

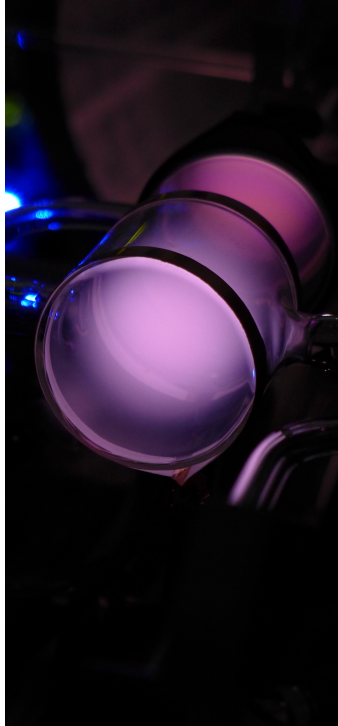
Development of a Polarized ^3He Beam Source for RHIC with EBIS

J. Maxwell

for the
BNL-MIT Polarized He3 Ion Source Collaboration

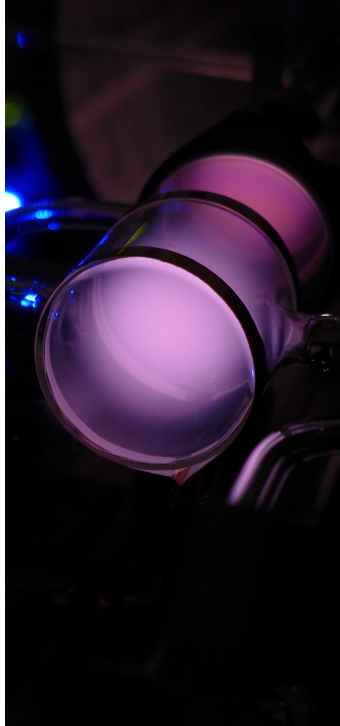


International Workshop on Polarized
Sources, Targets & Polarimetry
September 16th, 2015



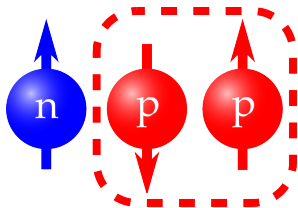
Outline

- ① Source Design
 - Electron Beam Ion Source
 - MEOP ^3He 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

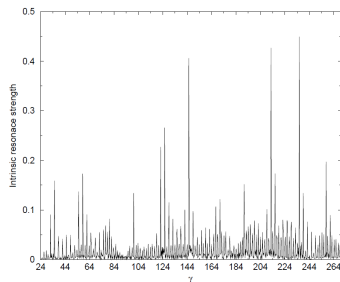
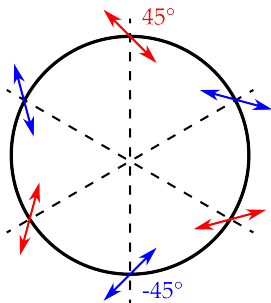


State	Probability
S	88.6%
S'	1.5%
D	8.4%

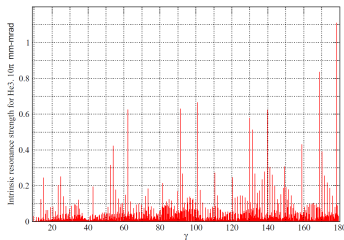
- S-state ^3He : nuclear spin carried by the neutron
- ^3He 's magnetic moment close to n, compatible with RHIC spin manipulation
- Polarized ^3He ions offer a “polarized neutron beam” for RHIC and a future EIC

Polarized ^3He at RHIC

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



p resonances

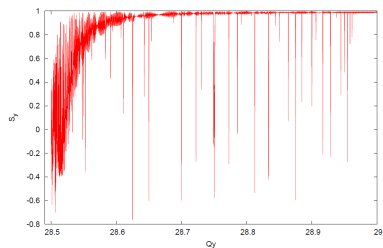
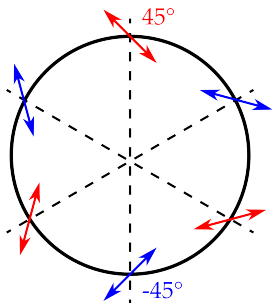


^3He resonances

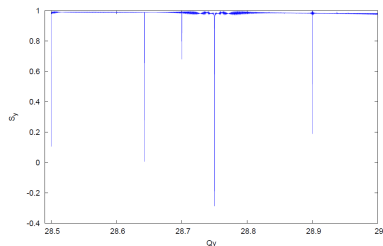
¹Bai, Courant *et al.*, BNL-96726-2012-CP, 2012.

Polarized ^3He at RHIC

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2 snakes

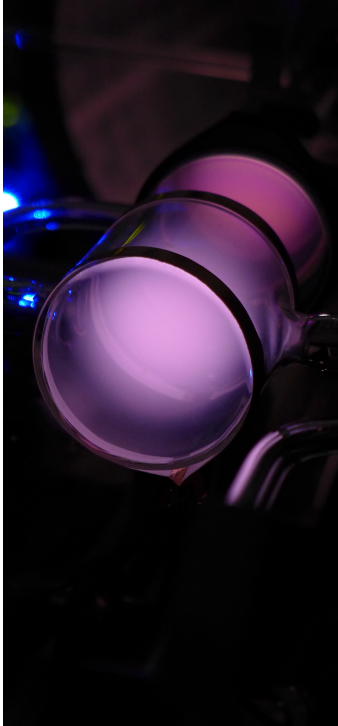


6 snakes

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History of ^3He Ion Sources

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

Our Proposal²

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

²A. Zelenski, J. Alessi, ICFA Newsletter (2003).

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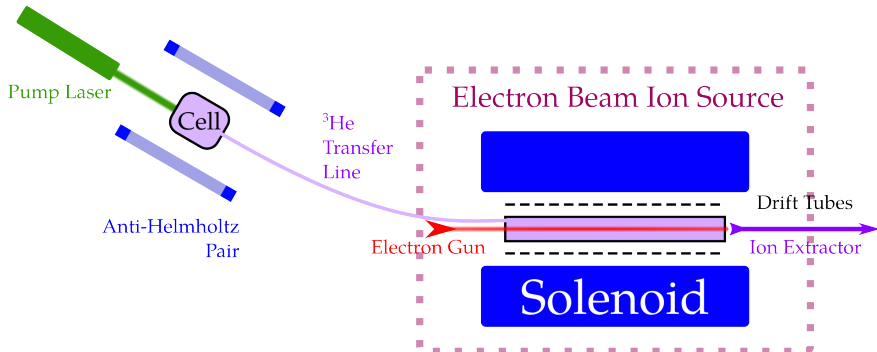
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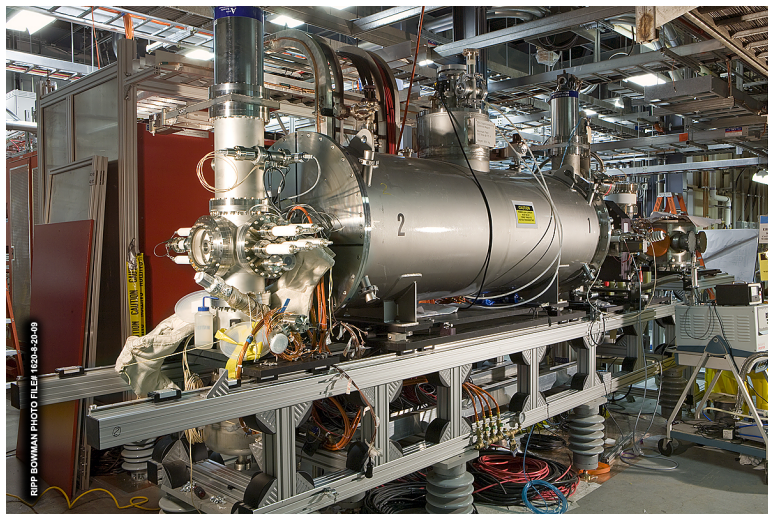
²A. Zelenski, J. Alessi, ICFA Newsletter (2003).

Source Design Goals

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

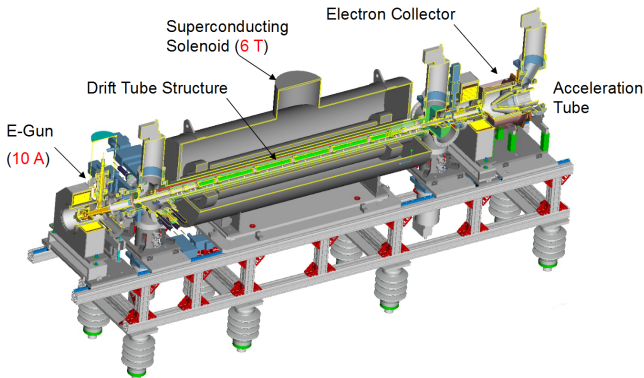


RHIC's Electron Beam Ion Source



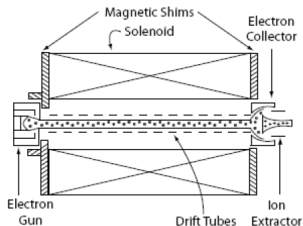
RHIC's Electron Beam Ion Source

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

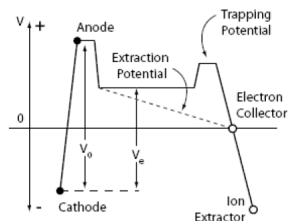


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(A)



(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

Periodic Table of the Elements

1 IA 1A																	18 VIIIA 8A																				
1 H Hydrogen 1.008																	2 He Helium 4.003																				
3 Li Lithium 6.941	4 Be Beryllium 9.012															5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180																
11 Na Sodium 22.990	12 Mg Magnesium 24.305	3 Al Aluminum 26.982	4 Si Silicon 28.086	5 P Phosphorus 30.974	6 S Sulfur 32.065	7 Cl Chlorine 35.453	8 Ar Argon 39.948									13 K Potassium 39.098	14 Ca Calcium 40.078	15 Sc Scandium 44.956	16 Ti Titanium 47.88	17 V Vanadium 50.942	18 Cr Chromium 51.996	19 Mn Manganese 54.938	20 Fe Iron 55.833	21 Co Cobalt 58.933	22 Ni Nickel 58.693	23 Cu Copper 63.546	24 Zn Zinc 65.39	25 Ga Gallium 69.723	26 Ge Germanium 72.61	27 As Arsenic 74.922	28 Se Selenium 78.09	29 Br Bromine 79.904	30 Kr Krypton 84.80				
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29	55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 208.980	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine 209	86 Rn Radon 222.018		
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Actinide Series	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [265]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [268]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Nh Nihonium [278]	114 Fl Flerovium [278]	115 Uup Ununpentium [278]	116 Lv Livermorium [277]	117 Uus Ununseptium [277]	118 Uuo Ununoctium [277]	119 Uue Ununennium [277]	120 Uuq Unquadium [277]	121 Uub Unbium [277]	122 Uut Untrium [277]	123 Uuq Unquadium [277]	124 Uuq Unquadium [277]	125 Uuq Unquadium [277]	126 Uuq Unquadium [277]	127 Uuq Unquadium [277]	128 Uuq Unquadium [277]	129 Uuq Unquadium [277]	130 Uuq Unquadium [277]	131 Uuq Unquadium [277]	132 Uuq Unquadium [277]	133 Uuq Unquadium [277]	134 Uuq Unquadium [277]	135 Uuq Unquadium [277]	136 Uuq Unquadium [277]	137 Uuq Unquadium [277]	138 Uuq Unquadium [277]
Lanthanide Series		57 La Lanthanum 138.905	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.965	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967																					
Actinide Series		89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]																					

D, $^3\text{He}^{2+}$, $^4\text{He}^{1+,2+}$, 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 $^3\text{He} \Rightarrow ^3\text{He}^{++}$ at nearly 100%

^3He Polarization

- EBIS has done much of the work for us!
- Need polarized ^3He ; pure sample for injection
- Revisit MEOP technique³ with modern lasers

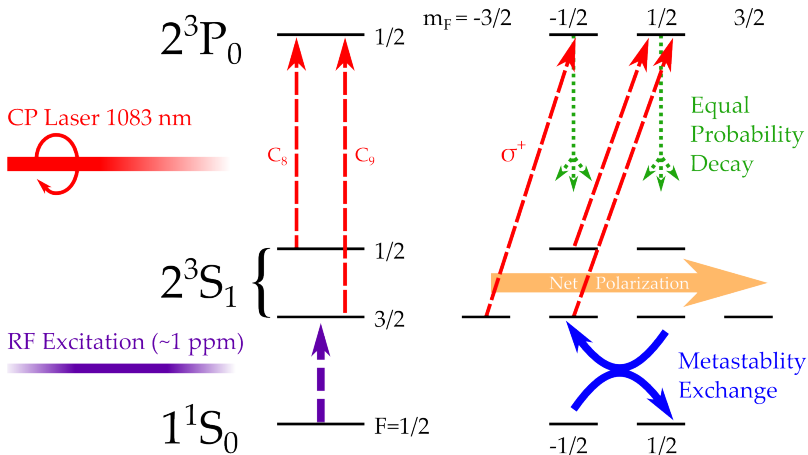
Metastability Exchange Optical Pumping

- Mature technique: polarized targets, medical imaging⁴
- Laser technological advances give 10 W @ 1083 nm easily
- Polarize at ≈ 1 torr, ≈ 30 G or higher
- Pure ^3He sample, faster than SEOP

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

⁴Kauczor *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: $e^- + ^3\text{He}^{++} \rightarrow ^3\text{He}^+$
 - Spin Exchange from Beam

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Depolarization from Field Gradients

From Schearer⁵, we have:

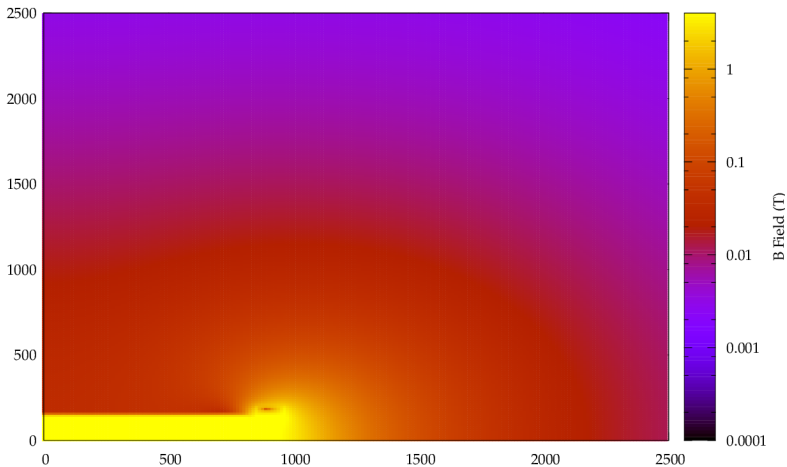
$$\frac{1}{\tau} = \frac{2}{3} \frac{|\Delta B_t|^2}{|B_l|^2} \langle v^2 \rangle \frac{\tau_c}{\omega_0^2 \tau_c^2 + 1}$$

- 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.

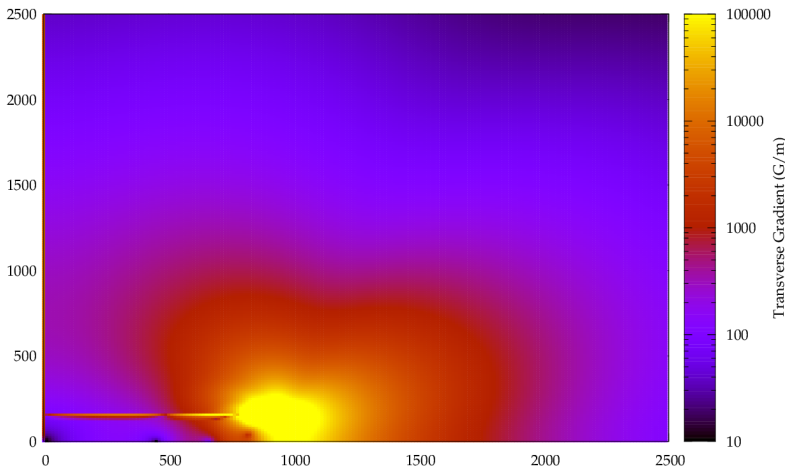
⁵Schearer, Walters, Phys. Rev. 139(5A) (1965).

Calculating Relaxation Time in EBIS B field



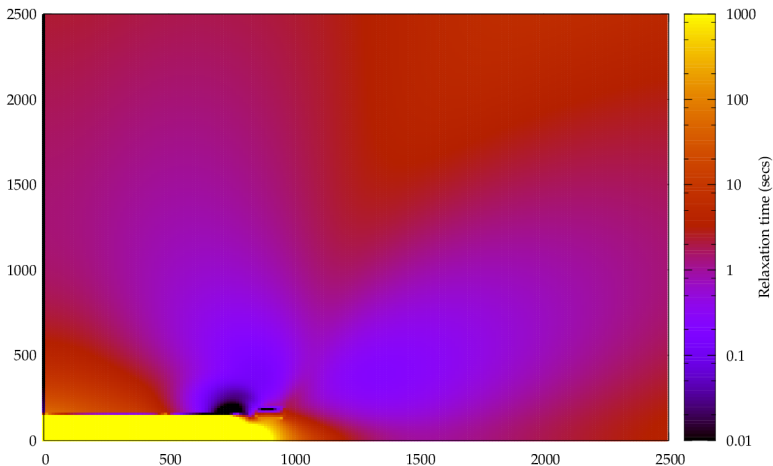
Map in mm of Field Magnitude

Calculating Relaxation Time in EBIS B field



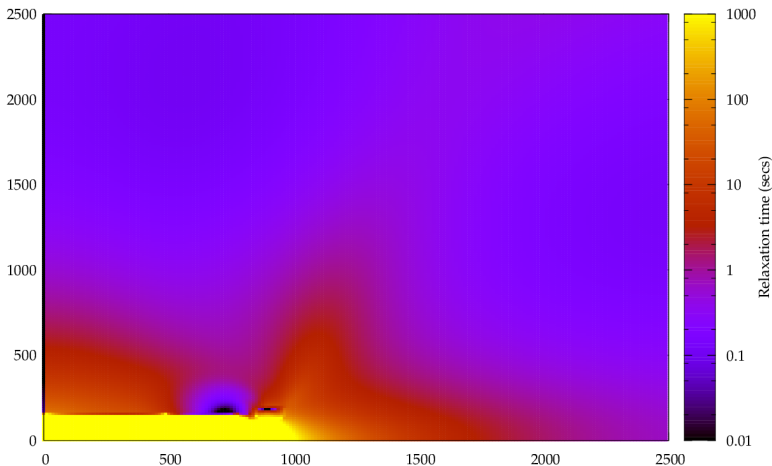
Map in mm of Transverse Field Gradient

Calculating Relaxation Time in EBIS B field



Map in mm Relaxation Time (1 torr)

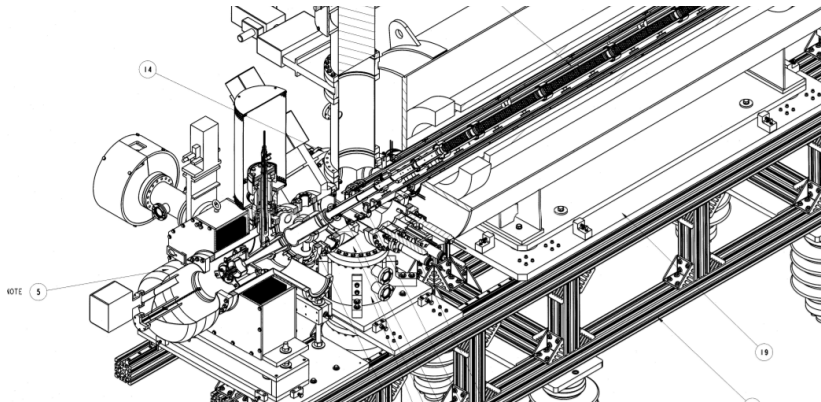
Calculating Relaxation Time in EBIS B field



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

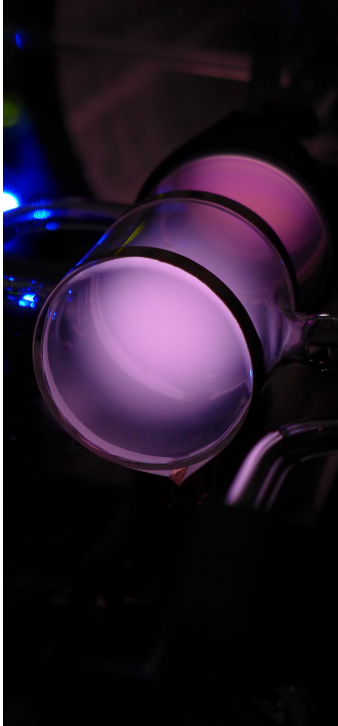
Two Source Design Options: Low or High Field?

- 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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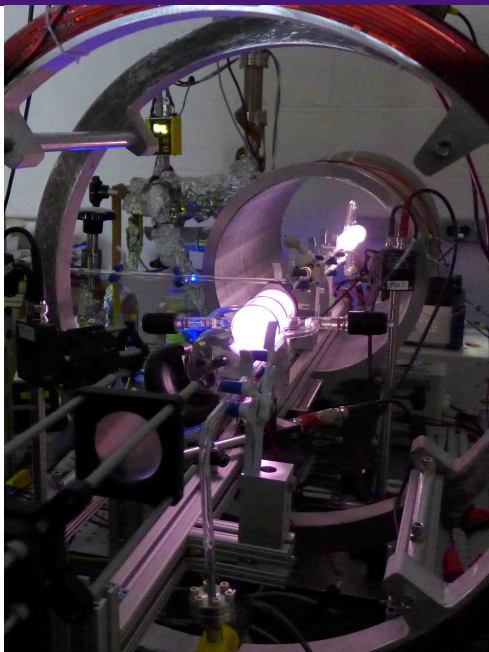


MIT Test Lab

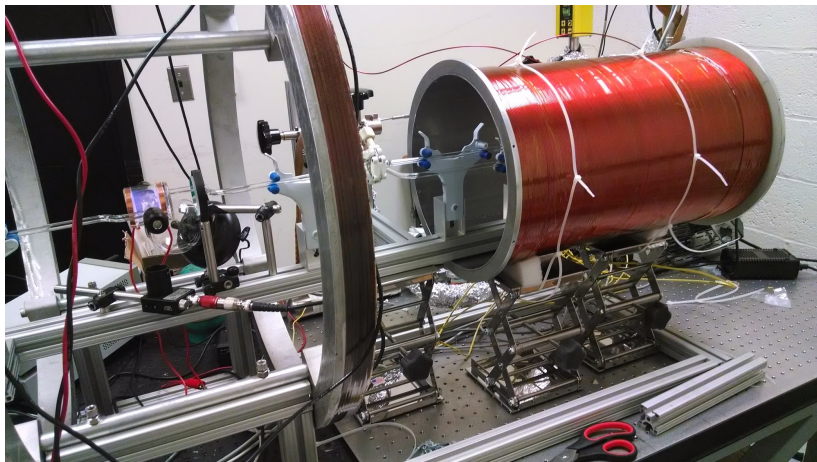
- Magnet, vacuum, laser setup
- 70% polarization achieved
- Allows flow of polarized gas between cells
- Observe polarization diffusion through region of depolarizing gradients⁶
- Test bed for polarization, transfer and data acquisition
- Discharge and optical probe polarimeter development⁷

⁶Maxwell, Epstein, Milner, NIM A (777), 2015.

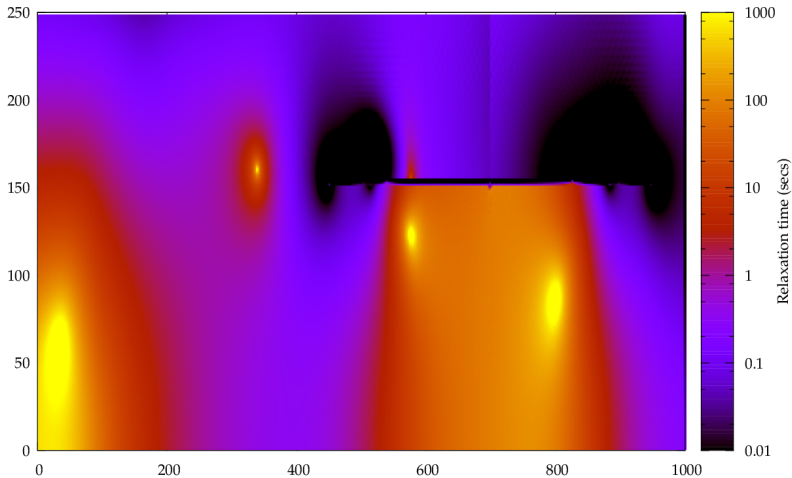
⁷Maxwell, Epstein, Milner, NIM A (764), 2014.



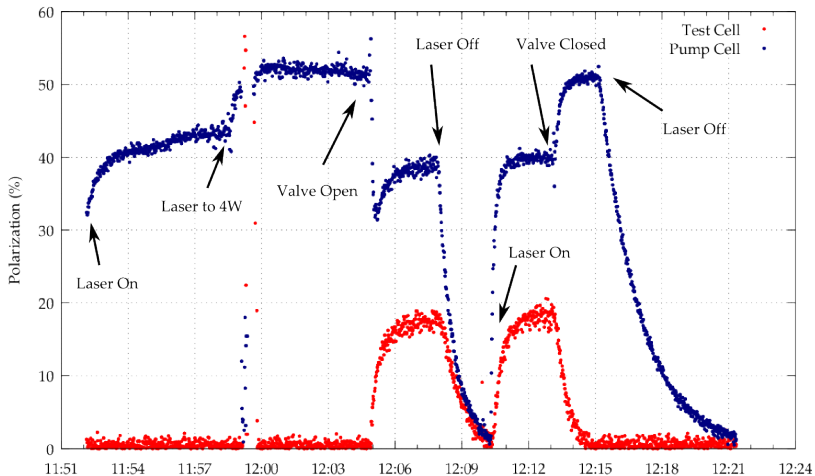
Transferring between B Fields via Diffusion



Relaxation Time Map, Helmholtz and Solenoid

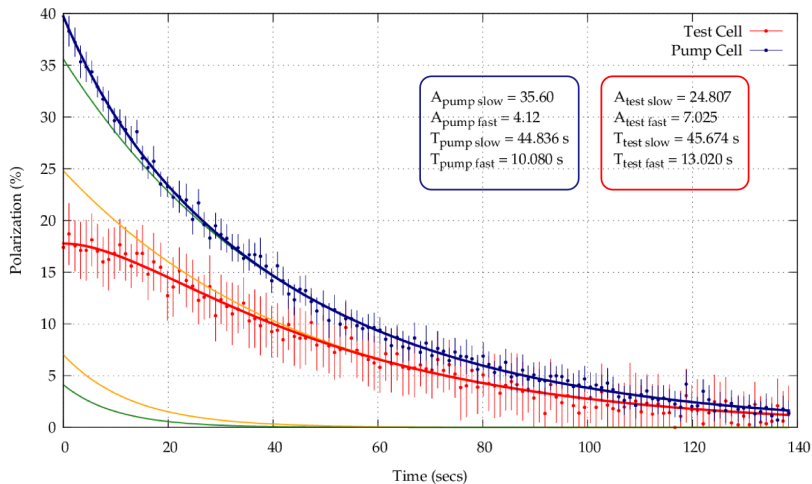


Polarization Transfer via Diffusion



Polarization measured via discharge light in each cell

Relaxation in Both Cells



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

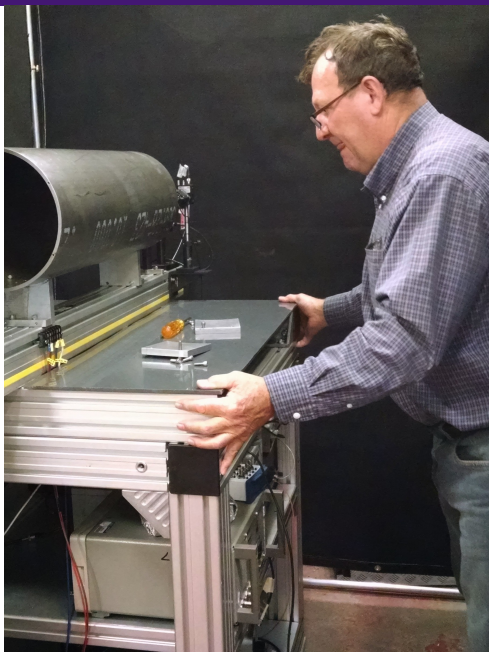
BNL Test Polarizer

- 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

Low Field Conclusions Thus Far

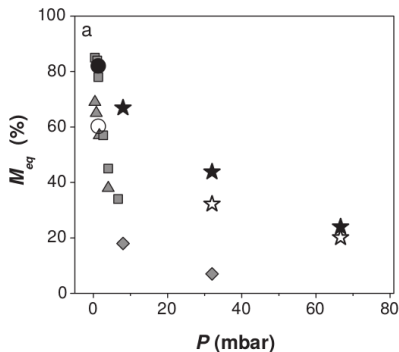
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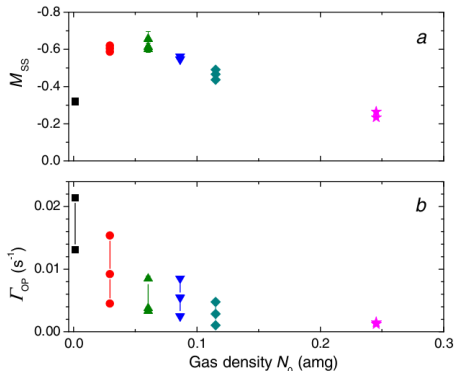
MEOP at High Magnetic Field

- 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



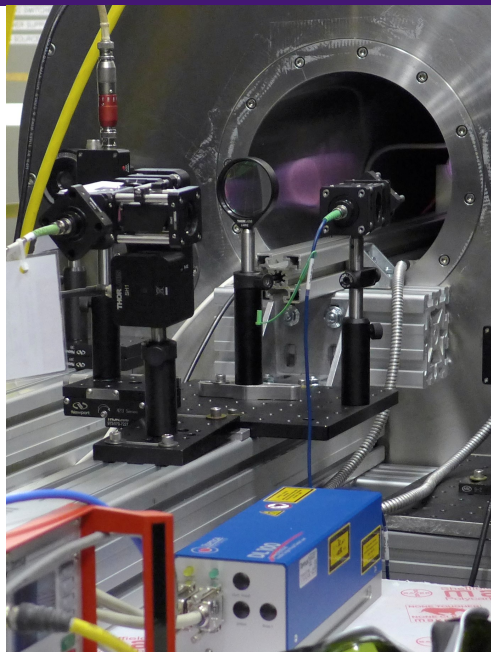
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- A. Nikiel *et al*,
Eur. Phys. J. D. 67,
2013
 - 4.7 T, 0.5 W OP laser
 - 1.3, 32, 67, 96, 128,
267 mbar
 - Noted trouble with
RF for 1 torr cell



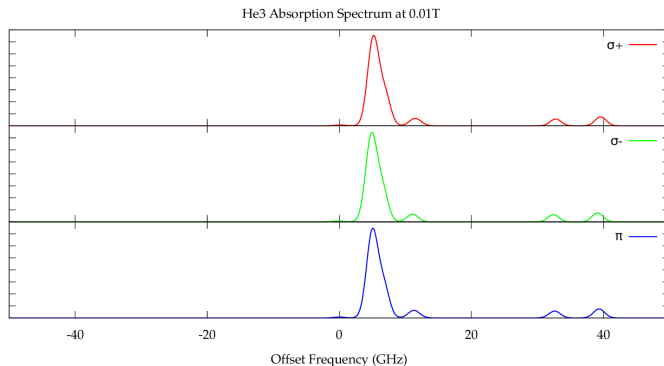
BNL High Field Tests

- 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 $2^3\text{S}-2^3\text{P}$ transitions to directly probe states^{8,9}

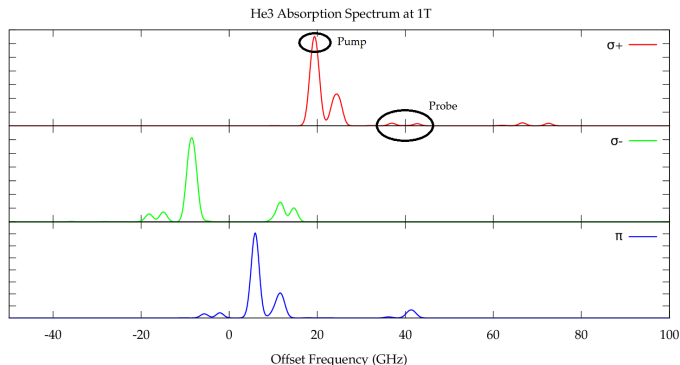


⁸Courtade *et al*, Eur. Phys. J. D 21 (2002).

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

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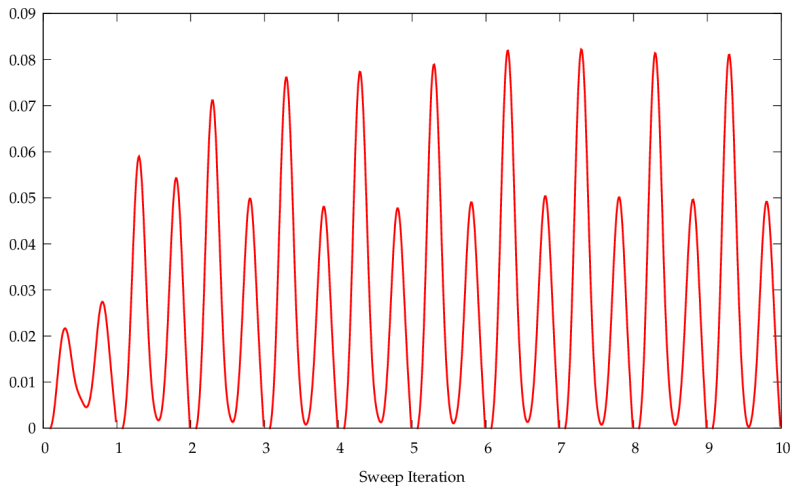
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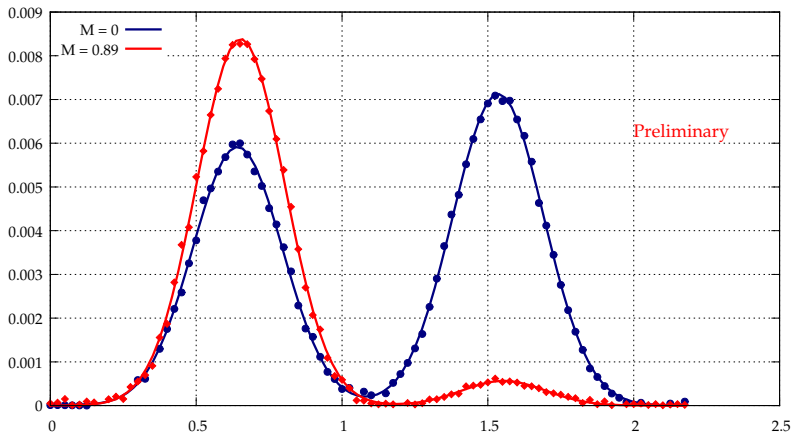
⁹Suchanek *et al*, Eur. Phys. Special Topics 144 (2007).

Measuring Optical Pumping

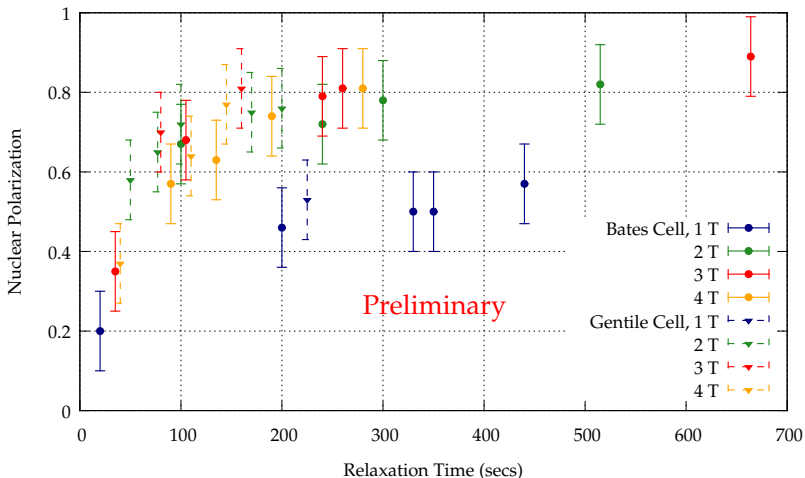


Measuring Optical Pumping

Probe Laser Absorption Peaks at Zero and High Polarization



High Field Polarization Results

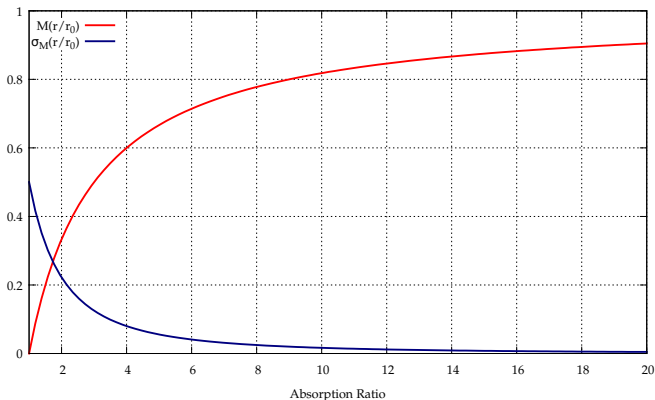


- Error set at 10% while measurement is investigated

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

- First results for MEOP at 3, 4 T and 1 torr, to near 90%
 - 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

High Field Conclusions Thus Far

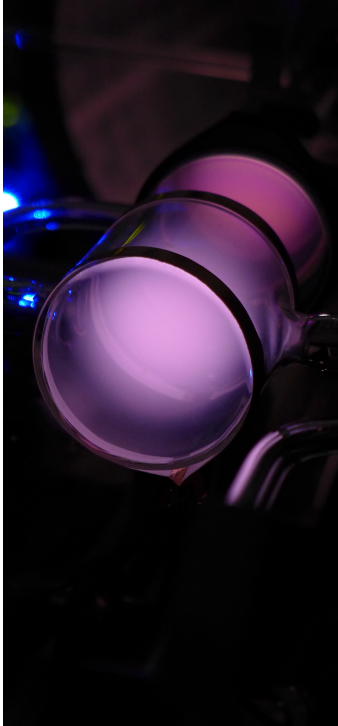
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Outline

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



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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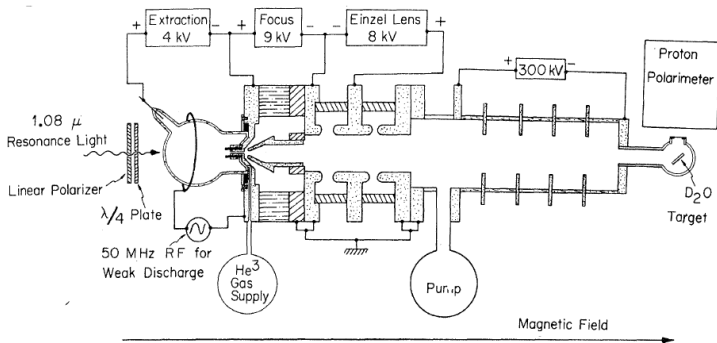
High Field Source Design: EBIS Upgrade

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



Polarized ^3He Source for JLab MEIC?

- Two EIC candidates, eRHIC and MEIC
- JLab does not have EBIS
- Revisit Rice source¹⁰ with modern techniques



¹⁰Baker, 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

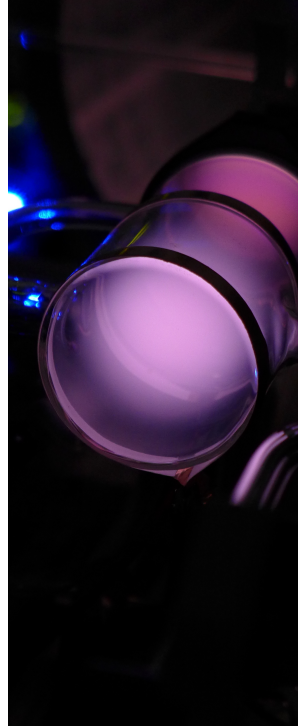
- P.J. Nacher, G. Collier

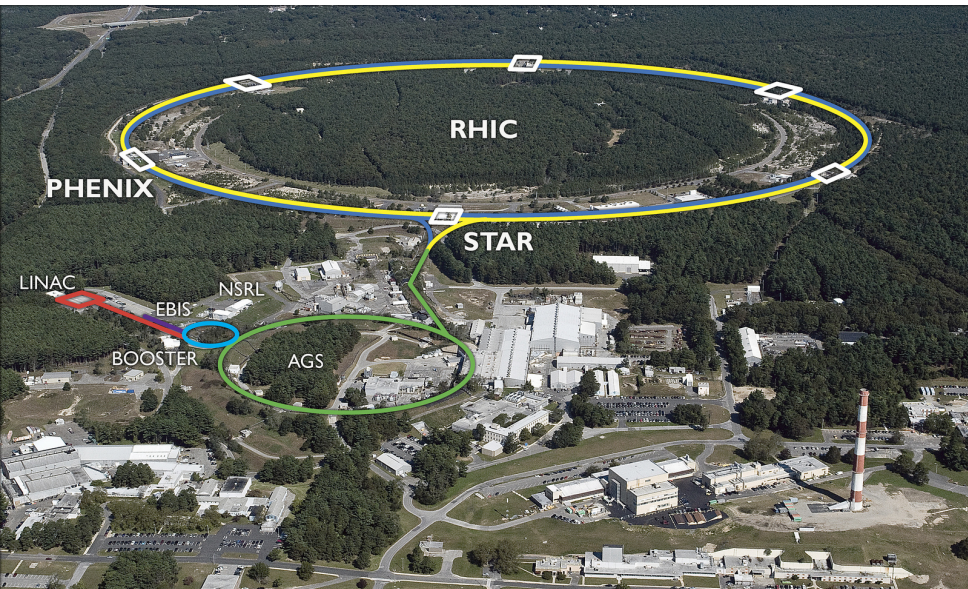
Work supported by

- DOE Office of Nuclear Physics, R&D for Next Generation Nuclear Physics Accelerator Facilities
- MIT Department of Physics



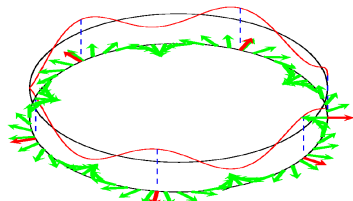
Thanks for your attention!



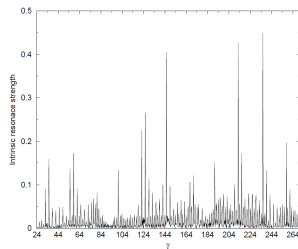


Maintaining Polarization in a Circular Collider

- 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 RHIC¹¹ →
- Siberian Snakes to the rescue
 - Rotate spin 180° , allow the wobble to unkink itself
 - Partial snakes can be used for some imperfections



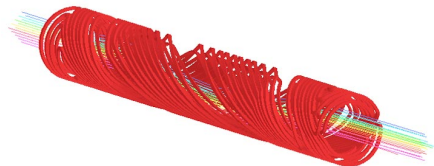
W. W. MacKay



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

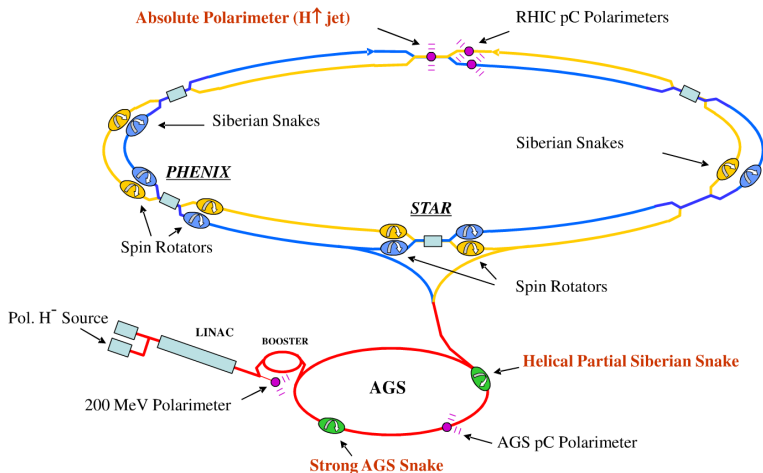
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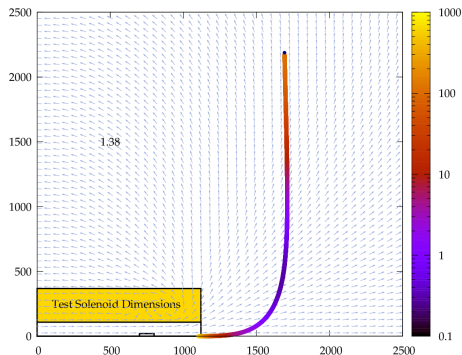
¹¹Bai, Courant *et al.*, BNL-96726-2012-CP, 2012.

RHIC Spin Manipulation



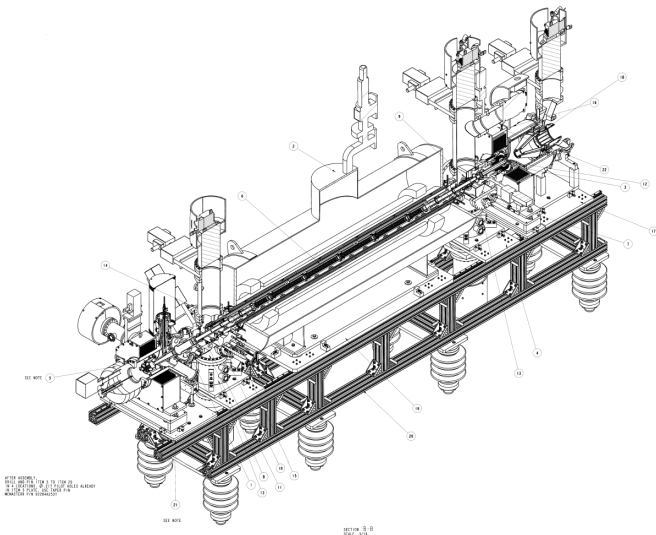
Transfer Path Relaxation Studies

- 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

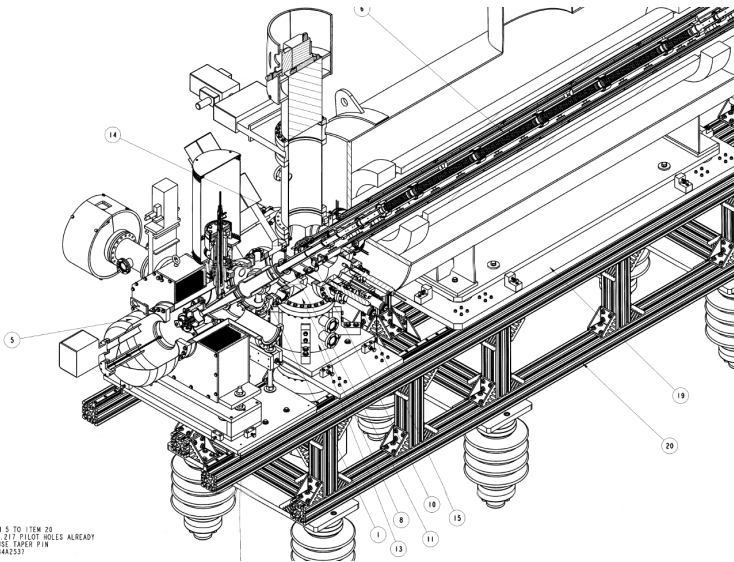


(Color scale in seconds)

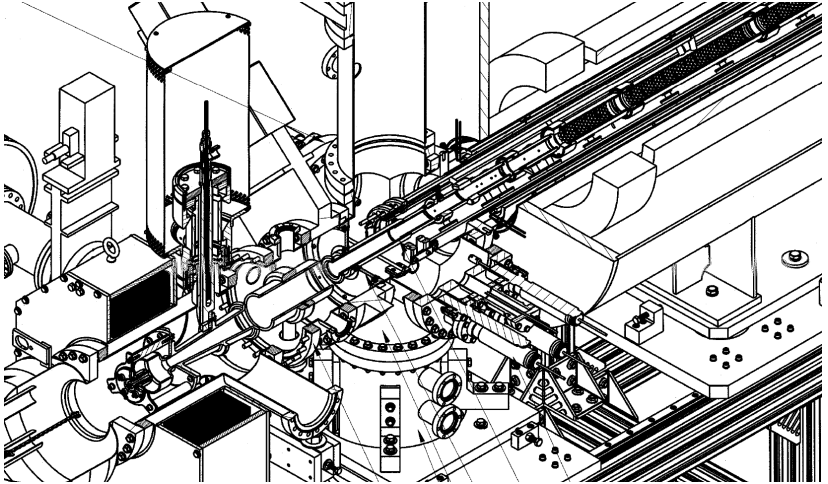
Constraints on Path into EBIS



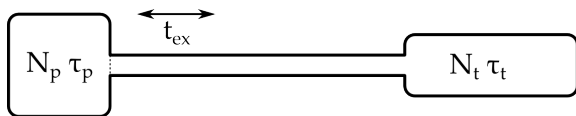
Constraints on Path into EBIS



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

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