FY2026 NPP LDRD Type B Pre-Proposal presentation

Modeling polarized atomic beams

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Introduction

Hadron polarimetry requirements

- **Absolute beam polarization determination on the $\leq 1\%$ level in a storage ring relies on the precisely measured nuclear polarization of an atomic jet**
  - Elastic scattering of identical particles, like in $\vec{p}\vec{p}$ scattering
  - Other ion species require a similar approach, i.e., $\vec{d}\vec{d}$ and $\vec{h}\vec{h}$ scattering

Absolute polarization calibration

Subsequent measurements of detector asymmetries with both polarized beam P and polarized targets Q, the beam polarization can be determined via

$$P = \frac{\epsilon_{\text{beam}}}{\epsilon_{\text{target}}} \cdot Q\,, \tag{1}$$

because in the elastic scattering of identical particles, A_y is the same regardless of which particle is polarized.

Motivation: Modeling Polarized Atomic Beams

- **Top Priority:** Regain ability to simulate/design polarized atomic beams
  - Critical competence, disappeared from academia in both the US and Europe, **foundational step, absolutely essential**, underpins all future progress.
  - A **postdoc of 2 years** will be sufficient to revitalize the critical atomic beam tracking instruments and restore the necessary simulation capabilities.
- The AGS is essential for maintaining high beam polarization across the accelerator chain, yet polarization losses need to be reduced further to provide

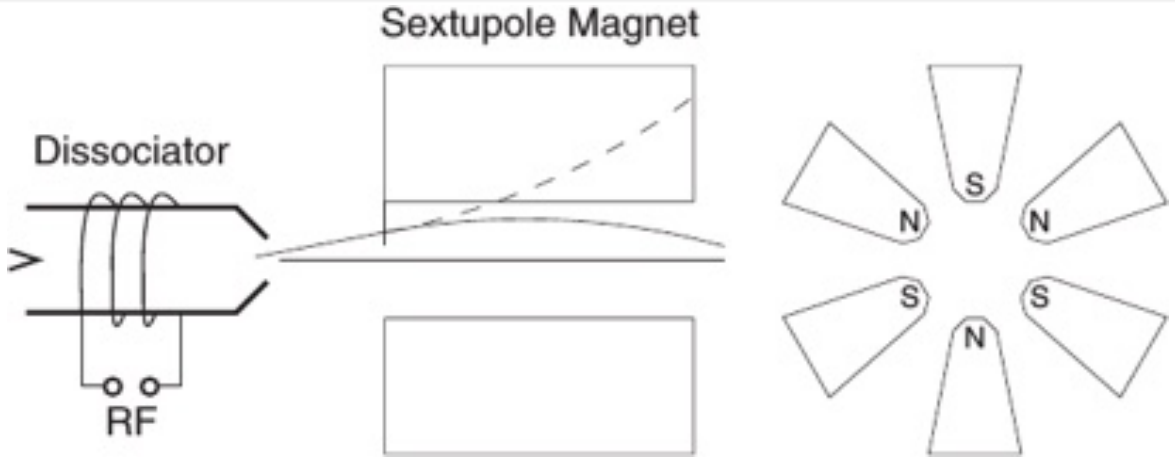
$$P \geq 70\% \quad \text{and} \quad \frac{\Delta P}{P} \leq 1\%. \tag{2}$$

  - A compact atomic beam source (ABS) is needed to improve required polarization diagnostics; it should fit AGS constraints.
    - A recommendations of the 21st C-AD Machine Advisory Committee in December, 2024, suggested precisely that.
  - **Components from COSY (worth $\approx 2\,\text{M\$}$)) enable the cost-effective development of a polarized ABS for the AGS** (see slides 17–18).
  - In addition to the AGS, the proposed approach will also support future projects planned at the LHC-B/CERN, the EIC, and others.
    - Project is independent of EIC (**it is off-project**).
    - It will ensure reliable performance of existing machines.

Physics and techniques of atomic beam sources (ABS)

Overview

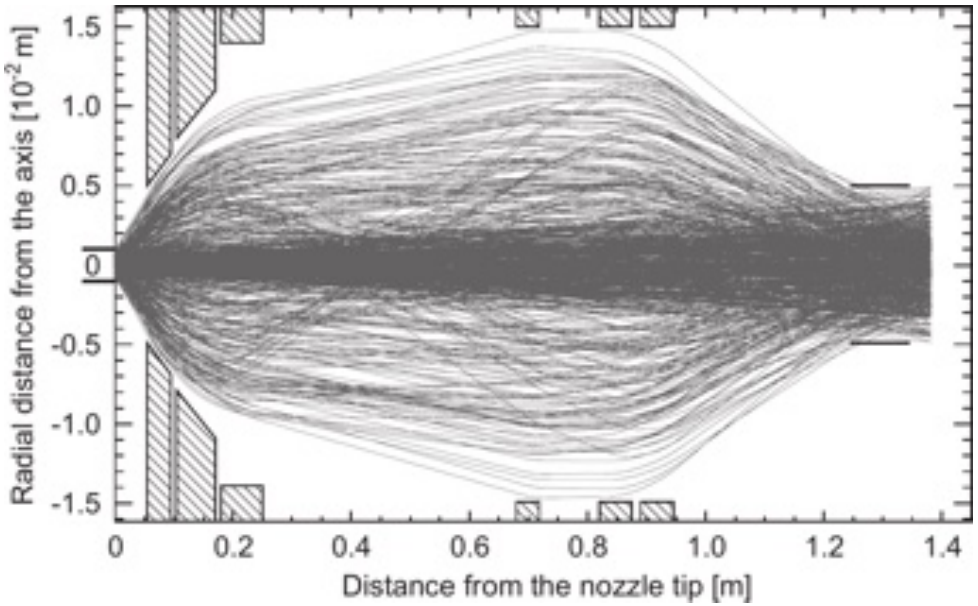
- Production of H and D ground-state atomic beams
- Dissociators, beam formation and accomodation
  - RF discharge dissociators
  - Microwave Dissociators
- State-separation magnets



- RF transitions
- Ionizers
- Polarized (gas) targets and storage cells

Designing a magnet system using tracking calculations

- Modern polarized ABS use four to six separated short sextupole magnets
- Field strengths and location of magnets determined by tracking calculations,
  - taking into account other requirements (optimum pumping, insertion of RF transition units, etc.).



- **Example from Ref.** [1]
- Projection of 3-dimensional trajectories of hydrogen atoms in hyperfine states $|1\rangle$ and $|2\rangle$:
- Effective magnetic moment $\mu_{\text{eff}} > 0$.

- Trajectories from nozzle ($\varnothing = 2\,\text{mm}$, $T_{\text{nozzle}} = 60\,\text{K}$) to storage cell:
  - Figure reflects optimized magnet system [1], using pole-tip fields of 1.5 T.
  - Positions and radial dimensions of nozzle, apertures of six magnets, and feeding tube are indicated.
  - (Note: vertical length of ABS limited by COSY tunnel)

International impact of the proposed project

- Anyone else working with polarized hadrons will benefit from the project, as all existing polarized sources are based on atomic beams.
  - LHC-B polarized target project [2]
  - Search for electric dipole moments using storage rings (see, e.g.,[3])
  - Feeding polarized fuel into a Tokamak fusion reactor [4]:
    - Proponents propose to increase the total cross section by exploiting the spin dependence of $\vec{d} + t \rightarrow {}^4\mathrm{He} + n$ and $\vec{d} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + p$, or the direct reactions $\vec{d} + \vec{d} \rightarrow {}^3\mathrm{He} + n$ or $\vec{d} + \vec{d} \rightarrow t + p$.
  - Ref. [5] includes rest gas effects by parametrization of attenuation measurements.
    - A more suitable approach would be a direct Monte Carlo simulation of the residual gas scattering including the Stern-Gerlach forces, as indicated in [6].
    - Approach will also benefit OPPIS and any other polarized ion source.

Goals and timeline of the project

Item	Time Interval	Goal
1	10/25 – 11/25	Familiarize with scientific background [1, 5, 7]
2	**12/25 – 11/26**	**Simulation calculations:**
	12/25 – 03/26	Modify existing code and verify changes by reproducing some of the results of Ref. [5]
	04/26 – 07/26	Simulation calculations for new ABS at AGS
	08/26 – 11/26	Simulation of Breit-Rabi polarimeter to allow for $\Delta P \leq 1\%$ absolute uncertainty determination
3	12/26 – 04/27	Transfer code to modern programming language[1], e.g., Matlab, for future applications
4	05/27 – 09/27	Finalize results of obtained findings

[1] We intend to make the modernized software open source to address the shortcomings of previous groups, as their codes were not available to the public.

Project deliverables and Personnel

Anticipated deliverables

1. Modify atom tracking code
2. Carry out simulation calculations for a new ABS at the AGS
3. Develop/simulate Breit-Rabi polarimeter for AGS target
   - $\Delta P \leq 1\%$ absolute polarization uncertainty determination
4. Transfer code to modern programming language, e.g., Matlab
5. Finalize results, publish obtained findings

Personnel

Project to be carried out by a PostDoc within a time period of 2 years

I'm concerned about the massive scale of the overall effort

- Many groups specializing in **polarization instrumentation & technology** for hadronic probes have disappeared in recent years, along with the valuable expertise they once contributed.
  - This contrasts sharply with the time when RHIC was conceived, when numerous experimental and theoretical groups from around the world provided and contributed expertise.
- The first two steps:
  1. *Feasibility study of a novel holding field scheme for polarized atomic jets* (FY25, LDRD C application), and
  2. *Modeling polarized atomic beams* (this application)

  are merely initial milestones.
  - Much work is needed to make the polarized $\vec{\text{H}}$-ABS operational at AGS, develop a robust detector concept, and establish methods for providing absolute polarization determination at AGS.
  - A similar workpackage is coming up to optimize and install the MIT $^3\vec{\text{He}}$ ABS in the AGS to provide absolute beam polarimetry.

Summary

Top Priority of proposed project:

Regain ability to simulate/design polarized atomic beams

- **This critical competence that disappeared from academia in both the US and Europe is an absolutely essential foundational step, as it underpins all future progress.**
- A 2-year postdoc will suffice to revive critical atomic beam tracking tools, providing the needed simulation capabilities.
- Total planned funding per year in FY26 and FY27:

Year	Duration	Start		End
FY26	12 months	10/01/25	–	09/30/26
FY27	12 months	10/01/26	–	09/30/27

  - Minor hardware requirements needed:
    - purchase suitable laptop
    - software licenses, e.g., Matlab

References

[1] M. Mikirtychyants, R. Engels, K. Grigoryev, H. Kleines, P. Kravtsov, S. Lorenz, M. Nekipelov, V. Nelyubin, F. Rathmann, J. Sarkadi, et al., "The polarized H and D atomic beam source for ANKE at COSY-Jülich," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **721**, 83 (2013), ISSN 0168-9002, URL http://www.sciencedirect.com/science/article/pii/S0168900213003483.

[2] C. A. Aidala et al., "The LHCSpin Project," (2019), URL https://arxiv.org/pdf/1901.08002.pdf.

[3] F. Abusaif et al. (CPEDM), *Storage Ring to Search for Electric Dipole Moments of Charged Particles – Feasibility Study* (CERN, Geneva, 2021), 1912.07881.

[4] G. Ciullo et al., "The PREFER (Polarization REsearch for Fusion Experiments and Reactors) - collaboration: purposes and present status," PoS **PSTP2019**, 002 (2020).

[5] T. Wise, M. Chapman, W. Haeberli, H. Kolster, and P. Quin, "An optimization study for the {RHIC} polarized jet target," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **556**, 1 (2006), ISSN 0168-9002, URL http://www.sciencedirect.com/science/article/pii/S0168900205018590.

[6] M. Gaisser, A. Nass, and H. Ströher, "DSMC simulations of polarized atomic beam sources including magnetic fields," Phys. Part. Nucl. **45**, 295 (2014).

[7] A. Vassiliev, V. Nelyubin, V. Koptev, P. Kravtsov, B. Lorentz, H. J. Marik, M. Mikirtytchiants, M. Nekipelov, F. Rathmann, H. Paetz gen. Schieck, et al., "24 segment high field permanent sextupole magnets," Review of Scientific Instruments **71**, 3331 (2000), URL http://scitation.aip.org/content/aip/journal/rsi/71/9/10.1063/1.1288264.

Spare slides

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

FY2026 NPP LDRD Type B Pre-Proposal

Modeling polarized atomic beams

Principal Investigator: **Frank Rathmann**

01/06/2024

@BrookhavenLab

FY2026 NPP LDRD Type B Pre-Proposal

Proposal title: **Modeling polarized atomic beams**

Primary Investigator: **Frank Rathmann**

Co-PI: **K. Oleg Eyser**

Other Investigators: **Vera Shmakova and Zhengqiao Zhang**

Indicate if this is a cross-directorate proposal: Yes ___ **No_×__**

If yes, identify other directorates/organizations:

Proposal Term: **24 months** From: **10/01/2025** To: **09/30/2027**

Brookhaven National Laboratory

FY2026 NPP LDRD Type B Pre-Proposal

Proposal Title: Modeling polarized atomic beams

Abstract:

The AGS plays a central role in preserving the beam polarization from the ion source to the RHIC/EIC peak energy. Current polarization losses in the accelerator chain are quantitatively not understood, and the implementation of an absolute beam polarimeter in the AGS would greatly improve the polarization diagnostics in the ring and the injector chain. (One of the recommendations of the 21st C-AD Machine Advisory Committee, held December 16 - 18, 2024, suggested precisely that.)

Due to structural limitations in the AGS tunnel, including the operation of the overhead crane, a direct duplication of the polarized RHIC HJET setup is therefore not possible. Instead, a more compact atomic beam source is required that fits within the AGS constraints while achieving high performance. This AGS HJET design must incorporate optimized sextupole magnet systems to maximize the target density at the interaction point. It requires the application of robust simulation tools to refine magnet positions, beam focus, and Breit-Rabi polarimeter design to determine the nuclear polarization of the atomic jet.

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Program: DOE program NP

Return on Investment:

The proposed initiative represents a decisive step towards the implementation of polarized atomic beams of H, D, and ^{3}He in the AGS, improving its performance across the accelerator chain. Key components from the COSY polarized physics program, confirmed available by Dr. Ralf Gebel (r.gebel@fz-juelich.de, managing Director, Institut für Kernphysik, Forschungszentrum Jülich, Germany, https://www.fz-juelich.de/en/ikp), will provide a solid and cost-effective foundation for an optimized hydrogen and later a deuterium polarized jet development, required also as a basis for the future development of a polarized deuteron ion source (worth approx. € 2 million, see attached list.

Similarly, the ^{3}He atomic beam source developed at MIT will also benefit and can be further enhanced using the resurrected atomic beam tracking tools. The developed tools will also benefit beam and internal target polarimetry in other accelerators, such the AGS, LHC, and the future EIC.

Broader impact on the activities at the laboratory:

The proposed cost-efficient approach for the construction of such a source is the reuse of polarization equipment from the former polarized COSY physics program at FZ Jülich (see attached list), for which no further use is foreseen.

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Broader impact on the activities at the laboratory: (cont'd)

To achieve the highest possible target density, it is mandatory to simulate polarized atomic beams [1], a capability that has unfortunately almost completely disappeared in academia in the US and Europe. In fact, all polarized hydrogen and deuterium atomic beam sources in operation today were developed more than two decades ago. The design of a new source or the redesign of an existing source, as well as the incorporation of recent advances, e.g., in the pole tip field of Halbach sextupole magnets, however, require the use of atomic beam tracking codes. Unfortunately, earlier tracking codes are not well documented and now need to be revived and updated with modern software tools.

To support this effort, we are proposing a targeted work package requiring LDRD-B funding to support a 2-year postdoc dedicated to atomic beam simulations. This fundamental modeling work will underpin the next generation of polarized atomic beam sources, providing absolute beam polarization determination in the AGS, and subsequently ensuring in the longer-term optimal polarization transmission.

The project itself is completely independent of the EIC project (it is off project), as the results will be applied to existing machines whose availability and performance for the EIC are to be ensured, but which are not themselves part of the EIC project. However, the proposed project will also be of great benefit for the planned implementation of a polarized gas jet target at the LHC-b experiment at CERN.

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References:

1. T. Wise, M.A. Chapman, W. Haeberli, H. Kolster, and P.A. Quin, *An optimization study for the RHIC polarized jet target*, Nucl. Instrum. Meth. **A 556**, 1 (2006), https://doi.org/10.1016/j.nima.2005.09.042.

Appendix:

Tentative list of available polarization equipment from FZJ, Jülich, Germany, as of December 15, 2024

1. 3 sets of permanent sextupole magnets (EDDA target with BRP, polarized source I and replacement, 24 segments with 1.35 T, age 25 years)
2. 2 electromagnets (similar to ETH, IUCF and PSI: 1.0 T tapered, 0.6 T 30 mm aperture)
3. Vacuum chambers for two atomic beam parts of the polar source "COSY"\Vacuum chambers for EDDA target and beam dump with BRP and QMS (identical to PQ!)
4. Time-of-flight spectrometer for atomic beams with chopper (Belov/Derenchuk)
5. Vacuum equipment for two sources and diagnostic chambers (pumps > 20 years old)
6. Mass spectrometer (Balzers, Leda), Ionivac (old design) for e.g. pitot tube measurements
7. Scanner for profile measurements with pitot tube
8. Dissociators (EDDA and polar source): > 4 units - identical in construction
9. Several 27 MHz fixed frequency amplifiers with auto-matchbox (600 W, 1000 W and 4000 W)
10. Cold heads and compressors for 25K - 80K operation; matching nozzles (Al)
11. Temperature controller (Leybold, Lakeshore 2-channel): (>) 2 units each

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Tentative list of available polarization equipment, cont'd

12. Pressure regulators and flow regulators (> 8 systems due to H2, D2, N2 and O2 addition)
13. Siemens controllers (2 systems)
14. 9 RF transition units with spare parts, 5 of which with "tunable" resonators
15. Fixed: 5.5 MHz, 1430 MHz and variable: 310-440 MHz
16. Tuners, circulators, amplifiers, sequencers for polarization cycles
17. Signal generators (R&S) SMX, SMY02, SMG ...
18. Magnetic field controllers for 2x4 units, incl. replacement
19. EDDA holding field power supplies
20. Linear target drives for EDDA filament target and ring polarimeter

15. Various auxiliary tools for assembly and tests (e.g. CuBe tool, Hall probes, adjustment aids, ...)

Total planned funding per year in FY26 and FY27

Resources applied for shall be used to fund a postdoc for 24 months in total. Minor hardware requirements needed would be either to purchase a modern laptop or to provide access to the supercomputing facilities at BNL, with the corresponding Matlab software licenses to be purchased as well.

FY26	12 months	10/01/2025	-	09/30/2026
FY27	12 months	10/01/2026	-	09/30/2027

One of the goals of the project is to transfer/translate the available customized software package, used in Ref. [1], into a modern language (e.g., Matlab) for future applications. We intend to make the modernized code publicly available, as this was one of the shortcomings of previous groups working on the subject.