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A Cost-Performance Evaluation of the Use of a 10 T Central Solenoid in INTOR

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A reference INTOR design has a central solenoid with a nominal peak flux density of 8 T, and an inductive burn capability of 200 s. Each central solenoid module is constructed using 50 kA superconducting NbTi cables. It has been suggested, but not recommended, that the burn time could be increased by swinging the OH solenoid from 10 T to - 10 T, using higher field Nb_3Sn superconductor. This study adopts a simple comparison method in order to discover whether performance measures such as volt-seconds and burn time improve faster than cost figures increase.

The simplest method available for such a comparison was to adopt a fixed scenario from a previous INTOR study and a fixed set of winding pack envelopes, and explore the feasibility of increasing the peak flux density to 10 T by increasing the peak current in the central solenoid. In the 8 T option all eleven of the winding packs were modeled as using NbTi, while all of them were modeled as using Nb_3Sn in the 10 T option. This modelling decision doesn't affect the basic tradeoff, and was done only to generate more information.

The conductor design approach was to use the two best characterized internal cable-in-conduit conductors for the two options: the Westinghouse LCP, bronze method, 486 × 0.7 mm strand conductor is used for the Nb_3Sn option and a 2,000 strand × 0.3 mm strand conductor is used for the NbTi option. The Nb_3Sn conductor design is used in the Westinghouse LCP design, the M.I.T./HFTF 12 T Coil design and in the TF system of Alcator DCT [SC83]. The NbTi strands are Fermicable strands, the mass quantity strand design used in American particle accelerators and commercially. The specific ICCS cable-in-conduit design is used in the Alcator DCT PF system design [SC83], the Alcator DCT TF insert design and in the design of the NbTi option for TFCX [SC84]. This cable-in-conduit design is not a 50 kA conductor. Because the current densities for the INTOR design are relatively low, we specify winding four conductors in parallel, so that each conductor is carrying 12.5 kA, while the leads are carrying 50 kA. As will be seen, this gives an extremely conservative design, especially for all PF coils other than the central solenoid. However, the significant parameters that determine the validity of the tradeoff are independent of the specific conductor design approach, as will be seen below.

The positions of the coils, taken from Table of the INTOR Critical Issues Assessment [ST82] are shown in Table 1. The currents and peak fields are shown in Table 2 and Table 3. The ampere-turn scenario is taken from Tables IX.2-23 and IX.2-25B in the INTOR Critical Issues document [ST82]. To the best of our knowledge, these tables constitute the only fully specified poloidal field/plasma scenario for INTOR. A 360 ms plasma initiation period is adopted from Table XVI-4. Disruption simulation is based on the electromagnetic model in the electromagnetics section of the Critical Issues document [ST82]. The only change made in the scenario is that the central solenoid, PF Coil 6 in the tables, is swung from -28 kA to -50 kA between 11 s and 211 s, instead of to -29 kA. The published current swing for coil 6 drives volt-seconds during burn in the wrong direction (i.e. it would drive the current down). A double-swung central solenoid is typical, as is the use of the central solenoid to cancel the resistive electric field in the plasma during burn. Also, the double-swing is technically feasible and does not increase the peak field in the winding over the worst field with the partial field. (Notice that the peak field is actually 8.46 T, not 8.0 T, whether the conductor is swung to - 29 kA or - 50 kA.) Thus, it seems clear that the published current of Coil 6 at 211 s represents a correctable error. When the coil is swung to - 50 kA, 13 V-s are available for the 200 s burn phase, as shown in Table 4. This would correspond to a burn voltage of 1/15.4 V, which is sufficiently close to the 1/20 V calculated. When the current in the conductor is increased to 15 kA (60 kA leads), the amp-turn swing in coil 6 increases from ± 60.2 MAT to ± 72.2 MAT, the peak flux density at the winding, during the course of the scenario, increases from 8.46 T to 10.1 T, and the available volt-seconds during burn increases from 13 V-s to 30 V-s. If 13 V-s represents a 200 s burn, 30 V-s would permit a 460 s burn. Thus, the benefit of increasing the current in the central solenoid by 20 % is to increase the total volt-second swing of the PF system by 15 % and the burn time by 130 %. If the plasma were dirtier than expected and required 15 % more volt-seconds to get established than required, the additional 17 V-s would make the difference between a long burn and no burn.

The original 8 T design, even though it was really 8.46 T, still has an adequate design margin. The maximum fraction of critical current in the conductor is only 0.44, as shown in Table 6. In a simple, free-standing solenoid, design values of 0.7 critical current are common. For the Nb_3Sn coil at 10.1 T, the maximum fraction of critical current is only 0.383. In a simple solenoid, design values of 0.5 critical current are common, though this should increase as the strain-sensitivity of Nb_3Sn in a conduit becomes well characterized by the U.S. conductor development program [MO84]. For the NbTi at 8.4 T, the energy margin vs. a disturbance, such as initiation or disruption, is 536 mJ/cc, as shown in Table 8. This is typical of the TF and PF designs for Alcator DCT and TFCX. For the Nb_3Sn at 10.1 T, the energy margin is 3,380 mJ/cc, which is extremely conservative. Notice that the outlet temperature of the coils was held at 4.0 K in all of the energy margin analyses. This corresponds to the outlet conditions of the TORE

SUPRA Upgrade coils, and represents a degree of helium subcooling in a forced circulation loop which is about the maximum feasible without significant cost penalties. For a real design, the high energy margins indicate that the outlet temperatures for all of the Nb_3Sn coils should be at least 5.3 K, as in the TFCX PF coils. The NbTi PF6 coil has a current-sharing temperature of 4.7 K. An outlet temperature of 4.3 K with reduced energy margin may be a favorable trade for the NbTi coils.

If the PF6 coils were run as a single coil, without modularization, the peak terminal voltage during initiation would be 125 kV for the nominal 8 T option, as shown in Table 10, and -151 kV for the nominal 10 T option, as shown in Table 11. Even for ICCS conductor, which has an individual ground wrap around each turn, the terminal voltage should be limited to 15-20 kV. This means that the 10 T option would require another 1-2 pairs of 50 kA cryogenic current leads and another 1-2 50 kA power supplies. If the voltage were limited to 17 kV, the 8 T design would require 22 power supplies and lead pairs, while the nominal 10 T design would require 24 power supplies and lead pairs, for an increase of 9 %. The additional lead pairs would correspond to the equivalent of an additional 1 kW of helium refrigeration at 4.2 K.

The pulsed loss generation from initiation is more severe than either a current-conserving (constant current, third column) or a flux-conserving (constant terminal voltage, fourth column) disruption in the present scenario, as shown in Tables 12 and 13. For the most conservative possible assumption, that no heat at all is removed during a cycle, the safety margin, expressed as the ratio of the energy margin to the pulsed energy deposited during a cycle ending in disruption is a factor of 9 in the NbTi PF6 and a factor of 35 in the Nb_3Sn coil. Alcator DCT and TFCX attempted to design to safety margins of 10. The large factor was considered appropriate, since it represented the product of moderately large uncertainties in both the superconductor and plasma behaviour. Both PF6 designs for INTOR have adequate margins against initiation and disruption.

The average stress in the PF coils were calculated, using a homogeneous, anisotropic model, making no assumptions about the particular structural support concept to be used. The results are shown in Tables 14 and 15. The radial stress in the PF6 coil increased by 44 %, while the axial stress increased by 53 %, indicating a probable increase in the cost of structure for PF6 of about 50 %. If the combined membrane stress in the conductor conduits were to be held to 250 MPa to meet fatigue criteria, the stress multiplier would have to be limited to 2.2, which is fairly low for a typical PF coil. However, since the conductor envelopes are only taking up 66 % of the available winding pack area in this design, a considerable volume of cowound strip or conduit thickening is permissible. There is also a moderate amount of volume on the outside for a steel case and a large amount of available volume on the inside of a column to hold axial support shelves. Therefore, without doing a detailed structural design, the 10 T option appears to be feasible.

Two cost figures for superconducting coils that appear in the 1984 Cost Specification for the Preconceptual TFCX Design Report [PP84] are the ampere-meter product, which is proportional to the winding cost, and the ampere-meter-peak field product, which is proportional to the cost of a well designed superconductor. The cost of structure is not, strictly speaking, proportional to either, but dimensionally scales more closely with the ampere-meter-field product. The 10 T option increases the ampere-meter total cost figure for the poloidal field system by 3 %, as shown in Tables 16 and 17. The ampere-meter-field total cost figure for the poloidal field system is increased by 9 %.

Conclusions

The change from a nominal 8 T to a nominal 10 T system has a second-order effect on both the volt-second capability of the poloidal field system and the costs associated with it. By contrast, there is a first-order increase in the burn time, under the reference scenario. This has to be tempered in two directions. On the one hand, the value of the machine mission may be a slow function of burn time (i.e. doubling the burn time does not double the value of the experiment). On the other hand, the risk associated with losing all of the burn time due to a relatively small change in the plasma impurity level must be substantially reduced with the buffer of an additional 17 V-s. Since the effect on the overall machine cost must be third-order, the 10 T option appears to be favored.

References

[MO84] D.B. Montgomery, "Superconductor qualification program for TFCX and Alcator DCT magnetic systems", Appl Supercond Conf, San Diego, CA, Sept 1984

[PP84] Princeton Plasma Physics Laboratory, TFCX Group, "Cost Specification: Addendum to the Preconceptual Design Report", Revision 2, June 22, 1984

[SC83] J.H. Schultz, "Stabilization and cooling requirements for the Alcator DCT superconducting magnet system", 10th Symp Eng Fus Research, Philadelphia, PA, Dec 1983

[SC84] J.H. Schultz, "Poloidal field system for TFCX", Appl SupercondConf, San Diego, CA, Sept 1984

[ST82] W.M. Stacey et al, "Critical issues for FED and INTOR", U.S. FED-INTOR Activity and U.S. contribution to the International Tokamak Reactor Phase-2A Workshop USA FED-INTOR/82-1, Oct 1982

Table 1

PF System Winding Pack Dimensions for INTOR:

Nominal 8 T Option

Coil	R (m)	Z (m)	R_1 (m)	R_2 (m)	Z_1 (m)	Z_2
PF1	10.000	4.800	9.701	10.299	4.502	5.099
PF2	6.450	5.450	6.167	6.733	5.167	5.733
PF3	3.550	5.450	3.299	3.802	5.198	5.701
PF4	2.250	4.450	2.168	2.332	4.368	4.531
PF5	1.350	4.600	1.074	1.627	4.324	4.877
PF6	1.350	0.000	1.117	1.584	-4.280	4.280
PF7	1.350	-4.600	1.074	1.627	-4.877	-4.324
PF8	2.250	-5.850	2.016	2.484	-6.084	-5.615
PF9	3.200	-6.850	2.726	3.674	-7.325	-6.375
PF10	6.000	-6.850	5.547	6.453	-7.303	-6.397
PF11	12.350	-5.500	11.809	12.891	-6.041	-4.959

Table 2

PF System Current and Winding Parameters for INTOR:

Nominal 8 T Option

Coil	I_{max}	B_{max}	n_{turns}	$I_{cond.max}$
	(MAT)	(T)	()	(kA)
PF1	5.35	3.820	428	12.5
PF2	4.80	3.526	384	12.5
PF3	3.80	3.088	304	12.5
PF4	0.40	1.843	32	12.5
PF5	4.58	4.906	368	12.5
PF6	60.18	8.456	4800	12.5
PF7	4.58	5.370	368	12.5
PF8	3.30	4.659	264	12.5
PF9	13.50	6.996	1080	12.5
PF10	12.30	4.932	984	12.5
PF11	17.57	6.805	1408	12.5

Table 3

PF System Current and Winding Parameters for INTOR:

Nominal 10 T Option

Coil	I_{max}	B_{max}	n_{turns}	$I_{cond.max}$
	(MAT)	(T)	()	(kA)
PF1	5.350	3.818	428.0	12.500
PF2	4.800	3.525	384.0	12.500
PF3	3.800	3.078	304.0	12.500
PF4	0.400	1.939	32.0	12.500
PF5	4.580	5.705	368.0	12.446
PF6	72.214	10.147	4800.0	15.045
PF7	4.580	5.718	368.0	12.446
PF8	3.300	4.621	264.0	12.500
PF9	13.500	6.976	1080.0	12.500
PF10	12.300	4.933	984.0	12.500
PF11	17.570	6.804	1408.0	12.479

Table 4

Volt-second Contributions of Each PF Coil: Nominal 8 T Option

Coil	$VS_{end,start-up}$ (V-S)	$VS_{end,flattop}$ (V-S)
PF1	-21.169	-21.169
PF2	9.965	14.655
PF3	4.471	4.471
PF4	0.000	0.000
PF5	-0.079	-0.079
PF6	-66.907	-84.606
PF7	-0.079	-0.079
PF8	0.000	0.000
PF9	10.438	10.438
PF10	21.173	21.173
PF11	-59.304	-59.304
Total	-101.491	-114.501

Table 5

Volt-second Contributions of Each PF Coil: Nominal 10 T Option

Coil	$VS_{end,start-up}$ (V-S)	$VS_{end,flattop}$ (V-S)
PF1	-21.169	-21.169
PF2	9.965	14.655
PF3	4.471	4.471
PF4	0.000	0.000
PF5	-0.079	-0.079
PF6	-66.907	-101.528
PF7	-0.079	-0.079
PF8	0.000	0.000
PF9	10.438	10.438
PF10	21.173	21.173
PF11	-59.304	-59.304
Total	-101.491	-131.422

Table 6

Minimum Fractions of Critical Current Density in the INTOR PF Coils:
Nominal 8 T Option

Coil	B_{max} (T)	T_{max} (K)	J_{noncu} (A/mm^2)	$J_{c,min}$ (A/mm^2)	$f_{crit,max}$
PF1	3.820	4.000	223.722	1580.859	0.142
PF2	3.526	4.000	223.722	1668.006	0.134
PF3	3.088	4.000	223.722	1830.076	0.122
PF4	1.843	4.000	223.722	2500.223	0.089
PF5	4.906	4.000	222.750	1326.477	0.168
PF6	8.456	4.000	224.388	505.275	0.444
PF7	5.370	4.000	222.750	1219.115	0.183
PF8	4.659	4.000	223.722	1383.655	0.162
PF9	6.996	4.000	223.722	843.049	0.265
PF10	4.932	4.000	223.722	1320.456	0.169
PF11	6.805	4.000	223.341	887.200	0.252

Table 7

Minimum Fractions of Critical Current Density in the INTOR PF Coils
Nominal 10 T Option

Coil	B_{max} (T)	T_{max} (K)	J_{noncu} (A/mm^2)	$J_{c,min}$ (A/mm^2)	$f_{crit,max}$
PF1	3.818	4.000	185.646	1740.984	0.107
PF2	3.525	4.000	185.646	1848.441	0.100
PF3	3.078	4.000	185.646	2028.151	0.092
PF4	1.939	4.000	185.646	2585.395	0.072
PF5	5.705	4.000	184.839	1204.038	0.154
PF6	10.147	4.000	223.438	583.350	0.383
PF7	5.718	4.000	184.839	1201.199	0.154
PF8	4.621	4.000	185.646	1482.371	0.125
PF9	6.976	4.000	185.646	958.047	0.194
PF10	4.933	4.000	185.646	1394.535	0.133
PF11	6.804	4.000	185.329	987.113	0.188

Table 8

Minimum Available Enthalpies of PF Conductors: Nominal 8 T Option

Coil	$T_{c,min}$ (K)	$T_{cs,min}$ (K)	$\Delta H_{he,min}$ (Const D) (mJ/cc)
PF1	7.431	6.945	2257.471
PF2	7.563	7.085	2376.118
PF3	7.760	7.301	2559.706
PF4	8.378	7.987	3150.749
PF5	6.942	6.448	1838.909
PF6	5.327	4.737	536.171
PF7	6.752	6.249	1672.869
PF8	7.054	6.560	1932.479
PF9	6.102	5.544	1091.055
PF10	6.931	6.434	1827.204
PF11	6.178	5.630	1161.502

Table 9

Minimum Available Enthalpies of PF Conductors: Nominal 10 T Option

Coil	$T_{c,min}$ (K)	$T_{cs,min}$ (K)	$\Delta H_{he,min}$ (Const D) (mJ/cc)
PF1	15.137	13.949	8549.484
PF2	15.356	14.216	8797.061
PF3	15.691	14.621	9174.495
PF4	16.546	15.645	10129.706
PF5	13.721	12.229	6959.500
PF6	10.890	8.251	3380.760
PF7	13.712	12.217	6948.845
PF8	14.535	13.215	7869.181
PF9	12.768	11.069	5898.692
PF10	14.300	12.929	7604.440
PF11	12.897	11.227	6042.151

Table 10

Peak Currents and Voltages on PF Coils: Nominal 8 T Option

Coil	$I_{lead.max}$ (kA)	$I_{lead.min}$ (kA)	$V_{term.max}$ (kV)	$V_{term.min}$ (kV)
PF1	0.000	-50.000	4.675	-5.792
PF2	50.000	0.000	29.367	-1.673
PF3	50.000	0.000	3.405	-0.482
PF4	50.000	0.000	0.032	-0.021
PF5	49.783	-2.987	0.338	-0.253
PF6	50.149	-50.149	7.091	-125.524
PF7	49.783	-2.987	0.378	-0.233
PF8	50.000	0.000	0.644	-0.449
PF9	50.000	0.000	4.282	-5.613
PF10	50.000	0.000	11.384	-6.623
PF11	0.000	-49.915	48.536	-70.782

Table 11

Peak Currents and Voltages on PF Coils: Nominal 10 T Option

Coil	$I_{lead.max}$ (kA)	$I_{lead.min}$ (kA)	$V_{term.max}$ (kV)	$V_{term.min}$ (kV)
PF1	0.000	-50.000	4.731	-5.833
PF2	50.000	0.000	28.578	-1.708
PF3	50.000	0.000	3.003	-0.458
PF4	50.000	0.000	0.016	-0.021
PF5	49.783	-2.987	0.244	-0.254
PF6	60.179	-60.179	8.658	-151.650
PF7	49.783	-2.987	0.371	-0.233
PF8	50.000	0.000	0.637	-0.440
PF9	50.000	0.000	4.087	-5.568
PF10	50.000	0.000	9.994	-6.539
PF11	0.000	-49.915	48.693	-73.397

Table 12

Worst Case Local Energy Depositions in Winding: Nominal 8 T Option

Coil	Cycle Energy (mJ/cm^3)	Initiation (mJ/cm^3)	Disruption (mJ/cm^3)	FCT Disruption (mJ/cm^3)
PF1	17.915	1.308	0.157	0.621
PF2	21.410	7.680	0.362	1.016
PF3	15.013	1.412	0.542	0.789
PF4	11.593	1.241	0.123	0.955
PF5	34.686	12.306	0.655	0.735
PF6	62.395	33.072	2.010	1.857
PF7	36.602	13.626	0.577	0.595
PF8	17.485	1.117	0.300	0.191
PF9	27.894	0.513	0.368	0.279
PF10	21.494	1.225	0.249	0.543
PF11	27.730	1.492	0.077	0.281

Table 13

Worst Case Local Energy Depositions in Winding: Nominal 10 T Option

Coil	Cycle Energy (mJ/cm^3)	Initiation (mJ/cm^3)	Disruption (mJ/cm^3)	FCT Disruption (mJ/cm^3)
PF1	21.979	1.463	0.217	0.729
PF2	25.445	7.584	0.389	1.252
PF3	17.186	15.065	0.642	0.901
PF4	13.478	1.401	0.145	1.103
PF5	39.367	14.496	0.732	0.854
PF6	92.031	45.142	2.690	2.428
PF7	40.626	15.666	0.631	0.750
PF8	19.791	1.451	0.498	0.1723
PF9	31.688	0.696	0.406	0.288
PF10	21.110	1.221	0.334	0.516
PF11	27.900	1.443	0.129	0.335

Table 14

Average Stresses in PF Coils, Homogeneous, Anisotropic Model: Nominal 8 T Option

Coil	$\sigma_{av.T}$ (MPa)	$\sigma_{av.Z}$ (MPa)
PF1	108.835	-0.898
PF2	29.851	0.577
PF3	28.573	0.966
PF4	19.532	1.414
PF5	26.748	6.664
PF6	70.849	11.195
PF7	43.369	-9.024
PF8	89.035	-2.915
PF9	115.654	-1.280
PF10	0.151	-0.743
PF11	174.191	0.708

Table 15

Average Stresses in PF Coils, Homogeneous, Anisotropic Model: Nominal 10 T Option

Coil	$\sigma_{av.T}$ (MPa)	$\sigma_{av.Z}$ (MPa)
PF1	108.353	-0.927
PF2	29.851	0.667
PF3	27.770	1.206
PF4	19.267	1.581
PF5	22.221	7.928
PF6	102.022	13.831
PF7	38.542	-10.271
PF8	87.558	-3.123
PF9	114.738	-1.601
PF10	0.151	-0.859
PF11	173.985	0.730

Table 16

Cost Figures for Poloidal Field System: Nominal 8 T Option

Coil	Amp-m (MA-m)	Amp-m-T (MA-m-T)
PF1	336.150	1284.154
PF2	194.527	685.985
PF3	84.760	261.759
PF4	5.655	10.422
PF5	38.849	190.587
PF6	510.453	4316.300
PF7	38.849	208.618
PF8	46.653	217.340
PF9	271.434	1898.859
PF10	463.699	2286.913
PF11	1363.385	9277.571
Total	3354.415	20638.510

Table 17

Cost Figures for Poloidal Field System: Nominal 10 T Option

Coil	Amp-m (MA-m)	Amp-m-T (MA-m-T)
PF1	336.150	1283.326
PF2	194.527	685.754
PF3	84.760	260.917
PF4	5.655	10.966
PF5	38.849	221.636
PF6	612.543	6215.474
PF7	38.849	222.128
PF8	46.653	215.566
PF9	271.434	1893.450
PF10	463.699	2287.540
PF11	1363.385	9276.317
Total	3456.505	22573.076