Optimization of Stellarator Power Plant Parameters

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for the ARIES Team

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UT-BATTELLE

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

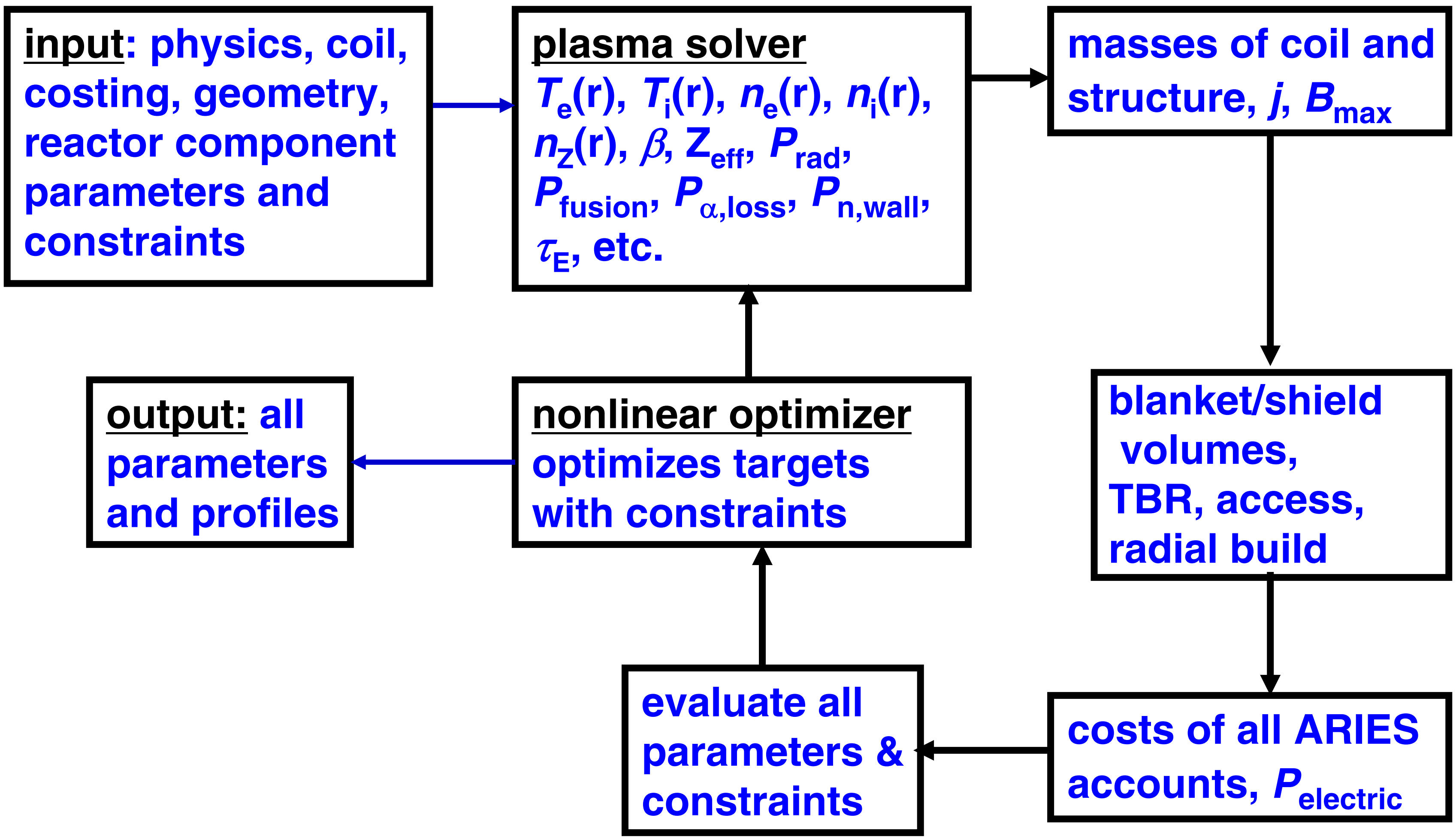
Parameter Determination

- $\langle R_{axis}\rangle$, $\langle a_{plasma}\rangle$, $\langle B_{axis}\rangle$
- $B_{max,coil}$, 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

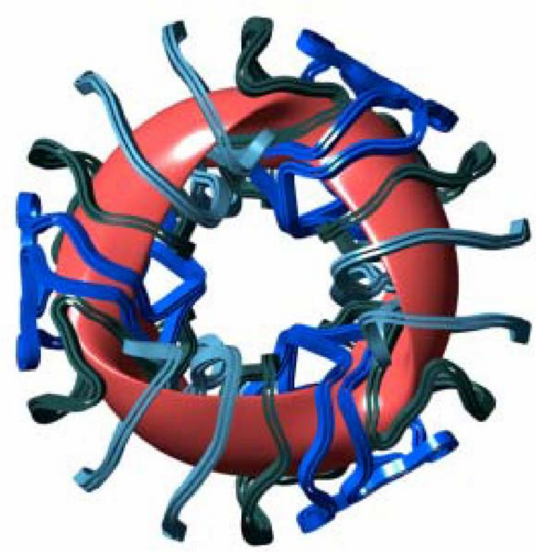
Systems Optimization Code

- **Minimizes core cost or CoE for a given plasma and coil geometry using a nonlinear constrained optimizer**
- **Iterates on a number of optimization variables**
  - **plasma: <T_i>, <n_e>, conf. multiplier; coils: width/depth of coils**
  - **reactor variables: <B_{axis}>, <R>**
- **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**

MHHOPT Reactor Optimization Code



Six Configurations Have Been Studied



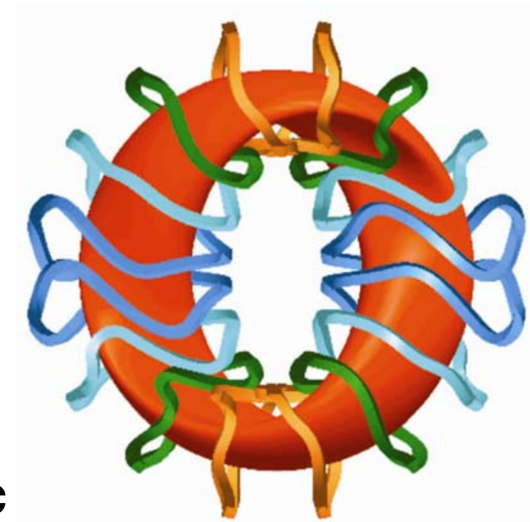
4 NCSX

port or sector (end) access

2 MHH2

access through ports

both quasi-axisymmetric



Key Configuration Properties	NCSX-1	NCSX-2	MHH2-8	MHH2-16
Plasma aspect ratio $A_p = \langle R \rangle / \langle a \rangle$	4.50	4.50	2.70	3.75
Wall (plasma) surface area/$\langle R \rangle^2$	11.80	11.95	19.01	13.37
Min. plasma-coil separation ratio $\langle R \rangle / \Delta_{min}$	5.90	6.88	4.91	5.52
Min. coil-coil separation ratio $\langle R \rangle / (c\text{-}c)_{min}$	10.07	9.38	7.63	13.27
Total coil length/$\langle R \rangle$	89.7	88.3	44.1	64.6
$B_{max,coil} / \langle B_{axis} \rangle$ for 0.4-m x 0.4-m coil pack	2.10	1.84	3.88	2.77

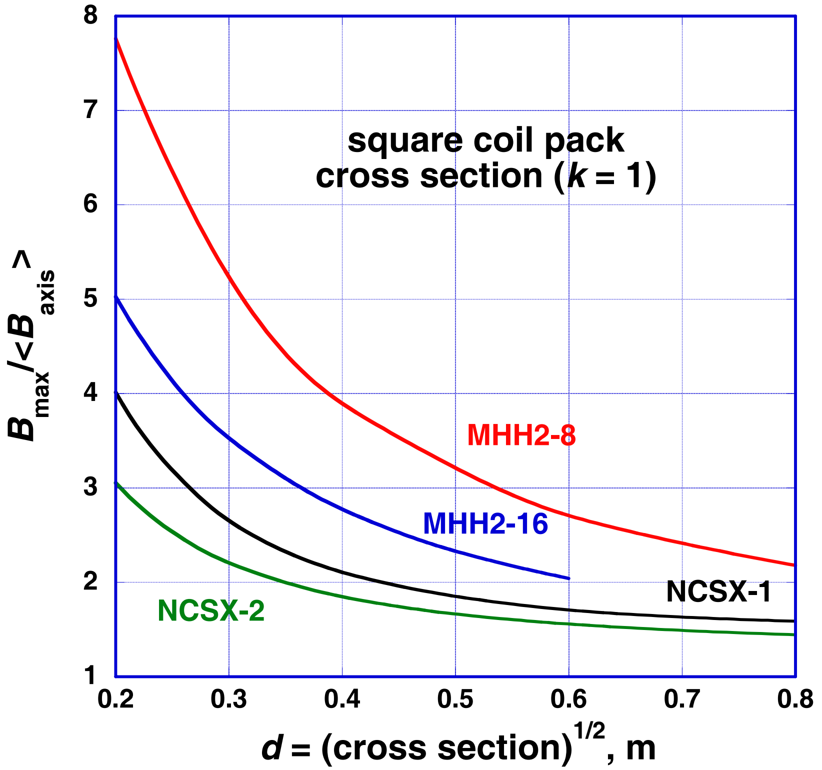
0-D Scaling of Main Reactor Parameters

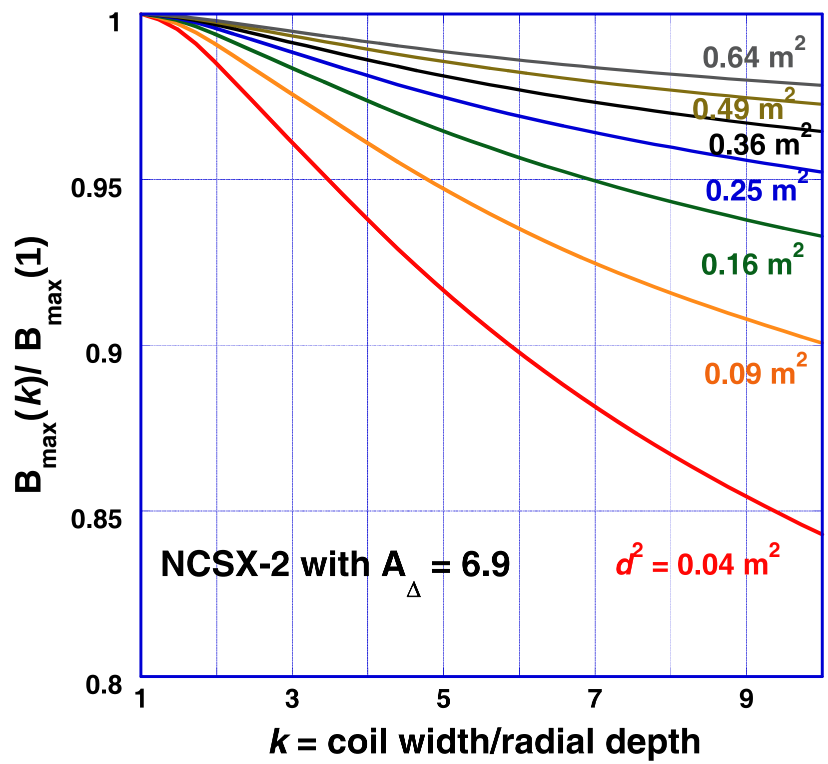
- **Maximize $\langle p_{wall}\rangle$ subject to $j_{SC}(B_{max})$ and radial build constraints**
  - blanket, shield, structure, vacuum vessel ~ wall area ~ $1/\langle p_{n,wall}\rangle$
  - volume of coils ~ $L_{coil}I_{coil}/j_{coil} \sim \langle R\rangle^{1.2} \sim 1/\langle p_{n,wall}\rangle^{0.6}$
  - blanket replacement and other costs independent of $\langle p_{n,wall}\rangle$
- **Fix maximum neutron wall loading $p_{n,wall}$ at 5 MW/m^2**
  - if peaking factor = 1.5 ⟶ $\langle p_{n,wall}\rangle$ = 3.3 MW/m^2
- **$\langle p_{wall}\rangle$ = 3.3 MW/m^2 ⟶ wall area = 480 m^2 for P_{fusion} = 2 GW**

  ⇒ $\langle R\rangle$ = 6.22 m for NCSX-1 vs. $\langle R\rangle$ = 14 m for SPPS
- **Chose $\langle\beta\rangle$ = 6%:** no reliable instability β limit, high equilibrium limit

  ⇒ $\langle B_{axis}\rangle$ = 5.80 T for NCSX-1
- **B_{max} on coil depends on plasma-coil spacing & coil cross section**
- **$\langle R\rangle$ and $\langle B_{axis}\rangle$ for the other cases are limited by the radial build and coil constraints to $\langle p_{n,wall}\rangle$ = 2.13–2.67 MW/m^2**

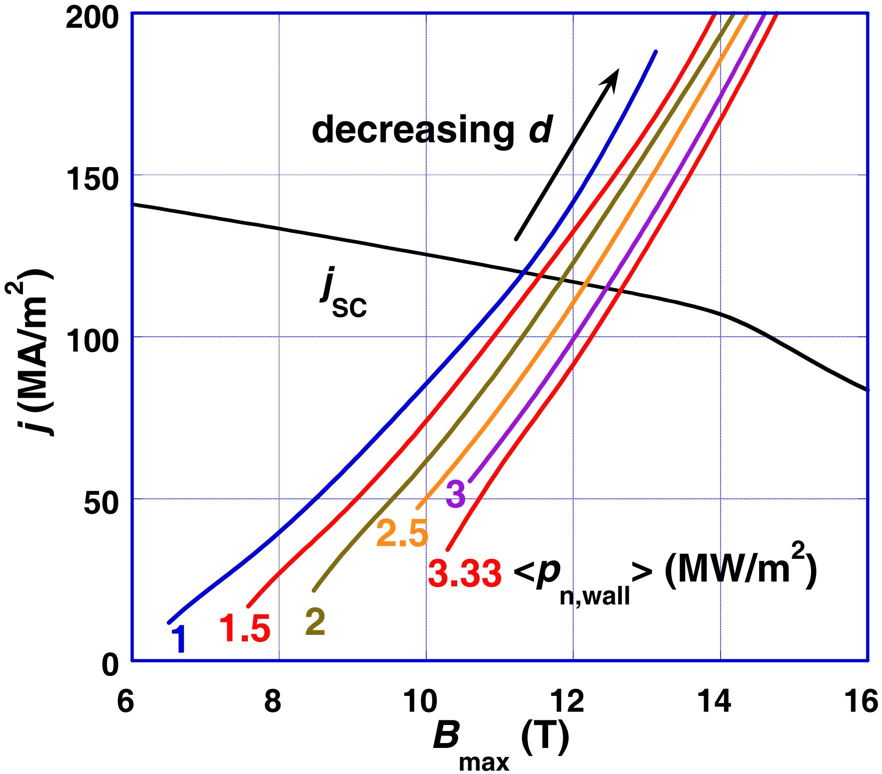
B_{max}/B_{axis} Depends on Coil Cross Section

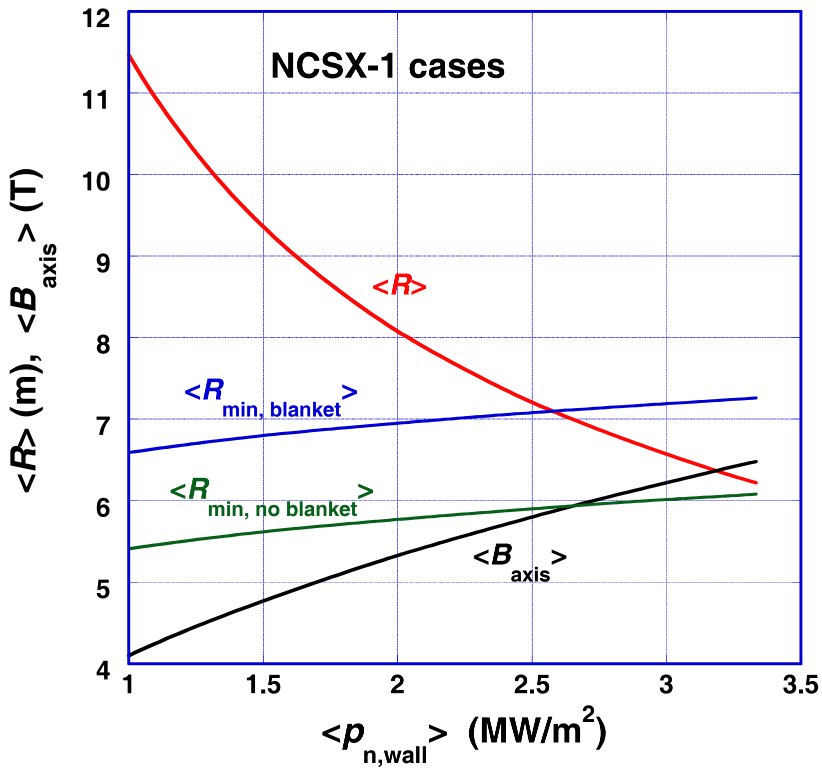




- Larger plasma-coil spacings lead to more convoluted coils and higher $B_{max}/<B_{axis}>$
- Minimum coil-coil separation distance determines k_{max}

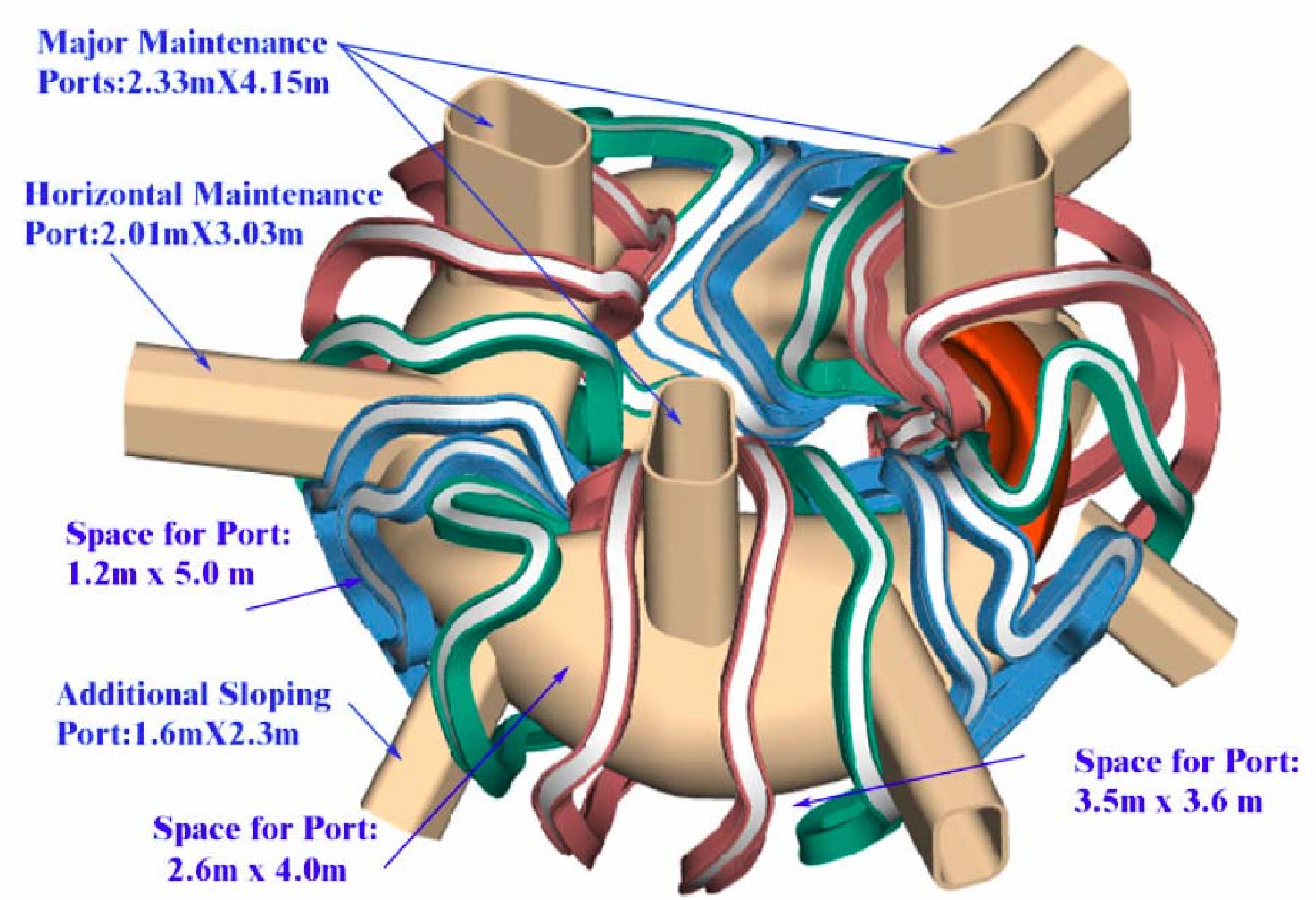
Parameters Depend on Neutron Wall Power





- The 0-D NCSX-1 values are determined by $p_{n,max}$ = 5 MW/m²
  - $\langle R \rangle$ = 6.22 m, $\langle B_{axis} \rangle$ = 6.48 T, B_{max} = 12.65 T
- $\langle R \rangle$, $\langle B_{axis} \rangle$, B_{max} and *d* are constrained for the other cases by radial build and the allowable current density in the supercon-ducting coils

Studied Port Maintenance Approach First

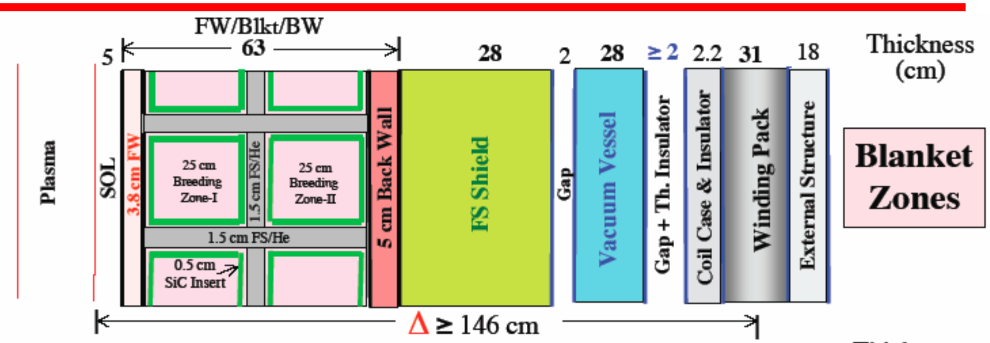


Blanket/Shield Concepts Studied

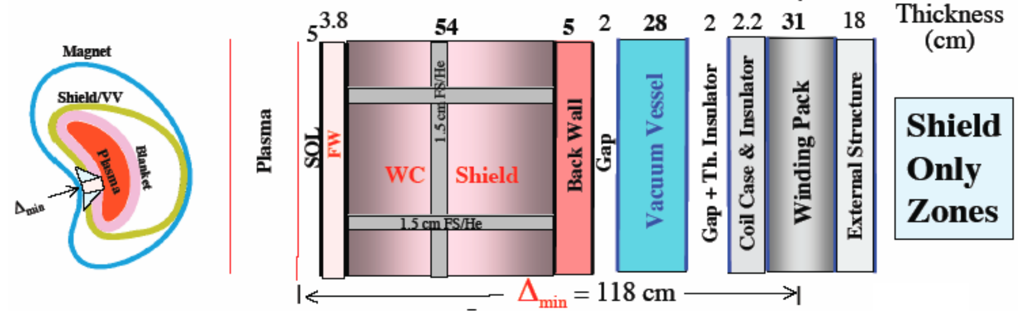
Breeder	Multiplier	Structure	FW/Blanket Coolant	Shield Coolant	VV Coolant
ARIES-CS:					
Internal VV:					
Flibe	Be	FS	Flibe	Flibe	H_2O
LiPb	–	SiC	**LiPb**	**LiPb**	H_2O
LiPb w/o SiC inserts	–	FS	He/LiPb	He	H_2O
LiPb w/ SiC inserts	–	**FS**	**He/LiPb**	**He**	H_2O
Li_4SiO_4	Be	FS	He	He	H_2O
External VV:					
LiPb*	–	FS	He/LiPb	He or H_2O	He
Li	–	FS	He/Li	He	He

Two Blanket/Shield Concepts Studied Here

1 **Self-cooled ^{17}Li-Pb blanket with SiC/SiC composite as structural material** ==>



- **NCSX-1 plasma allows shield-only zone** ==>



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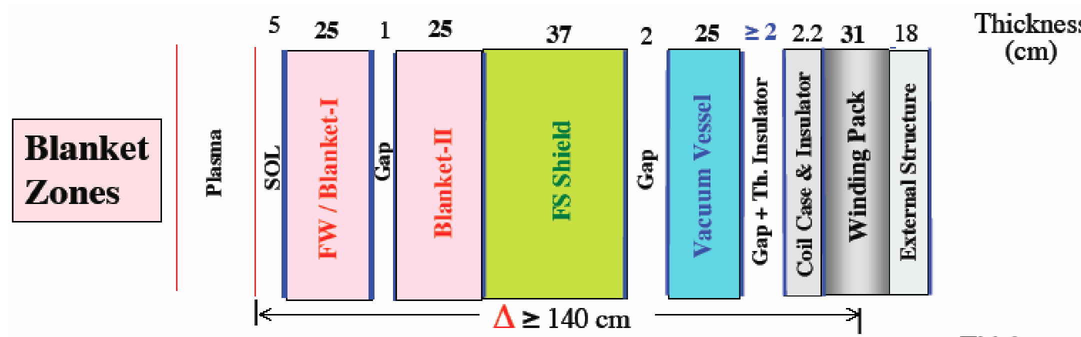
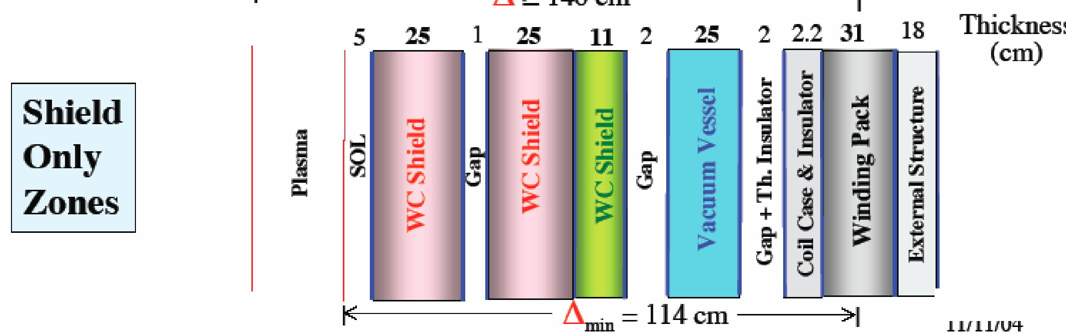
2 **Dual-coolant blanket with He-cooled steel structure and self-cooled ^{17}Li-Pb breeding zone** ==>



- **Also studying self-cooled flibe blanket with advanced ferritic steel and He-cooled ceramic breeder blanket with ferritic steel structure**



Typical Systems Code Summary

MHHOPTNEW code	NCSX-1 case	
LiPb/FS/He H2O-cooled int. vacuum vessel		
inflation factor	2004 year	
safety assurance flag	2	

FIGURE OF MERIT ....

58.2 Cost of Electricity

following CONSTRAINTS were selected:	
ignition = 1 target	1.00
max. volume averaged beta	0.06
sufficient radial build	
max. magnetic field at coil	16.00
max. ave. neutron wall load	3.00
maximum density = 2 x nSudo	
Electric Power (GW)	1.00
max. confinement multiplier	6.00

FINAL VALUES OF CONSTRAINTS:	
ignition margin	0.9998
volume averaged beta (%)	6.00
radial build margin	1.00
magnetic field at coil (T)	16.00
ave. neutron wall load (MW/m2)	2.55
maximum density (10**20 m-3)	4.50
Electric Power (GW)	1.00
ratio of tauE to conf. multiplier	4.00

VARIABLES selected for iteration		
major radius	5.00	20.00
field on axis	3.00	10.00
ion density	0.50	10.00
ion temperature	1.00	50.00
coil width	0.010	5.00
confinement multiplier	0.10	9.00

FINAL DESIGN	
major radius (m)	7.19
field on axis (T)	5.08
vol avg density (10**20 m-3)	2.32
density averaged temp (keV)	8.73
coil dimensions (m x m)	0.40 x 0.70
current density (MA/m2)	39.93

Typical Systems Code Summary

Plasma Parameters

central ion temp (keV)	13.13
center ion density (10**20 m-3)	4.73
center el. density (10**20 m-3)	5.24
fraction fuel to electrons	0.85
confinement time, taue (sec)	1.14
stored plasma energy (MJ)	334
volume averaged beta (%)	6.00
beta star (%)	9.85
fraction carbon impurity	1.00 %
fraction iron impurity	0.01 %
fraction helium	4.46 %
Z effective	1.45

Mass Summary

total nuclear island (tonnes)	6,316
mass utilization efficiency (kW/t)	158

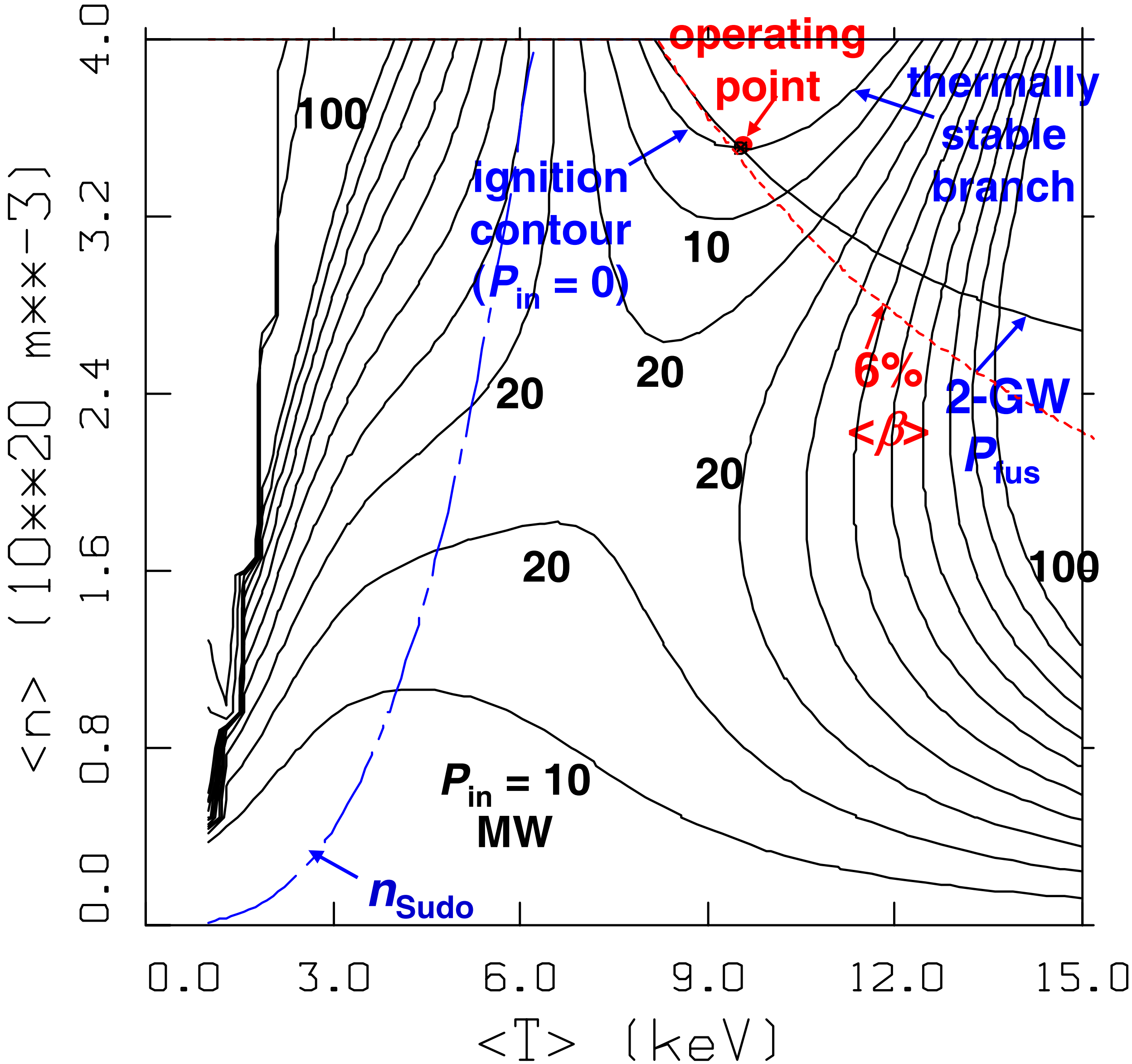
Power Balance

net electric power (MW)	1000.0
gross electric power (MW)	1054.9
fusion power (MW)	2092.9
thermal power (MW)	2344.1
α heating power (MW)	417.8
power in neutrons (MW)	1675.1
radiated power (MW)	217.3
fuel bremsstrahlung (MW)	133.8
carbon radiation (MW)	46.2
iron radiation (MW)	36.1
synchrotron radiation (MW)	1.3
conduction power (MW)	75.2
fusion power to plasma (MW)	292.4
fraction alpha power lost	30.0 %
radiated power fraction	74.3 %
neutron wall load (MW/m2)	2.55
radiated wall load (MW/m2)	0.35

NCSX-1: $\tau_E/\tau_E^{ISS\text{-}95}$ = 4.2, $\langle T \rangle$ = 9.5 keV, $\langle n \rangle$ = 3.5 10^{20} m^{-3}, $\langle \beta \rangle$ = 6.1%

H-ISS95 =

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



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

Values for Different Configurations

	NCSX-1	NCSX-2	MHH2-8	MHH2-16
$<p_{wall}>$, MW/m^2	2.55	1.27	1.08	2.25
$<R>$ (m)	7.19	10.14	8.74	7.22
$<B_{axis}>$ (T)	5.08	3.90	3.98	3.96
H-ISS95	4.00	4.55	3.30	4.84
CoE	58.2	86.9	70.5	58.0
$<R>/<a>$	4.5	4.5	2.7	3.75

- **Large range in device parameters and CoE: 58.2–86.9**
- **ISS-95 confinement improvement factor of 3.3 to 4.8 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**

Variation of Reactor Parameters with B_{max}

NCSX-1 B_{max}, T	j_{coil} MA/m^2	$\langle B_{axis} \rangle$ T	$\langle R \rangle$ m	$\langle \Gamma_{n,wall} \rangle$ MW/m^2	CoE
8	19.5	4.58	8.19	1.97	61.3
10	27.5	4.86	7.65	2.26	60.0
12	32.8	4.98	7.42	2.39	58.9
14	36.8	5.06	7.28	2.48	58.5
16	39.9	5.08	7.19	2.55	58.2

- Smaller $B_{max,\,coil}$ requires smaller $\langle B_{axis} \rangle$ even with larger coil pack size (smaller j_{coil})
- Larger coil size increases $\langle R \rangle$ and CoE and reduces $\langle \Gamma_{n,wall} \rangle$

Weak Variation of Reactor Parameters with Beta

NCSX-1 $\langle\beta\rangle$, %	$\langle R\rangle$ m	$\Gamma_{n,wall}$ MW/m^2	$\langle B_{axis}\rangle$ T	CoE	H-ISS95
3	7.47	2.36	6.97	59.38	
4	7.34	2.44	6.19	58.82	4.69
4.99	7.25	2.50	5.55	58.63	4.97
6	7.19	2.55	5.08	58.23	
7.02	7.14	2.56	4.75	58.04	5.30
7.61	7.10	2.60	4.42	62.51	5.86

- **Increasing $\langle\beta\rangle$ allows reduced $\langle B_{axis}\rangle$ and $\langle R\rangle$ but requires larger H-ISS95**
- **Relatively small change in CoE for $\langle\beta\rangle$ = 4-7%**

More peaked T(ρ = r/a) Requires Higher $<B_{axis}>$ and H-ISS95

$T(\rho)$ $(1-\rho^2)^n$	$<R>$ m	$<B_{axis}>$ T	CoE	H-ISS95
n = 1	7.15	4.76	58.1	3.78
n = 1.5	7.19	5.08	58.2	4.00
n = 2	7.23	5.40	58.4	5.87

- NCSX-1; relatively small effect on $<R>$ and CoE

Reducing Impurities Reduces Required H-ISS95

Impurity Level	NCSX-1 <*R*>, m	CoE	H-ISS95	f_{DT}	$f_{radiation}$
0.5%C .005%Fe	7.18	58.3	3.07	0.88	0.50
1%C .01%Fe	7.19	58.2	4.00	0.85	0.74

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

NCSX-1 P_α, lost	0	10%	15%	30%
$<R>$, m	7.19	7.19	7.19	7.19
H-ISS95	3.08	3.40	3.88	4.00

Higher $P_{electric}$ Reduces CoE

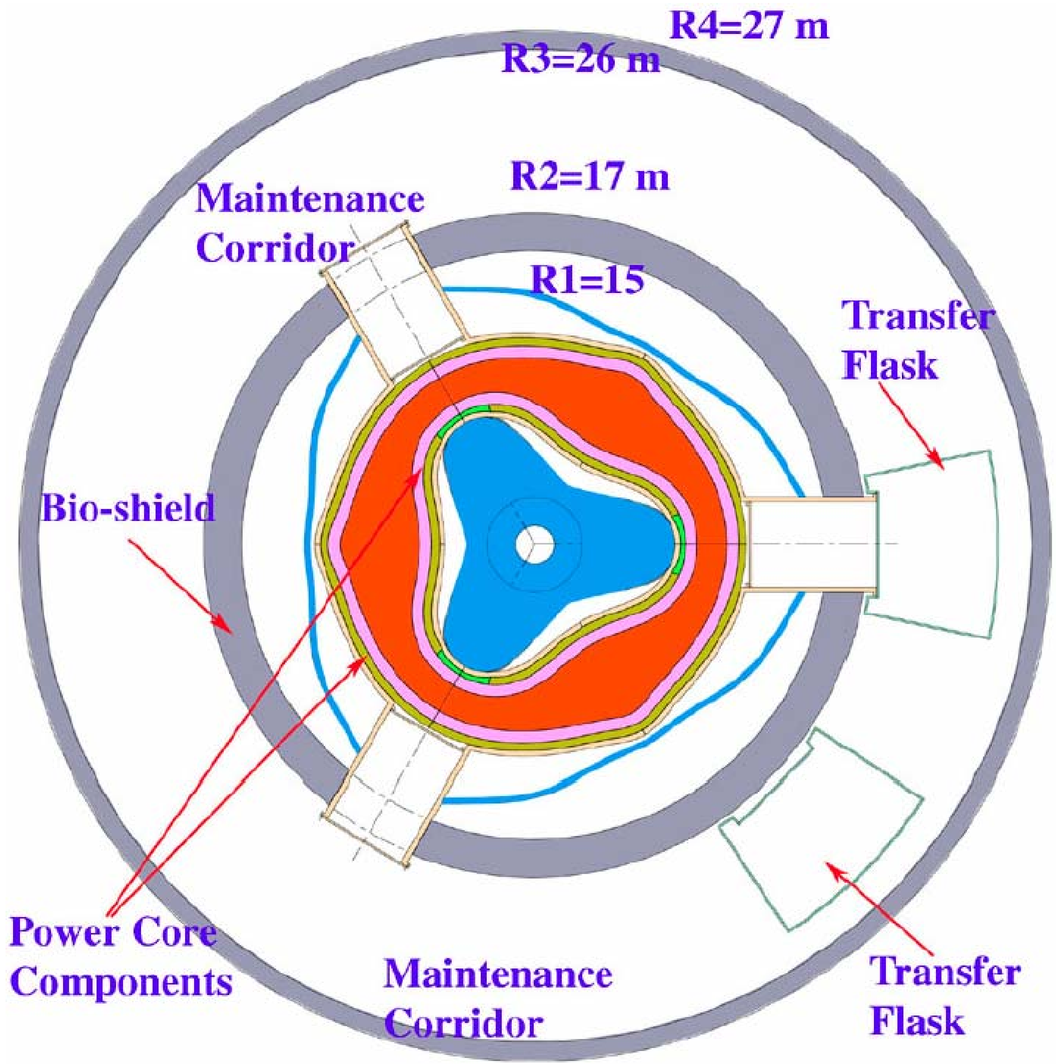
$P_{electric}$ GW	$\langle R \rangle$ m	$\langle B_{axis} \rangle$ T	CoE
1	7.19	5.08	58.2
1.5	7.25	5.58	49.4
2	7.32	6.04	45.3

- **Higher $P_{electric}$ requires higher $\langle B_{axis} \rangle$, larger coil pack size and somewhat larger $\langle R \rangle$**

Next Steps

- **Improve impurity and divertor treatments**
- **Complete refinements to costing algorithms (coil forces, tapered blanket)**
- **Analyze newer plasma/coil configurations with potential for alpha-particle power losses of 5-10%**
  - configurations examined thus far have alpha-particle power losses ~30%
- **Analysis needs to be refined with the 1-D systems/ cost optimization code**
  - modeling for sector maintenance approach
  - assumed plasma temperature profiles are not consistent with high edge radiation losses and need to be calculated self-consistently

Sector Maintenance Approach Next



- **Only looked at port maintenance approach thus far**

Summary

- Parameter determination integrates plasma & coil geometry with physics & engineering constraints and assumptions
- Initial results lead to factor ~2 smaller stellarator reactors ($\langle R \rangle$ = 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 for a given plasma/coil configuration; variation is in H-ISS95
- Next step is to analyze sector maintenance approach and new plasma/coil configurations