Design Point Trade Studies

J.H. Schultz
M.I.T. Plasma Science and Fusion Center

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

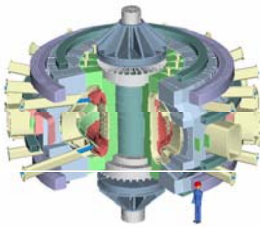
Princeton Plasma Physics Laboratory

Princeton, NJ

June 5-7, 2001

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 $t_{norm}=t_{flat}/\tau_J$
5. Mission Margins/Sensitivities



A New Spreadsheet of Fusion Ignition Reactor Experiment Sizing and Line-Item Equations

FIRESALE

Physics sizing from Uckan, Rutherford/Meade-profile macro

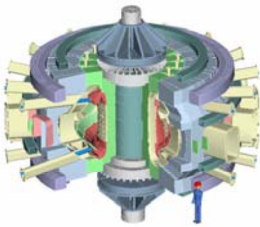
Costing originally from ITER

- replaced by scalings from FIRE budgetary estimates

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

Finds T10 with highest Q - Greenwald, Troyon, P_w n-constraints

- including ash-buildup based on assumed $\tau_p{}^*/\tau_E$



Calibration of Fusion Ignition Reactor Experiment Sizing and Line-Item Equations

FIRESALE

Cost equations altered to match Cost Estimate Summary

WBS	Description	Cost- $K
11	Magnets	120,437
12	PFCs	63,169
13	Vacuum vessel	30,906
14	Cryostat	1,782
15	Shielding	0
16	Remote Handling	52,597
17	Support Structure	15,000
18	In-Vessel Meas. Sys.	629
20	Heating & Current drive	107,427
30	Fueling & Vac. Pumping	25,145
40	Power systems	235,000
50	Diagnostics	10,975
60	Central I&C	13,492
70	Facilities and site	206,035
80	Machine Assembly, Inst., & Test	22,672
90	Project Support	157,740
	Total:	1,063,006
	Corrections	14,000
	Contingency (20 %)	215,401
	Total:	1,292,407

Sizing Model

$$\tau_{EIPB98} = 0.144\,H(y,2)\left(I_p^{\,0.93} R_o^{\,1.39} a^{0.58} B_t^{\,0.15} \kappa^{0.78} AMU^{0.19} n_{e20av}^{\;0.41}\right)P^{-0.69}$$

Physics	Engineering
$H(y,2)=1.1$	$P_w < 3$ MW/m^2 (n^o wall loading)
$\alpha_N=0.2$	$T_{hot,TF} < 373$ K
$\beta_N <1.6$ %	$T_{hot,CS} < 300$ K
$q_{lim} = 3.104$	σ_{max} (BeCu, 68% IACS) = 700 MPa
$\tau_\pi{*}/\tau_E = 6$	σ_{max} (Cu) = 300 MPa
$f_{Greenwald} < 0.75$	

Double Optimization Method

(1) TF/OH interface optimization

$t_{burn,TF} = t_{burn,OH}$ (TF/OH interface optimum for fixed Ro

Subtract 3 s from TF flattop for plasma heating

e.g. 24.5 s TF flattop = 24.5 s I flattop = 3 s heat + 21.5 s burn

No scaling of t_{heat} with plasma parameters

(2) Minimum Ro for "Mission Margin"

Mission: Long-pulse α-dominated plasmas

Margin=2: Q>=10; $t_{flattop}/\max(\tau_E, \tau_p^*, \tau_J) >= 2$

Margin=1: Q>=5; $t_{flattop}/\max(\tau_E, \tau_p^*, \tau_J) >= 1$

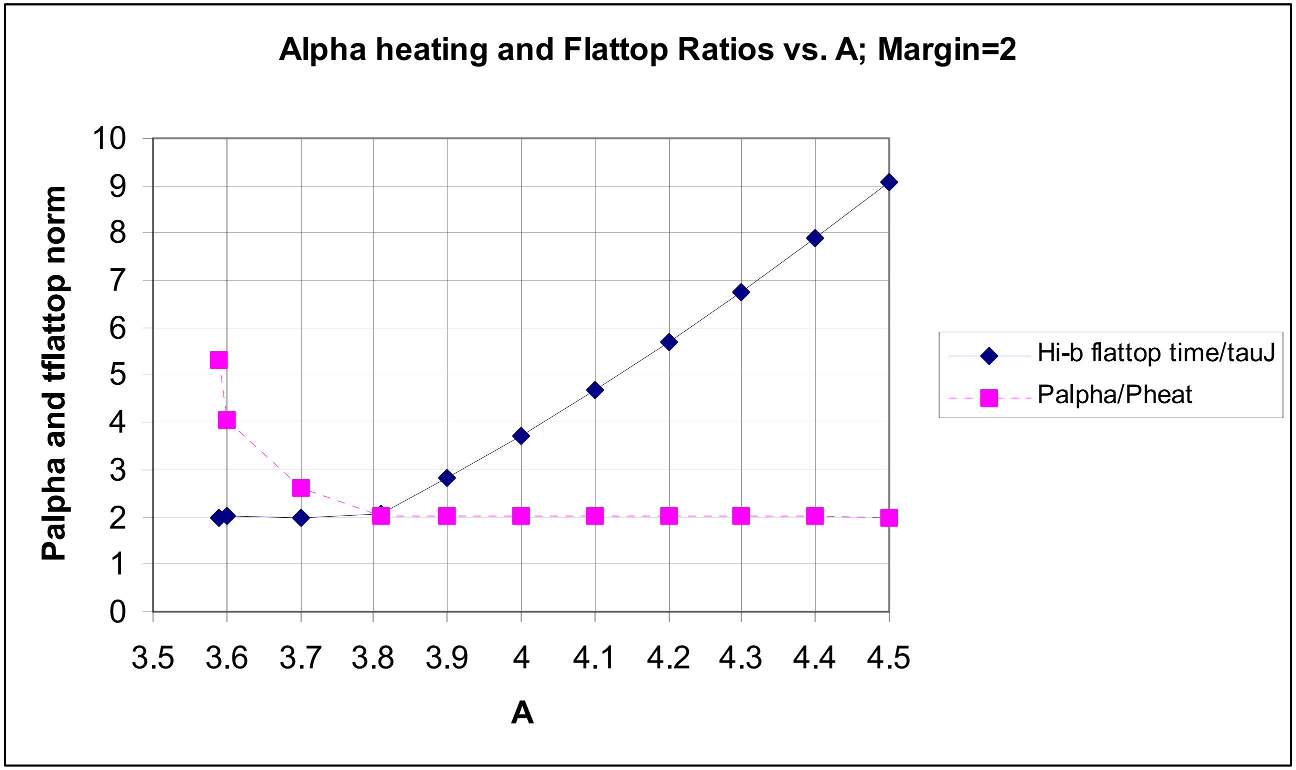
Double Optimization Method-II

(3) Parametric scans

Vary R_o vs. A, fixed Margin, B_t

Vary R_o vs. B_t, fixed Margin, A

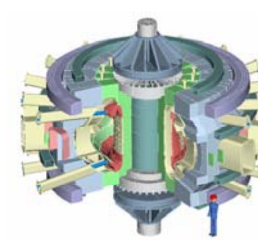
Dimensionless Margins > 2 vs. A



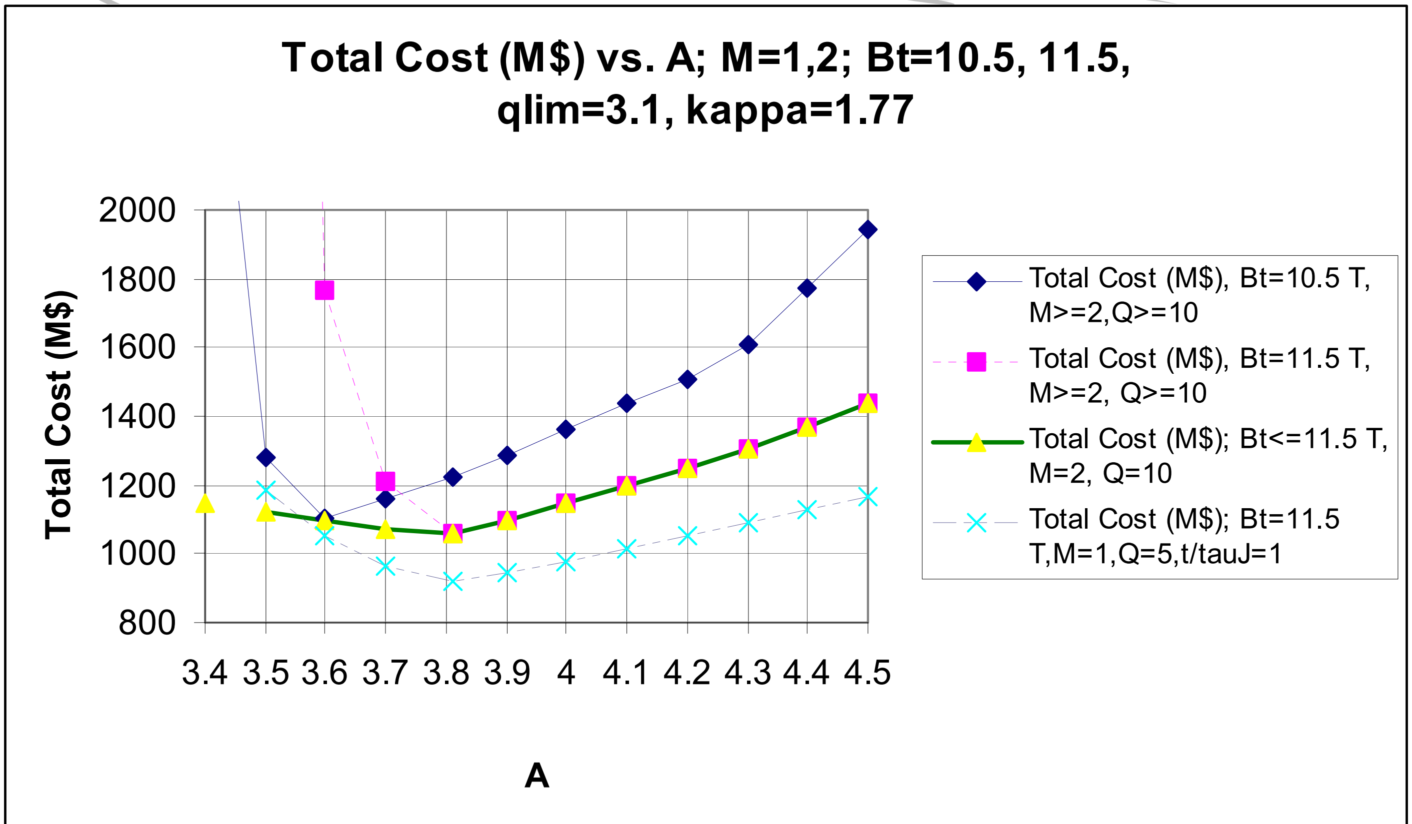
Alpha margin=Time margin=2 at optimum A=2.0/0.525

Rapid rise in time margin and heating margin off optimum A

All Double Optimization Studies are Bucked & Wedged



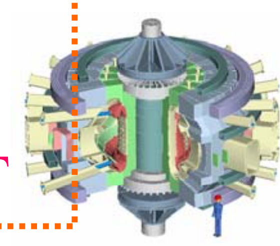
Comparison of "Mission Margin" =1, 2 Curves



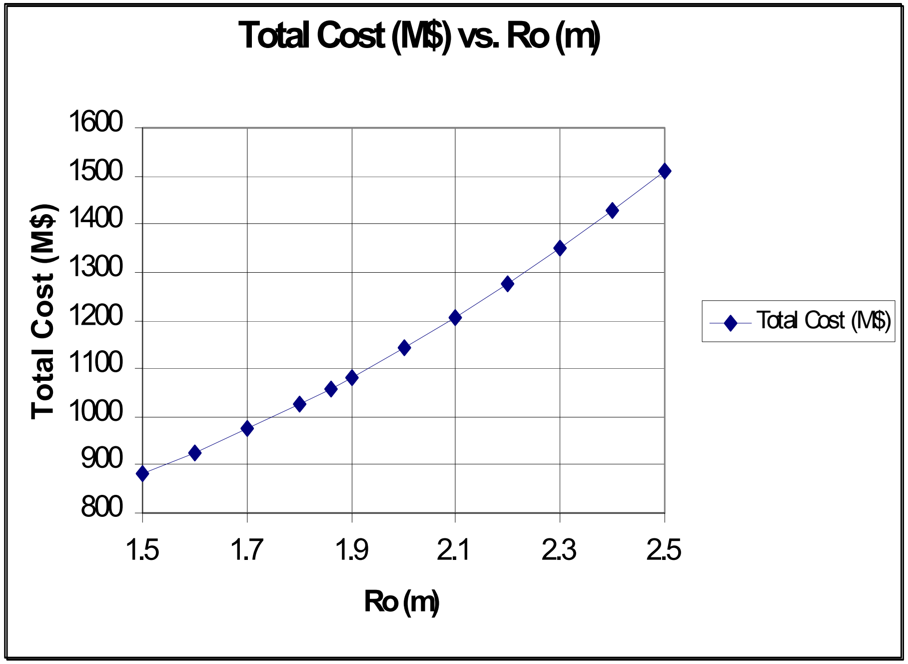
M2:Minimum Cost =$1.06 B @ R_o= 1.86 m, A=3.8, B_t=11.5 T

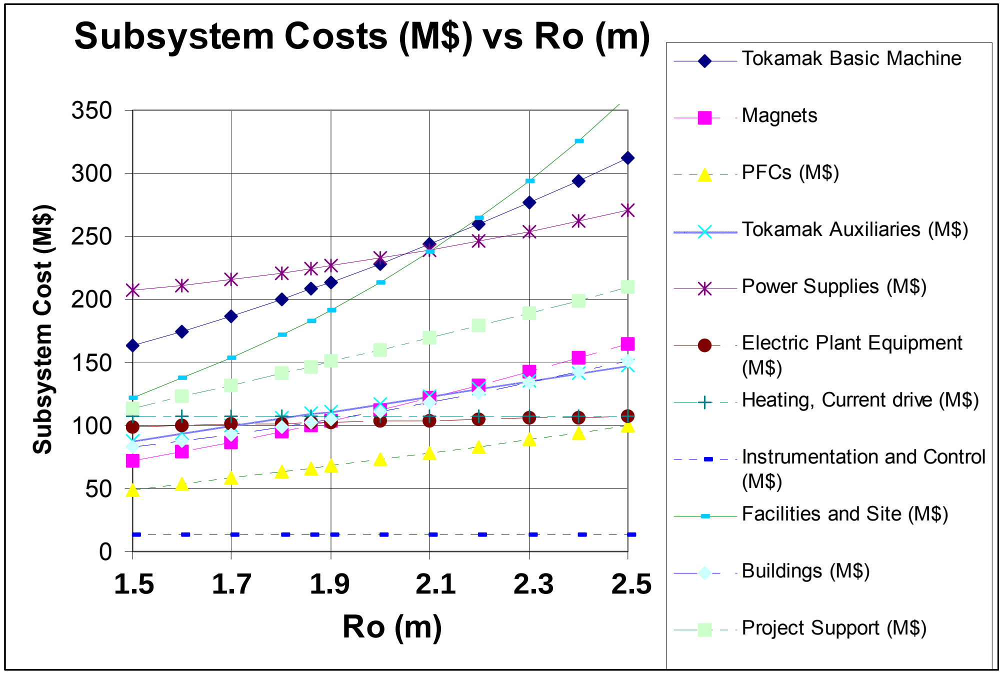
- M2 < $1 B, if phase auxiliary power

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





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

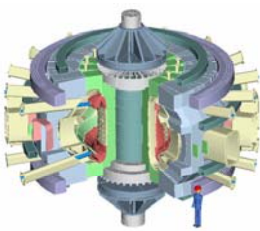
$/Ro Sensitivity = 1.01

$/Ro: Paux, I&C = 0

Magnets=1.64

Basic Machine=1.2510

Buildings=1.14



Triple Optimization Method

(1) TF/OH interface optimization

(2) Fix Ro, "Modified Mission Margin"

Margin=2: Q=AHAP; $t_{flattop}/\max(\tau_E, \tau_p^*, \tau_J) = 2$

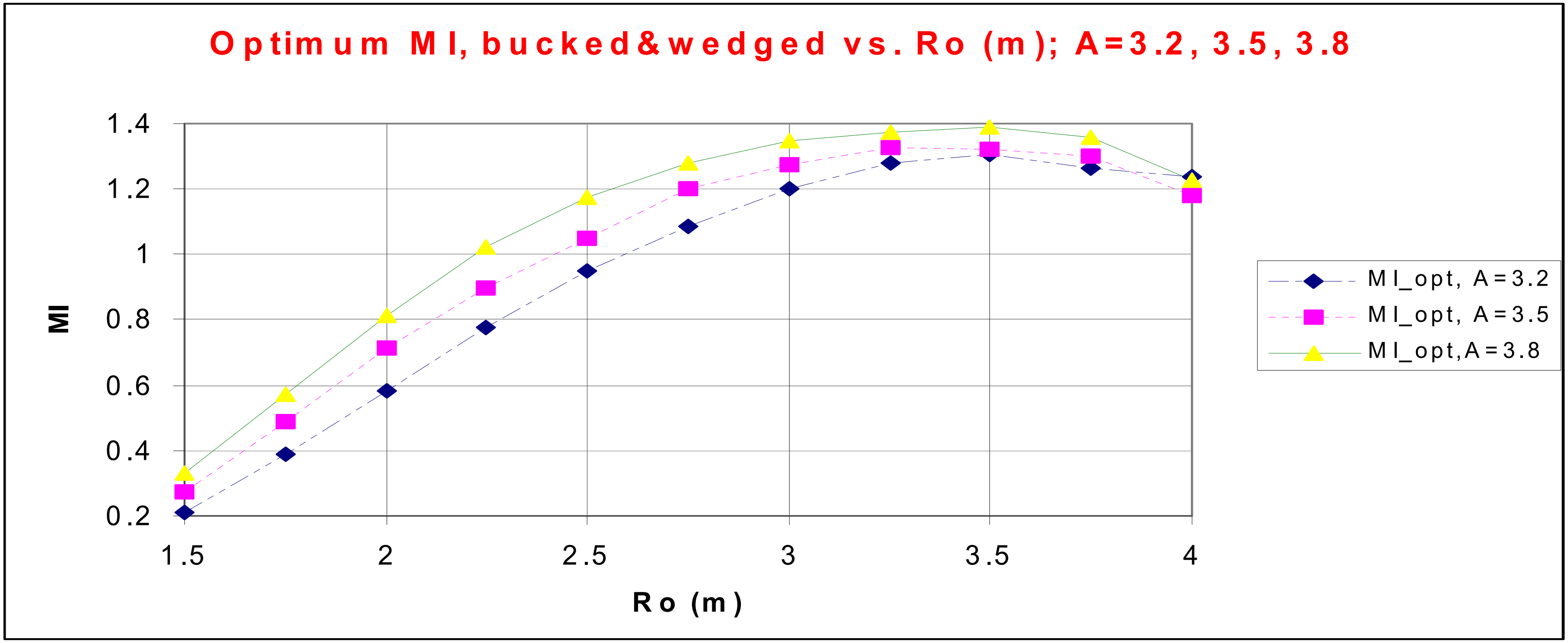
(3) Optimize T_{i10} and B_t for maximum MI(Ro,A)

- **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

MI Optimum vs Ro; A = 3.2, 3.5, 3.8



A=3.8 best, 1.5 m< R_o< 4 m;

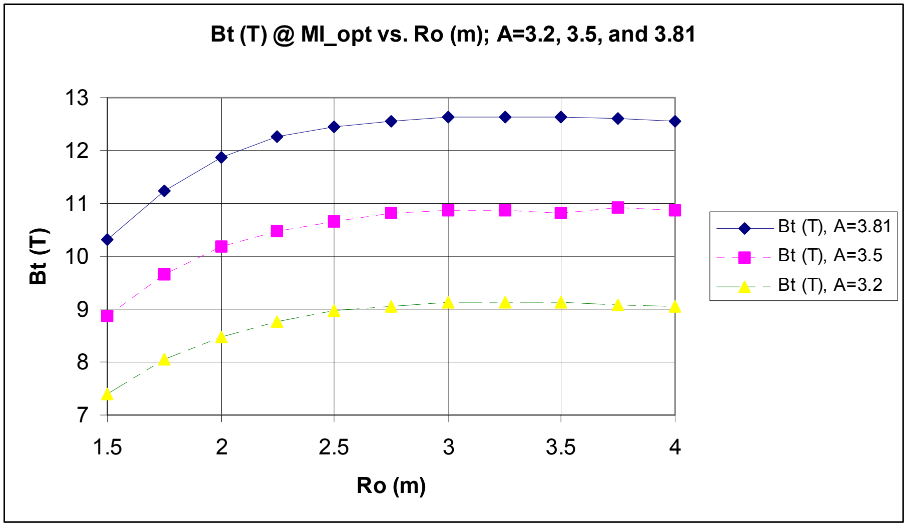
Q=10: R_{omin}(A=3.8)=1.85 m;(A=3.5)=1.95 m

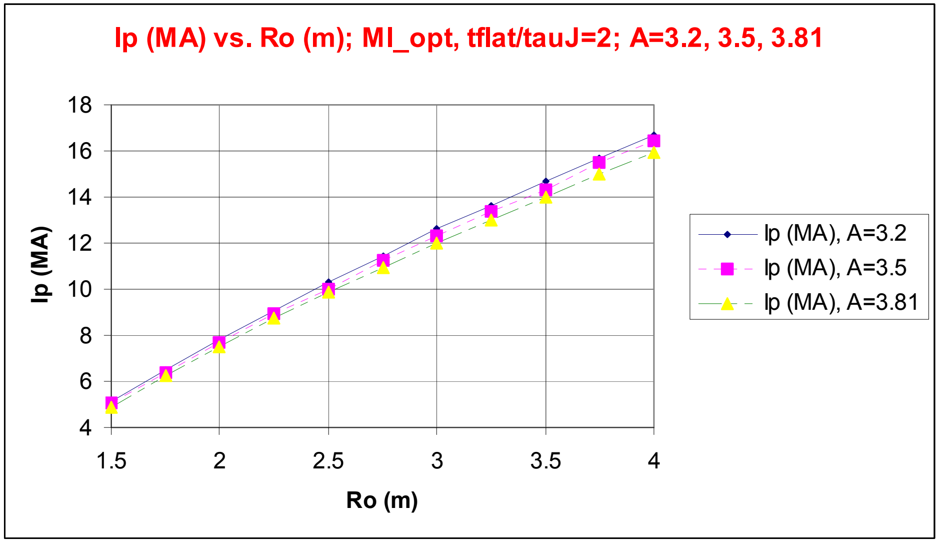
MI_{peak}=1.39 at R_o=3.5 m; $(MI/R_o)_{max}$=1/m (Sens=2.8)

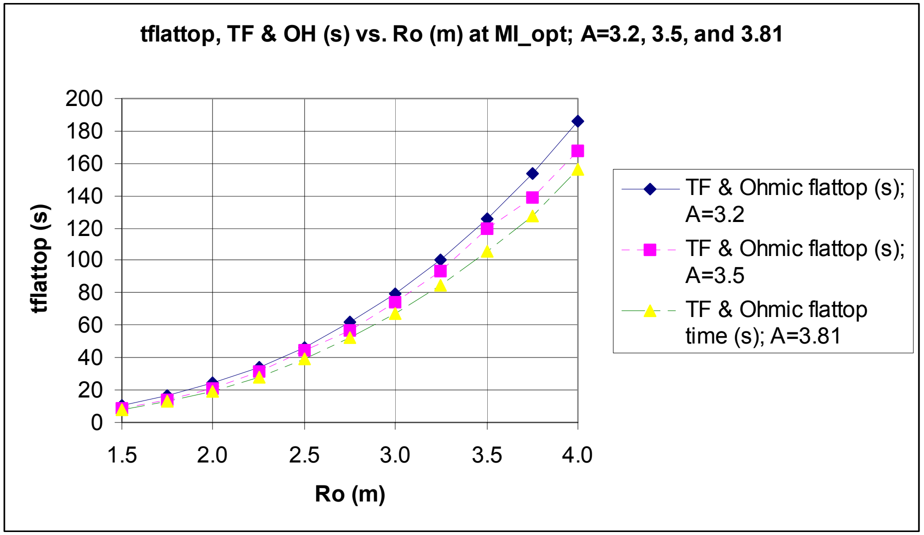
MIT Plasma Science and Fusion Center

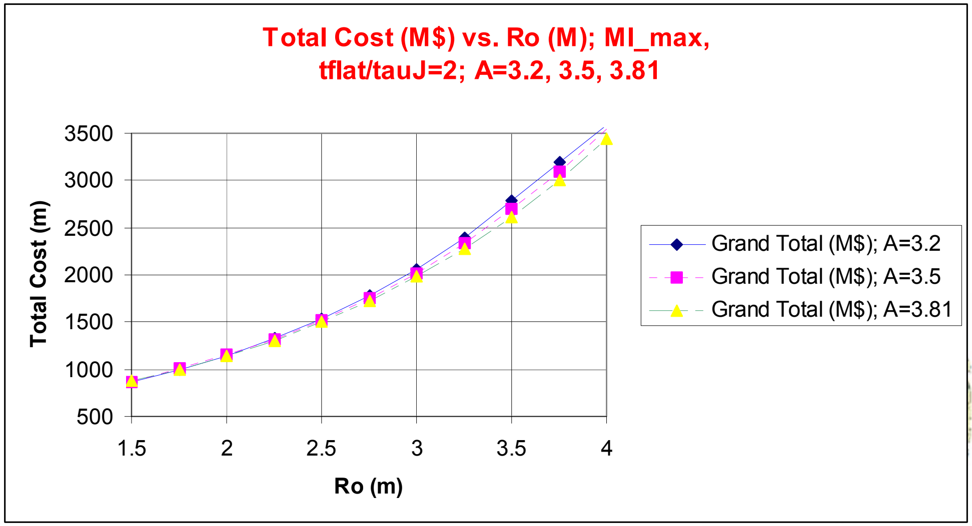
Fusion Technology & Engineering Division

FIRE Tradeoffs: MI_Opt vs. Ro (m)

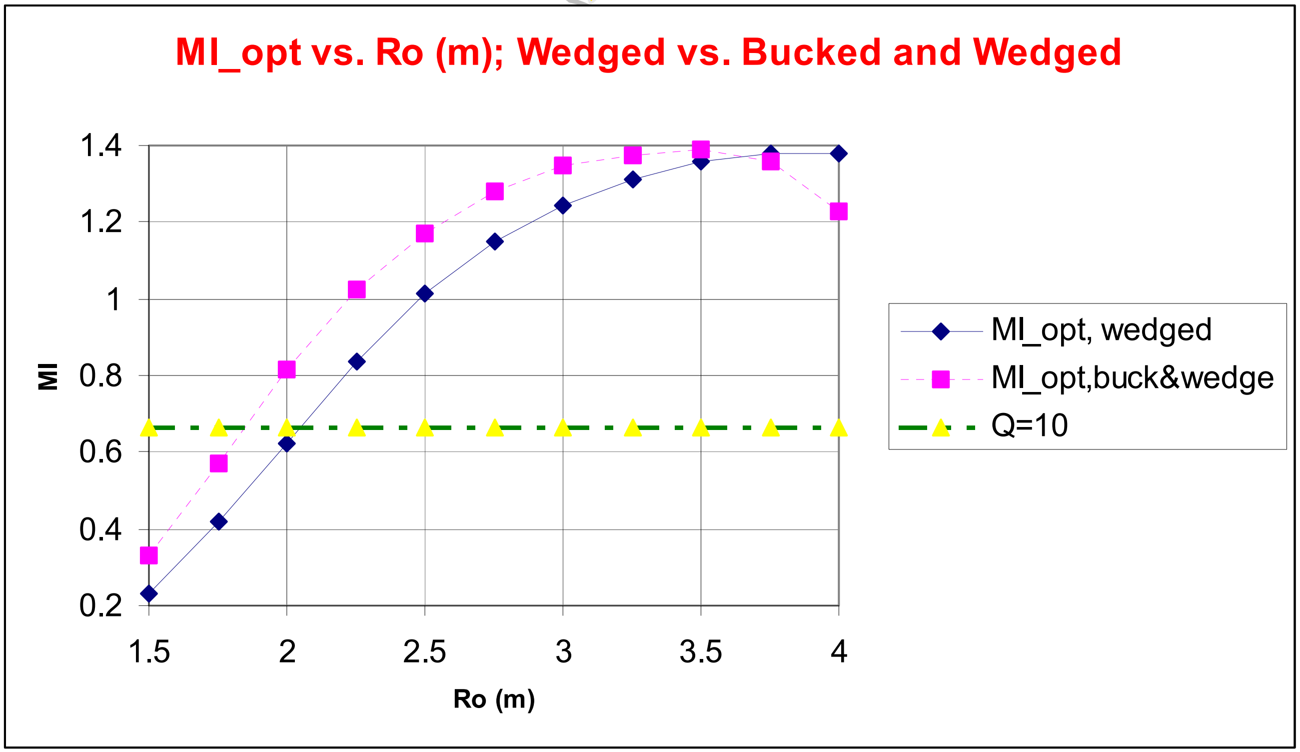








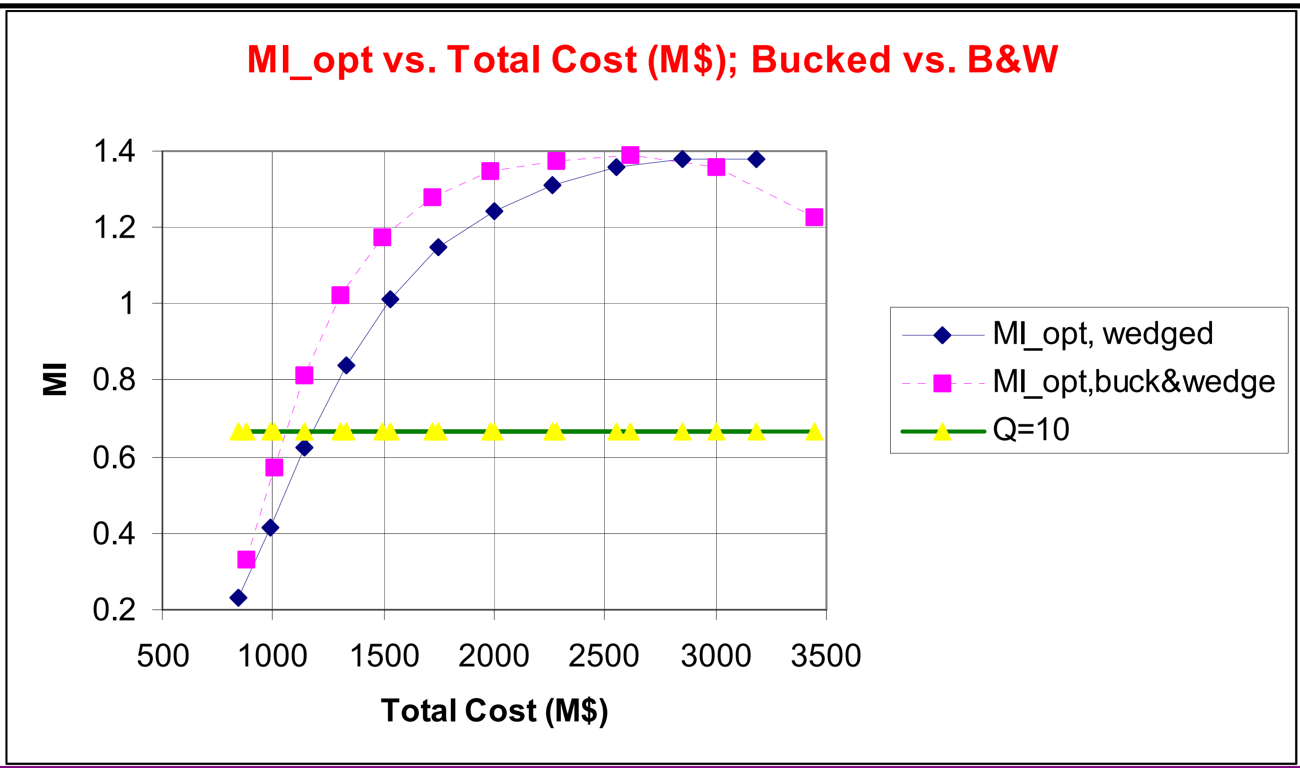
MI vs. Ro; W vs. B&W



$R_o(Q=10)$=1.85 m B&W, 2.05 m Wedged

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

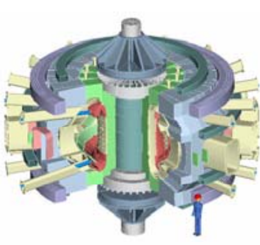
MI_{peak} = 1.39 for both, but at R_o=3.75 m for Wedged



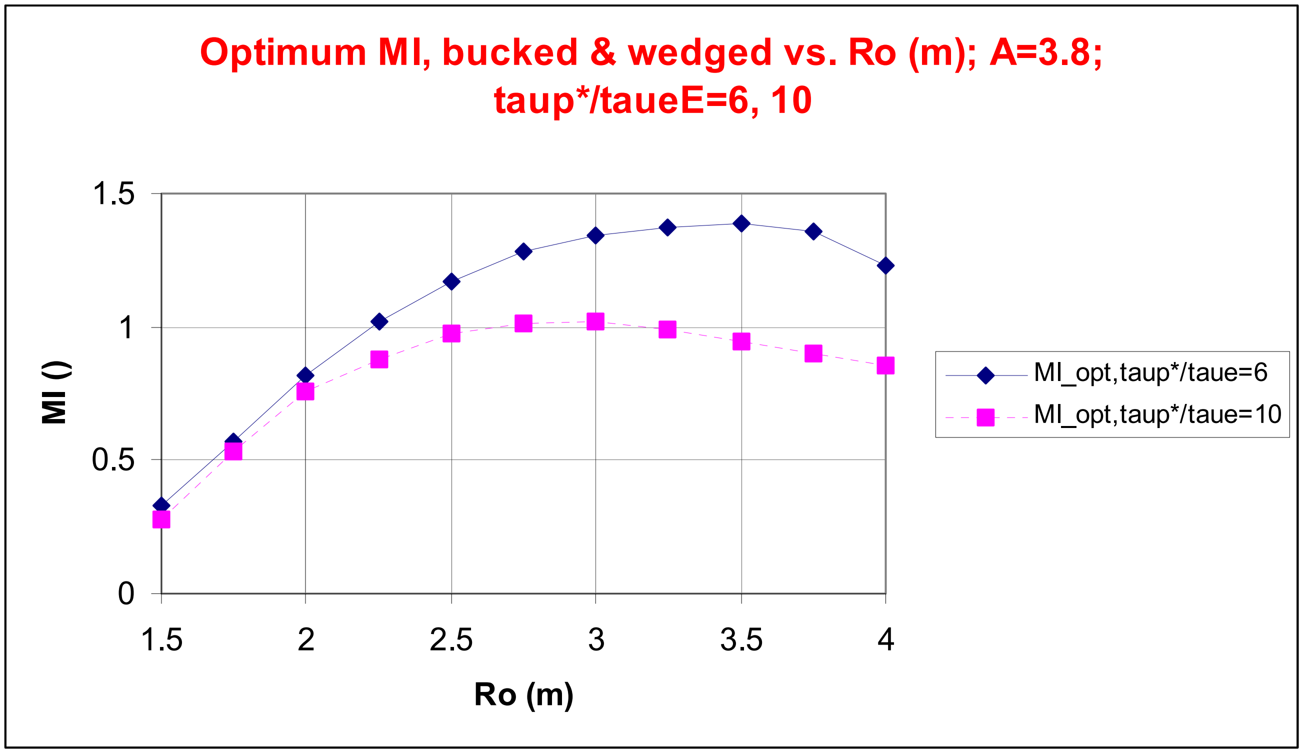
Cost (Q=10) = $1.19 B, Wedged; $1.06 B, B&W

MI Sensitivity@$1 B = 0.8 %/%

~ $300 M from Q=10 to Ignition; ~ $125 M Q=5 to 10

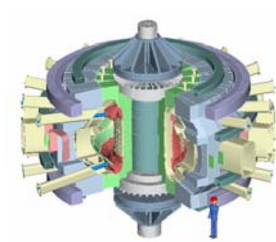


Effect of taup*/tauE on MI

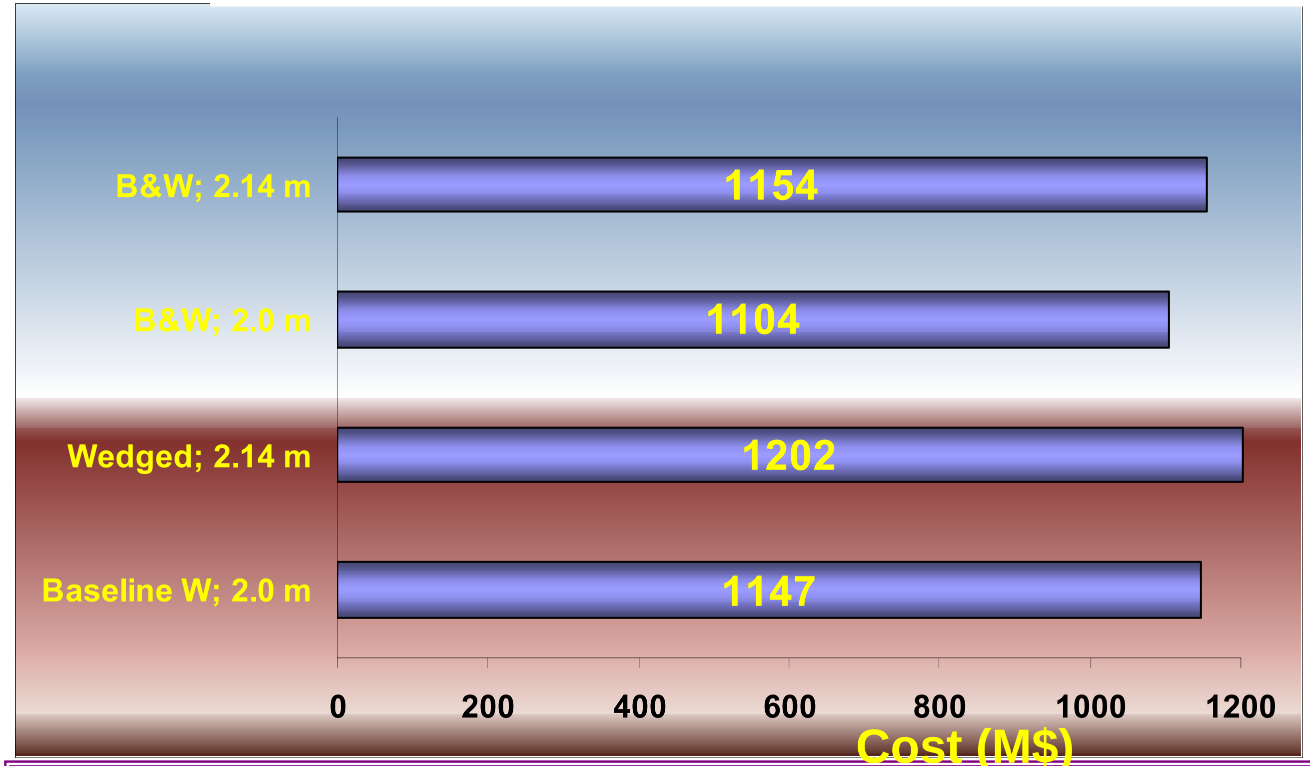


Peak MI decreases from 1.39 to 1.02, R_{opt} 3, vs 3.5 m

R_{omin}(Q=10) increases from 1.85 m to 1.90 m



Cost of 4 Design Options



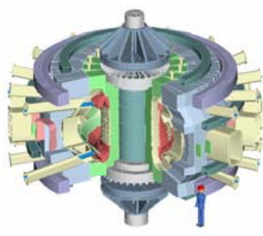
None of these machines has (quite) the same mission

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



Conclusions

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, τ_{flat}/τ_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