4PoM01-03

Design and Prototyping of a Novel Toroidal Magnet System for MOLLER Experiment at Jefferson Lab

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Abstract—**The Thomas Jefferson National Accelerator Facility (JLab) has designed a unique spectrometer system to measure the weak interaction between electrons. The experiment—Measurement of Lepton-Lepton Electroweak Reaction (MOLLER)—requires leveraging the recent 12 GeV electron beam upgrade and will run in JLab for three years. Focusing the signal for the MOLLER experiment requires five water-cooled toroidal magnets, each with unique geometry and with 7-fold symmetry. The five magnets operate in a vacuum and provide the magnetic field required to separate the incident beam electrons scattered from the target electrons (Møller scattering) and protons (elastic e-p scattering) in a liquid hydrogen target. The conceptual design was developed by the MOLLER Collaboration and was given to JLab in the form of amp turns and physical location, with additional physics requirements. This paper presents prototyping of the coils and magnet support system and discusses the lessons learned during the process along with the plans for full magnet testing and installation. The JLab Magnet Group along with the MOLLER Collaboration developed the specification document that includes keep out zones to design the set of magnets. JLab contracted the design of the first toroid magnet (TM0) of the magnet system to Massachusetts Institute of Technology. The other four toroid magnets (TM1 through TM4) have been designed by JLab and are in the process of fabrication and assembly. Prototype coils of TM1-TM4 were fabricated by Everson-Tesla Incorporated, PA (USA). This paper presents the unique challenges of the design, alignment, high current density, operating range, high radiation dose, and vacuum environment.**

***Index Terms*— spectrometer, toroid, water-cooled, vacuum, radiation, and epoxy**

I. Introduction

Thomas Jefferson National Accelerator Facility (Jefferson Lab) has designed a unique spectrometer system to precisely measure the weak mixing angle using Møller scattering. The experiment—Measurement Of Lepton-Lepton Electroweak Reaction (MOLLER)—will be carried out in Hall A at Jefferson Lab, where a 11 GeV longitudinally polarized electron beam will be incident on a liquid hydrogen target. Møller electrons (beam electrons scattering off target electrons) will be separated from background and focused by a novel toroidal magnet system which is part of the MOLLER spectrometer [1]. Other critical components of the spectrometer include precision collimators and particle scraping collars, beam pipes, large bellows, and a thin vacuum window. The signal electrons will be counted by a large array of quartz detectors which operate in air. To achieve the statics needed for this *measurement the MOLLER experiment will run for three years*.

The MOLLER spectrometer vacuum system is 27-m long has a maximum cross section of 2.6 m high and 2.4 m wide. High risk and complicated elements were prototyped to help ensure success. These included magnet coils and their support system, one Inconel 625 bellows, one 4-kA magnet power supply (MPS), and one thin particle exit window.

Jefferson Lab contracted the design of the first toroid magnet (TM0) in the magnet to Massachusetts Institute of Technology. The other four toroid magnets (TM1-4) were designed by Jefferson Lab. Prototype coils of TM1-4 have been fabricated by Everson-Tesla Incorporated (ETI), PA (USA) and were tested at Jefferson Lab (JLab).

II. Overview of MOLLER Spectrometer And Risk Assessment

Major components of the MOLLER spectrometer (Fig. 1) include:

- five water-cooled toroidal magnets to separate and focus the signal electrons;
- multiple collimators and particle scraping devices to keep the background low and improve the signal to noise ratio;
- six bellows (four stainless steel bellows and two Inconel 625 bellows) with internal diameters up to 1.4 m, which make up for fabrication tolerances, allow thermal expansion, and independent alignment;
- one drift pipe with thin exit widow to allow scattered electrons distance to travel in vacuum and to arrive focused at the detector array with minimum multiple scattering;
- one detector pipe which transports the primary electron beam, very high energy electrons scattered at very small angles, and forward-going photons generated in the target past the main

Submitted for review September 19, 2023

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detectors.

As part of the system risk management at Jefferson Lab, we are guided by a risk assisted matrix (RAM) [2]. For the highest risk items of MOLLER spectrometer, we decided to make prototypes. These included magnet coils, one MPS, one Inconel 625 bellows and one thin particle exit window for which failure in design or construction would adversely affect the MOLLER experiment.

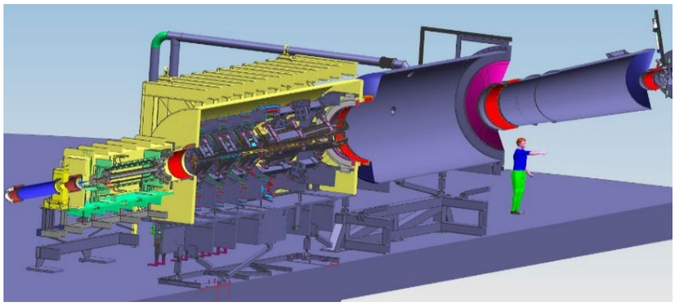

Fig. 1 Moller spectrometer system. Bellows are red; removable "top hats", yellow; thin exit window, magenta. Magnets are under the yellow top-hats.

III. Design of Toroidal Magnets

A. Magnet Specifications and Design Criteria

There were four specifications given to the JLab engineers as guidance for the MOLLER spectrometer magnet designs. First was the ampere-turns (NI); the second, conductor placement; the third, the allotted space envelope for placement of the coils and their supports; fourth, the conductor placement tolerance. The MOLLER Collaboration developed these requirements for each magnet and they were iterated to achieve focusing of the Moller (e-e) and Elastic (e-P) electrons at the detector.

JLab took this information and then surveyed water cooled magnet designs both on site and at other facilities to choose limits for critical parameters for the MOLLER magnets. We chose not to be overly conservative because this experiment only required the magnets to last 3 years versus something like an accelerator magnet which would usually need a 20-30 year lifespan. The three critical parameters used for the design included the pressure drop, water velocity, maximum temperature rise of the water and current density in the conductor. These and some other important parameters are listed as design limits in Table 1.

B. Magnet Design and Analysis

Coil geometry was provided by the collaboration. The odd shape of the last coil was needed to keep from over bending lower energy electrons and to add bending to the highest energy electrons. Dozens of minor changes in conductor designs were done using an excel spread sheet made in-house to work out possible options for conductor sizes matching the design requirements. Fluid velocity, water temperature rise and maximum allowable pressure drop were critical parameters in defining the conductor overall size, flow channel hole size and number of turns in the coil. The minimum bend radius of the chosen conductor required slight changes in the overall shape of the coils.

The final electro-magnetic parameters of five magnets are listed in Table 2. Once the design had stabilized it was optimized OPERA/TOSCA to perform electromagnetic field analysis with simplified single blocks of the required shape to create a blocky models. JLab recreated a tracking program from the Collaboration and independently created patterns of particles at the detector region Fig. 2, which saved iteration time. As the designs were finalized the TOSCA models were sent to the Collaboration and imported into GEANT [3] and this allowed the physicists evaluate and approve the final designs. The analysis included tolerances and offset studies verified with "worst-case" multiple coil/multiple offsets within the specified tolerances that considered physics optics with asymmetries within desired uncertainty [4], also the coils were aligned in conspiratorial way within tolerances that includes dipoles along the beamline.

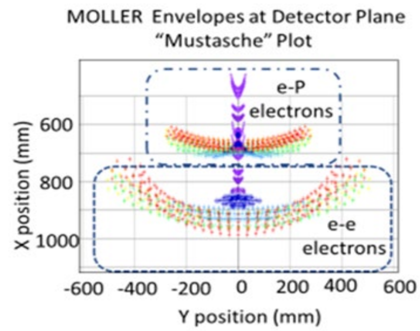

Fig. 2 Typical (moustache) plot showing Moller electrons e-e and elastic electrons e-P (tracks) focused at the main detector modelled in OPERA

Table 1. Design Limits For Spectrometer Magnets

Parameter	Units	Value	Comments
Water Velocity	m/s	< 4.57	Value may be too high for long life magnets
Current Density	A/mm^2	20	JLab has a few magnets with densities up to 40
Pressure drop	MPa	0.69	Supply system limit
Water temperature rise	°C	< 30	Emphasized because of loss of strength of the potting resin with temperature
Conductor bend radius	-	> 3.5×height of conductor	To assure accurate winding with minimal key-stoning
Maximum Current	A	< 4000	Magnet power supply cost consideration
Conductor Wall thickness	mm	> 1.8	Recommendation from conductor manufacturer

Fig. 3 shows the five magnet coils, one potted prototype coil, and four conductors, custom designed for the DS torus magnets. Fig. 4 shows the peak fields at the coils and also at the mid-plane between adjacent coils.

Torus field mapping along the bore is planned.

The magnet frames and support structure are very stiff (Fig. 5). When subjected to gravity loads, the radial deflection on the outer edge of TM1-3 coils is only 0.1 mm. Thus once aligned the motion of the coils is well within the required alignment tolerance. Because this is a relatively low field magnet the largest component of the mechanical stress in the coils derives from actual fabrication. This is due to the high curing temperature of the potting resin (CTD-403). During operation, the maximum von-Mises stress in the copper conductor is 18.6 MPa; the average von Mises stress is about 8.0 MPa; they are all less than 32 MPa—the yield stress of

conductor copper at 55 °C [5]. It should be noted the stress due to curing was ignored here.

TABLE 2. ELECTRO-MAGNETIC PARAMETERS OF SPECTROMETER MAGNETS

TM#	Nominal Current (A)*	Voltage (V)	Inductance (mH)	Resistance (Ω)	Peak Field (T)
TM0	1075	77.5	0.631	0.059	-
TM1	2230	40	0.153	0.015	0.25
TM2	2440	42	0.246	0.013	0.28
TM3	3372	57	0.348	0.013	0.35
TM4	3350	224	3.051	0.056	0.47

*Nominal currents, MPS are designed to provide 120% of nominal current. The overall weight of the downstream magnets only (enclosure included) is approximately 25 tons.

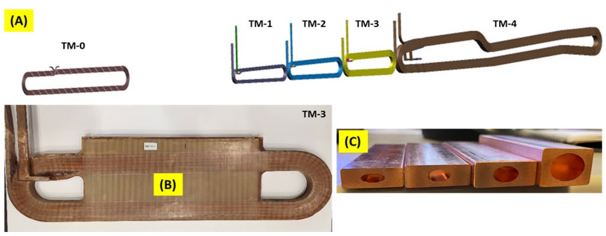

Fig. 3 (A) Five resistive toroidal magnets (TM0-TM4), (B) prototype of TM3 coil, and (C) downstream conductor cross-sections of TM1-TM4

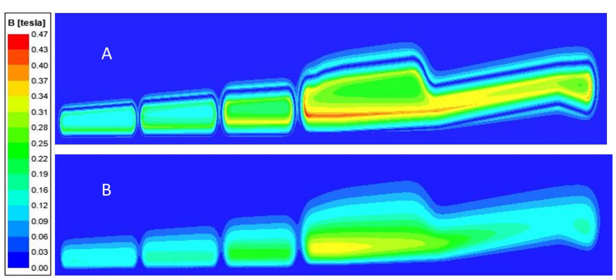

Fig. 4 (A) Field plot at coil mid-plane, (B) Field plot at sector mid-plane (between adjacent coils), (field maps calculated using Maxwell and OPERA were compared and found to be equivalent to 95%, thus Maxwell was used subsequently for faster computation)

The magnet frames and support structure are very stiff (Fig. 5). When subjected to gravity loads, the radial deflection on the outer edge of TM1-3 coils is only 0.1 mm. Thus once aligned the motion of the coils is well within the required alignment tolerance. Because this is a relatively low field magnet the largest component of the mechanical stress in the coils derives from actual fabrication. This is due to the high curing temperature of the potting resin (CTD-403). During operation, the maximum von-Mises stress in the copper conductor is 18.6 MPa; the average von Mises stress is about 8.0 MPa; they are all less than 32 MPa—the yield stress of conductor copper at 55 °C [5]. It should be noted the stress due to curing was ignored here.

TM4 coils are approximately 3.8 m long, double-pancake racetrack coils; the mass of each TM4 coil and three supports is 242.7 kg. To support the flexible and heavy TM4 coil, three supports are used. Fig. 6 illustrates the waviness of the horizontal coil under gravity; the vertical deflection changes from -1.1 mm to -1.6 mm and the maximum deviation from the linear line is approximately 0.15 mm, less than 1.0 mm, a requirement of the Moller collaboration. As the links are all adjustable, the deflection of the coil due to gravity will be adjusted away during alignment. The materials in the spectrometer in general and especially those in the magnet support system were strictly controlled.

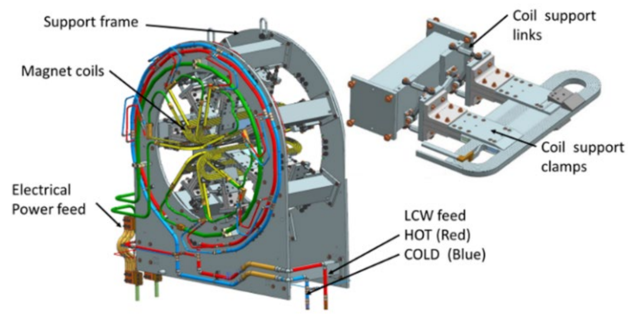

Fig. 5 - Magnet assembly and Magnet coil on a beam with adjustment linkages

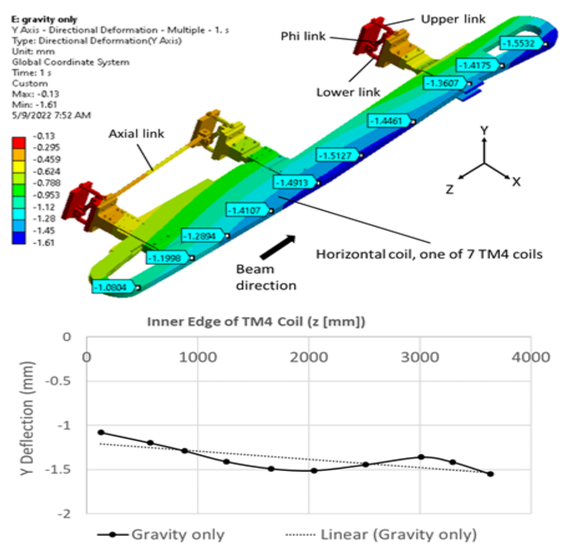

Fig. 6 - Vertical (Y) deflection of TM4 coil under gravity only. The maximum deviation from the linear line is approximately 0.15 mm, less than required 1.0 mm.

Generally, prohibited materials include ferromagnetic steel, elastomers, glues, and materials that can be activated with long half-life [4]. Fasteners in the magnet are either Silicon Bronze 651 or Brass 485 chosen for both high strength and low magnetic permeability. Stainless steel was allowed in some areas of the spectrometer but only after simulation by and permission from the MOLLER Collaboration on a case-by-case basis.

S2-glass reinforced CTD-403 is chosen to electrically insulate the conductors. Its mechanical integrity due to radiation and elevated temperature was a concern at the early design stage since the mechanical strength of irradiated S2-glass reinforce CTD-403 at elevated temperature had not been previously measured [6-13]. Jefferson Lab, Composite Technology Development, Inc., and the McClellan Nuclear Research Center of University of California at Davis partnered to measure the shear strength and flexural modulus of its irradiated specimens at 65 °C in a vacuum environment. At the dose of 165 MGy, the loss of shear strength of the composite samples was only 23% [14]. The MOLLER Collaboration performed radiation dose calculation on the magnet coils and provided shielding requirements where doses exceed 100 MGy over large areas of the coils.

IV. Coil Prototyping

A. *Fabrication and Testing of Prototype Coils*

Everson Tesla Inc. completed prototyping of four coils for the MOLLER experiment, one for each downstream torus magnet, TM1-4; these coils are identified as SC1-01, SC2-01, SC3-01 and SC4-01, respectively. As part of production, ETI performed first article inspection and testing of the prototype coils. This included pressure testing, helium mass spectrometer leak testing, resistance testing, inductance testing, and hi-pot testing (1.5 kV), most of these tests were also repeated at Jefferson Lab upon receipt.

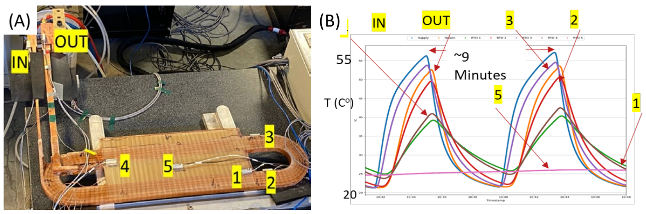

Fig. 7 (A) Locations of temperature sensors; (B) temperature changes of thermal cycles in the coil. Delamination was seen at the G10 interface with copper resulting in a change of the G10 design to improve structural integrity.

Due to the highest stresses predicted by analysis that would occur during coil potting, JLab requested the vendor to pot the SC3 alone vs the original plan to pot it with SC1 and SC2. This allowed JLab to inspect the coil and also to thermally cycle it. When it first came out of the mold at ETI and was tested all looked fine but upon arrival at JLab some small cracks were observed at the interface between the G10 inserts and the conductor. Upon thermal cycling (Fig. 7) the cracks grew rather dramatically. The g10 parts for SC1 and SC2 were modified by increasing the chamfers on the edges. When SC2 arrived, it was similarly thermally cycled and no cracking was observed.

Fig.8 Prototype SC4-01 for TM4

In addition to the thermal cycling, we performed additional inspections and testing, which included visual and physical inspections, powering tests, and conductor positional measurements within the potting glass resin system using a capacitive measurement probe and surveys of coil exterior flatness inspections (Fig. 8). The first prototype had an issue with cracking at the g10 to conductor interface. The chamfer on the g10 was increased for the last prototypes and this solved the cracking issue, all prototypes passed all tests.

V. Other Prototyping For MOLLER Spectrometer

A. *Bellows Prototyping*

Bellows#7 which has a 16” inside diameter was successfully built as a prototype to prove out that an Inconel 625 bellows could be made with high quality and to our specifications in stiffness. It also provided us knowledge that we could find a capable vendor. Hyspan Precision Products, Inc. fabricated the prototype Bellows#7 for Jefferson Lab. Acceptance tests indicates that it met the specifications. The welding quality of Inconel 625 was found excellent.

B. *Windows Prototyping*

The detector window is machined from a 3.175 mm thick Al 5083-H116 sheet (Fig. 9). It has seven machined thin regions for particles to pass and seven un-machined thick regions for support. The thickness of thin regions ranges from 0.94 mm to 1.55 mm. The hoop stress of the thin regions is limited to the minimum of $0.63\sigma_y$ and $0.35\sigma_{uts}$, which is 106 MPa for Al 5083-H116.

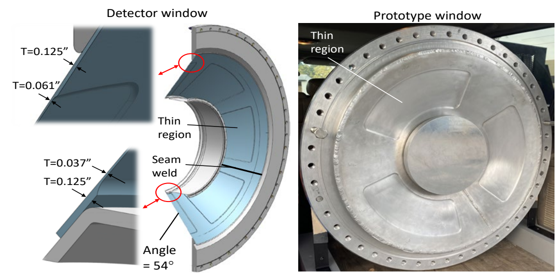

Fig. 9 Detector window CAD design and prototype window

A 1/3 scale prototype window with the same material from the same lot, and with the same hoop stress and same thicknesses as those of the detector window (Fig. 9) was fabricated to verify the design and fabrication techniques for the detector window. With a differential pressure of 0.152 MPa, it has the same hoop stress as that of the detector window under 0.101 MPa. The integrity of the prototype window was maintained when it was tested hydrostatically to 0.448 MPa. This indicates that the prototype window has a design factor of at least 2.96.

C. *MPS Prototyping*

The MPS for TM3 is being prototyped by OCEM in Italy. Some delays have occurred and many of those were due to supply chain issues. JLab sent staff members to visit the factory to assure that the device is moving forward and to discuss moving forward with the option to purchase the remaining 4 MPS’s. A factory acceptance test will take place prior to shipping the MPS to JLab.

VI. Conclusion and Outlook

The novel MOLLER magnets were designed with unique shapes and tight tolerances according to the specifications set by the collaboration and physics requirements. Four prototype coils, one prototype bellows, and one prototype window have been fabricated, all have completed planned testing. One 4 kA MPS has successfully completed sub-component testing and work is ongoing to complete its factory acceptance testing. The prototype coils were inspected and tested, these coils offered lessons learned, which were, where applicable, applied to future coil builds. The prototype bellows and window validated the design of these components.

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