3 The Neutrino Factory Accelerator Complex

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3.1 The Target System

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The Target System of the Neutrino Factory is considerably more than the target for the primary proton beam. It includes a high-field solenoid-magnet string for capture of low-energy pions from the target, as well as the infrastructure to house and support the target and capture magnets. Because of the high levels of activation of materials in the Target System, it includes substantial radiation shielding, and remote-handling capability.[5]

Early visions [1] of a target system for a Muon Collider considered (pulsed) toroidal collection (with a Li lens, as at a $\bar{p}$ source), which is limited to one sign of charged particles, and has not been demonstrated for the 50-Hz repetition rate specified for a Neutrino Factory. Pion collection with DC solenoid magnets was proposed in 1995 [2] and has since been the baseline concept. An additional advantage of solenoidal capture in a high-field magnet is that longitudinal-transverse emittance exchange occurs as the field strength decreases adiabatically along the capture channel [3], which provides initial transverse cooling of the secondary pions (at the expense of longitudinal heating). Issues of survival of a solid target in a 4-MW proton beam with $\approx$ 2-ns pulses led to consideration of a free-mercury-jet target [4], now the baseline. Physics feasibility of a mercury-jet target in a strong solenoid field and intense proton pulses was demonstrated in the MERIT experiment at CERN [5].[6]

Optimisation of particle production at fixed proton-beam power for maximal output of the Neutrino Factory [7] leads to various requirements on the proton driver (Table 1), and on the configuration of the Target System. Useful (low-energy) pion yield from the Hg target peaks at 8 GeV, which is taken to be the baseline value. The desired low-energy pions emerge from the side of the target, which favors a small proton-beam radius, and leads to the (demanding) requirement of geometric transverse emittance of 5 μm for the proton beam. The requirement of short proton bunches (1-3 ns) is based on the need for efficient capture of the secondary beam into rf bunches, so is not strictly a requirement by the Target System.

Table 1: Requirements on the Proton Driver from the Target System.

Parameter	**Value**
Kinetic energy	5–15 GeV
Average beam power	4 MW
	(3.125×10^{15} protons/s)
Repetition rate	50 Hz
Bunches per train	3
Total time for bunches	240 μs
Bunch length (rms)	1–3 ns
Beam radius	1.2 mm (rms)
Rms geometric emittance	< 5 μm
β^* at target	$\geq$ 30 cm

[5] The Final-Focus System of the primary proton beam may or may not be considered as part of the Target System. Also, the string of magnets in the Pion-Decay Channel prior to the Buncher will experience very high radiation loads, so from a technology perspective they are part Target System, although they are described in this document as part of the Front End.

[6] The MERIT experiment did not utilize a continuous-flow of mercury, which has been demonstrated at the Target System of the SNS at ORNL [6].

Pion production is maximized when the radius of the jet target is about 3 times that of the proton-beam rms radius, and the proton beam and target have a small tilt with respect to the axis of the capture-solenoid capture. The latter implies that the primary proton beam does not point into the Decay Channel, but off to the side of the Target System, where the mercury-collection pool serves as the beam dump.[7] The proton beam will disrupt the liquid target over most of its effective length ($\approx$ 2 interaction lengths = 30 cm), so the requirement of a fresh region of the jet as the target at 50 Hz implies the jet velocity must be 20 m/s (which also implies that gravitational curvature of the jet is negligible).

Useful particle production is higher for higher peak magnetic field in the Target System, and 20 T is taken as the baseline value. This is beyond the capability of a Nb-based superconducting magnet, so a hybrid magnet with a 15-T Nb_3Sn outer coil and a 5-T Cu inner coil is specified. Such a hybrid magnet (with 45 T peak field) has been constructed at the NHMFL [8].

The magnetic field in the target system "tapers" down from the peak of 20 T to 1.5 T in the Decay Channel that begins 15 m from the target.

The requirement of dissipation of the 4-MW proton-beam power inside the Target System is a major driver of the system design. Radiation damage to magnet conductors, particularly to organic insulation, limits their useful lifetime to ≈ 10 years of 10^7 operational seconds if the energy deposition by secondary radiation is 0.1 mW/g [9] (sometimes called the ITER limit). Simulations of energy deposition by FLUKA and MARS codes indicate that the inner radius of superconducting coils near the target must be 1.2 m to satisfy the ITER limit, via internal radiation shielding by He-gas-cooled tungsten beads. This large radius implies the magnets of the Target System would have a stored energy of $\approx$ 3 GJ, comparable to that of the ITER Central Solenoid [10] and the CMS central solenoid [11].

The 5-T Cu coil insert would experience much larger radiation dose, such that organic insulation could not be used; rather a MgO-insulated conductor is required, as developed at KEK [12].

Some 15% of the proton-beam energy is transported into the Decay Channel, mostly via scattered beam protons (and protons from nuclear breakup in the target). This requires mitigation via a chicane in the Decay Channel, and implies that the magnets in this channel must also be designed for high radiation dose, as in the Target System.

A vertical section of the Target System is shown in Fig. 1, and the target region, with the 20-T hybrid capture solenoid is shown in more detail in Fig. 2. This magnet module weighs $\approx$ 200 tons, which sets the scale for the infrastructure required for the Target System.

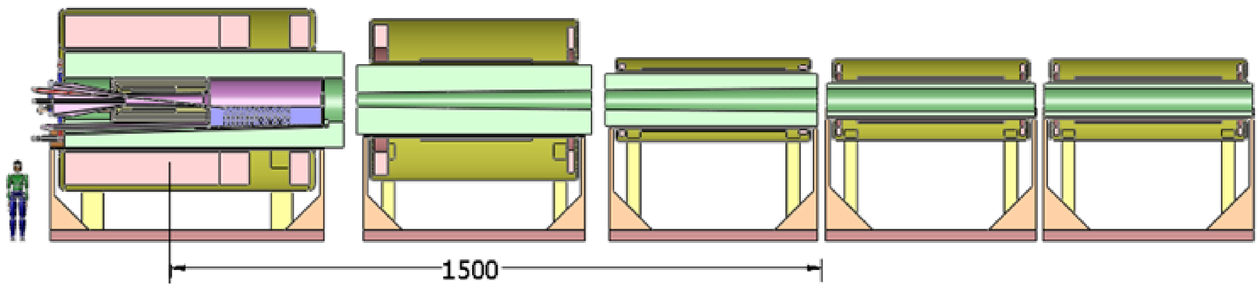

Figure 1: Vertical section of the three magnet modules of Target System (which nominally ends at $z = 1500$ cm) and the first two modules of the Decay Channel.

[7]Mitigation is required of splashes in this pool due to the entering mercury jet and the noninteracting part of the proton beam.

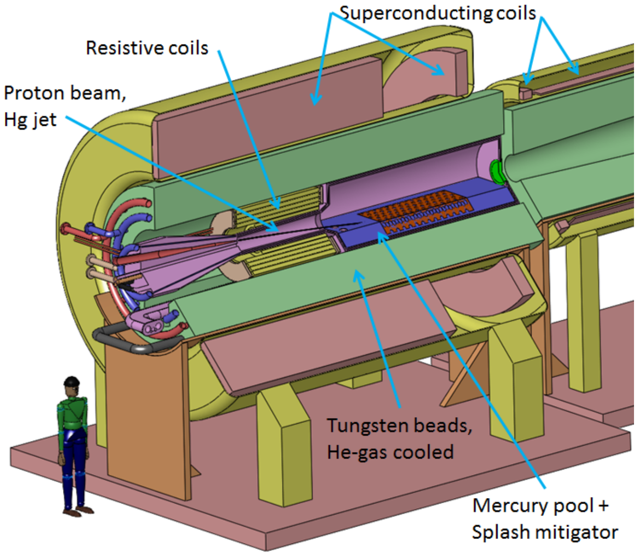

Figure 2: View of the 200-ton 20-T capture solenoid, with internal shielding by tungsten beads. The free-mercury jet target and the proton beam are tilted with respect to the magnetic axis, and impinge on the mercury-collection pool that also serves as the proton beam dump.

References

[1] D. Neuffer, *Design of Muon Storage Rings for Neutrino Oscillation Experiments*, IEEE Trans. Nucl. Sci. **28**, 2034 (1981).

[2] R.C. Fernow *et al.*, *Targets and Magnetic Elements for Pion Collection in Muon Collider Drivers*, AIP Conf. Proc. **352**, 134 (1995).

[3] R. Chehab, *A second order calculation of the adiabatic invariant of a charged particle spiraling in a longitudinal magnetic field*, J. Math. Phys. **19**, 937 (1978).

[4] R.B. Palmer *et al.*, *Muon Colliders*, AIP Conf. Proc. **372**, 3 (1996).

[5] K.T. McDonald *et al.*, *The MERIT High-Power Target Experiment at the CERN PS*, Proc. IPAC10, p. 3527.

[6] T. McManamy *et al.*, *Overview of the SNS target system testing and initial beam operation experience*, J. Nucl. Mat. **377**, 1 (2008).

[7] X. Ding *et al.*, *Optimized Parameters with a Mercury Jet Target*, Proc. PAC09, p. 2748.

[8] M.D. Bird *et al.*, *The NHMFL Hybrid Magnet Projects*, IEEE Trans. Appl. Supercon. **19**, 1612 (2009).

[9] J.H. Schultz, *Radiation Resistance of Fusion Magnet Materials*, IEEE Symp. Fusion Eng. p. 423 (2003).

[10] J.H. Schultz *et al.*, *The ITER Central Solenoid*, IEEE Symp. Fusion Eng. (2005).

[11] A. Hervé *et al.*, *Experience Gained From the Construction, Test and Operation of the Large 4-T CMS Coil*, IEEE Trans. Appl. Supercon. **18**, 346 (2008).

[12] K.H. Tanaka *et al.*, *Development of Radiation Resistant Magnets for JHF/J-PARC*, IEEE Trans. Appl. Supercon. **14**, 402 (2004).