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Magnets for the Tandem Mirror Fusion Power Reactor WITAMIR-I+

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MAGNETS FOR THE TANDEM MIRROR FUSION POWER REACTOR WITAMIR-I+

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The design of the magnet system for the Tandem Mirror Fusion Power Reactor WITAMIR-I is presented. The central cell of this reactor consists of 34 dc solenoid magnets with a diameter of about 8 m, spaced over a length of 165 m; the central cell magnetic field is 3.6 T. The design of these magnets is relatively simple. The requirements of the end plug magnets are more stringent. In our concept each end plug consists of one barrier mirror solenoid coil, of 3.4 m inner diameter, producing an on axis field of 14 T, two transition coils and a yin-yang pair with a maximum plug field of 6 T and a plug mirror ratio of 1.5. NbTi can be used for all coils except the high field plug solenoid for which Nb_3Sn is needed.

I. Introduction

WITAMIR-I is a tandem mirror reactor (TMR) with thermal barriers[1]. The original tandem mirror concept of plugging a solenoid with electrostatic potentials created by high particle density in the end plug cells was invented by Fowler and Logan[2], and independently by Dimov et al.[3] This concept required high magnetic fields and large amounts of neutral beam power to maintain the plug density, motivating Baldwin and Logan[4] to invent the thermal barrier concept: A potential dip between the central cell and plug which thermally insulates the plug electrons, allowing them to be efficiently heated with radio frequency power.

Studies then began[5,6,7] to investigate the prospects of a tandem mirror reactor based on the thermal barrier concept. WITAMIR-I is the first complete reactor study using a non-Boltzmann relation for the plug potential $\Delta\Phi$. The magnetic field, potential and density distribution is given in Fig. 1. The main features of the WITAMIR-I design are summarized in Table 1.

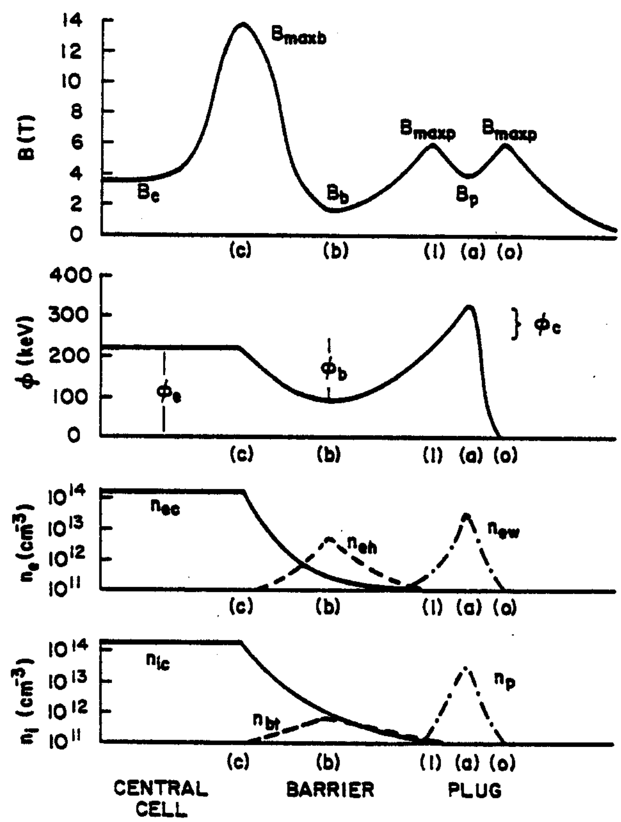

Fig. 1: On axis magnetic field, potential, ion and electron densities through WITAMIR-I.

Table 1

Main Characteristics of WITAMIR-I

Thermal Power	3000 MW
Net Electric Power	1536 MW
Net Electric Efficiency	39%
Reactor Q-Value	28
Neutron Wall Loading	2.4 MW/m^2
Central Cell Length	165 m
Central Cell Inner Diameter	1.93 m
Overall Length (Plug to Plug)	207 m

II. Magnet Design

WITAMIR-I has a set of 34 central cell solenoid magnets together with end plug magnets of more complex configuration, at each end a high field barrier coil and a yin-yang pair between two transition coils (see Fig. 2). 32 of the central cell magnets are identical while two magnets are oversized to provide space for neutral beam injection into the barrier region. The central cell solenoids are dc coils of 6.6 m inner diameter (9 m for the two oversized magnets). The design of these magnets is relatively simple. The on axis magnetic field in the central cell is 3.6 T with a field ripple of less than 5% at the plasma radius. The peak conductor field is less than 6.1 T (5.6 T in the oversized magnets).

The on axis field of 3.6 T in the central cell is followed by a steep rise to 14 T in the barrier coil. The field then declines in the thermal barrier region to 10% of the maximum value. In the yin-yang plug the field reaches a maximum of 6 T and a minimum of less than 4 T, providing a plug mirror ratio of better than 1.5. The main characteristics of the WITAMIR-I magnet system are given in Table 2.

+The WITAMIR-I design study has been supported by the Department of Energy, Office of Fusion Energy and the Wisconsin Electric Utilities Research Foundation.

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Table 2

Magnet Characteristics of WITAMIR-I

Coil Type	Unit	Central Cell Solenoid		Barrier Coil Solenoid	Transition Coils Reversed Cee-Coils	Yin-Yang Coils Yin-Yang
Number of Coils		32 + 2		2	2 + 2	2 + 2
Function		C.C. Field		Mirror	Change of Flux Bundle Cross Section	Mirror, Magnetic Well
Major Radius	m	4.3	5.7	2.71	2.0	1.66
Minor Radius	m	3.3	4.5	1.7	1.8	1.0
Sweep Angle	degree				65	90
Bundle Cross Section	m x m	1.4x1.0	1.6x1.2	5.00x1.01	1.4x0.9	2.1x0.36
Mean Turn Length	m	23.88	32.05	13.86	26.4	24.45
Volume of Winding	m^3	33.427	61.525	69.965	33.251	18.478
Weight of Winding	Tonnes	88.1	162.5	560	283	157
Overall Current Density	A/cm^2	950	800	1000/1500/2000	1480	1900
Ampere Turns	10^6 A-Turns	13.3	15.36	72.57	18.65	14.4
Self-Inductance per N^2	10^{-6} H/N^2	9.807	14.04	2.425	9.367	6.223
Stored Self-Energy	GJ	0.87	1.66	6.38	1.63	0.642
Operating Temperature	K	4.2		1.8	4.2	4.2
Field on Axis	T	3.6		14.	N/A	6
Max. Field on Conductor	T	6.1	5.6	15.1	8.1	8.1
Superconductor		NbTi		Nb_3Sn/NbTiTa/NbTi	NbTi	NbTi
Stabilizing Material		Al		Cu	Cu	Cu
Structure Material		Al		CuNb	SS	SS

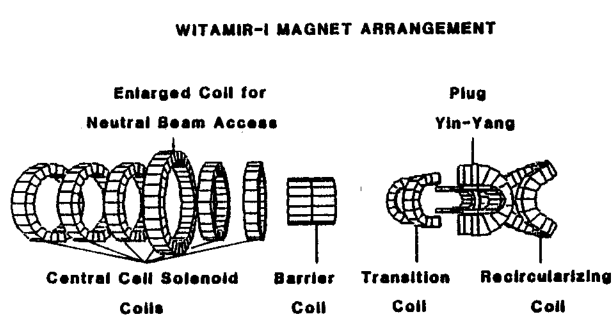

Fig. 2: Coil arrangement in WITAMIR-I.

The central cell magnets have been designed using conventional cryogenic stability criteria (see for example Ref. 8 or 9). The detailed features of our design have been previously given[10]. The code EFFI has been used for the calculations of fields, forces and inductances.[11]

The on axis field requirements shown in the upper part of Fig. 1 are fulfilled by keeping the peak conductor fields below 8.1 T in all magnets, with the exception of the barrier coil, where the peak field of the conductor reaches 15.1 T. Only for the barrier coil is Nb_3Sn needed. All other coils can use NbTi conductor at 4.2 K. The critical heat flux of 0.3 W/cm^2 is used for all coils at an operating temperature of 4.2 K. The overall current density in the NbTi coils does not exceed 1900 A/cm^2.

The recircularizing coil (RCP) in the end plug is an option. The use of this coil will be influenced by the construction of the plasma direct convertor. With a recircularizing coil, a spherical construction is possible while the construction must be elliptic without a recircularizer.

The barrier coil is a five meter long solenoid. There is an 8 cm wide space in the midplane of the coil for pellet injection for fuelling. The winding thickness is 1.0 m. Three conductor types are used in this coil; Nb_3Sn for conductor fields higher than 12 T, NbTiTa for conductor fields less than 12 T (to about 8-9 T) and NbTi for fields of about 8 T or less. The coil is cooled with He II.

The magnetic forces on the coils have been calculated for the case when all coils are in operation with the designed current densities. The most important result of the calculation is that in all C-shaped coils the absolute value of any in-plane (i.e. parallel to the broad face) or out-of-plane (i.e. perpendicular to the broad face) force is less than 0.5×10^6 N/cm. These forces are well below the high levels which so complicated our earlier design of a "classical" (i.e. without thermal barrier) end plug yin-yang[12]. The forces are well distributed over the four C-coils in the sense that no high peak forces occur in any coil. The line forces in the barrier coil are less than 1.0×10^6 N/cm in each part of the coil, while the line forces in the central cell solenoids are less than 0.3×10^6 N/cm (including the two oversized solenoids). The in-plane coil forces are always less than these values if the coils are energized alone.

The stored magnetic energy of WITAMIR-I is 78 GJ, about 43 GJ of which is stored in the central cell. The self energies of the coils are given in Table 2.

III. Conductor Design

Central Cell

The NUWMAK design for the conductor arrangement (disk configuration) is chosen for the central cell magnets[13] (see Fig. 3). It is an aluminum-stabilized NbTi conductor with an aluminum-alloy structure operating at 4.2 K. The characteristics of this design are:

- Aluminum minimizes the weight and cost;
- A working strain of 0.003 is chosen to maintain the resistivity of the aluminum stabilizer below 10^{-10} Ωm;[14]
- 2219-T87 aluminum alloy is used for the structure to ensure a good thermal contraction match between the structure and conductor.[15]

The 12000 A conductor, 3 cm wide and 1 cm thick, is embedded with fiberglass epoxy into the spiral grooves of an aluminum alloy structural disk (see Fig. 3). The conductor itself is encapsulated inside a skin 0.8 mm thick of high strength aluminum alloy to prevent plastic flow of the high purity aluminum due to the high magnetic forces. Alternative designs considered were:

- Al-stabilized conductor with stainless steel structure;
- Cu-stabilized conductor with stainless steel structure.

The first assembly was rejected due to the different thermal contraction coefficients between aluminum and stainless steel. The second one was rejected because the weight of the central cell magnets was approximately three times higher than in the chosen conductor design and was therefore more expensive.

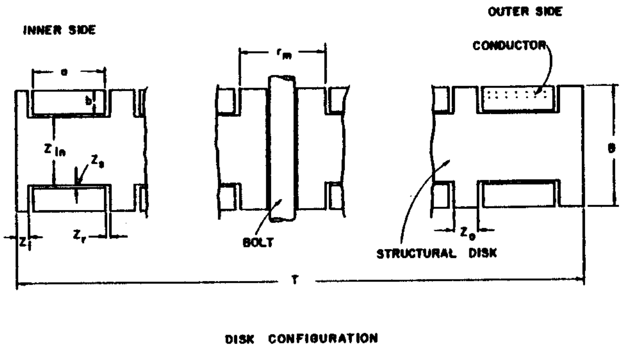

Fig. 3: Conductor placement in central cell solenoids.

Barrier Solenoid

Although the central cell solenoids are relatively straightforward, there are many complexities in the design of the high field plug solenoid. The large diameter (3.4 m inner diameter) and significant radial build (∿ 1 m), coupled with the high peak field (15.1 T), produce large stresses and problems with cooling and protection. In view of the demonstrated advantages of the He II cooling at 1.8 K for the difficult problem of a 15 T yin-yang in a "classical" tandem end plug, we have again applied this concept to a high field coil.[12]

The coil has been split into 3 subcoils operating at 1.8 K in the He II. This permits the inner section to be wound from Nb_3Sn (12-15 T), the central section from NbTiTa alloy[17] (8-12 T) and the outer section from NbTi (0-8 T). The coil is split at its mid-plane to permit pellet fuelling. We foresee that each section would be constructed from double pancakes.

Many of the important conductor parameters are given in Table 3. The general design of our conductor follows that of our previous design[12], in which the superconductor is soldered into a square Cu stabilizer (Fig. 4). The conductor itself is of simple design. Insulation between turns is G11-CR sheet and the cooling channels for the He II cooling are defined by a 50% coverage (32% in the outer section) of 4 mm thick (6 mm in outer coil) G11-CR strips.

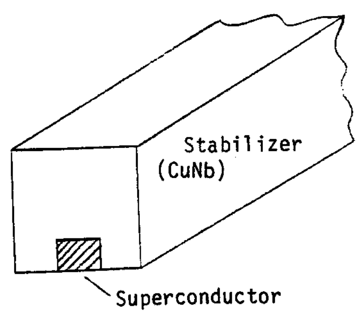

Fig. 4: Conductor for barrier solenoid.

Table 3

Characteristics of the Barrier Solenoid

		Inner	Central	Outer
Peak field	T	15	12	8
Block J_c	A/cm^2	1000	1500	2000
Superconductor		Nb_3Sn	NbTiTa	NbTi
Current	A	4000	6000	12000
Inner radius	m	1.7	2.03	2.31
ρ(stabilizer)	$\Omega m \times 10^{-10}$	13.5	11.5	10.1
Surface Heat Flux	W/cm^2	0.44	0.76	1.3
Channel Heat Flux	W/cm^2	1.09	1.7	2.0
Critical Length	m	1.25	0.9	0.45
Strengthener		CuNb	CuNb	CuNb
Conductor Stress	MPa	389	458	492
Conductor Strain	%	•35	•42	•45

The working stresses of the barrier solenoid are inevitably high. A conventional design, using hardened copper and stainless steel structure, was found to be very marginal in terms of its cryogenic stability. We have therefore made a second design using dispersion hardened copper, taking the values of resistivity and strength obtained by Harbison and Bevk[18] on in situ CuNb dispersions. Methods for large scale manufacture have recently been developed by Verhoeven and Finnemore.[19] The prime attractions are that $\rho(4.2) = 9 \times 10^{-8}$ Ωm for a yield stress of 120 ksi, enabling the stabilization and structural functions to be combined. The lower modulus of the CuNb means that the working strains of the 3 coil sections reach 0.35, 0.42 and 0.45% (Table 3).

Cooling of the coil is by atmospheric pressure He II at 1.8 K.[16] The reservoir will be at the outside surface of the coil where the heat exchanger will be located. Accordingly the cooling channel heat flux is designed to be smaller for the inner coil.

A full protection scheme has not been worked out. Using the adiabatic approximation, however, the coil may be safely discharged in 5 minutes for a peak voltage of less than 5 kV and a maximum temperature rise of less than 100 K.

Transition Coils and Yin-Yangs

The thermal barrier concept has brought a number of advantages to the yin-yang and transition coils, since the peak fields and size are reduced to a level at which they are comparable to the MFTF coils currently being built. The peak field of 8.1 T permits NbTi at 4.2 K to be used for the superconductor. One constraint which appears quite important in the design of conductors for these magnets is that the conductor aspect ratio be close to unity, in order to permit winding about 2 axes. A MFTF type conductor appears to have insufficient stability at the 15000 A operating current chosen for these coils. A recent proposal for an internally cooled, extended surface area conductor has been made by Lue and Miller[20]. These authors propose that an internally cooled cabled conductor have an external sheath (which is Cu stabilized in their design) which is vented to the main helium bath, approximately every 2 m. The conductor thus looks very similar to a force flow conductor with a punctured sheath. No pumping is required, since the conductor is immersed in the helium bath. When any normal region occurs, the helium becomes supercritical, producing a pressure surge and high local flow velocities. Experiments on this type of conductor show that, at a heat flux of 0.2 W/cm^2, the effective wetted perimeter of the strands in the cable is greater than 50%.[21] A conceptual design for a 15 kA 12 T Nb_3Sn conductor has already been proposed.[20]

In our design, 128 CuNbTi strands are cabled into a stainless steel jacket, with slots ∿ 0.2 cm apart for helium access to the main bath. The conductor current densities are 1480 A/cm^2 for the transition coils and 1980 A/cm^2 for the yin-yangs. The jacket thickness is about 0.2 cm, the internal void fraction 40% and the conductor is found to be cryostable if more than 21% of the shroud perimeter is wetted.

The transition and yin-yang coils can be discharged at 2 kV in less than 60 s for a maximum temperature rise of less than 100 K, according to the adiabatic approximation.

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