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A HIGH FIELD 1.3m SUPERCONDUCTING SPLIT COIL MAGNET WITH FORCED LIQUID HELIUM COOLING *

by

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SYMBOLS

$A_{n,s}$	Conductor cross sectional area
$2a_1$	Coil inner diameter
$2a_2$	Coil outer diameter
$2b$	Coil axial length
$2b_1$	Axial length of a coil section
c_p	Specific heat
d	Wire or strand diameter
f	Factor relating wire cross-section to cooling surface
$2g$	Axial gap between coil sections
h	Heat transfer coefficient
i	Current
k	Heat conductivity
K	Factor
N	Number of turns
S	Current density
s	Cooling surface area per unit length
T	Temperature
T_b	Bath temperature
T_c	Critical temperature of superconductor
t	Time
v_q	Velocity of quenching front
α	Ratio a_2/a_1
β	Ratio b/a_1
β_1	Ratio b_1/a_1
γ	Spacing ratio coil center to inner coil radius
σ	Density
ρ	Resistivity

ABSTRACT

The paper describes experiments with various superconducting type II cables and hollow conductor configurations, current distribution, size effect in superconductor and performance of multistranded superconducting stabilized cables and magnets. A 30 cm bore 70 kG split coil magnet with a total field energy of about 6×10^6 joules currently being built at SLAC is presented and a new superconducting coil configuration with forced liquid helium cooling introduced, which will produce about 55 kG in the center of the SLAC 1m liquid helium bubble chamber.

I. INTRODUCTION

In the design of large high field superconducting magnets with a field energy of 10^5 - 10^8 joules a few obvious facts are generally taken into consideration.

A. PERFORMANCE

The coil should operate and perform according to the short length characteristic and show no degradation or instabilities.

B. RELIABILITY

Once in a certain stage of operation,the coil should not quench, the propagation of heat in discrete areas should automatically be localized. Reducing the current should restore superconducting conditions, Field and current stability should be maintained over the period of operation. The superconductor shall maintain its stability without any sign of fatigue or degradation and withstand electromagnetic stresses. The change in field from one level to another for experimental purposes should be possible in an adequate short period without upsetting the system.

C. ECONOMY

To achieve the requirements (a) and (b) the proper balance between normal and superconducting materials in the coil is important. With proper amount of high electrical conductivity normal material surrounding the superconductor and adequate cooling,stable operation at the HI short sample characteristic may be achieved. However in a fully stabilized magnet[1] the ratio of superconductor to normal material is rather small and the coils resemble cryogenic magnets. Due to the poor space factor the initial cost of the magnet, power supply and cryostate is comparable to the water cooled magnet-power supply combination. However, operational cost of large superconducting magnets compared to water cooled magnets is exceedingly small.[2,3]

The basic work reported here is based on partially and fully stabilized coils. Magnets with a field in excess of 50 kG field in the center of a working area of several m^3 built with normal water cooled conductors and an iron shell have power requirements which are economically unsound. Considering also space requirements, experimental feasibility and ease of operation as shown in Section VI, superconducting magnets are quite attractive. Based on theoretical and experimental work by Steckly,[3] Whetstone,[4] and Lontai,[5] the stability requirement is based on the solution of the heat transfer differential equations in steady state condition.

Experimental results verify that in stabilized magnets, the product heat transfer and temperature difference $h(T_c - T_b)$ in the equation

$$s \cdot A_n \cdot h(T_c - T_b) = I^2 \cdot \rho_n \quad \text{(Watts/cm}^2\text{)}$$

depends on the cooling, the conductor geometry,the resistivity of the substrate and the magneto resistance of the normal material used. Values of $h(T_c - T_b)$ measured for short samples immersed in liquid helium do not necessarily represent coil configuration unless cooling is enhanced, which suggests new design aspects and in specific cases forced liquid helium cooling. A few experiments reported here indicate also that the so called size effect in superconducting wires is based on metallurgy, cold work and precipitation process. After the introduction of $Nb_3(Zr)$ wires in superconducting magnet design, wires with small diameters of 0.0254 cm were generally preferred. Larger diameter wires "degraded" more than 0.0254 cm wires when used in solenoids.

For stabilized conductors large diameter superconductors are preferred. $Nb_{2...3}(Ti)$ alloys have been developed which have shown practically no size current dependence up to diameters of 0.127 cm. This improvement allows the use of superconducting wires with diameters of 0.08 cm, or more in large stabilized magnets, and result in a considerable reduction in the magnet cost. In the next section a few coil configurations tested are discussed and experimental data presented.

II. PRELIMINARY EXPERIMENTS WITH SUPERCONDUCTORS AND STABILIZED COMPOSITE CABLES IMMERSED IN LIQUID HELIUM

Various superconducting-normal cable compositions have been tested and reported by Laverick.[6] Based on his work and experiments by Cornish,[7] a few coil configurations shown in Fig. 1a-1d were tested. The cables with various amounts of OFHC copper were bifilar wound with high resistance wire or strip such as manganin or nichrome. The interlayer insulation consisted of open weave oxidized copper or anodized aluminium mesh and glass fiber cloth sandwich to allow the helium to penetrate free around each turn. Test results with good and medium cooled small coils are given in Fig. 2.

According to these experiments poorly cooled magnets present steady state value of[8]

$$h(T_c - T_b) = 0.2...0.3 \text{ W/cm}^2$$

In good cooled magnets the above value may exceed values of 0.8 W/cm^2, and results in a substantial saving in the amount of normal material surrounding the superconductor. Figure 3 illustrates $h(T_c - T_b)$ values from various gap tests.

The various superconductors (Nb 22 at % Ti) used for short sample experiments had a diameter ranging from 0.0254 cm, to 0.08 cm. Their short sample HI characteristic is given in Fig. 4.

As mentioned above, with up to 60 kG of transverse magnetic field no size effect in Nb(22 at %) Ti can be observed contrary to measurements of Betterton et al. for Nb_3Zr.[9] The scatter in the current density values version field may be due to small diameter deviations and measurement errors, and to superconductor to copper joint effects.

The current carrying capacity of Nb(22 at %)Ti as function of wire tension is illustrated in Fig. 5. The measurements are performed at various transverse fields. After each quench the strain is released and the current carrying capacity measured again. The maximum tension value on the wire is obtained when the critical current at zero strain starts to degrade, which indicates a permanent wire damage.

Another important parameter in superconducting magnets is the charging time of the magnet, which is related to the magnet time constant. The field time constant, or the ratio $T = L/R_s$, is calculated from the coil inductance L and the shunt resistance R_s. The values of

$$\lambda(\alpha, \beta) = L/a_1 N^2 \qquad (1)$$

are given in Fig. 6. The shunt resistance may be calculated for each individual case of winding arrangement. The shunt resistance for the case in Fig. 1a is approximately:

$$R_s = \frac{\rho_{shunt}}{2d_{shunt}}$$

with d_s and ρ_s the diameter and resistivity respectively of the bifilar resistance wire.

The joint resistance from superconductor to the copper lead for all coil geometries described in this report does not exceed 10^{-8} ohms. Self fields generated by most coils were in the range of 20-72 kG in the center[10] and measured and calculated time constants are between 0.4 sec - 136 seconds.

III. HEAT PROPAGATION ALONG A SUPERCONDUCTING NORMAL MATERIAL COMPOSITE

If A_s and A_n represent the areas of the superconductor and the normal material, s the cooled surface area per unit length, i_s, and i_n the currents flowing through the superconductor and the normal material, the equation governing the speed of heat propagation is given by: (Fig. 7)

$$\frac{d^2\Theta}{dz^2} + \frac{c_{p_s} \cdot \delta_s}{k_s} \; \frac{\left(1 + \frac{A_n}{A_s} \cdot \frac{c_{p_n}}{c_{p_s}} \cdot \frac{\delta_n}{\delta_s}\right)}{\left(1 + \frac{A_n}{A_s} \cdot \frac{k_n}{k_s}\right)} \cdot v_q \; \frac{d\Theta}{dz} - \frac{h \cdot f\left(1 + \frac{A_n}{A_s}\right)^{\frac{1}{2}}}{k_s A_s^{\frac{1}{2}} \cdot \left(1 + \frac{A_n}{A_s}\right)} \cdot \Theta$$

$$+ \frac{(i_s + i_n)^2 \cdot \rho_s}{k_s A_s^2 \left(1 + \frac{A_n}{A_s} \cdot \frac{\rho_s}{\rho_n}\right)^2} \cdot \frac{\left(1 + \frac{A_n \rho_s}{A_s \rho_n}\right)}{\left(1 + \frac{A_n k_n}{A_s k_s}\right)} = 0 \qquad (2)$$

where $\Theta = T - T_b$ and the parameters $\rho \cdot c_p \cdot h$, δ and k are assumed to be in the operational region temperature independent.

With the solution:

$$\Theta = K + \left\{C_1 \, e^{(m^2+n)^{\frac{1}{2}} z} + C_2 \, e^{-(m^2+n)^{\frac{1}{2}} z}\right\} e^{-mz} \qquad (3)$$

Where

$$K = \frac{(i_n + i_s)^2 \rho_s}{h \cdot f\, A_s^{3/2}} \cdot \frac{1}{\left(1 + \frac{A_n}{A_s} \cdot \frac{\rho_s}{\rho_n}\right)\left(1 + \frac{A_n}{A_s}\right)^{\frac{1}{2}}}$$

$$m = \frac{c_{p_s} \cdot \delta_s}{2k_s} \cdot \frac{\left(1 + \frac{A_n}{A_s}\, \frac{c_{p_n} \cdot \delta_n}{c_{p_s} \cdot \delta_s}\right)}{\left(1 + \frac{A_n}{A_s} \cdot \frac{k_n}{k_s}\right)} \cdot v_q$$

$$n = \frac{h \cdot f}{k_s \cdot A_s^{\frac{1}{2}}} \cdot \frac{\left(1 + \frac{A_n}{A_s}\right)^{\frac{1}{2}}}{\left(1 + \frac{A_n}{A_s} \cdot \frac{k_n}{k_s}\right)}$$

The integration contents C_1 and C_2 are calculated from the boundary values:

For $z < 0$ and specifically for $z \to -\infty$, $\Theta = \Theta_n$ is finite, and $C_2 = 0$.

For $z = 0$ $\Theta = \Theta_c = \Theta_s = \Theta_n$ the critical temperature of the superconductor $C_1 = \Theta_c - A$.

Inserting C_1 and C_2 in Eq. (3) we get:

$$\Theta_n = K + (\Theta_c - K)\, e^{-mz} \left[e^{+(m^2+n)^{\frac{1}{2}} z}\right] \tag{4}$$

For $z > 0$ the wire is superconductive and $\rho_s = 0$, or $A = 0$

$$\Theta_s = \Theta_c\, e^{-mz} \left[e^{-(m^2+n)^{\frac{1}{2}} z}\right] \tag{5}$$

Equations (4) and (5) contain the unknown parameter v_q. This is determined by using the condition that the heat flow across the moving phase boundary at $z = 0$ must be continuous, in the absence of a latent heat term:

$$\left.\frac{d\Theta_n}{dz}\right|_{z=0} = \left.\frac{d\Theta_s}{dz}\right|_{z=0}$$

Applying this condition to Eqs.(4) and (5) we get for the heat speed of normal phase:

$$v_q = \frac{\sqrt{n}}{2} \cdot \frac{\frac{K}{\Theta_c} - 2}{\sqrt{\frac{K}{\Theta_c} - 1}} \cdot m' \qquad (6)$$

with

$$m' = \frac{2k_s}{c_{p_s} \cdot \delta_s} \cdot \frac{1 + \frac{A_n}{A_s} \cdot \frac{k_n}{k_s}}{1 + \frac{A_n}{A_s} \cdot \frac{c_{p_n}}{c_{p_s}} \cdot \frac{\delta_n}{\delta_s}}$$

Equation (6) enables us to describe three limiting cases:

<u>Case 1</u>

$$v_q = 0 \therefore \frac{K}{\Theta_c} = 2$$

This corresponds to a condition of static boundary equilibrium. If i_1 corresponds to the case $v_q = 0$, we get

$$i_1^2 = \frac{2h}{\rho_s} f \,(T_c - T_b) \cdot A_s^{3/2} \cdot \left(1 + \frac{A_n}{A_s} \cdot \frac{\rho_s}{\rho_n}\right)\left(1 + \frac{A_n}{A_s}\right)^{\frac{1}{2}} \qquad (7)$$

Modifying Eq. (7), assuming the resistivity ρ_s in a nonsuperconducting state is large compared to ρ_n (Fig. 8) and using the relation between cross section and surface area in contact with the coolant:

$$2f\,(A_n + A_s)^{\frac{1}{2}} = s$$

we get for the steady state condition

$$i^2 \cdot \rho_n = h(T_c - T_b) \cdot A_n \cdot s \tag{8}$$

as a stabilization condition.

Case 2

$$v_q = -\infty \ \therefore \ \frac{K}{\Theta_c} = 1$$

In this case no quenching will occur. If i_2 corresponds to this case we get

$$i_2 = \frac{i_1}{\sqrt{2}}$$

Case 3

Unstable case, where the heat may propagate further and $v_q > 0$.

This case is clearly defined by $\frac{K}{\Theta_c} > 2$. Specifically $v_q \rightarrow +\infty$ is the case where the current is increased to such a value that the whole coil is quenched simultaneously. In practice this case may never occur, due to the fact that the substrate surrounding the superconductor requires some time to warm up. But if the superconductor is not protected adequately by normal material, $v_q >> 0$ may happen quite readily.

Figure 9 illustrates the propagation of the heat front in the superconducting region, where $i_1 = i_c$ denotes the critical current in a steady state condition. The region $0 < i < i_2$ may be denoted as the absolute stable region, where no quench can happen.

For a given current the parameters ρ, h, A_n and s may be varied to achieve stable conditions. The heat transfer coefficient h is varied by using forced helium cooling; ρ_n is a function of the conductor material used and of the magnetic field at the conductor and in most cases is determined. The amount of normal substrate with the superconductor and the cooling surface can be varied with no great difficulties, which influences directly the factor $h\Delta T$ and therefore the stabilization effect.

IV. 70 kG, 30 cm HELMHOLTZ COIL

Referring to the HI characteristic of type II superconductors, the critical current of the superconductor in the high field region is rather modest. Nb_3Sn ribbon for this particular application was disregarded due to coil winding difficulties and lack of experience with the delicate ribbon produced by G. E.[11] and R.C.A.[12] The inner sections of the coil ranging from 74 kG to 35 kG are built from NbTi and the other section from heat heated Nb(25%)Zr rectangular shape cables.

The coil geometry is given in Table I and coil configuration in Fig. 10. Each coil section can be used separately if desired. Due to the advancement in cable technology it was decided to build this magnet out of stabilized square cables shown in Fig. 1a-1d. From magneto resistance measurement it was found that low temperature melting silver pure tin alloy as impregnant is quite adequate and is equal to the more expensive pure indium. Its greater advantage is that cables impregnated with this solder show greater strength in high field operation. The 3 coil sections are located between perforated stainless steel end plates. The hole configuration in each plate is such, that helium can penetrate between each superconducting layer. The cable is wrapped in nichrome or manganin strips and the layer insulation consists of oxidized copper and anodized aluminium screen sandwiched between two layers of glass cloth each 0.017 cm thick. The operating current through all sections was chosen to be 410 amperes. The total number of ampere turns in the coil is 4.63×10^6 and the coil energy is approximately 6×10^6 joule. The axial compressive forces are calculated to by 7×10^5 kG between coil sections.

TABLE I

30 cm, 70 kG Helmholtz Coil

Coil Section	a_1(cm)	α	β^a	N	Average S (A/cm^2)	Max. field at the Sup. Cond. (kG)	Space factor $\%^b$
I	15.24	1.838	0.958	5000	3500	75	10
II	28.56	1.2	0.512	2800	3900	55	8.5
III	34.9	1.364	0.418	7000	3600	40	6

[a] β is calculated for each coil section.

[b] Space factor is the ratio of superconductor to the coil cross section.

The weight of the cable used is approximately 1520 kG and the total weight of the coil 2500 kG. The amount of liquid helium required to cool down the coil from $78^{\circ}K$ to $4.2^{\circ}K$ utilizing the latent heat of helium is 750 liters. The total heat losses due to radiation from the dewar to environment (the current leads using a spiral configuration suggested by Williams[13]) and due to heat leak from heat conductivity is calculated to be 8 watts or equivalent to an amount of 12 liters of helium per hour being boiled.

The ratio between the amount of copper to the superconductor in the cable configuration was based on the conservative value of:

$$h(T - T_b) = 0.2 \ (W/cm^2)$$

The coil is copper limited and operates in a fully stabilized mode with a recovery current of 410 amperes, which was chosen to be the maximum operating current at 70 kG.

The magnet may operate either when completely immersed in liquid helium, in which the liquid helium is in close contact to all turns, or the helium may be pressurized through both coils from the two outer perforated plates, by means of a small pump. The coil is still immersed in liquid helium. The helium pressurized through the coil with a speed of approximately 5 cm/sec serves to prevent any built-up gaseous helium trapped inside the coil leading to heat sources.

V. FORCED LIQUID HELIUM COOLED SUPERCONDUCTOR IMBEDDED IN NORMAL MATERIAL

The importance of cooling in stabilized coil configurations is emphasized by Steckly[1] and shown explicitly in Section III. Improving the cooling leads to reduction of normal material surrounding the superconductor and to an improvement of the average current density, and therefore reduction in cost.

A possible solution to improve cooling is to imbed the superconductor in a normal material according to Fig. 11a-11d.

The superconducting wires of Fig. 11a are imbedded in grooves cut in the substrate. The superconductors are impregnated with tin and the grooves are closed after tinning by distorting the slot walls. In Fig. 11b and 11c the two halves of the substrate are swaged or cold welded after the superconductors are in place.

In the case of Fig. 11d, superconducting ribbons or wires are imbedded in the substrate. Here the superconductors should generally be placed as close as possible to the neutral bending axis, in order to prevent breaking during winding.

The hollow conductor is wound into double pancakes and the liquid helium pressurized through each hydraulic circuit in a close loop by an adequate liquid helium pump. In large magnets each individual hydraulic passage may exceed hundreds of meters. The performance of adequate splices according to Fig. 11e is simple. The pancakes may be insulated in the same manner as water cooled coils. The hydraulic passages are connected in parallel, electrically in series. The inlet of each hydraulic passage is connected over insulators to a high pressure vessel and the low pressure outlet to another plenum. The liquid helium flowing through the coil is collected through a system of high pressure transfer lines to a dewar, and is pressurized by a double acting helium pump,[14] through rectifying valves and heat exchangers. The experimental setup is given in Fig. 12. The helium circulates in a closed system and is kept under a pressure of several atmospheres in order to use it in the supercritical stage.

VI. 55kG, 1.36 m HELMHOLTZ COILS

In the past months a few projects using superconducting magnets in combination with large bubble chambers have been under investigation. The projects at Argonne and CERN[15, 16] deal with a 4.5 m liquid hydrogen bubble chamber magnet with a central field of 20-30 kG with iron return paths. The Brookhaven project specifies a field of 30-40 kG in the center, but without return yokes. All proposals enable the laboratories to perform experiments with charged particles having momentum higher than 10 GeV/c. A different approach is under investigation at SLAC. By 1969 the presently built water cooled bubble chamber magnet producing a field of 21 kG in the center of the 1m chamber should be replaced by a superconducting magnet, generating a field of 50-70 kG. The SLAC 1m bubble chamber, the optical system and the iron return path can be preserved; however, the vacuum tank, the expansion system and the coil support structure must be rebuilt. This modification matches the SLAC bubble chamber to particle momenta of 10 GeV/c. The proposed SLAC superconducting magnet is shown in Fig. 13. Table II compares the data of the present SLAC 21 kG magnet to the proposed 55 kG superconducting magnets. Figure 14 illustrates the schematic configuration of the superconducting magnet and refrigeration system.

Due to the change of the vacuum tank surrounding the magnet coils, the total length of the magnet is shorter. The axial width between the coils as well as the coil inner diameter can be reduced, which has been shown in Table II. However,

TABLE II

Magnet Coil Parameters for a 1.36 m ID 21 kG Water Cooled and 55 kG Superconducting Magnet

Coil Parameters	21 kG (Water Cooled)	55 kG (Superconducting)
a_1	68.5 cm	68 cm
α	2.06	1.96
β_1	0.275	0.305
β_2	0.483	0.4477
2g	35.5 cm	26 cm
γ_1	0.535	0.5
γ_2	0.742	0.64
I	11,000 amp	1000 amp
NI	3.98×10^6 At	11.696×10^6 At
N_1	128	4730
N_2	224	6966
Turns per layer (left coil)	8	55
Turns per layer (right coil)	14	81
Number of layers	16	86
Conductor dimensions	4.3×4.3 cm^2	0.635×0.635 cm^2
	1.9 cm diameter hole	0.3175 diam. hole
Number of hydraulic passages	11	220
Copper Weight	32×10^3 kg	22×10^3 kg
Weight of superconductor	--	545 kg
Average current density	5.1×10^2 A/cm^2	1.75×10^3 A/cm^2
Magnet Energy	13×10^6 joules	120×10^6 joules
Axial forces	1.0×10^6 kg	5×10^6 kg
Power requirement	3.4×10^3 kW *	225 kW

*The 55 kG water cooled magnet with the same dimensions would require a power of 56×10^6 watts.

the total available space is reduced. Three possibilities have been investigated for coil manufacturing:

a. The coils are manufactured in the same way as described in Section IV for the 30 cm magnet. The cable is current stabilized for 1000 amperes operational current and the coils current optimized.

b. The coils are manufactured as edge cooled double-pancakes. The current optimization in this particular case is hard to achieve.

c. The coils are manufactured from hollow conductors and wound in layers. The superconductors are incorporated in the hollow conductor substate as described in Section V. The coils are current optimized, in which the amount of superconductor in the substrate is matched to the field current density distribution in the coil. Due to ease in manufacturing,the dimensions of the substrate are unchanged.

The liquid helium is pressurized through the coil by means of a small helium pump circulating with about 8 cm^3/sec through each hydraulic circuit. The total amount of liquid helium required through the magnet is about 225 liters per hour and the pressure loss across the coil approximately 1 atm. Losses due to joules heating in the heads and in the series connections between layers, radiation losses to the hydrogen shield, and the power loss in the pump is 150 watts. The helium is circulated in a closed system in a supercritical state. It is estimated that about 10% of the helium is lost during the heat exchange process. As far as all coil sections are connected electrically in series, the magnet may operate in a persistent mode. Table II gives details of cooling and magnet operation. The magnet has an inductance of 240 henries, a minimum charging time of 1.7×10^3 seconds.

Two pumps are foreseen, with one pump as reserve in case of emergency. Each pump is adequate for 900 liters per hour helium flow, corresponding to 0.25 liters per second. The pump is double acting with 5 strokes per second. The pump bore diameter is 2.5 cm with a stroke of 10.2 cm. The design pressure for the whole closed system is chosen as 5 atm.

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FIGURE CAPTIONS

1a-1d. Cable geometries used in stabilized superconducting magnets.

1. Superconductor
2. Normal material (OFHC copper)
3. Bifilar or spiral wound high resistance material (manganin or nichrome)
4. Insulation
5. Metallic screen

1e. 7-cm bore, 75 kG superconducting magnet.

2. Short sample in small coil current and field curves.

3. $h\Delta T$ values measured in a "gap" test. The steep slope of curve d is due to the adequate length of the gap and poor copper conductivity.

4. Short sample characteristic of various sized Nb(22 at %) Ti wires.

5. Current-carrying capacity at various field levels as function of wire tension.

   1a, 2a, 3a. Current-carrying capacity at .5 kg/cm^2
   1b, 2b, 3b. Current-carrying capacity vs applied tension

   After each test at various tensions, the tension was relieved and the current-carrying capacity measured at .5 kg/cm^2 to determine the degradation of wire.

6. $\frac{L}{a_1, N^2} = \lambda(\alpha,\beta)$ for various values of α and β. For a_1 in cm L is in 10^{-9} Hy. The curves are computed for uniform current distribution using Lorenz Formula.

7. Schematic representation of a superconductor with internal liquid helium cooling.

8. Resistivity curves of Type II materials compared to pure copper.

   1. Nb_3Zr after heat treatment
   2. Nb_3Zr after being wound several times in a coil
   3. Nb(22 at %)Ti
   4. Pure copper after annealing
   5. OFHC copper

9. Speed of the quenching front vs current through the conductor.

10. 30 cm, 70 kG Helmholtz pair. Each coil section may also be energized separately.

11a-11d. Direct cooled superconducting-normal material conductor.

11e. Superconducting joint configuration.

12. Test setup for experiments with direct cooled superconducting pancakes.

13. Proposal for a 1.36 m, 55 kG superconducting bubble chamber magnet.

14. Schematic diagram of a cirect cooled superconducting magnet for refrigeration system.

$$\frac{d^2\Theta}{dz^2} + \frac{c_{p_s} \cdot \delta_s}{k_s} \quad \frac{\left(1 + \frac{A_n}{A_s} \cdot \frac{c_{p_n}}{c_{p_s}} \cdot \frac{\delta_n}{\delta_s}\right)}{\left(1 + \frac{A_n}{A_s} \cdot \frac{k_n}{k_s}\right)} \cdot v_q \; \frac{d\Theta}{dz} - \frac{h \cdot f\left(1 + \frac{A_n}{A_s}\right)^{\frac{1}{2}}}{k_s A_s^{\frac{1}{2}} \cdot \left(1 + \frac{A_n}{A_s}\right)} \cdot \Theta$$

$$+ \frac{(i_s + i_n)^2 \cdot \rho_s}{k_s A_s^2 \left(1 + \frac{A_n}{A_s} \cdot \frac{\rho_s}{\rho_n}\right)^2} \cdot \frac{\left(1 + \frac{A_n \rho_s}{A_s \rho_n}\right)}{\left(1 + \frac{A_n k_n}{A_s k_s}\right)} = 0$$

$$\Theta = K + \left\{ C_1 \, e^{(m^2+n)^{\frac{1}{2}} z} + C_2 \, e^{-(m^2+n)^{\frac{1}{2}} z} \right\} e^{-mz}$$

$$K = \frac{(i_n+i_s)^2 \rho_s}{h \cdot f\, A_s^{3/2}} \cdot \frac{1}{\left(1 + \frac{A_n}{A_s} \cdot \frac{\rho_s}{\rho_n}\right) \left(1 + \frac{A_n}{A_s}\right)^{\frac{1}{2}}}$$

$$m = \frac{c_{p_s} \cdot \delta_s}{2k_s} \cdot \frac{\left(1 + \frac{A_n}{A_s} \frac{c_{p_n} \cdot \delta_n}{c_{p_s} \cdot \delta_s}\right)}{\left(1 + \frac{A_n}{A_s} \cdot \frac{k_n}{k_s}\right)} \cdot v_q$$

$$n = \frac{h \cdot f}{k_s \cdot A_s^{\frac{1}{2}}} \cdot \frac{\left(1 + \frac{A_n}{A_s}\right)^{\frac{1}{2}}}{\left(1 + \frac{A_n}{A_s} \cdot \frac{k_n}{k_s}\right)}$$

$$\Theta_n = K + (\Theta_c - K)\, e^{-mz} \left[e^{+(m^2+n)^{\frac{1}{2}} z} \right]$$

$$\Theta_s = \Theta_c\, e^{-mz} \left[e^{-(m^2+n)^{\frac{1}{2}} z} \right]$$

$$\left.\frac{d\Theta_n}{dz}\right|_{z=0} = \left.\frac{d\Theta_s}{dz}\right|_{z=0}$$

$$v_q = \frac{\sqrt{n}}{2} \cdot \frac{\frac{K}{\Theta_c} - 2}{\sqrt{\frac{K}{\Theta_c} - 1}} \cdot m'$$

$$m' = \frac{2k_s}{c_{p_s} \cdot \delta_s} \cdot \frac{1 + \frac{A_n}{A_s} \cdot \frac{k_n}{k_s}}{1 + \frac{A_n}{A_s} \cdot \frac{c_{p_n}}{c_{p_s}} \cdot \frac{\delta_n}{\delta_s}}$$

$$i_1^2 = \frac{2h}{\rho_s} f (T_c - T_b) \cdot A_s^{3/2} \cdot \left(1 + \frac{A_n}{A_s} \cdot \frac{\rho_s}{\rho_n}\right)\left(1 + \frac{A_n}{A_s}\right)^{\frac{1}{2}}$$

$$2f (A_n + A_s)^{\frac{1}{2}} = s$$

$$i^2 \cdot \rho_n = h(T_c - T_b) \cdot A_n \cdot s$$

TABLE I

30 cm, 70 kG Helmholz Coil

Coil Section	a_1(cm)	α	β[a]	N	Average S (A/cm^2)	Max. field at the Sup. Cond. (kG)	Space factor %[b]
I	15.24	1.838	0.958	5000	2743	74	8
II	28.56	1.2	0.512	2800	3400	50	8.5
III	34.9	1.364	0.418	3500	3550	35	6

[a] β is calculated for each coil section.

[b] Space factor is the ratio of superconductor to the coil cross section.

TABLE II

Magnet Coil Parameters for a 1.36 m ID 21 kG Water Cooled and 55 kG Superconducting Magnet

Coil Parameters	21 kG (Water Cooled)	55 kG (Superconducting)
a_1	68.5 cm	68 cm
α	2.06	1.96
β_1	0.275	0.305
β_2	0.483	0.4477
2g	35.5 cm	26 cm
γ_1	0.535	0.5
γ_2	0.742	0.64
I	11,000 amp	1000 amp
NI	3.98×10^6 At	11.696×10^6 At.
N_1	128	4730
N_2	224	6966
Turns per layer (left coil)	8	55
Turns per layer (right coil)	14	81
Number of layers	16	86
Conductor dimensions	4.3×4.3 cm^2	0.635×0.635 cm^2
	1.9 cm diameter hole	0.3175 diam. hole
Number of hydraulic passages	11	220
Copper Weight	32×10^3 kg	22×10^3 kg
Weight of superconductor	--	545 kg
Average current density	5.1×10^2 A/cm^2	1.75×10^3 A/cm^2
Magnet Energy	13×10^6 joules	120×10^6 joules
Axial forces	1.0×10^6 kg	5×10^6 kg
Power requirement	3.4×10^3 kW *	225 kW

* The 55 kG water cooled magnet with the same dimensions would require a power of 56×10^6 watts.