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A PRELIMINARY DESIGN OF THE END PLUG MAGNET SYSTEM FOR A TANDEM MIRROR REACTOR

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Abstract

A conceptual design of the end plug magnet system for a tandem mirror reactor is presented. An innovative approach is needed, particularly in the Yin Yang coil, to satisfy the requirements of an adequate mirror ratio, high field (14-17 Tesla), high current density and the unusual geometry. Nb_3Sn superconductor is used and superfluid cooling is adopted to provide cryostability at the required high current density. The stabilizer used is high strength copper or stainless steel encased high purity aluminum. External structure is provided with heavy casings which surround the Yin Yang coils and are joined to each other at critical locations.

Introduction

The magnet system of a tandem mirror reactor may be divided into two major components, the long solenoid coils of the central cell (where most of the power is produced) and the coils of the end plug at the extremities of the central cell. The end plug coils stabilize and confine the plasma. Correct field shaping requires a non-circular plasma shape, dictating the use of Yin Yang or baseball coil types and, in addition, the magnetic field strength required to confine a high density, high temperature plasma is high (>> 10 Tesla). In order to meet the field requirements efficiently, it is desirable to locate the Yin Yang coil close to the plasma and to have a high current density in the coil winding.

Two factors make such an aim hard to achieve. First, a radiation shield some 70-80 cm thick is required to protect the magnet, thus considerably enlarging the winding dimensions. Second, the large transverse forces and high fields of the Yin Yang dictate a low winding current density and a thick structural support case. In consequence, an innovative approach is required for the design of a TMR end plug.

By contrast, the magnetic field requirements of the central cell are much more modest. Peak conductor fields of 2-3 Tesla and the solenoid geometry make the design of these coils much more straightforward.

In the present paper we describe the design of a high field (14.5 T) Yin Yang coil set for a classical TMR. More recent ideas have incorporated thermal barriers into the end plug design.(1,2) At present it appears that the thermal barrier concept will ameliorate the magnetic design of the end plug by (i) making the high field coil a solenoid and (ii) considerably reducing the peak field on the Yin Yangs and other non-solenoidal geometry coils. The plasma physics of such an end plug are, however, still sufficiently fluid that the need for a very high field Yin Yang magnet cannot be definitely ruled out.

Reference Design

After a considerable amount of design iteration the following critiera were established to frame the design of the end plug:

Maximum field in mirror throat	≥ 10 T
Maximum field at conductor surface	≤ 15 T
Mirror ratio	≥ 1.1
Mirror length	≤ 4.5 m
Radial well depth	$\geq 4\%$
Blanket and shield thickness	≥ 70 cm
Beam port aperture	$\simeq 80$ cm
Block current density in Yin Yang	$<1800 A/cm^2$
Yin Yang Current	≤ 20 MA

The configuration finally adopted was a split solenoid (fairly close to Helmholtz) with an inner high field Yin Yang. A section through the magnet is shown in Figure 1 and the design parameters are given in Table I. The maximum field at the conductor is 14.5 T while the on-axis fields are 11.04 T (maximum) and 9.69 T (central). The Yin Yang contributes 4.7 T to the central field, the solenoid pair 5.0 T. Since the design problems of the solenoid pair are fairly straightforward, the present paper principally confines itself to the design of the Yin Yang coils.

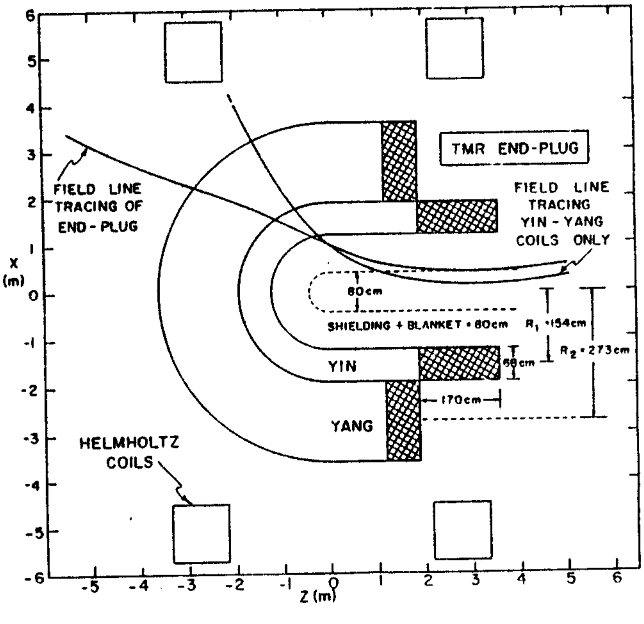

Fig. 1. End plug magnet configuration.

Magnetic Loads

The magnetic loads computed along the centerline of the Yin Yang set are shown in Figure 2. The figure depicts the load distribution on orthogonal planes of one quarter of the Yang coil. Plane B, which is parallel to the yz plane, contains 90° of the small

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radius of the Yang coil. Plane A contains 90^0 of the large radius of the Yang coil. Applied loads for the Yin coil are not shown since coil symmetry yields the same values as for the Yang coil.

Table I. Specifications of TMR Plug Coil

TMR Plug

Type of coil	Combination of Yin Yang and split solenoid
Stored energy (in one plug)	19.2 GJ
B_0 (at center)	9.69 T
Maximum field at mirror throat	11.04 T
Mirror ratio	1.14
Mirror length	4.1 m
Well depth	4.1%
Yin Yang	
Major radius	2.73 m
Minor radius	1.54 m
Cross section	0.68 m x 1.70 m
Current	20.81 MA
Maximum field on conductor	14.5 T
Solenoid	
Radius	5.0 m
Separation of two coils	2.75 m
Current	26 MA

Figure 2a shows the inplane load per unit length for the small radius arc of the Yang coil and the out-of-plane load per unit length for the large radius arc of the Yang coil. Figure 2b depicts the out-of-plane load per unit length for the small radius arc of the Yang coil and the inplane load per unit length for the large radius arc of the Yang coil.

These magnetic loads are large and it does not appear feasible to use the considerable strength of the conductor to take any of the transverse loads in tension. All the loads of the Yin Yang are thus taken to a stainless steel case 20 cm thick, working at 80 ksi.

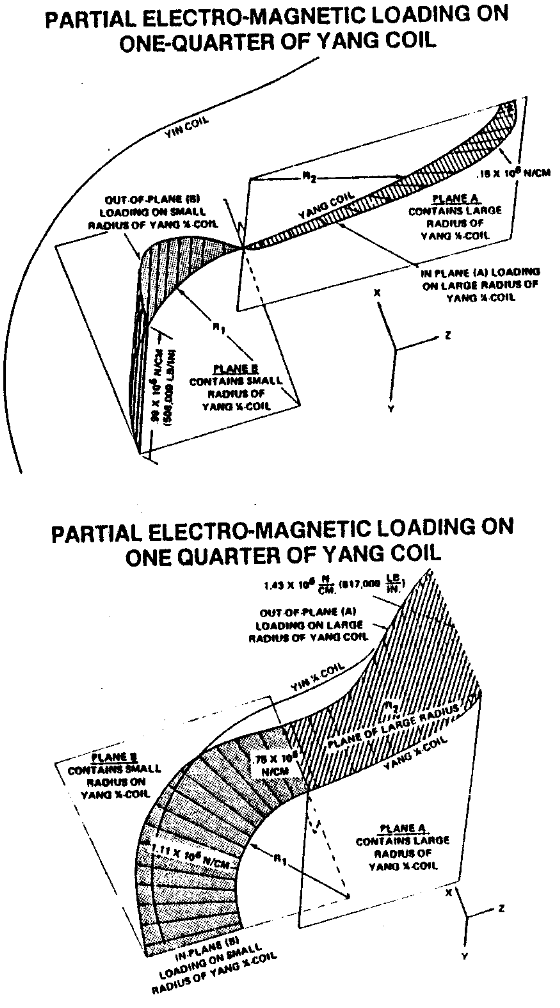
A summary of peak electromagnetically induced stresses and where they occur is presented in Table II. The results in no way exhaust the possibility for further optimization, but are simply shown to indicate the dependence of stress upon support stiffness and the possibility of shifting the maximum stress point.

A peak design stress of 80 ksi or two-thirds of the Y field point was the goal, since this permits the use of a variety of austenitic steels of good toughness, having 4K yield strengths of 120 ksi or more.

Most of the peak stresses were caused by bending with the larger values of moments occurring at the smaller coil radius where bending occurred about the axis with the lower area moment of inertia. However, there were occasional exceptions to this condition.

The results indicate a general feasibility of design and highlight the importance of the intra-coil supports, K_2. In fact, a K_2/K_1 ratio in excess of 3 appears desirable.

However, additional parametric studies are required to establish the effects of coil case and support stiffness (axial and bending) upon case stress and conductor strain. A structural design study of the coil case is necessary to help determine case shape, size, method of manufacture and assembly. In addition, a nonlinear contact analysis of the conductor bundle and load distribution through the coil cross-section is required to investigate the possibility of conductor crushing and local case stresses.



Figs. 2a and b: In-plane and out-of-plane loads on one quadrant of Yang coil.

Future analysis should also evaluate thick beam effects as the minimum radius to beam-depth ratio is larger than is recommended for use in thin beam theory. Along these same lines, the centroid of the coil loads will not act at the beam centerlines either and the model should be adjusted accordingly.

Conductor Design

Superconductor

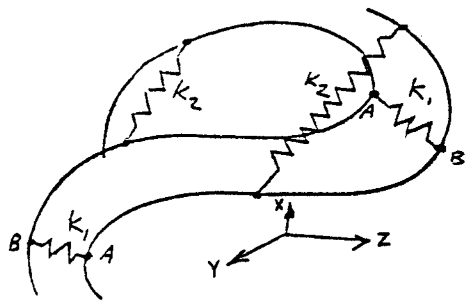
The peak field on the Yin Yang is 14.5 T so that only Nb_3Sn can be considered for this coil. Current densities, referred to the total bronze + Nb cross-section, are not however very large at 14.5 T and 4.2 K, values of around $225 A/mm^2$ being obtainable in optimized conductors. Since the main loads are transverse to the conductor, no credit can be taken for J_c enhancements under tensile stress. However, we have established (see Figure 3) that reducing the temperature to about 2K increases the available J_c to 330A/mm^2, an increase of ~ 50%.

In order to avoid damage to the conductor a maximum winding strain limit of 0.3% and an overall winding + electromagnetic strain limit of 0.5% was fixed.(4,5)

Table II. TMR Yin Yang Coils Maximum Stress - Summary

Case No.	K_1/K_{AXIAL}*	K_2/K_{AXIAL}*	S_{MAX} (KSI)	LOCATION OF S_{MAX}
1	0.03	1.0	55	B
2	0.3	1.0	59	A
3	0.3	0.3	62	A
4	3.0	1.0	60	A
5	0.3	0.03	76	A
6	0.3	3.0	59	A

*K_{AXIAL} is the uniform axial stiffness of the coil bundle and case itself.



Cooling

Although we initially considered cooling the Yin Yang magnets in pool boiling mode at 4.2 K, we rejected the option. Our main concerns were the narrow cooling channels available, the high stresses on them, the thick coil cross-section, the fact that the Yin Yang sees all orientations to the vertical and the consequent risks of vapor locking. The alternatives of force flow cooling and superfluid helium cooling were considered and we decided to design with superfluid helium. Advantages of this decision are that the recovery heat flux can be 5 to 6 times larger than for He I(6) and is independent of orientation since heat is transferred through the liquid by quantum mechanical conduction processes rather than by convection. Additional advantages are that operation at 1.8-2 K produces a 50% increase in the critical current density of the Nb_3Sn and the thermal conductivity of the He II is about 1000 times greater than pure Cu at this temperature.

A frequently cited disadvantage of reduced temperature operation is the increased refrigeration cost. Since, however, there are no pulsed fields in the TMR, there is little heat generated at the conductor operating temperature and the major heat loads can be taken at intermediate temperatures. We believe that the extra power for 1.8 K refrigeration will then be about 30% rather than the 300% commonly quoted and is therefore of negligible importance. A separate heat exchanger will however be needed to permit operation at ~ 1 atmosphere at 1.8-2 K. 1 atmosphere operation is principally dictated by the poor dielectric strength of low density He vapor.(7) An additional consideration is that the recovery heat flux is tripled from 0.6 W/cm^2 to 1.9 W/cm^2 on increasing the pressure(6) of 1.3 atmospheres from saturated vapor pressure. For these reasons, we believe He II cooling at 1.8 K and 1-1.5 atmospheres to be a logical choice for the cooling of the Yin Yang magnets.

Stabilizer

In view of the high fields and the low magnetoresistivity of Al, conductors utilizing both Al and Cu stabilizers were designed. It was assumed that both stabilizers would be radiation damaged up to 10^{-6} dpa(10) and that the magnetoresistivity could be estimated from Kohler plots.(8,9) An additional strain induced resistivity correction has been made for the high purity Al (RRR=4000) selected in our design to account for yielding (its yield strength is ~ 1 ksi at 4K).(12) Three quarter hard OFHC Cu was found to have a favorable combination of yield strength (30 ksi at 4K) and conductivity ($\rho(B=0)=2.9\times10^{-8}\Omega$cm).(11) The resultant values of ρ vs. B for Al (RRR=4000) and 3/4 hard OFHC Cu are shown in Figure 4. It can be seen that the Cu has ~ 10 times the resistivity of the Al at 14.5 T (1.2×10^{-8} vs. $10.6\times10^{-8}\Omega$cm).

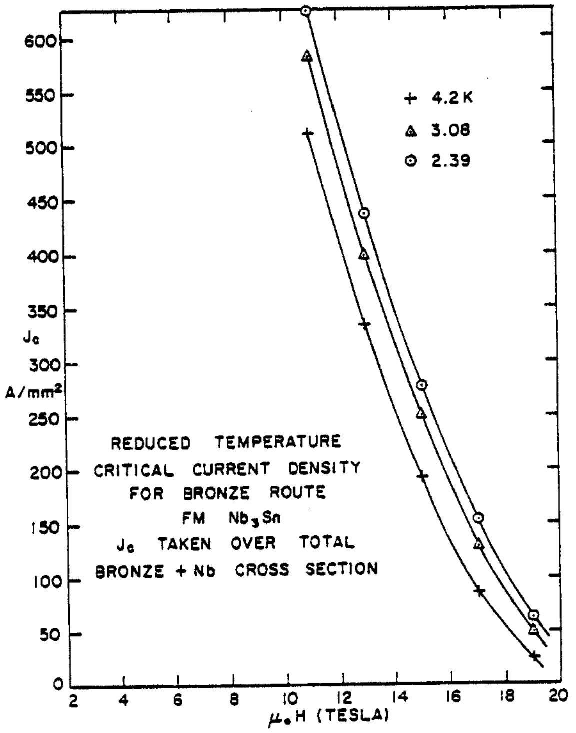


Fig. 3. Critical current density as a function of field for Nb_3Sn.

Conductor Configuration

We have made trial designs of conductors for the Yin Yang, two with Cu and one with Al. Each is designed for 5000A at 14.5 Tesla which is probably below optimum design current but fits well with our initial strain of 0.3%. The surface heat fluxes are adequate and our preferred 3/4 hard Cu conductor can be safely protected even at this relatively low current level.

In our designs we were guided by the extended internal surface conductor design being used for MFTF. Although the square cross section is not optimum for heat transfer it is a reasonable shape given the necessity to wind it about 2 axes.

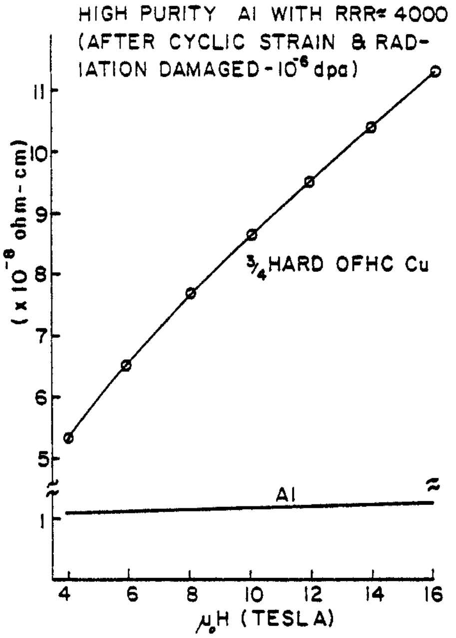


Fig. 4. Resistivity of high purity Al and 3/4 hard OFHC Cu.

The Al and Cu conductors proposed for the Yin Yang are shown in Figure 5. The bronze route Nb_3Sn superconductor is wrapped and soldered to high purity Al stabilizer and further encased with thin wall high strength Al alloy skin to prevent the possible plastic flow of aluminum stabilizer. The hexagonal conductor element is protected by a 3 mm wall stainless steel case from the accumulated magnetic load. The steel case is periodically slotted along the edges in order to permit helium circulation in the space between the conductor and the steel case.

Although the total accumulated load is high, the bearing stress on the high purity Al is low (3000 psi). For some precipitation hardened alloys of high purity aluminum, such as Al-Au, the σ_{02} (4.2 K) is 4-6 ksi and their resistivity is not excessively increased. In this case it may be possible to avoid the use of the high conductivity aluminum skin confinement and helium may be in direct contact with the stabilizer which would aid conductor fabrication and stability. A detailed specification of the Al conductor is listed in Table III. Under present circumstances, however, we do not believe that Al is a viable choice for a TMR Yin Yang conductor. The very low strength, bonding difficulties and low melting point (660°C) as compared to Nb_3Sn reaction temperatures (650-750°C) all contribute to making the fabrication of such a conductor difficult.

Copper conductors suffer from higher resistivity but can be strengthened to a sufficient extent that no separate strengthening element is required. As a result they are very suitable for the TMR Yin Yang. We have considered two possible stabilizers, 3/4 hard OFHC copper and in situ Nb-Cu. The newly developed in situ Cu-Nb composite exhibits extremely high strengths (100-300 ksi with ductility up to 15%)

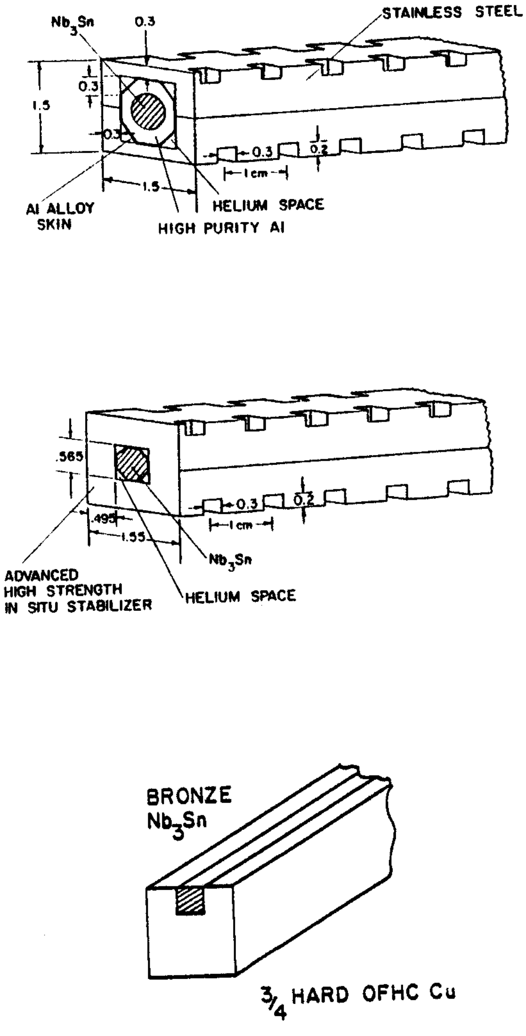


Fig. 5. Alternative conductor designs.

and RRR~20(14) A conductor design using in situ Cu-Nb is shown in Fig. 5b. The very high strength of this stabilizer may be a disadvantage during winding and probably requires that the bronze Nb_3Sn core be decoupled from the stabilizer so as to avoid an excessive compressive stress on the Nb_3Sn which would reduce its superconducting properties. For this reason, the bronze Nb_3Sn core is again shown as a hexagonal shaped element inside the wrapped and soldered Cu-Nb stabilizer.

Our preferred design, which uses essentially current state-of-the-art materials and fabrication technology, is the combination of 3/4 hard OFHC Cu and bronze Nb_3Sn shown in Fig. 5c. In this case, the conductor can be made extremely simple (i.e. like a bubble chamber conductor) with the superconducting composite soldered into a groove in the Cu. Even with insulation covering 50% of the surface area, the surface heat flux still only reaches 0.5 W/cm^2, a rather low value for superfluid He. It is possible therefore to dispense with internal grooves and have an extremely simple, but strong conductor.

Insulation

The insulation scheme used for MFTF appears to be satisfactory for the present design. G11-CR sheets provide the layer to layer insulation while tabs of G11-CR provide turn to turn insulation. Surface coverage is 50% making the maximum bearing pressure ~ 50 ksi. According to Becker,(15) such pressures can be safely withstood by G11-CR.

Safety and Protection

The stored energy in the plug is extremely large. The self energy of the Yin coil is $1.6x10^9$ joule, its self-inductance is 120H and its mutual inductance to the Yang coil is 44H. Should the stored energy of $1.6x10^9$ joules be uniformly deposited, the temperature of the coil would rise to 120 K. Under adiabatic conditions,(16) the Yin Yang pair with the OFHC Cu conductor can be driven down in 300 seconds, producing a maximum temperature of 300°K and a maximum voltage of 5 kV. Since the adiabatic approximation is pessimistic, we are confident that the Yin Yang pair can be adequately protected.

Acknowledgement

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Table III

Conductor Design Parameters

Stabilizer		OFHC Cu	In situ Cu-Nb	Al
Operating current		5000 A	5000 A	5000 A
Operating J_c in Nb_3Sn		200 A/mm^2	200 A/mm^2	200 A/mm^2
J_c 1.8K/14.5T		330 A/mm^2	330 A/mm^2	330 A/mm^2
Overall winding J_c		18 A/mm^2	18 A/mm^2	18 A/mm^2
Yield strength)	st. steel	--	--	140 ksi
At 4K)	stabilizer	39 ksi	120 ksi	-1 ksi
Working stress on stabilizer		25 ksi	36 ksi	3 ksi
Vol. fractions	st. steel	--	--	50%
	Al	--	--	14%
	Cu	64%	68%	--
	Bz + Nb_3Sn	9%	9%	9%
	He II	13.5%	11%	17%
	Insulator	13.5%	12%	11%
Heat generated/unit length		1.44 W/cm	1.81 W/cm	.71 W/cm
Heat generated/exposed surface area		0.5 W/cm^2	0.49 W/cm^2	.42 W/cm^2
Heat flux through cooling channel		1.44 W/cm^2	2 W/cm^2	2.05 W/cm^2
Critical heat transfer length		100 cm	60 cm	50 cm

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