ARIES-CS Systems Studies

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Workshop on Fusion Power Plants

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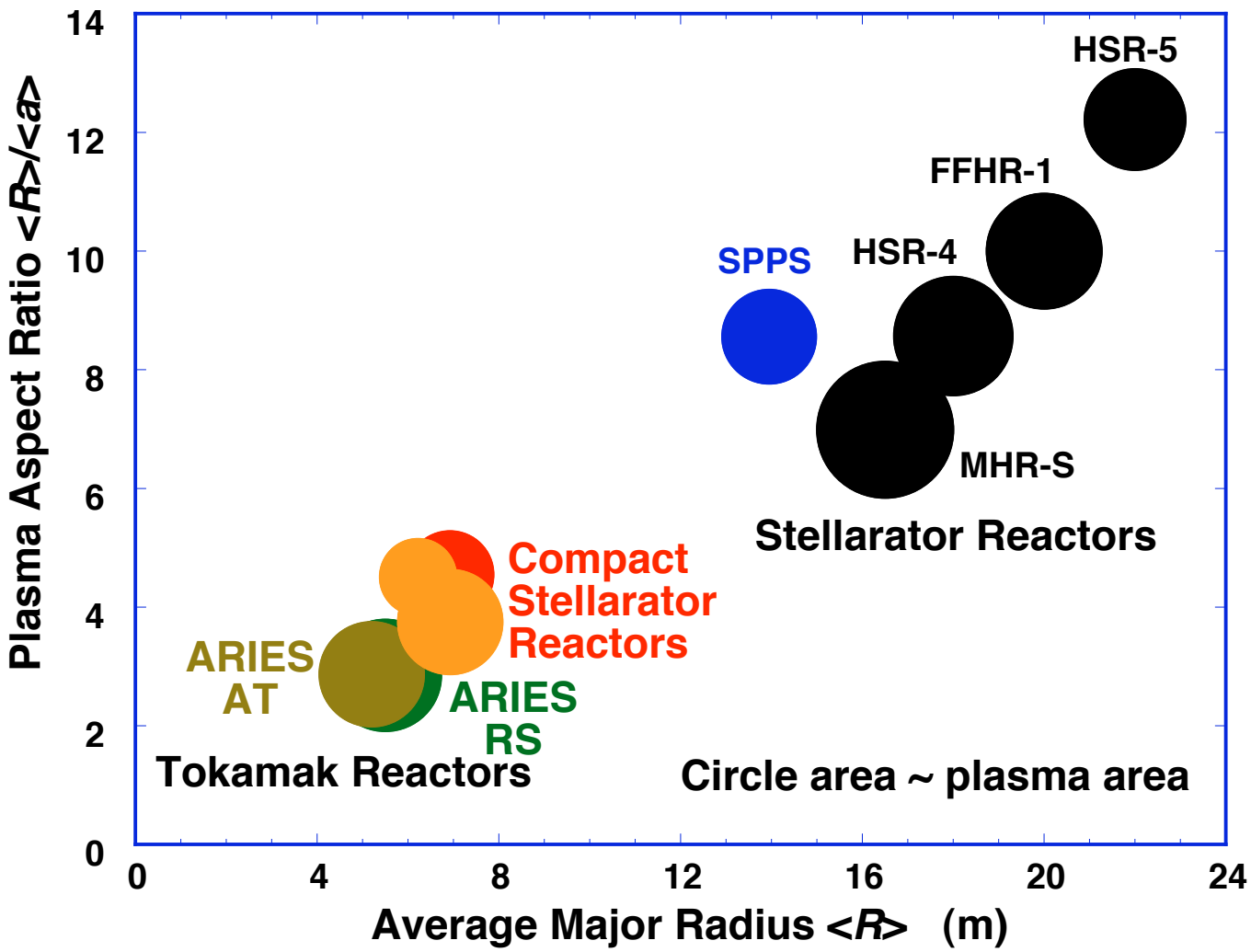
ornl

UT-BATTELLE

Goal: Stellarator Reactors Similar in Size to Tokamak Reactors

- Need a factor of 2-4 reduction → compact stellarators



Topics

- Optimization Approach
- Configuration Properties
- Coil, Blanket/Shield Models
- Systems Optimization Code
- Typical Case Results
- Parameter Variations and Scaling

Parameter Optimization Integrates Plasma/Coil Geometry and Reactor Constraints

Plasma & Coil Geometry

- Shape of last closed flux surface and $\langle R_{axis}\rangle/\langle a_{plasma}\rangle$, β limit
- Shape of modular coils and $B_{max,coil}/B_{axis}$ vs coil cross section, $\langle R_{coil}\rangle/\langle R_{axis}\rangle$, $\Delta_{min}/\langle R_{axis}\rangle$
- Alpha-particle loss fraction

Reactor Constraints

- Blanket and shield thickness
- $B_{max,coil}$ vs j_{coil} for superconductor
- Acceptable wall power loading
- Access for assembly/disassembly
- Component costs/volume

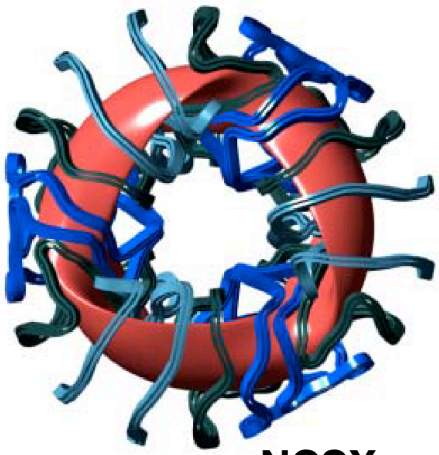
Parameter Determination

- $\langle R_{axis}\rangle$, $\langle a_{plasma}\rangle$, $\langle B_{axis}\rangle$
- $B_{max,coil}$, coil cross section, gaps
- $n_{e,I,Z}(r)$, $T_{e,i}(r)$, $\langle\beta\rangle$, P_{fusion}, P_{rad}, etc.
- Operating point, path to ignition
- Cost of components, operating cost → cost of electricity

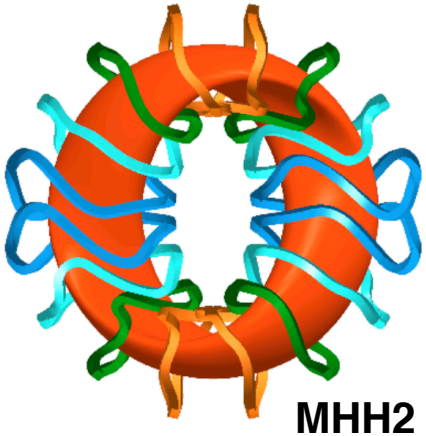
Requires non-linear constrained optimization

3 Plasma and Coil Configurations Studied

Key Configuration Properties	ARE	SNS	MHH2
Plasma aspect ratio $A_p = \langle R \rangle / \langle a \rangle$	4.55	6.00	2.66
Wall (plasma) surface area/$\langle R \rangle^2$	11.78	8.99	18.55
Minimum pl-coil dist. ratio $A_\Delta = \langle R \rangle / \Delta_{min}$	5.89	6.02	5.55
Minimum coil-coil dist. ratio $\langle R \rangle$/(c-c)	10.03	9.8	10.33
Total coil length/$\langle R \rangle$	89.9	63.5	91.0
$B_{max}/\langle B_{axis} \rangle$, 0.3 m x 0.3 m coil pack	2.63	2.54	2.69



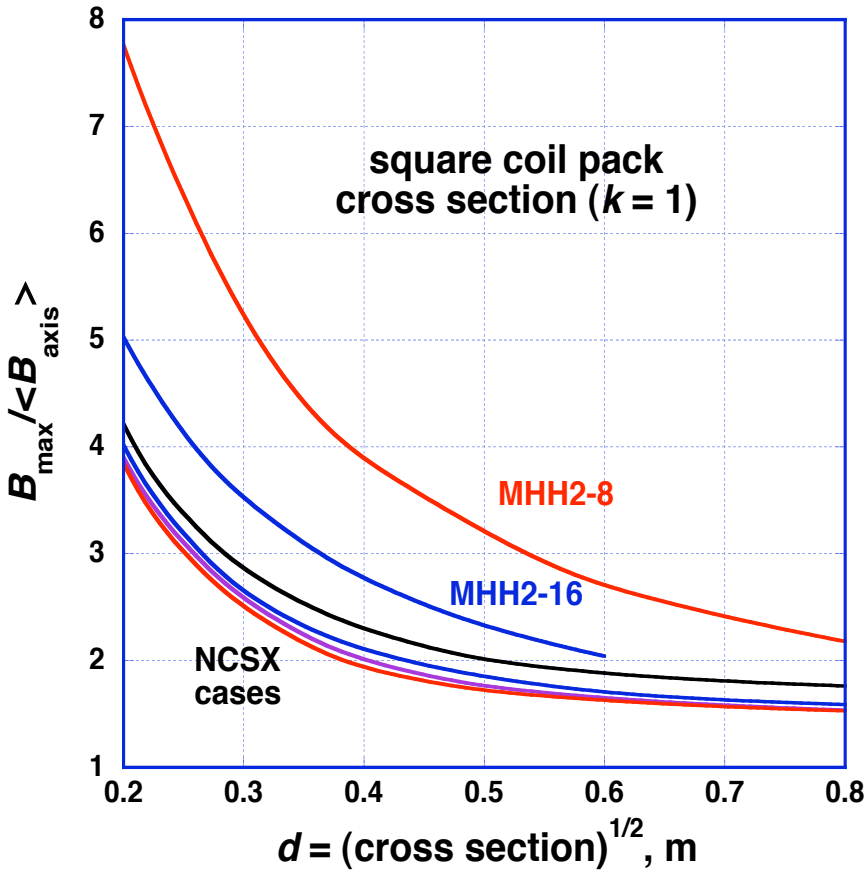
NCSX

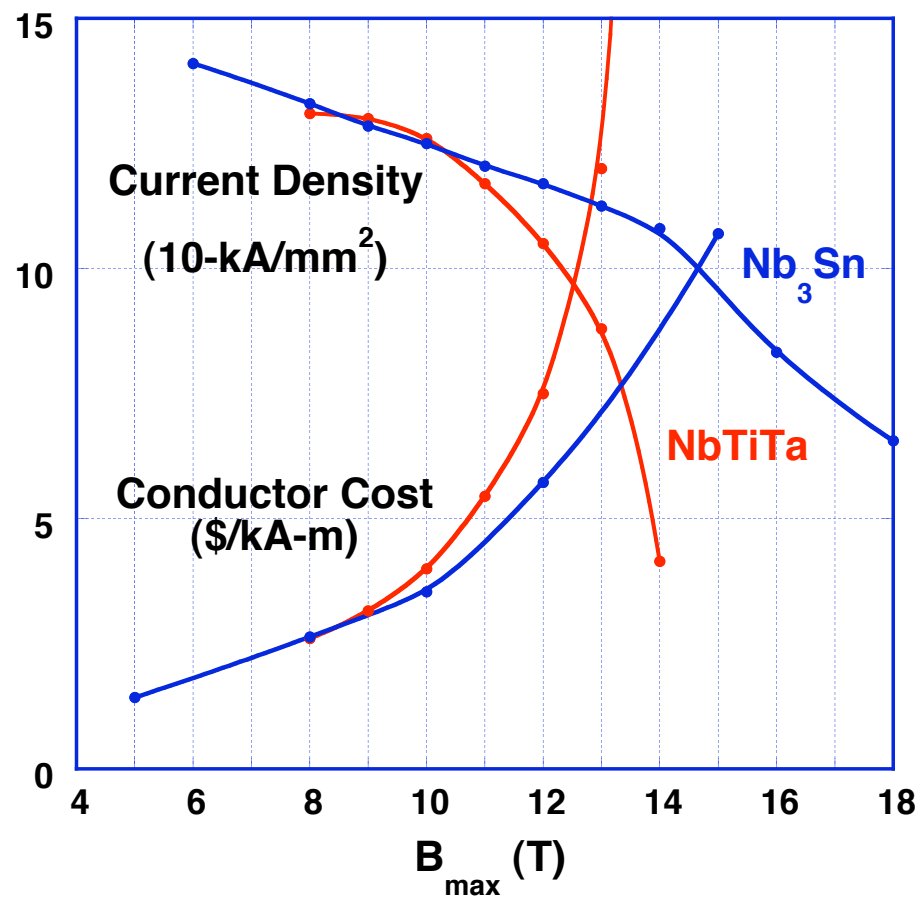


MHH2

- For given plasma + coil geometry, distances ~ $\langle R \rangle$
- $\langle R \rangle$ determined by min. distance between plasma and coils or by $\langle p_{wall} \rangle$ → wall area → $\langle R \rangle$
- $B_{max}/\langle B_{axis} \rangle$ varies rapidly with coil distance from plasma and coil pack dimensions
- only quasi-axisymmetric type of compact stellarators studied

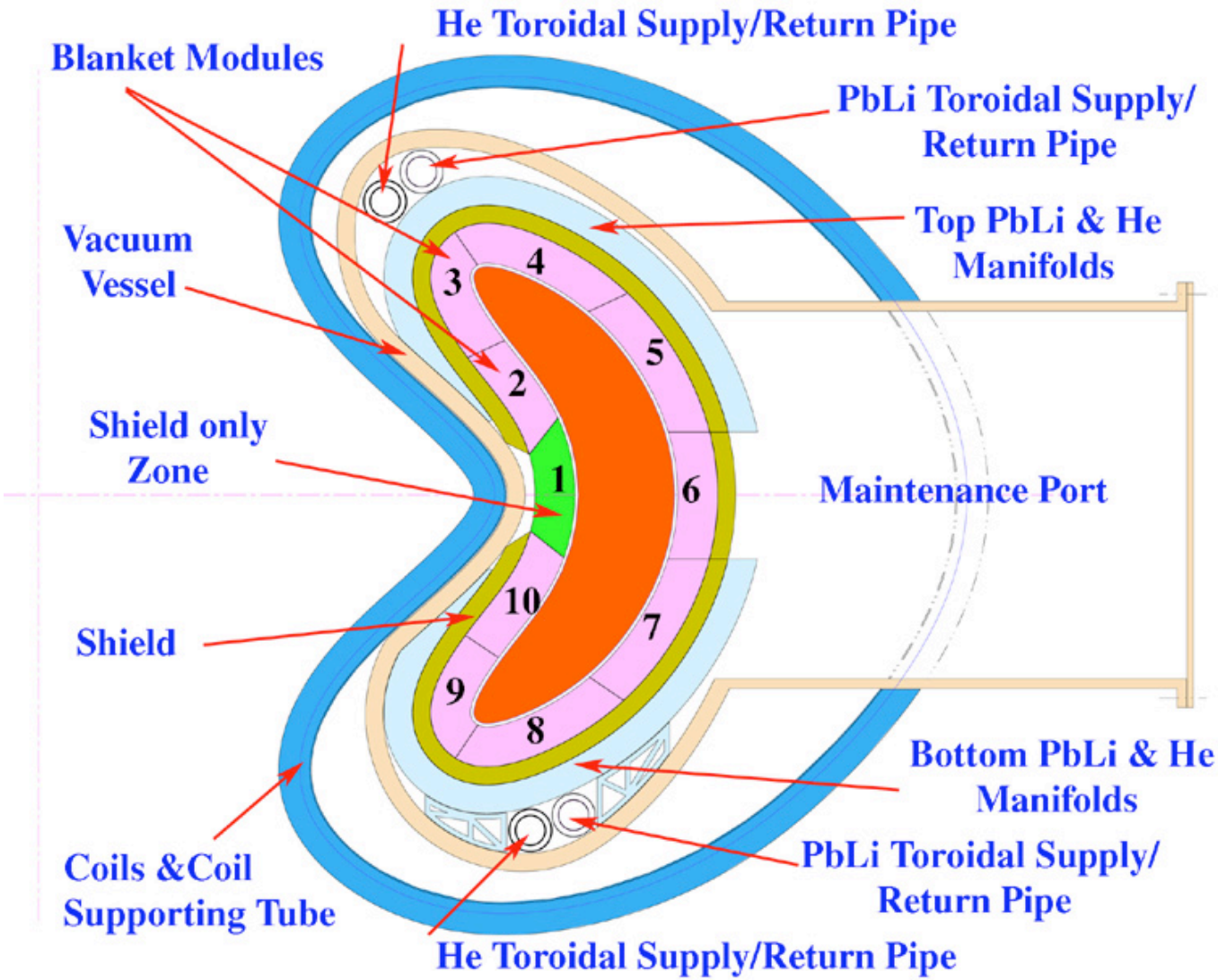
B_{max} on the Coils Is an Important Parameter





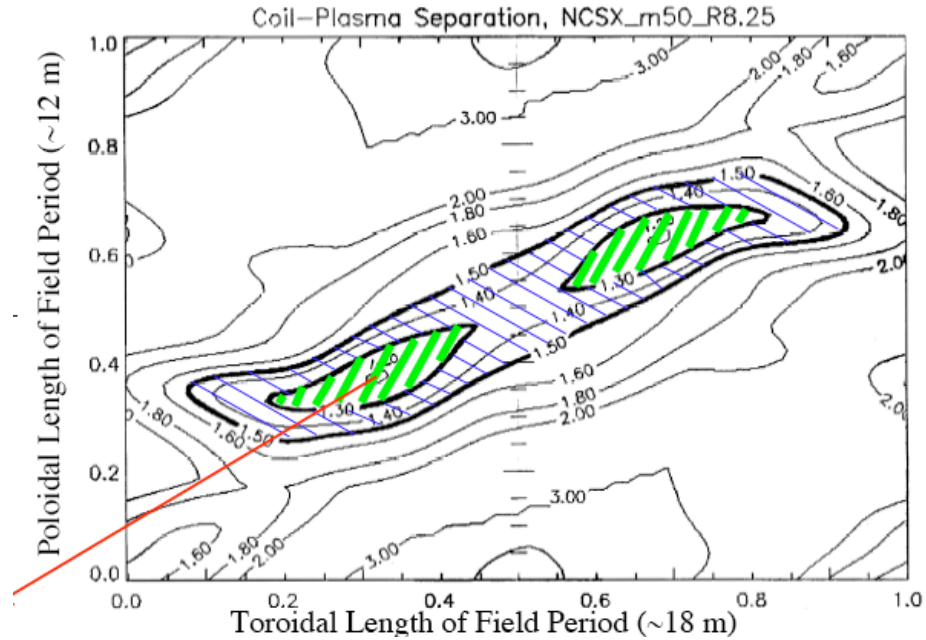
- Larger plasma-coil spacings lead to more convoluted coils and higher $B_{max}/\langle B_{axis}\rangle$; constrains value of $\langle B_{axis}\rangle$ if B_{max} is limited
- Coil current density and cost depend on B_{max}; Nb_3Sn examined first

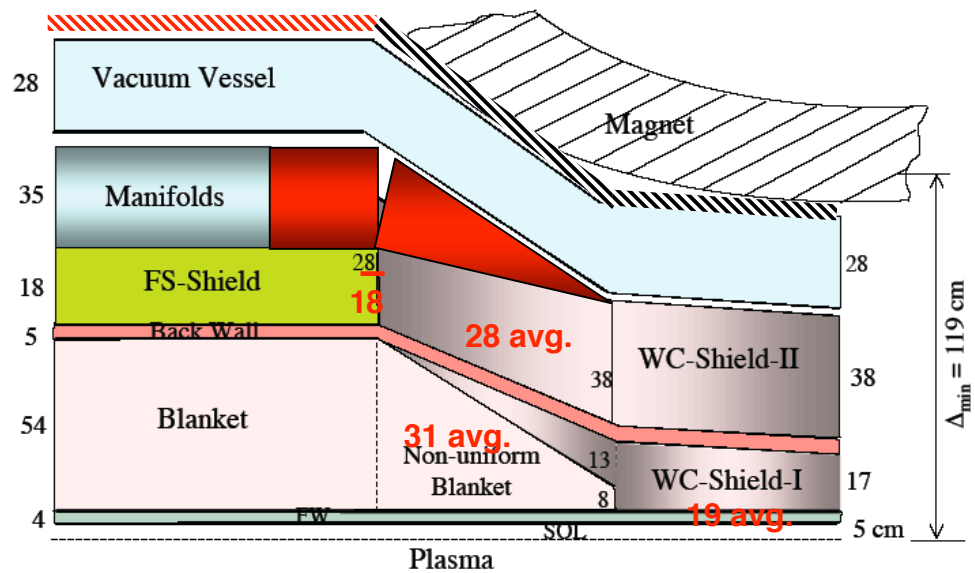
Minimum Coil-Plasma Distance Can Be Reduced By Using a Shield-Only Zone



NCSX Configurations Permit a No-Blanket Region

- Plasma-coil separation is small only over 5% of the wall area
- A transition region with tapered blanket and shield covers 10% of the wall area
- The full blanket covers 85% of the wall area
- Not possible with MHH2 configurations because coils are approximately same distance from plasma everywhere





Composition
(Nominal Blanket/Shield and Shield-only zones)
(no divertor info)

Component	Thickness	Coverage Fraction	Composition
FW*	3.8 cm	100%	34% FS Structure 66% He Coolant
Blanket*	54.3 cm	85%#	79% LiPb (90% enriched Li) 7% SiC Inserts (95% d.f.) 6% FS Structure 8% He Coolant
Back Wall*	5 cm	100%	80% FS Structure 20% He Coolant
FS Shield	18 cm	85%	15% FS Structure 10% He Coolant 75% Borated Steel Filler
Manifolds	35 cm	85%	52% FS Structure 24% LiPb (90% enriched Li) 24% He Coolant ?% SiC Inserts
WC Shield-I* (shield-only zone)	17-21 cm	5%	88% WC Filler 5% FS Structure 7% He Coolant
WC Shield-II (shield-only zone)	38 cm	5%	15% FS Structure 10% He Coolant 75% WC Filler
VV	28 cm	100%	28% FS Structure 49% **Water** 23% Borated Steel Filler

* Replaceable component.

\# For blanket and divertor,

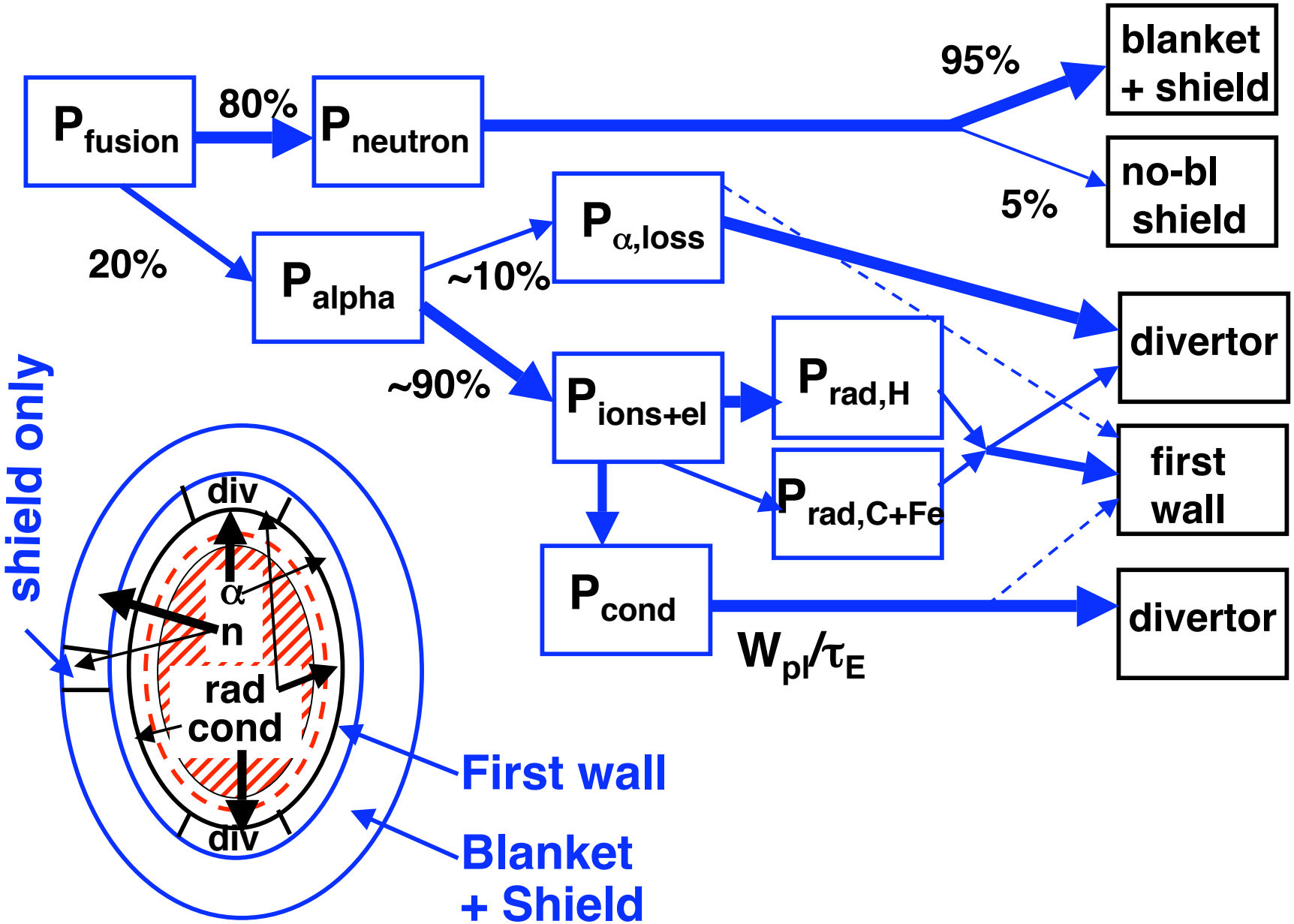
Systems Optimization Code

- Minimizes Cost of Electricity for a given plasma and coil geometry using a nonlinear constrained optimizer
- Iterates on a number of optimization variables
  - plasma: $\langle T_i \rangle$, $\langle n_e \rangle$, conf. multiplier; coils: width/depth of coils
  - reactor variables: $\langle B_{axis} \rangle$, $\langle R \rangle$
- Large number of constraints allowed (=, <, or >)
  - $P_{electric}$, β limit, confinement multiplier, coil j and B_{max}, clearance radially and between coils, TBR, neutron wall power density
- Large number of fixed parameters for
  - plasma and coil configuration, plasma profiles,
  - transport model, helium accumulation and impurity levels,
  - SC coil model (j,B_{max}), blanket/shield concepts, and
  - engineering parameters, cost component algorithms

Reference Models and Constraints

- **Plasma and Coil Geometry from 3-D optimization (L-P. Ku)**
  - ⇒ normalized distances for plasma-coil, coil-coil, coil length
  - ⇒ plasma aspect ratio and surface areas for plasma & coils
- **Plasma scaling and constraints**
  - ignited plasma; chosen $\langle\beta\rangle$ limit; slightly hollow $n_e(r)$; $p_{rad}(r)$
  - stellarator scalings: $\langle n_e\rangle < 0.5[PB/Ra^2]^{1/2}$ and $\tau_E/\tau_E^{ISS\text{-}95} < 2$ where $\tau_E^{ISS\text{-}95} \sim P_{heating}^{-0.59}\langle n_e\rangle^{0.51}\langle B_{axis}\rangle^{0.83}\langle R\rangle^{0.65}\langle a\rangle^{2.21}\iota_{2/3}^{0.4}$
- **Coil modeling (L-P. Ku, L. Bromberg)**
  - ⇒ $B_{max}/\langle B_{axis}\rangle$ vs plasma-coil distance and coil pack dimensions
  - $B_{max} < 16$ T; maximum conductor j and cost vary with B_{max}
  - coil-coil distance allows >2-m port size for maintenance
- **Blanket and shield models; $P_{electric}$ = 1 GW (L. ElGuebaly)**
  - dual coolant ($Li^{17}Pb$, He) blanket and shields (FS, WC)
  - $p_{n,wall,max} < 5$ MW/m^2, lifetime 15 MW-yr/m^2
  - peak/average = 1.52 for wall fluxes

Power Flows


P fusion
80%
P neutron
95%
blanket + shield
5%
no-bl shield
20%
P alpha
~10%
P α,loss
~90%
P ions+el
P rad,H
P rad,C+Fe
divertor
first wall
P cond
W pl/τE
divertor
shield only
div
α
n
rad
cond
div
First wall
Blanket + Shield

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	1.000	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	0.70	< 1.0
radial build margin $A_\Delta d_{min}/R$	1.00	< 1.0
confinement mult. H-ISS95	1.66	< 2.00
maintenance port width (m)	3.72	> 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**

Typical Systems Code Results

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

Stellarator Geometry-Dependent Components only Part of the Cost

Fractions of reactor core cost

modular coil	11.2%
coil structure	34.0%
blanket, first/back wall	7.3%
shield and manifolds	20.8%
cryostat	9.1%
plasma heating	6.2%
power supplies	6.4%

- Reactor core is 38.2% of total direct cost, which includes other reactor plant equipment and buildings
- Total direct cost is 51.8% of total capital cost
- Replaceable blanket components only contribute small % to COE

Component Mass Summary (tonnes)

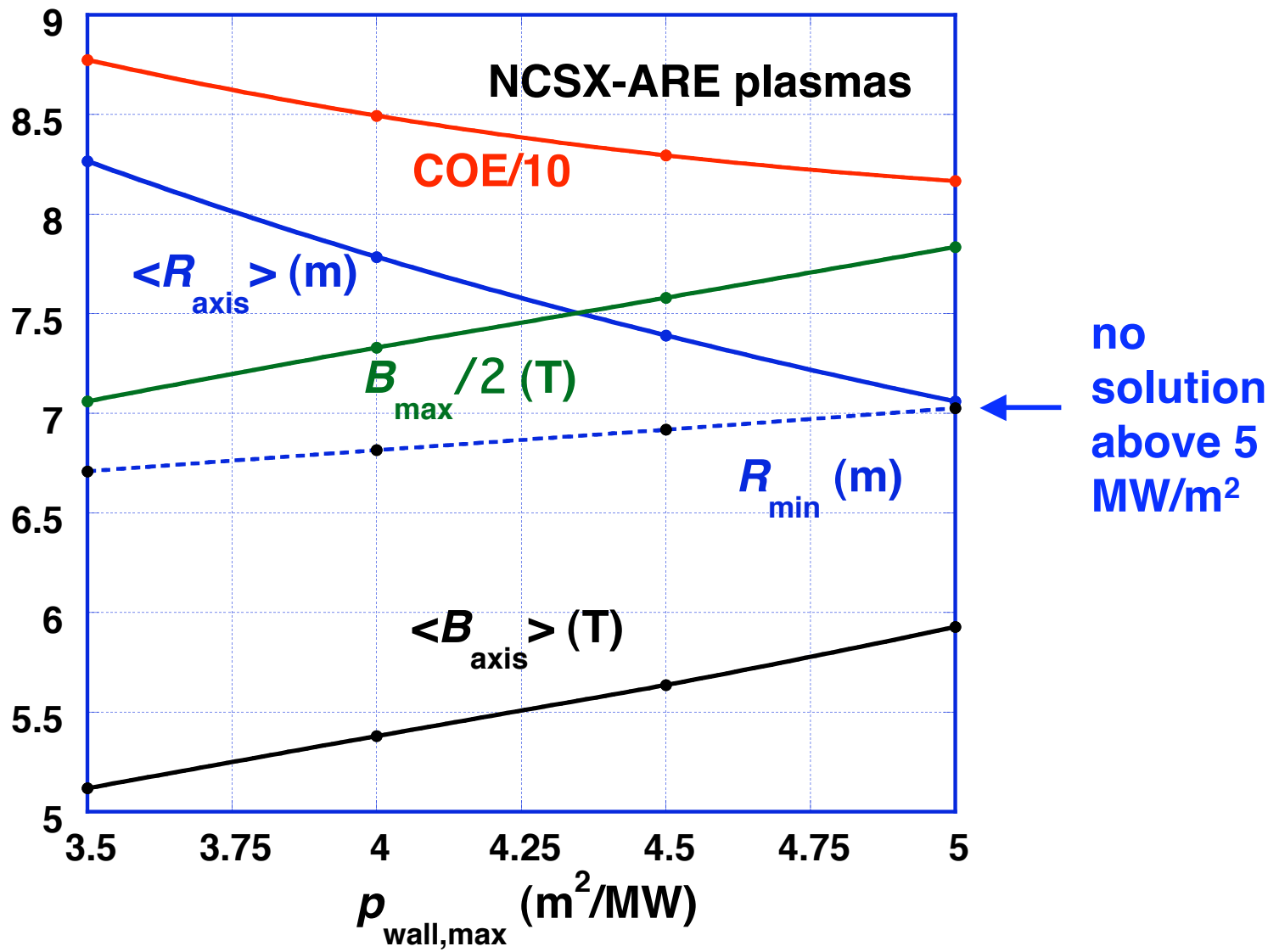
total modular coil mass	**6941.03**
conductor mass	514.88
coil structure mass	6426.15
strongback	1741.35
inter-coil shell	1317.06
bucking surface	3367.74
total blanket, first, back wall	**833.31**
first wall mass	61.81
front full blanket mass	517.34
front blanket back wall	221.47
second blanket mass	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**

Effect of Bucking Surface on Parameters

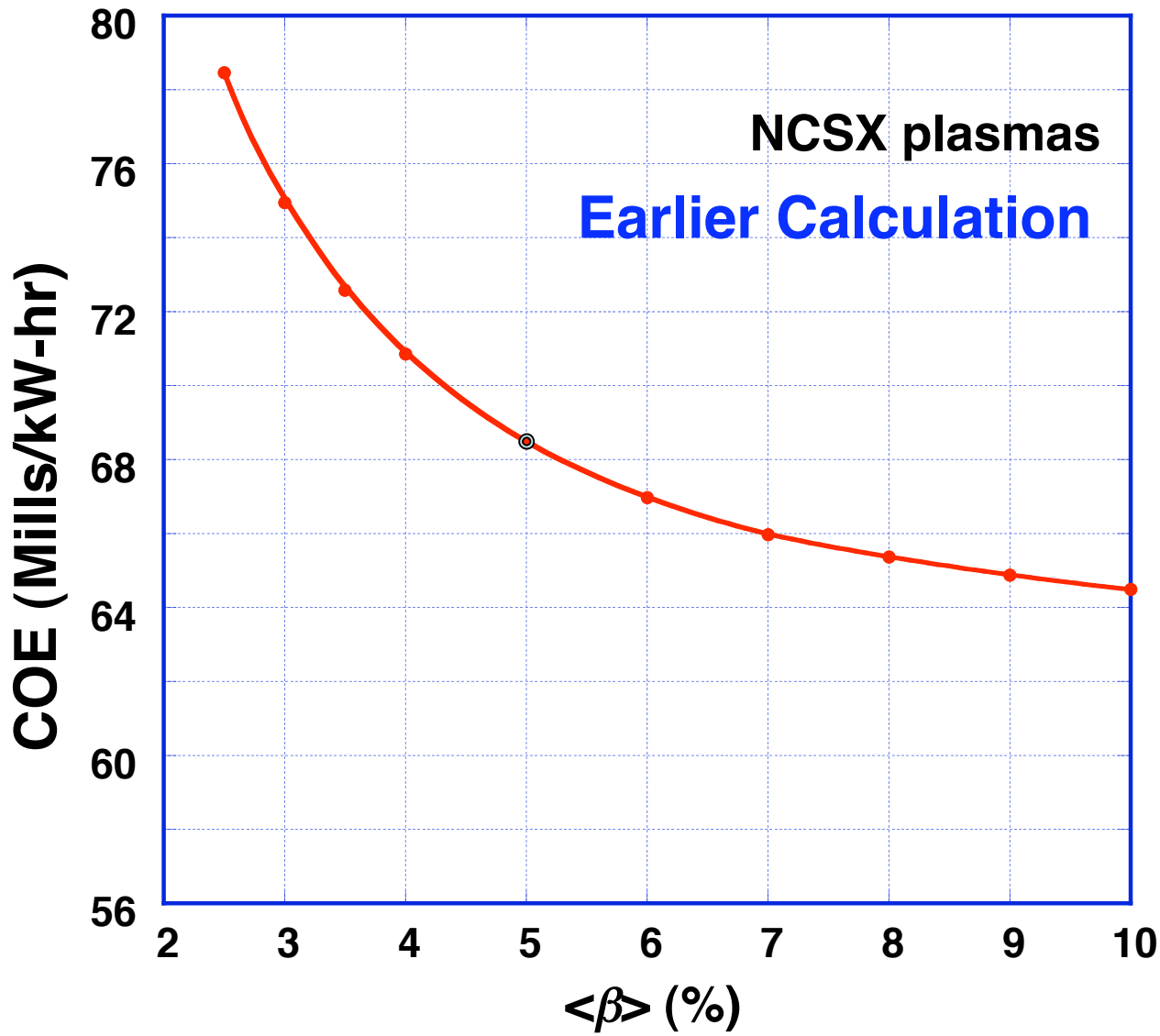
	Bucking Surface	NCSX Shell Approach
COE (2004 $) mills/kWhr	81.66	79.36
Coil structure cost (M$)	359.86	275.07
Coil structure mass (t)	6426	4912
nuclear island cost (M$)	876	785
nuclear island mass (t)	12,343	10,837

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



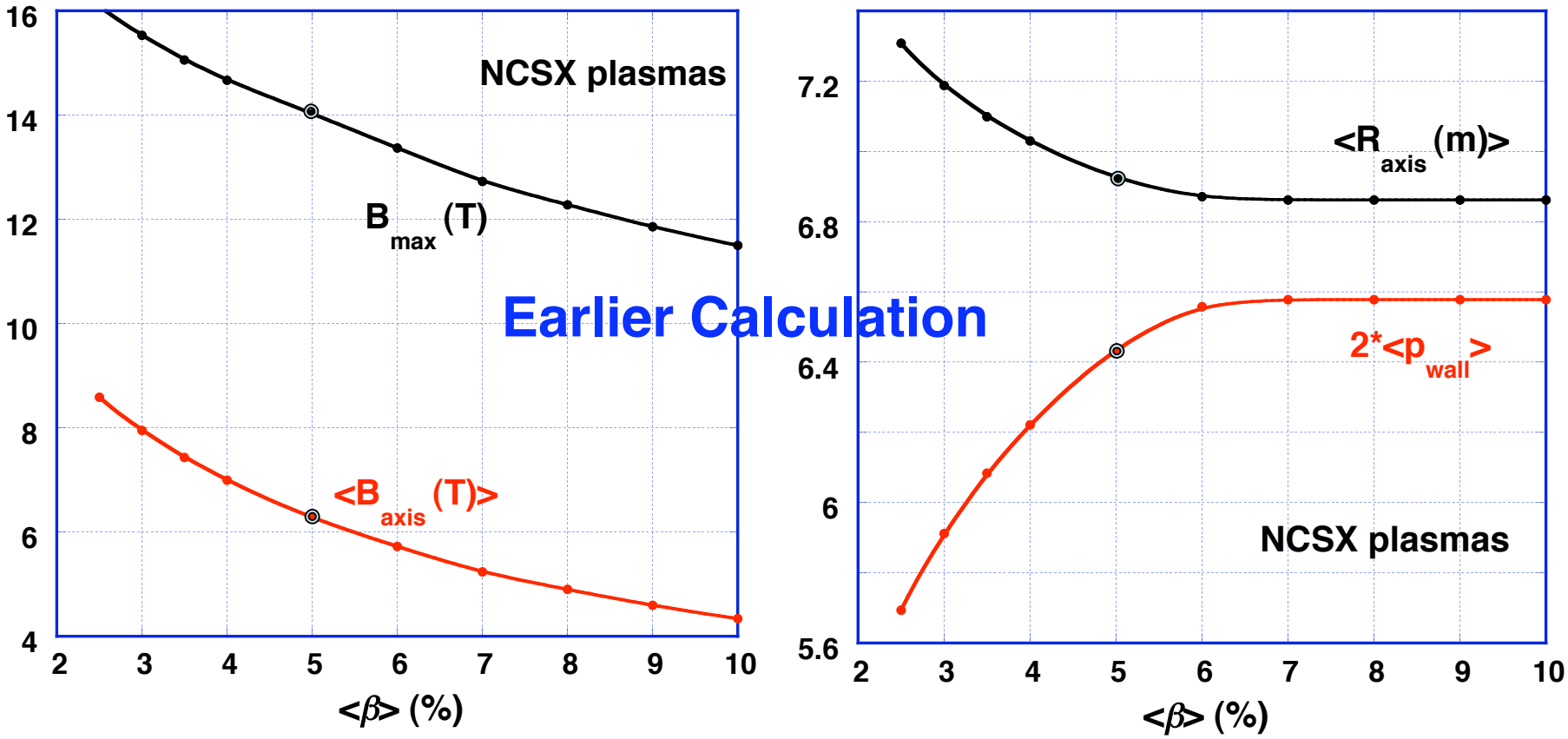
- Increasing p_{wall} decreases $\langle R_{axis} \rangle$ and COE until R_{min} limit is reached

COE Decreases with Increasing β



Only 6% decrease in COE as <β> increases from 5% to 10%

Variation of Reactor Parameters with β



- Increasing <β> allows reduced <B_{axis}> and <R> (until p_{wall} limit reached)

Summary

- **Parameter determination integrates plasma, reactor components, and coil geometry with physics & engineering constraints and assumptions**
- **The dominant factors in determining size and cost are p_{wall} and the plasma-coil distance**
- **Study leads to factor ~2 smaller stellarator reactors ($\langle R \rangle \sim 7$ m), closer to tokamaks in size**