# Development of a Polarized $^3$He Ion Source for RHIC

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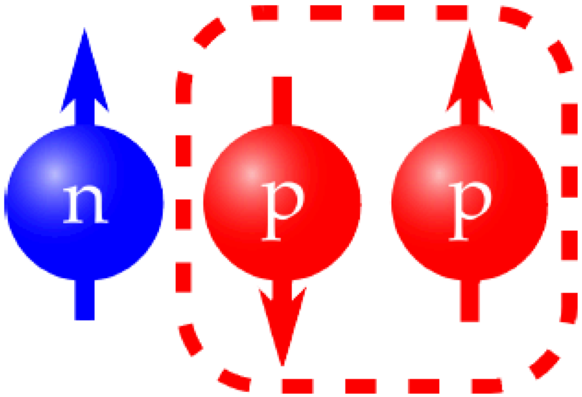
- Motivation
- R&D completed and achievements
- Plans

# Why a Polarized $^3$He Source?

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

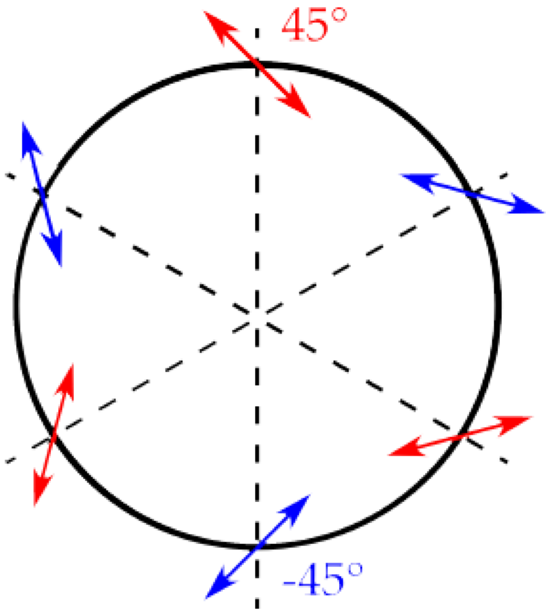


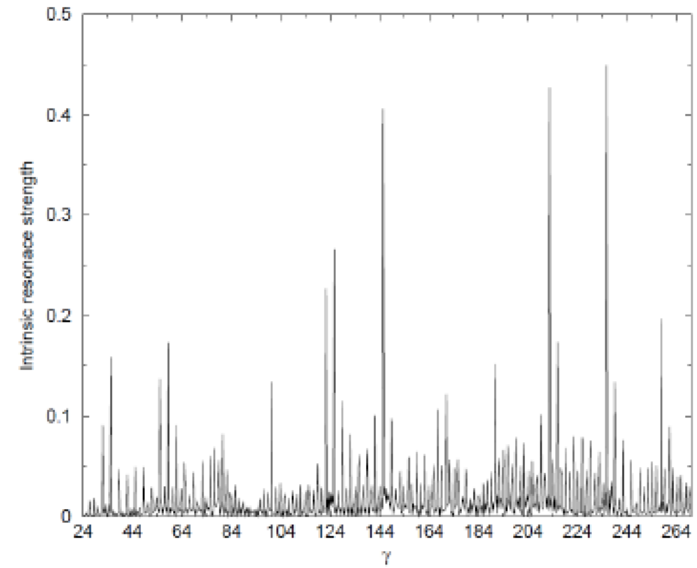

| State | Probability |
|---|---|
| S | 88.6% |
| S' | 1.5% |
| D | 8.4% |

- 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

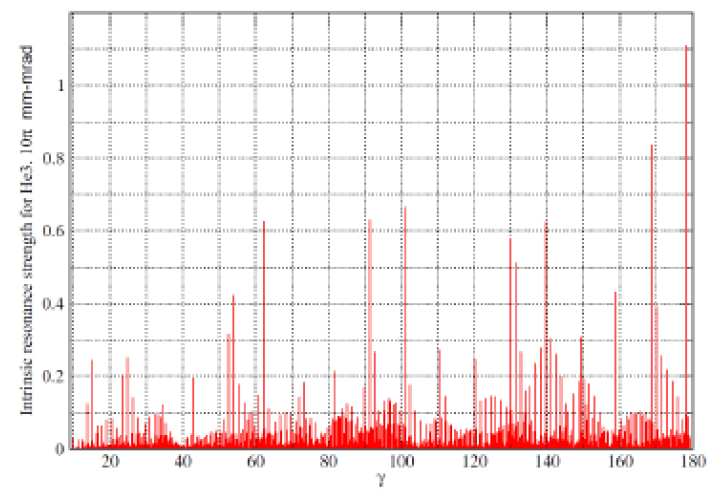
# Polarized $^3$He at RHIC

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




p resonances

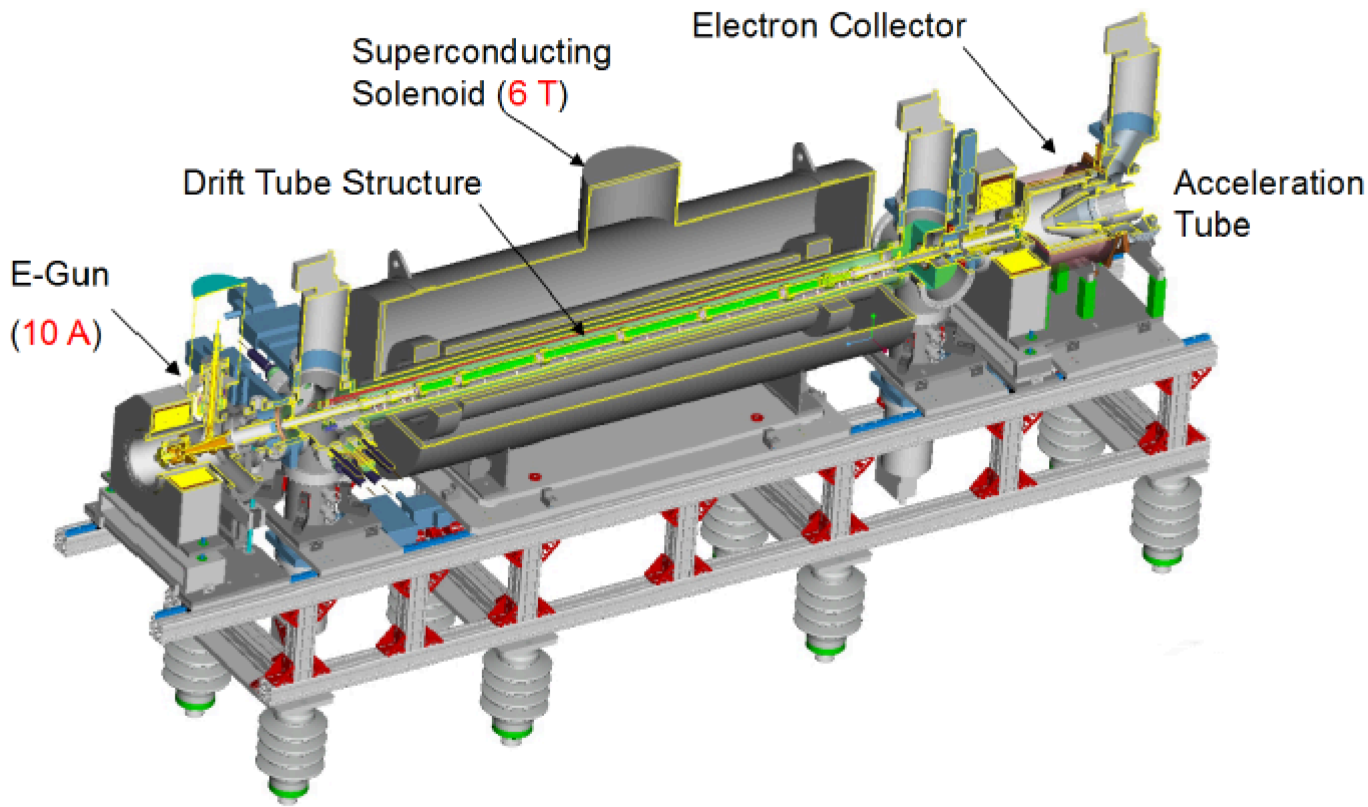



$^3$He resonances

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

# RHIC's Electron Beam Ionization 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

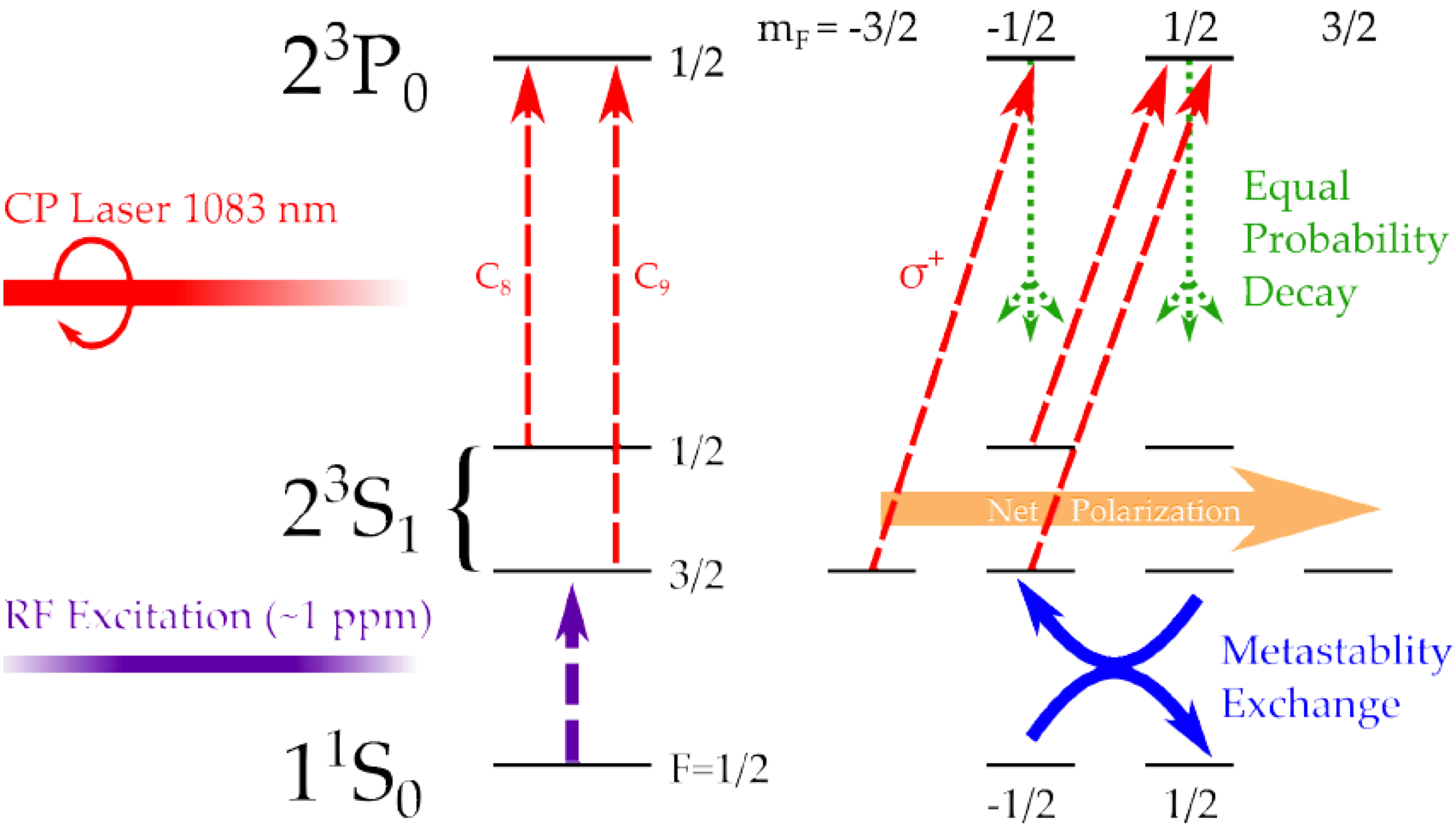


# Source Concept

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

- Polarize $^3$He gas using optical pumping and feed into EBIS.
- High magnetic field in EBIS should preserve nuclear polarization.
- Source design goals:
  - Polarize to $\sim$70% at 1 torr with 10 W laser
  - Transfer $\sim 10^{14}$ $^3$He/s to EBIS at 5 T & $10^{-7}$ torr
  - Deliver $1.5\times10^{11}$ $^3He^{++}$ ions per 20 $\mu$sec pulse

# Metastability Exchange Optical Pumping



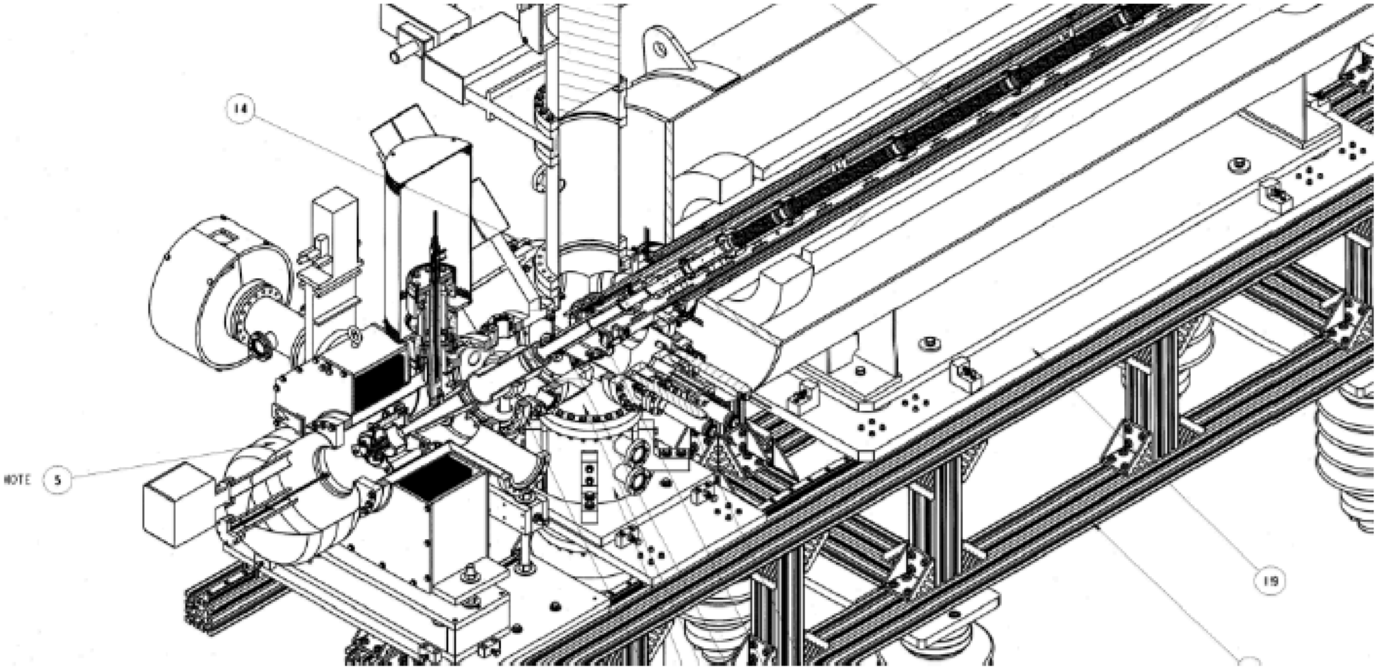
# Depolarization Processes

- Wall Bounces
  - 3 mm long, 0.1mm diameter leak: 1 torr to $10^{-7}$ torr
  - 1m long, 2mm diameter tube: $\approx 10^6$ bounces, $\approx 1$ 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.**

# Optically pump in low or high field?

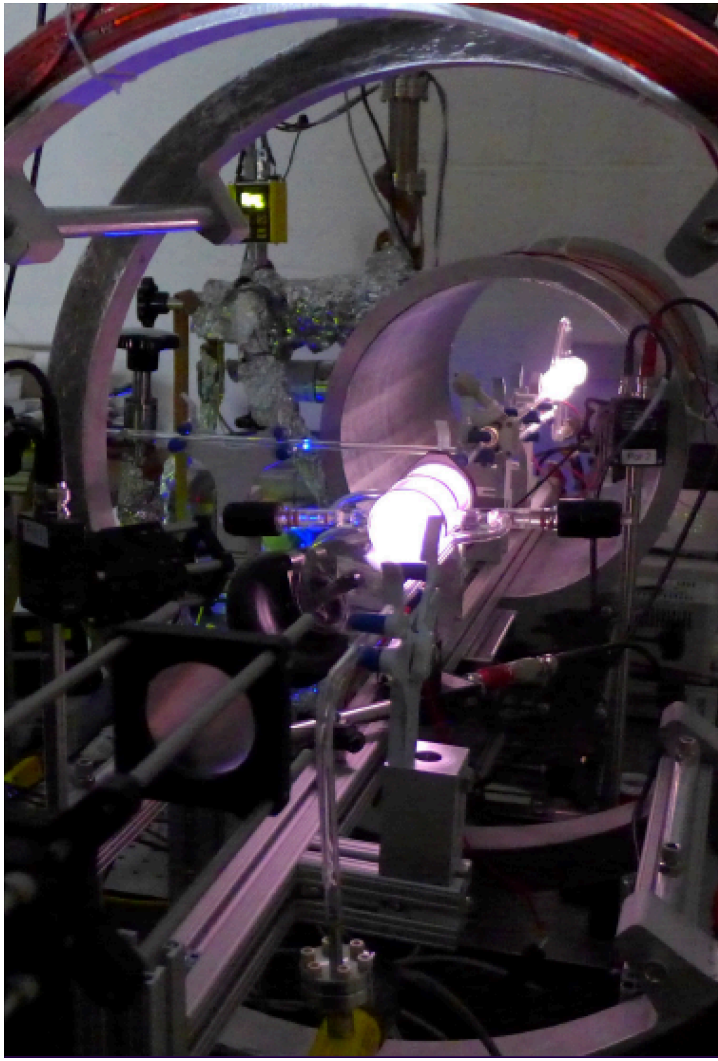
- Two design possibilities present themselves:
  - Polarize at 30 G in EBIS stray field using field correction, then transfer into EBIS
  - Polarize in EBIS, or nearby, extending field region



# 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[7]
- Test bed for polarization, transfer and data acquisition
- Discharge and optical probe polarimeter development[8]

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



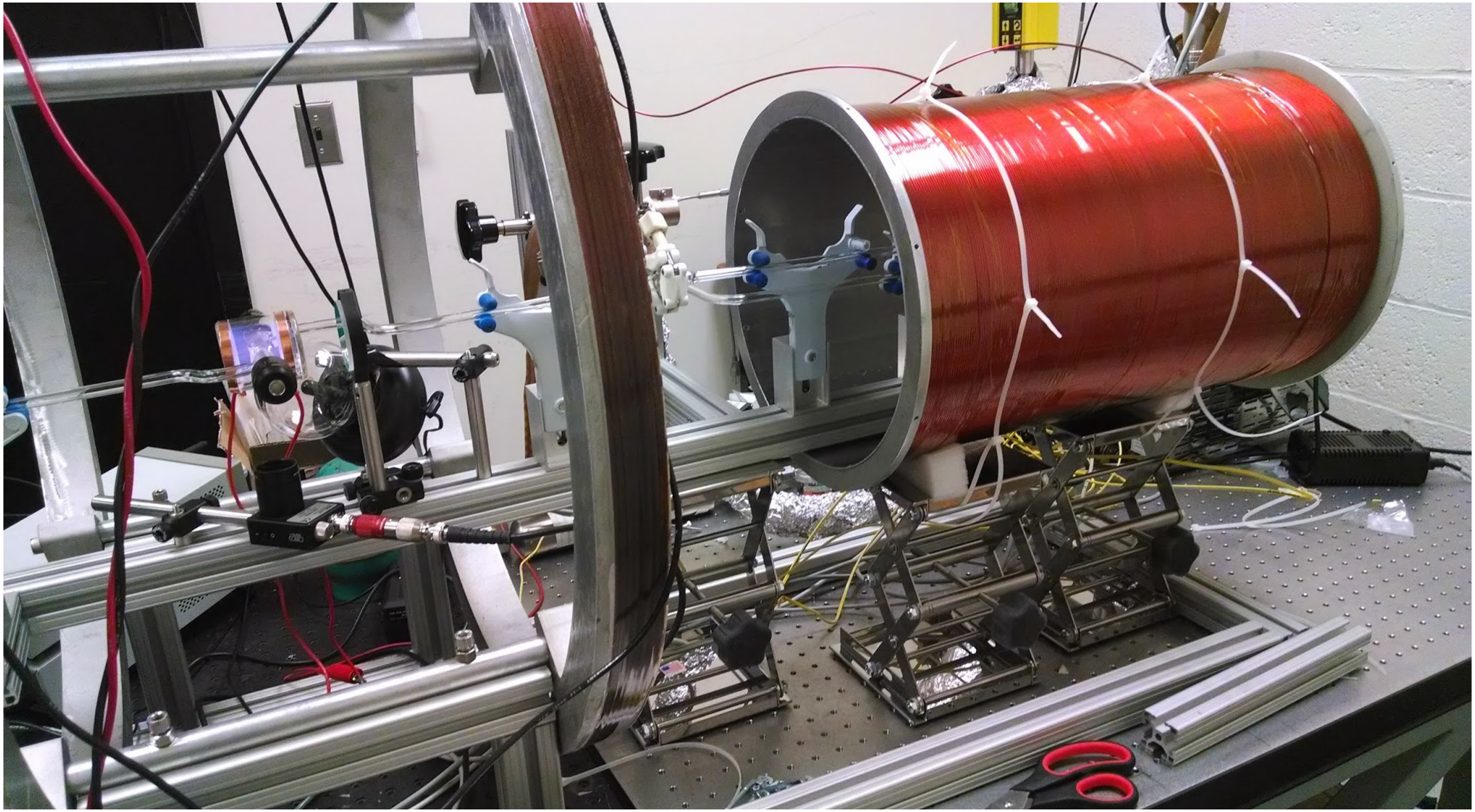
# Overview of R&D Activities

- We have developed the capability to optically pump polarized $^3$He gas at both low (≈30 Gauss) and at high fields (≈ 4 Tesla) at both MIT and BNL.
- We have developed a number of polarization techniques: 667 nm polarimeter and pump-probe polarimeter developed, NMR under development.

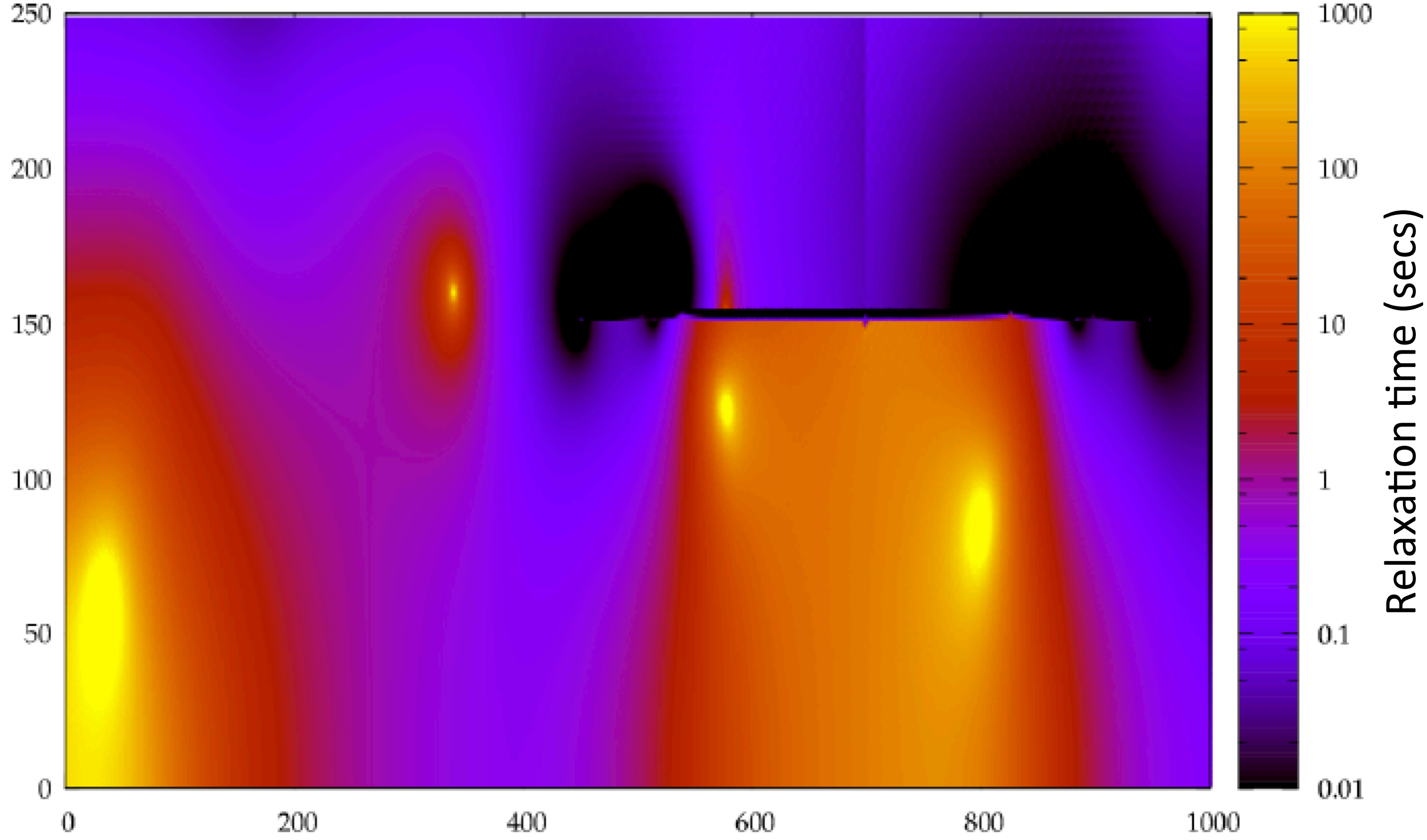
  J. Maxwell, C.S. Epstein and R.G. Milner, NIM A **764**, 215 (2014)
- Systems have been built to study polarized gas transfer between Helmholtz coil and solenoidal field. Measurements are in good agreement with expectation.

  J. Maxwell, C.S. Epstein, and R.G. Milner, NIM A **777**, 194 (2015)
- **High polarization of order 80% has been measured reproducibly in high field (4 Tesla) optical pumping in spare EBIS solenoid at BNL.**

# Spin Diffusion through Gradients



# Relaxation Time Map for Helmholtz+Solenoid



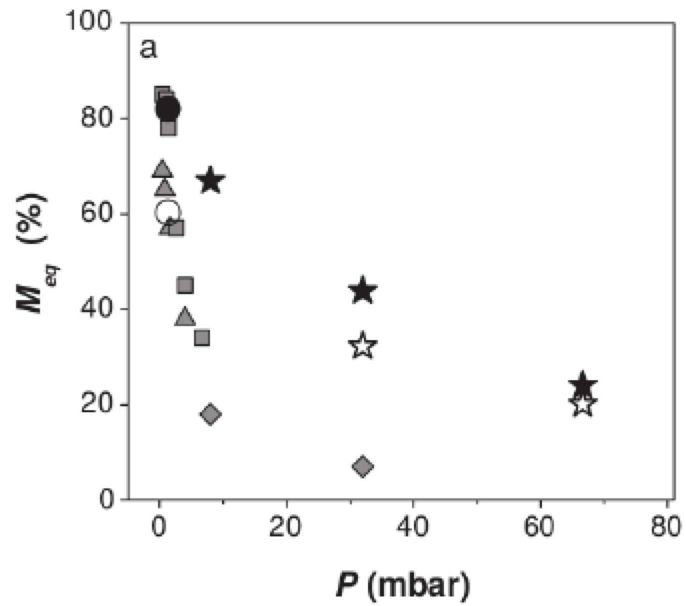
# Low Field Conclusions

- 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)
- A polarized source using low field MEOP and EBIS is feasible, if not easy
- Battle must be fought with the stray field both to polarize and to transfer, compromising the achieved polarization, however little

# MEOP at High Magnetic Field

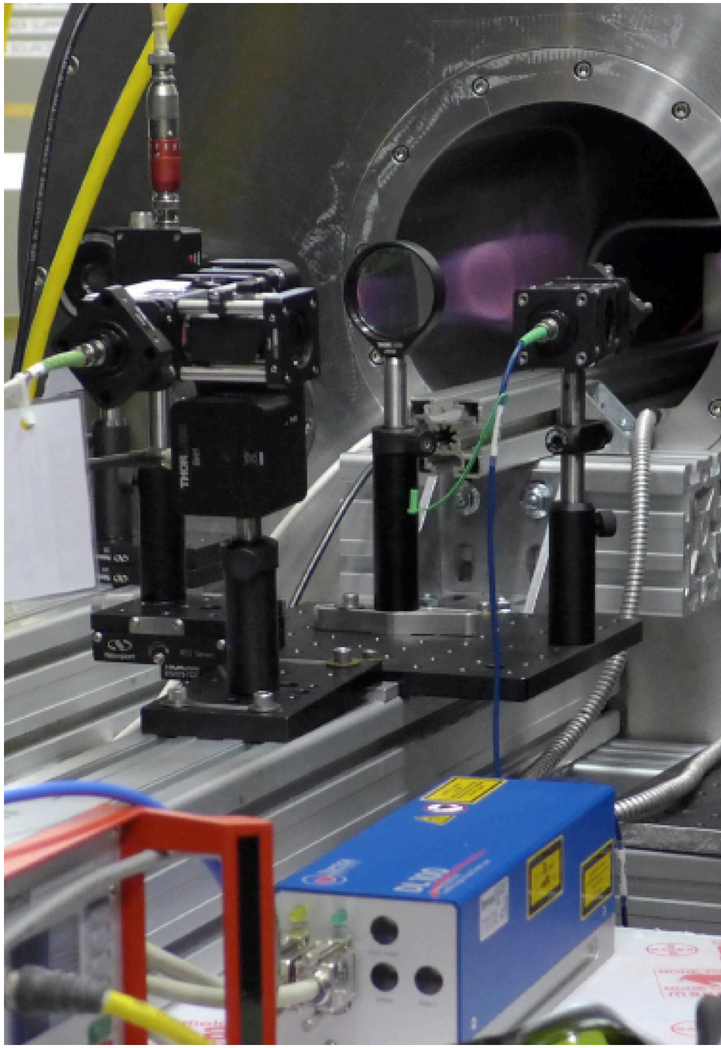
- European group (Paris, Krakow) researching high pressure MEOP, medical applications
- Pioneering achievements in pumping efficiency at high pressures leveraging fields above 1 T in last ten years

- 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



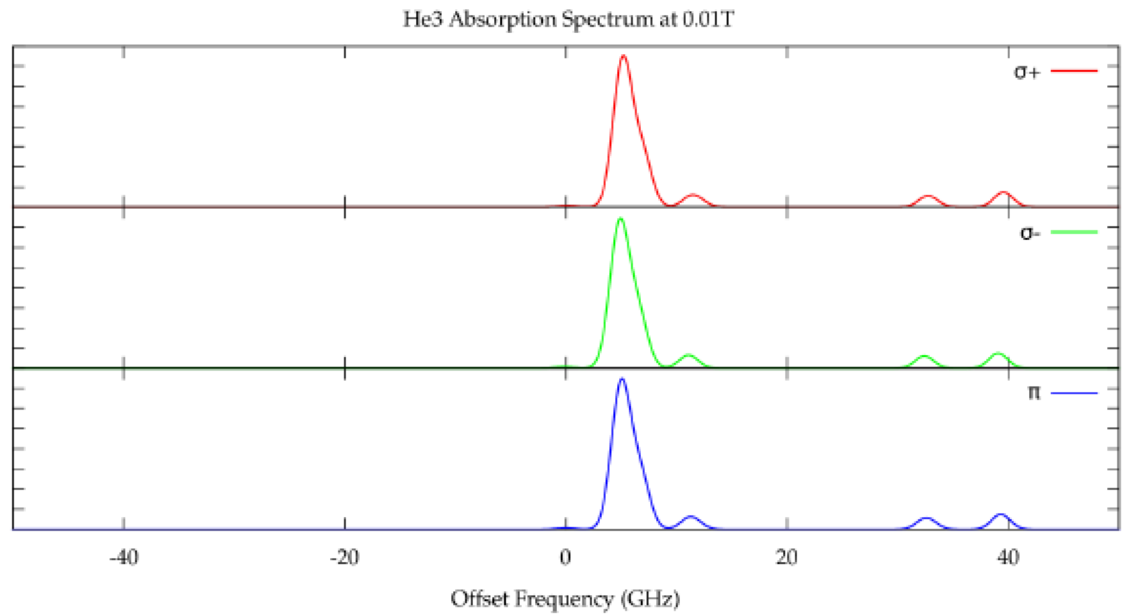
# BNL High Field Tests

- 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 Polarimeter

- High or low field, no calibration required
  - Sweep low power probe laser through two $2^3S-2^3P$ transitions to directly probe states[9,10]




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

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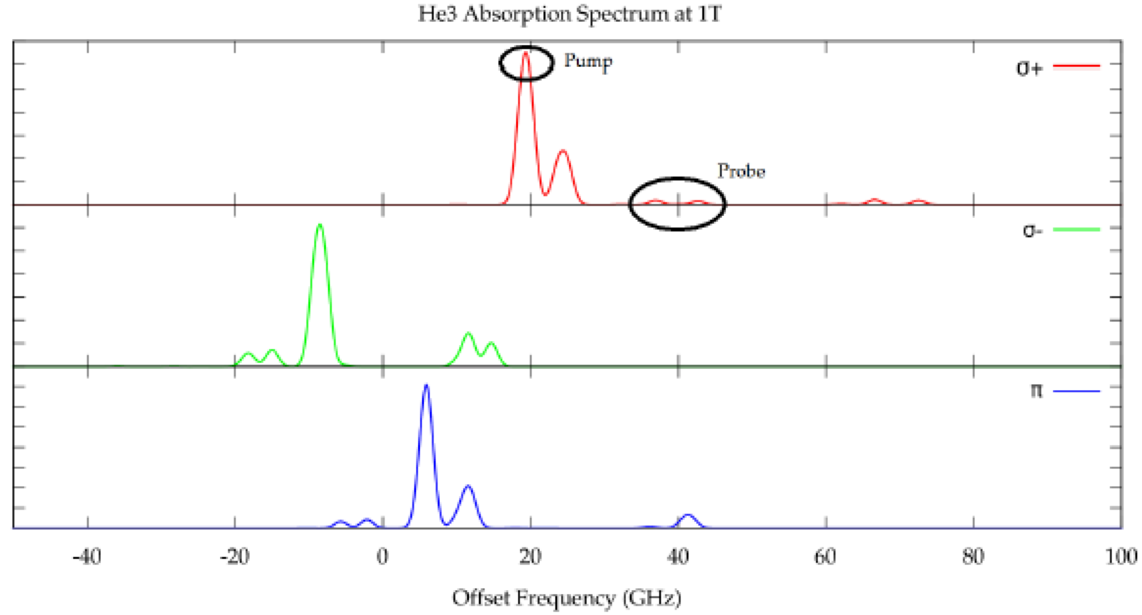


[9] Courtade *et al*, Eur. Phys. J. D 21 (2002).
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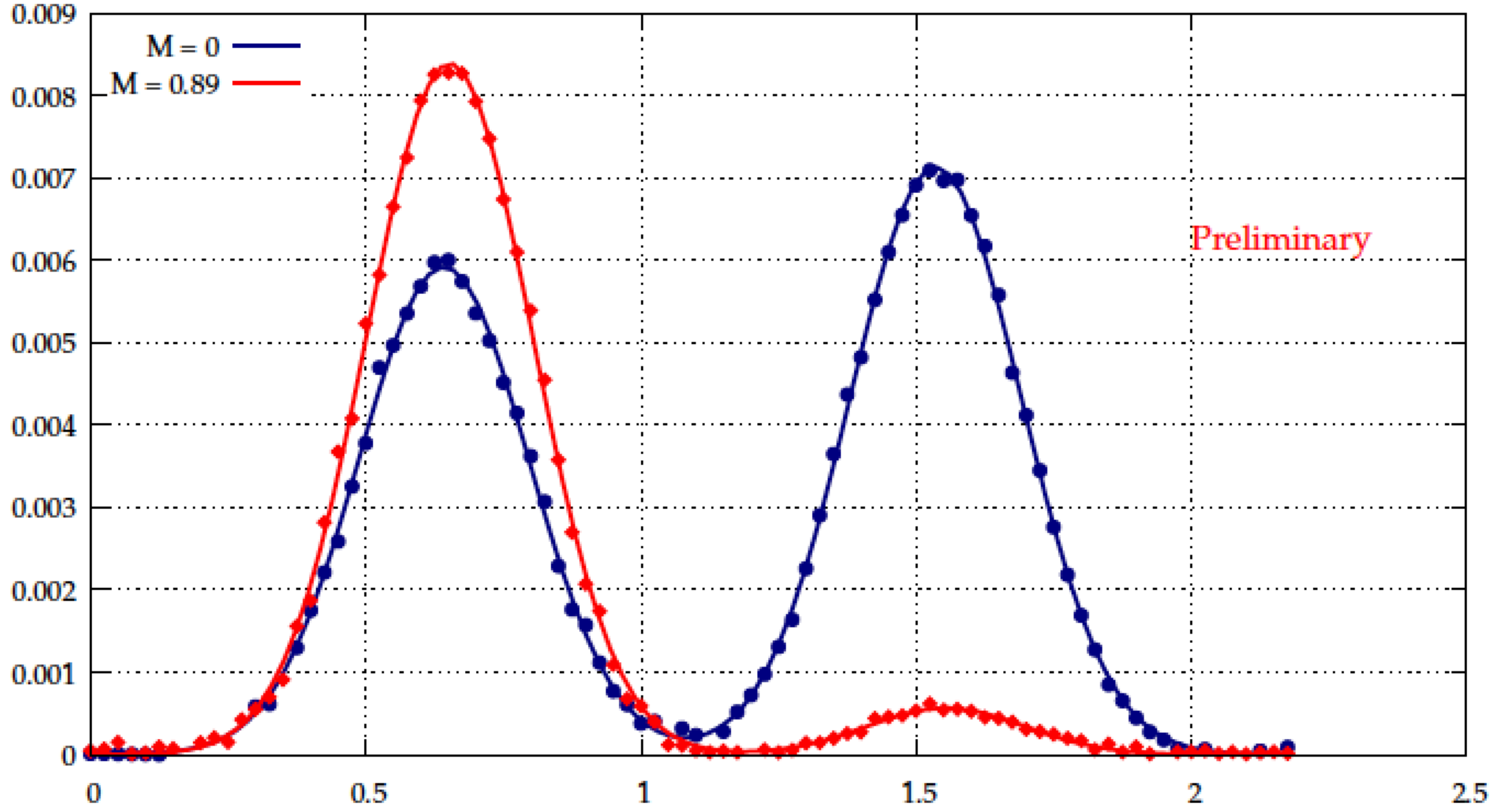
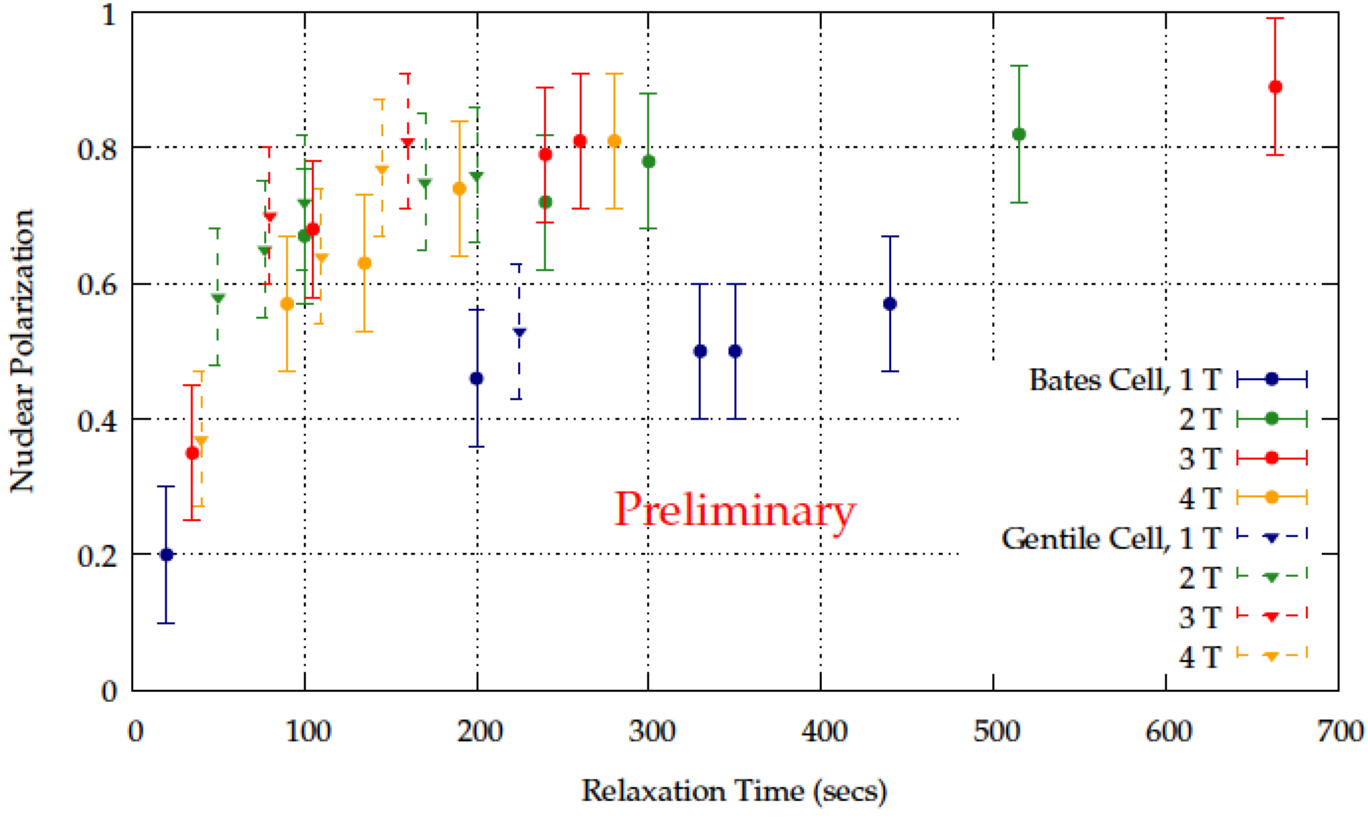
# Measured Optical Pumping

Probe Laser Absorption Peaks at Zero and High Polarization



# High Field Polarization Results



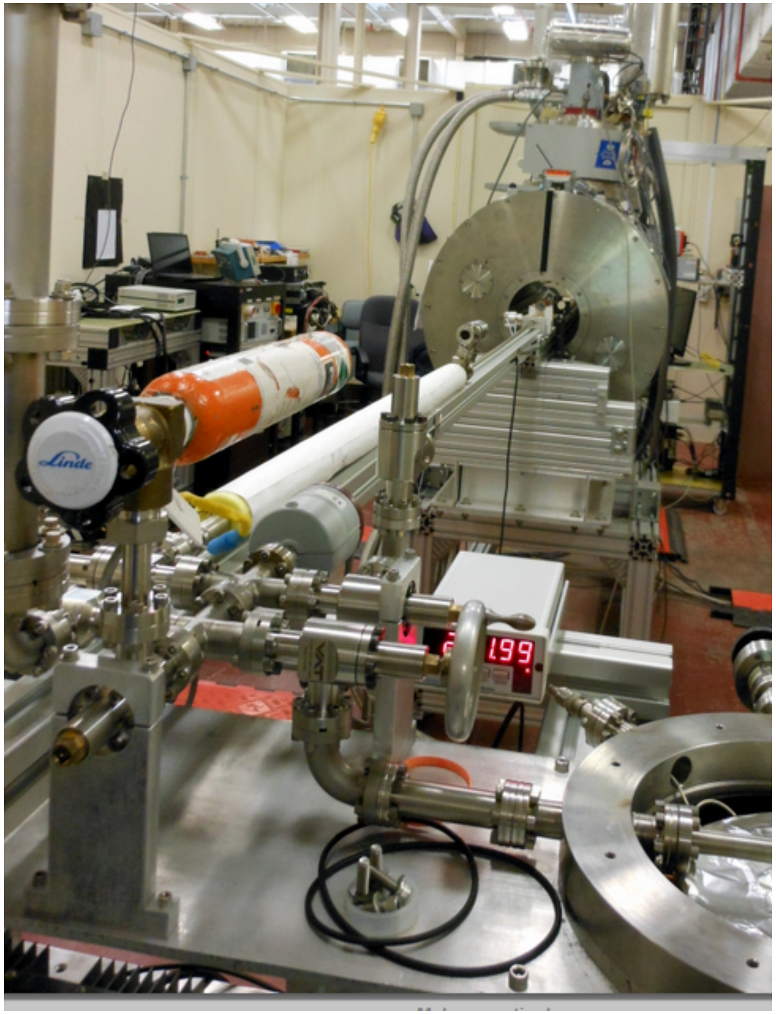

- Error set at 10% while measurement is investigated

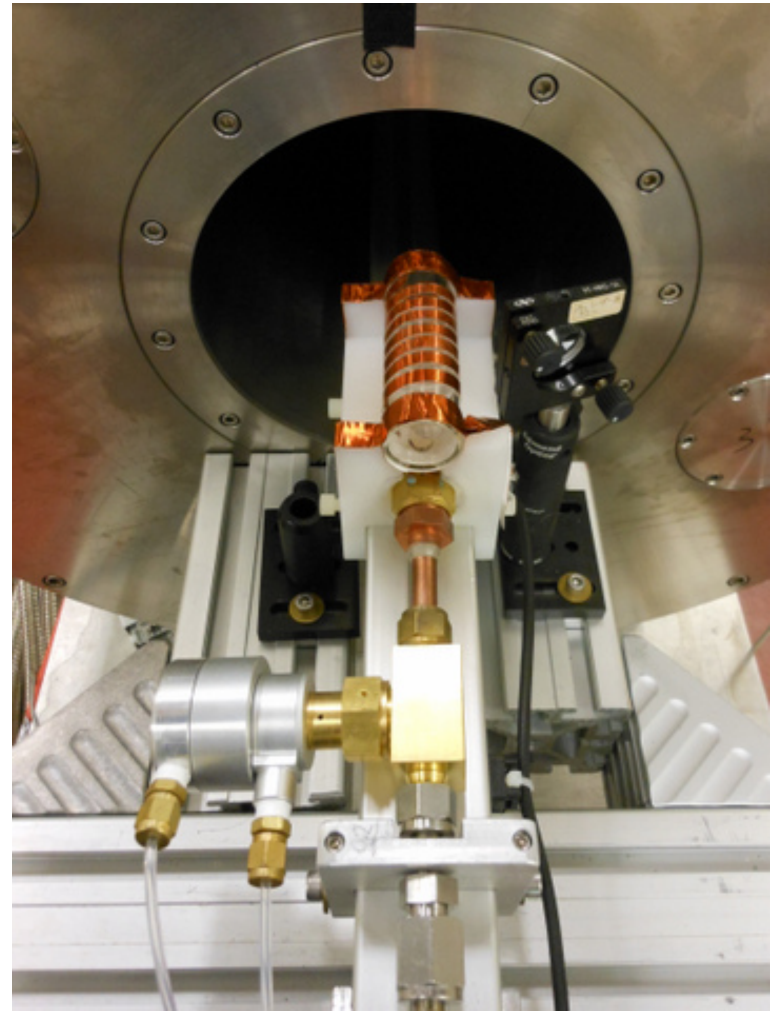
# High Field Conclusions

- High polarizations can be reached with 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 the 668 nm line used for low field polarization measurement)
  - At high field, transition split allows addressing just one state with OP
- 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

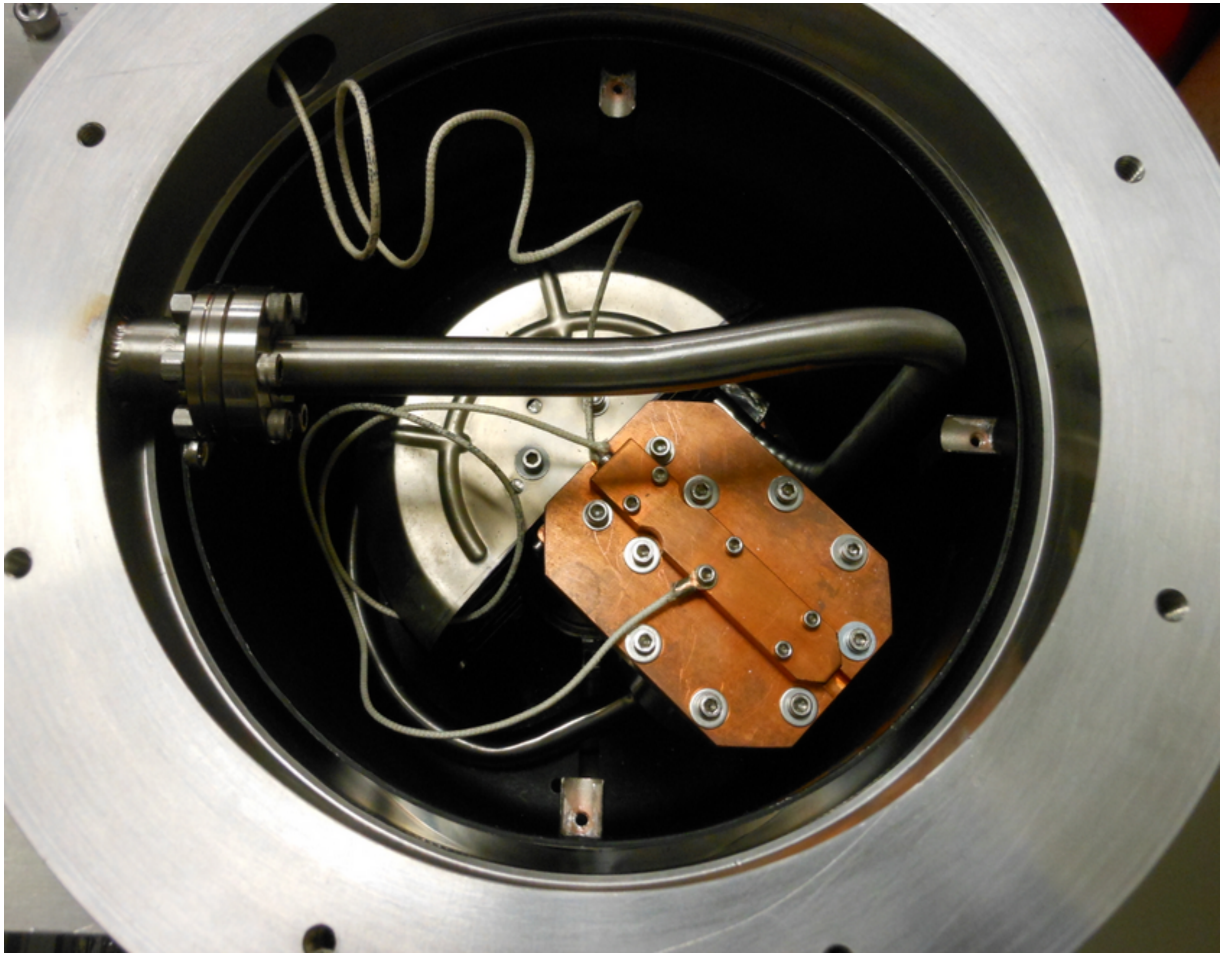
# New "open" $^3$He-cell and gas system for $^3$He-cell preparation and filling

# $^3$He-gas purification and filling system

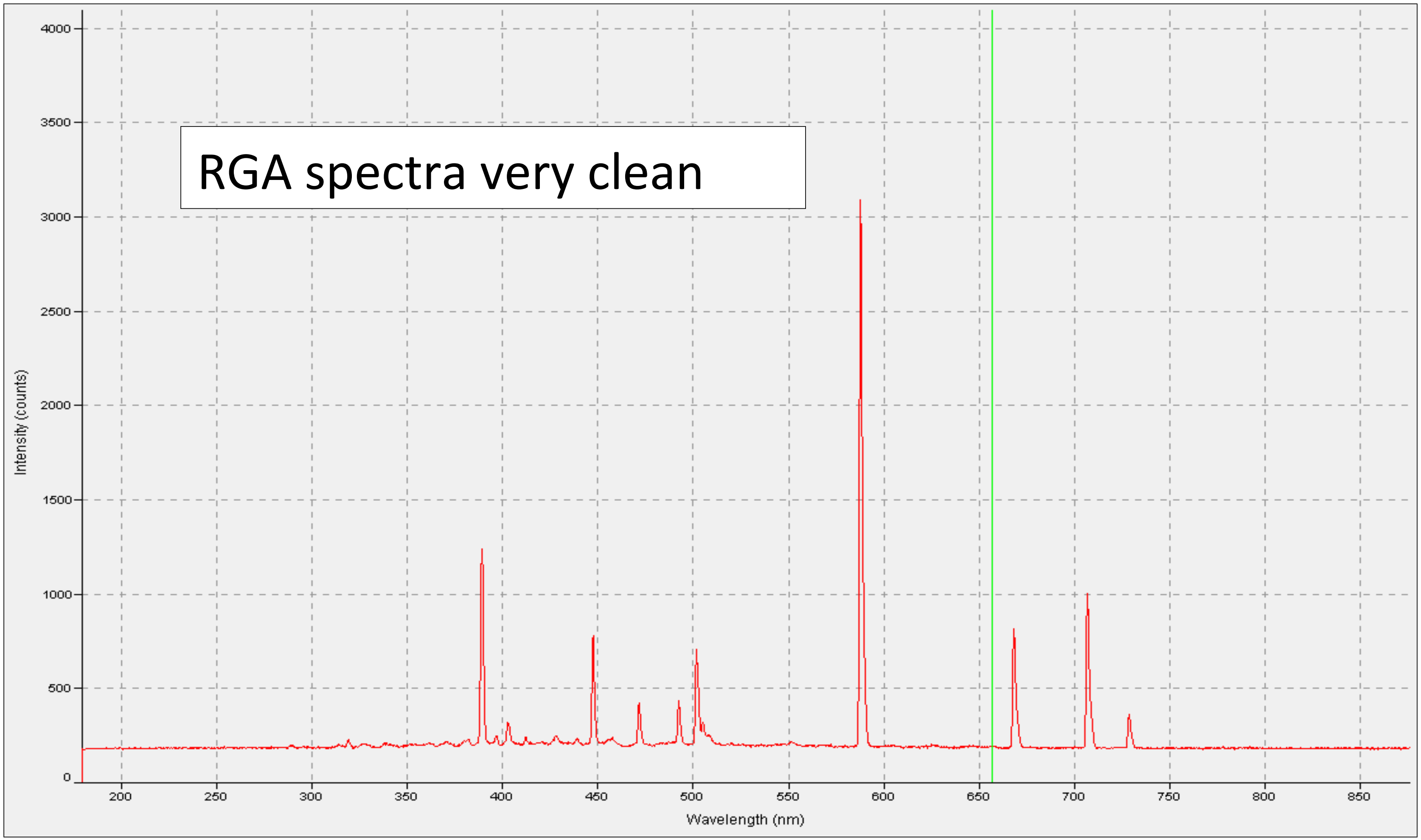


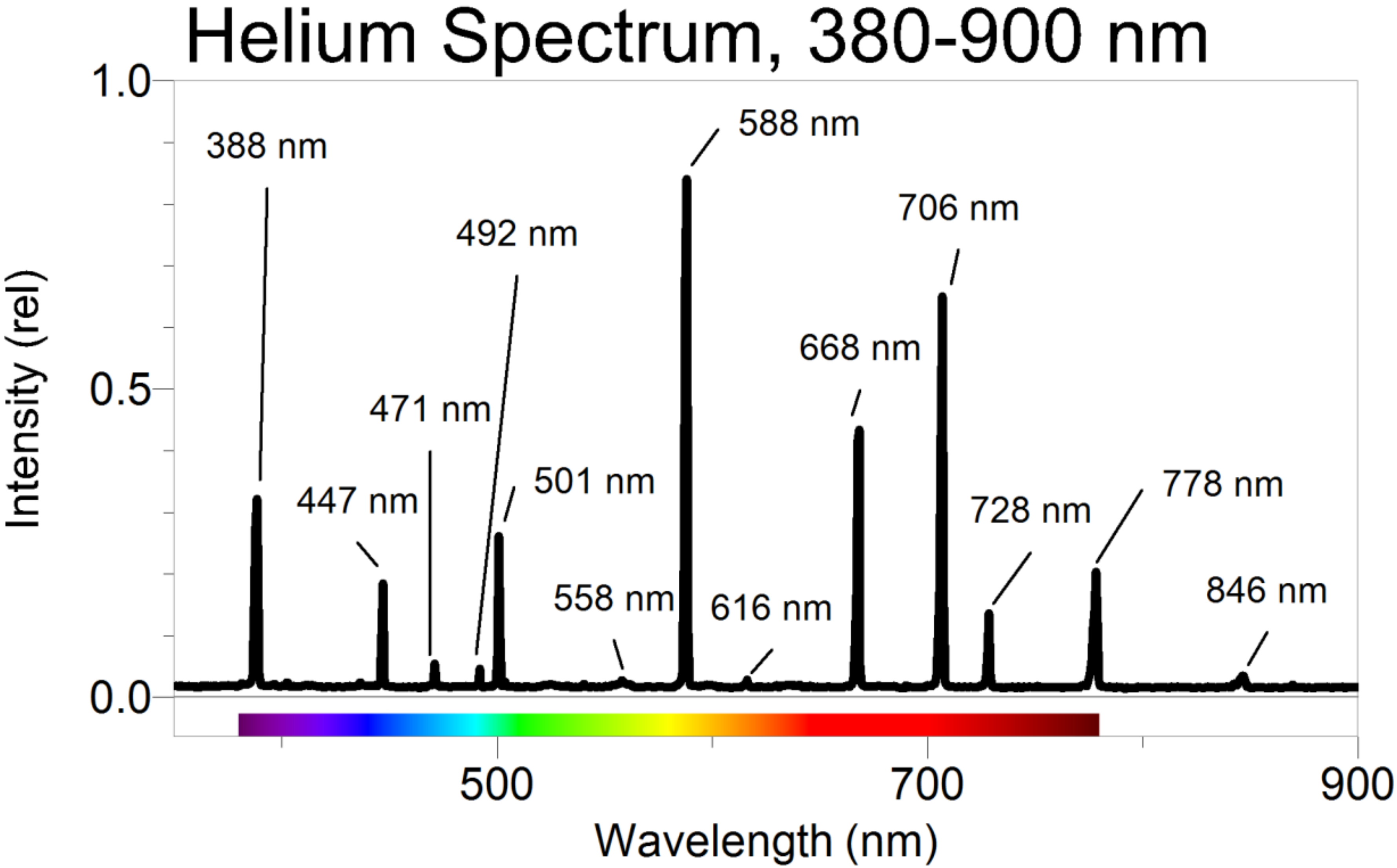



# $^3$He cryo- purification system built in CTI-8 cryopump.

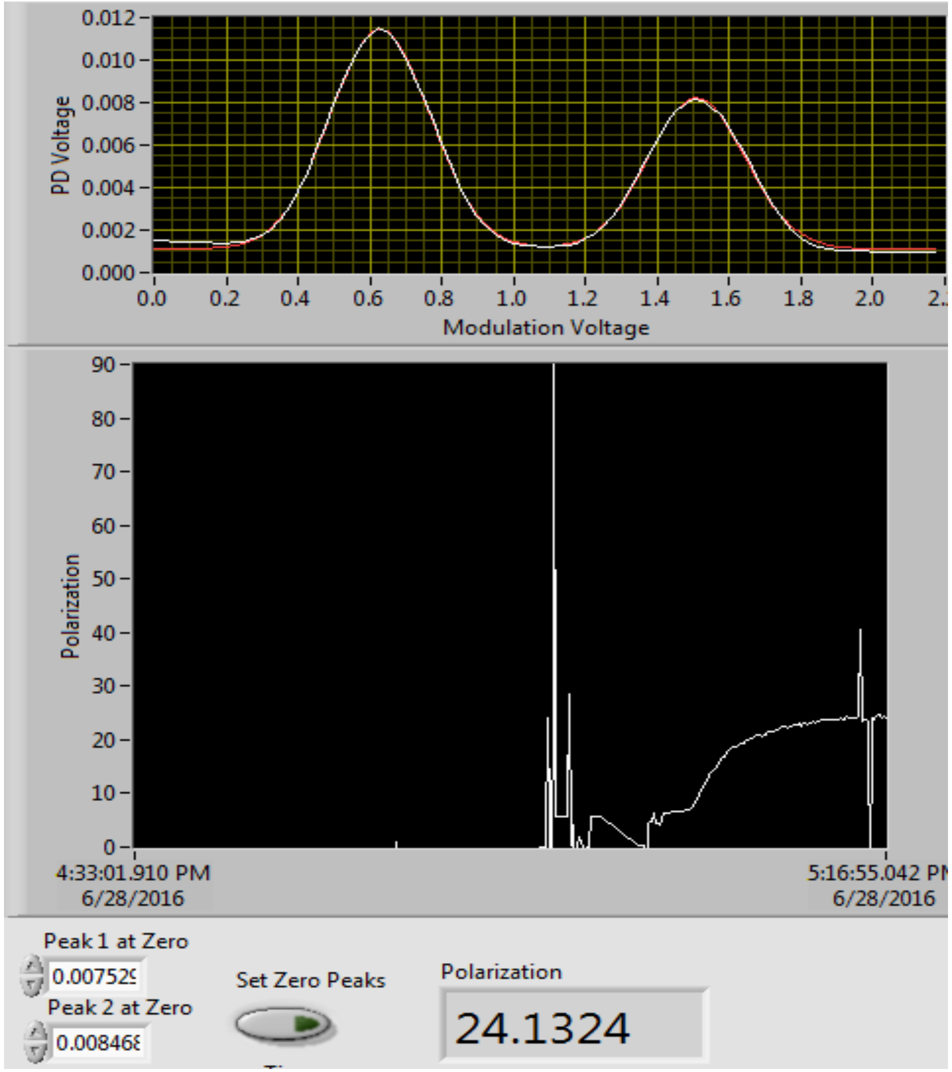


# June 21, He-fill with CP-pumping at 45deg. K. Very clean spectra, no hydrogen 656 nm line!

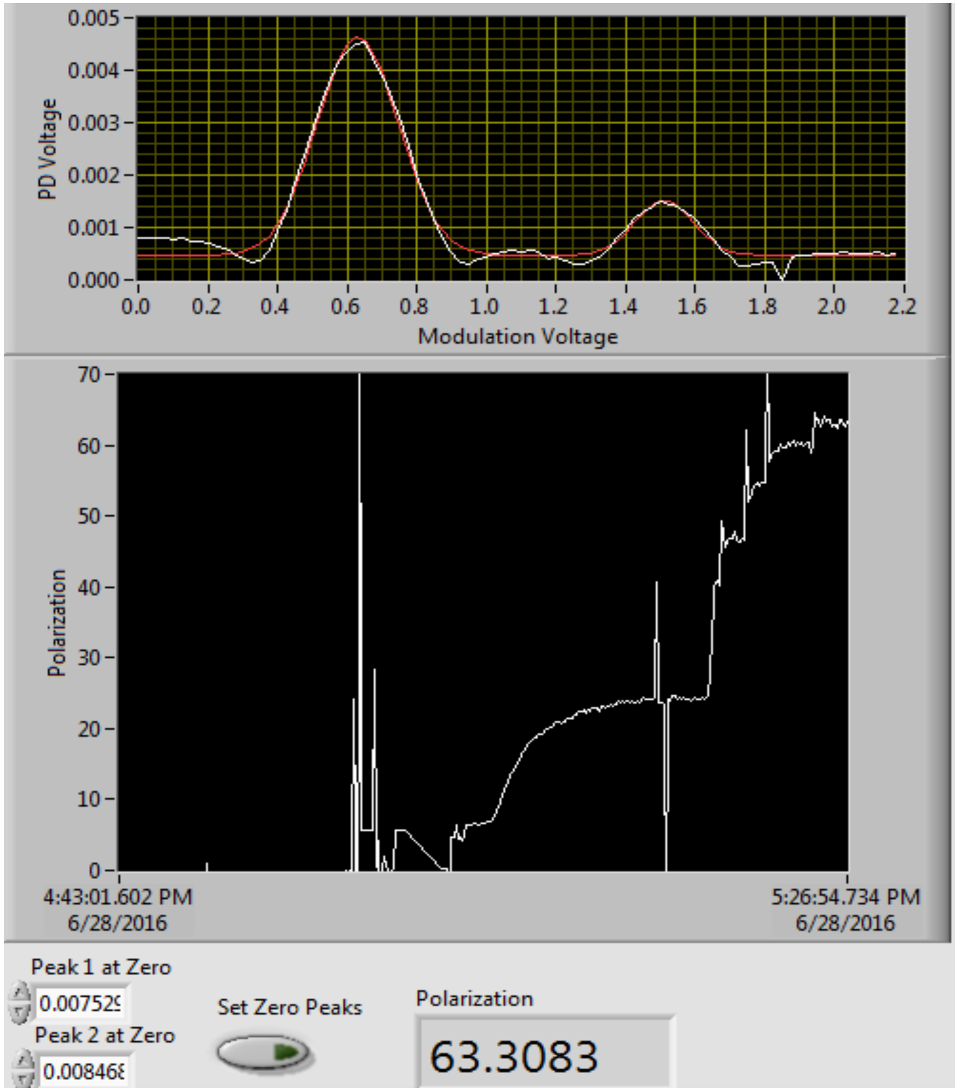



Helium Spectrum, 380-900 nm
1.0
0.5
0.0
Intensity (rel)
388 nm
447 nm
471 nm
492 nm
501 nm
558 nm
588 nm
616 nm
668 nm
706 nm
728 nm
778 nm
846 nm
500
700
900
Wavelength (nm)

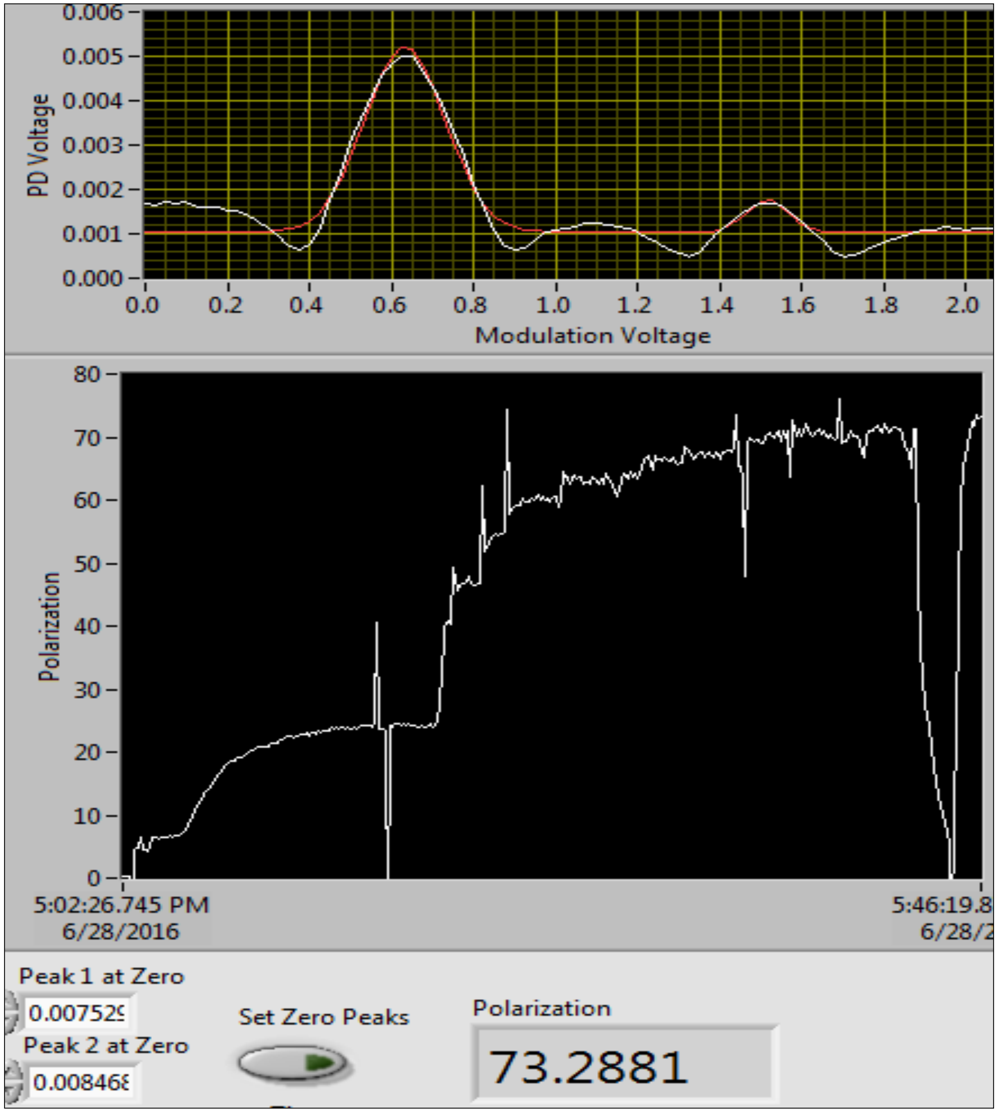
# 3.5 torr, Isolation Valve (IV)-open



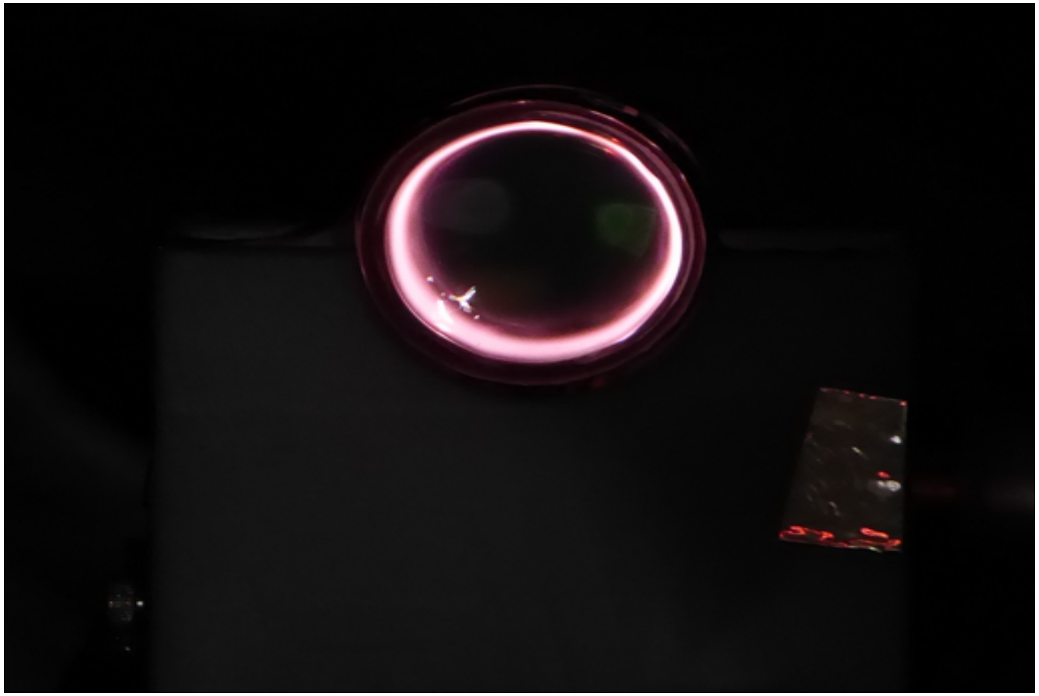
# 3.5 torr, Isolation Valve (IV)-closed, P=63%



# "Open cell", $^3$He-3.5 torr, Pol-73%



# RF-discharge in 2.0 T magnetic field
# $^3$He-cell diameter-25mm



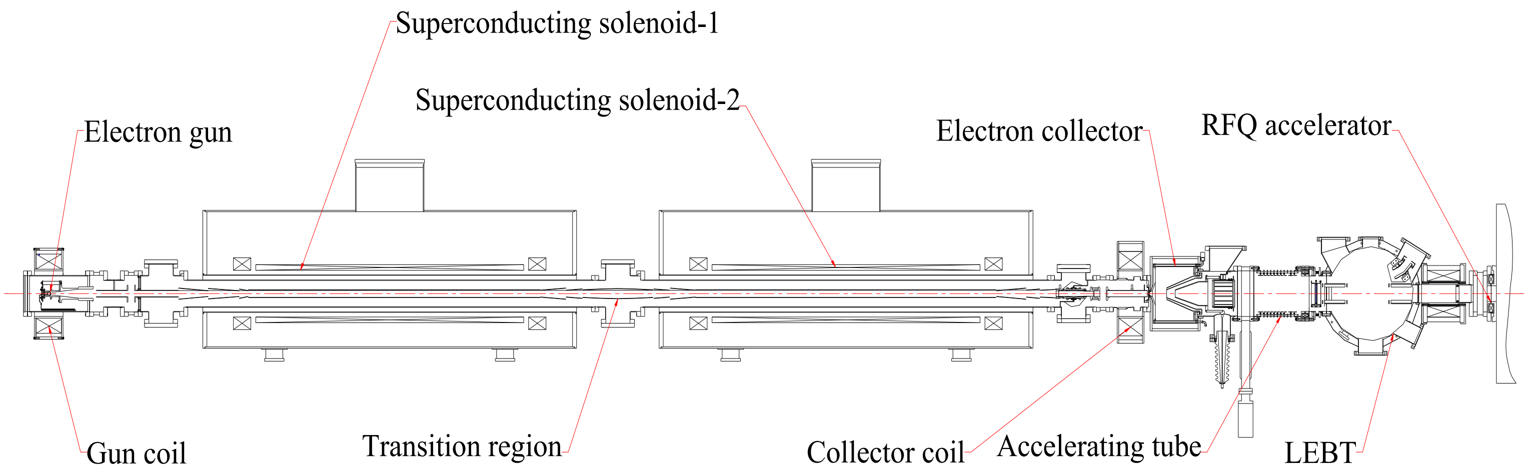
- RF-discharge parameters strongly affect maximum polarization.
- Optimization of the $^3$He -cell geometry (smaller diameter?) and electrodes for RF input should improve polarization.

# The Path Forward

- We have concluded that the high field optical pumping clearly offers the best path forward to realize a polarized $^3He$ ion source for RHIC
  - high nuclear polarization of atom
  - high degree of confidence that atom polarization is preserved in injection process
- A plan to implement this in a test configuration has been developed.
- Further, an NMR system has been built to absolutely measure in a second, independent way the high field nuclear polarization. This work is in progress.

# Tandem EBIS Concept

- Increase the EBIS intensity by increasing the trap length, using a second solenoid on axis. (Ion output is proportional to trap length).
- Since the same electron beam passes through both magnets/ traps, fewer extra power supplies and controls are needed.
- Uses the same electron gun and electron collector as presently used.




**Tandem EBIS, proposed by A. Pikin (BNL) at HIAT 2012 conference.**

# Proposed Extended Trap EBIS

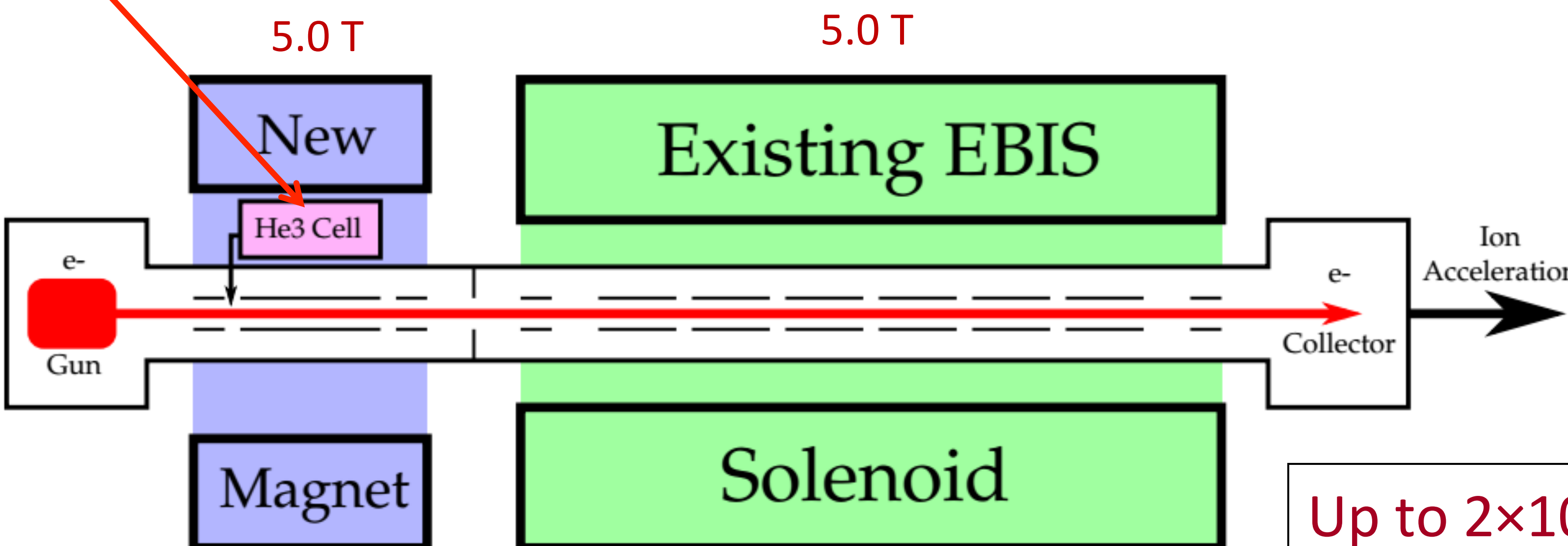
- This upgrade provides us an opportunity to incorporate features which will allow us to use the EBIS for optimal injection of polarized $^{3}He$ atoms.
- The design provides space in the bore to incorporate a polarizing cell at the beginning of the first coil.
- The design with a drift tube configuration in the first solenoid can be used as a "gas cell" region.
- This will benefit production of all gaseous beams – *e.g.* He4, 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).

# EBIS Upgrade with New Injector Solenoid for Polarized $^3He^{++}$ ion production

*BNL-MIT collaboration*

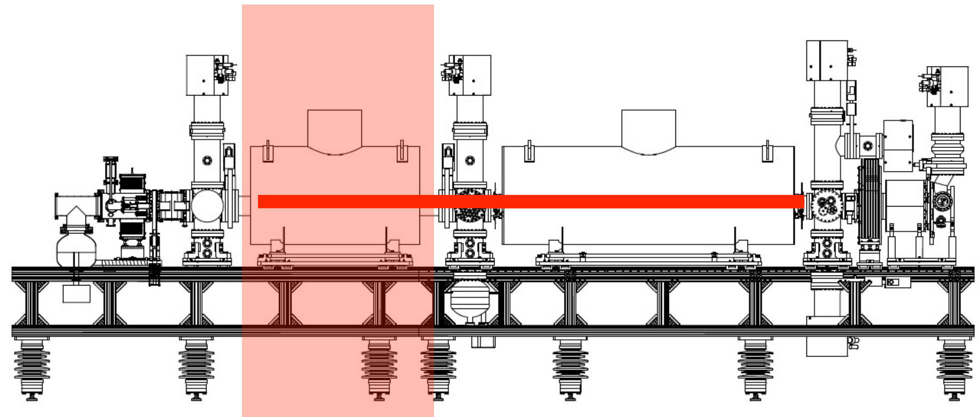
Optical pumping in High magnetic field

Polarization and ionization in high magnetic field will produce $^3He^{++}$ ion beam with $P \geq 80\%$




$^3He^+$ → Ionization to $^3He^{++}$ → Up to $2\times10^{11}$ $^3He^{++}$ ions/pulse

# Extended EBIS




- **Scope**
- Add superconducting solenoid for trap length extension, expect +40% Au intensity

- Early completion would shorten time for 2 highest energies in BES-II; also allows for next step in polarized $^{3}$He R&D

- **Cost and funding**

| FY2016 | 2017 | Total |
|---|---|---|
| $475k (P) | 1350k (P) | 1.8M |

- **Schedule**
- 2016 start (solenoid acquisition)
- 2020 planned completion

largest risk (cost, schedule and performance):
superconducting solenoid magnet

# Plan for EBIS upgrade for the Run-2019-20

- EBIS upgrade for higher heavy beams intensities and provisions for polarized $^{3}He^{++}$ ion beam.
- Second solenoid construction and spare solenoid upgrade in 2016-2017.
- At first upgraded EBIS will be used for the Gold run in 2019.
- Development of the $^{3}He$ source in 2016-2019.
- Polarized $^{3}He^{++}$ beam into RHIC of 2.0 x $10^{11}$ ions/pulse and 70 % polarization in 2020.

# Possible Schedule

**FY2016**

Superconducting magnet for trap length extension ordered

High field optical pumping measurements

Development of $^3He$ gas purification

**FY2017**

Superconducting magnet for EBIS extension delivered

Spare solenoid upgraded

NMR calibration of high field optical pumping measurements

Development of valve system and vacuum system

Design of feasibility experiment

**FY2018**

Construction of feasibility experiment

Design of RHIC $^3He$ polarimeter

**FY2019**

Upgraded EBIS used for Gold run

Completion of feasibility experiment

Construction of RHIC $^3He$ polarimeter

**FY2020**

Polarized $^3He^{++}$ beam of 2 x $10^{11}$ ions/pulse and 70% polarization in RHIC

# Summary

- The R&D effort has enabled development of key state-of-the-art MEOP technology at BNL and MIT.
- Studies of $^3$He spin transport in magnetic field gradients have been carried out and are well understood.
- High field optical pumping has been successfully developed. This was not anticipated at the beginning of this project.
- A tandem EBIS looks ideal for optimal $^3$He polarization delivery and a feasibility demonstration of a realistic source is being developed.
- This will require continued funding of the MIT effort as well as funds at BNL to configure the EBIS extended trap.
- We are on a path to have polarized $^3$He ions in RHIC early in the next decade.