PROCEEDINGS OF SCIENCE

1 K refrigerator for the CLAS12 Polarized Target

Design, Construction, and First Results

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A dynamically polarized target of protons and deuterons in irradiated NH3 and ND3 will be employed with the CLAS12 detector system to explore the spin structure of the nucleon in Hall B at Jefferson Lab. This target will feature a versatile, horizontal 1 K refrigerator that has been constructed by a collaboration of Christopher Newport University, Old Dominion University, the University of Virginia, and the JLab Target Group. A description of the challenges involved with designing the target for the CLAS12 experiments and the collaboration's solutions will be presented. These include a modular and compact design of the 1 K refrigerator and its ancillary equipment, as well as a novel mechanism for loading the target samples. Initial test results of the system will also be included.

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1. Introduction

The 12 GeV beam energy upgrade at Jefferson Lab has required a commensurable upgrade of many other systems at the lab. One of the more complex is the 12 GeV version of the CEBAF Large Acceptance Spectrometer (CLAS) in experimental Hall B [1]. The new spectrometer, CLAS12, was commissioned in 2018 and while featuring new and enhanced capabilities, it also creates compatibility issues with some previous target installations, including a polarized solid target that played a prominent role in the 6 GeV physics program [1, 2]. Therefore, a new polarized target, designed specifically for CLAS12, is under construction by a collaboration of Christopher Newport University, Old Dominion University, the University of Virginia, and the Jefferson Lab Target Group. The target system will be used to dynamically polarize solid ammonia samples, both NH_3 and ND_3, at 1 K and 5 T and will operate with beam-target luminosities up to 10^{35} cm^{-2} s^{-1}, the maximum permitted by the spectrometer [1].

The polarizing field for the target will be provided by a 5 T superconducting solenoid which is the basis for the CLAS12 Central Detector (CD), one of the spectrometer's two detector packages. In addition to this role for the polarized target, the solenoid also provides the magnetic field for tracking charged particles in the Central Detector, and shields the second, Forward Detector package from low energy, Møller-scattered electrons [1]. The ammonia samples will be cooled to 1 K using a bespoke ^{4}He evaporation refrigerator which is described below. The geometric constraints imposed by the Central Detector and its associated electronics dictate that the new target system be no more than 100 mm in diameter at the downstream end, while the nearest location for supporting the system is almost 4 meters upstream from the location of the ammonia sample. This implies a very long, horizontal cryostat for the target.

Our design was also guided by the expectation that the samples must be annealed at ~100 K every two days to repair the radiation damage incurred from the anticipated beam current (10 nA) and beam spot size (2 cm^2) and replaced after about ten days [3, 4]. Previous systems at JLab utilized vertical target ladders with more than one sample [2, 3, 5] in order to decrease the frequency of these operations. The horizontal design of the present target precludes such a ladder, and our intention is to anneal radiation-damaged samples offline and under more controlled circumstances using a separate, dedicated cryostat. The new target is therefore designed with some novel and innovative features that we hope will enable the rapid and reliable replacement of a spent target sample with a fresh one in only a few minutes.

2. The 1 K Refrigerator

The basic design of the 1 K ^{4}He evaporation refrigerator is similar to those built at CERN more than five decades ago [6]. Its major components are the liquid-vapor separator, liquid-vapor heat exchanger, and low-temperature bath of He-II. Additionally, a set of thin, superconducting coils are included inside the refrigerator to improve the uniformity of the solenoid for DNP. All components are located inside the pumping tube for the bath (Fig. 1), which is 254 mm at the room temperature end and necks down to 70 mm at the low-temperature end. The pump tube is constructed from composite materials incorporating segmented cylinders of 316SS foil laminated between glass fiber reinforced plastic: G10/SS/G10 and aluminum alloys, joined with two part epoxy. This laminated foil reduces the permeation of He through the G10 wall into the insulating vacuum (IV) [7]. This construction method is lighter, better insulating, and eliminates the tolerance problems that can arise due to warpage of typical welded-metal construction. The low-temperature portion of the pumping tube is surrounded by a copper C101 heat shield, and is contained within a stainless steel insulating vacuum (IV) vessel. A 6000 m^3hr^{-1} system of roots and rotary vane pumps connects to the pumping tube with standard vacuum fittings and pumps the He-II bath to a temperature below 1 K.

Liquid helium from a 500 L dewar is continuously transferred into the ~1 L separator vessel, where the vapor fraction is removed with the aid of a thin layer of 316SS mesh. The vapor, drawn from the separator by a small diaphragm pump, is used to cool a series of copper baffles located upstream of the separator as well as a heat exchanger for the above-mentioned copper shield. When the refrigerator is inserted into the pump tube, the heat exchanger mates with a heat sink incorporated in the pump tube wall to which the shield is fastened. Both the heat sink and heat exchanger are fabricated from aluminum and are conically shaped to provide a large contact area. The heat exchanger floats on a set of phosphor bronze coil springs that maintain a constant force between the two cones as the system cools from room temperature. With this design, it is possible to cool the shield below 15 K using a helium flow less than 0.04 g/s.

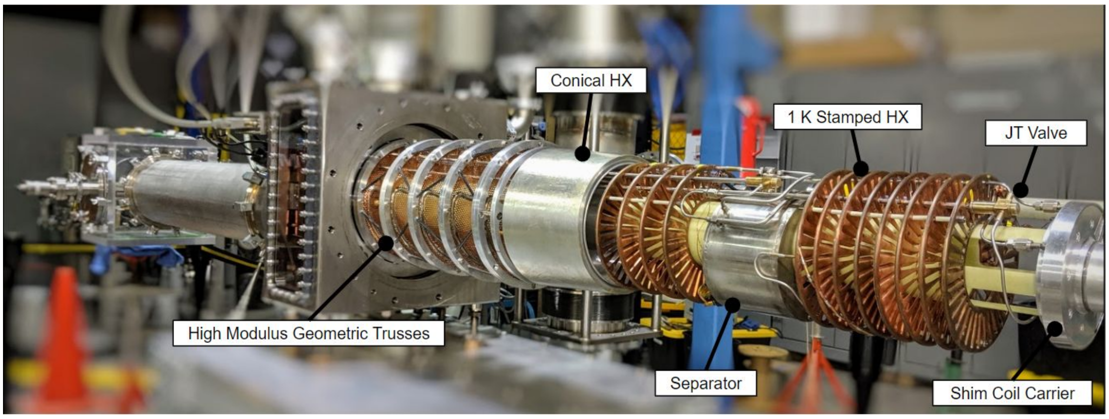

Figure 1. The 1 K evaporation refrigerator, detailing most of its major components. The refrigerator is suspended from the rear vacuum flange using a structure of high modulus carbon fiber trusses.

Liquid drawn from the bottom of the separator passes through a gas-vapor heat exchanger where it is cooled by vapor pumped from the He-II bath. The subcooled liquid then expands across a miniature Joule-Thompson valve, and is collected in the bath, which contains the ammonia target samples. A second valve bypasses both the separator and heat exchanger to enable rapid cooling from room temperature to about 2 K. Both valves are outfitted with stepper motors and optical encoders for remote operation. The heat exchanger consists of 3 mm copper tubing soldered to eight plates of copper C101 with stamped louvers for the passage of vapor. Cadmium zinc solder was chosen for its low superconducting critical temperature, Tc < 1.3 K [8]. All components inside of the pump tube are mounted to a backplate by a series of modular high modulus geometric truss structures. Unidirectional carbon fiber reinforced plastic trusses

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are epoxied into precision machined holes on the perimeter of aluminum rings in coplanar pairs far from the central axis. This maximizes the effective second moment of the area for the unit structures creating a self supporting internal skeleton.

Thus far all tests have been performed with a helium bath machined from a single piece of PTFE. In the future, a more radiation-tolerant replacement must be fabricated. It is outfitted with thermometers, a heater for cooling power measurements, and a capacitance-based level probe. The level probe, in conjunction with the miniature JT valve and a PID loop, can be used to maintain a constant level of helium within the bath. A novel aspect of the bath is that it is not fixed within the 1 K refrigerator (Fig. 2). Instead, using a spooling mechanism and tether, the bath can be retracted through the center of the pumping tube to a load lock (Fig. 3), where the ammonia samples can be removed and replaced while under a strong purge of helium gas. The tether consists of a wire harness sheathed in an aramid braid. Wiring for the bath's thermometry, level probe and heater are brought out through a low-noise slip ring commutator incorporated in the spooling mechanism. The bath rolls on a set of torlon bearings inside a serviceable insert consisting of a 50 mm G10 tube that extends from the load lock to the low-temperature portion of the refrigerator. NMR coils for measuring the target polarization are attached at the end of this insert, to which the 4 mm oversized waveguide for DNP is also fixed.

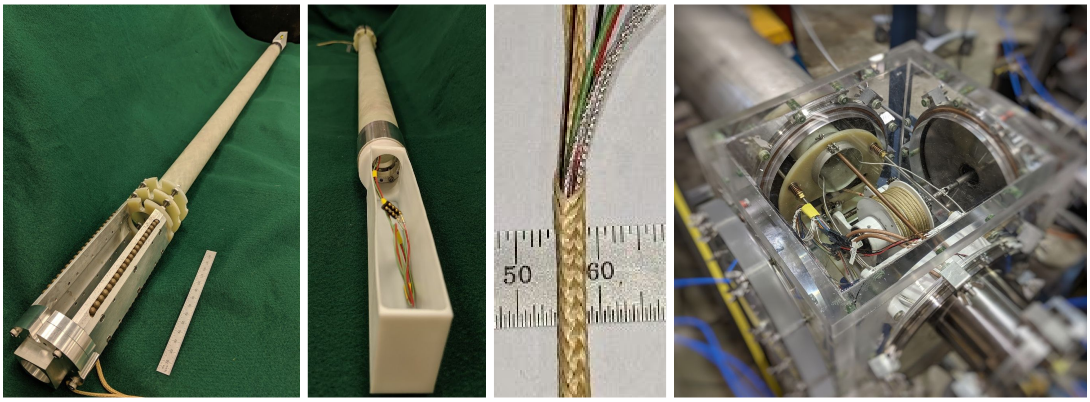

Figure 2. Retractable liquid helium bath for the ammonia samples. From left to right: downstream view detailing the torlon bearings for the bath, upstream view of the PTFE bath, tether, spooling mechanism and slip ring commutator.

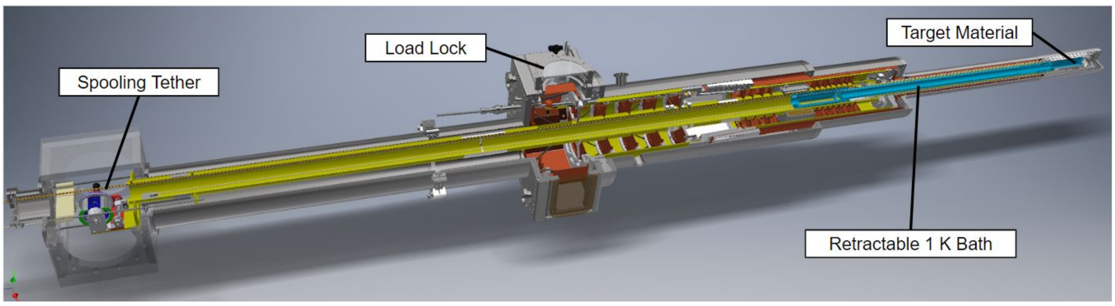

Figure 3. Sectioned view showing internal components.

The magnetic field uniformity of the Central Detector solenoid in the vicinity of the target is just within the 100 ppm needed for optimal dynamic polarization. Shim coils within the target cryostat may be used to further improve the uniformity for longer targets or to modify the field for dual anti-parallel polarized targets [9]. A demountable aluminum magnet carrier inside the pumping tube provides the structure for the superconducting shim coils and is cooled by the incoming liquid helium from the heat exchanger as well as the superfluid film from the 1K helium bath. It also serves as a multi-mode microwave cavity for the DNP target samples.

3. Target Samples

Prior to experiments in Hall B, perforated fluoropolymers cells with thin aluminum foil windows (Fig. 4) will be loaded with NH_3 or ND_3 and stored in LN2 storage dewars until needed. These preloaded cartridges will be quickly replaced by placing the refrigerator in stand-by mode, retracting the 1 K bath, and swapping the target cartridge under a helium gas purge. Over-irradiated material will be annealed offline in a separate cryostat, thus minimizing loss of beam time due to material conditioning. In our preliminary tests, thin disks of two-part epoxy doped with TEMPO substituted the ammonia target material [10]. Each disk is approximately 2 mm thick, with multiple disks stacked to achieve the desired length.

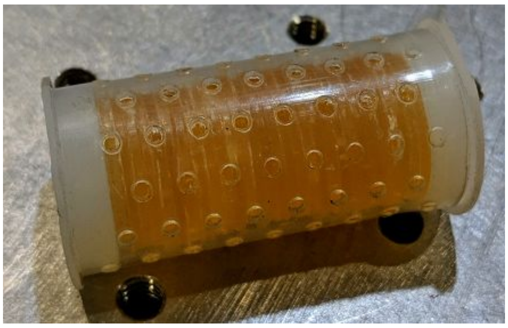

Figure 4. Perforated PCTFE target cartridge containing disks of TEMPO-doped epoxy.

4. Target Positioning

At the downstream end, the annular clearance between the target cryostat and the innermost components of the Central Detector(CD) is only 4 mm. Therefore, the cryostat must be positioned with considerable and repeatable precision to avoid damaging fragile detector elements. We also desire the ability to retract the cryostat from the CD with relative ease, should the target need service or repair during an experiment. These two requirements will be accomplished using a beam line cart with upper and lower levels, called the insertion frame and pump sled, respectively (Fig. 5).

The lower portion of the cart (pump sled) attaches to the Hall B rail system to permit approximately 5 m of travel along the beam line. The 6000 m^3h^{-1} roots pumping system and all other vacuum pumps for the target are mounted on the sled via a floating platform supported by rolling lobe air springs. The springs, in conjunction with edge-welded bellows on the main pumping line, ensure adequate vibration isolation between the roots pumps and refrigerator.

The upper portion of the cart (insertion frame) houses all electronics, cables, and gas piping needed to operate the target. It attaches to the pump sled in a manner analogous to a

Gough-Stewart kinematic platform and provides six degrees of freedom for precision alignment. The 1 K refrigerator is mounted on linear rails atop the insertion frame, which will allow the insertion and retraction of the refrigerator from the Central Detector without moving the pump sled. These "in-beam" and "out-of-beam" positions are illustrated in Figure 5 below. Moreover, this design will permit full assembly and testing the system in the Target Group Laboratory before it is transported to the experimental hall, thus reducing the installation time considerably.

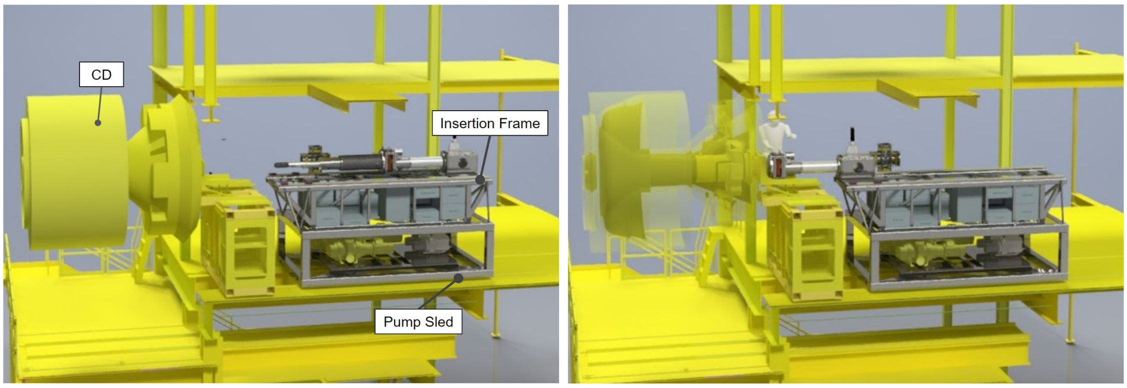

Figure 5. Left: The target in the "out-of-beam" position, as it will be transported to the experimental hall. The 1 K refrigerator is retracted over the insertion frame. Right: the target in the "in-beam" position. The 1 K refrigerator is inserted into the Central Detector (CD) and ready for beam. Upstream beamline elements are not visible.

5. Test Results

As of the time of this Workshop, there have been two preliminary, cold tests of the target system. The initial test focused on operation and performance of the 1K refrigerator, while loading and unloading target samples from the retractable helium bath was included in the second. Dynamic polarization and subsequent NMR measurements were made during utilizing TEMPO-doped epoxy samples during both test runs [11].

Automated control of the Joule-Thomson valves had not been implemented in time for the first test run, making precise control of the bath level difficult. However, this test verified the system functionality and the mechanical integrity of the overall composite construction, and a base (zero load) temperature of 0.9 K was observed. Automated valve control was possible for the second test run. The bath level could then be maintained with some precision, and preliminary cooling power measurements were made up to about 0.5 W. Unfortunately, both tests were hampered by oscillations in the delivery of 4.2 K liquid helium to the refrigerator, making stable measurements of the cooling power difficult. The oscillations are believed to be caused by an inefficient, commercial transfer line between the refrigerator and 500 L dewar. A new, higher efficiency line will be fabricated for the next test runs[2].

Target material change from start to finish was less than 15 minutes, with the average bath temperature reaching a maximum of approximately 80 K which is adequate for our purposes.

[2] Note added in proof: A higher efficiency line has eliminated the LHe oscillations during subsequent tests. Cooling powers will be published in the future.

Further refinement of the retractable bath system is expected to reduce both the time required to load samples into the bath and its temperature.

6. Summary

The preliminary test of the horizontal Solid Polarized Target for CLAS12 successfully demonstrated the expressed functionality of the target system. Operation of the 1 K refrigerator was predictable with microwave radiation and stable at a maximum heat load of 1.5 W at 1.187 K. Insight gained from testing the refrigerator and the prototype retractable bath insert has revealed critical refinements necessary for performance gains which will be utilized in the production version. These design implementations and further development has already begun and testing of the production version will take place in the summer of 2020.

7. Acknowledgments

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