Recent Results on Compact Stellarator Reactor Optimization

J. F. Lyon, ORNL

ARIES Meeting Sept. 3, 2003

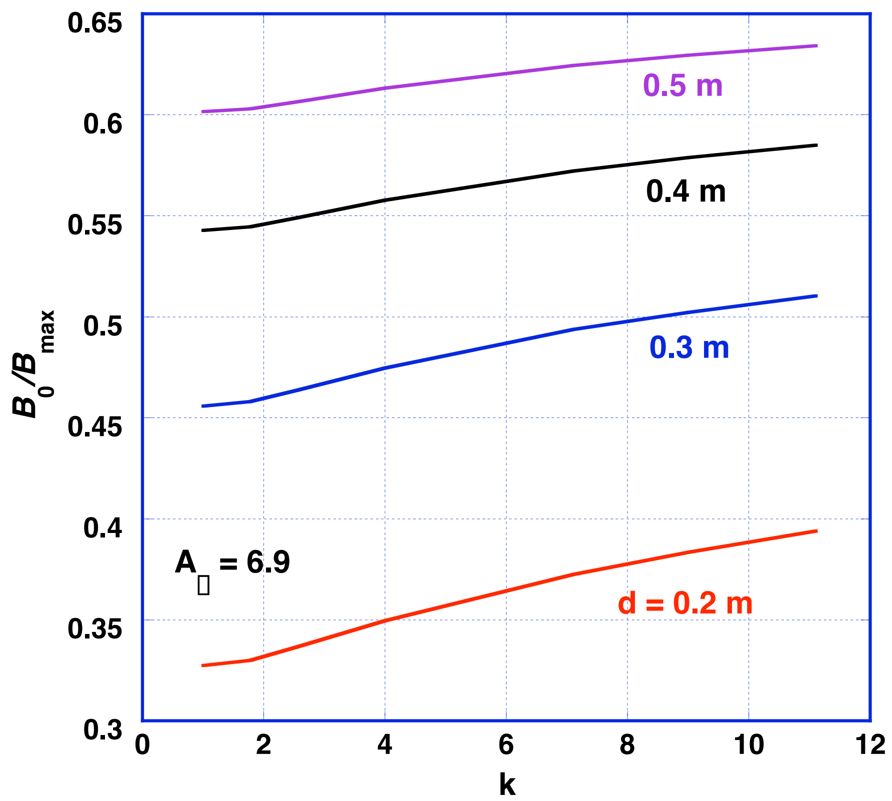
TOPICS

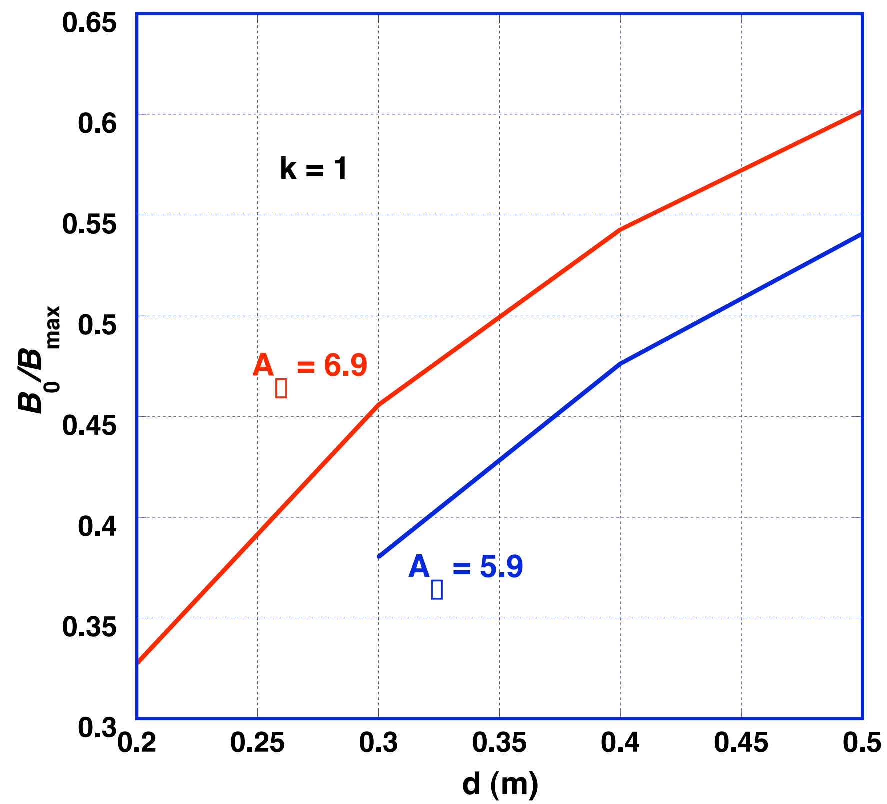
- Plasma and coil characterization
- 1-D POPCON calculations
- Improvements over May reference cases
    - A proposed new reference case
- Sensitivities to different assumptions
- Status of systems code calculations

Plasma and Coil Characterization

- **Plasma configuration**
  - $A_p = \langle R\rangle/\langle a\rangle$, ι_{limit}, $\iota(r/a)$
  - $n(r/a)$ and $T(r/a)$ shapes, C and Fe %
  - α-particle loss %, τ_{He}/τ_E
- **Modular coil parameters**
  - $A_\Delta = \langle R\rangle/\Delta_{min}$, d & k set the minimum value for $\langle R\rangle$
  - I_{coil} ($\propto$ $1/B_0\langle R\rangle$) & d determine $\langle j_{coil}\rangle$
  - $B_0/B_{max}(d,k)$ sets the maximum value for B_0
  - min. coil-coil distance/$\langle R\rangle$ sets the max. value for k
  - d = coil depth, k = coil aspect ratio
- **Plasma to coil distance**
  - $t = \Delta - d/2k^{1/2}$ = scrapeoff + first wall + blanket + shield + coil structure sets the min. value for $\langle R\rangle$

B_0/B_{max} depends on A, d & k





Plasma and Coil Candidates

- ✓ **Ku's three period 2/25/03 coils**
  - A_p = 4.5, $A_{\square}$ = 6.88, I_{coil} = 13 MA (R = 8.25 m, B_0 = 5.3 T),
  - B_0/B_{max} = 0.456 (R = 8.25 m, d = 0.3 m, k = 1)
  - min. coil-coil distance/<R> = 0.107; 30% □ loss
- ✓ **Ku's three period 8/1/03 coils**
  - A_p = 4.5, $A_{\square}$ = 5.9, I_{coil} = 16.5 MA (R = 8.3 m, B_0 = 6.5 T),
  - B_0/B_{max} = 0.38 (R = 8.3 m, d = 0.3 m, k = 1)
  - min. coil-coil distance/<R> = 0.099 ; 30% □ loss
- ? **Garabedian's two period 8/14/03 case**
  - A_p = 3.5, $A_{\square}$ = 5.53; potentially interesting
  - no information on I_{coil}, B_0/B_{max}, min. coil-coil dist.
  - insufficient information for assessments

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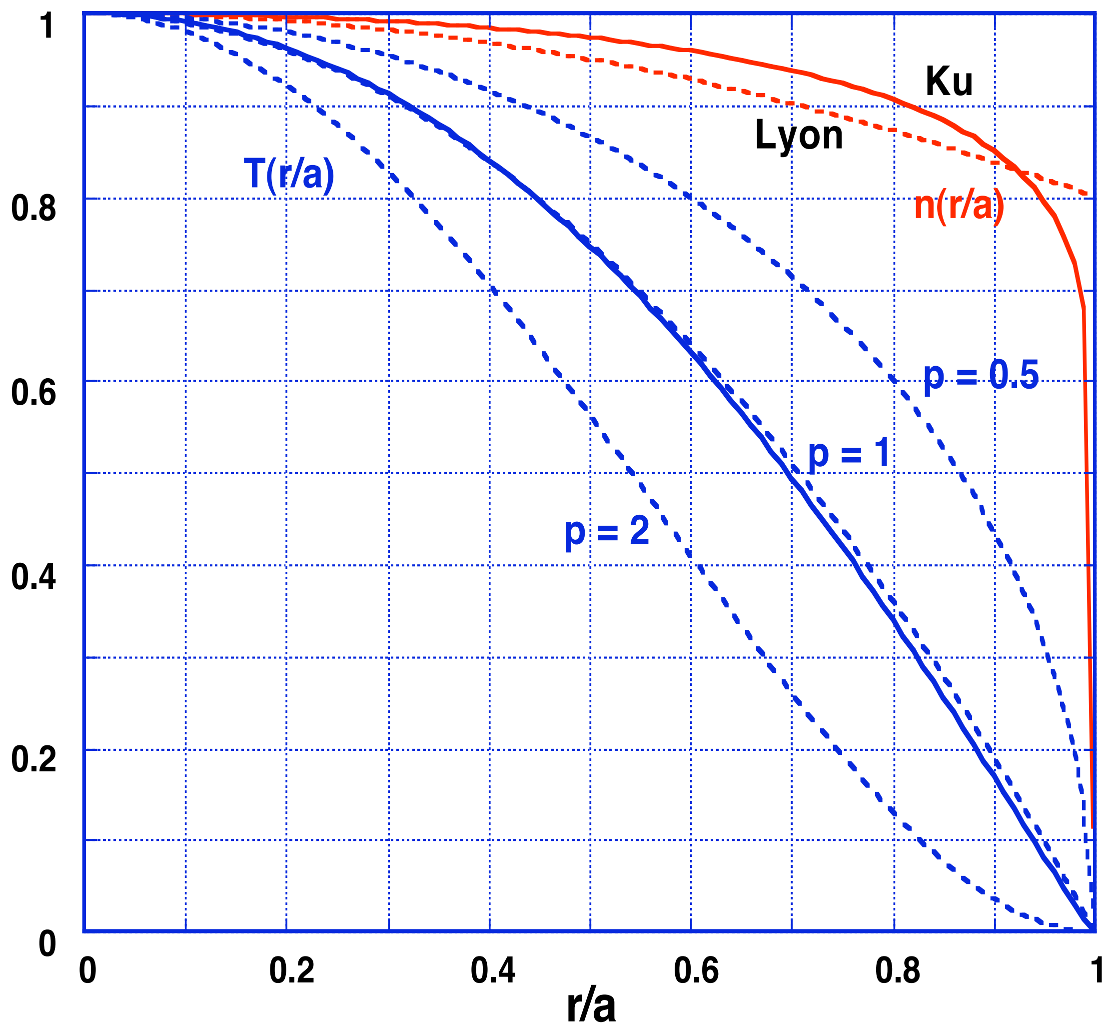
1-D POPCON Calculations

- **Input *variables***
  - magnetic configuration: $<R>$, $<a>$, B_0, $\iota(r/a)$,
  - plasma properties: $\tau_E^{ISS\text{-}95}$ multiplier H, τ_{He}/τ_E, α particle loss %, $n(r/a)$ & $T(r/a)$ shapes, C & Fe %
- **Constraints**
  - fusion power P_{fop}, $n < 2n_{Sudo}$, $\beta < \beta_{limit}$,
- **Calculated quantities**
  - oper. point: $<n>$, $<T>$, $<\beta>$, P_{fusion}, %He, %D-T, Z_{eff}
  - minimum ignited point: $<n>$, $<T>$, $<\beta>$, P_{fusion}
  - saddle point: $<n>$, $<T>$, $<\beta>$, P_{in}
  - $P_{in}(<n>,<T>)$ contours
  - $P_{rad}(<n>,<T>)$: coronal and bremsstrahlung; P_α losses

Profile Assumptions



Other Variables

P_{fus} = 2 GW

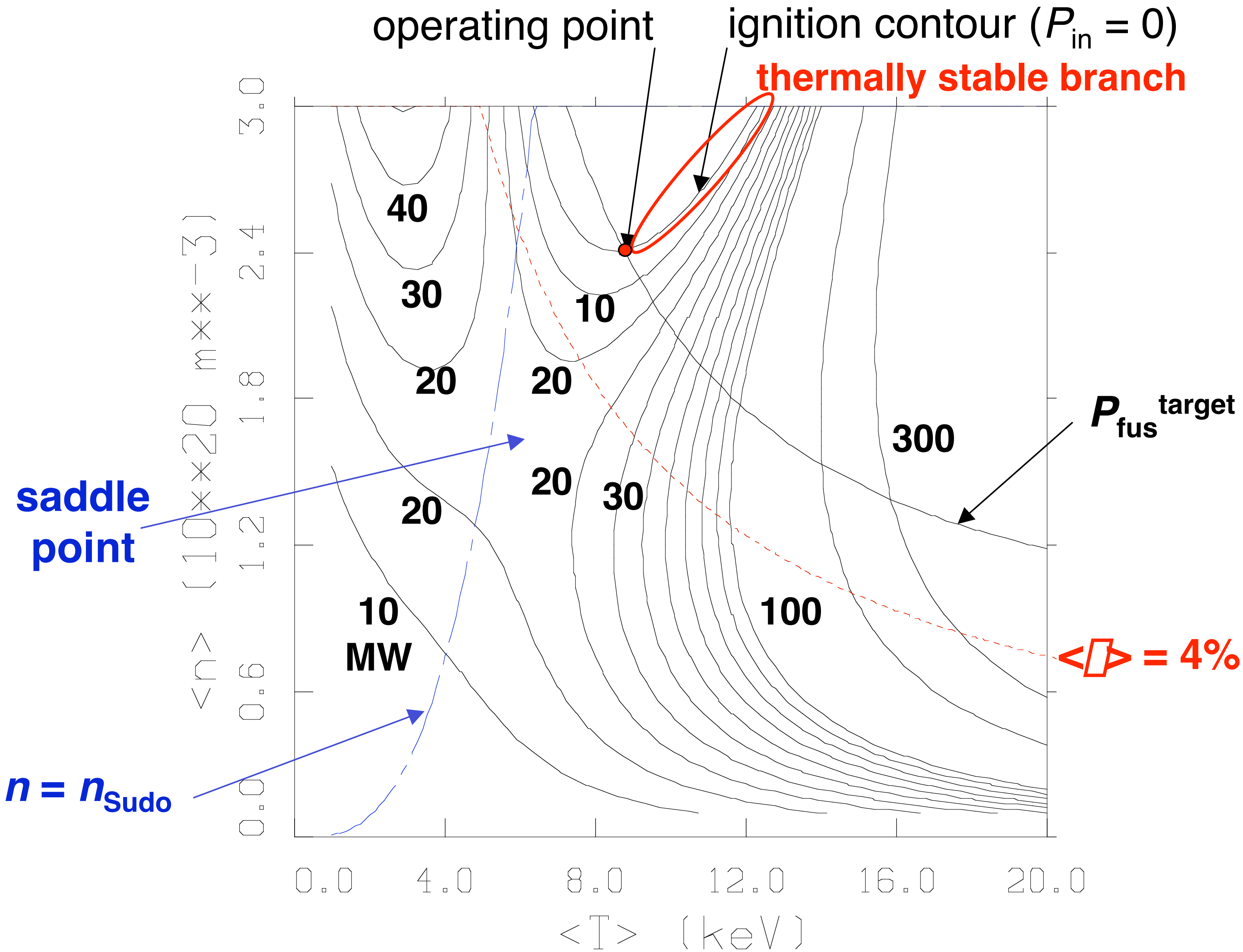
$H^{ISS\text{-}95}$ = minimum

30% □ loss

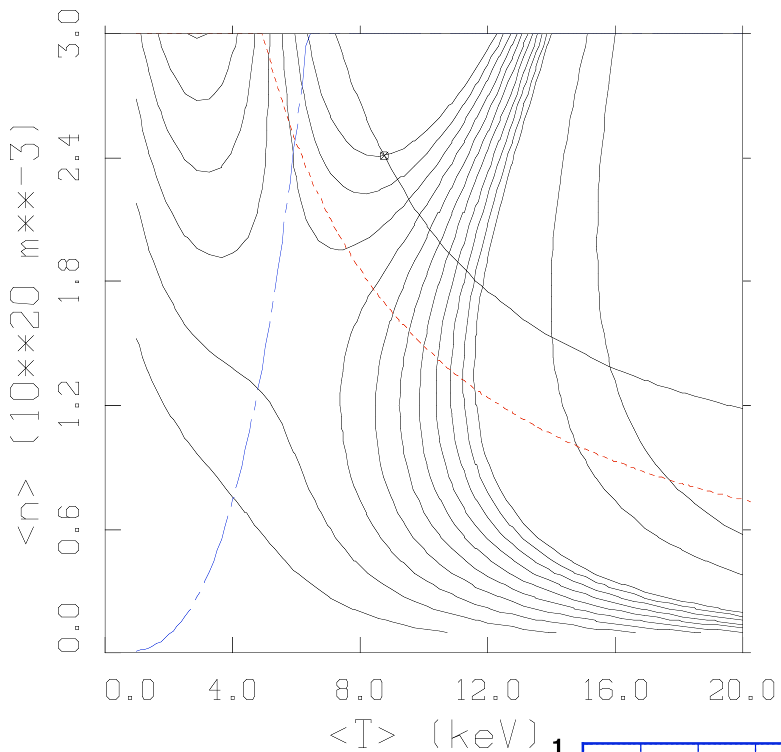
□$_{He}$/□$_{E}$ = 6

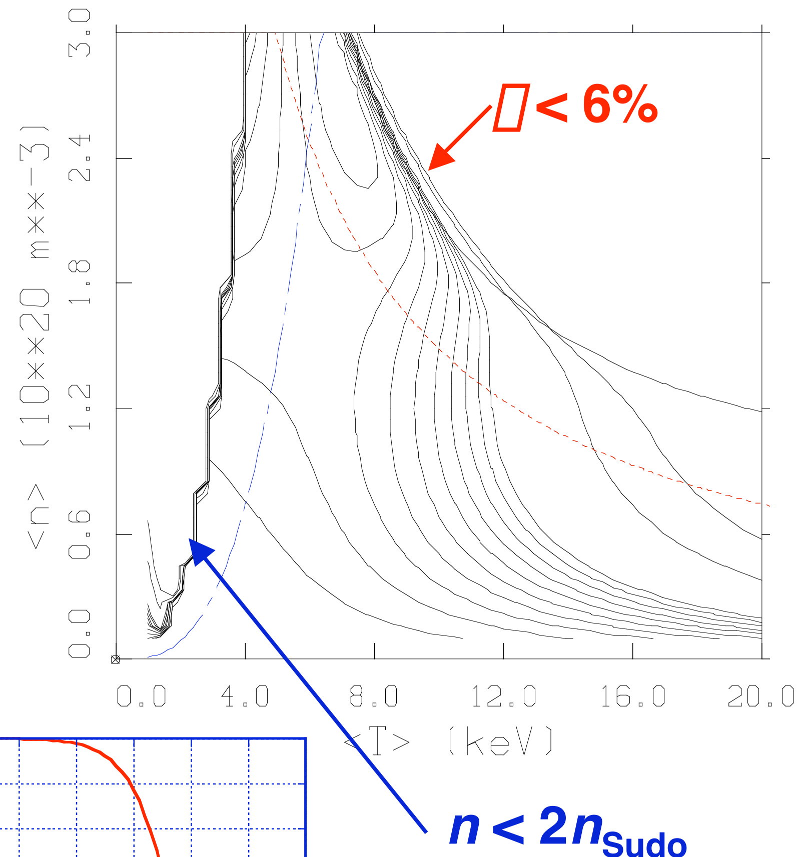
C 1%, Fe 0.01%

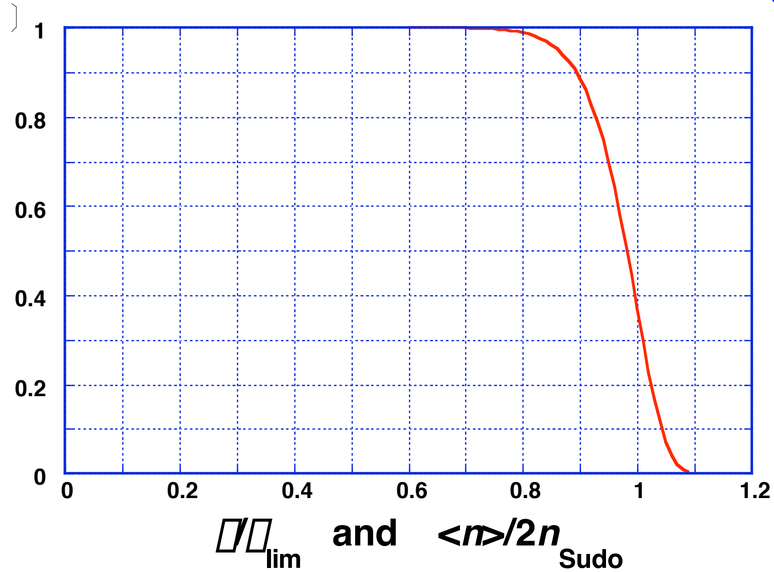
POPCON Features



Constraints Limit Operating Space







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  - **A proposed new reference case**
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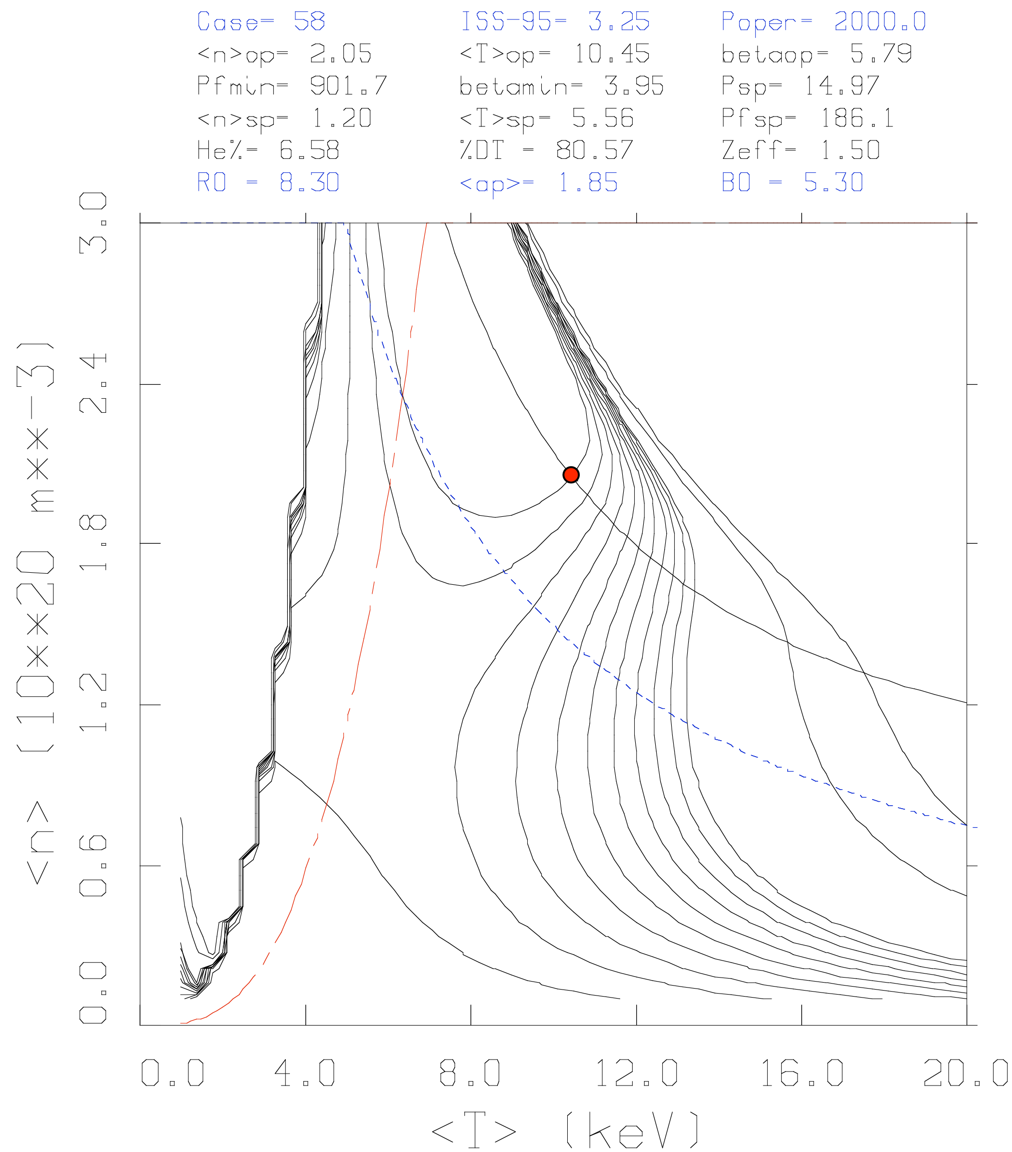
Drop Earlier (May 2003) Cases

Working Configuration for ARIES-CS study (5/3/2003)

Parameter	High-field Case	Larger Size Case
Device parameters		
□ (m)	**1.2**	**1.4**
coil cross section	20 cm x 20 cm	30 cm x 30 cm
$\langle R \rangle$ (m)	**8.3**	**9.68**
$\langle a \rangle$ (m)	1.85	2.15
V_p (m3)	550	872
S (m2)	780	1060
B_0 (T)	**6.4**	**5.65**
B_{max} (T)	19.4	14.4
$\langle j \rangle$ (kA/cm2)	40	17.4
Operating point		
$\langle n \rangle$ (10^{20} m^{-3})	1.86	1.51
$\langle T \rangle$ (keV)	11.9	11.6
$\langle$□$\rangle$ (%)	**4.08**	**4.15**
% He	7.4	7.3
% D-T	79	79
Z_{eff}	1.51	1.51
□$_n$ (MW/m^2)	2	1.56
Minimum ignition		
P_f (GW)	0.600	0.6
$\langle$□$\rangle$ (%)	2.22	2.22
Saddle-point heating power	~12 MW	~15 MW

Increasing <β> to 5.8% and β limit to 7% Improves Case with R = 8.3 m and B_0 = 5.3 T

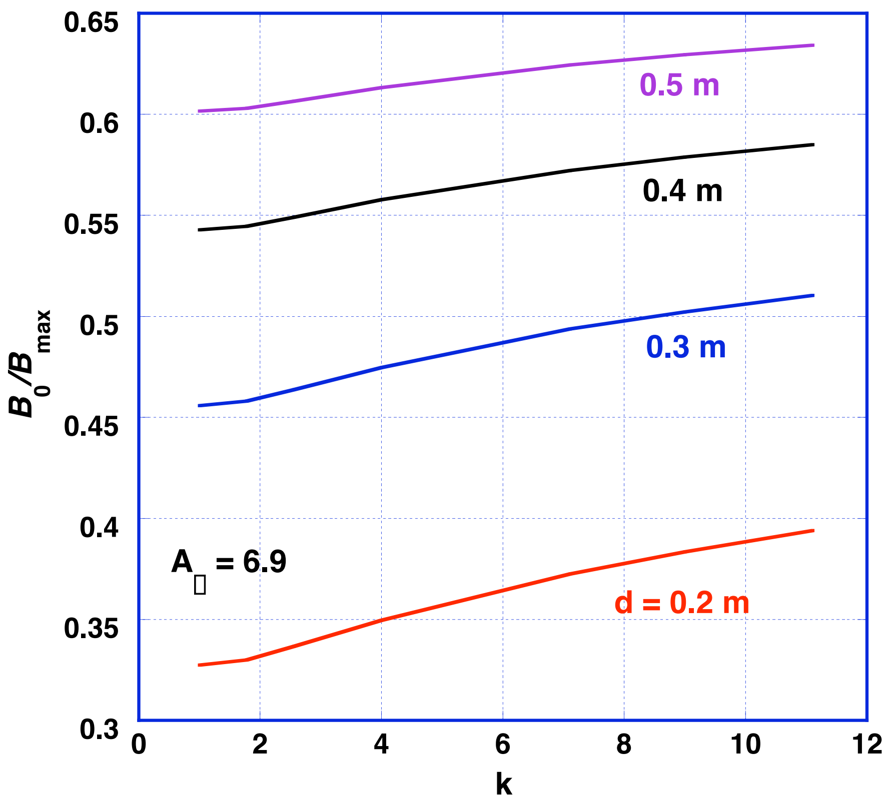


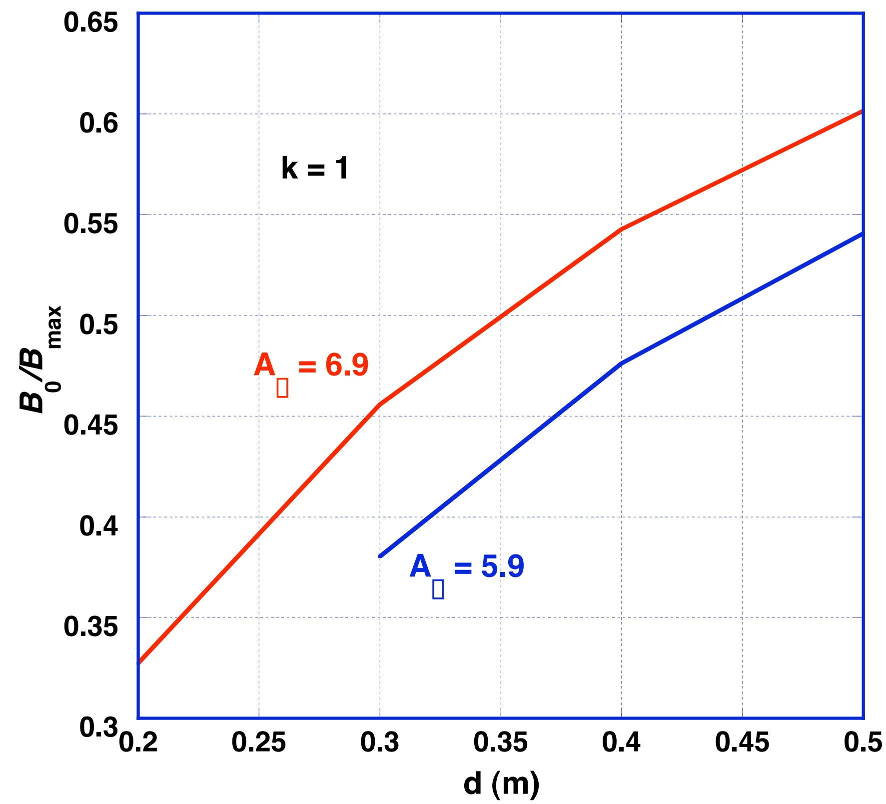
New Optimization Approach

- **Minimize $<R> = A_{\Box}(t + d/2k^{1/2})$ with constraints**
  - maximum B_0 that gives B_{max} on coil = 16 T
    (also looked at B_{max} = 14 T and 12 T)
  - $<j_{coil}>$ < 330 MA/m^2 for high-T_c superconductor
    (110–135 MA/m^2 if low-T_c Nb_3Sn)
  - minimum distance between coils > 0 (2.5-cm case)
- **Determine minimum H-ISS95 that satisfies**
  - fusion power P = 2 GW
  - operating point on thermally stable branch of ignition curve
  - average neutron wall loading < 4 MW/m^2
  - $\beta < \beta_{limit}$

Parameter Scaling (2/25/03 coil set)

- $<R> = A_{\square}(t + d/2k^{1/2})$; $t = 1.1$m (Laila, May 2003)
- $<j_{coil}> = 13\,(B_0/5.3)(R/8.25)/d^2$
- $B_0 = 16\ B_0/B_{max}(d,k)\ /\ \{(B_0/5.3)(R/8.25)\}$
- Min. coil-coil dist. $= 0.88(R/8.3) - k^{1/2}d - 2(0.025)$





Can Improve If Allow k > 1

Ku's 2/25/03 coil set   local TBR = 1.22   (8% no blanket, 2% penetrations)

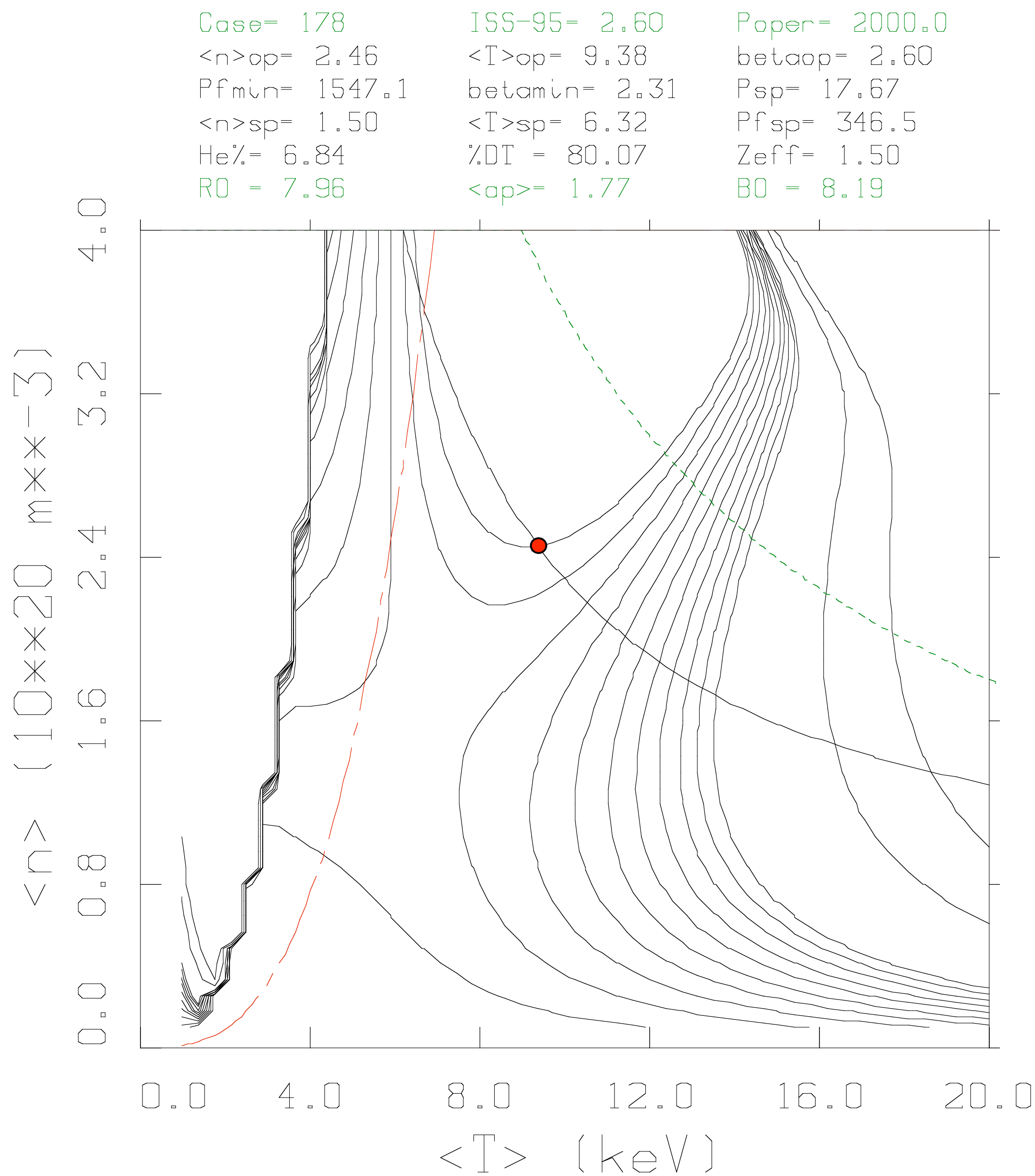
coil d	coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta
	1	8.26	1.83	5.23	321.24	0.63	0.99	2.49	1.60	6.02
	1.7777777	8.08	1.80	5.39	323.77	0.55	0.95	2.60	1.54	5.86
0.2 m	**2.56**	**8.00**	**1.78**	**5.56**	**330.32**	**0.48**	**0.93**	**2.65**	**1.51**	**5.60**
	4	7.91	1.76	5.83	343.00	0.39	0.91	2.71	1.48	5.17
	7.1111111	7.83	1.74	6.28	365.48	0.25	0.89	2.77	1.44	4.53
	9	7.80	1.73	6.49	376.23	0.18	0.88	2.79	1.43	4.26
	11.1111111	7.77	1.73	6.69	386.49	0.11	0.88	2.81	1.43	4.04
	16	7.74	1.72	7.02	404.06	-0.02	0.87	2.83	1.41	3.68

coil d	coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta
	1	8.60	1.91	7.00	198.75	0.57	1.07	2.30	1.74	3.17
	1.7777777	8.34	1.85	7.25	199.72	0.44	1.01	2.44	1.64	3.09
0.3 m	2.56	8.21	1.83	7.45	202.22	0.35	0.98	2.52	1.59	2.99
	4	8.08	1.80	7.75	206.98	0.21	0.95	2.60	1.54	2.83
	7.111111	**7.96**	**1.77**	**8.19**	**215.34**	**0.00**	**0.92**	**2.68**	**1.49**	**2.60**
	9	7.91	1.76	8.38	218.96	-0.11	0.91	2.71	1.48	2.51
	11.1111111	7.88	1.75	8.55	222.56	-0.21	0.90	2.73	1.46	2.42
	16	7.83	1.74	8.86	229.09	-0.42	0.89	2.77	1.44	2.28

coil d	coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta
	1	8.94	1.99	8.01	133.14	0.50	1.16	2.13	1.88	2.28
	1.7777777	8.60	1.91	8.36	133.58	0.33	1.07	2.30	1.74	2.22
0.4 m	2.56	8.43	1.87	8.60	134.69	0.21	1.03	2.39	1.67	2.16
	4	**8.26**	**1.83**	**8.92**	**136.81**	**0.03**	**0.99**	**2.49**	**1.60**	**2.07**
	7.1111111	8.08	1.80	9.34	140.36	-0.25	0.95	2.60	1.54	1.95
	9	8.03	1.78	9.52	141.99	-0.39	0.94	2.63	1.52	1.90
	11.1111111	7.98	1.77	9.68	143.51	-0.53	0.92	2.66	1.50	1.85
	16	7.91	1.76	9.95	146.24	-0.81	0.91	2.71	1.48	1.78

coil d	coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta
	1	9.29	2.06	8.55	94.44	0.44	1.25	1.98	2.03	1.89
	1.7777777	8.86	1.97	8.98	94.65	0.23	1.14	2.17	1.84	1.84
0.5 m	**2.56**	**8.64**	**1.92**	**9.26**	**95.21**	**0.07**	**1.08**	**2.28**	**1.76**	**1.79**
	4	8.43	1.87	9.60	96.27	-0.15	1.03	2.39	1.67	1.73
	7.1111111	8.21	1.83	10.04	98.02	-0.51	0.98	2.52	1.59	1.65
	9	8.14	1.81	10.21	98.81	-0.68	0.96	2.56	1.56	1.62
	11.1111111	8.08	1.80	10.35	99.55	-0.85	0.95	2.60	1.54	1.59
	16	8.00	1.78	10.61	100.87	-1.20	0.93	2.65	1.51	1.54

2/25/03 Coils with $R = 7.96$ m and $B_0 = 8.19$ T



Can Do Better with Ku's 8/1/2003 Coils

Ku's 8/1/03 coil set **local TBR = 1.29 (13% no blanket, 2% penetrations)**

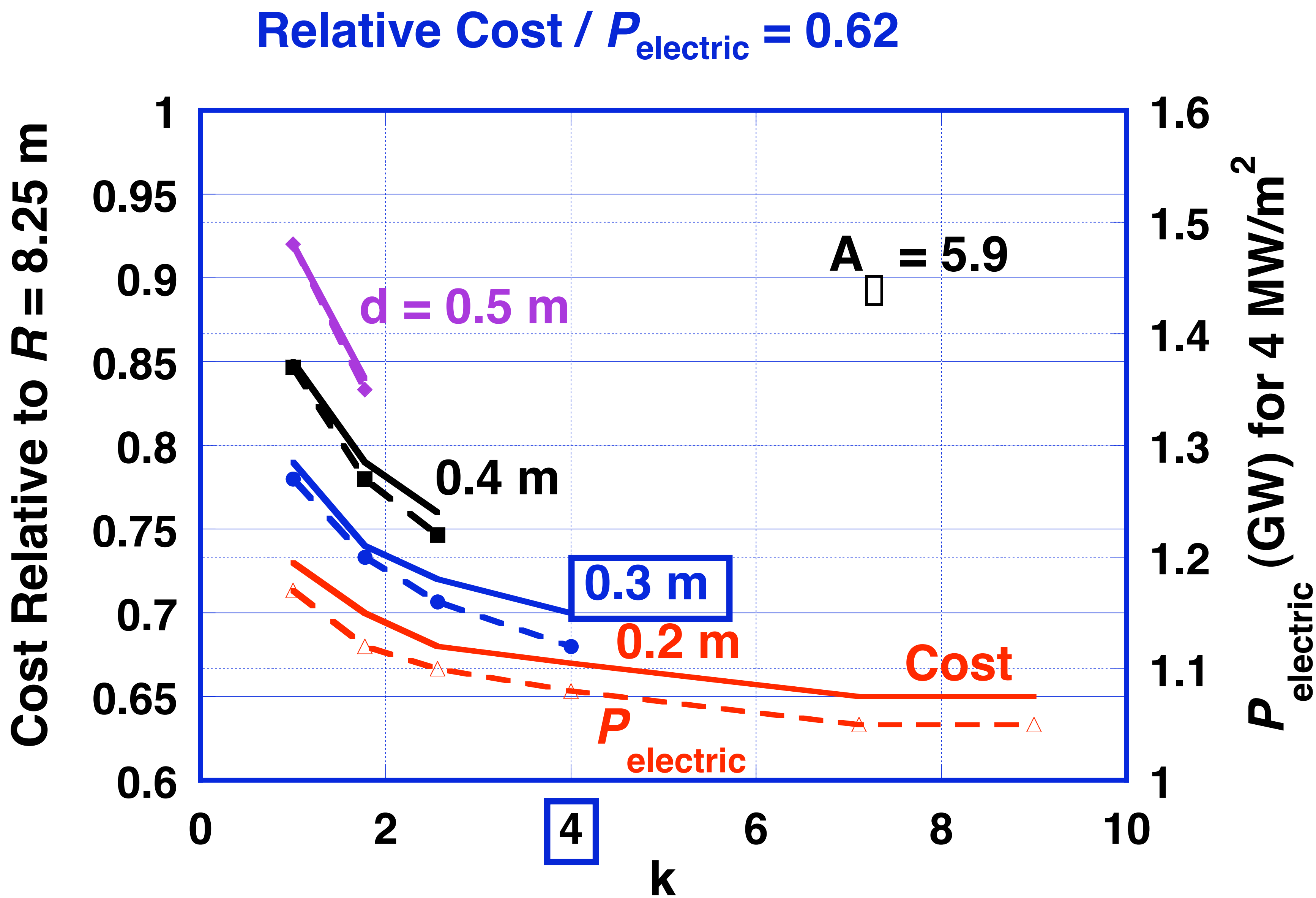
coil d	coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta
	1.00	7.08	1.57	4.54	245.63	0.45	0.73	3.42	1.17	10.09
	1.78	6.93	1.54	4.67	247.56	0.37	0.70	3.56	1.12	9.83
	2.56	6.86	1.52	4.82	252.58	0.31	0.68	3.64	1.10	9.39
0.2 m	4.00	6.79	1.51	5.06	262.32	0.22	0.67	3.71	1.08	8.66
	7.11	6.71	1.49	5.45	279.54	0.08	0.65	3.79	1.05	7.58
	9.00	**6.69**	**1.49**	**5.63**	**287.71**	**0.01**	**0.65**	**3.82**	**1.05**	**7.15**
	11.11	6.67	1.48	5.80	295.57	-0.05	0.65	3.84	1.04	6.76

coil d	coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta
	1.00	7.38	1.64	6.85	171.64	0.38	0.79	3.15	1.27	4.17
	1.78	7.15	1.59	7.09	172.45	0.26	0.74	3.35	1.20	4.06
	2.56	7.04	1.57	7.30	174.60	0.17	0.72	3.45	1.16	3.93
0.3 m	**4.00**	**6.93**	**1.54**	**7.59**	**178.75**	**0.04**	**0.70**	**3.56**	**1.12**	**3.72**
	7.11	6.82	1.52	8.02	186.01	-0.17	0.68	3.67	1.09	3.41
	9.00	6.79	1.51	8.20	189.13	-0.28	0.67	3.71	1.08	3.29
	11.11	6.76	1.50	8.37	192.22	-0.38	0.66	3.75	1.07	3.18

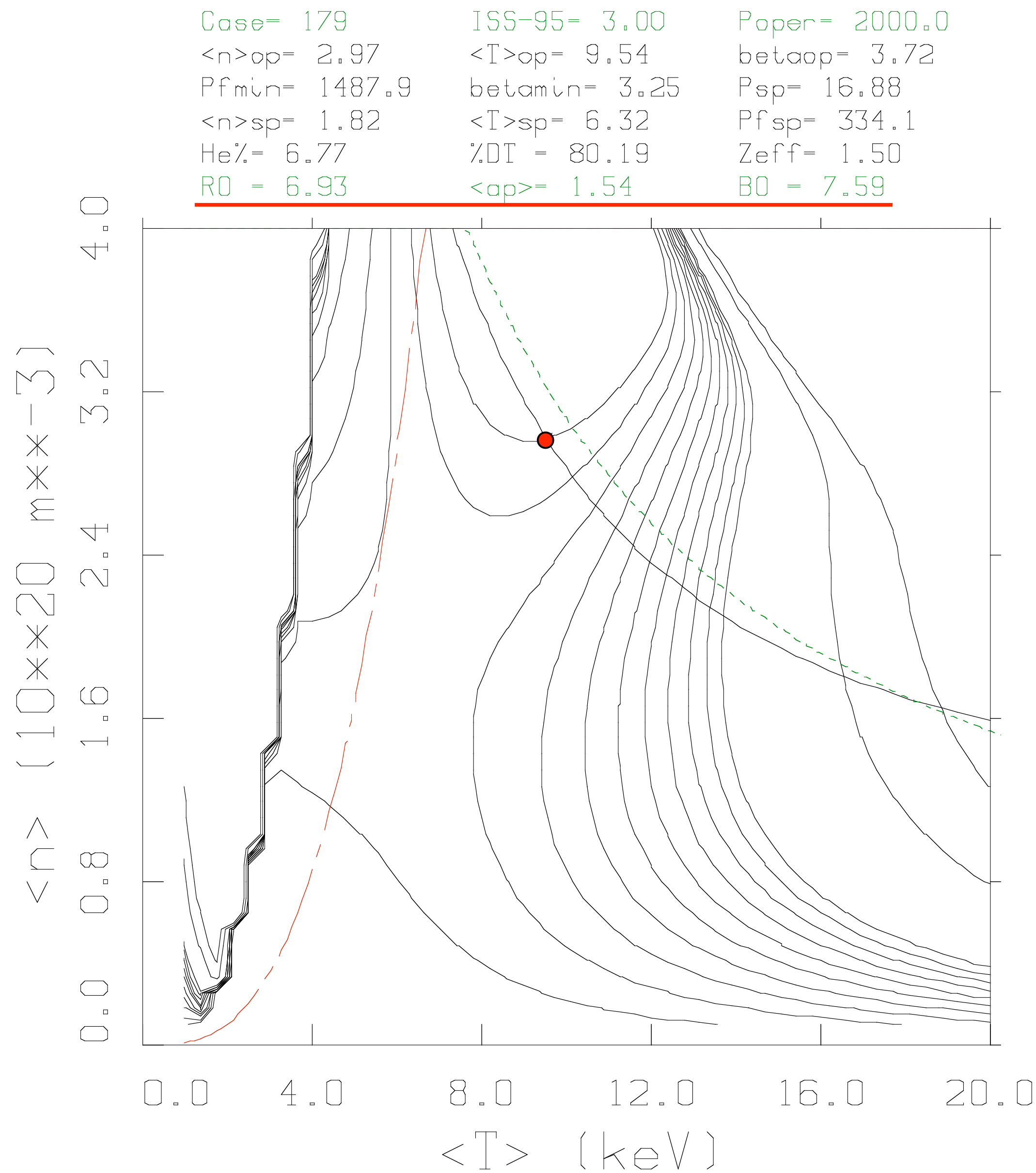
coil d	coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta
	1.00	7.67	1.70	8.24	120.88	0.31	0.85	2.92	1.37	2.71
	1.78	7.38	1.64	8.60	121.23	0.15	0.79	3.15	1.27	2.64
0.4 m	**2.56**	**7.23**	**1.61**	**8.85**	**122.31**	**0.03**	**0.76**	**3.28**	**1.22**	**2.57**
	4.00	7.08	1.57	9.18	124.25	-0.15	0.73	3.42	1.17	2.46
	7.11	6.93	1.54	9.62	127.41	-0.43	0.70	3.56	1.12	2.32
	9.00	6.88	1.53	9.80	128.91	-0.57	0.69	3.61	1.11	2.26
	11.11	6.84	1.52	9.96	130.33	-0.70	0.68	3.65	1.10	2.20

coil d	coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta
	1.00	7.97	1.77	9.02	87.85	0.24	0.92	2.71	1.48	2.14
0.5 m	**1.78**	**7.60**	**1.69**	**9.48**	**88.07**	**0.04**	**0.84**	**2.97**	**1.35**	**2.08**
	2.56	7.41	1.65	9.77	88.59	-0.11	0.80	3.12	1.28	2.03
	4.00	7.23	1.61	10.13	89.57	-0.33	0.76	3.28	1.22	1.96
	7.11	7.04	1.57	10.58	91.19	-0.68	0.72	3.45	1.16	1.87
	9.00	6.98	1.55	10.76	91.91	-0.86	0.71	3.51	1.14	1.83
	11.11	6.93	1.54	10.92	92.63	-1.03	0.70	3.56	1.12	1.80

Variation of Cost and Maximum Power



8/1/03 Coils with $R = 6.93$ m and $B_0 = 7.59$ T



New reference case?

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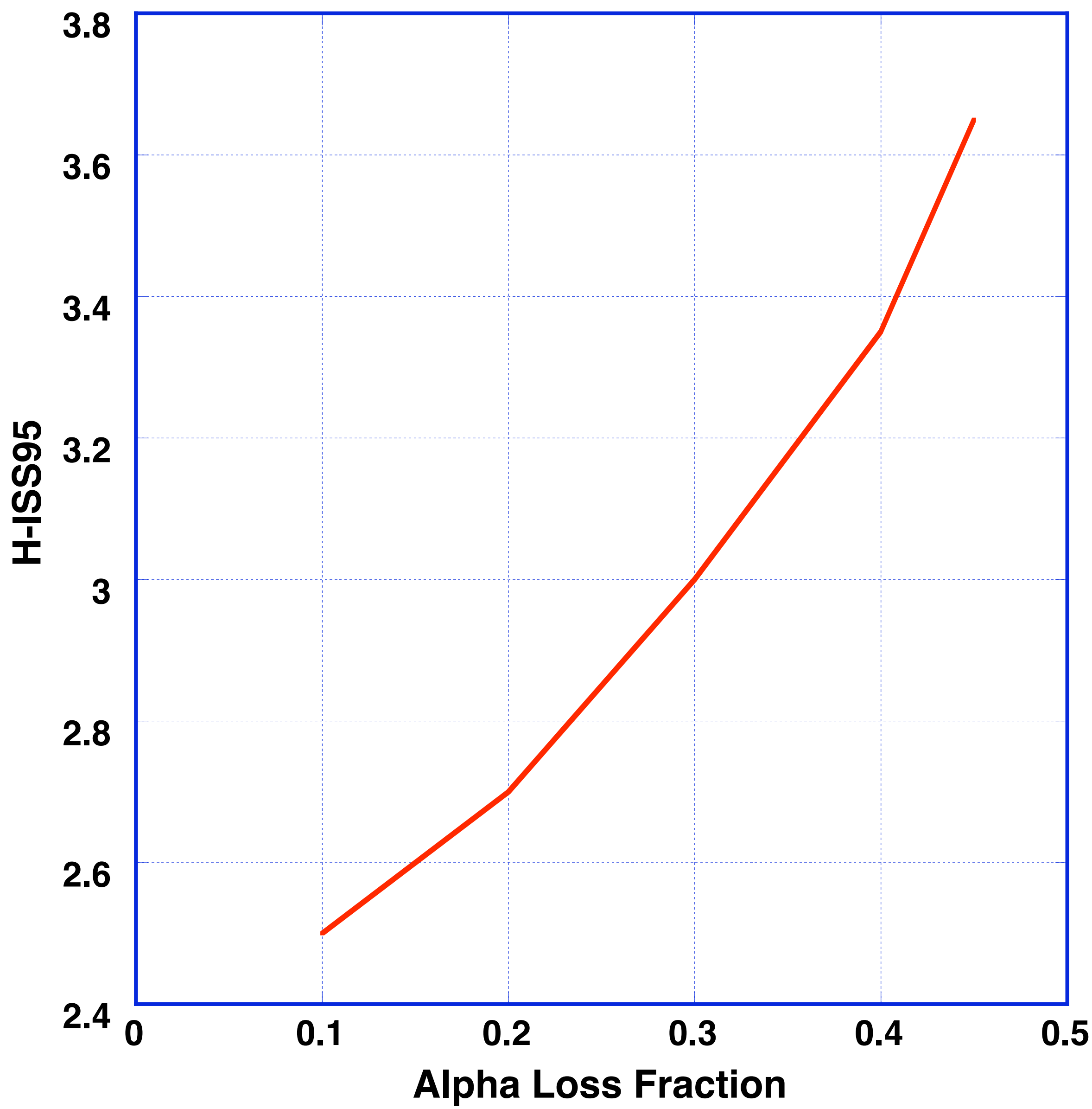
H-ISS95 Required Increases with Loss



Other Considerations

- Smallest $<R>$ leads to lowest cost
  - blanket, shield, and coil volume (for fixed j_{coil}) □ R^2

  □ gives R = 6.93 m, B_0 = 7.59 T, rel. cost = 0.7
  for t = 1.1 m, d = 3, k = 4, B_{max} = 16 T, high-T_c SC

- Other considerations
  - is t = 1.1 m OK? 1.2 or 1.3 m?
  - d = 0.3 m and k >> 1 OK?
  - B_{max} = 16 T OK? 14 T or 12 T?
  - high-T_c superconductor for larger $<j_{coil}>$ (and smaller d) or Nb_3Sn?

- P = 1.5 GW or 2 GW desirable?
  - larger $<R>$ but lower cost of electricity
  - higher □ and neutron wall loading

Smaller *t* Gives a More Attractive Reactor

Ku's 8/1/03 coil set **d = 0.3 m** **Bmax = 16 T**

t = 0.95 m

coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta	H-ISS95
1.00	**6.49**	**1.44**	**7.78**	**171.64**	**0.29**	**0.61**	**4.05**	**0.99**	**3.91**	**3.05**
1.78	6.27	1.39	8.10	172.45	0.17	0.57	4.34	0.92	3.80	3.02
2.56	6.16	1.37	8.34	174.60	0.08	0.55	4.49	0.89	3.68	2.98
4.00	6.05	1.34	8.70	178.75	-0.05	0.53	4.66	0.86	3.48	2.92
7.11	5.94	1.32	9.22	186.01	-0.26	0.51	4.83	0.83	3.18	2.82
9.00	5.90	1.31	9.43	189.13	-0.36	0.51	4.89	0.82	3.07	2.78
10.95	5.87	1.30	9.63	192.22	-0.46	0.50	4.93	0.81	2.96	2.75

t = 1.0 m

coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta	H-ISS95
1.00	**6.79**	**1.51**	**7.44**	171.64	0.32	0.67	3.71	1.08	4.00	3.08
1.78	**6.56**	**1.46**	**7.73**	**172.45**	**0.20**	**0.63**	**3.96**	**1.01**	**3.89**	**3.05**
2.56	6.45	1.43	7.96	174.60	0.11	0.60	4.10	0.98	3.77	3.01
4.00	6.34	1.41	8.29	178.75	-0.02	0.58	4.24	0.94	3.56	2.94
7.11	6.23	1.38	8.78	186.01	-0.23	0.56	4.39	0.91	3.26	2.85
9.00	6.20	1.38	8.98	189.13	-0.33	0.56	4.44	0.90	3.14	2.81
11.01	6.17	1.37	9.17	192.22	-0.43	0.55	4.48	0.89	3.04	2.77

t = 1.05 m

coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta	H-ISS95
1.00	**7.08**	**1.57**	**7.13**	171.64	0.35	0.73	3.42	1.17	4.08	3.10
1.78	**6.86**	**1.52**	**7.40**	172.45	0.23	0.68	3.64	1.10	3.98	3.07
2.56	**6.75**	**1.50**	**7.61**	174.60	0.14	0.66	3.75	1.07	3.85	3.03
4.00	**6.64**	**1.48**	**7.92**	**178.75**	**0.01**	**0.64**	**3.88**	**1.03**	**3.64**	**2.97**
7.11	6.53	1.45	8.39	186.01	-0.20	0.62	4.01	1.00	3.34	2.87
9.00	6.49	1.44	8.58	189.13	-0.31	0.61	4.05	0.99	3.22	2.83
11.05	6.46	1.44	8.75	192.22	-0.41	0.61	4.09	0.98	3.11	2.80

t = 1.1 m

coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta	H-ISS95
1.00	**7.38**	**1.64**	**6.85**	171.64	0.38	0.79	3.15	1.27	4.17	3.12
1.78	**7.15**	**1.59**	**7.09**	172.45	0.26	0.74	3.35	1.20	4.06	3.10
2.56	**7.04**	**1.57**	**7.30**	174.60	0.17	0.72	3.45	1.16	3.93	3.06
4.00	**6.93**	**1.54**	**7.59**	**178.75**	**0.04**	**0.70**	**3.56**	**1.12**	**3.72**	**2.99**
7.11	6.82	1.52	8.02	186.01	-0.17	0.68	3.67	1.09	3.41	2.90
9.00	6.79	1.51	8.20	189.13	-0.28	0.67	3.71	1.08	3.29	2.86
11.11	6.76	1.50	8.37	192.22	-0.38	0.66	3.75	1.07	3.18	2.82

Larger *t* Gives a Less Attractive Reactor

Ku's 8/1/03 coil set **d = 0.3 m** **Bmax = 16 T**

t = 1.0 m

coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta	H-ISS95
1.00	6.79	1.51	7.44	171.64	0.32	0.67	3.71	1.08	4.00	3.08
1.78	**6.56**	**1.46**	**7.73**	**172.45**	**0.20**	**0.63**	**3.96**	**1.01**	**3.89**	**3.05**
2.56	6.45	1.43	7.96	174.60	0.11	0.60	4.10	0.98	3.77	3.01
4.00	6.34	1.41	8.29	178.75	-0.02	0.58	4.24	0.94	3.56	2.94
7.11	6.23	1.38	8.78	186.01	-0.23	0.56	4.39	0.91	3.26	2.85
9.00	6.20	1.38	8.98	189.13	-0.33	0.56	4.44	0.90	3.14	2.81
11.01	6.17	1.37	9.17	192.22	-0.43	0.55	4.48	0.89	3.04	2.77

t = 1.1 m

coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta	H-ISS95
1.00	7.38	1.64	6.85	171.64	0.38	0.79	3.15	1.27	4.17	3.12
1.78	7.15	1.59	7.09	172.45	0.26	0.74	3.35	1.20	4.06	3.10
2.56	7.04	1.57	7.30	174.60	0.17	0.72	3.45	1.16	3.93	3.06
4.00	**6.93**	**1.54**	**7.59**	**178.75**	**0.04**	**0.70**	**3.56**	**1.12**	**3.72**	**2.99**
7.11	6.82	1.52	8.02	186.01	-0.17	0.68	3.67	1.09	3.41	2.90
9.00	6.79	1.51	8.20	189.13	-0.28	0.67	3.71	1.08	3.29	2.86
11.11	6.76	1.50	8.37	192.22	-0.38	0.66	3.75	1.07	3.18	2.82

t = 1.2 m

1.00	7.97	1.77	6.34	171.64	0.44	0.92	2.71	1.48	4.33	3.17
1.78	7.74	1.72	6.55	172.45	0.32	0.87	2.86	1.40	4.23	3.14
2.56	7.63	1.70	6.73	174.60	0.23	0.85	2.94	1.36	4.10	3.10
4.00	**7.52**	**1.67**	**6.99**	**178.75**	**0.10**	**0.82**	**3.03**	**1.32**	**3.88**	**3.04**
7.11	7.41	1.65	7.39	186.01	-0.11	0.80	3.12	1.28	3.56	2.94
9.00	7.38	1.64	7.55	189.13	-0.22	0.79	3.15	1.27	3.43	2.90
11.21	6.75	1.50	8.37	192.22	-0.38	0.66	3.75	1.07	3.18	2.82

t = 1.3 m

1.00	8.56	1.90	5.90	171.64	0.50	1.06	2.35	1.70	4.49	3.21
1.78	8.33	1.85	6.09	172.45	0.38	1.01	2.48	1.62	4.39	3.19
2.56	8.22	1.83	6.25	174.60	0.29	0.98	2.54	1.57	4.25	3.15
4.00	**8.11**	**1.80**	**6.48**	**178.75**	**0.16**	**0.96**	**2.61**	**1.53**	**4.03**	**3.09**
7.11	8.00	1.78	6.84	186.01	-0.06	0.93	2.68	1.49	3.69	2.99
9.00	7.97	1.77	6.99	189.13	-0.16	0.92	2.71	1.48	3.57	2.95
11.31	6.75	1.50	8.38	192.22	-0.39	0.66	3.75	1.07	3.18	2.82

Can Reduce B_{max} to 14 T or 12 T If Needed

Ku's 8/1/03 coil set

d = 0.3 m   t = 1.1 m   Bmax = 16 T

coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta	H-ISS95
1	7.38	1.64	6.85	171.64	0.38	0.79	3.15	1.27	4.17	3.12
1.7777777	7.15	1.59	7.09	172.45	0.26	0.74	3.35	1.20	4.06	3.10
2.56	7.04	1.57	7.30	174.60	0.17	0.72	3.45	1.16	3.93	3.06
4	**6.93**	**1.54**	**7.59**	**178.75**	**0.04**	**0.70**	**3.56**	**1.12**	**3.72**	**2.99**
7.1111111	6.82	1.52	8.02	186.01	-0.17	0.68	3.67	1.09	3.41	2.90
9	6.79	1.51	8.20	189.13	-0.28	0.67	3.71	1.08	3.29	2.86
11.1111111	6.76	1.50	8.37	192.22	-0.38	0.66	3.75	1.07	3.18	2.82

d = 0.3 m   t = 1.1 m   Bmax = 14 T

coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta	H-ISS95
1	7.38	1.64	5.99	150.19	0.38	0.79	3.15	1.27	5.44	3.46
1.7777777	7.15	1.59	6.21	150.89	0.26	0.74	3.35	1.20	5.31	3.43
2.56	7.04	1.57	6.38	152.78	0.17	0.72	3.45	1.16	5.14	3.38
4	**6.93**	**1.54**	**6.64**	**156.41**	**0.04**	**0.70**	**3.56**	**1.12**	**4.86**	**3.31**
7.1111111	6.82	1.52	7.02	162.76	-0.17	0.68	3.67	1.09	4.46	3.21
9	6.79	1.51	7.18	165.48	-0.28	0.67	3.71	1.08	4.30	3.16
11.1111111	6.76	1.50	7.33	168.20	-0.38	0.66	3.75	1.07	4.15	3.12

d = 0.3 m   t = 1.1 m   Bmax = 12 T

coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta	H-ISS95
1	7.38	1.64	5.14	128.73	0.38	0.79	3.15	1.27	7.41	3.89
1.7777777	7.15	1.59	5.32	129.34	0.26	0.74	3.35	1.20	7.23	3.85
2.56	7.04	1.57	5.47	130.95	0.17	0.72	3.45	1.16	6.99	3.80
4	**6.93**	**1.54**	**5.69**	**134.06**	**0.04**	**0.70**	**3.56**	**1.12**	**6.62**	**3.73**
7.1111111	6.82	1.52	6.02	139.51	-0.17	0.68	3.67	1.09	6.06	3.60
9	6.79	1.51	6.15	141.84	-0.28	0.67	3.71	1.08	5.85	3.55
11.1111111	6.76	1.50	6.28	144.17	-0.38	0.66	3.75	1.07	5.65	3.51

d = 0.4 m   t = 1.1 m   Bmax = 16 T

coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta	H-ISS95
1	7.67	1.70	8.24	120.88	0.31	0.85	2.92	1.37	2.71	2.65
1.7777777	7.38	1.64	8.60	121.23	0.15	0.79	3.15	1.27	2.64	2.63
2.56	**7.23**	**1.61**	**8.85**	**122.31**	**0.03**	**0.76**	**3.28**	**1.22**	**2.57**	**2.60**
4	7.08	1.57	9.18	124.25	-0.15	0.73	3.42	1.17	2.46	2.56
7.1111111	6.93	1.54	9.62	127.41	-0.43	0.70	3.56	1.12	2.32	2.50
9	6.88	1.53	9.80	128.91	-0.57	0.69	3.61	1.11	2.26	2.48
11.1111111	6.84	1.52	9.96	130.33	-0.70	0.68	3.65	1.10	2.20	2.45

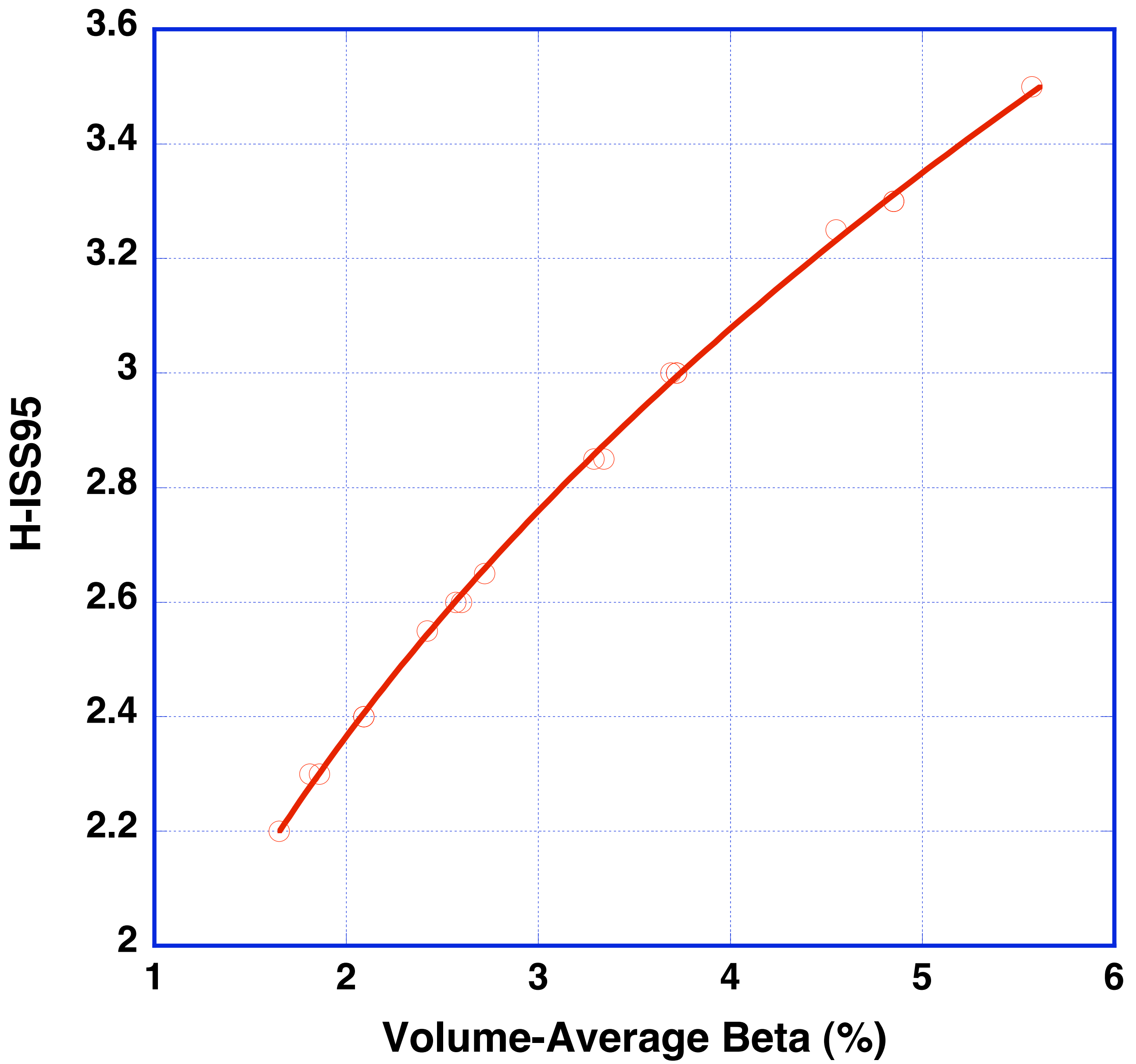
d = 0.4 m   t = 1.1 m   Bmax = 14 T

coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta	H-ISS95
1	7.67	1.70	7.21	105.77	0.31	0.85	2.92	1.37	3.54	2.94
1.7777777	7.38	1.64	7.52	106.08	0.15	0.79	3.15	1.27	3.45	2.91
2.56	**7.23**	**1.61**	**7.75**	**107.02**	**0.03**	**0.76**	**3.28**	**1.22**	**3.36**	**2.88**
4	7.08	1.57	8.03	108.72	-0.15	0.73	3.42	1.17	3.22	2.83
7.1111111	6.93	1.54	8.41	111.49	-0.43	0.70	3.56	1.12	3.03	2.77
9	6.88	1.53	8.57	112.79	-0.57	0.69	3.61	1.11	2.95	2.74
11.1111111	6.84	1.52	8.72	114.04	-0.70	0.68	3.65	1.10	2.88	2.72

d = 0.4 m   t = 1.1 m   Bmax = 12 T

coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta	H-ISS95
1	7.67	1.70	6.18	90.66	0.31	0.85	2.92	1.37	4.82	3.30
1.7777777	7.38	1.64	6.45	90.93	0.15	0.79	3.15	1.27	4.70	3.27
2.56	**7.23**	**1.61**	**6.64**	**91.73**	**0.03**	**0.76**	**3.28**	**1.22**	**4.57**	**3.24**
4	7.08	1.57	6.89	93.19	-0.15	0.73	3.42	1.17	4.38	3.19
7.1111111	6.93	1.54	7.21	95.56	-0.43	0.70	3.56	1.12	4.12	3.11
9	6.88	1.53	7.35	96.68	-0.57	0.69	3.61	1.11	4.01	3.08
11.1111111	6.84	1.52	7.47	97.75	-0.70	0.68	3.65	1.10	3.91	3.05

H-ISS95 Scales as $\langle \beta \rangle^{0.38}$



Nb_3Sn Coils Give a Less Attractive Reactor

Ku's 8/1/03 coil set d = 0.3 m Bmax = 16 T **Cost (4 MW/m2) = 0.62**

coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta
1	7.38	1.64	6.85	171.64	0.38	0.79	3.15	1.27	4.17
1.7777777	7.15	1.59	7.09	172.45	0.26	0.74	3.35	1.20	4.06
2.56	7.04	1.57	7.30	174.60	0.17	0.72	3.45	1.16	3.93
4	**6.93**	**1.54**	**7.59**	**178.75**	**0.04**	**0.70**	**3.56**	**1.12**	**3.72**
7.1111111	6.82	1.52	8.02	186.01	-0.17	0.68	3.67	1.09	3.41
9	6.79	1.51	8.20	189.13	-0.28	0.67	3.71	1.08	3.29
11.1111111	6.76	1.50	8.37	192.22	-0.38	0.66	3.75	1.07	3.18

d = 0.3 m t = 1.1 m Bmax = 14 T

coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta
1	7.38	1.64	5.99	150.19	0.38	0.79	3.15	1.27	5.44
1.7777777	7.15	1.59	6.21	150.89	0.26	0.74	3.35	1.20	5.31
2.56	7.04	1.57	6.38	152.78	0.17	0.72	3.45	1.16	5.14
4	**6.93**	**1.54**	**6.64**	**156.41**	**0.04**	**0.70**	**3.56**	**1.12**	**4.86**
7.1111111	6.82	1.52	7.02	162.76	-0.17	0.68	3.67	1.09	4.46
9	6.79	1.51	7.18	165.48	-0.28	0.67	3.71	1.08	4.30
11.1111111	6.76	1.50	7.33	168.20	-0.38	0.66	3.75	1.07	4.15

d = 0.3 m t = 1.1 m Bmax = 12 T

coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta
1	7.38	1.64	5.14	128.73	0.38	0.79	3.15	1.27	7.41
1.7777777	7.15	1.59	5.32	129.34	0.26	0.74	3.35	1.20	7.23
2.56	7.04	1.57	5.47	130.95	0.17	0.72	3.45	1.16	6.99
4	**6.93**	**1.54**	**5.69**	**134.06**	**0.04**	**0.70**	**3.56**	**1.12**	**6.62**
7.1111111	6.82	1.52	6.02	139.51	-0.17	0.68	3.67	1.09	6.06
9	6.79	1.51	6.15	141.84	-0.28	0.67	3.71	1.08	5.85
11.1111111	6.76	1.50	6.28	144.17	-0.38	0.66	3.75	1.07	5.65

d = 0.4 m t = 1.1 m Bmax = 16 T

coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta
1	7.67	1.70	8.24	120.88	0.31	0.85	2.92	1.37	2.71
1.7777777	7.38	1.64	8.60	121.23	0.15	0.79	3.15	1.27	2.64
2.56	**7.23**	**1.61**	**8.85**	**122.31**	**0.03**	**0.76**	**3.28**	**1.22**	**2.57**
4	7.08	1.57	9.18	124.25	-0.15	0.73	3.42	1.17	2.46
7.1111111	6.93	1.54	9.62	127.41	-0.43	0.70	3.56	1.12	2.32
9	6.88	1.53	9.80	128.91	-0.57	0.69	3.61	1.11	2.26
11.1111111	6.84	1.52	9.96	130.33	-0.70	0.68	3.65	1.10	2.20

d = 0.4 m t = 1.1 m Bmax = 14 T

coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta
1	7.67	1.70	7.21	105.77	0.31	0.85	2.92	1.37	3.54
1.7777777	7.38	1.64	7.52	106.08	0.15	0.79	3.15	1.27	3.45
2.56	**7.23**	**1.61**	**7.75**	**107.02**	**0.03**	**0.76**	**3.28**	**1.22**	**3.36**
4	7.08	1.57	8.03	108.72	-0.15	0.73	3.42	1.17	3.22
7.1111111	6.93	1.54	8.41	111.49	-0.43	0.70	3.56	1.12	3.03
9	6.88	1.53	8.57	112.79	-0.57	0.69	3.61	1.11	2.95
11.1111111	6.84	1.52	8.72	114.04	-0.70	0.68	3.65	1.10	2.88

d = 0.4 m t = 1.1 m Bmax = 12 T

coil k	R axis (m)	<a> (m)	Max B axis	jc (MA/m2)	d c-c min	Cost factor	Wall load	PE max	Beta
1	7.67	1.70	6.18	90.66	0.31	0.85	2.92	1.37	4.82
1.7777777	7.38	1.64	6.45	90.93	0.15	0.79	3.15	1.27	4.70
2.56	**7.23**	**1.61**	**6.64**	**91.73**	**0.03**	**0.76**	**3.28**	**1.22**	**4.57**
4	7.08	1.57	6.89	93.19	-0.15	0.73	3.42	1.17	4.38
7.1111111	6.93	1.54	7.21	95.56	-0.43	0.70	3.56	1.12	4.12
9	6.88	1.53	7.35	96.68	-0.57	0.69	3.61	1.11	4.01
11.1111111	6.84	1.52	7.47	97.75	-0.70	0.68	3.65	1.10	3.91

TOPICS

- Plasma and coil characteristics
- 1-D POPCON plots
- Improvements over May reference cases
  - A proposed new reference case
- Sensitivities to different assumptions
- **Status of systems code**

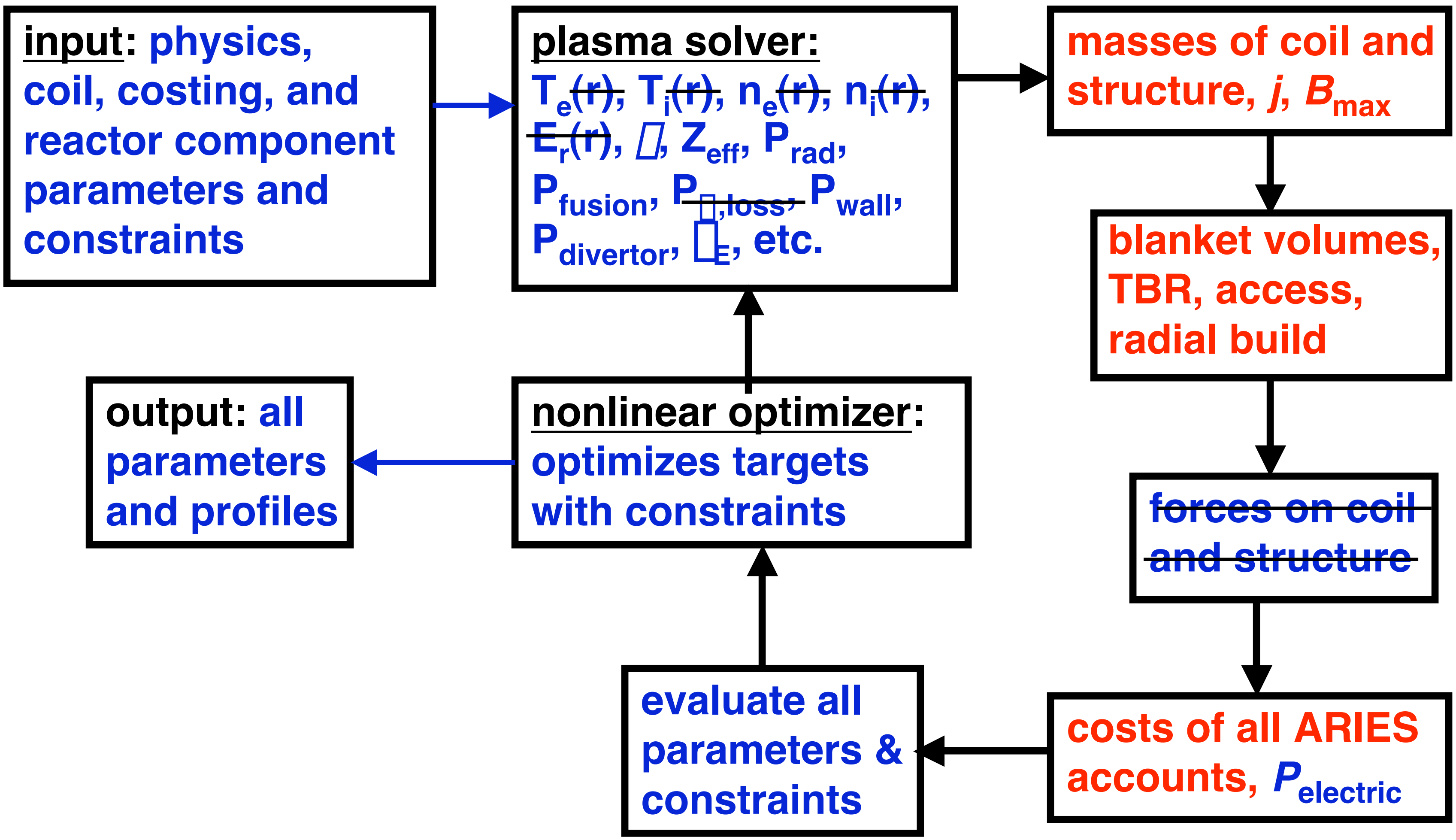
Systems Code Being Updated

- Have upgraded to current math libraries and operating system
- Incorporating plasma and modular coil geometry
  - plasma shape, plasma-coil separations, B_{max}(d,k), etc.
- Will update outdated ARIES-IV cost and materials models from Les Wagner
- Can use Ku's B_{max}(d,k)/B_0 as model for coils?
- Will use Bromberg's model for $<j>(B_{max})$
- Still need to decide on a number of parameters and constraints

Simplified MHHOPT Optimization Approach

- Minimizes core cost or size or COE with constraints for a particular plasma and coil geometry using a nonlinear constrained optimizer with a large number of variables
- Large number of constraints allowed (=, <, or >)
  - $P_{electric}$, ignition margin, □ limit, ISS-95 multiplier, radial build, coil j and B_{max}, plasma-coil distance, blanket and shielding thicknesses, TBR, access for divertors and maintenance, etc.
- Large number of fixed parameters for plasma and coil configuration, plasma parameters and profiles, transport coefficients, cost component algorithms, and engineering model parameters
- Calculates (and iterates on) a large number of variables
  - plasma: T_e~~(r)~~, T_i~~(r)~~, n_e~~(r)~~, n_e~~(r)~~, ~~E_r(r)~~, □, Z_{eff}, H-ISS95, power components (coronal and bremsstrahlung radiation, ~~□i, □e), □ losses,~~ etc.
  - coils: max. & min. width/depth of coils, clearance between coils, components volumes and costs, j, B_{max}, ~~forces~~
  - reactor variables: B_0, $<R>$, blanket volumes, TBR, neutron wall loading, $P_{electric}$, divertor area, access between coils, radial build, etc.
  - costs: equipment cost, annual operating cost, total project cost

MHHOPT Reactor Optimization Code



Input Parameters

- **Configuration geometry**
  - plasma aspect ratio, surface area, coil aspect ratio, closest approach aspect ratio, $\square_{limit}$, $\square$(r), ~~ripple$_{effective}$(r)~~, etc.
- **Reactor component parameters**
  - inside & outside shield thickness; coil width and depth
  - blanket thickness inside & outside, under and between coils
  - coil case & dewar thickness inside, outside, top & bottom for modular coils and VF coils; scrapeoff thickness
  - first wall and reflector thickness; coil to cryostat gap
  - ~~allowable nuclear heating in coil~~; $j_{max}(B)$
  - blanket energy multiplication
- **Cost assumptions**
  - modular and VF costs /kg
  - costs and multipliers for blanket and shield
  - duty factor, inflation, safety assurance

Output

- **Plasma parameters and profiles**
  - <*R*>, B_0, W_{plasma}, $□_E$, H factors, <*□*>, *□**, n_{Fe}/n_e,n_O/n_e, Z_{eff}
  - <T>, T_{i0}, $T_{i,edge}$, T_{e0}, $T_{e,edge}$, ~~$□_0/T_{e0}$~~, <n>, n_{i0}, n_{e0}, $<n>/n_{Sudo}$, n_{DT}/n_e,
  - ignition margin, P_{fusion}, $P_{electric}$, $P_{neutron}$, $P_{charged}$, $P_{divertor}$, components of P_{rad} and P_{wall}, P_{loss}
- **Coil parameters**
  - modular & VF coil dimensions, currents, forces, inductance, stored energy, *j*, B_{max}, case thickness
- **Reactor parameters**
  - blanket area accessible and blocked, inboard and outboard shield thickness, cryostat gap, access between coils

Output (cont.)

- Cost elements
  - land & structures; power supplies; impurity control; heat transport; power conversion; startup power
  - blankets & first wall; shields; modular & VF coils; structure; vacuum vessel
  - turbine plant equipment; electric plant equipment; misc. plant equipment; special materials; total direct cost
  - construction; home office; field office; owner's costs; project contingency; construction interest; construction escalation; total capital cost
  - unit direct cost; unit base cost; total unit cost; capital return; O&M costs; blanket/first wall replacement; decommissioning allowance; fuel costs; cost of electricity
- Summary of all component masses & mass utilization
- Dimensions of each element in the radial build

Summary

- We should drop the earlier (May) reference cases
  - (1) B_{max} & $<j_{coil}>$ too high or (2) $<R>$ too large
- Have improved the reactor parameters by choosing
  - Ku’s 8/1 coil configuration (smaller $A_{\square}$)
  - set B_{max} = 16 T and k = 4 (coil-coil distance > 0)
- B_{max} = 14 T or 12 T, t = 1.2 or 1.3 m, Nb_3Sn also possible, but larger reactors
- Not enough data to assess Garabedian’s case
- Systems code being resurrected
  - needs updated cost assumptions
  - need to agree on other assumptions