Development of an Absolute Polarimeter and Spin-Rotator for a Polarized He-3 Ion Source at RHIC and Polarimetry for High Energy He-3 Beams

PI

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U.S. DEPARTMENT OF ENERGY

Acknowledgements

BNL:

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MIT:

R. G. Milner, M. Musgrave

Polarized ^{3}He Source

Funding	PI	R&D Report Priority # (Row No)	Panel Priority Rating	Panel sub Priority
FY 2018-2019 Lab Based R&D BNL	D. Raparia, BNL R. G. Milner, MIT	6	High	A

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.

2017 Jones EIC R&D Report

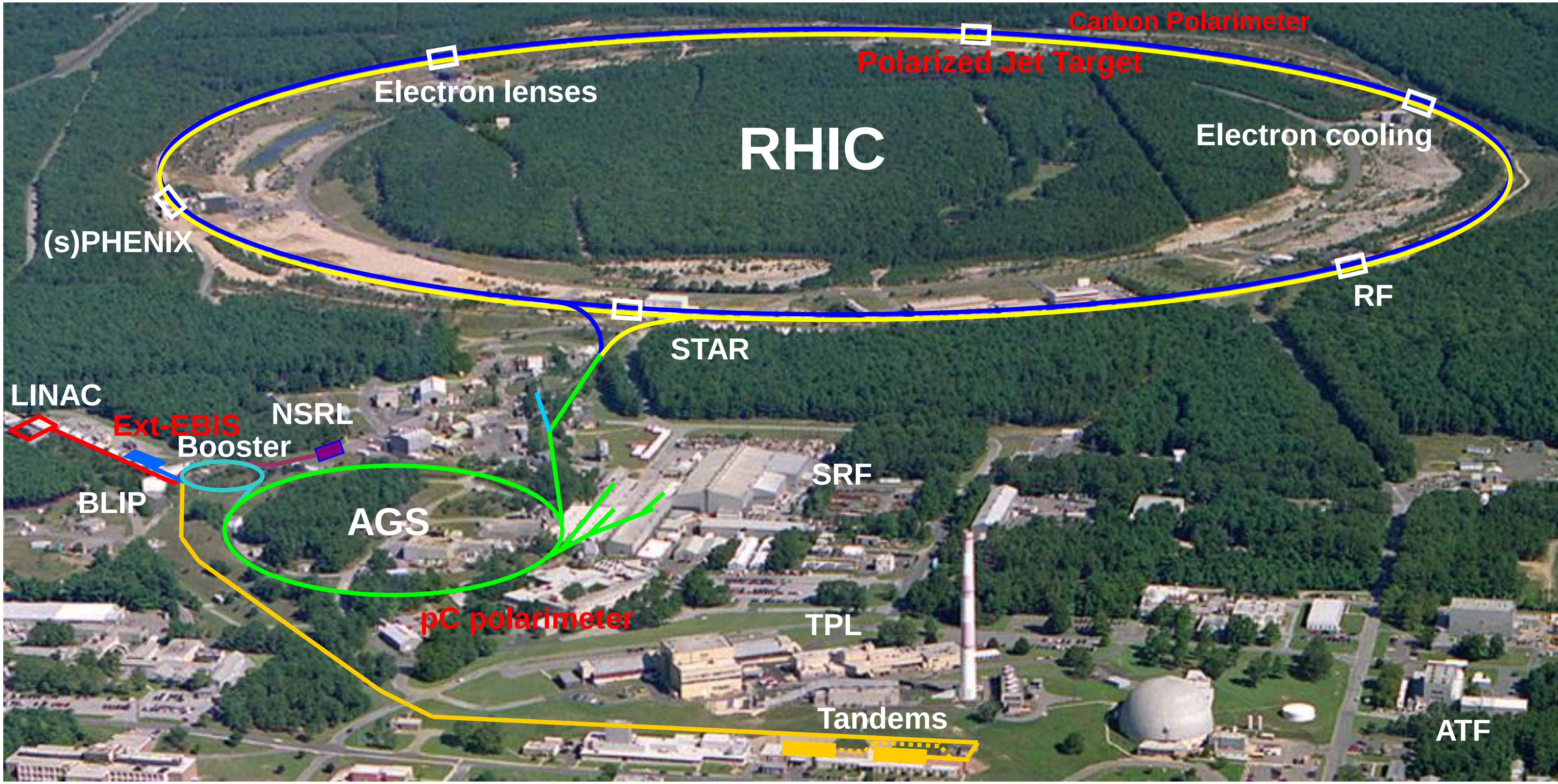
Outlines

- Introduction
- He-3 Source Development
- Spin Rotator Chicane
- Absolute He-3 Polarimeter
- High Energy Polarimetry
- Conclusions

Objectives

- Continued support for polarized He-3 ion source development.
- Development of a spin-rotator to produce transverse beam polarization for the polarimeter and further beam transport and acceleration into the Booster, AGS, and RHIC.
- Development of the precision absolute polarimeter at the EBIS linac at beam energy 5-6 MeV for the polarized He-3^{++} beam commissioning, optimization, and monitoring.
- Simulations of high-energy He-3 polarimetry in AGS and RHIC.
- Determine detector and polarimeter setup requirements for an EIC.

Polarized He-3 in the RHIC Accelerator Complex



- He3 ion source up to 90% polarization (Ext-EBIS)
- He3 spin rotator and absolute polarimeter
- Polarimetry for high energy He-3 beams

He-3 Source Development

Production of polarized $^3He^{++}$ 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.

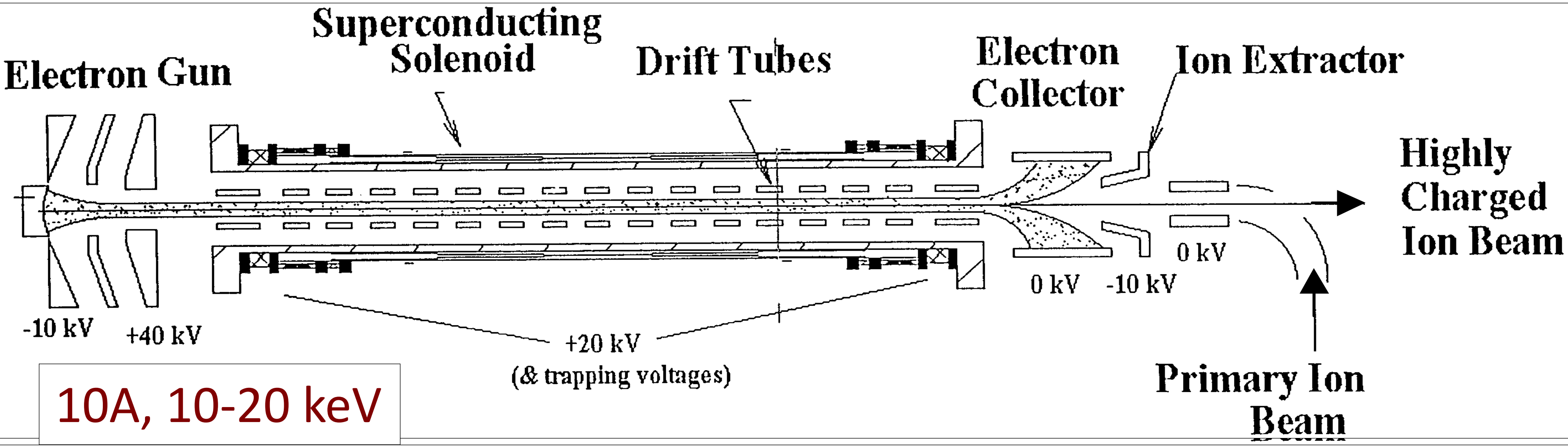
EBIS is used for efficient ionization and accumulation of polarized $3He^{++}$ ions to the full capacity of about $(2.5\text{-}5.0)\cdot 10^{11}$, $3He^{++}$ ions in 20 **μ**s pulse ~10.0 mA-peak current

Polarization (longitudinal) ≥ 80%

Compatibility with the operational EBIS for heavy ion physics.

Spin flip for every source pulse in the beam transport line

Principle of EBIS Operation



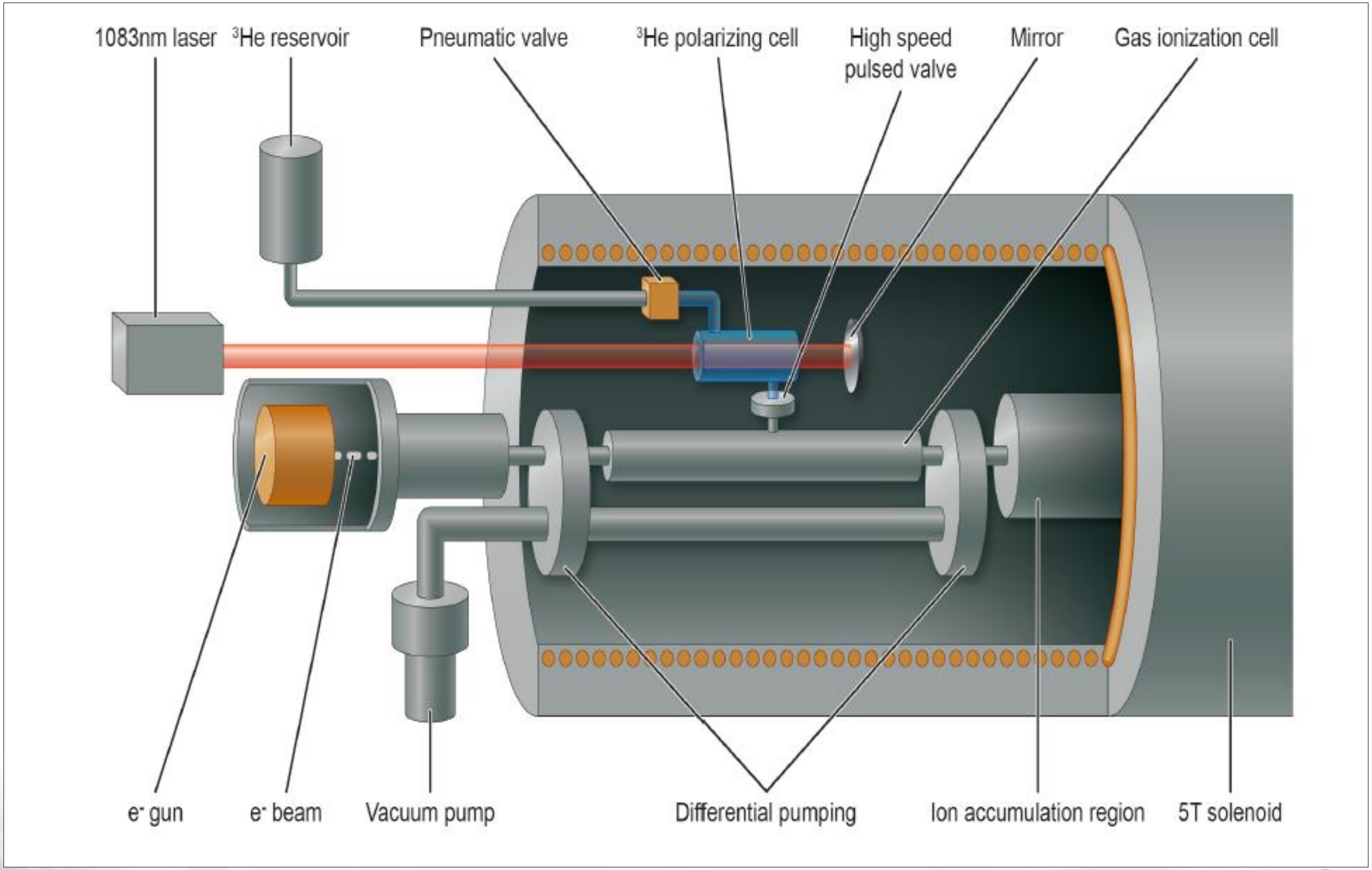
10A, 10-20 keV

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

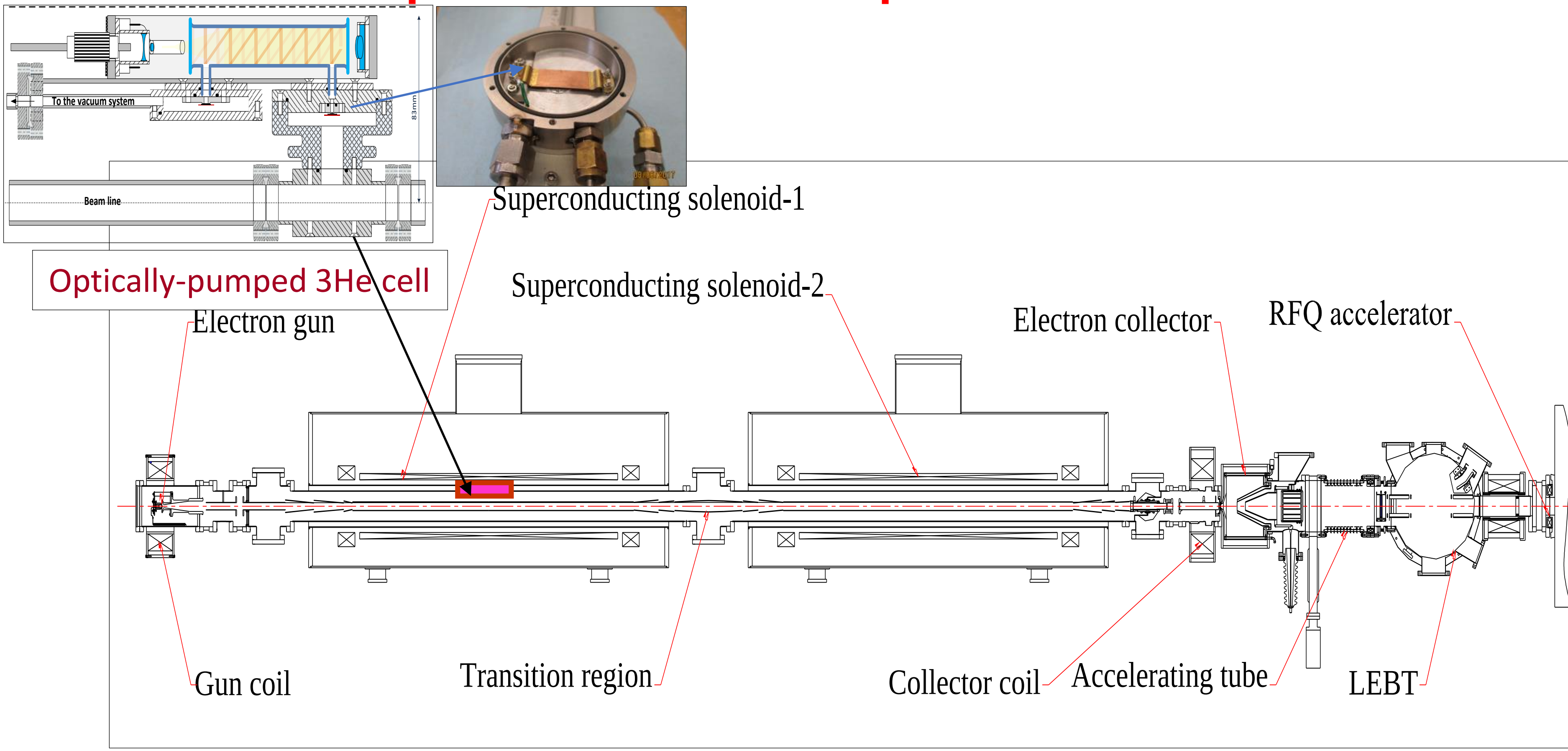
- *The total charge of ions extracted per pulse is ~ (0.5 – 0.8) x (number electrons in the trap ~$1.0 \cdot 10^{12}$)*
- *Ion output per pulse is proportional to the trap length and electron current.*
- *Ion charge state increases with increasing confinement time.*
- *Output current pulse is independent of species or charge state!*

Polarized He-3 Cell in Extended EBIS

Musgrave



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



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

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

Simulation Results for ^{3}He Injection into EBIS

Musgrave

Step sequence	Time
^{3}He gas injection	0.5 ms
Diffusion into ionization cell	2 ms
Injected gas pressure falls 50%	5 ms
Ionization of ^{3}He to ^{3}He$^+$	~10 ms per gas injection
Time constant for $^3He^+ \rightarrow {}^3He^{++}$ conversion	1 ms
Pump down to 10^{-9} torr	~30 ms
5 Hz EBIS pulse repetition rate	200 ms
Switching time between species	1 second

All results are encouraging for the project!

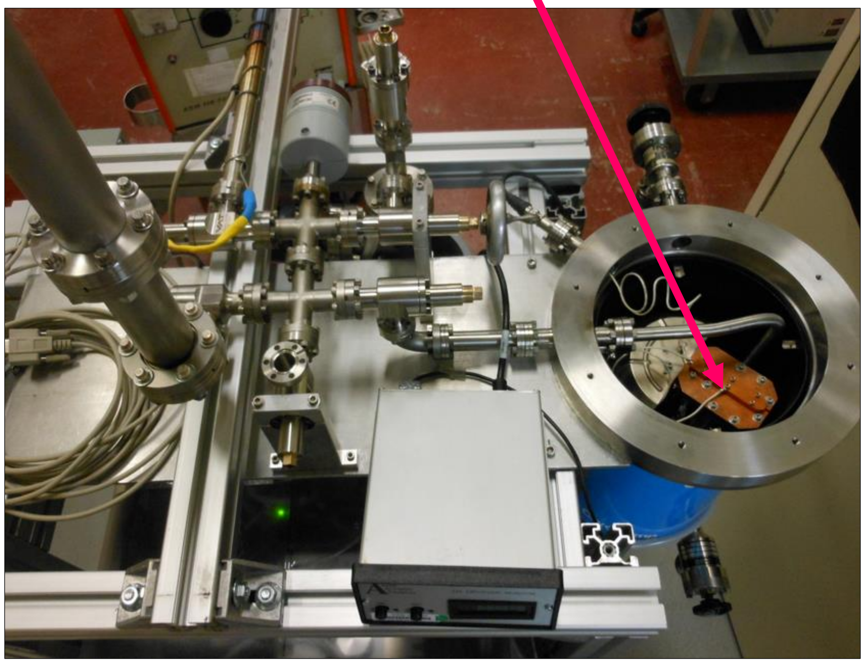
Data for gas injection will be collected after installation of the Extended EBIS in the summer of 2020.

Polarization Measurement in Open Cell Concept at OPPIS 3T Solenoid

3He-gas purification and filling system

Zelenski, Atoian

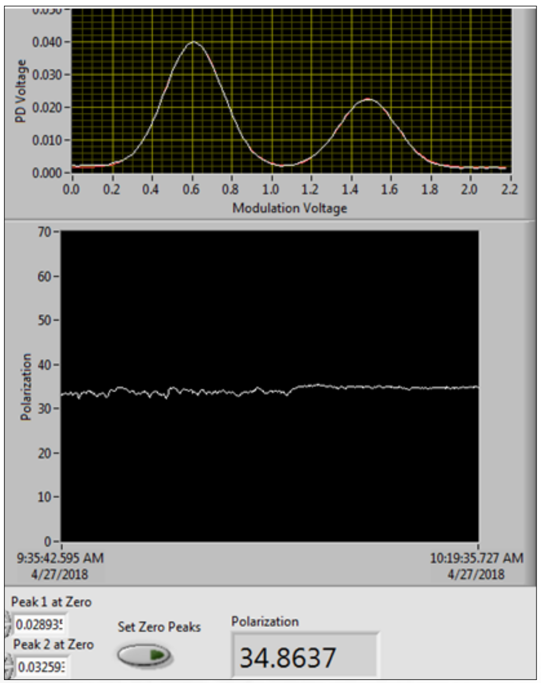
Modified Cryo-pump for 3He purification and storage



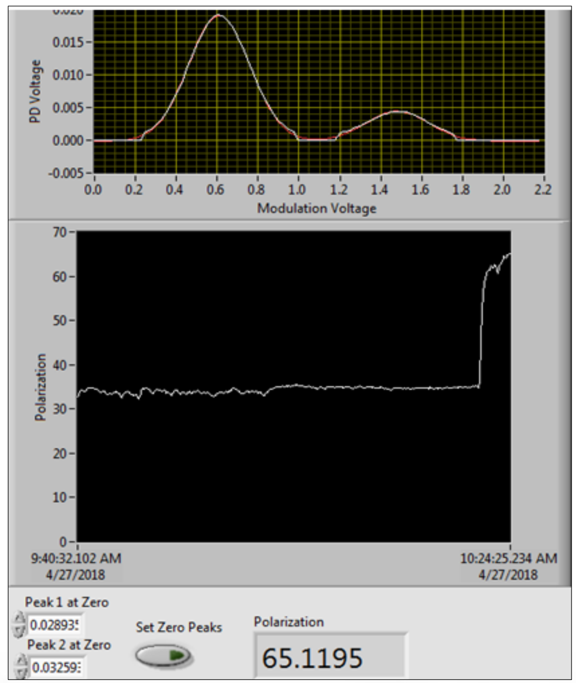
Polarization measurements

Zelenski, Atoian

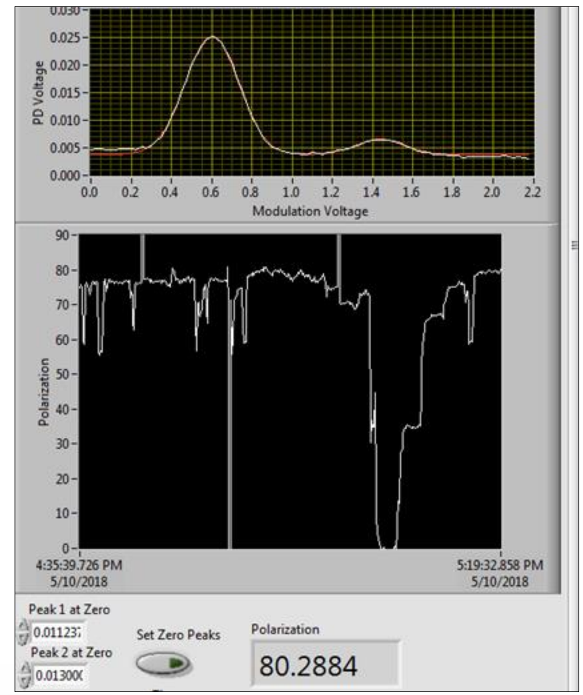
Isolation Valve (IV) open	Isolation Valve (IV) closed	Polarization equilibrium



34.9%



65.1%



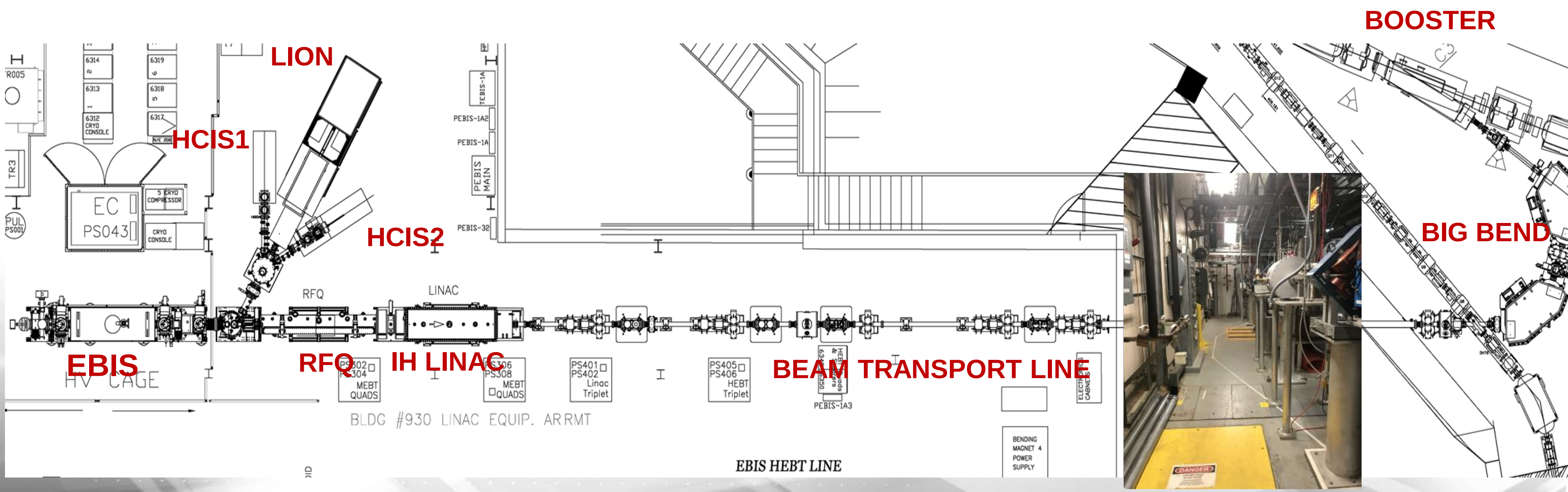
80.3%

Spin Rotation Chicane

EBIS Preinjector (2 MeV/u)

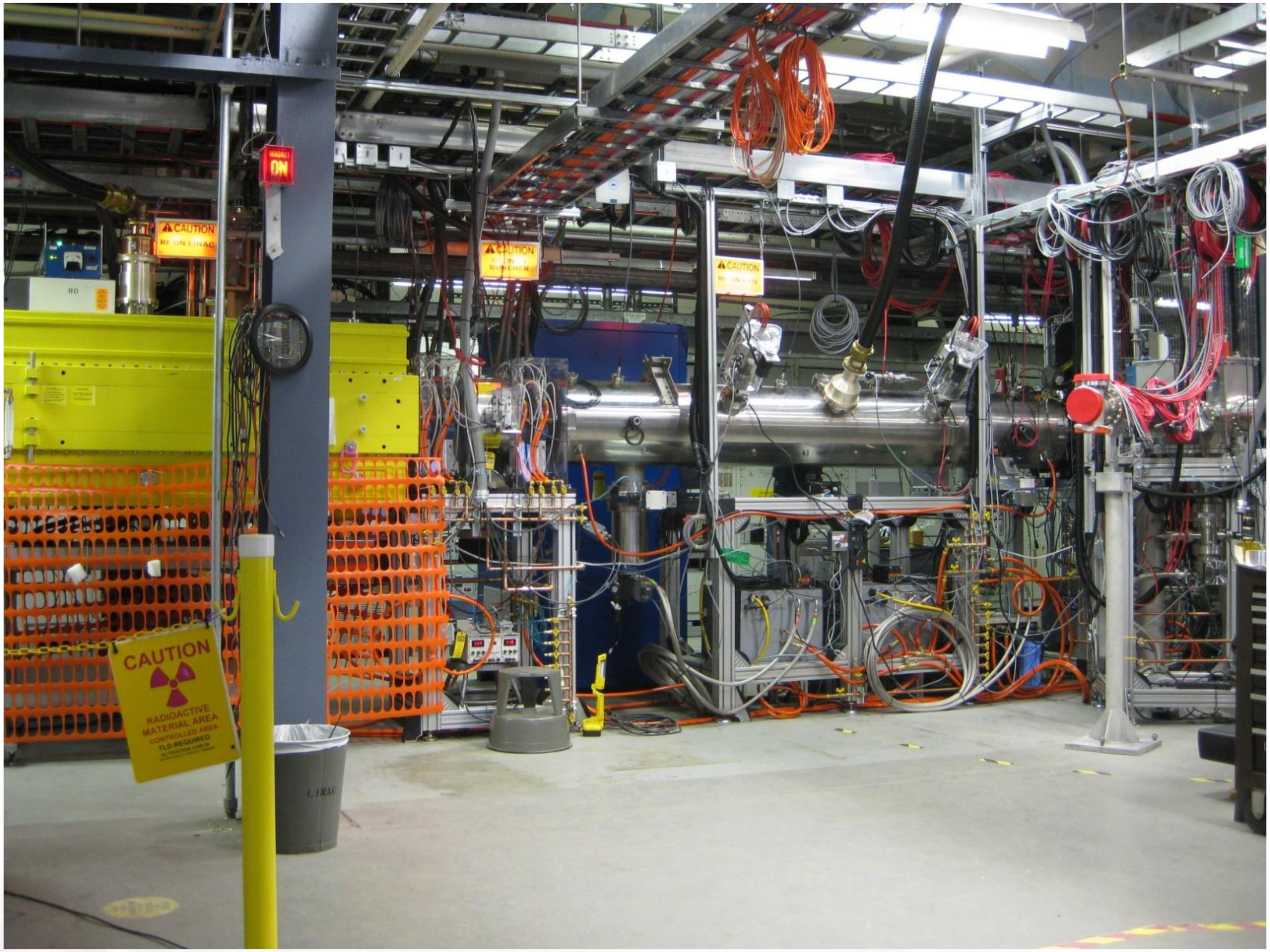
- Extended EBIS upgrade will provide polarized $^3He^{++}$ ions (5x 10^{11} particles) at 80% polarization
- The longitudinally polarized $^3He^{++}$ beam is produced in the EBIS. Polarization must be rotated to vertical direction for polarization measurements and further beam transport and acceleration in the Booster, AGS and RHIC

Ions	He - U
Q / m	≥1/6
Current	> 1.5 emA (20 μs)
Pulse length	10-40 μs
Rep rate	5 Hz
Output energy	2 MeV / u
Time to switch species	1 second

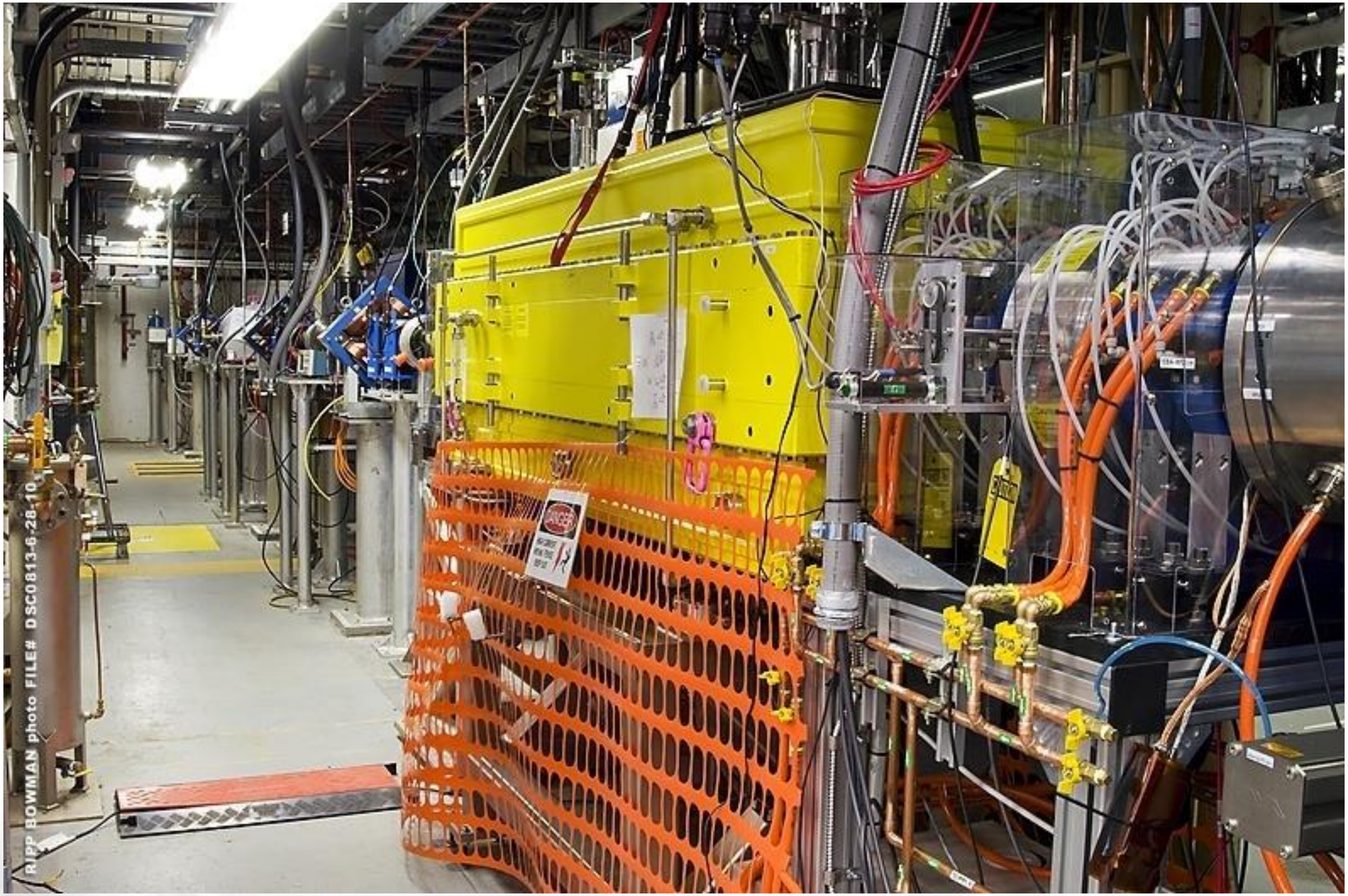


EBIS

RFQ. MEBT, and Linac



Linac and EBIS-to-Booster (ETB)Transport

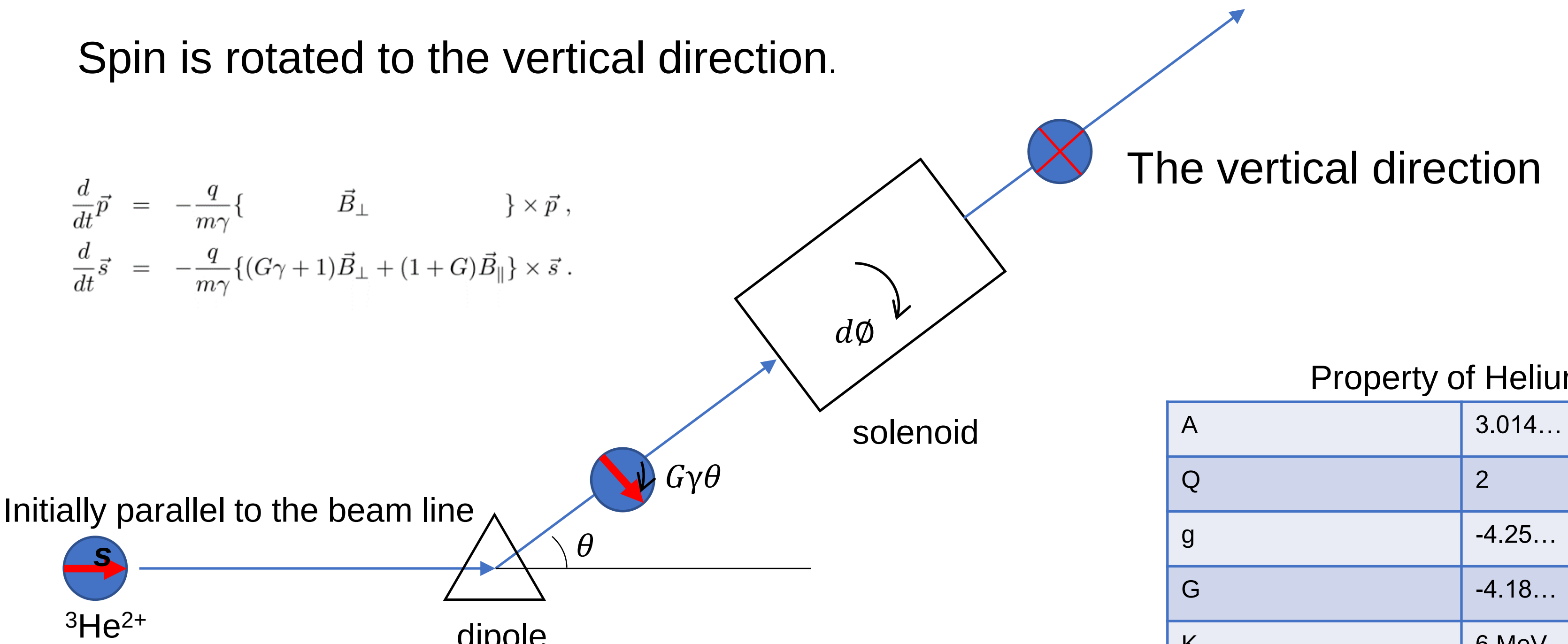


Spin Rotation by Dipole and Solenoid

Used this approach to spin rotate for polarized proton at OPPIS

Spin is rotated to the vertical direction.

$$\frac{d}{dt}\vec{p} = -\frac{q}{m\gamma}\{ \vec{B}_\perp \} \times \vec{p}\,,$$
$$\frac{d}{dt}\vec{s} = -\frac{q}{m\gamma}\{(G\gamma+1)\vec{B}_\perp + (1+G)\vec{B}_\parallel\} \times \vec{s}\,.$$



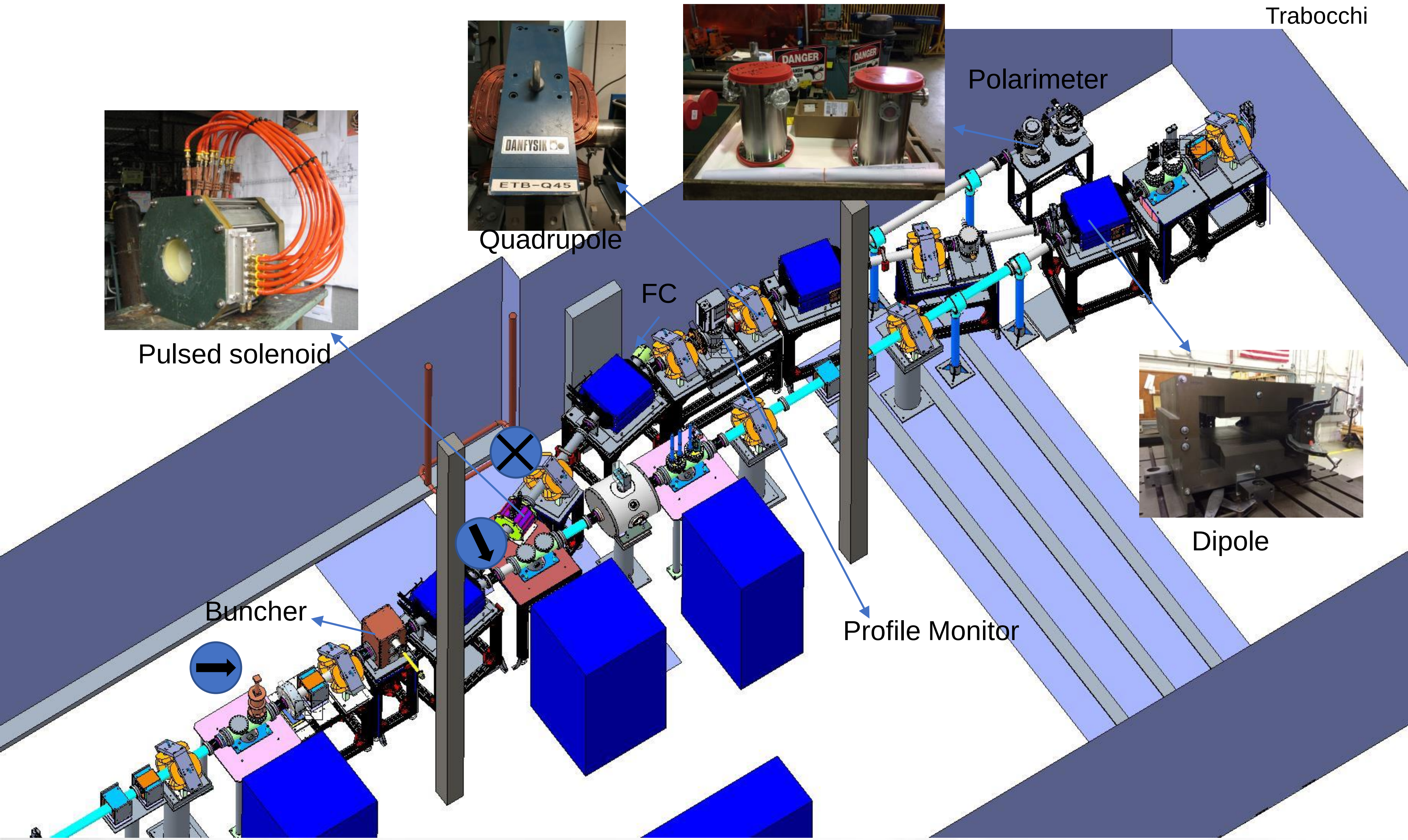
$G\gamma\theta = -90^o \rightarrow \theta = 21.5^o$

Property of Helium ion

A	3.014…
Q	2
g	-4.25…
G	-4.18…
K	6 MeV
γ	1.0021..

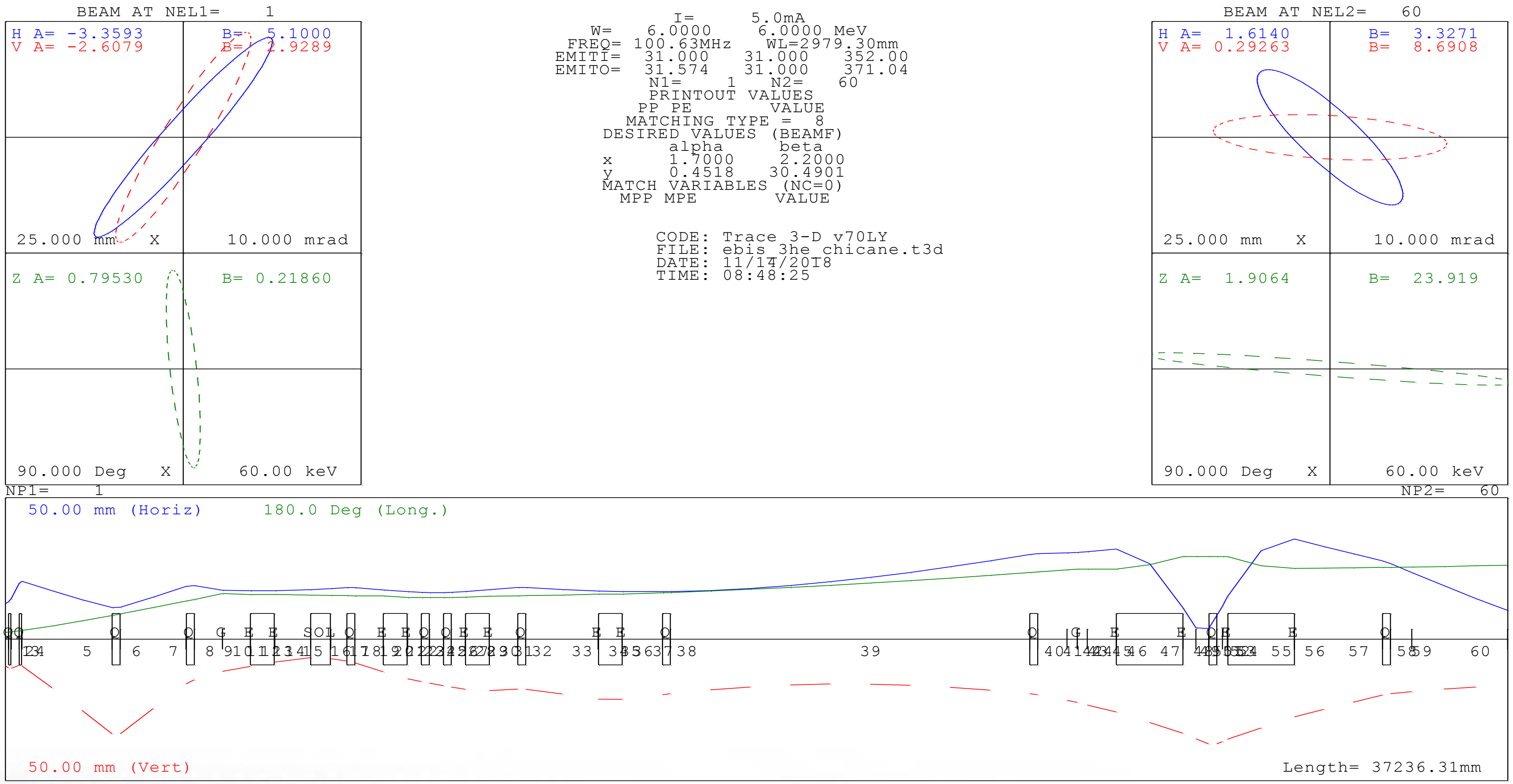
Chicane for $^{3}He^{2+}$ Spin Rotation

Trabocchi



Beam Optics for $^{3}He^{2+}$ with 5 mA and 2 π mm mrad (TRACE3D)

S. Ikeda



Status

- 4 Quadrupoles and power supplies
- 1Solenoid , Pulsed Power Supply (Dec 2019)
- 4 Dipoles,   Power supply, 2 pulse (March 2020), 2 DC
- 4 New steering magnets and Power supplies
- Buncher (March 2020), RF source
- 1 Profile monitor
- 1 Current monitor
- Vacuum components

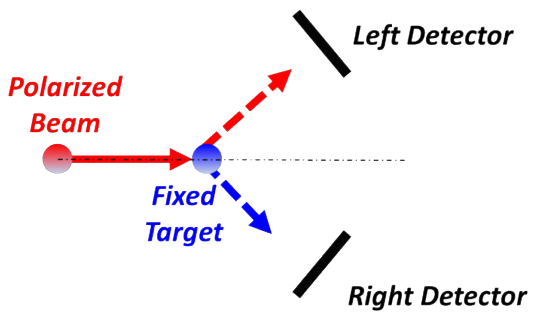
Key
Green: Delivered
Blue: Delivery by March 2020
Installation: Summer 2020
Commissioning : Fall 2020

He-3 Polarimeter

Elastic Scattering ^{3}He on ^{4}He

Atoian

- To determine the beam polarization, the spin correlated asymmetry (a) of ^{3}He scattering on the gas ^{4}He target (~ 5 Torr) will be measured.
- This scheme has been successfully used at BNL (p-carbon and jet polarimeter)



$$a = A_N P = \frac{\sqrt{N_R^{\uparrow} N_L^{\downarrow}} - \sqrt{N_R^{\downarrow} N_L^{\uparrow}}}{\sqrt{N_R^{\uparrow} N_L^{\downarrow}} + \sqrt{N_R^{\downarrow} N_L^{\uparrow}}}$$

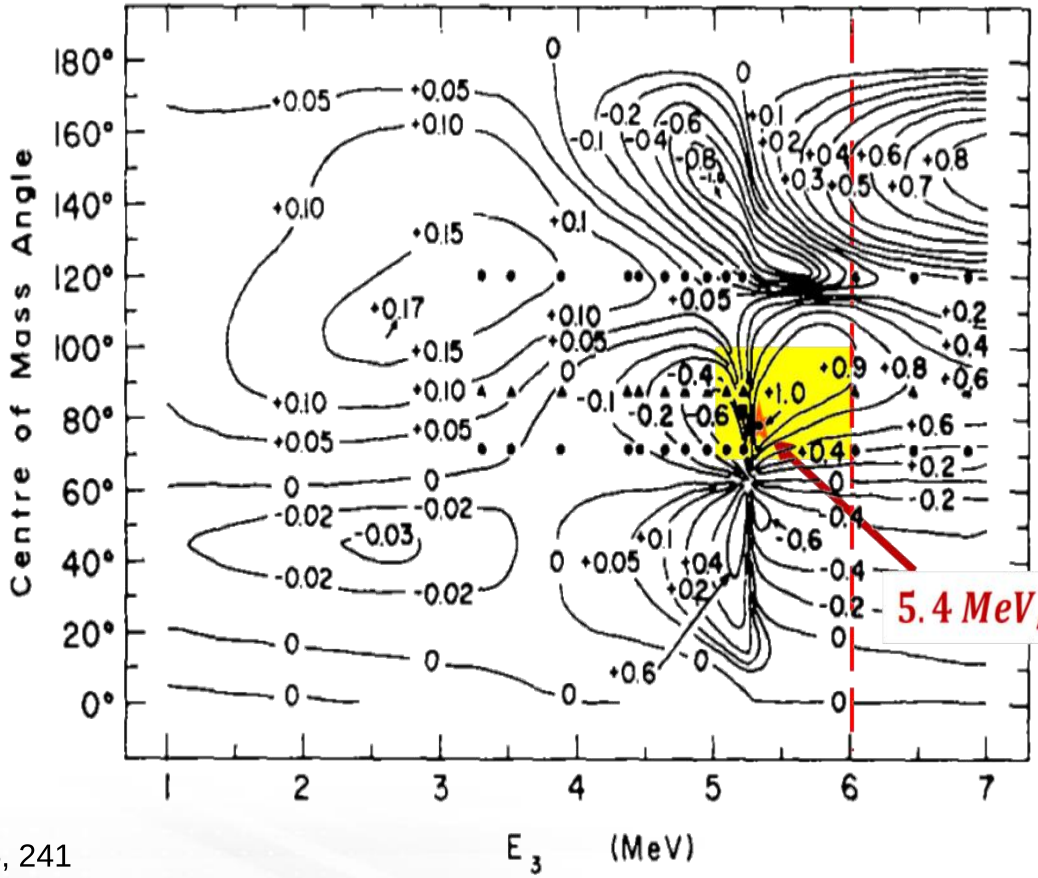
where P is the beam polarization and A_N is analyzing power

Analyzing power in ^{3}He-^{4}He elastic scattering at 5.3 MeV beam energy and 53.6° angle is closed to 100%

Analyzing Power

Atoian

- A_N is function of E_B and θ_{CM}
- Spin ½ scattered from spin-0 must have [P]=1, for (E,θ)
- Experimental data [1] for ^{3}He-^{4}He,
- P=1 at E_{He3} ~5.3 MeV θ_{CM} ~91°
- Later analysis of data [2] P=1, at E_{He3}~5.4 & θ_{CM} ~79°
- At 6 MeV, A_n > 0.9 and θ_{CM} ~96°



[1] D. M. Hardy et al., Phys. Lett. 31B, 355 (1970).

[2] W. R. Boykin, S. D. Baker, D. M. Hardy, Nucl. Phys. A **195**, 241 (1972).

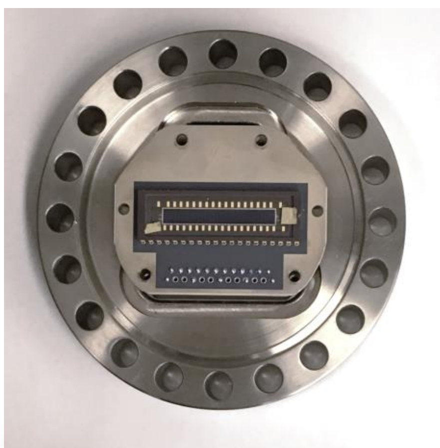
Test Setup for 6 MeV Polarimeter

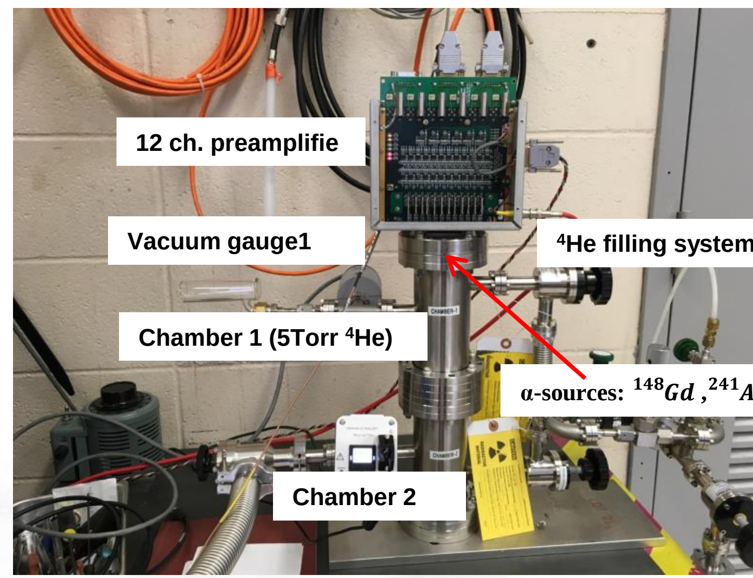
Atoian, Poblaguev, Zelenski

Requirements: 32 channel ,frequency 1 Hz, bunch length 20 µs, event rate ~ 160 kHz/channel , 100 event/bunchVME64x crate, Acromag XVME-650 single board computer (SBC) , Two 250 14- waveform digitizer SIS3316-14

Data flow rate ~0.3 M byte/sec. 30 GB/day,

pC 12 Channel Preamplifier board





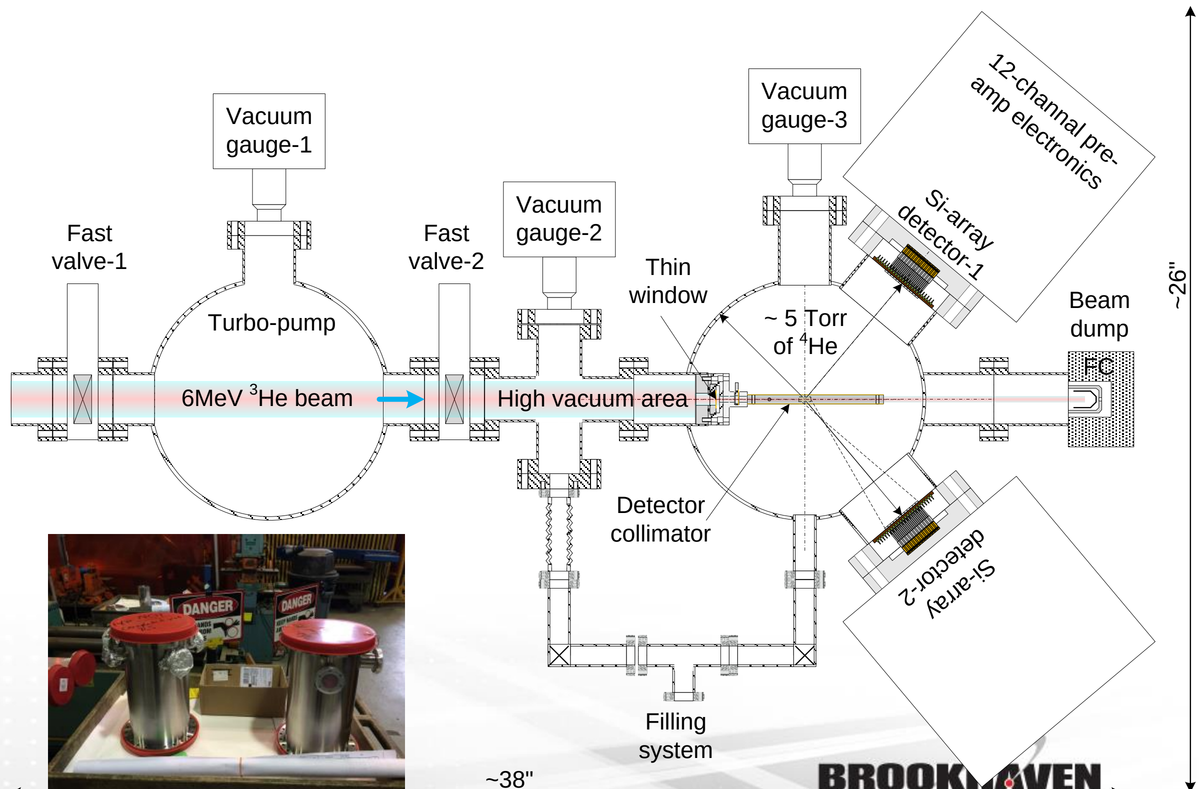
Hamamatsu PIN array S4114-35Q

Polarimeter Design

Atoian, Poblaguev, Zelenski

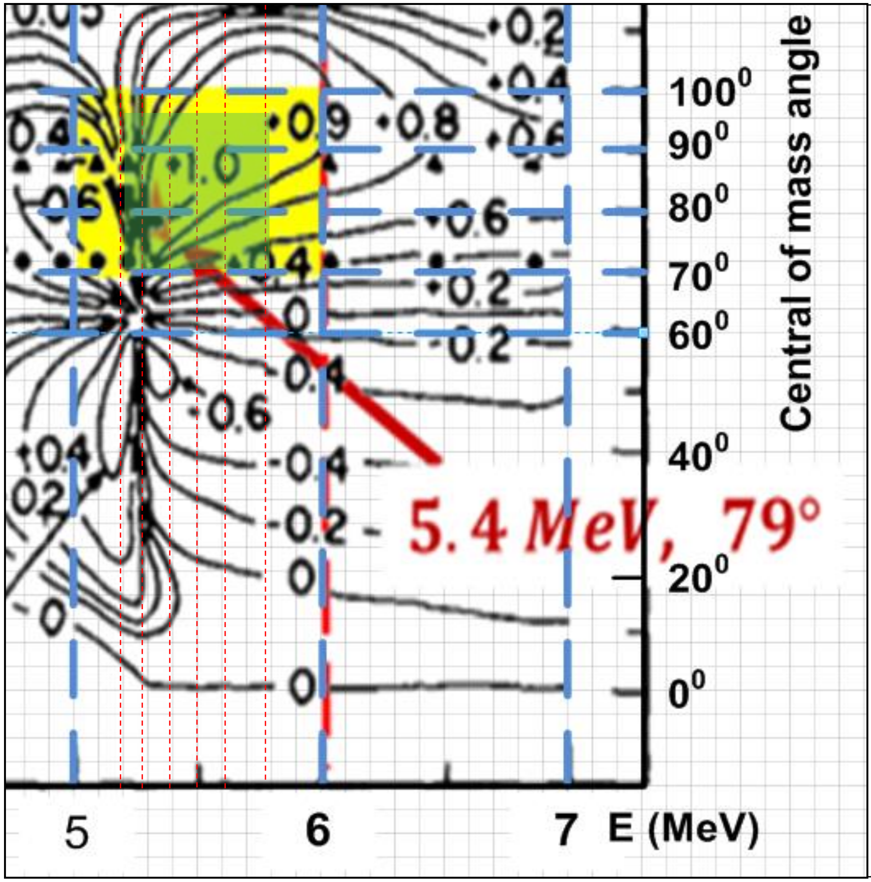
- ^{4}He gas at 5 Torr
- Thin Be, Al, or Ni window
- Target length of 1 cm (define by collimators)
- Two SI detectors at 10 cm from target $\theta_{Lab} = \pm 49.75°$

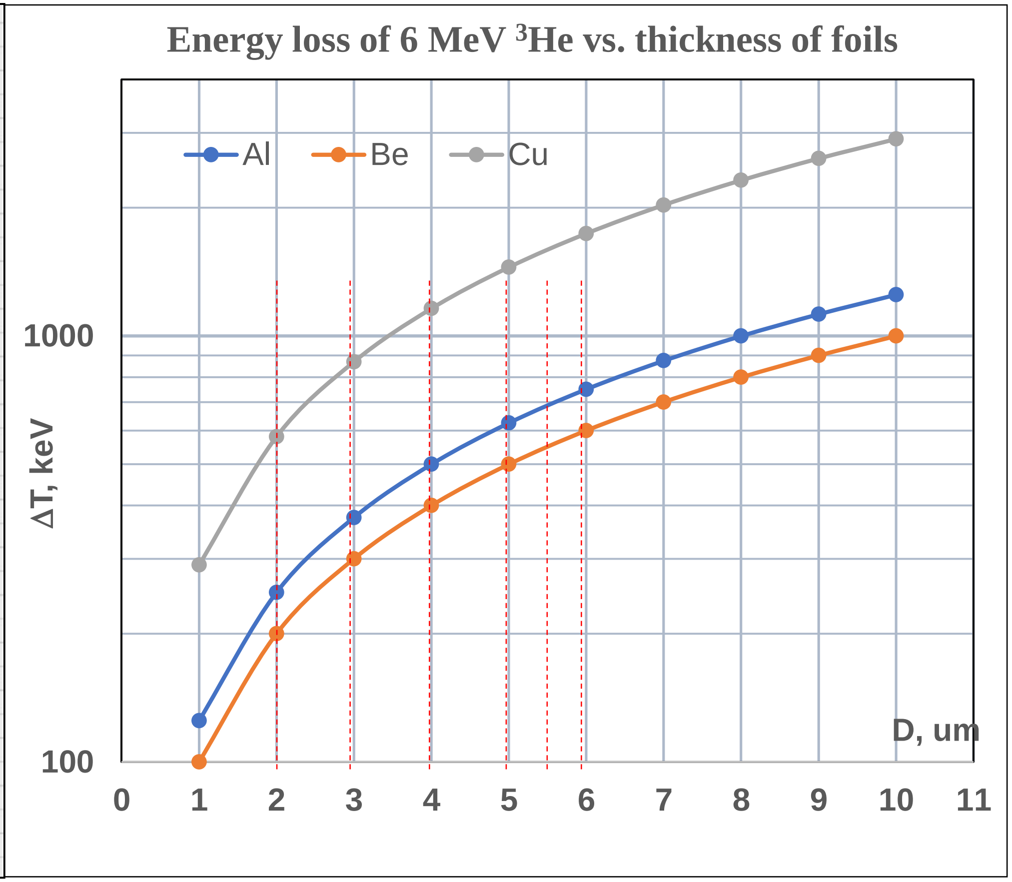
Angles: $69° < \theta_{CM} < 100°$
Energy: 2.6-4.2 MeV for ^{3}He
1.5-2.4 MeV for ^{4}He
Energy Resolution $\sigma_e/E < 2\ \%$
Time resolution $\sigma_t < 0.2$ ns
Angular resolution $\sigma_\theta \sim 1.2°$
(=> $\sigma_E{}^g$ 0.1 MeV)



Vacuum window

Atoian





Absorber	Vacuum window	Al foil-1	Al foil-2	Al foil-3	Al foil-4	Al foil-5
Thickness, um	2	+1	+1	+1	+0.5	+0.5
Beam energy, MeV	5.75	5.625	5.50	5.375	5.25	5.125

The energy of the ^{3}He beam can be increased or decreased by up to 140 keV in total by the buncher.

Status of Polarimeter

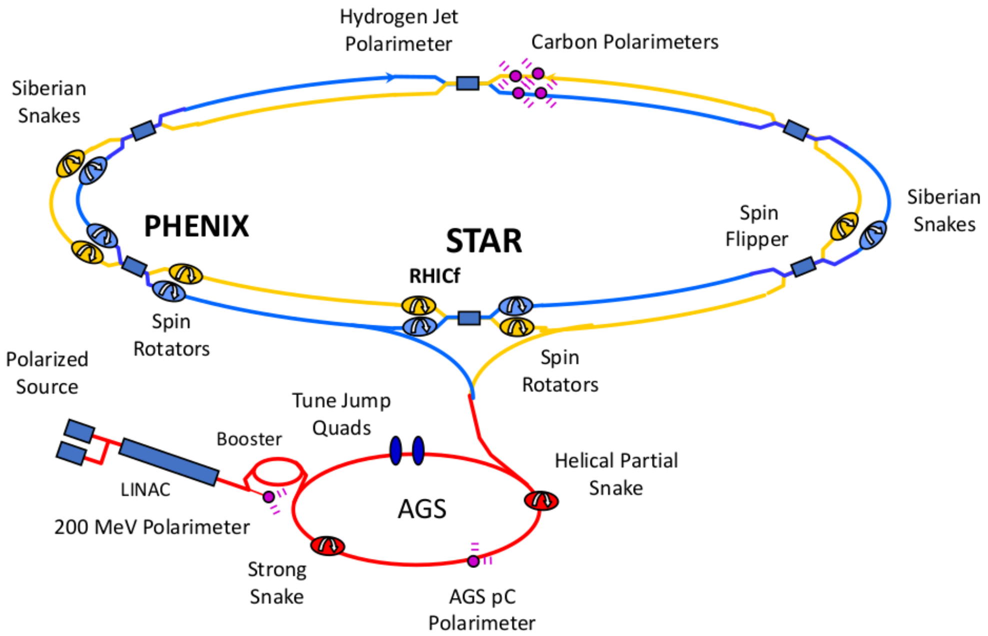
- Nov 2018: The main components of the prototype DAQ (VME crate, SBS And WFSs) are acquired. The assembly completed and tested
- Jan 2019: Testing of prototype polarimeter using α-source (^{148}Gd, 3.183 MeV & ^{251}Am, 5.486 MeV) is completed
- Oct 2019: Polarimeter chamber and vac components
- Nov 19: Assembly of Polarimeter in progress
- Dec 2019: Testing polarimeter at Tandem
- Dec 2020: Testing polarimeter with un-polarized ^{3}He at EBIS
- Dec 2021: Commissioning polarimeter with polarized ^{3}He at EBIS

High Energy Polarimetry

Hadron Polarimetry

S. Nunes, E. C. Aschenauer,

- In contrast to lepton polarimetry, **hadron polarimetry doesn't use a physical process that can be calculated from first principles**
- A **two-tier measurement** is needed at RHIC: one for the **absolute polarization** (with low statistical power), and one for **relative polarization** (with high statistical power)
- At **RHIC**, the absolute polarization is measured with the **H-Jet polarimeter**, and the relative polarization is measured by 4 **proton-carbon polarimeters**



- There are also **local polarimeters** at the experimental **interaction** regions, to define the spin direction and the degree of rotation in the experimental area
- RHIC requirements: **precision** measurements, **polarization profile** and **lifetime** to know **polarization in collisions** in experiments
- **EIC requirements**: same as for RHIC, and **bunch by bunch polarization**, systematic uncertainty ~1%

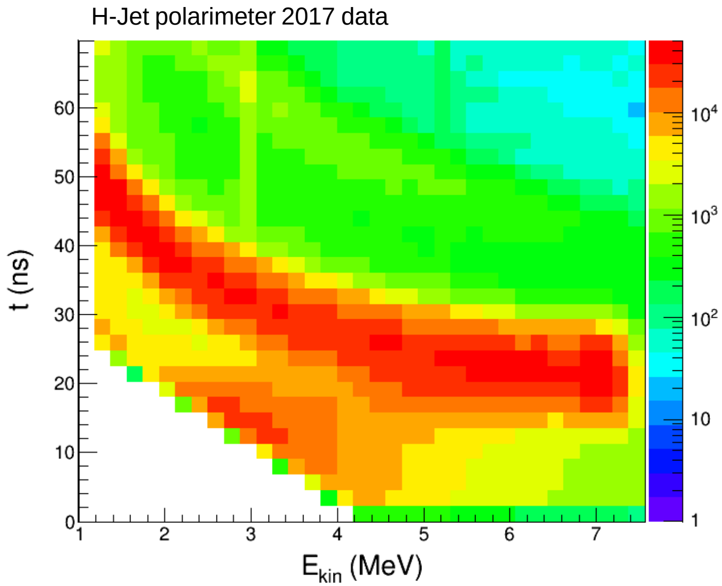
Challenges for hadron polarimetry at the EIC

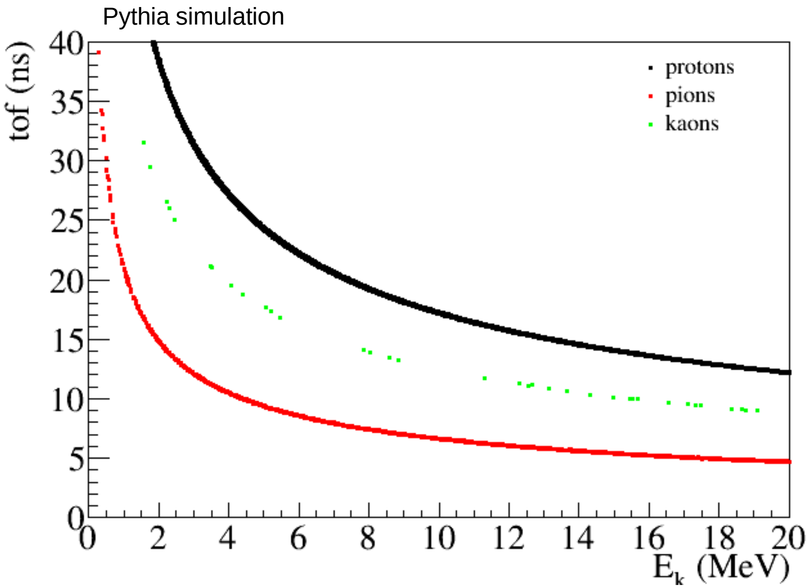
S. Nunes, E. C. Aschenauer,

- Background to elastic scattering events (of p, d and h)
  - "Prompts" from the following bunch
  - Ideas for improvements: **second layer of silicon detectors** can be installed in the polarimeters to **veto "prompt" background** (to be tested in 2021 in pC and H-Jet polarimeters)
  - Other materials could be used for more stable nuclear targets
  - Polarimeter Silicon detectors and associated electronics (now: wave form digitizers) can be upgraded to get better timing resolution
- Deuteron small asymmetry
  - From the simplest model, **helion asymmetries are ~80% of proton**, whereas **D asymmetries are ~8% of the proton asymmetries (both on jet and carbon polarimeters)**
- Deuteron and helion breakup
  - **Decay products** have different kinematics and unknown asymmetry, **should be vetoed**

Pythia results for backgrounds in pp interactions (H-Jet polarimeter)

S. Nunes, E. C. Aschenauer,





- Particles produced in inelastic pp collisions are background to elastic scattering events
- Pythia 6 used with a mix of physical processes
- Beam and detector effects need still to be included → will smear the distributions

Deliverable and Schedule

Spin rotation chicane	Dec 2020
He-3 Polarimeter @ 6 MeV	Dec 2020
Detector and polarimeter	
Polarimetry requirements for an EIC	Sep 2020

Installation of the spin rotator chicane will depend NSRL and RHIC running schedule
Availability of polarized He-3 will dependent on the commissioning of the Extended EBIS.

Summary of Expendirures

	FY 10 + FY 11	FY 12 + FY13	FY 14 + FY 15	FY 16 + FY 17	FY18 +Fy19	Totals
	(AY$)	(AY$)	(AY$)	(AY$)	(AY$)	(AY$)
a) Funds allocated					2,442,000	2,442,000
b) Actual cost to date					1,902,307	1,902,307

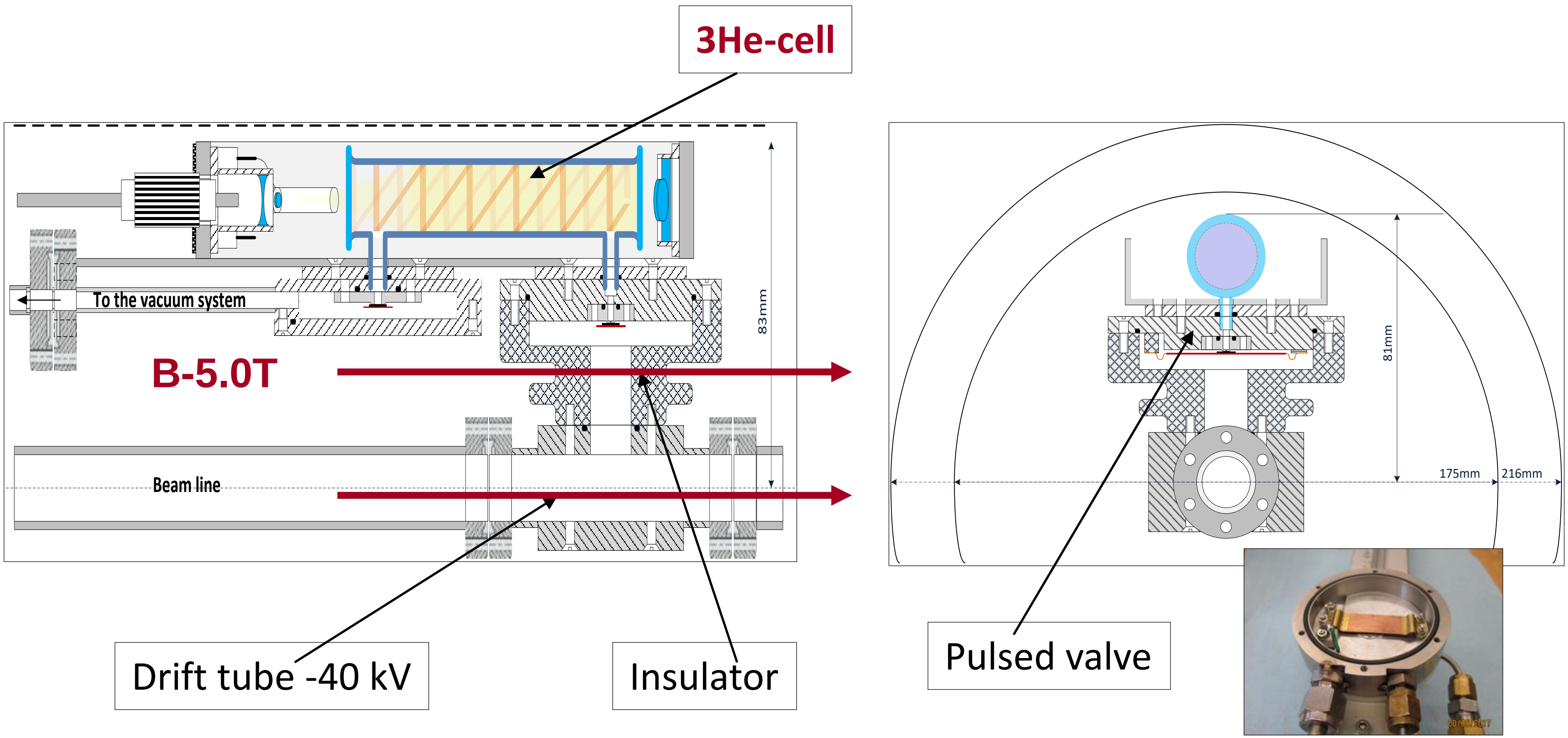
Conclusions

- High polarization (>80%) of 3He was achieved in the “open” cell in the high magnetic field.
- Physics design of chicane and dipole, solenoid and buncher design completed and most the components are delivered and remaining will be delivered by Spring 20, installed in Summer 20 and commissioned in Fall 20.
- Polarimeter construction started, will be tested in Dec 19 with beam in tandem with He-3 beams, installed in Summer 20 and commissioned in Fall 20.
- A postdoc was hired and high energy polarimeter simulation are underway to determine the requirements for an EIC needs.

Backup slides

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

Zelenski, Ritter, Musgrave



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.

Electron Beam

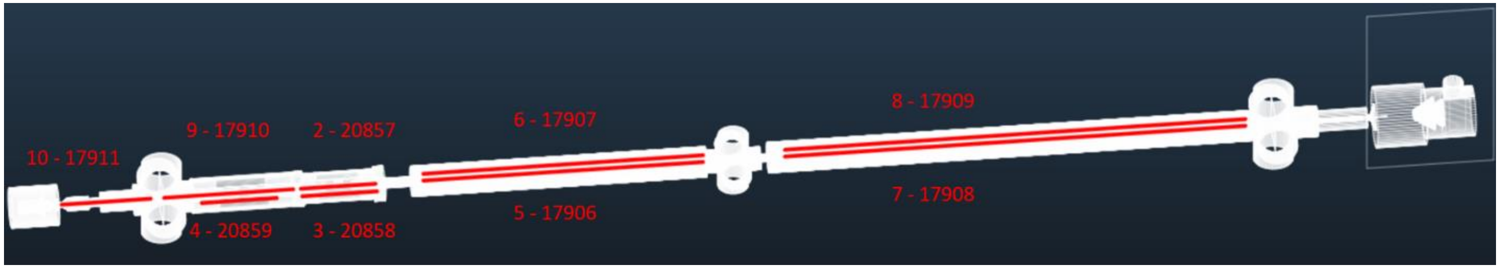
Proportion of ^3He ionized after 20 ms

Length:	10 cm	20 cm	30 cm	50 cm
1 cm (0.5 cm ends)	0.142	0.263	0.372	0.537
1 cm (1 cm ends)	0.0556	0.132	0.224	0.411
2 cm (0.5 cm ends)	0.123	0.184	0.218	0.257
2 cm (1 cm ends)	0.0382	0.0695	0.0997	0.155
2 cm (2 cm ends)	0.0176	0.0355	0.0557	0.101
3 cm (0.5 cm ends)	0.097	0.121	0.131	0.141
3 cm (1 cm ends)	0.0349	0.0576	0.0747	0.0988
3 cm (2 cm ends)	0.0158	0.0278	0.039	0.06

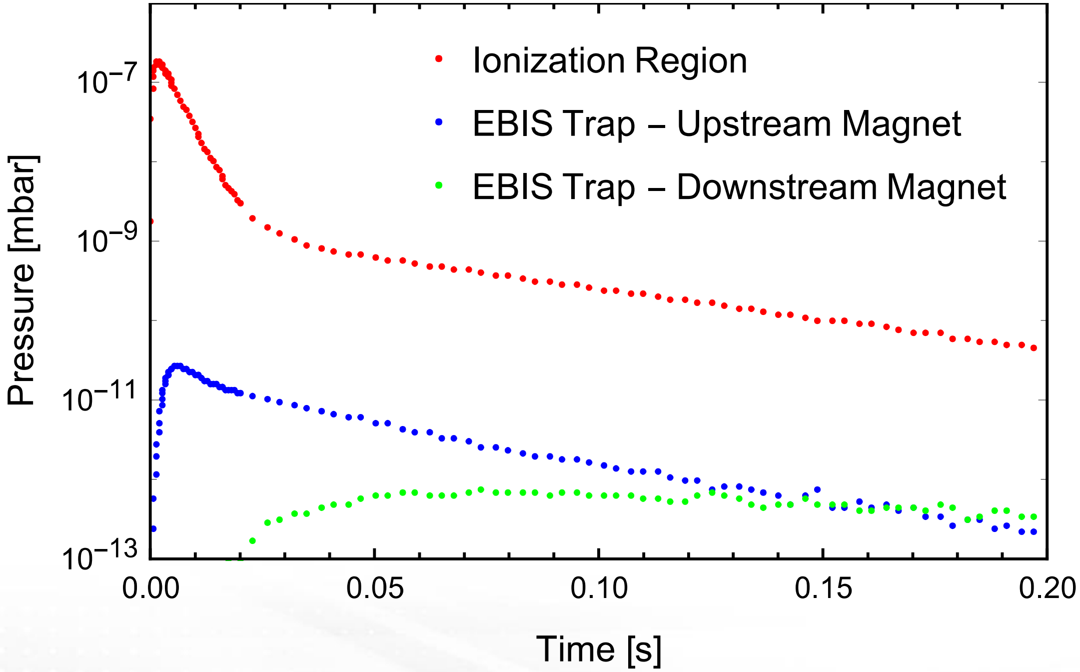
$$S = \frac{16 I \sigma}{3\pi^2 e r_e v_{gas}}$$

- For an e-beam of 25 keV there is a ≈0.5% probability that ^3He is ionized during traverse of the e-beam.
- Treat the e-beam as an ideal pump with 99.5% transparency.

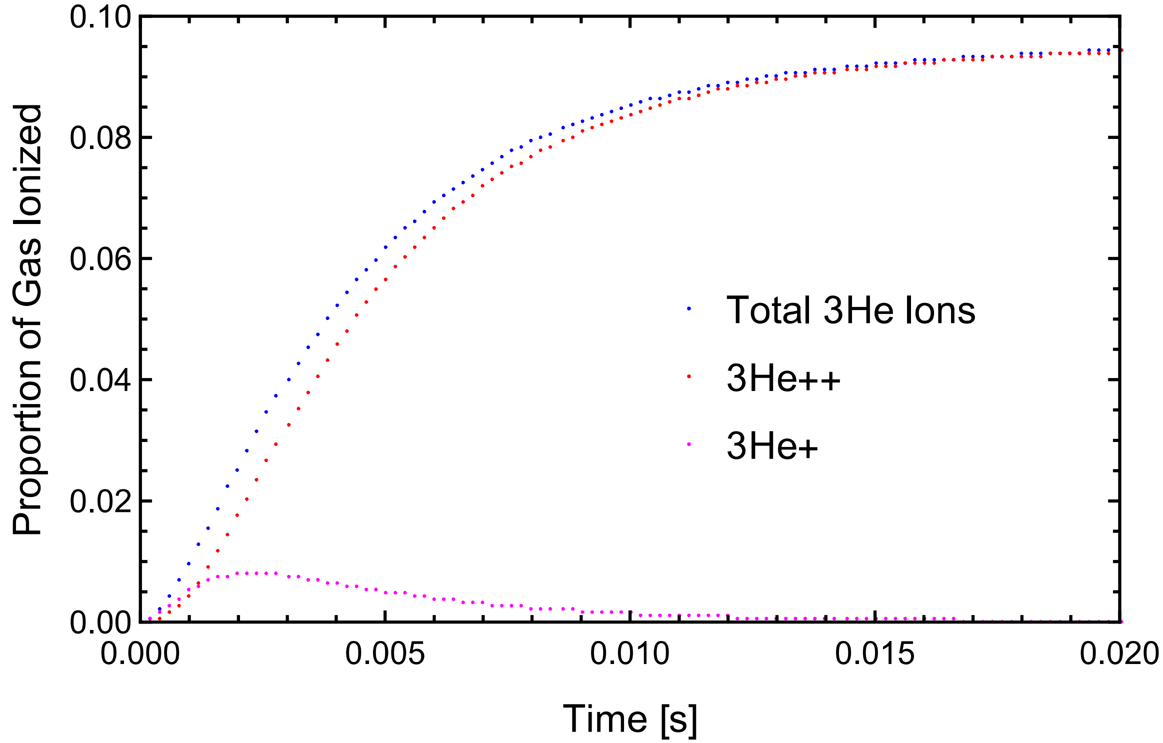
Gas Diffusion and EBIS Vacuum



- 2.65 x 10^{12} ^{3}He atoms injected
- 10 A, 25 keV e-beam
- 10^{-10} mbar EBIS vacuum



Electron Beam Ionization of ^{3}He



Quadrupoles

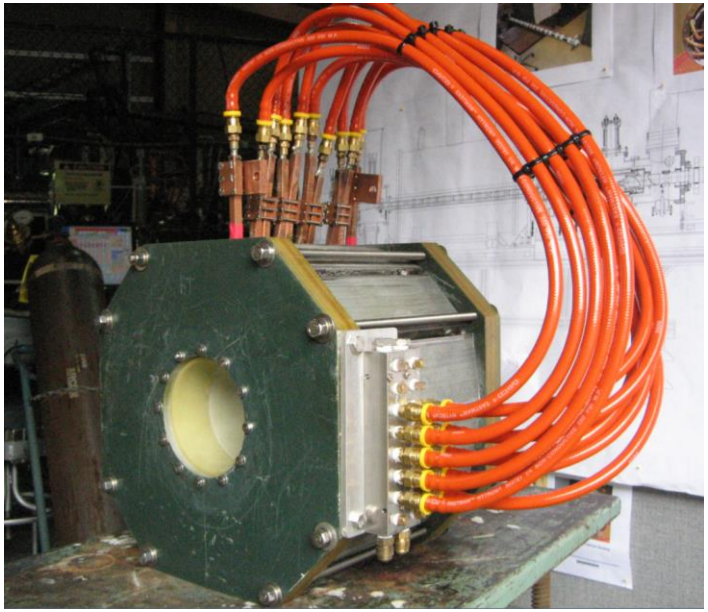
- Same quads as used in the existing line ETB (have them)
- Similar power supplies will be used
  - KEPCO BOP 50-20GL (delivered)

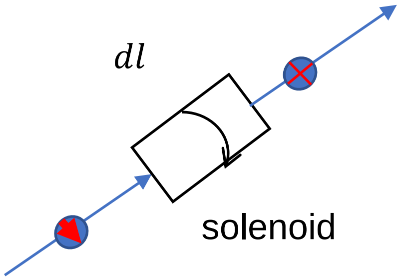
BOP 1 KILOWATT SERIES (GL, EL SUFFIX) MODEL TABLE

MODEL (1)	d-c OUTPUT RANGE (2)		CLOSED LOOP GAIN		RIPPLE AND NOISE	
	E_O MAX. (3) (V d-c)	I_O MAX. (A d-c)	VOLTAGE CHANNEL G_V (V/V)	CURRENT CHANNEL G_I (A/V)	VOLTAGE MODE	CURRENT MODE
1000 WATT						
BOP 10-100GL or EL	0 to ±10	0 to ±100	1.0	10.0	0.02%	0.01%
BOP 20-50GL or EL	0 to ±20	0 to ±50	2.0	5.0	0.02%	0.01%
BOP 36-28GL or EL	0 to ±36	0 to ±28	3.6	2.8	0.02%	0.01%
BOP 50-20GL or EL	0 to ±50	0 to ±20	5.0	2.0	0.02%	0.01%

(1) Models with GL suffix include built-in standard GPIB and RS 232 digital interfaces.
Models with EL suffix include built-in standard LXI Ethernet (LAN) and RS 232 digital interfaces.

LEBT Solenoid in RHIC-EBIS line





- $d\emptyset = -(1+G)\frac{qB}{p}dl = \frac{\pi}{2}$
  -> $Bdl = 0.15$ Tm
- NI ~ 120 kA turns

- 1.2 T, 230 mm, 0.27 T m > 0.15 T m
- 1800 A in conductor
- 10ms, 5 Hz
- 1.49 mH, 22 mΩ

Will use LEBT solenoid, the polarity can be reversed every super cycle.

- 5 Hz rep rate

or 1sec–2.4sec–1sec flat-top pulse

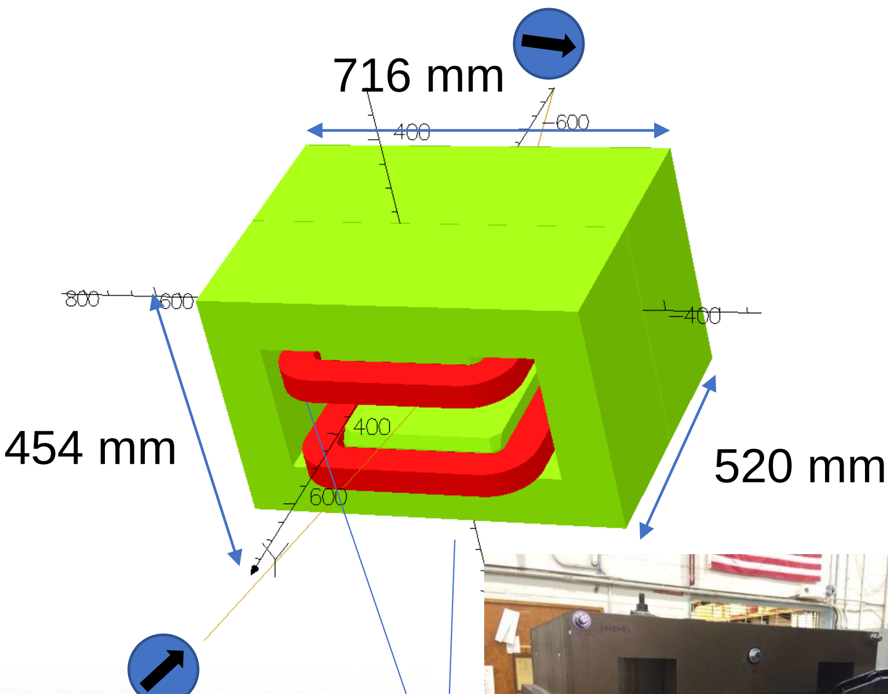
- Polarity change in 1~2 sec
- Will be ready by Dec 31 2019

Dipole

S. Ikeda

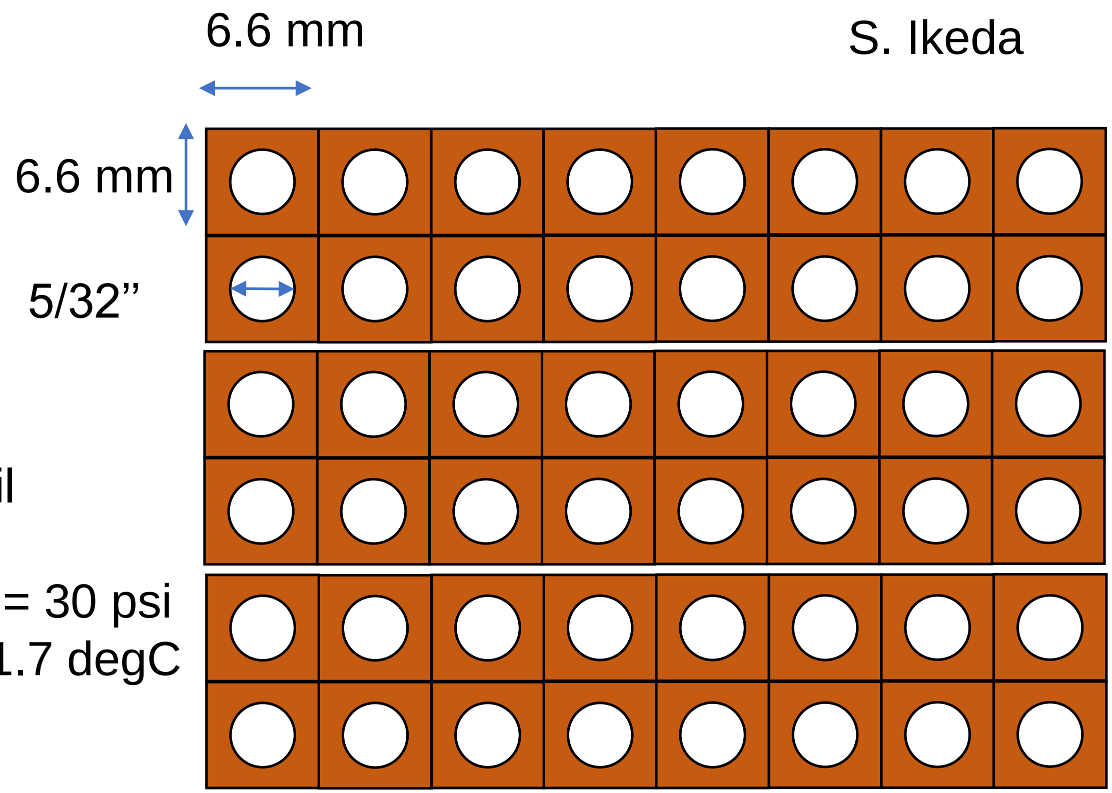
- Two dipoles on the existing line should be pulsed.
  - Rise and fall time < 1 sec
  - flat-top duration ~ 2.4 sec (12 pulses x 200 ms)
- Two in the chicane can be DC.

B	1.90 kG
Radius of curvature	1.60 m
Bend angle	21.5°
B.dL	0.115 T-m
Effective length	0.60 m
Gap height	110 mm
Pole width	300 mm
Weight	1 ton
Total current	2 x 8.4 kA
Stored energy	380 J



3 of 2x8 pancake coils for each coil

S. Ikeda

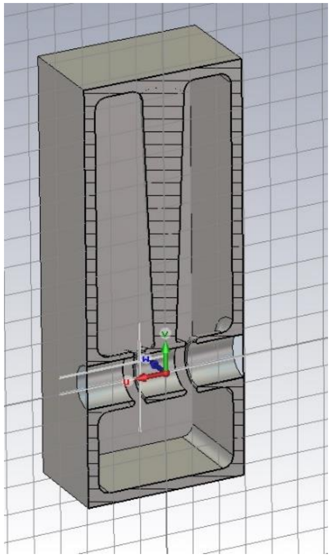


- Turn number = 48 for each coil
- Current in conductor = 174 A
- Pressure Drop per 1 pancake = 30 psi
- Temperature rise per 1 pk = 11.7 degC
- Resistance = 0.12 Ω
- Inductance = 30 mH
- DC power supply (acquired)
- Pulsed PS to be delivered Jan 2020

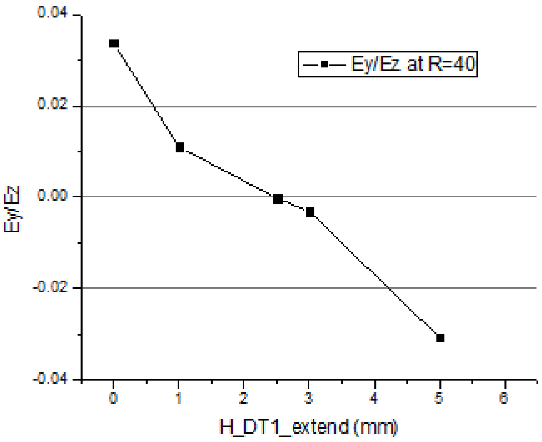
T. Kanesue

Buncher Cavity

- Quarter wave resonator
- Frequency 100.625,
- Energy 2 MeV/amu
- 200 X 720 X 255 mm
- DT diameter 80 mm
- Effective voltage 40kV
- Q 10300
- Z 17 MΩ/m
- Power < 0.5 kW
- To be delivered by Mach 2020

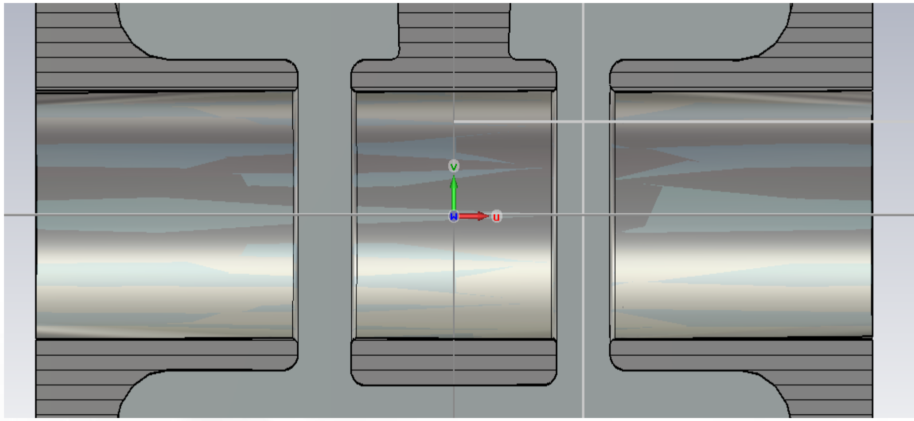


Buncher model
CST



E_y / E_z at the center of gap.

$$\int \frac{E_y}{E_z} = -5.10^{-4}$$



Systematic Error

- A discrepancy between the actual effective analyzing power $A_N^{(eff)}$ and assumed A_N

$$\delta A_N = A_N^{(\mathrm{eff})} - A_N.$$

- The rate, r, correlated inefficiency ε= kr of the event detection results in systematic errors in the polarization measurement. Pile up, dead time , background, calibration

$$\delta P/P \approx \langle\varepsilon\rangle(1-a^2)$$

- Estimated systematic error

$$(\sigma_P/P)_{\mathrm{syst}} \lesssim 0.5\%.$$