Development of absolute polarimeter for the low energy $^3He^{++}$ ion beam

Beam Polarization and Polarimetry at EIC

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Introduction

In 2003 A. Zelenski, J. Alessi proposed of production $^3He^{++}$ 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 an important part of the ongoing EBIS upgrade project and 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

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Research and Development for Next Generation Nuclear Physics Accelerator Facilities

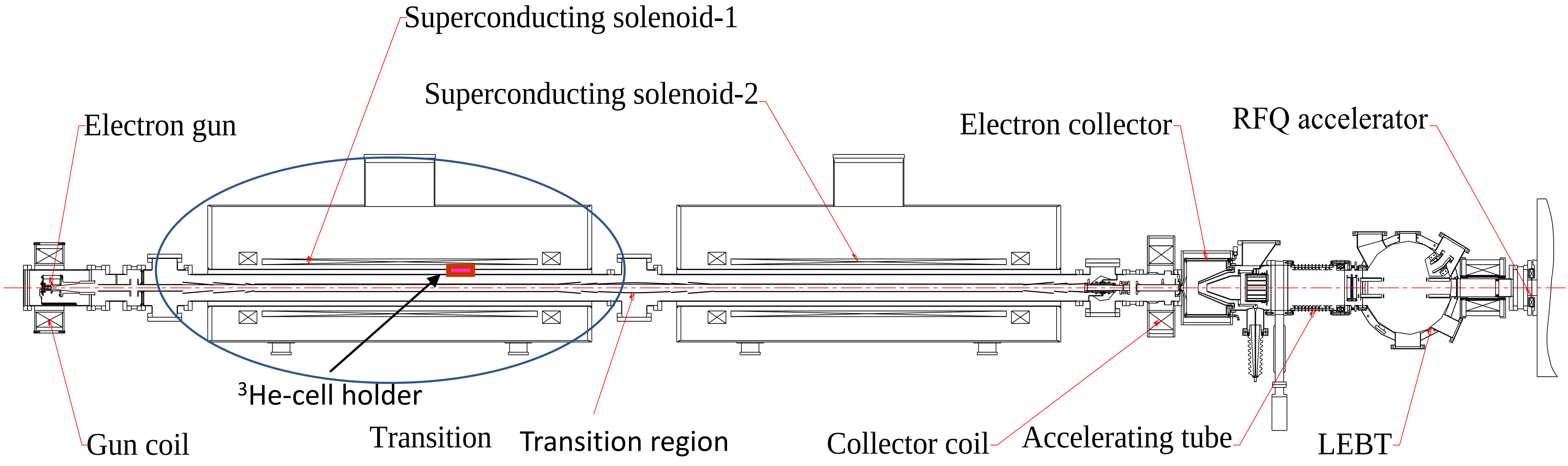
… A doubly polarized electron-ion collider (EIC) is the best way to examine the internal structure of the proton and neutron. The technology to accelerate polarized proton beams has been well established at RHIC. However, studying the structure of the neutron requires the acceleration of polarized $^3He^{++}$, 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.

Updated EBIS (part-1): new “extended” SC Solenoid-1

The Extended EBIS upgrade is approved by the Accelerator Improvement Project at BNL. The main purpose of this upgrade is to increase the intensity of the ion beam, but it also provides the necessary infrastructure for a polarized 3He ion source.

One part of this update is to add a second SCS. The polarized ^{3}He ion source for the EIC will be mounted on this solenoid. The polarized ^{3}He gas will be injected through a fast pulse valve in the ion trap region of the EBIS. The atoms of the ^{3}He gas will be ionized by the intense electron beam in the Solenoid-1.

After, the ^{3}He ions will be trapped and bred to the $^3He^{++}$ state in the downstream Solenoid-2.



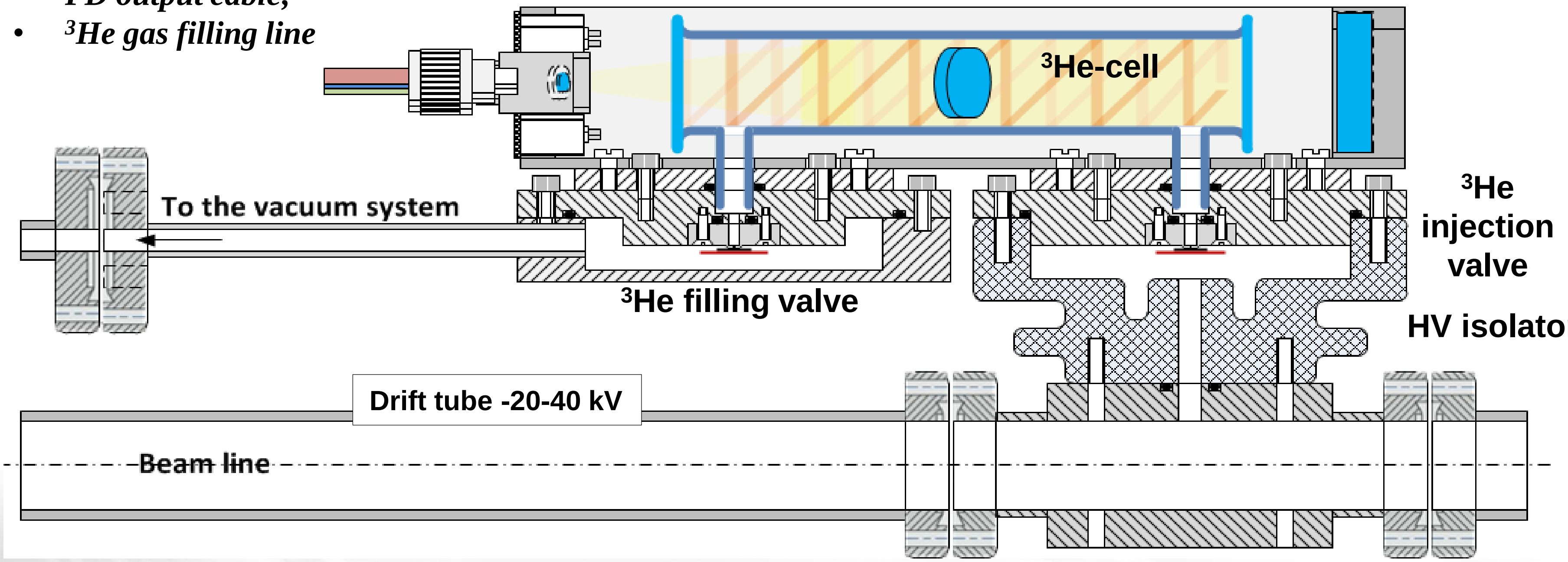
Holder ^{3}He-cell with filling and injection valves inside the EBIS SC Solenoid-1

Procedure to polarize the ^{3}He gas:

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

Inputs& outputs:

- *RF- discharge cable;*
- *pumping laser high power optic fiber;*
- *probe laser optic fiber;*
- *^{3}He spectra control fiber;*
- *filling valve pulse cable;*
- *Injection valve pulse cable;*
- *PD output cable;*
- *^{3}He gas filling line*

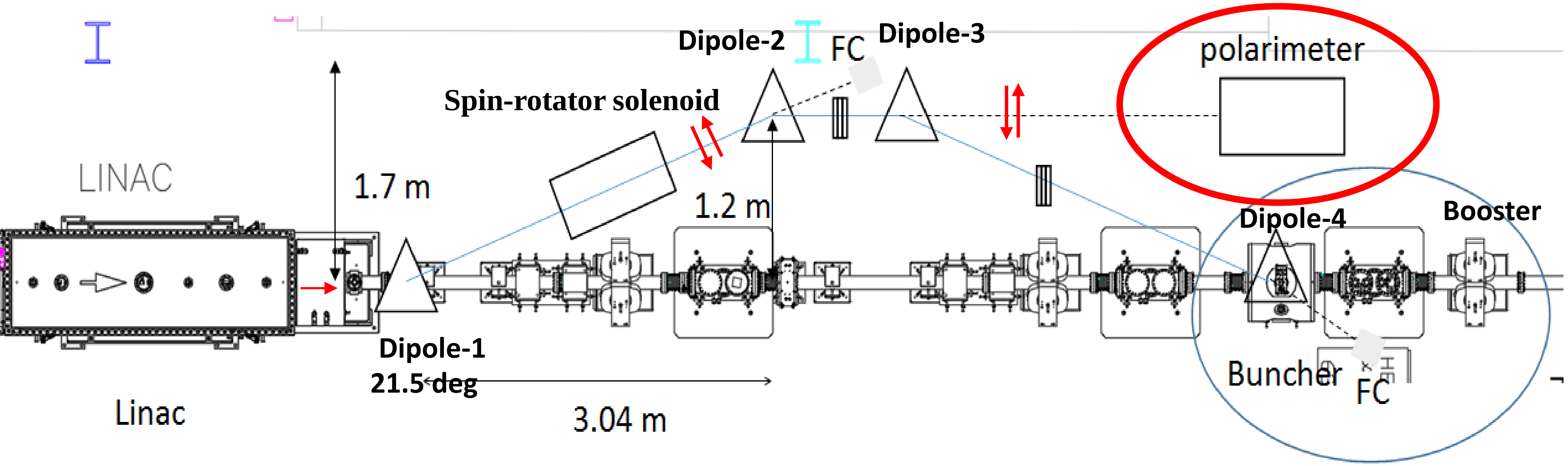


Upgraded EBIS (part-2): new spin rotator and ^{3}He polarimeter

After EBIS LINAC, the polarized ^{3}He beam will have an energy of 6MeV with a longitudinal spin direction. The longitudinal polarization is at first rotated to transverse direction using the 21.5 deg bending magnet (Dipole-1).

The spin-rotator will change the spin direction to the vertical . The spin-rotator will be a pulsed solenoid with reversible field to enable spin-flip on an EBIS pulse-by-pulse basis. The vertically polarized beam will be returned back to the straight HEBT line by the system of three dipole magnets (2,3,4) after the spin rotator solenoid. The polarimeter can be installed in the straight beam line section after the dipole magnet (2).

With spin-flip we can measure polarization of the beam by a standard configuration of left/right symmetric Si strip detectors, much like the proton-carbon polarimeters in AGS and RHIC, or H-jet polarimeters in RHIC.

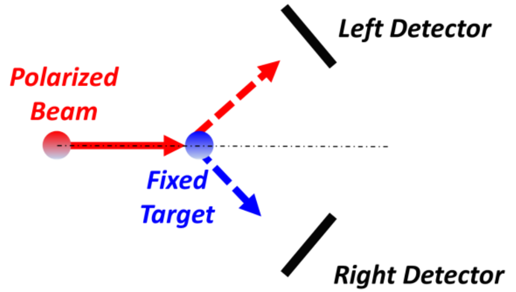


Proposed method: polarimeter at 6.0 MeV beam energy

We suggest a standard configuration for a polarimeter with left/right symmetric Si strip detectors.
We will measure the spin correlated asymmetry of ^{3}He ions scattering on the ^{4}He gas target to determine the polarization of ^{3}He beam.
The asymmetry 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 asymmetry and the beam spin up/down luminosity asymmetry.



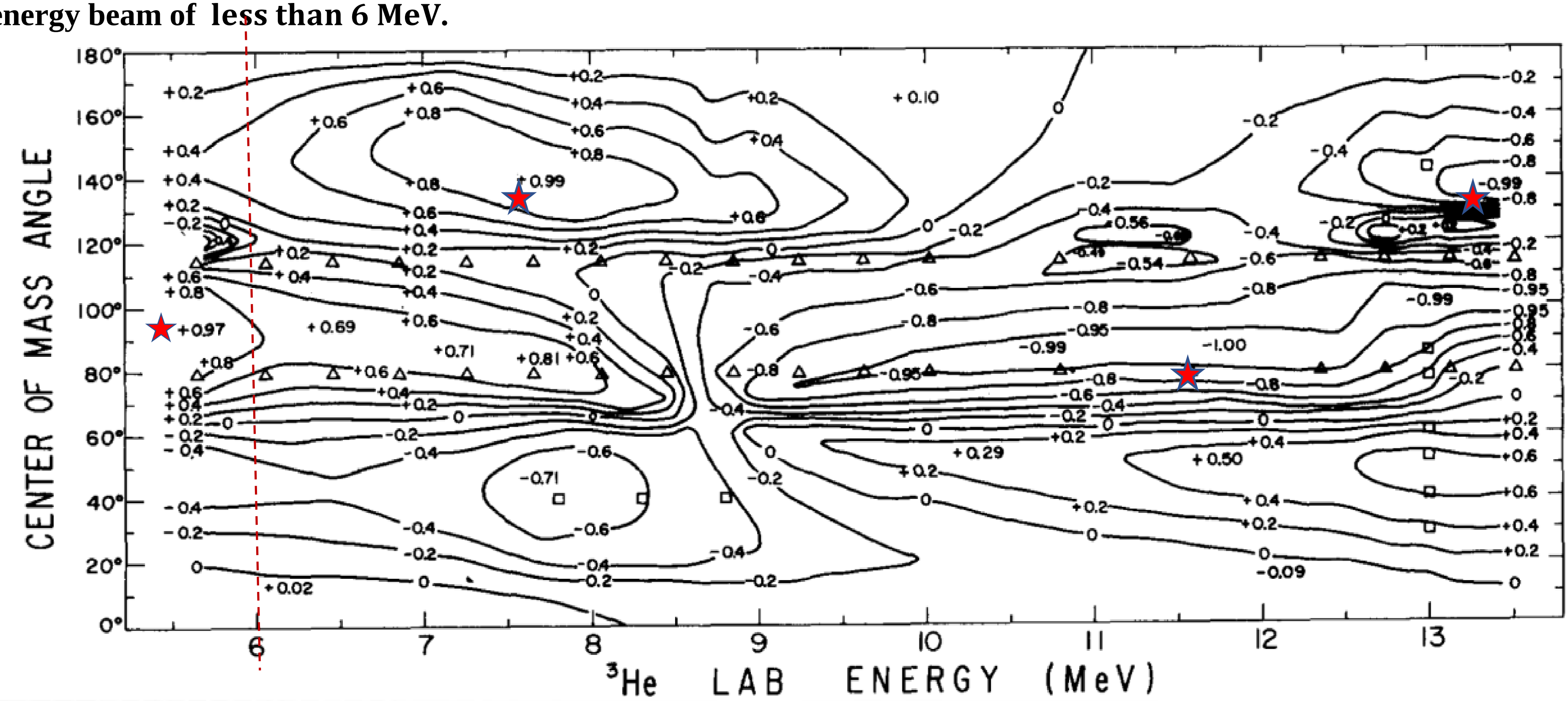
A schematic plan view of the left/right symmetric polarimeter to measure polarization of the vertically polarized beam.

The accuracy of the polarization measurement depends on:

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

Proposed method: analyzing power of ^3He-^4He scattering

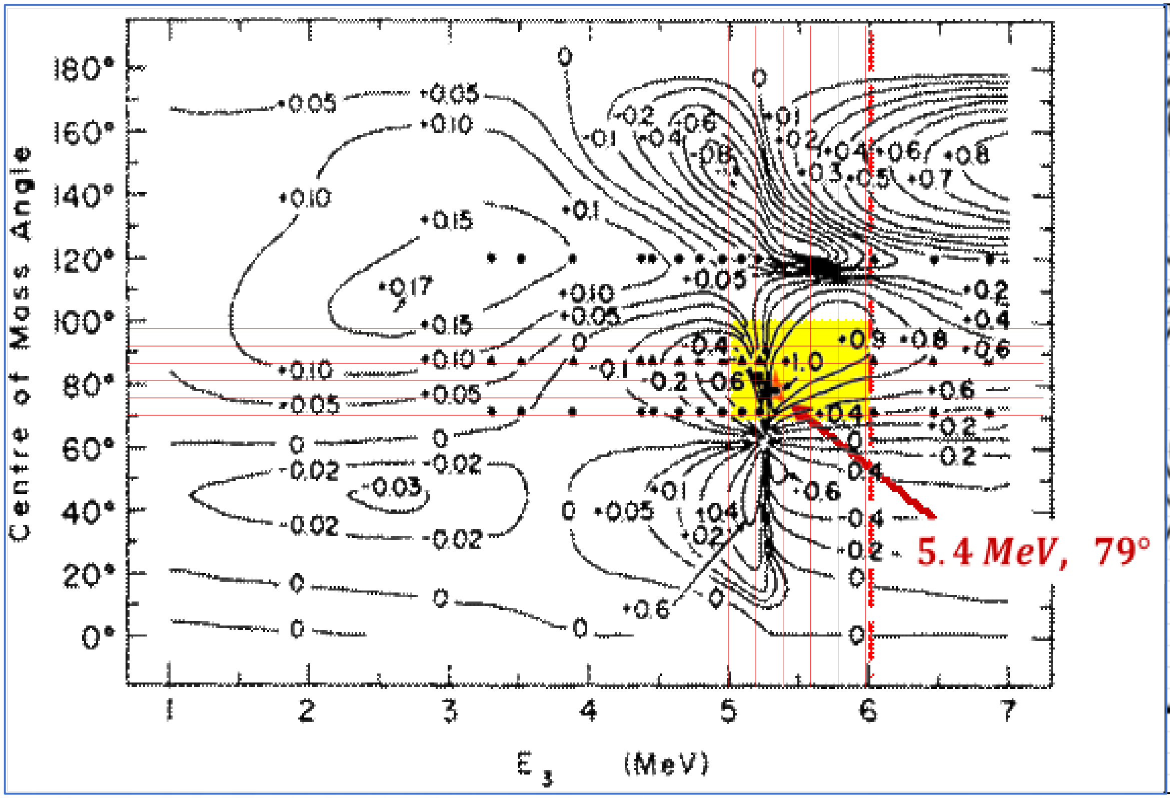
The elastic scattering of the low energy polarized ^3He ion was intensively studied experimentally and theoretically about 50 years ago. According to [1] the analyzing power for elastic ^3He-^4He scattering is a function of the beam kinetic energy and the CM scattering angle - $A_N(E_{beam},\theta_{CM})$ and can reach 100% at several points (E,θ). Because EBIS Linac's energy is 6 MeV, 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 ^3He-^4He scattering at an energy beam of less than 6 MeV.

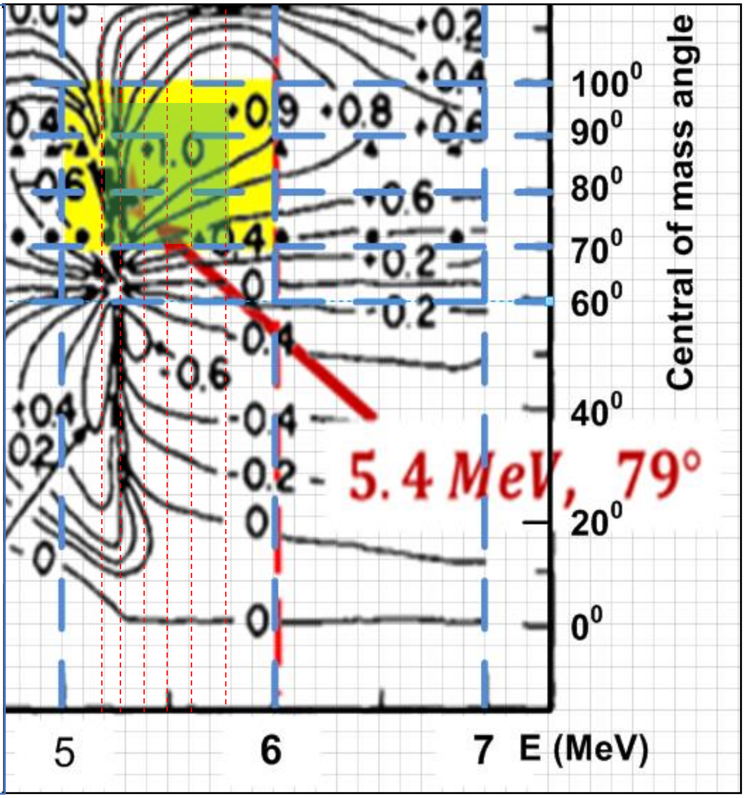


[1] D.M. HARDY et al. "POLARIZATION IN ^3He + ^4He ELASTIC SCATTERING", ***Pys. Let. Vol.31B, #6, 16 March 1970, p. 355-357***

Proposed method: analyzing power of ^3He-^4He scattering

This point is E_{beam}≈5.3 MeV and θ_{CM}≈91° [1], but the exact location of this point was not well determined. Later on, 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 area of (E_{beam},θ_{CM}) what will include this point.



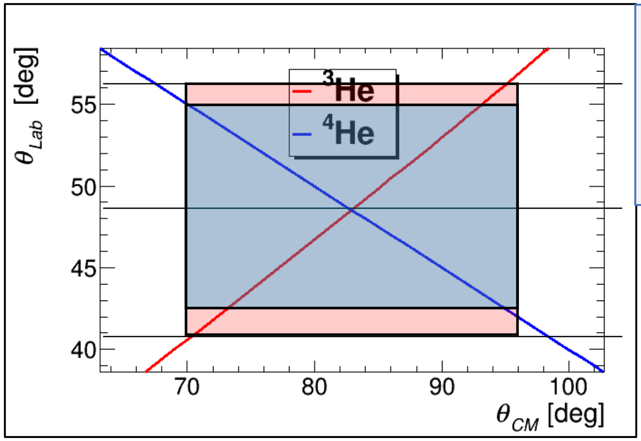


[1] G.R. PLATTNER et al. "ABSOLUTE CALIBRATION OF SPIN -1/2 POLARIZATION", *Pys. Let. Vol. 36B, #3, 6 Sep 1971, page 211-214*

[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).

Kinematics of elastic ^3He-^4He scattering

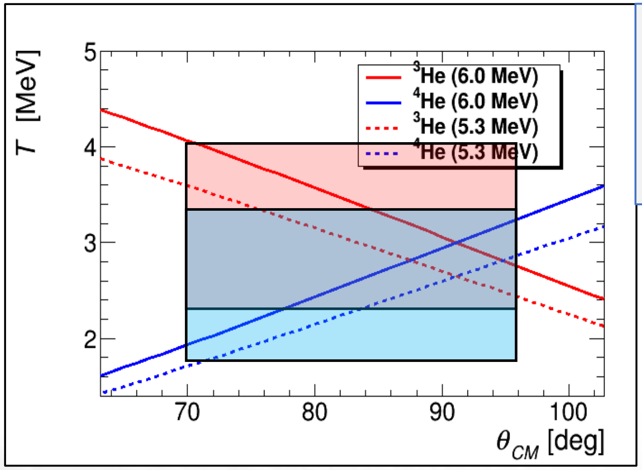
Kinematics of elastic ^{3}He- ^{4}He ***scattering***



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 –> (42° - 54°).



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

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

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

The kinematics allows 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 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 to 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 mass scattering angles $70° < \theta_{CM} < 96°$).

Detector

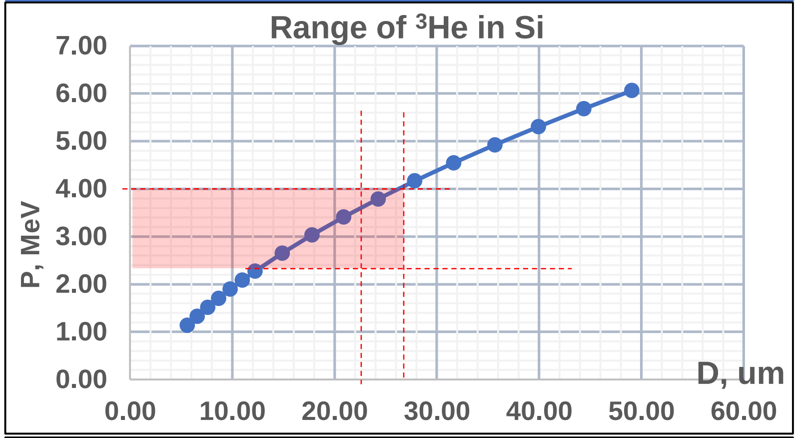
The requirement of the angle and energy range and an accuracy of measured energy can be satisfied by Hamamatsu Si-photodiode array S4114-35Q

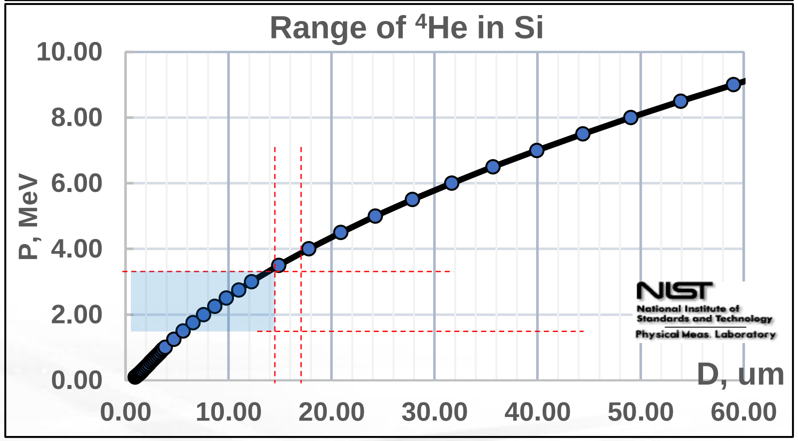
- ***number of channels: 35***
- ***channel size: 0.9mm x 4.4mm***
- ***depletion region >30mkm***

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

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

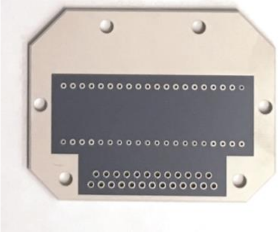
For a readout, several Si strips can be combined into one readout channel. The detector can be equipped with a standard 12-channel preamplifier and a shaper from the pC and H-jet polarimeters in RHIC.



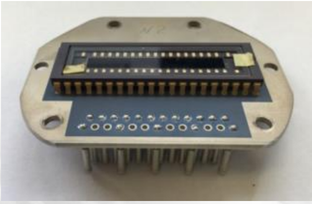


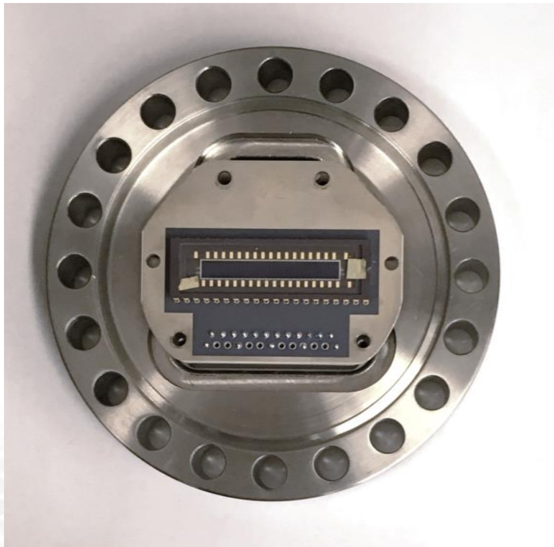
Hamamatsu photodiode array S4114-35Q mounted on the ceramic board and connect with D-sub vacuum thru connector on the flange.

Ceramic board

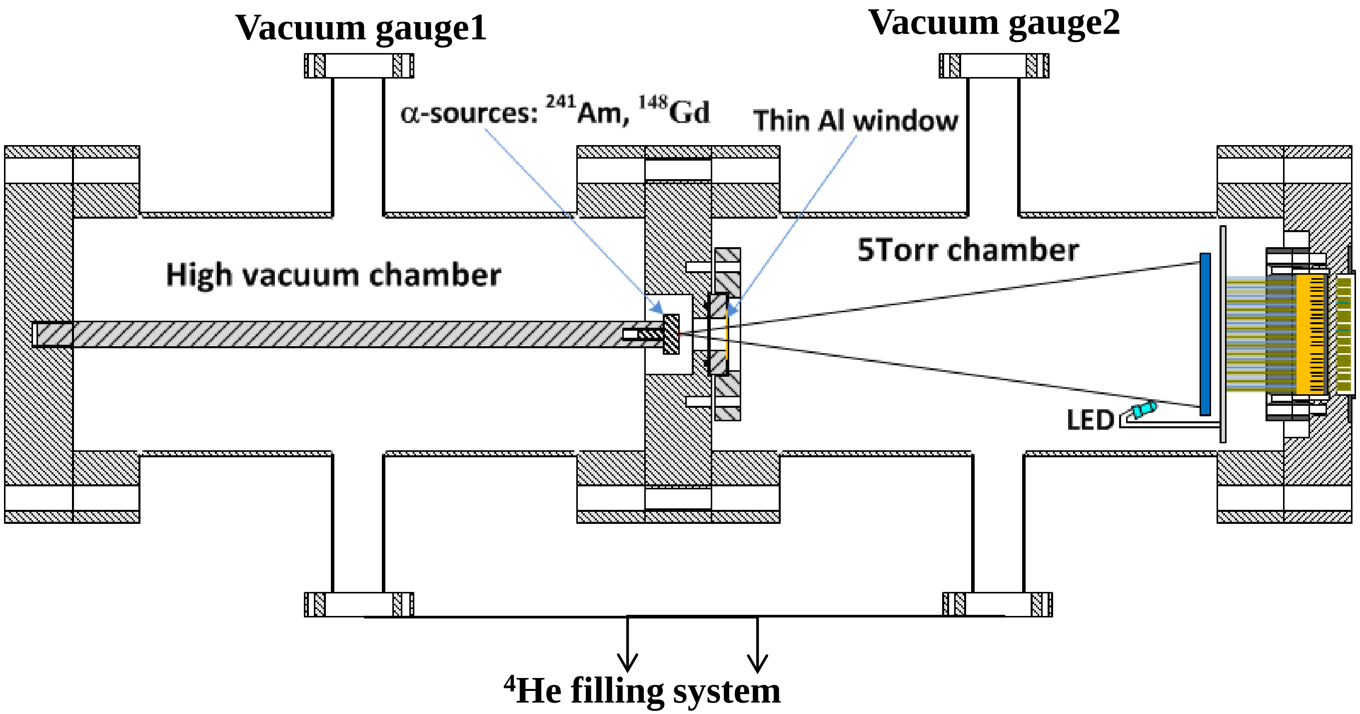


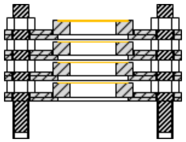
Detector





First step of prepared the polarimeter (with LED and α-sources)

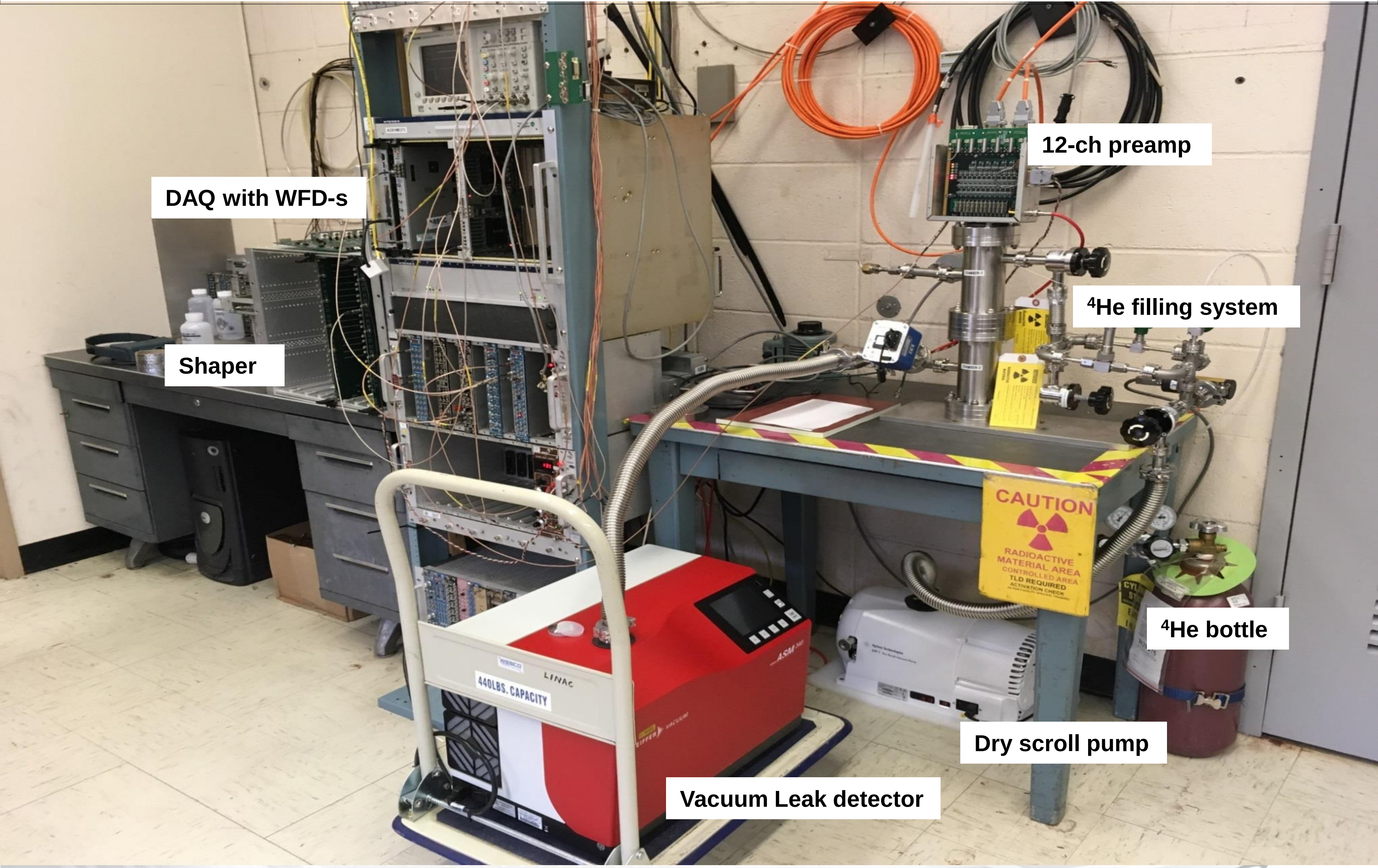




We studied:

- **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;**
- **…**

First step: test setup #1 for 6 MeV polarimeter (with LED and α-sources)



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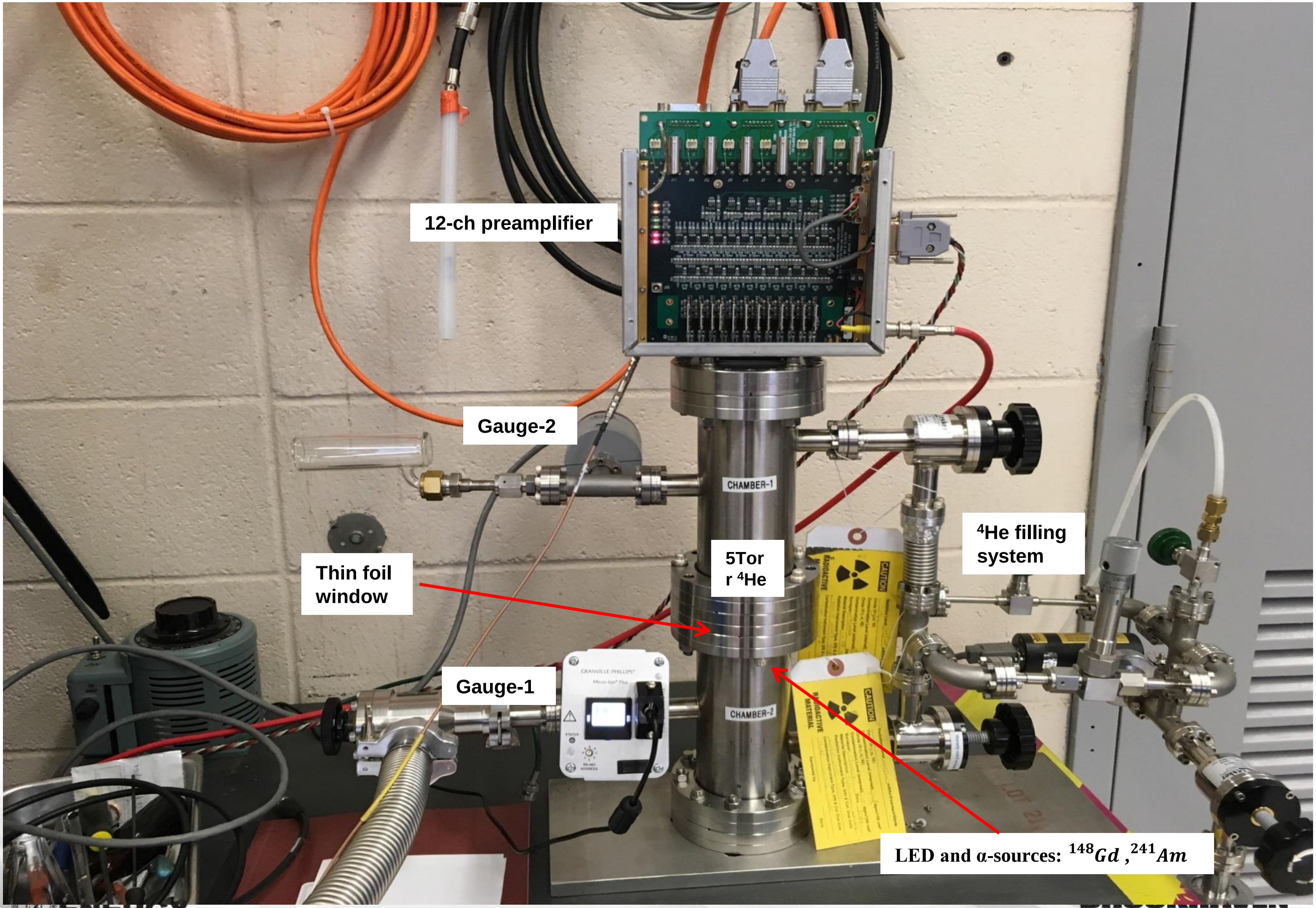
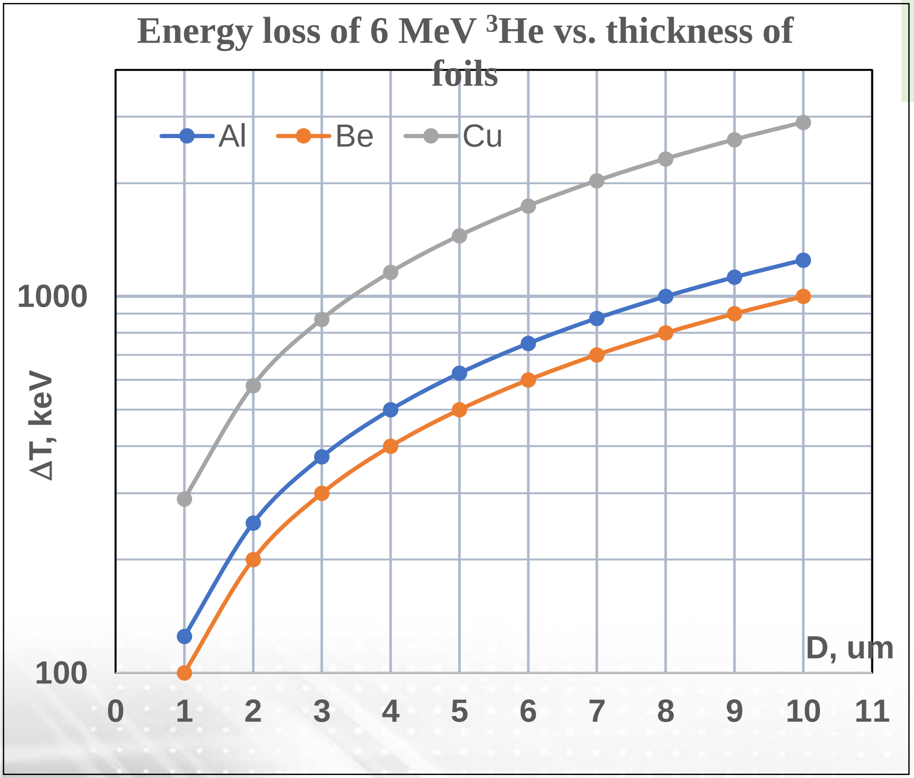
First step: test setup #1 for 6 MeV polarimeter (with LED and α-sources)



Vacuum window

	Be (z=4)	Al (z=13)	Ni (z=28)	$T(^3\mathrm{He})$
	~580	483	~364	5.28 MeV
dE/dx, MeV cm^2/g	~555	460	~348	5.65 MeV
	~530	440	~335	6.03 MeV
ρ, 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

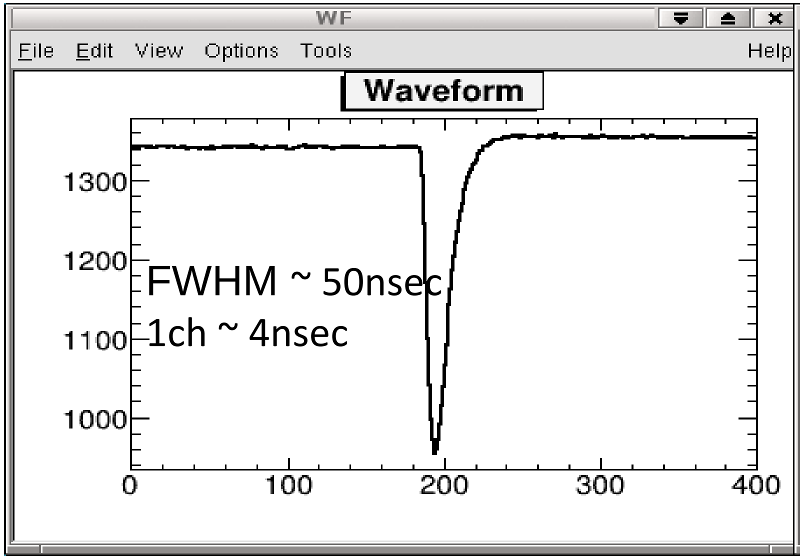
$2\ \mu m$ of Ni - ($\theta_0 = 0.028 \rightarrow \sigma_x \sim 3.5\ mm$)

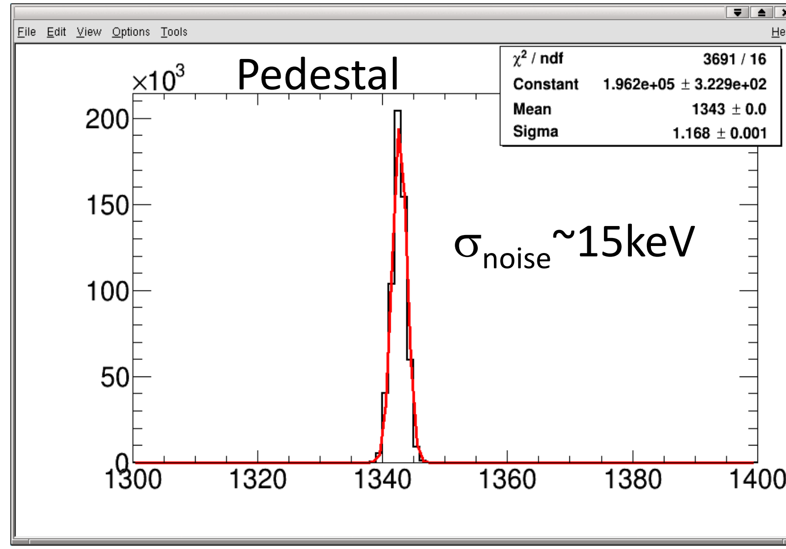
if distance to detector is $L = 125\ mm$.

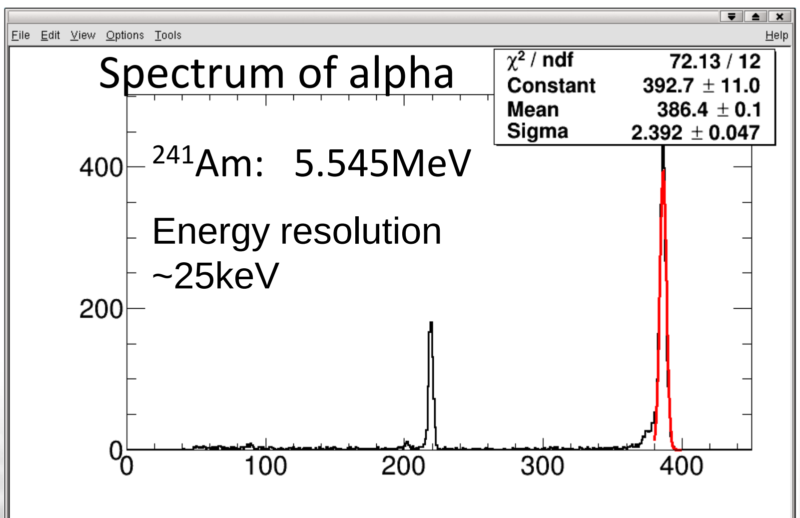
10 mm “target length” gives $\sigma_x \approx 2.5\ mm$.

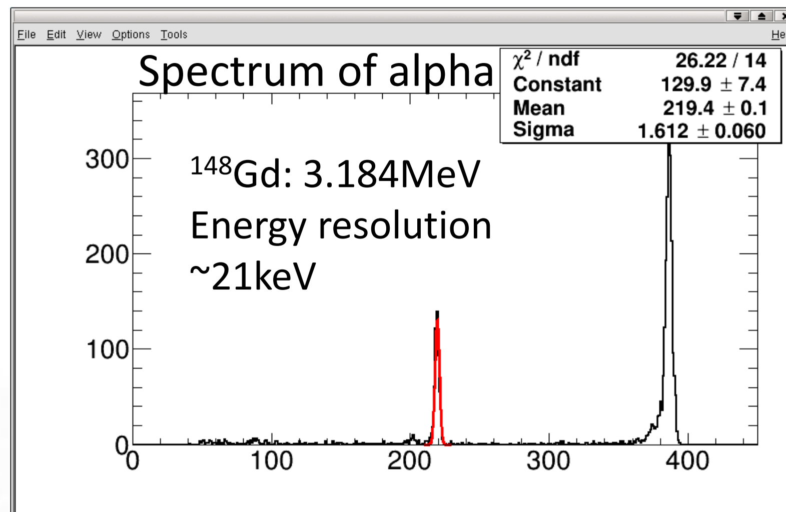
Alpha spectrum of ^{148}Gd and ^{241}Am by Hamamatsu Si array detector (S4114 35N)+preamplifier(charge)+shaper(CNI).

Sigma noise ~15keV; energy resolution: ^{148}Gd (3.184MeV) ~21keV; ^{241}Am ~25keV; FWHM ~50nsec



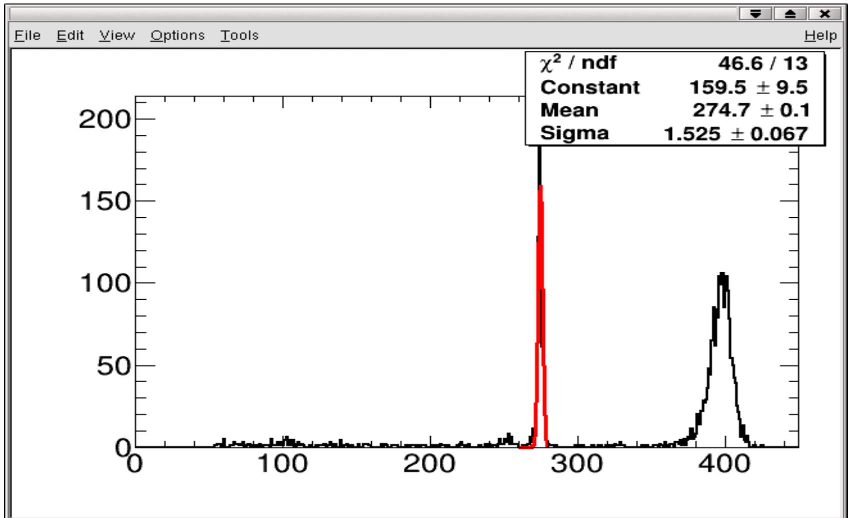


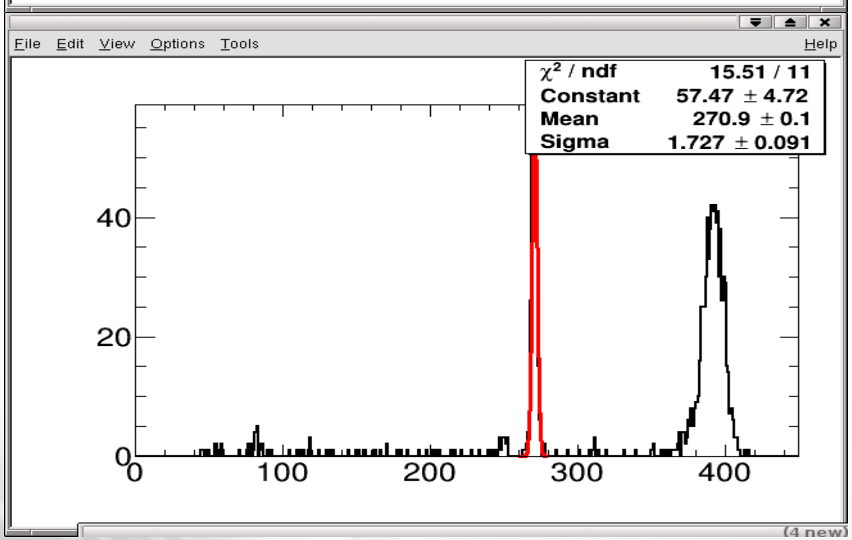




Absorption energy of alpha in ^{4}He gas

The expected absorbed energy of the scattered particles in a 5 Torr ^{4}He gas is ~ 15keV (the distance between the target and the detector is 5")

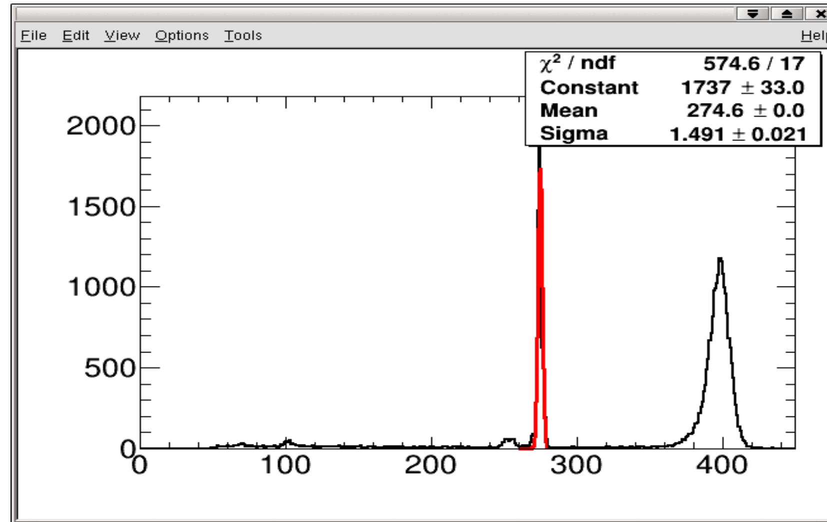


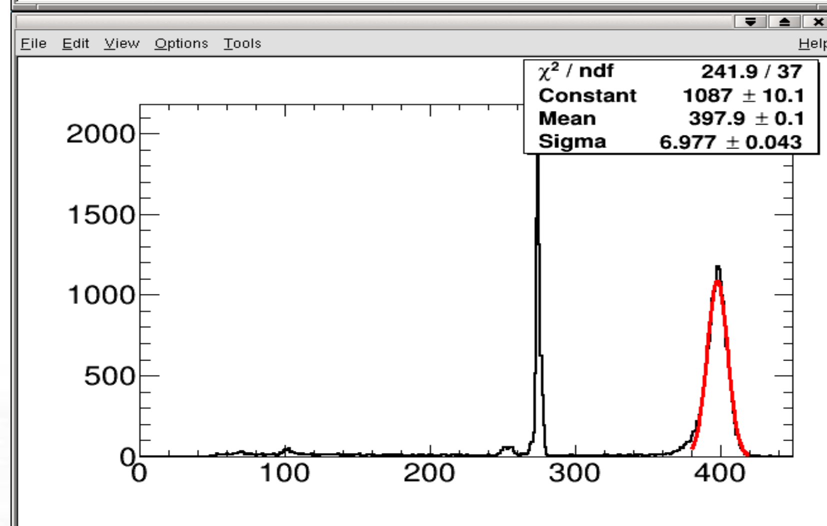


Energy loss of alpha in 10mkm Al foil

^{241}Am is before the Al foil (10mkm thick) and ^{148}Gd is after Al-foil.

ΔT ~ 1.2 MeV (120keV/mkm)





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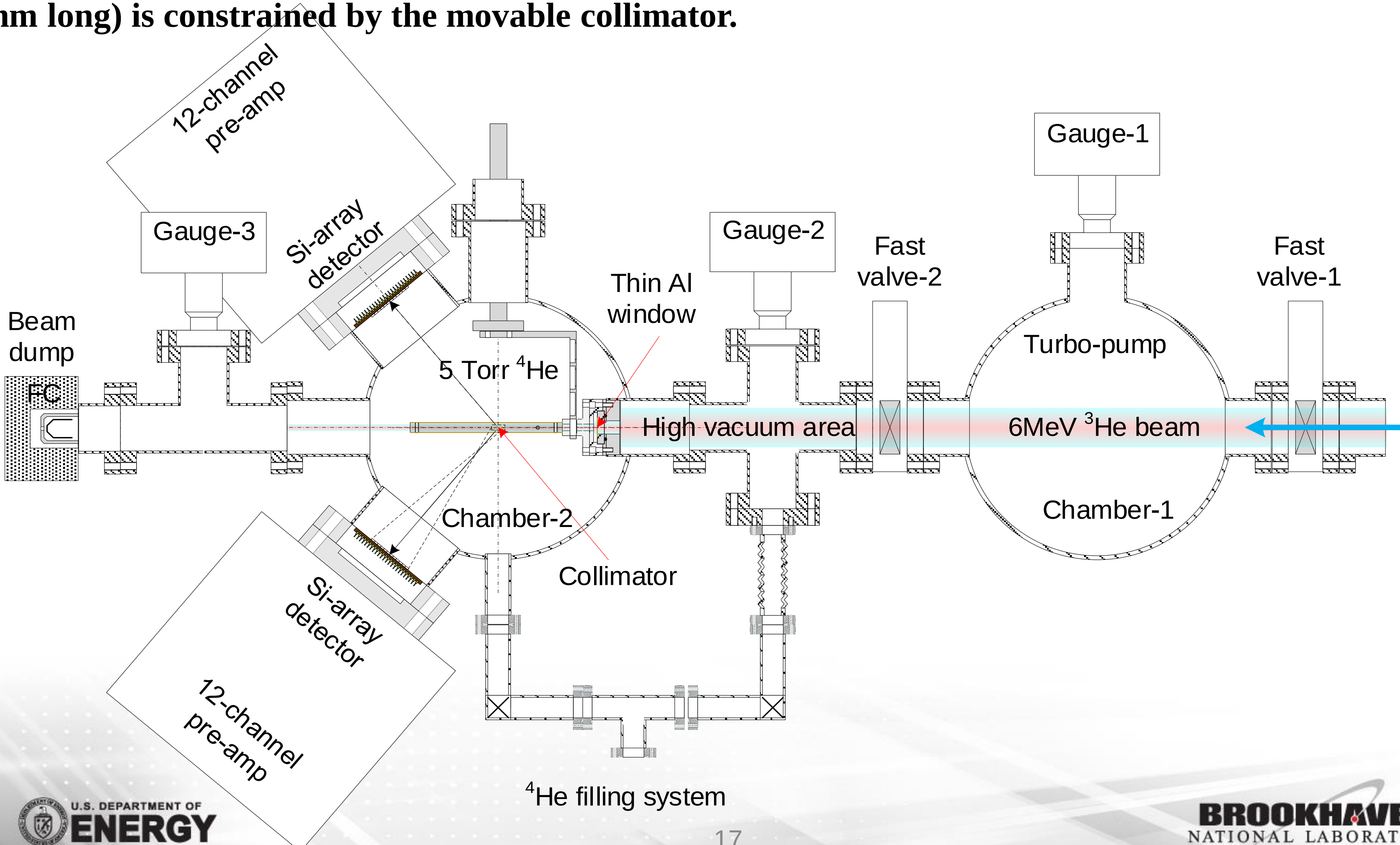
Second step: setup #2 for 6 MeV polarimeter (with ^{3}He beam at Tandem)

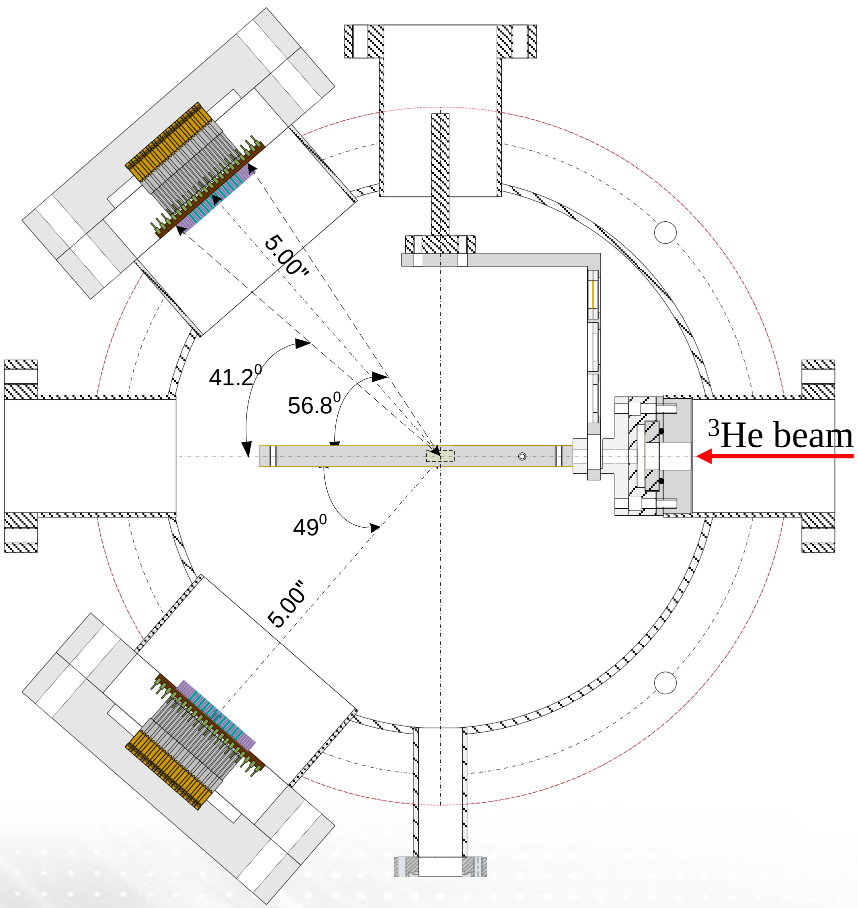
The requirements to the geometry and measured energy range can be satisfied by the next design and developed polarimeter. The polarized ^{3}He beam has entered the scattering chamber through a very thin window (~1.8 um of Al foil) to minimize beam energy losses.

The scattering chamber is filled with 5 Torr ^{4}He gas. The effective size of the target (~5mm high and 8mm long) is constrained by the movable collimator.



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

Two Si detectors are in the chamber at $\theta_{Lab}\sim 49°$ and 5” from the “center of the target”. The chosen detector will cover the center of mass angles 70°< θ_{CM} <96° (40°< θ_{Lab} <60°). The 30 μm depletion region of detector is sufficient enough 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:

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

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

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

For Data Acquisition we are using VME 250 MHz 14-bit waveform digitizers (SIS3316-250-14). These WFDs will allow us to record the full (20 us/ 5000 samples) bunch signal in every readout channel which is essential for monitoring the possible rate dependent systematic errors. The expected data rate per readout channel will be less than 10 and does not seem to be a problem.

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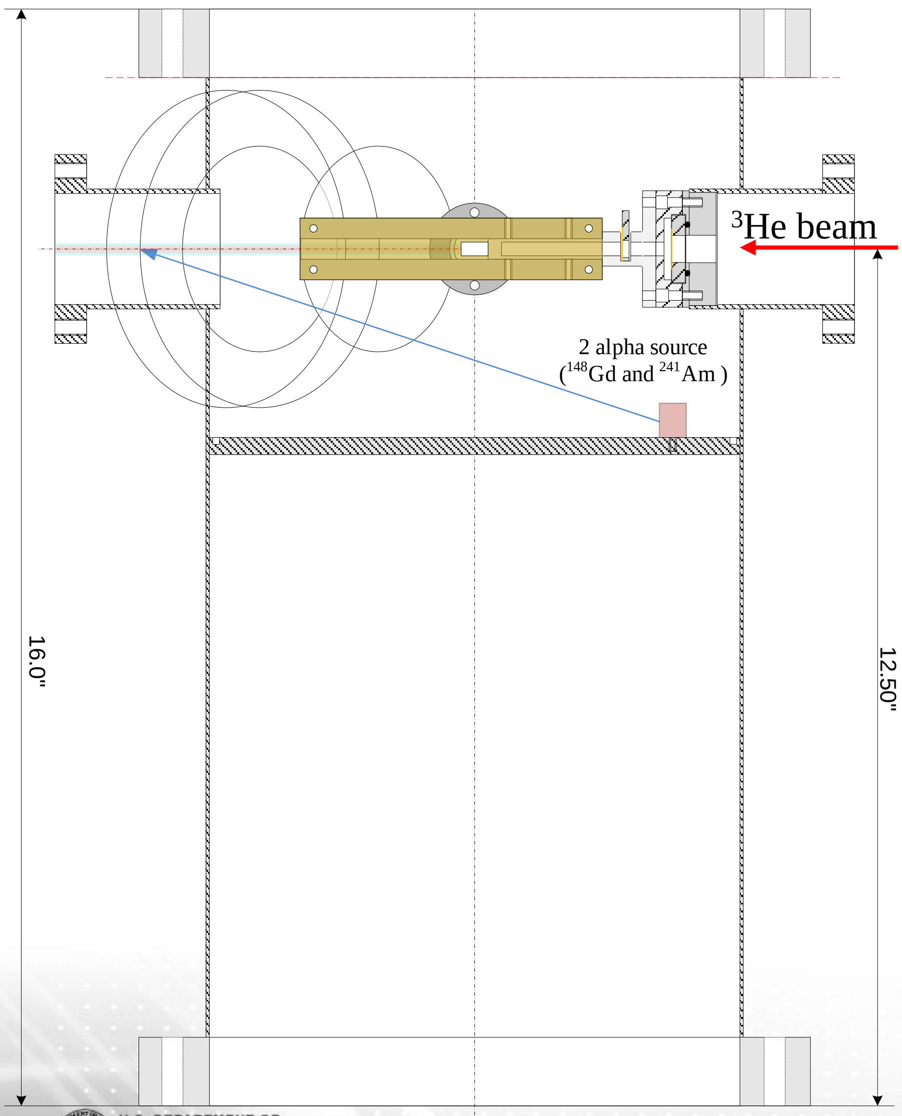
Calibration and monitoring of energy and time

Side view



Two α-sources (^{148}Gd -3.183MeV and ^{241}Am −5.486MeV) will be used for energy calibration and monitoring.
Both 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

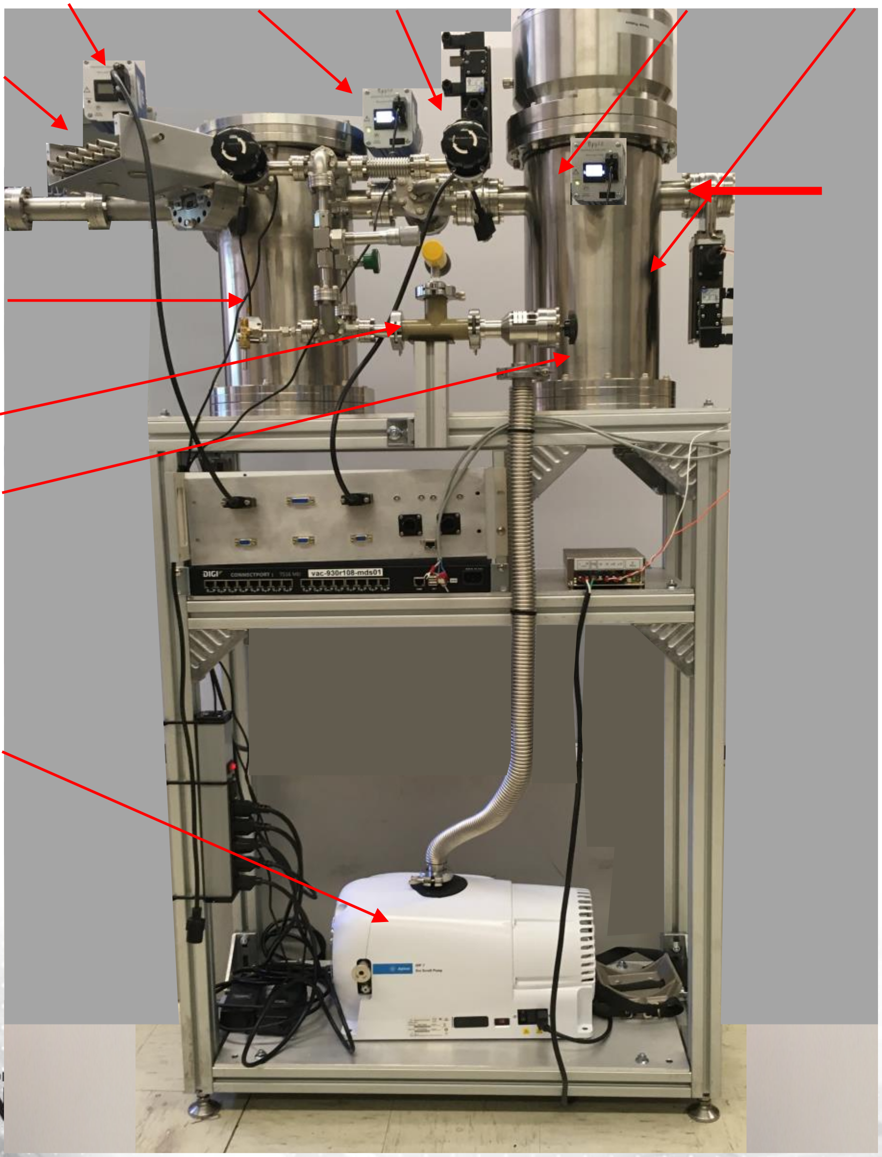
a) **measured energy E;**
b) **corelated scattering angles (the strip number) θ;**
c) **time coincidence and**
d) **difference in time of flight for scattered ^{3}He and recoiled ^{4}He.**

- $E_{3He} + E_{4He} = E_{beam}$ **(σ_E ~ 20 keV);**
- **Left − right** $counsidence$ **($\sigma_t \lesssim$0.2 ns);**
- $t_{He} = \frac{L(\theta)}{c}\sqrt{\frac{M_{He}}{2E_{He}}}$

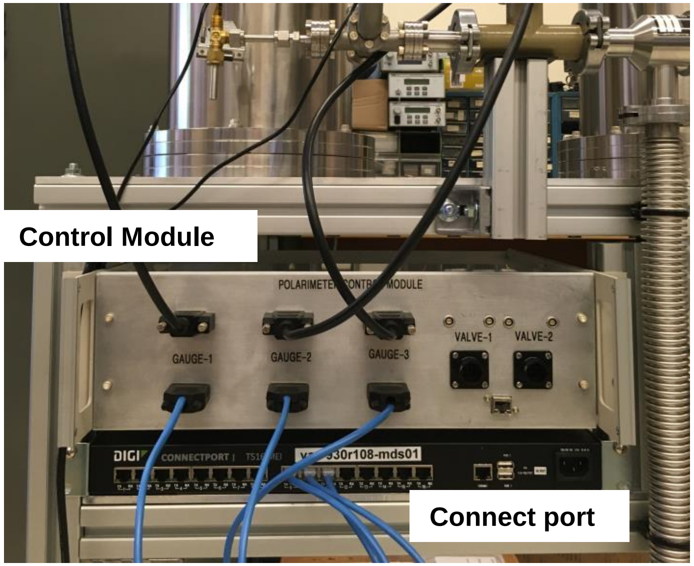
(separately for ^{3}He and ^{4}He, $L(\theta)$is the distance to the Si strip).
These equations can help to strongly suppress background events and to separate ^{3}He and ^{4}He signals.
Si detectors are not sensitive to backgrounds, such as neutrons and gammas from other beam lines.

Second step: setup #2 for 6 MeV polarimeter (with ^{3}He beam at Tandem)

We have prepared a complete detector. After the final study of all the parameters of the polarimeter (except for self-calibration) on the Tandem beam, the polarimeter will be ready for installation in the EBIS beam line.



Polarimeter Control Module

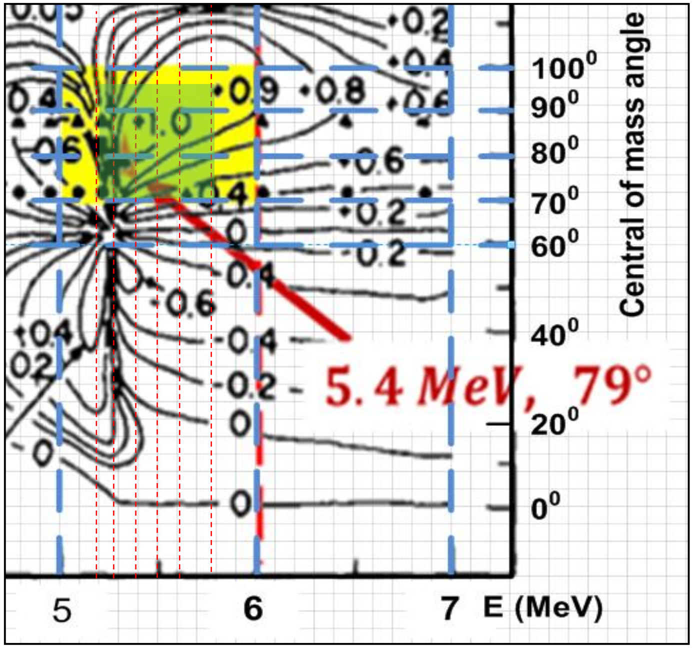


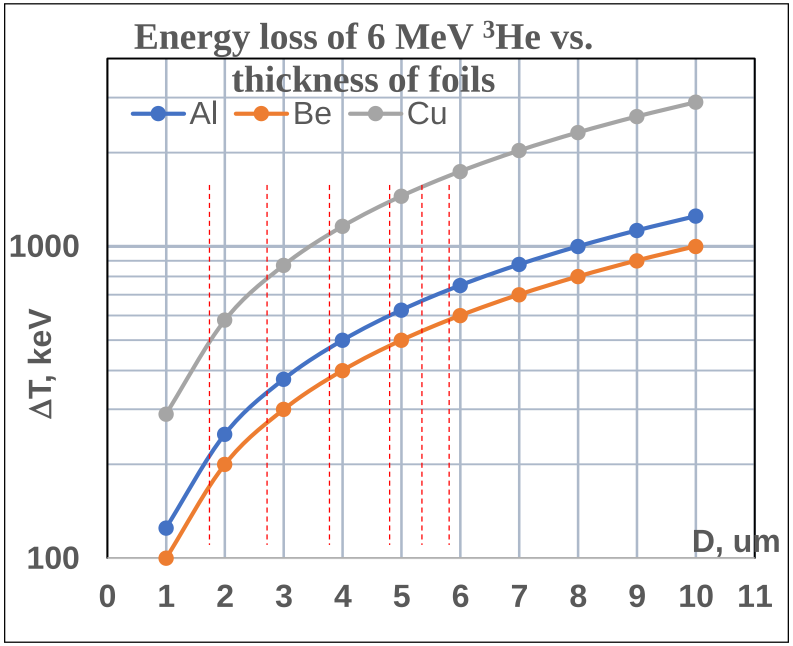
By Tandem beam we plan to study ^{3}He-^{4}He scattering:

- **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;**
- **…**

Third step: self-calibration procedure of the polarimeter at EBIS

For 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

Expected Characteristics of the beam and polarimeter

Beam parameters:

- beam polarization — 70 %
- beam energy — 6 MeV
- total intensity — 2×10^{11} sec^{-1}
- intensity in polarimeter — $\sim 1 \times 10^{11}$ 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: — $(70\text{-}95)^0$
- energy range: — (1.0-4.0) MeV
- noise (PED) σ_{noice} — ~ 15keV
- energy resolution σ_E — ~ 20keV
- time resolution for 1MeV σ_t — ~ 0.2 ns
- signal FWHM — ~ 50 ns
- energy spread (after ~7mkm Al) $\sigma_E{}^*$ — ≲ 80keV
- expected rate — ~100 event/pulse

Summary

- ❑ **The complete test of polarimeter on the BNL Tandem (a non polarized ^3He and ^4He continuous beam) in spring of 2021. We studding next:**
  - **the coincidences between two arms for recognize ^3He /^4He :**
  - **background;**
  - **^3He /^4He separation;**
  - **energy and time resolution of detector;**
  - **absorption energy in the vacuum window;**
  - **absorption energy on the Al foil vs. thickness;**
  - **deposited energy in ^4He gas vs. pressure;**
  - **…**
- ❑ **Prepare the polarimeter for installation on the EBIS line at 2021**
- ❑ **Possibility of upgrade:**

- *Number of readout channels;*
- *Increase a detection angle. (available same kind Hamamatsu Si array detector with 54 strips);*
- *Increase a distance from the scattering point to the detector. (The efficiency of time resolution in background suppression, dilution of the beam halo related background);*
- *Order a special Si detector (size, granularity, thickness).*

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