Systems Code Results: Impact of Physics and Engineering Assumptions

J. F. Lyon, ORNL

ARIES Meeting Sept. 15, 2005

Topics

- Optimization Approach
- Plasma and Coil Treatment
- Systems Optimization Code
- NCSX reference case results
- Parameter scans and variations
- Next steps

Approaches Used to Define Reactor Parameters

- **1-D systems cost optimization code**
  - calculates self-consistent plasma and component parameters
  - minimizes cost of electricity
- **1-D power balance determines plasma parameters and path to ignition**
  - incorporates density and temperature profiles; overall power balance; radiation, conduction, alpha-particle losses
- **0-D scoping study determines device parameters**
  - calculates $\langle R_{axis} \rangle$, $\langle B_{axis} \rangle$, $\langle \beta \rangle$, $\langle p_{n,wall} \rangle$, B_{max}, j_{coil}, etc. subject to limits and constraints
- **Sensitivity to models, assumptions & constraints examined at each stage**

Parameter Optimization Integrates Plasma/Coil Geometry and Reactor Constraints

Plasma & Coil Geometry

- Shape of last closed flux surface and $<R_{axis}>/<a_{plasma}>$, β limit
- Shape of modular coils and $B_{max,coil}/B_{axis}$ vs coil cross section, $<R_{coil}>/<R_{axis}>$, $\Delta_{min}/<R_{axis}>$
- 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

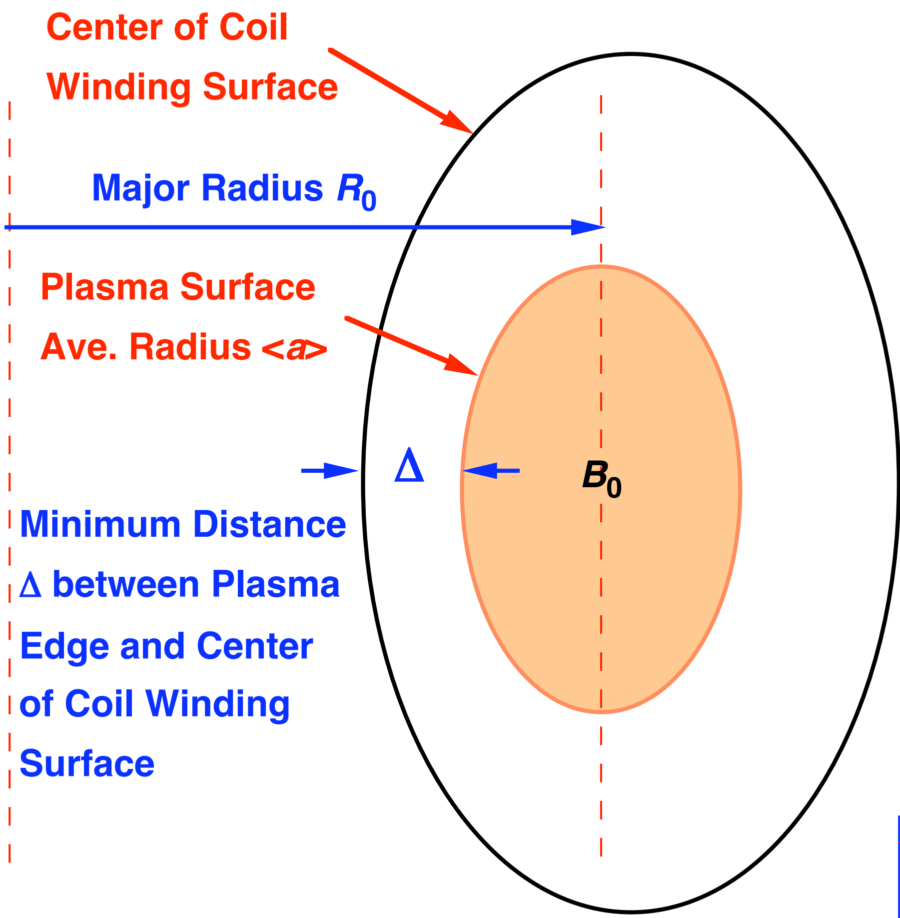
- $<R_{axis}>$, $<a_{plasma}>$, $<B_{axis}>$
- $B_{max,coil}$, coil cross section, gaps
- $n_{e,I,Z}(r)$, $T_{e,i}(r)$, $<\beta>$, P_{fusion}, P_{rad}, etc.
- Operating point, path to ignition
- Cost of components, operating cost $\rightarrow$ cost of electricity

Reactor Core (Plasma and Coil) and Operating Point Optimizations are Separate

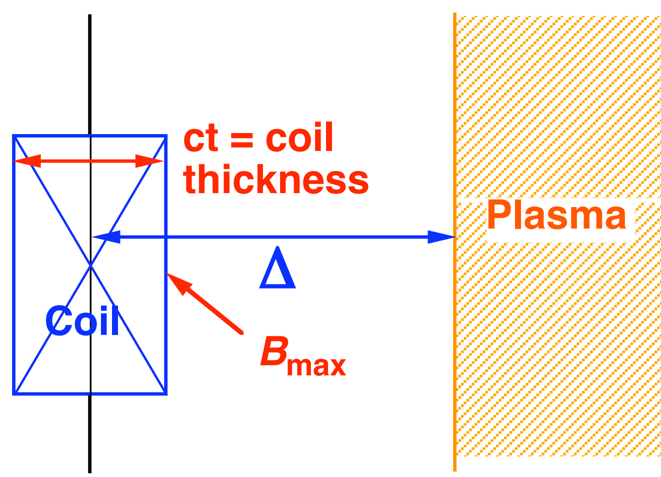
- **Reactor core optimization leads to a *fixed* plasma and coil geometry**
  - **integrated 3-D plasma/coil optimization code**
  - ⇒ **plasma shape, aspect ratio, coil geometry**
  - ⇒ **β limits, helical ripple, edge geometry**
  - ⇒ **plasma-coil and coil-coil spacings, etc.**

- **Operating point optimization leads to plasma parameters, profiles, field and component sizes**
  - **1-D systems code incorporating complex plasma and coil geometry and stellarator physics modules**

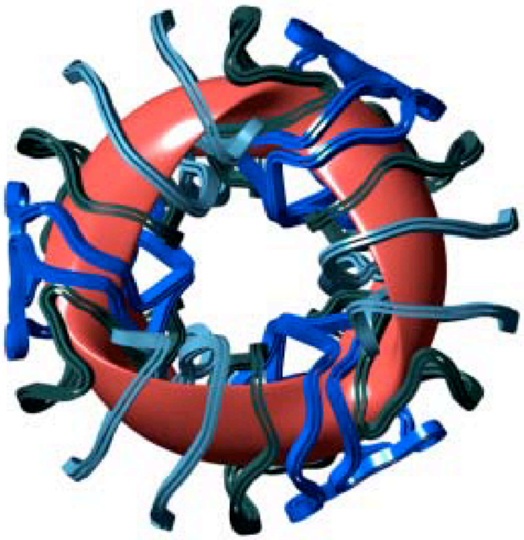
Minimum Reactor Size Is Determined by Δ



- A configuration is character-ized by the ratios $A_\Delta = R_0/\Delta$, $A_p = R_0/<a>$, and B_{max}/B_0
- The minimum reactor size is set by $R_0 = A_\Delta(D + ct/2)$ where D is the space needed for scrapeoff, first wall, blanket, shield, coil case, and assembly gaps
- Cost ∝ surface area ∝ A_Δ^2/A_p

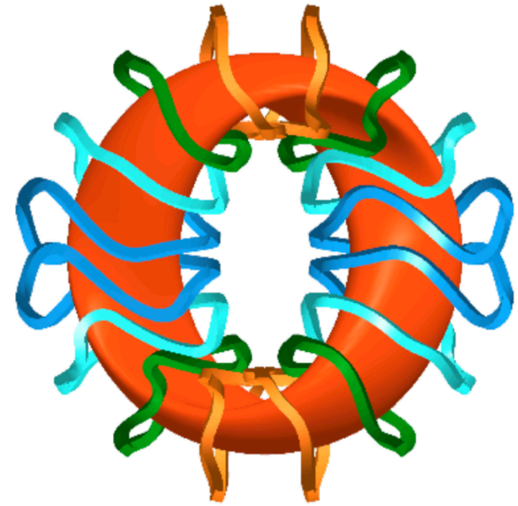


Several Plasma and Coil Configurations Have Been Studied



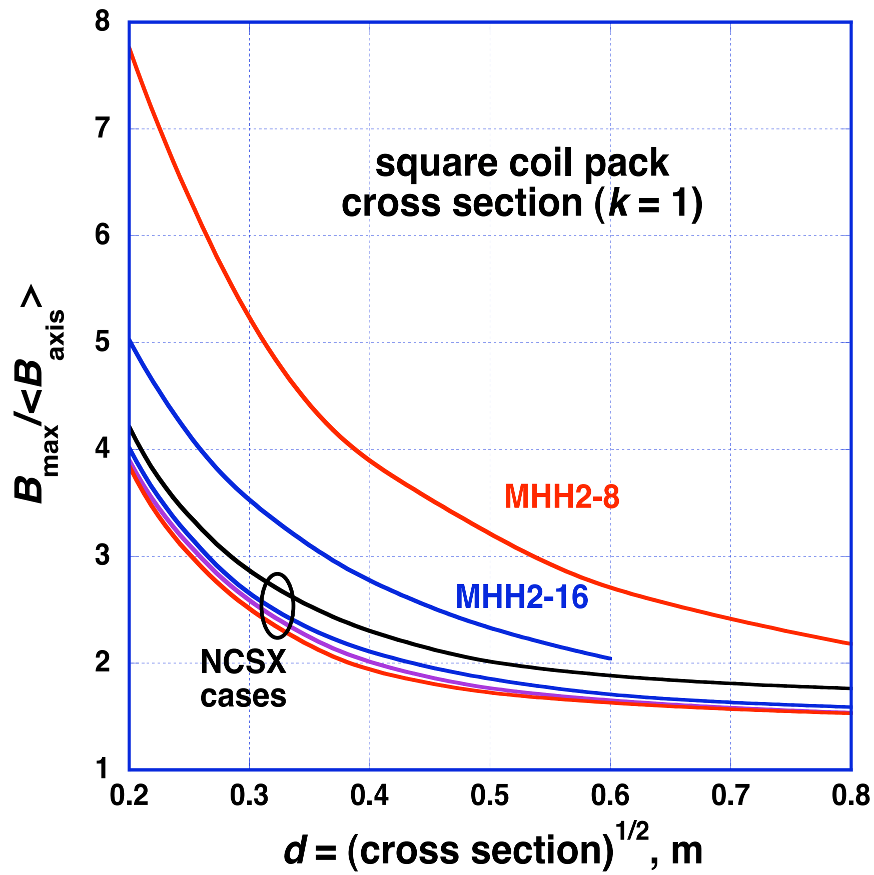
6 NCSX	2 MHH2
port or sector (end) access	only access through ports

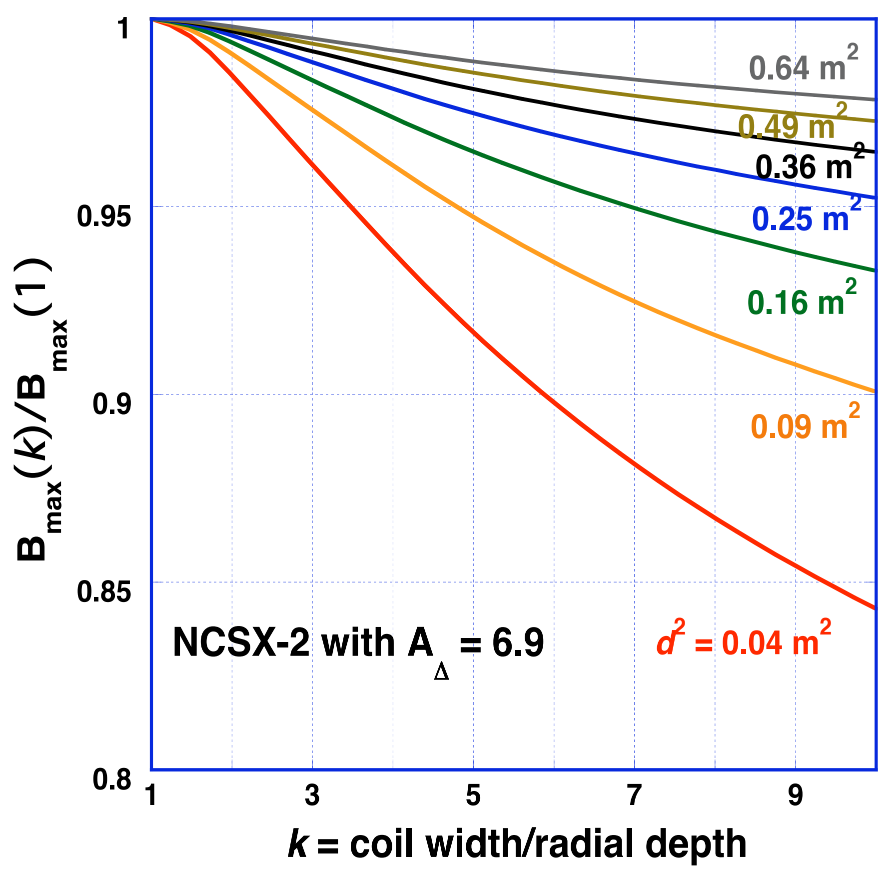
both quasi-axisymmetric



Key Configuration Properties	NCSX KXC	NCSX KZD	NCSX KWC	NCSX Z01	MHH2 8 coil	MHH2 16 coil
Plasma aspect ratio $A_p = \langle R \rangle / \langle a \rangle$	4.50	4.50	4.50	4.50	2.70	3.75
Wall (plasma) surface area/$\langle R \rangle^2$	11.80	11.80	11.80	11.80	19.01	13.37
Min. pl-coil dist. ratio $A_\Delta = \langle R \rangle / \Delta_{min}$	5.69	5.89	6.10	6.82	4.91	5.52
Min. coil-coil dist. ratio $\langle R \rangle$/(c-c)	10.11	10.04	9.64	9.35	7.63	13.27
Total coil length/$\langle R \rangle$	90.7	90.0	88.6	88.2	44.1	64.6
$B_{max}/\langle B_{axis} \rangle$, 0.4 m x 0.4 m coil pack	2.30	2.10	2.00	1.93	3.88	2.77

B_{max}/B_{axis} Depends on Coil Cross Section

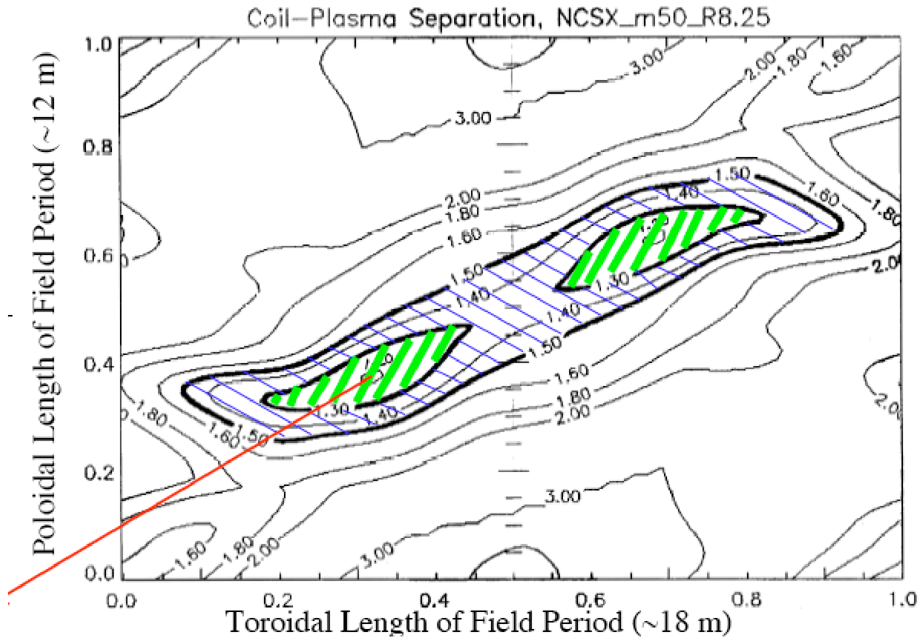


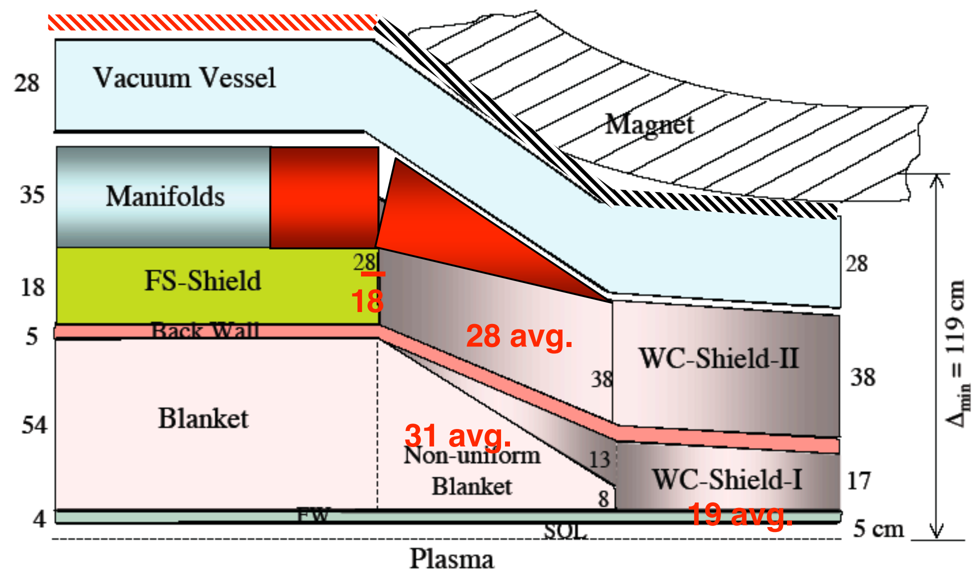


- Larger plasma-coil spacings lead to more convoluted coils and higher $B_{max}/<B_{axis}>$
- Minimum coil-coil separation distance determines k_{max}

NCSX Configurations Permit a No-Blanket Region

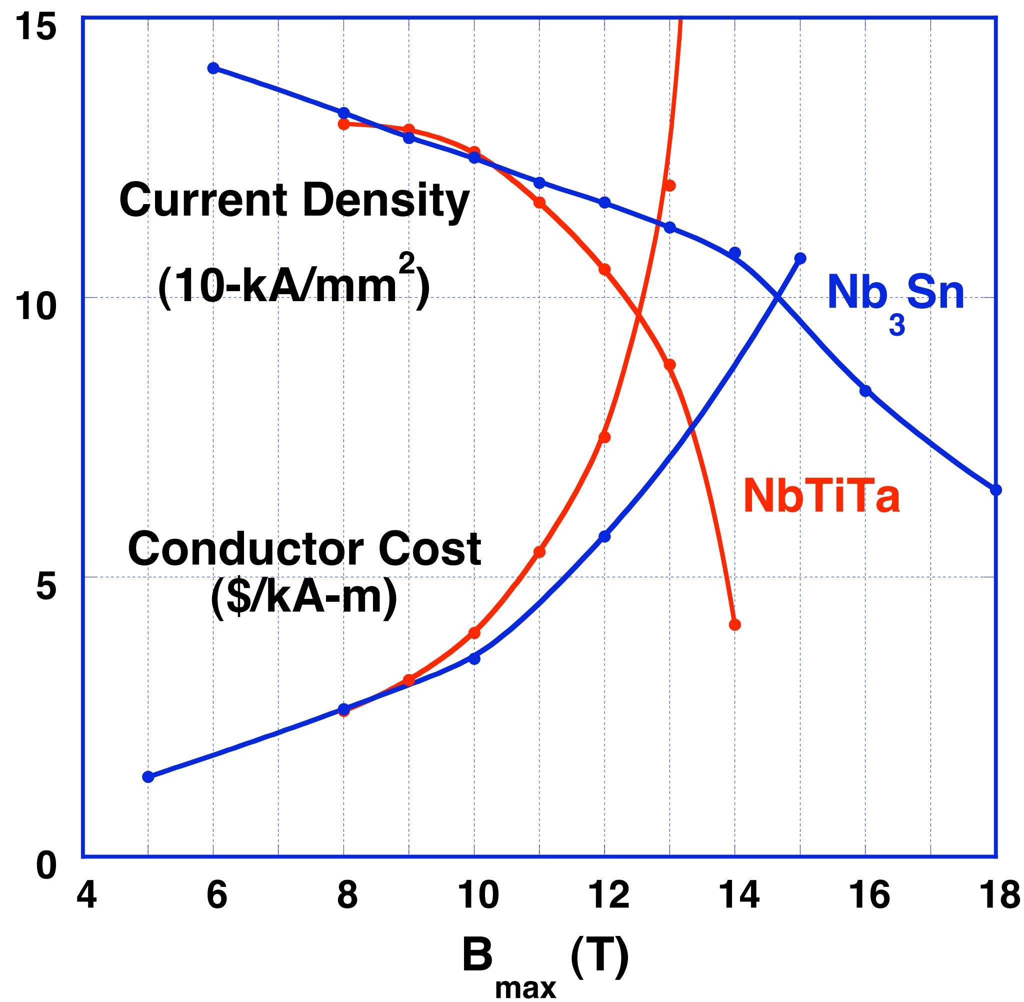
- Plasma-coil separation is small only over 5% of the wall area
- A transition region with tapered blanket and shield covers 10% of the wall area
- The full blanket covers 85% of the wall area
- Not possible with MHH2 configurations because coils are same distance from plasma everywhere



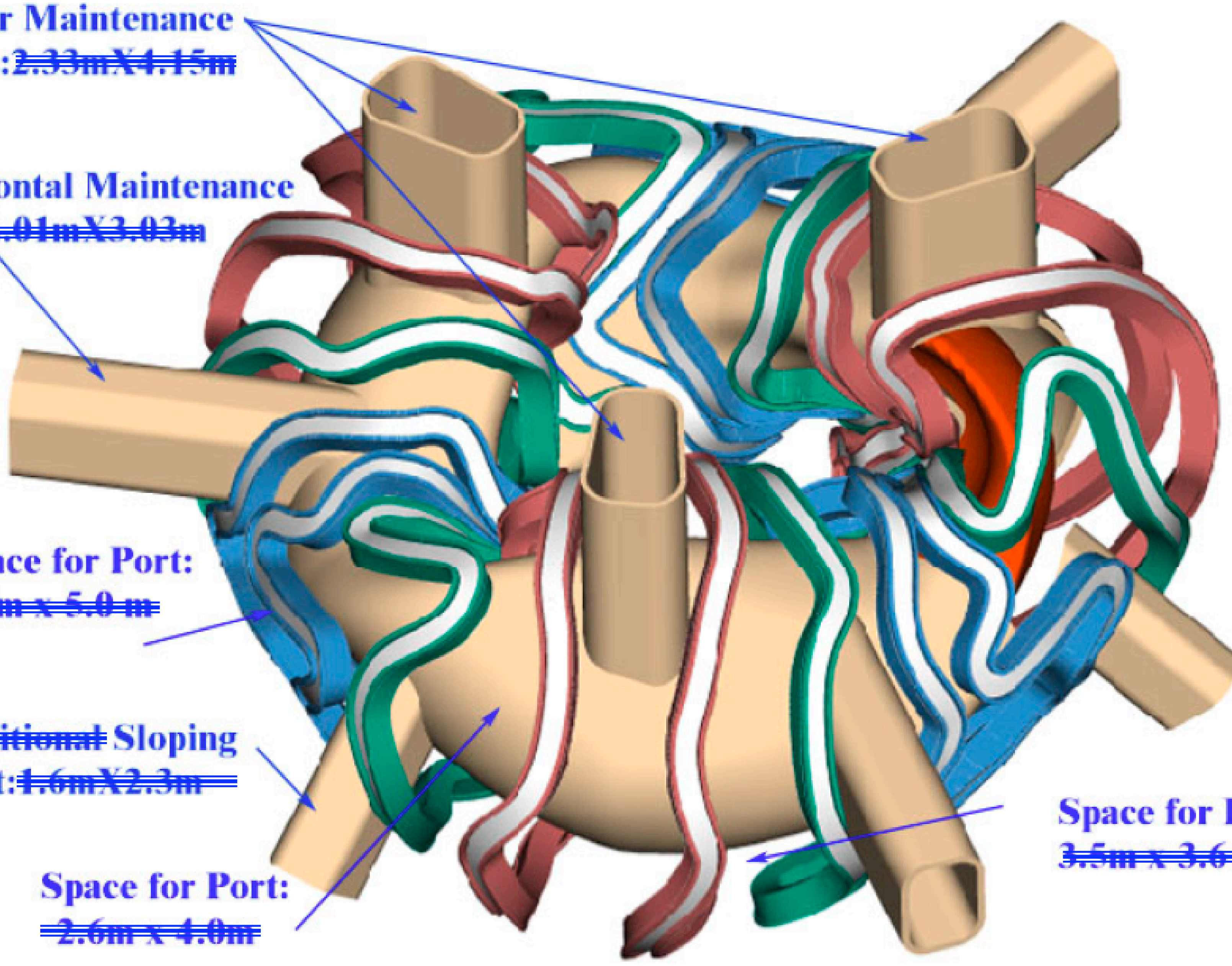


Conductor j and Cost Varies with B_{max}

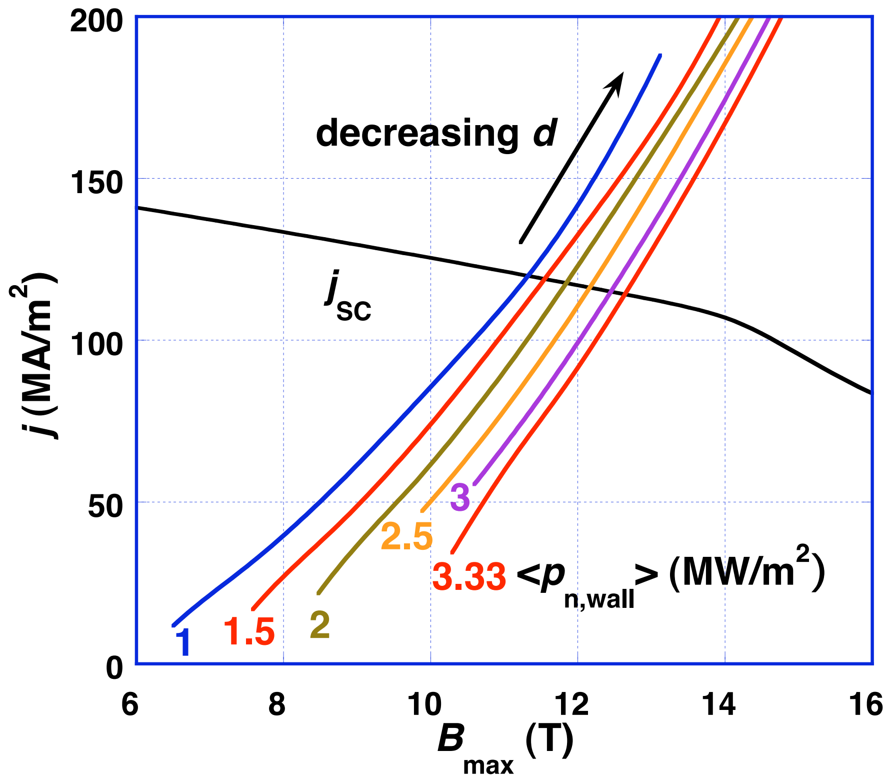
- **Conductor cost =**
  const $B_{axis}\langle R\rangle^2[f(B_{max})]$
- **Cost of winding coil =**
  conductor mass x \$80/kg
  const $B_{axis}\langle R\rangle^2/j(B_{max})$
- **Coil structure =**
  volume x 7800 kg/m^3 x
  \$56/kg = $k_3\langle R\rangle^2$

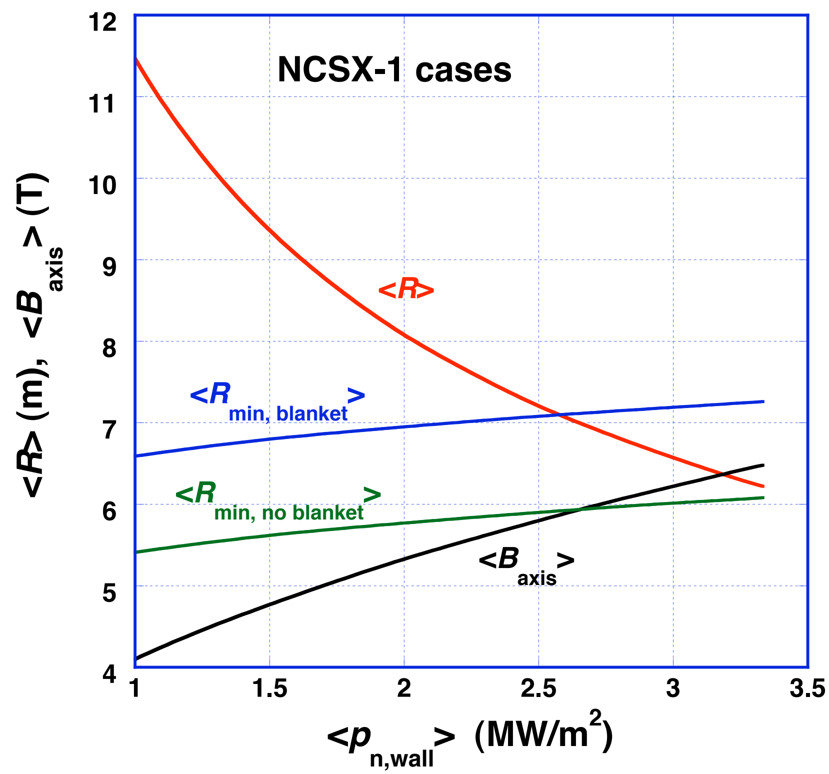


Studied Port Maintenance Approach



Parameters Depend on Neutron Wall Power





- **0-D NCSX values are determined by $p_{n,max}$ = 5 MW/m^2**
  - **$\langle R\rangle$ = 6.2 m, $\langle B_{axis}\rangle$ = 6.5 T, B_{max} = 12.7 T**

0-D Scaling of Main Reactor Parameters

- **Maximize <p_{wall}> subject to $j_{SC}(B_{max})$ and radial build constraints**
  - blanket, shield, structure, vacuum vessel ~ wall area ~ 1/<$p_{n,wall}$>
  - volume of coils ~ $L_{coil} I_{coil} / j_{coil}$ ~ <R>$^{1.2}$ ~ 1/<$p_{n,wall}$>$^{0.6}$
  - blanket replacement and other costs independent of <$p_{n,wall}$>
- **Fix maximum neutron wall loading $p_{n,wall}$ at 5 MW/m^2**
  - peaking factor = 1.52 ⟶ <$p_{n,wall}$> = 3.3 MW/m^2
- **<p_{wall}> = 3.3 MW/m^2 ⟶ wall area = 480 m^2 for P_{fusion} = 2 GW**

  ⇒ <R> = 6.2 m for NCSX vs. <R> = 14 m for SPPS
- **Chose <β> = 6%:** no reliable instability β limit, high equilibrium limit

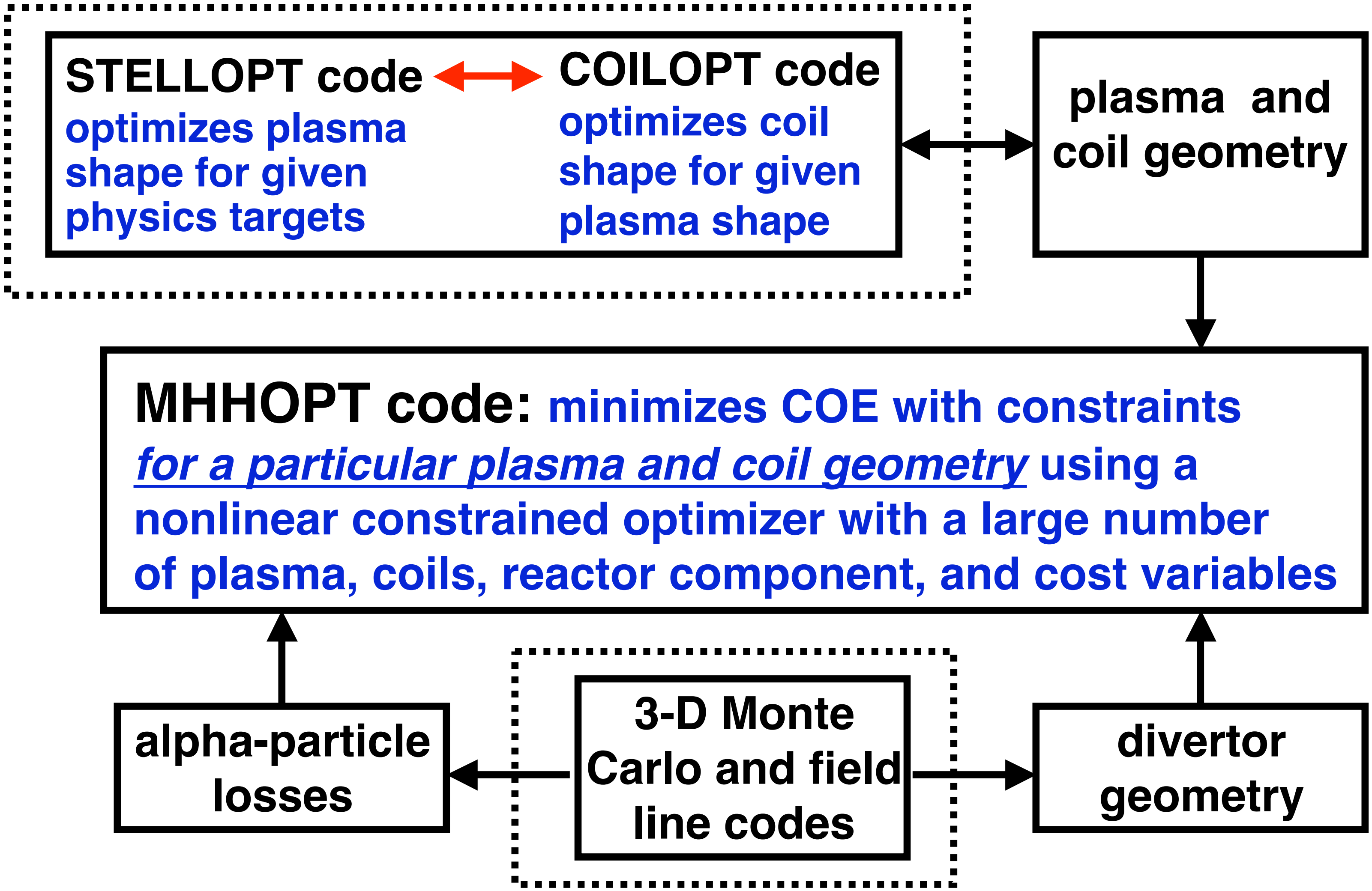
  ⇒ <B_{axis}> = 5.8 T for NCSX
- **B_{max} on coil depends on plasma-coil spacing & coil cross section**

Systems Optimization Code

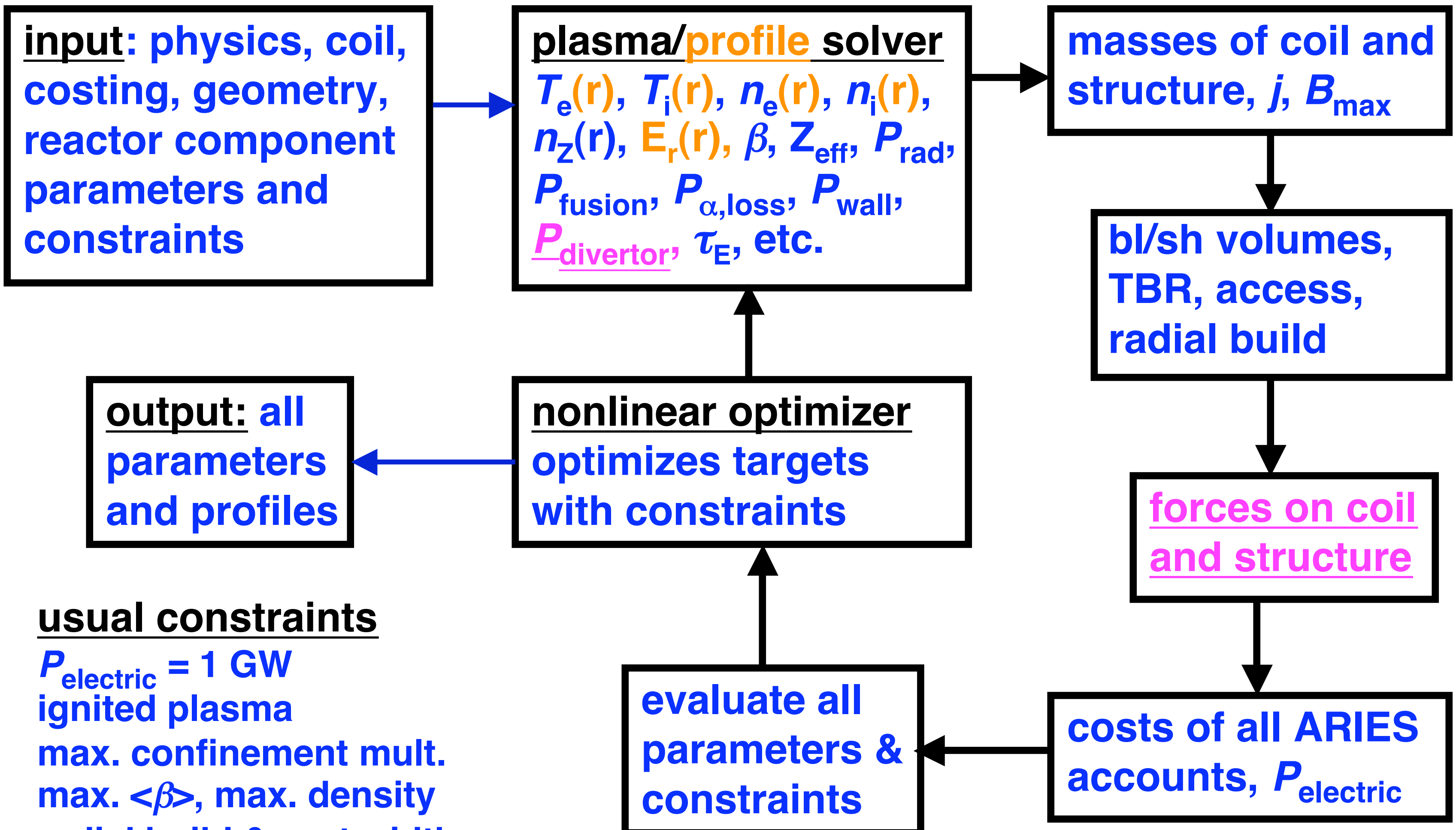
- **Minimizes Cost of Electricity for a given plasma and coil geometry using a nonlinear constrained optimizer**
- **Iterates on a number of optimization variables**
  - plasma: $\langle T_i \rangle$, $\langle n_e \rangle$, conf. multiplier; coils: width/depth of coils
  - reactor variables: $\langle B_{axis} \rangle$, $\langle R \rangle$
- **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

Optimization Approach

- Iterates on a large number of variables
  - <u>plasma:</u> $T_e(r)$, $T_i(r)$, $n_e(r)$, $n_e(r)$, β, Z_{eff}, H-ISS95, power components (coronal and bremsstrahlung radiation, α => i, α => e), α losses, etc.
  - <u>coils</u>: max. & min. width/depth of coils, clearance between coils, components volumes and costs, j, B_{max}, forces
  - <u>reactor variables</u>: B_0, $\langle R \rangle$, blanket volumes, TBR, neutron wall loading, $P_{electric}$, divertor area, access between coils, radial build, etc.
  - <u>costs</u>: equipment cost, annual operating cost, total project cost, CoE


STELLOPT code
optimizes plasma shape for given physics targets
COILOPT code
optimizes coil shape for given plasma shape
plasma and coil geometry
MHHOPT code: minimizes COE with constraints *for a particular plasma and coil geometry* using a nonlinear constrained optimizer with a large number of plasma, coils, reactor component, and cost variables
alpha-particle losses
3-D Monte Carlo and field line codes
divertor geometry

MHHOPTNEW Reactor Optimization Code



usual constraints

$P_{electric}$ = 1 GW
ignited plasma
max. confinement mult.
max. $\langle\beta\rangle$, max. density
radial build & port width
max. B_{max} on coil
max. $\langle p_{n,wall}\rangle$

existing parts   will update   no plans to use

Component and Cost Models

- Geometry factors for blankets, shields, vacuum vessel and coils from L-P Ku
- Blanket/shield models from L. ElGuebaly
  - 3 blanket/shield areas (with fractions)
  - $\langle p_{wall} \rangle$ limit and shield thickness
- Updated ARIES costing algorithms
  - 2004 costs for blanket/shield/vacuum vessel from L. Waganer and for coils from L. Bromberg
  - inflation factor from 1980 for other costs
- Compare results against 0-D optimization and 1-D POPCON calculations

Determination of Plasma Parameters

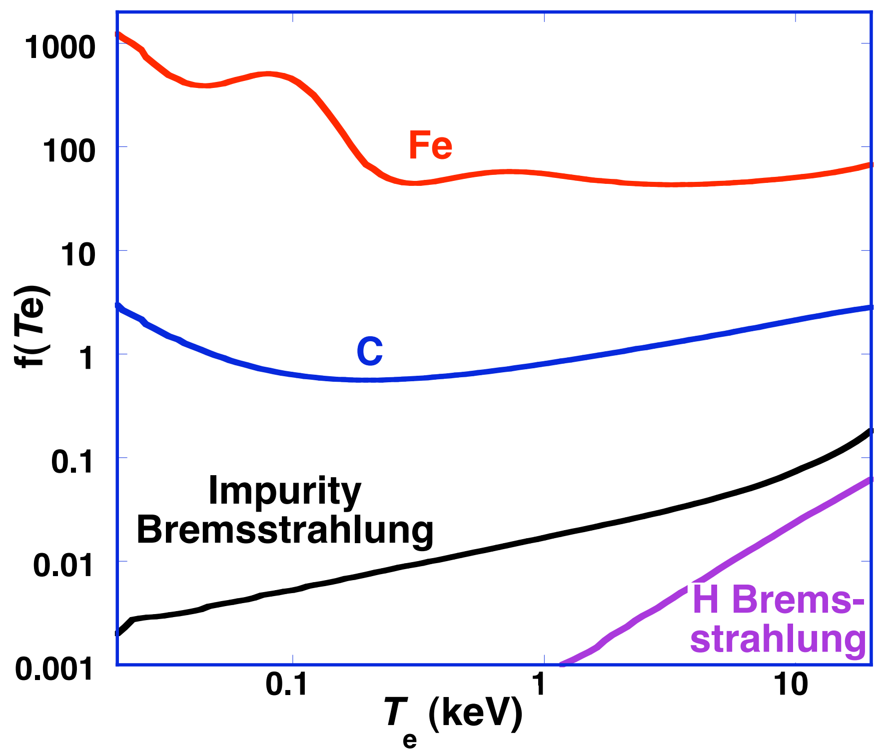
- **Too many variables, need to make some assumptions**
  - **choose H-ISS95 < 6**
    - **assuming improvements due to quasi-symmetry and experience**
  - **choose impurity levels: 0.5% C and 0.005% Fe**
  - **20% alpha-particle losses (better cases have been developed)**
  - **choose $\tau_{He}^{*}/\tau_{E} = 6$**
- **Choose profile shapes**
  - **choose hollow $n_e(r)$ with center/peak = 0.8**
  - **choose $T \sim$ parabolic$^{1.5}$**
    - need better transport model (χ, E_r) to determine self-consistent $T_e(r), T_i(r)$
    - full 1-D model with self-consistent E_r is in the systems code
- **Test sensitivity to these assumptions**

Treatment of Impurities

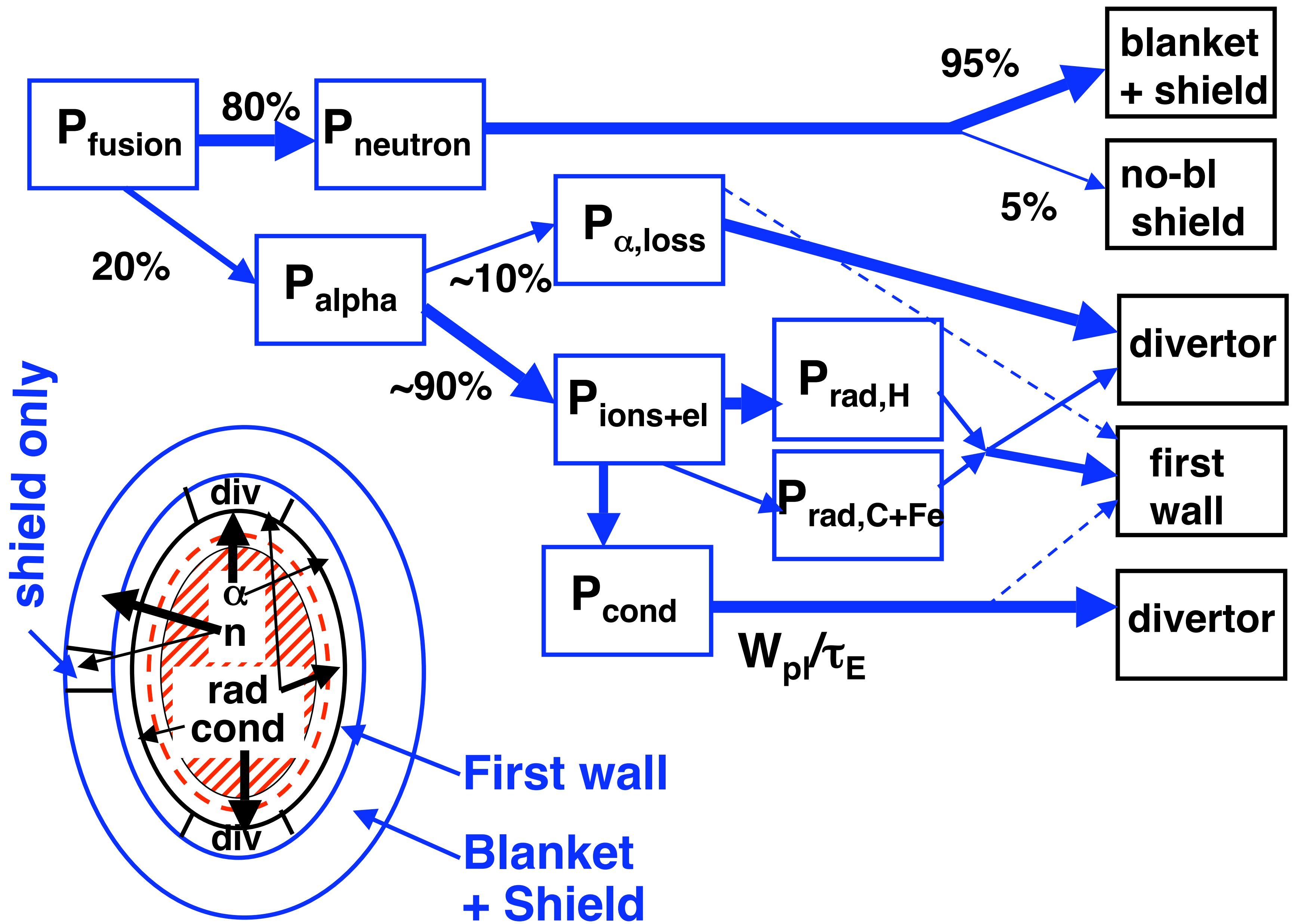
- $n_e = n_{DT} + \Sigma Z n_Z$, so impurities reduce P_{fusion} through
  - reduced n_{DT}^2 and β^2 ($\sim n_e + n_{DT})^2$; $P_{fusion} \sim n_{DT}^2 \sim \beta^2 B^4$
  - reduced T_e (hence T_i) through radiative power loss
  - requires higher B or H-ISS95 or larger R to compensate
- carbon ($Z_C = 6$) for low Z & iron ($Z_{Fe} = 26$) for high Z

Standard corona model: line radiation and electron-ion recombination

$p_{radiation} \sim n_e n_Z f(T_e)$



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

Typical Systems Code Summary

NCSX case (NKZD)

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

inflation factor	2004 year

following CONSTRAINTS were selected:

ignition = 1 target	1.00
Electric Power (GW)	1.00
volume averaged beta	0.05
sufficient radial build	
maximum neutron wall load	5.00
maximum jcoil/jSC(Bmax)	1.00
maximum density = 2 x nSudo	
max. confinement multiplier	6.0
minimum port width	2.0

VARIABLES selected for iteration

major radius	5.00	16.00
field on axis	3.00	10.00
ion density	1.00	10.00
ion temperature	1.00	20.00
coil radial depth	0.03	1.00
confinement multiplier	0.10	9.00

FIGURE OF MERIT ....

66.9 Cost of Electricity

FINAL VALUES OF CONSTRAINTS:

ignition margin	1.00
Electric Power (GW)	1.00
volume averaged beta (%)	5.00
radial build margin	1.00
max. neutron wall load (MW/m^2)	5.00
jcoil/jSC(Bmax)	1.00
average/maximum density	0.93
ratio of tauE to conf. multiplier	4.23
maintenance port width (m)	2.28

FINAL DESIGN

major radius (m)	6.73
field on axis (T)	6.19
max. field on coil (T)	14.03
volume avg. density (10^{20} m^{-3})	4.03
density averaged temp (keV)	6.08
coil dimensions (m x m)	0.18 x 0.65
current density (MA/m^2)	107

Typical Systems Code Summary

Plasma Parameters

central ion temp (keV)	9.15
central ion density (10^{20} m^{-3})	8.59
central elec. density (10^{20} m^{-3})	9.11
fraction fuel to electrons	0.91
confinement time, taue (sec)	0.95
stored plasma energy (MJ)	343
volume averaged beta (%)	5.00
beta star (%)	8.21
fraction carbon impurity	0.5 %
fraction iron impurity	0.005 %
fraction helium	3.11 %
Z effective	1.25

Mass Summary

total nuclear island (tonnes)	5,078
mass LiPb coolant (tonnes)	3,264
total mass (tonnes)	8,342

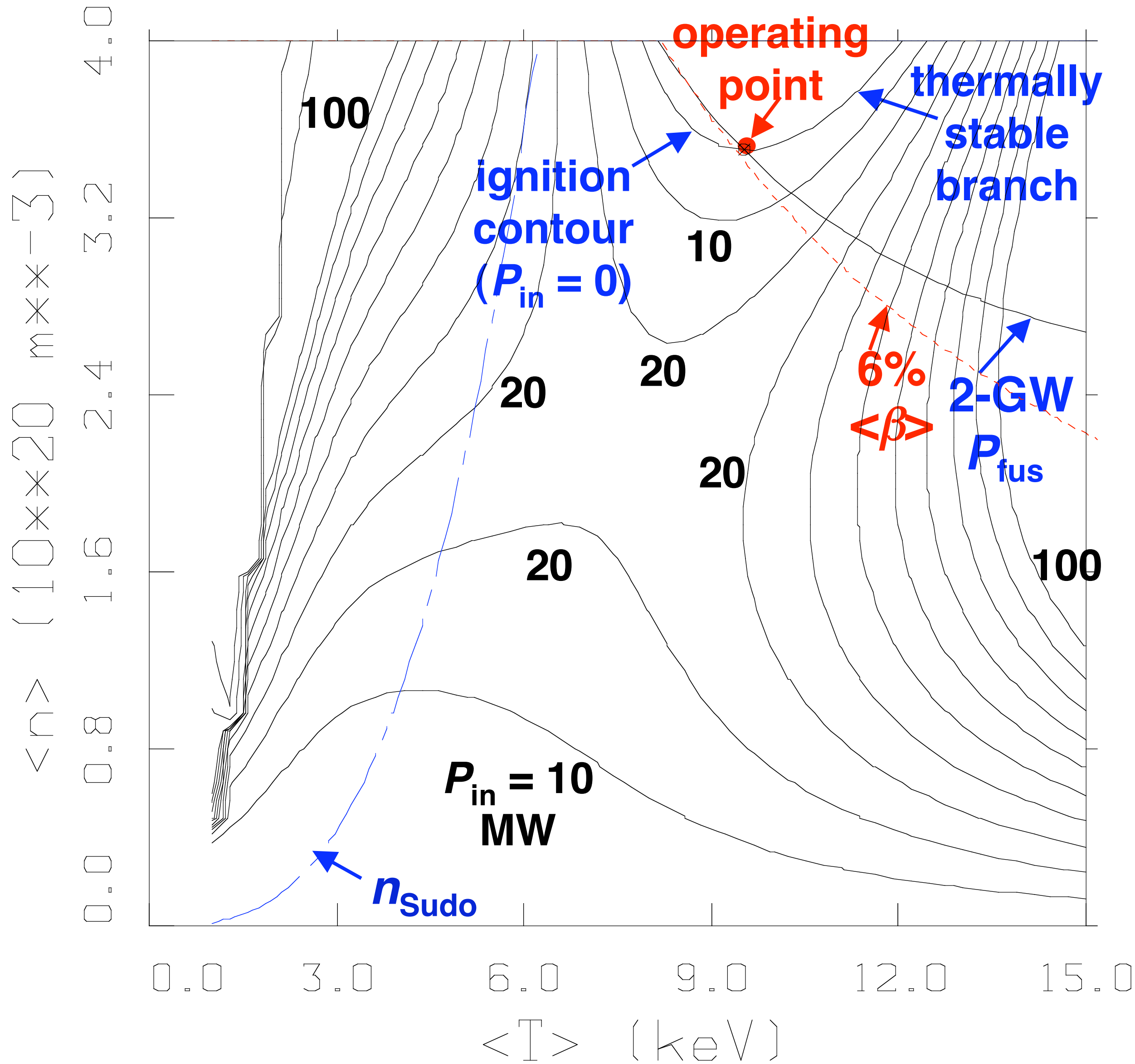
Power Balance

net electric power (MW)	1000
gross electric power (MW)	1054.9
fusion power (MW)	2258.5
thermal power (MW)	2511.6
α heating power (MW)	450.9
power in neutrons (MW)	1807.6
radiated power (MW)	349.5
fuel bremsstrahlung (MW)	238.1
carbon radiation (MW)	53.0
iron radiation (MW)	57.4
synchrotron radiation (MW)	1.0
conduction power (MW)	11.2
fusion power to plasma (MW)	360.7
fraction alpha power lost	20.0 %
radiated power fraction	77.5 %
ave neut wall load (MW/m^2)	3.29
ave rad wall load (MW/m^2)	0.64

NCSX: $\tau_E/\tau_E^{ISS\text{-}95}$ = 4.2, $<T>$ = 9.5 keV, $<n>$ = 3.5 10^{20} m^{-3}, $<\beta>$ = 6.1%

H-ISS95 =

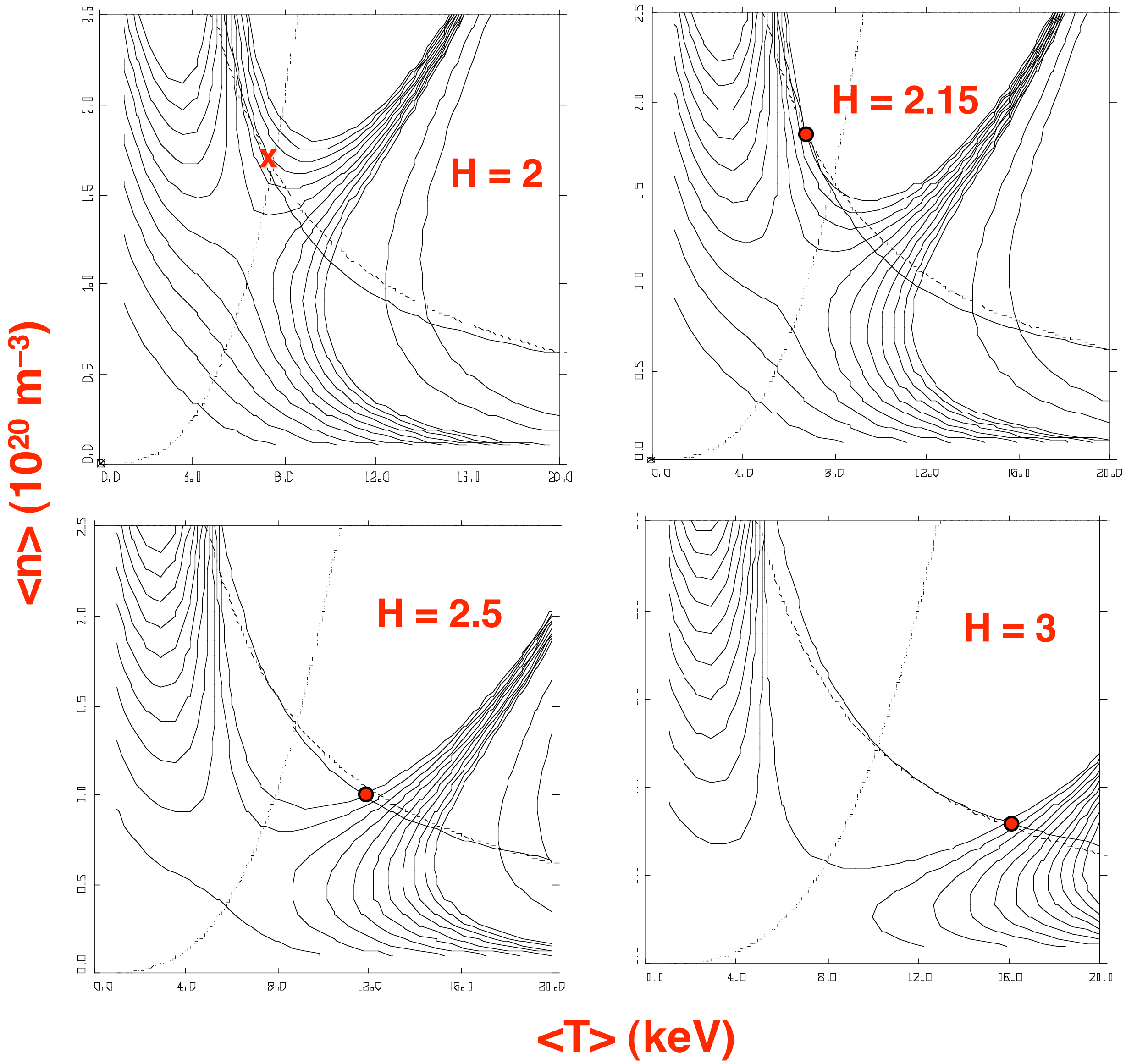
$\tau_E/\tau_E^{ISS\text{-}95}$



- $\tau_E^{ISS\text{-}95} = 0.26 P_{heating}^{-0.59} <n_e>^{0.51} <B_{axis}>^{0.83} <R>^{0.65} <a>^{2.21} \iota_{2/3}^{0.4}$

Operating Point Moves to Higher $<T>$ with Lower $P_{startup}$ as ISS95 Multiplier H Increases

- **Example:** R = 9 m, B = 5 T, 5% α losses, τ_{He}/τ_E = 6



Component Cost Summary (2004$)

total mod coil + str cost	**138.2**
mod coil SC cost	69.0
rest mod coil pack cost	15.8
coil structure cost	53.4
total VF coil cost	0.0
divertor coil cost	0.0
total coil cost	138.2
bucking cylinder cost	0.0

total blanket, first/back wall	**56.4**
first wall cost	5.8
front full blanket cost	24.5
front blanket back wall cost	24.5
second blanket cost	0.0
transition blanket cost	1.6

total vacuum vessel cost	**49.9**
full blanket vac vessel cost	43.1
shield-only vac vessel cost	2.1
transition vac vessel cost	4.8

shield cost and back wall	**97.9**
ferritic steel shield cost	33.6
1st shield-only WC shield cost	2.6
shield-only back wall cost	20.5
2nd shield-only WC shield cost	6.4
1st transition WC shield cost	2.2
trans shield back wall cost	22.7
2nd transition WC shield cost	10.1

cost of manifolds	**147.5**
full manifold cost	99.5
transition manifold cost	48.0

cost of liquid metal coolant	**166.5**

Values for Different Coil Configurations

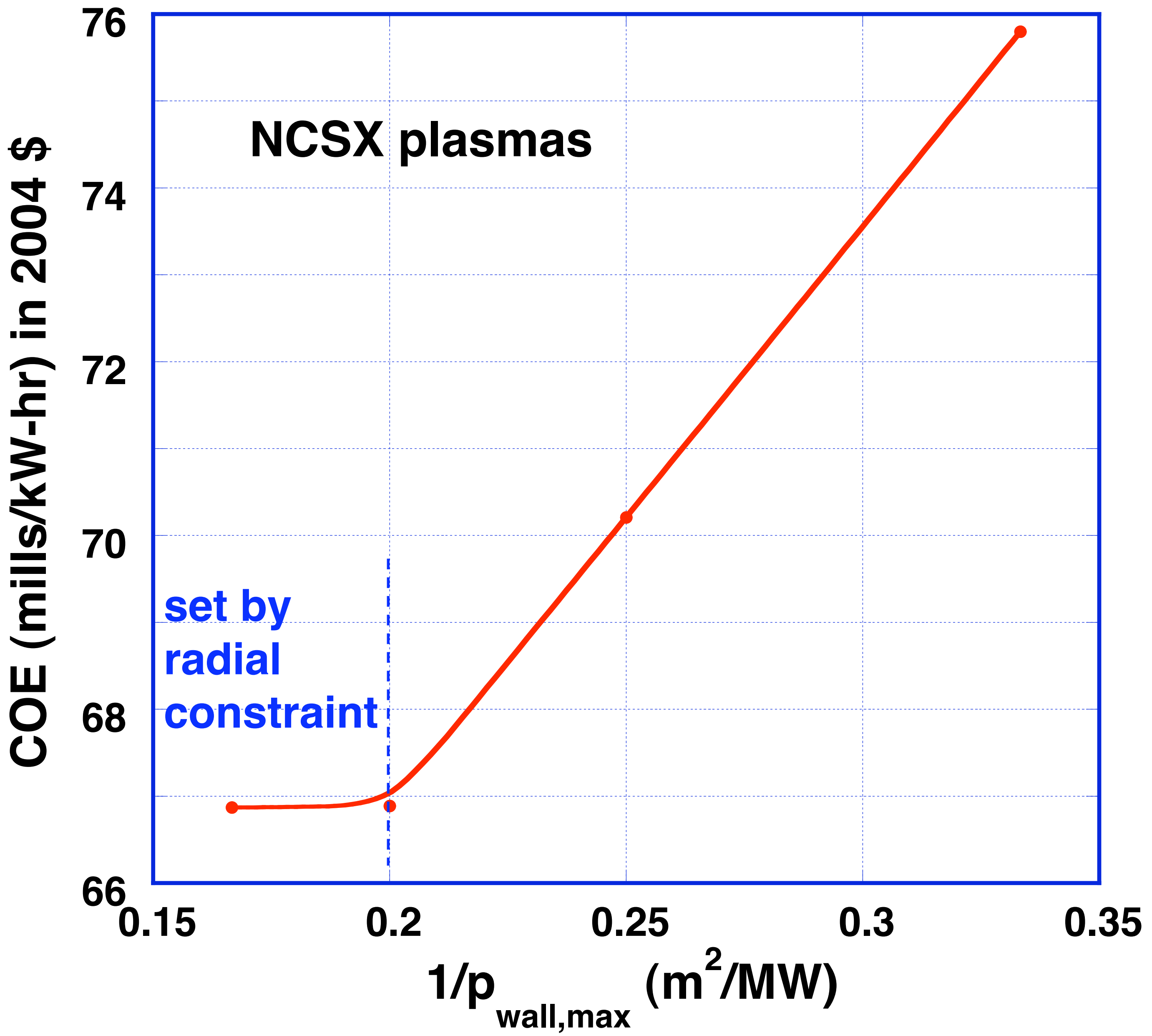
A_Δ	5.69	5.89	6.1	6.82
$\langle R \rangle$ (m)	6.67	6.73	6.90	7.62
$\langle B_{axis} \rangle$ (T)	6.23	6.19	6.09	5.56
B_{max} (T)	14.7	14.0	13.5	11.9
H-ISS95	4.09	4.23	4.41	3.23
CoE	67.4	66.9	67.6	70.5

- **ISS-95 confinement improvement factor of 3.2 to 4.4 is required; present stellarator experiments have up to 2.5**
- **ISS-2004 scaling indicates $\varepsilon_{eff}^{-0.4}$ improvement, so compact stellarators with very low ε_{eff} should have high H-ISS values**

Values for Different p_{wall} Limits

Max. p_{wall}	3 MW/m^2	4 MW/m^2	5 MW/m^2	6 MW/m^2
$\langle R \rangle$ (m)	8.72	7.54	6.73	6.72
$\langle B_{axis} \rangle$ (T)	5.04	5.63	6.18	6.21
B_{max} (T)	11.3	12.8	14.0	14.1
H-ISS95	3.61	3.77	4.22	4.22
CoE	75.8	70.2	66.9	66.9

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

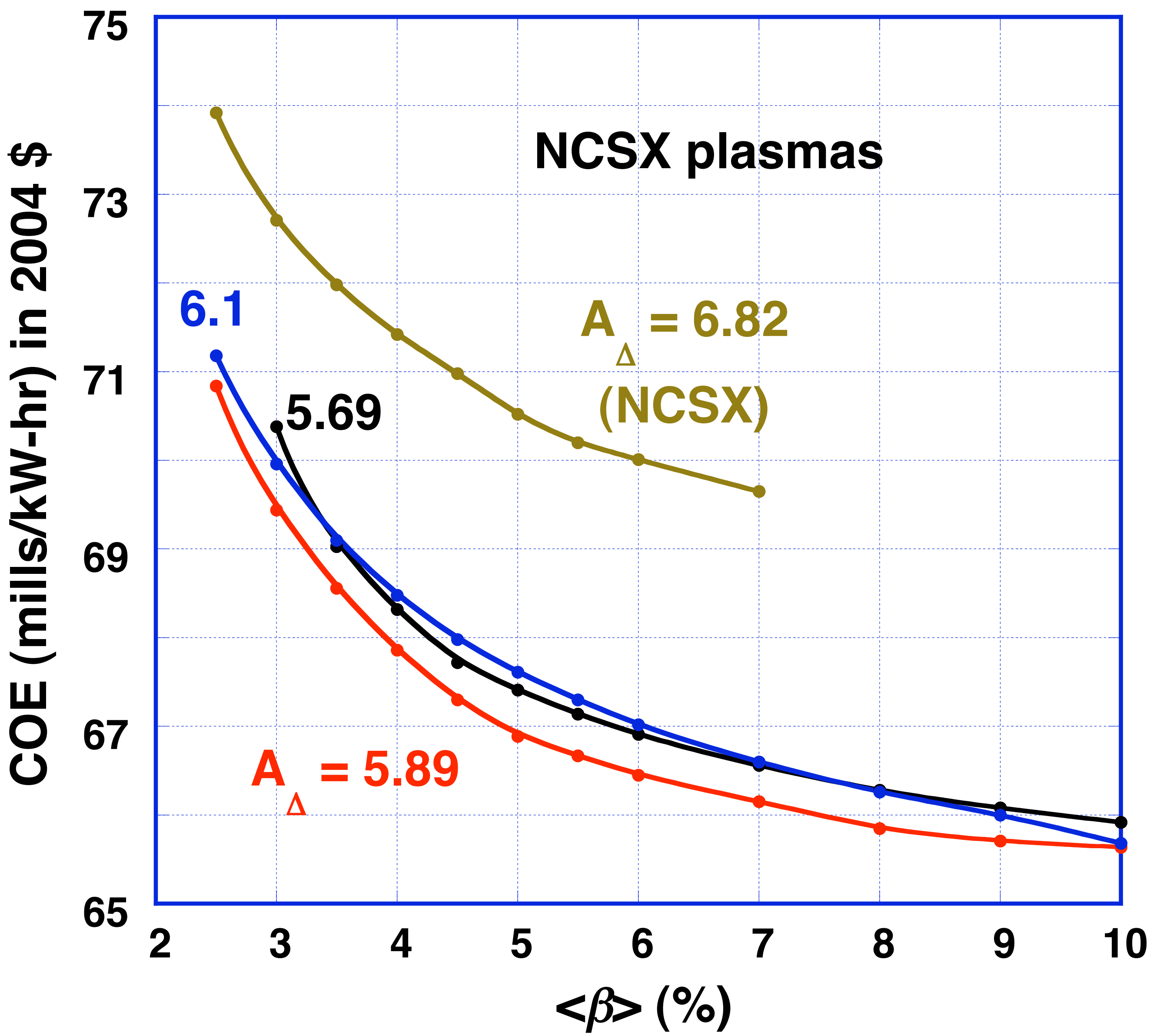


Weak Variation of Reactor Parameters with β

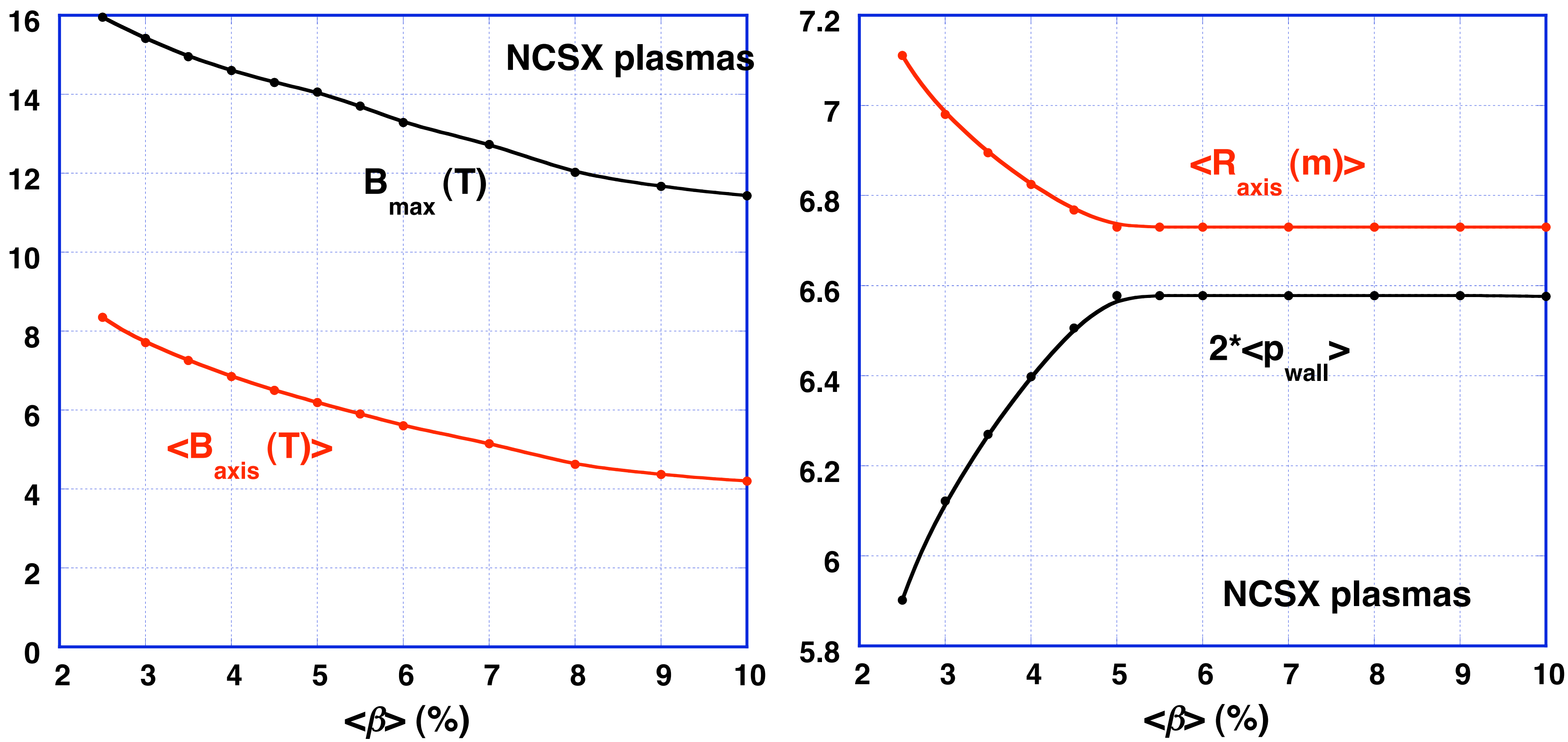
$\langle\beta\rangle$, %	$\langle R_{axis}\rangle$ m	$p_{n,wall}$ MW/m^2	$\langle B_{axis}\rangle$ T	B_{max} T	CoE
2.5	7.11	2.95	8.36	15.96	70.8
3	6.98	3.06	7.71	15.42	69.4
4	6.83	3.20	6.86	14.60	67.9
5	6.73	3.29	6.19	14.06	66.9
6	6.73	3.29	5.61	13.29	66.5
7	6.73	3.29	5.15	12.73	66.2
8	6.73	3.29	4.63	12.03	65.9
9	6.73	3.29	4.37	11.67	65.7
10	6.73	3.29	4.20	11.44	65.6

- Increasing $\langle\beta\rangle$ allows reduced $\langle B_{axis}\rangle$, B_{max} and $\langle R\rangle$

Weak Variation of COE with β and A_Δ

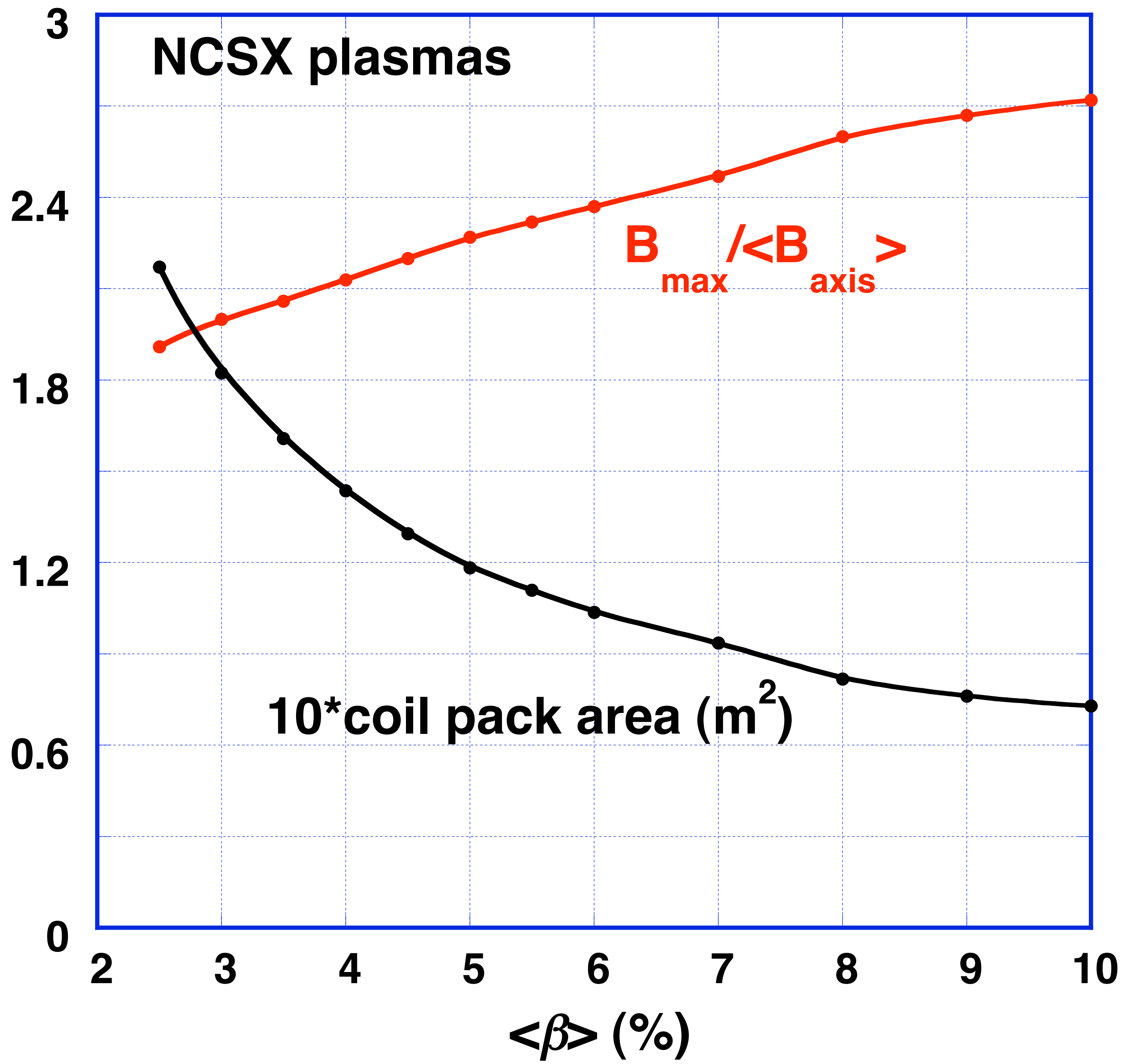


Variation of Reactor Parameters with β



- Increasing $\langle\beta\rangle$ allows reduced $\langle B_{axis}\rangle$ and $\langle R\rangle$ (until p_{wall} limit) but requires larger H-ISS95

Variation of Coil Parameters with β



Parameters Insensitive to Profile Assumptions

Variation	$\langle n \rangle, 10^{20}\ \mathrm{m}^{-3}$	$\langle T \rangle$, keV	H-ISS95	$\langle \beta \rangle$, %
Base case	3.51	9.52	4.15	6.09
Peaked n	3.36	9.85	4.00	6.03
0.1 n_{pedestal}	3.53	9.46	4.10	6.09
0.2 n_{pedestal}	3.57	9.34	4.05	6.09
T parabolic	3.23	10.82	4.40	6.36
T parabolic^2	3.60	9.01	4.00	5.92
0.1 T_{pedestal}	3.28	10.68	4.40	6.37
0.2 T_{pedestal}	3.22	11.11	4.50	6.50
Peaked n_Z	3.42	9.97	4.15	6.21
T screening	3.48	9.15	3.75	5.81

Larger H-ISS95 is Required to Offset Higher Alpha-Particle Losses

$f_{a,loss}$	$\langle R_{axis} \rangle$ m	$\langle B_{axis} \rangle$ T	H-ISS95	CoE
0	6.73	6.18	4.23	66.9
20%	6.73	6.19	2.71	66.9

Next Steps

- Incorporate ν^* as target
- neoclassical impurity profiles
- 1-D calculation of $T_e(r)$ & $T_i(r)$
- NbTi(Ta) coils
- Field period maintenance approach

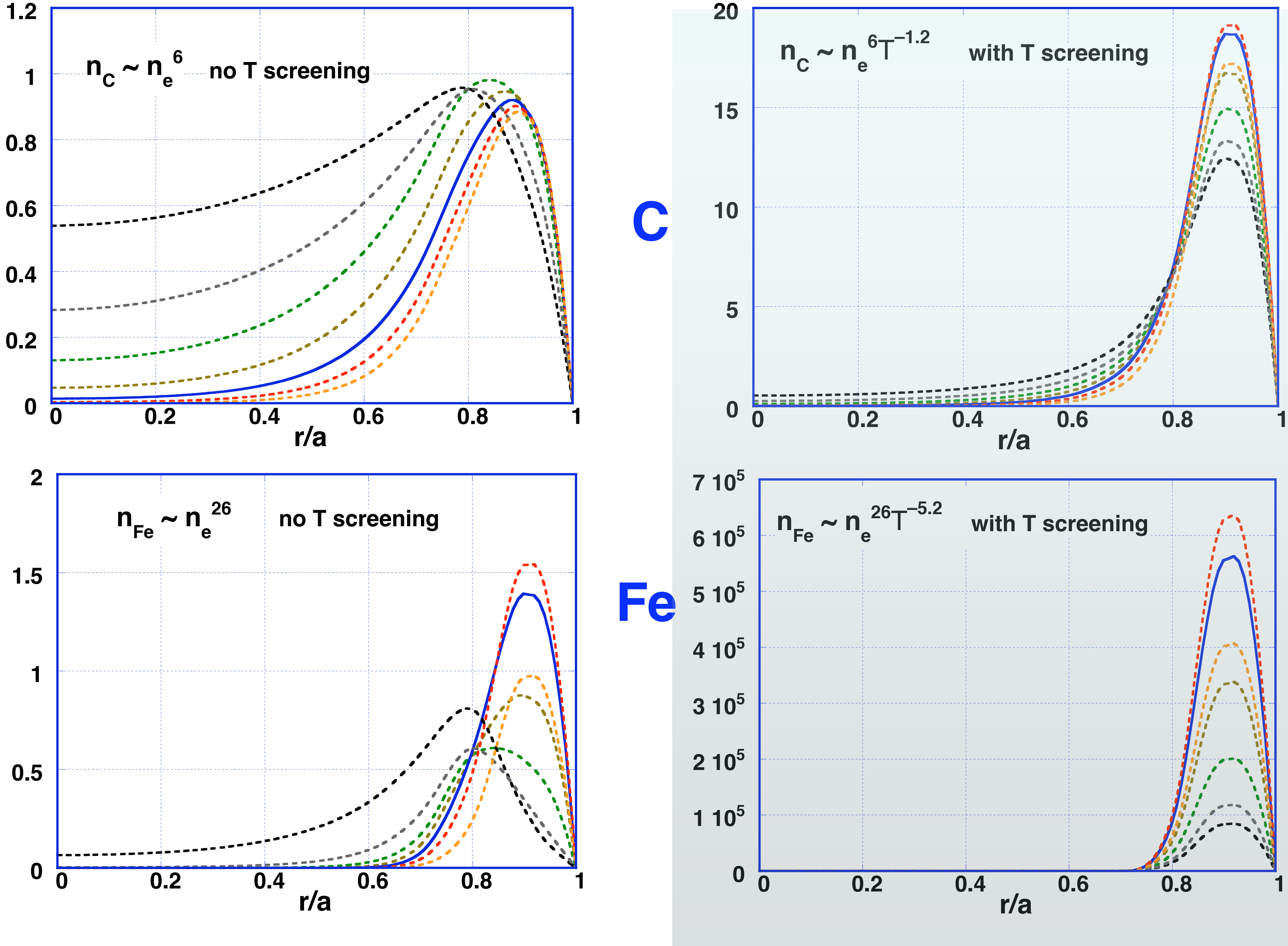
Further Modeling of Impurities Is Possible

- **Present approach**
  - assumes $n_C = f_C n_e$ & $n_{Fe} = f_{Fe} n_e$; f_Z = constant thruout plasma, so $n_Z(r)$ has same (slightly hollow) profile as $n_e(r)$
- **Use neoclassical model for impurity profiles**
  - $n_Z(r) = n_e(r) \times \langle f_Z \rangle (n_e/n_{e0})^Z \, [T_e/T_{e0}]^{-Z/5}$
  - conservative approach: ignore $[T_e/T_{e0}]^{-Z/5}$ term because it probably is not applicable in stellarators

  ⇒ $n_Z(r)$ more peaked near edge since $n_e(r)$ is hollow for regime of interest

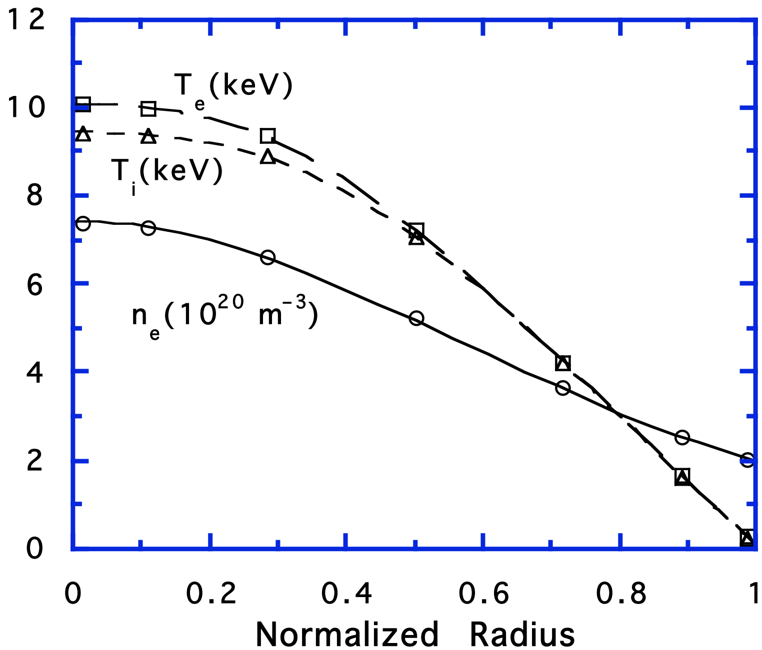
  ⇒ $n_Z(r)$ peaked at center if $n_e(r)$ peaked

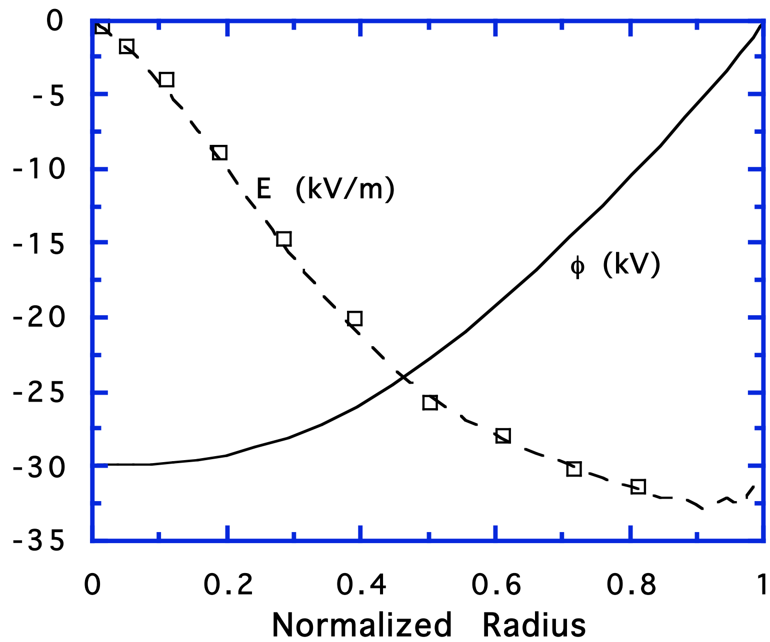
Impurity Density Profiles



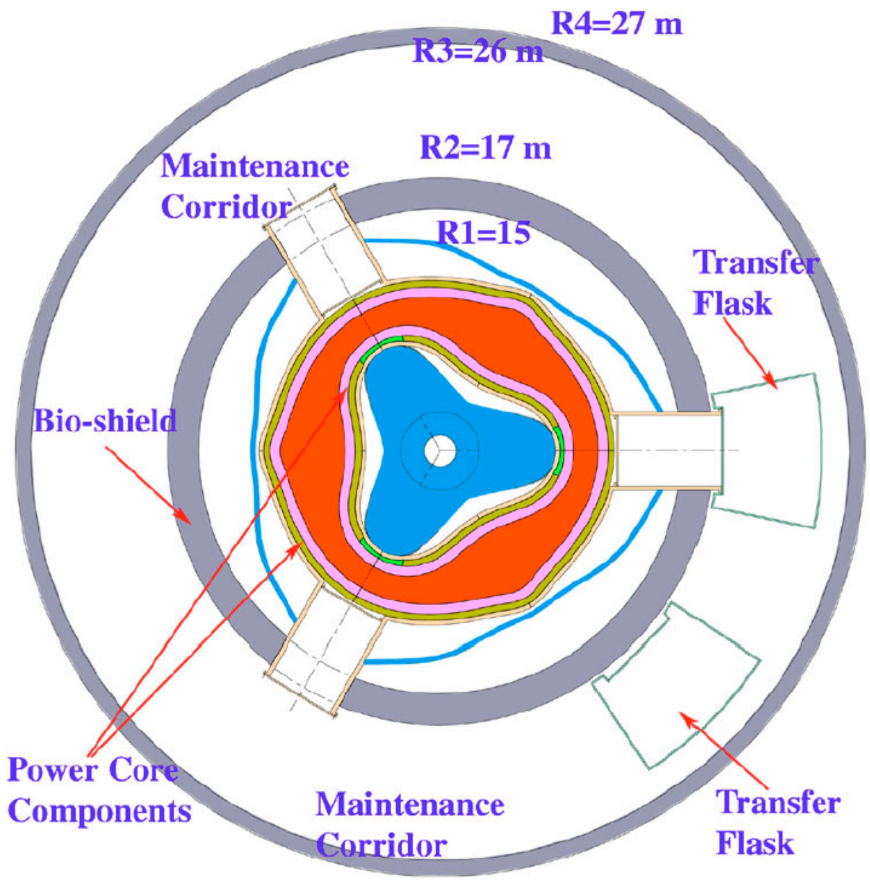
Full 1-D Transport Matrix Calculations are in Systems Code

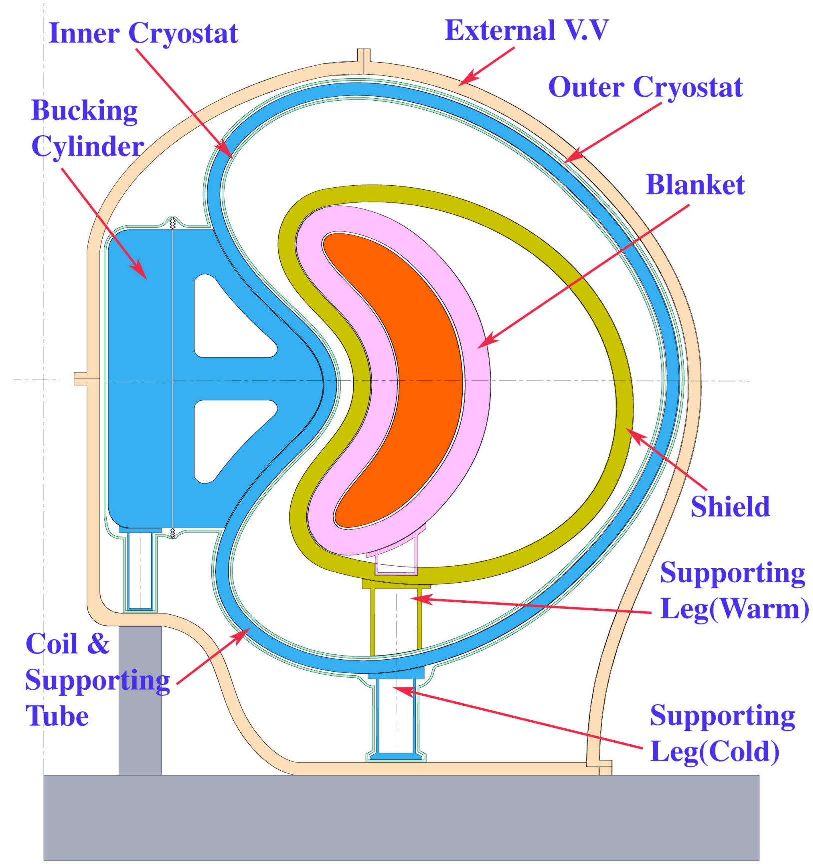
- **Example case: R_0 = 12 m, a_p = 1.5 m, B_0 = 7 T, P_{fus} = 3 GW (thermal), edge helical field ripple $\varepsilon_h(r = a_p)$ = 0.1**

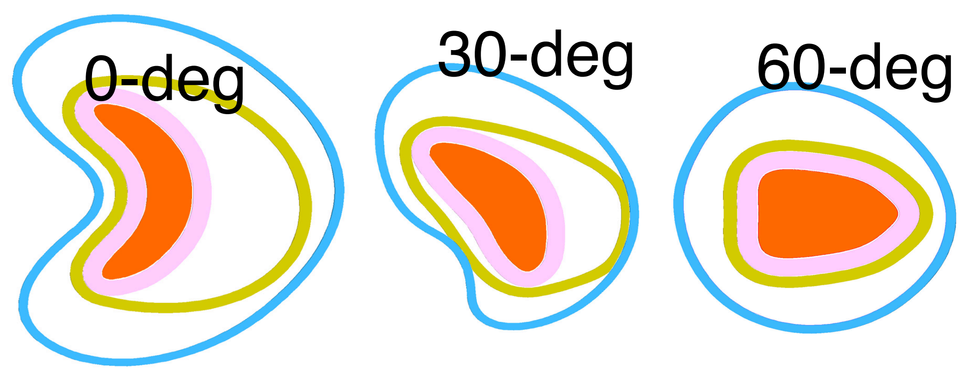




Field Period Maintenance Approach







Summary

- Parameter determination integrates plasma & coil geometry with physics & engineering constraints and assumptions
- Results lead to factor ~2 smaller stellarator reactors (<*R*> = 7–8 m), closer to tokamaks in size
- Examined 6 different plasma/coil configurations and two blanket/shield concepts
- CoE is relatively insensitive to assumptions (β, $f_{\alpha,loss}$) for a plasma/coil configuration; variation is in H-ISS95
- Further steps: incorporate ν^* as target, 1-D calculation of $T_e(r)$ & $T_i(r)$, NbTiTa coils, field period maintenance approach