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THE IMPACT OF MAXIMUM TF MAGNETIC FIELD ON PERFORMANCE AND COST OF AN ADVANCED PHYSICS TOKAMAK*

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Abstract: Parametric studies were conducted using the Fusion Engineering Design Center (FEDC) Tokamak Systems Code to investigate the impact of variation in the maximum value of the field at the toroidal field (TF) coils on the performance and cost of a low q_ψ, quasi-steady-state tokamak. Marginal ignition, inductive current startup plus 100 s of inductive burn, and a constant value of epsilon (inverse aspect ratio) times beta poloidal were global conditions imposed on this study. A maximum TF field of approximately 10 T was found to be appropriate for this device.

Introduction

Systems trade studies defining the impact of variation in the maximum value of the field at the toroidal field (TF) coils were conducted for a low q_ψ (safety factor), quasi-steady-state tokamak through the use of the Fusion Engineering Design Center (FEDC) Tokamak Systems Code [1]. Low q_ψ is desirable in that reducing the value of q_ψ allows a higher beta limit; low q_ψ (less than 2) also achieves a reduction in plasma disruptivity. High beta serves to improve fusion performance and reduce device size while reduced disruptivity improves the reactor relevance of the tokamak concept.

Quasi-steady-state operation is predicated on utilizing rf current drive in conjunction with conventional inductive means to initiate and maintain plasma current. Recent successful demonstration of lower hybrid current drive in PLT, Alcator C, Versator II, and JIPP T-II, albeit at modest plasma densities, has introduced such a possibility. A proposed plasma operating scenario consists of alternating cycles of high density plasma burn (~1000 s), during which time the plasma current is maintained by flux linkage from the ohmic heating solenoid, followed by a period of low density rf current device plasma operation (~100 s), during which time the ohmic heating (OH) solenoid is recharged for the next high density plasma burn cycle. Table 1 shows reference parameters for a low q, quasi-steady-state tokamak about which the trade studies were conducted.

This paper is an update to a portion of the FED-A system trade studies [2]. A revised FEDC systems code and revised unit costs values were used in this study.

Methodology

The trade study to determine the impact of maximum TF field on performance and cost was conducted in the following manner.

(1) Constant plasma physics, characterized by ignition, inductive startup plus 100 s of inductive burn, and a value of $\epsilon\beta_p$ of 0.5, was maintained as the maximum toroidal field was

Table 1. Reference parameters for an advanced physics tokamak

Description	Value
Geometry	
Major radius, R	4.35 m
Plasma radius, a	0.90 m
Plasma elongation, κ	1.2 m
Aspect ratio, A	4.85 m
Scrape-off layer	0.15 m
Plasma	
Average ion temperature, $\langle T_i \rangle$	10 k[illegible]
Safety factor (edge), q_ψ (flux-surface-averaged)	1.8
Effective charge (during burn), Z_{eff}	1.5
TF ripple (peak-to-average), edge	1.0%
Plasma current, I_p	3.9 MA
Average electron density, $\langle n_e \rangle$	1.8×10^{20} m^{-3}
$\epsilon\beta_p$	0.5
Total beta, $\langle\beta\rangle$	5.8%
Toroidal field at plasma, B_T	5.16 T
Q	Ignited
Operating mode	
Burn time, t_{burn}	100 s, 1000 s[a]
Fusion power, P_{fus}	262 MW
Startup time, t_{ss}	26 s
Number of full field current pulses/lifetime	3×10^4
Shield	
Average neutron wall load at plasma edge	1.24 MW/m^2
Inboard shield material	Stainless steel
Inboard thickness (excluding spool armor, gaps, scrape-off)	72 cm
Dose rate to TF coil insulation	1×10^9 rad
Time after shutdown to permit personnel access (2.5 mrem/h)	24 h
Outboard shield thickness (stainless steel)	133 cm
TF coils	
Number	12
Peak design field at winding, B_m	10 T
Conductor winding current density, J_w	2200 A/cm^2
Overall current density, J_{OA}	1465 A/cm^2
Megampere turns	112
PF coils	
Total flux capability	67.5 Wb
EF flux	23.2 Wb
OH flux	44.3 Wb
Total maximum ampere-turns	50 MAT
OH maximum field allowable at coil	7 T
Conductor winding pack current density, J_{wp}	1400 A/cm^2
Plasma heating and current drive	
Startup ECH power	3.5 MW
Bulk heating and current drive lower hybrid power	25 MW

[a] 100 s provided by PF system in the absence of noninductive current drive, 1000 s with partial noninductive current drive.

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varied. Ignition was maintained by varying the plasma minor radius until the losses were balanced by the fusion alpha power. INTOR scaling ($\tau_e \sim n_e a^2$) was assumed. Inductive volt-second for startup and burn were achieved by varying the plasma aspect ratio (i.e., major radius for a given value of minor radius to satisfy ignition). Beta poloidal was varied directly as the aspect ratio in order to maintain $\varepsilon\beta_p$ = 0.5, where ε is the inverse aspect ratio.

(2) The inboard shield thickness was varied as a function of neutron wall loading in order to maintain a dose rate to the TF coil insulation of 1×10^9 rads. An integrated burn time of 0.95 years was used, which is equivalent to 30,000 pulses at 1000 s per pulse.

(3) The outboard shield thickness was sized to maintain the shutdown dose rate at 2.5 mrem/h 24 h after shutdown.

(4) The magnetic field ripple at the plasma edge was maintained at a value of 1.0%, or less, by varying the TF coil outer leg radius.

(5) A relatively slow plasma current startup time (20 s) was used based on the assumption of a conducting shell close to the plasma. The slow ramp time allows a reduction in the poloidal field (PF) system power supplies.

(6) The required individual PF coil currents were scaled as a function of plasma current, as the square of the distance from the plasma to the coil center and inversely as the coil radius squared. The reference PF configuration, to which this scaling relationship was applied, was generated based on MHD considerations and is shown in Fig. 1.

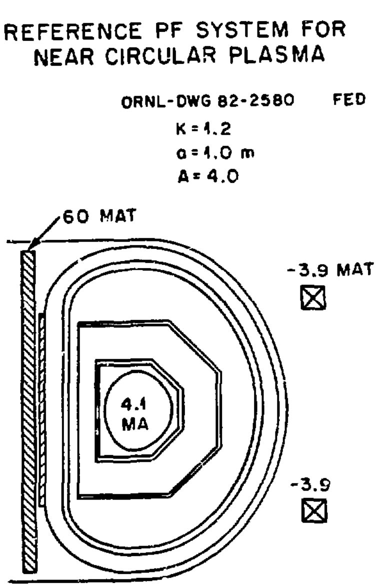

Fig. 1

Results

The impact on total system performance and cost of varying the TF maximum field from 8 to 12 T was determined. The TF windings for the 8-10-T maximum field coils were composed of NbTi superconductor and copper. The 11- and 12-T winding featured a graded conductor with the 0-10 T portion being NbTi and copper and the high field portions being Nb_3Sn and copper.

The current densities and unit costs of the winding packs were varied as a function of maximum toroidal field. The cost of the winding packs was based on \$90/kg for NbTi and \$180/kg for Nb_3Sn conductor. The 11- and 12-T conductors were graded and costed assuming NbTi up to 10 T and Nb_3Sn for the remainder of the winding. The current density over the winding pack varies from 2500 A/cm^2 at 8 T to 2200 A/cm^2 at 10 T for the NbTi winding. For the graded conductor, the current density for the NbTi portion is taken as 2200 A/cm^2, and the higher field Nb_3Sn portions vary from 1950 A/cm^2 at 11 T to 1700 A/cm^2 at 12 T. The resulting average winding pack current densities and unit costs are shown in Table 2 as a function of maximum TF field.

Table 2. Current density and unit cost as a function of maximum toroidal field used in the system analysis

B_{max} (T)	J_{Nb_3Sn}[a] (A/cm^2)	J_{wp}[b] (A/cm^2)	T_{wp} (K)	$/kg$_{wp}$	Conductor composition
12	1700	2115	3.2	105	Nb_3Sn, NbTi, Cu
11	1950	2180	3.1	98	Nb_3Sn, NbTi, Cu
10		2200	3.0	90	NbTi, Cu
9		2350	4.1	90	NbTi, Cu
8		2500	4.2	90	NbTi, Cu

[a]Current density in Nb_3Sn portion of the winding.

[b]Average current density across the winding pack.

The resulting relative capital cost as a function of maximum toroidal field and plasma radius is presented in Fig. 2. Note that 100 s of burn is maintained throughout by varying the plasma aspect ratio and that $\varepsilon\beta_p$ = 0.5. In general, this figure shown that cost increases for an increasing minor radius (constant B_{max}) or for an increasing value of B_{max} (constant plasma minor radius). A boundary of marginal ignition is also shown in Fig. 2, relating maximum field, plasma size, and capital cost. Capital cost variation for configurations sized for 8 to 10 T is seen to be slight (within ±1%) but going to be 12 T requires a cost increase of ~6% relative to the 10-T configuration. Tables 3 and 4 present a summary of parameters and cost breakdowns along the ignition boundary. The cost values in Table 4 are representative of direct capital costs only and do not include allowances for engineering, installation, or contingency. It is seen that although the 10-T case suffers a 50% increase in TF coil cost from the 8-T case this increase is compensated for by a decreased cost of shield, PF coils, and electrical systems due primarily to a reduced minor radius and a reduced value of plasma current (Table 3). This compensation is no longer as effective for the 12-T case because of a decreased percentage reduction in plasma size and current encountered in going from 10 to 12 T compared to going from 8 to 10 T. In addition,

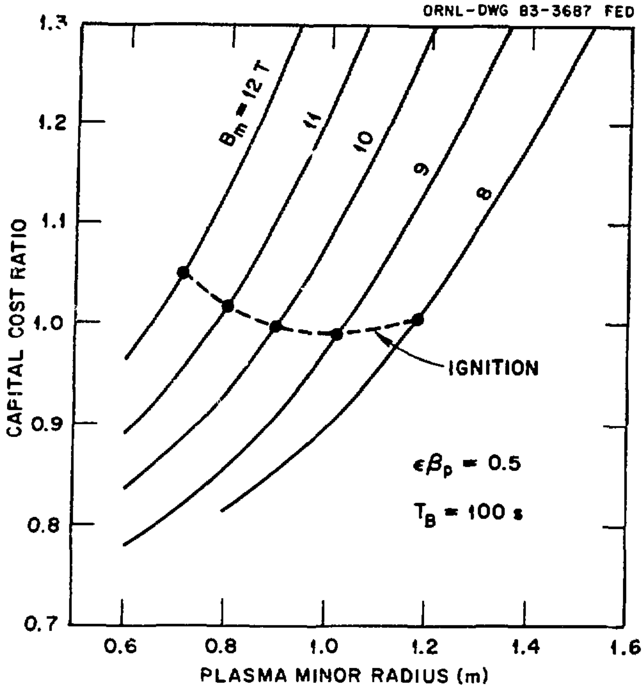

Fig. 2

Table 3. Ignition parameters vs B_{max}, where $q_\psi = 1.8$, $\kappa = 1.2$, $\epsilon\beta_p = 0.5$, and $T_B = 100$ s

	B_{max} (T)		
	8	10	12[a]
J_{wp} (A/cm²)[b]	2500	2200	2115
J_{QA} (A/cm²)[c]	1725	1465	1365
TF coil megampere-turns	77	112	153
Minor radius, a (m)	1.18	0.90	0.72
Aspect ratio, A	3.61	4.85	6.28
Major radius, R_0 (m)	4.27	4.35	4.49
Beta, β (%)	9.0	5.8	4.2
Field on axis, B_T (T)	3.59	5.16	6.79
Plasma current, I_p (MA)	5.2	3.9	3.1
PF flux (Wb)	74.1	67.5	63.6
Wall loading, L_p (MW/m²)	0.92	1.24	1.55
Fusion power, P_{fus} (MW)	254	262	271
Relative cost, $\$_R$	1.008	1.00	1.057

[a]Graded NbTi/Nb_3Sn.

[b]Current density over the winding pack.

[c]Overall current density including structure.

Table 4. Direct cost summary at marginal ignition as a function of B_{max}

	B_{max} (T)		
	8	10	12
Shield	104.9	89.8	82.0
TF coils	63.3	95.9	147.9
PF coils	30.9	22.0	17.5
Plasma heating	80.4	75.6	73.4
Electrical	27.8	22.8	21.9
Heat transport	18.3	19.7	19.7
Facilities	119.3	114.7	112.7
Other	205.4	204.7	206.9
Total	650.3	645.2	682.0
Relative cost	1.008	1.000	1.057

there is a greater increase in required major radius encountered in going from 10 to 12 T (14 cm) compared to going from 8 to 10 T (8 cm).

It is also of interest to determine the cost variation with maximum field at constant neutron wall loading (the requirement for marginal ignition is relaxed). The boundary for neutron wall loading of 1.0 MW/m² is shown in Fig. 3. It is seen that the capital cost achieves a shallow minimum at a value of 11 T. However, this minimum is only 1% lower than the value obtained for a value of B_{max} of 10 T.

For the constraints considered in this study, it appears that a value of B_{max} of 10 T is appropriate for the Advanced Physics Tokamak and that higher toroidal field strengths are not necessary.

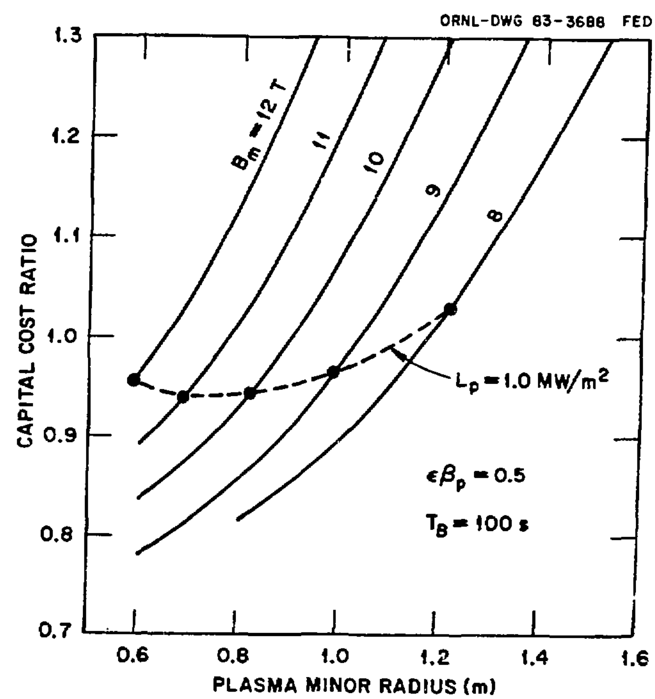

Fig. 3

Because of the potential significance of this conclusion, it is of interest to assess its sensitivity to some of the assumptions imposed in this study. Figure 4 shows the impact of reducing the fixed value of $\epsilon\beta_p$ from 0.5 to 0.4 for tokamaks sized while achieving ignition and 100 s of burn. Again, fields in the range of 9-10 T achieve a minimum cost, which is about 5% below the 12-T case.

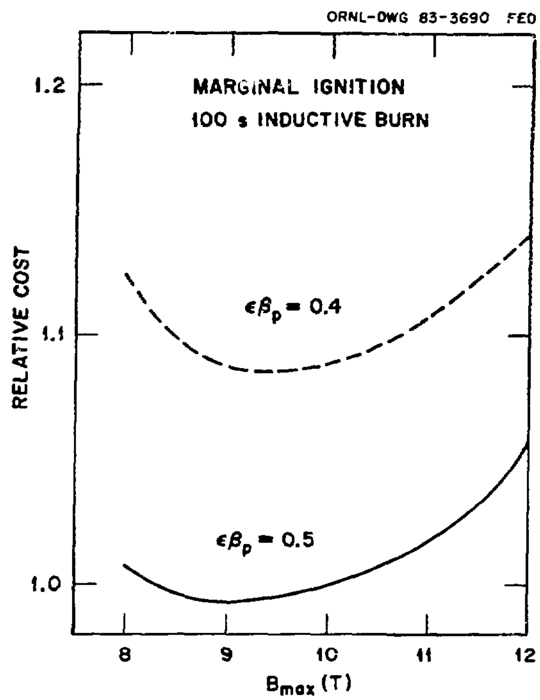

Fig. 4

The effect of varying B_{max} on unit capital cost (capital cost divided by the plasma fusion power) is also examined. Again, an inductive plasma burn time of 100 s and an $\epsilon\beta_p$ of 0.5 are maintained. The boundary of marginal ignition is shown in Fig. 5. It is seen that the unit capital cost minimizes at a maximum toroidal field of 10 T. Therefore, the conclusion of B_{max} = 10 T being near optimal for an advanced physics tokamak is not sensitive to the assumed values of $\epsilon\beta_p$ or on whether the optimization is based on capital cost or unit capital cost.

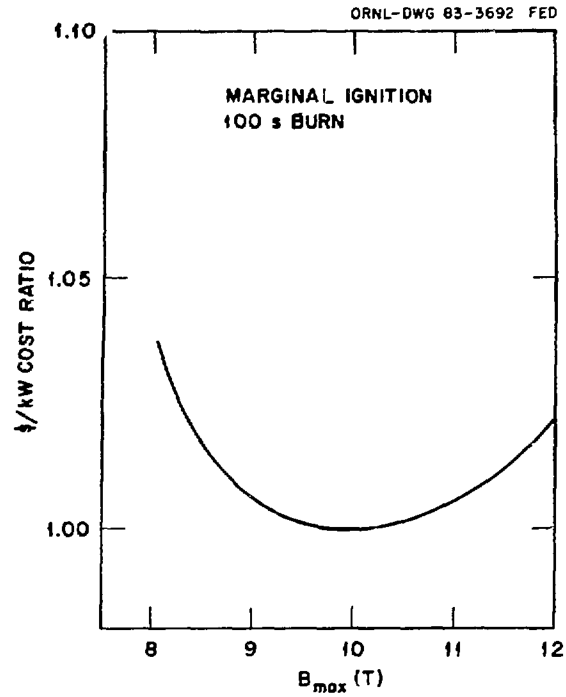

Fig. 5

Conclusions

- The perception that higher fields are always desirable for a tokamak reactor is not necessarily correct. This study indicates, for the constraints imposed, that the change of capital cost with maximum field is slight with a variation of less than 5% in total system cost for a change in maximum toroidal field from 8 to 12 T. A shallow minimum in total system cost occurs at about 10 T.
- The minimization of capital cost at approximately 10 T is not sensitive to changes in the value of $\epsilon\beta_p$.
- The minimization of capital cost at approximately 10 T is not sensitive to whether the analysis is constrained to constant ignition or constant neutron wall loading.
- The minimization of unit capital cost ($/kW) occurs at a maximum TF field of approximately 10 T.

Reference

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2. Y-K. M. Peng and P. H. Rutherford, "FED-A, An Advanced Performance FED Based on a Low Safety Factor and Current Drive," Oak Ridge Natl. Lab Report, ORNL/FEDC-83/1, August 1983.