3He⁺⁺ ion source development at RHIC

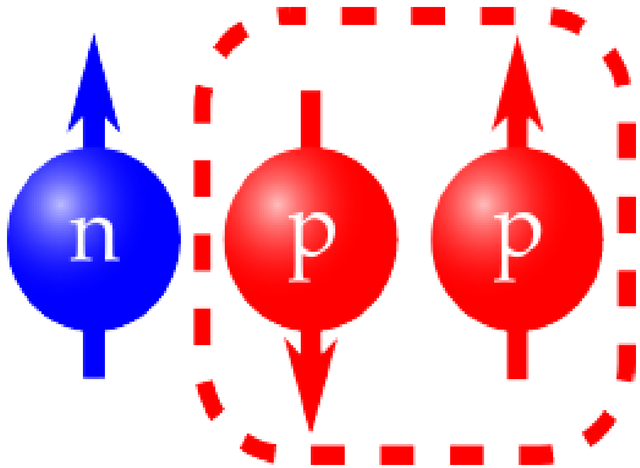
A.Zelenski, J.Alessi, E.Beebe, J.Ritter, A.Pikin,G.Atoian, BNL
J.Maxwell, R.Milner, LNS, MIT

$3He^{++}$ polarization technique using Electron Beam Ion Source

- 3He metastability-exchange polarization in the high magnetic field
- Optical pumping, polarization measurements.
- Sealed cell
- Open cell, gas purification system

Why a Polarized Helium 3 Source?

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



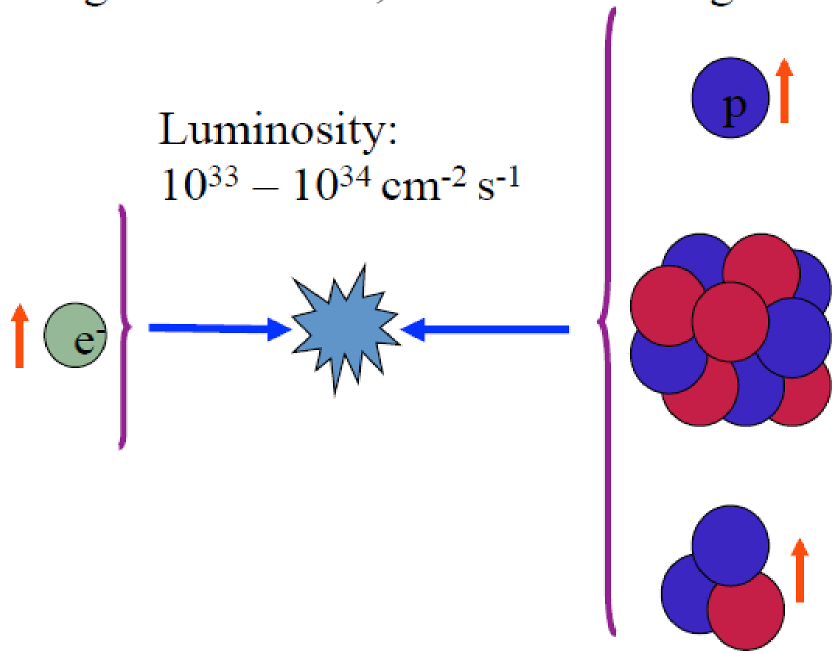
State	Probability
S	88.6%
S'	1.5%
D	8.4%

- 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 eRHIC

eRHIC: Electron Ion Collider at BNL

Add an electron accelerator to the existing $2.5B RHIC
including existing RHIC tunnel, detector buildings and cryo facility

80% polarized electrons:
2.6 – 21.2 GeV



70% polarized protons
25 - 250 (275*) GeV

Light ions (d, Si, Cu)
Heavy ions (Au, U)
10 - 100 (110*) GeV/u

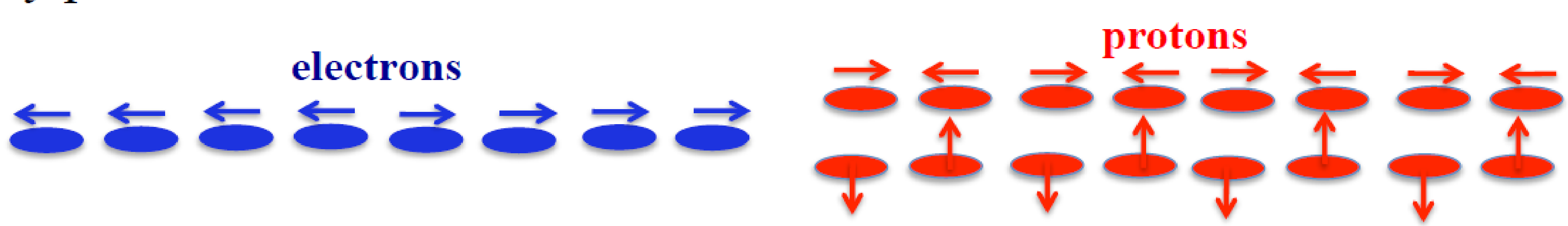
Pol. light ions (He-3)
17 - 167 (184*) GeV/u

Center-of-mass energy range: 20 – 145 GeV

Full electron polarization at all energies

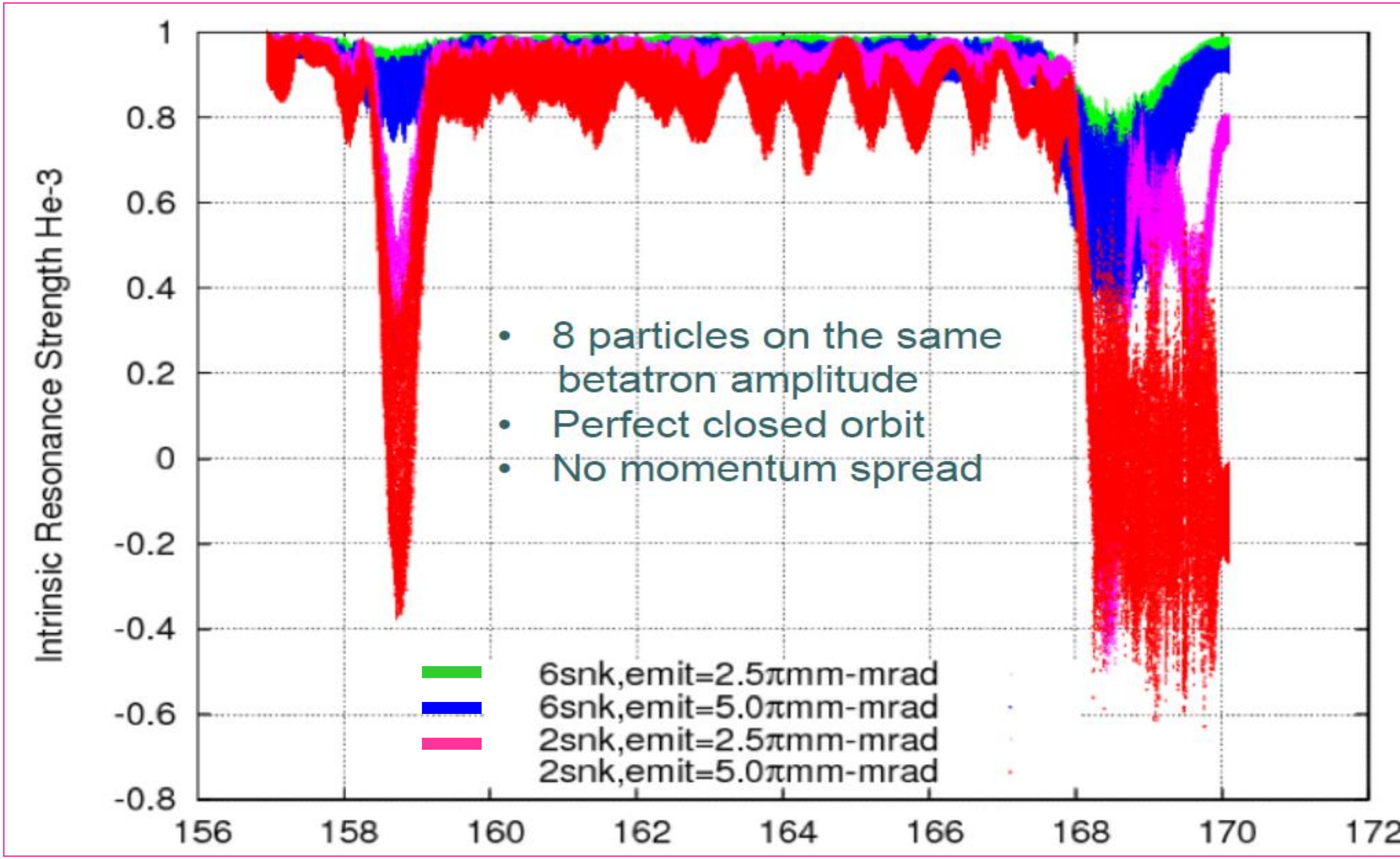
Full proton and He-3 polarization with six Siberian snakes

Any polarization direction in electron-hadron collisions:



* It is possible to increase RHIC ring energy by 10%

3He++ spin tracking in eRHIC with 6-snakes



Requirements to the $^3He^{++}$ source

- Intensity ~ $2\cdot10^{11}$ $^3He^{++}$ ions in 10 us pulse ~4.0 mA
- Maximum polarization > 80%
- Spin flip every pulse
- Compatibility with the operational EBIS for heavy ion physics

- Polarimetry ?

Polarized ^3He sources. Status 1984.

Source	Current	Polarization	Emittance	Beam Energy	Energy Spread	Ion
Birmingham	50 pnA	55-65%	70 mm mrad.	29 keV	100 eV	$^3He^{++}$
Laval	100 nA	95%	25 mm mrad.	12 keV		$^3He^{+}$
Rice/Texas A&M	8 μA	11%	10mm mr $MeV^{1/2}$	16 keV	10-50 eV	$^3He^{+}$

No new operational ^3He ion sources were built. A number of new ideas were proposed and tested (not successfully).

Spin-exchange and "metastability-exchange" techniques for ^3He atoms polarization were greatly improved due to laser development and demanding applications.

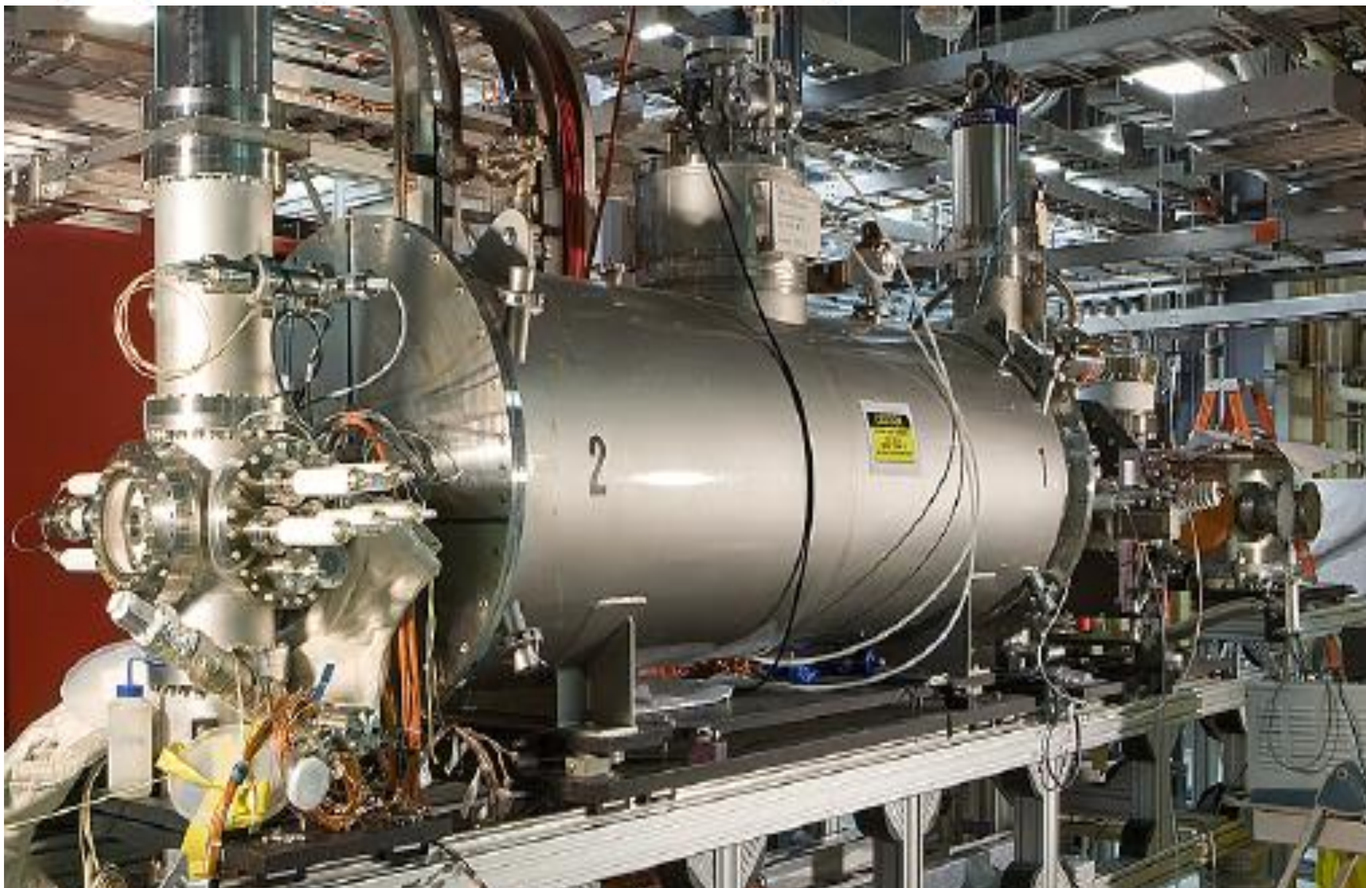
Production of polarized $^3He^{++}$ beam in EBIS.

A.Zelenski, J.Alessi, ICFA Beam Dynamics Edition Newsletter **30**, p.39, (2003)

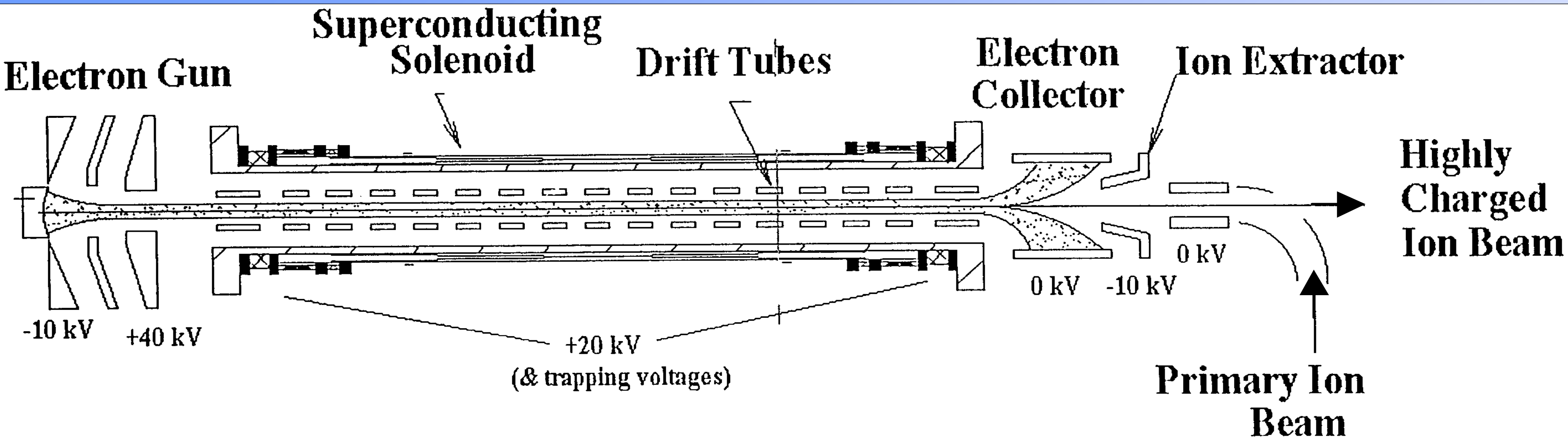
- Injections of ^3He gas polarized in the external cell into EBIS.
- ^3He polarization inside the EBIS in high magnetic field. No polarization losses during beam transport through gradient magnetic field.
- EBIS is used for efficient ionization and accumulation of polarized $3He^{++}$ ions

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



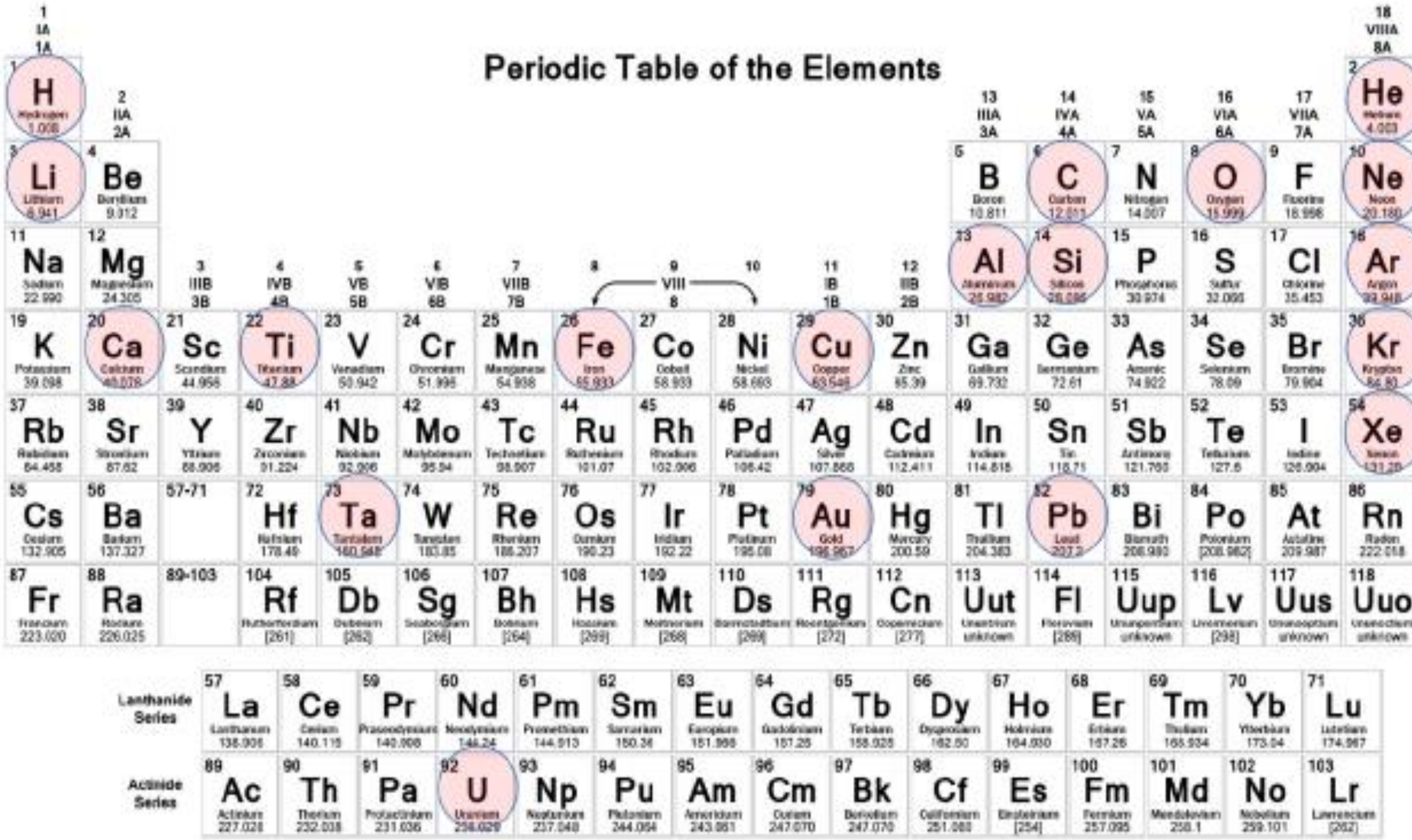
Principle of EBIS Operation



Radial trapping of ions by the space charge of the electron beam.
Axial trapping by applied electrostatic potentials at ends of trap.

- The total charge of ions extracted per pulse is ~ (0.5 – 0.8) x (# electrons in the trap)
- Ion output per pulse is proportional to the trap length and electron current.
- Ion charge state increases with increasing confinement time.
- Output current pulse is ~ independent of species or charge state!

EBIS Beams Run to Date

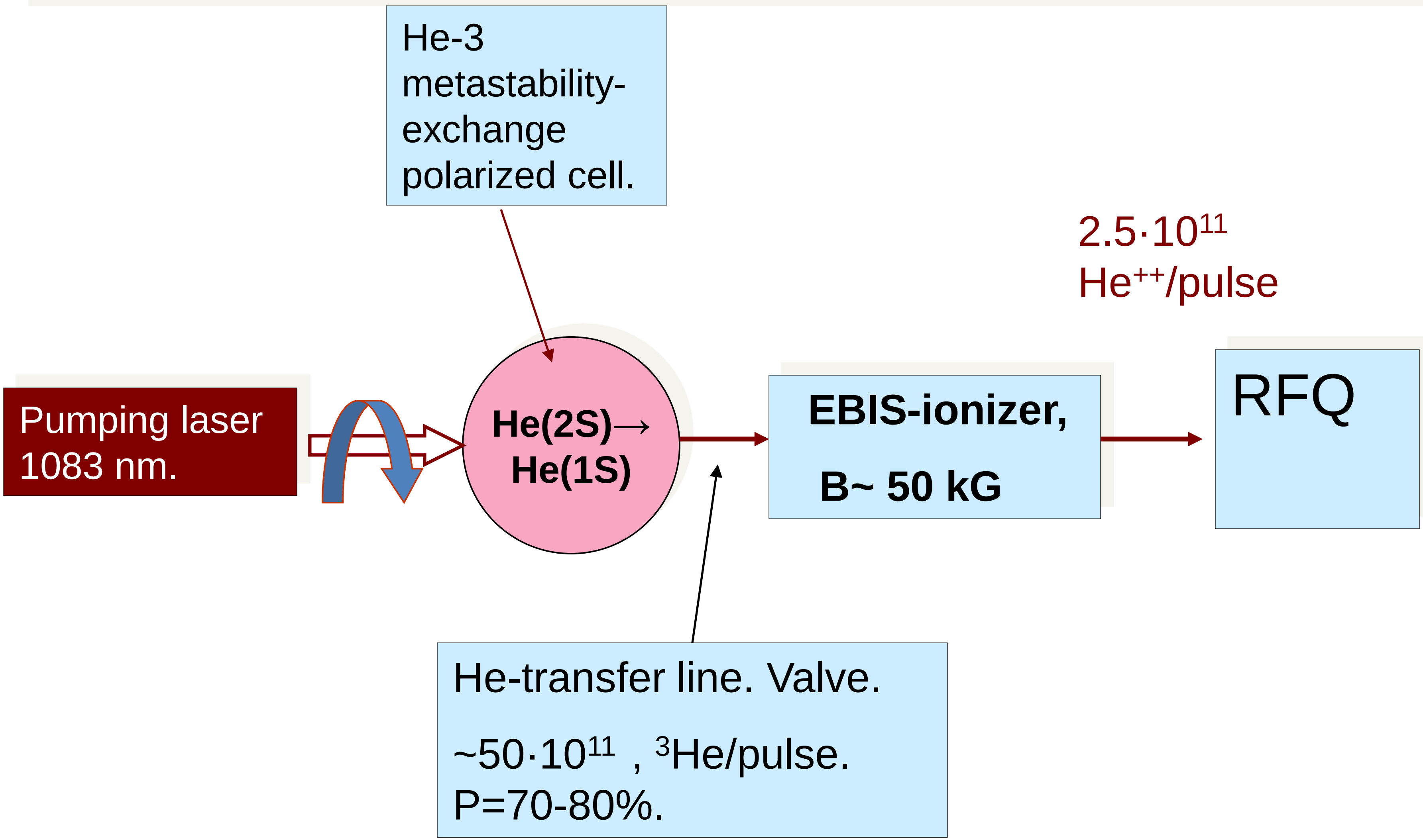


D, $^3He^{2+}$, $^4He1^{+,2+}$, Li^{3+}, C^{5+}, O^{7+}, Ne^{5+}, Al^{5+}, Si^{11+}, Ar^{11+}, Ca^{14+}, Ti^{18+}, Fe^{20+}, Cu^{1+}, Kr^{18+}, Xe^{27+}, Ta^{38+}, Au^{32+}, Pb^{34+}, U^{39+}. Capable of $^3He \Rightarrow {}^3He^{++}$ at nearly 100%

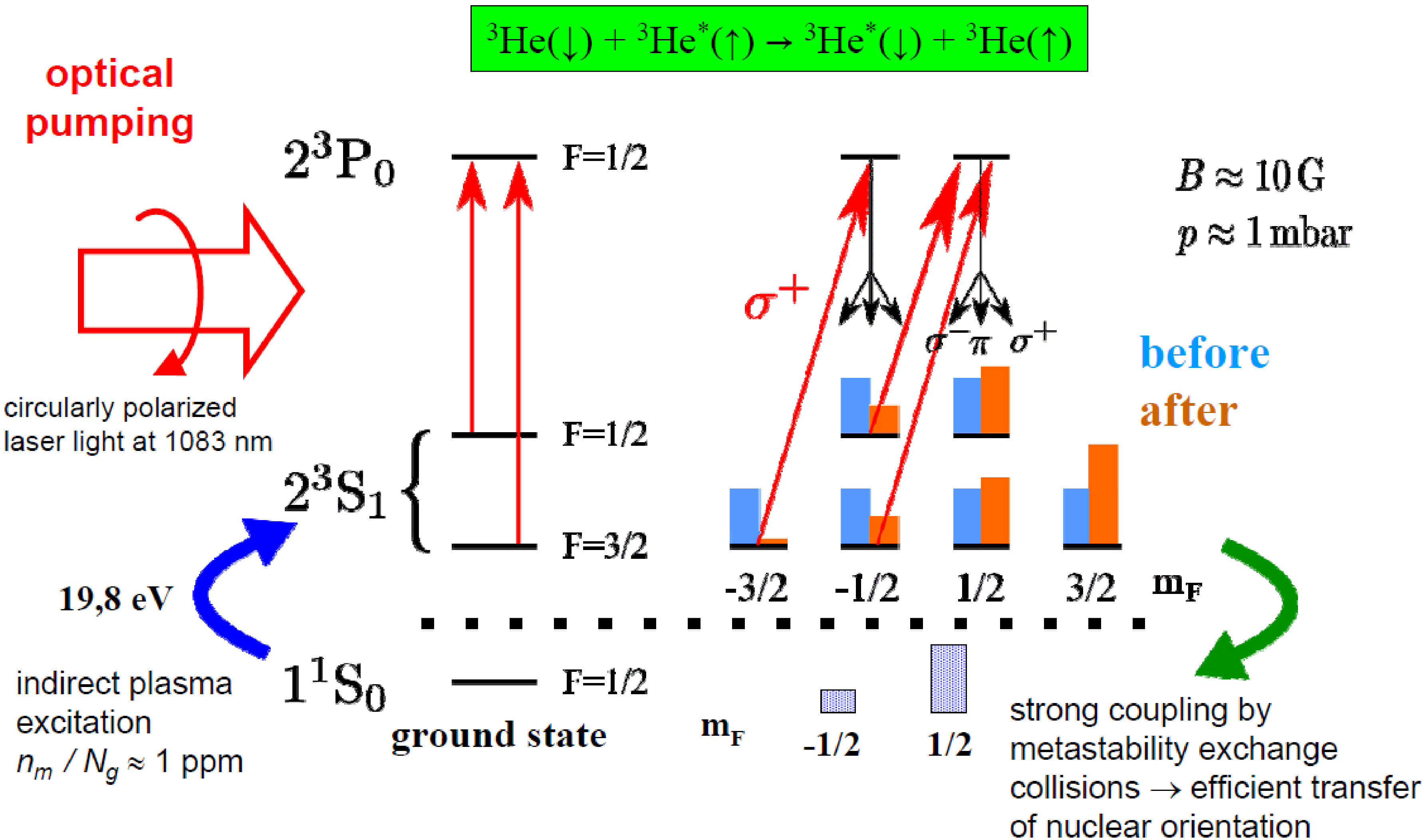
Production of polarized $^3He^{++}$ beam in EBIS.

A.Zelenski, J.Alessi, ICFA Beam Dynamics Edition

Newsletter **30**, p.39, (2003)



Principle of Metastability Exchange Optical Pumping (MEOP) in ^3He



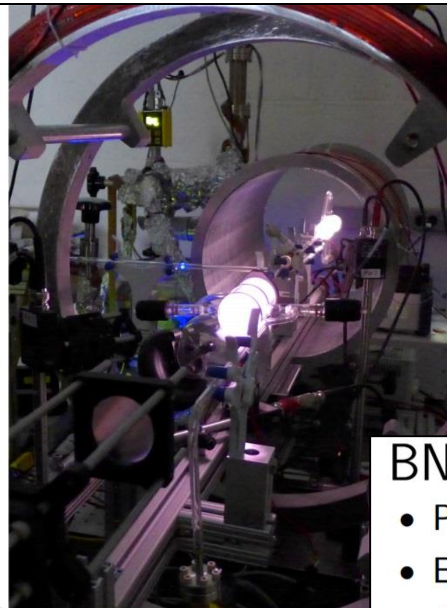
MIT-BNL collaboration on polarized $^3He^{++}$ ion source development

J.Maxwell, C.Epstein, R.Milner, MIT
J.Alessi, E.Beebe, A.Pikin, J.Ritter
G.Atoian, A.Zelenski, BNL

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
- Test bed for polarization, transfer and data acquisition
- Discharge and optical probe polarimeter development[5]

[5]Maxwell, Epstein, Milner, NIM A (764), 2014.



BNL Test Polarizer

- Polarizer on movable stand
- EBIS 5 T spare solenoid
- Allows polarization at any location in the stray field
- Initial results from test at 1 T with sealed cell, max 50%
  - 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

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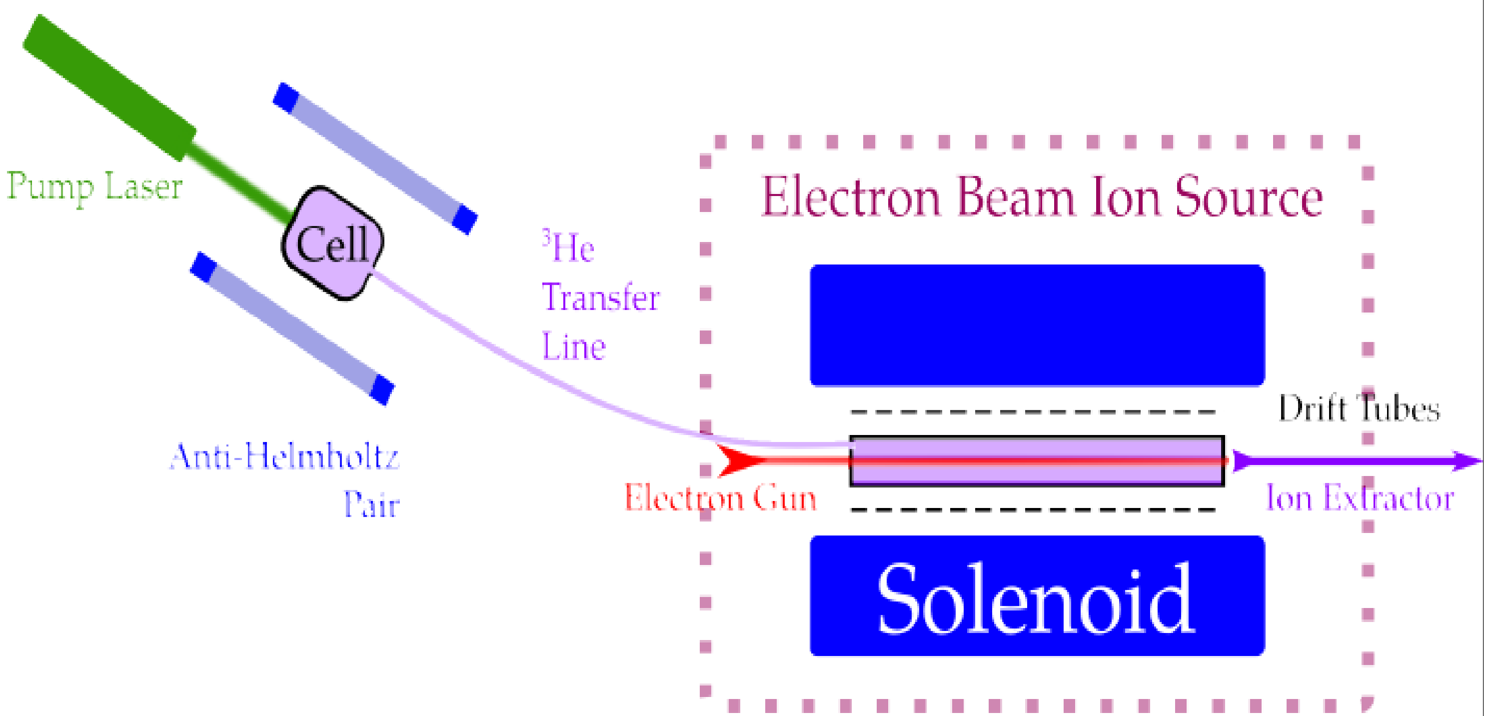
Injection of polarized 3He-gas in EBIS

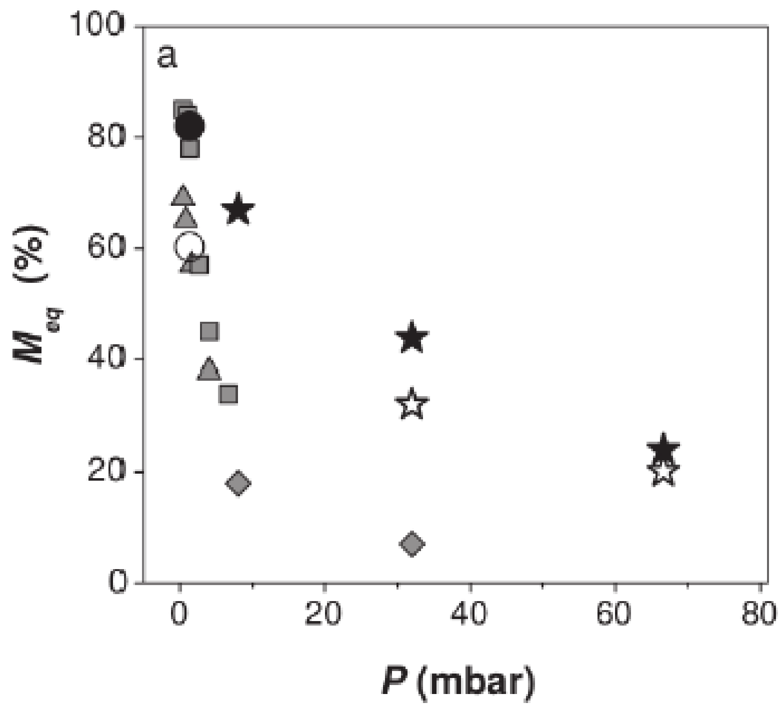
- Polarize to ~70% at 1 torr with 10 W laser
- Transfer ~10^{14} ^{3}He/s to EBIS at 5 T & 10^{-7} torr
- Deliver 1.5×10^{11} ^{3}He^{++} ions per 20 μsec pulse



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

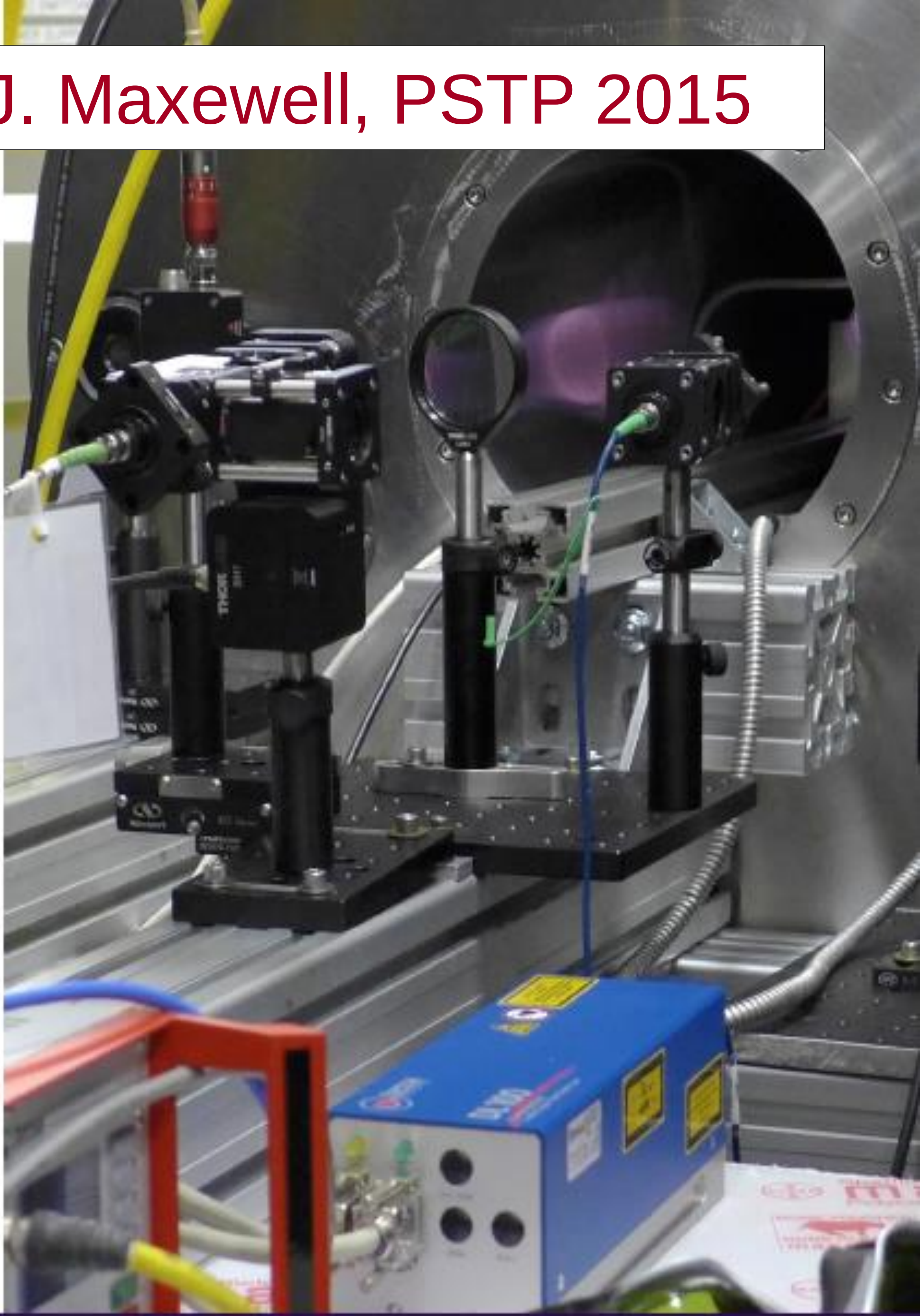
- M. Abboud, Europhys. Lett. 68, 2004
  - 1.5 T; 0.5, 2 W OP laser
  - 1.3, 8, 32, 67 mbar
  - Circles and stars are at 1.5 T, others at low field



BNL High Field Tests

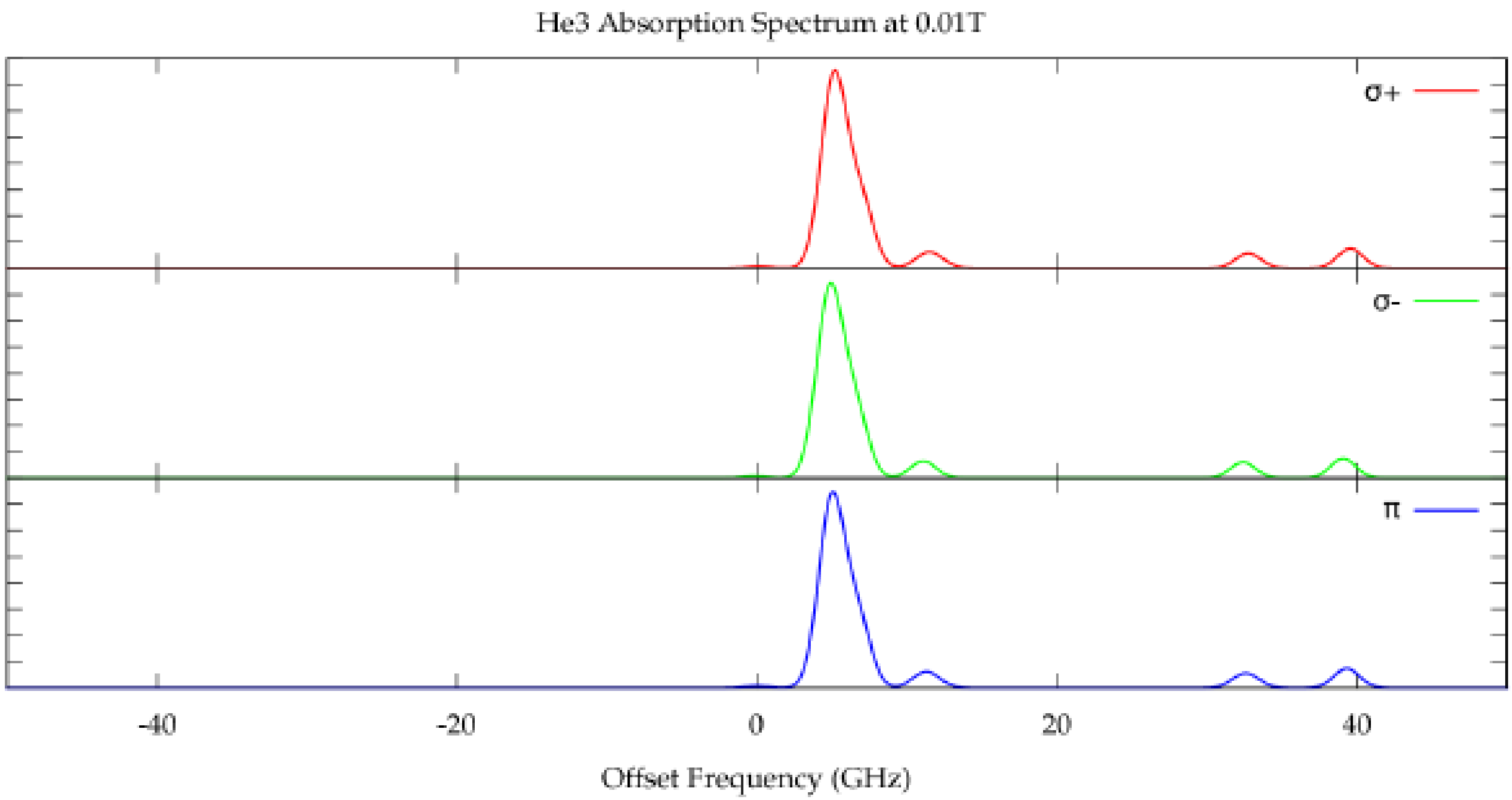
J. Maxwell, PSTP 2015

- 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



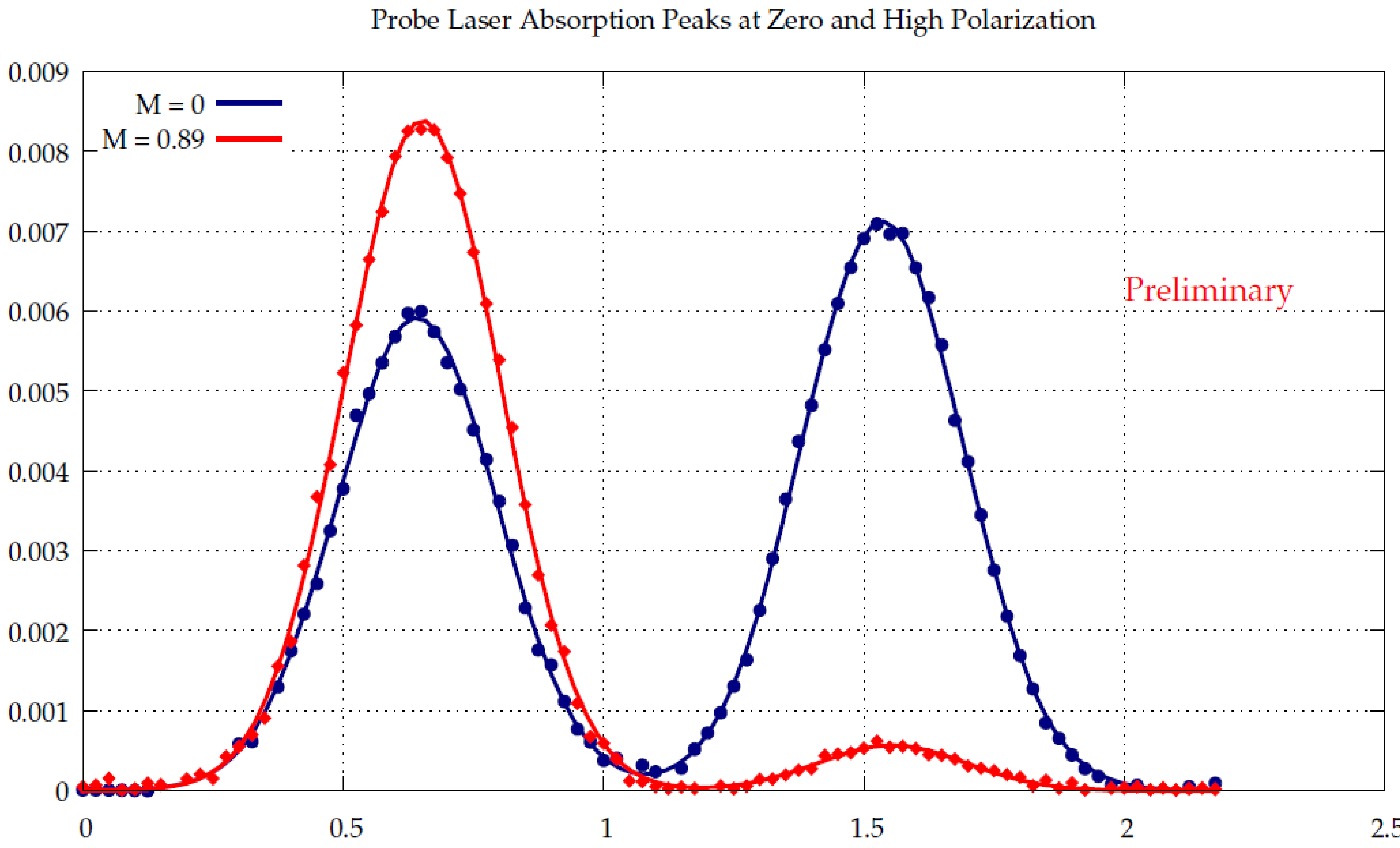
Optical Probe Polarimetry

- 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]

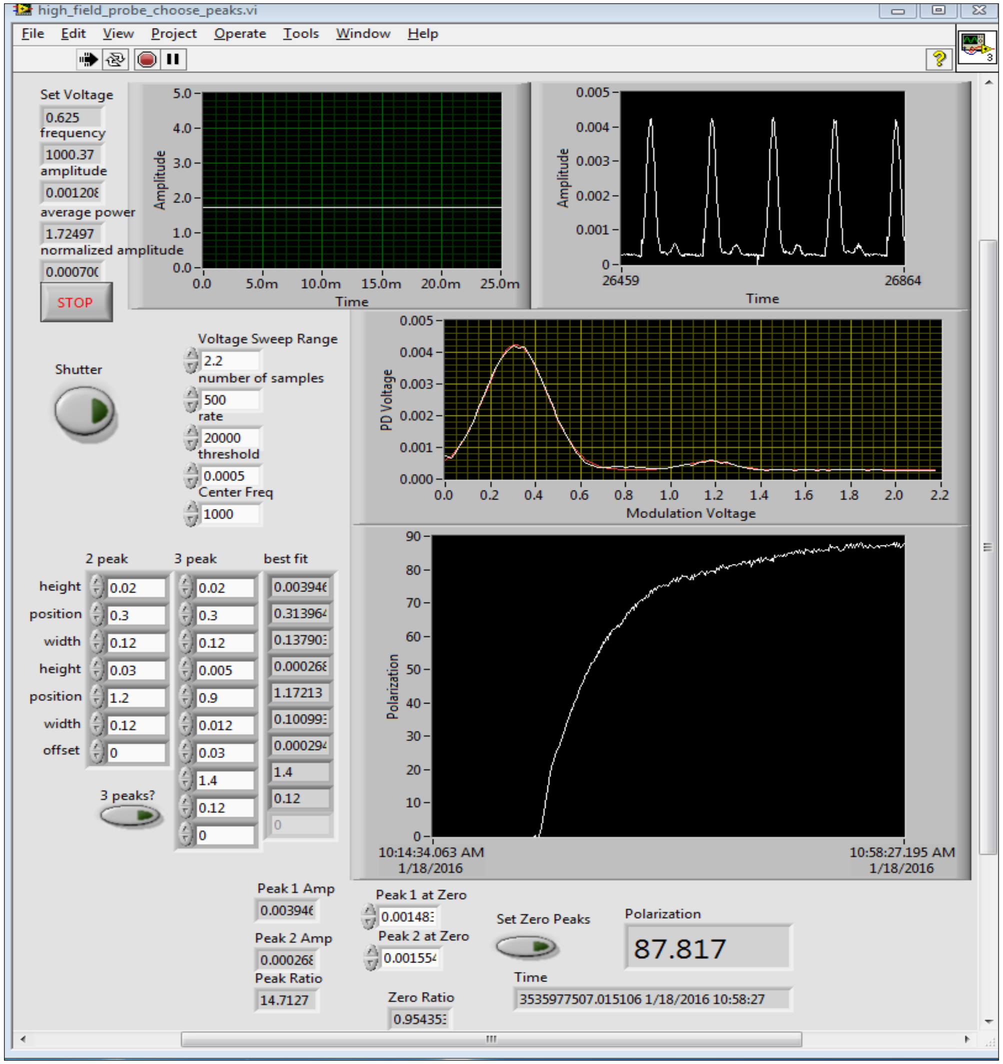


[8] Courtade *et al*, Eur. Phys. J. D 21 (2002).
[9] Suchanek *et al*, Eur. Phys. Special Topics 144 (2007).

Measuring Optical Pumping

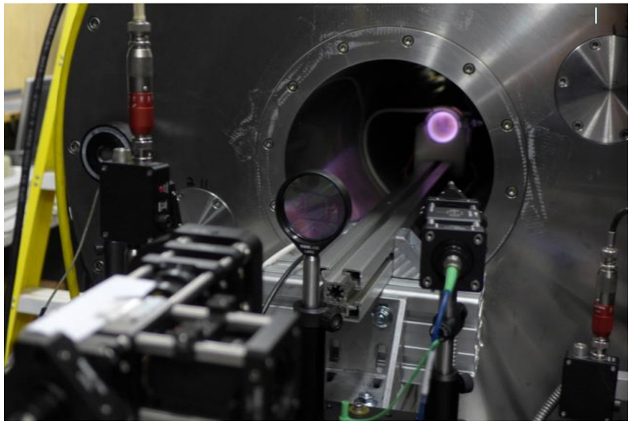


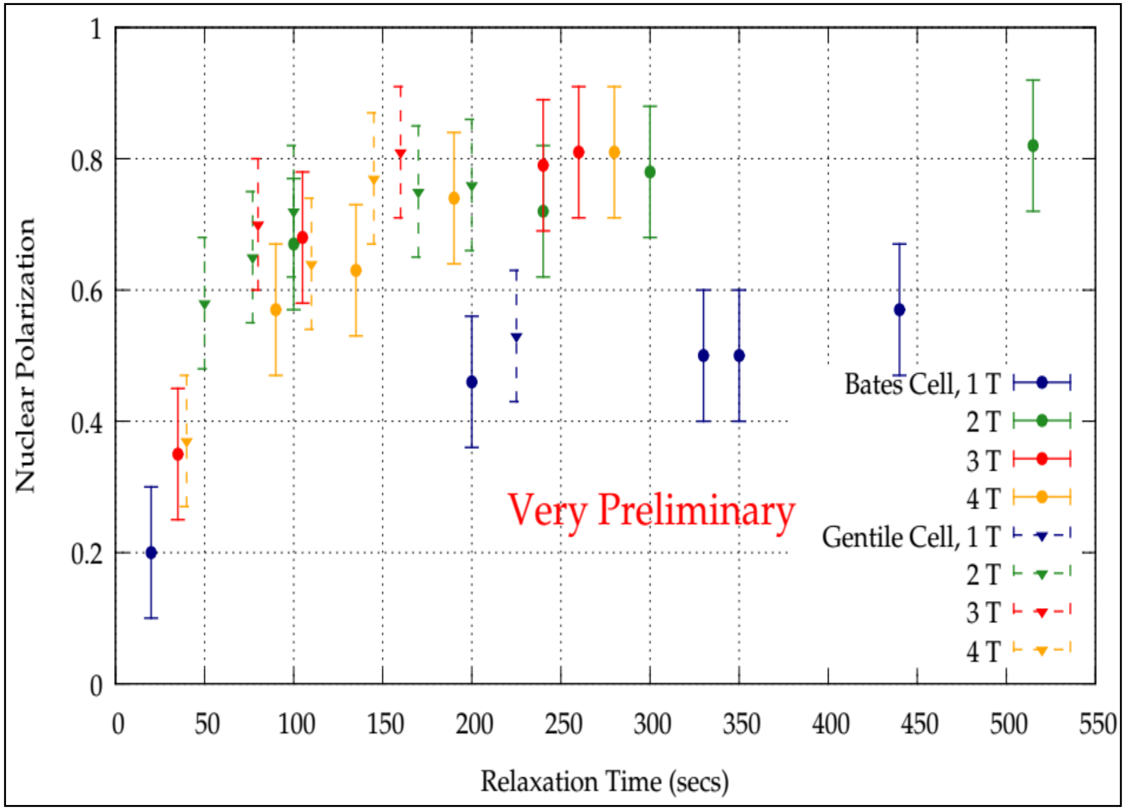
Jan18,2016, Sealed cell-Pol.- 88%



Probe laser absorption polarimer, J.Maxwell-2015

3He -polarization in high magnetic field using 5.0 T spare EBIS solenoid at BNL, 2015





80-84 % polarization was measured in experiments with sealed 3H-cell in high magnetic field.

High Field Conclusions Thus Far

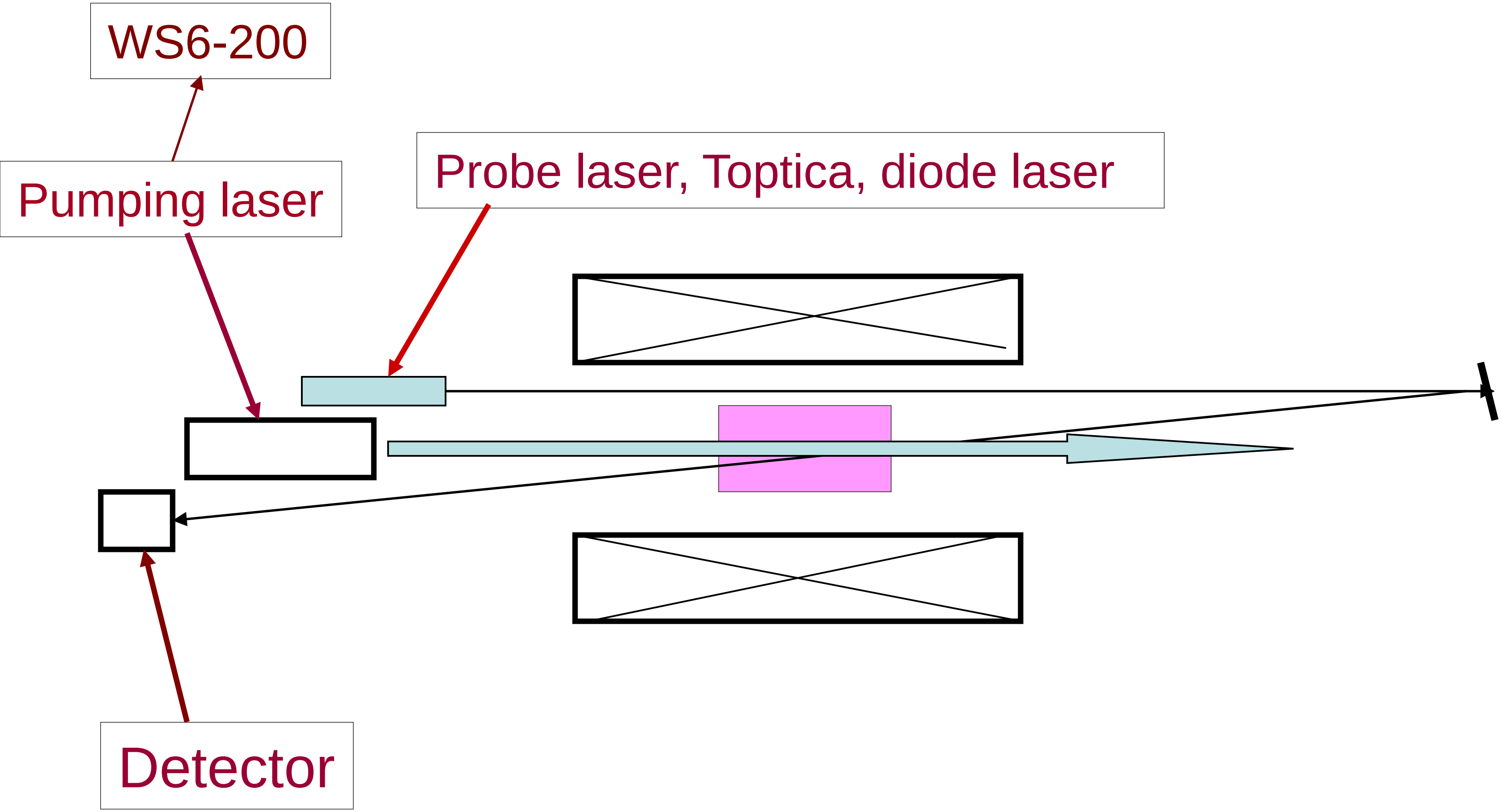
- First results for MEOP at 3, 4 T and 1 torr, to near 90%
  - With discharge off, $T_1 = 2.7$ hours
- Not only is this possible but it's easy!
  - Cell which we struggled to get to 70% at 30 G reach over 80% at high field
  - Field uniformity a given at high field

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

J. Maxewell, PSTP 2015

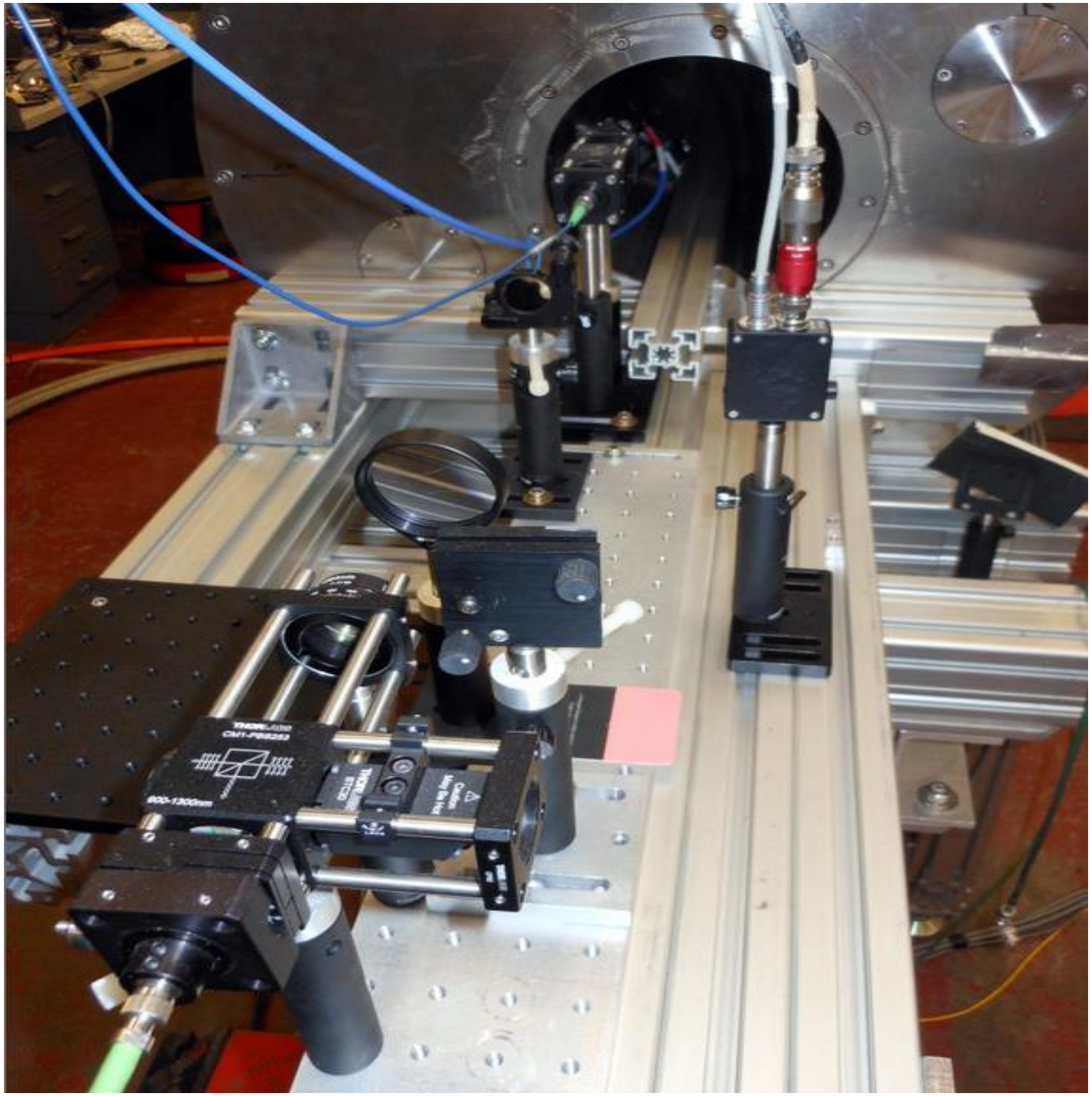
Optical pumping laser layout



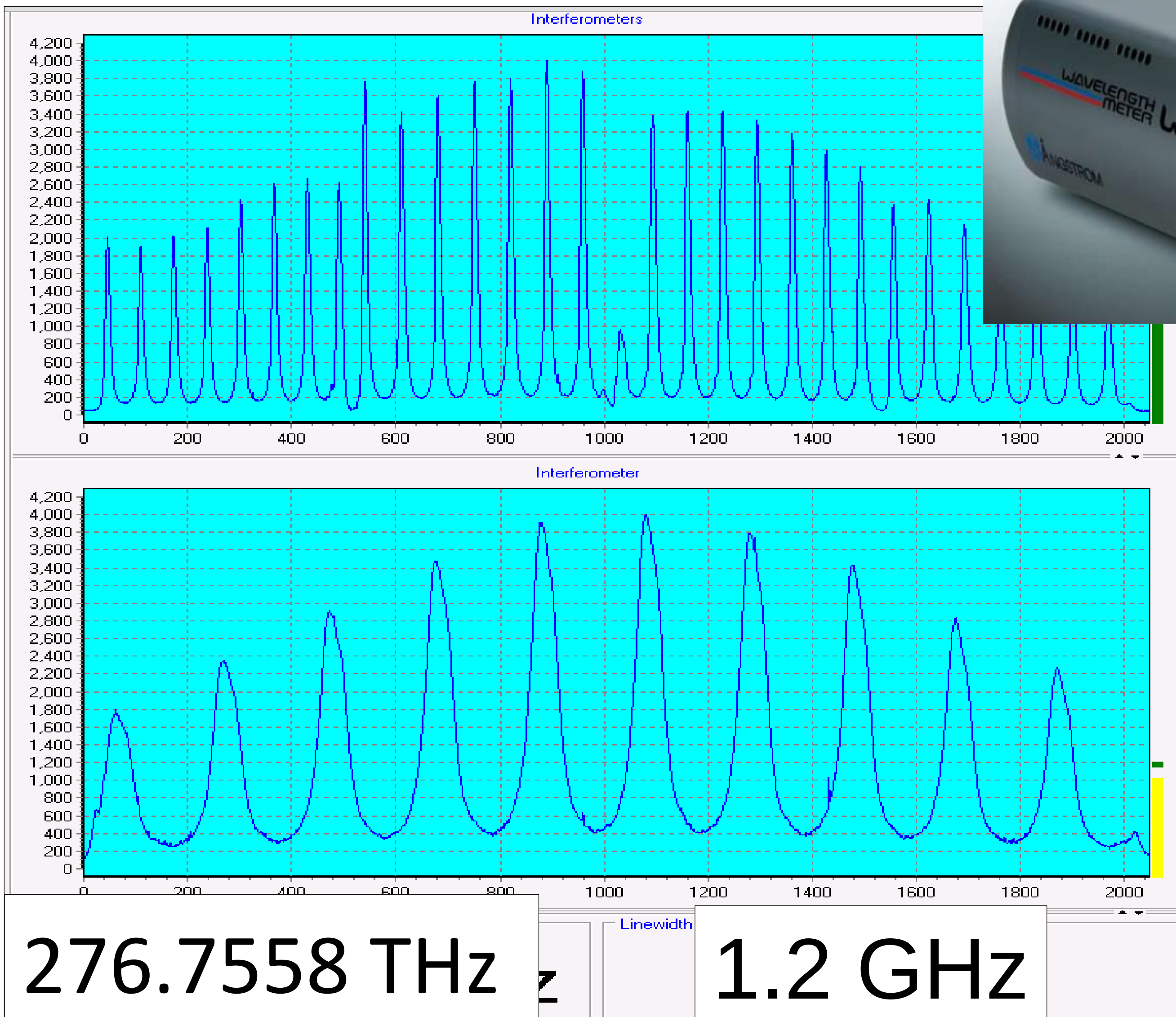
P
u
m
p
i

Pumping laser-Keopsys 10 W
1083 nm- fiber laser

3He Laser system for optical pumping and polarization measurements



Laser wavelength and Line-width control, with wavelength meter WS6-200

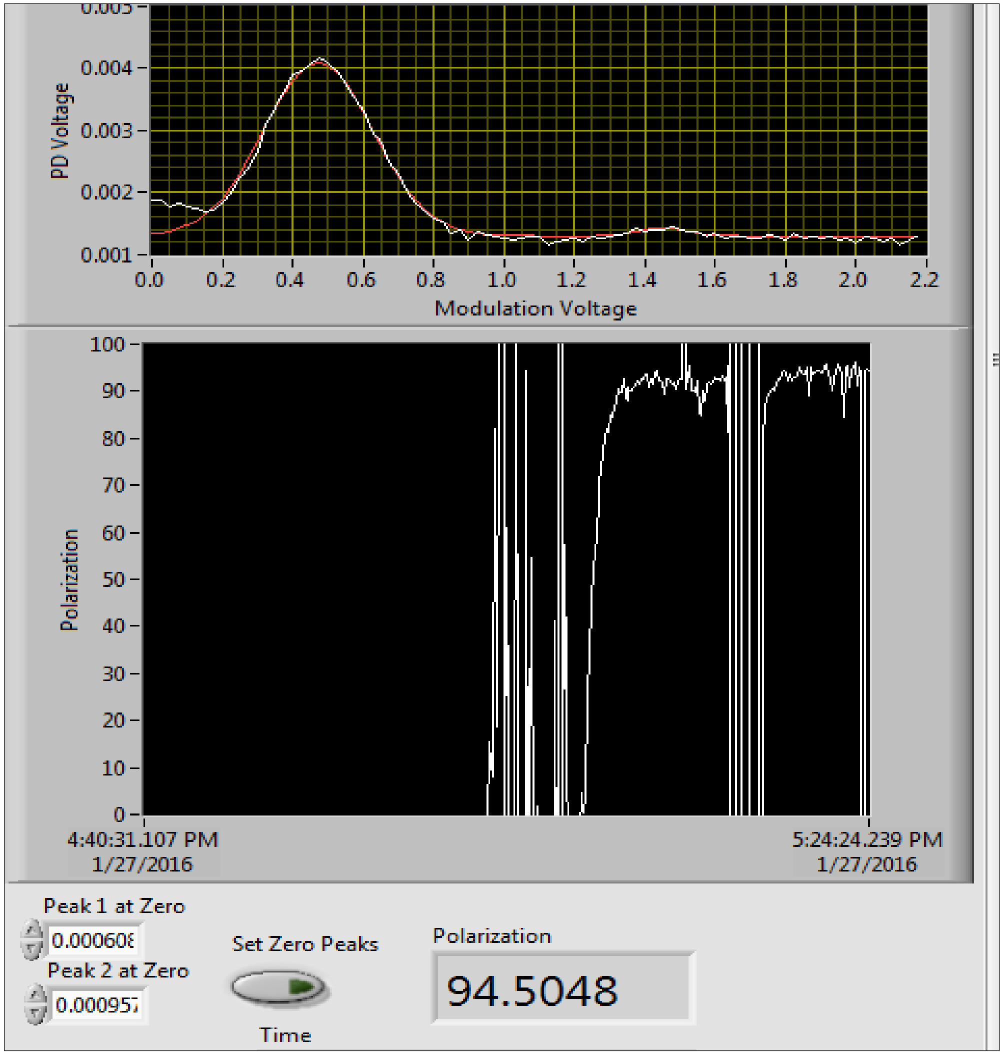


276.7558 THz

1.2 GHz

1083 nm

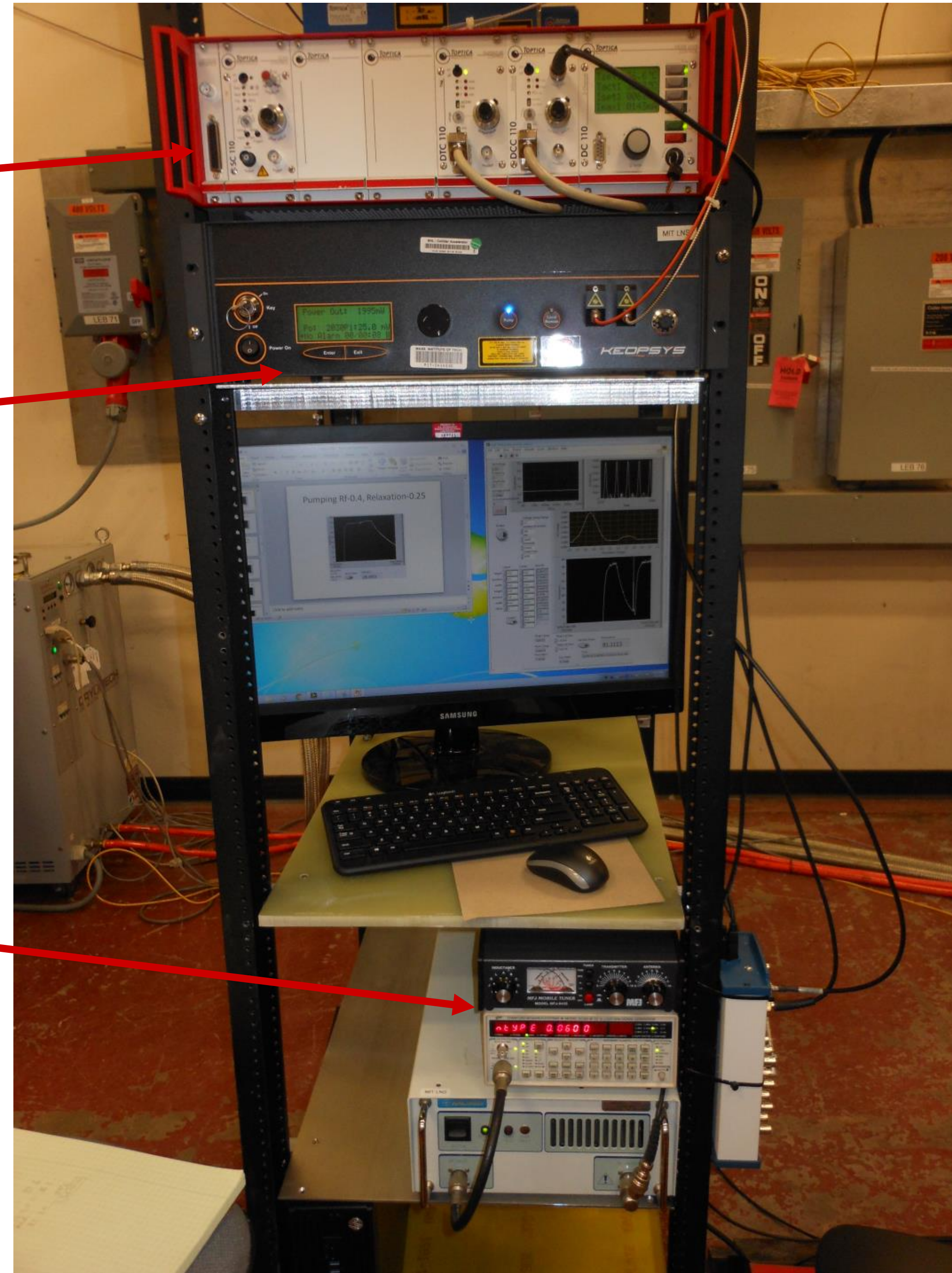
Jan18,2016, Sealed cell-Pol.- 94.5%,



Probe laser controller

Pumping laser controller

RF master oscillator and amplifier



High Field Conclusions Thus Far

- First results for … o near 90%
  - With discha…
- Not only is this …
  - Cell which w… 0 G reach over 80% at…
  - Field unifor…

High polarizations…

- At high field, O…
- Zeeman splitting reduces electron-nucleus spin coupling for polarization, but also inhibits relaxation channels (such as 668 nm line used for low field measurement)
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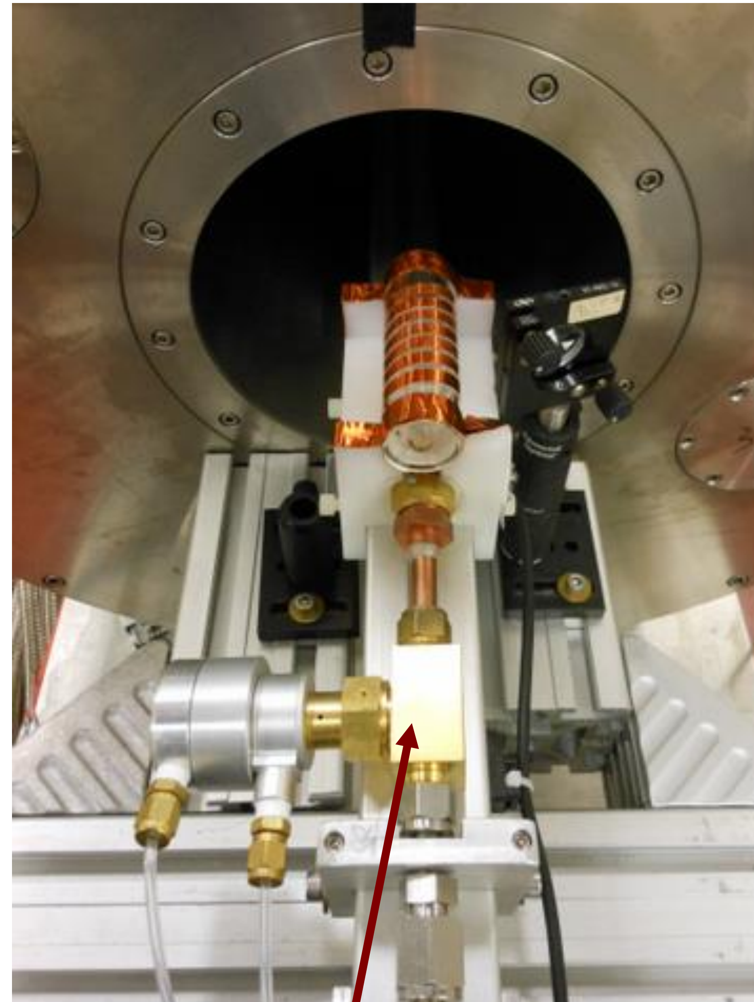
J. Maxewell, PSTP 2015

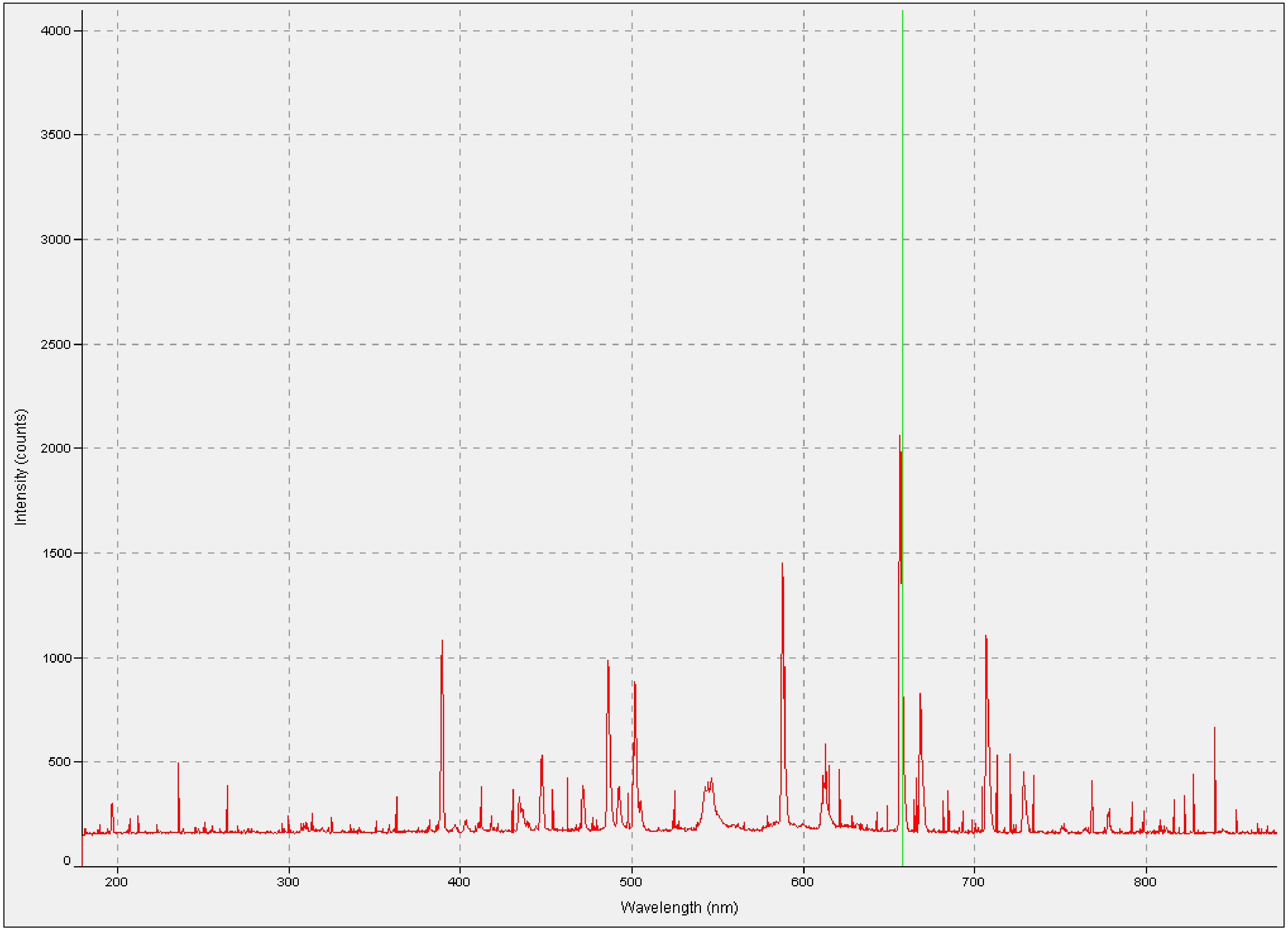
New “open” 3He-cell and gas system for 3He-cell preparation and filling

3He-gas purification and filling system

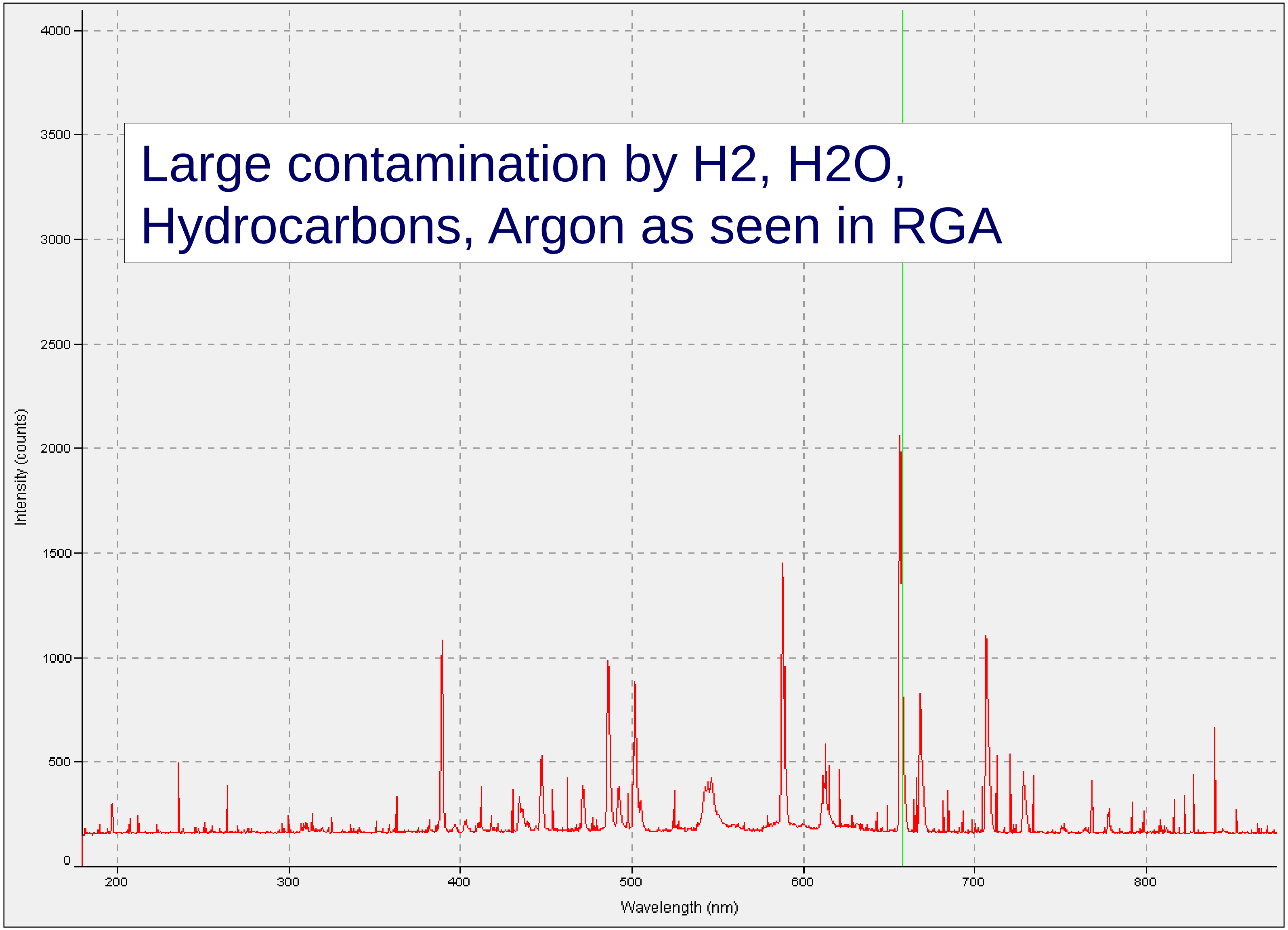


Non-magnetic pneumatic remotely controlled Isolation Valve: IV

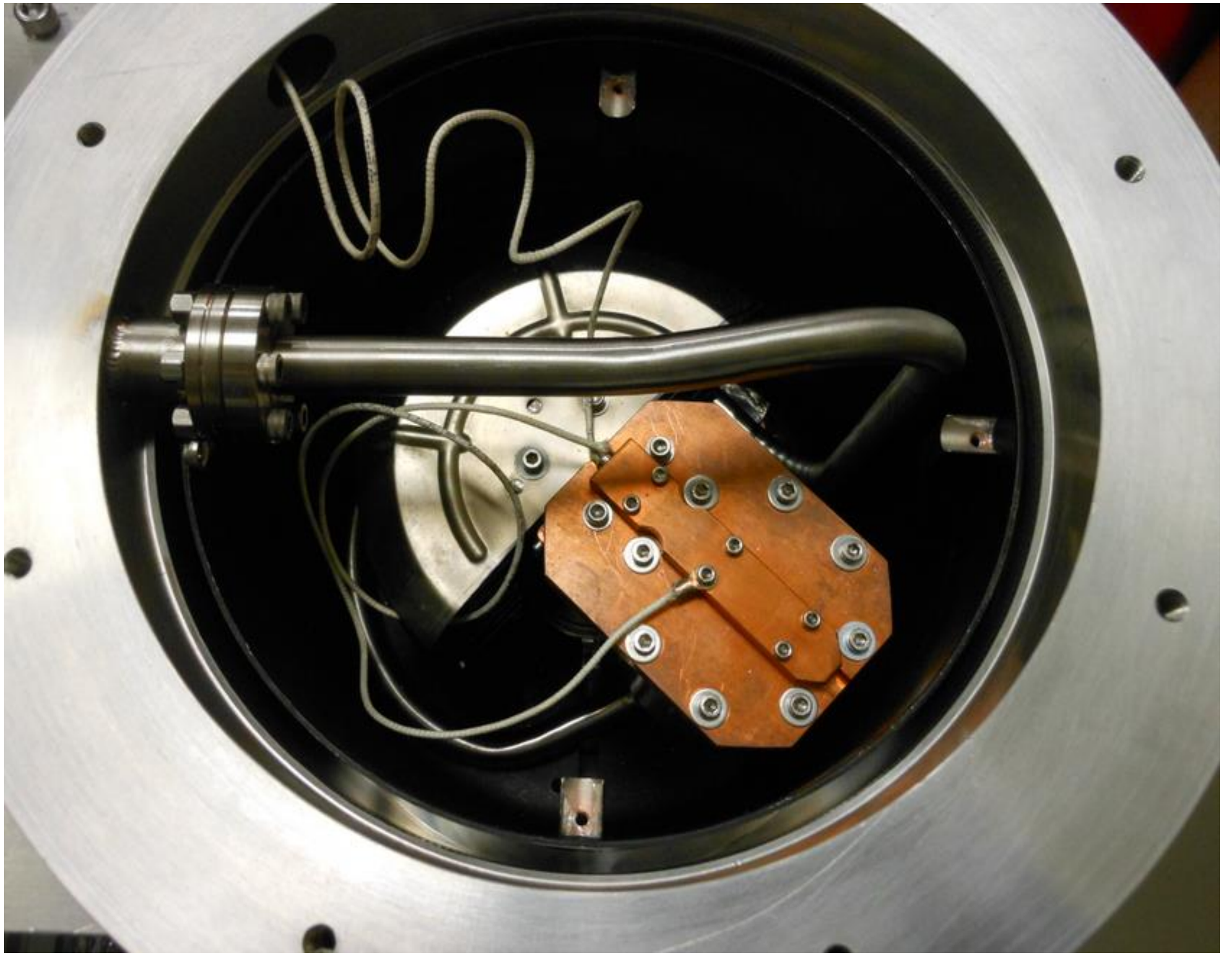
He-cell valve closed, RF-33.4 MHz, Amp-0.100, He-3-1.08 torr



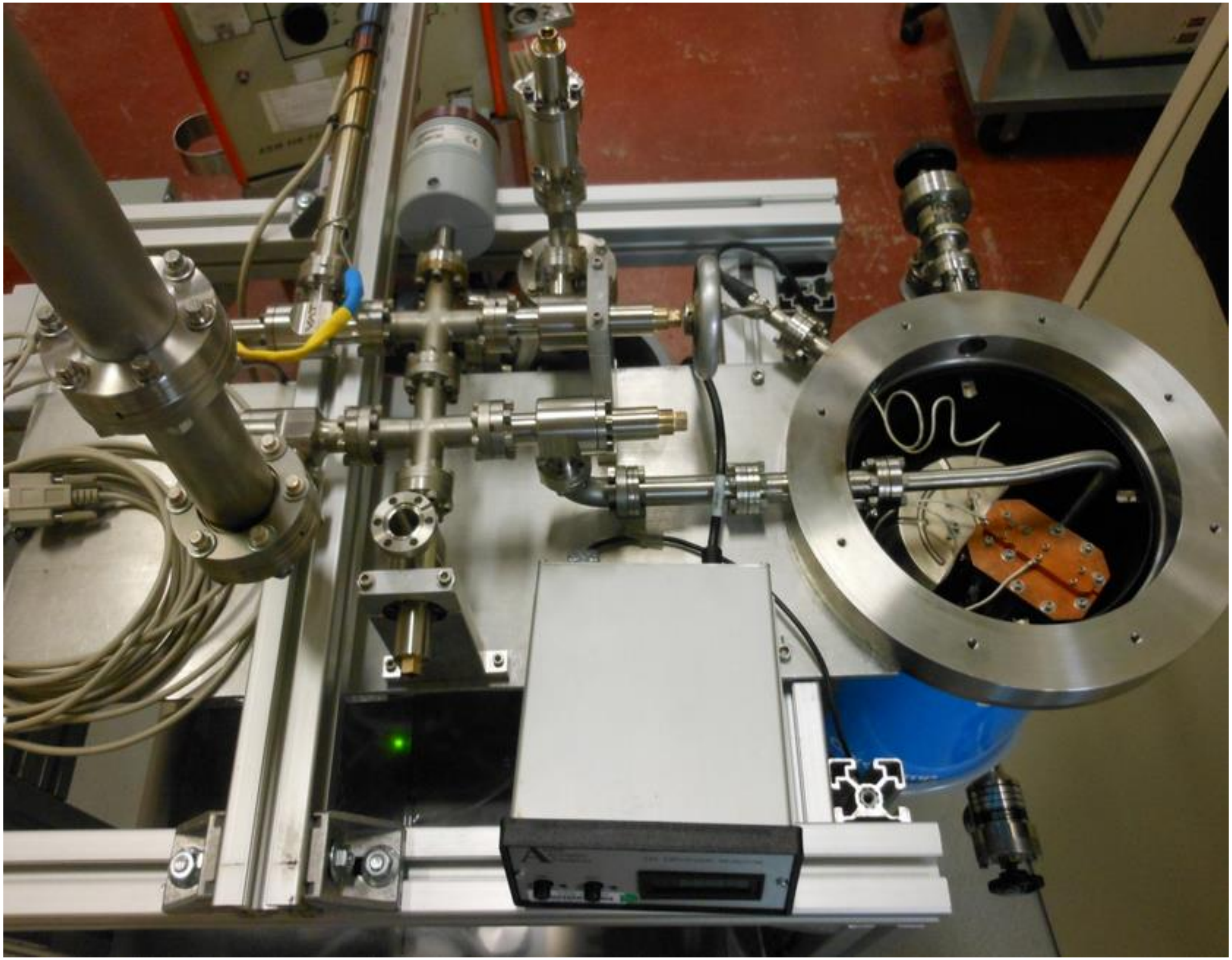
He-cell valve closed, RF-33.4 MHz, Amp-0.100, He-3-1.08 torr



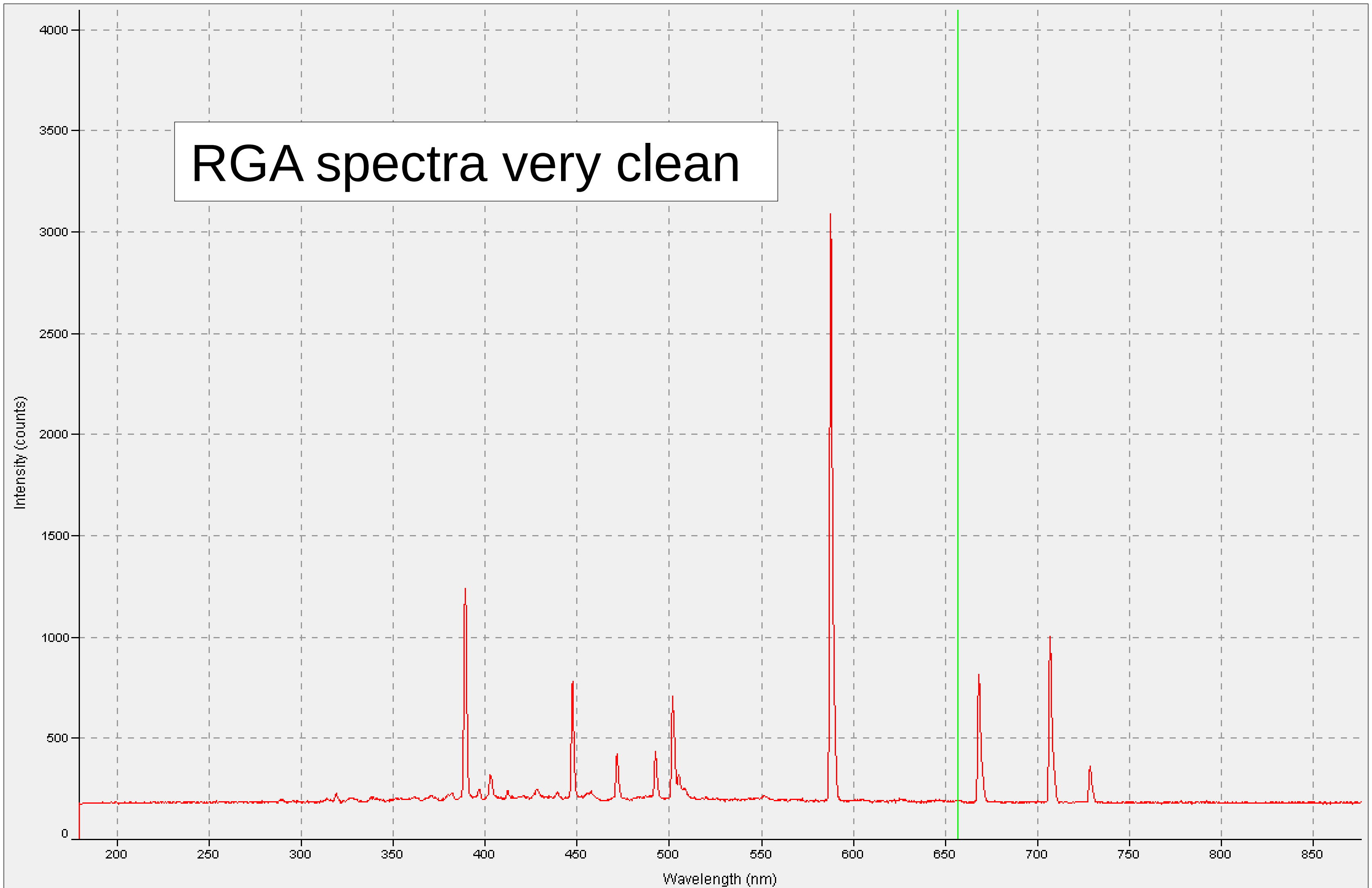
3He cryo- purification system built-in CTI-8 cryopump.

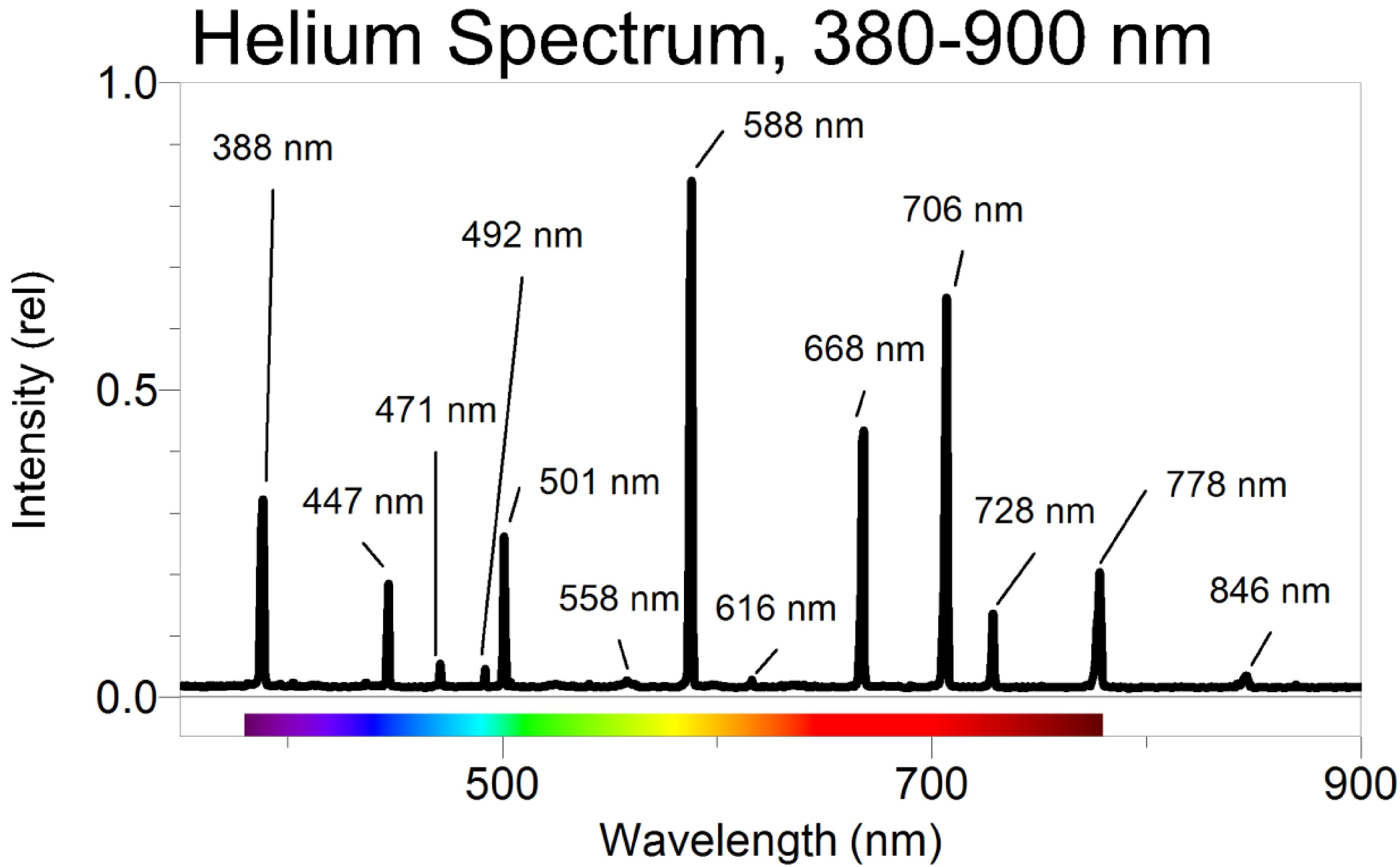


3He-gas purification and filling system

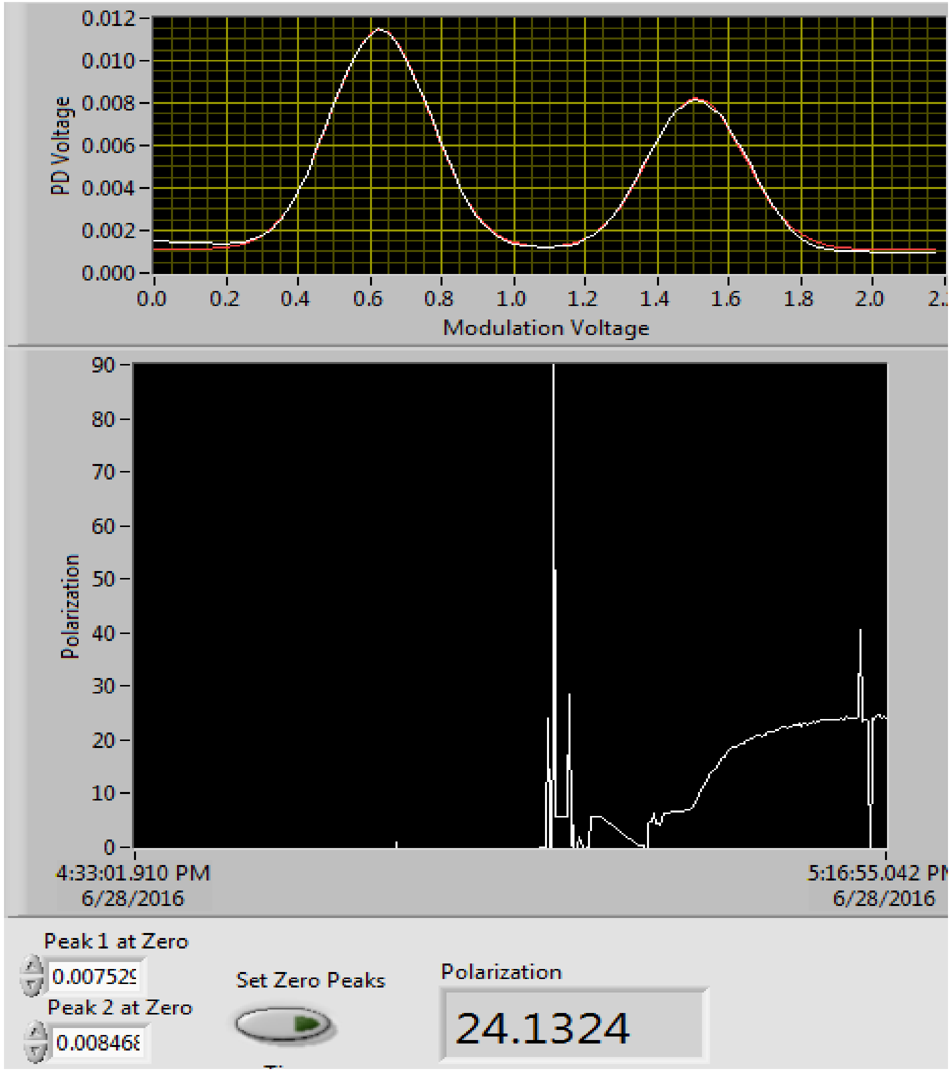


June 21, He-fill with CP-pumping at 45deg. K. Very clean spectra, no hydrogen 656 nm line!

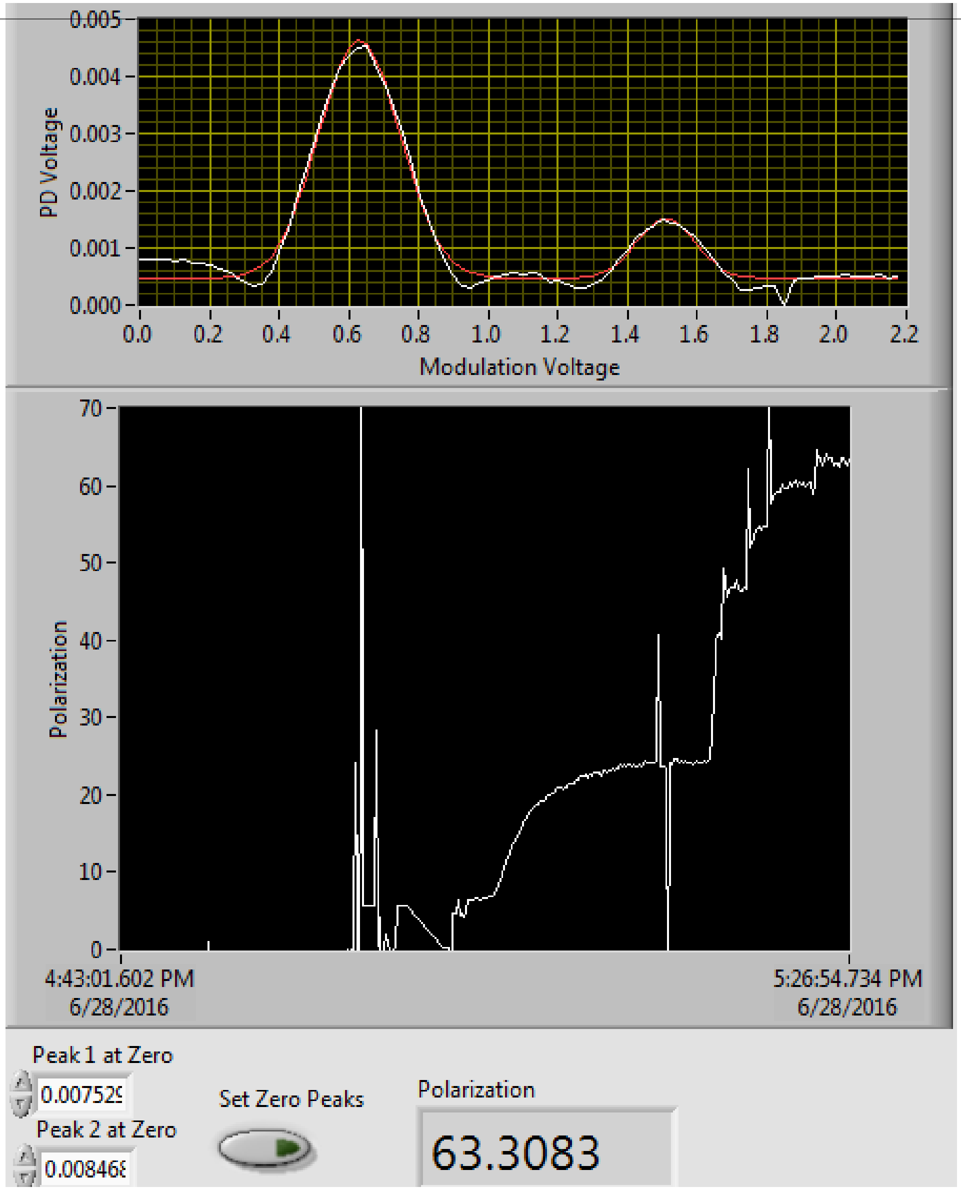



Helium Spectrum, 380-900 nm
1.0
0.5
0.0
Intensity (rel)
388 nm
447 nm
471 nm
492 nm
501 nm
558 nm
588 nm
616 nm
668 nm
706 nm
728 nm
778 nm
846 nm
500
700
900
Wavelength (nm)

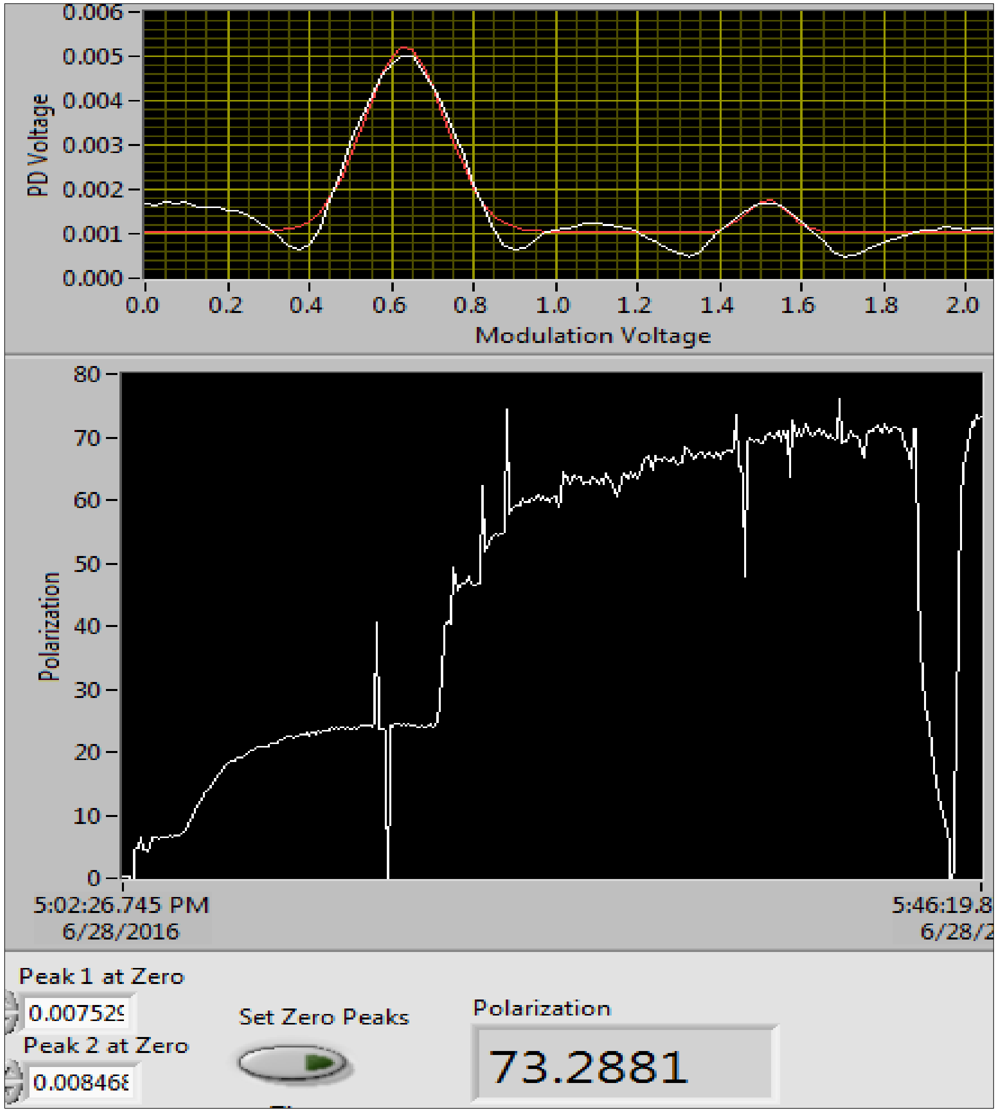
3.5 torr, Isolation Valve (IV)-open



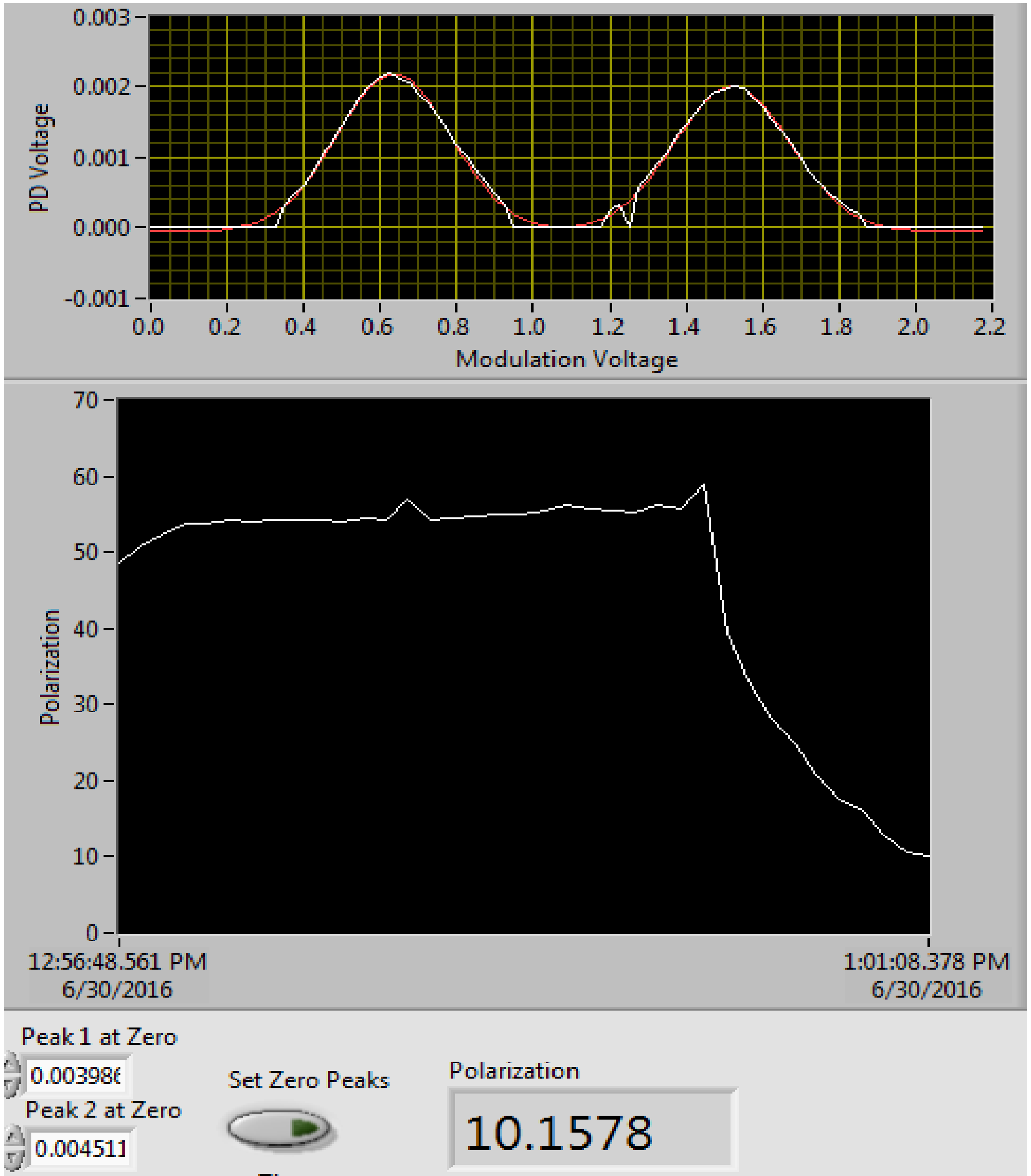
3.5 torr, Isolation Valve (IV)-closed, P=63%



“Open cell”, 3He-3.5 torr, Pol-73%



June 30, 3.0 torr, 56%, relaxation time -30 s



RF-discharge in 2.0 T magnetic field. 3He-cell diameter-25mm

RF-discharge parameters strongly affect maximum polarization.

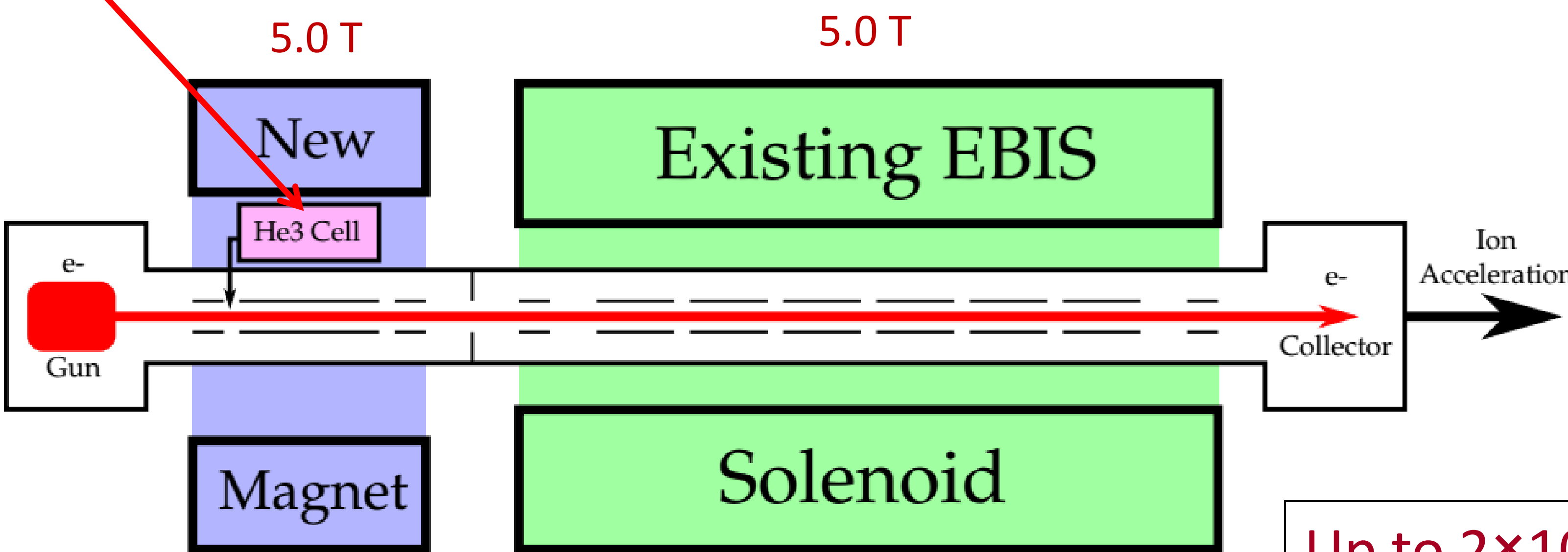
Optimization of the 3He -cell geometry (smaller diameter?) and electrodes for RF input should improve polarization.

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 2×10^{11} $^3He^{++}$ ions/pulse

Depolarization due to lower field in the gap between two solenoids.

- Critical field for $3He^{+}$ ions is 3.1 kG.
- Therefore, about 10 kG field is required at the point of second Ionization He^{+} to He^{++} to minimize depolarization.
- The design of solenoid with this high field in the gap is feasible.
- Due to reduced probability of ionization in the gap (low electron current density), this requirements can be somewhat relaxed.

Extended EBIS

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

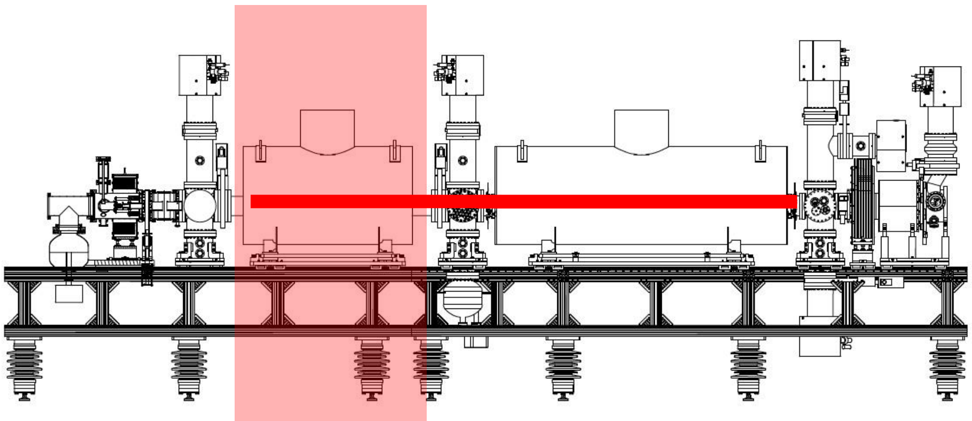
•(early completion would shorten time for 2 highest energies in BES-II; also allows for next step in polarized ^{3}He R&D)

•**Cost and funding**

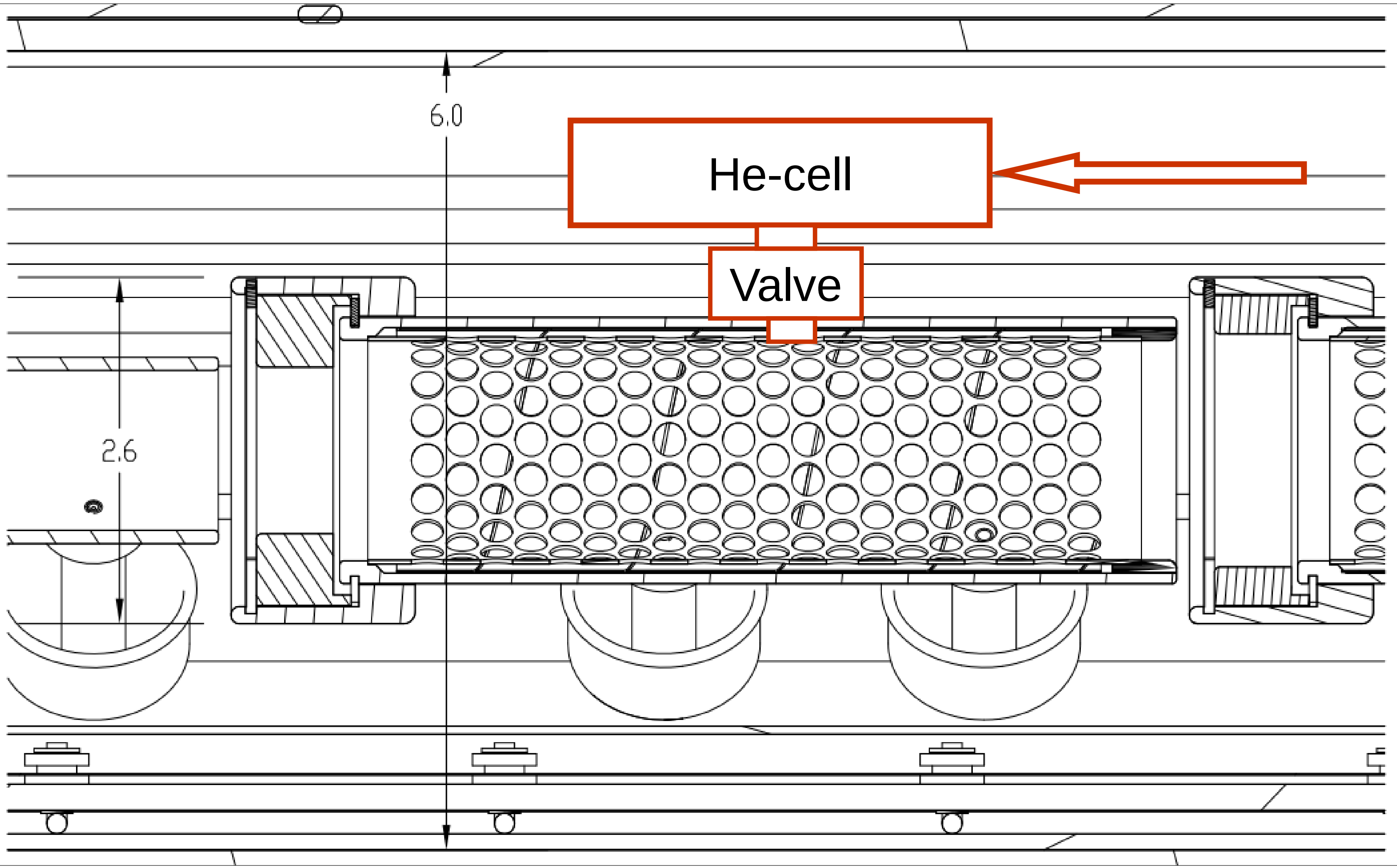
FY2016	2017	Total
$475k (P)	1350k (P)	1.8M

•

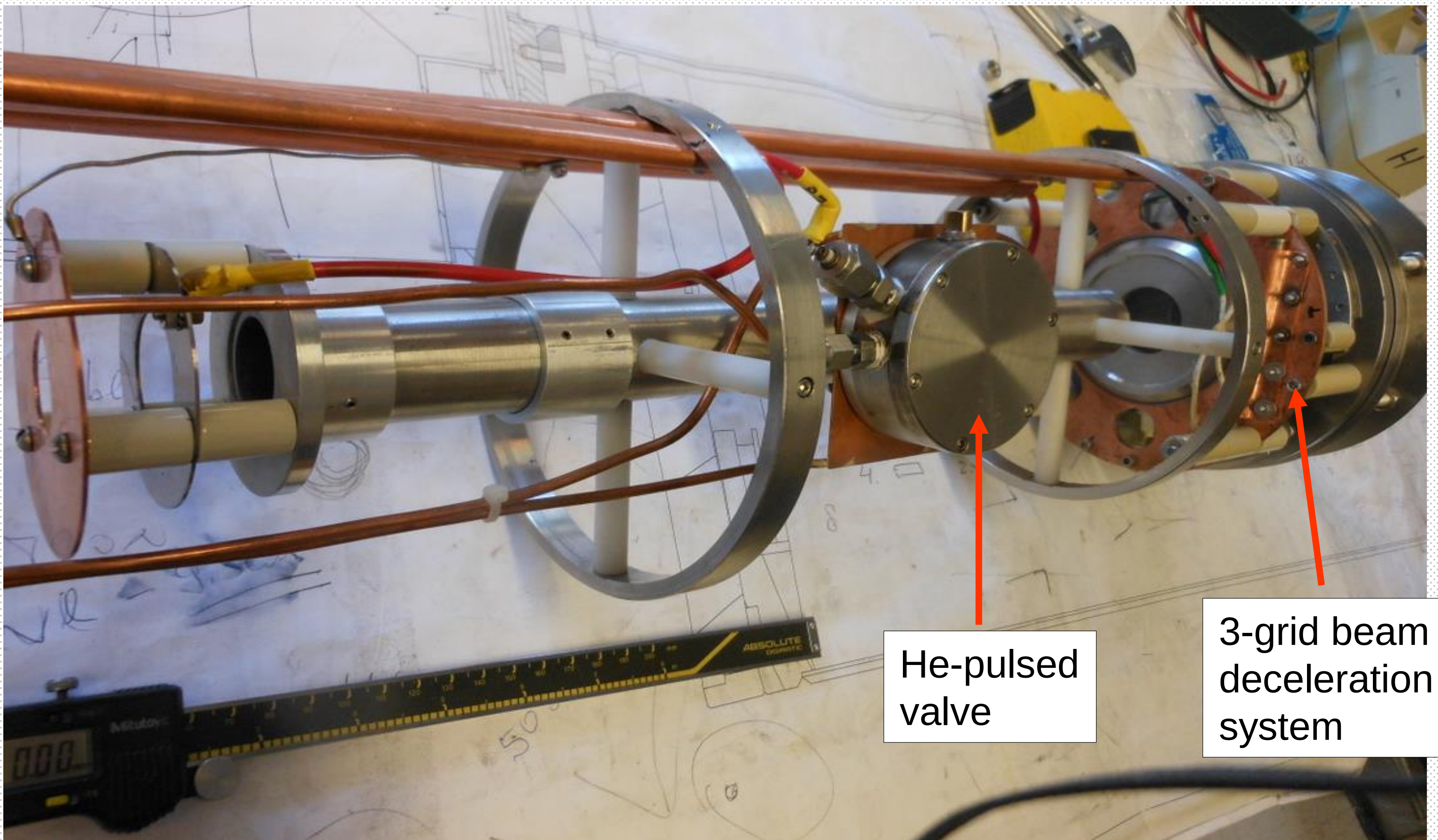
•**Schedule**
•2016 start (solenoid acquisition)
•2020 planned completion
largest risk (cost, schedule and performance): superconducting solenoid magnet



EBIS center drift tube

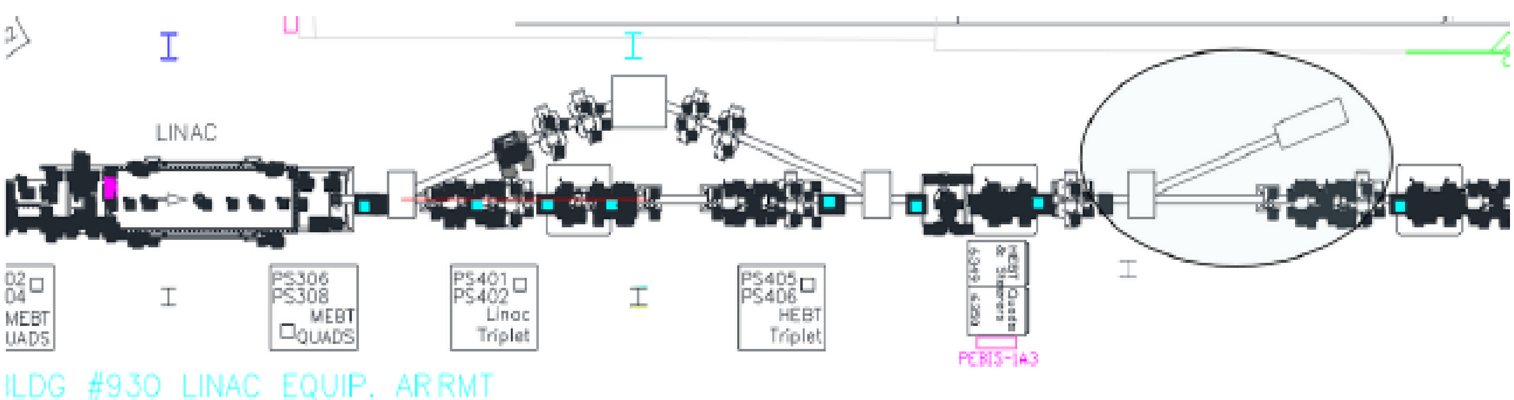


He-ionizer cell and three-grid energy separation system



5.3 MeV Helium3–Helium4 Polarimeter

- Transverse polarized ^{3}He beam on unpolarized ^{4}He at 5 torr[10], early design by C. Epstein
- At 5.3 MeV, asymmetry due to polarization goes to 1 at 91° center of mass $\rightarrow$ ^{3}He at 53.6°and 2.66 MeV
- Recoil ^{4}He as a background at 1.83 MeV, so use 500 μm partially depleted silicon detector for energy resolution
- At 50% polarization, expect 3.7% accuracy in 1 minute



[10] G.R. Plattner, A.D. Bacher. Physics Letters B 36.3 (1971)

Plan for EBIS upgrade for the Run-2019-20

- EBIS upgrade for higher heavy beams intensities and provisions for polarized $3He^{++}$ 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 3He part in 2016-1018.
- Polarized $3He^{++}$ beam of 2.0*10^11 ions/pulse and 80 % polarization in 2020