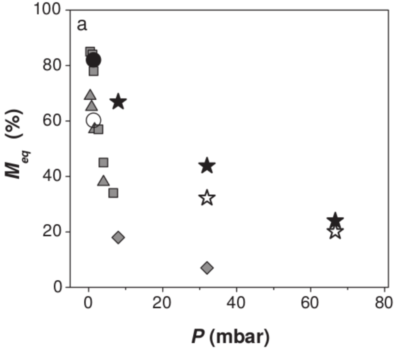
MEOP at High Magnetic Field

- 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



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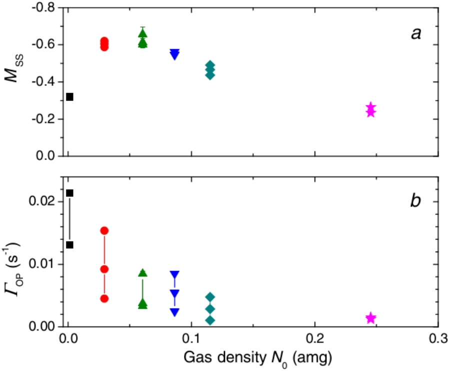
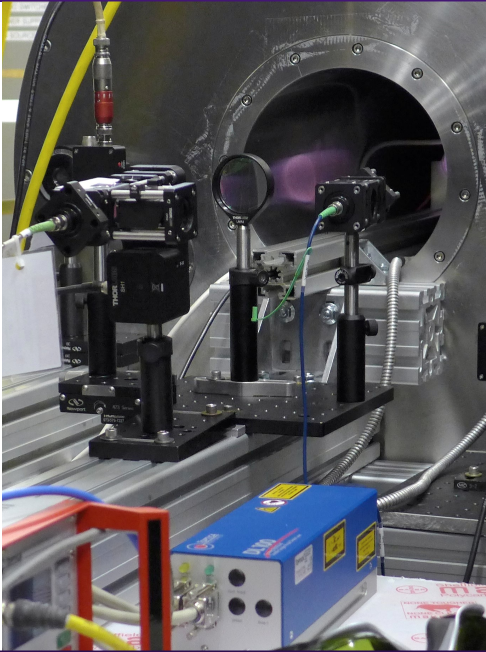
- A. Nikiel *et al*, Eur. Phys. J. D. 67, 2013
  - 4.7 T, 0.5 W OP laser
  - 1.3, 32, 67, 96, 128, 267 mbar
  - Noted trouble with RF for 1 torr cell



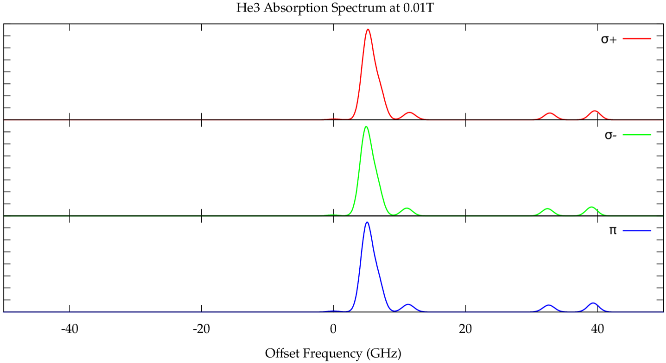
BNL High Field Tests

- EBIS spare solenoid at 1, 2, 3, and 4 T
- Low field polarimetry technique not effective above 10 mT
- High-field polarimetry with low power probe laser
    - AM on discharge for lock-in detection
- Sealed cells at 1 torr with two cell geometries
    - 5 cm OD, 5 cm long
    - 3 cm OD, 10 cm long



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[8,9]



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

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

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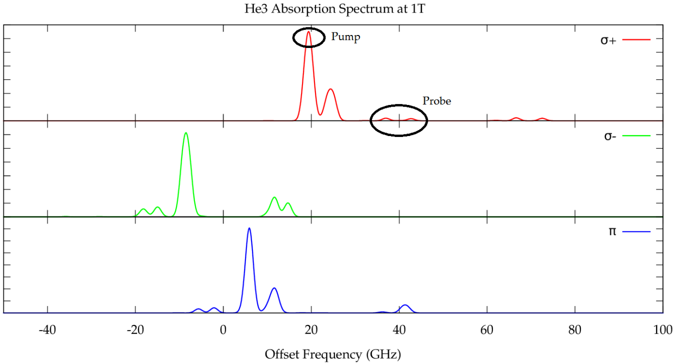

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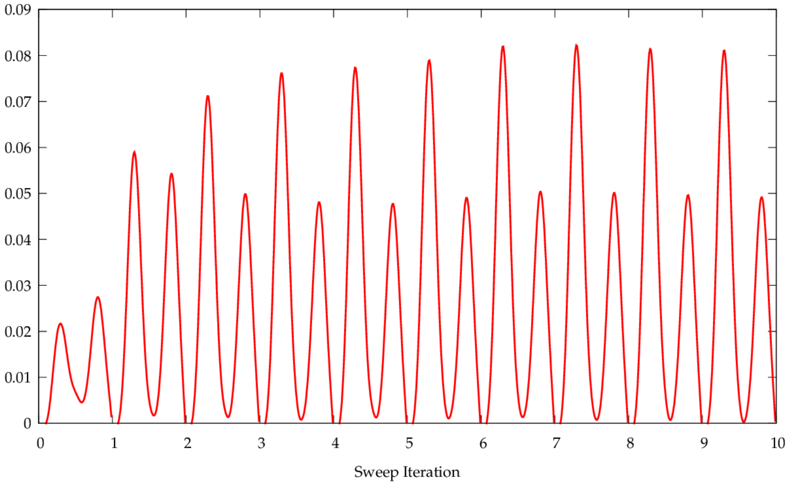
Measuring Optical Pumping



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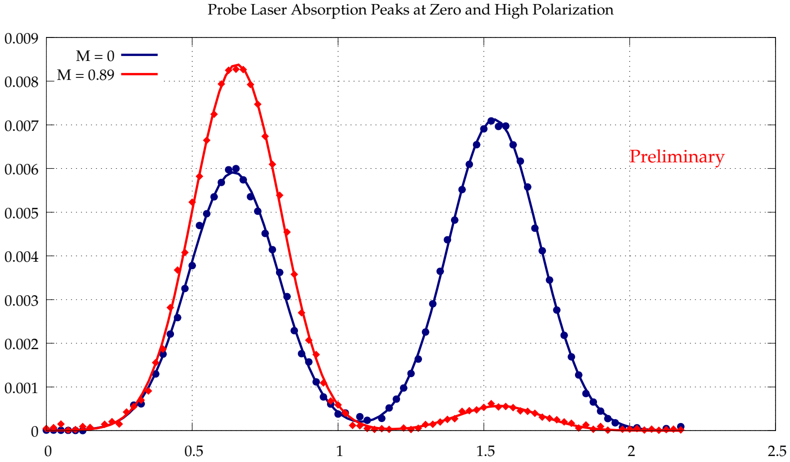
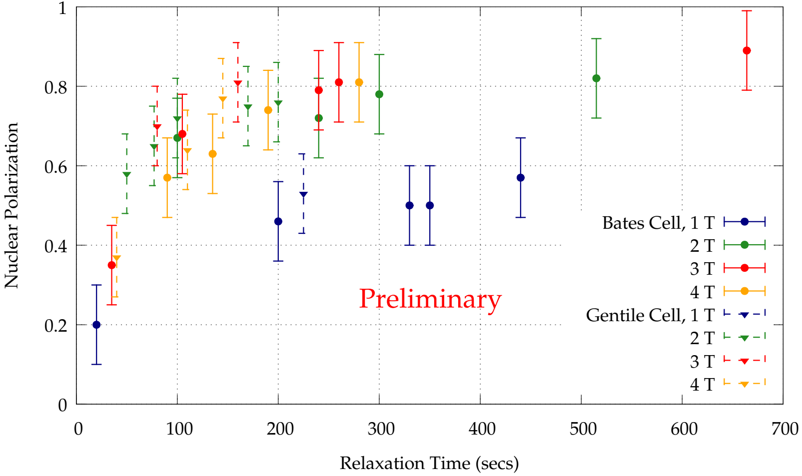


High Field Polarization Results

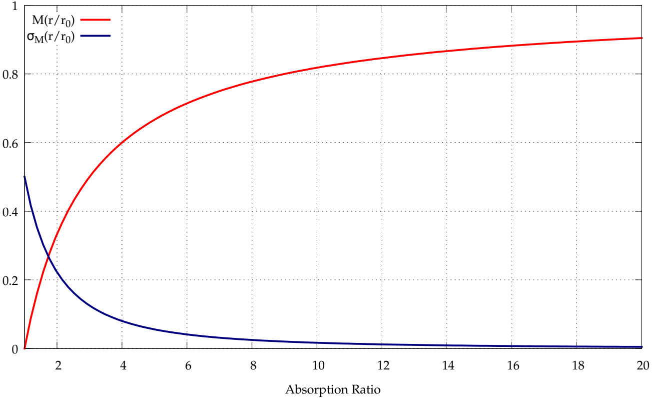


- Error set at 10% while measurement is investigated

Thoughts on Probe Measurement Error

- Intense probe can cause over-estimation of polarization
  - Talbot: as much as 5% at M=0% and 1% at M=10%

$$M(r/r_0) = \frac{r/r_0 - 1}{r/r_0 + 1}, \quad \sigma_M(r/r_0) = \frac{2\sigma_{r/r_0}}{1 + (r/r_0)^2}$$



High Field Conclusions Thus Far

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  - With discharge off, $T_1 = 2.7$ hours
- Not only is this possible but it's easy!
  - Cell which we struggled to get to 70% at 30 G reach over 80% at high field
  - Field uniformity a given at high field

High polarizations from MEOP over 1 T

- At high field, OP and ME both still work
- Zeeman splitting reduces electron-nucleus spin coupling for polarization, but also inhibits relaxation channels (such as 668 nm line used for low field measurement)
- Transition split allows pumping just one state with laser

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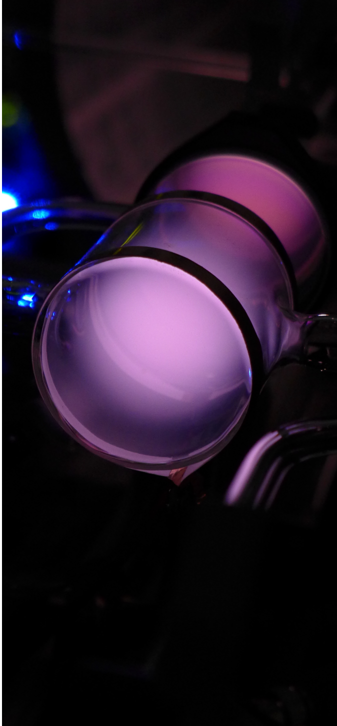

Looking forward

- To corroborate probe polarimeter results, NMR system has been built, under initial tests
- We can polarize near EBIS operating fields, avoiding the transfer through depolarizing gradients
  - High field source design offers best chance of success
- High field source is under initial design process by BNL collider and accelerator team
- Preliminary plan for magnet construction, spare solenoid reinforcement, low energy polarimetry and test
  - Estimated 3-4 years until test source operational and swap with EBIS can be performed

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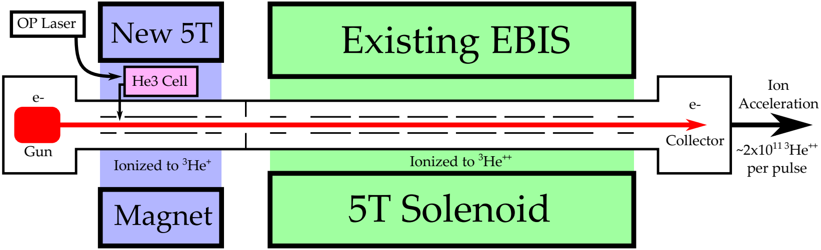
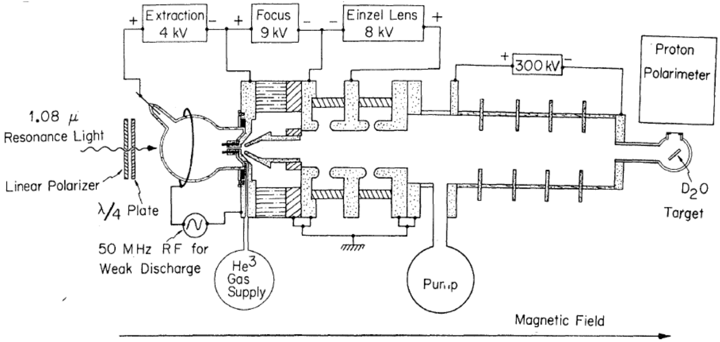
High Field Source Design: EBIS Upgrade

- New solenoid-injector section will improve EBIS operation with all gases, allow polarized ^{3}He^{++}
- Lengthened ion trap brings increased heavy ion yield
- Test can be built and tested without affecting EBIS operation: goal $> 80\%$ polarization ^{3}He^{++} beam



Polarized ^{3}He Source for JLab MEIC?

- Two EIC candidates, eRHIC and MEIC
- JLab does not have EBIS
- Revisit Rice source[10] with modern techniques



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[10] Baker, PRL 20, 14 (1968)

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, J. Maxwell, R. Milner
    - Bates technical support

We gratefully acknowledge the advice of

- P.J. Nacher, G. Collier

Work supported by

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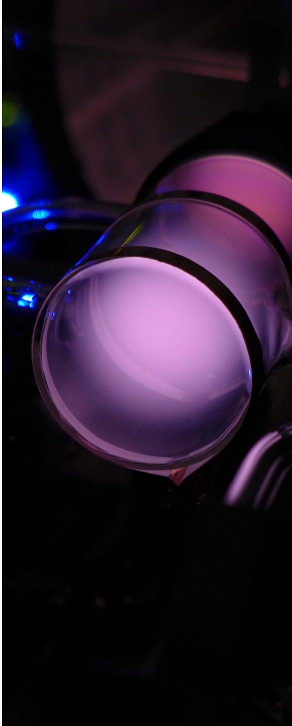
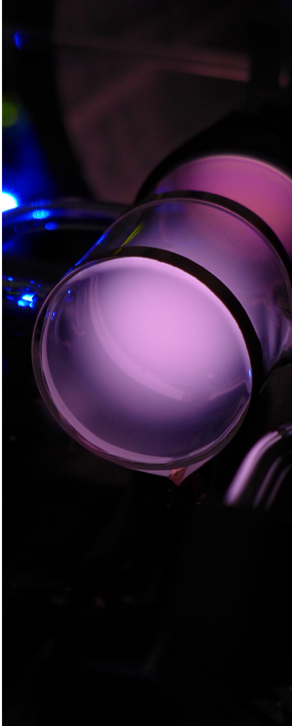
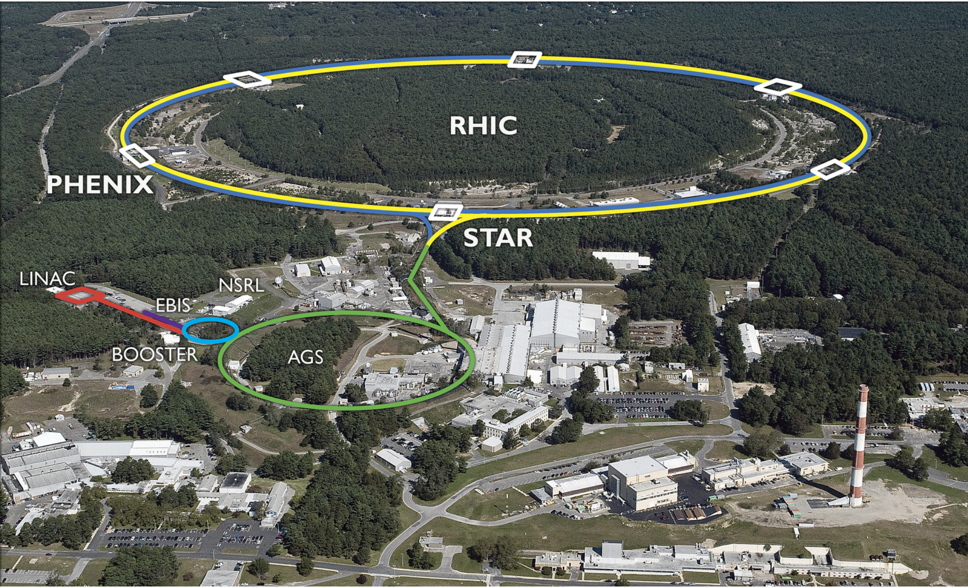
- MIT Department of Physics



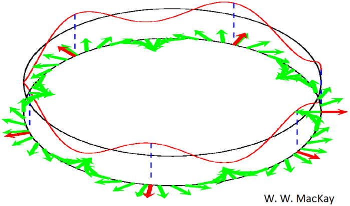
Thanks for your attention!



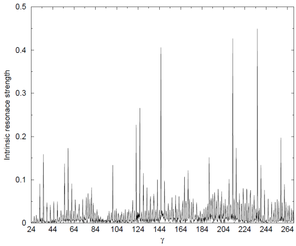

RHIC
PHENIX
STAR
LINAC
NSRL
EBIS
BOOSTER
AGS

Maintaining Polarization in a Circular Collider

- Spinor precesses as bent in B field
- Depolarizing resonances
  - Spin precession frequency = frequency of perturbing B field
  - Imperfection: $\nu_s = G\gamma = n$
  - Intrinsic: $\nu_s = G\gamma = Pn + \nu_y$
  - Anomalous g-factor G
  - Resonances for p in RHIC[11]→
- Siberian Snakes to the rescue
  - Rotate spin 180°, allow the wobble to unkink itself
  - Partial snakes can be used for some imperfections



W. W. MacKay



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[11] Bai, Courant *et al.*, BNL-96726-2012-CP, 2012.

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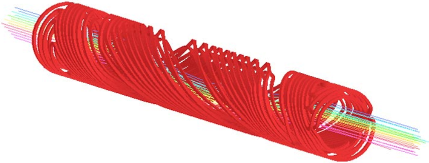

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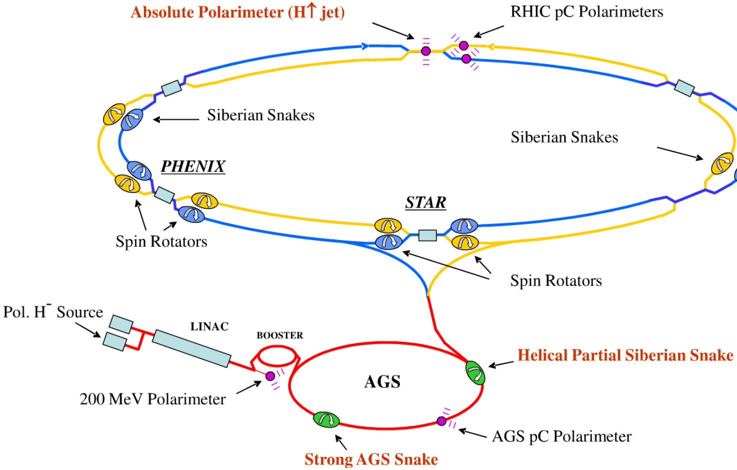
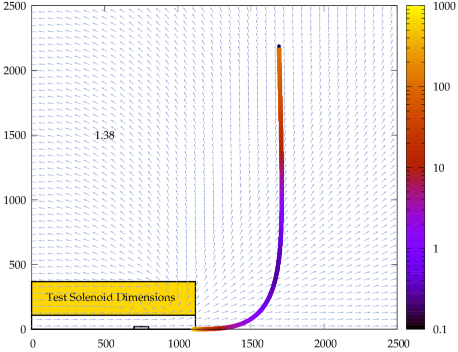
RHIC Spin Manipulation



Transfer Path Relaxation Studies

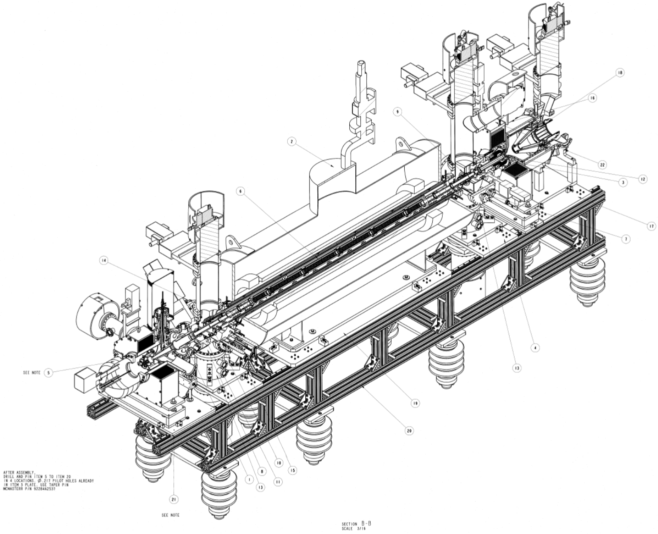
- Investigating possible paths into EBIS with solenoid field map, calculating relaxation time at each point

- 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

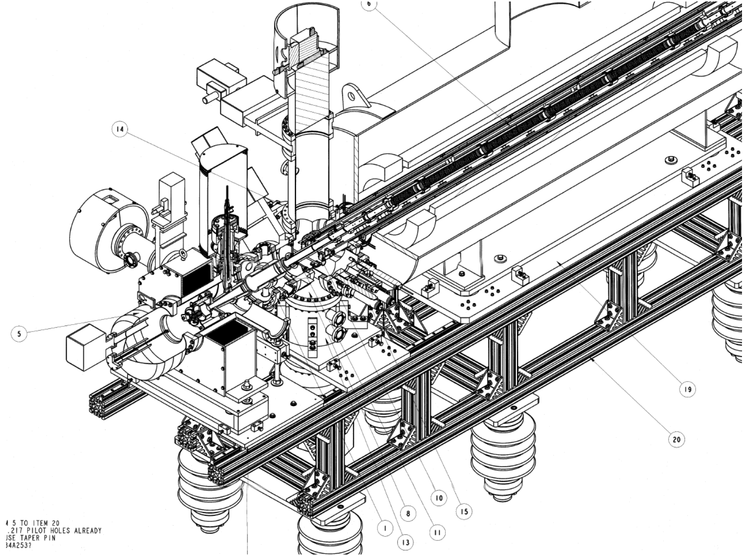


(Color scale in seconds)

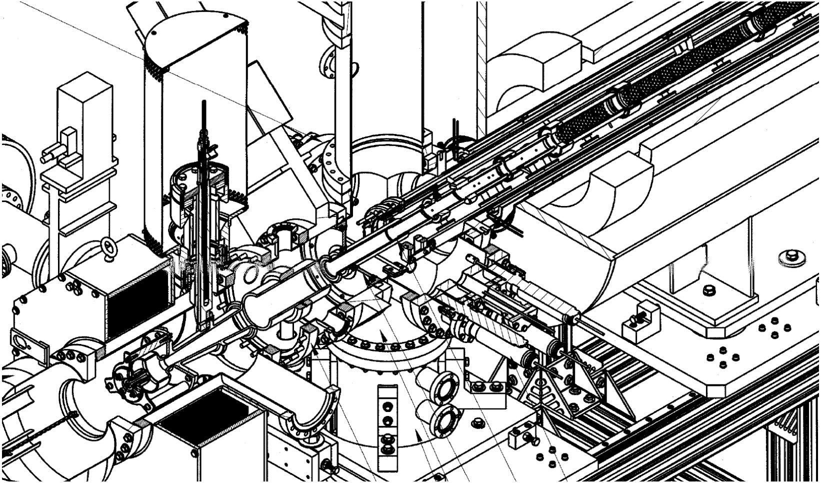
Constraints on Path into EBIS



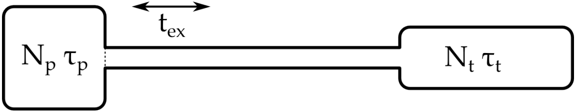
Constraints on Path into EBIS



Constraints on Path into EBIS



Test of Polarization Diffusion Measurement



$$\begin{pmatrix} \dot{P}_p(t) \\ \dot{P}_t(t) \end{pmatrix} = \begin{pmatrix} -\left(\frac{1}{\tau_p} + \frac{N_t}{N}\frac{1}{t_{\text{ex}}}\right) & \frac{N_t}{N}\frac{1}{t_{\text{ex}}} \\ \frac{N_p}{N}\frac{1}{t_{\text{ex}}} & -\left(\frac{1}{\tau_t} + \frac{N_p}{N}\frac{1}{t_{\text{ex}}}\right) \end{pmatrix} \begin{pmatrix} P_p(t) \\ P_t(t) \end{pmatrix}$$

- 5 variables describe system (initial pols, decays, transfer)
- Solution is sum of two exponentials
- Relate to 4 fit parameters of measured relaxation curve

$$P_p(t) = a_s e^{-t/\tau_s} + a_l e^{-t/\tau_l}$$