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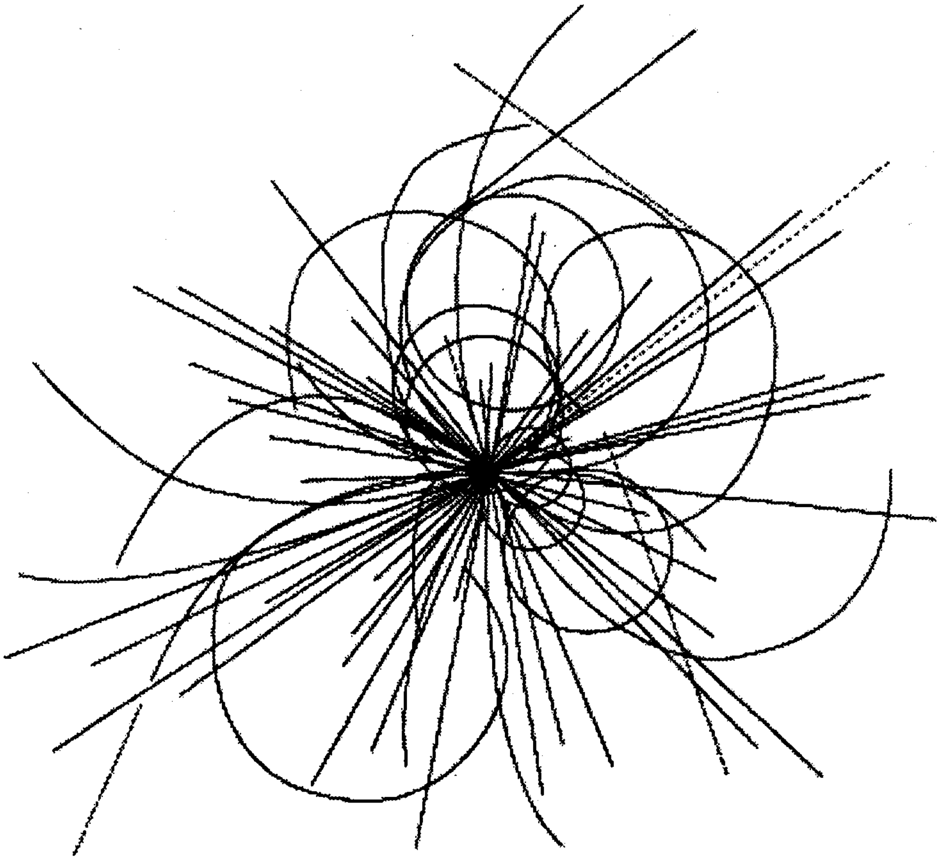

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CONDUCTOR DESIGN FOR THE GEM DETECTOR MAGNET

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INTRODUCTION

The Gammas, Electrons, Muons (GEM) Detector, one of the two large detectors planned to be built at the SSC, features high muon momentum resolution. This is achieved by magnetization (by a huge magnet, about 20 m in diameter and 31 m long) of roughly 10,000 m^3 of space within the muon chambers. The GEM Detector Magnet[1] should be designed to operate with highest possible reliability level to ensure maximum availability of the Detector Systems. That means that the magnet and the conductor should be as stable as practically possible. The conductor should be reliably protected against overheating and electrical breakdown in the case of a quench or fast discharge. For reliability reasons, the magnet dump voltage is relatively low, 500 V to ground, which implies low current density in the conductor. Table 1 lists general requirements for the conductor.

There are several conductor options for such a big magnet and the final choice of the conductor is always a tradeoff between the performance, cost, reliability, quality assurance, R&D efforts, and readiness of industry to manufacture the conductor.

Table 1. General requirements for GEM conductor

Central field	T	0.8
Peak field in winding	T	1.6
Operating temperature	K	4.5 – 4.8
Maximum hot spot temperature in a quench event	K	100
Maximum Dump Voltage to ground	V	500
Stored Energy	GJ	2.5
Charging time	hr	8

Indirectly Cooled Conductor (ICC) has been used in most detector magnets for high energy physics so far.[2,3] Forced Flow Cooled conductors (FFC), with smooth channels for helium circulation showed good stability and reliability in magnets for fusion research.[4,5] The third option is the Cable-in-Conduit Conductor (CICC), where strands are in intimate contact with helium for stabilization. CICC was tested in several magnets for fusion[6,7] and energy storage[8] and showed very

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high stability and low ac losses. Although ac loss is not an issue in dc magnets, high conductor stability is a very attractive feature in a big magnet such as GEM. Table 2 shows comparative energy margins for these three conductor types.

Table 2. Energy margins for different conductor options for GEM.

	ICC (20 kA)	FFC (20 kA)	CICC (50 kA)
Energy margin, J/m	7	50	315
Equivalent displacement, mm	0.35	2.5	7

It is worth noting that for a monolith conductor with high current and, consequently, with a big cross section of stabilizer, the stability is affected by slow diffusion of the current from the superconducting cable to the stabilizer.[9] Proper design of the conductor can relax this phenomenum, especially in FFC, but slow current diffusion still substantially affects stability. In CIC conductor, the cable is evenly distributed and this effect does not take place if distribution of the current over the cross section is uniform.

These numbers show that for the CIC conductor the tolerable disturbances are so large that coil design can eliminate the very laborious and delicate operation of impregnation, which saves a lot of winding time and effort which is why cable-in-conduit was chosen for the GEM Magnet. Although the winding seems to be easier to make with CIC, essential efforts should be applied on quality assurance/quality control during CIC manufacture and verification tests. Figure 1 shows the cross section of the GEM conductor.

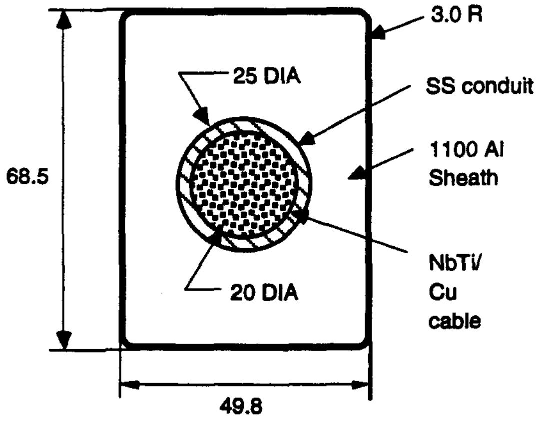

Figure 1. Cross section of the GEM Conductor. Dimensions are in mm.

RATIONALE AND CONDUCTOR DESIGN

Operating Current. Higher current is desirable from protection considerations, smaller number of lengths and joints, smaller number of turns in the magnet, smaller amount of insulation and better mechanical integrity. Lower current offers lower cryogenic loads due to the current leads, easier manufacture and transportation, less expensive current supply, distribution and protection equipment. The 50 kA operating current is chosen as a reasonable compromise within industry manufacturing capability.

Conductor Length. A conductor length of 1140 m is chosen to be the maximum practicable from the manufacturing point of view. The coil design uses one length of the conductor for one coil segment. There are 24 coil segments altogether for a total conductor length of 27.4 km.

Parameters of the Strand. To take advantage of the high heat capacity of the helium in the conduit, one has to provide the conditions, corresponding to the "well cooled regime," where heat transfer from the strand in the normal state should be higher than Joule heat generation. The criterion describing those conditions is :

$$\mathbf{I_{op} \le (hPA_{Cu}(T_c - T_b) / \rho_{Cu})^{0.5}} \qquad \text{where:}$$

I_{op} – operating current, A; h – heat transfer coefficient (W/m^{2}K); P – wetted perimeter (m); A_{Cu} – area of copper stabilizer in cable (m^2); ρ_{Cu} – copper stabilizer resistivity (Ohm*m); T_c – critical temperature (K); and T_b – initial helium temperature (K). On the other hand, the enthalpy of the helium available in the event of a disturbance is driven by the temperature of the current sharing between the SC filaments and copper matrix, so the lower the ratio I_{op}/I_c, the more the energy margin is. For GEM this ratio is chosen conservatively at 0.25. Table 3 lists the strand parameters for GEM CICC.

Table 3. Main parameters of the strand

Parameter	Value
Total wire length in the magnet (km)	13,041
Total weight of the wire in a magnet (kg)	46,250
Wire diameter (mm)	0.73
Cu:SC ratio	3.6:1
NbTi filament size (μm)	<40
I_c @ 2 T & 4.2 K (at 10^{-5} V/m) (A)	>400
Matrix material	Type 101 Copper, (Oxygen Free)
RRR in the wire	>150
Twist pitch (mm)	20

Cable. The cable is designed to be fully transposed, 4-stage right-hand twisted, made of 450 strands. The cabling pattern is 3x5x5x6. The final cable is wrapped with 304 SS tape 0.05 mm thick with a 40-50% overlap to keep tight tolerances on the cable diameter and to eliminate appearance of "bird caging" during cable spooling on shipping spools. The total cable length is – 24 x 1150 m piece lengths = 27.6 km. Cable weight/piece is about 1920 kg.

Cable in Conduit. In the event of a quench, the conduit will experience high pressure[10] up to 340 ATM. To ensure high quality of the conduit, 304L steel is chosen because of its excellent weldability. To date, at least two different manufacturing methods have been used for CIC Conductor. Both methods start by cabling superconducting strand, and then encasing the cable in stainless-steel conduit. The first manufacturing method consists of feeding flat stainless steel strip along with the superconducting cable through a five-stage tube mill machine followed by TIG seam weld. In the second approach, the required length of cable is pulled through an oversized conduit which is assembled in full length out of butt welded seamless (i.e., extruded) tubes.

An advantage of the second approach is that the length of the welds is much shorter, and butt welds are much easier to inspect. However, there is no experience with pulling a cable through 1 km of conduit and this issue is currently under study. After reduction, in both options, the ID of the conduit will be 20 mm, the OD will be – 25 mm and the void fraction of the cable will be 37%, which will minimize internal disturbances inside the conduit.

Aluminum Sheath. Aluminum sheath is added around the conduit and serves as a shunt in the event of a quench, keeping the hot spot temperature below the design value of 100 K. For economy Al 1100 is chosen as a material for the sheath with RRR = 17. Total weight of the sheath in the GEM Magnet is about 190 tons.

Electrical joints. Electrical connections will be done between those coil segments using specially designed joints. To provide maximum reliability, joints will have a built-in cooling path (secondary loop) for heat removal which is separate from the conduit. The joint design and length of the joint should accommodate tolerances of the conductor length and uncertainties arising during the winding process (expected to be in the 30–50 cm range). For the redundancy, there will be secondary leak-tight containment added around the joints when assembled in the field. Electrical resistance of the joint is expected to be less than 0.5 nOhm at 50 kA.

PREPRODUCTION EVALUATION AND VERIFICATION PROGRAM

Although the objective of the GEM conductor design is to use existing technology well within the state of the art, reliability concerns imply that some verification and justification steps should be taken.

Strand. No Verification is required. This is within normal industry capability.

Cable. There are several issues which should be addressed in this program, such as: what should be diameter of the take-up spool to eliminate excessive deformations of the cable and SS tape on the last stage, whether the last stage of cabling will give a mechanically stable configuration, and whether annealing of the cable is necessary after the last stage. Manufacturing experiments showed that the 3x5x5x6 pattern is possible without substantial problems, though the take-up reel should have a diameter more than 1 m. Additional efforts are required to understand the RRR value during the cabling process.

Conduit. The primary issues for the conductor are establishment of the QA/QC procedure and verification of at least one technique for assembling the cable-in-conduit. Design of the cryogenic leak test facility is now in progress. Some preliminary estimates carried out for evaluation of the friction force for pulling the cable in the conduit indicates that it can cause a yield of the copper in the cable.[11] A pulling experiment on 60–100 m conduit is planned in the near future to obtain experimental data.

Aluminum Sheath. Different types of Al sheath design were evaluated. Bending experiments have been conducted to understand the behavior of the sheath-conduit interface, keystoning effect, and prospective effects for the winding procedure. The effect of welding on the temperature inside the conduit was also studied. As a result, the preferred design of the sheath is established, which is two symmetric profiles with two longitudinal welds. This minimizes conductor distortion and eases the manufacture and transportation of the aluminum sheath. The shipping spool diameter is specified as well.

Joints. Significant efforts were put to develop stable and reproducible technology for the joint assembly and also to increase joint reliability. High conductivity aluminum was introduced in the design to limit heat generation in the joint at temperatures above the critical down to 10–12 W, which can be easily taken by mass flow of only 0.5-1 g/s. Subscale joints were manufactured and tested. These tests confirmed that the target value of the joint resistance of 0.3–0.5 nOhm is achievable.

Conductor Test Experiment. To demonstrate the conductor performance in conditions close to the GEM magnet requirements before the beginning of full production, we plan to carry out a conductor test experiment with the main objectives: verification of the conductor performance at full and higher current; measure the operating margin; measure stability to external and internal disturbances; study propagation of the normal zone; study current transfer to the sheath at a quench; simulate heating the conductor as a result of the quench and study hot spot temperature; verify joint design and mass flow rate through the joint; and study stability of the joints against the external disturbances. This test is planned to be performed on about 60 m of the GEM conductor wound on a mandrel 1.1 m in diameter and about 1 m high. It is expected that this test coil could be charged up to 100 kA, then stresses on the conductor will be comparable with stresses on the conductor in GEM. Table 4 lists the main parameters of the test coil in comparison with GEM.

Table 4. Comparison of the Test coil parameters with GEM.

Parameter	Test coil at 50 kA	at 100 kA	in GEM
Stored Energy, kJ	400	1600	2.5e6
Maximum Field in Winding, T	1.7	3.4	1.6
Max Hoop Stress, MPa	4	16	24.7
Compressive Axial Stress, MPa	1.33	5.3	5.7

CONCLUSION

Rationale and design parameters of the cable-in-conduit conductor for GEM have been presented. The current evaluation and verification program results in clarification and improvements of some design features and manufacturing approaches. The planned conductor test experiment should demonstrate performance of the conductor and joints, and verify design parameters.

REFERENCES

1. B.A. Smith, P.G. Marston, et al., "Design concept for the GEM detector magnet," presented at the 1992 ASC, Chicago, IL, Aug. 23-28, 1992.
2. J.M. Baze, et al. "Design, construction and test of the large superconducting solenoid Aleph," *IEEE Trans.on Mag.*, Vol. 24, No. 2, p. 1260, March 1988.
3. P.T.M. Clee and D.E. Baynham, "Towards the realisation of two 1.2 Tesla superconducting solenoids for particle physics experiments," *Proc. Int. Conf. MT-11*, Tsukuba, Japan, Vol.1, p. 206, 1988.
4. D.P. Ivanov et al., "SC toroidal field coils of Tokamak-7," *Atomnaya Energia*, 45, (1979) 3, p. 171.
5. V.A. Alkhimovich, I.O. Anashkin, et al. "The current capacity tests of the Tokamak T-15 Nb_3Sn toroidal coil assembly," *IEEE Transactions on Magnetics*, Vol. 27, No. 2, 1991, p. 2057-2059.
6. M.S.Lubell, J.A. Clinard et al. "The IEA Large Coil Task Test Results in ISMTF," *IEEE Transactions on Magnetics*, Vol. 24, No. 2, 1988.
7. M.M.Steevs, M.O.Hoenig, et al., "Progress in the manufacture of the US-DPC test coil," *IEEE Transactions on Magnetics*, Vol. 25, No. 2, pp. 1738-1741, March 1989.
8. S.D. Peck and P.H. Michels, "Test results from the 200kA SMES/ETM conductor," Presented at ASC-90, Snowmass, Colorado, 24-28 Sept., 1990.
9. D.E. Baynham, N.V. Fetisov, N.N. Martovetsky, "Stability of indirectly cooled conductors with large cross section," Presented at ASC-92, Chicago, August 23-28, 1992.
10. Minervini, J.V., et al., "Cable-in-Conduit Conductor Concept for the GEM Detector Magnet," presented at the *1992 Applied Superconductivity Conference*, Chicago, IL, Aug. 23-28, 1992.
11. R.L. Huddleston, "Summary of GEM Magnet Cable/Conduit Assembly Analysis," Feb. 10. 1993, private communication.