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ABSTRACT

Witamir-I, a tandem mirror reactor, is a study by the University of Wisconsin fusion engineering design group. Various engineering aspects and physics considerations are presented. Witamir-I is a high Q device with particularly attractive maintenance features and blanket characteristics.

1. INTRODUCTION

Witamir-I [1] is a tandem mirror reactor (TMR) with thermal barriers. The original tandem mirror concept of plugging a solenoid with electrostatic potentials created by high density in end plug cells was invented by Fowler and Logan [2], and independently by Dimov, et al. [3]. It required 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 (RF) power. Studies of a thermal barrier TMR then began [5], [6] using a Boltzmann relation between density, potential, and electron temperature. Subsequent work by Cohen, et al. [7] found that the Boltzmann relation for the plug potential, $\Delta\phi$, must be replaced by

$$e\Delta\phi = T_{ep} \ln\left[\frac{n_p}{n_b}\left(\frac{T_{ec}}{T_{ep}}\right)^{\nu_c}\right] \qquad (1)$$

where ν_c ranges from 0.5 to 1.5 and $\nu_c \approx 0.5$ for the Witamir-I magnetic field configuration; $\nu_c = 0$ is the Boltzmann case; n_p and n_b are the plug and barrier densities; and T_{ec} and T_{ep} are the central cell and plug electron temperatures. Non-zero ν_c makes high $\Delta\phi$ more difficult to achieve, and increases power flow between plug and central cell electrons which decreases Q, the ratio of fusion power out to plasma input power. Witamir-I is the first complete reactor study using non-zero ν_c and including the effect of using RF power to create a hot mirror-trapped electron population in the barrier to enhance ϕ_b, the thermal barrier potential.

The following sections discuss some features of the Witamir-I parameter set, engineering aspects of the main reactor regions, and plasma physics considerations.

2. PARAMETERS

Magnetic field, potential, and density profiles are shown in Fig. 1 for one end of Witamir-I. ϕ_b is created by the density drop from neutral beam charge exchange pumping and flux tube expansion as the magnetic field falls from 14 T to 1.4 T. ϕ_c, which confines central cell ions, is created by RF heating of plug electrons and by neutral beam injection. ϕ_e is the ambipolar potential occurring because electrons are more collisional than ions and scatter more quickly into the loss cone. The hot electron density, n_{eh}, is created by RF heating at the barrier center. Power, machine, and plasma parameters are listed in Table 1. The pumping parameter, g_b, is the ratio of total barrer ion to passing ion density.

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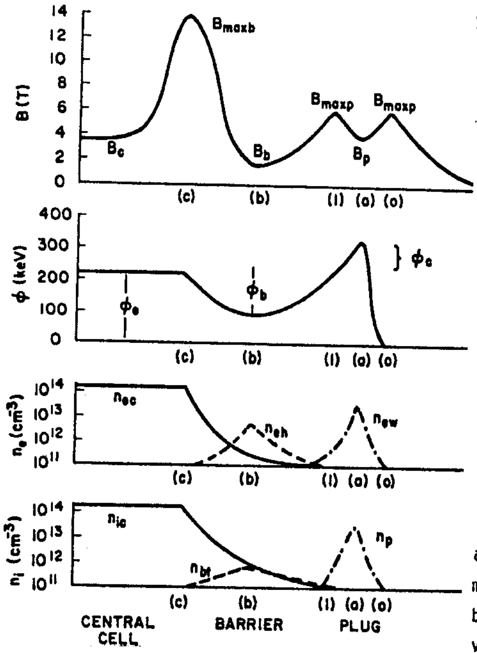

Fig. 1. Magnetic field, potential, and density for one end of the machine.

A 3000 MW fusion power plant is chosen in order to give 1200 to 1500 MWe of gross electric power. Then, Q = 30 gives a reasonable value of about 100 MW of input power to the plasma. In particular, total RF power is less than 50 MW. High Q requires a central cell with short radius and long length because input power is proportional to barrier and plug volumes which are tied to central cell radius through magnetic flux conservation, while fusion power output is proportional to central cell volume = $\pi r_c^2 L_c$. A small radius allows smaller magnetic field coils for a given field strength, giving less expensive coils.

3. CENTRAL CELL

An inherent advantage of a TMR is the accessibility of the blanket and shield for maintenance. Figure 2 shows a blanket module being removed from the reactor. Accessing the various coils, blanket modules, and shield

TABLE 1

Power and Machine Parameters

Powers are given as absorbed plasma power without efficiencies folded in.

Parameter	Value	
Q	28.0	
Fusion power	3000.	MW
Neutron wall loading	2.4	MW/m^2
Central cell power density	11.3	MW/m^3
Plug ECRF power	16.5	MW
Plug neutral beam power at 500 keV injection	2.4	MW
Plug trapping fraction	0.13	MW
Barrier ECRF power	33.3	MW
Barrier neutral beam power		
9.6 keV injection	12.7	MW
190. keV injection	42.5	MW
Central cell surface heat load	2.75	W/cm^2
Plug surface heat load	3.43	W/cm^2
Barrier surface heat load	80.0	W/cm^2
Central cell wall radius	0.97	m
Central cell length	165.	m
Barrier length	10.	m
Plug length	5.5	m
Central cell magnetic field	3.6	T
Barrier maximum field	14.0	T
Barrier minimum field	1.4	T
Plug maximum field	6.0	T
Plug minimum field	4.0	T

Plasma Parameters

Central Cell		
Density	1.51×10^{14}	cm^{-3}
Ion temperature	32.5	keV
Electron temperature	32.8	keV
Potential, ϕ_c	102.	keV
Beta, β_c	0.40	
Plasma radius	0.72	m
$(n\tau)_{ic}$	7.8×10^{14}	sec cm^{-3}
Barrier		
Density average	6.9×12	cm^{-3}
Mean hot electron energy, E_{eh}	270.	keV
Passing electron fraction, F_{ec}	0.27	
Pumping parameter, g_b	2.0	
Pumping fraction at low energy	0.95	
Pumping fraction at high energy	0.05	
Potential, ϕ_b	141.	keV
Beta, β_b	0.235	
Plasma radius average	0.59	m
Plug		
Density average	2.7×10^{13}	cm^{-3}
Mean ion energy	905.	keV
Electron temperature	123.	keV
Potential, $\phi_c+\phi_e$	326.	keV
Cohen parameter, ν_c	0.5	
Beta, β_p	0.64	
Plasma radius	0.77	m
$(n\tau)_{ip}$	9.8×10^{13}	sec cm^{-3}

modules simply requires hydraulically moving an element to the most convenient hatch and moving others out of the way.

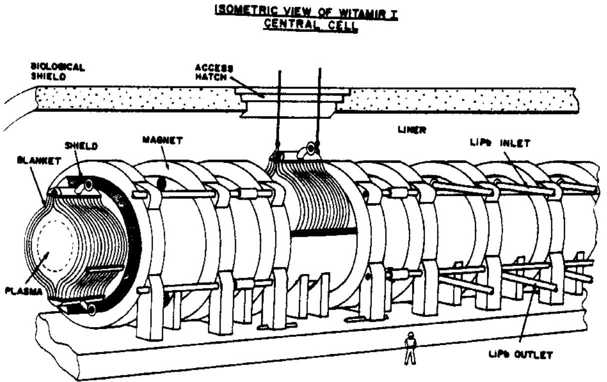

Fig. 2. . Blanket module removal.

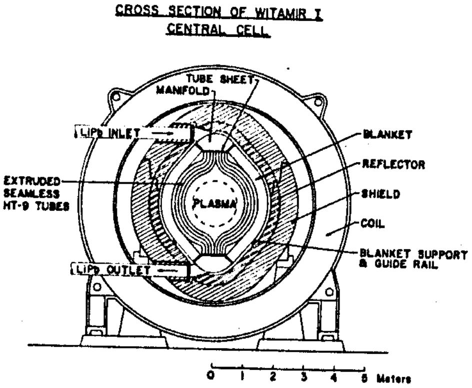

Fig. 3. Central cell cross-section.

A cross-section of the central cell is shown in Fig. 3. The support scheme is simple and practical, and the blanket design, which is easy to fabricate and may be factory assembled, is particularly appealing. There is negligible thermal stress, and the part of the blanket nearest the plasma is made of extruded, seamless HT9 tubes with no welds exposed to the plasma.

As the tritium breeder and coolant, $Li_{17}Pb_{83}$ was chosen since it has low tritium solubility, thus reducing the tritium inventory, and is relativity inert to water, thus minimizing the consequences of an accident. A detailed analysis of the blanket [8] yields an excellent energy multiplication of 1.37, and a tritium breeding ratio of 1.07.

The central cell magnets, which give 3.6 T on axis from slightly over 6 T on the conductor, are made of NbTi and Al, and present no difficulties. Ripple is less than 5%. Figure 4 shows the magnetic field coils for one end of the machine. The oversized central cell coil will be discussed in sec. 4.

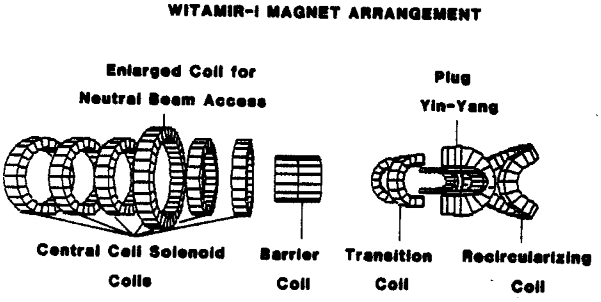

Fig. 4. Magnets for one end.

4. BARRIER

Because the thermal barrier concept is a very recent addition to TMR design, experimental verification of some plasma physics questions remains. In particular, maintenance of a large electron temperature differential must be verified, and details of the pumping process must be explored.

The barrier field coil consists of three concentric cylinders, giving 14 T on axis and a maximum of 15 T on conductor. The inner, middle, and outer coil superconductors are Nb_3Sn, NbTiTa, and NbTi, all stabilized by Cu and operated at 1.8°K.

Ions scattering into the barrier must be "pumped" out to maintain a density dip and thus ϕ_b. Witamir-I implements this by charge exchange off of neutral beams injected at approximately 10°. Insertions of these requires the enlargement of one central cell coil on each end (see Figs. 4 and 5). The beams are focused near the central cell end of the barrier coil.

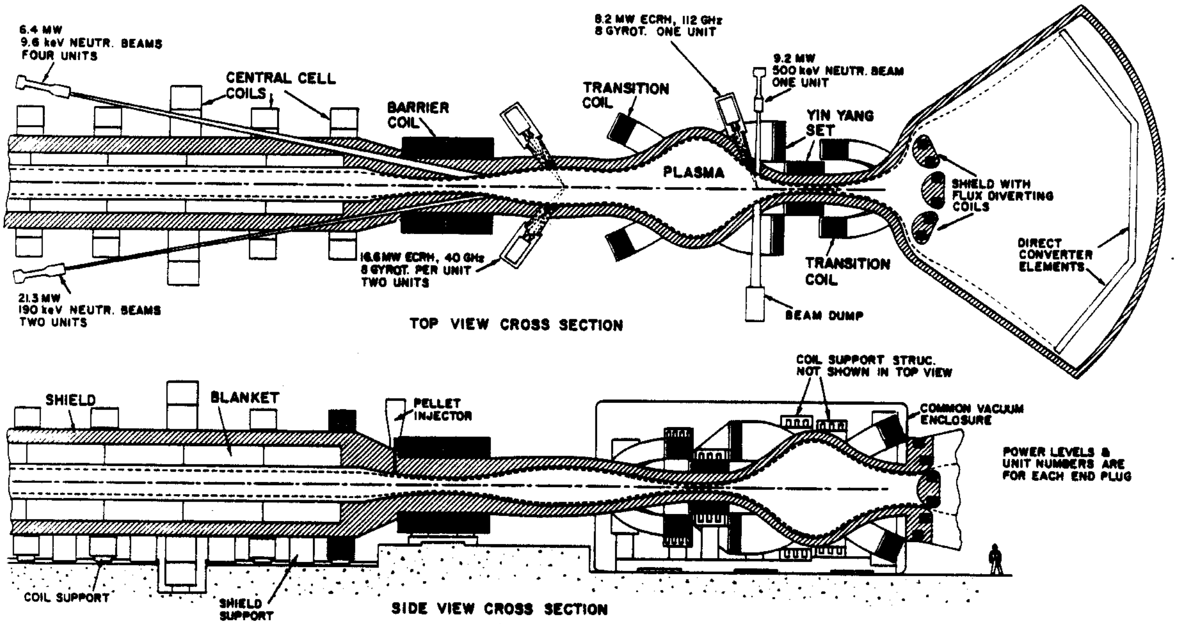

Fig. 5. One end of WITAMIR-I.

Electron cyclotron range of frequencies (ECRF) heating will be used at the bottom of the barrier to create a hot, mirror-trapped electron population [4]. This will reduce the number of electrons passing through both central cell and plug, thus giving a larger ϕ_b because the central cell electrons have approximately a Boltzmann distribution. The transport system designed for this purpose is shown in Fig. 6.

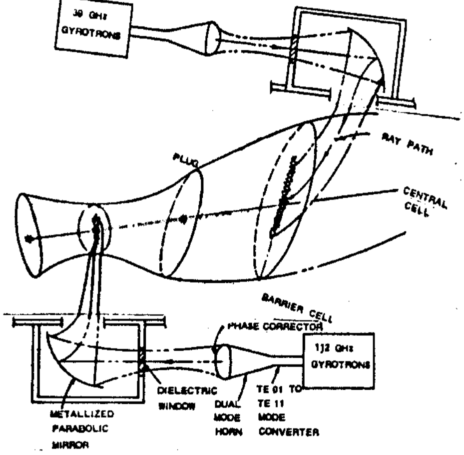

Fig. 6. ECRH transport system (not to scale).

ECRF heating in the barrier complicates the physics and machine while allowing higher Q and some lower technology requirements. Although the barrier ECRF option is chosen here, it should be stressed that a tandem mirror reactor without barrier ECRF seems viable, if not quite as attractive, in terms of Q.

5. PLUG AND DIRECT CONVERTOR

The plug region is essentially a minimum-B mirror machine, for which much experimental work exists, so theory is generally well-based. The Witamir-I magnet design (see Fig. 5) has a maximum of about 8 T at the yin-yang conductors, which are NbTi cooled to 4.2°K; stabilization is by Cu, and forces are manageable.

Neutral beam injection at 500 keV requires negative ion technology, which is in a developmental stage. It presently appears difficult to build a TMR without neutral beam energy $\gtrsim 150$ keV, where negative ion technology is required.

Two options were considered for heating plug electrons: 1) ECRF heating in the plug at about the 4 T point, and 2) ion cyclotron range of frequencies (ICRF) heating in the middle of the plug. The first, chosen for Witamir-I, is being developed. The second, while technologically preferable, poses physics questions. Figure 6 shows the ECRF transport system.

The field from the recircularizing coil shown in Fig. 4 goes into a direct convertor which electrostatically drains energy from ions that escape over ϕ_c. By maintaining ϕ_c slightly higher on one end of the machine, essentially all ions will escape out the other end, thus necessitating a direct convertor on only one end of the machine. It will handle approximately 502 MW of power at an efficiency of 67%.

6. PLASMA PHYSICS

A detailed description of the plasma physics model is contained in [1]. Much of the physics, especially of the barrier, is based on work in [9], with suitable changes for differences in magnetic field configuration, etc. The main terms in the power balance are heating by fusion alphas, neutral beams, or ECRF power, balanced by end loss, radiative processes, and energy carried out by charge exchange neutrals from the pumping process. Internally, collisional energy conduction and convection are also important.

The central cell ions are deuterium and tritium. Protons are used in the plugs because the consequent absence of fusion neutrons from plug fusions allows the yin-yang coils to be designed with only central cell streaming neutrons in mind. Better microstability is also expected because protons have smaller gyroradii than deuterium or tritium.

MHD stability questions remain with regard to the magnetic field design, with theory indicating a maximum central cell beta, the ratio of plasma pressure to magnetic field pressure, of about 25% and experiments exceeding theoretical beta limits. The value 40% was chosen for central cell beta here, and seems reasonable in light of probable future improvements in the field design and the fact that the MHD theory is somewhat tentative.

7. CONCLUSIONS

The Witamir-I study shows that high Q operation appears feasible with all magnets except possibly the barrier coil within extrapolatable technology. Neutron streaming has a minimal effect on the end plugs. A TMR is easier to maintain than a tokamak because of the linear geometry and wide coil spacing, and the excellent energy multiplication of 1.37 makes the $Li_{17}Pb_{83}$ blanket look very attractive.

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