A HIGH-FIELD PULSED SOLENOID MAGNET FOR LIQUID METAL TARGET STUDIES

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Abstract

The target system for a muon collider/neutrino factory requires the conjunction of an intense proton beam, a high-Z liquid target and a high-field solenoid magnet. We describe the design parameters for a pulsed solenoid, including the magnet cryogenic system and power supply, that can generate transient fields of greater than 10T with a flat-tops on the order of 1 second. It is envisioned to locate this device at the Brookhaven AGS for proof-of-principle testing of a liquid-jet target system with pulses of 10^{13} protons.

THE TARGETRY CONCEPT

A muon collider or a neutrino factory based on a muon storage ring [1] require intense beams of muons, which are obtained from the decay of pions produced in proton-nucleus collisions. To maximize the yield, pions of momentum near 300 MeV/c should be captured. For proton energies above 10 GeV, the pion yield per unit of proton beam energy is larger for a high-Z target. For proton beam energies in the MW range, beam heating would melt or crack a stationary high-Z target, so a moving target must be used. A mercury jet target is the main focus of BNL E951 [2], although R&D is also being conducted on a carbon target option as might be suitable for a low-energy proton source, and conceptual studies have been carried out for rotating-band targets, a tantalum/water target, and a liquid-lithium target.

The low-energy pions are produced with relatively large angles to the proton beam, and efficient capture into a decay and phase-rotation channel is obtained by surrounding the target with a 20-T solenoid magnet, whose field tapers down to 1.25 T over several meters [3], as sketched in Fig. 1. Pion yield is maximized with a mercury target in the form a 1-cm-diameter cylinder, tilted by about 100 mrad with respect to the magnetic axis. To permit the proton beam to interact with the target over 2 interaction lengths, the proton beam is tilted by 33 mrad with respect to the mercury jet axis.

The use of a mercury jet target raises several novel issues. The rapid energy deposition in the mercury target by the proton beam leads to intense pressure waves that can disperse the mercury. Further, as the mercury enters the strong magnetic field eddy currents are induced in the mercury, and the Lorentz force on these currents could lead to distortion of the jet. On the other hand, the magnetic pressure on the mercury once inside the solenoid will damp mechanical perturbation of the jet. To address these issues an R&D program is now underway.

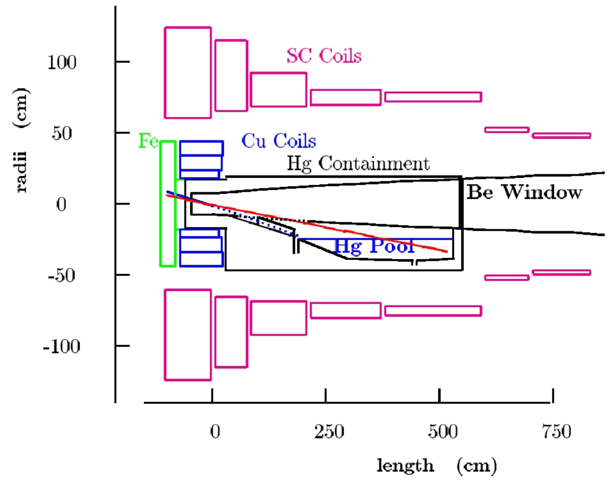

Figure 1: Concept of targetry based on a mercury jet and proton beam at 100 mrad and 66 mrad, respectively, to the axis of a 20-T solenoid magnet.

THE TARGETRY R&D PROGRAM

In the USA, R&D on targetry for a neutrino factory and muon collider has been formalized as BNL experiment 951 [2]. This project maintains close contacts with related efforts in Europe [4] and in Japan [5].

The broad goal of E951 is to provide a facility that can test all the major of a liquid or solid target in intense proton pulses and in a 20-T magnetic field.

Present E951 activities focus on the interaction of intense proton pulses with targets in zero magnetic field. European targetry studies have emphasized the interaction of mercury jets with a magnetic field, the operation of rf cavities near high-power targets, and target material evaluation.

Mercury Jet + Proton Beam

The present R&D program on mercury jets is an outgrowth of work at CERN in the 1980's in which a prototype mercury jet was prepared, but never exposed to a beam.

Experiment 951 is conducted in the A3 beamline of the BNL AGS into which a single bunch of up to 5×10^{12}

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24-GeV protons can be extracted and brought to a focus as small as 0.6×1.6 mm^2. The dispersal of both static and moving mercury targets by the proton beam was observed via two high-speed cameras using shadow photography. The principal results obtained thus far are summarized elsewhere [6]. Figure 2 shows results from a mercury target that was exposed to pulses of 2-4×10^{12} 24-GeV protons. Dispersal velocities of up to 15 m/s were observed. A key result is that the dispersal of mercury was confined to that part of the jet directly intercepted by the proton beam.

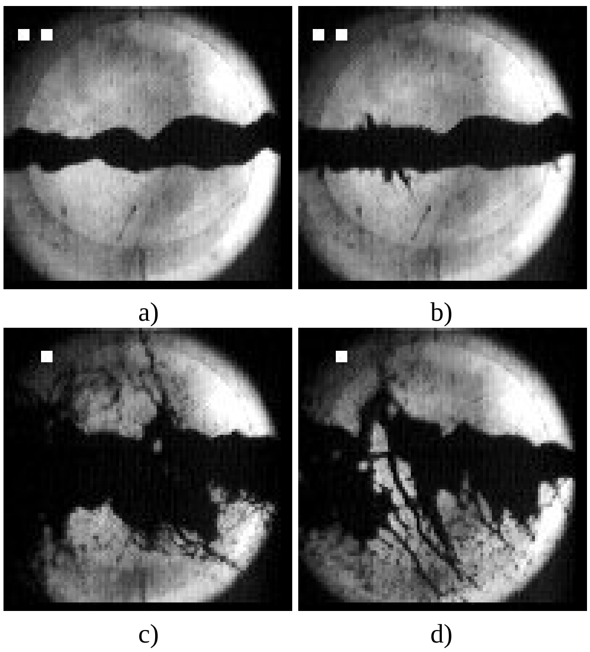

Figure 2: Hg jet interaction with 3.8×10^{12} 24-GeV protons; $t =$ a) 0 ms; b) 0.75 ms; c) 10 ms; d) 18 ms.

Thus, it appears that the dispersal of mercury by a proton beam is dramatic, but not violent, and that the dispersal will be a relatively modest issue for a target facility that operates at 15 Hz.

Mercury Jet + 15-T Magnet

A 4-mm-diameter mercury jet of velocity 12 m/s has been injected int a 15-T magnet [6] with typical results as shown in Fig. 3. By placing the nozzle of the jet well into fringe field of the magnet, disruptive effects of eddy currents are avoided. Furthermore, the high magnetic pressure of the central field suppresses the Rayleigh instability of the jet, in comparison to the case of zero field.

Mercury Jet + Proton Beam + 15-T Magnet

Having conducted successful tests of the separate interaction of a mercury jet with a proton beam, and with a 15-T magnet, the next step is a combined test of mercury jet plus intense proton beam plus a 15-T magnet, in a configuration prototypical of that suitable for a neutrino factory or muon collider.

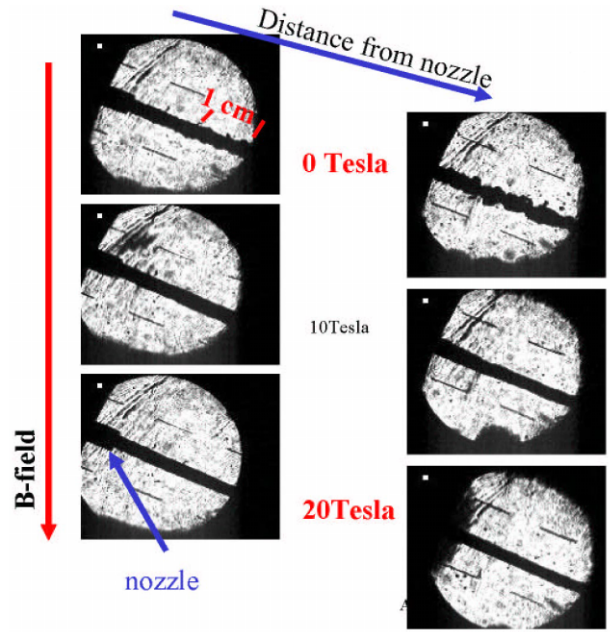

Figure 3: The Rayleigh instability of a mercury jet is suppressed by high magnetic fields.

A design of a 15-T pulsed solenoid magnet for this purpose has been completed [3, 7], as illustrated in Figs. 4-7. The copper coils are cooled by liquid nitrogen to reduce their resistance, and hence the power requirements [8]. The time dependence of key magnet parameters during pulse are illustrated in Fig. 4.

The magnet consists of 3 concentric copper coils, mounted inside a common cryostat, as shown in Fig. 5. Extensive ANSYS simulations have been made of the mechanical and thermal performance of the magnet [7], some of which are summarized in Fig. 6. The cooling scheme for the coils is illustrated in Fig. 7.

The pulsed magnet system is intended to be operated for less than 1,000 pulses, including checkout as well as data taking with proton beams. As such, it appears most cost effective to provide the 4.5-MW pulsed power with an array of batteries, rather than a rectified DC power supply.

Construction of this magnet system is expected to begin later this year, and could be completed in 3 years.

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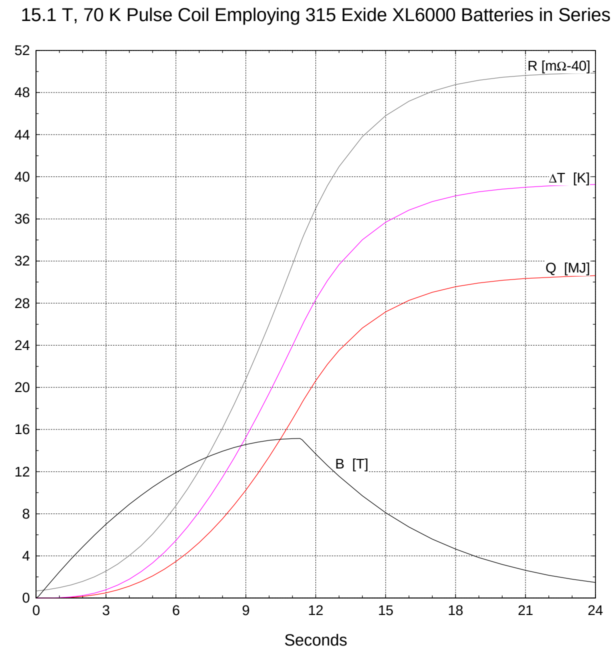

Figure 4: Behavior of the 15-T magnet during a pulse. The peak current is 7200 A at a peak voltage of 600 V. Approximately 30 MJ of energy is dissipated in the magnet, which raises its temperature from 70 to 110K.

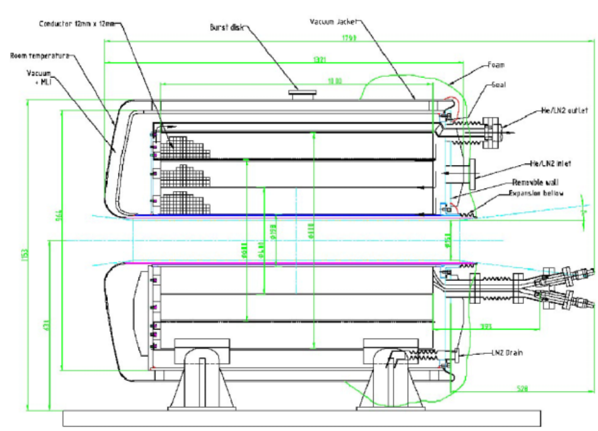

Figure 5: Longitudinal cross section of the 15-T pulsed magnet, showing the 3 coil packages and cryostat [7].

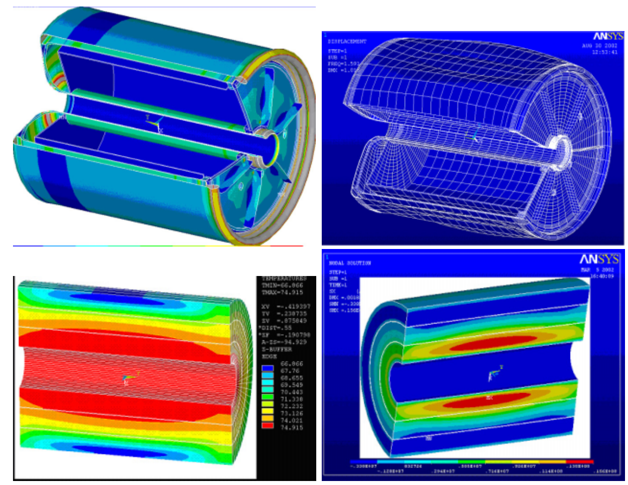

Figure 6: Top: structural analysis of the cryostat. Bottom: thermal and structural analysis of the coils. From [7].

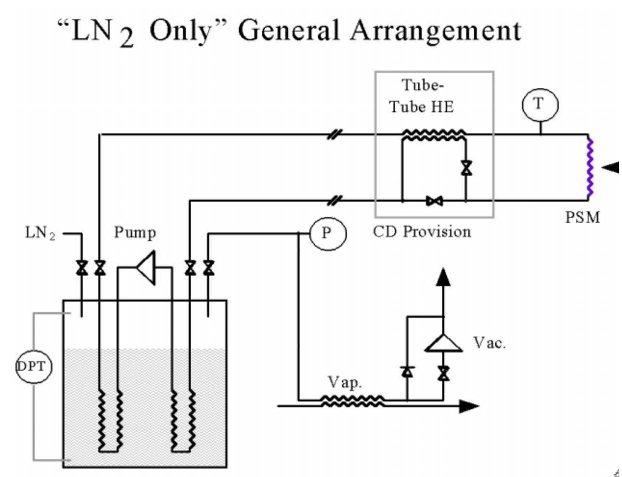

Figure 7: Scheme for cooling the pulsed magnet via flow of He gas that passes through a LN_2 heat exchanger [8].

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