Systems Code Refinements and Updated Information

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ARIES Meeting Jan. 23, 2006

Topics

- **Revisions and additions requested at Nov. meeting**
- **Detailed results for Reference ARE case**
- **Comparison with earlier ARIES reactor cases**
- **Impact of lower p_{wall} and higher actual B_{max}, bucking area and divertor area**
- **Work in progress, refinements needed**

Nov. Meeting Action Items

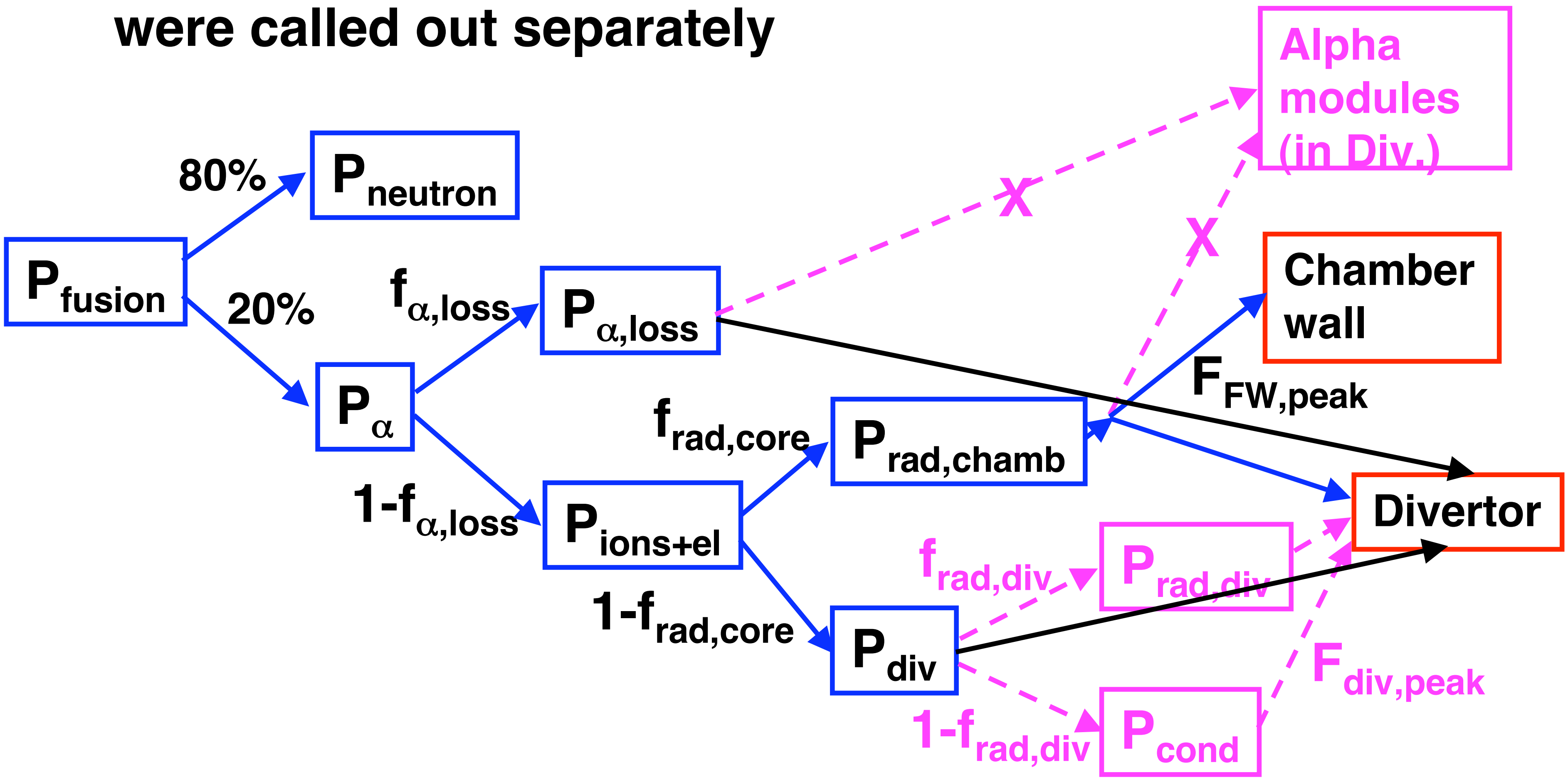
1. Correct arithmetic total of Account 21 and check all totals -- DONE

2. Correct Systems Code to agree with general structure of previous ARIES Power Flow chart

- NOT REQUIRED: WAS ALREADY THAT WAY (Rene's chart)

Systems Code Power Flows

- **Rene's Nov. figure same as my previous flow diagram except Alpha Module part of divertor (of unknown fraction) and unknown internal flows in divertor region were called out separately**



Nov. Meeting Action Items

3 **Modify algorithms and input data to reflect the use of Gross Thermal Efficiency: DONE, ADDED TO PRINTOUTS**

- **Rene Raffray supplied new gross efficiency values and He pumping power requirements**
  - **thermal efficiency = 0.4523 - 0.007451*wload*1.52**
  - **He pump,blanket: P = 26.677 + 14.427*wload*1.52**
  - **He pump,divertor: P = 28 MW**
  - **balance of plant: 2% of gross electric power**

Nov. Meeting Action Items (cont.)

4 Revise cost modeling (Account 22.2) to account for dual coolant heat transfer and transport including heat exchangers (partially Nb) and Brayton turbines

– Cost2221 is primary (LiPb) coolant system

$Cost2221 = 234.*((pthh*fLiPbcool/3500.)^{0.55} + (pthh*fHecool/3500.)^{0.55}) + 0.012*pthh*fLiPbcool$

– Cost2223 is secondary (He) coolant system

$Cost2223 = 75.*(pthh/3500.)^{0.55})$

5 Change data input for Primary Structure to reflect gravity supports (Account 22.1.5) -- DONE

– $Cost2215 = corevol*0.184*7.8\ 10^{-3}*0.95*25. *finflat/1.6348*0.94$

Nov. Meeting Action Items (cont.)

6 **Include coil structure (strongback and inter-coil tube) in Coil Volume and Cost -- WAS ALREADY THERE**

7 **Recheck Replaceable FWBS and divertor Annual cost -- ON MY LIST**

8 **Cost for Impurity Control is too low - $7M should be more like $55M -- WAS OK?; need good algorithm**

– **Laila: It’s 14 M$ for ARIES-RS, 4 M$ for ARIES-AT, and 12 M$ for SPPS, so 7 M$ is not too far off**

9 Other issues in Laila's presentation

- a. Increase shield volume by 10% to account for penetration and local shields -- DONE
- b. Move "Heat Rejection System" out of Account 23 and list as separate Account 26 -- CALLED 27 FOR NOW, IS 23.3 IN ARIES SYSTEM CODE
  - Cost27 = finflat*(pthh-pet)*37.546/2300.*1.02
- c. Fix "Reactor Building" Account 21.2 -- WAS OK, USE UNTIL BETTER ALGORITHM
  - $\text{Cost212} = 47.16*(\text{Vrb}/80000.)^{0.62}*0.9*\text{finflat}$
  - $\text{Vrb} = 4.*(\text{r0}+\text{rs}+9.)^{2}*(3.*\text{rs})+1.75\ 10^{5}$
  - rs = r0/acoil + cw + ccthback
- d. Include cryostat in Account 22.1.6
  - Laila's flat steel cylinder used with R = 16 m, h = 18 m, 8-cm thickness, $38.9/kg

Nov. Meeting Action Items (cont.)

10 Use ARIES-AT unit cost for WC (65 \$/kg) instead of Les' value (24.4 \$/kg) -- DONE

11 Add placeholder for divertor cost -- NOT REQUIRED, WAS ALREADY THERE

Nov. Meeting Action Items (cont.)

12 Do not accept design changes until after code revisions -- IN PROGRESS

13 After revisions, correct coil structure modeling in the code should be based upon the then-current design basis -- USING XUEREN'S TWO APPROACHES, THICKNESSES BELOW SCALED BY B^2R^2

- base approach -- outer ~2/3 of shell: coil strongback 65 cm, intercoil structure 35 cm;
  inner ~1/3 of shell: bucking surface 85 cm
- alternate approach -- coil strongback 65 cm, inter-coil structure 35 cm, no additional bucking surface
- will modify if further results from Xueren

Effect of Bucking Surface on Parameters

	Bucking Surface	NCSX Shell Approach
COE (2004 $) mills/kWhr	81.66	79.36
Coil structure cost (M$)	359.86	275.07
Coil structure mass (t)	6426	4912
nuclear island cost (M$)	876	785
nuclear island mass (t)	12,343	10,837

- Consequences for cryostat design if separate bucking surface?

System Code Convergence

VARIABLES selected for iteration and ranges

major radius	5.0 to 20.0 m;	field on axis	3.0 to 10.0 T
ion density	1.0 to 10.0 10^{20} m^{-3};	ion temperature	1.0 to 50.0 keV
half coil depth	0.01 to 5.0 m;	calculated H-ISS95	0.1 to 9.0

CONSTRAINTS	**value**	**target**
ignition margin	1.0000	1.0
electric power (GW)	1.000	1.00
volume averaged beta (%)	5.00	5.00
mag field at coil (T)	15.67	< 16.00
max neut wall load (MW/m^2)	5.00	< 5.00
average/maximum density	0.696	< 1.0
radial build margin $A_\Delta d_{min}/R$	1.00	< 1.0
confinement mult. H-ISS95	1.661	< 2.00
maintenance port width (m)	2.412	> 2.00
$j_{coil}/j_{max}(B_{max})$	1.00	< 1.0

- **convergence to a solution where all constraints are satisfied is still an art**
- **common problem for multi-dimensional nonlinear constrained optimizers**

- **Reference parameters: B_{max} multiplier = 1.25, bucking surface ~1/3 of shell, divertor 10% of wall area**

Summary for Reference ARE Case

MHHOPTNEW code NCSX-1 case (KZD)

modified LiPb/FS/He H2O-cooled internal vacuum vessel with SiC inserts and tapered blanket

inflation factor	2004 year

following CONSTRAINTS were selected:

ignition = 1 target	1.00
max. volume averaged beta	0.05
sufficient radial build	
max. neutron wall load	5.00
maximum density = 2 x nSudo	
Electric Power (GW)	1.00
max. confinement multiplier	2.00
min. port width	2.0
jcoil/jmax	< 1

VARIABLES selected for iteration

major radius	5.00	20.00
field on axis	3.00	10.00
ion density	1.00	10.00
ion temperature	1.00	50.00
coil width	0.01	5.00
confinement multiplier	0.10	9.00

FIGURE OF MERIT ....

81.66 Cost of Electricity (2004 $)

FINAL VALUES OF CONSTRAINTS:

ignition margin	1.00
volume averaged beta (%)	5.00
radial build margin	1.00
max. neutron wall load (MW/m^2)	5.00
average/maximum density	0.70
Electric Power (GW)	1.00
ratio of tauE to conf. multiplier	1.66
maintenance port width (m)	3.72
jcoil/jmax	1.00

FINAL DESIGN

major radius (m)	7.06
field on axis (T)	5.93
volume avg. density (10^{20} m^{-3})	3.11
density averaged temp (keV)	7.16
coil dimensions (m x m)	0.22 x 0.68
current density (MA/m^2)	86.9

Typical Systems Code Summary

Plasma Parameters

central ion temp (keV)	10.77
central ion density (10^{20} m^{-3})	6.76
central elec. density (10^{20} m^{-3})	7.03
fraction fuel to electrons	0.93
confinement time, taue (sec)	0.79
stored plasma energy (MJ)	352
volume averaged beta (%)	5.00
beta star (%)	8.21
fraction carbon impurity	0
fraction iron impurity	0.005 %
fraction helium	3.66 %
Z effective	1.11

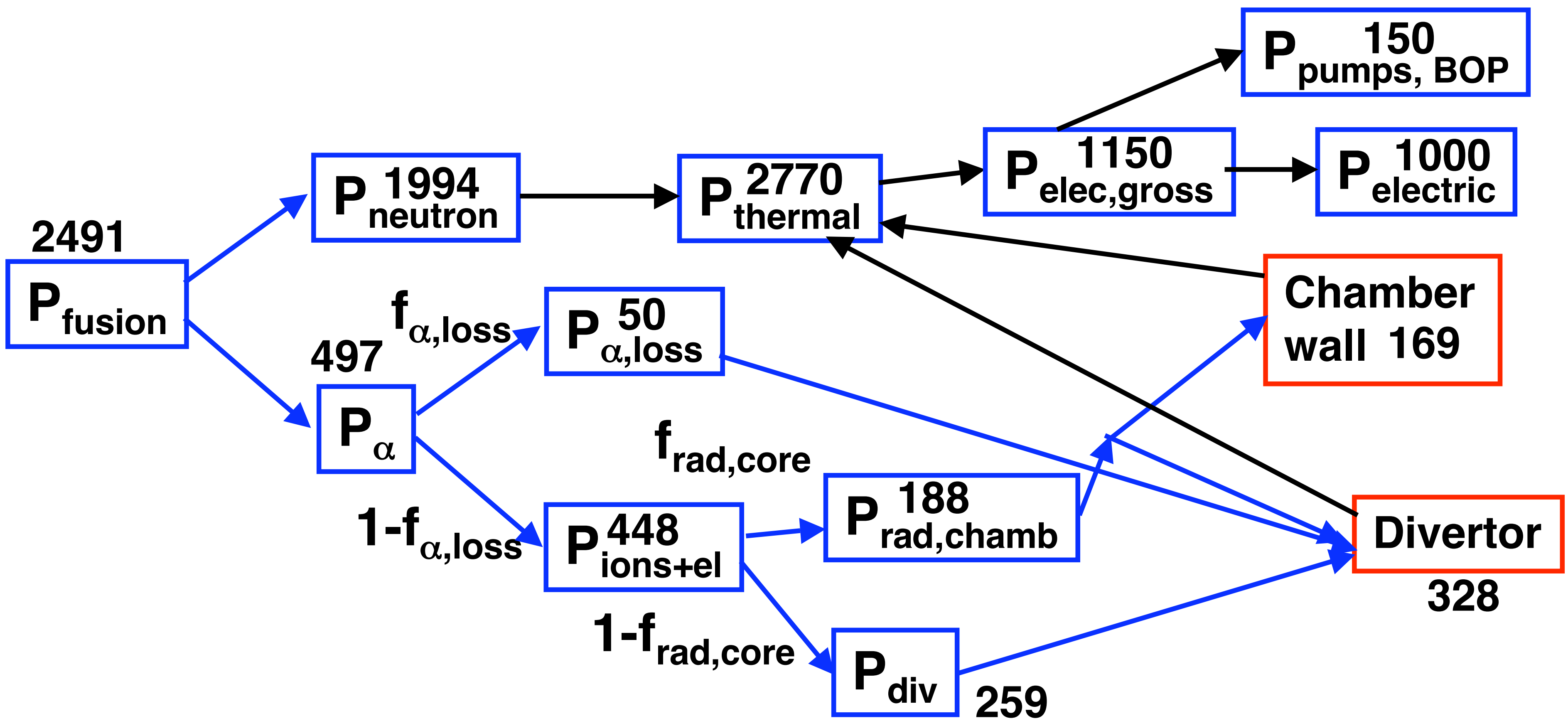
Mass Summary

total nuclear island (tonnes)	12,343

Power Balance

net electric power (MW)	1000
gross electric power (MW)	1149.8
fusion power (MW)	2491.2
thermal power (MW)	2770.3
α heating power (MW)	497.3
power in neutrons (MW)	1993.9
radiated power (MW)	188.4
fuel bremsstrahlung (MW)	153.7
iron radiation (MW)	33.4
synchrotron radiation (MW)	1.3
conduction power (MW)	259.2
fusion power to plasma (MW)	447.6
fraction alpha power lost	10.0 %
radiated power fraction	37.9 %
max neut wall flux (MW/m^2)	5.00
peak thermal flux (MW/m^2)	0.72
ave. divertor flux (MW/m^2)	5.41

Power Flows for ARE Case



Component Cost Summary (2004$)

total mod coil + str cost	**477.98**
mod coil SC cost	97.52
mod coil winding cost	20.60
coil structure cost	359.86
strongback	97.52
inter-coil shell	73.76
bucking surface	188.59
total blanket, first/back wall	**76.94**
first wall cost	6.37
front full blanket cost	44.92
front blanket back wall cost	22.81
second blanket cost	0.00
transition blanket cost	2.84
total vacuum vessel cost	**54.93**
full blanket vac vessel cost	47.49
shield-only vac vessel cost	2.31
transition vac vessel cost	5.13
primary structure cost	**45.95**

shield cost and back wall	**107.25**
ferritic steel shield cost	45.61
1st shield-only WC shield cost	7.04
shield-only back wall cost	1.13
2nd shield-only WC shield cost	17.19
1st transition WC shield cost	5.94
trans shield back wall cost	2.49
2nd transition WC shield cost	27.86
penetration shield cost	13.83
cost of manifolds	**98.81**
full manifold cost	93.63
transition manifold cost	5.18
total nuclear island cost	**875.70**
cost of LiPb in core	64.39
nuclear island + core LiPb	940.09

Component Mass Summary (tonnes)

total modular coil mass	**6941.03**
conductor mass	514.88
coil structure mass	6426.15
strongback	1741.35
inter-coil shell	1317.06
bucking surface	3367.74
total blanket, first, back wall	**833.31**
first wall mass	61.81
front full blanket mass	517.34
front blanket back wall	221.47
second blanket mass	0.00
transition blanket mass	32.70
total vacuum vessel mass	**1228.24**
full blanket vac vessel mass	1061.86
shield-only vac vessel mass	51.74
transition vac vessel mass	114.64
primary structure mass	**3127.17**

shield mass and back wall	**1920.42**
ferritic steel shield mass	1174.48
1st shield-only WC shield mas	87.50
shield-only back wall mass	10.95
2nd shield-only WC shield mas	209.77
1st transition WC shield mass	73.76
trans shield back wall mass	24.14
2nd transition WC shield mass	339.83
penetration shield mass	177.35
mass of manifolds	**1266.78**
full manifold mass	1200.37
transition manifold mass	66.41
total nuclear island	**12,343.00**
mass of LiPb in core	3156.26
nuclear island + core LiPb	15,499.26

Component Volumes Summary (m^3)

total modular coil volume	**916.48**	
conductor volume	93.61	
coil structure volume	823.87	
strongback	223.25	
inter-coil shell	168.85	
bucking surface	431.76	
total FW, blanket, BW volume	**412.97**	
first wall volume	23.31	1.621
front full blanket volume	333.12	1.911
front blanket back wall vol	35.49	2.207
second blanket volume	0.00	2.232
transition blanket volume	21.05	1.795
total vacuum vessel volume	**308.76**	
full blanket vac vessel vol	266.93	2.964
shield-only vac vessel vol	13.01	2.455
transition vac vessel vol	28.82	2.720
primary structure volume	**400.92**	

total shield + back wall volume	**227.38**	
ferritic steel shield volume	167.30	2.343
1st shield-only WC shield vol	6.24	1.735
shield-only back wall volume	1.75	1.855
2nd shield-only WC shield vol	16.39	2.087
1st transition WC shield vol	5.26	1.985
trans shield back wall vol	3.87	2.045
2nd transition WC shield vol	26.56	2.227
penetration shield volume	22.74	
volume of manifolds	**312.32**	
full manifold volume	295.95	2.629
transition manifold volume	16.37	2.472
volume of nuclear island	**2579.83**	
volume of LiPb in core	354.76	

r_{mid}(m) in blue

Typical Cost Summary (2004 $)

COST SUMMARY (M$)			% of 99	% of 22.1
20	Land	12.822	0.463	
21	Structure	346.675	12.513	
22.1.1	Bl. & 1st wl.	76.936	2.777	7.278
22.1.2	Shield	219.897	7.937	20.801
22.1.3	Magnets	477.981	17.252	45.214
22.1.4	Supp. Heating	65.915	2.379	6.235
22.1.5	Primary Str.	45.953	1.659	4.347
22.1.6	Reactor Cryostat	95.725	3.455	9.055
22.1.7	Power Supply	67.954	2.453	6.428
22.1.8	Impurity Cont	6.790	0.245	0.642
22.1.9	Direct En. Conv	0.000	0.000	0.000
22.1.1	ECH breakdown	0.000	0.000	0.000
22.1	Total	1057.152	38.157	100.00
22.2	Heat transport	448.858	16.201	
22	Reactor Plant Eq.	1705.457	61.557	
23	Turbine Plant Eq.	290.540	10.487	
24	Electric Plant Eq.	132.775	4.792	
25	Misc. Plant Eq.	67.097	2.422	
26	Special Material	160.969	5.810	
27	Heat Rejection	54.184	1.956	

Cost Element Breakdown

COST COMPONENTS in 2004 year M$

Cost 20 (Land) =	12.822	constant
Cost 21.1 (site improvements) =	22.651	constant
Cost 21.2 (reactor building) =	148.944	$V_{reactor\ building}^{0.62}$
Cost 21.3 (turbine building) =	41.132	$(\eta_{th}P_{th})^{0.75}$ + constant
Cost 21.4 (cooling system) =	9.962	$(\eta_{th}P_{th})^{0.3}$
Cost 21.5 (PS building) =	12.269	constant
Cost 21.6 (misc. buildings) =	102.495	constant
Cost 21.7 (vent. stack) =	2.424	constant
Cost 21 (Structure) =	346.675	

$P_{th} = P_n \times gloem + P_\alpha$

Cost Element Breakdown

Cost 22.1.1.1 (FW)	6.366	
Cost 22.1.1.3 (BL + BW)	70.569	
Cost 22.1.1 (Bl/BW & 1st wl.)	76.936	7.278%
Cost 22.1.2 (Sh/BW/man)	219.897	20.801%
Cost 22.1.3 mod coils	128.117	
Cost 22.1.3 VF coils	0.000	
Cost 22.1.3 divertor	0.000	
Cost 22.1.3 mod coil struct	359.865	
Cost 22.1.3 (coils + str)	477.981	45.214%
Cost 22.1.4 (Heating)	65.915	constant 20 MW
Cost 22.1.5 (Primary Str.)	45.953	core volume
Cost 22.1.6 (Vac. Sys.)	95.725	cryostat
Cost 22.1.7 (Power Sup.)	67.954	constant
Cost 22.1.8 (Imp. Control)	6.790	
Cost 22.1.9 (Dir. Ener. Conv.	0	
Cost 22.1.10 (ECH) =	0	
Cost 22.1 (Core) =	1057.152	

Cost Element Breakdown

Cost 22.2.1 prim. coolant	367.848	$P_{th}^{0.55}$
Cost 22.2.2 interm. coolant	0.000	
Cost 22.2.3 sec. coolant	81.009	$P_{th}^{0.55}$
Cost 22.2 (Heat transport)	448.858	
Cost 22.3 aux. cooling	3.519	P_{th}
Cost 22.4 rad. waste	6.270	P_{th}
Cost 22.5.1 fuel injection	14.017	constant
Cost 22.5.2 fuel processing	16.453	constant
Cost 22.5.3 fuel storage	7.009	constant
Cost 22.5.4 atm T recover.	3.325	constant
Cost 22.5.5 H2O T recover.	7.009	constant
Cost 22.5.6 BL T recover.	7.009	constant
Cost 22.5 fuel handling	54.821	constant
Cost 22.6 other plant equip	57.208	P_{th}
Cost 22.7 I&C	44.189	constant
Cost 22 (Reactor Plant)	1705.457	(inc. 2% spare parts)

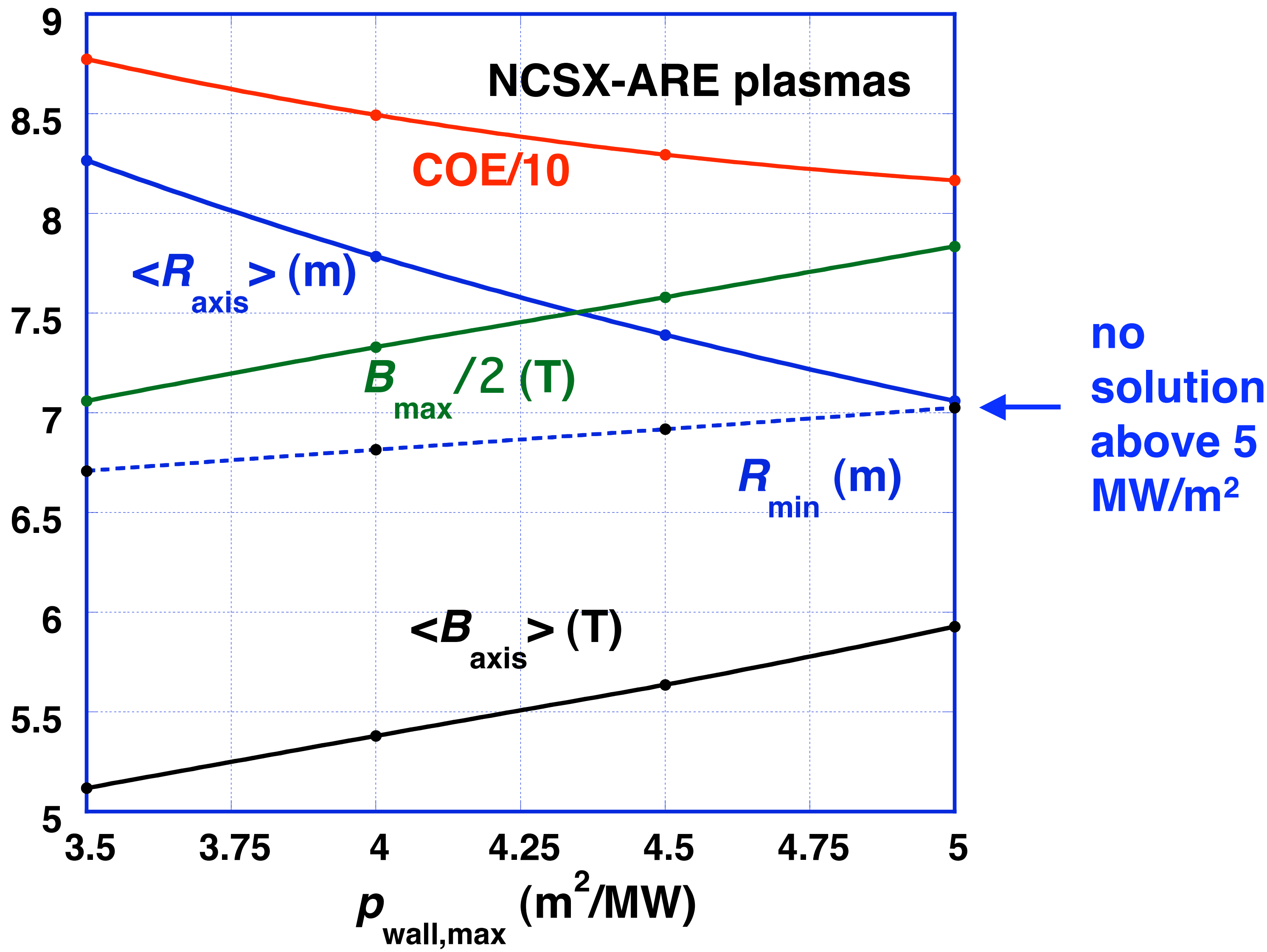
Cost Element Breakdown

Cost 23 (Turbine Plant)	290.540	$(\eta_{th}P_{th})^{0.83}$ + constant
Cost 24 (Electric Plant)	132.775	$(\eta_{th}P_{th})^{0.49}$
Cost 25 (Misc. Plant Eq.)	67.097	$(\eta_{th}P_{th})^{0.59}$
Cost 26 (Spec. Matls.)	160.969	V_{LiPb}
Cost 27 Heat Rejection	54.184	$P_{th} - (\eta_{th}P_{th})$

Values for Different p_{wall} Limits

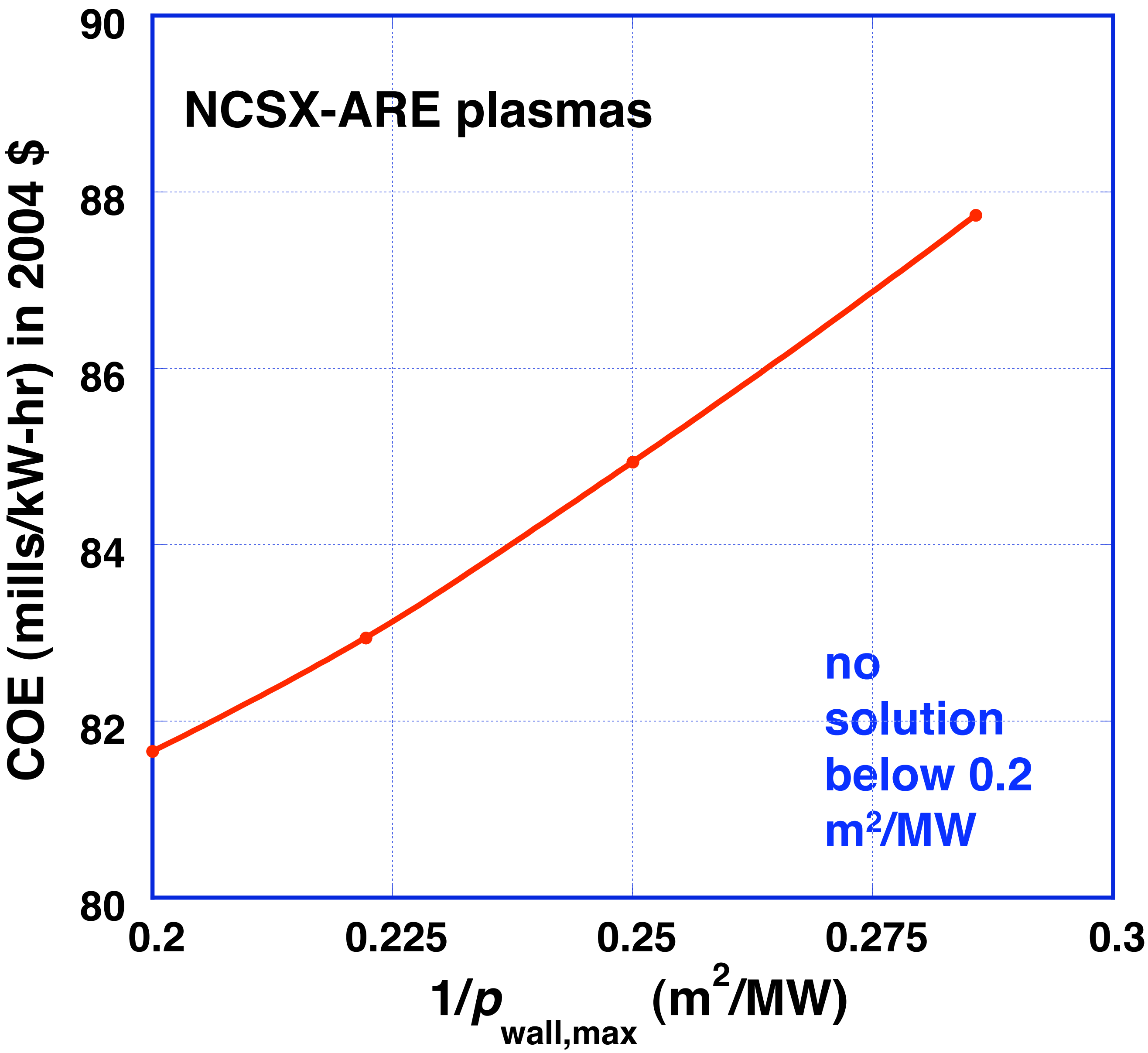
Max. p_{wall}	3.5 MW/m^2	4 MW/m^2	4.5 MW/m^2	5 MW/m^2
$<R>$ (m)	8.27	7.79	7.39	7.06
$<B_{axis}>$ (T)	5.12	5.38	5.64	5.93
B_{max} (T)	14.1	14.7	15.2	15.7
$<R>_{min}$	6.71	6.82	6.92	7.03
CoE	87.7	84.9	82.9	81.7

Parameter Variation with $p_{n,wall,\ max}$



- Increasing p_{wall} decreases $\langle R_{axis} \rangle$ and COE until R_{min} limit is reached

Cost Varies as $1/\langle p_{n,wall} \rangle$



Comparison of General Plant Costs (1992 $)

Parameter	CS	AT	RS	SPPS
<R>, m	7.06	5.20	5.52	13.95
<B_{axis}>, T	5.93	5.86	7.98	4.94
<β>, %	5.0	9.2	5.0	5.0
FPC Mass, tonnes	12,343	5,226	12,679	21,430
CoE, mills/kW$_e$h (1992 $)	66.5	56.6	75.7	74.9
90 Total Direct Cost (M$)	2255	1757	2189	2261
20 Land	10.4	10.6	10.4	10.4
21 Structure	282.2	335.5	331.0	332.5
22 Reactor Plant Equip.	*1388*	*900.3*	*1386*	*1487*
23 Turbine Plant Equip.	236.5	243.0	284.4	254.0
24 Electric Plant Equip.	108.1	110.3	110.6	103.6
25 Misc. Plant Equip.	54.6	50.1	56.2	51.9
26 Special Materials	131.0	83.8	11.1	21.1
27 Heat Rejection	44.1	23.3		
22+26 Reactor Plant + LM	1519	984.1	1397	1508

- Only Reactor Plant Equip. contains stellarator costs

Comparison of General Plant Costs (1992 $)

Cost (M$)	CS	AT	RS	SPPS
21 Structure	282.2	335.5	331.0	332.5
21.2 reactor building	121.3	n. a.	n. a.	141.6
21.6 misc. buildings	83.4	n. a.	n. a.	112.7
22 Reactor Plant Equip.	1388	900.3	1386	1487
22.1 reactor equipment	*860.6*	*519.9*	*966.4*	*1115*
22.2 heat transport	365.4	209.9	258.3	217.8

- **While the reactor equipment is the largest cost component, the costs of structure (buildings) and heat transport are also large**

Comparing Costs with AT, RS & SPPS

Cost (M$)	CS	AT	RS	SPPS
22.1 Reactor Equipment	860.6	519.9	966.4	1115
Cost of stellarator parts	630.7 73%	274.9 53%	516.3 53%	750.9 67%
22.1.1 blanket & 1st wall	62.6	67.9	74.3	71.5
22.1.2 shield, BW, man.	179.0	73.3	168.0	289.8
22.1.3 coils	389.1	133.7	274.0	389.6
22.1.4 heating	53.7	41.0	164.2	54.2
22.1.5 primary structure	37.4	29.8	53.4	152.9
22.1.6 vacuum systems	77.9	109.2	159.2	85.4
22.1.7 power supplies	55.3	56.1	55.3	55.3
22.1.8 impurity control	5.5	4.5	13.6	12.0
22.1.10 ECH startup	0	4.4	4.3	4.3

Comparing Masses with AT, RS & SPPS

Mass (tonnes)	CS	AT	RS	SPPS
FW/Blanket/BW	833	255	585	251
Shield, BW, man.	3187	882	4235	9453
Coils	6941	1525	3280	4191
Structure	3127	----	1627	5365
Vacuum Vessel	1228	1415	1357	2171
Fusion Power Core	12,343	5,226	12,679	21,430
LM Core Coolant	3,156	5,269	223	175
FPC + Coolant	15,499	10,495	12,902	21,605

Nov. Meeting Action Items (cont.)

14 After revisions, generate parameters for advanced LiPb/SiC design with 58% thermal conversion efficiency -- ON MY LIST

15 After revisions, generate parameters for 2 PF configuration (get radial build from Laila) -- ON LIST

OTHER ITEMS ON MY LIST

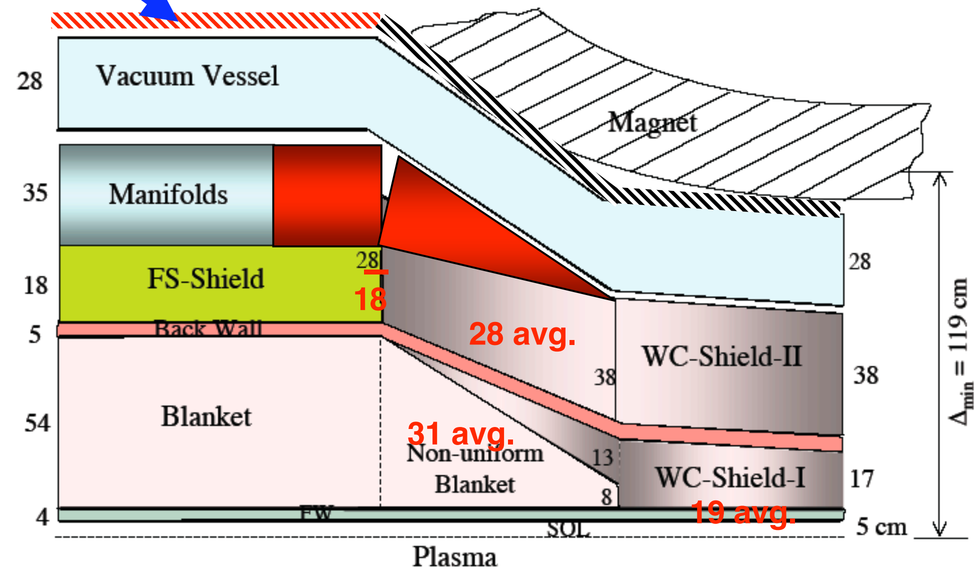
- Add cost of helium coolant
- Reanalyze SNS and NCSX A_Δ-scan cases
- More parameter scans and sensitivity tests, n(r), T(r)
- Add ln(p_{wall}/2) correction to shield thickness
- Modify alpha loss according to L.P. Ku's calculations
- Need NbTi(Ta) case??

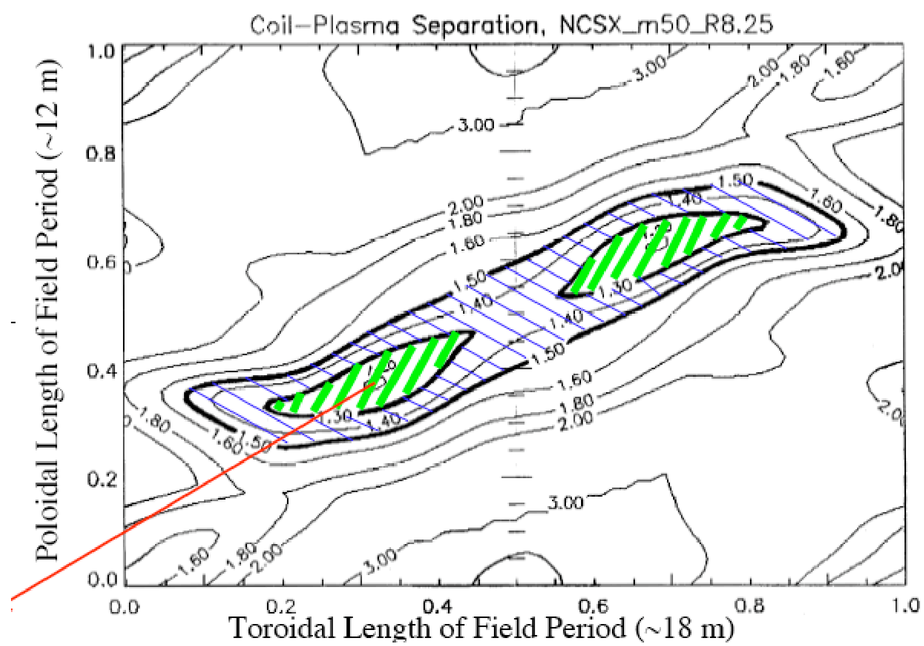
Refinements Needed

- VF or control coils not considered yet in designs, needed for startup?
- Effect of manifold design on Δ_{min} and $<R>_{min}$
- Allowable maximum $p_{n,wall}$
- Better calculation of $B_{max}/<B_{axis}>$
- Divertor power peaking and additional costs?

Need to Check $\Delta(\phi,\theta)$ for Vacuum Vessel to Coil Winding Surface

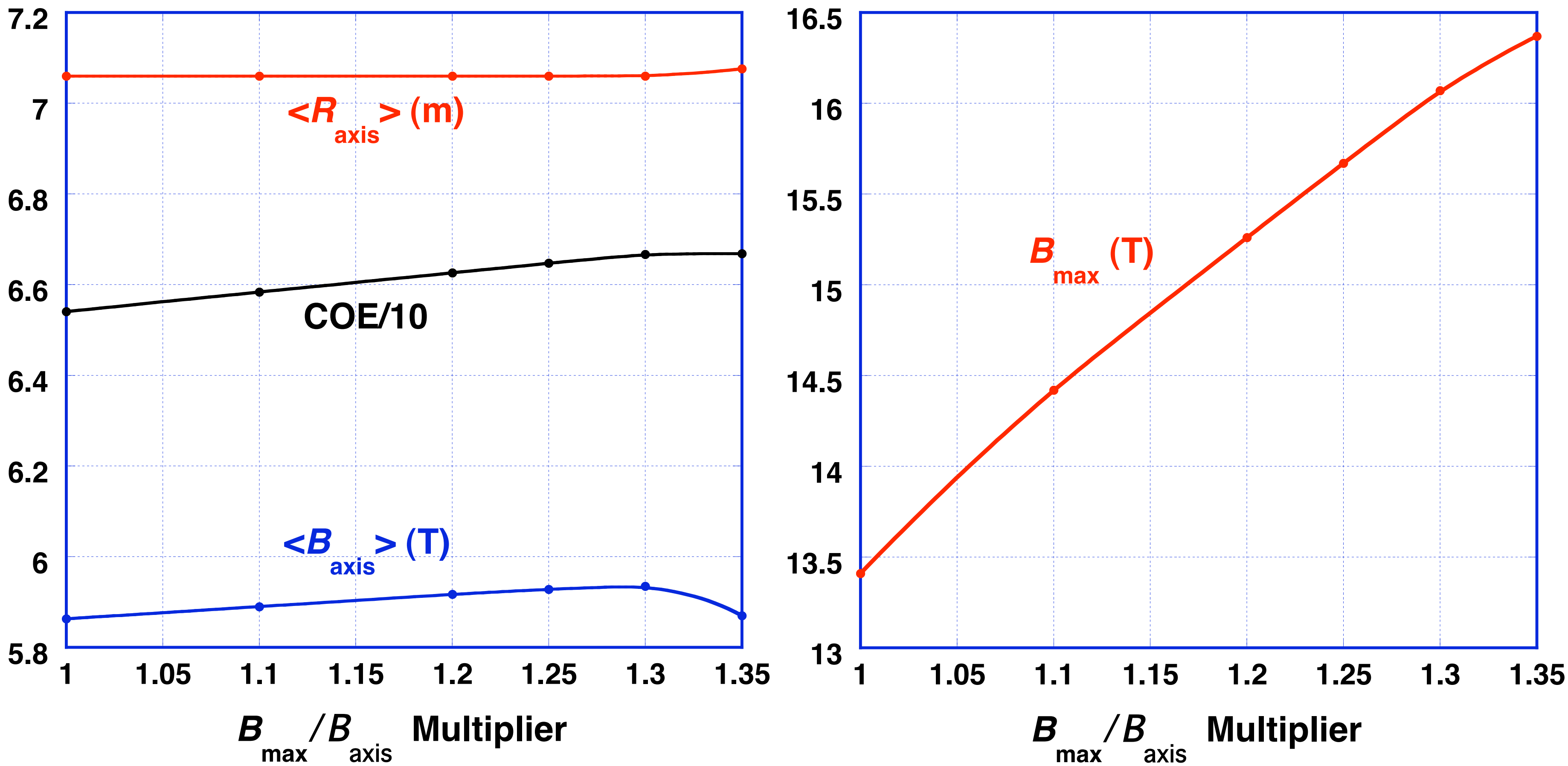
- Only done so far for no-blanket region
- Is there sufficient clearance for other regions?
  - 59 cm difference
- Need to revise Δ_{min} or OK for NCSX cases?



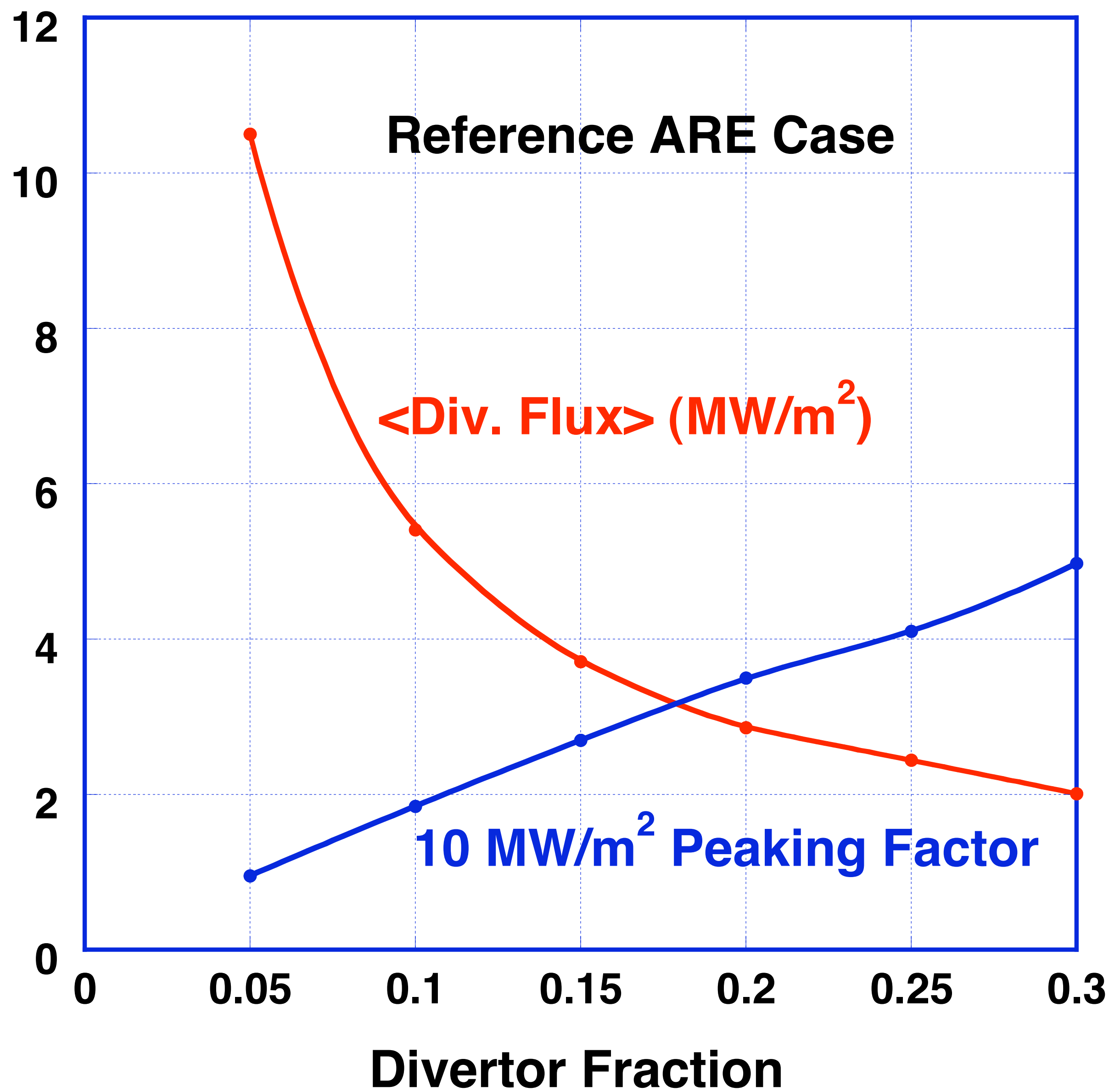


Studied Underestimation of $B_{max}/\langle B_{axis}\rangle$

- **Filamentary coil calculations underestimate $B_{max}/\langle B_{axis}\rangle$ (by ~25%?), but relatively small effect**



Allowable Divertor Peaking Factor Not Large



Summary

- Addressed most of the revisions and additions requested at Nov. meeting
- Detailed results for Reference ARE case
- Compared with earlier ARIES reactor cases
- Impact of lower p_{wall} and higher actual B_{max}, bucking area and divertor area
- Work in progress, refinements needed