Design Point Trade Studies

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Review of FIRE TF, PF, Structures, VV, PFC's, Fueling and Pumping
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Design Point Studies

1. Costing of 4 "Reference" Options
2. Equalization of TF/CS "burn times"
   - optimization of TF/CS interface
3. Scan of A, Bt for "Fixed Mission"
   - Margin=2 and Margin=1
4. Optimization of Bt for Qmax at fixed \( t_{\text{norm}} = t_{\text{flat}} / J \)
5. Mission Margins/Sensitivities
Physics sizing from Uckan, Rutherford/Meade-profile macro

Costing originally from ITER
  - replaced by scalings from FIRE budgetary estimates

\( \text{ITER}_{\text{IPB98}}^\text{H(y,2)} \) scaling

Finds T10 with highest Q - Greenwald, Troyon, \( P_w \) n-constraints
  - including ash-buildup based on assumed \( \tau_p^*/\tau_E \)
Cost equations altered to match Cost Estimate Summary

<table>
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<tr>
<th>WBS</th>
<th>Description</th>
<th>Cost- $K</th>
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<td>11</td>
<td>Magnets</td>
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<td>Contingency (20 %)</td>
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<td>Total:</td>
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\[ \tau_{EIPB98} = 0.144 H(y,2) \left( I_p^{0.93} R_o^{1.39} a^{0.58} B_t^{0.15} \kappa^{0.78} AMU^{0.19} n_{e20av}^{0.41} \right) P^{-0.69} \]

**Physics** | **Engineering**
---|---
H(y,2)=1.1 | P<sub>w</sub> < 3 MW/m<sup>2</sup> (n° wall loading)
\( \alpha_N = 0.2 \) | T<sub>hot,TF</sub> < 373 K
\( \beta_N < 1.6 \% \) | T<sub>hot,CS</sub> < 300 K
q<sub>lim</sub> = 3.104 | \( \sigma_{\text{max}} \) (BeCu, 68% IACS) = 700 MPa
\( \tau_{\pi^*}/\tau_E = 6 \) | \( \sigma_{\text{max}} \) (Cu) = 300 MPa
\( f_{\text{Greenwald}} < 0.75 \)
(1) TF/OH interface optimization

\[ t_{\text{burn,TF}} = t_{\text{burn,OH}} \] (TF/OH interface optimum for fixed Ro

Subtract 3 s from TF flattop for plasma heating

\[ \text{e.g. } 24.5 \text{ s TF flattop} = 24.5 \text{ s I flattop} = 3 \text{ s heat} + 21.5 \text{ s burn} \]

No scaling of \( t_{\text{heat}} \) with plasma parameters

(2) Minimum Ro for "Mission Margin"

Mission: Long-pulse \( \alpha \)-dominated plasmas

Margin=2: \( Q \geq 10; \frac{t_{\text{flattop}}}{\max(\tau_E, \tau_{p*}, \tau_J)} \geq 2 \)

Margin=1: \( Q \geq 5; \frac{t_{\text{flattop}}}{\max(\tau_E, \tau_{p*}, \tau_J)} \geq 1 \)
(3) Parametric scans

Vary $R_o$ vs. $A$, fixed Margin, $B_t$

Vary $R_o$ vs. $B_t$, fixed Margin, $A$
Alpha margin=Time margin=2 at optimum A=2.0/0.525
Rapid rise in time margin and heating margin off optimum A
All Double Optimization Studies are Bucked & Wedged
M2: Minimum Cost = $1.06 B @ R_o = 1.86 m, A=3.8, B_t=11.5 T
- M2 < $1 B, if phase auxiliary power

M1: Minimum Cost = $0.92 B @ R_o = 1.59 m, A=3.8, B_t=11.5 T
Cost (M$) vs Ro; Subsystem Sensitivity

$R_o$; $B_t=11.5$ T, $A=3.8$, $q_L=3.1$, not fixed mission

$/R_o$ Sensitivity = 1.01

$/R_o$: Paux, I&C = 0
Magnets=1.64
Basic Machine=1.2510
Buildings=1.14
(1) TF/OH interface optimization

(2) Fix Ro, "Modified Mission Margin"
Margin=2: \[Q=AHAP; \frac{t_{\text{flattop}}}{\max(\tau_E, \tau_p, \tau_J)} = 2\]

(3) Optimize \(T_{i10}\) and \(B_t\) for maximum MI(Ro,A)
   - \(B_t\) as high as possible with magnet constraints
   - Select \(T_{i10}\) to optimize MI with \(n_{eav}\) constraints

(4) Separate spreadsheets for Wedged, B&W designs

(5) Triple optimization well-behaved at low A
A=3.8 best, 1.5 m<\text{R}_o<4$ m;

$Q=10$:\ $R_{\text{omin}}(\text{A}=3.8)=1.85$ m; $(\text{A}=3.5)=1.95$ m

$\text{MI}_{\text{peak}}=1.39$ at $R_o=3.5$ m; $(\text{MI/R}_o)_{\text{max}}=1/m$ (Sens=2.8)
$R_0(Q=10)=1.85 \text{ m B&W, } 2.05 \text{ m Wedged}$

$Q_{opt}(R_0=2 \text{ m})= 22 \text{ B&W, } 8.4 \text{ Wedged}$

$MI_{peak} = 1.39 \text{ for both, but at } R_0=3.75 \text{ m for Wedged}$
Cost (Q=10) = $1.19 B, Wedged; $1.06 B, B&W
MI Sensitivity@$1 B = 0.8 %/%
~ $300 M from Q=10 to Ignition; ~ $125 M Q=5 to 10
Effect of $\tau_{up}/\tau_{auE}$ on MI

Optimum MI, bucked & wedged vs. Ro (m); A=3.8; $\tau_{up}/\tau_{auE}=6, 10$

Peak MI decreases from 1.39 to 1.02, $R_{opt}$ 3, vs 3.5 m

$R_{omin}(Q=10)$ increases from 1.85 m to 1.90 m
None of these machines has (quite) the same mission. Even (seemingly) identical plasmas, have different engineering margins.

2.14 m ~ $100 M more than 2.0 m
- saves $50 M, because 20 MW, not 30 MW $P_{aux}$

B&W $50 M$ less than Wedged
1. FIRESALE "tuned" to find smallest fixed-mission tokamaks for wedged or bucked&wedged options

2. Minimum size/cost M(2) machine ~ 1.85 m x $1.06 B
   - < $1 B with site credits or deferred RF
(Achieves all cost/mission objectives: Q=10, $\tau_{\text{flat}}$/\tau_J=2, Cost<$1 B)

3. FIRE* costs $50-100 M more than FIRE (MI~0.2 higher)
   - B&W: possible savings of 0.2 m x $130 M @ Q=10

4. Maximum MI for "FIRE-class" machine ~ 1.4
   - limited by alpha poisoning