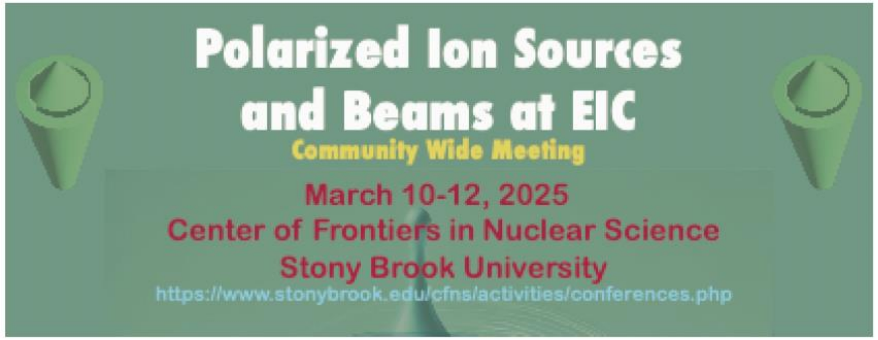
Polarized Ion Sources for EIC

On behalf of the EPIOS scientific consortium

- Stony Brook meeting, March 10-12, 2025
- EPIOS scientific consortium
- Science case
- Status of polarized ion source development
- Future path



Community-wide meeting
Polarized Ion Sources and Beams

Organized by Deepak Raparia (BNL), Frank Rathmann (BNL),
Jaydeep Datta (SBU), Richard Milner (MIT), and Zein-Eddine Meziani (ANL)

Center for Frontiers
in Nuclear Science

Goals of the meeting

- to raise the visibility in the EIC and spin communities of the exciting scientific case for spin measurements;
- to assess, in the context of the considerable scientific motivation, the status of ion source development for EIC;
- to identify critical path R&D essential for a successful polarized EIC program that can be implemented on day-1;
- to motivate the education and training of a new generation of young physicists with expertise in spin polarization technology. This will be essential for realization of the EIC polarized program.

The major points arising from the meeting were:

- It must be realized that the adaption of a well-understood polarization technique into a reliable ion source operating at maximum performance injecting with high reliability into an accelerator requires a sustained R&D effort by a critical mass of suitably skilled personnel for about a decade.
- If we consider the major polarization experimental efforts in nuclear physics over the last half century, university-based research groups played an essential role in developing the technical capabilities and in attracting and training the generations of physicists who carried out the research.
- The EIC science demands the widest available range of polarized ions and innovative source technologies must be pursued.
- The EIC accelerator design team must make it a priority to develop ion spin control and manipulation from source to collisions of the deuteron ^{3}He, ^{6}Li and ^{7}Li nuclei.
- It is recommended that a specific amount of funding be set aside to target R&D associated with the realization of polarized ion beams at EIC. This would support education and training of young physicists with the necessary expertise.
- It is recommended that a focused multi-week program on the science case for polarized ion beams at EIC being organized at the Institute for Nuclear Theory in the next year.
- It is recommended that an annual summer school for young physicists on the science and technical realization of polarized ion beams at EIC be established. Existing summer schools and the U.S. Particle Accelerator School can be leveraged to include relevant lectures and classes.
- It is recommended that the BNL $\vec{\text{T}}$andem be utilized to secure the future with $\vec{d}$ and $^6\vec{\text{Li}}$ ions, as there is not sufficient space available for these sources at BNL EBIS.
- We identify the AGS as a very valuable platform to carry out beam studies of polarized sources, polarized beams and spin manipulators in the era when RHIC is dark. We recommend that EPIOS and the BNL-CAD together consider the possibilities and develop a plan that takes advantage of the AGS.

Polarized Ion Sources

Overall status and availability

- The EIC will use
  - polarized **protons** ($\vec{\frac{1}{2}}$) and **helions** ($\vec{\frac{1}{2}}$),
  - later on possibly **deuterons** ($\vec{1}$), and
  - heavier nuclei like **lithium**, i.e., $^6\mathrm{Li}$ ($\vec{1}$) and $^7\mathrm{Li}$ ($\vec{\frac{3}{2}}$).
- **Ion sources** for
  - polarized protons (available)
  - polarized ^{3}He (needs work)
  - polarized deuterons
    - will be inherited from Jülich (soon, then needs work)
    - not trivial for HSR as $G_d = -0.143$ small (needs work)
  - polarized lithium (needs a lot of work)

Polarimetry requirements for hadron beams in EIC

- **The EIC promises to provide proton beam polarizations of $P \geq 0.7$ with a relative uncertainty of $\Delta P/P \leq 1\%$.**
- **Absolute proton beam polarization calibration relies on measured nuclear polarization of atomic jet using Breit-Rabi polarimeter.**
- Polarization calibration needed for each ion species, as presently applied to for protons:
  - elastic scattering of identical particles $\Rightarrow$ beam polarization inferred from known target polarization.
  - $\vec{p}\vec{p}$ elastic scattering,
  - $^3\overrightarrow{\mathrm{He}} - {}^3\overrightarrow{\mathrm{He}}$ elastic scattering,
  - $\vec{d}\vec{d}$ elastic scattering, and,
  - $^6\overrightarrow{\mathrm{Li}} - {}^6\overrightarrow{\mathrm{Li}}$ elastic scattering.
- **Polarization calibration of other species also from nuclear polarization measurement of atomic targets using BR or similar type polarimeter**

March meeting outcomes

- We have formed

  EPIOS (**E**IC **P**olarized **IO S**ource) scientific consortium

  to continue to advance the realization of polarized ion beams at EIC.
- Plan meetings about every six months: Stony Brook, ANL, MIT,……
- Immediate tasks:
  - Writing and will publish the whitepaper based on the meeting
  - Will propose an INT scientific workshop for 2026-2027
  - Explore initiation of annual summer school, starting in 2026
- DNP Workshop ***Polarized Ion Beams at EIC***, proposed by Z.-E. Meziani and R. Milner approved. DNP meeting in Chicago Oct 17-20, 2025. EPIOS meeting at DNP meeting.

Realizing the Scientific Program with Polarized Ion Beams at EIC

The EPIOS Scientific Consortium

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(Dated: July 6, 2025)

Science case for polarized ion beams at EIC

- to provide polarized neutron targets;
- to study how the nucleon's quark and gluon spin distributions can be modified in the nucleus;
- to access the new parton and transverse momentum distributions that allow full three-dimensional imaging of the proton, neutron and nuclei;
- to carry out pioneering searches for spin-1 and higher components, e.g. *exotic gluons*, in the nucleus.

Experimental considerations

- realization of pure electron-nuclear scattering, unlike current fixed-target experiments, where the polarized nucleus is embedded in a significant amount of extraneous material;

- straightforward control of the ion spin direction from transverse to longitudinal with respect to the beam direction;

- detection of particles scattered close to the beamline;

- efficient tagging of spectator systems, which travel in the laboratory with high energy close to the beam direction.

Quark and gluon structure of nucleon spin

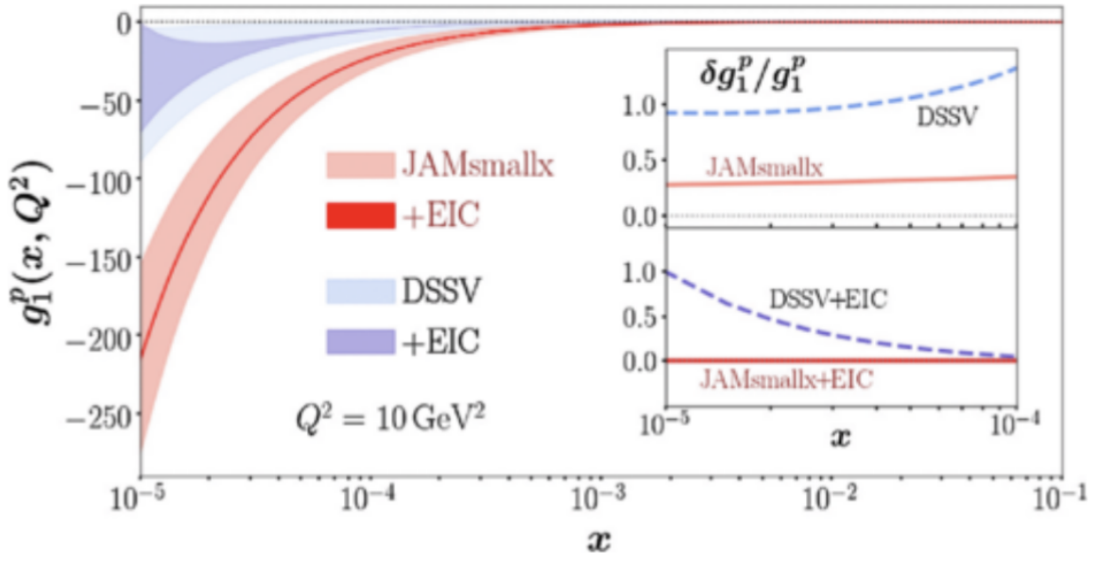

FIG. 1: The gluon helicity distribution is determined from the Q^2 evolution of the g_1^p structure function. The curves above are extracted from the DSSV and JAMlowx global analysis [6] and show the associated errors with (darker) and without (lighter) EIC data. The curves diverge for $x < 0.001$ due to the application of different theoretical evolution formalisms.

Flavor spin distribution

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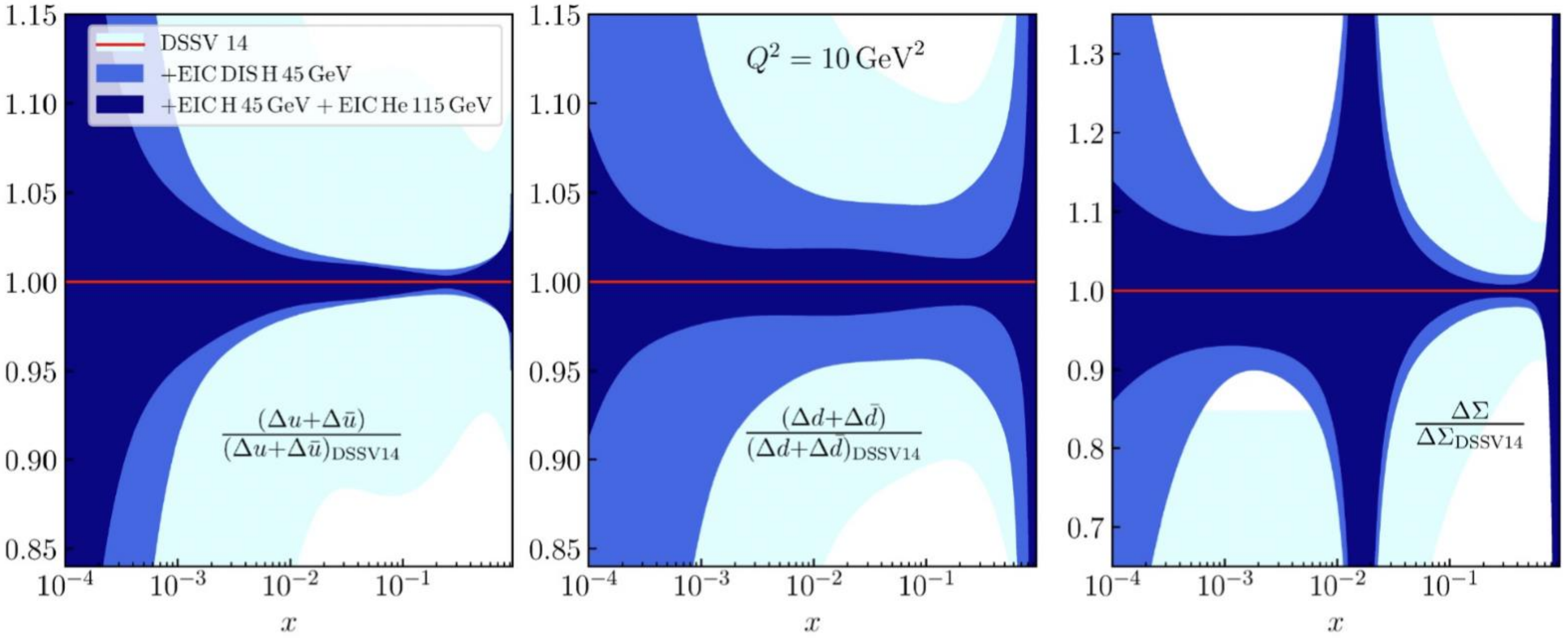

FIG. 2: The impact of projected inclusive scattering data off polarized proton and ^{3}He beams at the EIC on the relative uncertainties of the extracted up, down and quark singlet helicity distributions.

Mapping the full 3D structure

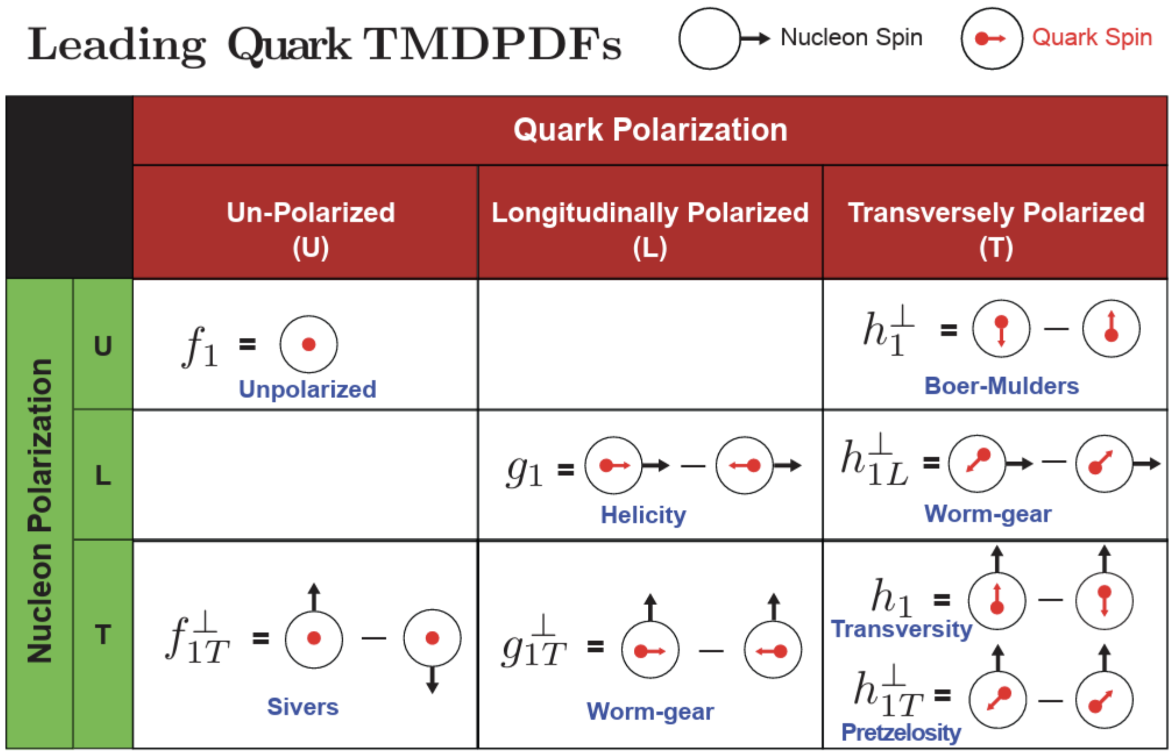

Figure 1.7: Leading power spin dependent quark TMDPDFs. The red dot and black circle represent the quark and nucleon, while the red and black arrow represent their spin direction, respectively.

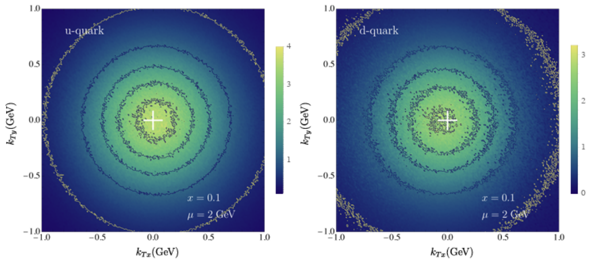

Figure 5.11: Tomographic scan of the nucleon via the momentum space quark density function $\rho_{1;q\leftarrow h^{\uparrow}}(x, \vec{k}_T, \vec{S}_T, \mu)$ defined in Eq. (5.27) at $x = 0.1$ and $\mu = 2$ GeV. Panels are for u and d quarks. The variation of color in the plot is due to variation of replicas and illustrates the uncertainty of the extraction. The nucleon polarization vector is along $\hat{y}$-direction. The figures are from Ref. [378].

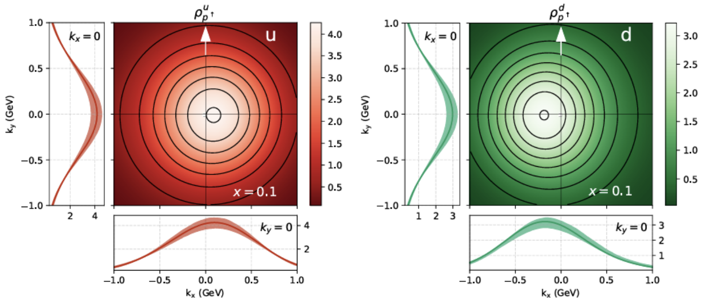

Figure 5.12: The density distribution $\rho^{a}_{p^{\uparrow}}$ of an unpolarized quark with flavor a in a proton polarized along the $+y$ direction and moving towards the reader, as a function of (k_x, k_y) at $Q^2 = 4$ GeV^2. The figures are from Ref. [365].

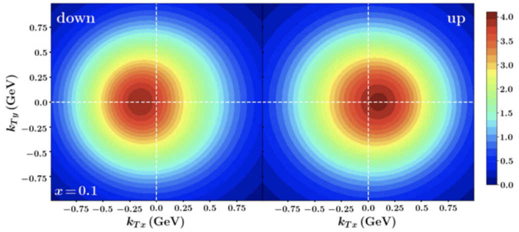

Figure 5.13: The density distribution of an unpolarized up and down quarks using Sivers functions from Ref. [18].

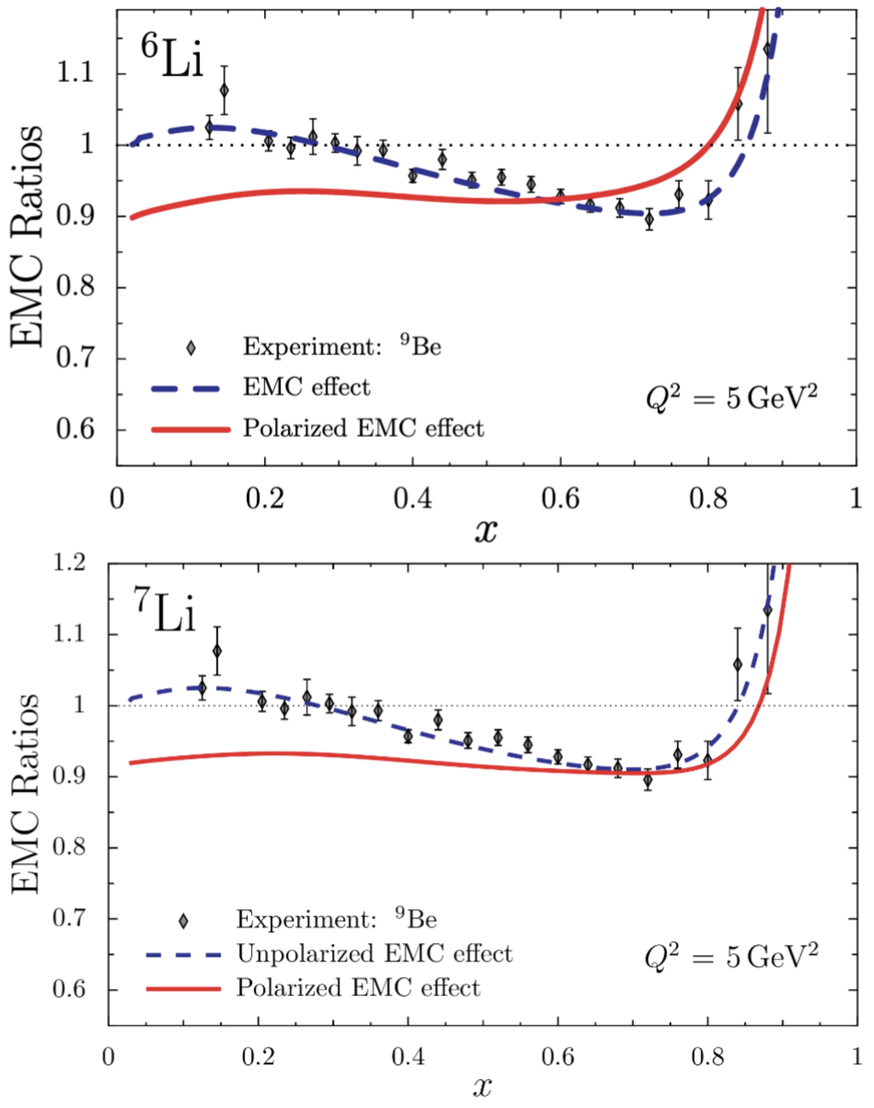

FIG. 3: Results for the EMC and polarized EMC effects in ^{6}Li and ^{7}Li, where the latter predictions are from Ref. [56].

Is the nucleon spin structure modified in the nuclear medium?

Exotic gluon states in the nucleus?

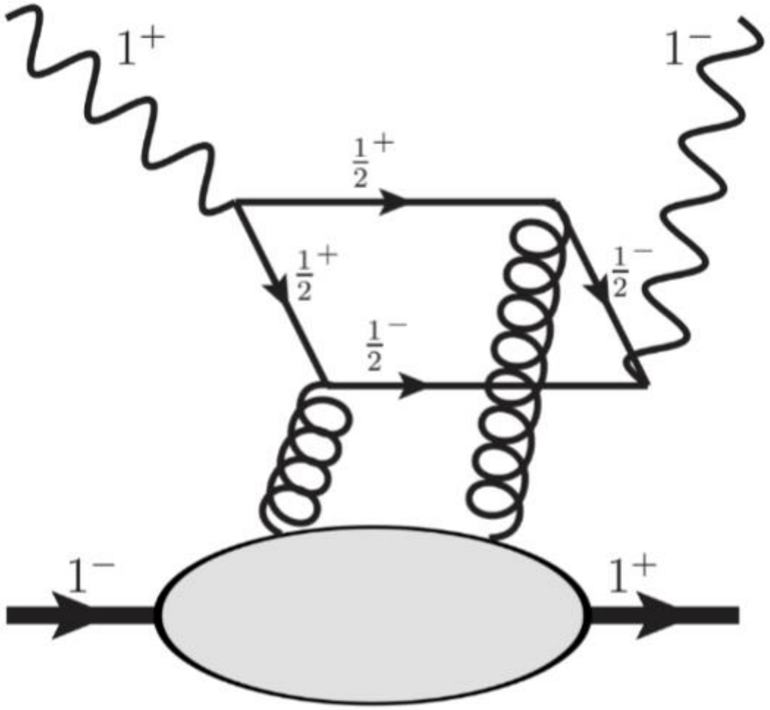

FIG. 4: Example of leading DIS process sensitive to $\Delta(x, Q^2)$ [63].

Polarized Ion Source R&D

- Polarized proton
  - OPPIS reliability and performance
- Polarized deuteron
  - COSY deuteron source being transferred to BNL
  - likely utilize BNL tandem
- Polarized He-3
  - optically pumped source using EBIS being developed by BNL-MIT coll.
  - 6 MeV polarization measurement planned when RHIC ends operations
  - absolute polarimeter using existing ABS source under development
- Polarized Li-6 and Li-7
  - optically pumped source development getting underway at ANL

Scale of task before us

- OPPIS: multi-decade, 30 physicists, 10 engineers, 5 postdocs/students
- HERMES H/D target: 40 graduate student years, 50 postdoc/senior years
- HERMES He-3 target: 10 graduate student years, 12 postdoc senior years, two years of engineering
- SLAC He-3 target: 35 person years
- SLAC H/D target: 20 person years
- Ongoing He-3 source development at BNL: 12 physicists, 4 postdocs

Scale of EIC polarized ion source effort is estimated as ~ 200 FTE

AGS is an essential test bench for development of polarized sources and beams

- We have of order a decade to develop the polarization technology that is essential for EIC science. This includes:
  - polarized ion sources (^{2}H, ^{3}He, ^{6}Li and ^{7}Li)
  - polarimeters
  - spin manipulation in AGS and RHIC using solenoids and snakes
- We require maximum stable polarization and collision luminosity at the IP.
- The AGS is a local to EIC, is an integral element of the EIC accelerator and should be made available after RHIC operations cease.

Abstract

Polarized ion beams at the Electron Ion Collider are essential to address some of the most important open questions at the twenty-first century frontiers of understanding of the fundamental structure of matter. Here, we summarize the science case and identify polarized ^{2}H, ^{3}He, ^{6}Li and ^{7}Li ion beams as critical technology that will enable experiments which address the most important science. Further, we discuss the required ion polarimetry and spin manipulation in EIC. The current EIC accelerator design is presented. We identify a significant R&D effort involving both national laboratories and universities that is required over about a decade to realize the polarized ion beams and estimate (based on previous experience) that it will require about 200 FTEs (about 20 FTE *per annum* (*p.a.*)) of personnel, including graduate students, postdoctoral researchers, technicians and engineers. Attracting, educating and training a new generation of physicists in experimental spin techniques will be essential for successful realization. The R&D effort is synergistic with research in atomic physics and fusion energy science.