

$^3\text{He}^{++}$ ion source development at RHIC

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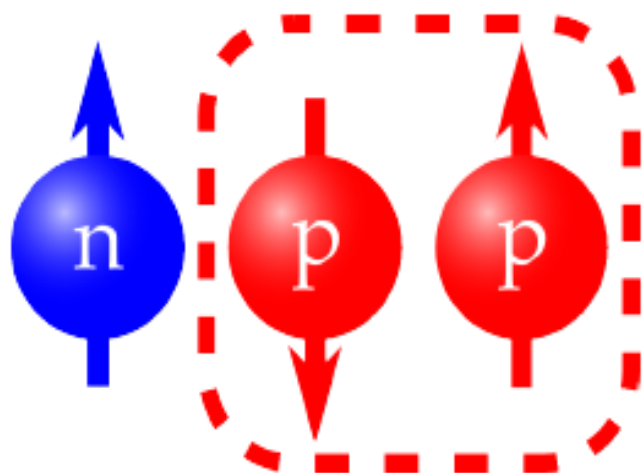
$^3\text{He}^{++}$ polarization technique using Electron Beam Ion Source

- ^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



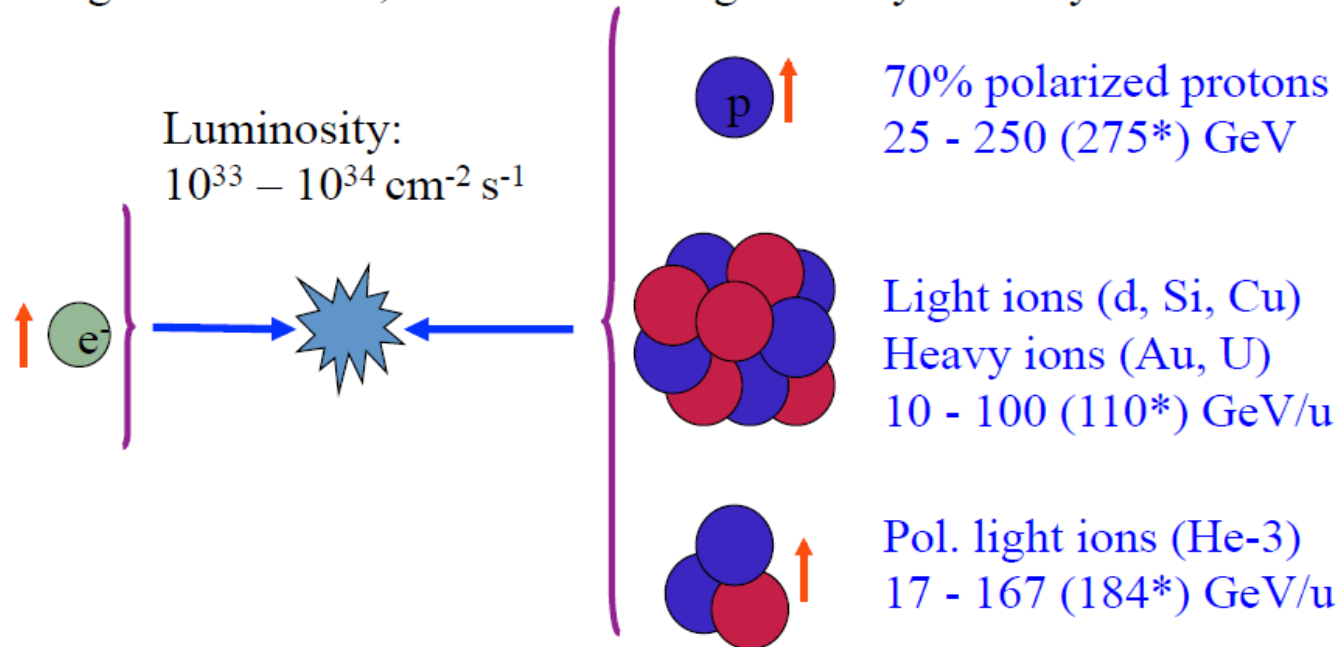
State	Probability
S	88.6%
S'	1.5%
D	8.4%

- S-state ^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 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

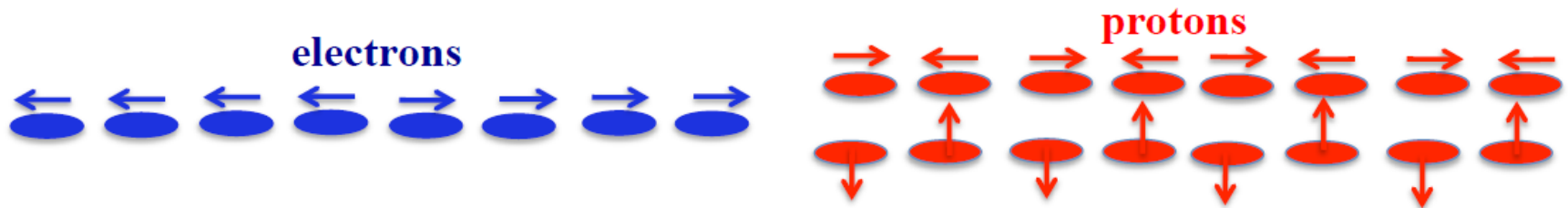


Center-of-mass energy range: 20 – 145 GeV

Full electron polarization at all energies

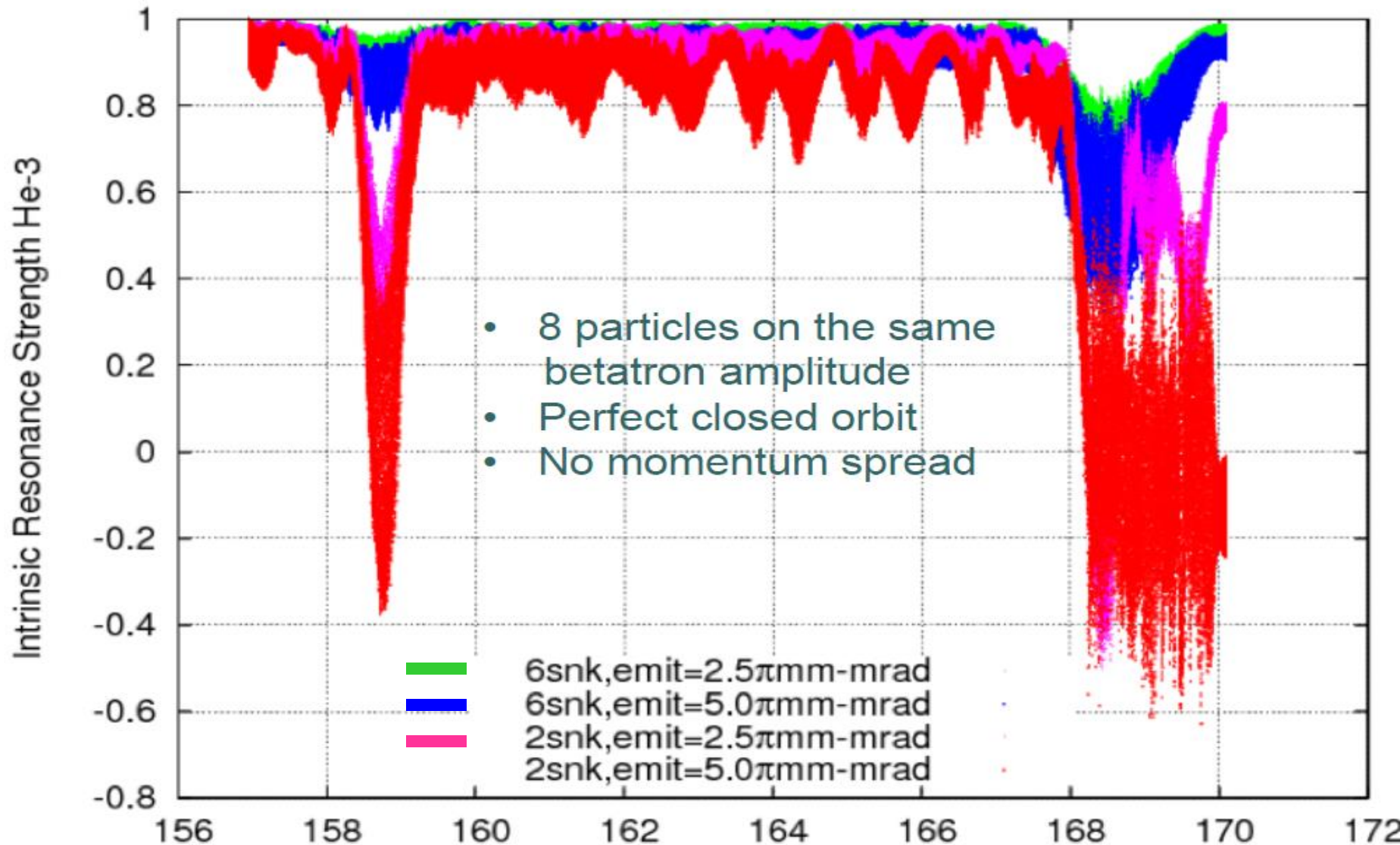
Full proton and He-3 polarization with six Siberian snakes

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 ${}^3\text{He}^{++}$ source

- Intensity $\sim 2 \cdot 10^{11}$ ${}^3\text{He}^{++}$ 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 pA	55-65%	70 mm mrad.	29 keV	100 eV	$^3\text{He}^{++}$
Laval	100 nA	95%	25 mm mrad.	12 keV		$^3\text{He}^+$
Rice/Texas A&M	8 μA	11%	10mm mr $\text{MeV}^{1/2}$	16 keV	10-50 eV	$^3\text{He}^+$

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 $^3\text{He}^{++}$ beam in EBIS.

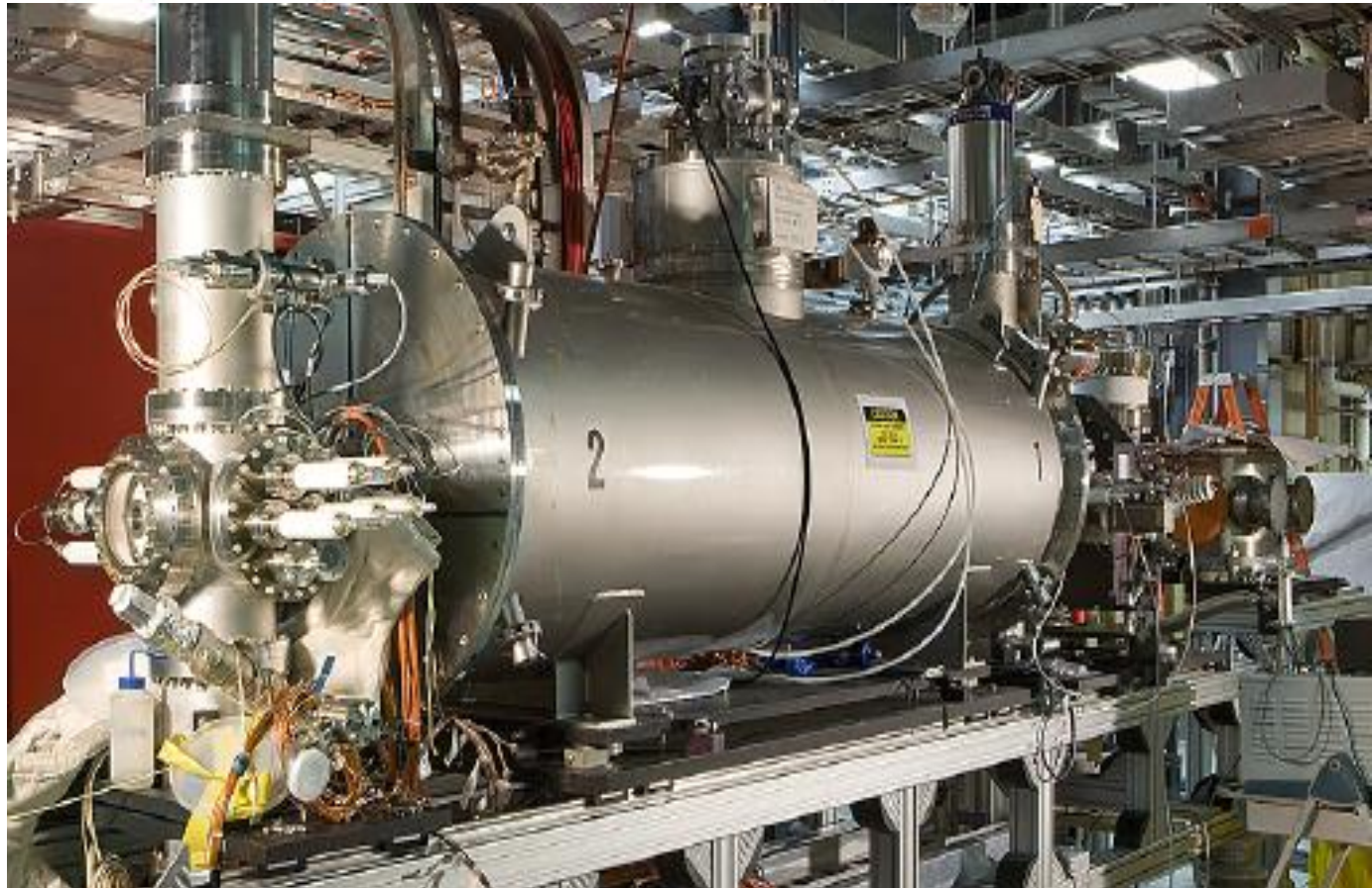
A.Zelenski, J.Alessi, ICFA Beam Dynamics Edition

Newsletter 30, p.39, (2003)

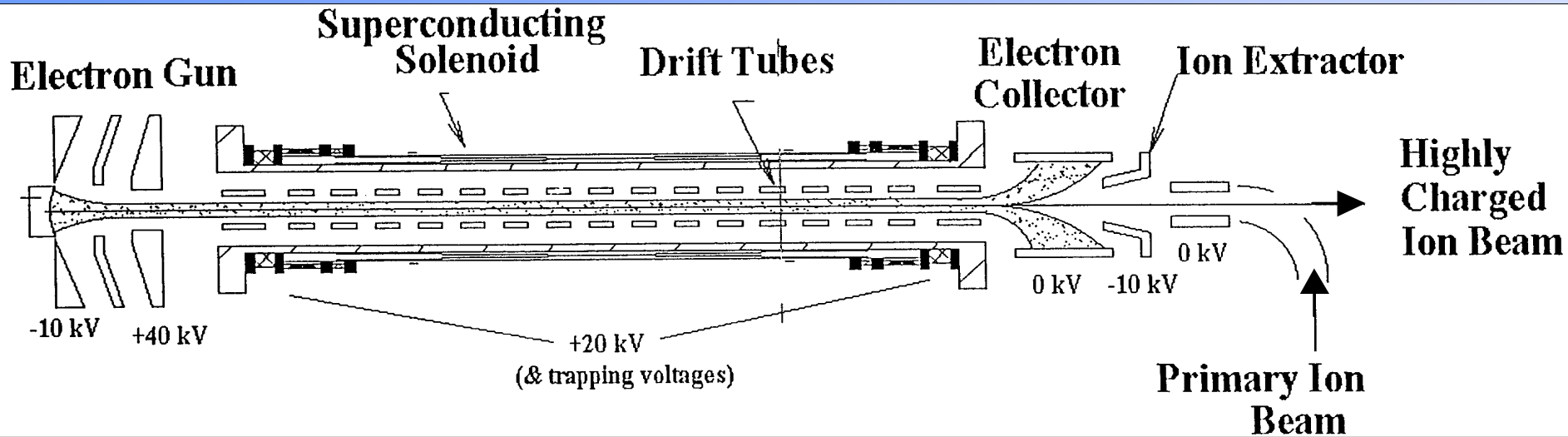
- Injections of ^3He gas polarized in the external cell into EBIS.
- ^3He polarization inside the EBIS in high magnetic field. No polarization losses during beam transport through gradient magnetic field.
- EBIS is used for efficient ionization and accumulation of polarized $^3\text{He}^{++}$ ions

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/cm² 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 $\sim (0.5 - 0.8) \times (\# \text{ electrons in the trap})$
- 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 \sim independent of species or charge state!

EBIS Beams Run to Date

Periodic Table of the Elements

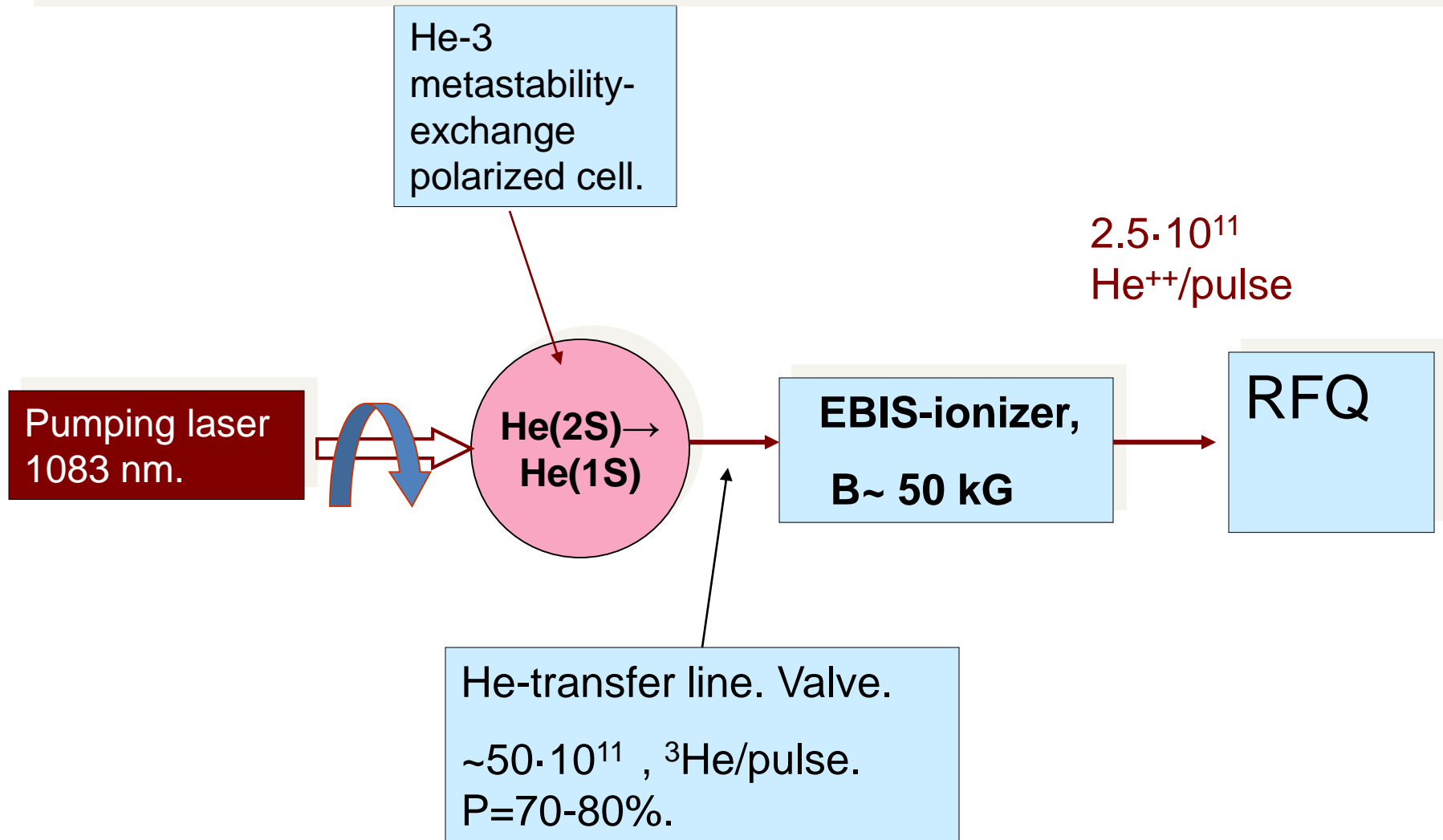
1 1A 1A	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305	3 IIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.833	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 84.458	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 121.757	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 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [210]	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 [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [293]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown
			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
			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%

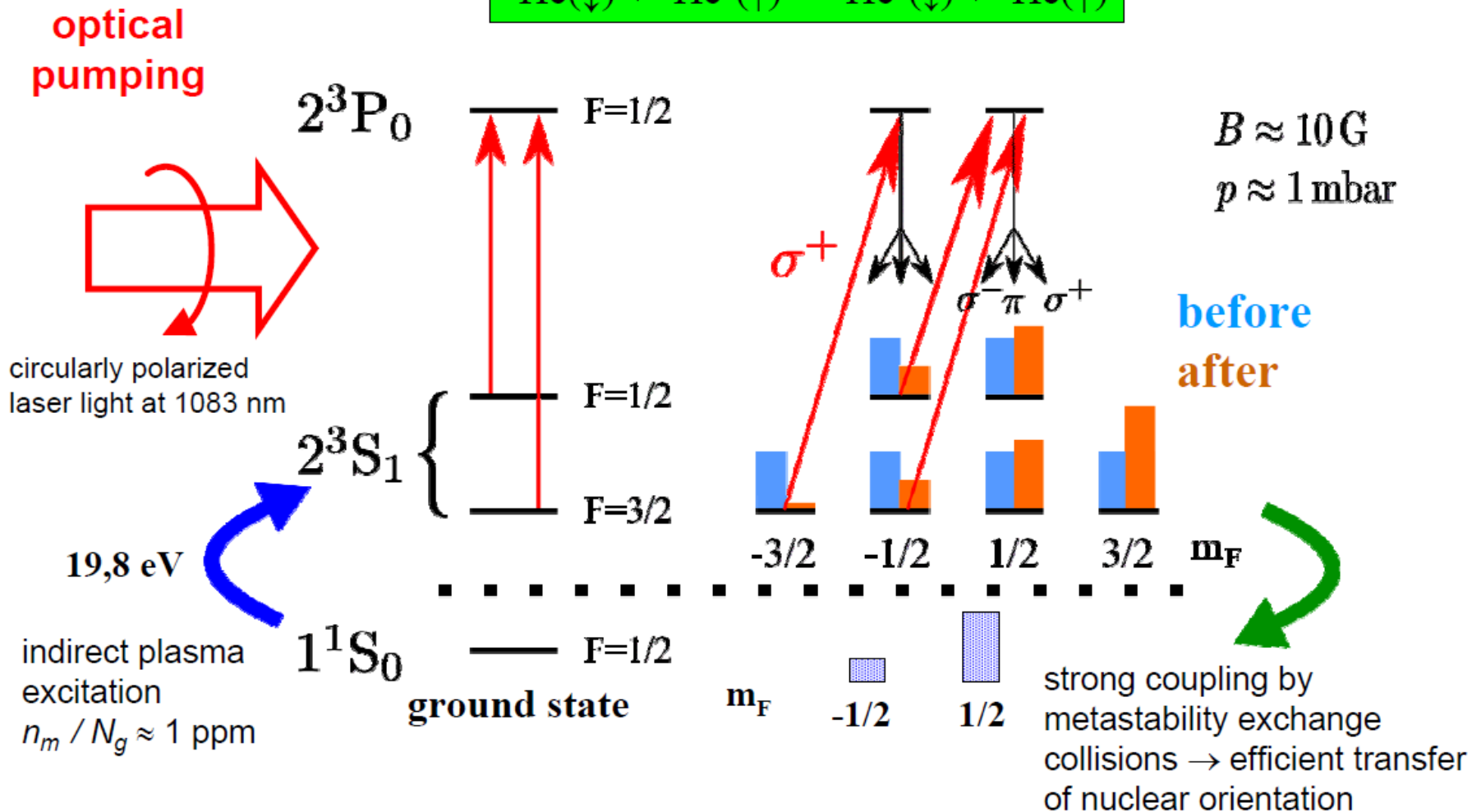
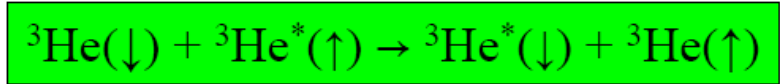
Production of polarized $^3\text{He}^{++}$ beam in EBIS.

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

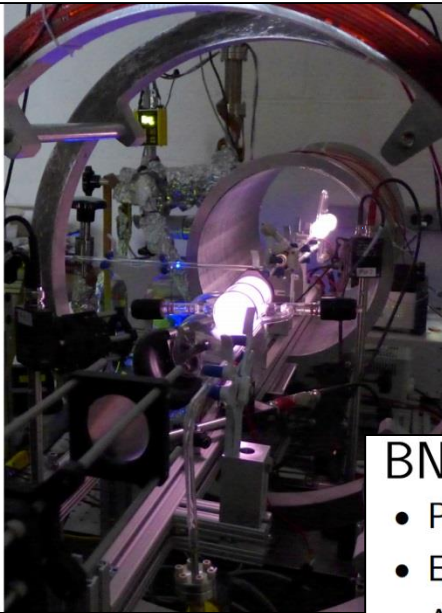


MIT-BNL collaboration on polarized $^3\text{He}^{++}$ ion source development

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 development⁵

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



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

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



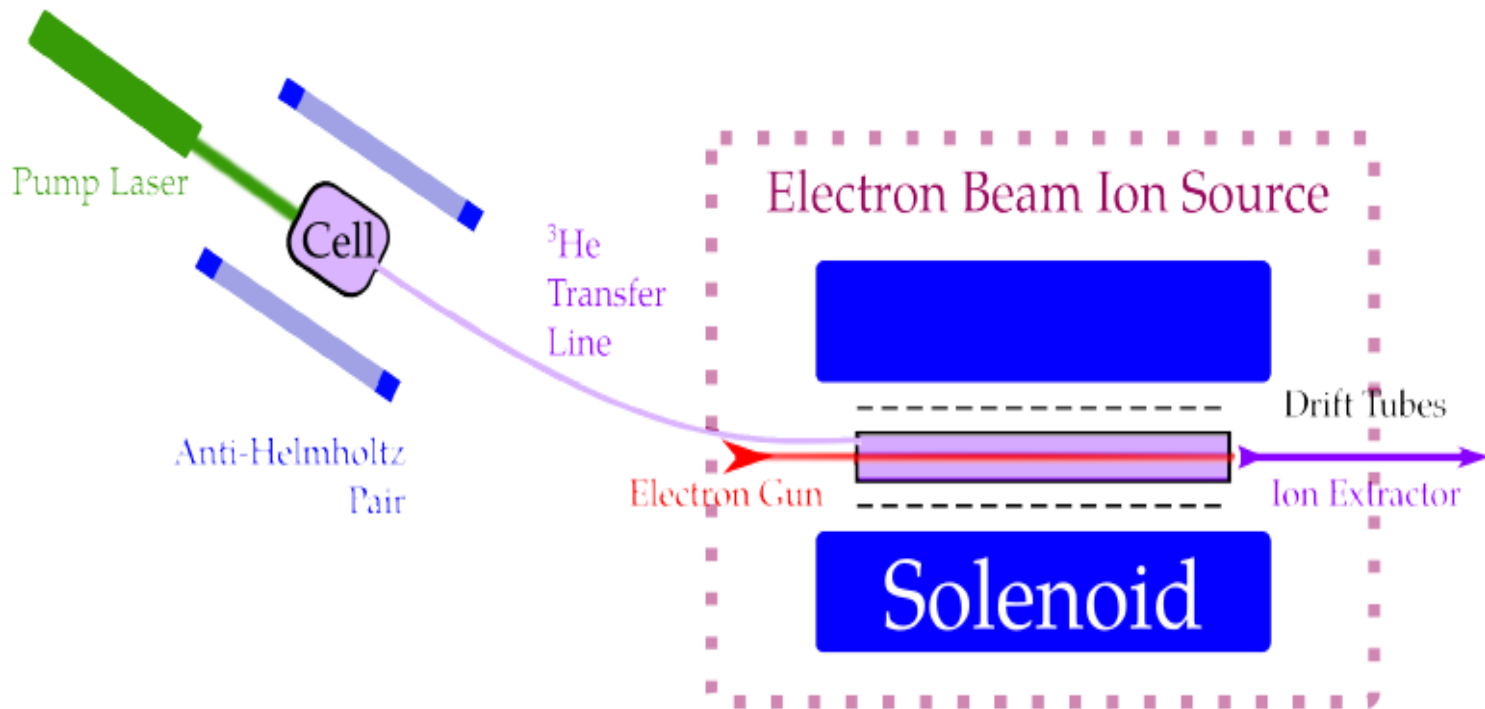
BNL Test Polarizer

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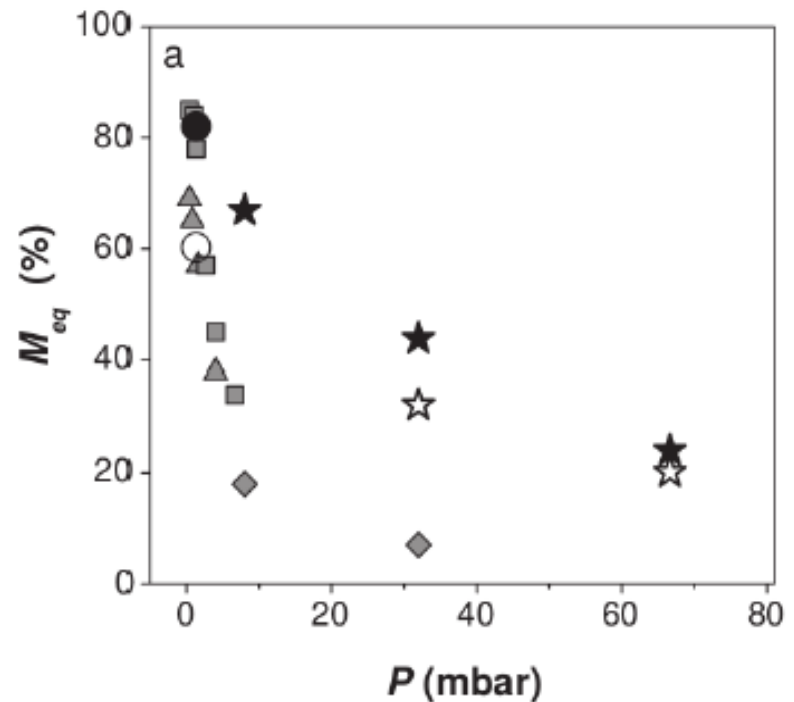
Injection of polarized ^3He -gas in EBIS

- Polarize to $\sim 70\%$ at 1 torr with 10W 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



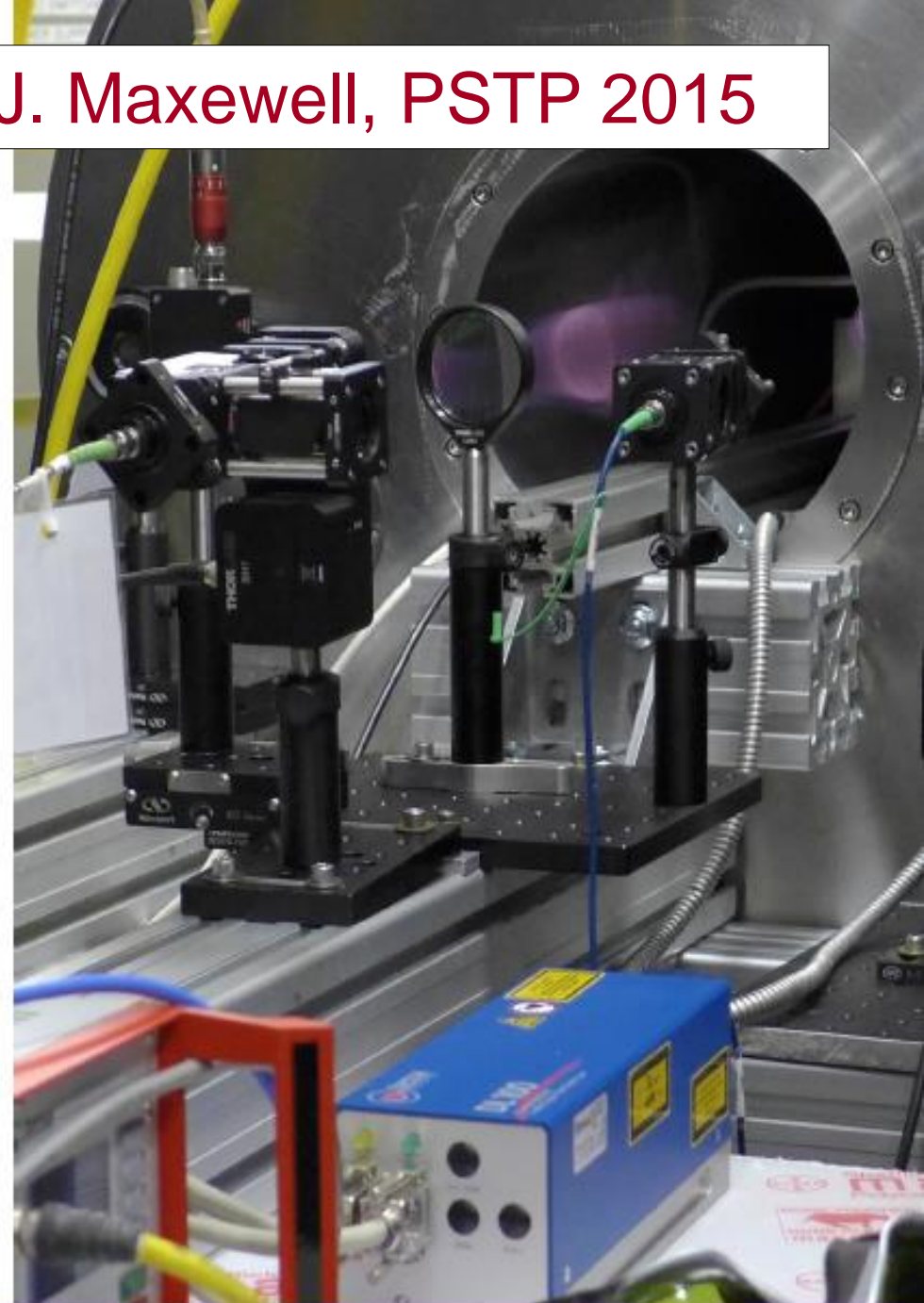
MEOP at High Magnetic Field

- 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



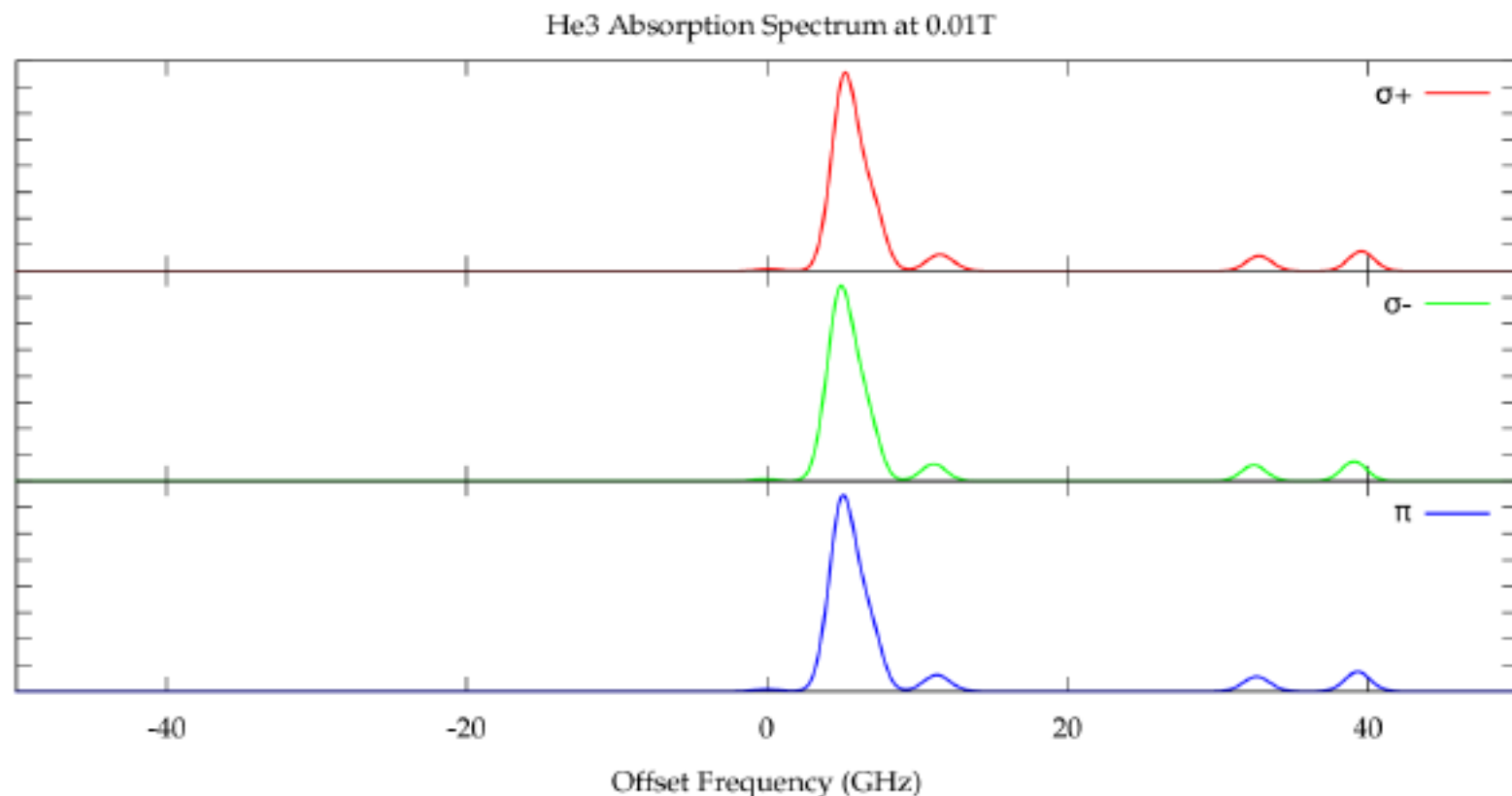
BNL High Field Tests

- 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 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}

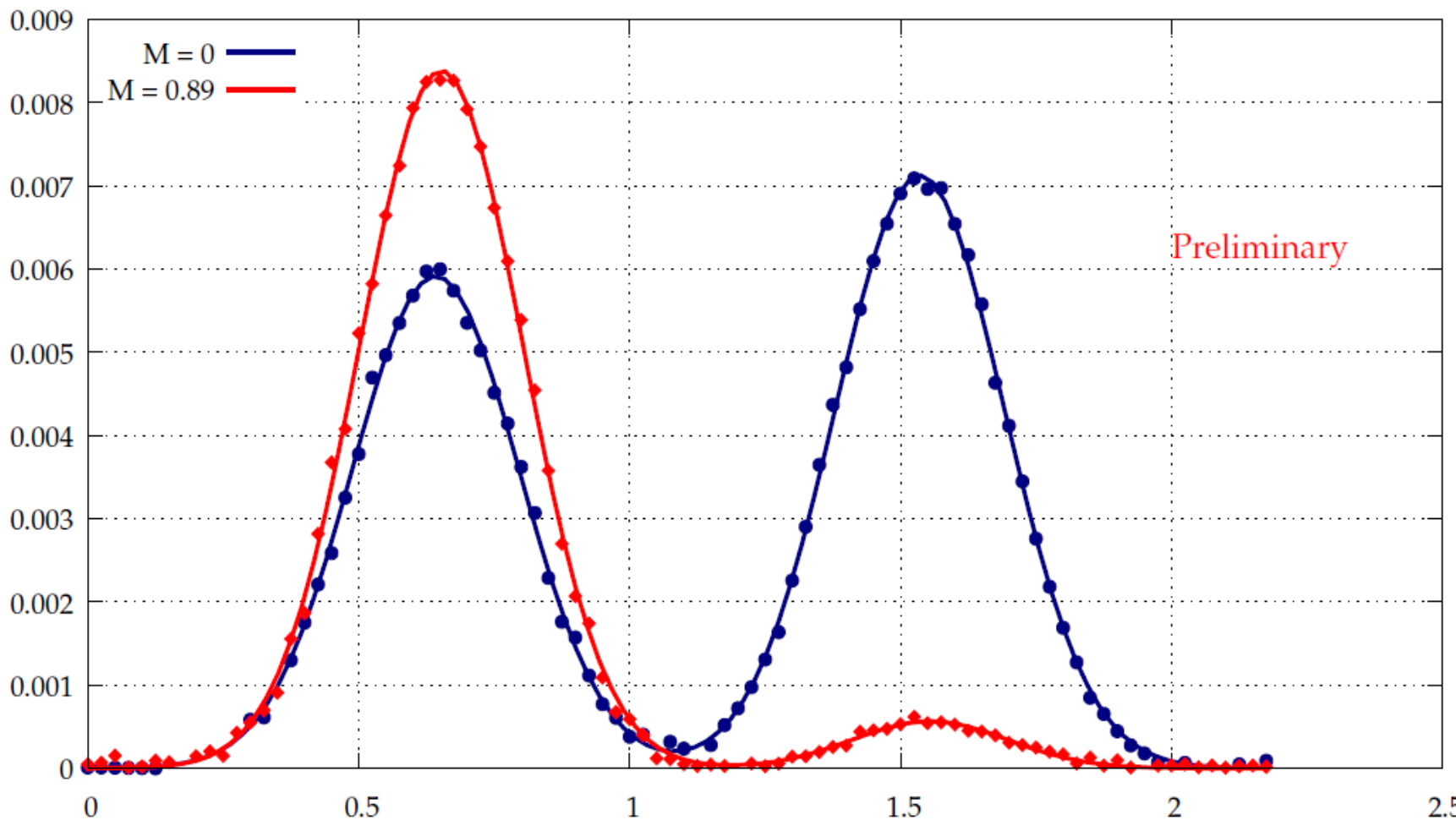


⁸Courtade *et al*, Eur. Phys. J. D 21 (2002).

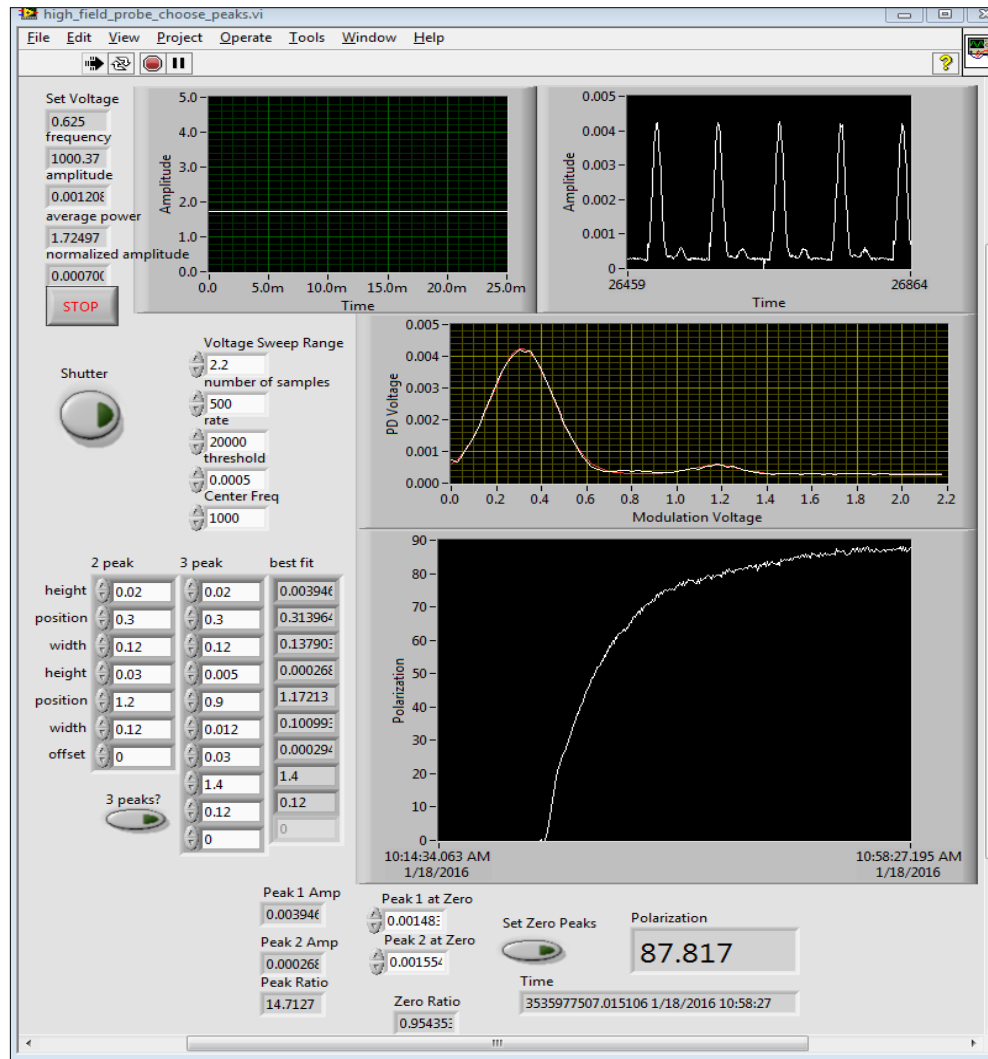
⁹Suchanek *et al*, Eur. Phys. Special Topics 144 (2007).

Measuring Optical Pumping

Probe Laser Absorption Peaks at Zero and High Polarization

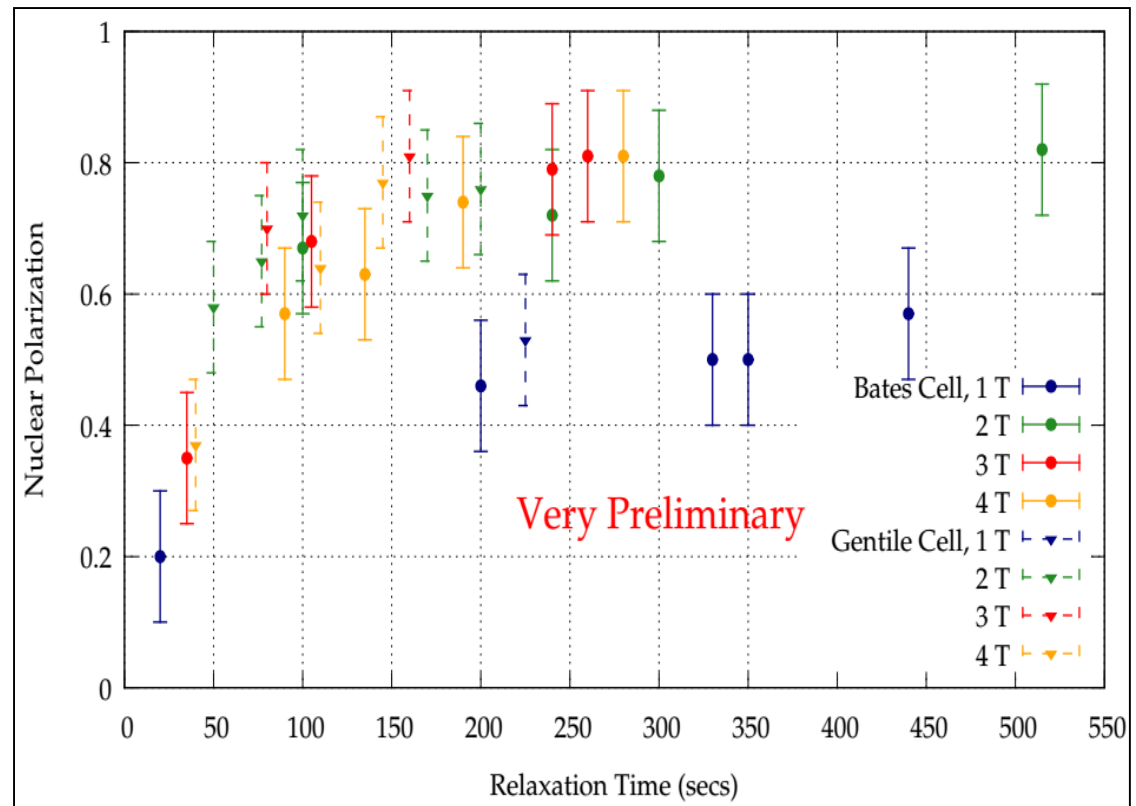
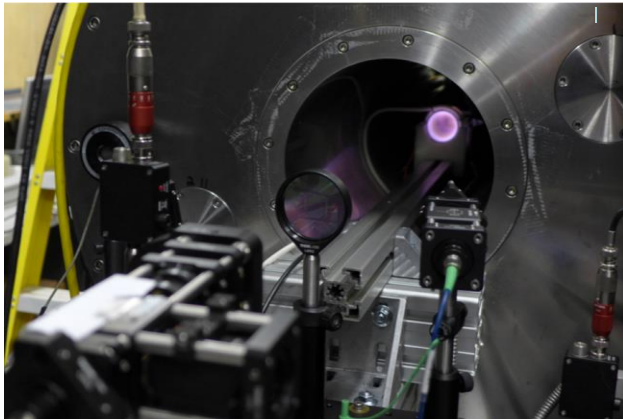


Jan18,2016, Sealed cell-Pol.- 88%



Probe laser absorption polarimeter, 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.

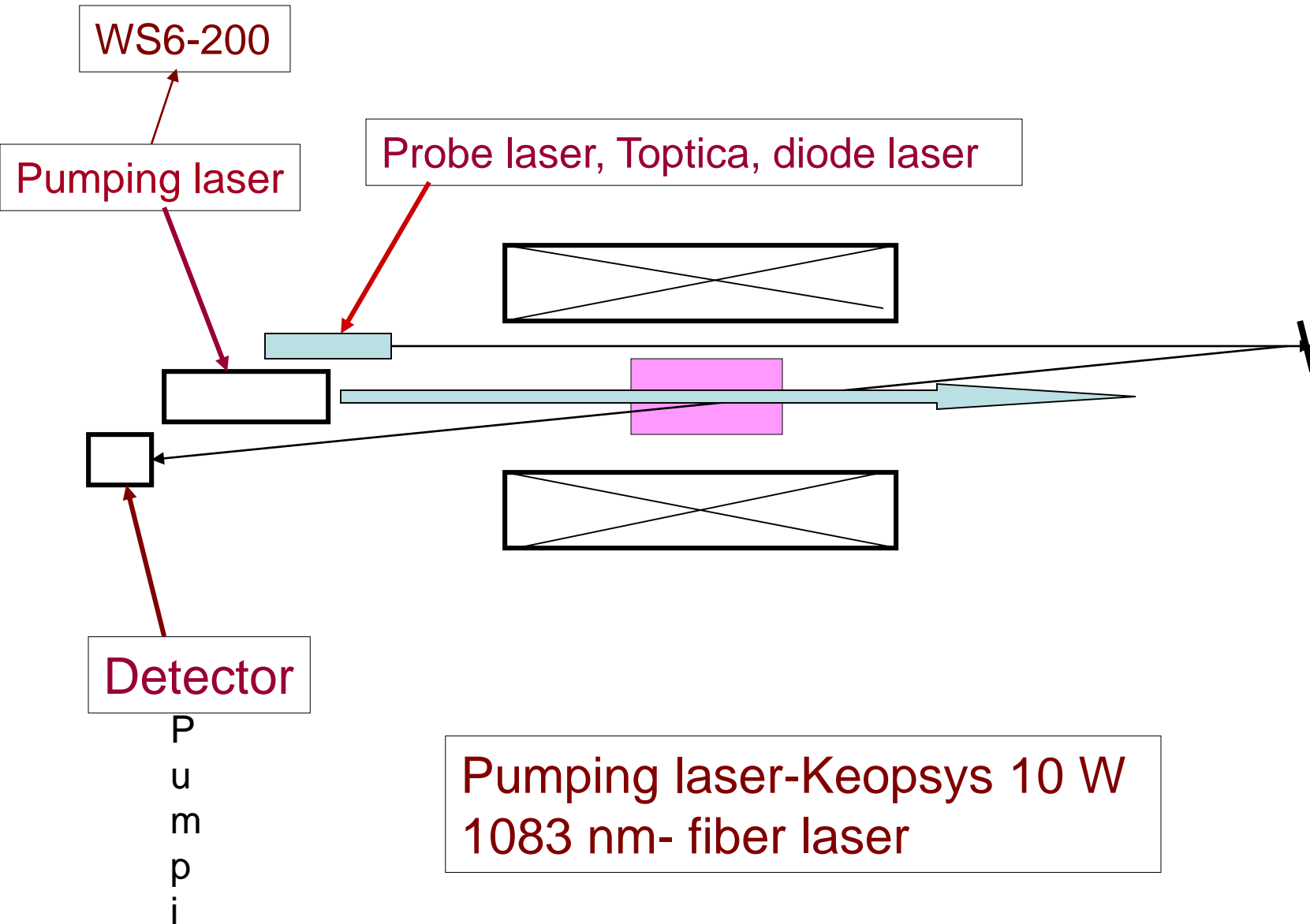
High Field Conclusions Thus Far

- 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

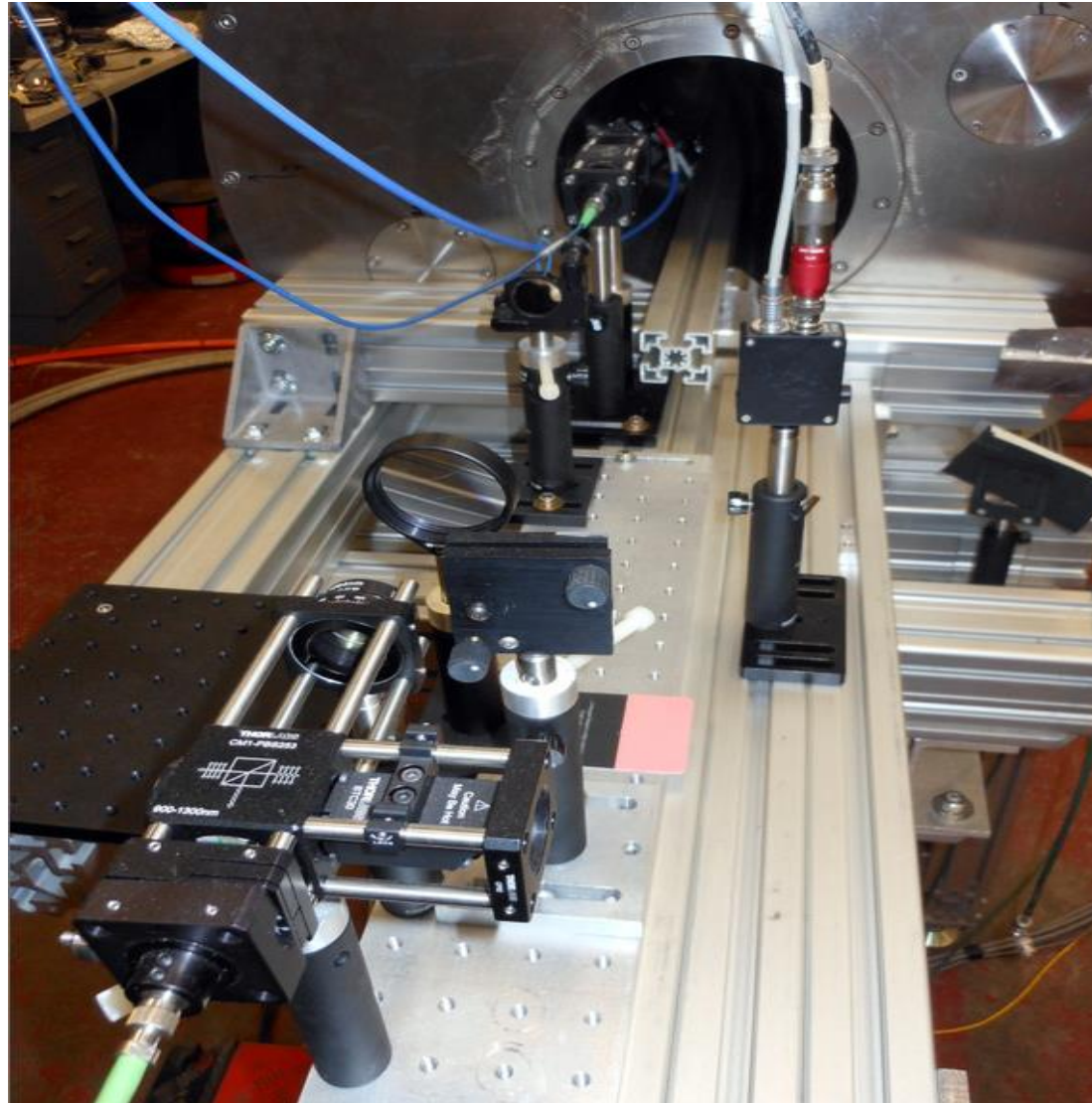
High polarizations from MEOP over 1 T

- 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

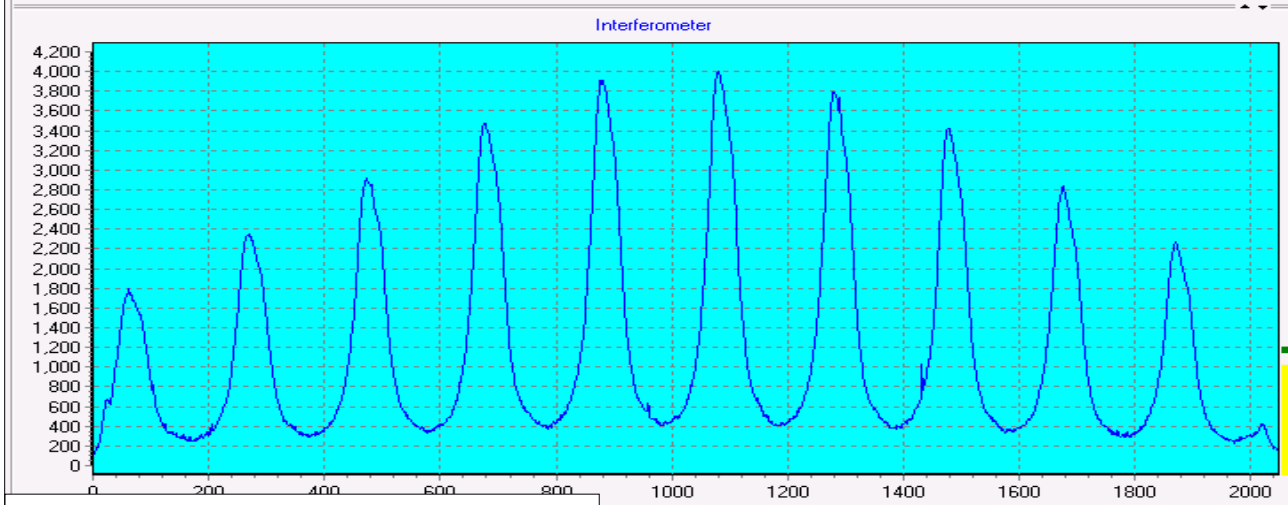
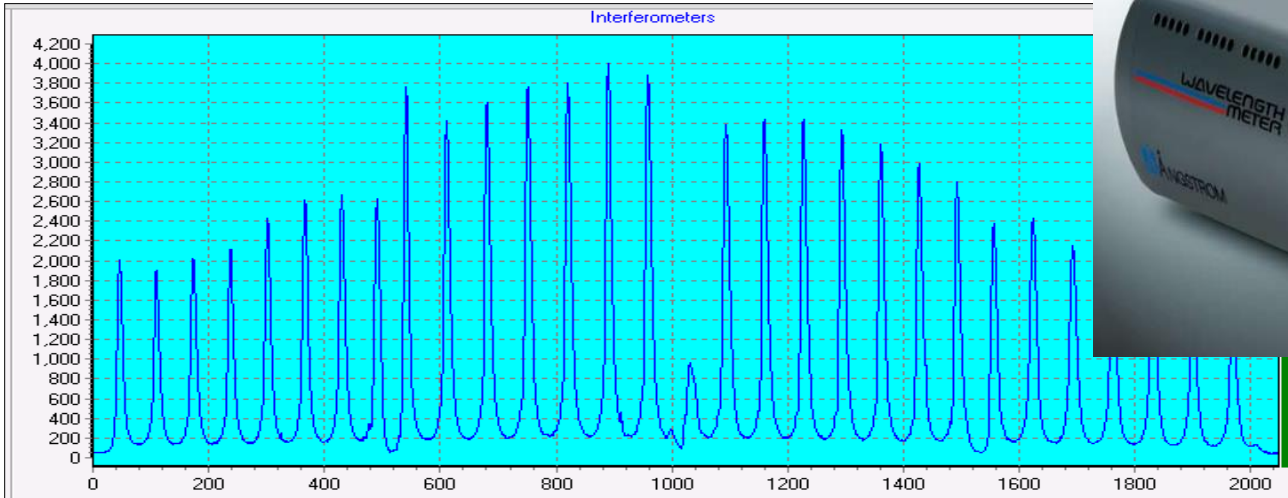
Optical pumping laser layout



^3He Laser system for optical pumping and polarization measurements



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



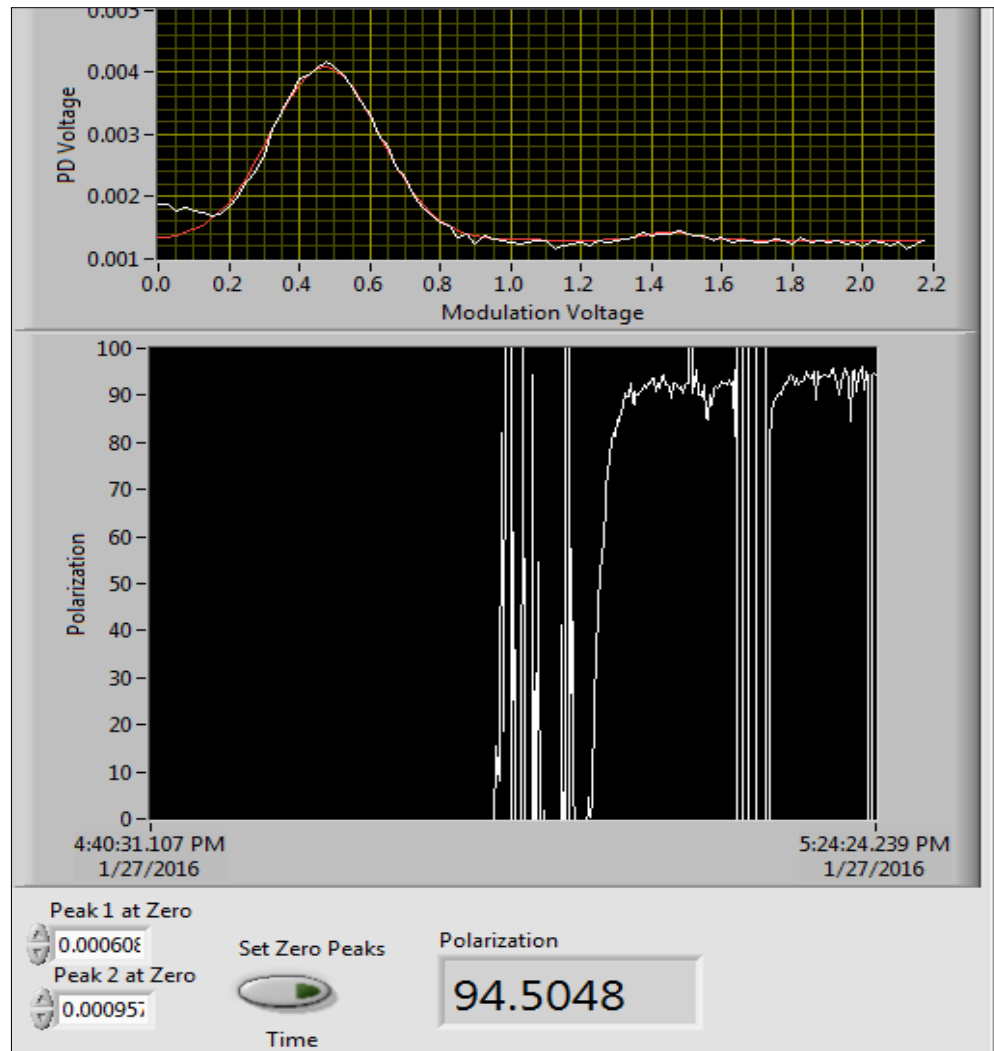
1083 nm

276.7558 THz

Linewidth

1.2 GHz

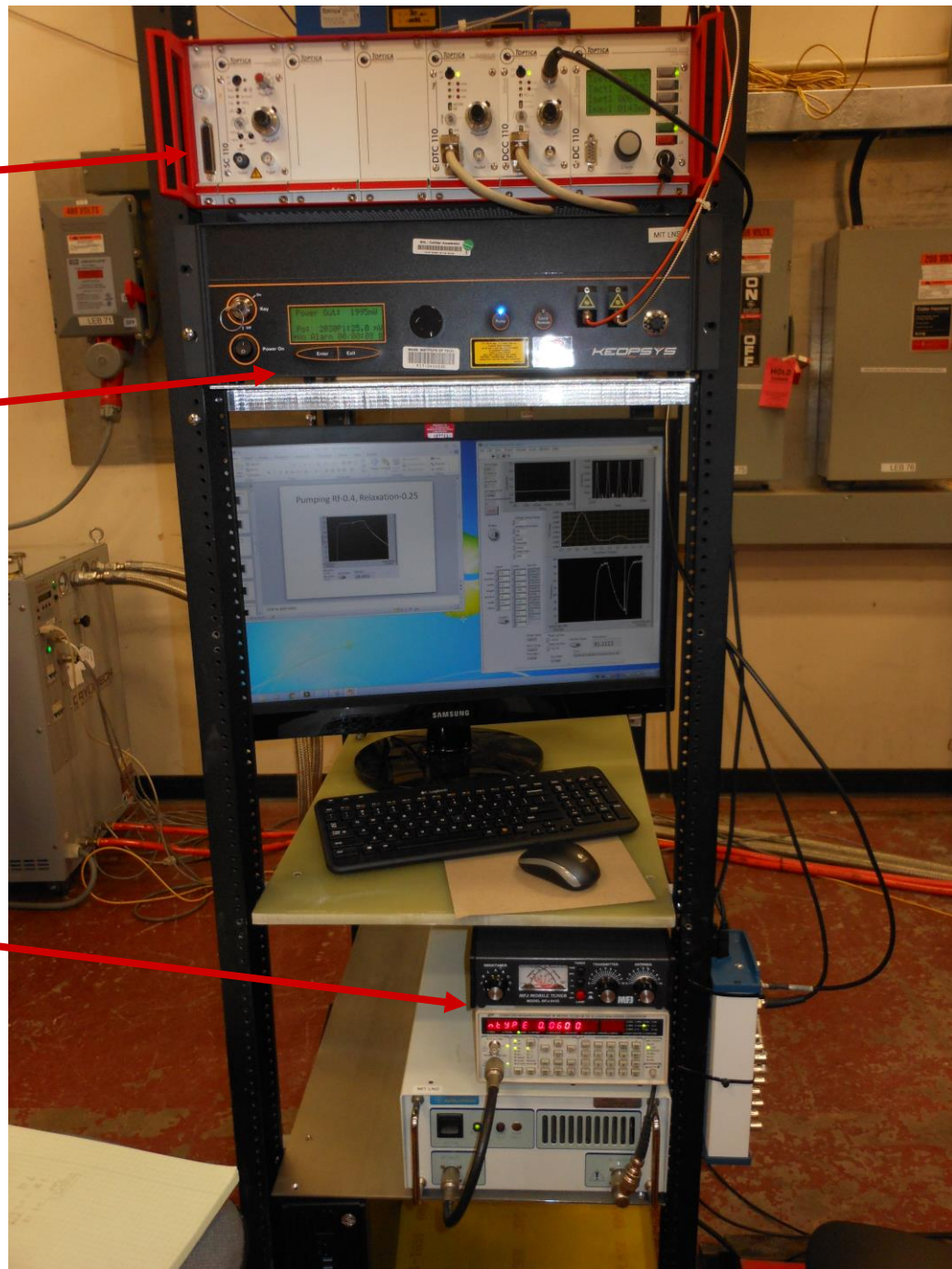
Jan18,2016, Sealed cell-Pol.- 94.5%,



Probe laser controller

Pumping laser controller

RF master oscillator and amplifier



High Field Conclusions Thus Far

- First results for ρ near 90%
 - With discharge
- Not only is this ρ near 90%
 - Cell which was able to reach 100 G
 - over 80% at 100 G
 - Field uniform



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)
- Transition split allows pumping just one state with laser

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

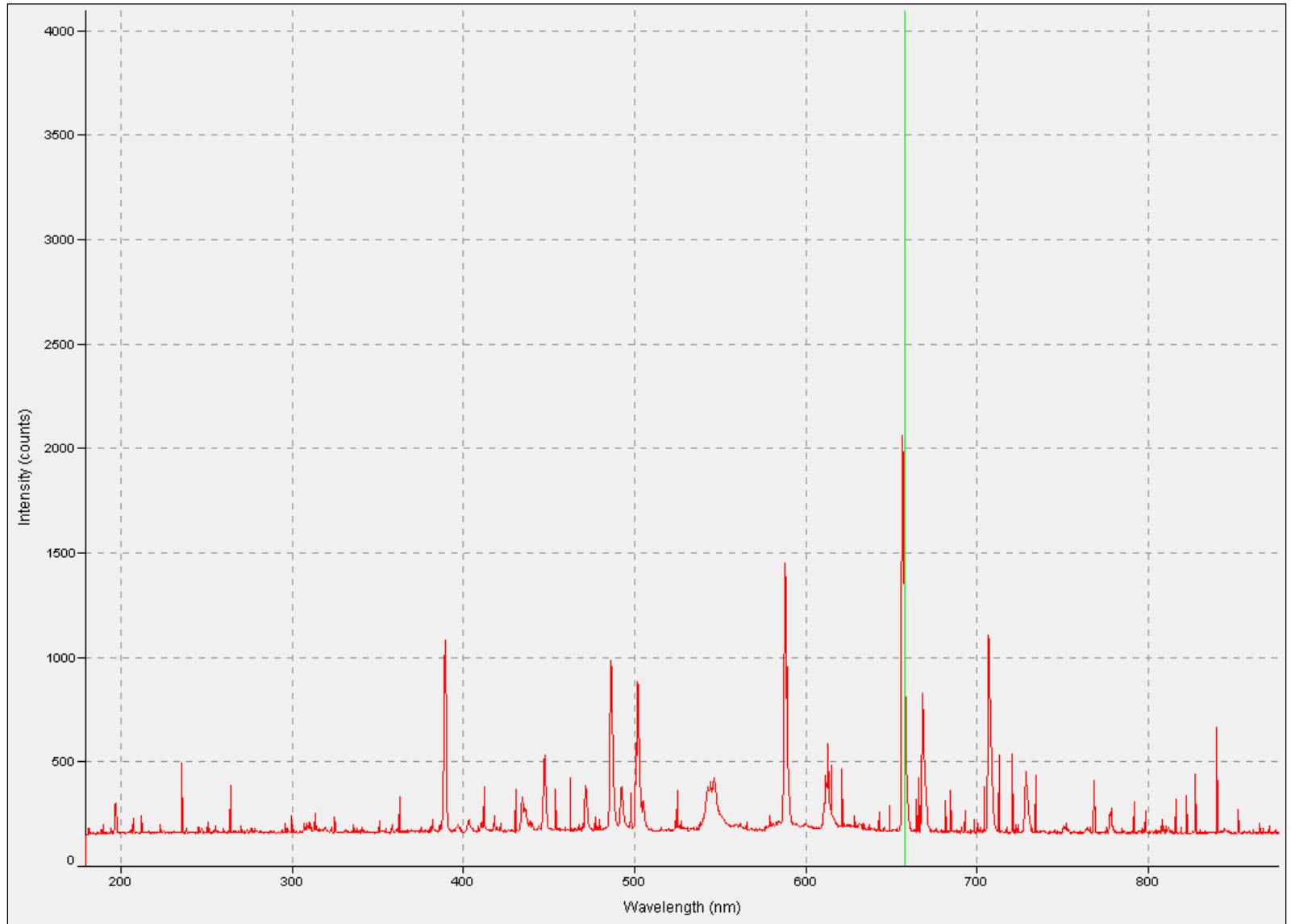


^3He -gas purification and filling system

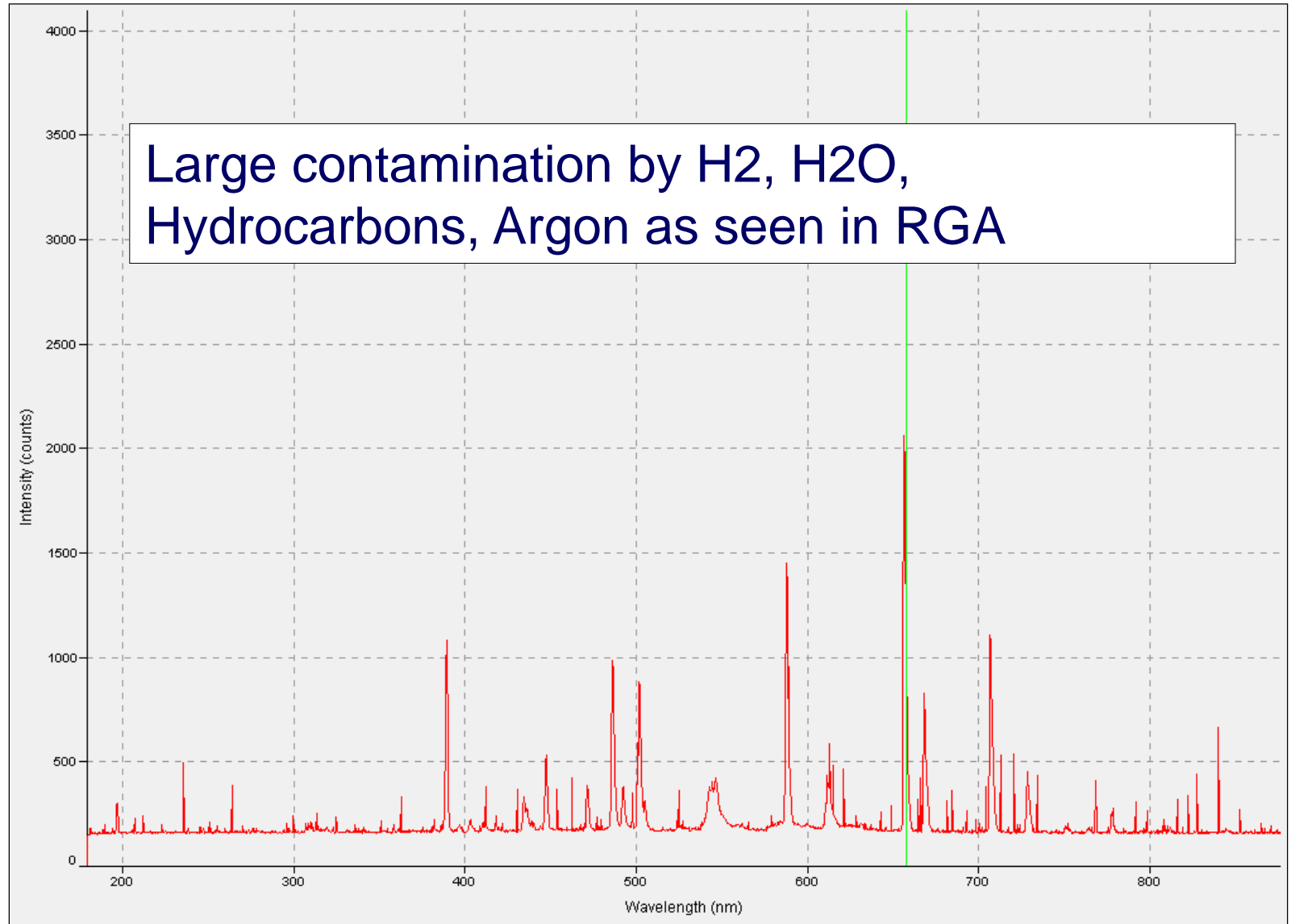


Non-magnetic pneumatic remotely controlled Isolation Valve: IV

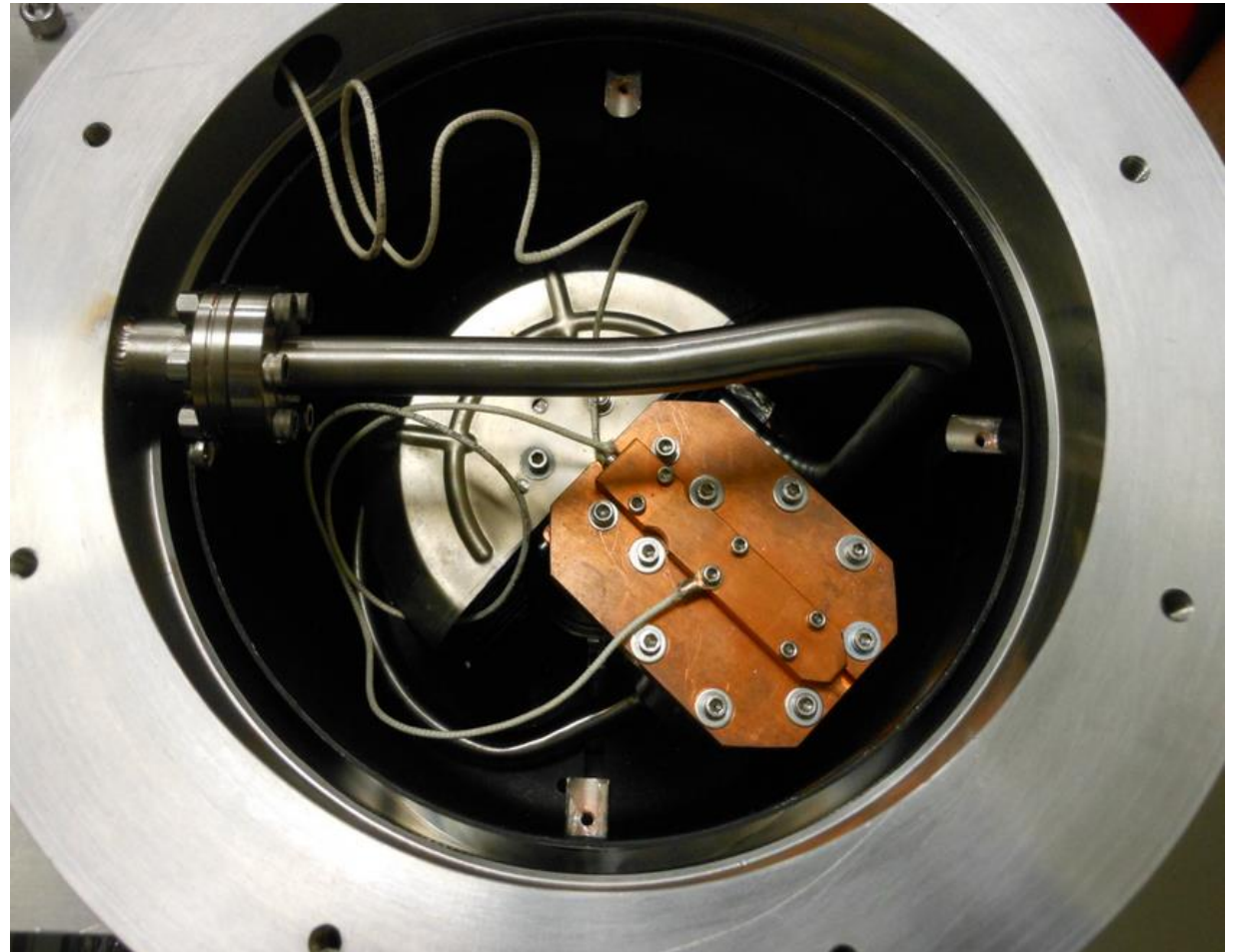
He-cell valve closed, RF-33.4 MHz, Amp-0.100,
He-3-1.08 torr



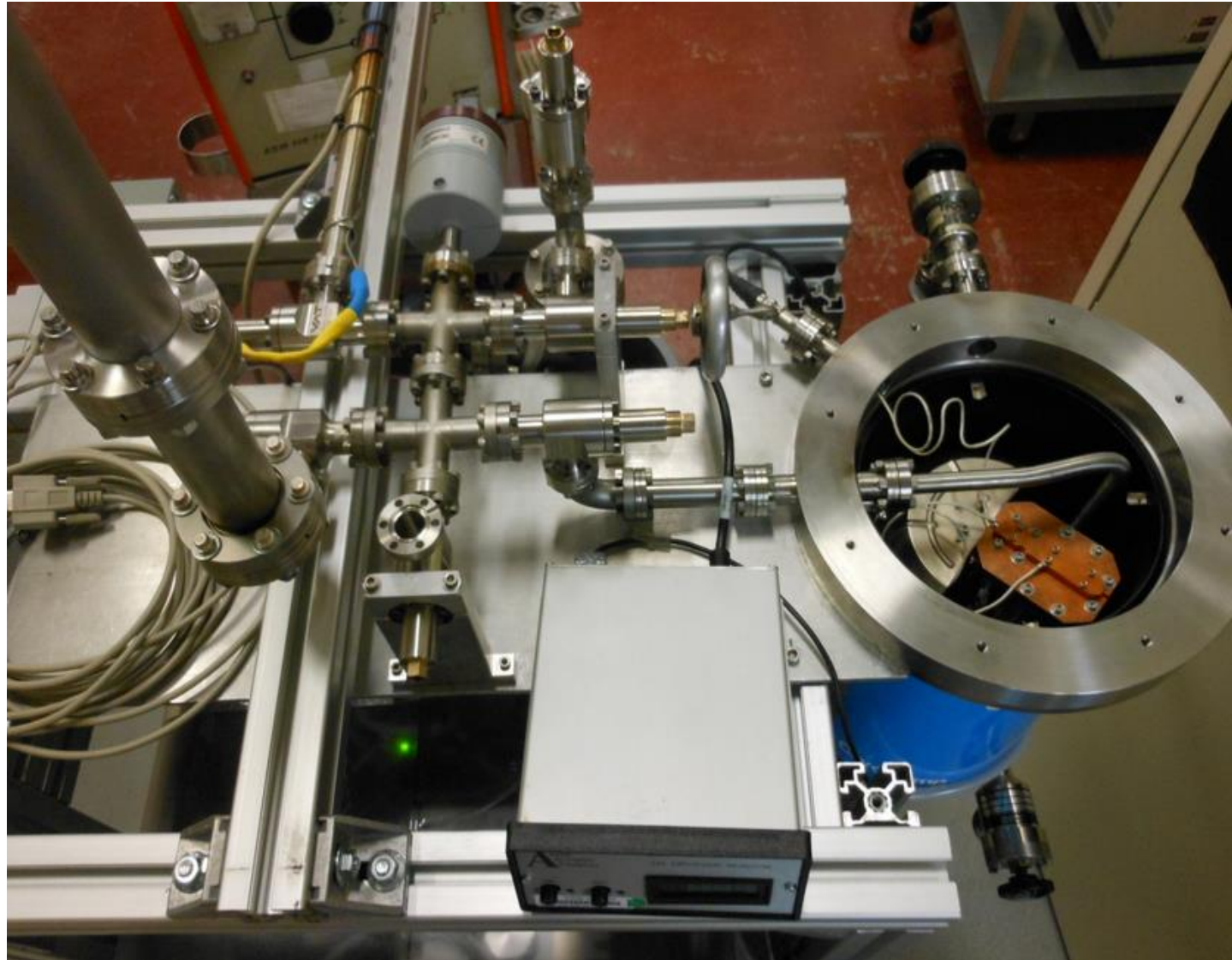
He-cell valve closed, RF-33.4 MHz, Amp-0.100,
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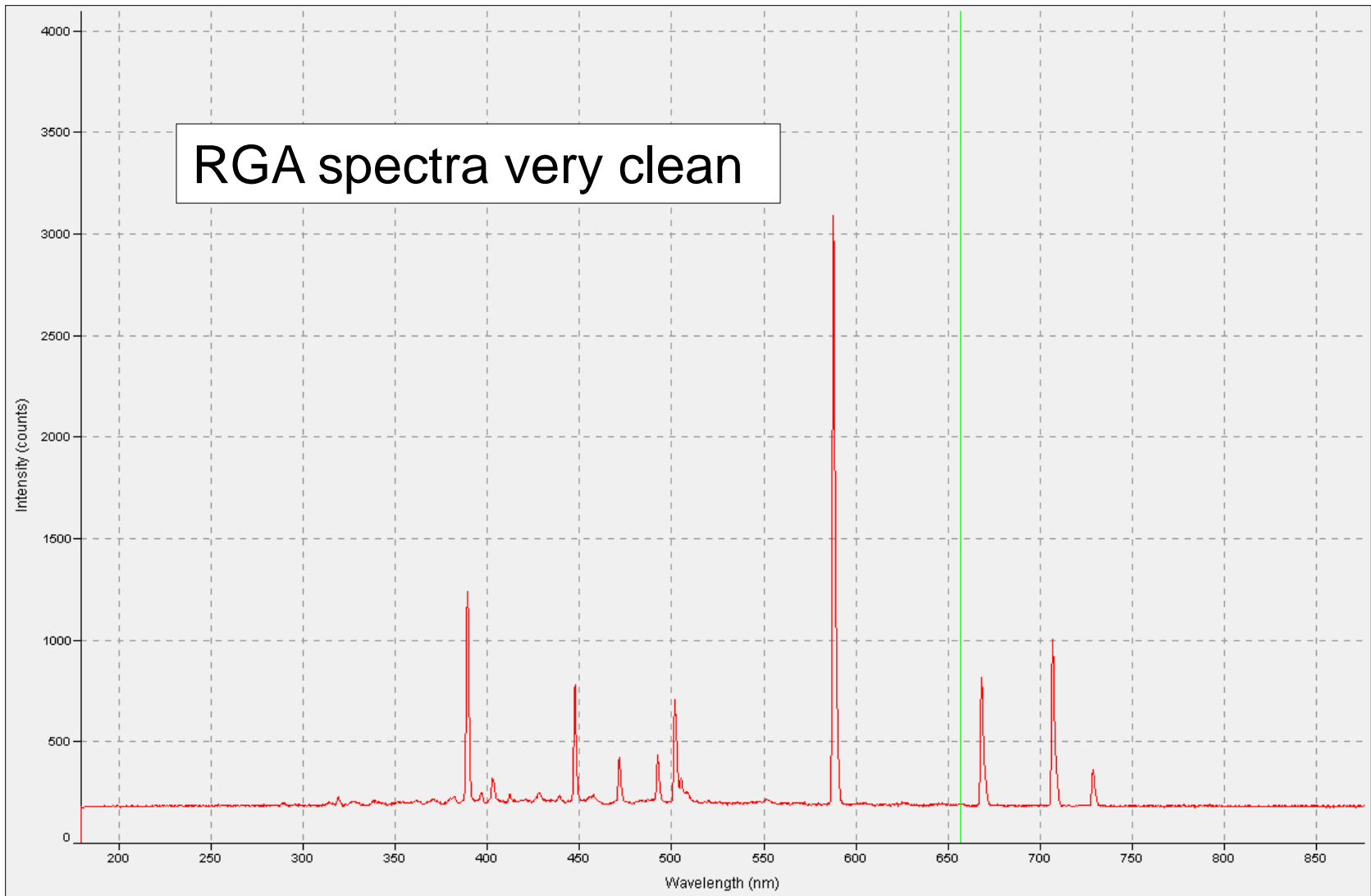
^3He cryo- purification system built-in CTI-8 cryopump.



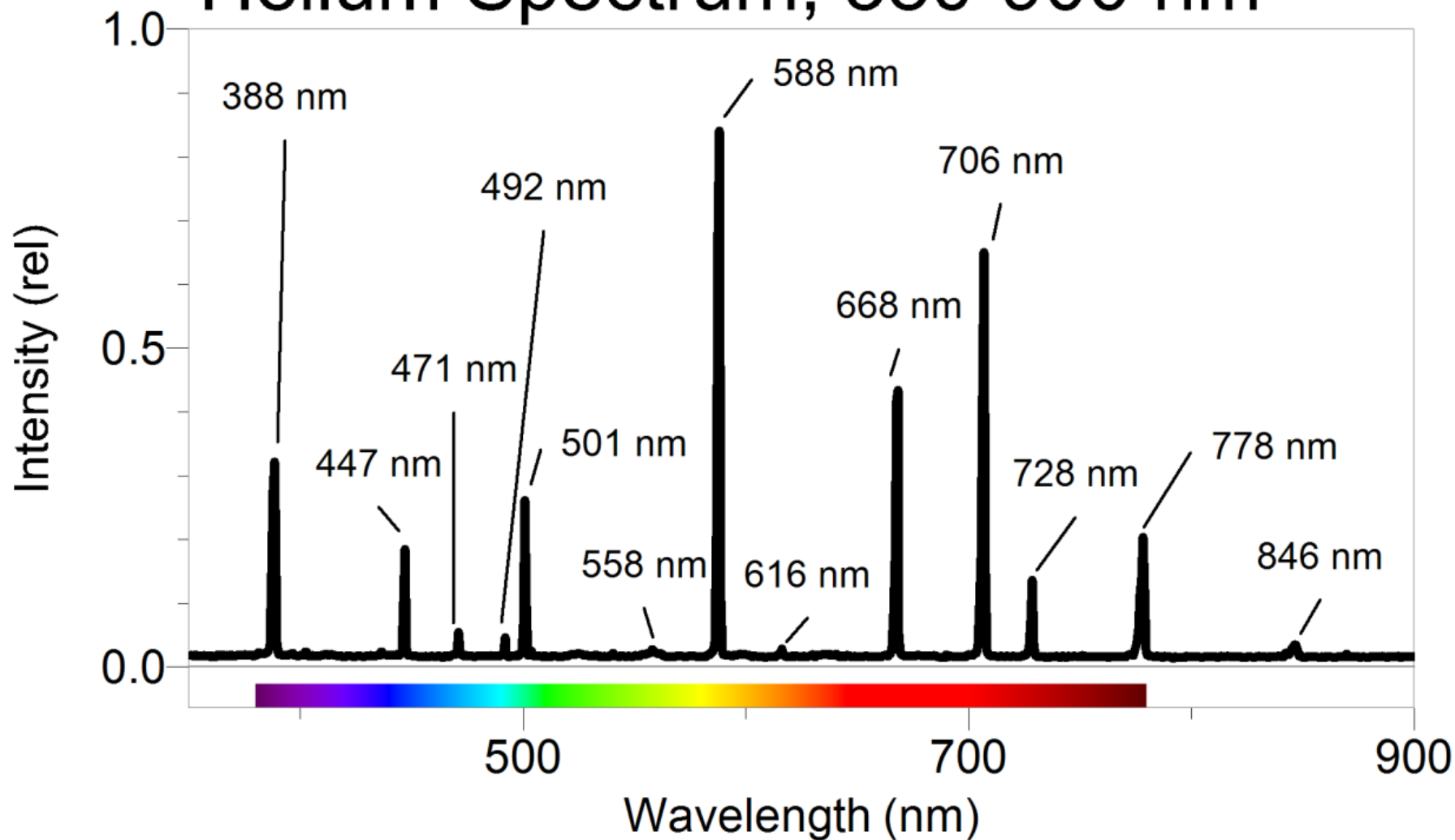
^3He -gas purification and filling system



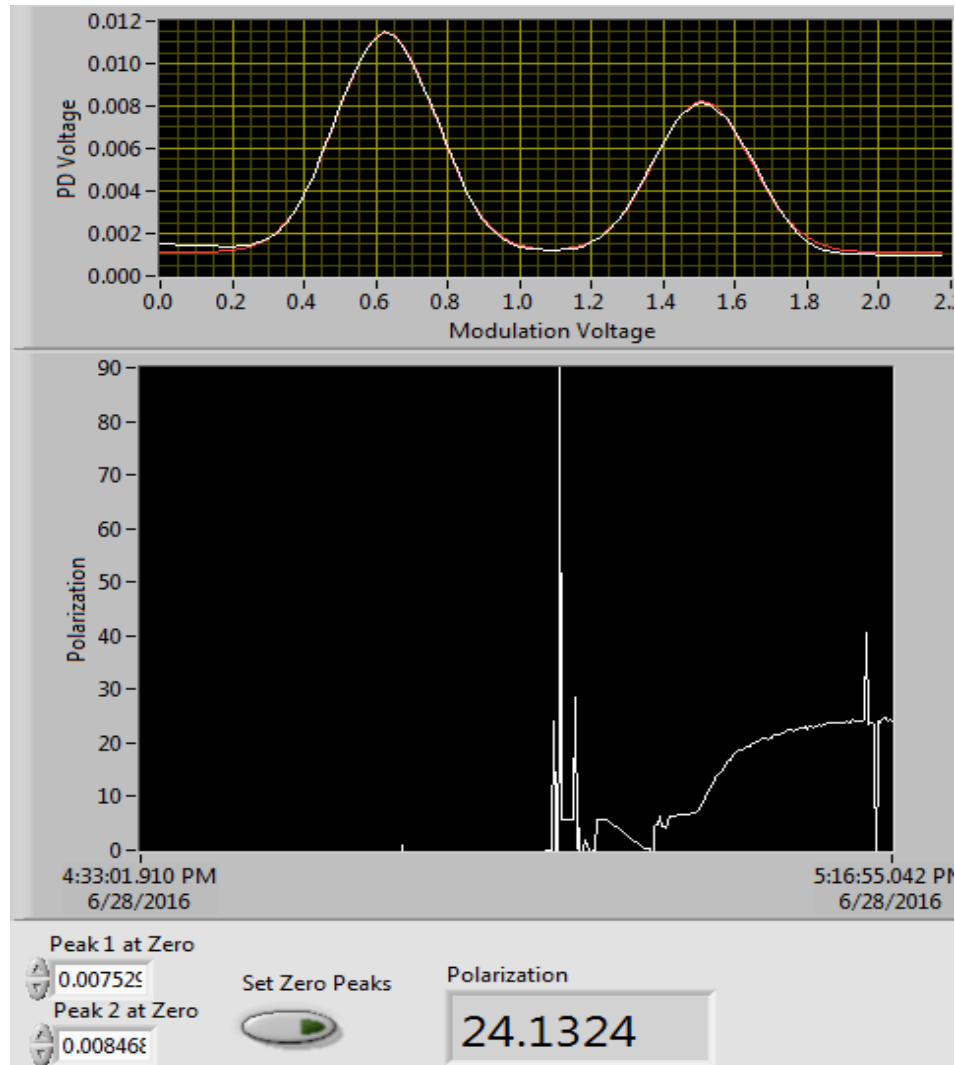
June 21, He-fill with CP-pumping at 45deg. K. Very clean spectra, no hydrogen 656 nm line!



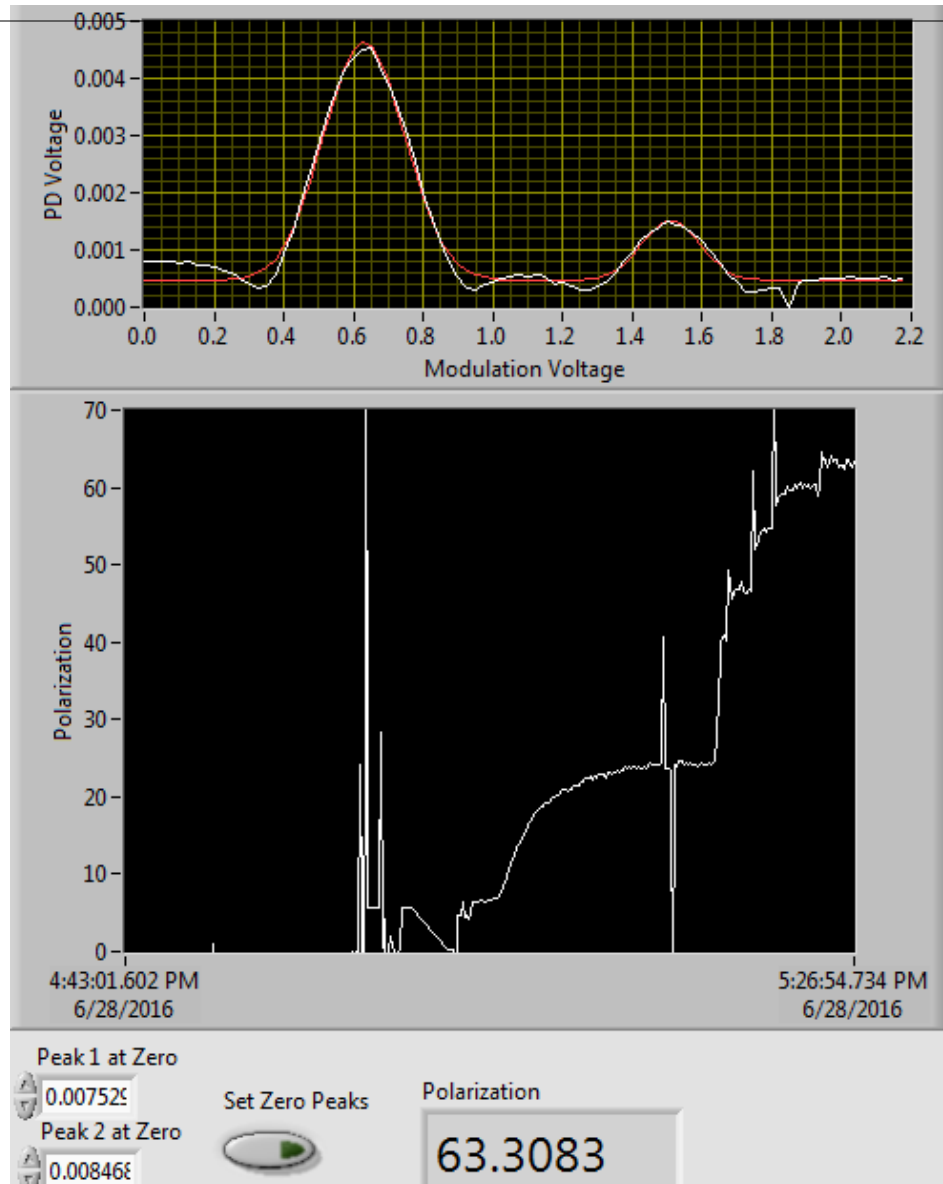
Helium Spectrum, 380-900 nm



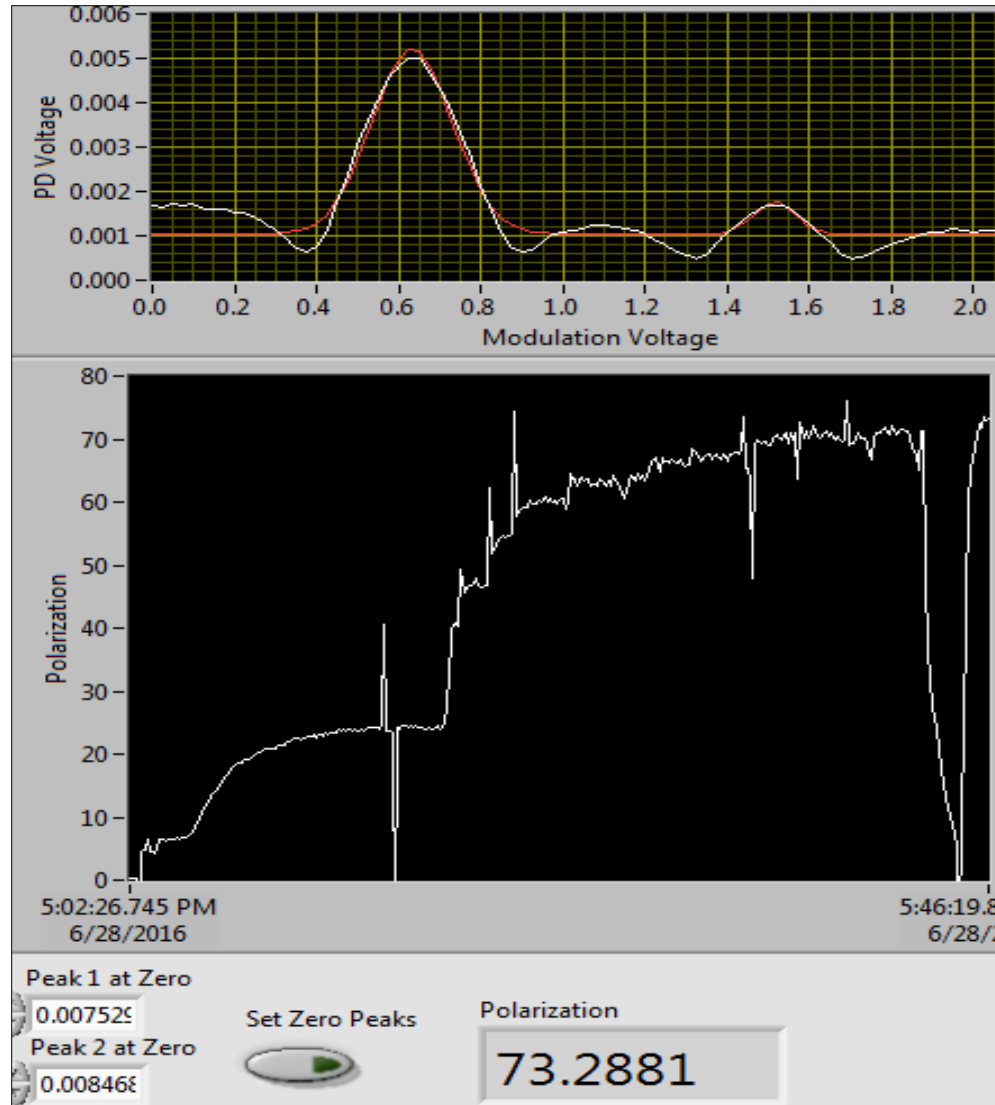
3.5 torr, Isolation Valve (IV)-open



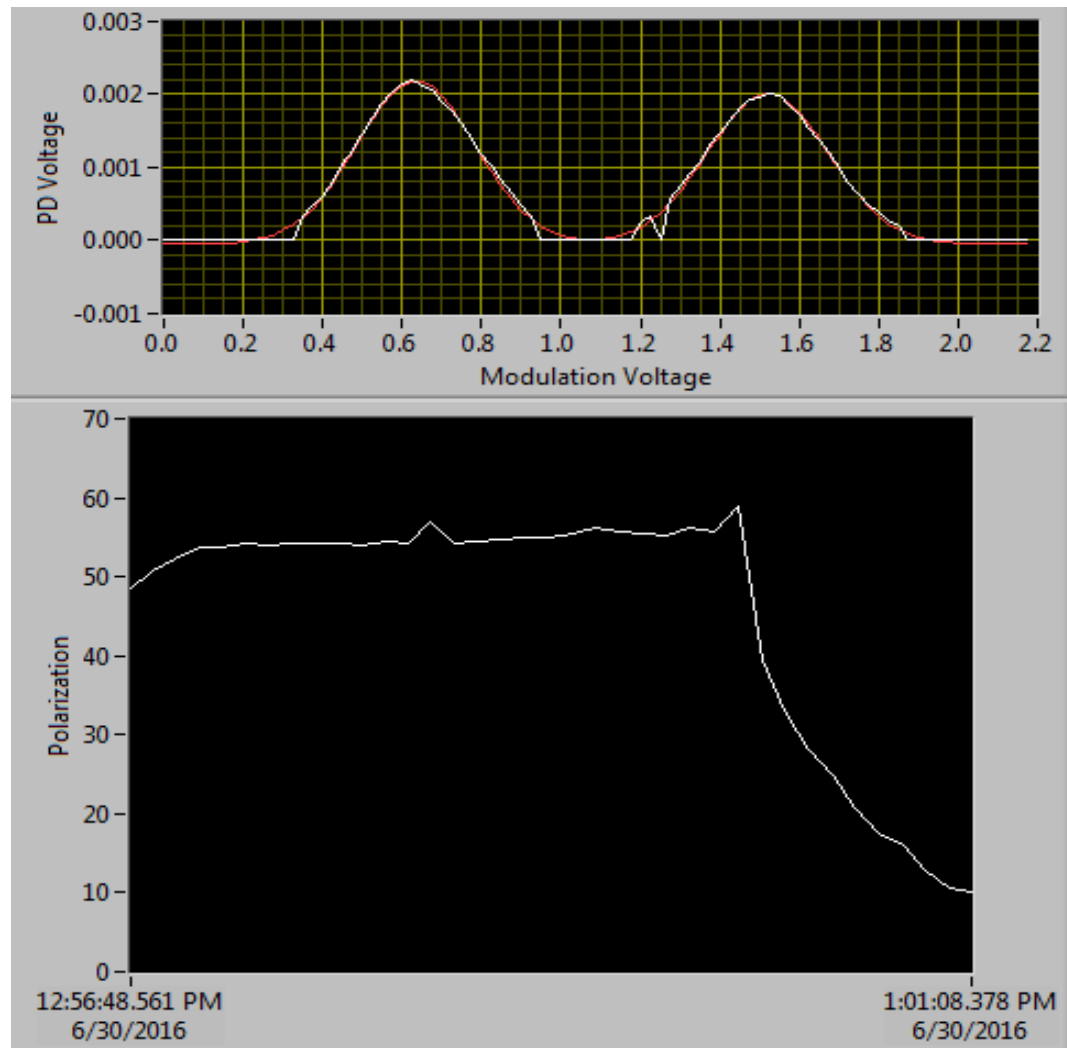
3.5 torr, Isolation Valve (IV)-closed, P=63%



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



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



Peak 1 at Zero

0.003986

Peak 2 at Zero

0.004511

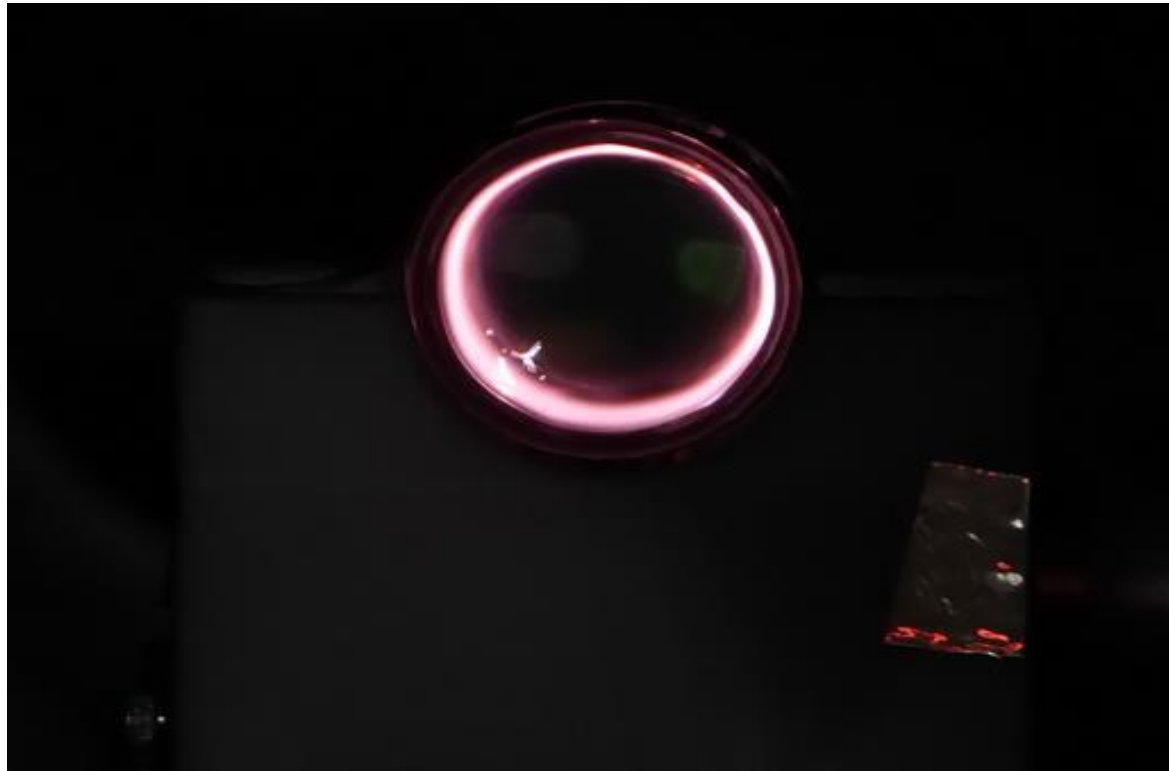
Set Zero Peaks



Polarization

10.1578

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



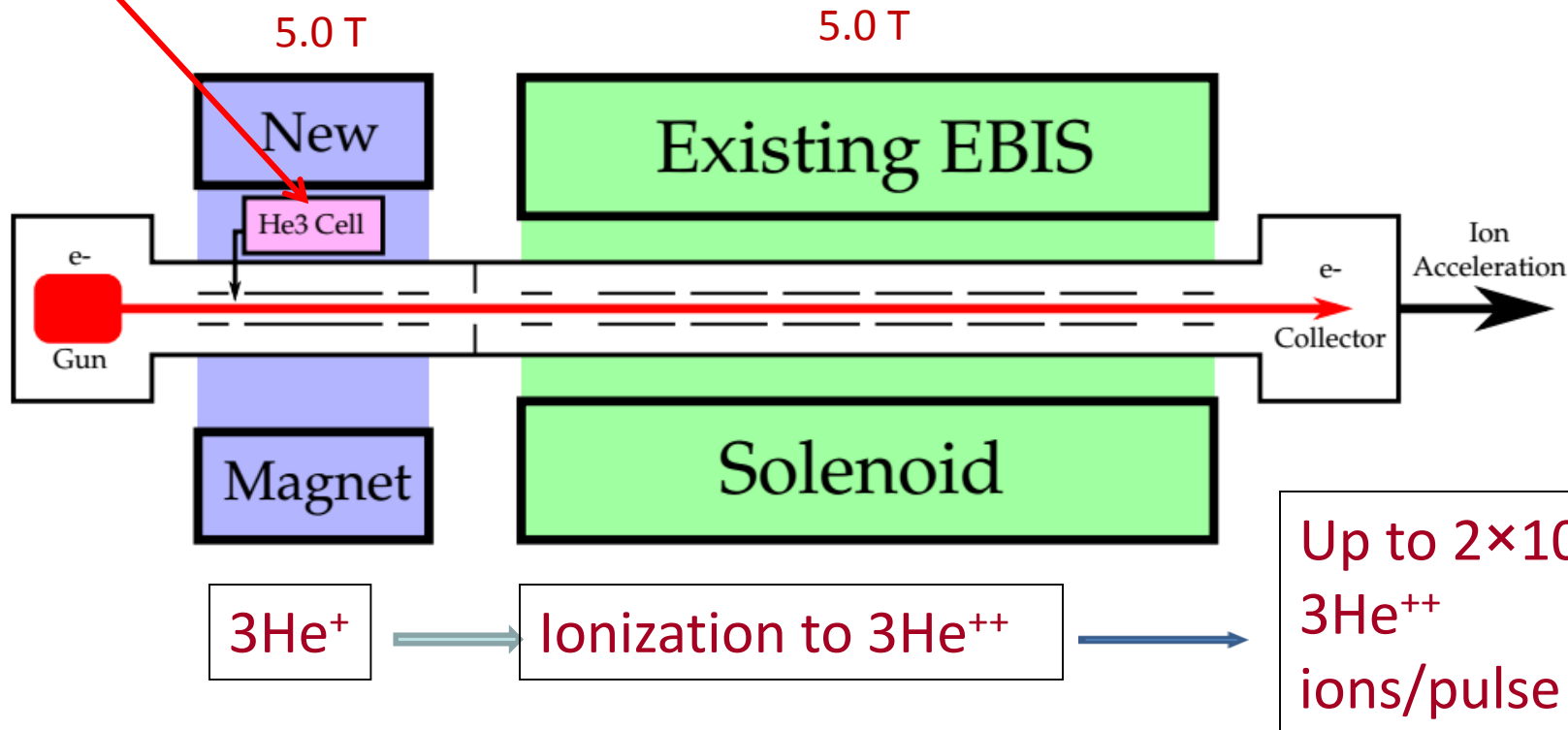
RF-discharge parameters strongly affect maximum polarization.
Optimization of the 3He -cell geometry (smaller diameter?) and electrodes for RF input should improve polarization.

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 $P \geq 80\%$



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 ³He R&D)

- Cost and funding**

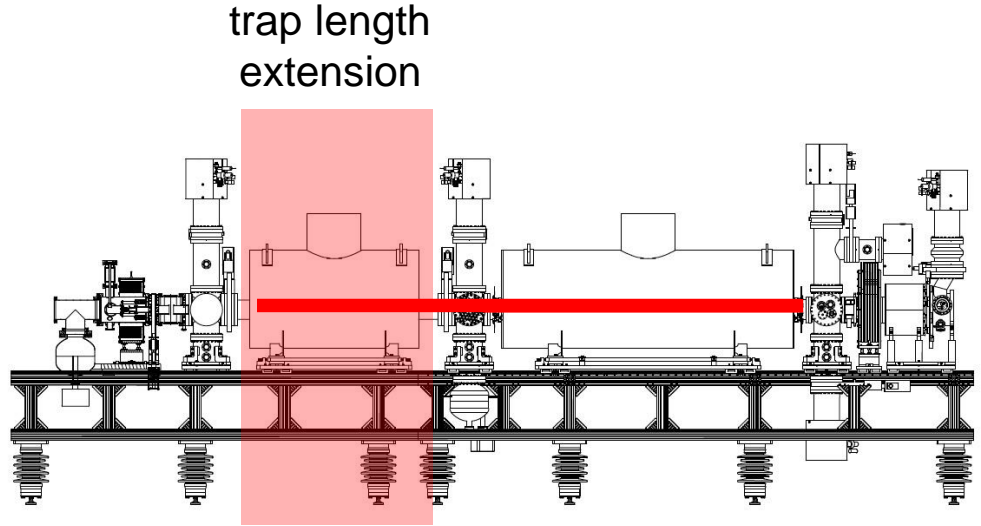
FY2016	2017	Total
\$475k	1350k	1.8M
(P)	(P)	

-

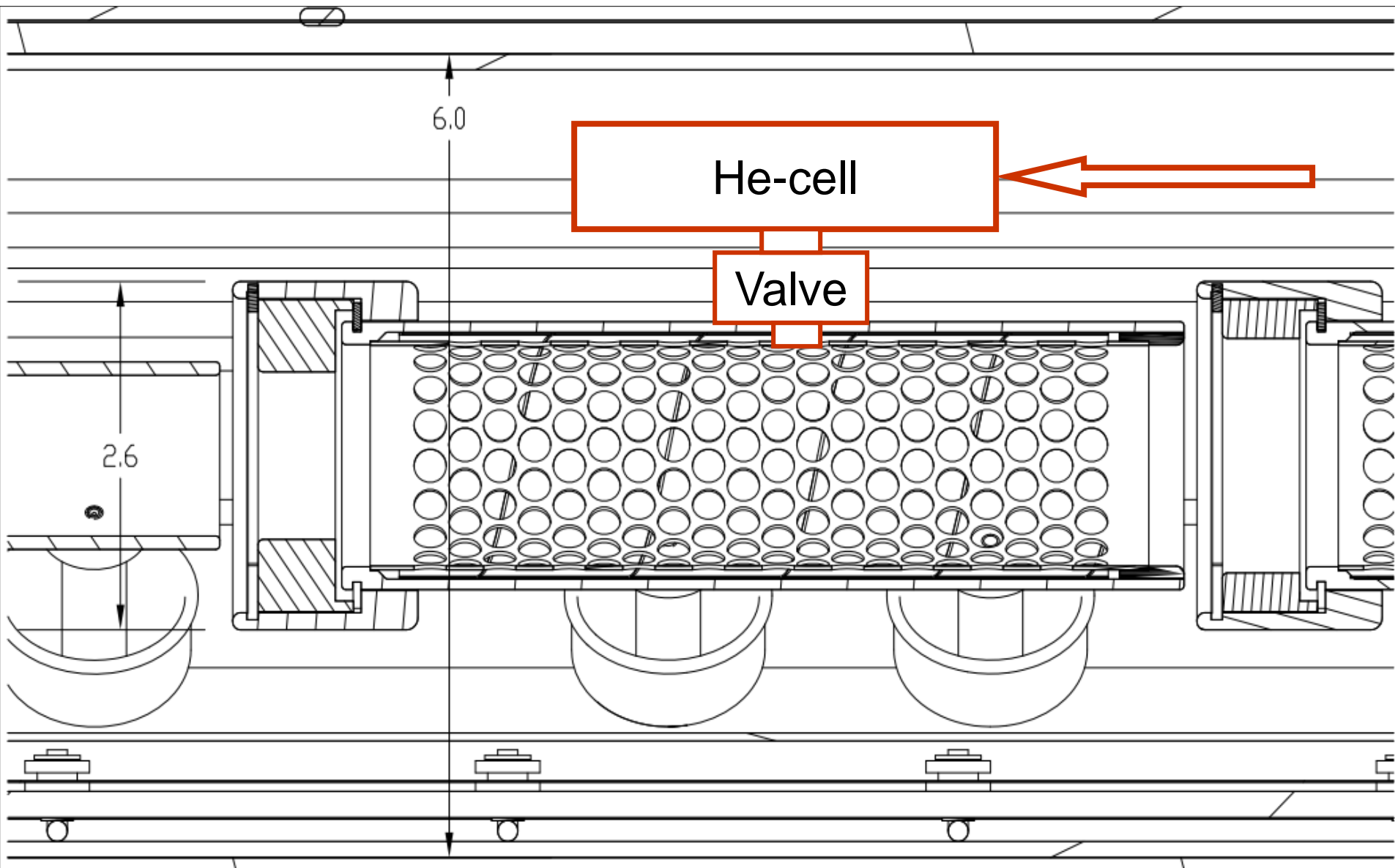
- Schedule**

- 2016 start (solenoid acquisition)
- 2020 planned completion

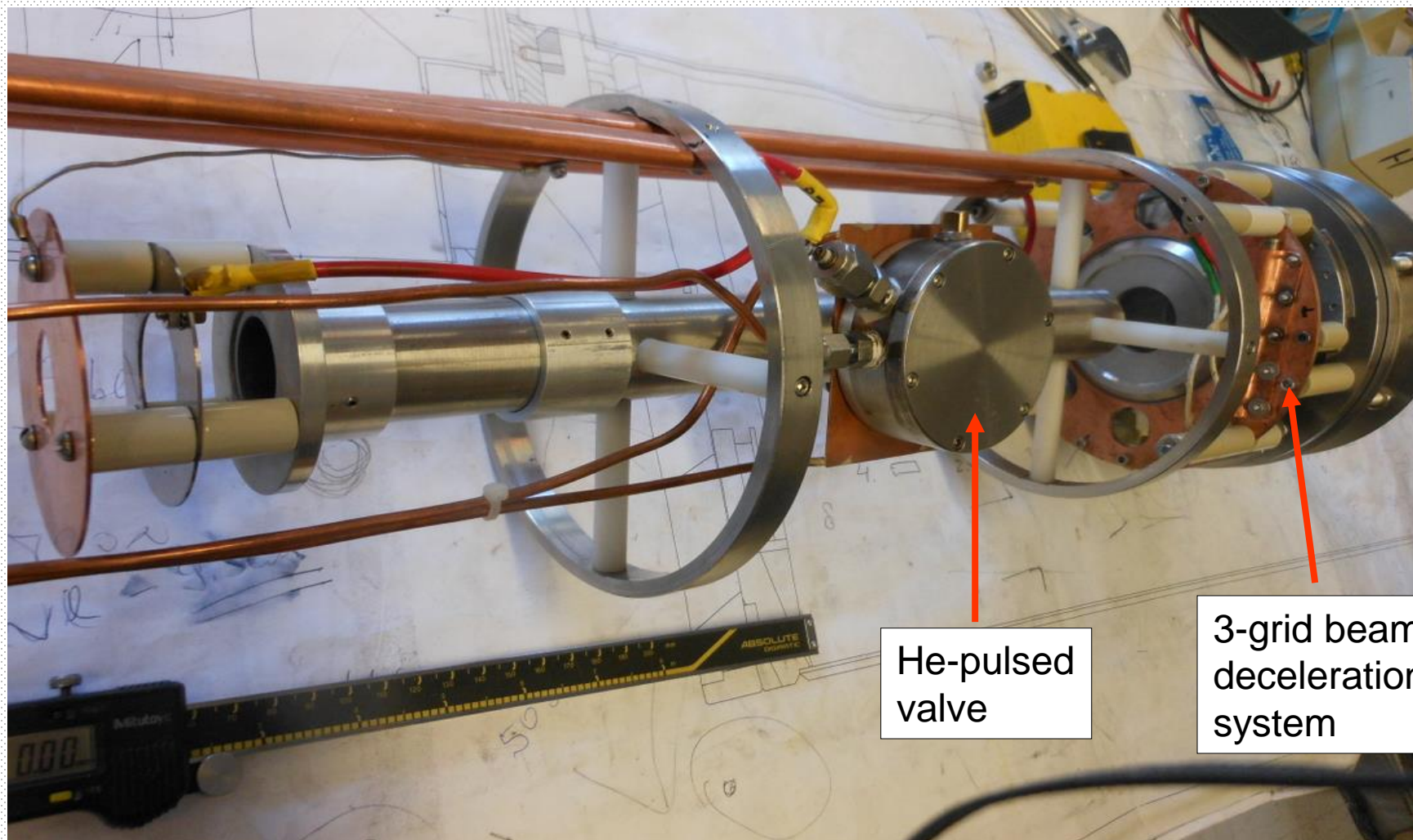
largest risk (cost, schedule and performance):
superconducting solenoid magnet



EBIS center drift tube



He-ionizer cell and three-grid energy separation system

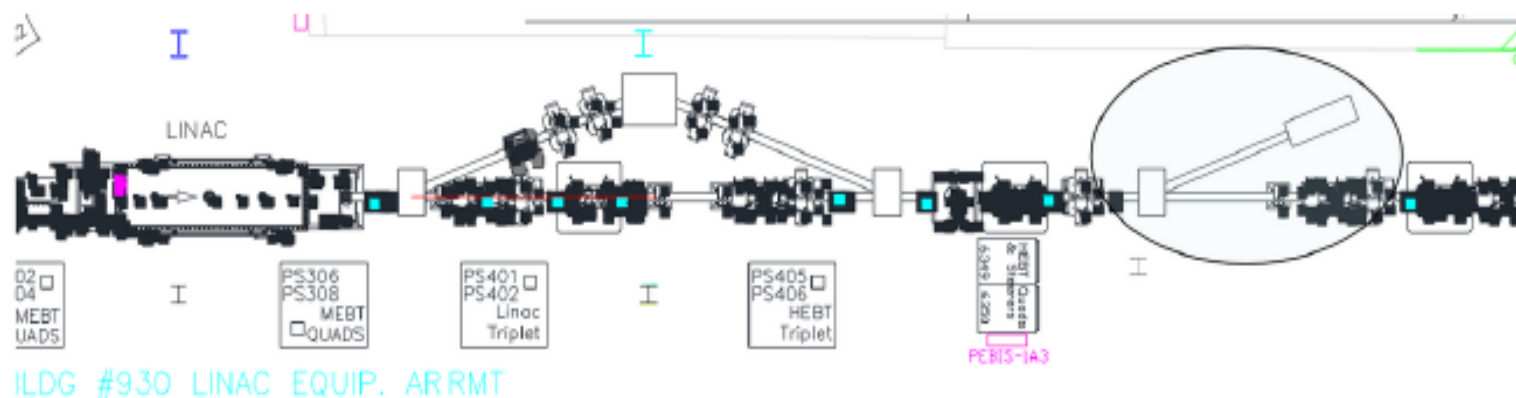


He-pulsed valve

3-grid beam deceleration system

5.3 MeV Helium3–Helium4 Polarimeter

- Transverse polarized ^3He beam on unpolarized ^4He at 5 torr¹⁰, early design by C. Epstein
- At 5.3 MeV, asymmetry due to polarization goes to 1 at 91° center of mass \rightarrow ^3He at 53.6° and 2.66 MeV
- Recoil ^4He as a background at 1.83 MeV, so use $500\ \mu\text{m}$ partially depleted silicon detector for energy resolution
- At 50% polarization, expect 3.7% accuracy in 1 minute



¹⁰G.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 2016-2018.
- Polarized 3He^{++} beam of 2.0×10^{11} ions/pulse and 80 % polarization in 2020