A 15-T PULSED SOLENOID FOR A HIGH-POWER TARGET EXPERIMENT

H.G Kirk*, *BNL, Upton, NY 11973, USA*
I. Efthymiopoulos, A. Fabich, F. Haug, *CERN, CH-1211 Genève 23, Switzerland*
P. Titus, *MIT/PSFC, Cambridge, MA 02139, USA*
K.T. McDonald, *Princeton University, Princeton, NJ 08544, USA*
J.R.J. Bennett, T.R. Edgecock, *CCLRC, RAL, Chilton, OX11 0QX, UK*

Abstract

The MERIT experiment, to be run at CERN in 2007, is a proof-of-principle test for a target system that converts a 4-MW proton beam into a high-intensity muon beam for either a neutrino factory complex or a muon collider. The target system is based on a free mercury jet that intercepts an intense proton beam inside a 15-T solenoidal magnetic field. Here, we describe the design and initial performance of the 15-T, liquid-nitrogen-precooled, copper solenoid magnet.

INTRODUCTION

A muon collider or neutrino factory requires intense beams of muons, which are obtained from the decay of pions. Pion production by a proton beam is maximized by use of a high-Z target such as a liquid mercury jet. Efficient capture of low-energy secondary pions (for transfer into the subsequent muon accelerator complex) requires that the target system be immersed in a strong magnetic field of solenoidal geometry.

This magnetic field should stabilize the mercury flow in regions of nearly uniform field, but it perturbs the liquid metal jet as it enters the field. Hence, the behavior of the mercury jet plus an intense proton beam inside a strong magnetic field needs to be understood better before resources are committed to a larger facility. The MERIT experiment [1, 2] is to be conducted at CERN in 2007 for this purpose.

The magnets for the target system at a neutrino factory [3] or muon collider will be superconducting [4]. To minimize costs for the MERIT proof-of-principle experiment, we will use a pulsed, copper magnet that is precooled to 77K by LN_2 to lower the coil resistance, and thereby the requirements for the $\approx$ 5-MW power supply [5].

The magnet consists of 3 concentric copper coils, mounted inside a common cryostat, as shown in Fig. 1. The expected behavior of the magnetic field B, coil resistance R, temperature rise ΔT of the coils, and the Joule heating Q is shown in Fig. 2 as a function of time over the $\approx$ 20 s duration of a pulse.

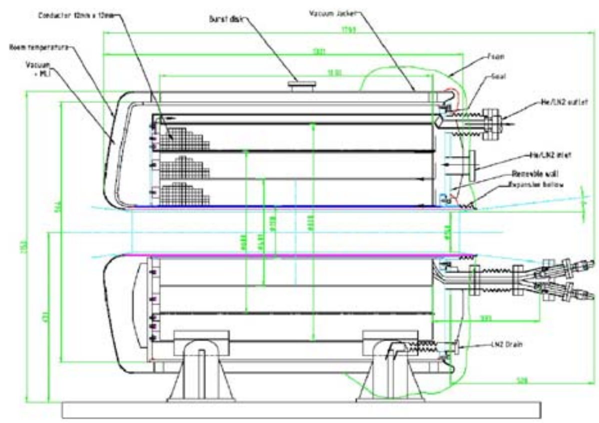

Figure 1: Longitudinal cross section of the 15-T pulsed magnet, showing the 3 coil packages and cryostat [6].

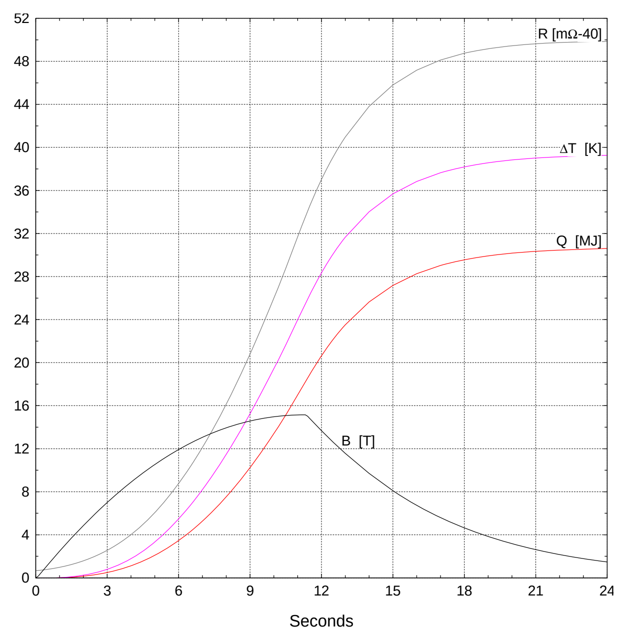

Figure 2: Calculated behavior of the 15-T magnet during a pulse. The peak current is 7200 A at a peak voltage of 700 V. Approximately 30 MJ of energy is dissipated in the magnet, which raises its temperature from 80 to 120 K.

* hkirk@bnl.gov

MAGNET DESIGN

Cost issues dictated a modest coil design. Power-supply limitations dictated a compact, low-inductance, high-packing-fraction design. A three-segment, layer-wound solenoid was chosen for the pulsed magnet. Each segment is 10-cm thick, 100-cm long and consists of 624 turns in 8 layers of 78 turns. The inner radii of the three segments are 15, 25 and 35 cm, and their masses are 750, 1250 and 1750 kg. The three segments are connected in series via external leads.

The conductor is 13-mm square, solid, cold-worked OFHC copper. Three different keystone geometries were used, one each for each coil segment.

Prior to each magnet pulse, liquid-nitrogen flows through 3-mm-thick axial and circumferential channels located between coil segments, as seen in Fig, 6. Only 2 of the 8 layers of a coil segment are in direct contact with the coolant, so that thermal conduction through 3 layers of conductors is relied on for cooling between layers 1 and 4, *etc*. Is it expected that the 30 MJ of heat deposited in the magnet during a single pulse can be removed in $\approx$ 30 min, which represents the minimum cycle time of the magnet.

COOLDOWN SIMULATION

To model the transient heat conduction coupled with LN_2 flow in the magnet, a finite-difference numerical program was written. The analysis starts with a specified mass flow of 100 g/s of LN_2 which is apportioned to the 4 sets of axial coolant channels based on the flow area of each channel. The model includes surface heat transfer characteristics based on 2-phase nitrogen flow. The cooling is actually pool cooling, and relies on circumferential channels to clear bubbles to the top of the magnet..

The model indicates that the magnet should be cooled in 20 min from its temperature of 120 K just after a 15-T pulse back to a temperature of 80 K for the next pulse, as shown in Fig. 3. To minimize activation of LN_2 by the proton beam, the liquid left in the magnet at 80 K will be flushed out by N_2 gas, requiring 10 min for this operation. Hence, the entire cooling cycle is 30 = 20 + 10 min.

STRESS ANALYSIS

An ANSYS model [6] of the von Mises stress due to the Lorentz forces during 15-T operation is shown in Fig. 4.

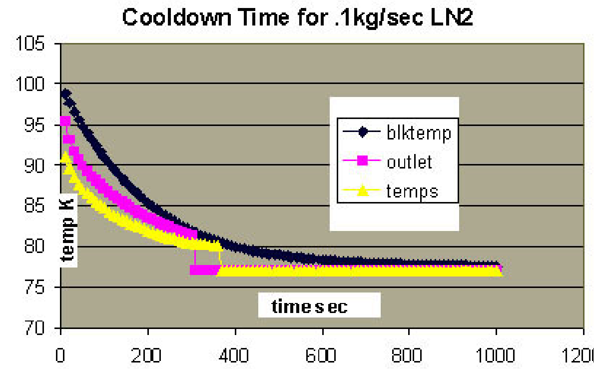

Figure 3: Model of the cooldown by LN_2 over 20 min of 40 K temperature rise of a 15-T magnet pulse.

The peak stress is 133 MPa, well below the allowable of 200 MPa. However, the hoop stress is sufficient to pulling the coil apart slightly in the radial direction, so that appropriate parting planes were provided in the coil build.

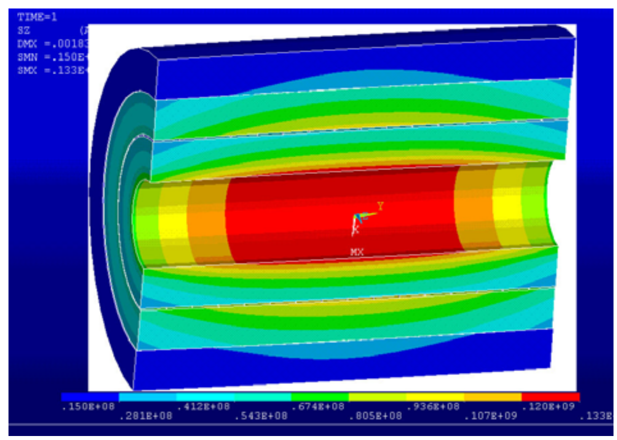

Figure 4: von Mises stress due to the Lorentz forces during 15-T operation.

The largest thermal stresses on the magnet occur during cooldown, when the axial tension can reach 50 MPa in the layers in contact with the coolant, as shown in Fig. 5. This stress is beyond the strength of epoxy-copper bonds, so Kapton strips were placed between every eighth turn in the channel-facing layers to provide axial strain relief.

Many other sources of stress have been analyzed, including those in the cryostat, and all found to be of lesser significance [6].

MAGNET FABRICATION

The coil segments were wound, impregnated with epoxy, and nested together by Everson-Tesla of Nazareth, PA. The fabrication of the cryostat and the insertion of the coil segments into the cryostat was performed by CVIP in Emmaus, PA. The nested set of 3 coil segments is shown in Fig. 6, and the completed magnet is shown in Fig. 7.

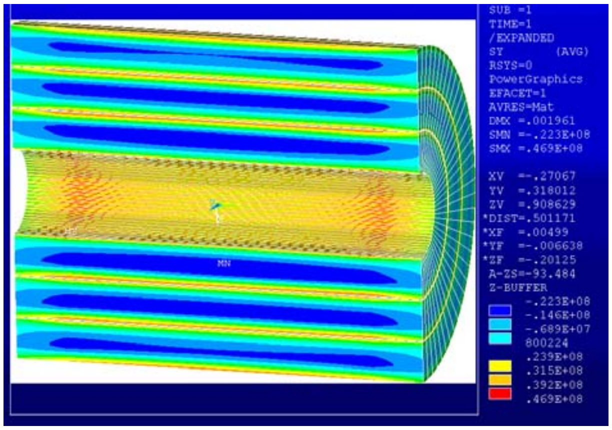

Figure 5: Axial stress during LN_2 cooldown.

Figure 6: The nested set of 3 coil segments. The axial and circumferential grooves are visible on the outer surface of the coil.

INITIAL TESTS

Initial tests of the magnet were performed at the MIT Pulsed Test Facility in March 2006. The magnet reached the design field of 15-T during a pulse of 7500 A and 550 V, as indicated in Fig. 8.

Integration of the magnet with the mercury jet system will take place in Fall 2006.

ACKNOWLEDGMENTS

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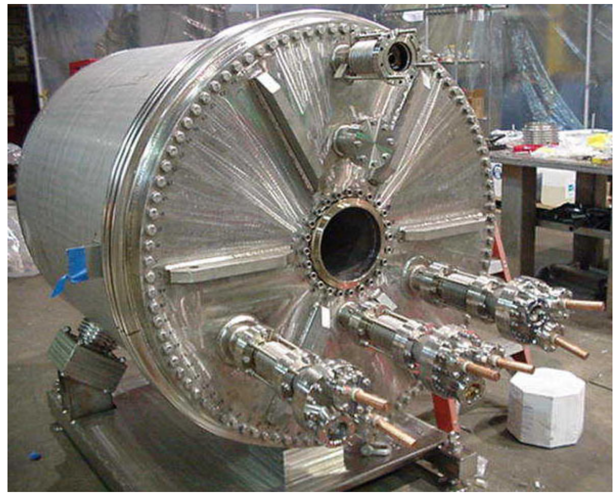

Figure 7: The 15-T magnet in its cryostat, January 2006.

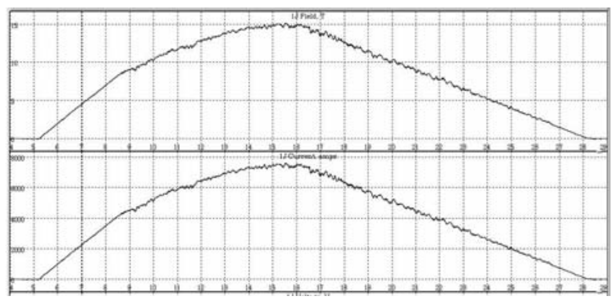

Figure 8: Magnetic field and current traces during a 15-T pulse at MIT, March 2006.

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