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Beams of polarized hadrons at EIC: Action plan to address acute challenges

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Abstract

In the recent years, more and more groups in the field of polarization instrumentation and technology have disappeared, taking their expertise in the experimental technologies with them. When the RHIC was conceived, there were numerous experimental and theoretical groups around the world from which experts could be recruited to build new instruments, powerful sources, specialized detector systems, investigate new approaches and concepts, and much more. We should recognize that we presently are in a critical situation regarding the availability of skilled individuals to provide and service the required instruments to make the EIC a success.

We need to rejuvenate the field of polarization technology, especially for hadrons, and significantly expand education and training efforts. The document highlights a number of key areas that require attention. Three scientists/engineers/postdocs and at least one or two PhD students should be sought immediately to start building a group capable of tackling the future tasks and challenges in hadron polarimetry at the EIC.

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1 Absolute hadron beam polarimetry

1.1 Introduction

Absolute beam polarimetry at RHIC relies on the determination of the vertical beam polarization component p_y. Various methods can be used to measure the polarization of a stored beam. For protons scattered from an unpolarized carbon nucleus, the degree of polarization in the ring can be deduced from the left-right count rate asymmetry

$$\epsilon_{\text{beam}} = \frac{\text{L} - \text{R}}{\text{L} + \text{R}} = A_y \cdot P \,, \tag{1}$$

where L and R are the counts recorded in the left and right detectors, A_y is the analyzing power, which is a measure of the polarization sensitivity of the scattering process, and P the absolute value of the beam polarization. At high energies in the AGS, RHIC, and in the Hadron Storage Ring (HSR) of the Electron-Ion Collider (EIC), there are no scattering processes available for which the analyzing power A_y is known with sufficient accuracy to perform an absolute and highly accurate measurement with an uncertainty of a few percent [1]. The goals for polarimetry at EIC are even more ambitious [2], requesting proton beam polarization of 70% and relative uncertainty of 1% or less.

The interference of electromagnetic and strong interaction at small scattering angles provides sizable analyzing power for elastic proton-proton (and proton-nucleus) scattering (see, e.g., Fig. 6 in [3]). This analyzing power constitutes the basis of the RHIC high-energy (absolute) polarimeters and is derived from the same electromagnetic amplitude that generates the anomalous magnetic moment of the proton. Experiment E704 at Fermilab used 200 GeV/c polarized protons from hyperon decay to detect the asymmetry in the scattering from a hydrogen target [4]. The largest analyzing power A_y was about 0.04 with large statistical errors. Calculations agreed with these measurements, but are subject to uncertainties in the amplitudes of the strong interaction. Therefore, an accurate calibration of the reaction is required. The high-precision beam polarization calibration developed for RHIC [1] makes use of an ion beam that passes through a beam of polarized hydrogen atoms with known nuclear polarization, and one measures the left-right ratio in the number of scattered particles [see Eq. (1)]. The sign of the target polarization is periodically reversed to compensate for asymmetries caused by differences in detector geometry or efficiency in the left and right directions. This yields the target asymmetry $\epsilon_{\text{target}} = A_y \cdot Q$, where Q denotes the target polarization. A measurement of the corresponding asymmetry with beam particles determines ϵ_{beam}, and since in elastic proton-proton scattering the analyzing power A_y is the same regardless of which proton is polarized, the absolute beam polarization is given by

$$P = \frac{\epsilon_{\text{beam}}}{\epsilon_{\text{target}}} \cdot Q \,. \tag{2}$$

The absolute polarization calibration for the beam thus relies completely on the precisely measured nuclear polarization of the atomic beam in the Breit-Rabi polarimeter. Besides polarized protons $\vec{p}$, also polarized deuterons $\vec{d}$, polarized $^3\overrightarrow{\text{He}}$ (helions h), and possibly heavier nuclei such as $^3\overrightarrow{\text{Li}}$ are envisioned to be used in the EIC. As one of the scientific pillars of the project [2], besides luminosity and collision energy, we emphasize here again that the EIC shall provide proton beam polarizations of more than 70% with a relative uncertainty of 1% or less. To provide absolute beam polarization calibration, the procedure described above will have to be applied for each ion beam species.

1. Calculations/theoretical estimates of all relevant polarization observables in the CNI region should be performed for:

(a) $\vec{p}\vec{p}$ elastic scattering,

(b) $^3\overrightarrow{\mathrm{He}} - {}^3\overrightarrow{\mathrm{He}}$ elastic scattering,

(c) $\vec{d}\vec{d}$ elastic scattering, and possibly at some later time,

(d) $^6\overrightarrow{\mathrm{Li}} - {}^6\overrightarrow{\mathrm{Li}}$ elastic scattering.

These estimates are required to optimize the detector systems for the different beam species and the for the specific spin dependencies of the different reactions.

2. The corresponding theoretical effort should be triggered. The lead time for these kind of theoretical studies is measured in years. Potential candidate theorists or groups willing to make a long-term commitment for the subject should be identified, and the investigations should start right away.

The worrying problem behind points 1 (b), (c), and (d) in particular is that the estimated timescales for the development of the corresponding beams and polarimeters are about 5 to 10 yr. In the case of the $^3\overrightarrow{\mathrm{He}}^{++}$ beam for instance, the source development alone took rather 10 yr time, and work hasn't even started on the absolute polarimetry in the AGS and the HSR. For point 1 (a), the technologies are known in principle, but the groups that once had the required expertise no longer exist. In addition, providing 70% beam polarization with 1% absolute error for the EIC requires more and better instruments, also in the AGS, because the polarization transmission in the accelerator chain should be optimized during the time when EIC is built. The opportunity to use this time window at the AGS for testing and commissioning should not be missed.

Decision have to be made how to proceed and on which systems to focus on. Thus we need to develop a list of priorities and a battle plan. Not every item can be worked on in parallel. But without a significant increase in the number of individuals being trained and working on these issues, there is the imminent danger that what little expertise is still accessible in the international environment will also soon retire. The situation is critical and will have a devastating effect on the achievement of the EIC's objectives if we do not intervene to reverse the trend.

1.1.1 Proton beams

On a timescale of about one year, after the completion of RHIC operations (FY25), the HJET needs to undergo a major refurbishment. The plan for this involves the following steps:

1. After run 25 (late fall 2025), bring source from IP12 to Bldg. 510 and refurbish HJET to enable absolute beam polarimetry at EIC. Items that need to be addressed are:

   (a) Replace all turbo pumps.

   (b) Recable slow control system and build interface to experimental slow control system EPICS.

   (c) Make room for a quadrupole mass spectrometer at the Breit-Rabi polarimeter.

   (d) To allow remote switching of source operation from $\vec{\mathrm{H}}$ and $\vec{\mathrm{D}}$ beam and vice versa *without* hardware changes, source shall be equipped with dual-function RF transition units for $\vec{\mathrm{H}}$ and $\vec{\mathrm{D}}$ (while system is mounted in the high bay at Bldg. 510).

   (e) Another aspect of modifications at the HJET concerns an upgrade of the emittance measurement capability via residual gas fluorescence [5; 6] to also allow for the emittance measurement in the horizontal plane.

   (f) Reinstall HJET at IP4 in 2029.

2. Design and construct a similar HJET for AGS for absolute polarization measurement and 3D reconstruction of the beam spin vector. To this end, a FOA has been submitted to DOE, see [7], which is presently still pending.

   (a) Due to space restrictions at AGS, the RHIC HJET design can't be used as is and the configuration of the sextupole magnet system needs to be reassessed and optimized to match the needs at the new location.

   (b) Also the ABS for AGS should provide $\vec{\mathrm{H}}$ or $\vec{\mathrm{D}}$ atomic beams upon remote switching (see item 1d above).

   (c) Revisit the atom tracking codes (see also Sec. 2) that was used to design the magnetic focusing system of the HJET [8]:

      i. Considered to be a major effort. The knowledge how to design magnetic focusing systems based on permanent magnets is not readily available anymore. The design of such systems [9] should be revisited and potential improvements should be incorporated, as it was done for the HJET.

      ii. The expertise should be built up again and should be maintained for years to come. Tracking codes should be published and competently maintained to serve polarization technology for the EIC physics in the future.

      iii. AI and machine learning tools and methods could be used to fully simulate and optimize polarized sources from discharge to target region and polarimeter, for the benefit of nuclear physics at EIC. State-of the-art molecular flow simulators can be adopted to include magnetic focusing and beam attenuation from the deflected/recombined atoms, as discussed, e.g., in [10]. Such an approach can be applied to all atomic beam sources that are eventually required at the EIC, $\vec{\mathrm{H}}$, $\vec{\mathrm{D}}$, and $^3\overrightarrow{\mathrm{He}}$.

3. Upgrades of the detector systems of the hadron beam polarimeters are suggested to fully exploit the spin dependence. The $\left(\vec{\frac{1}{2}}\right) + \left(\vec{\frac{1}{2}}\right)$ case exhibits angular distributions of the outgoing elastically scattered particles where the azimuthal angles are modulated with, e.g, $\sin\phi$ and $\sin(2\phi)$ [11]. The polarimeter detector systems should make it possible to detect these modulations, as this will extend the capabilities of polarimetry towards the determination of the complete 3D beam spin vector (see Sec. 1.2).

   Other combinations of spins of the particles in the initial state, such as $\left(\vec{\frac{1}{2}}\right) + \left(\vec{1}\right)$ in $\vec{p}\vec{d}$ scattering are not part of the baseline of the EIC project. Since the lead time is long, we should anticipate that such polarization measurements will be needed in later phases of the EIC physics program and address the associated polarimetry issues early on.' The spin-spin and spin-tensor correlation parameters in $\vec{p}\vec{d}$ elastic scattering, e.g., exhibit azimuthal modulations that involve in addition $\sin(3\phi)$ terms (see Eqs. (6, 7) of [12]).

1.1.2 Deuteron beams

The polarized hydrogen jet target (HJET) can be readily converted into a deuterium atomic beam source, a DJET. For polarized deuteron beams at HSR and AGS, the measurement of the full 3D spin vector can be envisioned as well (see Sec. 1.2).

1. Although the magnetic moment of the deuteron is small ($G = -0.1426$) and would usually prevent having longitudinal beam polarization in the HSR, it has been shown recently

that imperfection spin resonances in HSR can be overcome using the Siberian snakes and the detector solenoids operated as partial snakes [13]. This has the advantage of ensuring longitudinal polarization at $|G\gamma| = 3 \times$ integer, together with vertical orbit bumps.

2. Develop a system of rf transition units for D atoms for the injection of hyperfine states into the target region.
   (a) Most efficient would be the design of a versatile system of rf transition units that can provides both sets of rf transitions for H and D beams, so that in going from one beam species to the other a mechanical exchange of the transition units is not required anymore (see item 1d on page 3). This is not only simpler, but would also enable a more flexible switch from one type of atomic beam to another *during* runs.

3. Absolute polarimetry for polarized deuteron beam will require a polarimeter that detects $\vec{d}\vec{d}$ elastic scattering. Like in the $\vec{p}\vec{p}$ case, use will be made of the polarization of the deuterium jet target determined in the BRP and translated into an absolute measurement of the deuteron beam polarization in the HSR through a measurement of the corresponding asymmetries for the $(\vec{1}) + (\vec{1})$ scattering in a suitable detector system.
   (a) The detector system needs to identify *dd* elastic scattering making use of the forward tagger to veto unwanted deuteron breakup reactions in both the beam and the target deuteron. As already mentioned earlier (item 3, page 4), the spin dependence becomes increasingly more complex with higher spins of the colliding particles in the initial state. $\vec{d}\vec{d}$ elastic scattering involves 8 analyzing powers and 32 spin correlation parameters (see Sec. 14.3 of [14]), and the asymmetries include terms with $\sin(4\phi)$.

4. The holding field scheme at the target has to be adopted for deuterons as well. In addition, as vector and tensor components in the atomic jet target will be present, the Breit-Rabi polarimeter (BRP) scheme has to be revisited, as in the case of D, background will not only stem from polarized gas, but also from unwanted polarization components in the DJET.
   (a) A quadrupole mass analyzer should be inserted on the atomic beam as part of the BRP. In addition, a pit below the HJET should be provided at IP4 to allow for better access to the lower chambers of the source as is presently possible at IP12.

5. Build a deuteron ion source for EIC
   (a) The HJET, modified for $\vec{\mathrm{D}}$ atoms can be used also to build a versatile deuteron ion source. A suitable ECR ionizer will be needed to inject the beam into the accelerator chain before the RFQ at EBIS.
   (b) A low energy polarimeter for $\vec{d}$C scattering needs to be implemented at EBIS to determine the beam polarization before injection into the booster ring.

1.1.3 ^{3}He ($\vec{h}$) beams

In order to accomplish absolute beam polarimetry for helions, similar to what has been achieved for proton beams at RHIC, a $^3\overrightarrow{\mathrm{He}}$ atomic beam source is needed at the AGS and at the HSR. Such a source can be built for EIC on the basis of the neutral $^3\overrightarrow{\mathrm{He}}$ atomic beam source developed at MIT-Bates.

The initial concept is described in [15][1]. The ABS beam has a temperature around 1 K and produces a flux of $\approx 10^{14}$ atoms/s. The beam polarization is of the order of $\approx 99.5\%$. The source uses a 1 m long quadrupole magnet as a polarizer. The present ABS has gone through major upgrades including cryogenic component re-engineering to improve the angular focus and to steer the beam. The device shall be further optimized to serve as an internal jet target for absolute $^3\overrightarrow{\mathrm{He}}^{++}$ beam polarimetry based on $\vec{h}\vec{h}$ elastic scattering.

1. A target for absolute $^3\overrightarrow{\mathrm{He}}$ polarimetry should be developed and tested in the AGS first, as after run 25, there will be no further opportunities to test anything at RHIC until its reincarnation as HSR after 2032.

2. Once the above is accomplished, the $^3\overrightarrow{\mathrm{He}}$ target should be duplicated for the EIC, where a 2 m long section is foreseen at IP4 between the CNI polarimeter and the HJET (see Fig. 1).

3. Relative beam polarimetry at AGS and EIC can be established with the existing carbon polarimetry infrastructure, potentially also making use of the forward tagger system to discriminate ^{3}He breakup products with a polarized $^3\mathrm{He}^{++}$ beam to detect primarily $\vec{h}$C scattering [16].

1.1.4 ^{6}Li beams

Spin-1 ^{6}Li nuclei have a similar magnetic moment as deuterons. The benefit of $^6\overrightarrow{\mathrm{Li}}$ for the EIC physics program is that it provides spin-1 particles with different nuclear binding than deuterons. The magnetic moment of ^{6}Li, $\mu(^6\mathrm{Li}) = 0.8220454(25)\mu_N$, is comparable to that of the deuteron, $\mu(d) = 0.879\mu_N$, so that overcoming depolarization resonances in AGS and HSR for ^{6}Li and $\vec{d}$ beams should be pretty similar [13].

1.2 3D beam polarimetry: complete determination of $\vec{p} = (p_x, p_y, p_z)$

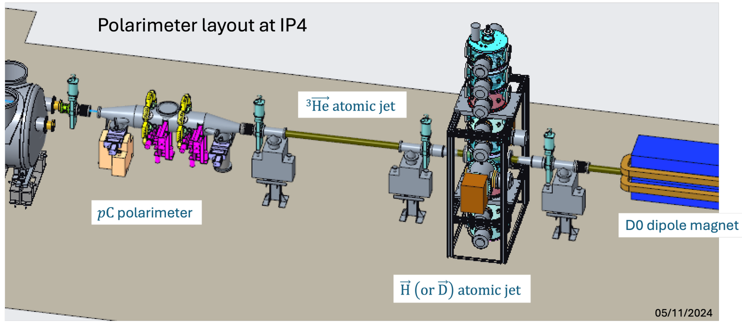
Absolute beam polarimetry presently relies on the determination of the vertical beam polarization component p_y. The full information about the 3D beam polarization spin vector, i.e., in addition p_x and p_z is not reconstructed because the information from the *pp* elastic scattering is only partially digested with the current detector system [11; 17]. At the beginning of 2024, we submitted an LDRD-B application on exactly this topic [18], but unfortunately the project was not considered worthy of funding by the laboratory superiors at the BNL.

1. Exploiting the full *pp* spin dependence requires detector simulations and a detector upgrade, plus a holding field upgrade at the HJET at the future IP4 to enable weak magnetic holding field orientations along arbitrary directions $\vec{B} = (\vec{B}_x, \vec{B}_y, \vec{B}_z)$, as shown in [11].

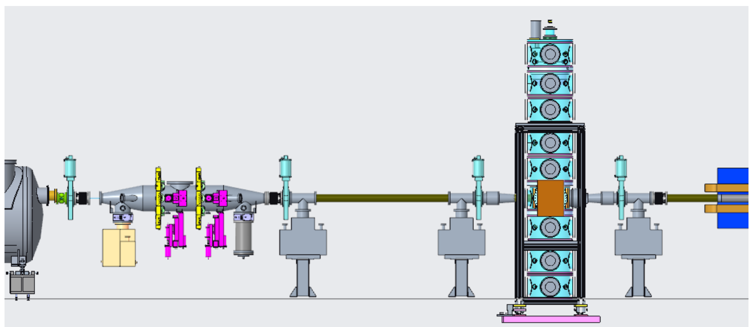
2. Going beyond the $\vec{p}\vec{p}$ case, realistic simulations will require theoretical estimates of the polarization observables in the CNI region for $^3\overrightarrow{\mathrm{He}}$-$^3\overrightarrow{\mathrm{He}}$ and $\vec{d}\vec{d}$ elastic scattering. For d beams, 3D polarimetry shall also enable the determination of the vector and tensor polarization components. The related theoretical effort should be started immediately as the lead time is long.

[1] see also https://bateslab.mit.edu/projects/nedm

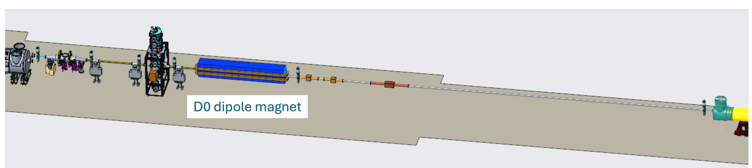
[2] CAD drawings were kindly provided by Eric Link (elink@bnl.gov).



(a) pC, ^{3}He and HJET/DJET polarimeter.



(b) Side view, as shown in panel (a).



(c) Full view of the polarimeter section. At the end of the magnet-free drift region behind the D0 magnet, the tagging system will be installed to allow for vetoing of unwanted breakup ejectiles.

Figure 1: Setup of the beam polarimeters in IP4[2]. The beam moves to the right.

2 Simulation tools

Simulation tools are widely used in many areas of research and development, but in the field of polarization technology in spin physics, standard simulation tools are rather an exception.

1. Simulation tools for polarized sources and targets.
   (a) It can be clearly stated that the knowledge how to simulate and optimize the design of a modern polarized atomic beam sources is almost lost.
   (b) Polarization physics would benefit greatly from the ability to simulate complete source systems, including the scattering of residual gas in the vacuum system [10]. It should be emphasized that to date we have not understood why the RHIC HJET delivers about $\approx 20\%$ more beam than predicted by the atomic spin tracking developed and applied by its designers [8].
2. Spin tracking programs for charged particles.

(a) The relatively small spin tracking and spin dynamics community worldwide would greatly benefit from having a few well-supported simulation tools at their disposal.

(b) Similar to the role GEANT plays for the design of complex detector systems, there should be a preferred framework for spin tracking in accelerator physics.

(c) Over the years, I have seen many students struggle with the use of spin tracking codes (e.g., BMAD and COSY-Infinity, etc.), it often took them more than half a year to be productive. Improved user interfaces might help to make the learning curve steeper.

3 How to improve the situation of polarization technology

We need to have a broad discussion about how the tasks described above can be approached and how the field of polarization technology can be rejuvenated to make EIC a success. In this respect, funding is one issue, next to recruiting the talents and securing their long-term commitment.

Some items for discussion:

1. Improving the general visibility of polarization as one of the most important topics within the EIC project is necessary. Without addressing the acute challenges in polarization technology, the EIC will not be able to fulfill its mission. At present, the subject of polarization technology and polarimetry is somewhat hidden and barely visible in the organization chart.

2. The EIC project management schedule seems to be the wrong place to accommodate activities that go beyond the HJET and CNI polarimeters as they are currently operated at RHIC. However, to achieve the ambitious goals of the EIC, namely a high polarization in the HSR of 70% with low systematic uncertainties of 1%, aconsiderable increase in resources should already be targeted now, which should flow into the training and further education of the future EIC group of polarization experts who will then run the show.

3. The future of spin physics with $\vec{d}$ and $^3\overrightarrow{\mathrm{He}}^{++}$ beams will no longer even be an option if we wait a few more years to get our act together. By then, even the few experts still active on the international stage will have retired. The scale at which young talent is needed to achieve anything beyond polarized proton beams at EIC is frighteningly large and the timescales are long compared to the anticipated lifetime of the EIC itself.

4. Funding and support for AGS operations should be made available specifically for the development of polarization technology while the EIC is being built, but outside of the EIC project itself.

   (a) Implementing an HJET/DJET system at AGS will lead to a significant reduction of unwanted polarization components in the beam that were previously inaccessible experimentally. By implementing the proposed system in the AGS *before* the EIC goes into operation for initial commissioning, the optimization of the polarization transmission in the AGS could be worked on and completed. This will allow routine experimental verification of the spin evolution in the ring.

   (b) Another benefit of the approach to use the AGS for the development of polarization technology while EIC is built will be that it could save a few months in the overall EIC commissioning effort and hence save significant costs. This would possibly also shorten the time to the first physics results with polarized beams from the EIC.

5. For the start, three scientists/engineers/postdocs and at least one or two doctoral students should be sought. They should work on the tasks listed below. It should be clear that this can only be the very beginning of forming a strong polarization group that shall be able to handle the future tasks:

Person #	**Tasks to be addressed**
1	**Simulation studies** (a) Develop an atomic beam tracking code i. Simulate and optimize polarized atomic beam sources from discharge to target and polarimeter, making use of state-of-the-art molecular flow simulators that include magnetic focusing and beam attenuation (see p. 4, 2(c)iii and p. 7, 1b). The approach is applicable to all types of atomic beam sources ($\vec{\mathrm{H}}$, $\vec{\mathrm{D}}$, and $^3\overrightarrow{\mathrm{He}}$) that will eventually be required at EIC, and may benefit from advances in AI and machine learning tools. ii. Once (i) above is accomplished, advances in permanent magnetic materials can be exploited to improve the sextupole and quadrupole magnet systems of modern sources. (b) Detector systems to provide absolute polarimetry of $\vec{\mathrm{H}}$, $\vec{\mathrm{D}}$ and $^3\overrightarrow{\mathrm{He}}$ targets i. Develop detector systems for $\vec{\mathrm{H}}$, $\vec{\mathrm{D}}$, and ^{3}He targets, including the required tagging capabilities to identify elastic recoils and veto unwanted breakup ejectiles for the polarimeter region at IP4 (see Fig. 1).
2	**Polarized $\vec{\mathrm{H}}$ and $\vec{\mathrm{D}}$ atomic beam sources** (a) Dual function RF transition units for $\vec{\mathrm{H}}$ and $\vec{\mathrm{D}}$ atoms. (b) Breit-Rabi polarimeter upgrade for RHIC and development for the AGS target. system should serve both $\vec{\mathrm{H}}$ and $\vec{\mathrm{D}}$ atomic beams. A quadrupole mass analyzer to achieve smaller systematic polarization errors should be integrated. (c) Design and construction of an internal HJET/DJET target for absolute $\vec{p}$ and $\vec{d}$ polarimetry at the AGS. (d) Upgrade of RHIC HJET in Bldg. 510.
3	**Polarized atomic beam sources for ^{3}He polarimetry** (a) Develop atomic ^{3}He jet target and jet atomic beam polarimeter for absolute beam polarimetry at the AGS. (b) Once the AGS system is fully commissioned and operational, the system should be duplicated and implemented at IP4 in the HSR.

6. Some more ideas how to find talent:

(a) Workshops should be organized and aspects of polarization technology should be presented at universities to reach and attract potential groups and students. We should also reach out to interested university groups internationally to work on the necessary hardware developments.

(b) We should actively combat the prejudice that physicists who deal with hardware do not do physics. In particular, we need to attract those students who are willing to solve hardware-related scientific questions and who are up to the challenge. Simply copying what was realized a quarter of a century ago seems completely unattractive to the kind of people we should be looking for. And why shouldn't students working on such questions get PhDs if they develop a new instrument for precision polarization measurements, for example?

(c) Personnel already working at the lab or other DOE labs could make important contributions to addressing the necessary hardware developments through education and training, i.e., reaching out to technicians and engineers and supporting them in their transition to becoming experts in some aspect of polarization technology.

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