The MAP Target System R&D Program

August 15, 2010

Abstract

We outline a program of engineering design and simulation for a target station and pion production/capture system for a 4-MW proton beam at the front end of a Muon Collider or a Neutrino Factory. The target system consists of a free liquid-mercury jet immersed in a high-field solenoid magnet capture system that also incorporates the proton beam dump.

1 Introduction: the Target System Baseline

The requirements for a Muon Collider/Neutrino Factory [1] (some of which are summarized in Table 1) call for a target capable of intercepting and surviving a 4-MW pulsed (15–50 Hz) proton beam. The target, the proton beam dump, and a shield/heat exchanger are to be located inside a channel of superconducting solenoid magnets (see Fig. 1) that capture, confine and transport secondary pions and their decay muons, of energy 100–400 MeV, to the bunching, phase-rotation, cooling and acceleration sections downstream. Most of the 4-MW beam power is dissipated within a few meters of the target, i.e., inside the solenoid channel, which presents a severe challenge that has only been partially addressed to date [2]. Rather, the main effort over the past decade has been in exploring a concept for the target and, to a lesser extent, the proton beam dump.

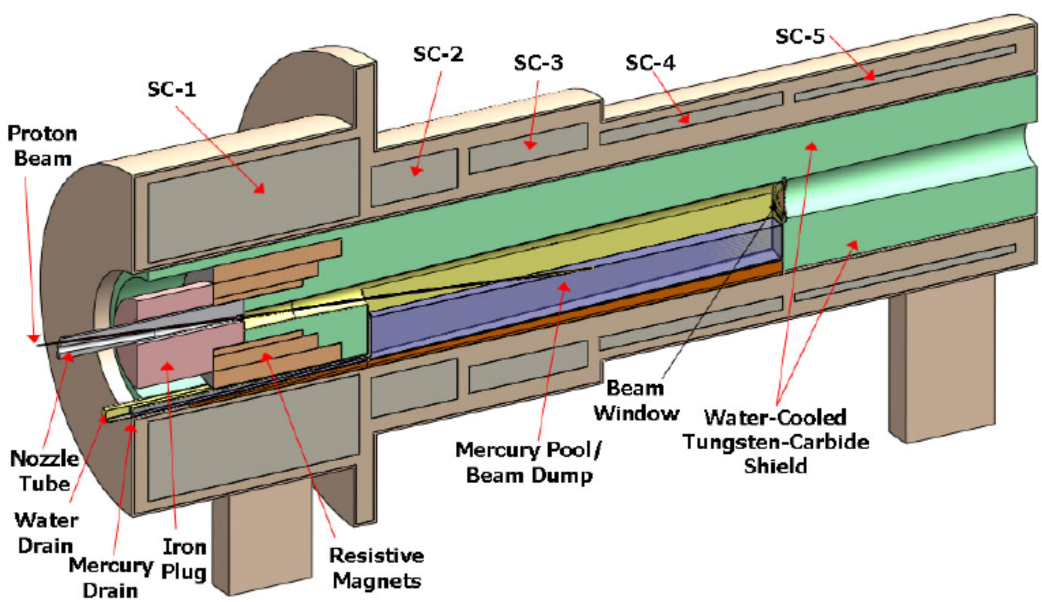

Fig. 1. Baseline target-system concept.

Table 1. Baseline proton beam parameters.

Parameter	Value
Proton beam energy	8 GeV
Repetition rate (Neutrino Factory)	50 Hz
Repetition rate (Muon Collider)	15 Hz
Bunch structure (Neutrino Factory)	3 bunches, 200 μs total
Bunch structure (Muon Collider)	1 bunch
Bunch length	2 ± 1 ns
Beam radius	1.2 mm (rms)
Beam power	4 MW (3.125×10^{15} protons/s)

Maximal production of low-energy pions is obtained with a proton beam of 1–2 mm (rms) radius and a target of radius 2.5 times this value, such that the secondaries exit the side of the target rather than its end.[2] The resulting high density of energy deposition in the target makes it questionable whether any passive solid target could survive at 4-MW beam power. Schemes for a set of moving solid targets are not very compatible with the surrounding solenoid magnets. Hence, the baseline target concept [3] is for a free liquid-mercury jet target.* The present baseline parameters of the target are summarized in Table 2.

Table 2. Baseline target parameters.

Parameter	Value
Target type	Free mercury jet
Jet diameter	8 mm
Jet velocity	20 m/s
Jet/solenoid axis angle	96 mrad
Proton beam/solenoid axis angle	96 mrad
Proton beam/jet angle	27 mrad
Capture solenoid (SC-1) field strength	20 T

This target concept has been validated by R&D over the past decade, culminating in the MERIT experiment [4] that ran in the Fall of 2007 at the CERN PS. The experiment benefited from the intensity of the beam pulses (up to 30×10^{12} ppp) and the flexible beam structure available for the extracted PS proton beam. Key experimental results include demonstration [5] that:

- The magnetic field of the solenoid greatly mitigates both the extent of the disruption of the mercury and the velocity of the ejected mercury after interception of the proton beam. The disruption of a 20-m/s mercury jet in a 20-T field is sufficiently limited that 70-Hz operation is feasible without loss of secondary particle production.

* The intense pressure waves in a liquid target due to a pulsed beam lead to damage/failure of any pipe that contains the liquid in the interaction region. Thus, the baseline is for a free liquid jet.

- Individual beam pulses with energies up to 115 kJ can be safely accommodated.
- Subsequent proton beam pulses separated by up to 350 μs have the same efficiency for secondary particle production as does the initial pulse.
- Two beam pulses separated by more than 6 μs disrupt the mercury independently.

The mercury jet is collected in a pool (which also serves as the proton beam dump) inside the solenoid magnet channel, as shown in Fig. 1. Disruption of this pool by the mercury jet (whose mechanical power is 20 kW) and by the non-interacting part of the proton beam is nontrivial, and needs further study.

The superconducting magnets of the target system must be shielded against the heat and the radiation damage caused by secondary particles from the target (and beam dump). A high-density shield is favored to minimize the inner radii of the magnets. The baseline shield concept is for water-cooled tungsten-carbide beads inside a stainless steel vessel (of complex shape, as indicated in Fig. 1). However, issues remain with the present baseline concept, and effort is needed to address these.

The solenoid magnets of the target system vary in strength from 20 T (SC-1 in Fig. 1) down to 1.5 T in the subsequent constant-field transport channel. This adiabatic reduction in field strength permits the solenoid magnet string to reduce the rms emittance of the secondary particles. [6]† A peak field of 20 T in magnet SC-1 provides good capture of the secondary pions. Further study is warranted to optimize the capture channel design (which improves with the use of a higher initial field).

A 20-T field is beyond the capability of Nb_3Sn, so magnet SC-1 is proposed as a hybrid of a 14-T superconducting coil with a 6-T hollow-core copper solenoid insert. A 45-T solenoid of this type of construction has been operational since 2000 at the National High Magnetic Field Laboratory [7], and a 19-T magnet of this type with 16-cm-diameter bore exists at the Grenoble High Magnetic Field Laboratory [8] (and was used in an earlier phase [9] of our R&D program). A topic for further study is possible fabrication of SC-1 as a high-T_c magnet with no copper solenoid insert, which could provide more space for internal shielding of SC-1 and/or permit operation at a higher field for improved capture.

The target system (and also the subsequent π/μ solenoid transport channel) will be subject to considerable activation such that, once beam operation begins, all subsequent maintenance must be performed by remote-handling equipment. The infrastructure associated with the target hall, including its remote-handling equipment and hot cells for eventual processing of activated materials, will be the dominant cost of the target system.

2 Future Plans

The target system comprises subsystems with a wide variety of issues that deserve further study, via simulation, engineering design, and hardware testing, as reviewed briefly below. The interrelated character of these issues is such that they cannot be addressed separately, but rather via an integrated design effort.

† The "true" emittance of a beam cannot be reduced by non-dissipative elements such as magnets, but the rms emittance can be reduced by magnets when, as in the present case, it greatly exceeds the "true" emittance.

2.1 **Simulations and Engineering Design**

2.1.1 **Mercury-Jet–Proton-Beam Interactions in a Magnetic Field**

Simulation of the interaction of a free mercury jet in a magnetic field when subjected to intense, pulsed energy deposition by a proton beam is a state-of-the-art problem in computational physics. For several years, R. Samulyak of SUNY Stony Brook has led an effort to enhance the FronTier code to address this challenging problem [10], with increasingly sophisticated results. An example is shown in Fig. 2 of how high magnetic fields suppress the disruption of a mercury jet. Effort is ongoing to simulate one of the subtler effects of the mercury-beam interaction—the apparent (transient) reduction in the speed of sound within the mercury after a beam pulse.

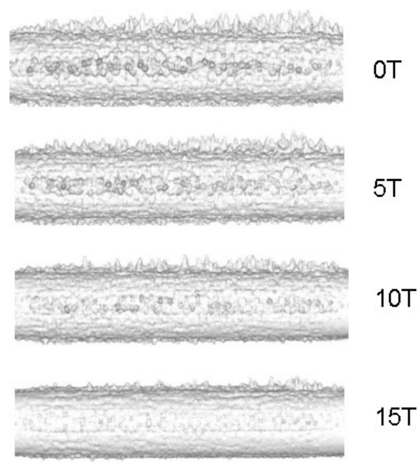

Fig. 2. FronTier [10] simulation of the suppression of filamentation of a mercury jet by high magnetic field.

2.1.2 **High-Reynolds-Number Flow of Mercury from a Nozzle**

One aspect of the MERIT experiment that deserves further study is that the quality of the 1-cm-diameter mercury jet at 15–20 m/s velocity was rather poor. [5] To address this, a program of simulation has recently begun, led by F. Ladiende of SUNY Stony Brook. It is too early to report results of this effort, other than preliminary studies of the flow of mercury in the piping that fed the nozzle in the MERIT experiment, an example of which is shown in Fig. 3. [11]

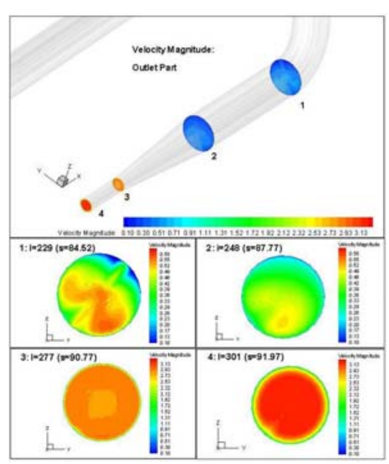

Fig. 3. Velocity profiles at four sections near the nozzle of the MERIT mercury delivery pipe. [11]

2.1.3 **Solid-Target Options**

It is prudent to maintain some level of effort for solid-target options, such as a radiation-cooled graphite or beryllium target that would be replaced every few weeks. More speculative options include a flowing tungsten-powder target [12] and a rotating band of tungsten targets [13].

2.1.4 **Optimization of Pion Production in the Target**

Many factors influence pion production in the target, including proton beam energy, target material, target radius, target length, and target and beam angles with respect to the magnetic axis. Simulations of pion production at the target station of a Muon Collider have been performed using the MARS code [14] since at least 1997 [15], and must be continued with greater sophistication in order to optimize the various parameters.

It is worth noting that the simulations of particle production in the target rely on extrapolations from experimental data that contain some inconsistencies [16] in the region of parameter space of interest to the Muon Collider or Neutrino Factory. Assessment of the seriousness of this issue in ongoing. The Fermilab MIPP experiment [17] affords an opportunity to investigate this issue further and, to this end, the MIPP proponents have recently proposed to study particle production from a mercury target. Such data would, of course, be of great interest to MAP.

2.1.5 **Proton Beam Dump**

One of the many challenges of the Muon Collider/Neutrino Factory target system is the placement of the proton beam dump inside the superconducting magnet channel. The baseline design is to use the pool that collects the mercury from the target jet as the beam dump. This concept leads to substantial challenges due to the perturbation of the pool by the jet and beam (Fig. 4) [18], and due to the flow of mercury out of the target system [19].

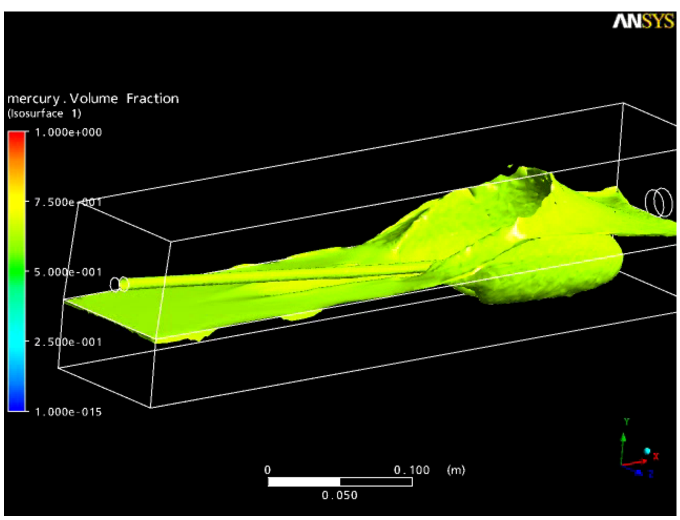

Fig. 4. ANSYS simulation [18] of a mercury jet entering a mercury pool.

2.1.6 **The Internal Shield**

A major challenge of the target system is to dissipate 4 MW of beam power inside the superconducting magnet string without either quenching the magnets or drastically shortening their operational lives due to radiation damage. Space is very limited for the shield, and the geometry is awkward as the shield envelops the mercury pool and the copper magnet (see Fig. 5). The shield must be cooled by a liquid; water is assumed in the baseline scenario, but mercury remains an option.

The baseline shield scenario uses tungsten-carbide beads cooled by water. Unfortunately, initial calculations assumed an effective density of the beads (80% that of tungsten-carbide) that cannot be achieved with beads of a single radius. Use of multiple bead radii or tungsten-carbide sheets with machined micro-channels raises issues of whether a water-flow rate sufficient to keep the water from completely vaporizing in portions of the shield is achievable. Furthermore, the coolant must enter and exit the system from the upstream end, where the shield cross section is much smaller than at its downstream end. To address this issue, and to consider alternatives [20] with, say, tantalum shielding with long channels for the coolant, or shielding with mercury, simulations of heat transfer in complex geometries are required. We are presently exploring the prospect of such simulation with the Peles group at RPI [21]. Initial simulations using the MARS15 code indicate that the current shielding approach would result in ~25 kW of power being deposited within magnet SC-1 alone [22]. This is not considered acceptable and must be addressed. The search for a solution is complicated by the present lack of clear criteria on how much shielding is required for viable operation of the superconducting magnets in the presence of pulsed heating and radiation damage from secondary particles from the target.

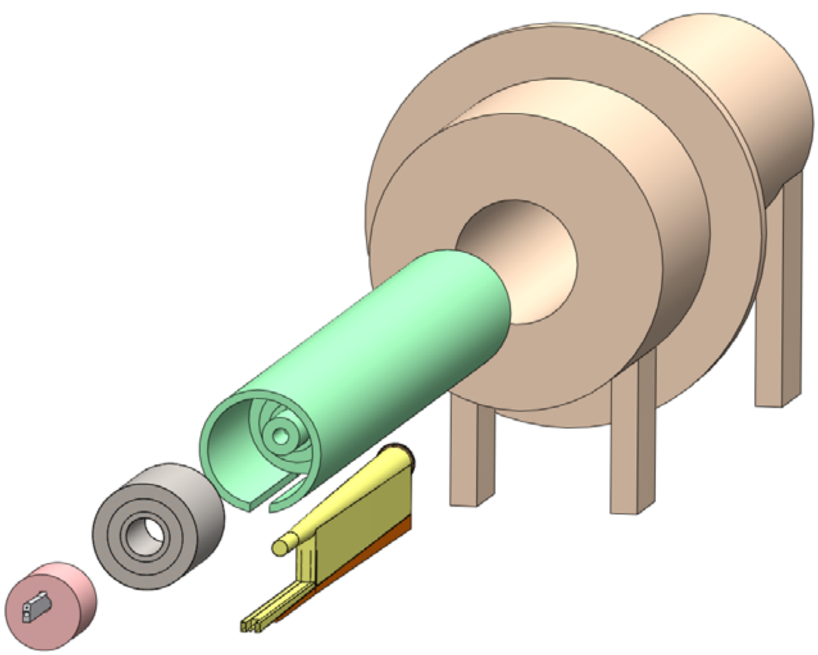

Fig. 5. Tentative scenario [19] for assembly of the iron plug, the copper magnet, the mercury collection chamber and the internal shield within the target system magnets.

2.1.7 **Magnet Design**

The design of the first magnet, with a baseline field of 20 T is challenging. The use of a 6-T water-cooled, hollow-conductor copper solenoid insert is required if the superconducting outsert is to be made from Nb_3Sn. This copper magnet receives a very high radiation dose (while acting as a partial shield of the superconducting outsert) and is anticipated to be a replaceable component with a lifetime of 4 years or less. If the presence of this copper magnet leads to a requirement for thicker shielding and a concomitant increase in inner diameter of the superconducting outsert, we must consider the option of using only a 14-T Nb_3Sn magnet, or development of a large-bore high-T_c magnet, or more likely a high-T_c–Nb_3Sn hybrid [23]. Tests of YBCO indicate that it has good resistance to radiation damage [24].

Another issue is the very large axial forces between the various magnets of the target system. A further complication is the requirement that the axial field profile in the beam-jet interaction region be smooth, such that the mercury jet is minimally perturbed as it enters this field. The baseline scenario calls for an iron plug at the upstream end of the first magnet, through which the proton beam and mercury jet enter. The presence of this plug adds considerable complexity to the mechanical design of the system.

2.1.8 **Optimization of Emittance Reduction by the Target System Magnets**

If a secondary beam is created in a region of high magnetic field, and transported through a region of adiabatically reduced field, then, in principle, both the longitudinal and transverse emittance can be reduced [6]. The baseline design of the target system, in which the field drops from 20 T to 1.5 T over 12 m, provides such rms emittance reduction (or alternatively, permits capture of a larger number of secondary pions into the aperture of the 1.5-T solenoid transport channel). A global optimization of the target system plus capture channel magnetic fields remains to be performed.

While better performance can be obtained with a higher field than 20 T in the first target-system magnet (SC-1), engineering reality may require us to use a lower field. A related issue is the rapidity of the reduction of the field strength from 20 T to 1.5 T. The effect of the transverse-momentum "kick" on the muons in the decay $\pi \to \mu\nu$ is less if the decay occurs in a higher magnetic field, which may favor a slower falloff of field with position than in the present baseline.

2.1.9 **Mercury Flow Loop, Remote Handling Maintenance Systems, Target Hall**

Before building a target system for a Muon Collider or Neutrino Factory, substantial effort will be needed on the engineering of infrastructure issues such as the target hall, the remote handling systems for maintenance, and the mercury flow loop.

2.2 **Hardware R&D**

2.2.1 **Nozzle Tests**

As previously mentioned, the performance of the 1-cm-diameter nozzle for the mercury jet in the MERIT experiment was poorer than desired at jet velocities of 15–20 m/s. A program of simulation and design is therefore under way with the goal of developing a better nozzle. In practice, this issue cannot be left only to design, but must be addressed in laboratory tests once a revised design is developed. The nozzle tests must be performed with mercury, but neither a proton beam nor a magnetic field are needed.

2.2.2 **Splash Mitigation in the Mercury Collection Pool/Proton Beam Dump**

Another difficult hydrodynamic issue is the perturbation of the mercury collection pool by the impinging mercury jet (and to a lesser extent by the non-interacting proton beam). Once a candidate design for splash mitigation has been well simulated, it will be desirable to test this in the laboratory. Again, the tests can be conducted without magnetic field or proton beam, but with a quasi-continuous mercury jet of 20 m/s.

2.2.3 **Coolant Flow in the Internal Shield**

It would be prudent to test the coolant flow patterns in a full size mockup of the shield geometry to ensure that there are no restricted-flow regions.

3 Summary

The design of the target system encompasses a suite of engineering requirements, for the mercury nozzle, the beam dump, the internal shield, the solenoid magnets, the mercury supply loop, remote handling and the target hall, all of which interact. Among the diverse disciplines involved are cryogenics, magnet design, mechanical engineering, fluid flow, and thermal management. Other activities requiring attention include magnetohydrodynamics studies to advance our understanding of the complex dynamics of the Hg jet in a strong magnetic field and an intense proton beam, pion-yield optimization (coordinated with the parameters of the entire Muon Collider/Neutrino Factory front end), and possibly even additional pion-yield measurements.

References

[1] M.M. Alsharo'a *et al.,* Status of Neutrino Factory and Muon Collider Research and Development and Future Plans, Phys. Rev. ST Accel. Beams **6**, 081001 (2003).

[2] X. Ding *et al.,* A Pion Production and Capture System for a 4 MW Target Station, Proc. 2010 Int'l. Part. Accel. Conf. (Kyoto), THPEC102, http://www.hep.princeton.edu/~mcdonald/mumu/target/ipac10/thpec092.pdf

[3] S. Ozaki *et al*., Feasibility Study II of a Muon-Based Neutrino Source (June 14, 2001), http://www.cap.bnl.gov/mumu/studyii/FS2-report.html

[4] J.R.J. Bennett *et al.,* Studies of a Target System for a 4-MW, 24-GeV Proton Beam, proposal to the ISOLDE and Neutron Time-of-Flight Experiments Committee, CERN-INTC-P-186 (April 26, 2004), http://www.hep.princeton.edu/~mcdonald/mumu/target/cern_proposal.pdf

[5] K.T. McDonald *et al.,* The MERIT High-Power Target Experiment at the CERN PS, Proc. 2009 Part. Accel. Conf. (Vancouver, Canada), TUGRI03, http://www.hep.princeton.edu/~mcdonald/mumu/target/pac09/tu4gri03.pdf

[6] K.T. McDonald, The Capture Solenoid as an Emittance-Reducing Element (Jan. 14, 2010), http://www.hep.princeton.edu/~mcdonald/mumu/target/targettrans72.pdf

[7] 45-T Hybrid, NHMFL, http://www.magnet.fsu.edu/mediacenter/features/meetthemagnets/hybrid.html

[8] Magnet M8, GHMFL, http://ghmfl.grenoble.cnrs.fr/spip.php?rubrique77&lang=en

[9] A. Fabich, High Power Proton Beam Shocks and Magnetohydrodynamics in a Mercury Jet Target

for a Neutrino Factory, Ph.D. thesis (U. Vienna, Nov. 2002), http://www.hep.princeton.edu/~mcdonald/mumu/target/thesis-2002-038.pdf
[10] R. Samulyak *et al.,* Computational algorithms for multiphase magnetohydrodynamics and applications to accelerator targets, submitted. to Cond. Matter Phys. (July 6, 2010), http://www.hep.princeton.edu/~mcdonald/examples/accel/samulyak_cmp_10.pdf
[11] Y. Zhan, Hg Supply Piping Simulation (No MHD) (Jan. 29, 2010), http://www.hep.princeton.edu/~mcdonald/mumu/target/Yan/yan_070210.pdf**;** W. Li and F. Ladiende, Mercury Flow through a Long Curved Pipe (Jan. 26, 2009), http://www.hep.princeton.edu/~mcdonald/mumu/target/Ladiende/Results-Summary.pdf.
[12] C. Densham, The Potential of Fluidised Powder Target Technology in High Power Accelerator Facilities, Proc. 2009 Part. Accel. Conf. (Vancouver), WE1GRC04, http://www.hep.princeton.edu/~mcdonald/mumu/target/pac09/WE1GRC04.pdf
[13] T.R. Edgecock *et al.,* Overview of Solid Target Studies for a Neutrino Factory, Proc. 2010 Int'l. Part. Accel. Conf. (Kyoto), THPEC089, http://www.hep.princeton.edu/~mcdonald/mumu/target/ipac10/thpec089.pdf
[14] The MARS Code System: http://www-ap.fnal.gov/MARS/
[15] N.V. Mokhov and A. Van Ginneken, Pion Production and Targetry at $\mu^+\mu^-$ Colliders, (Dec 17, 1997), AIP Conf. Proc. 441, 320 (1998), http://www.hep.princeton.edu/~mcdonald/examples/accel/mokhov_aipcp_441_320_98.pdf
[16] J. Strait, N. Mokhov and S. Striganov, Comparisons between MARS and HARP Data (July 24 2009), http://www.hep.princeton.edu/~mcdonald/mumu/target/Strait/strait_marsvsharp.pdf.
[17] The MIPP Experiment (Fermilab E-907), http://ppd.fnal.gov/experiments/e907/.
[18] T. Davenne et al., Mercury Beam Dump Simulations (Dec. 15, 2008), http://www.hep.princeton.edu/~mcdonald/mumu/target/Davenne/davenne_121708.pdf
[19] V.B. Graves and C. Caldwell, Neutrino Factory Target Cryostat Review (Aug. 12, 2010), http://www.hep.princeton.edu/~mcdonald/mumu/target/graves/graves_081210.pdf
[20] K.T. McDonald, Materials for the Target System Internal Shield (June 29,2010), http://www.hep.princeton.edu/~mcdonald/mumu/target/targettrans74.pdf
[21] A. Peles, http://www.rpi.edu/~pelesy/lib/research_interests.htm .
[22] See, for example, X. Ding, Comparison of Power Depositions in SC1 Coil (June 29, 2010), https://pubweb.bnl.gov/~kirk/Target_Studies/2010_06_29/xding_ED.ppt .
[23] R.C. Gupta, private communication (Aug. 13, 2010).
[24] R.C. Gupta *et al.*, HTS for Magnets in High Radiation Enviornments (June 18, 2010), http://www.bnl.gov/magnets/Staff/Gupta/Talks/cimtec/cimtec2010-%20FK-7.pdf .