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Summary

Engineering design considerations have been developed for a compact ignition test reactor. The objectives of the ignition test reactor are to demonstrate ignition and to study alpha particle dominated heating and burn control. A key feature is a Bitter type magnet operated at a stress level high enough to avoid an excessively large magnet and yet low enough to achieve more than 10,000 full power full pulse length (8 sec) cycles with a large factor of safety on magnet life. The insulator in this magnet design should permit the attainment of more than 50,000 burn-sec without the use of neutron shielding. A parametric study to examine the trade offs between peak stress of the TF coil, flat top time of the magnet and magnet cyclic lifetime has been performed. An illustrative design has been developed for a neutral beam heated device that includes adiabatic compression in major radius. A comparable device which would be directly heated with RF is also described. In addition preliminary design features have been developed for a flexible device in which either compression boosted neutral beam heating or direct heating could be utilized.

1. Introduction

Design concepts have been developed for a compact tokamak ignition test reactor which uses strong auxiliary heating. The objectives of the ignition test reactor are:

- To demonstrate ignition (i.e., a self-sustaining fusion reaction) in a deuterium-tritium plasma.
- To evaluate methods of obtaining ignition and to study the operating characteristics of ignited plasmas. The ignition test reactor would thus provide a vital data base for the design of practical power producing reactors.

The ignition test reactor designs considered here have the following features:

- The plasmas are operated at high density and high magnetic field to decrease the plasma size required for ignition.[1]
- High performance cryogenically cooled copper magnets with no shielding between the plasma and the magnet are used to facilitate a compact design and to allow long pulse operation;[2,3] the toroidal field flat top could last longer than 15 seconds.
- Strong auxiliary heating is used to obtain ignition over a wide temperature range.
- In order to achieve a high confidence level of reaching ignition the extrapolation of plasma physics is conservative and there are margins in physics and technology.
- In order to provide an extensive data base on ignited operation and burn control, the device would be designed for at least 10,000 full power DT shots with a 5 sec burn time.

2. Design Options for Auxiliary Heating

Two types of auxiliary heating have been considered: the use of neutral beam heating followed by adiabatic compression in major radius, and direct heating of the plasma by either neutral beams or rf.

The use of compression in conjunction with neutral beam heating is attractive for a number of reasons:

- The use of compression significantly increases the penetration of neutral beams. Centrally peaked power deposition of 160 keV neutral beams can be obtained for a modest ignition temperature (central ion temperature ≈ 12 keV) where relatively high plasma densities must be employed.[4]
- The use of compression after initial neutral beam heating provides insurance that the desired operating temperature can be obtained even if there is a decrease in plasma energy confinement with increasing temperature.
- Compression facilitates plasma shutdown.
- Compression and decompression can be used for burn control.[5]

Direct heating of a tokamak plasma with neutral beams is facilitated by operation at high temperature (central ion temperature $\geq$ 25 keV). At these high temperatures, the values of $n\tau_e$ required for ignition (and hence the neutral beam penetration requirements) are greatly reduced.[6] However, operation at these high temperatures is further away from present operating regimes in tokamaks and may be strongly affected by increased transport losses.

Another possible means of direct heating is to use ion cyclotron or lower hybrid heating. However, there is not yet sufficient experimental information to ensure a high confidence level for heating to ignition with rf.

Three main design options for the ignition test reaction have been identified based upon the above considerations.[2] The parameters for these options are shown in Table I.

The "compression boosted" design, option 1, utilizes a compression ratio in major radius of 1.5. The major radius of the initial plasma is 2.0 m and the major radius of the final plasma is 1.3 m. The vacuum chamber is horizontally elongated in order to minimize the stored energy and the size of the magnet. The toroidal field magnet parameters of this design are given in Table 2. A detailed description of the toroidal field magnet for design option 1 is given in the next section. Direct heating of the final plasma in design option 1 may be difficult because of the large distance between the port and the final plasma.

Design option 2 would utilize direct heating and would have a compression ratio of 1.1 for burn control.

A third design option would be well suited for both "compression boosting" and for direct heating by enlarging the vacuum chamber of design option 1 to a

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Table 1 Design Options for Ignition Test Reactors

	Option 1	Option 2	Option 3 "Compression boosting"	Option 3 "full bore"
compression ratio, $C = R_f/R$	1.5	1.1	1.5	1.1
Major radius of final plasma	1.33	1.28	1.42	1.7
Minor radius of final plasma	0.50	0.52	0.47	0.75
B_t (T)	9.5	9.0	10.4	8.7
Margin of safety[2]	1.5	1.5	1.5	3.2
$(\sigma_{cu})_{max}$ (MPa)	290	260	290	
Fatigue lifetime, full power cycles	10,000	10,000	13,000	
Stored Energy (MJ)	840	510	1,200	
Auxiliary Heating Power (MW)	14	12	14	19
Weight of TF coil (10^3 Kg)	320	180	410	
Resistive power of TF (at 77°K) (MW)	45	43	65	

nearly circular shape. If direct heating were desired, a large plasma which would nearly fill the vacuum chamber would be used. This plasma would have a larger margin of safety against increased energy loss and beta limits than would the final plasma used in a "compression boosted" scenario. This design option might also allow the use of noncircular plasmas and increases the flexibility for studying various burn control techniques such as induced ripple.[7]

Table 2

Toroidal Field Magnet Parameters for Design Option I

Dimensions	
Height (m)	2.4
Outer Radius, R_{out} (m)	2.95
Inner Radius, r_{ohm} (m)	0.38
Major Radius of center of magnet bore (m)	1.65
B_T at center of magnet bore (T)	7.6
Field at final plasma (T)	9.5
Peak field (T)	17.1
Total TF current (A)	63×10^6
Stored energy (J)	840×10^6
Stresses (MPa)	
Circumferential	80
Vertical tensile at inboard trunk, ave	290
Bending stresses, max	290
Resistive power (at 77°K) (MW)	45
Resistive power (after 8s flat top) (MW)	90
Energy dissipation per 8s pulse	
Electrical (GJ)	1.0
Nuclear (6s ignited operation) (GJ)	0.4
Peak magnet temperature, 8s flat top (°K)	280
Weight (10^3 kg)	320
Liquid nitrogen evaporation per 8s pulse (l)	15000

In order to provide sufficient drive for the large plasma in design option 3, a larger OH system is needed. As a result there is an increase in the major radius of the toroidal field magnet. Preliminary parameters for design option 3 are given in Table 1.

3. Design Features of Toroidal Field Magnet

The requirements of the TF system are the repeated generation of a 9.5 Tesla field for as long a pulse as is compatible with limitations of temperature rise, and for at least 10,000 full power full length cycles. The target of the design is a total flat top time at 9.5 T of 100,000 seconds, providing more than 50,000 total burn seconds of ignited operation.

The toroidal field coil is a Bitter type magnet similar to the ALCATOR devices.[8] The Bitter magnet offers a number of advantages relative to other configurations for the toroidal field coil:

1) The plates of the magnet are monolithic in the direction of the principal stresses; the design is thus insensitive to shear stress that can result from bending.
2) The bending stresses in the throat are low by design.
3) Negligible temperature gradient is generated across the throat of the magnet, resulting in low thermal stresses.
4) The lower stresses in the Bitter concept relative to other configurations lead to longer fatigue lifetime.
5) Plane insulation can be used between turns allowing the choice of inorganic or partially organic insulation readily available in sheet form.
6) During ignited operation of the ITR, the radiation induced degradation of insulation will occur mainly in the region close to the burning plasma; the undamaged insulation would still prevent electrical breakdown between the turns.
7) During assembly, the large number of identical sub-units of the magnet are interchangeable. This allows simple replacement of faulty elements.

Liquid nitrogen cooling is used to permit the high current density operation which facilitates the construction of a compact magnet and allows for long pulse operation. During the pulse, the magnet is inertially cooled. The TF coil in a DT pulse is heated by ohmic and neutron heating. The peak temperature at the end of the flat top occurs at the throat of the magnet and reaches ~ 220°K for a 8-second full power DT pulse. The required time to recool the magnet to 77 K after an 8-second full power DT pulse is ~ 3/4 hour.

The magnet design has 256 turns (plates) and is divided into 8 modules. The modules are preclamped by the use of external tension bands as on the ALCATOR C machine. The plates are made of cold-worked oxygen-free copper and high strength austenitic steel.

The modular construction of the magnet eases the remote handling maintenance that would be required after the initiation of D-T operation. Any module could be removed from the assembly for major repairs and replaced by a spare module.

The ports for diagnostics and neutral beam access are located in the flanges between modules. There is both vertical and horizontal access. The horizontal ports are used mainly for near perpendicular neutral beam injection.

3.a Bitter Type Configuration

Figure 1 shows the general configuration of the magnet system for design option 1. A typical Bitter plate is shown in Figure 2. The copper-to-steel ratio in the throat of the magnet is 2:1. The turn-to-turn connection occurs in the outer periphery of the magnet.

The steel and copper in the Bitter plates are joined in a composite subsystem by one of a number of methods now under-going evaluation. These include rollbonding, explosive welding, brazing, soldering, cementing and keying. The rollbonding and explosive welding are being actively investigated.

Keys between adjacent turns are also being considered. These keys will also reduce reliance on friction between plates to transfer the forces necessary to balance the torsion resulting from the interactions between the poloidal field and the TF current.

The keys for torsional shear control are conceived as a series of high strength steel bolts through the mating steel components of adjacent plates with the insulator between them. The bolts are in insulated sleeves; they will be located on the outer edges of the plates. The bolts are 3.5 cm in diameter on 7.5 cm centers to control bearing and shear. This arrangement also provides modularization of each octant in the magnet.

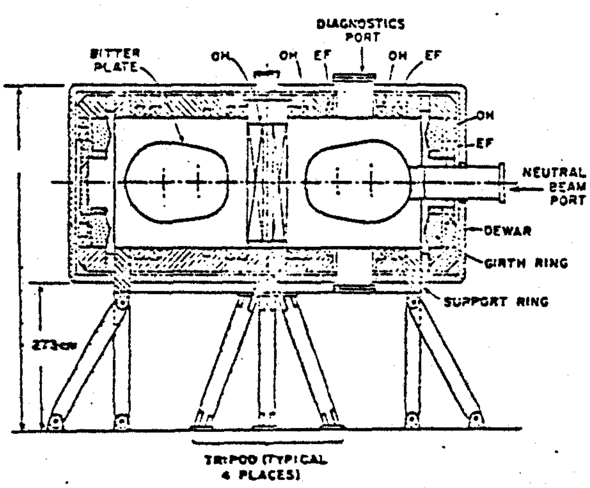

Figure 1 Plan View of the Magnet

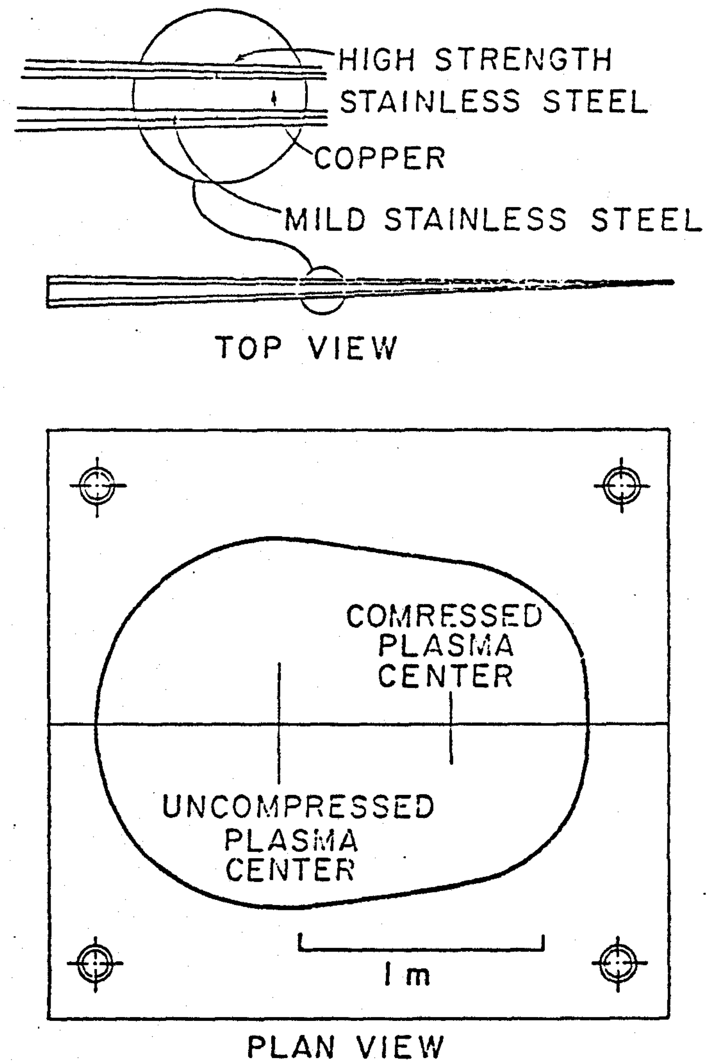

Figure 2 Plan and Top Views of Typical Bitter Plate

Alternate possibilities, now under consideration, include bolting entirely through adjacent plate composites in a staggered array or using large pads between mating steel components of adjacent plates. This leads to high bearing pressures, however, which requires a search for an appropriate pad insulator.

The Bitter plates are arranged in 8 sectors. There are flanges between sectors which facilitate assembly and remote maintenance. The assembly of plates and flanges is held together by a set of girth bands at the outside edge of the plates.

Eight apertures are provided for neutral beam injection. The access ports enter the TF coil at the flange locations. Each port has an effective cross sectional area of 0.12 m^2 and is located symmetrically about the mid-plane of the TF coil. It is angled at 10° with respect to the perpendicular to provide co-injection of the beam. Figure 3a and 3b show a neutral beam injection port configuration. Three turns are affected on one side of the port. The copper component of the TF plates affected by the ports is shaped around the side of the port away from the flange.

Figure 3b also shows the vertical ports. Each has a cross sectional area of 0.012 m^2; they would be used mainly for diagnostics.

A sketch of the girth bands, the port, the flange and the steel extensions is shown in Figure 4. The steel reinforcement is truncated above and below the horizontal port and is extended radially outward. The girth bands (which are attached to these extensions) resist the vertical forces generated in the turns affected by the port.

3.b Stress Analysis

The TF magnet is designed to accommodate radial compression of the plasma. The wide aspect ratio of the toroidal coil aperture gives rise to large stresses which are comparable to ALCATOR C.[8]

The stresses in the toroidal field magnet have been calculated using a finite element method. The steel, copper and insulation were treated separately to determine the load distribution and the inter-element shears.

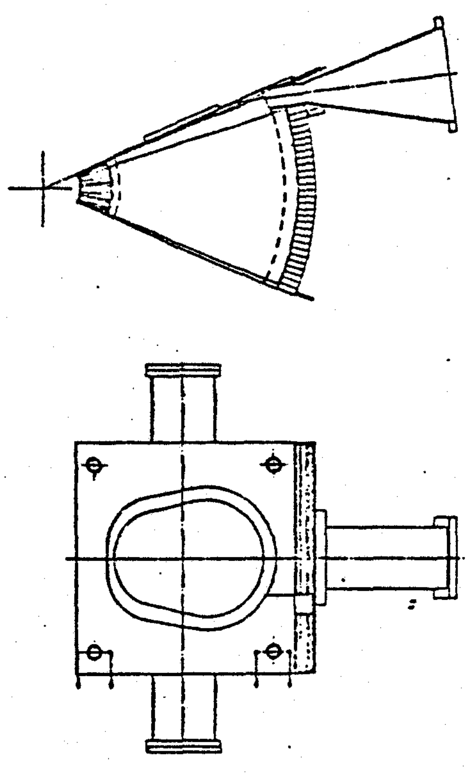

Figure 3 Top View and Elevation of Module Octant

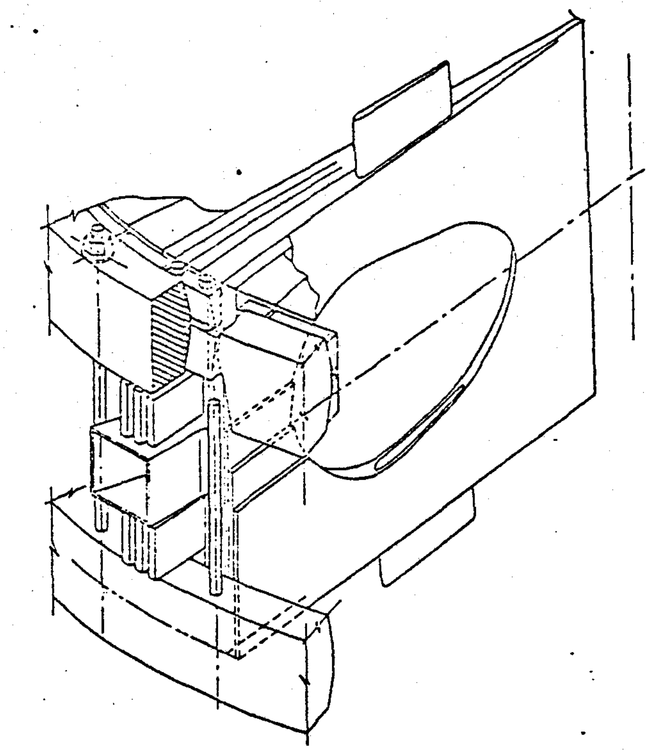

Figure 4 View of Port and Girth Band Structure

The net used in the finite element analysis is shown in Figure 5 and the stresses in the copper at several sections are shown in Figures 6a - 6d. The peak membrane stresses occur in the throat of the magnet and are ~ 300 MPa. Note that the stresses are relatively constant across the cross-sections.

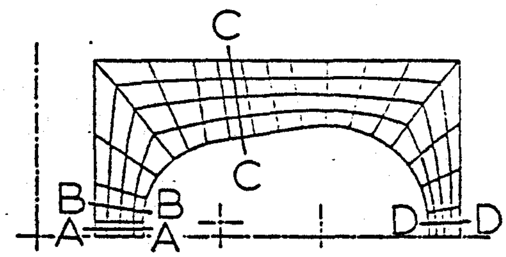

Figure 5 Finite Element Gridwork for Bitter Plate Analysis

The poloidal field interacts with the TF current to induce a torsional couple between the top and the bottom of the TF coil. In discrete coil systems, this couple results in what is called the overturning moment. In a Bitter plate configuration, the structural continuity of the TF system causes it to behave like a hollow torus.

The torsional shear stresses that are applied to the plate are ~ 15 MPa, acting vertically in the throat of the magnet and ~ 7 MPa acting horizontally in the horizontal legs. Only in the region close to the throat of the magnet is the face pressure large enough to induce frictional shear of this magnitude. Outside this region the shear load is transferred by the keys described above.

The thermal stresses in the toroidal field coil at the end of a 8-second full power DT pulse are small. This is because in a Bitter plate configuration the transverse temperature gradients at the throat of the magnet are negligibly small.

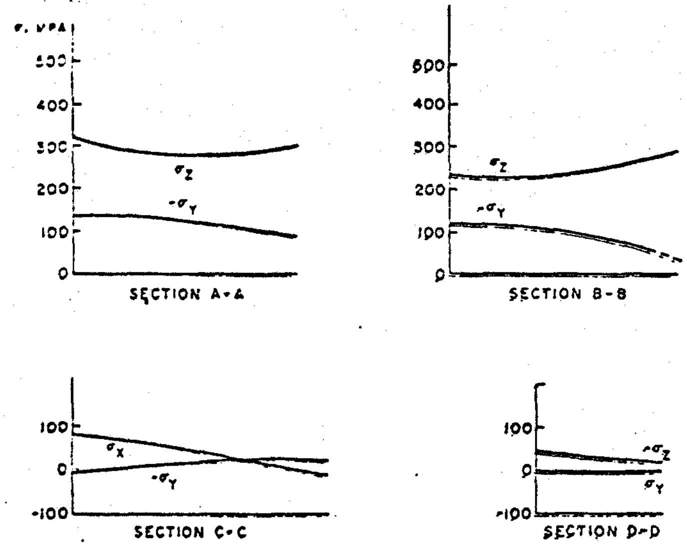

Figure 6 Calculated Copper Stresses Sections indicated in Figure 5.

3.c Material Properties

The lifetime of the magnet (if the insulation problem can be solved) would be determined by fatigue failure. Figure 7 shows the allowable stresses for a given number of cycles for both high strength steel and copper, for room temperature and liquid nitrogen temperature operation. As this lifetime is determined by crack propagation, in the relatively thin plate design under consideration the lifetime is determined by the stresses in the plane of the plate. From Figure 6a - 6b the value of the stresses in the copper for the design parameters of Table I are - 300 MPa. For these stresses, the copper will last - 10^5 cycles for peak temperatures of - 250°K. The design criteria is therefore satisfied with a safety factor in lifetime of 10. As the stresses in the steel are approximately twice the copper stresses, it would last approximately the same number of cycles.

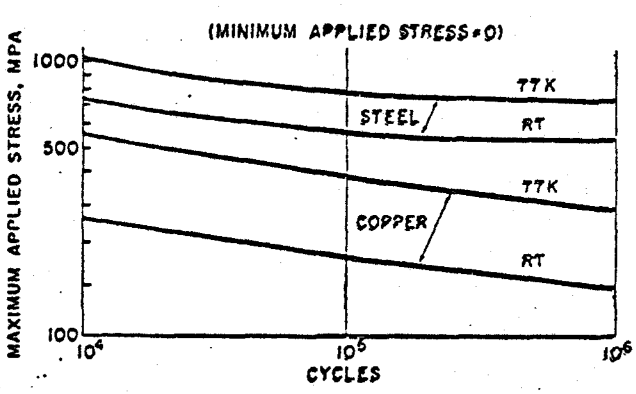

Figure 7 Fatigue Curves for Copper and Steel

It is not expected that the neutron fluence will affect the lifetime of the copper and steel in the toroidal field coil. However, the neutron irradiation of the copper will result in significant increase in its resistivity.

A critical material of the TF magnet is the insulation. The lifetime of the insulator is influenced by mechanical stresses and by irradiation. During the lifetime of the ITR, the insulation will be exposed to a neutron fluence of - 10^{20} n/cm^2.

In a full power pulse the stresses applied to the insulation are:

Face pressure	150 MPa
Shear stress parallel to face	15 MPa
Strain parallel to face	0.003

Data on insulation properties under these conditions are lacking. A materials test program for the insulation is underway. The program investigates the effects of stress, temperature and irradiation. A brief discussion of this program is given below.

3.d Materials Testing Program

The materials testing program has been designed to provide data on strength, stiffness, fatigue life, friction wear and the electrical conductivity of the candidate structural materials in the ITR environment. It has involved an extensive literature search which has revealed large gaps in the data base needed to design the magnet. The search has also revealed conflicting information on many points and unclear statements about the test conditions.

The magnet design calls for an insulator in the form of large sheets approximately 1/2 mm thick loaded normal to the planes of the sheets. Tests at MIT on thin sheets of unirradiated organic insulators at room temperature indicate considerably greater strength than commonly reported. Samples of G-7 (silicone matrix and fiberglass) have been found to withstand more than 10^4 compressions at 330 MPa with no sign of degradation.

Materials being considered for the insulators are mica, quartz cloth with polyimide matrix, aromatic epoxy with S-glass G-10 and woven ceramics. Due to the low friction coefficient of mica paper on copper, the torsion can not be restrained by frictional forces alone. Therefore, if mica is used additional means of shear transfer between plates are necessary.

G-7, G-10 and G-11 are now being irradiated in a reactor to obtain a preliminary data base for survivability.

The metals are not expected to be as severely damaged by radiation as the insulators. For that reason, preliminary decisions about the steel and copper are being made on unirradiated samples. A fracture mechanics analysis appears to support that approach.

3.e Toroidal Field Ripple

There are two sources of toroidal field ripple in the ignition test reactor: horizontal ports, and the flanges (the vertical port is entirely within a flange). The ripple due to the horizontal ports is shown in Figure 8. The ripple is defined as:

$$\frac{\Delta B}{B} = \frac{B_{min} - B_{ave}}{B_{ave}}$$

The presence of the horizontal ports gives rise to ripple that is significant only in the outer region of the precompressed plasma; the ripple can be reduced further, if need be, by enlarging the horizontal toroidal cavity.

The ripple due to the presence of a flange whose thickness is 1° in an otherwise perfectly isotropic Bitter TF coil is shown in Figure 9. The ripple is approximately constant throughout the volume occupied by the plasma. This ripple can be reduced by increasing the current density of the turns adjacent to the flange and could be eliminated by removing the flange altogether. It may be necessary to reduce the number of magnet plates in the toroidal field magnet in order to reduce the ripple from the vertical port and the flange; a reduced number of plates will make it possible to replace stainless steel with a flange or a port without affecting the conductor.

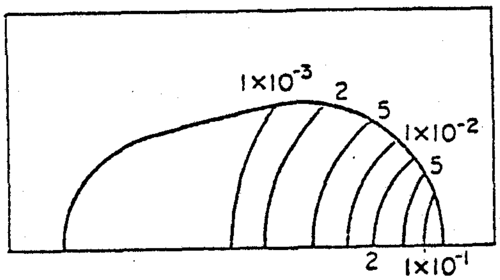

Figure 8 Toroidal Field Ripple due to Horizontal port

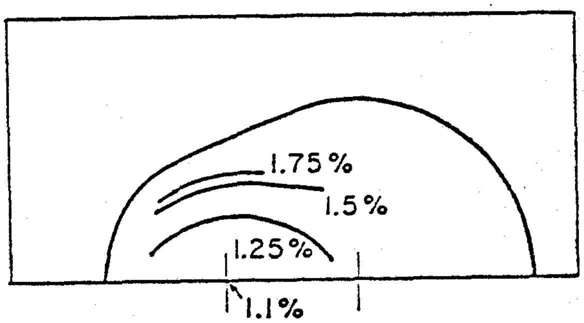

Figure 9 Toroidal Field Ripple due to the Presence of 8 flanges, per Degree of Flange.

4. Additional Systems

A brief description is given below of the neutral beam and the poloidal field systems. More extensive discussions can be found in reference 2.

4.a Poloidal Field System

The compression boosting technique for design option 1 places difficult requirements on the poloidal field system. The plasma should be compressed in a time less than a energy confinement time. The energy swing required for plasma compression is $\lesssim 70$ MJ. The compression time results from a tradeoff between neutral beam power and poloidal field power during compression. For a compression time of 0.2 seconds, the beam power has to be increased by 1 MW over the value needed for truly adiabatic compression.[2]

To provide the energy required by the poloidal field during the compression, an inductive storage system is proposed for the power source. A set of copper-wound inductors at 77°K are charged in series and discharged in parallel. Once energized, the poloidal field coils are fed from a rectifier supply. During the decompression prior to the end of the pulse the energy is allowed to dissipate in dump resistors.

Due to the small thickness of the Bitter plates the penetration time of the poloidal field through the TF coil is $\lesssim 40$ ms. Even for 0.1 second compression the perturbation on the applied vertical field is only about 5%.

4.b Neutral Beam Heating System

Compression boosting reduces the neutral beam energy required to heat the plasma in the precompressed state in design option 1. 14 MW of 160 KV Deuterium beams are sufficient. The heating pulse length is ~ 1 second. The eight neutral beam ports provide the necessary access. The required average neutral beam intensity is 1.4 KW/cm^2.

5. Conclusions

Design options for ignition test reactors have been considered. A detailed engineering study has been performed on one of the options. The problem areas have been identified, and work is in progress to resolve them. A materials testing program is under way to test materials suitability and survivability in the ignition test reactor environment.

Acknowledgments

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