PHYSICS OPTIMIZATION OF THE COMPACT IGNITION TOKAMAK (CIT)

W .T. Reiersen, J. A. Schmidt, Princeton Plasma Physics Laboratory
Princeton University
P. O. Box 451
Princeton, NJ 08543

D. B. Montgomery
Massachusetts Institute of Technology
175 Albany Street NW17/288
Cambridge, MA 02139

Abstract

The Compact Ignition Tokamak (CIT) is planned as the next major step in the U.S. fusion program. Its overall objective is to produce ignited plasma discharges. In order to realize this objective, plasma parameters must be established which are consistent with recognized theoretical and operational limits and which constitute the most cost effective path to ignition. Key parameters to be established include the plasma safety factor (q), elongation (κ), plasma current (I), toroidal field (B), and aspect ratio (A). Each of these parameters were considered in optimizing the present baseline wedged design. The CIT design team is presently developing a bucked design with enhanced plasma performance. A similar effort to optimize the bucked design is underway.

Optimization Procedure

The optimization procedure involved use of a systems code developed for CIT. The code features a 0-D plasma model which is used to evaluate plasma performance. Algorithms have been incorporated into the the systems code to evaluate stresses in the TF inner leg and central solenoid. These stress algorithms have been extensively checked against detailed structural analyses. Thermal and electrical properties for a wide range of materials have been built into the code for the calculation of peak temperatures, power, and energy requirements.

The first step in the optimization procedure is to fix limits on the minimum MHD safety factor (q) and maximum elongation (κ). Operating at reduced q is desirable because the plasma current can be increased without an increase in toroidal field or minor radius thereby improving performance. For CIT, a safety factor of 3.2 was chosen as the limit based on data which shows that the improvement in confinement with increased plasma current saturates at about q=3 for elongated plasmas. Also, operational difficulties with plasma disruptivity appear to be more severe with q<3 for elongated plasmas. Operating at increased elongation is desirable for the same reason as reduced q - the plasma current can be increased without an increase in toroidal field or minor radius although the vertical height of the machine must increase. The maximum elongation was set at 2 to minimize plasma control problems associated with the vertical instability.

Once the minimum safety factor and maximum elongation are established, the system code is used to determine a self-consistent set of design points based on physics performance and engineering constraints such as peak temperatures, stresses, and envelope requirements for the vacuum vessel, first wall, and gaps. Physics performance was evaluated using Kaye-All-Complex (KAC) scaling[1] where

$$\tau_E = .067\, M^{0.5}\, \kappa^{0.25}\, I^{0.85}\, n_{e,20}{}^{0.1}\, B^{0.3}\, a^{0.3}\, R^{0.85}\, P^{-0.5}$$

where M is the average atomic mass, I is the plasma current in MA and P is the input power to the plasma in MW. The line averaged electron density, $n_{e,20}$, is in units of 10^{20} / m^3 and equal to

$$n_{e,20} = 2B/Rq_{eng}$$

where $q_{eng} = 5a^2\kappa B/RI$. The volume averaged beta was limited to

$$<\beta> = 3\times10^{-8}\, I/ aB.$$

The fusion power was limited to 500 MW based on divertor temperature constraints. For the design points considered, the limitation on fusion power kept the operating beta well below the established limit. The flattop time was set at 5 s to allow sufficient time for the plasma to get to ignition and remain in the ignited state for several energy confinement times. The plasma rampup and rampdown times were fixed at 7.5 s to allow modest plasma current ramp rates and reasonable power requirements for the magnet systems.

The conductor assumed for both the TF inner leg and central solenoid was copper:Inconel laminate. The laminate composition was varied to allow stress and temperature limits to be simultaneously met, thereby providing the most efficient design. Preshot temperatures in the magnet systems were fixed at 80K allowing liquid nitrogen cooling. Peak temperatures in the magnet systems were held below 320K based on consideration of mechanical properties of the insulator and uncertainties associated with the coil protection systems. Average stresses in the TF inner leg were limited to 2/3 of the yield strength of the laminate calculated according to the parallel mixture rule. Average stresses in the central solenoid were limited to 1/2 of the yield strength of the laminate. The constraint on the central solenoid appears more severe because radially, the central solenoid is composed of multiple turns instead of the single turn found in the TF. Detailed analysis and testing indicates that at these stress levels, the TF inner leg and central solenoid should meet the performance objectives with an adequate margin of safety.

Once a self-consistent set of design points is established subject to these physics requirements and engineering constraints, a cost analysis is done to determine the minimum cost design. For this exercise, a relative cost for each system was derived from a detailed cost breakdown for the baseline wedged design. The relative cost for each system was then assumed to scale according to the scale factors listed in Table 1. The benefits and risks of choosing the minimum cost design are then assessed.

System	Relative Cost	Scale Factor
TF	0.164	TF Stored Energy
PF	0.075	$R_{oh}^2 \times a$
VV/FW/Divertor	0.059	R x a
ICRH	0.084	1
Diagnostics	0.070	1
I&C	0.011	1
Vacuum Pumping	0.013	1
Ex-Vessel R/M	0.026	1
In-Vessel R/M	0.036	R^2
Tritium Systems	0.025	1
Shielding	0.008	R
Cryogenic Systems	0.014	R^2
Facilities	0.116	R
Power	0.164	TF Stored Energy§
Assembly	0.066	R^2
Design Integration	0.030	1
Project Management	0.041	1
	1.000	

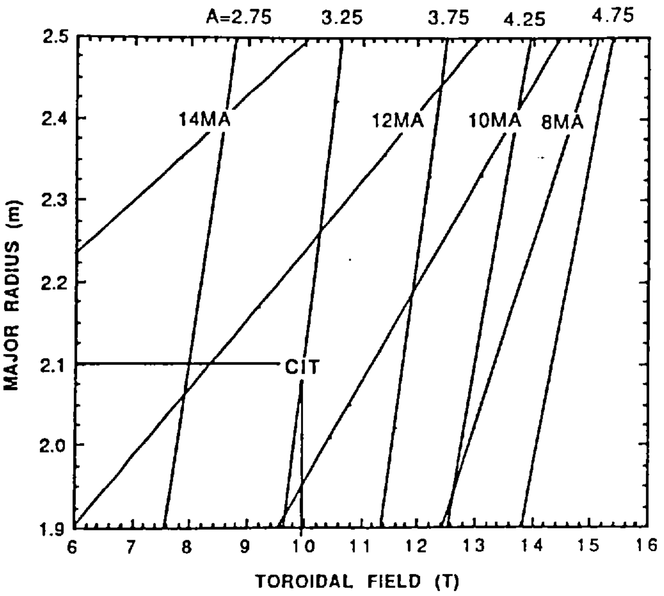
§ - The relative cost of power systems was scaled by $RC=RC_0\ [1.6 \times TFSE/TFSE_0 - 0.6]$ to reflect site credits

Table1 - Relative Cost and Scale Factors Used For Cost Analysis

Optimization of the Wedged Design

A map of the engineering design space was constructed using the systems code and is illustrated in Figure 1. The engineering design space represents possible design options for the wedged configuration. Parameters for the baseline wedged design are provided in Table 2.

Figure 1 - Map of Engineering Design Space for the Wedged Design



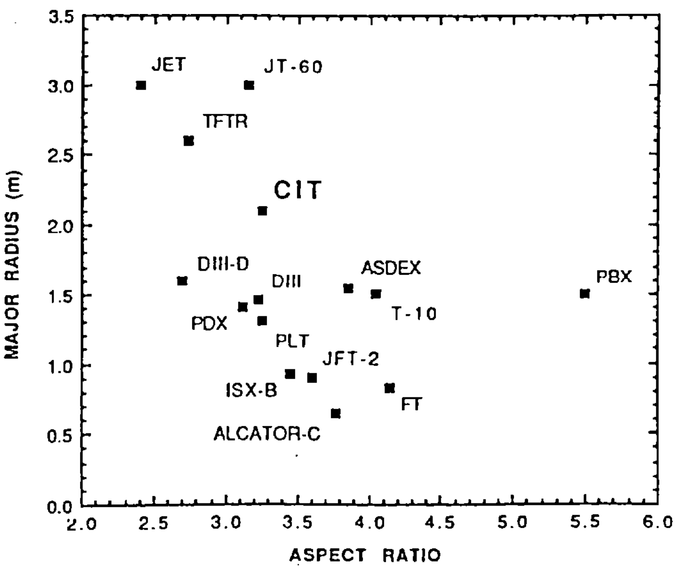
Parameter	Units	Wedged	Bucked
Major Radius	m	2.100	2.138
Minor Radius	m	0.646	0.662
Aspect Ratio		3.25	3.23
Elongation§		2.0	2.0
Safety Factor§		3.2	3.2
Plasma Current	MA	11.0	12.3
Toroidal Field	T	10.0	11.0

§ - For divertor plasmas, the elongation and safety factor are measured at the 95% flux surface

Table 2 - Plasma Parameters for the Baseline Wedged and Bucked Designs

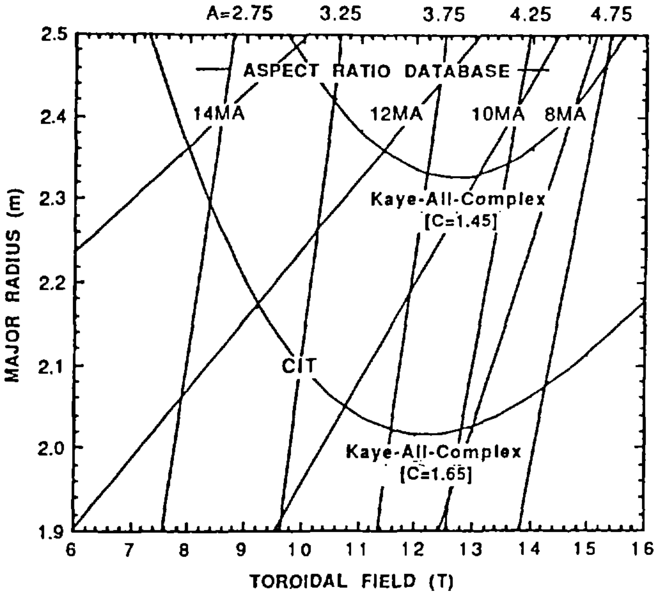
For the design options covered in Figure 1, the aspect ratio ranges from 2.5-5. Aspect ratios for existing machines cover approximately the same range as shown in Figure 2. However, much of the recent experimental data comes from the big machines (TFTR, JET, JT-60, and D-III-D) which all have low aspect ratios in the range of 2.5-3.2. The narrow band in aspect ratio from which the bulk of experimental data comes makes the statistical significance of aspect ratio in empirical scaling expressions low. The importance of this observation will be discussed later.

Figure 2 - Aspect Ratios in Experimental Database



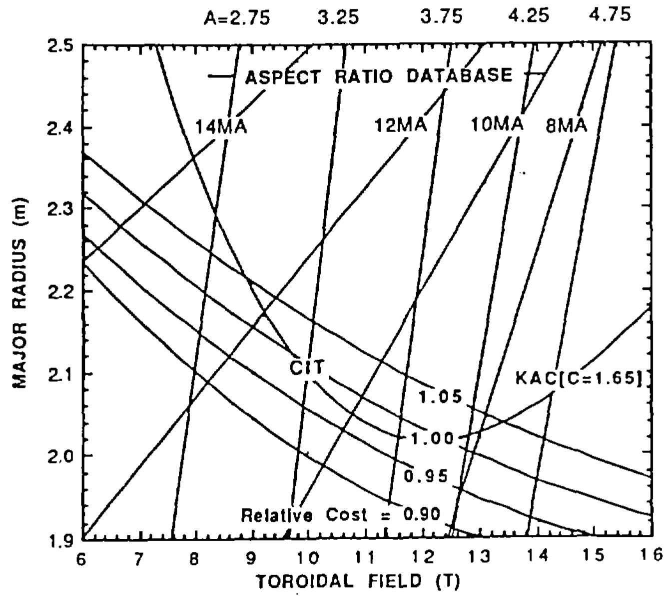
Plasma performance was evaluated assuming Kaye-All-Complex (KAC) scaling. This scaling is derived from what is believed to be the most extensive and current database of tokamak discharges. In order to achieve ignition with KAC scaling, the baseline wedged design requires a confinement enhancement of 1.65 over L-mode. This level of confinement enhancement over L-mode has been regularly achieved on JET and D-III-D H-mode discharges and on TFTR supershot discharges. Figure 3 shows contours of constant ignition margin given KAC scaling with confinement enhancement factors of 1.65 and 1.45. In order to decrease the confinement enhancement required for ignition from 1.65 to 1.45, an increase in major radius of at least 0.22 m would be required. It may also be seen in Figure 3 that assuming a confinement enhancement of 1.65 for ignition, the major radius can be decreased by almost 0.1 m by increasing the toroidal field to 12 T and reducing the plasma current to 9 MA. The aspect ratio of this device would be approximately 4. However, cost analysis indicates that the minimum major radius does not imply minimum cost.

Figure 3 - Constant Ignition Margin Contours (KAC Scaling)



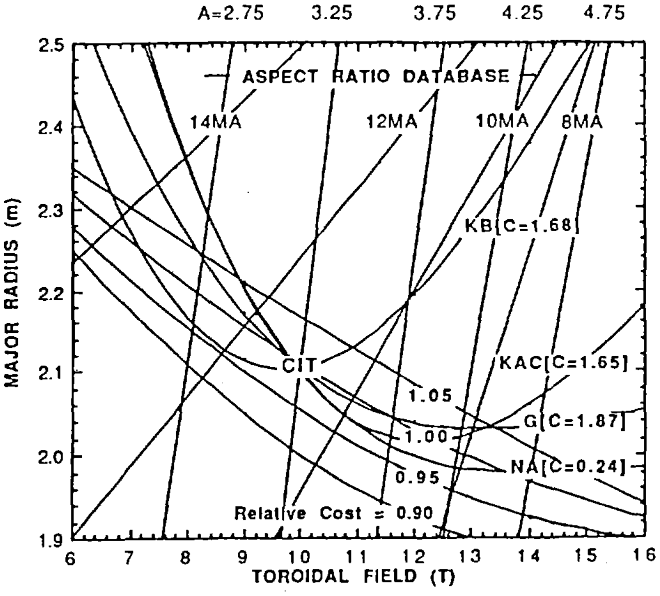
Contours of constant cost have been overlaid on the map of engineering space in Figure 4. The most cost effective design would be the one which has the minimum cost at fixed plasma performance. Evaluating plasma performance with KAC scaling, the optimum design point from solely from the perspective of cost would have an aspect ratio of 3.5 and would allow a decrease in cost of 3% relative to the baseline. However, there are other factors which should be considered prior to drawing any conclusions.

Figure 4 - Constant Cost Contours



It was previously noted that the narrow band in aspect ratio from which the bulk of experimental data comes, makes the statistical significance of aspect ratio in empirical scaling expressions low. Figure 5 shows contours of constant ignition margin for other scaling expressions overlaid on the cost contours from Figure 4. Some scaling expressions such as NeoAlcator[1] appear to optimize at higher aspect ratios (A=3.7). Others such as Goldston[1] scaling appear to optimize at approximately the same aspect ratio (A=3.5) while still others such as Kaye-Big[1] appear to optimize at lower aspect ratio (A=2.8). For any of these alternate scaling expressions, the potential cost advantage relative to the baseline cost is very small, less than 5%. The aspect ratio of the baseline wedged design (A=3.25) seems a prudent choice. Plasma performance in a lower aspect ratio device (A<3) would suffer with Goldston and NeoAlcator scaling. Likewise, plasma performance in a higher aspect ratio device (A>3.5) would suffer with Kaye-Big scaling.

Figure 5 - Constant Ignition Margin Contours (Alternate Scalings)



There are other considerations which also favor not increasing the aspect ratio of the baseline wedged design. Higher aspect ratio designs have reduced port are because the radial location of the TF inner leg increases. Demand for port area on CIT is very strong due to requirements for ICRH heating, diagnostics, vacuum pumping, and in-vessel remote maintenance. The reduced port area associated with a higher aspect ratio design would be difficult to accommodate. Higher aspect ratio designs have necessarily higher toroidal field which requires higher frequency heating systems. Higher frequency heating systems, both ICRH and ECRH, are more difficult and require more development work. As the aspect ratio increases, the PF coils become further separated from the plasma making shaping increasingly difficult. No exact thresholds have been set where these design considerations pass from manageable to unmanageable. However, it is clear that these qualitative considerations support the conclusion that increasing the aspect ratio of the present baseline wedged design would not be a prudent course of action.

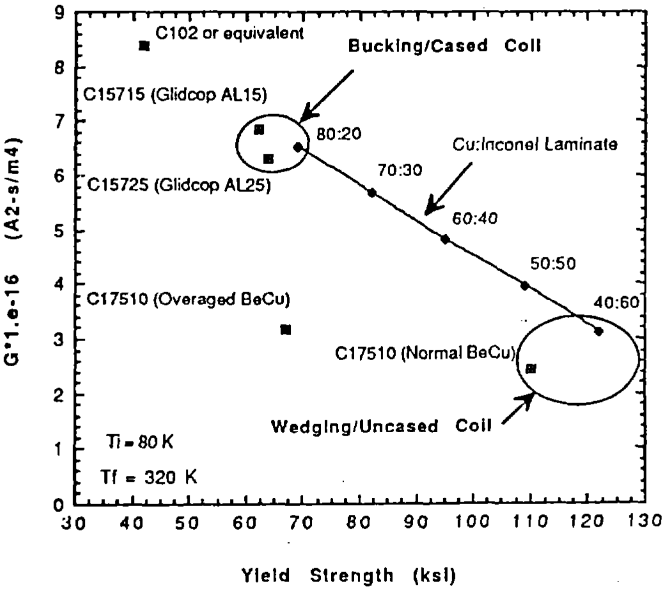
Optimization of the Bucked Design

There is always pressure to increase ignition margin because of the uncertainties associated with confinement projections. On the baseline wedged design, increasing plasma performance such that ignition could be achieved with a confinement enhancement of 1.45 over L-mode instead of 1.65 would require an increase of at least 0.22 m in major radius and a cost increase of at least 30%. However, achieving such an increase in performance with no increase in major radius was recognized as a possibility with a bucked configuration.

In a bucked configuration, the TF centering forces on the inner leg are reacted primarily by bearing on a bucking cylinder or the central solenoid rather than by hoop compression of the inner leg. Bearing on the central solenoid is more efficient because the bearing loads from the TF reduce the hoop tension in the central solenoid due to self-forces thereby providing a mutual benefit. In a wedged configuration, out-of-plane loads on the TF inner leg result in high shear in the turn-to-turn insulation. However, because the insulation is in strong compression, high shear stresses can be sustained. In a bucked configuration, the hoop compression in the inner leg is small or nil. Therefore, in developing the bucked configuration, the TF inner leg was fully cased to provide a torque structure for out-of-plane loads.

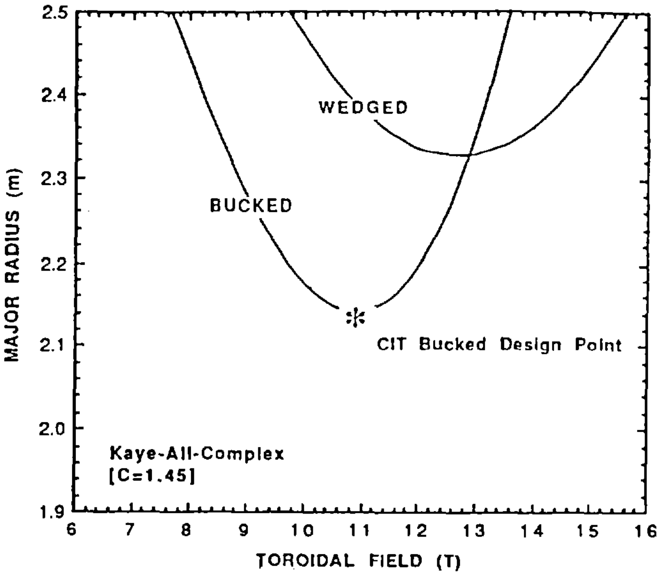
A number of the groundrules were also changed for the bucked configuration. Stress levels in the TF inner leg and central solenoid conductors tend to decrease and conductivity requirements tend to increase. Modest strength, high conductivity alloys such as Glidcop AL15 (C15715) can now be effectively employed. Figure 6 depicts potential conductor options with their nominal yield strengths and current carrying capacities ($G=\int J^2 dt$). Copper:Inconel laminate (with different Cu:Inconel ratios) is still a conductor option but the primary candidate in the TF inner leg and central solenoid was assumed to be AL15. For this scoping study, the TF case stress at the midplane was limited to 75 ksi (1/2 the yield strength of Nitronic40 at 80K) to allow for peaking in case stresses off the midplane. The peak TF conductor stress at the midplane was limited to 54 ksi (85% the yield strength of AL15) because the midplane value appears to be at or near the maximum. The peak PF conductor stress at the midplane was limited to 32 ksi (1/2 the yield strength of AL15) to allow peaking off the midplane and stress concentrations in transition regions.

Figure 6 - Yield Strengths and Current Carrying Capacities for Various Conductor Options



Given these engineering constraints, a set of design points was developed using the CIT systems code with a confinement enhancement required for ignition of 1.45 assuming KAC scaling. This contour of of constant ignition margin is shown in Figure 7. The present design point for the bucked option appears to be very close to the optimal aspect ratio. Also shown in Figure 7 is the same contour for the wedged option. The apparent advantage in major radius is >0.20 m for the bucked option. Relative costs have not yet been established. Scoping studies of the bucked option are still being performed to assist in developing and optimizing the bucked design.

Figure 7 - Constant Ignition Margin Contours (Bucked and Wedged Configurations)



Summary

A systematic approach for physics optimization of CIT designs has been employed in developing the wedged design. The same approach is presently being used to optimize the bucked design. Values of κ (2) and q (3.2) were chosen to maximize performance without adding to the level of risk or difficulty. Both designs appear to optimize at modest aspect ratios (3.2-3.5) assuming KAC scaling. Other scaling expressions lead to different optima in aspect ratio, some being higher and some being lower. However, modest aspect ratio designs do not perform badly with any of the scaling expressions considered and are representative of the database from which the scalings expressions are derived. Therefore, a modest aspect ratio is considered a prudent choice. Plasma heating, port access, and plasma shaping considerations suggest avoiding high aspect ratios. Field and current values have been chosen consistent with ignition margin objectives. For the baseline wedged design, a confinement enhancement of 1.65 over KAC L-mode is required for ignition. For the baseline bucked design, the ignition margin is even higher, requiring only a confinement enhancement factor of 1.45 over KAC L-mode. Confinement enhancements of this magnitude are routinely seen on JET, D-III-D, and TFTR and appear to be a reasonable expectation for CIT.

References

[1] S.M. Kaye, "Survey of Energy Confinement Scaling Expressions", ITER Specialists' Meeting on Energy Confinement, May 24-27, 1988, Garching, Federal Republic of Germany