The Muon Collider/Neutrino Factory Target R&D Plan

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1. Updating the Target-System Baseline

The present target-system baseline was established in 2001 during the Neutrino Factory Feasibility Study II,[1] and is sketched in Fig. 1. It consists of a pulsed, 4-MW proton beam incident on a free mercury jet target that flows at 20 m/s inside a 20-T solenoid capture magnet. The mercury is collected in a pool, that also serves as the proton beam dump, before recirculating. A window, through which the desired secondary pion beam exits, isolates the mercury volume from the downstream pion transport. The 20-T magnet is a combination of a 14-T superconducting outsert and a 6-T hollow-copper conductor insert. An iron plug smoothes the field profile at the upstream end of the 20-T magnet to limit the perturbation of the incoming mercury jet, which flows at an angle to the magnetic axis. A subsequent string of superconducting magnets tapers the field strength down to 1.5 T in the pion-decay and bunching/phase rotation channel (not shown). These superconducting magnets are protected by a shield of water-cooled tungsten-carbide beads against the thermal load and the radiation damage induced by secondary particles.

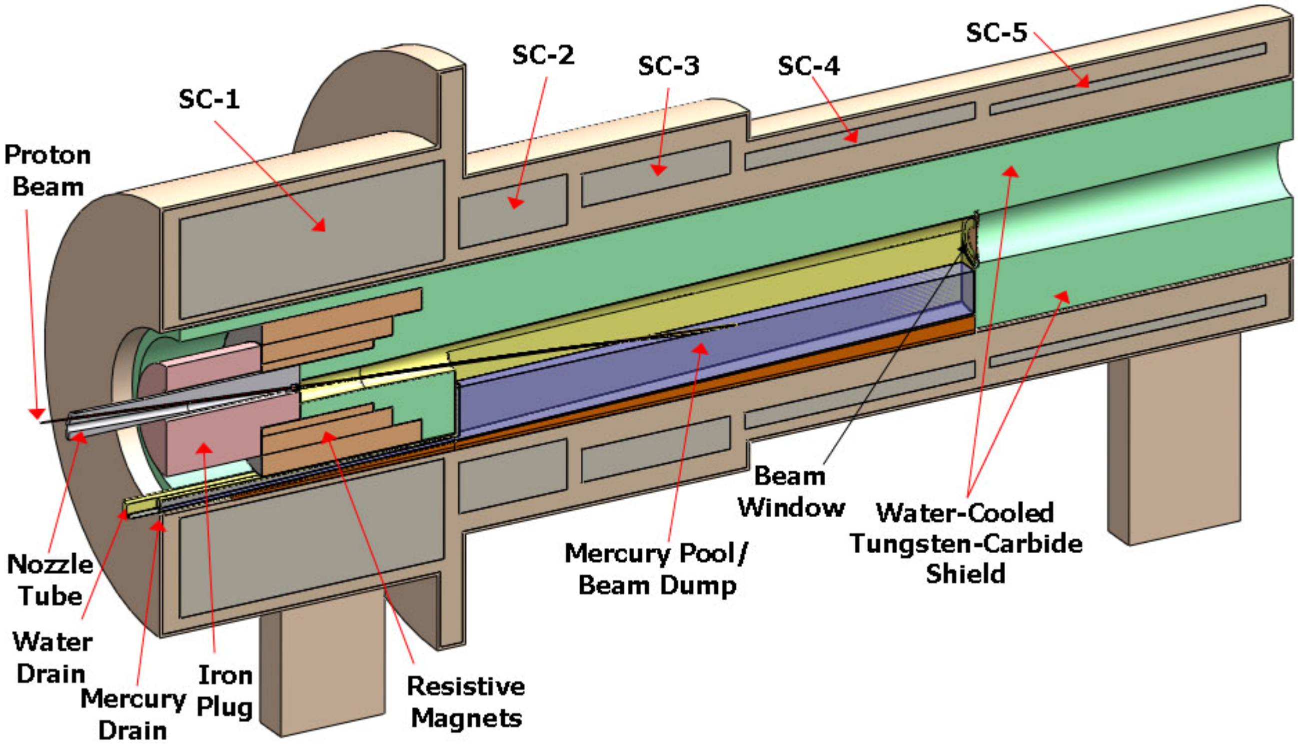

Fig. 1. Baseline target-system concept.

While this baseline concept remains sound, and the use of a free mercury jet validated by the CERN MERIT experiment,[2] the details of this concept should be updated to insure a robust, buildable design. A step in this direction has recently been taken in the context of the Interim Design Report of the International Design Study for a Neutrino Factory,[3] but detailed technical justification of the updates will not be available at the time of release of this Report (Dec. 2010). Rather, such technical understanding of a revised target-system baseline is to be that main theme of target-system R&D in the Muon Accelerator Program[4] over then next several, as delineated below.

2. **Target R&D**

The target system (Fig. 1) is comprised of subsystems with a wide variety of issues that deserve further study, via simulation, engineering design, and hardware testing, as reviewed briefly below in this section. The interrelated character of these issues is such that they should not be addressed separately, but rather via an integrated design effort led by a physicist and a (chief) engineer.

2.1. Simulations and Engineering Design

2.1.1. Mercury Jet-Proton Beam Interactions in a Magnetic Field

Simulation of the interaction of behavior of a free mercury jet in a magnetic field when subject 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 SUNT Stony Brook has led an effort to enhance the so-called FronTier code to address this challenging problem,[5] with increasingly sophisticated results. An example is shown in Fig. 2 of how high magnetic fields suppress the disruptions 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.

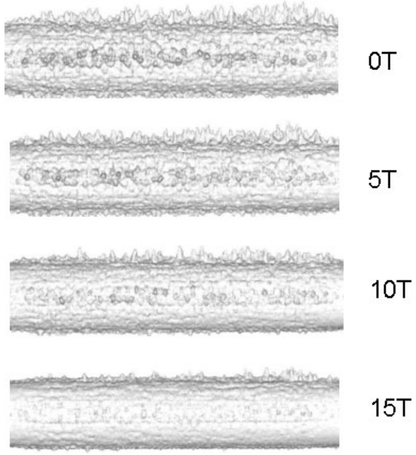

Fig. 2. FronTier simulation of the suppression by high magnetic field of filamentation of a mercury jet.[5]

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.[2] To address this issue 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, one plot of which is shown in Fig. 3.[6]

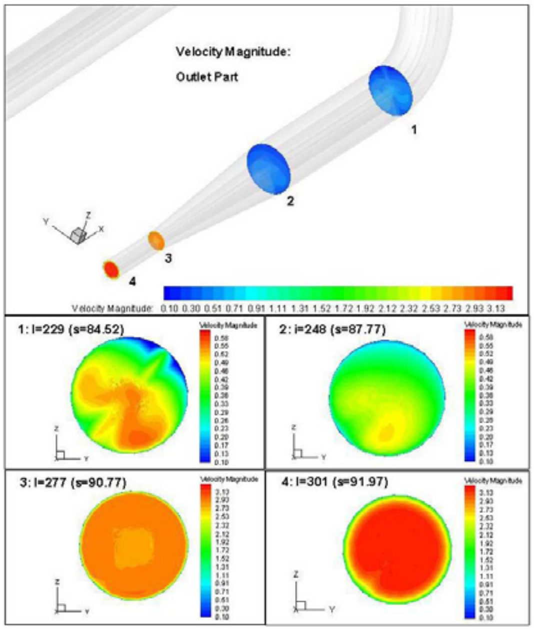

Fig. 3. Velocity profiles at four sections near the nozzle of the MERIT mercury delivery pipe.[6]

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-power target,[7] and a rotating band of tungsten targets.[8]

2.1.4. Optimization of the Pion Production in the Target

Many factors influence the pion production in the target: proton beam energy, target material, target radius, target length, 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[9] since at least 1997,[10] and need to be continued with greater sophistication so as to optimize the various relevant parameters.

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 as to the perturbation of the pool by the jet and beam (Fig. 4),[11] and to the flow of the mercury out of the target system.[12]

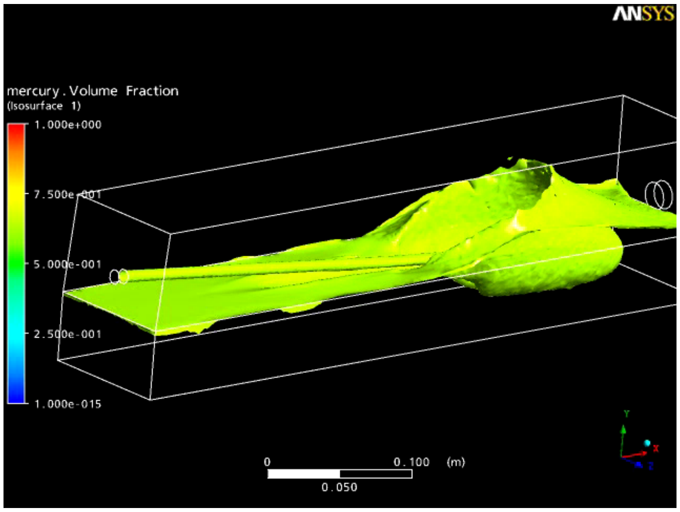

Fig. 4. ANSYS simulation of a mercury jet entering a mercury pool.[11]

2.1.6. The Internal Shield

A major challenge of the target system is the dissipation of the 4-MW of beam power inside the superconducting magnet string without quenching of the magnets, or extreme shortening of the 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 (Fig. 5). The shield must be cooled by a liquid; water in the baseline scenario, but with mercury as an option.

The baseline scenario is for a shield of tungsten-carbide beads cooled by water. However, the baseline assumed an effective density of the beads (80% of the density of tungsten-carbide) that cannot be achieved with beads of a single radius. Use of multiple bead radii or tungsten-carbide sheets with machined microchannel raises issues of whether that water flow could be sufficient to keep the water form completely vaporizing in portions of the shield. Furthermore, the coolant must enter and exit the system from the upstream end, where the shield cross section is much smaller than in its downstream region. Initial simulations using the MARS15 code indicates that the current shielding approach allows for ~25 kW of power to be deposited within magnet SC-1 alone.[13] This is not considered acceptable and must be addressed.

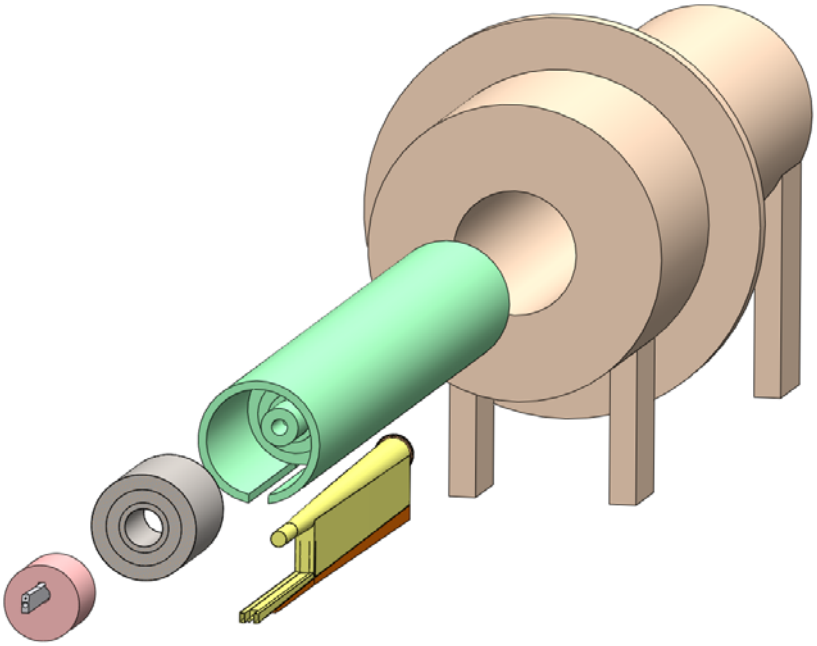

Fig. 5. Tentative scenario for assembly of the iron plug, the copper magnet, the mercury collection chamber and the internal shield within the target system magnets.[12]

The search for a solution is complicated by the present lack of a clear criterion as to 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.

The baseline scenario for the internal shield of the superconducting magnets is a vessel filled with tungsten-carbide spheres, cooled by water flow. As the geometry of the internal shield is complex, it is not evident that sufficient uniformity of the water flow can be achieved to avoid regions in which there is only steam rather than water, which could then lead to local melting of the shield wall. To address this issue, and to consider alternatives[14] 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.[15]

2.1.7. Magnet Design

The design of the first magnet, with baseline field of 20 T is challenging. The use of a 6-T water-cooled, hollow core 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 consequent larger inner diameter the superconducting outsert, such that the latter is untenable, we must consider the option of only a 14-T Nb_3Sn magnet, or development of a large-bore high-T_C magnet (or more simply, a high-T_C-Nb_3Sn hybrid;[16] tests of YBCO indicate that it has good resistance to radiation damage[17]).

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, with as-yet unresolved technical issues.

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

Although the "true" emittance of a beam is an invariant under transport through a system of magnets, the rms emittance (which is of more practical importance than the possibly filamented "true" emittance) is affected by details of the magnetic transport. If the 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.[18] The baseline design of the target system, in which the field drops from 20 T to 1.75 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 1.75-T solenoid transport channel). A global optimization of the target system plus capture channel magnetic fields has never been performed, while numerous changes in the latter have been considered in recent years. Hence, it is timely that this issue be simulated in the near future.

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 (such as 14 T as might be obtained in a Nb_3Sn magnet. A related issue is the rapidity of the reduction of the field strength from 20 T to 1.75 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 slowly falloff of field with position than in the present baseline.

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

When it comes time to build 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. As such, a program of simulation and design is underway with the goal of developing a better nozzle. This issue should not, however, be left only to design, but should be addressed in laboratory tests once a revised design is developed, on the time scale of 2 years. The nozzle tests should be performed with mercury, but a proton beam and magnetic field are not 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 noninteracting 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 quasicontinuous mercury jet of 20 m/s

2.2.3. **Coolant Flow in the Internal Shield**

Should the baseline continue to be a water-cooled shield with high-Z beads, it would be prudent to test the coolant flow patterns in a full size mockup, for which inexpensive low-Z beads will suffice.

2.2.4. **Further Particle Production Experiments**

The simulations of particle production in the target system rely on extrapolation from experimental data that unfortunately have various inconsistencies in the relevant regions of parameter space.[19] Assessment of the seriousness of this issue is ongoing, but it may well be desirable to collect additional data relevant to particle production at a Muon Collider/Neutrino Factory. The Fermilab MIPP experiment[20] affords an opportunity for such studies.

3. **Estimate of Required Resources**

An emerging result is that the baseline internal-shielding of the target-system magnet, as defined in the Neutrino Factory Study 2,[1] is not viable for operation with an 8-GeV, 4-MW proton driver. MARS calculations using this baseline indicate that 25 kW of power would be deposited within SC-1 alone,[13] which needs to be reduced by an order of magnitude. 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, which interplay with each other. Amongst the diverse disciplines involved are cryogenics, magnet design, mechanical engineering, fluid flow, and thermal management. Due to the interlocking nature of these activities in the present context it is desirable to address them by a team led by a physicist and project engineer. These tasks will require a team of 3 FTEs active for four years. 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.

Table 3. Summary of requested resourses.

Item	Years	FTE	M&S
MHD simulations	3	1.5	
Pion-yield optimization	2	1	
Integrated design			
Project engineer	4	2	
Nozzle development	3	2	$200k
Solid target options	2	0.5	
Beam dump	3	3	$200k
Internal shield	3	4	$200k
Magnet design	2	2	
Hg loop	1	0.5	
Remote handling	1	0.5	
Target hall	1	0.5	
Pion-yield measurements	2	1	$200k
Totals		18.5	$800k

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