15T Pulsed Magnet for Mercury Target Development, Neutrino Factory and Muon Collider Collaboration

P. H. Titus, H.Kirk ,K. Mcdonald P. Spampinato,V. Graves, D.Rakos, A. Fabich,' J. Lettry, D.Nguyen

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Solenoid ?

Abstract too long!

***Abstract*—MIT - PSFC is providing the design and analysis of a pulsed copper coil that can produce 15T with sufficient bore volume for use with mercury target experiments. This experiment has been designated the MErcury Intense Target ~~(MERIT) project.~~**

A muon collider, or neutrino factory require intense beams of muons which are obtained from pion decay. Pion production from a proton beam interaction is maximized by use of a high Z target such as a mercury jet. A magnetic field is needed for particle confinement. The target R&D effort involves analytic simulation and experimental investigation of the mercury flow.

MIT - PSFC is providing the design and analysis of the pulsed ~~copper coil~~ that can produce 15T . The coil is a three segment concentric set of layer wound coils. It is an inertially cooled normal copper coil with a solid conductor and annular cooling channels. The repetition rate is two shots per hour, with about 20 minutes allowed for cooldown and 10 minutes allowed for venting the remaining LN2 to avoid activation. Periodic warm-up is planned to avoid Ozone accumulation. Coil Manufacture has been performed by Everson-Tesla in Nazareth PA. Mating with the cryostats is being done by CVIP in Emmaus PA. Pre-operational testing of the magnet is being done at MIT in the PTF test facility in 2005. Testing with the mercury jet cassette is planned at MIT in 2006. Status of manufacture, and testing is presented. Configurations of the mercury system and the system installation at CERN are described.

Brookhaven, Princeton, CERN, Oak Ridge, and other collaborators are developing mercury jets as targets where the interaction zone with a proton beam is in a field of up to 22 T. Previous tests at Brookhaven used smaller diameter jets interacting with the AGS proton beam. The next round of mercury tests at CERN will have a 1 cm jet with the proton beam and magnetic field.

Index Terms— **Mercury Jet, Mercury, Target, , Pulsed Magnet , ~~Muon Beam~~**

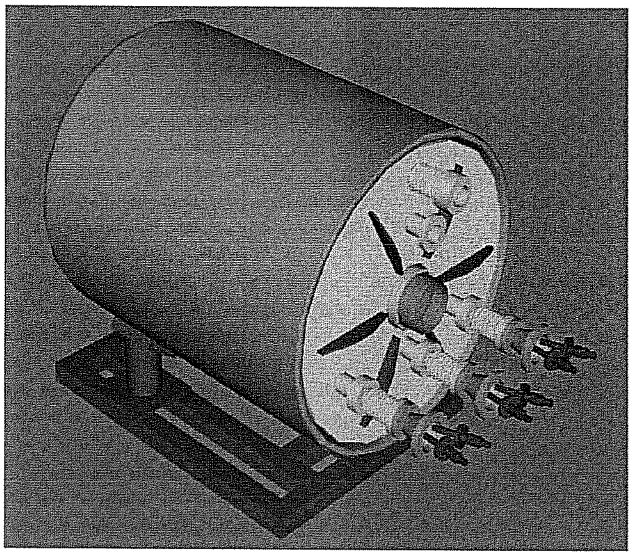

Fig. 1 Early Rendering of the Exterior of the Magnet Assembly

I. INTRODUCTION

The 15 Tesla pulsed magnet is component of a "next step" experiment in the investigation of using a Mercury jet as

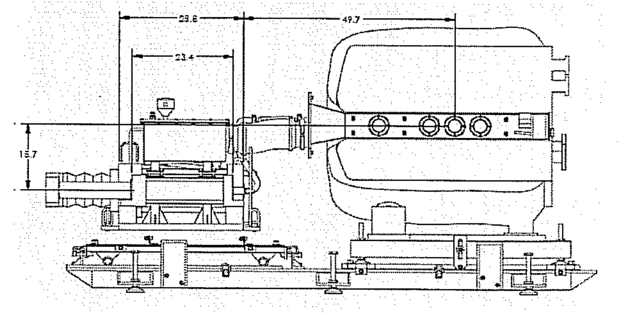

Fig. 2 Stainless Steel Mercury Cassette with the Magnet

Manuscript received September 16, 2005. This work was supported in part by the U.S. Department of Energy under Grant . Peter H. Titus is with the Plasma Science and Fusion Center, 189 Albany Street, Cambridge Ma 02139, 617 253 1344; (e-mail: tituspsfc.mit.edu)

Harold Kirk is with Brookhaven National Laboratory, Upton NY,
Kirk Mcdonald is with Princeton University, Princeton NJ.
Philip. Spampinato, and Van. Graves are with Oak Ridge National Laboratory, Oak Ridge Tenn,
D.Rakos is with Everson Tesla Corporation, Nazareth, PA
Adrian. Fabich and J. Lettry are with CERN, Geneva Switzerland
David Nguyen is with CVIP Emaus Pennsylvania

a high Z target interacting with a proton beam. The liquid jet target has some advantages over a solid target. It can readily remove heat and it reforms after each beam interaction. However the beam energy deposited in the jet is large enough to violently disrupt the jet reducing its usefulness as a target. The magnetic field may stabilize the mercury flow, or eddy currents interacting with the magnetic field may have a deleterious effect.. The behavior of the mercury jet in this environment needs to be understood before resources are committed to the larger experiments.

II. Experiment Objectives

A. Intended Applications

A muon collider, or neutrino factory require intense beams of muons which are obtained from pion decay. Pion production from a proton beam interaction is maximized by use of a high Z target such as a mercury jet. A magnetic field is needed for particle confinement

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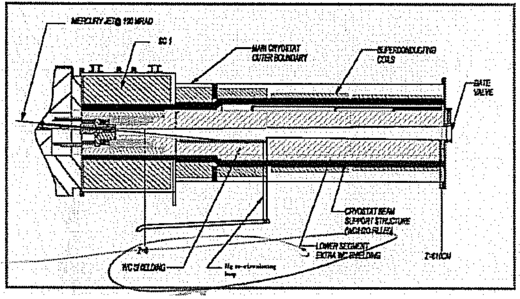

Fig. 3 The Neutrino Factory Cross Section Showing Mercury Jet Target in a High Magnetic Field

details too small

B. Previous Experiments

Investigations have been made of the effects of a proton beam interacting with the jet at Brookhaven. Experiments with a mercury jet in a 20 Tesla field have been performed at CERN [2] These experiments have addressed the proton beam interaction and field interaction separately. The pulsed magnet currently under manufacture and to be pre-operationally tested at MIT is intended to be a part of an experiment that combines these two environments and can investigate coupled effects.

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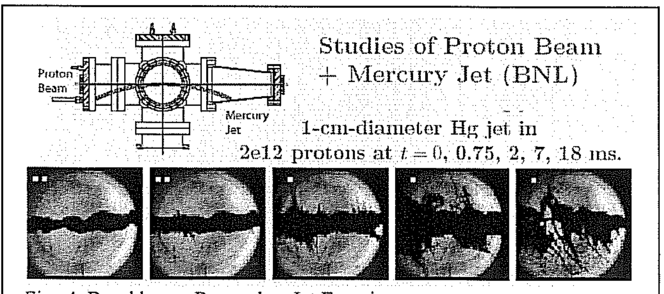

Fig. 4 Brookhaven Beam plus Jet Experiment

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Figures not referenced in text.

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C. MERIT/nTOF11 Mercury Target Experiments

Experiment Parameters:

Magnet
15 Tesla magnetic field
Peak field duration ~1 sec
Magnet cool-down time ~20 minutes
Pulse repetition rate 30 minutes
Hg Jet
1-cm diameter, 20 m/s, delivered to coincide with magnet peak field
Required flow rate of 1.57 liter/s
Environment
24 GeV proton beam, up to 28x1012 (TP) per 2μs spill
1-atm air environment inside target delivery system primary containment
Total integrated dose 104 rads
Geometry
Hg jet 100 mrad off magnet axis
Proton beam 67 mrad off magnet axis
Jet intersects beam at magnet Z=0
Up to 100 target cycles for the CERN test delivered in a pulse-on-demand mode

III. 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. The original sizing of the magnet was n=done by Robert Weggel at Brookhaven and included copper cryogenic and magneto resistivity changes. 7kA and 700 volts DC are needed to power the magnet.

TABLE 1 I

Coil Build in meters, Turns and Weights Used in the Stress Analysis

Seg#	r	z	dr	dz	Turns	Wt. kg
1	.15	0	.098	1.0	624	748
chan	.2	0	.002	1.0		0
2	.25	0	.098	1.0	624	1247
chan	.3	0	.002	1.0		0
3	.35	0	.098	1.0	624	1745

See Table format

The three segments are connected in series, but could be connected in parallel for other power supply options. A 15 second pulse is needed to obtain a 15 Tesla flat top. Thermal conduction through 4 layers of conductors is relied on for cooling between shots. The conductor is half inch square, cold worked OFHC copper. Three grades ~~of keystone~~ geometries were used one each for each coil segment. The coil is inertially cooled with options for liquid nitrogen or gaseous Helium cooling between shots. Coolant flows through annular axial channels in the coil formed by the spaces between coil segments. The original design accommodated 30K Helium gas cooling at 15 atmospheres. The present intended cooling scheme is LN2 bath cooling. The cooling scheme has gone through a number of evolutions to match available power supplies and cryogenic services. Midway through manufacture, circumferential grooves were added to the coils, to accommodate bubble clearing in the LN2 bath

SI units

cooling mode, Epoxy impregnation has been performed by Everson-Tesla in Nazareth PA. Mating with the cryostats is being done by CVIP in Emmaus PA. Pre-operational testing of the magnet is being done at MIT in the Pulsed Test Facility (PTF) in 2005. Facility modifications, and the tests are discussed. Testing with the mercury jet cassette is planned at MIT in 2006. The jet system is to be a fully sealed system, minimizing mercury safety concerns.

previously stated in abstract

IV. MAGNET ANALYSIS

A. *Stress Due to Lorentz Forces*

The stresses deviate only slightly from what would be expected of a solenoid. Because the coil is segmented, shear stresses at the ends are relieved. The channel ribs could not support the shear stress if they were bonded. The inner segment is nearly free standing making the radial pressure at the segment 1 to segment 2 interface manageable for the reduced cross section of the ribs.

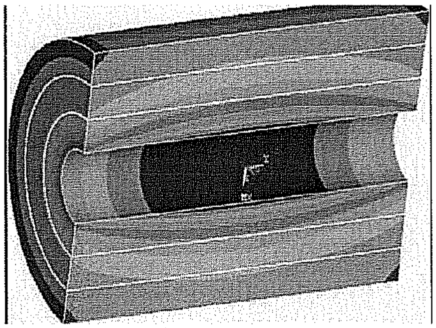

Fig. 5 Coil Von Mises Stress

Stress [illegible]

TABLE 2

II

Stress Summary for ¼ Hard Copper Specified by Everson/Tesla

Location	Load Case	Peak Von Mises Stress	Allowable	Factor of Safety at 100K
ID Seg 1	3 Coils fully energized No Gaps	166 (Tresca) τ_L	270 MPa at 100K 1/4 Hard Copper w/ID CW	1.6
ID Seg 2	3 Coils fully energized w/ Gaps	107	207MPa RT ~250 MPa at 100K, 1/4 Hard Copper	2.33
ID Seg 3	3 Coils fully energized w/ Gaps	40	207MPa RT ~250 MPa at 100K, 1/4 Hard Copper	6.25

Same column

B. *Stress Due to Cooldown Temperature Distribution*

Cooling of the magnet is via the annular gaps between the coil segments. Thermal conduction from the surface of the channels causes a radial gradient in temperature that produces axial tension stresses. The axial tension near the channels is approaching 50 MPa, beyond the design capacity of epoxy systems bonded to copper. Figure 6 shows the stress distribution near the channels. No special surface prep or bonding agent was used on the copper conductor. Kapton strips were placed between every eighth turn in the channel facing layers to provide additional axial strain relief.

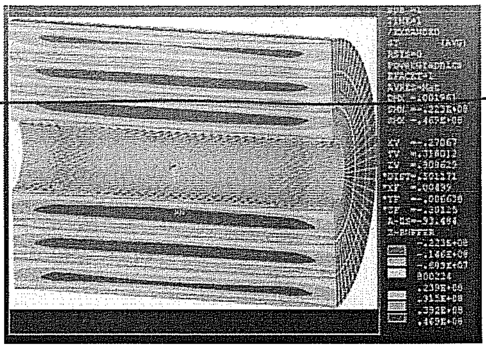

Fig. 6 Axial Stress due to Cooldown

C. *Numerical Simulation of Cooldown Times*

In order to model the transient heat conduction coupled with Helium gas or LN2 channel flow, a finite difference numerical, single purpose program was written. The analysis starts with a specified mass flow which is apportioned to the 4 coolant channels based on the flow area of each channel. Coolant flow characteristics are modeled, including velocity Reynolds number, and surface heat transfer characteristics. Analyses were first performed for Helium axial flow. The program was then modified for forced axial 2 phase Nitrogen flow. . Cooling is actually pool cooling, and relies on circumferential channels to clear bubbles.

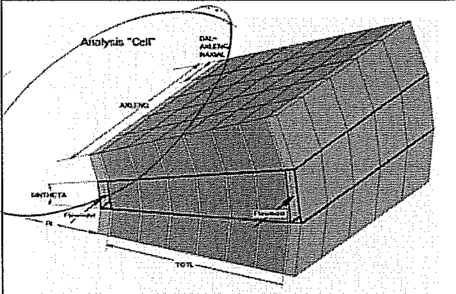

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Fig. 7 Finite Difference Cooldown Model

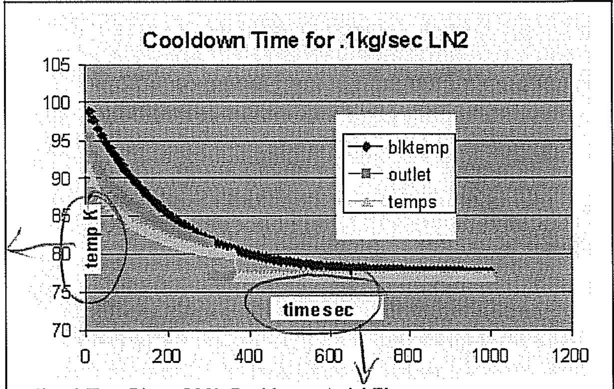

Fig. 8 Two Phase LN2 Cooldown, Axial Flow

V. MAGNET FABRICATION

A. Magnet Winding and Impregnation

Coils were would on a precisely machined mandrel that had a 0.5mm taper on the radius over the length of the coil. They were layer wound on a Broomfield winding machine at Everson-Tesla (E-T). The taper was intended to allow removal of the mandrel via press and/or combinations of coil heating and mandrel cooling. . Epoxy impregnation has been performed by E-T in Nazareth PA. Mating with the cryostats is being done by CVIP in Emmaus PA.

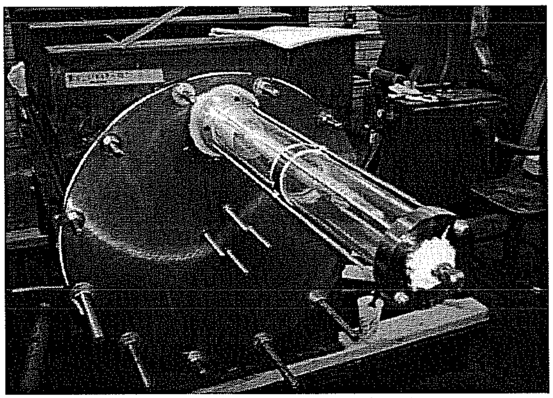

Fig. 9 Segment 1 Impregnation Mold and Site Glass

VI. MAGNET MANUFACTURING CHALLENGES

A. Keystone Effects

The magnet is constructed of three segments. Different anti-keystoning was specified for each of the three segments based on the mid build radius of curvature. Test winding confirmed the spec, but the actual winding produced a larger effect at the ID than was anticipated.

B. Last Turn Wound High, Copper Lost

? Winding and clamping of the last turn proved difficult ant there was a tendency for the last turn to "pop-out" as the lead/joint breakout was formed. This was most pronounced on the inner segment. Machining of the OD of this coil cut away the insulation, and removed some copper cross section. More had to be removed to allow for the coolant channel. The effected area is shown in figure 10. A transient conduction analysis was performed to qualify the loss of metal.

C. Switch from Helium Gas to LN Cooling

The cooling scheme has gone through a number of evolutions to match available power supplies and cryogenic services. In the middle of coil fabrication, the project decided that Helium gas cooling would not be used, and liquid nitrogen would be the preferred method of cooling. Surface heat transfer coefficients for N2 Gas cooling were insufficient to obtain the desired 20 minute cooldown times. Pool boiling coefficients were needed. Provisions were made to fully immerse the coil in LN2 and provide vertical (circumferential) cooling grooves to allow natural circulation flow. Silicon Bands wrapped around the coil formed these grooves and served a second purpose as impregnation dams to preclude epoxy flow around the outside of the coil winding.

D. Dry Spots, Coil 2 and 3 Re-impregnated

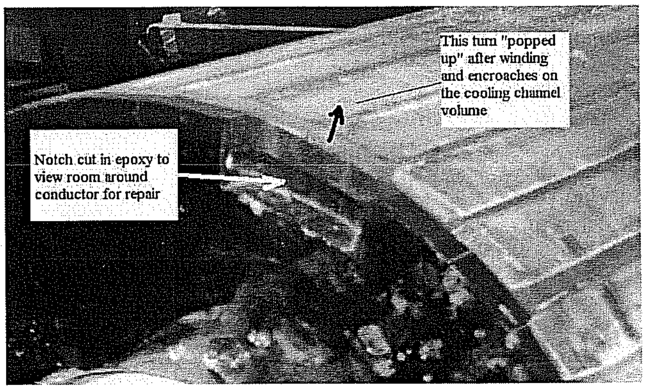

Fig. 10 Area with Lost Copper Cross Section

Grooves in the winding mandrel had been included to provide rotational registration of the three segments. These were intended to engage the axial grooves on the next segment. When the system was converted to LN2 cooling these grooves were partially filled – in segments 2 and three. To allow circumferential flow. The longitudinal grooves in the mandrel provided an epoxy feed when segment 1 was ? impregnated. Epoxy feed for segments 2 and 3 ~~had to~~ come from the coil end, and probably from ~~an imperfectly~~ dammed OD. Coils 2 and 3 had to be re-impregnated with re-machined ID mandrels fitted with an armalon sheet with feed logic ? intended to reach the dry spots

E. Nesting of Coils

Slight variations in the OD machining and molded ID geometry of the coils made nesting the concentric coils a concern and a major milestone in the project. This process was rather dramatic with the inner coils cooled in their impregnation molds with LN2 and the outer coils heated by running current through them from a welding power supply. The warmed coil waqs lowered onto the chilled coil after

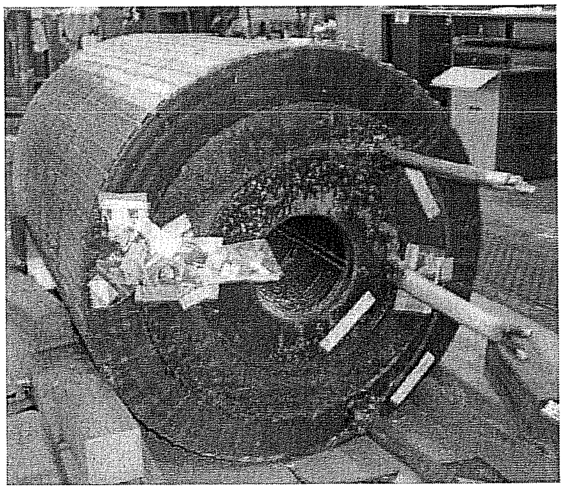

Fig. 11 Nested and Instrumented Coils

quickly removing the impregnation mold. This was successfully done in July 2005

F. *Draining of LN2 Volumes in the Tilted Vessels*

The cryostat included a shroud that was intended to control the axial flow of Helium gas. The shift to LN2 cooling, and the need to tip the axis of the coil up for proper impingement of the proton beam and mercury jet, produced some trapped volumes that would not naturally drain. A drain is being added in the low-end corner of the shroud, and a drain pipe extension is being added to reach the low-end corner of the cryostat so that cryostat pressure will blow out the residual LN2 after the cooldown. Two Capacative level sensors and an array of descrete (Zener Diode based) level sensors has have been added to monitor the LN2 during cooldown, and to verify successful drainage of residual LN2.

G. *Addition of Vessel Fillers*

To reduce the inventory of LN2 that needs to be purged from the vessel between shots, fillers will be added to interior voids not needed for coolant flow. The dished head of the cold vessel represents a large void space that requires a filler. Glass bead filled epoxy is proposed. Unfortunately the dished head had been welded to the cold vessel shell prior to the decision to fill the head, so a larger component will need to be handled when curing the epoxy. The annular space between the cold vessel and magnet shroud will be filled with G-10 Strip

VII. MAGNET PRE-OPERATIONAL TESTING

The tests performed at MIT are intended to first, exercise the magnet to it's design field of 15T, second verify that the cryogenic system can provide a 20 minute cooldown time between experimental pulses – with an additional 10 minute allowance to remove all LN2. The MIT PTF infrastructure will be used to conduct the experiments, including power supplies, controls, data acquisition, and liquid nitrogen supply.

A. *Objectives*

- Demonstrate the capability of the magnet to operate successfully at 15 T
- Characterize the electrical performance of the magnet to verify simulations (measure inductance and resistance of the magnet and demonstrate applicability of the power supply specifications)
- Characterize the cooldown and operating displacements to verify analyses, and provide input to the mercury jet cassette design.
- Characterize the fields in the bore and in the ends of the magnet that might effect the mercury jet behavior

Mercury jet tests in the magnetic field (exclusive of the proton beam) may also be performed at MIT

B. *Cryogenic System for MIT Tests*

The simplest system possible is intended for use at MIT. It has been complicated somewhat by the need to demonstrate that it is possible to restrict the residual LN2 inventory to a small amount. Demonstration of the capability to repetitively pulse and cool within the 30 minute target value is not anticipated. Demonstration of the ability to flush liquid nitrogen in the cold vessel is planned. Measurements of the residual LN2 will be done by a slow measure of the volume and temperature of N2 gas. .

VIII. MERCURY CASSETTE DESIGN

The Mercury system is discussed in greater detail in reference [2]. It consists of a main Mercury hydraulic cylinder which drives the jet, which in turn is driven by a conventional hydraulic system. Testing of the mercury system together with the magnet is expected at MIT in 2006, after the pre-operational testing of the magnet. At CERN as well as at MIT it is advantageous to have the jet system to be a fully sealed system, minimizing mercury safety concerns. The magnet is designed to cluster electrical and cryogenic connections on one end, leaving the other end free for the jet components. One sided entry of the mercury cassette is also needed to avoid breaking the mercury boundary. The jet and magnet must be inclined with respect to the proton beam, and drainage of the mercury jet spray makes it necessary to reverse the pumped flow direction for the jet., Fiberoptic viewing and lighting equipment must also fit within the .16m warm bore, making the cassette that fits into the bore a challenging design effort.

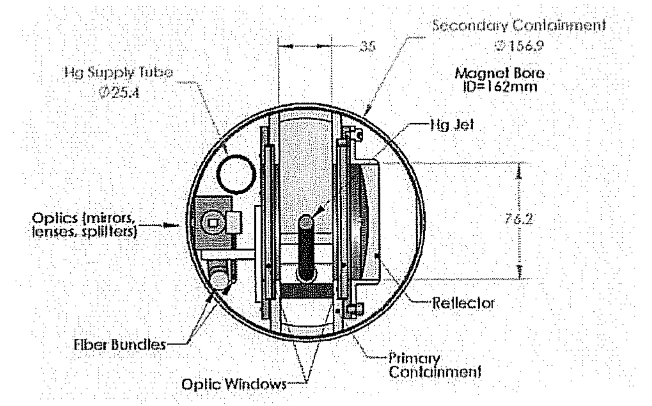

Fig. 12 Cross Section of the Mercury Jet Cassette

The main features of the mercury system that interface with the magnet system are the geometry of the warm bore tube, including alignment; clearances around the vessels; and the magnetic field in and outside the bore. Stray fields outside the main experimental volume were found to excessively load jet hydraulic cylinder components..

To quantify the magnetic loading on the hydraulic components, a non-linear magnetic analysis was performed. An iron cylinder of .6 m length, an inner radius of .1 m and thickness of .05 m was used to model the inventory of magnetic material in the mercury jet system. The air gap between iron cylinder and magnet was varied from .5 to 2.3m in steps of .6m by introducing a series of 4 materials modeling the cylinder that were sequentially made either air or iron. The loads are a very strong function of this air gap. When the gap was reduced to .2 meter, the load was .4MN. Magnet cold mass supports were not designed for large lateral loads. One solution is to increase the air gap separation between the magnet and mercury injection cylinders to a meter or more. The option of using non-magnetic materials for what otherwise would be commercial components may be financially unattractive, but remains an option.

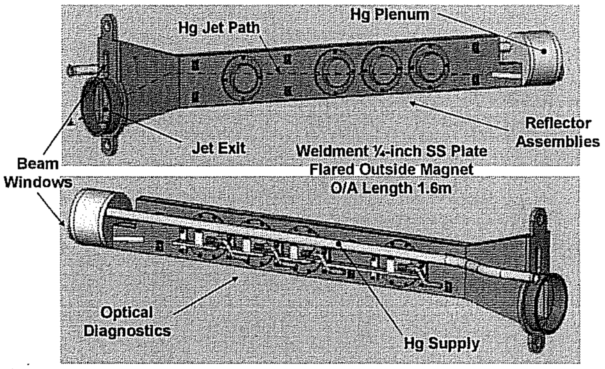

Fig. 13 Cutaway of the Mercury Jet Cassette

IX. TEST ARRANGEMENT AT CERN

The MErcury Intense Target (MERIT) project was officially approved by CERN in April of 2005, and was designated nTOF11. It will be installed in the TT2A tunnel, with Nitrogen gas being vented to the TT10 tunnel. The magnet and mercury cassette are mounted on a common skid. Installation is being studied to verify that the assemblies can be brought in around shielded bends in the tunnels.

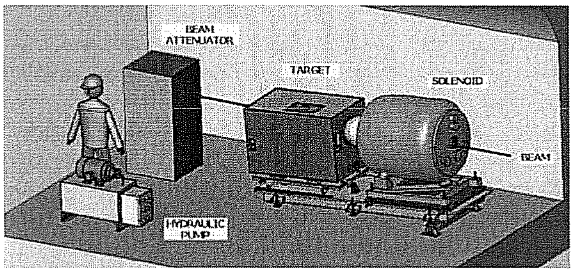

Fig. 14 The MERIT Experiment in the TT-2A Tunnel

X. CURRENT STATUS/CONCLUSIONS

The coils have been wound, impregnated, successfully nested, instrumented, and shipped to the vessel manufacturer. The cryostat and Vacuum jackets are being assembled around the magnet. Many of the vessel sub-components have been fabricated.

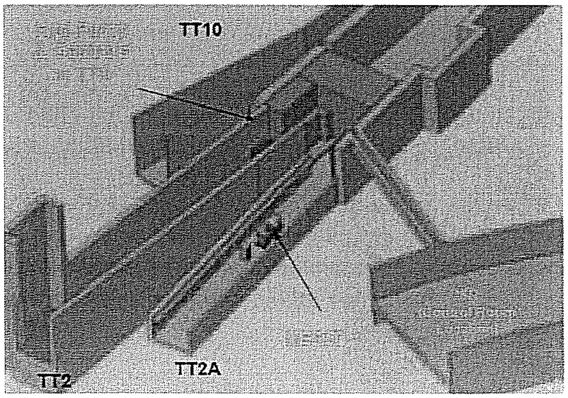

Fig. 15 Location of the MERIT Experiment at CERN

The MIT test cell area has been cleared of large components. The PTF power supply, controls, data acquisition, and over-voltage protection are being upgraded. N2 vent line installation has begun with the roof penetration being installed .

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