DESIGN STUDY FOR 20 T, 15 CM BORE HYBRID MAGNET WITH RADIATION-RESISTANT INSERT FOR PION CAPTURE*

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Abstract

To capture pions the Neutrino Factory and Muon Collider Collaboration needs a field of ~20 T throughout a cylinder 15 cm in diameter and 60 cm long, falling over the next 18 m to 1.25 T, while the bore increases fourfold inversely as the square root of the field. We propose a hybrid system. The superconducting magnet is of world-class parameters, storing 600 MJ and including a coil to generate 14 T in a bore of ~1.3 m. Intercoil forces reach 100 MN. For high radiation resistance, the insert coil is of mineral-insulated hollow conductor, as developed for the Japan Hadron Facility; it would require 12 MW to generate 6 T. Needed is research to develop a more efficient hollow conductor or radiation-resistant insulator for a Bitter coil.

1 SYSTEM PARAMETERS

For a neutrino factory one can generate pions by bombarding a target with a multi-GeV proton beam of 1 MW or more. As the target, the Collaboration's "Feasibility Study II" proposes a mercury jet or a moving metal band. A solenoidal magnetic field bends the pion trajectories into helices; 20 T in a bore of 15 cm captures pions with a transverse momentum up to 225 MeV/c.

The desired field profile is uniform over the target, followed by a gradual transition to the much lower field of subsequent components of the neutrino factory. For minimal particle loss the optimum field profile is $B(z) = B_0/[1+kz/L]$, where B_0 is the field at $z = 0$, the downstream end of the target, and $k+1$ is the ratio of B_0 to the field at $L = 18$ m, the downstream end of the transition region. Within the target region itself, $-l < z < 0$, the field should sag no more than ~5% near its ends, to limit the field gradient that tends to shear the jet of mercury entering and leaving the target region.

To generate this field we employ magnets of three types: superconducting (SC), resistive and ferromagnetic. SC magnets generate almost all the field, except near the target. There one needs a resistive insert that, with shielding only 10 cm, not 30 cm, thick, can survive the intense radiation emanating from the target. Just upstream of the target region is a ferromagnetic plug, to contribute ~1.0 T. Its field gradient cancels some of the field inhomogeneity of the other coils, which tends to shear the jet of mercury. Figure 1 shows the on-axis field profile of the proposed magnet system: $B_{max} = 20$ T, $B_0 = B(-l) = 19$ T, and $B(L) = 1.25$ T ($k = 14.2$).

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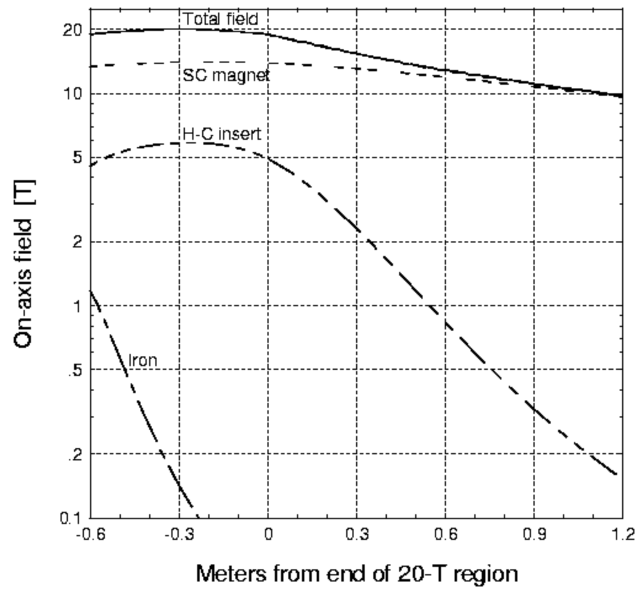

Figure 1: On-axis field of pion capture magnet near target. At the midplane of the target region, z = –0.3 m, the superconducting magnet generates 14 T and the resistive insert, 6 T. The iron halves the field gradient near –0.6 m, thereby improving the entry of the mercury jet into the region.

Figure 2 sketches the magnets and cryostat in the upstream, intense-field region of the system, to the downstream end of the proton-beam absorber, 6 m from the end of the target. Table I lists the most important parameters of the hollow-conductor and first eight superconducting coils.

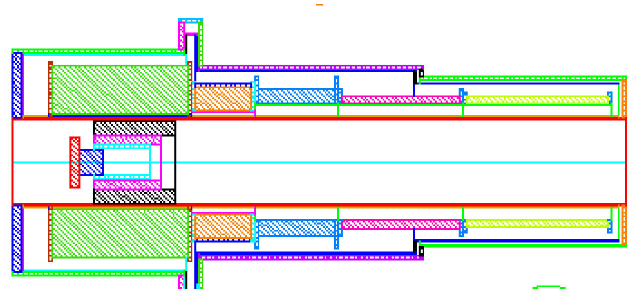

Figure 2: Cryostat and coils of pion capture magnet to end of beam absorber, 6 m downstream from target region. Shown: ferromagnetic plug (stepped cylinder, of T cross section); hollow-conductor insert magnet; tungsten-carbide shielding outside insert; cryostat; and first five superconducting (SC) coils. SC coils further downstream extend the field tail to 1.25 T at z = 18 m.

Table I: Parameters of Hollow-Conductor and Superconducting Magnets of Pion Capture Magnet for Neutrino Factory

	Units	HC 1	HC 2	HC 3	SC 1a	SC 1b	SC 2	SC 3	SC 4	SC 5	SC 6	SC 7	SC 8
Avg. current density	A/mm^2	24.9	18.9	15.6	24.1	28.1	28.7	37.5	46.6	53.1	68.2	71.5	73.5
Winding inner radius	cm	17.8	23.2	35.5	63.7	83.6	68.7	76.3	76.3	76.3	42.3	42.3	42.3
Winding outer radius	cm	23.2	35.5	49.2	82.6	117	89.2	89.9	84.0	83.0	46.2	45.9	45.4
Winding radial build	cm	5.4	12.3	13.7	18.9	33.3	20.4	13.6	7.7	6.7	3.9	3.6	3.1
Upstream end, z_1	cm	-70	-70	-70	-138	-138	92	217	343	468	600	727	854
Downstream end, z_2	cm	2	21	23	82	82	207	333	458	583	713	840	968
Coil length, $z_2 - z_1$	cm	72	91	93	220	220	115	115	115	115	2x50	2x50	2x50
Volume of windings	m^3	.05	.21	.34	1.91	4.60	1.17	.82	.45	.39	.11	.10	.09
Approx. peak field	T	20.0	18.6	16.0	14.1	9.4	10.6	6.8	5.1	4.1	3.4	2.8	2.4
Avg. hoop tension	MPa	107	108	107	217	222	209	194	180	165	97	84	75
Conductor fraction	%	33.1	32.9	33.0	8.5	2.9	3.5	2.7	4.8	3.9	4.1	3.8	3.6
Copper fraction	%	48.6	48.4	48.5	20.9	19.6	22.7	26.6	33.3	37.6	55.9	56.2	56.4
Structural fraction	%	11.7	12.0	11.8	30.7	37.5	33.7	30.7	21.9	18.5	0	0	0
Superconductor vol.	liters				162	131	42	22	21	15	4	4	3
Copper mass	tonnes	.23	.94	1.51	3.57	8.09	2.38	1.95	1.33	1.30	.54	.50	.43
Stainless steel mass	tonnes	.05	.20	.32	4.58	13.5	3.08	1.96	.76	.56	0	0	0

2 SUPERCONDUCTING MAGNETS

2.1 Baseline System: Mercury Target

The superconducting magnet system is a formidable engineering challenge, especially SC #1, that is to generate 14 T in a 1.3 m bore. An excellent precedent is the 140 ton coil [1] for the International Thermonuclear Experimental Reactor. It has generated 13 T in a 1.6 m bore and stores 600 MJ, the same as the entire pion capture magnet. It and SC coils #1-5 use cable-in-conduit conductor (CICC), which is the conductor of choice for large magnets operating at many kA. For the downstream coils, which experience lower hoop stresses and much lower axial loads, Rutherford cables are more economical.

2.2 Alternative Target: Rotating Band

An alternative target to the mercury jet is a rotating band of metal [2], such as the system in Figure 3.

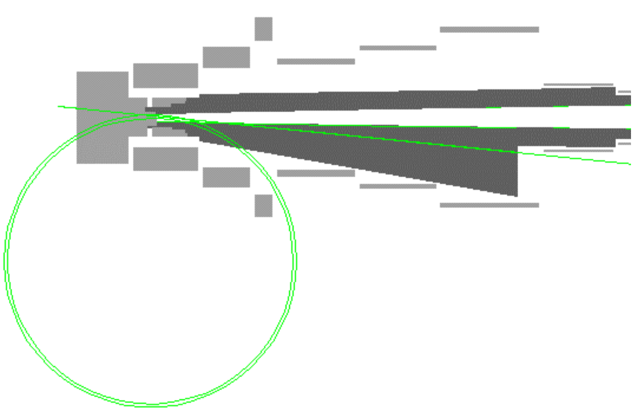

Figure 3: X-section of rotating band target. Rollers move band, of 5 m diameter, at ~1 m/s, through the high-field region, openings in the iron plug (left) and shielding (dark gray) and in the cryostat (not shown) housing the upstream superconducting coils (light gray rectangles).

This entails additional design challenges beyond those for Figure 2: increasing the size of SC coils #2 and #3 (to thread the band inside them), redesigning the cryostat to accommodate the band exit port, and shielding SC coils #2-#4 from radiation, either directly from the band itself, or else leaking from the target through this port. The design requires additional calculations of the energy deposition throughout these coils.

2.3 Intercoil Forces

The axial loads on the high-field coils are huge. Figure 4 shows that the peak cumulative axial load (at the downstream end of SC #1) is over 100 MN, or 10,000 metric tons. These loads dictate that the first five SC coils all reside in the same cryostat. The loads on the low-field coils (z > 6 m) cumulate to only 2.5 MN.

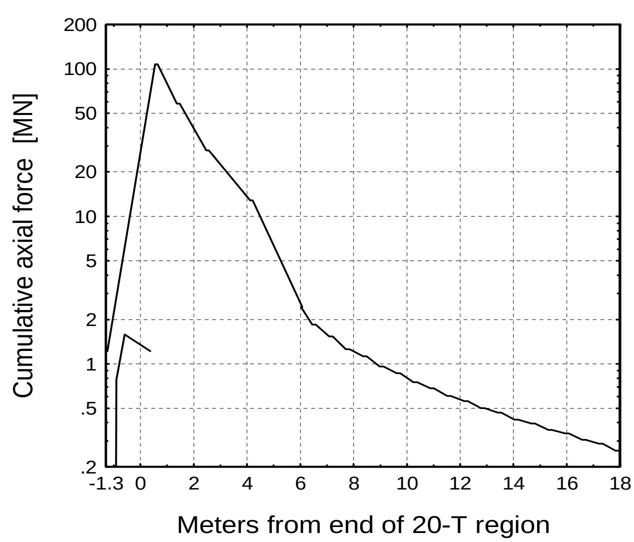

Figure 4: Force on components of pion capture magnet. Upper curve: peak force is 100 MN. Lower curve: Force on resistive insert magnet and iron is only 1.5 MN.

3 RESISTIVE MAGNET

3.1 Japan-Hadron-Facility Hollow-Conductor

The Study II baseline design employs the mineral insulated conductor [4] developed by K. Tanaka et al. for the Japan Hadron Facility (JHF). The insulation is MgO powder sandwiched between the conductor and its copper sheath. The conductor shown in figure 5 is 24 mm square overall, with 37% conductor, 28% insulation and 18% sheath; 17% is for cooling.

Figure 5: Mineral-insulated hollow conductor developed for Japan Hadron Facility. End-on view: white layer is insulation of MgO powder sandwiched between the hollow conductor and its sheath, both of copper. Side view: conductor termination, brazed of several parts that confine the MgO and hold the glossy white ceramic ring that keeps the sheath isolated from the conductor.

3.2 Coil Using JHF Hollow Conductor

As with the SC magnet, the resistive insert, too, presents formidable engineering challenges. Radiation doses and neutron flux densities are very high. MARS calculations by Mokhov of FNAL reveal that each operational year ($2x10^7$ s) adds a dosage of up to ~10^9 J/kg (10^9 grays, or 10^{11} rads) and a neutron flux of ~$2x10^{19}$ n/cm^2, despite ~10 cm of shielding by water-cooled tungsten carbide to attenuate the neutron flux and the gamma dose by factors of 10 and 40, respectively. The hoop stresses are very high. Hollow conductors, with their copper soft for fabricability, will require considerable reinforcement. Neutrons will so embrittle the conductor [3] that one must support the conductor as if it were glass, or else periodically to heat it to at least 150°C, to anneal it before embrittlement becomes too severe.

Figure 6 shows the end view and cross section of a design with three sizes of JHF hollow conductor. Surrounding each subcoil is a strong cylinder to reinforce the conductor against Lorentz forces. All terminations are at the upstream end. All conductors are electrically in series and hydraulically in parallel. By winding six (!) conductors in parallel in each layer and cooling with 10 °C water at 30 atmospheres pressure, as at the National High Magnetic Field Laboratory, each conductor should carry 15 kA with a bulk temperature rise of <60 °C and a peak conductor temperature of <80 °C.

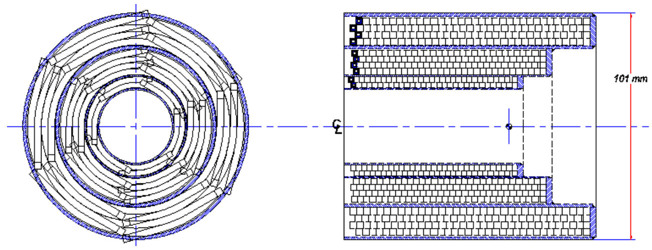

Figure 6: End view and X-section of insert magnet using mineral-insulated hollow conductor developed for the Japan Hadron Facility. Every layer employs six hydraulic paths in parallel, to achieve short hydraulic paths.

3.3 R & D Needed for More Efficient Inserts

A more efficient hollow conductor would have a sheath that is much stronger than copper and insulation that is thinner—perhaps anodized aluminum [5], or a ceramic coating [6] or wrap [7]. If the insulation could survive radiation when wet, then one could consider a Bitter magnet, such as the one at MIT's Francis Bitter National Magnet Laboratory that, at 9 MW, contributed 11 T to a hybrid magnet that generated 22.5 T in a 15 cm bore.

A Bitter magnet will require a research and development program. One must verify that radiation will not immediately induce arcing through the water. The insulator—undoubtedly a ceramic—must survive high radiation and the hostile environment of any Bitter magnet: high clamping pressures, temperatures and water velocities. Finally, the conductor must not deteriorate too much in strength and ductility when irradiated for at least a few months. A successful outcome of such R & D could save several megawatts and many millions of dollars of capital cost in power supplies and superconducting magnets.

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