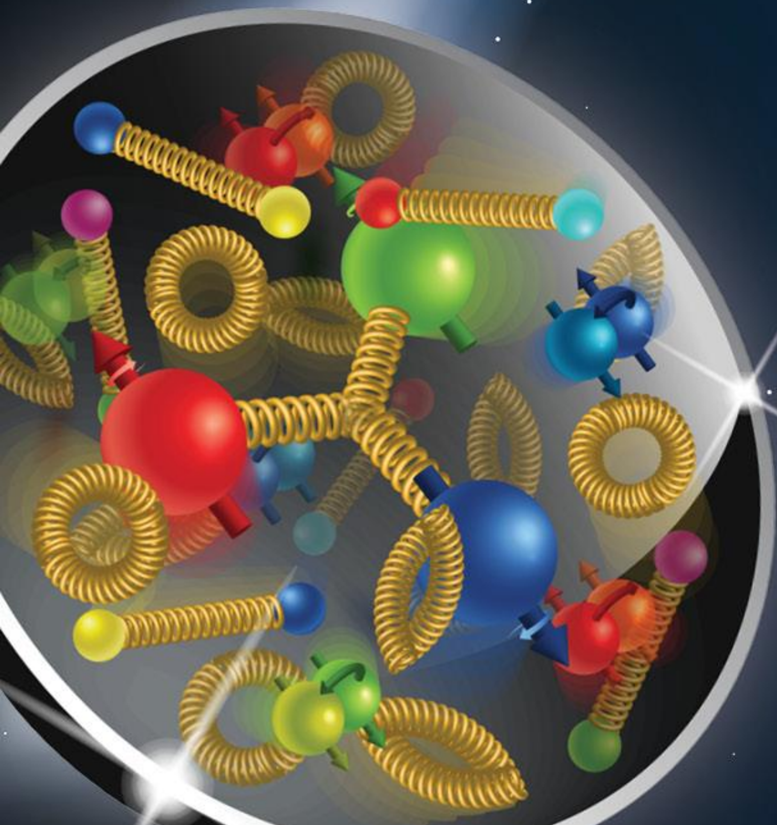
Polarized 3He++ Ion Source Development at BNL



Nuclear Physics Accelerator R&D

PI Meeting

Anatoli Zelenski, BNL

November 13-14, 2018

Electron Ion Collider – eRHIC

BROOKHAVEN NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY | Office of Science

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R.Milner, M. Musgrave, MIT

Polarized 3He++ ion source development at BNL

Funding Source	PI	R&D Report Priority #	R&D Panel Priority Rating	Total $
FY17 Base and Additional	**Anatoli Zelenski**	**6**	**Hi-A**	**$190K BNL + $135K MIT**

The only ion beam species that requires R&D and experimental demonstration is the generation and acceleration of a polarized ^{3}He beam. A robust and high quality R&D program is underway as a collaborative effort between BNL and MIT and results are very promising. This R&D (if successful)

could already contribute to the existing science program at BNL. It is proposed to accelerate a polarized ^{3}He beam in RHIC in 2020, which will provide a full validation of this technical component for the EIC. This proposed R&D includes upgrades to the EBIS that could result in higher ion beam intensities for heavy ions as well. This work will benefit all concepts that have been proposed.

***Polarized 3He++ beam can be accelerated in the AGS and RHIC Using existing "Siberian snakes*"**

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 ^{3}He ion sources were built. A number of new ideas were proposed and tested (not successfully).

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

Production of polarized $^{3}He^{++}$ beam in EBIS. BNL-MIT collaboration

- ^{3}He polarization by optical pumping and metastability-exchange technique inside the EBIS in high (5.0T) magnetic field. No polarization losses in $3He^{+}$ state.

- EBIS is used for <u>efficient ionization</u> and <u>accumulation</u> of polarized $3He^{++}$ ions to the full capacity of about $(2.5\text{-}5.0)\cdot 10^{11}$, $3He^{++}$ ions.

Proposal of production of polarized $^{3}He^{++}$ beam in EBIS.
A.Zelenski, J.Alessi, ICFA Beam Dynamics Newsletter** 30, **p.39, (2003)

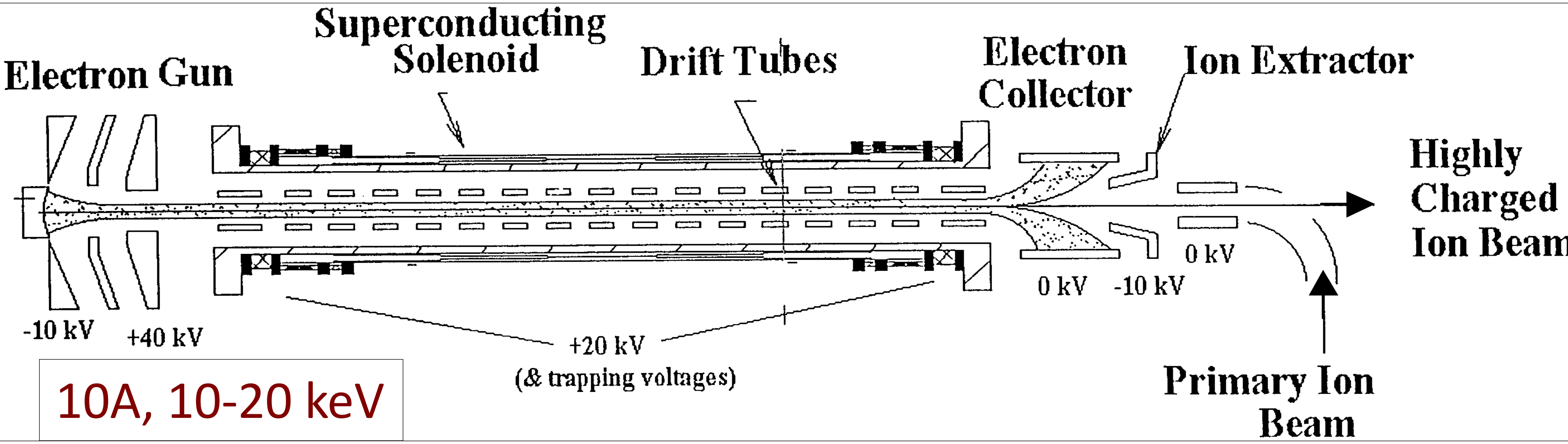
Requirements to the 3He^{++} source

- Intensity ~ $5 \cdot 10^{11}$ 3He^{++} ions in 20 us pulse ~10.0 mA-peak current
- Maximum polarization > 80%
- Compatibility with the operational EBIS for heavy ion physics.
- Spin flip in the beam transport line.

Polarized 3He++ ion source development

- ***3He optical pumping polarization in the high magnetic field.***
- ***3He purification and filling system for the "open" cell configuration.***
- ***3He injection valve development***
- ***Extended EBIS development for 3He++ ion production***
- ***Spin rotator and 3He-4He polarimeter development in 6.0 MeV beam line.***

Principle of EBIS Operation



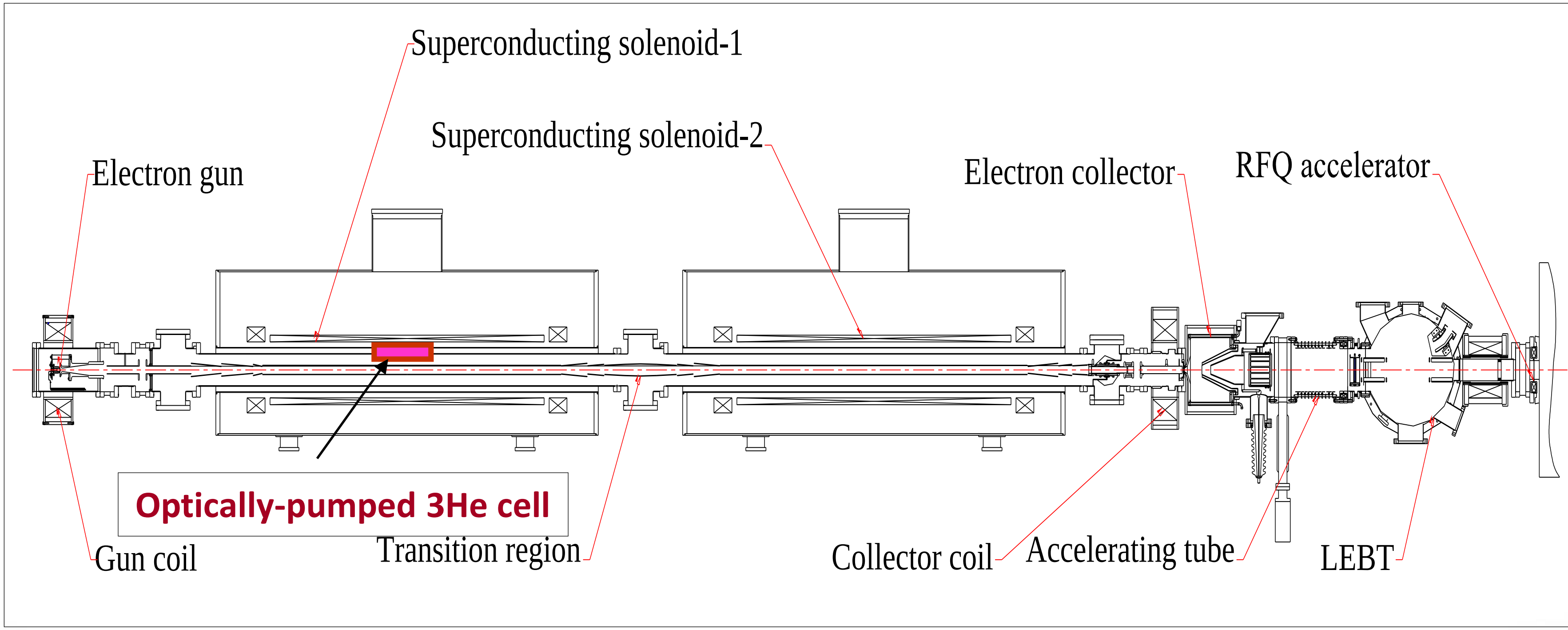
10A, 10-20 keV

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 (number electrons in the trap ~1.0·10^{12})***
- ***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!***

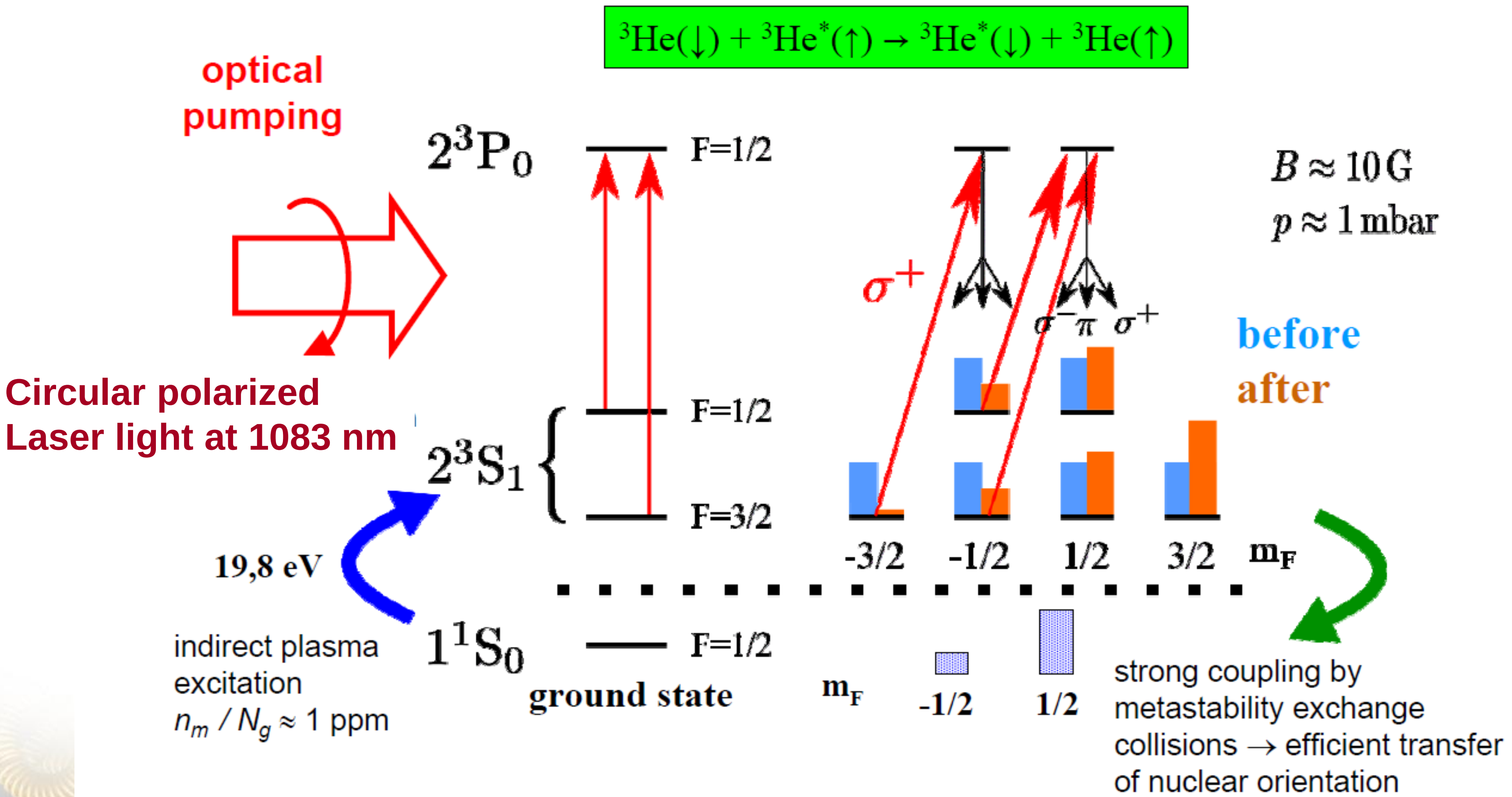
"Extended" EBIS upgrade with new "injector" solenoid for polarized $3He^{++}$ ion production

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

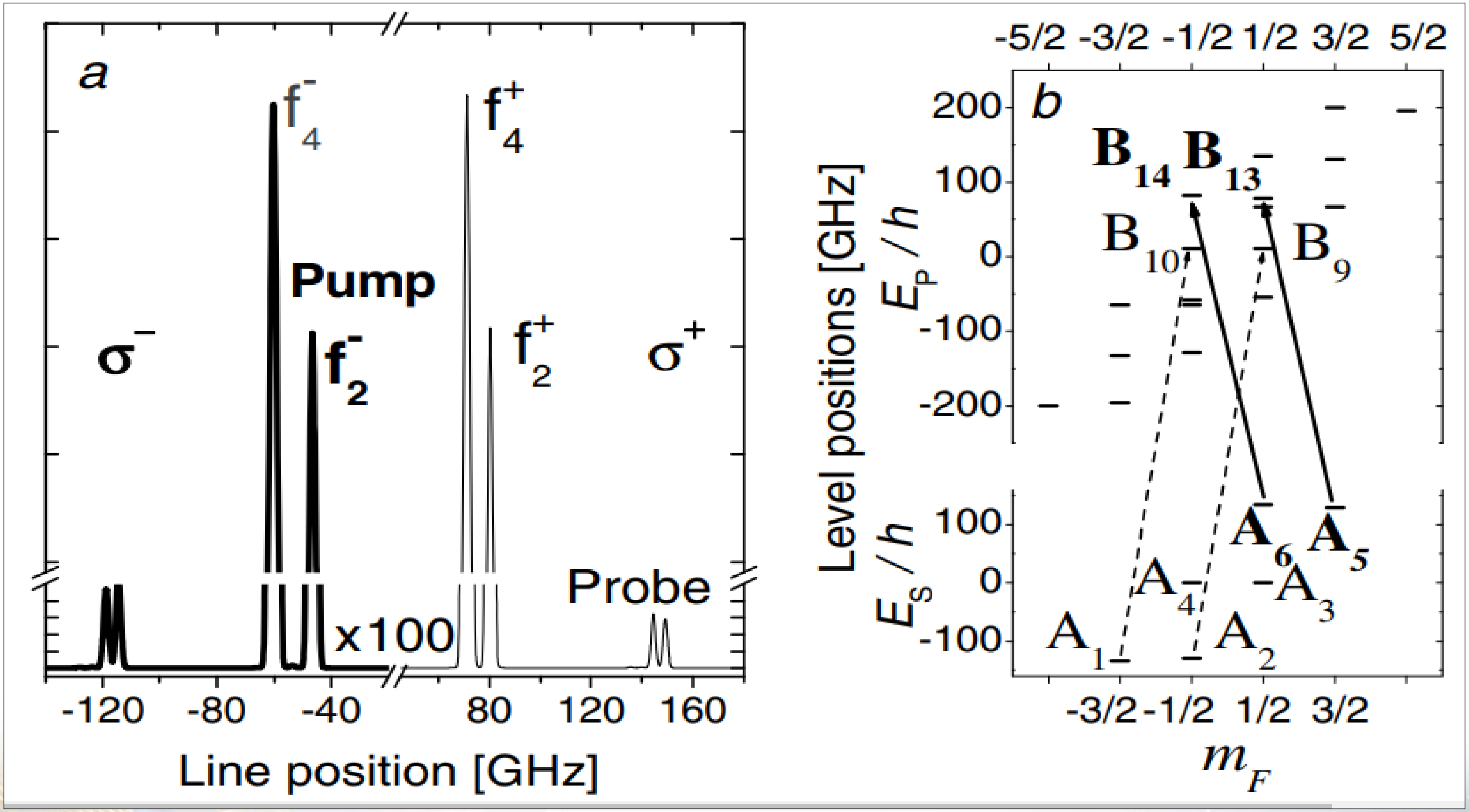


$3He^{+}$ → Ionization to $3He^{++}$ → Up to 5×10^{11} $3He^{++}$ ions/pulse

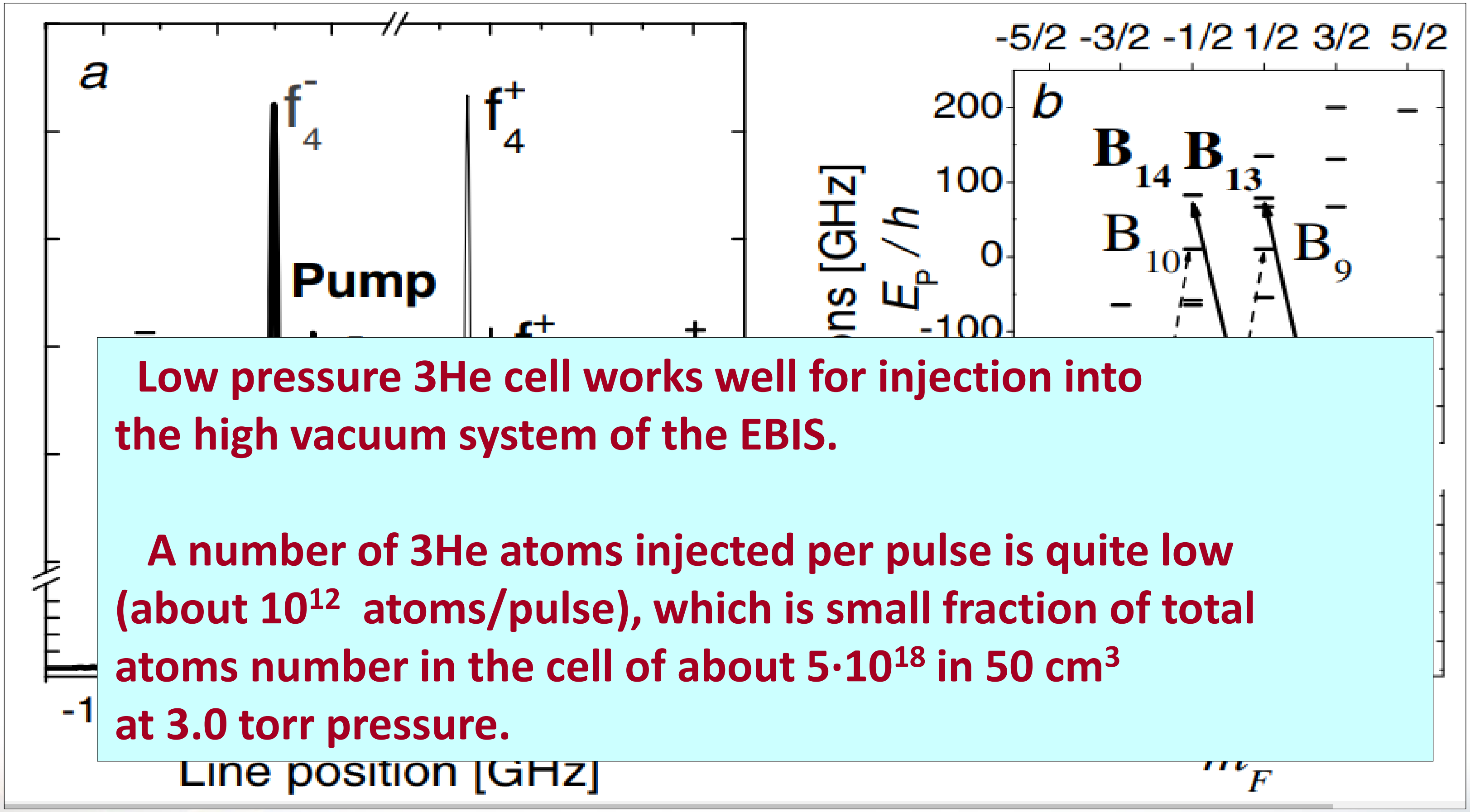
Principle of Metastability Exchange Optical Pumping (MEOP) in ^3He



3He optical pumping in high 2.0-5.0T magnetic field



3He optical pumping in high 2.0-5.0T magnetic field



Low pressure 3He cell works well for injection into the high vacuum system of the EBIS.

A number of 3He atoms injected per pulse is quite low (about 10^{12} atoms/pulse), which is small fraction of total atoms number in the cell of about $5 \cdot 10^{18}$ in 50 cm^3 at 3.0 torr pressure.

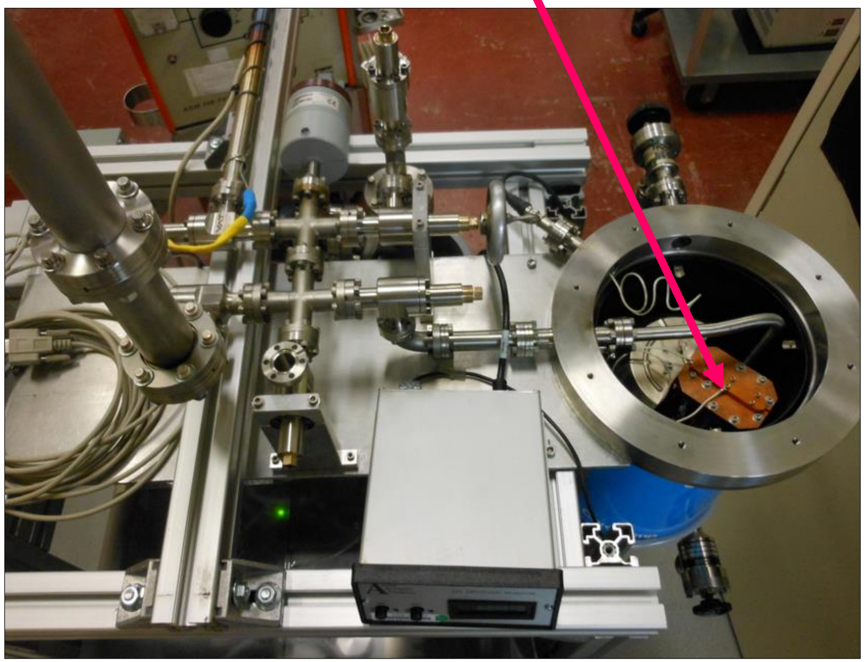
RF-discharge in 3.0 T magnetic field. 3He-cell diameter-25mm

RF-discharge parameters strongly affect maximum polarization.

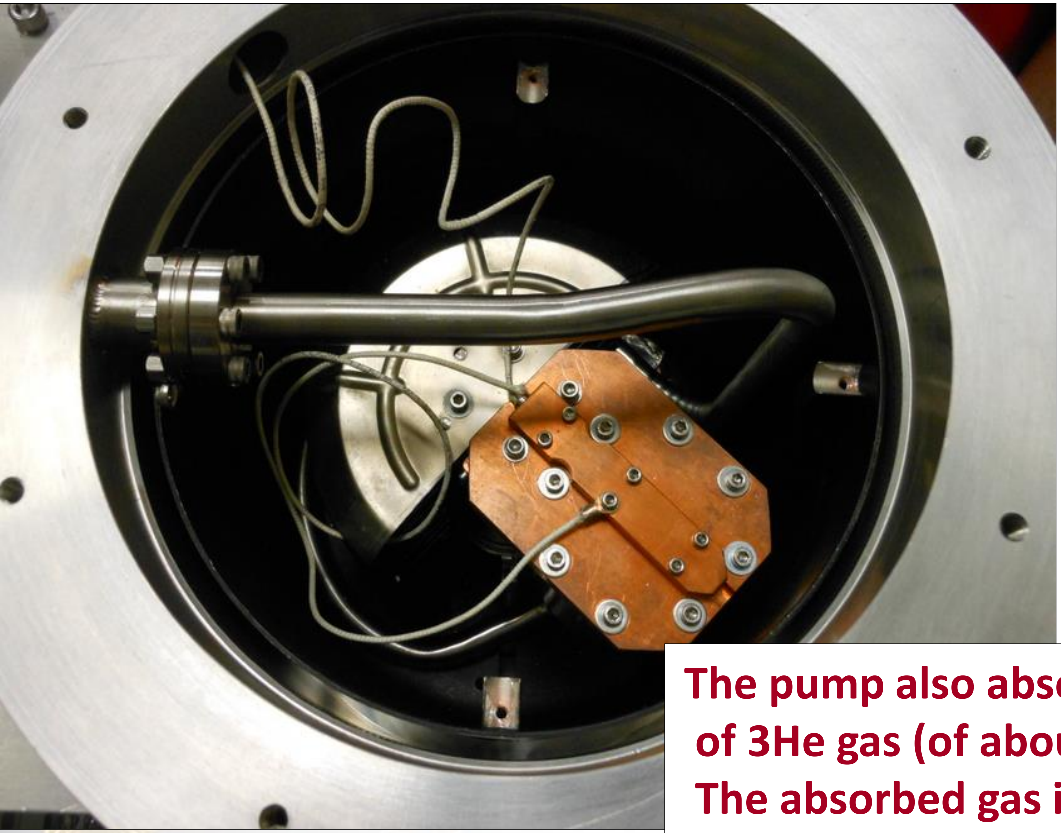
Optimization of the 3He -cell geometry (smaller diameter?) and electrodes for RF input should improve polarization.

3He-gas purification and filling system

Modified Cryo-pump for 3He purification and storage

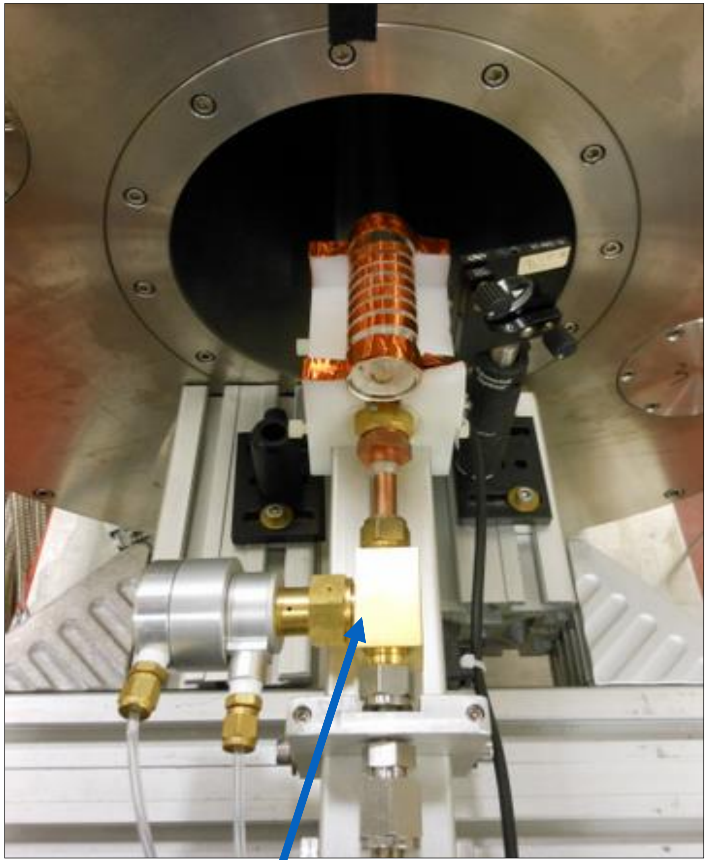


3He cryo- purification system built-in CTI-8 cryo-pump. The pump is pumping all gases except for helium to the level below 10^{-7} torr



The pump also absorbs quite a significant amount of 3He gas (of about 100 sccm).
The absorbed gas is released by the pump vessel heating.
This provides gas storage and supply for 3He-cell operation at the optimal pressure value.

3He-gas purification and filling system

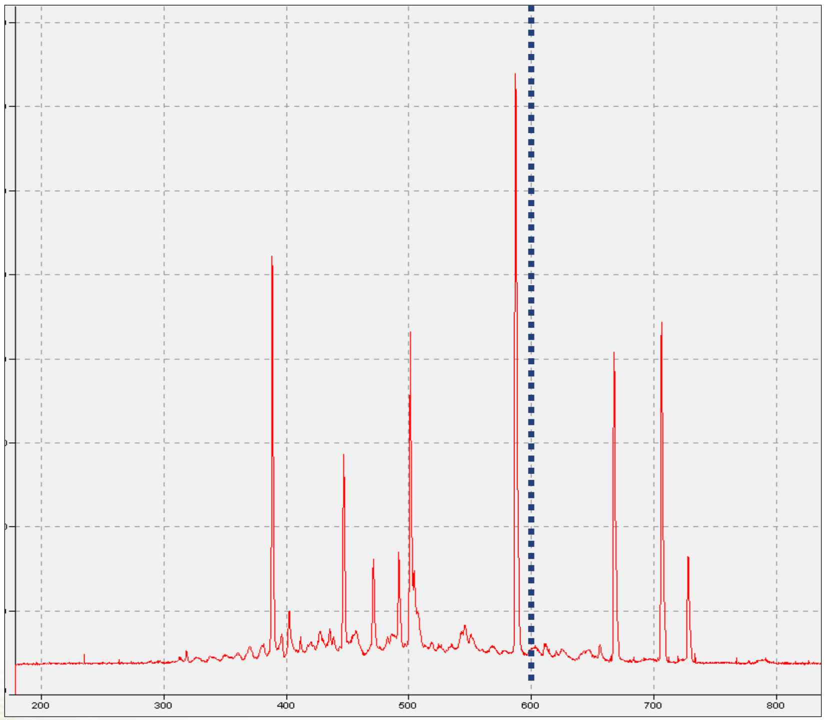


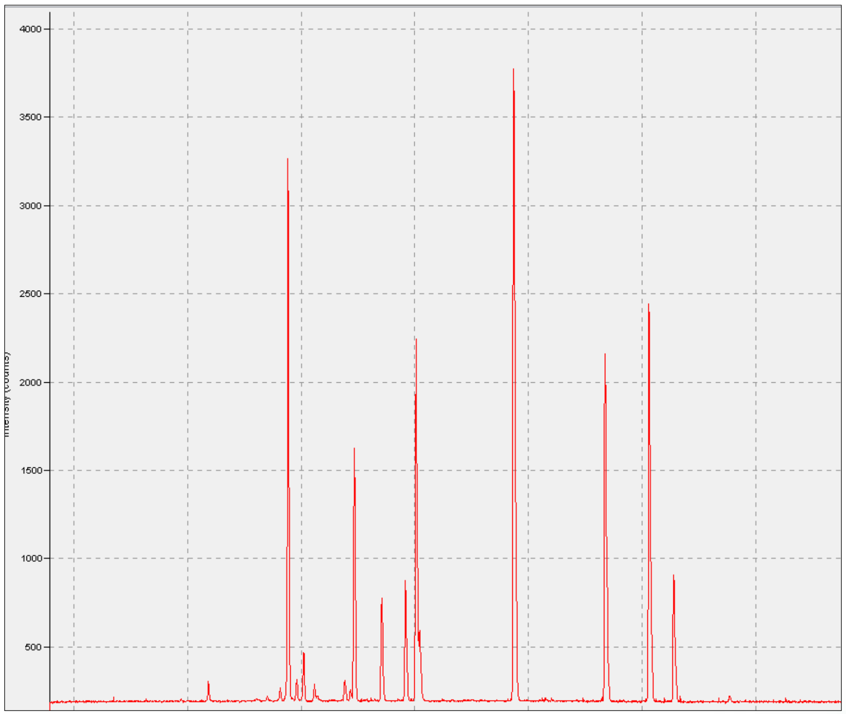
Non-magnetic brass pneumatic remotely controlled Isolation Valve

3He cell cleaning by RF discharge

Impurities in 3He gas from the cell walls out-gassing

After 20 hrs Rf –discharge cleaning





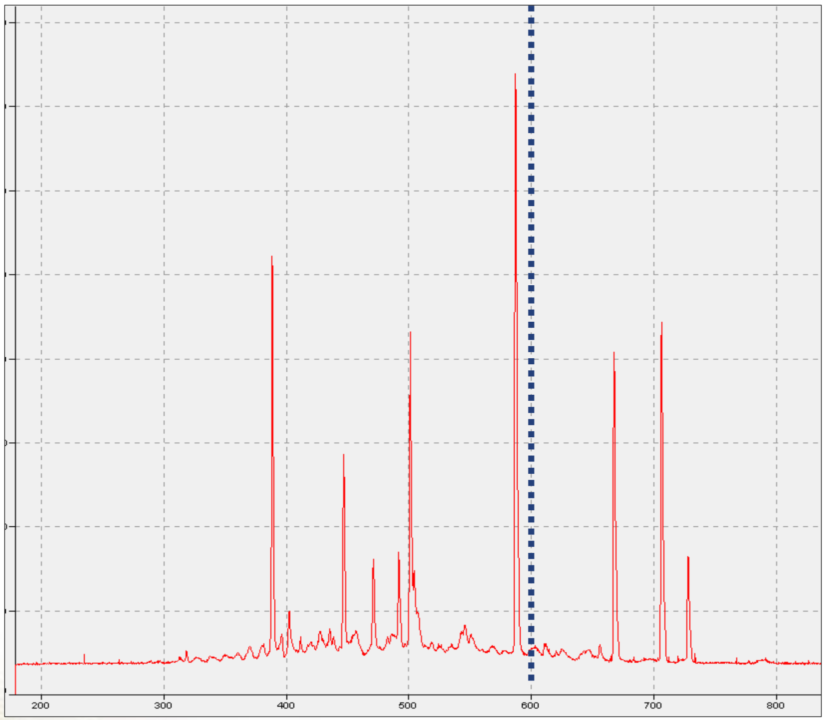
600 nm

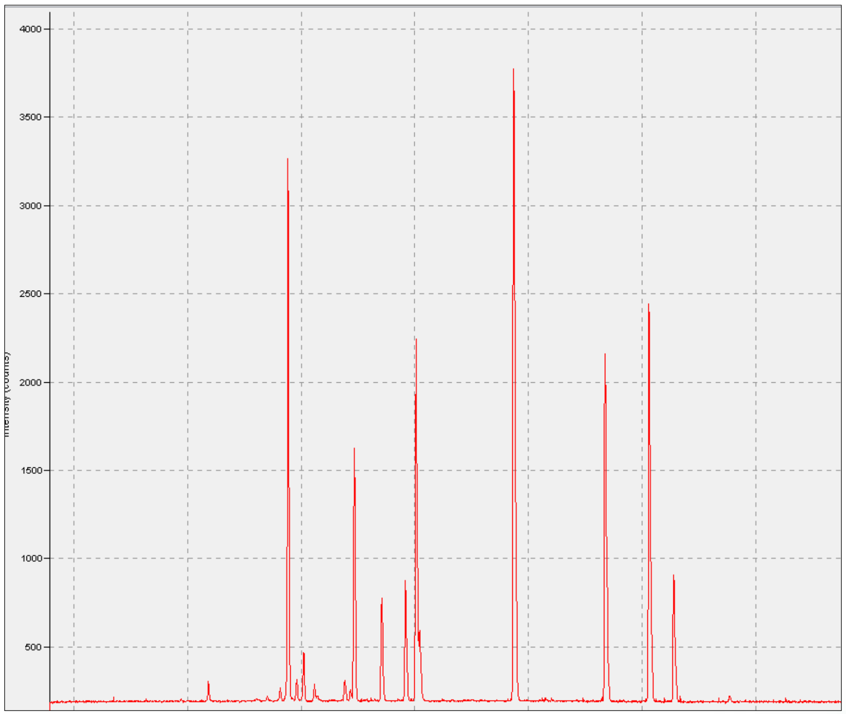
3He optical spectra

3He cell cleaning by RF discharge

Impurities in 3He gas from the cell walls out-gassing

After 20 hrs Rf –discharge cleaning



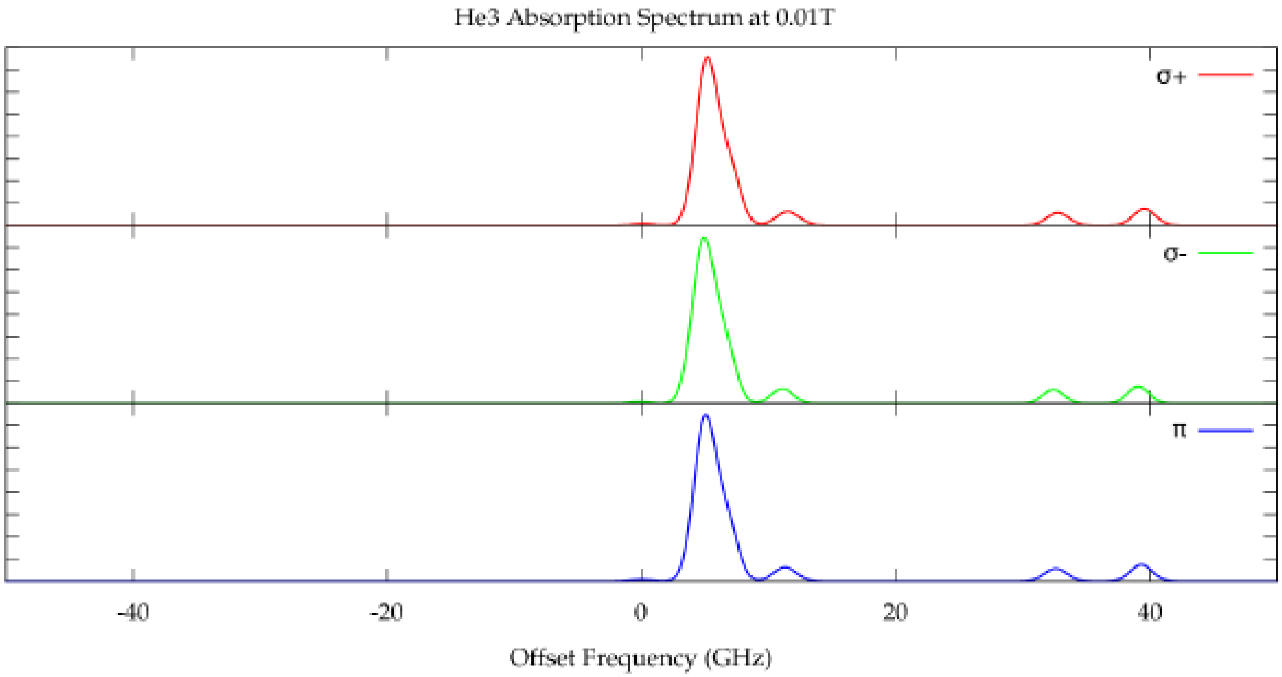


600 nm

3He optical spectra

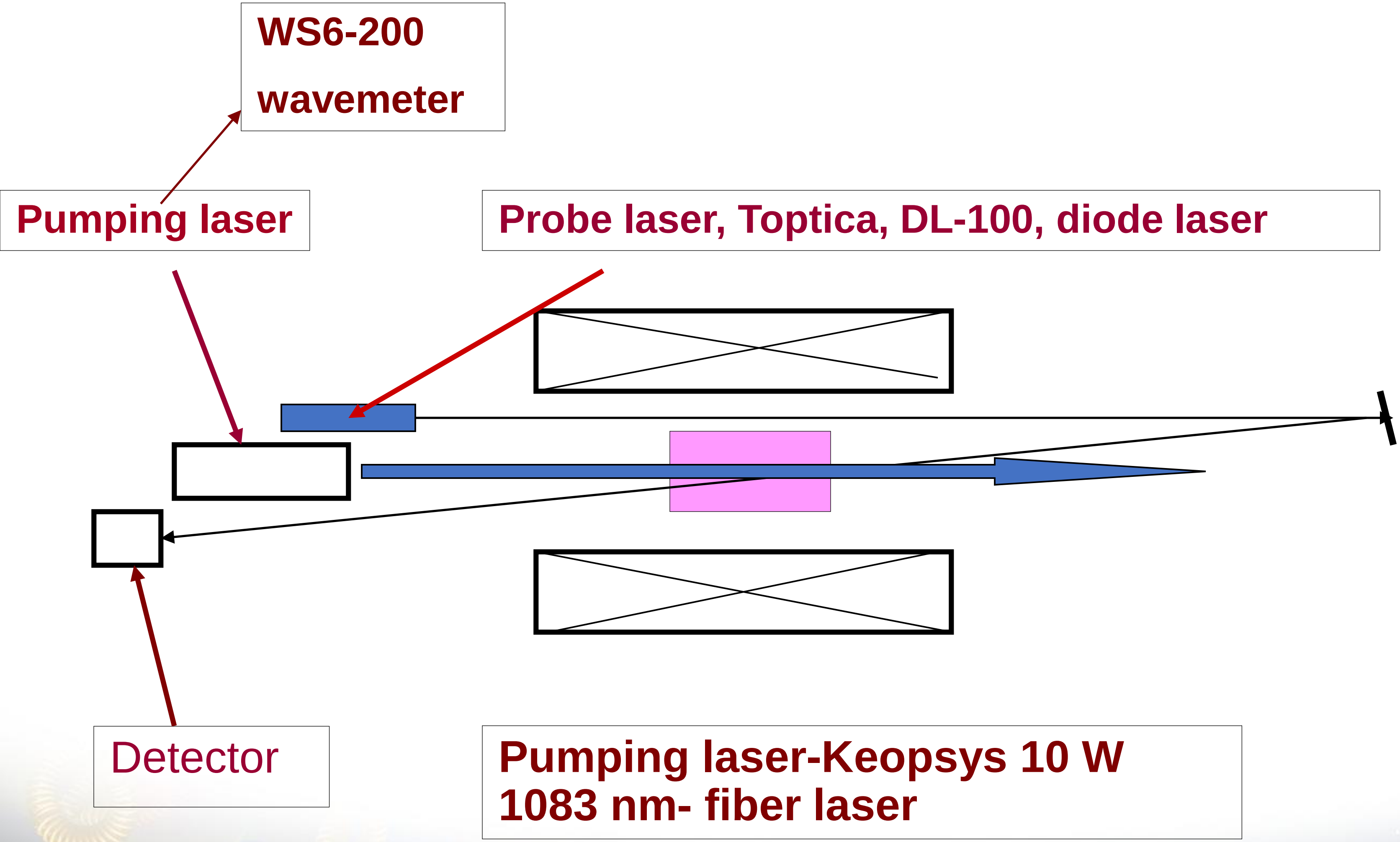
Probe laser absorption Polarimetry

- 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).

Optical pumping and probe lasers layout

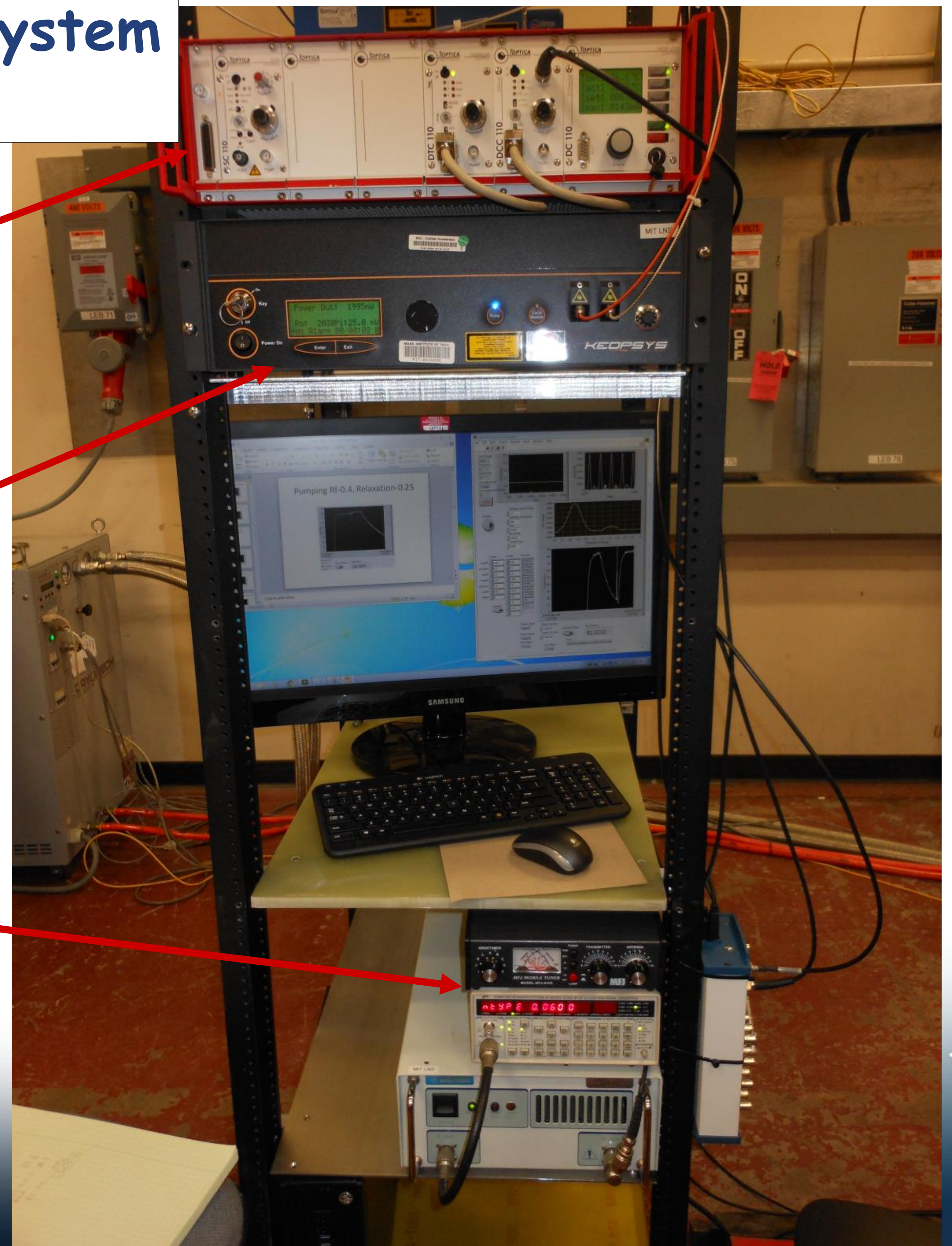


Lasers , RF and control system In one movable rack

Probe laser controller

Pumping laser controller

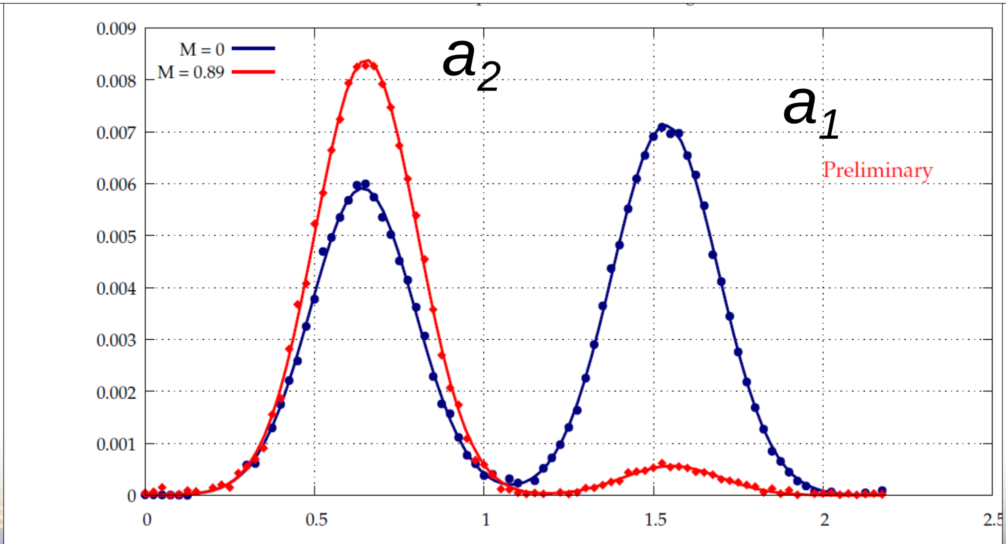
RF master oscillator and amplifier



Polarization measurements by the probe laser absorption technique

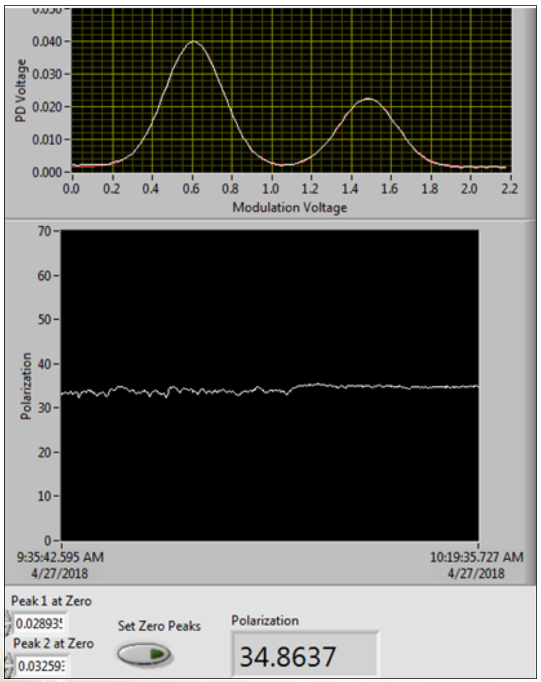
At spin-temperature equilibrium, the populations a_1 and a_2 of the probed Zeeman sublevels satisfy: $a_2/a_1 = e^{\beta} = (1+M)/(1-M)$. As long as this equilibrium prevails, the nuclear polarization is given by:

$$M = \frac{(a_2/a_1 - 1)}{(a_2/a_1 + 1)}. \tag{10}$$



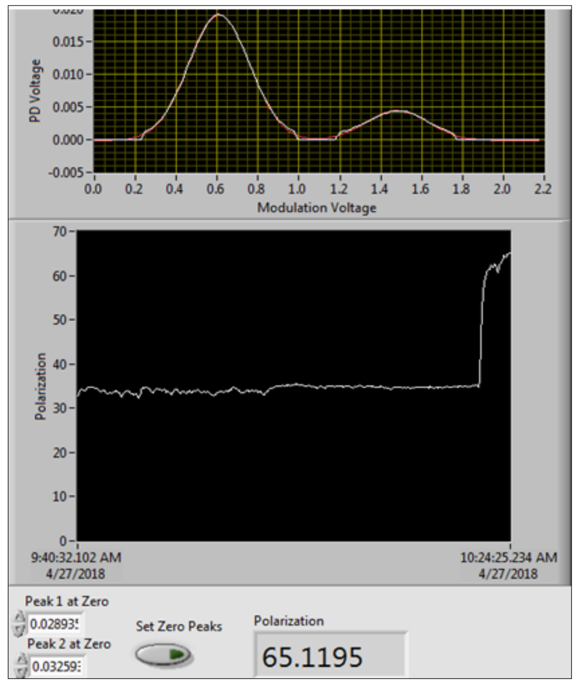
Polarization measurements

Isolation Valve (IV) open



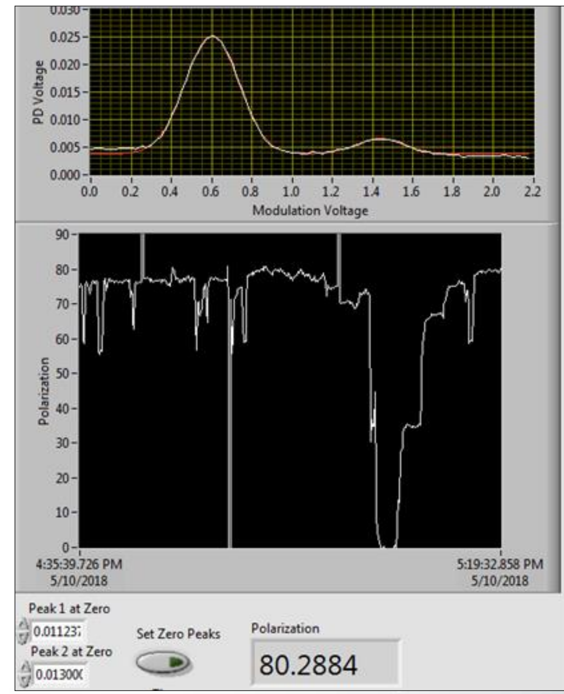
34.9%

Isolation Valve (IV) closed



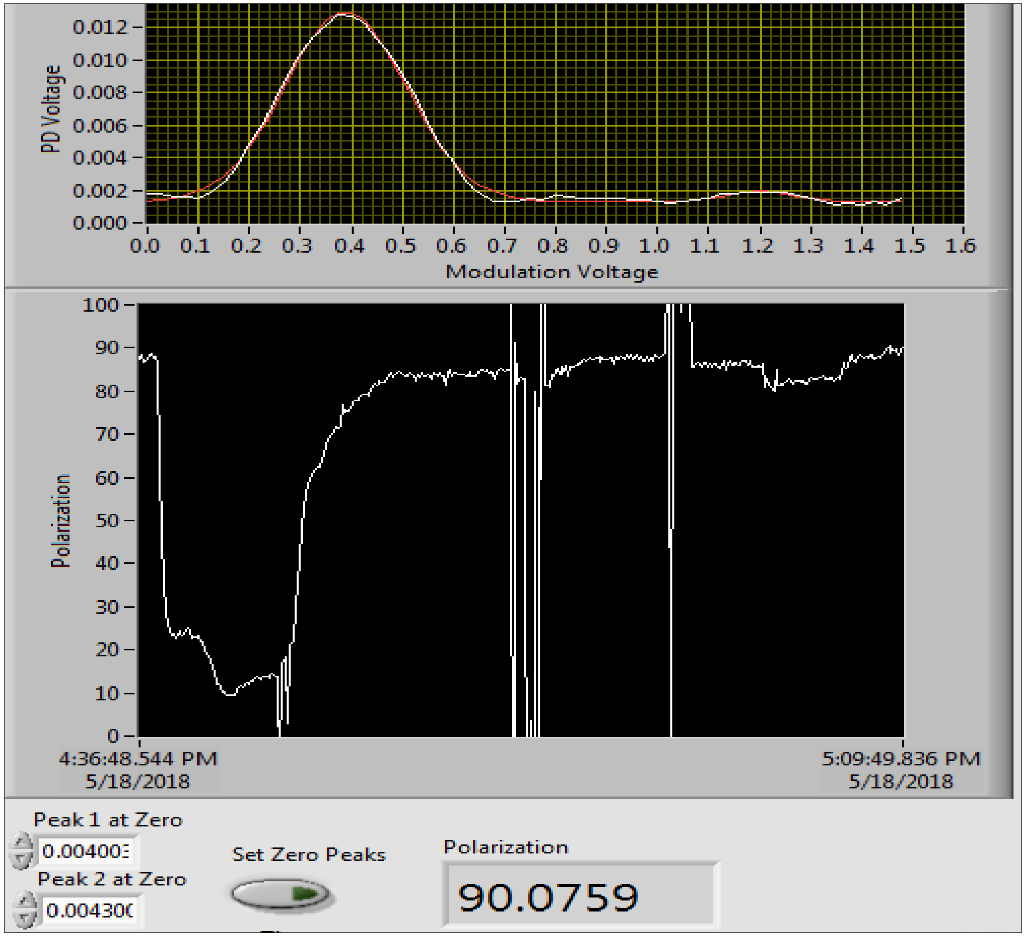
65.1%

Polarization equilibrium



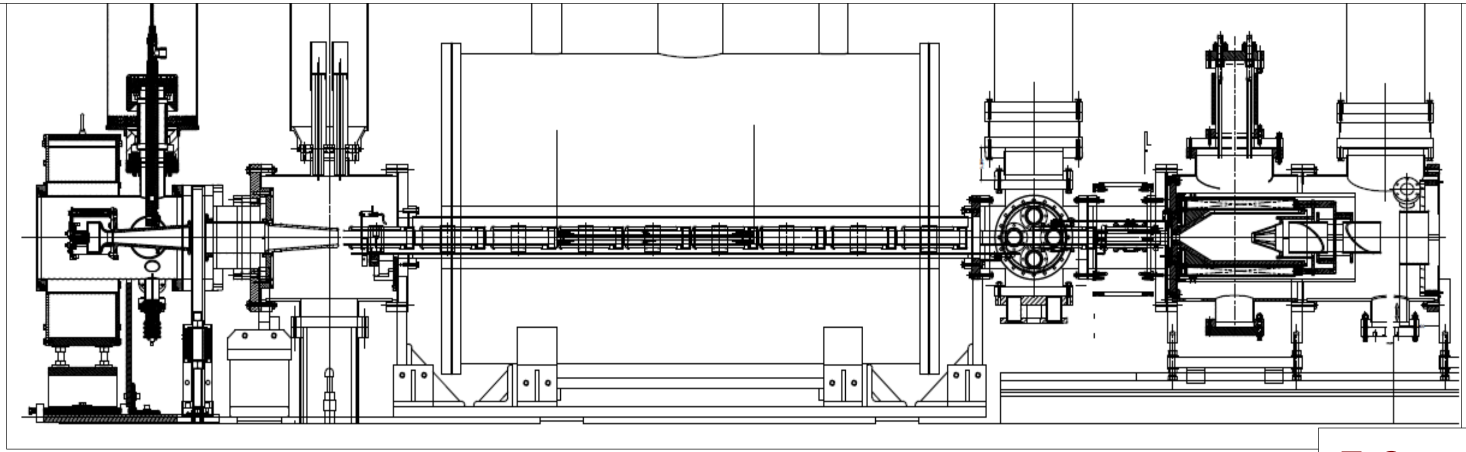
80.3%

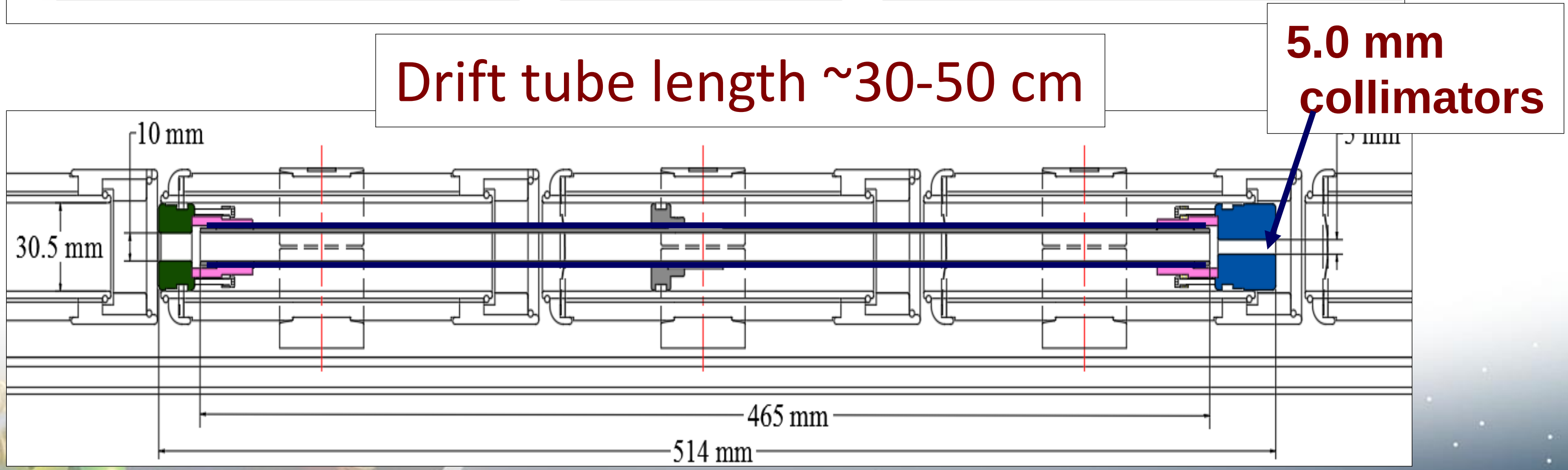
Laser power-3.5 W, mirror "in", Pol-90+/-5%



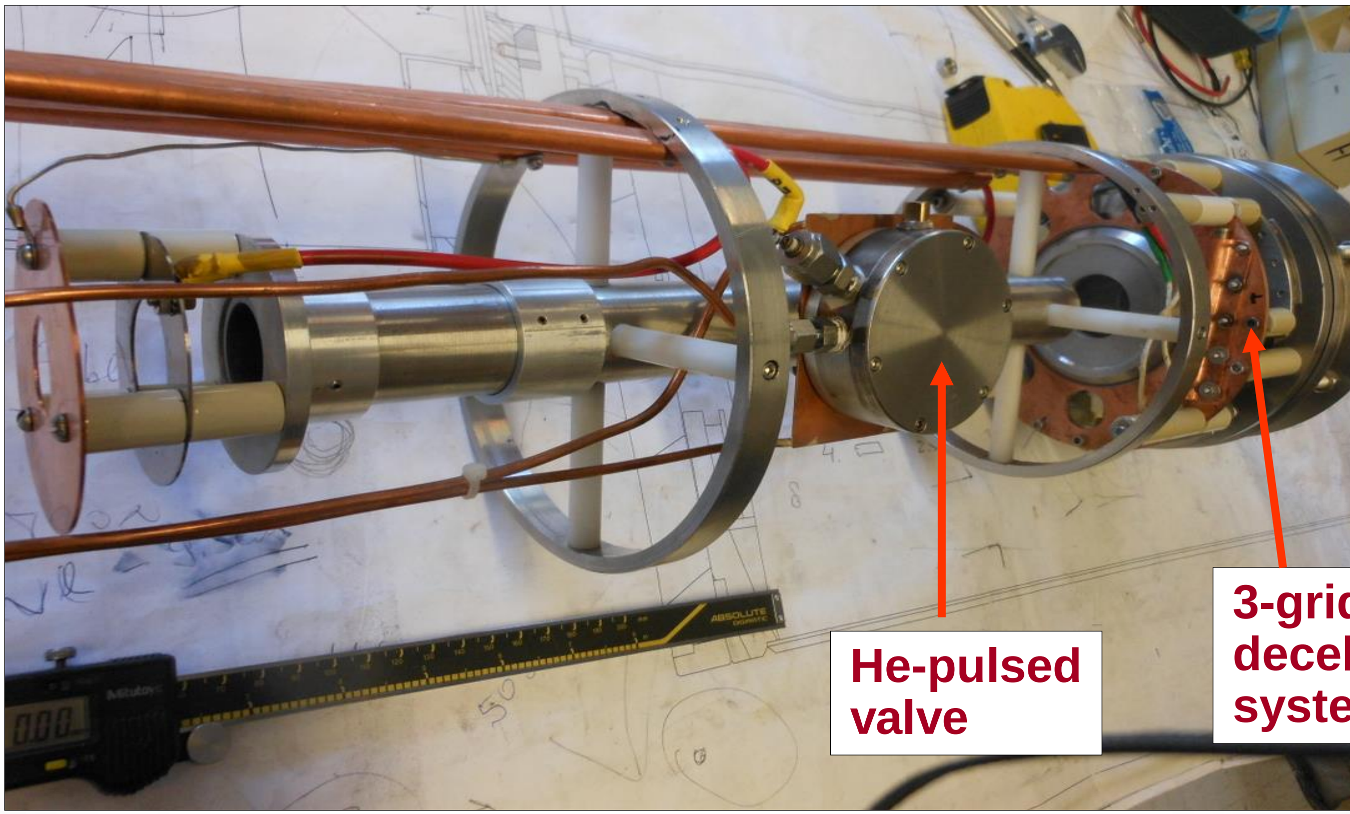
Feasibility study of the small 10 mm diameter drift tube in EBIS with pulsed gas injection in the center

Long, small diameter drift tube works like a 3He storage cell, which reduces gas load to the EBIS vacuum system and increases polarization due to ionization localization in the high magnetic field region.



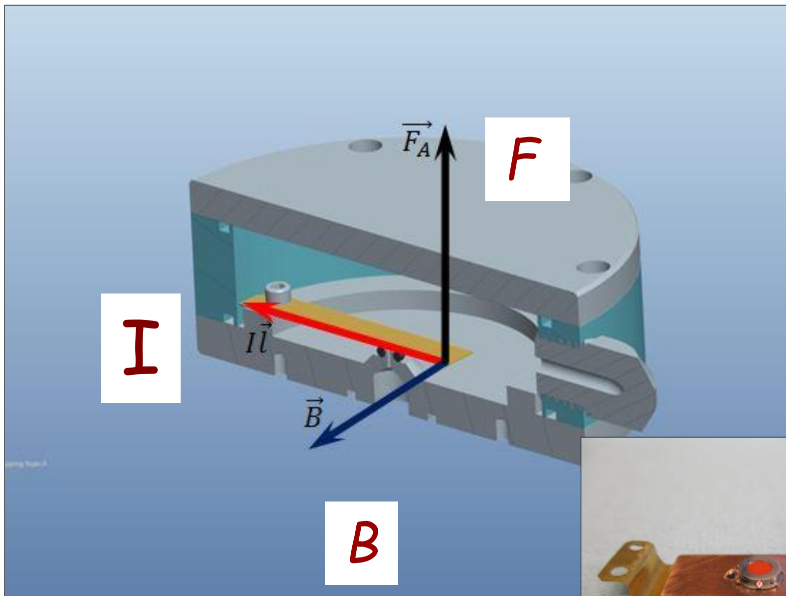


RHIC OPPIS (Optically-Pumped Polarized H- Ion Source) He-ionizer cell and 3-grid energy separation system

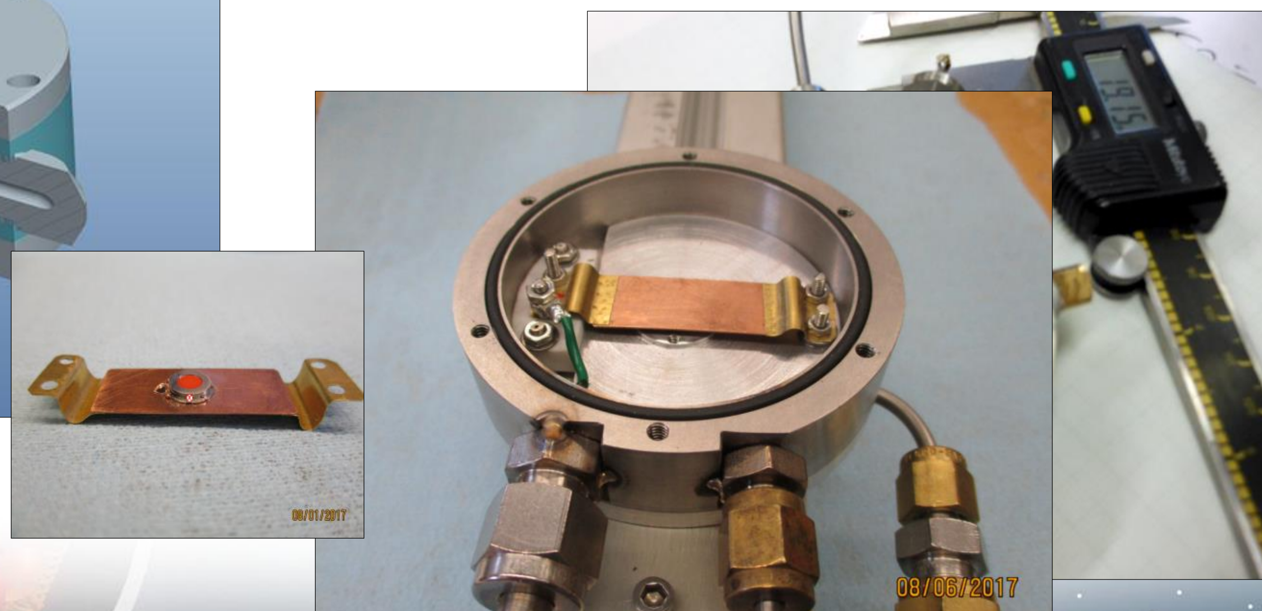


"Electro-dynamic" valve operation principle

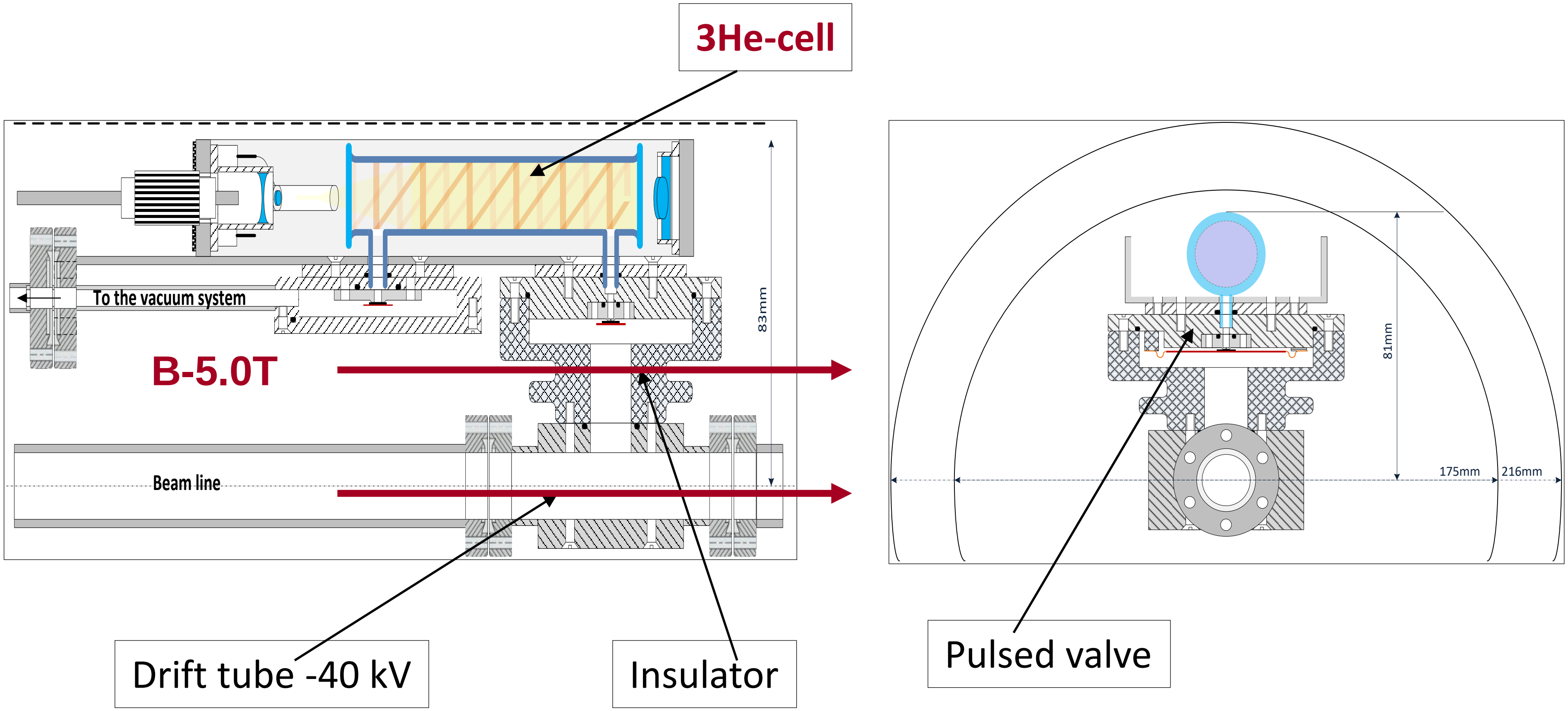
Lorentz (Laplace) force moves the flexible conducting plate in the high (~ 3-5 T) magnetic field.
For I=10 A, L=5 cm, F=2.5 N. Current pulse duration ~100-500 us



$$d\vec{F_A} = I[d\vec{l}\ \vec{B}]$$



3He –optically-pumped cell in the high magnetic field



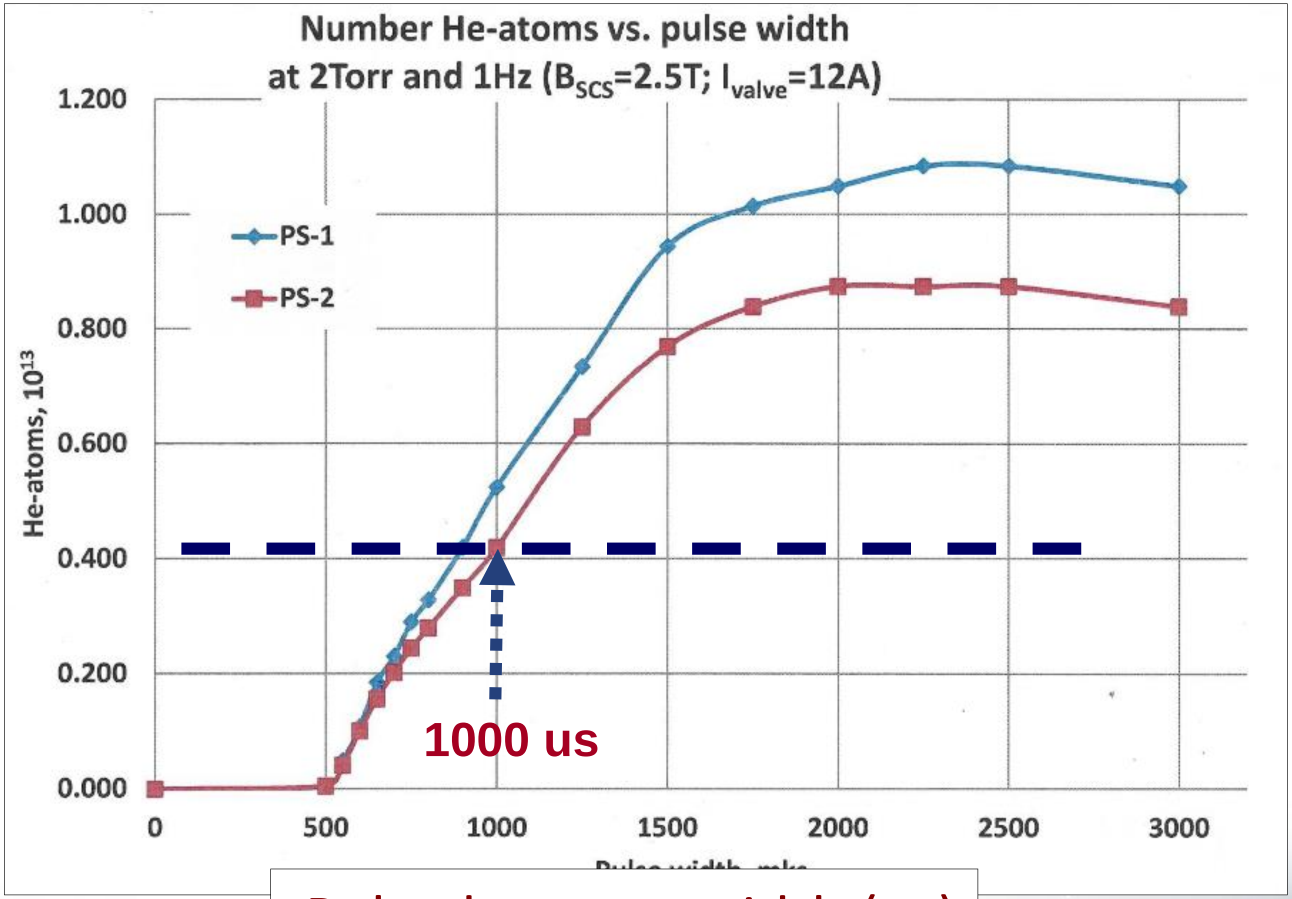
Long, small diameter drift tube works like a 3He storage cell, which reduces gas load to the EBIS vacuum system and increases polarization due to ionization localization in the high magnetic field region.

Assembly of the valve and insulator

In the 2.0 T solenoid field the 1.0" long insulator is holding 40 kV voltage difference in between valve and drift tube up to 0.1 Torr He-gas pressure "magnetic isolation".

Pulsed 3He valve operation in 2.0T solenoid.
He-flow vs. pulsed current width

$4 \cdot 10^{11}$ 3He
Atoms per/pulse

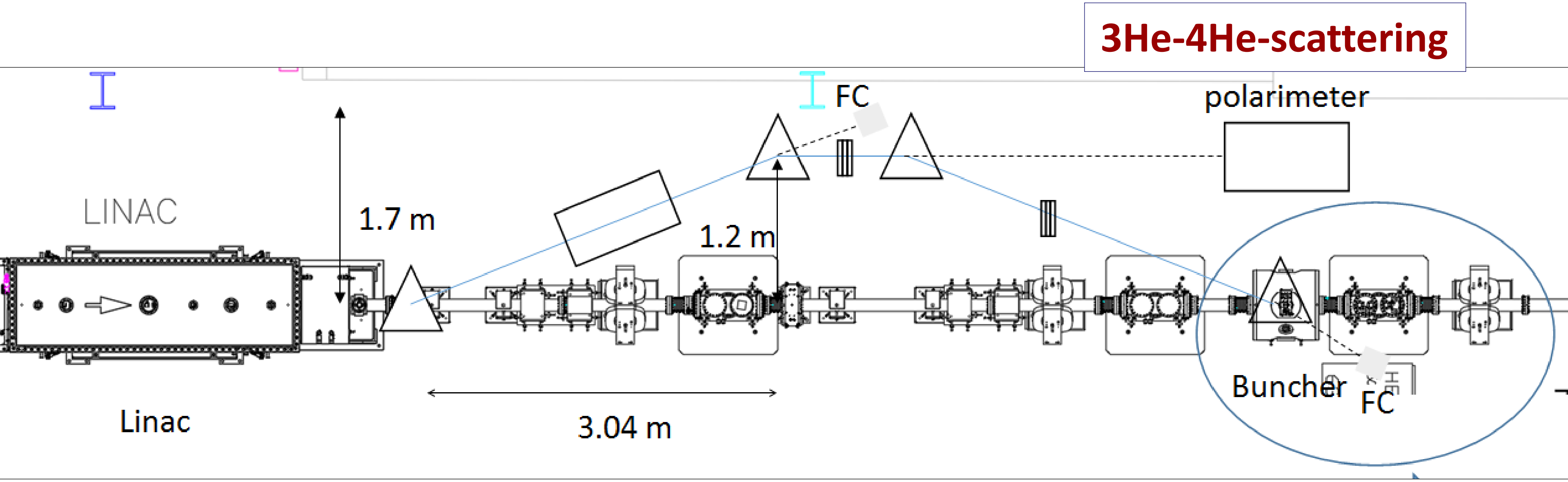


Pulsed current width (us)

Extended EBIS superconducting solenoids, April 2018

5.0 T field, about 1.0 T field at minimal solenoid separation- 25 cm

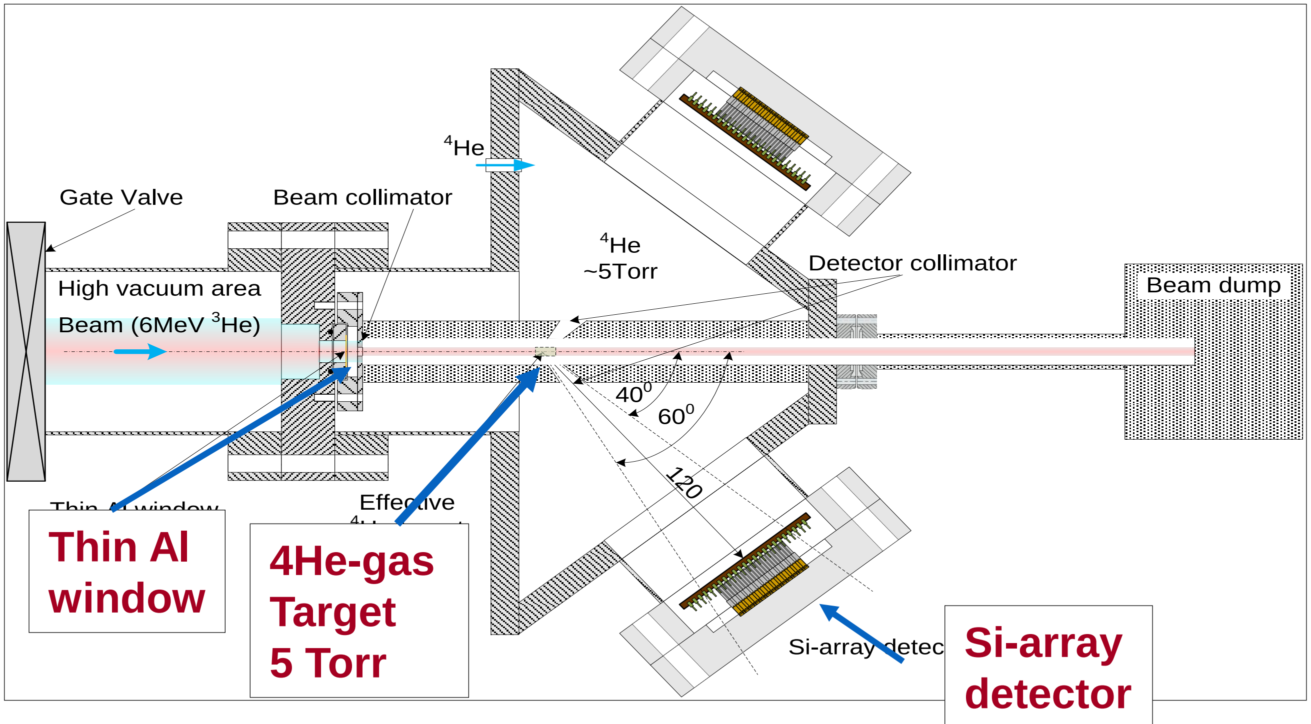
3He^{++} spin-rotator and polarimeter in the EBIS HEBT line at 6.0 MeV beam energy



The development of the 3He polarizing apparatuses, the spin-rotator, and the nuclear polarimeter at the 3He++ ion beam energy 6.0 MeV (in the high-energy beam transport line after the EBIS drift-tube Linac) is funded by the DOE Research and Development Funds for the Next Generation Nuclear Physics Accelerators Facilities.

3He-4He scattering polarimeter at 5.3 MeV beam energy

3He++ beam
6.0 MeV



Analyzing power in 3He-4He elastic scattering at 5.3 MeV beam energy and 53.6° - angle is close to 100%.

Cost and Schedule

Lab Base R&D	FY10+FY11	FY12+FY13	FY14+FY15	FY16+FY17	Totals
a) Funds allocated				325,000	516,927
b) Actual costs to date				146,138	146,138

Purchaces: $41k +$28k-of new pumping and probe lasers are in progress

Activity	Start Date	End Date
Acquisition of Post Doc Researcher		August 2017
Simulation Study on Polarized 3 He	September 2017	March 2018
Interpretation of experimental results and development of improvement to the process	April 2018	August 2018

Summary

- Polarized 3He++ production is important part of the ongoing extended EBIS "upgrade" project.

- High polarization of 3He was achieved in the "open" cell in the high magnetic field.

- A new technique of 3He purification system (based on cryo-pumping) was developed to meet the strict requirements for high polarization.

- A new type of the pulsed electromagnetic valve was developed for 3He injection into the drift tube.

- The 3He++ source, spin-rotator and polarimeter development is funded by DOE grant: F2018-19 Research and Development for Next Generation Nuclear Physics Accelerator Facilities.

FY 2018 Research and Development for Next Generation Nuclear Physics Accelerator Facilities

Funding Opportunity Number: DE-FOA-0001848

Announcement Type: Initial

CFDA Number: 81.049