AI-Optimized Polarization at Jefferson Lab

Patrick Moran, The College of William & Mary

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Instituto Superiore di Sanità, Roma, Italia

Introduction

Motivation

Polarized sources and targets are complex, dynamical systems.

Experiments at Jefferson Lab rely on human operators to control and optimize the performance of these systems.

Can AI/ML control exceed the performance of human operators?

Potential benefits both in terms of improved statistics and cost savings.

AI-Optimized Polarization (AIOP)

AIOP is a 2-year, DOE-funded project that began in March 2024.

An initiative of the Experimental Physics Software and Computing Infrastructure (ESPCI) group at Jefferson Lab.

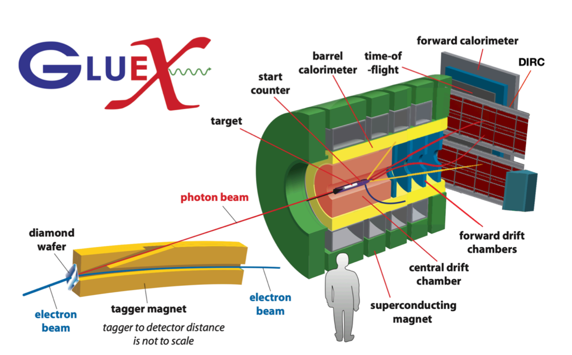
Consists of two sub-projects:

1. Polarized Photon Beam;
2. Polarized Cryogenic Target.

Polarized Beam at GlueX

The GlueX Experiment at Hall D

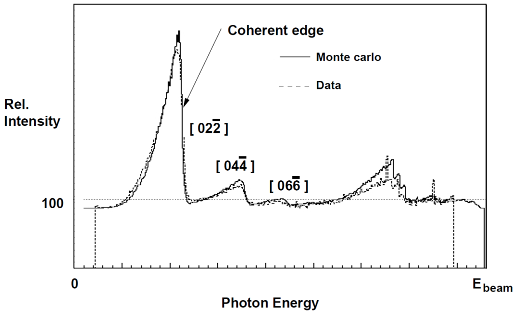
GlueX uses a polarized photon beam to search for and measure exotic hybrid mesons predicted from lattice QCD.

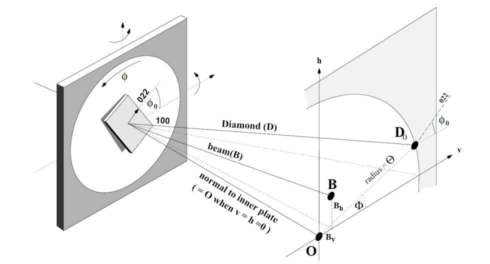


GlueX Photon Beam

The interaction of the CEBAF electron beam with a thin ($\sim 50\mu m$) diamond radiator produces a polarized photon beam via coherent bremsstrahlung radiation.

The position of the primary peak (E_γ) is determined by the orientation of the diamond and the position of the beam on the crystal.



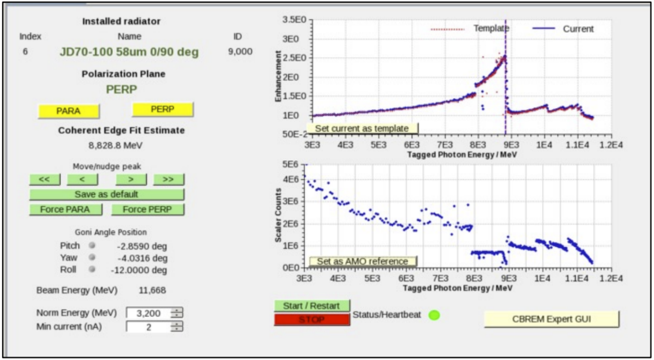


The diamond is mounted on a goniometer which can be rotated with respect to the x, y, and z axes o the lab frame (called pitch, yaw, and roll angles, respectively).

The **roll** angle determines the polarization plane and is held constant.

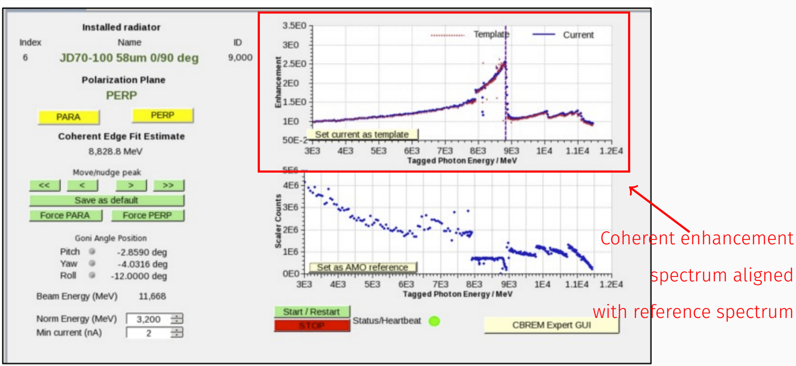
The **pitch** and **yaw** angles determine the location o the coherent bremsstrahlung peak and, if necessary, are adjusted at the start of a run.

Goniometer Control GUI



The Hall D polarized photon source control GUI.

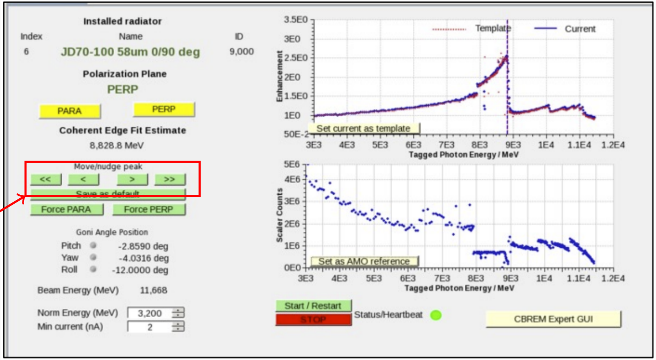
Goniometer Control GUI



The Hall D polarized photon source control GUI.

Goniometer Control GUI

Buttons to nudge spectrum left or right

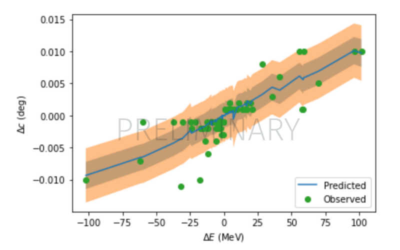


The Hall D polarized photon source control GUI.

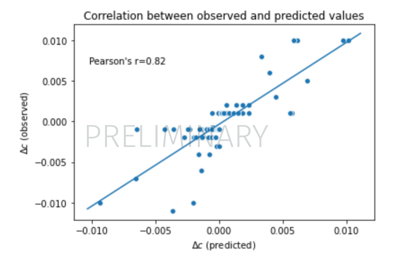
Gaussian Process Regression

Can we train a surrogate model on existing GlueX data to learn the complex dynamics affecting the polarization?

Gaussian Process Regression is a flexible, non-parametric approach to regression, which allows for uncertainty quantification in predictions.



A GP trained on the coherent edge positions and beam positions to predict the change in angle.



The observed vs. predicted values for the change in angle.

Polarized Target

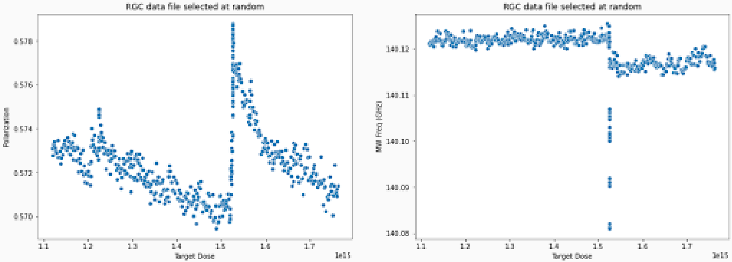
Dynamic Nuclear Polarization at Jefferson Lab

DNP has been used in Halls A-C at Jefferson Lab.

Most commonly-used materials are irradiated solid ammonia (NH_3) and deuterated ammonia (ND_3).

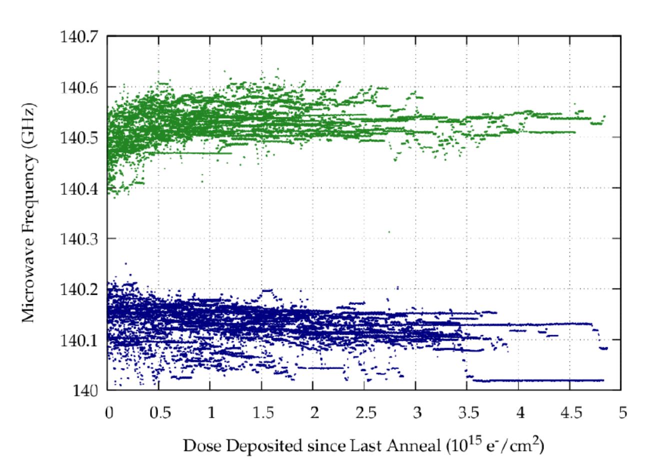
Polarized target operation requires constant monitoring and adjustment throughout data-taking.

Shift workers manually adjust the microwave frequency



Example increase in polarization (left) after operator decreased microwave frequency (right). The data was taken from an experiment during Run Group C in Hall B.

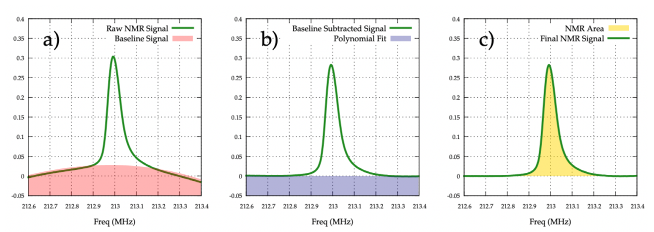
The optimal frequency is not straightforward to predict



Chosen microwave frequency versus beam dose since the last anneal in Hall C for positive (green) and negative (blue) polarization.

Measuring the Polarization

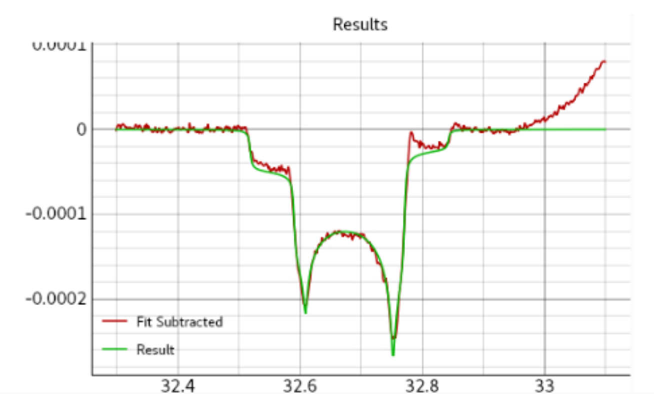
The target polarization is measured using continuous-wave NMR. Requires performing background subtraction.



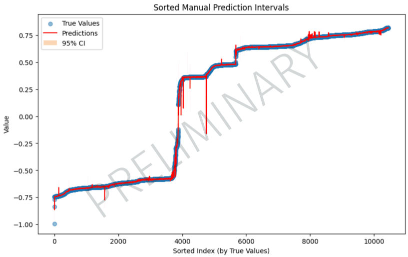
NMR signal extraction process for a polarized proton target. From left to right: background subtraction, residual subtraction, signal integration.

Measuring the Polarization

Extracting the polarization is even more difficult for deuteron which has a characteristic double NMR peak.

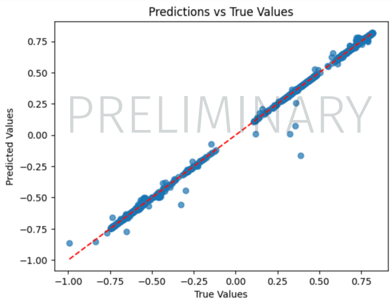


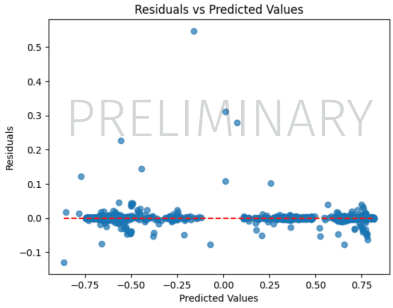
Gaussian Process Regression



Input Variables Used
Means and std. dev. of NMR curves
Target dose
Calibration constants
Microwave frequency
Target temperature
Solenoid current
Beam current

Gaussian Process Regression

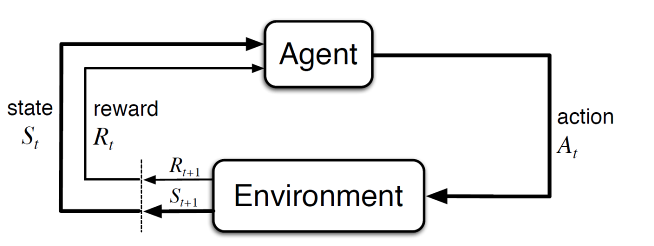




Reinforcement Learning

Reinforcement Learning is a machine learning paradigm where an agent learns to make decisions by taking actions in an environment to maximize cumulative rewards.

Can we use our surrogate models to define an environment for an RL agent to learn an optimal policy?



Work currently in progress.

Conclusion

Summary

AIOP seeks to optimize nuclear using AI/ML for experimental control.

Preliminary results shown using ML to learn a surrogate model for a polarized photon beam and polarized target.

Plan to integrate with the JLab experimental hall controls system in 2025-26.

Results could help lay the foundation for future autonomous experiments at other facilities (e.g. EIC).

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Collaborators

***David Lawrence, PhD** (physics)* — *PI*
Expertise: Physics, C++, software framework, online systems
Jefferson Lab

***Thomas Britton, PhD** (physics)* — *Co-PI*
Expertise: Physics, software, OSG, AI DQM
Jefferson Lab

***Torri Jeske, PhD** (physics)*
Expertise: Experimental Nuclear Physics, Data Analysis, Detector Calibration
Jefferson Lab

Armen Kasparian, MS (CpE)
Expertise: Data Science, Reinforcement Learning
Jefferson Lab

***Malachi Schram, PhD** (physics)*
Expertise: Data Science Dept. Head
Jefferson Lab

***Hovanes Egyian, PhD** (physics)* — **consulting*
Expertise: Physics, Polarized Photon Source
Jefferson Lab

***Naomi Jarvis, PhD** (physics)* — *Co-PI* **consulting*
Expertise: Physics, Detectors, Calibration
Carnegie Mellon University

Jiawei Guo, Grad. Student CMU
Carnegie Mellon University

***Cristiano Fanelli, PhD** (physics)* — *Co-PI*
Expertise: Faculty - Physics, Data Science
William & Mary

***Patrick Moran, PhD** (physics)*
Expertise: Postdoc - Physics, Data Science
William & Mary

***James Maxwell, PhD** (physics)* — **consulting*
Expertise: Polarized Cryotargets
Jefferson Lab

***Chris Keith, PhD** (physics)* — **consulting*
Expertise: Target Group Lead
Jefferson Lab

Questions?

References i

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Backup Slides

Effect of Diamond Thickness

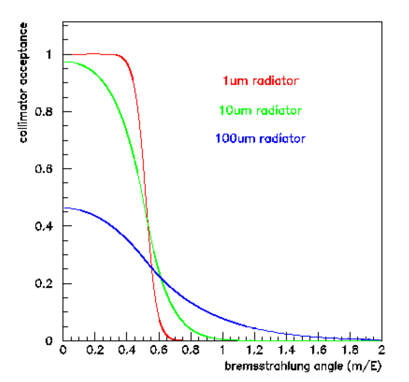

Figure 1: The collimation acceptance vs. bremsstrahlung angle for three different diamond radiator thicknesses.

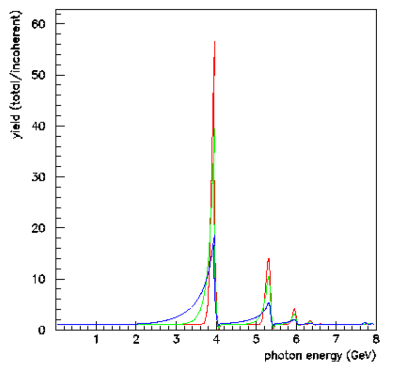

Figure 2: The coherent enhancement spectrum after collimation for three diamond radiator thicknesses.

Crystal Coordinate System

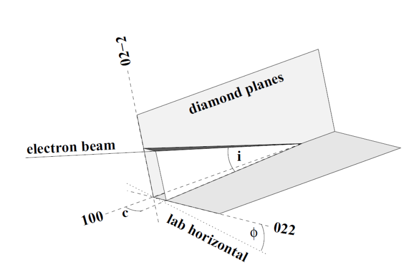

Figure 3: Angles in the diamond reference frame. Reproduced from K. Livingston (2009) in NIM A.

$$c \approx \frac{k}{gE_0\left[\frac{1}{E_c} - \frac{1}{E_0}\right]}$$

with k,g constant.

- Adjusting the angle c adjusts the coherent edge position E_c.
- ϕ determines the orientation of the polarization. ϕ = 0° or 90° for PARA/PERP orientation of polarization.