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ANALYSIS OF TANDEM MIRROR REACTOR PERFORMANCE

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ABSTRACT

Parametric studies are performed using a tandem mirror plasma point model to evaluate the wall loading Γ and the physics figure of merit, Q (fusion power/injected power). We explore the relationship among several dominant parameters and determine the impact on the plasma performance of electron cyclotron resonance heating in the plug region.

These global particle and energy balance studies were carried out under the constraints of magnetohydrodynamic (MHD) equilibrium and stability and constant magnetic flux, assuming a fixed end-cell geometry.

We found that the higher the choke coil fields, the higher the Q , wall loading, and fusion power due to the combination of the increased central-cell field B_c and density n_c and the reduced central-cell beta β_c . The MHD stability requirement of constant $B_c^2 \beta_c$ causes the reduction in β_c . In addition, a higher value of fusion power can also be obtained, at a fixed central-cell length, by operating at a lower value of B_c and a higher value of β_c .

1. INTRODUCTION

Nuclear fusion may become an important energy option in the future because of its readily available fuel and the acceptable environmental and safety aspects of fusion devices.

Magnetic fusion plasma confinement falls into two categories: (1) closed systems, in which the magnetic lines of force close on themselves, and (2) open-ended systems, in which they do not. The tokamak concept is the leading example of a closed confinement system; the tandem mirror concept is the leading example of an open-ended confinement system.

The tandem mirror concept evolved from the simple mirror cell shown in Fig. 1(a). The simple geometry is subject to magnetohydrodynamic (MHD) instabilities, however, which can result in a rapid loss of plasma from the system. To stabilize the configuration, the minimum- B mirror cell, shown in Fig. 1(b), was developed. This arrangement leads to the formation of a magnetic well in which the magnetic field induction B increases in every direction from the center. Even with gross MHD stability, some plasma is still lost out the ends of the mirror cell due to the collisional scattering of particles into the loss cone. Studies¹ have shown that a single-mirror-cell reactor can only achieve slightly more power than it consumes ($Q \sim 1$).

In late 1976, Dimov² and Fowler and Logan³ realized the benefit of connecting two mirror cells by a cylindrical region with a solenoidal magnetic field. They independently proposed the tandem mirror concept shown in Fig. 1(c). Detailed reactor studies of the first tandem mirror yielded a predicted $Q \sim 5$ (ref. 4).

In order to lower the high-energy neutral beam requirements for sustaining the end-plug plasma, Baldwin and Logan proposed the "thermal barrier" concept⁵ in which the plug electron temperature is raised above that of the central-cell electrons, thus thermally isolating the two electron species.

This tandem mirror thermal barrier concept uses a region of minimum electrostatic potential that confines the electrons but ejects low-energy ions. Because of the high thermal velocity of the electrons, their temperature T_{ec} is normally uniform along the magnetic field lines. However, if potential valleys can be established between the central cell and the end plugs, then electron flow can be impeded. It is, therefore, possible to use microwave heating in the plugs to make the plug electron temperature T_{ep} much greater than the central-cell electron temperature, T_{ec} . As a consequence, high values of T_{ep} will provide a larger central-cell potential ϕ_c without requiring a high end-plug density n_p . Also, the reduced plug pressure reduces the required magnetic field and neutral beam injection energy in the end plugs. Analyses of reactor designs using the thermal barrier concept have yielded $Q \sim 20-30$ (ref. 6).

Figure 2 illustrates the different axial profiles for magnetic field, plasma potential, and plasma density found in a tandem mirror with and without thermal barriers. An example of a tandem mirror reactor (TMR) with thermal barriers is the configuration examined during the Lawrence Livermore National Laboratory (LLNL) Mirror Advanced Reactor Study (MARS),⁷ which is shown in Fig. 3.

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(a) SIMPLE MIRROR

(b) MINIMUM-B MIRROR

(c) TANDEM MIRROR

Fig. 1. Evolution of a tandem mirror.

Fig. 2. Magnetic field intensity, plasma potential, and plasma density along the axis of a tandem mirror system with and without one type of thermal barrier.

Fig. 3. MARS profiles.

2. APPROACH

With MARS as a basis, a number of prominent physics and engineering parameters of a TMR with thermal barriers were examined using the global energy and particle balance code TMRBAR.⁸ The physics constraints applied to these analyses are given in Appendix A; parameters are defined in Appendix B.

The equations solved by the TMRBAR code include particle and energy balances for the central-cell and end-cell species, quasi neutrality, and potentials and temperatures at cardinal points for a set of given power outputs and field profiles.

The cardinal points chosen for MARS-like mirror fusion reactors are indicated in Fig. 4 and include the central cell, the transition region, the geodesic curvature peak, the anchor inner and outer mirrors, the anchor midplane, the plug inner and outer mirrors, the plug midplane, and the sloshing ion injection points.

For a given set of input, TMRBAR calculates the steady-state plasma conditions for a TMR. Key parameters supplied to TMRBAR include (1) the magnetic fields and beta values at the cardinal points; (2) the desired fusion power output; (3) the length of the central cell, transition region, anchor, and plug; (4) the alpha particle concentration in the central cell; (5) the ratios of trapped to passing ion density; and (6) initial guesses of temperature and potentials. Most of the input parameters are dependent on one another because they must adhere not only to the physics constraints given in Appendix A but also to the restriction of a fixed configuration. For example, as the value of the trapped ion current ratio H is increased at constant fusion power, the magnetic field and beta values in the central cell must be adjusted accordingly, due to the increase in the trapping current. Likewise, if the choke coil field $B_{\max}$ is varied, then the central-cell values of magnetic field and beta, as well as the fusion power, must be changed simultaneously to satisfy the constraint of constant magnetic flux.

In Sect. 3, the sensitivity of key physics and engineering quantities to various configurational and operational changes is examined via parametric analysis. The results presented show not only the behavior of the two figures of merit, Q and Γ , but also the interdependence of several important tandem mirror parameters. The results are given for parametric analyses of the central cell and of the plug region.

For the plug region, studies were made on the effects of varying the plug magnetic field B_b and beta β_b , B_b alone, the density fraction of central-cell electrons at the plug F_{ec} , and the ratio of passing and trapped ions to passing ions at the plug, g . For the central cell, studies were made on the effects of varying the coil field $B_{\max}$, the ion cyclotron resonance heating (ICRH) power P_{ICRH} , the ratio of trapped ion current given by Fokker-Planck calculations to that given by the Futch-LoDestro square-well calculation H , and the central-cell magnetic field B_c and beta β_c . Also included is the impact of applying Shearer's electron cyclotron resonance heating (ECRH) power requirement calculation formula⁹ to the central-cell parametric analyses. The difference between the original algorithm for computing the loss term of the hot electron power balance equation¹⁰ and Shearer's algorithm is that the latter treats scattering, drag, and synchrotron radiation losses more completely. As a result, it predicts approximately 40% higher losses than the original algorithm.

Fig. 4. MARS end-plug baseline profiles.

3. RESULTS

3.1 STUDIES OF THE PLUG REGION

3.1.1 Variation of B_b and β_b

Because the plug region provides good curvature for a TMR, it is desirable to optimize the plug beta β_b . Consequently, we first examine the plug magnetic field B_b and β_b to determine if an optimum exists under the constraints of constant-beta-corrected B_b ($B_b\sqrt{1-\beta_b} = \text{const}$). In carrying out this investigation, we chose to keep the fusion power P_{fusion} , the H factor, the choke coil field B_{max} , B_c , and β_c constant while adjusting the central-cell length L_c and the ion and electron temperatures T_c and T_{ec} to conform to all constraints under a set of chosen values for B_b and β_b . Three sets of B_b and β_b values were selected for this study (refer to Table 1), and the results are detailed in Fig. 5. Increasing β_b by 25% and B_b by 10% brings about increases of 36% in Q , 6% in both L_c and T_c , and 3% in T_{ec} . Concomitantly, there is a 34% decrease in the ECRH power requirements P_{ECRH} and a 7% decrease in Γ resulting from an increase in T_c and a decrease in the central-cell ion density n_c . In general, improved plasma performance can be obtained at higher values of B_b and β_b , but no optimum for B_b or β_b is observed.

3.1.2 Variation of B_b Alone

The effect of higher values of B_b alone on the plasma performance is examined here. The input data used for this investigation are similar to those used in the MARS study. Table 2 and Fig. 6 detail the study conditions and results as B_b ranges from 1.5 to about 3 T. Among the findings, it is observed that as B_b increases, the wall loading Γ stays essentially unchanged, because of the assumption of fixed β_c and β_b , while Q decreases. The study also reveals that better performance can be obtained by reducing the value of B_b , which leads to a decrease in the ECRH power requirements. However, when B_b is reduced, the spacing between plug mirrors should be changed, and the plasma may not have MHD stability.

3.1.3 Variation of g and G

With β_b , B_b , B_{max} , H , and L_c held constant, the effect of varying g and G is examined. The difference between G (the ratio of sloshing, trapped, and passing ion density to passing ion density) and g is constrained to be 2.0 (see Table 3). In other words, the sloshing ion density is twice as large as the passing ion density in the plug region. Decreases in β_c , the central-cell plasma radius r_c , and Q result from the decreased value of g , as shown in Fig. 7. Figure 7(c) is particularly interesting, for it indicates a maximum as well as a minimum. The sensitivity of the ion temperature and P_{ECRH} to variations in g is also shown in Fig. 7.

Figure 7(a) indicates that r_c decreases as g increases because more ions are trapped in the end-cell region. As expected, for a fixed P_{fusion} and L_c , the wall loading Γ increases and r_c decreases. However, when the desired fusion power output is allowed to fall along with r_c due to increased g values, Γ decreases because the central-cell ion density n_c drops

Table 1. Variation of B_0 and β_0

Constants for this analysis:			
$\beta_c = 0.425$	$F_{ac} = 0.03$	$L_i = 22.0$ m	
$B_c = 4.7$ T	$g = 2.75$	$P_{fusion} = 2615$ MW	
$B_{max} = 24$ T	$G = 4.75$	$P_{ICRH} = 2615$ MW	
	$H = 0.67$		
	$B_0 = 2.97$ T, $\beta_0 = 0.75$	$B_0 = 2.78$ T, $\beta_0 = 0.65$	$B_0 = 2.71$ T, $\beta_0 = 0.60$
L_c m	130.8	125.0	123.0
n_0 cm ⁻³	3.314×10^4	3.393×10^4	3.519×10^4
r_0 cm	48.92	49.38	48.76
r_i cm	49.34	49.74	48.97
T_c keV	28.41	27.71	26.75
T_{ec} keV	23.73	23.52	23.10
P_{ECRH} MW	83.75	95.25	112.62
Q	29.23	25.31	21.55
Γ , MW/cm ²	3.848	3.999	4.102

Fig. 5. Impact of B_0 and β_0 on (a) Q and Γ , (b) L_c and P_{ECRH} , and (c) T_c and T_{ec} .

Table 2. Variation of B_0

Constants for this analysis:

$$\begin{array}{lll}
 \beta_c = 0.75 & F_{sc} = 0.03 & H = 0.67 \\
 \beta_c = 0.425 & g = 2.75 & L_1 = 22 \text{ m} \\
 B_c = 4.7 \text{ T} & G = 4.75 & P_{\text{fusion}} = 2615 \text{ MW} \\
 B_{\text{max}} = 24 \text{ T} & & P_{\text{ICRH}} = 0
 \end{array}$$

	$B_0 = 2.97 \text{ T}$	$B_0 = 2.00 \text{ T}$	$B_0 = 1.50 \text{ T}$
$L_c, \text{ m}$	130.8	132.4	132.4
$n_c, \text{ cm}^{-3}$	3.314×10^4	3.326×10^4	3.301×10^4
$r_c, \text{ cm}$	48.92	48.51	48.72
$r_t, \text{ cm}$	49.34	48.92	49.17
$T_c, \text{ keV}$	28.41	28.31	28.51
$T_{sc}, \text{ keV}$	23.73	23.64	23.77
$F_{\text{ICRH}}, \text{ MW}$	83.75	48.90	40.97
Q	29.23	58.24	64.91
$\Gamma, \text{ MW/cm}^2$	3.848	3.825	3.813

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Fig. 6. Impact of B_0 on P_{ICRH} and Q .

Table 3. Variation of g and G

Constants for this analysis:

$$\begin{array}{lll} \beta_c = 0.75 & F_{ec} = 0.03 & L_c = 130.8 \text{ m} \\ B_c = 2.97 \text{ T} & H = 0.67 & L_t = 22 \text{ m} \\ B_{\max} = 24 \text{ T} & & P_{ICRH} = 0 \end{array}$$

	$g = 2.0,$ $G = 4.0$	$g = 2.75,$ $G = 4.75$	$g = 3.5,$ $G = 5.5$
$P_{\text{fusion}}, \text{ MW}$	2615	2615	1150
$n_c, \text{ cm}^{-3}$	3.174×10^4	3.550×10^4	2.405×10^4
$r_c, \text{ cm}$	50.28	46.98	44.12
$r_t, \text{ cm}$	46.88	47.39	47.65
$T_c, \text{ keV}$	29.53	26.62	29.33
$T_{ec}, \text{ keV}$	24.32	22.84	24.67
β_c	0.522	0.425	0.276
$B_c, \text{ T}$	4.24	4.70	5.05
$P_{\text{ECRH}}, \text{ MW}$	108.0	135.8	119.4
Q	23.06	18.57	9.39
$\Gamma, \text{ MW/cm}^2$	3.669	3.964	1.861

Fig. 7. Impact of g on (a) r_c and β_c , (b) Q and Γ , and (c) T_c and P_{ECRH} .

sharply. Despite the large reduction in P_{fusion} (by 1465 MW), P_{ECRH} decreased only 16.4 MW. The continued need for almost 120 MW of ECRH power explains why the Q value decreases monotonically with increasing g values. Of particular interest are the local maximum and minimum values exhibited by P_{ECRH} and T_c . This behavior may be partially caused by the large drops in both P_{fusion} and β_c , which result from satisfying the constraints of Appendix A. As a whole, the findings indicate an improvement in plasma performance with decreasing g for $g > 2$.

3.1.4 Study of F_{ec}

The fourth end-cell parametric analysis focuses on F_{ec} , an important parameter used by TMRBAR to compute the required microwave power for sustaining the hot electrons. In this study, the central-cell temperatures T_c and T_{ec} , field B_c , and β_c (in addition to F_{ec}) were allowed to change while P_{fusion} , L_c , and B_{max} were held constant. Parameters are tabulated in Table 4. Figure 8 shows that the ECRH power requirements increase along with F_{ec} . This leads to a decrease in Q by 8% as F_{ec} increases from 0.01 to 0.04. From these results, we may conclude that the lower the F_{ec} value, the better the performance will be.

3.2 STUDIES OF THE CENTRAL CELL

The impact on tandem mirror performance of variations in H , B_{max} , B_c , and β_c is reported here. Also included in the discussions is the influence on performance of J. Shearer's ECRH formulation,⁹ which takes into account losses about 40% higher than those assumed for the Mirror Fusion Test Facility (MFTF-B).¹⁰

3.2.1 Variation of H

Investigations of the effect of varying H included three studies. First, the H value was varied from 0.63 to 0.83 with Shearer's formulation included. Table 5 and Fig. 9 summarize the findings. During this study, the H value, P_{fusion} , T_c , and T_{ec} were varied simultaneously while L_c , B_c , β_c , and B_{max} were held constant. Increasing H from 0.63 to 0.83 lowered the two figures of merit, Q and Γ , by 23% and 45%, respectively. This is the result of a large decrease in P_{fusion} and a relatively smaller reduction in P_{ECRH} . The central-cell temperatures T_c and T_{ec} were found to increase with H (see [Fig. 9(c)]), while P_{fusion} and the central-cell ion density decreased.

Second, the values of P_{fusion} , L_c , and B_{max} were fixed, while H , T_c , T_{ec} , B_c , and β_c were allowed to vary. Results are given in Table 6 and Fig. 10. The increase in H causes a decrease in β_c , T_c , and r_c and a subsequent increase in Γ . The decline in central-cell temperature and plasma radius is responsible for the reduction in β_c [see Fig. 10(a)] and the increase in Γ [see Fig. 10(b)], respectively. Hence, it is advantageous to operate a TMR at lower H values if possible.

Third, values of H ranging from 0.9 to 2.0 were considered. The H factor corrects for the effects of the magnetic and potential profiles, as well as the treatment of multiple

Table 4. Variation of F_{ec}

Constants for this analysis:

$\beta_0 = 0.75$	$g = 2.75$	$L_1 = 22.0$ m
$B_0 = 2.97$ T	$G = 4.75$	$P_{fusion} = 2615$ MW
$B_{max} = 24$ T	$H = 0.67$	$P_{ICRH} = 0$
	$L_c = 130.8$ m	

	$F_{ec} = 0.01$	$F_{ec} = 0.03$	$F_{ec} = 0.04$
n_e, cm^{-3}	3.563×10^4	3.550×10^4	3.574×10^4
r_e, cm	46.97	46.98	46.81
r_i, cm	46.70	47.39	47.21
T_e, keV	26.42	26.62	26.43
T_{eo}, keV	22.71	22.84	22.74
β_e	0.443	0.425	0.425
B_e, T	4.60	4.70	4.70
P_{ECRH}, MW	127.8	135.8	138.3
Q	19.72	18.75	18.25
$\Gamma, \text{MW/cm}^2$	3.942	3.964	3.974

Fig. 8. Impact of F_{ec} on Q and P_{ECRH} .

Table 5. Variation of H using Shearer's ECRH power calculation method (variable fusion power)

Constants for this analysis:

$$\begin{array}{lll} \beta_b = 0.75 & B_c = 4.7 \text{ T} & L_c = 130.8 \text{ m} \\ \beta_c = 0.425 & B_{\max} = 24 \text{ T} & L_1 = 22.0 \text{ m} \\ B_b = 2.97 \text{ T} & \epsilon_{\infty} = 0.03 & P_{\text{ICRH}} = 0 \\ g = 2.75 \end{array}$$

	$1/H = 1.2$	$1/H = 1.4$	$1/H = 1.5$	$1/H = 1.6$
P_{fusion} , MW	1925	2370	2615	2810
T_c , keV	33.83	28.51	26.62	25.29
T_{ec} , keV	26.88	23.99	22.84	22.08
n_c , cm^{-3}	2.771×10^4	3.292×10^4	3.550×10^4	3.740×10^4
r_c , cm	47.16	46.82	46.98	47.37
r_b , cm	47.48	47.22	47.39	47.79
P_{ECRH} , MW	118.6	127.4	135.8	144.3
Q	15.32	17.87	18.57	18.82
Γ , MW/ cm^2	2.910	3.602	3.964	4.234

Fig. 9. Impact of H on (a) P_{fusion} and P_{ECRH} , (b) Q and Γ , and (c) T_c and T_{ECRH} with variable fusion power.

Table 6. Variation of H with fixed fusion power

Constants for this analysis:			
$\beta_0 = 0.75$	$F_{oc} = 0.03$	$L_1 = 21.1$ m	
$B_0 = 2.97$ T	$\xi = 2.75$	$P_{fusion} = 2615$ MW	
$B_{max} = 24$ T	$G = 4.75$	$P_{ICRH} = 0$	
	$L_c = 150$ m		
	$1/H = 1.2$	$1/H = 1.4$	$1/H = 1.6$
n_c, cm^{-3}	3.431×10^4	2.246×10^4	2.118×10^4
r_c, cm	63.69	66.90	67.94
r_i, cm	38.37	38.95	38.25
T_c, keV	25.95	28.91	29.72
T_{oc}, keV	21.86	22.99	23.39
β_c	0.6	0.65	0.7
P_{ECRH}, MW	78.05	80.48	77.74
Q	32.36	31.25	32.44
$\Gamma, \text{MW/cm}^2$	2.506	2.389	2.338

Fig. 10. Impact of H on (a) Γ and β_c and (b) r_c and T_c with fixed fusion power and L_c .

trapped ion distributions. Before the physics freeze on MARS in December 1982, preliminary estimates obtained by LLNL suggested a trapped ion ratio of $H \approx 2/3$ for the MARS baseline. More recent estimates by Devoto¹¹ indicate that the values of H should be corrected to around 1.5. We may conclude from Table 7 and Fig. 11 that the lower the H value, the better the performance. These results are consistent with the findings of the two preceding studies. We cannot, however, legislate the value of H since it is a property of the magnetic field and potential profile, as well as the ratio of trapped-ion to passing ion density.

3.2.2 Variation of $B_{\max}$

Magnetic potentials created by magnetic field profiles are responsible for plasma confinement in a tandem mirror device. Consequently, the highest magnetic field of a tandem mirror device, the choke coil field $B_{\max}$, affects the potential profile profoundly. Because of the dominant nature of this parameter, it is of great importance to understand how reactor performance is affected by variations in $B_{\max}$. Two studies were performed. The first concentrated on the variation of $B_{\max}$. The second took into account the effects of increased losses in estimating the ECRH power requirements.

The results of the first study are summarized in Table 8 and Fig. 12; those of the second study are detailed in Table 9 and Fig. 13. It should be noted that the global energy balance constraint (Appendix A) requires that $B_{\max}$, B_c , and β_c be changed simultaneously. The results of both studies indicate that increasing $B_{\max}$ increases B_c , P_{fusion} , P_{ECRH} , Γ , and Q but reduces β_c , T_c , and r_c . The increase in the magnetic pressure results in the decrease in β_c . Furthermore, due to the MHD stability requirement ($B_c^2 \beta_c = \text{const}$) and the principle of conservation of magnetic flux, the value of B_c increases while the central-cell radius r_c decreases. Hence, as P_{fusion} increases, the wall loading increases accordingly. Although both P_{fusion} and P_{ECRH} increase with $B_{\max}$, the difference in their magnitudes results in better plasma performance at higher values of $B_{\max}$. The incorporation of enhanced drag losses in the plug electron power balance leads to higher ECRH power requirements and a subsequent sizable reduction of Q (from 29.16 to 18.57), as shown in Tables 8 and 9.

3.2.3 Addition of P_{ICRH}

The addition of ICRH power to the central cell can also lead to a number of plasma performance changes. We addressed the effect on performance due to the addition of P_{ICRH} . Three cases, corresponding to 0, 15, and 30 MW of input ICRH power, were investigated; the results are tabulated in Table 10 and plotted in Fig. 14. In Table 10 and Fig. 14(c), it is observed that adding ICRH power to the central-cell ions leads to a substantial increase in P_{fusion} and Γ , accompanied by slightly reduced operating temperatures in the central cell. However, as can be seen from Table 10, P_{ECRH} increases monotonically with P_{ICRH} . This effect is expected because at fixed B_b and β_b more ECRH power is needed to sustain the end cell as the central-cell temperatures decrease. Because of the comparable increases in both P_{ECRH} and P_{fusion} , the Q value suffers a moderate decrease of 13% with the addition of 30 MW of ICRH power. There may be a further reduction in performance, depending on the particular ECRH model used. With increased drag losses

**Table 7. Variation of H with fixed fusion power
and $0.909 \leq H \leq 2.0$**

Constants for this analysis:			
$\beta_b = 0.75$	$B_{max} = 24 \text{ T}$	$G = 4.75$	
$\beta_c = 0.89$	$F_{oc} = 0.03$	$L_t = 22 \text{ m}$	
$B_b = 2.97 \text{ T}$	$g = 2.75$	$P_{fusion} = 2615 \text{ M}$	
$B_c = 3.25 \text{ T}$		$P_{ICRH} = 0$	
	$H = 1/1.1$	$H = 1.54$	$H = 2.0$
$L_c, \text{ m}$	108.0	150.0	175.0
$n_0, \text{ cm}^{-3}$	3.736×10^4	3.116×10^4	2.724×10^4
$r_0, \text{ cm}$	50.22	47.37	48.11
$r_v, \text{ cm}$	36.56	34.49	35.02
$T_0, \text{ keV}$	25.42	30.30	34.39
$T_{ec}, \text{ keV}$	21.90	24.61	26.88
$P_{ECRH}, \text{ MW}$	50.58	39.54	38.46
Q	48.94	61.78	62.17
$\Gamma, \text{ MW/cm}^2$	4.103	3.070	2.605

Fig. 11. Impact of H on Q and L_c with fixed fusion power.

Table 8. Variation of $B_{\max}$

Constants for this analysis:

$$\begin{array}{lll} \beta_0 = 0.75 & g = 2.75 & L_c = 130.8 \text{ m} \\ B_0 = 2.97 \text{ T} & G = 4.75 & L_t = 22.0 \text{ m} \\ F_{ec} = 0.03 & H = 0.67 & P_{ECRH} = 0 \end{array}$$

	$B_{\max} = 24 \text{ T}$	$B_{\max} = 20 \text{ T}$	$B_{\max} = 18 \text{ T}$
P_{fusion} , MW	2615	1877	1433
n_c , cm^{-3}	3.31×10^4	3.08×10^4	2.02×10^4
r_c , cm	49.02	53.70	56.15
r_t , cm	37.29	27.15	37.02
T_c , keV	28.14	30.83	33.33
T_{ec} , keV	23.75	25.17	26.62
β_c	0.425	0.480	0.502
P_{ECRH} , MW	83.94	78.57	74.99
Q	29.16	22.28	17.71
Γ , MW/cm^2	3.84	2.47	1.78

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Fig. 12. Impact of $B_{\max}$ on (a) B_c and β_c , (b) r_c and T_c , (c) Q and Γ , and (d) P_{fusion} and P_{ECRH} .

Table 9. Variation of $B_{\max}$ with ECRH power calculation including enhanced drag losses

Constants for this analysis:

$$\begin{array}{lll} \beta_0 = 0.75 & g = 2.75 & L_c = 130.8 \text{ m} \\ B_0 = 2.97 \text{ T} & G = 4.75 & L_t = 22 \text{ m} \\ F_{ec} = 0.03 & & P_{\text{ECRH}} = 0 \end{array}$$

	$B_{\max} = 24 \text{ T}$	$B_{\max} = 20 \text{ T}$	$B_{\max} = 18 \text{ T}$
$P_{\text{fusion}}, \text{ MW}$	2615	1800	1300
$n_c, \text{ cm}^{-3}$	3.550×10^7	2.557×10^7	1.973×10^7
$r_c, \text{ cm}$	46.98	51.67	54.47
$r_t, \text{ cm}$	47.39	47.42	47.66
$T_c, \text{ keV}$	26.62	29.69	33.76
$T_{ec}, \text{ keV}$	22.84	24.76	27.06
β_c	0.425	0.477	0.497
$P_{\text{ECRH}}, \text{ MW}$	135.8	123.8	117.1
Q	18.57	13.99	10.60
$\Gamma, \text{ MW/cm}^2$	3.964	2.434	1.652

Fig. 13. Impact of $B_{\max}$ on (a) B_c and β_c , (b) r_c and T_c , (c) Q and Γ , and (d) P_{fusion} and P_{ECRH} with effects of enhanced drag losses included.

Table 10. Addition of P_{ICRH}

Constants for this analysis:			
$\beta_h = 0.75$	$B_{max} = 24 \text{ T}$	$G = 4.75$	
$\beta_c = 0.334$	$F_{ec} = 0.03$	$H = 0.67$	
$B_h = 2.97 \text{ T}$	$g = 2.75$	$L_c = 130.8 \text{ m}$	
$B_c = 5.3 \text{ T}$		$L_t = 22 \text{ m}$	
	$P_{ICRH} = 30 \text{ MW}$	$P_{ICRH} = 15 \text{ MW}$	$P_{ICRH} = 0$
$P_{fusion} \text{ MW}$	2462	2125	1831
$n_0 \text{ cm}^{-3}$	3.38×10^4	3.16×10^4	2.87×10^4
$r_0 \text{ cm}$	46.2	45.0	44.9
$r_b \text{ cm}$	38.1	37.1	37.0
$T_c \text{ keV}$	28.9	30.8	32.5
$T_{ec} \text{ keV}$	22.9	24.1	26.2
$P_{ECRH} \text{ MW}$	90.8	81.8	76.8
Q	19.4	20.6	21.9
$\Gamma \text{ MW/cm}^2$	3.90	3.43	2.96

Fig. 14. Impact of P_{ICRH} on (a) T_c and T_{ec} , (b) P_{fusion} and P_{ECRH} , and (c) Q and Γ .

taken into account in the electron power balance,⁹ the figures of merit Q and Γ drop as much as 36% (from $Q = 21.9$ in Table 10 to $Q = 13.98$ in Table 11) and 7%, respectively. Despite these differences in absolute values, the results shown in Table 11 and Fig. 15 indicate that the higher the value of P_{ICRH} input to the central cell at ignition conditions, the poorer the Q value will be.

3.2.4 Variation of B_c and β_c

Changes in plasma performance due to the simultaneous variation of P_{fusion} , B_c , and β_c , with $B_c^2\beta_c$ unchanged, were investigated. With H , L_c , and B_{max} held fixed, both the central-cell ion and electron temperatures and the end-cell ECRH power requirements increase with higher values of the central-cell field B_c . The increase in B_c also contributes to a reduction in the central-cell radius r_c and P_{fusion} . As a consequence, the two figures of merit are reduced, Q by 40% and Γ by 27%, as B_c increases from 3.0 to 3.24 T. The details of this study are indicated in Table 12 and Fig. 16. The ECRH model of ref. 9 was applied to examine the effect on plasma performance of the variation of B and β_c combined with increased electron drag loss. Results of this study can be found in Table 13 and Fig. 17. In Fig. 17(c), the value of P_{ECRH} actually decreases with increasing B_c , as opposed to the slight increases with higher values of B_c shown by Fig. 16(c). Despite the decrease in P_{ECRH} , the Q value still decreases with increasing B_c , because the reduction in P_{fusion} overwhelms the benefit brought about by decreasing the value of P_{ECRH} [see Fig. 17(c)]. Comparing the rate of change in Q with that of B_c between Tables 12 and 13, one quickly realizes that the increased electron drag losses⁹ reduce the impact of B_c variations on Q from a 2.34% change in Q per unit change in B_c to a 1.71% change.

Table 11. Addition of P_{ICRH} using Shearer's power calculation method

Constants for this analysis:

$$\begin{array}{lll} \beta_0 = 0.75 & B_c = 5.1 \text{ T} & H = 0.67 \\ \beta_e = 0.355 & B_{max} = 24 \text{ T} & L_c = 130.8 \text{ m} \\ B_0 = 2.97 \text{ T} & F_{ec} = 0.03 & L_t = 22 \text{ m} \\ g = 2.75 \end{array}$$

	$P_{ICRH} = 30 \text{ MW}$	$P_{ICRH} = 15 \text{ MW}$	$P_{ICRH} = 0$
$P_{fusion}, \text{ MW}$	2462	2200	1831
$n_{e0}, \text{ cm}^{-3}$	3.662×10^4	3.447×10^4	3.149×10^4
$r_0, \text{ cm}$	44.45	43.78	44.01
$r_t, \text{ cm}$	47.45	46.73	46.96
$T_c, \text{ keV}$	26.29	27.43	29.29
$T_{ec}, \text{ keV}$	21.67	22.76	24.45
$P_{ECRH}, \text{ MW}$	141.1	129.2	122.0
Q	13.98	14.75	15.41
$\Gamma, \text{ MW/cm}^2$	3.972	3.589	3.186

Fig. 15. Impact of P_{ICRH} on (a) T_c and T_{ec} , (b) Q and Γ , and (c) P_{fusion} and P_{ECRH} with effects of enhanced drag losses included.

Table 12. Variation of B_c and β_c

Constants for this analysis:

$$\begin{array}{lll}
 \beta_0 = 0.75 & F_\infty = 0.03 & L_c = 150 \text{ m} \\
 B_0 = 2.97 \text{ T} & g = 2.75 & L_1 = 21.12 \text{ m} \\
 B_{\max} = 24 \text{ T} & G = 4.75 & P_{\text{ICRH}} = 0 \\
 & H = 0.65 &
 \end{array}$$

	$B_c = 3 \text{ T},$ $\beta_c = 0.70$	$B_c = 3.11 \text{ T},$ $\beta_c = 0.65$	$B_c = 3.24 \text{ T},$ $\beta_c = 0.60$
$P_{\text{fusion}}, \text{ MW}$	2615	2256	1923
$n_0, \text{ cm}^{-3}$	2.188×10^4	2.054×10^4	1.924×10^4
$r_0, \text{ cm}$	67.94	65.70	63.48
$r_c, \text{ cm}$	38.25	38.25	38.25
$T_0, \text{ keV}$	29.72	31.35	33.69
$T_\infty, \text{ keV}$	23.39	24.45	25.50
$P_{\text{ECRH}}, \text{ MW}$	77.74	78.37	79.45
Q	32.44	27.68	23.18
$\Gamma, \text{ MW/cm}^2$	2.34	2.09	1.85

Fig. 16. Impact of B_c on (a) Q and Γ , (b) r_c and T_c , and (c) P_{fusion} and P_{ECRH} .

Table 13. Variation of B_c and β_c with ECRH power calculation including a 40% increase in electron drag losses

Constants for this analysis:			
$\beta_0 = 0.75$	$F_{ec} = 0.03$	$L_c = 130.8$ m	
$B_0 = 2.97$ T	$g = 2.75$	$L_1 = 22$ m	
$B_{max} = 24$ T	$G = 4.75$	$P_{ICRH} = 0$	
	$H = 0.67$		
	$B_c = 3$ T, $\beta_c = 0.70$	$B_c = 3.11$ T, $\beta_c = 0.65$	$B_c = 3.24$ T, $\beta_c = 0.60$
P_{fusion} , MW	2880	2615	2400
n_{e0} , cm^{-3}	3.666×10^4	3.550×10^4	3.412×10^4
r_0 , cm	48.44	46.98	46.07
r_1 , cm	47.75	47.35	47.48
T_0 , keV	25.82	26.62	27.60
T_{e0} , keV	22.37	22.84	23.46
P_{ECRH} , MW	141.8	135.8	132.1
Q	19.62	18.57	17.49
Γ , MW/ cm^2	4.23	3.96	3.72

Fig. 17. Impact of B_c on (a) Q and Γ , (b) r_c and T_c , and (c) P_{fus} and P_{ECRH} with effects of enhanced drag losses included.

4. CONCLUSIONS

From the results of the parametric analyses, the following conclusions can be drawn.

- With fixed L_c and H , it is advantageous to design for a higher value of P_{fusion} that allows a higher value of β_c at lower fields. Alternatively, for a fixed P_{fusion} it is possible to operate with a shorter central-cell length.
- It is beneficial to operate at the highest choke coil field permitted by technology, because the higher this magnetic field is, the more fusion power can be produced. (There is, of course, the issue of recirculating power to the normal insert coil.)
- With L_c , β_c , B_c , and B_{max} constant, adding ICRH power to the central cell results in a substantial increase in P_{fusion} and Γ but a moderate decrease in Q . Alternatively, for a fixed P_{fusion} , a substantial decrease in L_c is realized.
- With B_c , β_c , P_{fusion} , and B_{max} constant, an improved plasma performance can be achieved at a lower value of B_b . This is true because with fixed β_b , ECRH power requirements decrease with decreasing B_b . However, if β_b is varied under the constraints of constant-beta-corrected B_b , a higher value of B_b is desirable because the central-cell ion density decreases, as opposed to being constant.
- The increased electron drag loss in computing the ECRH power requirements amplifies the advantage of using a higher value of B_{max} but reduces the plasma performance for the case of adding ICRH power to the central cell at ignition.
- With H , L_c , and B_{max} constant, a decrease in g results in increased Q mainly because of lower ECRH power requirements. However, an optimum value for Γ seems to exist at $g = 2.75$.
- A low τ_{ec} value would yield a better plasma performance because less ECRH power is required to provide collisional filling of cold electrons into the thermal barrier.
- For fixed B_c and β_c , it is best to operate at the lowest H value possible. A higher H value would require a longer L_c for a given Q value.

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Appendix A

CONSTRAINTS

The following constraints were applied during the parametric analyses.

1. Approximate global energy balance for ignition conditions at $P_{ICRH} = 0$ with constant ϕ_c , g , L_c , T_c , T_{ec} , L_t , and L_i :

$$(B_i/B_{\max})^2 B_c \sqrt{1 - \beta_c} \left[1 + 0.044(B_{\max}/B_i) \right]^{3.33} = \text{const} .$$

2. Trapped particle stability for fixed end-cell fields and dimensions:

$$3.6 \times 10^3 (g_b n_{\text{pass}}/n_c) (B_d/r_c^2) \sqrt{1 - \beta_c} \geq 0.5 .$$

3. Conservation of magnetic flux:

$$r_c^2 B_c \sqrt{1 - \beta_c} = \text{const} .$$

4. MHD stability:

$$B_c^2 \beta_c = \text{const} ,$$

$$B_b \sqrt{1 - \beta_b} = \text{const} ,$$

$$B_i/B_c = \text{const} ,$$

$$\beta_i \leq 0.066 ,$$

$$\beta_c \leq 0.90 .$$

Appendix B

DEFINITIONS OF PARAMETERS

B_b	Vacuum magnetic field of the plug bottom, T
B_c	Vacuum magnetic field of the central cell, T
B_{max}	Peak magnetic field of the choke coil, T
B_t	Vacuum magnetic field of the transition region, T
C_α	Thermal alpha particle density fraction of the central cell
F_{ec}	Density fraction of central-cell electrons at the plug bottom
g	Ratio of passing and trapped ion density to passing ion density at the plug bottom
G	Ratio of passing, trapped, and sloshing ion density to passing ion density
H	Ratio of the trapped ion current from Fokker-Planck calculations to the trapped ion current from the Futch-LoDestro square-well calculations
L_c	Length of the central cell, m
L_t	Length of the transition region, m
n_c	Ion density of the central cell, cm^{-3}
n_{pass}	Passing ion density of the plug region, cm^{-3}
P_{fusion}	Fusion power generated, MW
P_{ECRH}	ECRH power input, MW
P_{ICRH}	ICRH power input, MW
Q	Ratio of fusion power generated to total power input
r_c	Radius of the central cell, cm
T_c	Ion temperature of the central cell, keV
T_{ec}	Electron temperature of the central cell, keV
$\bar{\beta}_b$	Volume-averaged beta of the plug
$\bar{\beta}_c$	Volume-averaged beta of the central cell
$\bar{\beta}_t$	Volume-averaged beta of the transition region
ϕ_e	Electron confinement potential of the central cell, keV
Γ	Neutron wall loading, MW/cm^2

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