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POLOIDAL FIELD COIL AND CURRENT DISTRIBUTION STUDY FOR THE TOROIDAL FUSION CORE EXPERIMENT (TFCX)*

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Abstract: The Toroidal Fusion Core Experiment (TFCX) is a proposed concept for an ignited, long-pulse, current-driven, next step tokamak device. The poloidal field (PF) coil configuration has major impact on the size and cost of a tokamak machine. The purpose of this trade study was to determine the achievable values of plasma triangularity and elongation consistent with mechanical configuration and plasma performance requirements. The study was made with three sets of PF coil configurations: (1) PF coils ~~are located~~ external to the (TF) coil, (2) all PF coils ~~are located~~ inside the TF coil bore, and (3) a hybrid configuration with some coils inside and some outside of the TF coil bore. The impact of plasma shape, profile, and coil locations on the distance between the plasma boundary and separatrix are presented. It is concluded that the plasma scrape-off requirements for removing impurities with a single null limiter can only be satisfied if the triangularity is limited to ~0.30 for an elongation of 1.6.

The external discrete PF coil configurations with only superconducting (TFCX-S) and hybrid (TFCX-H) TF coils are discussed which satisfy the plasma performance and the mechanical integration requirements. The time variation of currents in all the PF coils for the entire pulse cycle period is also developed. PF coil configurations are compared on the basis of the coil, power supplies, and motor generator set costs. The coil cost is the dominant component of the PF system cost for a charge-up time of 30 s. The total cost of the PF system increases with external coils, as compared to the internal coils, as the plasma triangularity is increased. However, the incorporation of internal PF coils is rather difficult in TFCX due to mechanical integration and maintenance requirements.

Introduction

A tokamak magnet system consists of toroidal field (TF) and poloidal field (PF) coils. The PF coils perform the function of plasma shaping, equilibrium and heating. The PF coil configuration influences the magnetic and structural design of the TF and PF coils. For these reasons, a number of trade studies were performed to determine the PF coil configuration for TFCX, with emphasis on reducing the device cost. The practical limits were also determined for the plasma triangularity and elongation consistent with mechanical configuration and other plasma performance requirements (heating and equilibrium). These trade studies and the final PF configurations for TFCX are described, together with time variations of currents during the pulse cycle. The impact of engineering constraints (e.g., peak field at any PF coil ≤8 T) and continuous scrape-off requirements on the PF configuration are also discussed.

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PF Coil Distribution Studies

These trade studies were performed by varying the plasma triangularity (0.2 to 0.7), elongation (1.6 to 2.5), and average beta (4% to 5.5%), and with external, internal, and hybrid PF coil configurations. Another constraint on this study was to satisfy the plasma scrape-off requirements for removing impurities by a single null pump limiter [1]. The study was performed with the (FEDC) (MHD) equilibrium code and the systematic procedure developed previously [2]. The configuration development is initiated with 50 PF coils located around the TF coil perimeter. This simulates a continuous current sheet. The discrete PF coil locations are identified by surveying the currents in the 50 coils. For each set of discrete PF coil configurations, the coil, power supplies, and motor generator (MG) set costs are calculated for relative comparison. The coil cost is the most dominant component of the PF system cost for a charge-up time of 30 s. The total cost of the PF system, as a function of triangularity, increases sharply with external coils, as compared to the internal coils.

Plasma Parameters

PF configuration studies are performed, with the plasma parameters listed in Table 1, at the end of the burn period (t = 340 s). The plasma center is located at 3.60 m, and the PF coils are located symmetrically with respect to the plasma for the limiter option.

Table 1. Plasma parameters for PF trade study

Major radius (R_0), m	3.60
Minor radius (a), m	0.80
Plasma current I_p for high β_p, A	6×10^6
TF field on axis, T	~7.0
Plasma elongation (K)	~1.6 to 2.5
Plasma triangularity (δ)	~0.2 to 0.7
q at the axis	~1.0
Poloidal (high) β_p	~1.50 to ~2.0
Average high β	~4.0% to ~5.5%
Scrape-off layer (outboard), cm	~5
Scrape-off layer (inboard), cm	~10

Assumptions

The primary function of the PF coils for the trade study is to provide the external field necessary for plasma equilibrium — it does not have to ohmically heat the plasma. The details of coil locations, currents, and equilibrium flux surfaces for all options explored are given in Ref. [3].

External PF Configuration

This option was studied with a 50-coil idealized PF configuration and with eight discrete coils. The results of the external PF configurations studies are shown in Fig. 1. The sum of ampere-turns in all coils increases more rapidly as a function of plasma triangularity for the discrete PF coils than for the idealized 50-coil set (see Fig. 1). The total ampere-turns requirement is ~53 MA for δ = 0.2. Idealized configuration requires 157 MA for δ = 0.7. The same ampere-turns are needed for achieving δ = 0.5 with the discrete coil configuration. This ampere-turn requirement is a factor of three more than that for δ = 0.2.

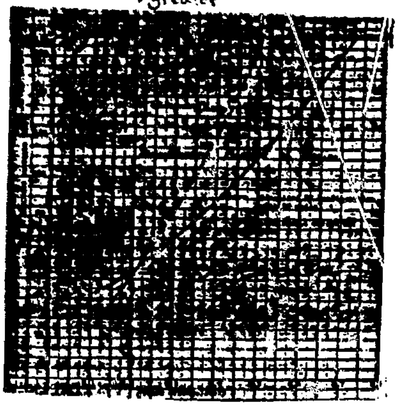

Fig. 1.

The equilibrium flux surfaces have the same pattern for an idealized and discrete PF coil configuration. The scrape-off flux surface becomes discontinuous for δ > 0.3, and separatrix starts forming closer to the plasma boundaries as the triangularity is increased. Furthermore, the size of D coils (at the top and bottom of the plasma in the inboard region) in the discrete configuration become too large for δ = 0.5; they could not be accommodated in the given configurational space.

The impact of plasma current profiles and the details of the plasma boundary shape on the shape of the scrape-off region have been discussed previously [1,4]. Sensitivity of the shape of field lines in the plasma scrape-off region to different boundary shapes is shown in Fig. 2. A more "rounded" D-shaped cross section has more favorable scrape-off properties. These changes in the plasma boundary shape need to be further refined in the future studies.

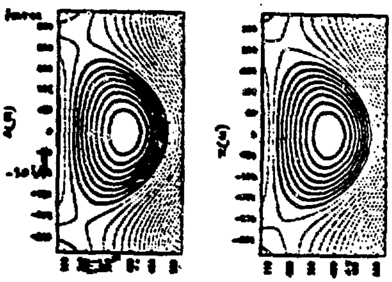

Fig. 2.

Plasma Elongation Dependence

Reasonable PF configurations could be developed if the plasma elongation is increased at higher triangularities (~0.7). The total ampere-turns, as a function of elongation, are shown in Fig. 3 for idealized PF configuration with 50 coils. A linear dependence is observed between the plasma elongation and ampere-turn needed at constant triangularity of ~0.7. However, even for a plasma elongation of 2.5, the total ampere-turns are still large. Equilibrium flux surface becomes discontinuous and separatrix is formed. A feasible PF system could not be developed at higher elongation (~2.5) and triangularity (~0.7).

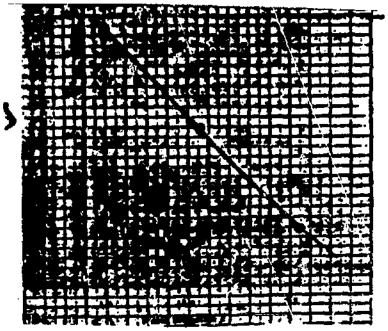

Fig. 3.

Internal PF Configuration

Studies were made with PF coils located inside the TF coil bore in order to investigate the higher plasma triangularity requirements. The results are summarized in Fig. 4 with idealized 50 coils and with discrete 8 coils. The total ampere-turns need is 10 MA-turns for δ = 0.2 and is 20 MA-turns for δ = 0.7. However, the scrape-off flux surface becomes discontinuous if the plasma triangularity exceeds ~0.3. The internal PF coils cannot be accommodated in the present TFCX configuration due to the lack of space and the selected maintenance approach.

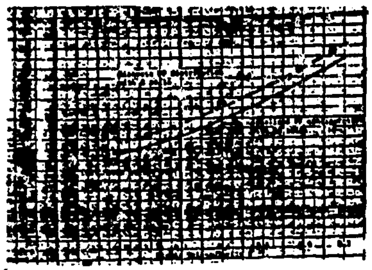

Fig. 4.

Hybrid PF Configuration

The plasma requirements could be satisfied with a hybrid set of PF coils; i.e., a few coils (D coils on top and bottom) are located inside the TF bore and a few (ring coils in the outboard region and central solenoid) are located outside the bore. This option was investigated with only a discrete set of five coils for plasma triangularities (0.31 to 0.52) and elongation (1.55 to 1.80). It is possible to achieve higher plasma triangularity (~0.5), but the discontinuous scrape-off flux surfaces are generated in the top and bottom regions. This hybrid configuration can possibly be used for providing a divertor action at higher plasma triangularity.

PF System Cost

PF system cost and other related parameters (total ampere-turns, ampere-meters of conductor, stored energy in the magnets, and volt-seconds delivered to the plasma) are all calculated by utilizing computer codes and the cost algorithm is described in Reference [2].

The PF system cost and volt-seconds are calculated on the basis of a current ramp from zero to the nominal value of current in each coil in 30 s (the ramp rate is generally not the same for all the coils). The PF system costs presented in this section should, therefore, only be used for comparing alternate PF configurations. More meaningful cost numbers are generated with the FEDC Systems Code.

The PF system cost dependence on the plasma triangularity δ with discrete external, internal, and hybrid coils is shown in Fig. 5. The cost of all external PF system increases rapidly, as compared to the internal PF coils, as a function of triangularity. This is because the internal coils are relatively closer to the plasma and are more effective as compared to the external coils for shaping the plasma. The hybrid PF system cost is not strongly impacted by the triangularity in the range of ~0.3 to 0.5. This may be related to the fact that the plasma elongation was not constrained in these iterations. The external PF system is most costly.

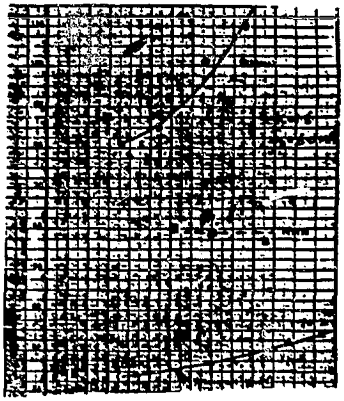

Fig. 5.

The PF system cost (comprising of coil cost, power supply cost, and MG set cost) versus total ampere-turn-meters of the conductor is shown in Fig. 6. It is evident from this figure that the PF system (coils + power supplies + MG sets) cost is linearly dependent on the total ampere-meters of the conductor. This indicates that the PF system cost should be optimized [2] on the basis of total ampere-turn-meters of the conductor, rather than the total currents (MA-turns) in the coils. The coil cost is the most dominant component (see Fig. 6). Replacing a large number of coils carrying similar currents by a smaller set of coils reduces the coil cost but increases power supply cost with negligible change in total cost.

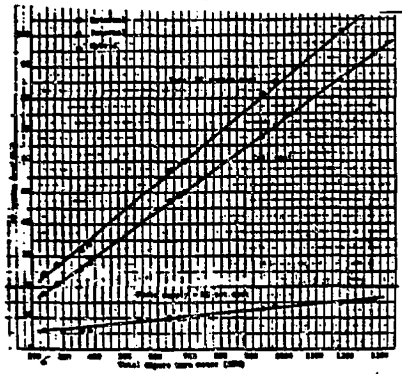

Fig 6.

Discussion

The main difficulty in designing for a plasma triangularity greater than ~0.3 with any configuration (external, internal, and hybrid) is the discontinuity in the scrape-off flux surface for high plasma triangularities (~0.5 to 0.7). This discontinuity in the scrape-off flux surface could be accommodated by providing two limiters or divertors, one in the top and one in the bottom regions of the plasma. However, double-null limiter concept cannot be accommodated in the present TFCX configurational space.

On the basis of this trade study, the plasma triangularity and elongation were limited to 0.30 and 1.6, respectively, for TFCX using external PF coils. The following section provides a description of PF coil configurations for TFCX with these limitations.

PF Configuration for TFCX-S

The TFCX-S plasma requirements are listed in Table 2 for the beginning (t = 40 s) and the end (340 s) of the burn period (300 s). The PF coils are located symmetrically with respect to the plasma as shown in Fig. 7. Coil nomenclature and numbering scheme is also shown in the figure. Each coil cross section is proportional to the current in the coil. The PF coil locations, currents, volt-seconds contributed by each coil, are given in Table 3 at t = 40 s and t = 340 s.

Table X. TFCX-S at 10 T: Plasma Parameters

Parameter	t = 40 s	t = 340 s
Major radius	3.750 m	3.751 m
Minor radius	1.070 m	1.071 m
Beta (volume averaged)	6.096%	6.063%
Plasma current	7.700 MA	7.700 MA
Field on axis	4.339 T	4.339 T
Safety factor (axis)	0.951	0.955
Elongation	1.599	1.600
Upper triangularity	0.299	0.305
Lower triangularity	0.299	0.305
Closed scrapeoff inner thickness	7 cm	7 cm
Closed scrapeoff outer thickness	3 cm	4 cm
Volt-seconds required	17.1	
Loop voltage	0.057 V	

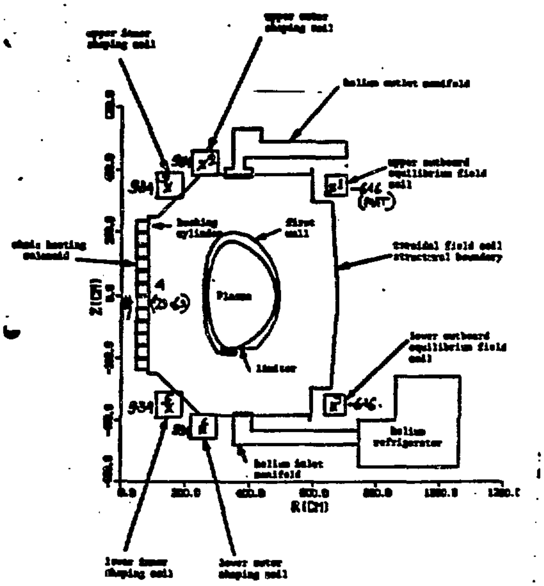

Fig. X. TFCX-S at 10 T: Configuration and PF Coil Numbering Scheme (MA)

Fig. 7.

Coil	Coil Location		Ampere-Turns (MA)		Volt-seconds (V-s)		
	Mean Radius R_n (m)	Mean Height from Plasma Axis Z_n (m)	t = 40 s (Start of burn)	t = 340 s (End of burn)	t = 40 s (Start of burn)	t = 340 s (End of burn)	Δt = 300 s Provided during burn
[illegible]	1.900	3.900	0.34	5.00	4.31	2.31	-2.00
[illegible]	1.900	-3.900	0.34	5.00	4.31	2.31	-2.00
[illegible]	2.600	4.200	9.34	8.26	8.91	7.88	-1.03
[illegible]	2.600	-4.250	9.34	8.26	8.91	7.88	-1.03
[illegible]	6.700	3.500	-6.16	-6.46	-10.43	-19.31	-8.88
[illegible]	6.700	-3.500	-6.16	-6.46	-10.43	-19.31	-8.88
[illegible]	0.660	Z	23.62	-28.37	4.42	-3.30	-9.72
Sum of absolute currents			73.30	67.79			
Total volt-seconds					-5.90	-23.54	-17.53

Z Equal current centers at Z_n = ±0.200, ±0.600, ±1.000, ±1.400, ±1.800, ±2.200.

The ohmic heating (OH) central solenoid provides sufficient volt-seconds in conjunction with other PF coils for a 300-s burn. The central solenoid provides more than half of the total volt-seconds needed and the remaining volt-seconds are contributed by the shaping and equilibrium field (EF) coils (Table 3). The peak field is 8 T at the central solenoid and the shaping coils (#3 through #5). Peak field at the remaining coils is <8 T.

The current waveforms for all the PF coils are shown in Fig. 8 for the entire pulse cycle period. The ohmic heating solenoid is charged to 20.64 MA in 30 s (i.e., -30 s to 0 s) prior to plasma current initiation and startup. The solenoid current is maintained at this level during rf startup (0 to 30 s). The solenoid current is increased to 23.62 MA during the heating phase (30 to 40 s), to compensate for the resistive losses in the plasma. The solenoid current is changed from +23.62 MA to -28.37 MA during the burn period (40 s to 340 s) to provide required volt-seconds for the 300-s burn. The currents in the remaining coils are ramped from zero to their peak value in 40 s. All PF coils are discharged to zero in 30 s (t = 340 to 370 s) at the end of the burn phase.

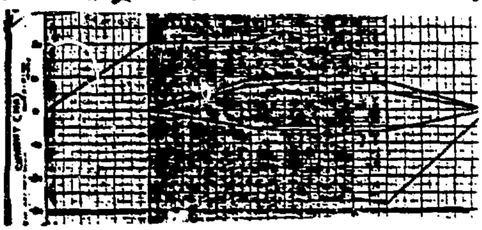

Fig. 8.

Equilibrium flux surfaces at the beginning and end of the burn are shown in Fig. 9. The plasma boundary is defined by the flux lines closing on themselves. The closed flux surfaces shown by dotted lines define the plasma scrape-off region (~7 cm in the inboard and ~4 cm on the outboard to the plasma). Scrape-off is needed for impurity removal.

This PF coil configuration discussed above satisfies the plasma performance requirements and is consistent with mechanical system integration (Fig. 7) and maintenance requirements, with the exception of the lower outboard equilibrium field (#7) coil. This coil is trapped under the TF coils. If this coil fails, it would be difficult to replace (the replacement time could be long). If the coil #7 fails during

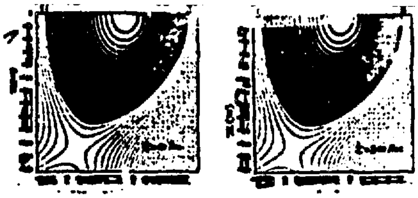

Fig. 9.

the life of the machine, it is proposed to be replaced with a larger-radius coil. This new coil will satisfy all requirements except the plasma triangularity — it would be reduced to ~0.25 instead of 0.30, as in the baseline.

TF Configuration for TFCX-H

The plasma requirements for this case are listed in Table 4 for the beginning (t = 40 s) and the end (t = 340 s) of the burn period (300 s). The midplane of the plasma is offset by 15 cm vertically above the horizontal midplane of the TF coils for effective utilization of the space inside the TF coil bore and for satisfying the mechanical system integration requirements. The PF coils are located asymmetrically with respect to the plasma as shown in (Fig. 10). The PF coil locations, currents, and volt-seconds contributed by each coil at t = 40 s and t = 340 s are given in Table 5. The coil nomenclature and numbering scheme is the same as in Fig. 7 for TFCX-S.

Table 4. TFCX-H at 8 T: Plasma Parameters

Parameter	t = 40 s	t = 340 s
Major radius, m	3.600	3.600
Minor radius, m	0.970	0.970
Beta (volume averaged), %	5.294	5.274
Plasma current, MA-turns	7.231	7.231
Field on-axis, T	4.84	4.84
Safety factor (axis)	0.971	0.975
Safety factor (edge)	1.964	1.973
Elongation	1.599	1.600
Upper triangularity	0.298	0.296
Lower triangularity	0.297	0.296
Closed scrapeoff inner thickness, cm	6	6
Closed scrapeoff outer thickness, cm	3	4
Volt-seconds required		28.9
Loop voltage		0.063

The ohmic heating (OH) central solenoid located inside the bucking cylinder has no current at t = 40 s and has -30.24 MA at t = 340 s. The solenoid is sized to provide the required volt-seconds for obtaining a 300-s burn. As before, the central solenoid provides more than half of the total volt-seconds requirement and the remaining volt-seconds are provided by the shaping and equilibrium field coils (see Table 5). The peak field on the central solenoid and the shaping coils (#3 to #5) is ~8 T, whereas the rest of the coils have peak fields <8 T.

The time variation of currents in all the PF coils is shown in Fig. 11 for the entire pulse cycle. The ohmic heating solenoid is charged from 0 to -1.98 MA prior to plasma current initiation (-30 to 0 s) and kept at this level of current during plasma startup (0

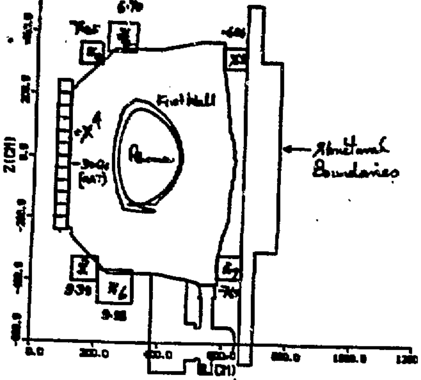

Fig. 10

Table 5. TFCX-H at 8 T — Coil Locations and Currents

Coil	Coil Location: Mean Radius R_m (m)	Coil Location: Mean Height from Plasma Axis Z_m (m)	Ampere Turns (MAT): t = 40 s (Start of burn)	Ampere Turns (MAT): t = 340 s (End of burn)	Volt-seconds (V-s): t = 40 s (Start of burn)	Volt-seconds (V-s): t = 340 s (End of burn)	Volt-seconds (V-s): Δt = 300 s Provided during burn
3 X	1.700	3.300	7.05	2.75	4.36	1.70	-2.66
5 X	1.700	-3.640	9.39	2.75	5.05	1.48	-3.57
2 X	2.650	3.850	7.05	6.70	7.64	7.26	-0.38
6 X	2.650	-4.190	9.39	9.98	8.06	9.41	0.55
1 X	6.230	3.200	-5.85	-6.26	-17.42	-18.63	-1.21
7 X	6.230	-3.540	-7.25	-7.69	-19.81	-21.02	-1.21
9 X	0.900	a	0.00	-30.24	0.00	-10.93	-10.93
Sum of absolute currents			45.98	66.36			
Total volt-seconds					-11.52	-30.73	

(a) Equal Current Centers at Z_m = ±0.200, ±0.600, ±1.000, ±1.400, ±1.800, ±2.200.

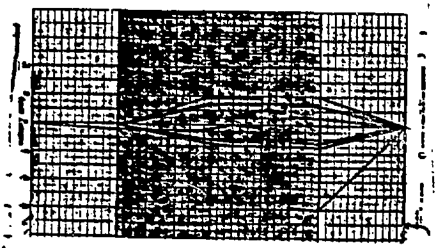

Fig. 11.

(0 to 30 s). The solenoid current is brought to zero level during plasma heating phase (30 to 40 s) to compensate for the resistive losses in the plasma. All PF coils are discharged to zero current in 30 s (t = 340 to 370 s) at the end of the burn phase.

Equilibrium flux surfaces at the beginning and end of the burn are shown in Fig. 12. The continuous scrape-off layer thicknesses are ~6 cm and ~4 cm inboard and outboard to the plasma, respectively. These dimensions of the continuous scrape-off layer thicknesses are used for the limiter design.

Fig. 12

Conclusions

This study has shown that for the TFCX device, the plasma elongation is limited to 1.6 and triangularity is limited to 0.3. Adequate continuous scrape-off thickness can be provided for impurity removal. PF coil configurations developed for TFCX-S and TFCX-H are consistent with plasma, mechanical system integration, and maintenance requirements.

References

[1] D. J. Strickler and Y-K. M. Peng, "Poloidal Field Coil System of the Fusion Engineering Device," in Proceedings of the 9th Symposium on Engineering Problems of Fusion Research, p. 515, 1981.

[2] V. C. Srivastava and S. S. Kalsi, "A Unified Study for Determining Poloidal Field Location for a Tokamak," Presented at the Fifth Topical Meeting on Technology Fusion Energy, Knoxville, TN; published in Nuclear Technology/Fusion, vol. 4, p. 1357, 1983.

[3] V. C. Srivastava, "PF Coil Distribution Study for TFCX," FEDC Report, FEDC-R-83-E/M-006, 1983.

[4] C. A. Flanagan, "TFCX Document," Fusion Engineering Design Center, Oak Ridge National Laboratory (to be published).

TFCX ??

Fusion Engineering Design Center, Oak Ridge National Laboratory

Fig. 1. Plasma triangularity vs ampere-turns in PF coils with idealized and discrete PF distribution for $\underline{K} = 1.6$.

Fig. 2. Equilibrium Flux (??) Surfaces (??) with the same elongation ($K = 1.6$) and triangularity ($\delta = 0.38$), but different details of the plasma boundary shape.

Fig. 3. Plasma elongation dependence on ampere-turns needed for PF coils with triangularity $\delta = 0.7$.

Fig. 4. Plasma triangularity vs total ampere-turns needed with internal idealized and discrete PF coils for plasma elongation of 1.6.

Fig. 5. — Relative Cost Variation of PF System With External, Hybrid, and Internal discrete PF Coils.

Fig. 6 PF system cost vs total ampere-turns-meters of conductor. ??

Fig. 7. TFCX-S at 10 T @ Coil locations and currents.

Fig. 8. TFCX-S at 10 T @ Poloidal current waveforms.

Fig. 9. Equilibrium flux surfaces at the beginning ($t = 40$ s) and end ($t = 340$ s) of burn for TFCX-S.

Fig. 10. TFCX-H at 8 T @ PF configuration, numbering scheme, and structural boundaries with maximum currents in the coils.

Fig. 11. TFCX-H at 8 T @ Poloidal coil Current Waveforms.

Fig. 12. Equilibrium flux surfaces at the beginning ($t = 40$ s) of burn for TFCX-H.

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