OPTICALLY-PUMPED POLARIZED $^3He^{++}$ ION SOURCE AND ABSOLUTE POLARIMETER DEVELOPMENT AT RHIC

Workshop on Polarized Sources Targets and Polarimetry 2022 (PSTP22)

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September 26-30, 2022

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U.S. DEPARTMENT OF ENERGY

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Outlines

- **Introduction**
- **Polarized ^{3}He ion source as part of the EBIS upgrade**
- **Polarized ^{3}He ion source**
- **Spin-Rotator**
- **6MeV ^{3}He polarimeter**

Introduction

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

Now polarized $^3He^{++}$ production is a part of the ongoing EBIS upgrade project.
The development of the polarized ^3He ion source is being done as a collaboration between BNL and Massachusetts Institute of Technology (MIT).

The spin-rotator and polarimeter is funded by DOE Grant Research and Development for Next Generation Nuclear Physics Accelerator Facilities.

U. S. Department of Energy
Office of Science | Nuclear Physics FY 2018
Research and Development for Next Generation Nuclear Physics Accelerator Facilities

… A doubly polarized electron-ion collider (EIC) is the best way to examine the internal structure of the proton and neutron. The technology to accelerate polarized proton beams has been well established at RHIC. However, studying the structure of the neutron requires the acceleration of polarized $^3He^{++}$, which carries ~90% of its polarization in the neutron, and to match the unprecedented statistical precision an EIC will provide, it is indispensable to have high precision measurements of the hadron beam polarization. For this reason, development of a polarized ^3He ion beam has been identified as an R&D priority by the EIC Advisory Committee in 2009 and the Office of Nuclear Physics Community Review in 2017.

EBIS upgrade: second "extended" SC Solenoid (part-1)

The Extended EBIS upgrade is approved by the Accelerator Improvement Project and is presently under development at BNL. The main purpose of this upgrade is to increase the intensity of the ion beam.

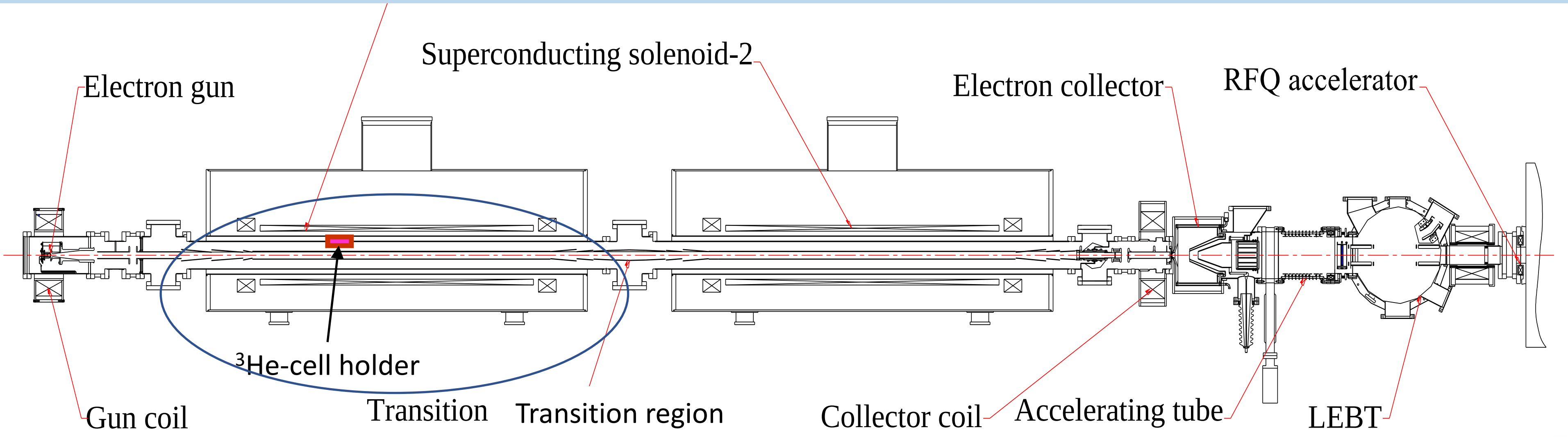
The installation of a second solenoid as part of this upgrade.

This makes it possible to create a source of polarized ^{3}He ion source for the RHIC and the future EIC.

One of goals of this upgrade is a polarized $^3He^{++}$ ions source with up to ~ $5 \cdot 10^{11}$ ions/pulse.

The polarized ^{3}He ion source will be mounted on the Solenoid-1.

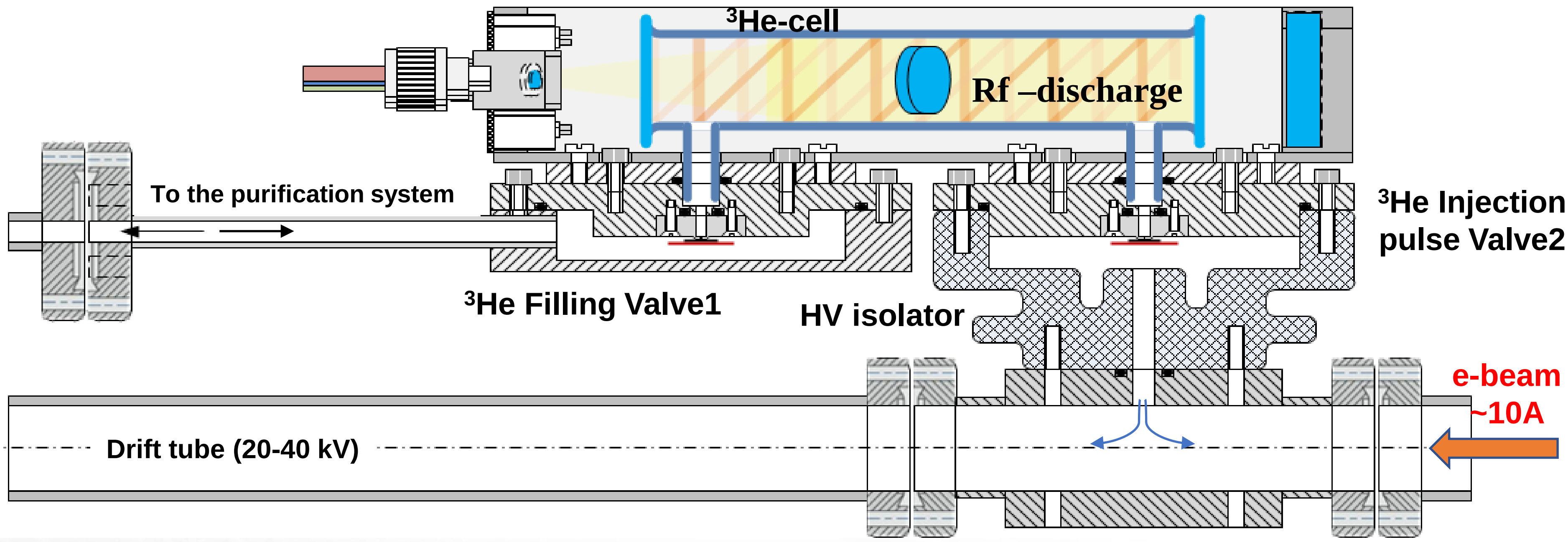
- **The atoms of the ^{3}He gas will be polarized by Metastability Exchange Optical Pumping (MEOP) technique and**
- **After injected through a fast pulse valve in the ion trap region of the EBIS.**
- **There the ^{3}He ions will be trapped and bred to the $^3He^{++}$ state.**



Holder ^{3}He-cell with filling and injection valves inside the EBIS SC Solenoid-1

Procedure to polarize the ^{3}He gas at high magnetic field:

- Prepare the ^{3}He gas for polarization by the purification system; Valve1-open/ Valve2-close
- Polarize the ^{3}He gas inside the glass-cell by a MEOP technique; Valve1-close/ Valve2-close
- Continually control the polarization of the injected ^{3}He gas by using the Optical Probe polarimeter;
- Inject a polarized ^{3}He portions into drift tube (beam line) through the pulsed valve (~2-3*10^{12} atoms/pulse); Valve1-close/ Valve2-open
- Ionize the polarized atoms of ^{3}He by electron beam (~10 A).

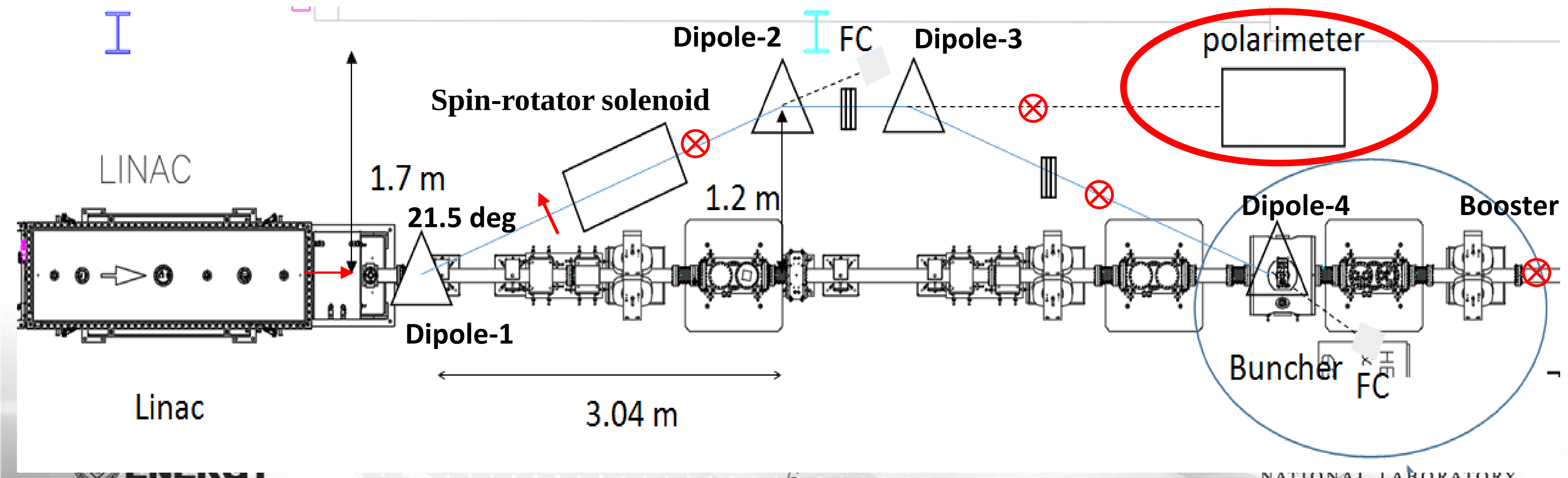


EBIS upgrade: Spin-Rotator and ^{3}He polarimeter (part-2)

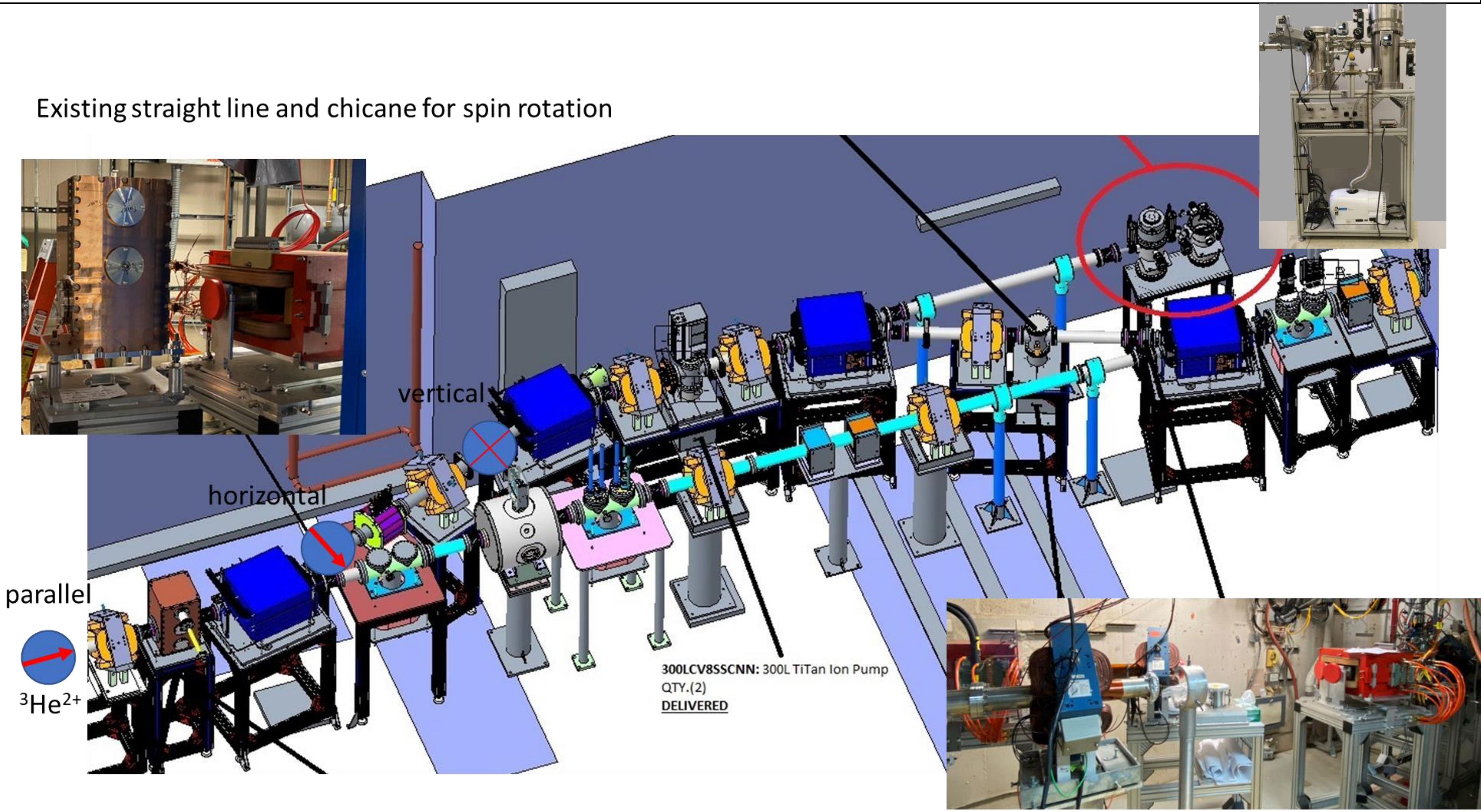
After acceleration by EBIS LINAC, the polarized $^3He^{++}$ beam will have an energy of 6MeV with a longitudinal spin direction.

- The longitudinal polarization of beam is at first rotated to transverse direction using the 21.5 deg bending magnet (Dipole-1) and after
- the Spin-Rotator will change the spin direction to the vertical . The Spin-Rotator is a pulsed solenoid with reversible field to enable spin-flip on an EBIS pulse-by-pulse basis.
- Vertically polarized beam will return to the straight HEBT line by the system of dipole magnets (2,3,4).

The polarimeter will install in the straight section after the Dipole-3 magnet. With a spin-flip, we can measure polarization of the beam with a standard configuration of left/right symmetric Si-strip detectors (in the same way as the 200MeV pC polarimeter at LINAC, or pC polarimeter at AGS and RHIC, or the H-jet polarimeters at RHIC).



Existing straight line and chicane for spin rotation



- The spin rotation will be done by the combination of dipole magnet and solenoid in the chicane.
- All components are placed and being aligned.

^{3}He polarimeter

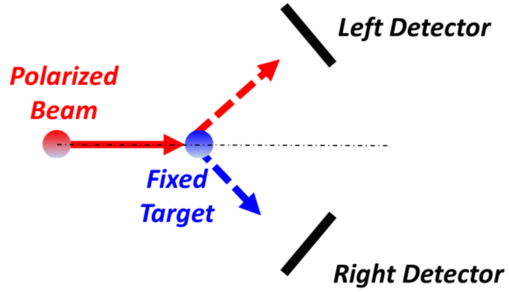
We suggest a standard configuration for a polarimeter with left/right symmetric Si strip detectors.
By a measuring, the spin correlated asymmetry of ^{3}He (beam ions) scattering on the ^{4}He (gas target) to determine the polarization of ^{3}He beam.

The asymmetry a could be found from the number of detected scattered particles $N_{LR}^{\uparrow\downarrow}$ in left/right (L/R) detectors depending on the beam spin (↑↓):

$$a = A_N P = \frac{\sqrt{N_R^{\uparrow} N_L^{\downarrow}} - \sqrt{N_R^{\downarrow} N_L^{\uparrow}}}{\sqrt{N_R^{\uparrow} N_L^{\downarrow}} + \sqrt{N_R^{\downarrow} N_L^{\uparrow}}} \quad \text{and} \quad \sigma_a = \sqrt{\frac{1-a^2}{N_R^{\uparrow}+N_R^{\downarrow}+N_L^{\uparrow}+N_L^{\downarrow}}} = \sqrt{\frac{1-a^2}{N_{tot}}},$$

where P is the beam polarization, A_N - analyzing power and σ_a - statistical accuracy.
The square root formula strongly suppresses systematic errors associated with left/right detector acceptance and the beam spin up/down luminosity asymmetry.

A schematic plan view of the left/right symmetric polarimeter to measure polarization of the vertically polarized beam.

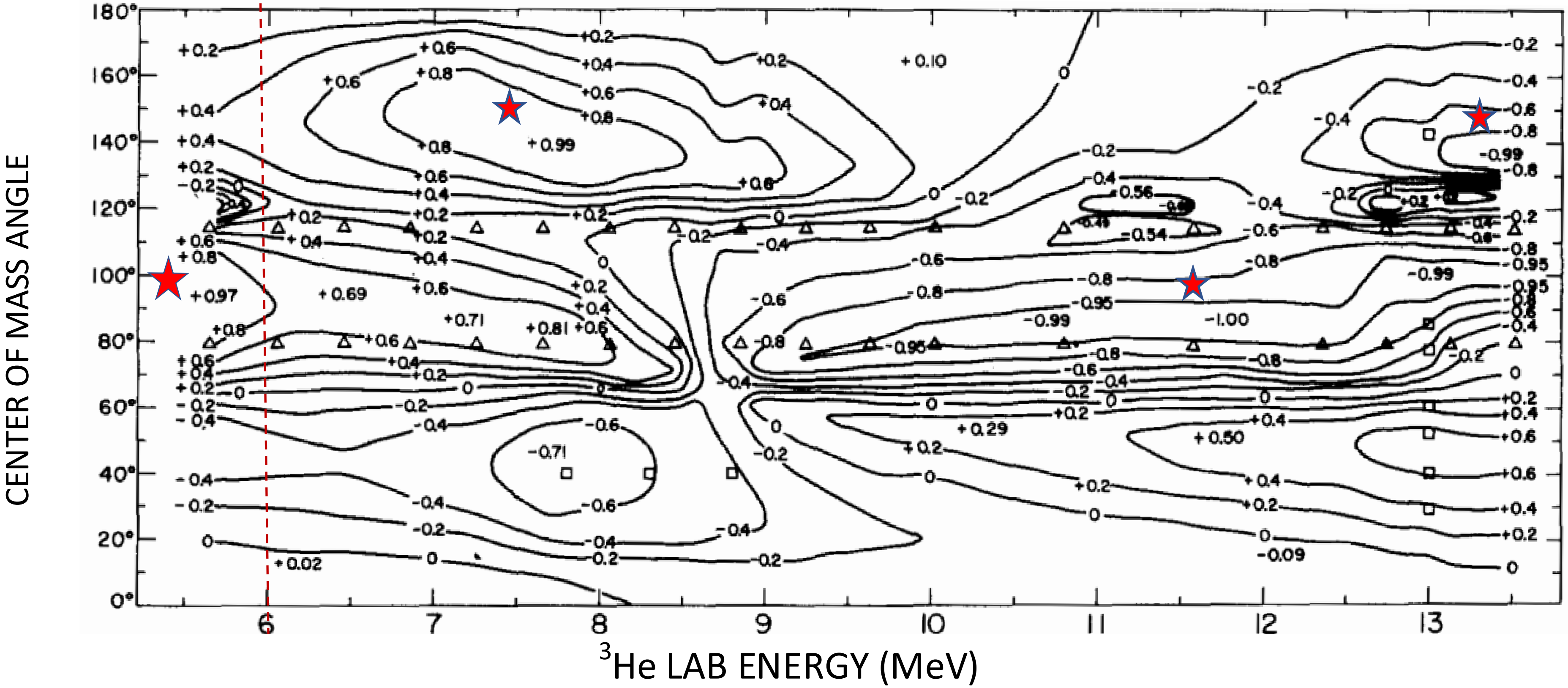


The accuracy of the polarization measurement depends on:

- knowledge of effective analyzing power A_N in the measured area;
- calibration and control of the measured energy;
- energy and time resolution of detectors;
- data collection rate;
- a rate effect (pileup);
- suppress backgrounds;
- …

A_N-analyzing power of ^{3}He-^{4}He scattering

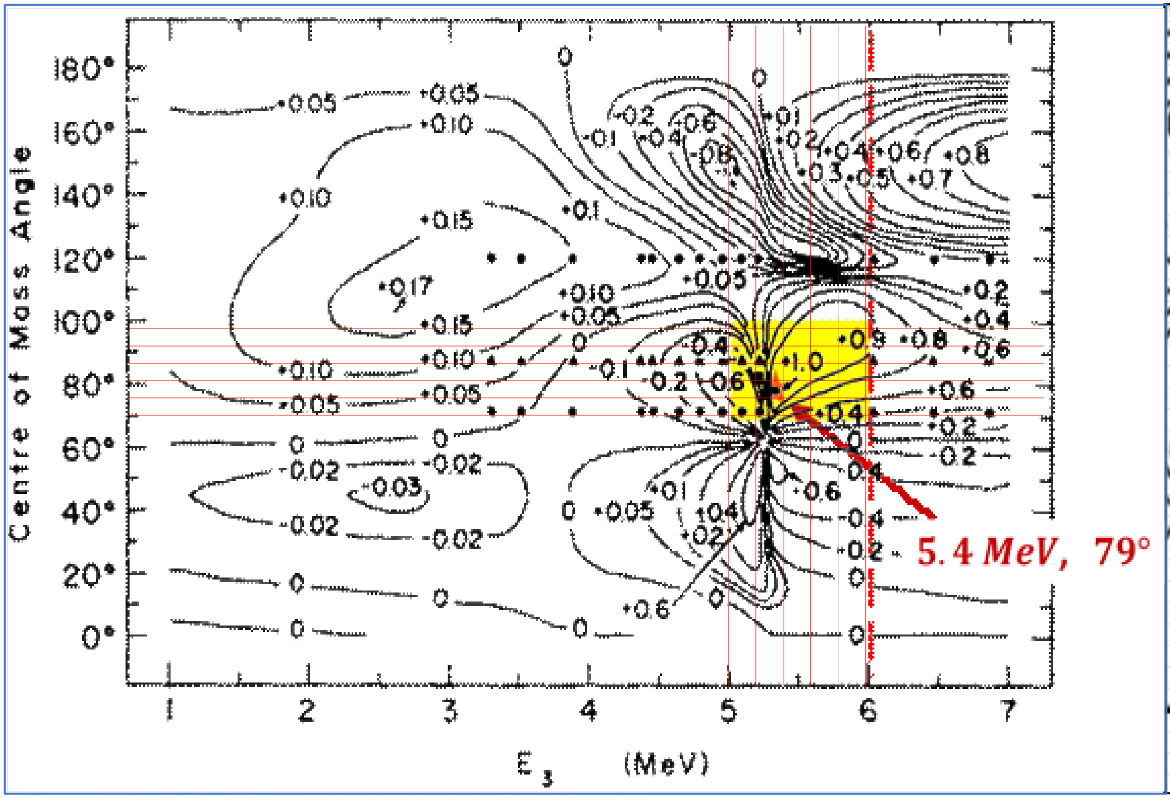
The elastic scattering of the low energy polarized ^{3}He ion was intensively studied experimentally and theoretically about 50 years ago. According to [1] the analyzing power for elastic ^{3}He-^{4}He scattering is a function of the beam kinetic energy and the CM scattering angle - $A_N(E_{beam},\theta_{CM})$ and can reach 100% at several points (E,θ). Because the EBIS Linac energy is 6MeV, we can use one of the 100% points (E_{beam}≈5.5 MeV and θ_{CM}≈90°) to develop a self-calibrated polarimeter. One more advantage of this point: there is no inelastic contribution in the ^{3}He-^{4}He scattering at an energy beam of <6MeV.

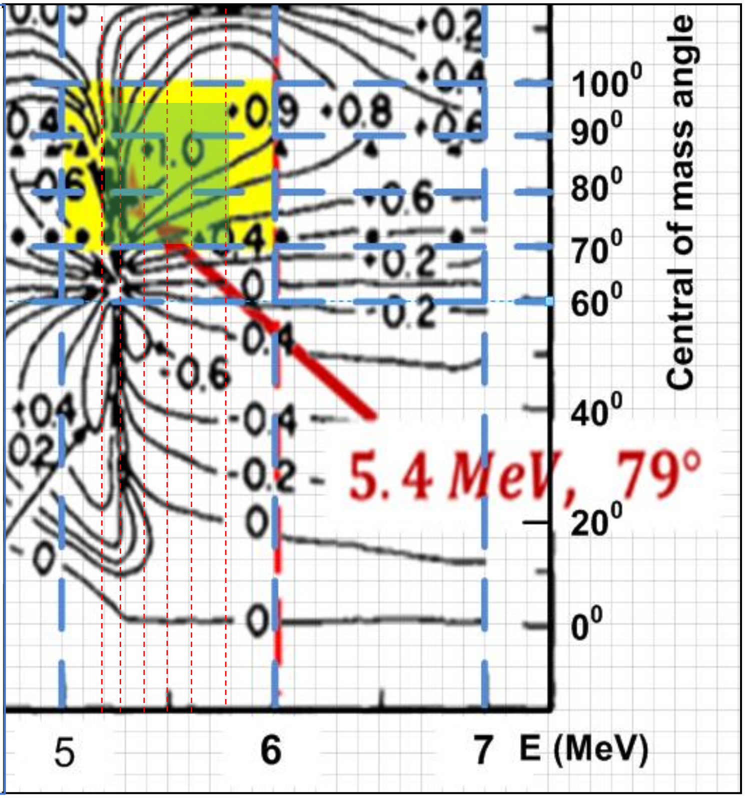


[1] D.M. HARDY et al. "POLARIZATION IN ^{3}He + ^{4}He ELASTIC SCATTERING", *Pys. Let. Vol.31B, #6, 16 March 1970, p. 355-357*

A_N-analyzing power of ^3He-^4He scattering

This point is E_{beam}≈5.3 MeV and θ_{CM}≈91° [1]. Later, the location of this point was evaluated as E_{beam}≈5.4 MeV, θ_{CM}≈ 79° (Ref. [2]). For measure of polarization, we must have the possibility to detect collisions in the area of (E_{beam},θ_{CM}) which will include this point.

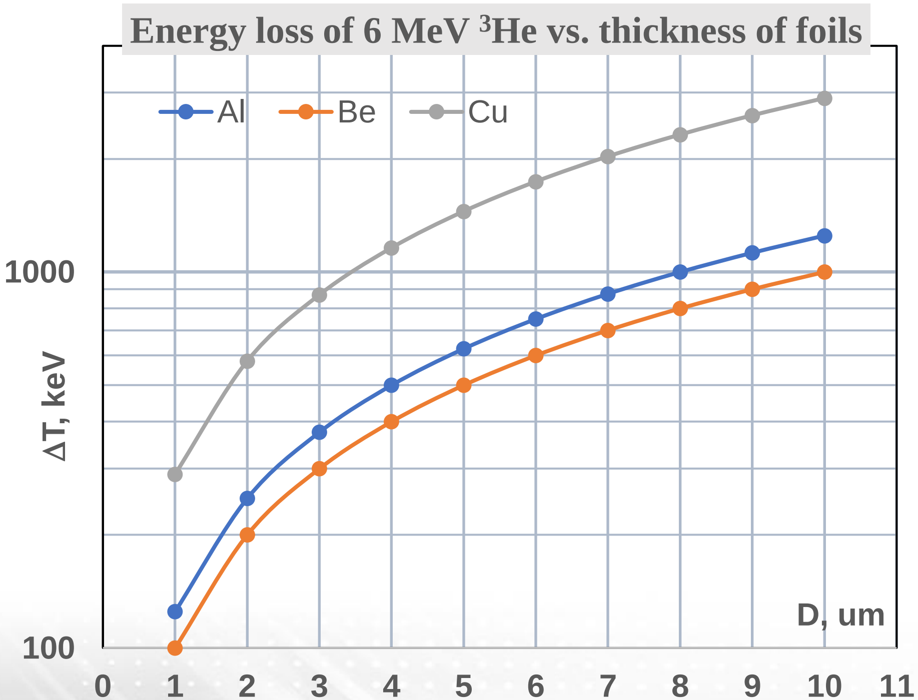




[1] G.R. PLATTNER et al. "ABSOLUTE CALIBRATION OF SPIN -1/2 POLARIZATION", *Pys. Let. Vol. 36B, #3, 6 Sep 1971, page 211-214*
[2] W.R.Boykin, S.D.Baker, D.M.Hardy, "Scattering of ^{3}He and ^{4}He from polarized ^{3}He between 4 and 10 MeV," Nucl. Phys. A **195**, 241 (1972).

Vacuum window

	Be (z=4)	Al (z=13)	Ni (z=28)	$T(^3\mathrm{He})$
dE/dx, MeV cm^2/g	~530	440	~335	6.03 MeV
ρ, $\mathrm{g/cm}^3$	1.848	2.699	8.902	
X_0, cm	35.28	8.897	1.424	



Multiple scattering:

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p} z\sqrt{x/X_0}\,[1 + 0.038\ln(x/X_0)] \approx \frac{13.6}{T}\,\frac{z}{2}\sqrt{x/X_0}$$

	$1\ \mu m$ (6) Be	$1\ \mu m$ (5) Al	$1\ \mu m$ (2) Ni
ΔT, MeV	~0.100 (~0.600)	~0.125 (~0.625)	~0.310 (~0.620)
θ_0, mrad	3.9 (9.5)	7.7 (17.3)	19.3 (27.7)

To reduce ^{3}He beam energy $6.0 \rightarrow 5.4$ MeV, we need:
$6\ \mu m$ of Be - ($\theta_0 = 0.010 \rightarrow \sigma_x \sim 1.2\ mm$) or
$5\ \mu m$ of Al - ($\theta_0 = 0.017 \rightarrow \sigma_x \sim 2.1\ mm$) or
$2\ \mu m$ of Ni - ($\theta_0 = 0.028 \rightarrow \sigma_x \sim 3.5\ mm$)
if distance to detector is $L = 125\ mm$.
10 mm “target length” gives $\sigma_x \approx 2.5\ mm$.

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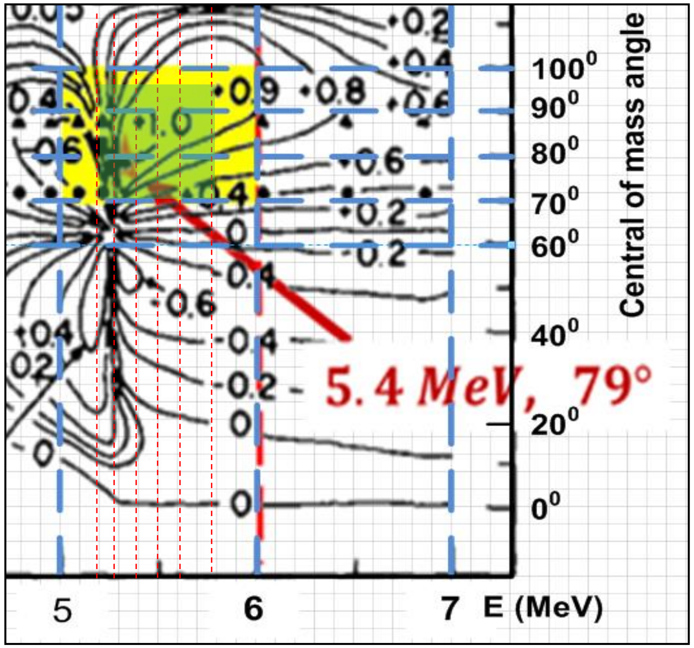
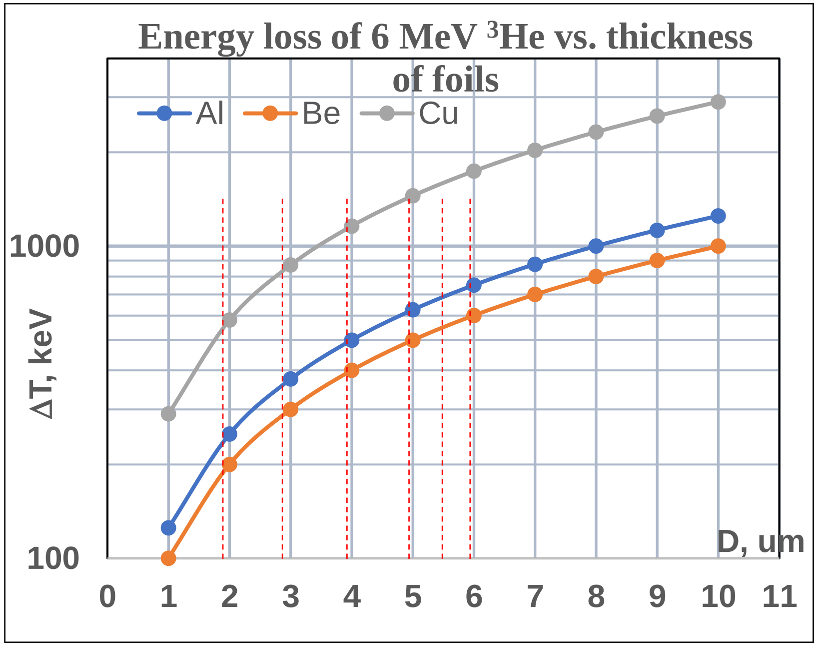
Self-calibration procedure of the polarimeter

For a precise measurement of polarization, we must find the asymmetry in a selected area (E_{beam},θ_{CM}) by scanning the energy of the beam. The maximum value of the asymmetry determines the parameters of 100 percent analyzing power A_N (energy and angle). One possibility of changing the beam energy is using the beamline buncher (to 140 keV), the other is the use of an absorber of different thicknesses.

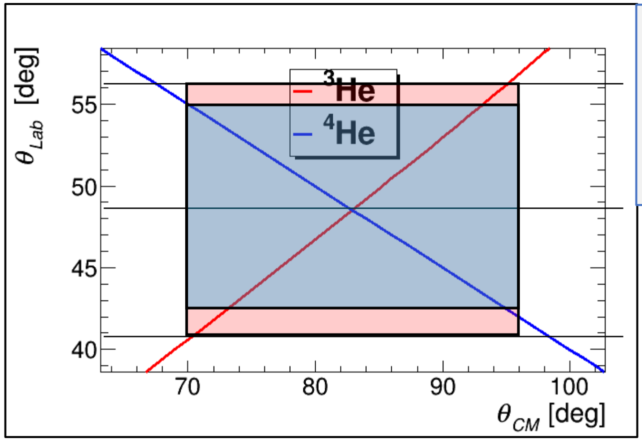




Absorber	Vacuum window (Al)	Al foil-1	Al foil-2	Al foil-3	Al foil-4	Al foil-5
Thickness, um	2	+1	+2	+3	+3.5	+4
Beam energy, MeV	5.75	5.625	5.50	5.375	5.25	5.125

Kinematics of elastic ^{3}He-^{4}He scattering

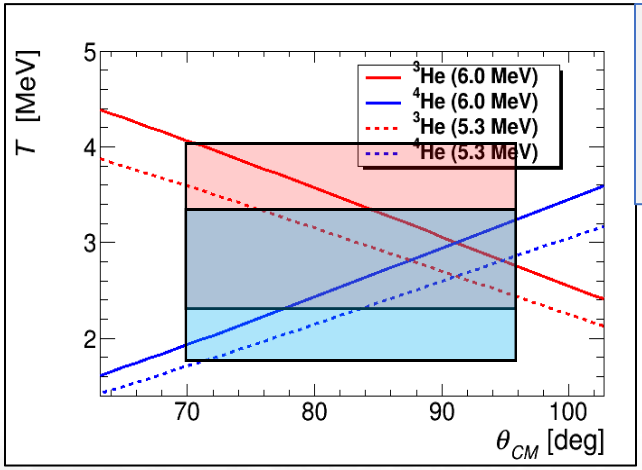
Kinematics of elastic ^{3}He- ^{4}He ***scattering***



The laboratory system scattering $^3\boldsymbol{He}$ (red line) and recoil $^4\boldsymbol{He}$ (blue line) angles versus center of mass scattering angle $\boldsymbol{\theta_{CM}}$.

Laboratory angle range of detected (θ_{CM}≈70°-96°):

- ^{3}He –> (41° - 56°);
- ^{4}He –> (54° - 42°).



The scattered and recoil kinetic energies versus corresponding laboratory system angle.

Energy range of detected at (θ_{CM}≈70°-96°):

- ^{3}He –> (4.0- 2.2)MeV;
- ^{4}He –> (1.5- 3.3)MeV.

The kinematics allow us to detect both scattered ^{3}He and recoiled ^{4}He in one detector which is very helpful for background suppression.
For that, the detector's opening angle $\Delta\theta_{det}$ should be larger than

$$\Delta\theta_{det} \geq 19.5° + 1.63 \times (\theta_{CM}^{\max} - 96°)$$

where $\theta_{CM}^{\max}$ is a maximal center of mass scattering angle which must be included in the data analysis. For the $\theta_{CM}^{\max} = 96°$, the detector must cover the laboratory angles

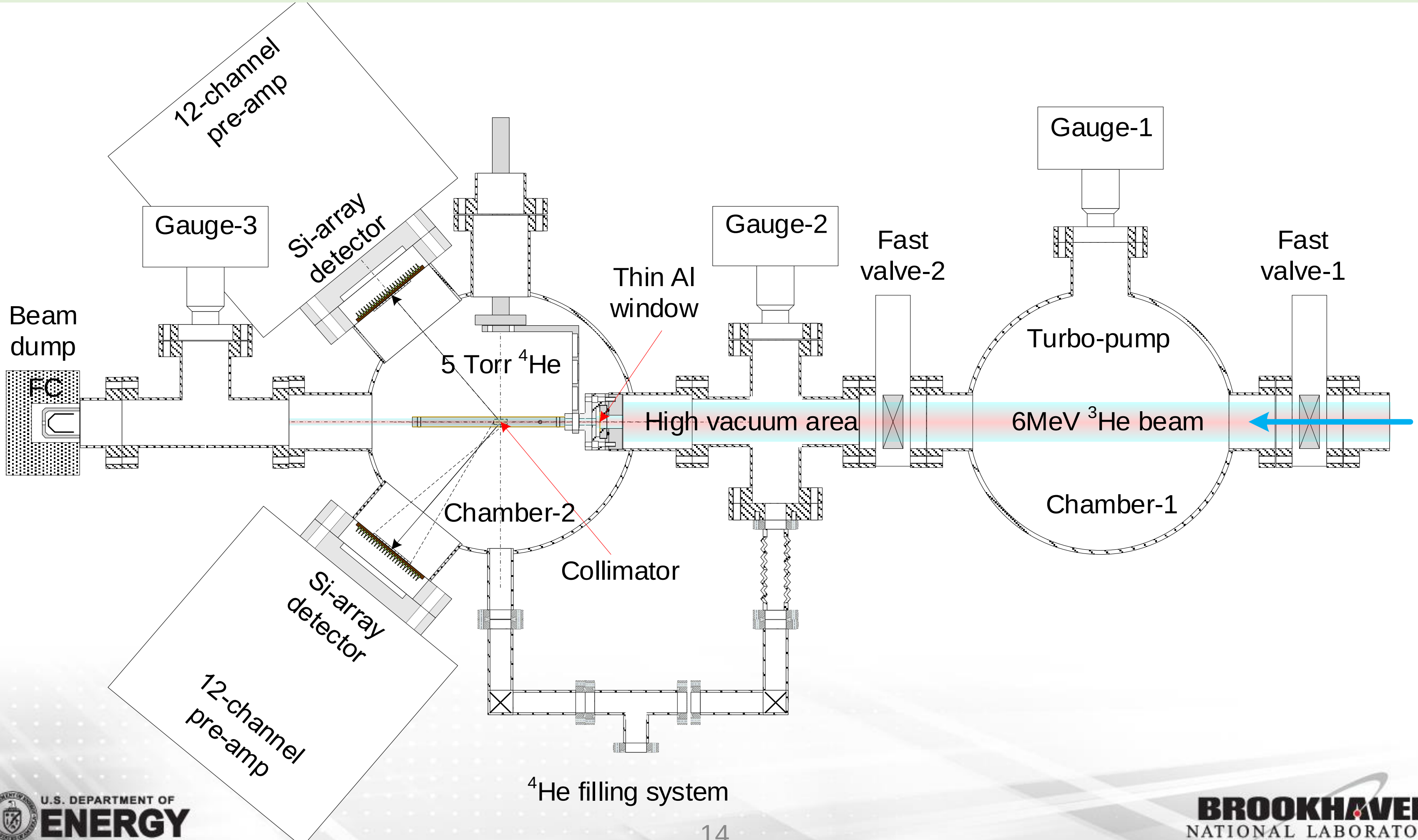
$$41° < \theta_{Lab} < 56°,$$

which corresponds to the center of the mass scattering angles

$$70° < \theta_{CM} < 96°.$$

Setup of 6 MeV polarimeter

The requirements to the geometry and measured energy range can be satisfied by the next design and developed polarimeter. The polarized ^{3}He beam has entered the scattering chamber through a very thin window (~1.8 um of Al foil) to minimize beam energy losses (~200keV).
The scattering chamber is filled with 5 Torr ^{4}He gas. The effective size of the target is ~ 5mm high and 8mm long. The thickness of the absorber is constrained by the movable collimator.



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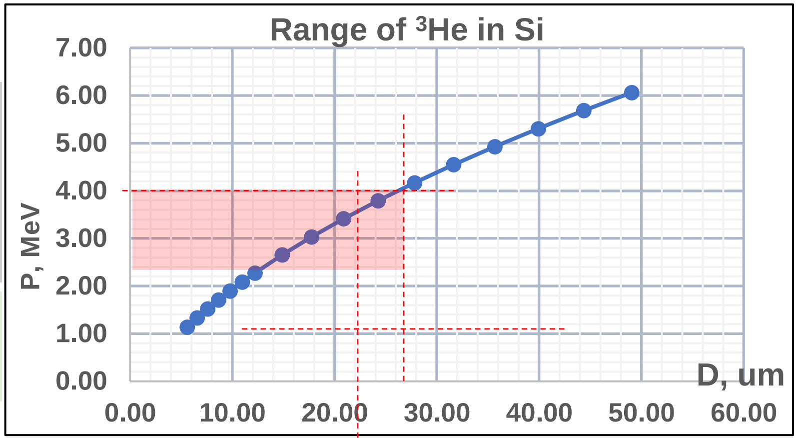
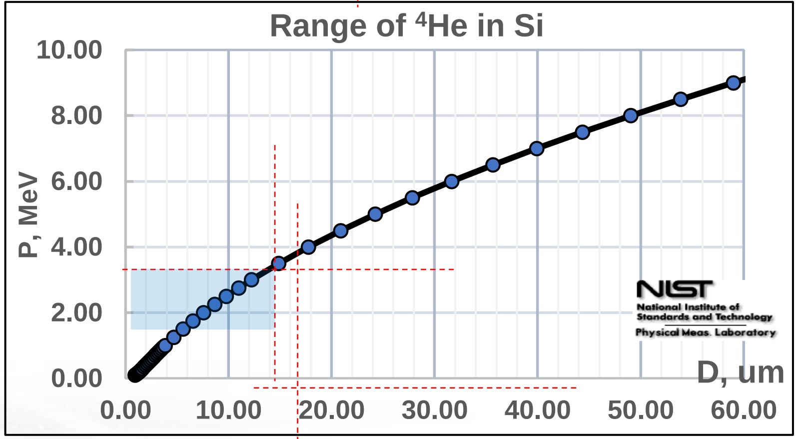
The requirement of the angle and energy range and an accuracy of measured energy can be satisfied by Hamamatsu Si-photodiode array S4114-35Q

- ***channel size: 0.9mm x 4.4mm***
- ***number of channels: 35ch (35*0.9mm~32mm)***
- ***depletion region >30 um***

Range of ^{3}He and ^{4}He ions with an expected energy in the Si is:

- ^{3}He –> (12- 27) um;
- ^{4}He –> (5- 15) um

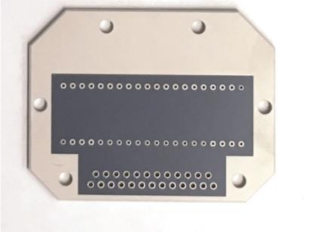




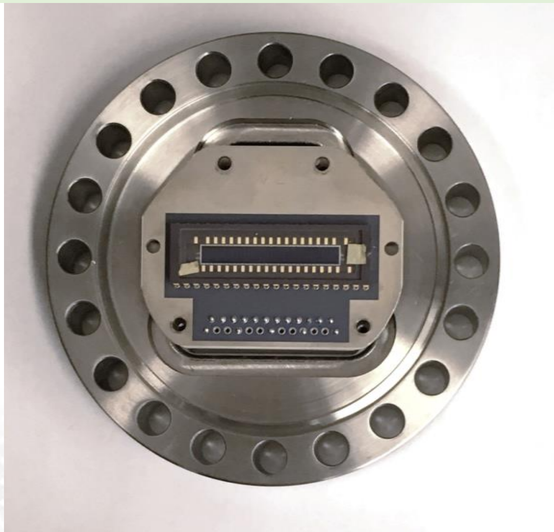
Electronics: For a readout, several Si strips can be combined into one readout channel. The detector can be equipped with a standard 12-channel preamplifier and a shaper from the pC and H-jet polarimeters in RHIC.

Hamamatsu photodiode array S4114-35Q is mounted on the board and connected with a D-sub vacuum thru connector on the flange.

Ceramic board



Detector



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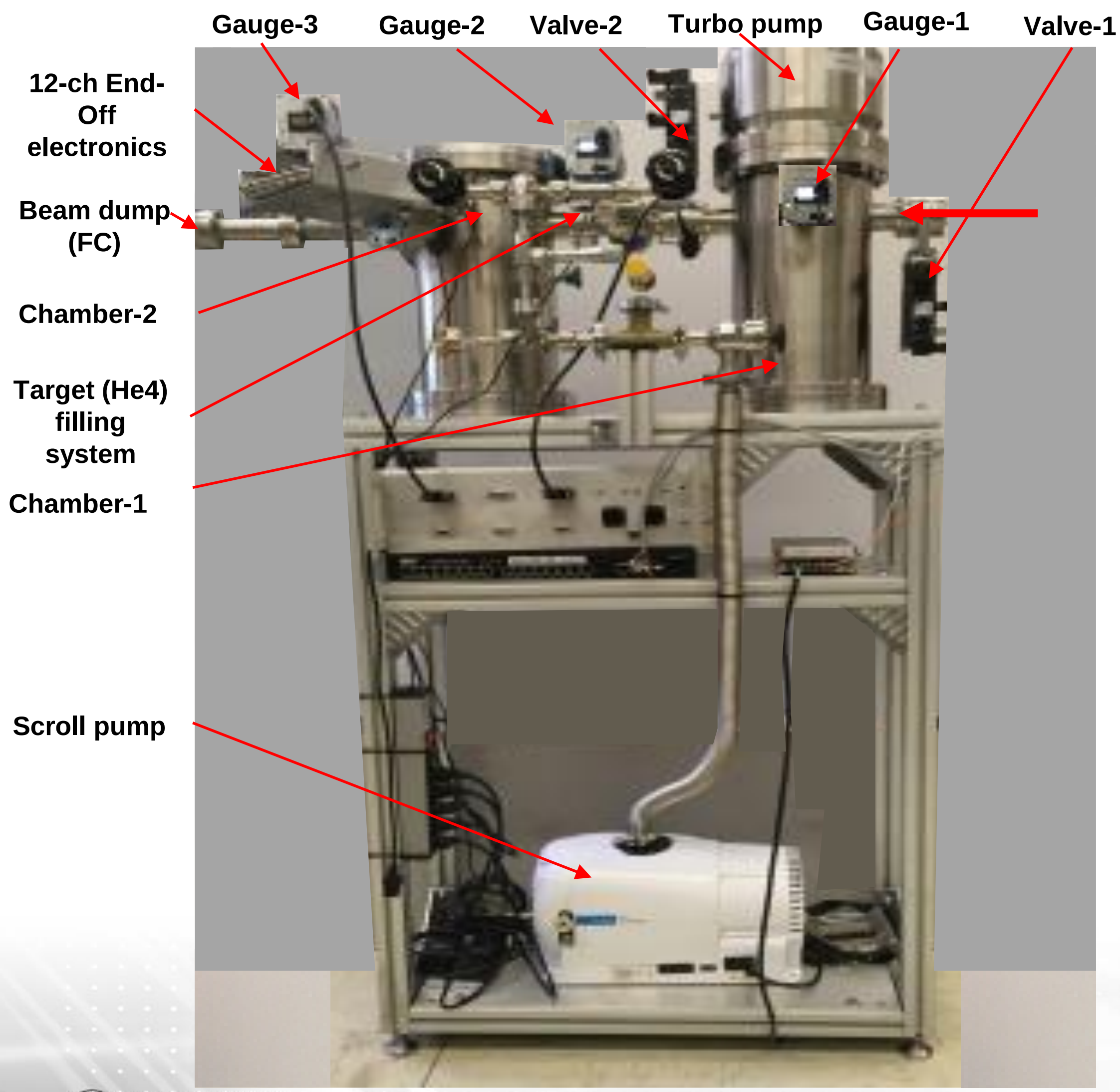
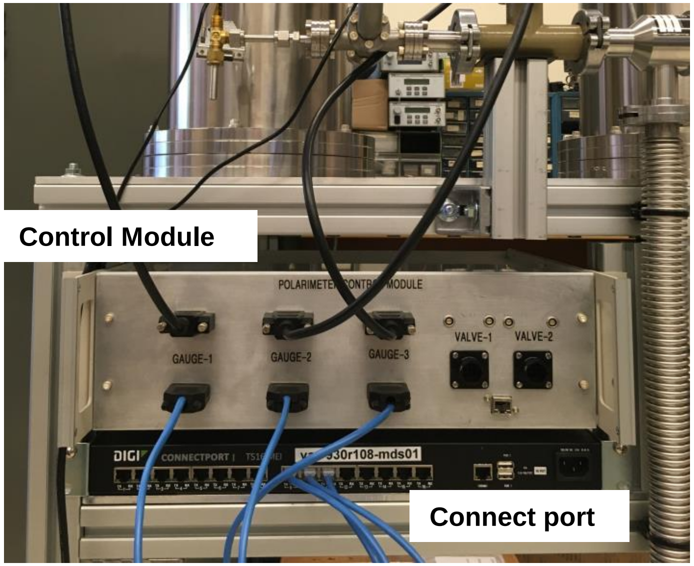
Setup of 6 MeV polarimeter

We have prepared a complete detector with the requirement geometry, measured the energy range and is ready for installation in the EBIS beam line.



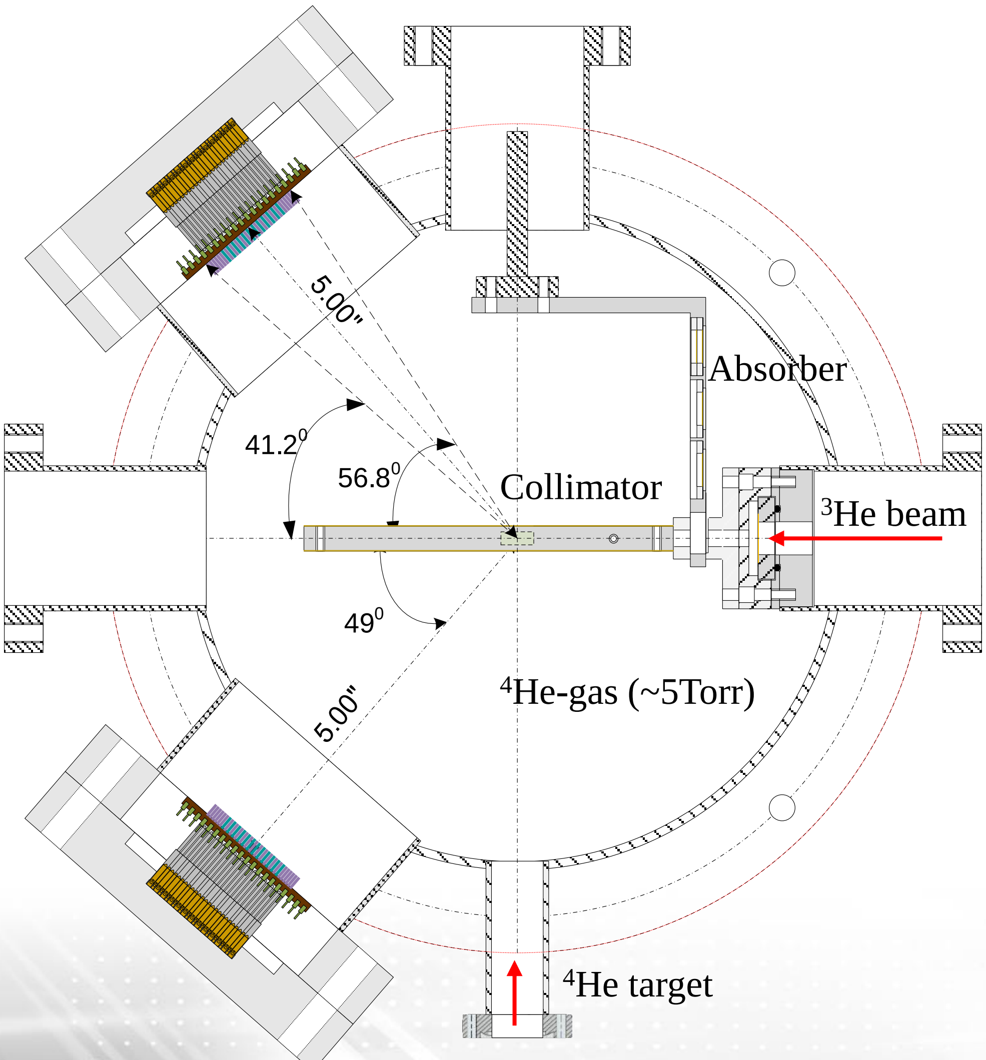
Polarimeter Control Module



With the beam we plan to study:

- **Kinematics of elastic ^{3}He-^{4}He scattering;**
- **energy distribution of the ^{3}He-^{4}He pair;**
- **energy and time resolution;**
- **electronics and DAQ;**
- **data collection and analysis of events;**
- **controlling and monitoring the detectors;**
- **vacuum control system;**
- **communication system;**
- **…**

^{3}He-^{4}He scattering polarimeter at 6.0 MeV beam energy



Two Si detectors are in the chamber at θ_{Lab}~49° and 5" from the "center of the target". The chosen detector will cover the center mass angles 70°< θ_{CM} <96° (41.2°< θ_{Lab} <56.8°). The 30 µm depletion region of the detector is sufficient to stop 5.5 MeV ^{3}He and 5.8 MeV ^{4}He (the detected particles energy range is ~ 2.3-4.0 MeV for ^{3}He and ~ 1.5-3.1 MeV for ^{4}He).

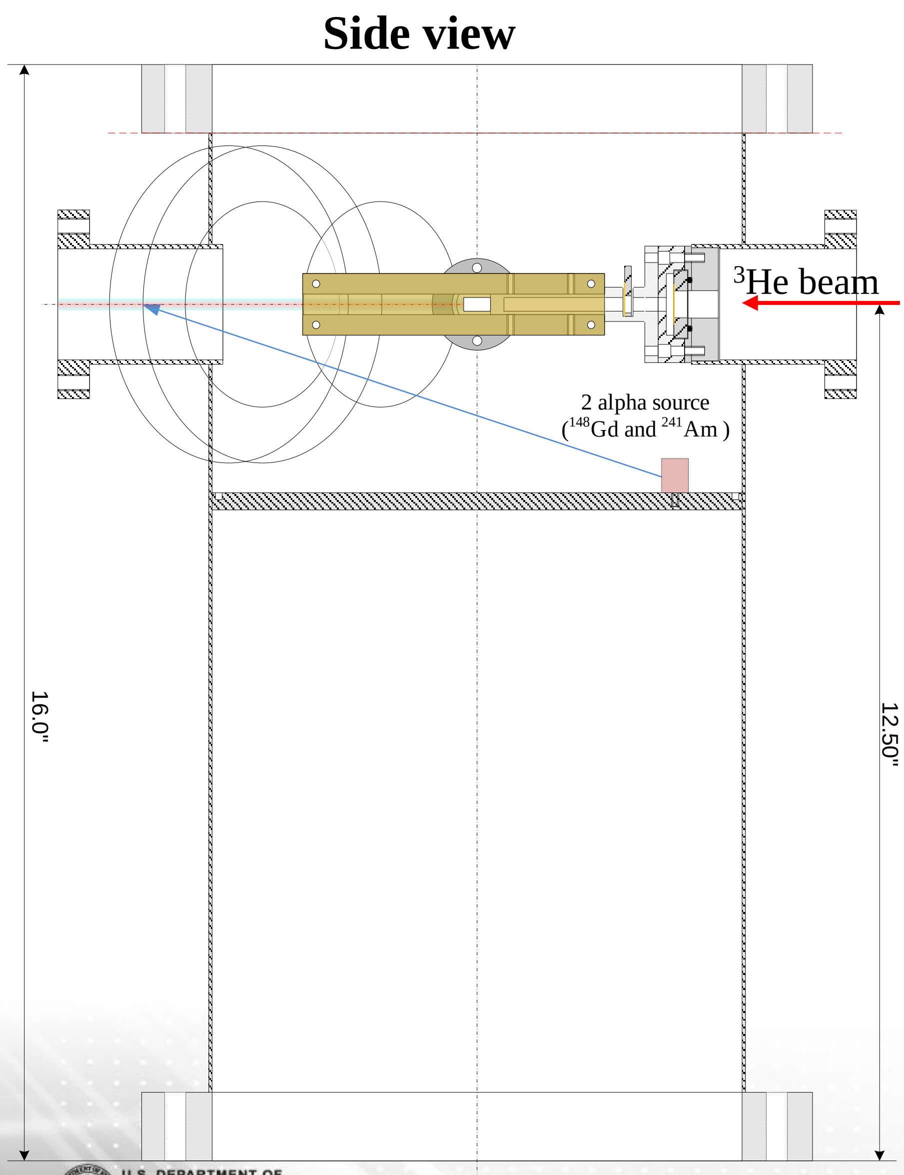
The time resolution of alpha at 1MeV range is better then $\sigma_t \lesssim 0.2$ ns.
Difference time of flight for scattered ^{3}He and recoiled ^{4}He:

$$\delta t = t_L - t_R = (L_L/c)\sqrt{M_L/2T_L} - (L_R/c)\sqrt{M_R/2T_R}$$

$$\delta t|_{^3He\,^4He} - \delta t|_{^4He\,^3He} = \pm\left|\sqrt{M_{^4He}} - \sqrt{M_{^3He}}\right| \times \left(\frac{L_L/c}{\sqrt{2T_L}} + \frac{L_R/c}{\sqrt{2T_R}}\right) \geq \pm 2.5\ \text{ns}$$

allows us to strongly recognize an elastic scattered ^{3}He ^{4}He pair and to suppress systematic errors.

Suppression of a systematic errors



Calibration and monitoring of energy and time

Two α-sources (^{148}Gd -3.183MeV and ^{241}Am~5.486MeV) will be used for energy calibration and monitoring.
Both a dead-layer and gain can be determined in such a way. We will calibrate and monitor a time by flashing a blue LED on all channels of the silicon array.

To suppress systematic errors, we can use

- **measured energies E_{3He} and E_{4He}**
  $E_{3He} + E_{4He} = E_{beam}$ (σ_E ~ 20 keV);
- **corelated scattering angles (the strip number) θ;**
- **time coincidence- left/right counsidence**
  ($\sigma_t \lesssim$0.2 ns);
- **difference in time of flight for scattered ^{3}He and recoiled ^{4}He.**
  $\delta t = t_L - t_R \geq \pm 2.5$ ns
- **Si detectors are not sensitive to backgrounds, such as neutrons and gammas from other beam lines.**

All of this can help to strongly suppress background events.

Data Acquisition

The Data Acquisition of polarimeter consist of:

- VME crate - VME64x
- Single Board Computer - Acromag XVME-6510-1161-LF (A Single Board Computer serves both as VME controller and DAQ PC.)
- and WFD - VME 250 MHz 14-bit waveform digitizers (SIS3316-250-14)

Readout parameters of polarimeter:

- Number of channels - 12*2=24;
- Bunch frequency -1 Hz;
- Duration of frequency - 20us;
- Event rate - ~160kHz/channel (~100 events/bunch total)

The selected WFDs will allow us to record the full (20 µs/ 5000 samples) bunch signal in every readout channel, which is essential for monitoring the possible rate dependent systematic errors. The expected data flow is relatively very low < 0.3 Mbyte/sec. For the MBLT64 data transfer, single bunch data readout will take ~10-15 ms. The rest of the bunch period (1 sec) is enough for a detailed data analysis. According to our experience with the HJET polarimeter, detailed analysis including full fit of the signal waveforms takes only 100-200 ms for 1 Mbyte of acquired data (~5000 events). The accumulated data will not exceed 30 GByte/day (3-4 TByte per RHIC Run).

A prototype of the DAQ (VME crate, SBC, and WFD) were assembled and the readout software was developed. The DAQ prototype, was successfully tested.

Expected Characteristics of the beam and polarimeter

Beam parameters:

- beam polarization ~70 %
- beam energy ~6 MeV
- total intensity $\sim 2 \times 10^{11}\ \mathrm{sec}^{-1}$
- intensity in polarimeter $\sim 1 \times 10^{11}\ \mathrm{sec}^{-1}$
- bunch frequency 1 Hz
- bunch duration 20 µsec to Buster

(bunch duration to the polarimeter can be extend to 200 µsec (prevent pile-up effect)

The expected characteristics of the 6 MeV polarimeter based at the following parameters of the ^{3}He beam:

- covered of center mass angle: $\boldsymbol{\theta_{CM}}$~(70-96)^0
- energy range: **E**~(1.0-4.0) MeV
- noise (PED) $\boldsymbol{\sigma_{noice}}$~ 15keV
- energy resolution $\boldsymbol{\sigma_E}$~ 20keV
- time resolution for 1MeV $\boldsymbol{\sigma_t}$~ 0.2 ns
- signal FWHM ***t***~ 50 ns
- expected rate ***N***~100 event/pulse

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Summary

- The polarized ^{3}He ion source

  Tested and ready to install on the EBIS:
  - Purification and filling system for preparation of ^{3}He gas for polarization;
  - ^{3}He gas purity control with spectrometer;
  - Polarization of ^{3}He gas by a MEOP technique (was achieved ~90% with a "sealed" cell and ~75% with "open" cell);
  - Monitor polarization continually with the Optical Probe polarimeter;
  - Injection valve with required parameters;
  - HV isolation of the ^{3}He source from the EBIS drift tube.
- Chicane for spin rotation
  - All components are placed and being aligned.
- 6MeV polarimeter

  Ready for installation on the EBIS line:
  - The polarimeter is basically ready;
  - Electronics (preamplifiers and shapers) tested and mounted;
  - Data acquisition is basically ready.

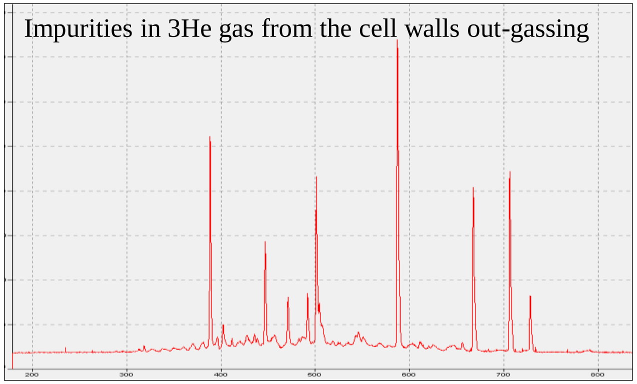
  Incomplete preparations:
  - **Control and monitoring system;**
  - **PLC system.**

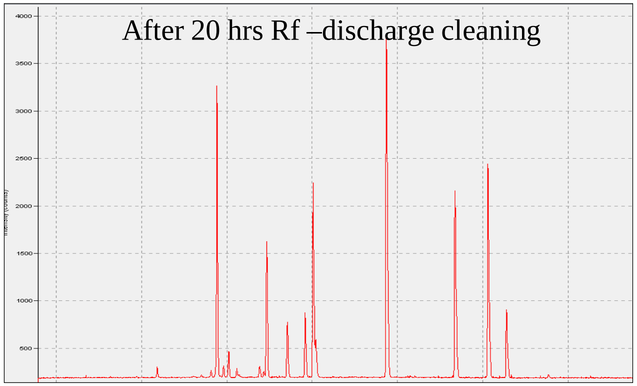
  Upgradable:
  - *Number of reading channels;*
  - *Increasing the range of detection angle (available in the same kind of Hamamatsu Si array detector with 54 strips);*
  - *Order a special Si-detector (size, granularity, thickness).*

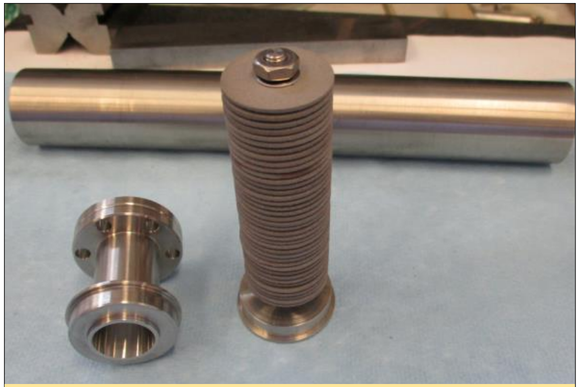
Backup

^{3}He-gas purification and filling system

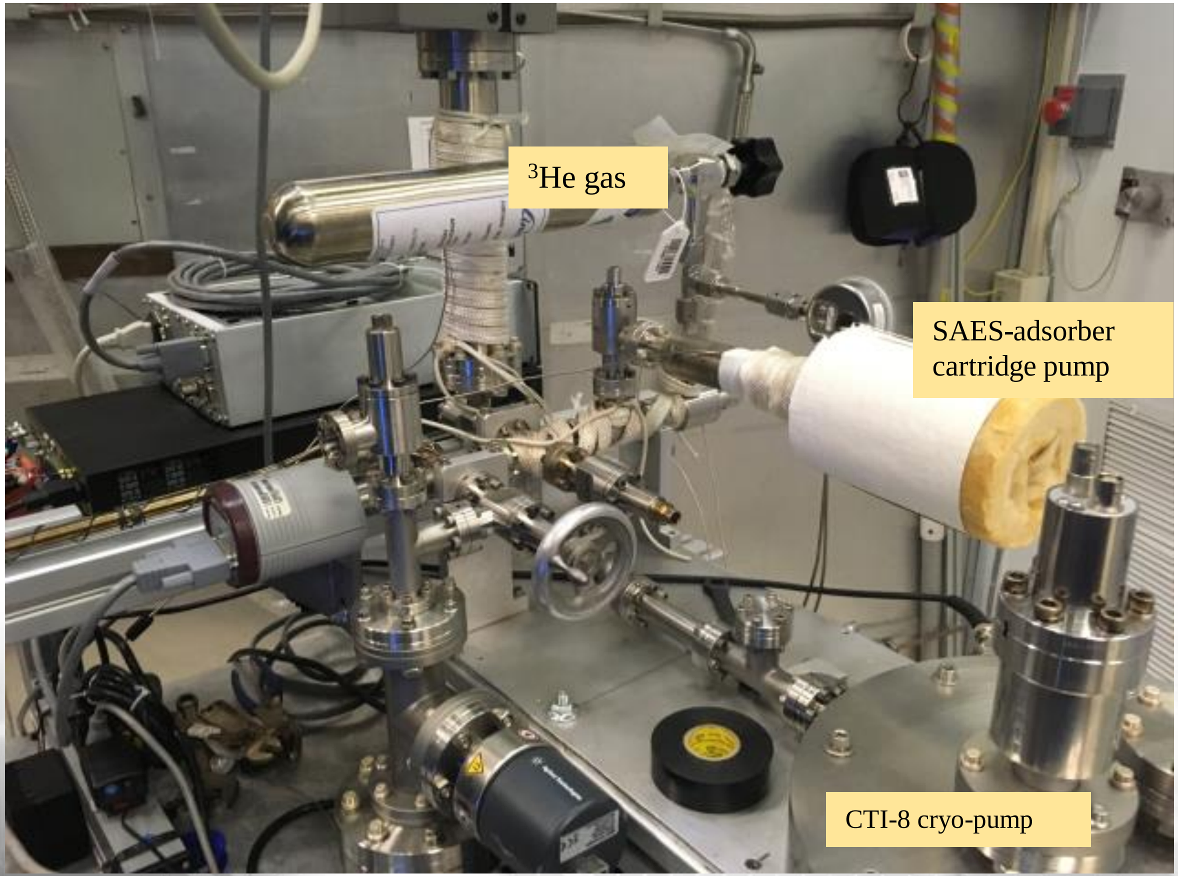
The purity of ^{3}He is controlled by monitoring of the gas spectrum.



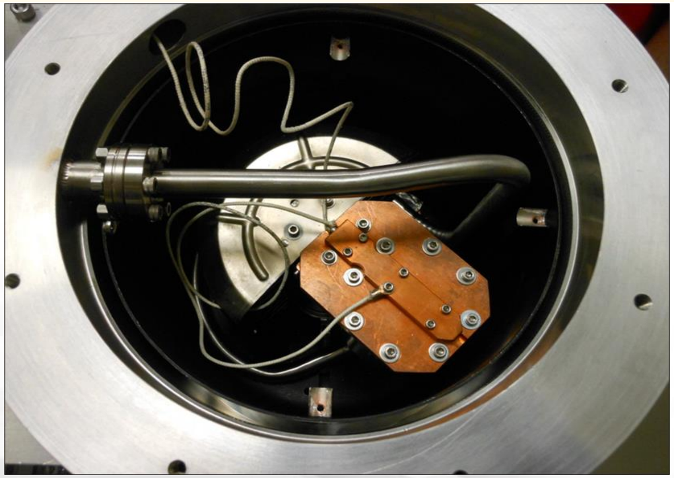




SAES-adsorber cartridge pump

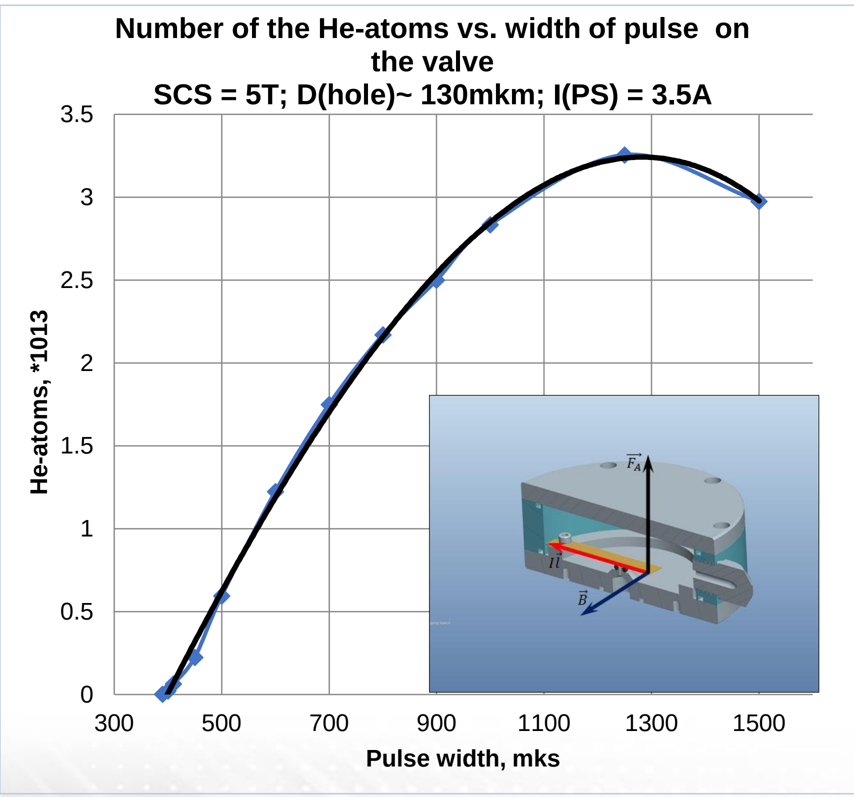


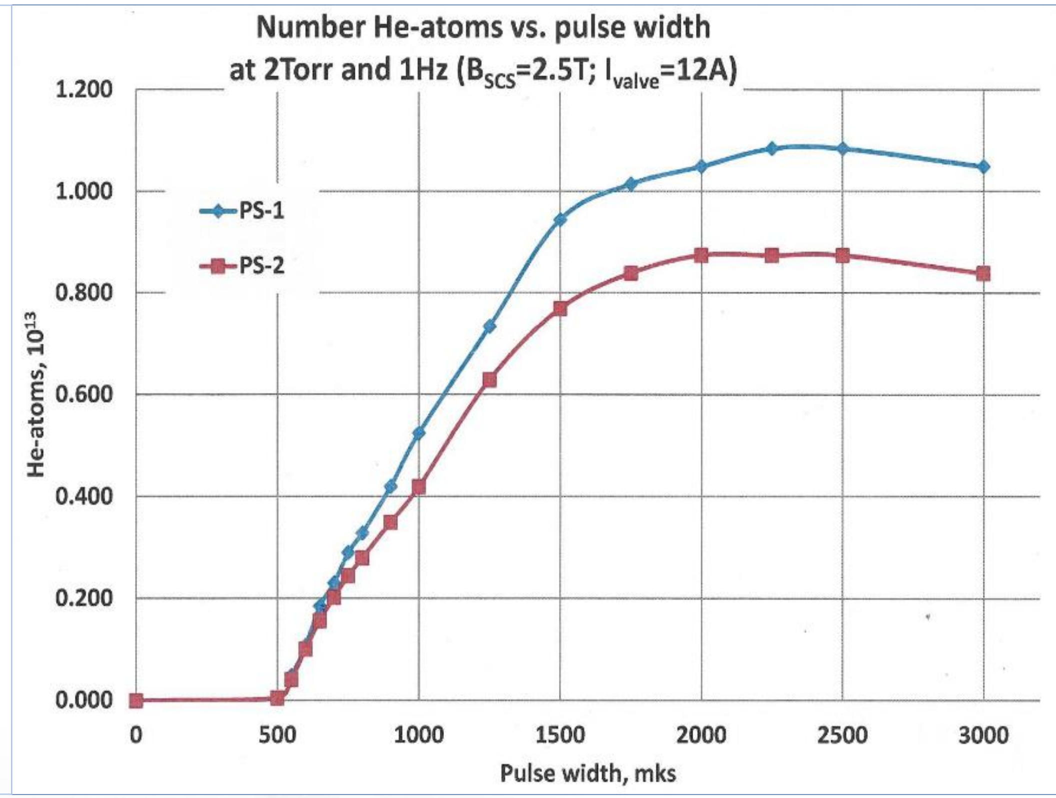
^{3}He cryo-part of the purification system built-in CTI-8 cryo-pump. It's pumping all gases except for helium to the level below 10^{-7} torr. The pump also absorbs a significant amount of ^{3}He gas (~100 SCCM). The absorbed gas is released by the pump vessel heating. This provides gas storage and supply for ^{3}He-cell operation.



Injection valves

The ionization of polarized ^3He gas injected in the EBIS trap is produced in a 50 kG field. This field will greatly suppress the depolarization in the intermediate He^+ single charge state. The charge ratio $He^{++}/He^+ >> 1$. The number of He^{++} ions is limited to maximum charge which can be confined in EBIS (about $2.5x10^{11}$ of $^3He^{++}$/pulse) and it is sufficient to obtain ~10^{11} He^{++}/bunch in RHIC.





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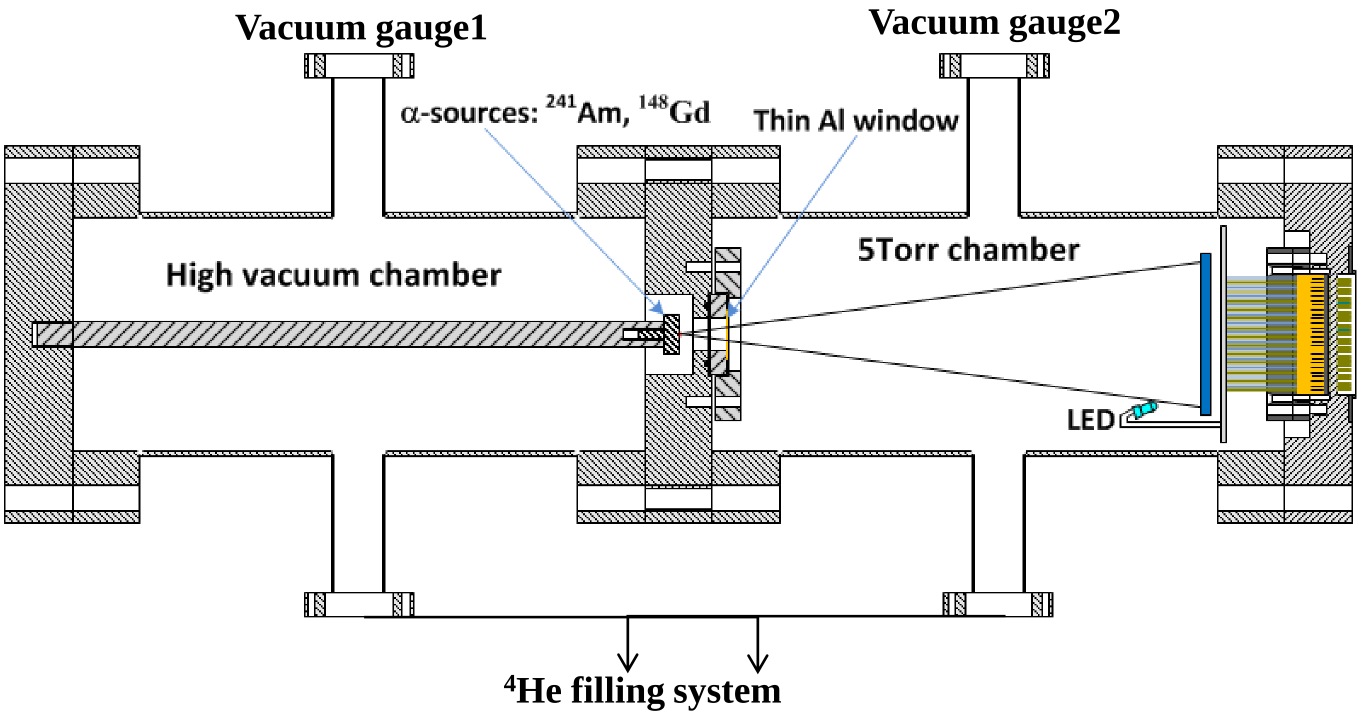
Test setup for 6 MeV polarimeter (with LED and α-sources)



We studied:

- **mechanical properties of thin foil for the window;**
- **vacuum properties of the foil;**
- **A safety procedure of filling 5Toor ^{4}He-gas in chamber;**
- **electronics: amplifier , shaper and DAQ;**
- **the time and energy resolution of the Si-detector vs. shaping time (by alpha sources);**
- **the time resolution of the Si-detector (by pulse LED lightening);**
- **energy absorption in ^{4}He gas vs. pressure;**
- **energy absorption in window vs. thickness of foil;**
- **…**

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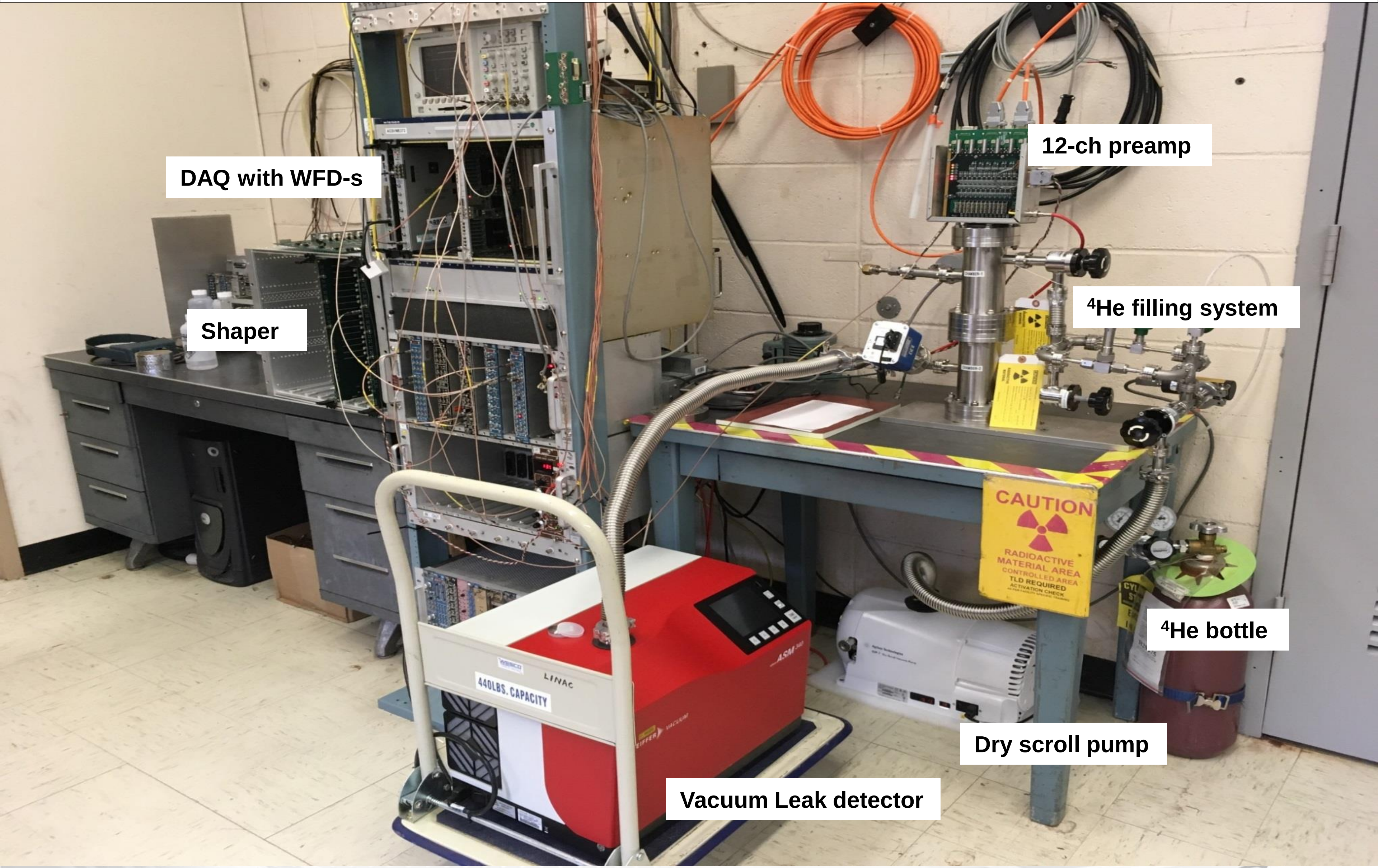
Test setup for 6 MeV polarimeter (with LED and α-sources)



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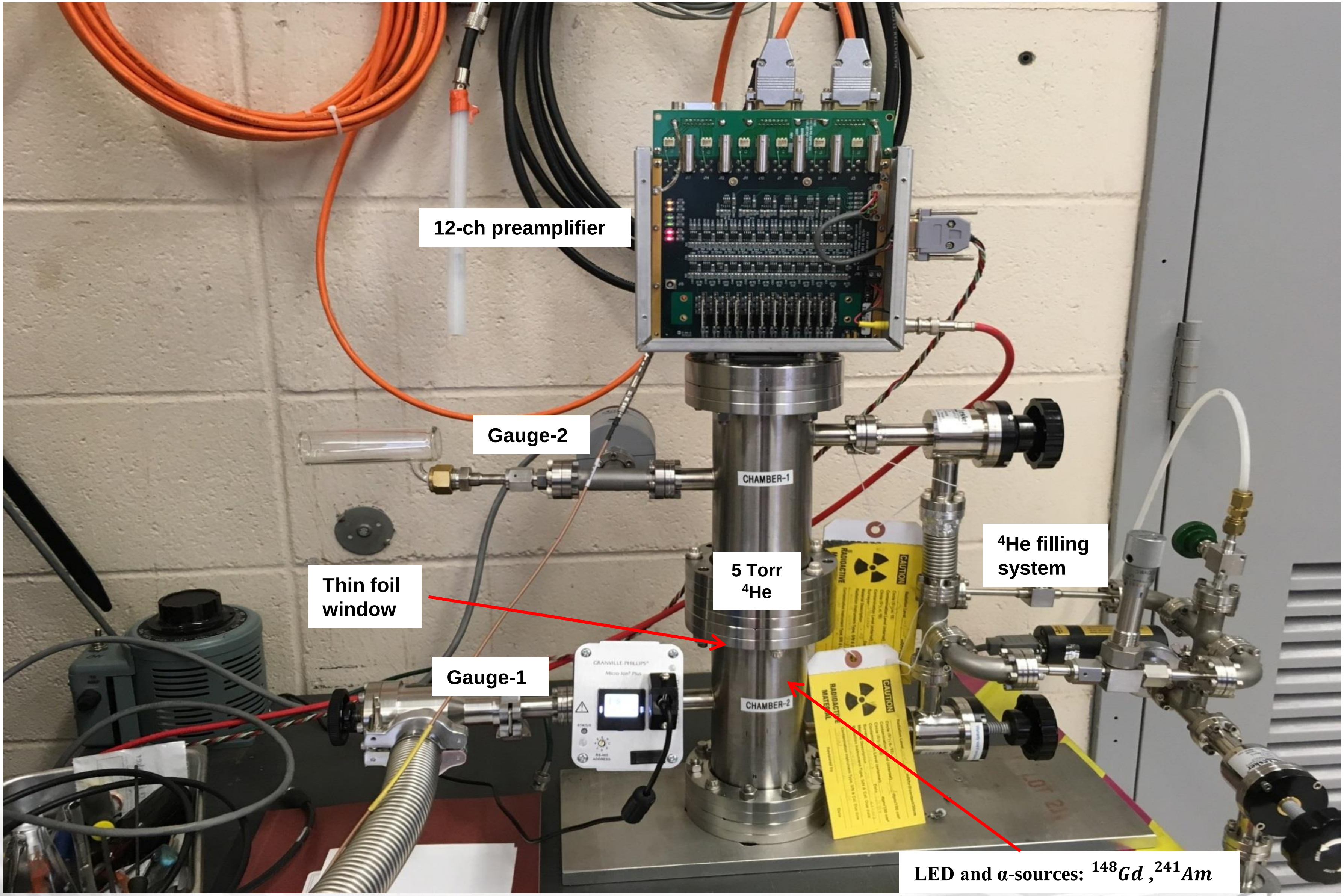
Test setup for 6 MeV polarimeter (with LED and α-sources)



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Alpha spectrum of ^{148}Gd and ^{241}Am by Hamamatsu Si array detector

Alpha spectrum of ^{148}Gd and ^{241}Am by Hamamatsu Si array detector (S4114 35N) + preamplifier(charge) + shaper.
Sigma noise ~15keV; energy resolution: ^{148}Gd (3.184MeV) ~21keV; ^{241}Am ~25keV; FWHM ~50nsec