Polarized Deuteron Beams

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https://indico.cfnssbu.physics.sunysb.edu/event/648/

Outline

Introduction & Physics Motivation

Why Polarized Deuterons at the EIC?

- EIC baseline includes polarized p and $^3\vec{\text{He}}$, but **not** polarized deuterons

- Deuteron is the simplest spin-1 nucleus: unique access to
  - neutron spin structure (flavor separation with p data)
  - tensor observables b_1, T_{2q}, absent for spin-$1/2$
  - small-x gluon imaging via diffractive vector-meson production

- DIS with spectator proton tagging $\Rightarrow$ clean access to neutron spin structure with controlled nuclear effects [1]

New observables with $\vec{d}$

- g_1^n, g_2^n via inclusive DIS

- b_1: tensor-polarized structure function [2, 3]

- Spatial imaging of polarized gluons at small x [4]

- Unique nuclear spin-1 QCD laboratory

Why Polarized Deuterons at the EIC?

EPIOS mandate [5]

"The EIC accelerator design team must make it a priority to develop ion spin control and manipulation from source to collisions of the deuteron, ^3He, ^6Li and ^7Li nuclei."

Technology path

- Dedicated source & injector R&D required $\Rightarrow$ long lead times
- Polarized deuterons and heavier ions **not** in EIC baseline
- Detailed spin-dynamics studies show deuteron polarization can be preserved in the EIC energy range [6]
- **Start now** to be ready when the science program requires it

Polarized Deuterons for the EIC: Feasibility [6]

Key property:

Anomalous magnetic moment $G = -0.1426$ is very small

- Full Siberian snake requires $B_s L \approx 2400\,\mathrm{Tm}$ at $100\,\mathrm{GeV/n}$ ($103\,\mathrm{Tm}$ for protons) $\Rightarrow$ not feasible

- But: resonances are **weak** and **sparse** $\Rightarrow$ handle individually

- Spin transport through AGS-to-HSR transfer line is clean

HSR energy range: 10–137.5 GeV/n ($|G\gamma| = 1.5$–20.9**)**

19 imperfection resonances:

- IP6 detector solenoid ($15\,\mathrm{Tm}$) acts as partial snake
- Required partial snake strength: $\chi/\pi = 0.45\%$ (spin rotation 0.0045π)
- high polarization transmission through each resonance

Intrinsic resonances ($G\gamma = N \pm \nu_y$**):**

- Tune jump $\Delta\nu_y = 0.03$ over 50 turns
- 3 quadrupoles at $1000\,\mathrm{A}$ / $100\,\mathrm{V}$
- high polarization transmission through each resonance

Polarization Preservation at the EIC is feasible

Overall result [6]

- Acceleration to $> 100\,\mathrm{GeV/n}$ feasible
- Overall high polarization preservation efficiency anticipated
- Longitudinal polarization at detectors achievable at discrete energies ($|G\gamma| = 3n$, i.e. $\approx$ every 19.7 GeV)
- No major new hardware required, IP6 detector solenoid and a modest tune-jump system sufficient

Bottom line

The physics case is compelling and the accelerator physics is understood.

The missing piece: a polarized deuteron source and injector.

COSY Polarized Deuteron Source

A Unique Opportunity: The COSY Polarized $\vec{d}$ Source

- Polarized deuterium ion source was operated at COSY, FZJ, Germany [7]

- **COSY closed in 2023**
  source $\Rightarrow$ surplus equipment

- Available to BNL at a **fraction of replacement value**

> **Selected equipment (2 shipping containers)**
>
> 3 sextupole magnet sets   2 electromagnets   Vacuum chambers
> ToF spectrometer   3 mass spectrometers   Dissociators   9 RF
> transition units   Signal generators   Holding field PSUs   Cold
> heads & compressors (25–80 K)   Siemens controllers   . . .

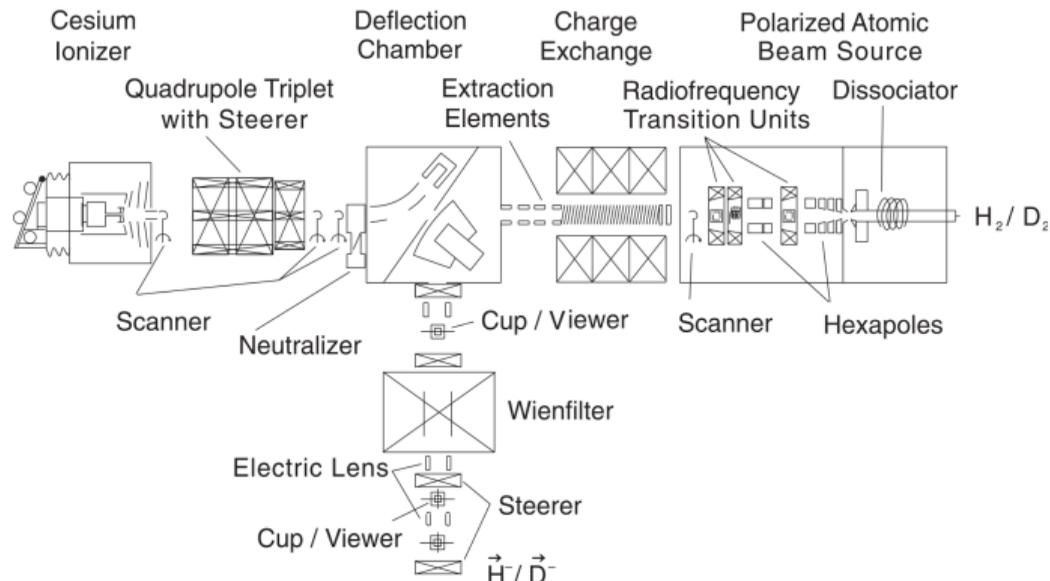**Proposal submitted Dec. 10, 2025**

- DOE NP Advanced Accelerator R&D call (FY2026)
- PI: D. Steski (BNL)   Co-PIs: D. Raparia, F. Rathmann (BNL)
- Duration: 2 years   Budget: $1.975M

Transfer modalities

Transfer of equipment from FZJ to BNL is being worked out: logistical and regulatory details non-trivial

The COSY Polarized $\vec{d}$ Source: Working Principle

Layout of the COSY polarized source [7]

1. Polarized Atomic Beam Source (ABS)

- D_2 dissociated in RF discharge, cooled to $\sim 30\,\mathrm{K}$
- Hexapoles focus polarized D^0 beam
- RFT1–3 select P_z/P_{zz} polarization state

The COSY Polarized $\vec{d}$ Source: Charge Exchange

2. Cesium beam source
- Cs^+ thermionically ionized at $\sim 45\,kV$
- Neutralizer efficiency $> 90\%$
- Fast neutral Cs^0 beam for charge exchange

3. Charge exchange & extraction
- Highly selective reaction: $\vec{D}^0 + Cs^0 \rightarrow \vec{D}^- + Cs^+$
- Nuclear polarization fully preserved
- Wien filter sets spin orientation before injection
- D^- extracted and bent $90°$ into beamline

Beam parameters (COSY operation) [8]

Current: $I = 50\,\mu A$ Energy: $T = 4.5\,keV/u$
Emittance: $3.6\,\pi\,mm\,mrad\,MeV^{-1/2}$ Beam radius: $\approx 5.5\,mm$

Can deliver polarized H^- **and** D^- without hardware modification
Source has been used as a workhorse for the COSY spin physics program [9]

# The COSY Polarized $\vec{d}$ Source: Polarization Modes

Ideal and measured polarizations for all 8 source configurations [7]:

- LEP: Low Energy Polarimeter at $T_d = 75.6$ MeV ($p_d = 539$ MeV/c)
- EDDA: elastic $\vec{d}p$ scattering at $p_d = 1042$ MeV/c

| Mode	P_z^{id}	P_{zz}^{id}	I_0^{id}	RFT1	RFT2	RFT3	P_z^{LEP}	P_z^{EDDA}	P_{zz}^{EDDA}
0	0	0	1	Off	Off	Off	0.000 ± 0.010	0	0
1	$-2/3$	0	1	Off	Off	On	-0.516 ± 0.010	-0.499 ± 0.021	0.057 ± 0.051
2	$+1/3$	$+1$	1	Off	On	Off	0.257 ± 0.010	0.290 ± 0.023	0.594 ± 0.050
3	$-1/3$	-1	1	Off	On	On	-0.272 ± 0.010	-0.248 ± 0.021	-0.634 ± 0.051
4	$+1/2$	$-1/2$	2/3	On	On	Off	0.356 ± 0.013	0.381 ± 0.027	-0.282 ± 0.064
5	-1	$+1$	2/3	On	On	On	-0.683 ± 0.013	-0.682 ± 0.027	0.537 ± 0.064
6	$+1$	$+1$	2/3	On	Off	Off	0.659 ± 0.013	0.764 ± 0.027	0.545 ± 0.061
7	$-1/2$	$-1/2$	2/3	On	Off	On	-0.376 ± 0.013	-0.349 ± 0.027	-0.404 ± 0.065

Installation Plan at BNL Tandem

The BNL Collider-Accelerator Complex
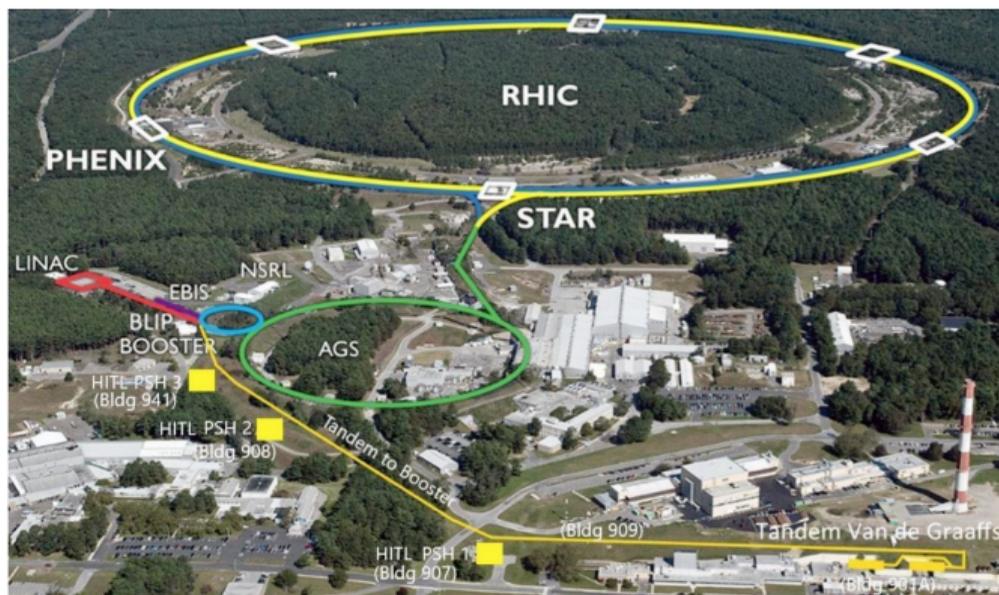
- RHIC, AGS, Booster, LINAC, EBIS; Tandem Van de Graaffs as injector
- 900 m Tandem-to-Booster (TtB) transfer line
- Polarized $\vec{d}$ source at Tandem $\Rightarrow$ direct path to AGS and EIC via TtB

The BNL Tandem Van de Graaff Facility
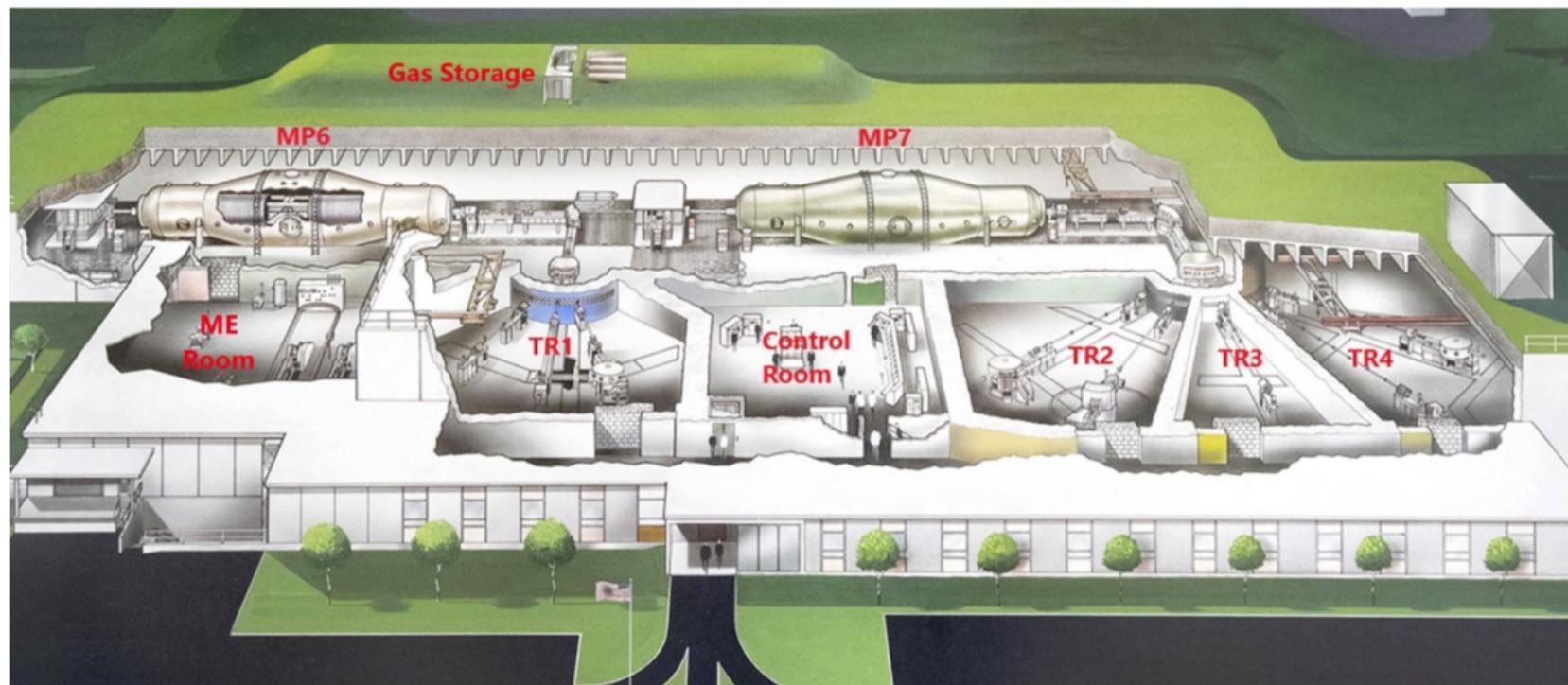
The BNL Tandem Van de Graaff Facility

- Space at EBIS limited $\Rightarrow$ **polarized $\vec{d}$ source to be installed at Tandem**
- Two 15 MV MP-class Tandems
  - MP6, MP7
  - High Voltage Engineering Corporation (HVEC)
- Commissioned 1970
  - low energy nuclear physics
- Supplied Au beam for RHIC
  - FY23, FY25
- Unpolarized d for Au-d runs in RHIC:
  - 2003, 2008, 2016, 2023

Location of the Polarized Deuterium Ion Source
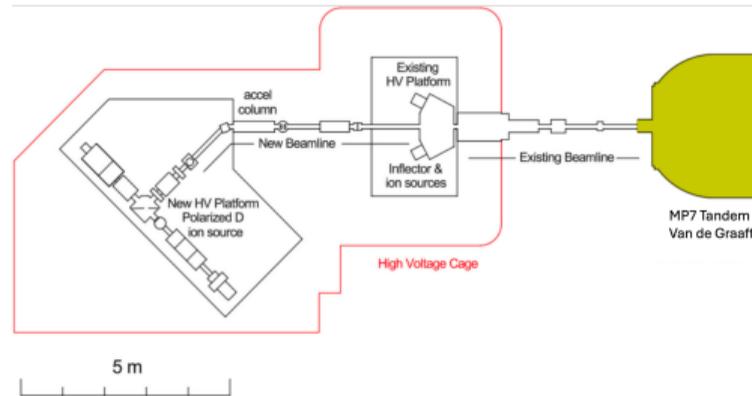
- New HV platform between MP6 and MP7; polarized D$^-$ injected at $\sim$150 keV through zero-degree port into MP7

- **Beam transport:** 9 keV D$^-$ from Wien filter $\rightarrow$ ES quadrupole doublet $\rightarrow$ 45° electrostatic deflector (aligns beam to MP7 axis) $\rightarrow$ 120 kV accelerating column $\rightarrow$ 120 keV $\rightarrow$ ES quadrupole triplet for matching into existing MP7 injection line

- During polarized D$^-$ operation: existing unpolarized source switched off; existing MP7 capabilities otherwise fully preserved

- Decommissioned MP6$\rightarrow$TR1 beamline dismantled to make space; bypass MP6$\rightarrow$TR2, TR4, TtB remains
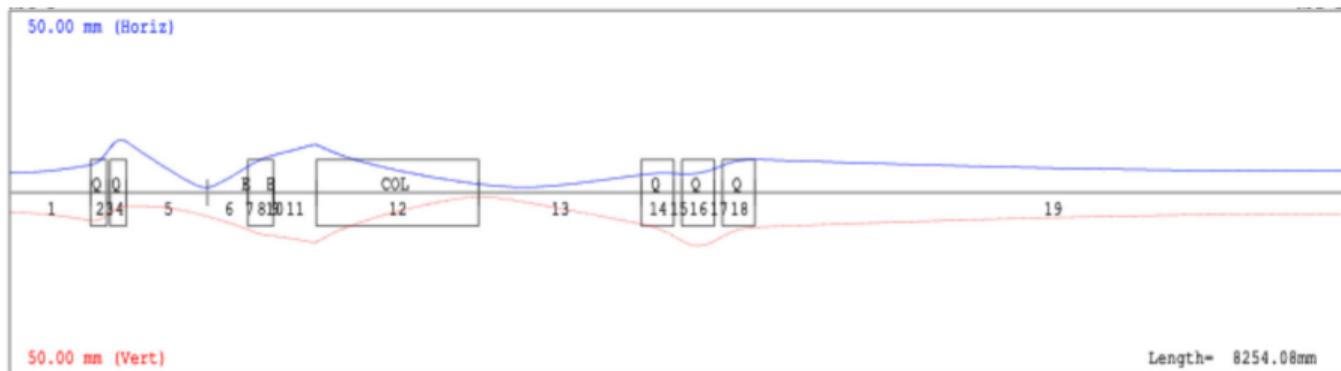
New Beamline Design: Source to MP7

9 keV section:

- ES quadrupole doublet + steerers
- Faraday cup (FC1) + emittance scanner
- 45° ES deflector ($\rho = 0.20$ m) aligns beam to MP7 axis

120 kV column: $T = 9 \to 120$ keV

- Faraday cup (FC2) + profile monitor
- ES quadrupole triplet for matching into existing MP7 injection line
- Steerers; handoff at $z = 8250$ mm

Beam envelope along transfer line (horizontal, vertical); TRACE2D, total length 8254 mm

- Table of design values for the beam line given on slide 30

Tandem Polarimeter

Polarization Measurement: Spin-1 Cross Section

**Spin-dependent differential cross section:**

$$\sigma(\theta, \phi) = \sigma_0(\theta)\left[1 + \tfrac{3}{2}P_z A_y(\theta)\cos\phi + \tfrac{1}{2}P_{zz}\left(A_{xx}(\theta)\sin^2\phi + A_{yy}(\theta)\cos^2\phi\right)\right]$$

- P_z: vector polarization; P_{zz}: tensor alignment
- **Extracting P_z:** left-right asymmetry ($\phi = 0°$ vs $180°$):

$$\varepsilon_{\mathsf{LR}} = \frac{L - R}{L + R} \approx \frac{3}{2}P_z A_y \quad \Rightarrow \quad P_z \approx \frac{2}{3}\frac{\varepsilon_{\mathsf{LR}}}{A_y}$$

- **Extracting P_{zz}:** requires the full azimuthal dependence $\sim A_{xx}\sin^2\phi + A_{yy}\cos^2\phi \Rightarrow$ detectors at *multiple ϕ angles* needed, not just left-right
- This is why the LEP uses **4 groups of detectors** (L, R, U, D):
  - L/R probe A_{yy} ($\cos^2\phi$ term); U/D probe A_{xx} ($\sin^2\phi$ term)
  - combining all four groups separates A_{xx} and $A_{yy} \Rightarrow$ extracts P_{zz}
  - tensor powers small at 75 MeV but sizeable at $\sim$15 MeV tandem energies

The Low Energy Polarimeter (LEP)
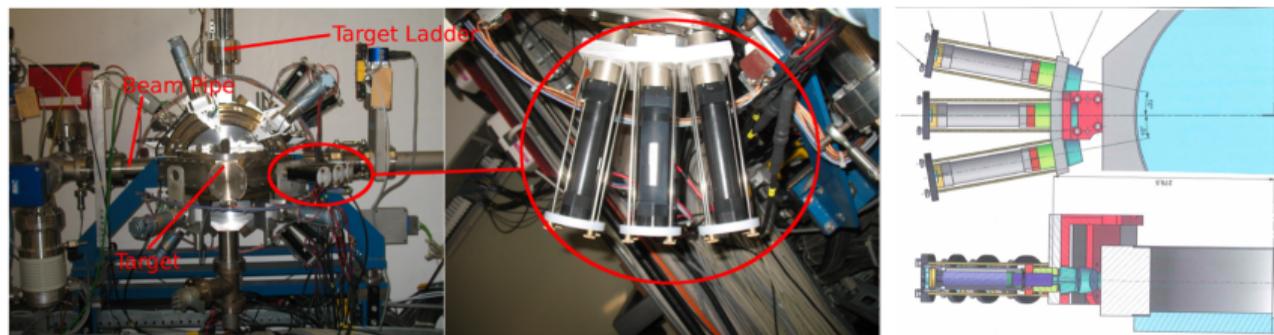
- Formerly in COSY injection line; to be installed at high-energy end of MP7
- Thin C or CH_2 targets (0.1–0.5 mm); elastic scattering to measure polarization
- 12 plastic scintillator detectors in 4 groups (L, R, U, D)
- Left-right asymmetry $\varepsilon_{LR} \approx \frac{3}{2} P_z A_y \Rightarrow$ vector polarization P_z; up-down asymmetry sensitive to P_{zz}
- FPGA-based digital readout: sustained rates 30–150 kHz per detector group

Tandem Polarimeter: Concept
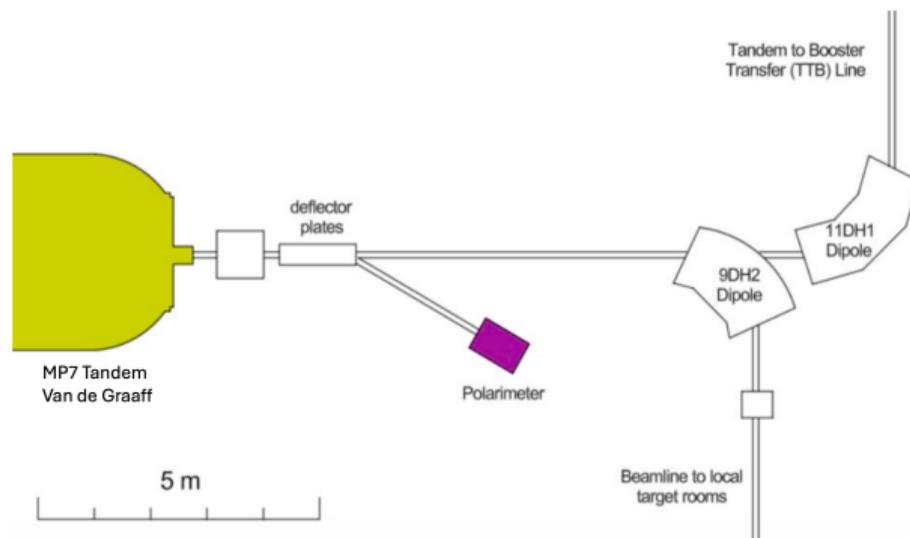
- LEP installed at high-energy end of MP7
- Deflector plates divert beam to polarimeter
- One pulse passes to TtB, alternate pulse to polarimeter ⇒ continuous monitoring during Booster injection
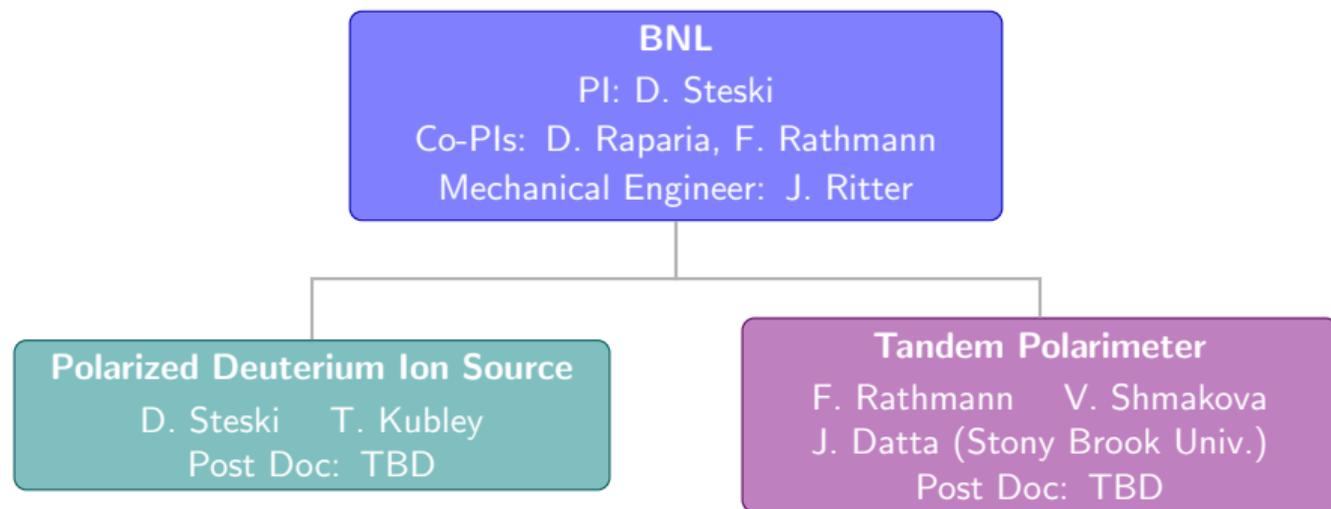- Analogous to scheme at 200 MeV Linac for OPPIS proton polarimetry [10]

Polarization Observables at Tandem Energies

- At COSY injection energy (75 MeV): tensor analyzing powers T_{2q} too small
  $\Rightarrow$ polarimetry relied entirely on iT_{11}
- At tandem energies ($\sim$15 MeV): tensor observables T_{2q} **sizeable**
  $\Rightarrow$ simultaneous extraction of P_z and P_{zz}
- Comprehensive study of elastic scattering of 15 MeV deuterons by Irshad & Robson [11] for ^{52}Cr (Chromium), ^{90}Zr (Zirconium), ^{122}Sn (Tin):
  - full set $\{iT_{11}, T_{20}, T_{21}, T_{22}\}$ measured within optical-model framework including tensor interactions
  - standard laboratory target materials
- Note: $iT_{11} \equiv \sqrt{\frac{3}{2}} A_y$ and $T_{20} \equiv \frac{1}{\sqrt{2}} A_{zz}$ connect spherical to Cartesian analyzing powers (slide 31)
- Available analyzing powers combined with measured asymmetries
  $\Rightarrow$ extract P_z and P_{zz} behind tandem;
  detector acceptance may be optimized with respect to these data

Use measured asymmetries to extract P_z and P_{zz} and tune the RF transition units of the deuterium atomic-beam source

Project Organization

Project Organization

BNL
PI: D. Steski
Co-PIs: D. Raparia, F. Rathmann
Mechanical Engineer: J. Ritter

Polarized Deuterium Ion Source
D. Steski   T. Kubley
Post Doc: TBD

Tandem Polarimeter
F. Rathmann   V. Shmakova
J. Datta (Stony Brook Univ.)
Post Doc: TBD

Conclusion & Outlook

Conclusion & Outlook

- **Physics case:** polarized $\vec{d}$ at EIC scientifically indispensable
  - unique access to neutron spin structure, tensor observables b_1, T_{2q}, small-x gluon imaging
  - deuteron polarization preserved to $> 100\,\text{GeV/n}$ in EIC HSR with 95% efficiency [6]
- **Unique opportunity:** COSY polarized $\vec{d}$ source available to BNL
  - COSY shutdown end of 2023; source available at fraction of replacement value
- **Installation plan:** new HV platform at BNL Tandem (MP7)
  - $9\,\text{keV} \rightarrow 120\,\text{keV}$ transport line designed; existing MP7 capabilities fully preserved
- **Tandem polarimeter:** COSY LEP repurposed at high-energy end of MP7
  - P_z and P_{zz} simultaneously measurable at $\sim$15 MeV [11]
- **Project:** BNL team in place; proposal submitted Dec. 2025 to DOE NP

> **This is the critical first step toward polarized deuteron beams at EIC**

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Spare slides

F. Rathmann et al. (BNL)

Beamline Elements: Source to MP7

Proposed layout

- from DOE NP proposal, Dec. 2025, not yet public)
- *Triplet position schematic; exact *z*-positions finalized during optics design

Z	Element	L	Grad./V	r	Comment
(mm)		(mm)		(mm)	
0	Entrance	–	–	5	$T = 9\,\text{keV}$
100	FC1	100	–	–	9 keV current
200	Emitt. scanner	100	–	–	9 keV Twiss
500	ES quad (F)	100	$\pm 340\,\text{V}$	25	ES doublet
620	ES quad (D)	100	$\mp 380\,\text{V}$	25	ES doublet
730	Steerer (X)	50	$\pm 1000\,\text{V}$	–	Centering
750	Steerer (Y)	50	$\pm 1000\,\text{V}$	–	Centering
1525	ES 45° bend	160	$\rho = 0.20\,\text{m},\ \pm 900\,\text{V}$	20	Aligns to MP7
1700	Accel. column	1000	120 kV	50	$T = 120\,\text{keV}$
2800	FC2	100	–	–	120 keV current
2900	Profile monitor	100	–	–	Transverse profile
3800*	ES triplet	700	$+670/ -1400/ +870\,\text{V}$	25	120 keV matching
4500	Steerer (X)	100	$\pm 1000\,\text{V}$	25	Centering
4600	Steerer (Y)	100	$\pm 1000\,\text{V}$	25	Centering
8250	Exit ion source	–	–	–	Handoff to magnetic optics

Cartesian and Spherical Analyzing Powers

Conversion between Cartesian and spherical bases:

$$iT_{11} = \sqrt{\tfrac{3}{2}}\, A_y, \qquad T_{20} = \tfrac{1}{\sqrt{2}}\, A_{zz}, \qquad T_{21} = -\tfrac{1}{\sqrt{3}}\, A_{xz}, \qquad T_{22} = \tfrac{1}{2\sqrt{3}}(A_{xx} - A_{yy})$$

Inverse relations:

$$A_y = \sqrt{\tfrac{2}{3}}\, iT_{11}, \qquad A_{zz} = \sqrt{2}\, T_{20}, \qquad A_{xz} = -\sqrt{3}\, T_{21}$$

$$A_{xx} = -\tfrac{\sqrt{2}}{2}\, T_{20} + \tfrac{1}{\sqrt{3}}\, T_{22}, \qquad A_{yy} = -\tfrac{\sqrt{2}}{2}\, T_{20} - \tfrac{1}{\sqrt{3}}\, T_{22}$$

- Cartesian tensor is traceless: $A_{xx} + A_{yy} + A_{zz} = 0$
- Connects to spherical analyzing powers used in deuteron scattering and three-nucleon calculations
- $P_z \leftrightarrow iT_{11}; \quad P_{zz} \leftrightarrow T_{20}$