PROCEEDINGS OF SCIENCE

SpinQuest Polarized Target System

Vibodha Bandara[a,*] **and Dustin Keller**[b]

[a] *University of Colombo, Sri Lanka*
[b] *University of Virginia*

E-mail: vibodha@iat.cmb.ac.lk, dustin@virginia.edu

The SpinQuest experiment at Fermilab uses a solid-state polarized ammonia target held at a magnetic field of 5 T, immersed in liquid helium-4, which is held at approximately 1K by the evaporation refrigerator. The refrigerator provides the required cooling power during the dynamic nuclear polarization (DNP) process and the high intensity interaction with the 120 GeV proton beam from the Fermilab main injector. The refrigerator was designed in compliance with the American Society of Mechanical Engineers (ASME) to operate safely at Fermilab. The high pumping capacity ($17,000\ m^3/h$) roots stack provides the required pumping speed during DNP production data taking and a custom-made radiation hard flow control valve regulates the refrigerator temperature during the thermal equilibrium calibration measurements. The frequency of the microwave generator, an Extended Interaction Oscillator (EIO), is automated to keep the maximum polarization while the (Nuclear Magnetic Resonance) NMR system continuously measures the polarization of the target material. In this talk, an overview of the SpinQuest polarized target system will be presented as well as a brief report of recent commissioning activities and target performance during the early production runs in 2024.

20th International Workshop on Polarized Source, Targets, and Polarimetry (PSTP2024)
22-27 September 2024
Jefferson Lab, Newport News, VA

*Speaker

https://pos.sissa.it/

PoS(PSTP2024)037

1. Overview of the polarized target setup

The SpinQuest experiment at Fermi National Accelerator Laboratory (Fermilab) is designed to study the spin structure of protons[1]. The experiment utilizes a 120 GeV proton beam from the main injector to interact with the solid polarized ammonia target[2], a crucial component of the experiment. The polarization of the target material is achieved through the Dynamic Nuclear Polarization (DNP) process[3], which requires the target materials to be at a low temperature (<1K) in a homogeneous 5T magnetic field. The output frequency of the microwave generator, the Extended Interaction Oscillator (EIO), is adjusted to sustain optimal polarization. Meanwhile, the Nuclear Magnetic Resonance (NMR) system continuously monitors and precisely measures the polarization of the target material. The He4 evaporation refrigerator, located on the central axis of the superconducting magnet, provides the necessary cooling power for the target materials during both the Dynamic Nuclear Polarization (DNP) process and the beam interaction. The upper section of the experimental hall, called the cryo platform, includes the liquefaction plant, root pumps, and essential electronics supporting the target system. Below, the superconducting magnet and the proton beam line reside in the area referred to as the target cave.

2. The superconducting magnet

The superconducting magnet manufactured by Oxford Instruments generates the 5T magnetic field required for the polarization of the target materials during the DNP process. The magnet is equipped with a 150-liter liquid helium dewar that provides LHe to the superconducting coils and, through a vacuum-insulated U-tube, to the evaporation refrigerator positioned at the magnet's central axis. The magnet coil is made from a superconducting wire containing $7\mu m$ NbTi filaments, arranged in hexagonal bundles and embedded within a copper matrix. The coils are then encased in a 316 stainless steel former and secured with epoxy to prevent any movement caused by the Lorentz force when the magnet is energized [4]. The liquid nitrogen shield minimizes the heat load into the liquid helium space. The helium boil-off from the magnet dewar is efficiently captured by the helium recovery compressor of the liquefaction plant through a pneumatic flow control valve. This valve, operating within a PID control loop, regulates the magnet dewar pressure to maintain it at the desired level. The liquid level of the magnet is determined using a supper conducting level probe installed in one of the magnet risers.

The magnet bore, through which the proton beam passes, has a 40 mm × 100 mm rectangular profile, precisely matching that of the upstream collimator as illustrated in figure1. During beam commissioning, the magnet coils were ramped up to 74.47 A using an Oxford Instruments MercuryiPS power supply.

3. The evaporation refrigerator

The refrigerator is located in the center axis of the super conducting magnet (figure 2). The estimated cooling power of the refrigerator is above 5W at 1 K. The three target cells of the target insert assembly are filled with the target materials and then placed in the liquid helium bath within the refrigerator nose.

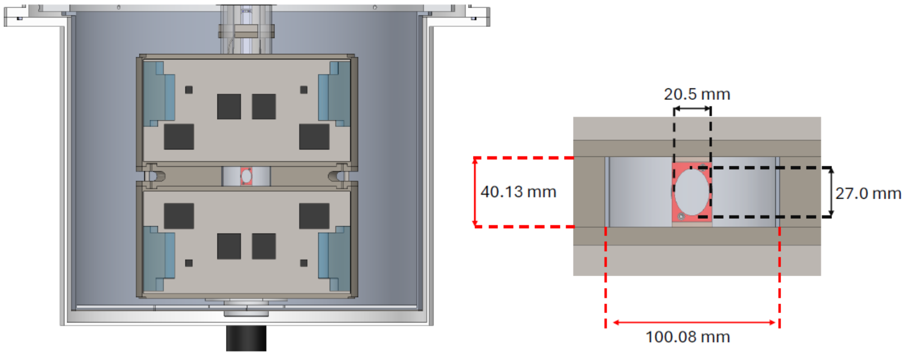


Figure 1: The magnet bore is 40mm x 100mm rectangle space and the proton beam passes through the center of the bore.

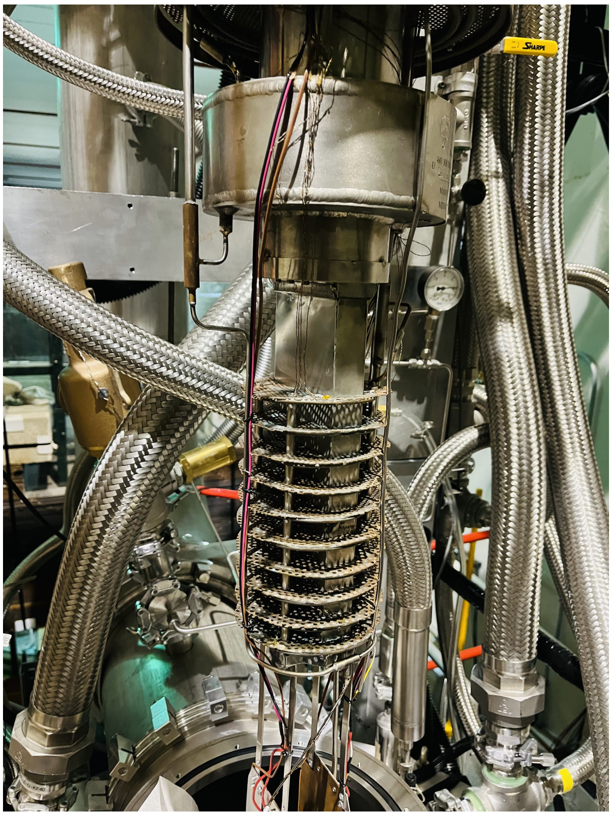


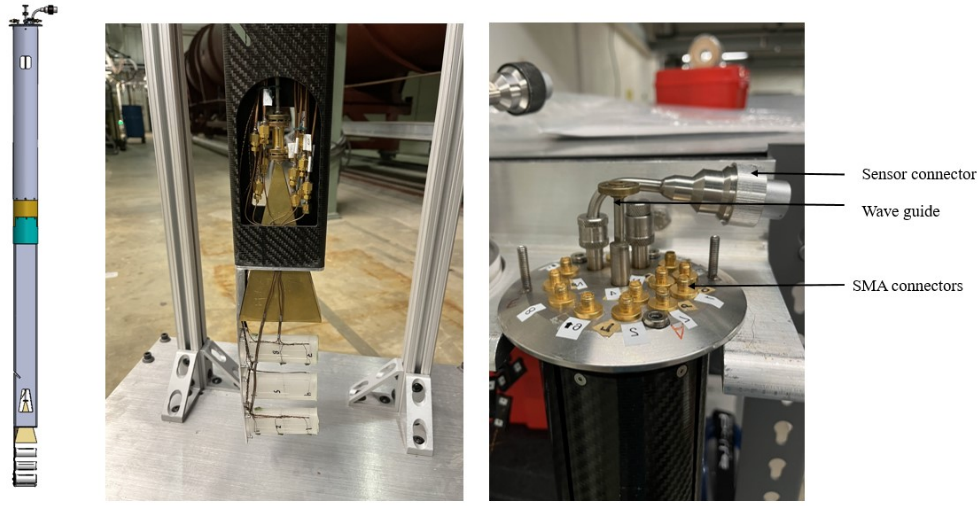
Figure 2: The figure shows the evaporation refrigerator before installing in the magnet. The liquid separator and the heat exchanger are clearly visible in the image.

Figure 3: The pumping stack consists of three roots blowers and one backing pump. The 12" inlet piping goes down to the target cave and connects to the refrigerator through a gate valve

The phase separator vessel of the refrigerator was ASME (American Society of Mechanical Engineers) stamped in accordance with the requirements of the Fermilab cryogenic safety committee. According to the ASME BPVC.VIII [5], the phase separator was treated as a separate pressure vessel. Liquid helium enters the phase separator from the magnet helium reservoir along a vacuum-isolated transfer line. The liquid within the separator can access the nose reservoir through two distinct paths: the run valve path and the bypass valve path. In the first route, the liquid traverses the heat exchanger before entering the fridge nose. In the second route, the liquid bypasses the heat exchanger, making its way directly to the fridge nose. In the normal operation, the liquid helium level in the nose is controlled by adjusting the opening of the run valve.

The roots pump stack efficiently pumps the liquid in the nose, consequently cooling it to nearly 1K[6]. The pump stack consists of two Oerlikon roots pumps, each with a capacity of $8400m^3/h$, connected in parallel. These are backed by an additional $8400m^3/h$ Oerlikon roots pump, and finally, a rotary vane pump with a capacity of $840m^3/h$ serves as the backing pump (figure 3). The total volumetric flow rate of the pump stack is $17,000m^3/h$. The 12" pipe from the roots inlet is connected to the refrigerator turret through a pneumatic On/Off gate valve.

Thermal equilibrium (TE) measurements between 1-3 K are extremely important in characterizing the calibration constants of the NMR[7]. Calibration constant at different TE temperatures will improve the absolute polarization measurements. However, achieving TE measurements at temperatures ranging from 1 to 3 K is not feasible with the current high-capacity roots pumping



(a) (b) (c)

Figure 4: (a) The target insert (b) The three target cells and the microwave horn (c) The top flange of the insert

setup. Despite opening the gate valve in conjunction with the backing pump, the resulting flow is excessive for TE measurements. Hence, a radiation-hard flow controller is needed to effectively govern the outlet flow from the refrigeration system. Furthermore, such a flow controller is essential for maintaining the liquid in the nose for a longer period (during non-beam duration).

A motorized actuator assembly has been designed for a 2” NPT ball valve, with the primary objective of controlling the valve’s opening by precisely rotating the valve shaft through motorized mechanisms. The installation of the valve involved bypassing the gate valve within the target cave.

4. The target insert and positioning

The target insert contains three cells filled with the target material (NH3/ND3) and placed in the refrigerator. Each cell, oval-shaped, 8 cm long, and made from Kel-F material, is designed to operate at low temperatures and withstand exposure to the proton beam. To ensure precise measurements, each cell has three NMR loops for polarization monitoring and three-chip resistors to map the microwave profile along its length. Cernox sensors are placed in both the top and bottom cells to measure the temperature of the target materials precisely. This accurate temperature monitoring plays a critical role in optimizing the annealing process. The insert has a total length of 64.5 inches, with the assembly’s body constructed from carbon fiber to minimize thermal conductivity. The top flange of the insert is a 4-inch sanitary blank flange, which contains SMA connectors for the NMR, a microwave waveguide connection, and connectors for the chip resistors and Cernox sensors. A gold-plated microwave horn is positioned just above the target cell assembly to emit microwaves to the cells (figure 4).

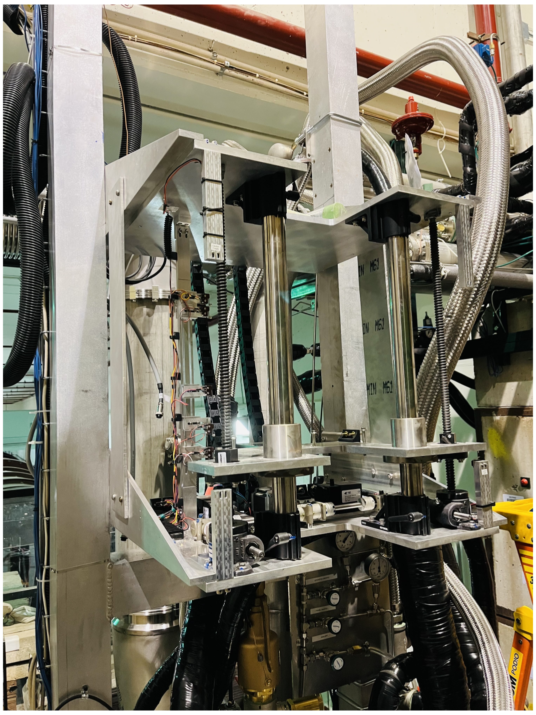


Figure 5: The target lifter system installed in the target cave

Each target cell aligns with the beam using the target lifter system, which is driven by a stepper motor and two ball screw jacks. The moving table is attached to an aluminum structure, referred to as the ladder, which securely clamps to the target insert (figure 5). The resolution of the target lifter is 0.005 mm, enabling precise fine movements that are essential for accurately aligning the target cells with the beam.

5. The microwave system

The thermal equilibrium polarization of the protons is enhanced by driving spin-flip transitions with microwave radiation, a process known as Dynamic Nuclear Polarization (DNP). The Extended Interaction Oscillator (EIO) generates microwaves at approximately 140 GHz.The EIO is located on the moving table of the target lifter setup. The output of the EIO is connected to a D-band three-port waveguide directional coupler with a 40 dB coupling level. The coupled port interfaces with an EIP frequency counter via a D-band harmonic mixer, facilitating real-time frequency measurement of the microwave signal. Downstream of the D-band waveguide bend, a D-to-V-band transition waveguide, followed by a 10 dB attenuator, is installed to attenuate the microwave power. A rectangular-to-circular waveguide converter is then connected, followed by a 16.5-inch-long circular waveguide leading to the target insert's microwave entry port (figure6). A 54.2-inch-long circular waveguide extends from the top of the target insert and is terminated with a gold-plated horn above the target cells. The output of the EIO is determined by the cathode voltage, and the frequency is fine-tuned by adjusting the size of its resonant cavity. The EIO is powered by a Varian VPW 2838A2 power supply and utilizes an external chiller to ensure optimal thermal stability. The tuning mechanism features a

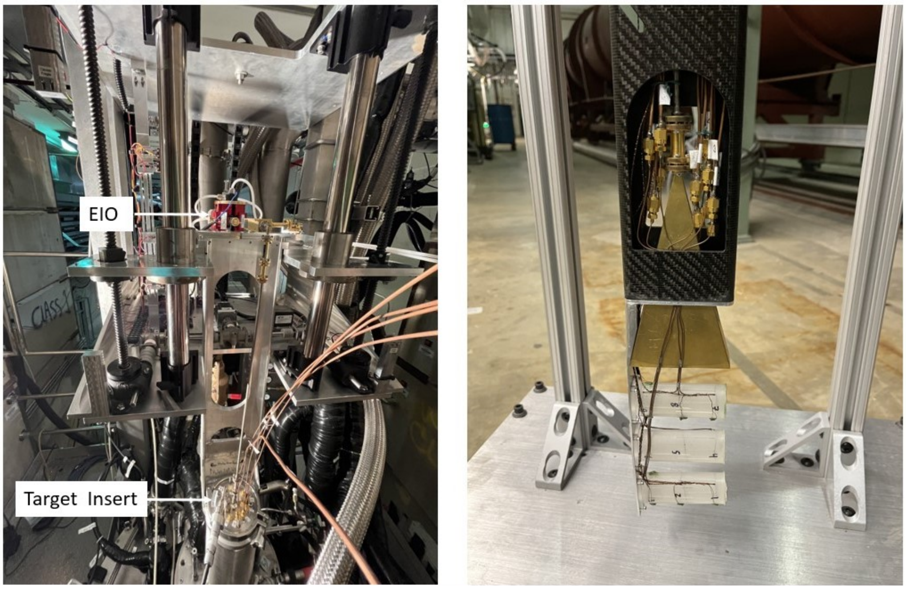


Figure 6: The left image illustrates the configuration of waveguides connecting the EIO to the target insert, while the right image shows the microwave horn installed in the target insert

high-resolution stepper motor coupled to the EIO's shaft, facilitating frequency adjustments with an exceptional precision of 0.001 GHz in full-step mode. An automation algorithm adjusts the output frequency to maintain maximum polarization, supporting both negative and positive polarization states.

6. NMR System

The experiment uses multiple Continuous Wave (CW) Nuclear Magnetic Resonance (NMR) systems to measure the polarization of the materials accurately. The NMR coils embedded within the target materials are connected to a tuned RF-resonant circuit called the Liverpool Q-meter[8]. This circuit generates a time-varying magnetic field perpendicular to the static magnetic field by applying a radio frequency (RF) signal at the Larmor frequency. The Larmor frequency depends on the type of nucleus and the strength of the external magnetic field. Under a 5T external magnetic field, the Larmor frequency is 213 MHz for protons and 32.7 MHz for deuterons. Then the polarization is computed from the output of the Q-meter. The UVA standard NMR system incorporates three Q-meters, each interfacing with one of the NMR coils embedded in the target cells. The UVA AI-based NMR system enhances this capability with an advanced software interface, leveraging artificial intelligence to optimize the determination of the area under the Q-curve, thereby increasing the accuracy of the results. In the UVA Cold NMR system, the tuning circuitry is seamlessly integrated with the target materials, effectively eliminating the cable length between the NMR loop and the tuner. This integration significantly enhances the signal-to-noise ratio, improving the overall sensitivity and performance of the system. Finally, the LNAL NMR system is a VME-based, compact NMR setup that features a remote tuning capability [9].

Figure 7: The operational relief valve of the magnet, the parallel plate valve is located at the outside of the experimental hall

7. The safety and integrity of the target system

The nominal working pressure of the magnet helium space is approximately 1 psig during regular operations. However, during the LHe filling process, the magnet pressure rises to nearly 5 psig. A 5-psig parallel plate relief valve has been installed in the helium return piping, functioning as an operational relief mechanism. Additionally, to safeguard the magnet dewar in the event of an insulation vacuum loss or a quench, the magnet return path is equipped with a 12 psig, 4-inch rupture disk as a safety relief device. The magnet and the helium separator of the refrigerator are connected through a vacuum-insulated U-tube, allowing the transfer of LHe from the magnet to the separator. This configuration effectively combines the magnet helium space and the separator into a single system. However, in the case of an insulation vacuum loss, the separator, which contains LHe, cannot rely on the magnet's safety relief system. This is due to the U-tube becoming a high-impedance path with limited flow capacity under such conditions. To address this limitation, the separator is treated as an independent pressure vessel. A 5-psig operational relief valve and a 15-psig safety relief valve have been installed on the separator to ensure its pressure safety and operational reliability.

Furthermore, the refrigerator space is equipped with a 0.5-psig operational relief valve and a 15-psig safety relief valve. Additionally, the magnet nitrogen space is connected to a 35 psig safety relief valve to ensure the pressure safety. Figure 7 illustrates the operational relief valve of the magnet.

The seal between the magnet top flange and the shell space of the refrigerator, as well as the seal between the top flange and the magnet body, is crucial for maintaining the insulation vacuum of the magnet system. During the magnet and refrigerator filling processes, the area around these seals can get very cold, compromising the quality of the insulation vacuum. To mitigate this issue, automated heat tapes have been installed around these areas to prevent the seals from freezing

All electronic systems in the target cave are designed to withstand the high-radiation environment. For instance, all encoders for the moving actuators are constructed using rotary/linear

Figure 8: The turbo molecular pump is shielded with borated plastic to reduce radiation exposure

potentiometers, avoiding the use of solid-state encoders. Additionally, racks containing commercial electronic equipment are shielded with borated plastic to minimize radiation exposure. Finally, the turbo molecular pump for the magnet insulation vacuum space, located beneath the beam window, is also covered with borated plastic to reduce the impact of radiation (figure 8).

8. The target system performance and summary

During the beam commissioning phase, a 26% polarization was successfully achieved for the CH2 material (figure 9), marking the first polarization activity in the SpinQuest experiment and setting a significant milestone in the experiment's progress [10]. The target insert was loaded with NH3 material, achieving a maximum polarization of 96% at a microwave frequency of 140.14 GHz[11].

Successful annealing routines were performed during the commissioning period using the manually controlled annealing system currently in place. The Cernox sensor on the target cell was continuously monitored throughout the process. As a result of the annealing, the saturated negative polarization increased from 38% to 86%, demonstrating the effectiveness of the annealing procedure and the hardware setup [11]. A computer-controlled annealing system is currently under development to fully automate the annealing process, enhancing precision and efficiency.

During the nominal production running, the liquid helium consumption was approximately 100 liters per day, while the liquefaction plant produced 200 liters per day, ensuring sustainable system operation. The heat load from the proton beam into the target cells was 0.4 watts when the beam intensity was $2X10^{12}$ protons per 4.4 seconds. This was estimated based on the helium boil-off caused by the beam. The cooling power of the refrigerator was around 5 watts at 1.1 K. Helium consumption can be further reduced by adding more control to the microwave power. Currently, a variable microwave attenuator is under development to remotely control the maximum microwave

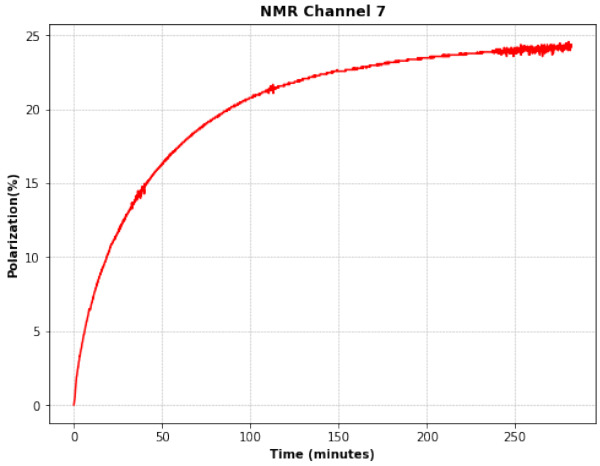


Figure 9: The graph shows the polarization of CH2 material and this is the first polarization attempt of the SpinQuest experiment

power delivered to the target cell, adjustable between 0 and 1.2 watts. This system will enable the application of full microwave power during the polarization ramp-up phase and reduced power during polarization maintenance. Additionally, plans are underway to modulate the microwave frequency to further enhance the overall polarization of the target cells.

A quench commissioning procedure was performed during the beam series, the details of which are thoroughly discussed in[11].

In conclusion, the SpinQuest polarized target system has performed as expected during the beam commissioning phase. The design efforts dedicated to ensuring the target cave's resilience to high radiation levels have proven successful, highlighting the robustness of the system under operational conditions.

References

[1] D. Keller A. Klein and K. Liu et al. *E1039 FNAL proposal SEAQUEST Document 1720-v3*, 2016.

[2] D. G. Crabb, C. B. Higley, A. D. Krisch, R. S. Raymond, T. Roser, J. A. Stewart, and G. R. Court. Observation of a 96*Phys. Rev. Lett.*, 64:2627–2629, May 1990.

[3] DG Crabb and W Meyer. Solid polarized targets for nuclear and particle physics experiments. *Annual Review of Nuclear and Particle Science*, 47(1):67–109, 1997.

[4] Zulkaida Akbar and Dustin Keller. Thermal Analysis and Simulation of the Superconducting Magnet in the SpinQuest Experiment at Fermilab. *PoS*, PSTP2019:057, 2020.

[5] Irawan Josodipuro. Development of a pressure vessel qualification methodology and testing-proposal enhancement to asme bpvc certification. In *Pressure Vessels and Piping Conference*, volume 86144, page V001T01A060. American Society of Mechanical Engineers, 2022.

PoS(PSTP2024)037

[6] Tapio O Niinikoski. *The Physics of Polarized Targets*. Cambridge University Press, 2020.

[7] D Keller. Uncertainty minimization in nmr measurements of dynamic nuclear polarization of a proton target for nuclear physics experiments. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 728:133–144, 2013.

[8] GR Court, DW Gifford, P Harrison, WG Heyes, and MA Houlden. A high precision q-meter for the measurement of proton polarization in polarised targets. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 324(3):433–440, 1993.

[9] Mikhail Yurov, Patrick L. McGaughey, and Jacqueline Mirabal-Martinez. A New Target Polarization Measurement System for the Fermilab Polarized Drell-Yan SpinQuest Experiment. *PoS*, PSTP2019:059, 2020.

[10] Muhammad Farooq, W. Ahmed, and D. Keller. The SpinQuest (E1039) experiment's polarized target system. *PoS*, SPIN2023:209, 2024.

[11] Kenichi Nakano. Beam commissioning result of polarized target at spinquest. In *PSTP*, 2024. https://indico.jlab.org/event/823/contributions/15143/attachments/11815/18441/PSTP2024_KenichiNakano.pdf.