PROCEEDINGS OF SCIENCE

AI-Optimized Polarization at Jefferson Lab

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The AI-Optimized Polarization project seeks to develop experimental control applications for polarized targets and beams at Jefferson Lab using AI/ML. This paper will focus on two ongoing efforts involving a cryogenic polarized target and a linearly-polarized photon beam. Firstly, cryogenic targets, such as those used in Halls B and C (and approved for Hall D), are complex systems that are sensitive to a number of factors, including the temperature, beam currents, and the microwave and NMR apparatus. Secondly, the Hall D photon beam polarization depends on the optimal orientation of a diamond radiator, which produces coherent bremsstrahlung radiation from the electron beam incident upon it. Manual operation of both systems is tedious and error prone; implementing well-designed, interpretable control systems that incorporate AI is expected to lead to improved real-time polarization. AI optimization of nuclear physics experiments will lead, not just to cost-savings, but also to more efficient and higher-quality data, and this project will help to lay the foundation for future autonomous experiments.

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1. Introduction

The optimization of polarized targets and beams is essential for advancing nuclear and particle physics research, particularly at Jefferson Lab (JLab), where precision experiments rely on these systems [1–3]. This work focuses on two critical applications: cryogenic polarized targets and a linearly polarized photon source. Dynamically polarized targets, employing proton and deuteron materials such as irradiated ammonia, are indispensable for probing nuclear spin structure. These systems, operating under extreme conditions of low temperature and high magnetic fields, have enabled numerous experimental programs at JLab, both during its 6 GeV era and the current 12 GeV upgrade. Similarly, the polarized photon source plays a pivotal role in the GlueX experiment, facilitating the study of exotic hybrid mesons and beam asymmetry analyses, along with a broader experimental program including the Charged Pion Polarizability [4] and Short Range Correlations [5] experiments.

Despite their importance, the operation of both polarized targets and photon sources requires continuous manual intervention by experts, leading to inefficiencies and variability in performance. For cryogenic targets, parameters such as microwave frequency must be periodically adjusted to maintain polarization, while for the photon source, the coherent peak position is manually aligned to ensure optimal polarization and photon statistics. These processes are time-intensive and prone to human error. Recent advancements in artificial intelligence (AI) and machine learning (ML) offer promising solutions to these challenges. By implementing robust, uncertainty-aware AI/ML systems, it is possible to automate these adjustments in real time, increasing stability, enhancing polarization, and significantly improving the statistical precision of experimental results.

Integrating AI/ML techniques into these systems not only addresses immediate operational challenges but also lays the groundwork for the broader application of autonomous control in nuclear and high-energy physics experiments. This effort complements existing AI-driven control systems, such as the AI for Experimental Controls (AIEC) initiative [6], and paves the way for future multi-system optimization frameworks. By reducing reliance on manual control and improving system performance, this work advances the pursuit of self-driven experimental setups that align with global physics objectives.

2. Polarized Photon Beam

The GlueX experiment at Jefferson Lab's Hall D is designed to study the nature of confinement in quantum chromodynamics (QCD), the theory of the strong interaction that binds quarks and gluons into hadrons. The goal is to search for and study exotic hybrid mesons that could provide insight into the role of gluons in the formation of hadronic matter. The GlueX detector is optimized to measure the production and decay of these exotic states with high precision, combining capabilities in particle identification, tracking, and calorimetry to reconstruct the complex final states resulting from photon-proton collisions [7].

In order to produce the photon beam needed to carry out this physics program, a thin diamond radiator is placed upstream of the GlueX detector as shown in Figure 1. The interaction of the electron beam with the crystal lattice of the radiator produces an enhancement of linearly polarized photons via coherent bremsstrahlung, which is strongly correlated with the beam's polarization.

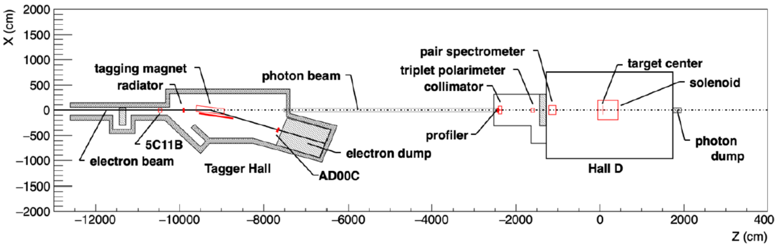

Figure 1: Schematic of the GlueX beamline, showing the positions of the diamond radiator, beam position monitors, collimator, detector, etc. Reproduced from [7].

Maintaining the stability of this peak is critical, as its position directly affects polarization quality and photon statistics, which are essential for precise measurements and robust data collection.

Currently, manual adjustments are made at the beginning of each experimental run to align the coherent peak within 10 MeV of its nominal position. These adjustments involve tuning the goniometer that controls the diamond's orientation, based on electron and photon beam parameters such as energy and position. However, beam fluctuations during data-taking can cause the peak to drift, leading to smearing of the polarization enhancement and reducing the figure of merit (FOM) for GlueX and other experiments. This drift not only diminishes polarization but also forces stricter energy cuts that limit usable data and increase systematic uncertainties in measurements.

To address these challenges, an AI-driven control system is proposed to dynamically and continuously tune the coherent peak in real time. Leveraging beam data from the MYA EPICS archive, the system will automate goniometer adjustments to maintain the peak's position within the optimal range. By preventing peak smearing, this system will ensure higher polarization stability, increase photon statistics, and enhance the overall FOM of Hall D experiments. Additionally, improved control of the goniometer will reduce systematic uncertainties in polarization measurements obtained through triplet polarimetry, directly benefiting GlueX and other Hall D programs.

3. Cryogenic Polarized Targets

Polarized target systems at Jefferson Lab are essential for probing nuclear spin structures and advancing nuclear physics research. These systems employ dynamically polarized proton and deuteron targets, typically made from irradiated solid ammonia (NH_3) or deuterated ammonia (ND_3). Prepared through irradiation and cryogenic storage, these materials achieve high nuclear polarization—up to 90% for protons and 40% for deuterons—under ultra-low temperatures (1 K) and strong magnetic fields (5 T). Polarization is induced using microwave-driven spin transitions, with frequent annealing at elevated temperatures (80–100 K) to mitigate beam-induced damage to the target material. The intricate interplay of factors, including beam current, temperature, and microwave frequency, governs the performance of these systems.

Maintaining optimal polarization during experiments presents significant challenges. The beam creates additional radicals in the material, reducing polarization over time. Periodic adjustments to the microwave frequency are required to compensate for these effects, along with annealing to restore the target material's properties. Currently, these adjustments are performed manually by

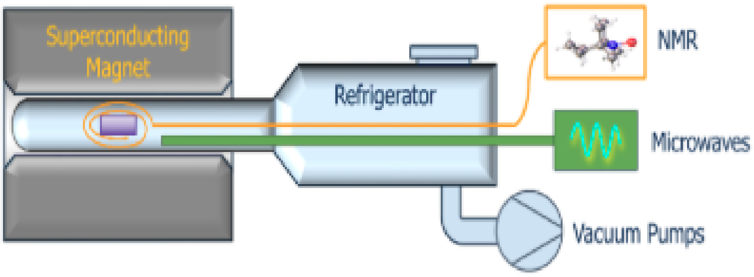

Figure 2: Schematic of the cryogenic target system, showing the superconducting magnet, refrigeration system, NMR, microwave source, and vacuum pumps.

trained operators, whose expertise and experience heavily influence the stability and efficiency of the polarization process. However, this approach introduces inconsistencies and delays, potentially compromising the experimental FOM, which scales with the square of the polarization.

Advancements in artificial intelligence (AI) and machine learning (ML) provide an opportunity to revolutionize the operation of these systems. By leveraging historical data streams from past experiments, AI/ML techniques can automate the dynamic adjustments of microwave frequency and other critical parameters. This automation would reduce reliance on human intervention, minimize errors, and improve polarization stability. The enhanced precision in polarization measurement and control not only accelerates data collection but also contributes to higher-quality experimental outcomes by increasing the effective FOM. These developments represent a significant step toward self-driven experimental setups, advancing the broader goals of nuclear physics research.

4. AI/ML for Experimental Control

Using state-of-the-art AI/ML techniques, we can seek to improve upon the error-prone manual operation of nuclear physics experiments, thereby increasing the efficiency and quality of data collection. Reinforcement learning (RL) is a machine learning paradigm in which an agent learns to make decisions by interacting with an environment to maximize a reward signal. Unlike supervised learning, which relies on labeled data, RL involves trial-and-error exploration to develop a policy that maps states to actions, optimizing cumulative rewards over time. The agent observes the state of the environment, selects an action, and receives feedback in the form of rewards, which guide its learning process. This approach is particularly well-suited for dynamic and uncertain systems, making it valuable for experimental control in fields like physics. Here, RL can autonomously optimize the experimental parameters to achieve specific objectives.

One of the challenges in applying RL to experimental control is that real-world experiments can be slow, expensive, and data-limited. To address this, Gaussian Processes (GPs) can be employed as surrogate models within the RL framework. GPs are probabilistic, non-parametric models that estimate unknown functions based on observed data. They provide not only predictions, but also uncertainty estimates, which make them ideal for guiding exploration in environments where data collection is costly. In experimental setups, a GP can approximate the dynamics of the environment

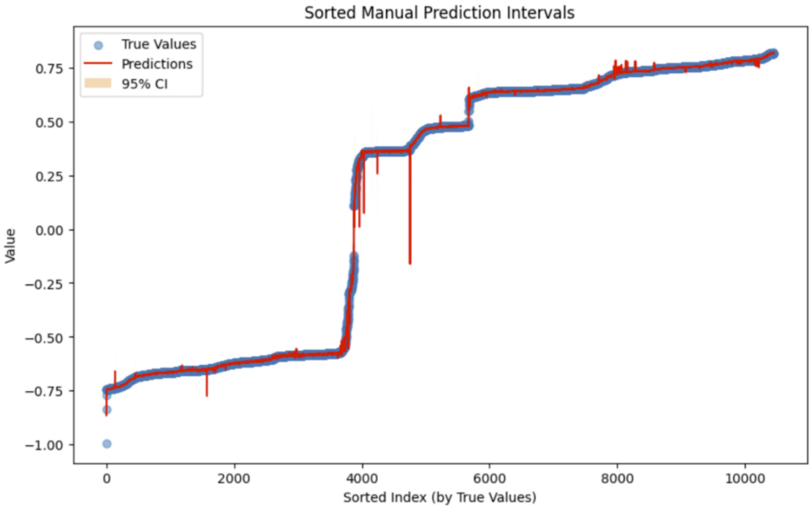

Figure 3: Predictions of the Gaussian Process trained on polarized target data match the polarization values from data.

or the reward function, enabling the RL agent to simulate outcomes and make decisions without requiring physical interaction with the system. This significantly improves the efficiency of learning by reducing the reliance on direct experimentation.

In order to train our surrogate models of the polarized source and polarized target systems, we used historical data from the GlueX EPICS archive and the CLAS12 Run Group C archives, respectively. The input features for the target data were the solenoid current, electron beam current, target temperature, target dose, microwave frequency, calibration constants, NMR signal and background means and standard deviations. The input features for the polarized source were the diamond lattice angle. The results show good predictability of the polarization and increase confidence in using Gaussian Processes as surrogate models for training RL agents.

5. Conclusion

The integration of AI and ML techniques into the control systems of polarized targets and photon sources represents a transformative advancement in experimental nuclear physics. These technologies address longstanding challenges associated with the manual operation of these systems, including inefficiencies, variability, and the potential for human error. For cryogenic polarized targets, AI-driven automation promises to dynamically optimize microwave frequencies and improve polarization stability, enhancing the overall figure of merit (FOM) and the quality of experimental outcomes. Similarly, for the polarized photon source in Hall D, real-time tuning of the coherent peak ensures higher polarization and photon statistics, directly benefiting critical programs such as GlueX.

By leveraging reinforcement learning and Gaussian Processes, this approach enables autonomous optimization of experimental parameters with reduced reliance on costly and time-intensive trial-and-error experimentation. The successful application of surrogate models trained on historical data from the GlueX EPICS and CLAS12 archives demonstrates the viability of this framework for improving system performance in dynamic and complex environments. These advancements lay the groundwork for the broader application of AI/ML in experimental physics, moving toward self-driven experimental setups capable of achieving global physics objectives.

Future work will focus on extending these methods to additional experimental systems, integrating multiple AI-driven subsystems under a unified optimization framework. By reducing operational complexity and improving data collection efficiency, this work represents a critical step toward achieving fully autonomous experimental facilities in nuclear and particle physics.

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