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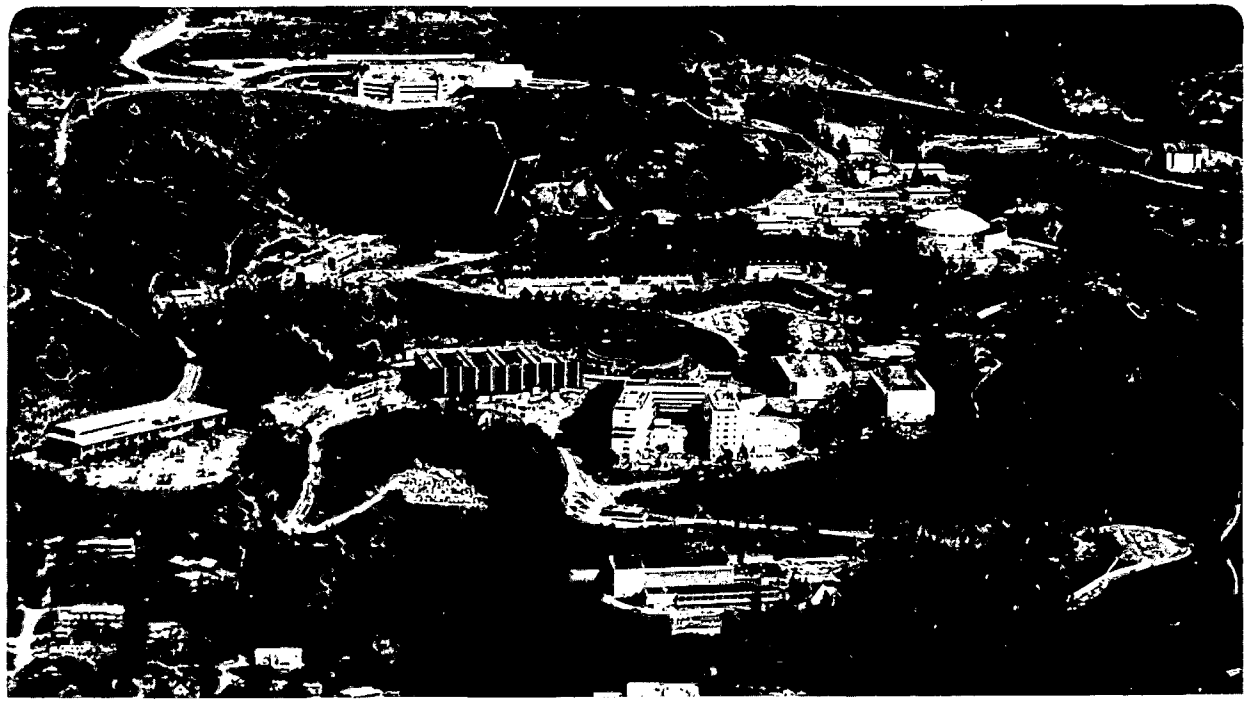

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SANDIA MAGNET AND CRYOSTAT

TITLE

MAGNET SYSTEM MASS VS. MAGNETIC FLUX, STORED ENERGY AND MAGNETIC MOMENT

Bill Cowin of Sandia National Laboratory, Albuquerque, NM, has asked me to look at how one might minimize coil and cryostat mass while maximizing the total magnetic flux and magnet stored energy in a magnet which might be used in a flux compression power supply which might provide power to a high-powered laser. This engineering note presents the results of looking at seven different superconducting solenoid magnet configurations which result in figures for (1) stored magnetic energy per gram of magnet system mass, (2) magnetic flux per gram of magnet system mass, and (3) magnetic moment per gram of magnet system mass. The magnet system mass includes coil conductor, coil secondary circuits, coil support structure, coil leads and plumbing, and the coil cryostat.

Before proceeding with the seven cases, it is useful to look at the scaling relationships between stored energy and mass and total magnetic flux and mass. In general, the larger the solenoid magnet diameter the larger the stored energy and flux in the useful region. In a magnet of given current density, which scales three-dimensionally, the stored energy goes up with the sixth power of dimension and total flux goes up as the cube of the dimension. To first order the coil mass goes up as the cube of the dimension. In large magnets, this kind of scaling does not hold because of limits imposed by superconductor performance and magnetic strain.

The exact scaling depends very much on the size of the solenoid. Up to say one meter in diameter, the current density in a solenoid is limited by the critical current density in the superconductor. Above about 1 meter in diameter magnetic strain becomes the limiting factor in the current density within the windings.[1] Other factors come into play such as the amount of stored energy per active current carrying mass (mass of the superconductor plus any secondary circuits) but these become important as magnetic strain comes into play. In a high current density magnet, it is desirable to limit average strain under magnetic forces to about 0.15 per cent in order to prevent coil training.[2] Peak or concentrated strains up to 0.25 per cent can be permitted.

In order to meet the magnetic strain criteria one must limit either conductor current density or stored energy per unit solenoid length. If one assumes that the superconductor carries about one

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third of the total magnetic force, one finds the following design relationship between stored energy per unit magnet coil length and current density in the superconductor plus matrix material:[1,3]

$$E_L J^2 \lesssim 2 \times 10^{24} \ J\ A^2 m^{-5} \qquad \text{-1-}$$

where E_L is the stored magnetic energy per unit solenoid length (Jm^{-1}) and J is the current density in the superconductor plus matrix (Am^{-2}). When equation 1 is applied in solenoids or torroids with one third of the stress carried by the superconductor, an average strain of less than 0.15 per cent will result.

Equation 1 is taken independently of any quench protection criteria, such as quench back time[4] and the general quench protection criteria which states that[1,3]

$$\varepsilon E J^2 \leq 10^{23} \ J\ A^2 m^{-4} \qquad \text{-2-}$$

where

$$\varepsilon \simeq \left[1 - \frac{M_{12}^2}{L_1 L_2} \right] \qquad \text{-2a-}$$

where E is the stored magnetic energy of the entire magnet on a set of leads; J is the matrix plus superconductor current density; ε is one minus the coupling coefficient between two circuits which have self inductances L_1 and L_2 and a mutual inductance M_{12}. Lawrence Berkeley Lab has designed large high-current density solenoids which have an ε from 0.005 to 0.05 depending on the design details for the superconducting coil (circuit 1) and the shorted secondary circuit (circuit 2).

When a large high current density solenoid is built one must avoid strain concentrations and one must make sure the coil gas a high modulus so that forces can be carried by the superconductor and the adjoining force containing structure.[1] In general, the stored energy

per unit mass of active circuit materials (i.e., the superconductor including its matrix material and the secondary circuits) is limited to an upper limit of 15 J per gram[4] (this imposes an upper limit temperature of 100-120K in the coil when the energy is spread evenly in the active circuit materials).

By the use of indirect cooling with forced two-phase helium and the use of high strength, high modulus, low-mass banding, one can make the magnet cold mass as little as 1.5 times the active circuit mass. As a result, the upper limit for stored energy per unit cold mass is about 10 J per gram. A more reasonable limit for stored energy per unit cold mass might be 8 J per gram.

The Lawrence Berkeley Lab has built its high current density magnet cryostats from aluminum. Even in the best of circumstances, an aluminum cryostat vacuum vessel has about the same mass as the coil it houses. (The TPC magnet cryostat has almost twice the mass of coil because the cryostat is also an eleven-atmosphere pressure vessel as well as a vacuum vessel.) By the judicious use of composite materials (i.e. Kevlar epoxy, glass epoxy and carbon epoxy) and honeycomb material (i.e. Hexel), it is possible to reduce the cryostat mass by a factor of two. The result is a magnet stored energy of 5 to 7 J per gram of total magnet system mass. (When one uses an all-metal cryostat the stored energy per unit mass is from 3.5 to 5.5 J per gram.)

Let us look at seven magnet designs which have been built, are being built or are proposed. These magnets are divided into two categories so that one can investigate the effect of magnet length on various parameters. These are the long magnets with 3.3m coil lengths and the short magnets with 0.5 to 0.7m coil lengths. The seven cases which are to be compared are:

Long magnets 3.3m long --

1) The old TPC magnet built with two layers 0.9 x 3.6mm superconductor and an ultrapure aluminum circuit. The cooling circuit forms the banding.[5]

2) The new TPC magnet built with two layers 1.0 x 3.6mm superconductor and a two-layer copper circuit 1.0 x 3.6mm. This coil has additional banding and a separated cooling circuit. The increase in mass is mostly in the active circuit.

3) A light version of the TPC magnet with the same conductor as the previous case. The copper layer is replaced with

two layers of 1.0 x 3.6mm ultrapure aluminum clad with hard aluminum. The aluminum banding is replaced by boron aluminum tape. The TPC cryostat is replaced by a non-pressure vessel built of aluminum, magnesium aluminum and metal-cored Hexel.

Short magnets 0.5 to 0.7m long --

4) The B coil which has two layers of 1.0mm diameter superconductor with a 1-to-1 copper to superconductor ratio (all other superconductors are 1.8-to-1 copper to superconductor ratio). The cooling tube acts as banding. The cryostat is the warm bore cryostat built by Sandia.[6]

5) The C coil which has two layers of 1.5mm diameter superconductor and two layers of banding plus the cooling tube.[7] The cryostat assumed is the warm bore cryostat which is being designed by LBL which has a mass of 1430 kg.[8]

6) The proposed new Sandia magnet with 14 layers of 1.0 x 3.6mm superconductor, two layers of 1.0 x 3.6mm copper, a 19mm-thick bore tube, 30mm of aluminum banding and a separate cooling tube.[9] The cryostat is the same one as in Case 5. (This cryostat is designed to support the explosion containment vessel.)

7) A light version of the new Sandia magnet with 12 layers of 1.0 x 3.6mm superconductor, two layers of 1.0 x 3.6mm ultrapure aluminum, a 19mm thick bore tube, 20mm of boron aluminum banding and a separate cooling tube. The cryostat has a thin aluminum bore tube and Hexel outer shells. The projected mass of this cryostat is 600 kg. (This cryostat could not support the explosion containment vessel.)

TABLE 1 compares the basic parameters of the seven magnet cases. Included are the ampere turns at design current, the stored magnetic energy at design current (with no iron), the average magnetic flux in the bore at design current, and the magnetic moment at design current. The active mass (coil plus secondary circuits), the cold mass (all parts which are at 4K), and the total mass (cold mass plus cryostat mass) are given for the seven cases. Stored energy per unit

TABLE 1. A comparison of stored energy per unit mass, magnetic moment per unit mass and magnetic flux per unit mass for seven magnet designs

Parameter		Long Magnets			Short Magnets			
		Old TPC Magnet	New TPC Magnet	Light TPC Magnet	B Magnet	C Magnet	Conservative Sandia Magnet	Light Sandia Magnet
Diameter of Coil ID	(m)	2.17	2.17	2.17	1.00	2.00	2.00	2.00
Length of Coil	(m)	3.30	3.30	3.30	0.46	0.70	0.70	0.70
ID of Cryostat	(m)	2.04	2.04	2.04	0.89	1.90	1.90	1.90
OD of Cryostat	(m)	2.36	2.36	2.36	1.23	2.30	2.30	2.30
Length of Cryostat	(m)	3.84	3.84	3.84	0.79	1.25	1.25	1.25
Ampere Turns at Design Current	(A)	4.69×10^6	4.69×10^6	4.69×10^6	0.77×10^6	1.24×10^6*	2.83×10^6	2.83×10^6
Stored Magnetic Energy at Design Current	(J)	10.8×10^6	10.8×10^6	10.8×10^6	0.33×10^6	1.92×10^6*	10.0×10^6	10.0×10^6
Magnetic Moment at Design Current	(Am^2)	17.3×10^6	17.3×10^6	17.3×10^6	0.60×10^6	3.90×10^6*	8.89×10^6	8.89×10^6
Average Magnetic Flux	(T)	∿1.50	∿1.50	∿1.50	∿1.07	∿1.05	∿2.39	∿2.39
Active Mass	(kg)	890	1250	860	49	188	760	670
Cold Mass	(kg)	1550	1950	1300	79	375	1330	1100
Total Mass	(kg)	4850	5250	2440	470	1805	2760	1700
Energy/g Active Mass	(Jg^{-1})	12.14	8.64	12.56	6.73	10.21	13.16	14.93**
Energy/g Cold Mass	(Jg^{-1})	6.97	5.54	8.31	4.19	5.12	7.52	9.09
Energy/g Total Mass	(Jg^{-1})	2.22	2.06	4.43	0.70	1.06	3.62	5.88
Magnetic Moment per gram Total Mass	(Am^2g^{-1})	3.59	3.31	7.13	1.28	2.16	3.21	5.21
Flux per gram Total Mass	(Weber g^{-1})	1.14×10^{-6}	1.06×10^{-6}	2.27×10^{-6}	1.79×10^{-6}	1.82×10^{-6}	2.72×10^{-6}	4.42×10^{-6}

*Critical Current
**Just below the practical upper limit of 15 Jg^{-1}

active mass, per unit cold mass and per unit total mass are given in the TABLE. The magnetic moment per unit total mass and the magnetic flux (given in Webers) per unit total mass are also presented.

From TABLE 1, one can observe the following: 1) The TPC magnet does not use material effectively but if it had no pressure vessel it would be a lot better. 2) In general, the short solenoid probably has a stored energy per unit total mass and a higher flux per unit total mass. 3) The long solenoids appear to have more magnetic moment per unit mass. 4) When one compares the C magnet with B magnet, one finds that the stored energy per unit cold mass and per unit active mass is higher for C magnet (the larger diameter magnet). B magnet is designed to the current density limit of the superconductor rather than the strain limits C magnet is designed to. On the other hand, the amount of flux per unit cold mass is greater for the smaller magnet because magnetic flux scales differently from stored energy.

From TABLE 1 and the basic scaling laws it appears that the following design conditions apply:

Stored energy per unit total mass $\approx$ 4 - 5 Jg^{-1}

and

Total magnetic flux per unit total mass $\approx$ 4 - 6 x 10^{-6} Webers g^{-1}

The optimum design favors short rather than long magnets in both cases. The optimum diameter is different if one optimizes stored energy per unit mass than if one optimizes total magnetic flux per unit mass. Further study could yield an optimal design in either case.

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