Optimization of Stellarator Reactor Parameters

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for the ARIES Team

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Rationale for Compact Stellarator Reactor Study

- German HSR with R/a = 10.5 has R = 18-22 m
- ARIES SPPS (~1994) reduced reactor size and cost
  - R = 14 m due to R/a = 8 and larger plasma-coil spacing
  - estimated CoE same as ARIES-IV tokamak reactor
  - configuration was *not* optimized, less developed physics
- LHD-based reactors also have R ~ 14 m
- New optimized compact stellarators have R/a = 2.7-4.5

 this should lead to smaller R and lower CoE

Parameter Determination Integrates Plasma/Coil Geometry and Reactor Constraints

Plasma & Coil Geometry

- Shape of last closed flux surface and $\langle R_{axis}\rangle / \langle a_{plasma}\rangle$, □ limit?
- Shape of modular coils and $B_{max,coil}/B_{axis}$ vs coil cross section, $\langle R_{coil}\rangle / \langle R_{axis}\rangle$, $□_{min} / \langle R_{axis}\rangle$
- 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
- $n_{e,I,Z}(r)$, $T_{e,i}(r)$, $\langle □\rangle$, P_{fusion}, P_{rad}, etc.
- Operating point, path to ignition

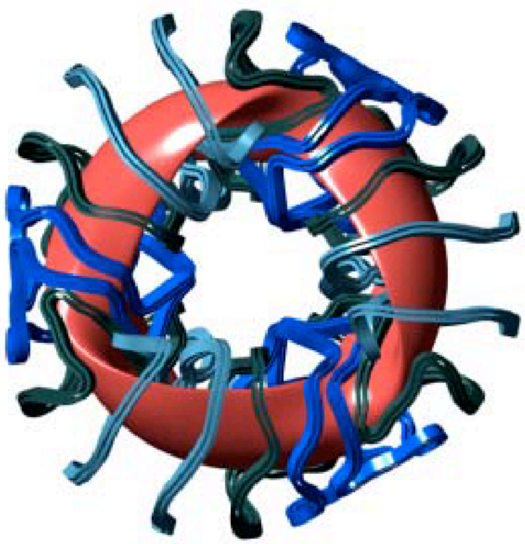
* Cost of components, operating cost → cost of electricity

* discussed in separate systems code paper

Staged Approach in Defining Parameters

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

Four Configurations Have Been Studied



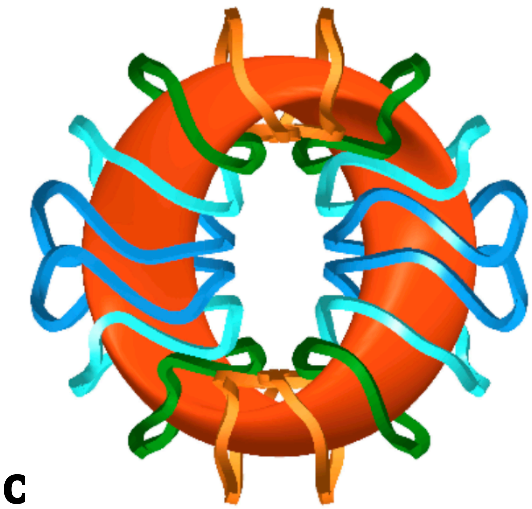
NCSX

port or sector (end) access

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 $\langle R \rangle$/□$_{min}$	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

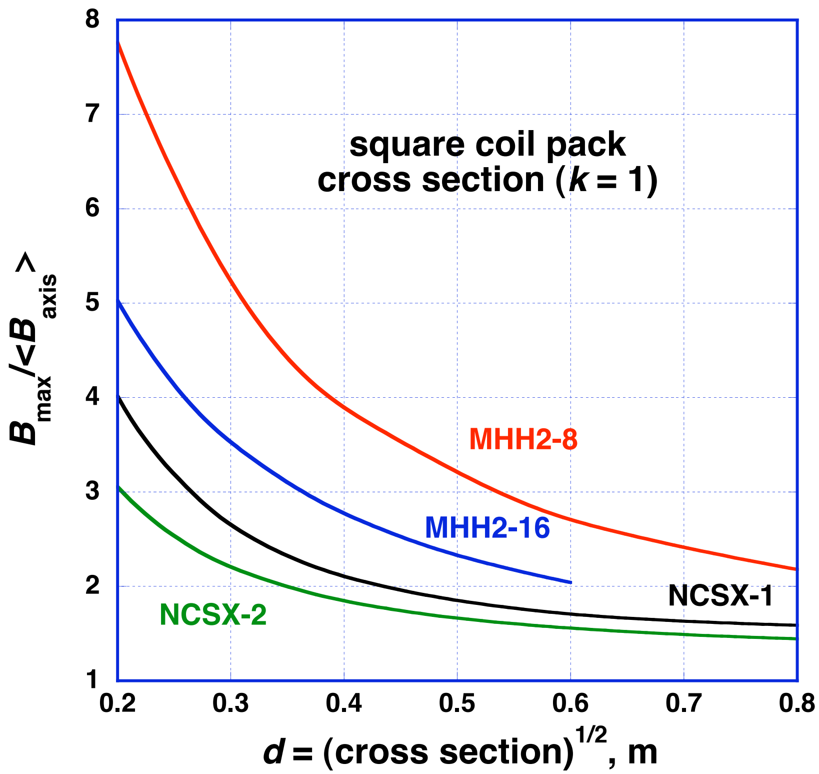
0-D Determination of Main Reactor Parameters

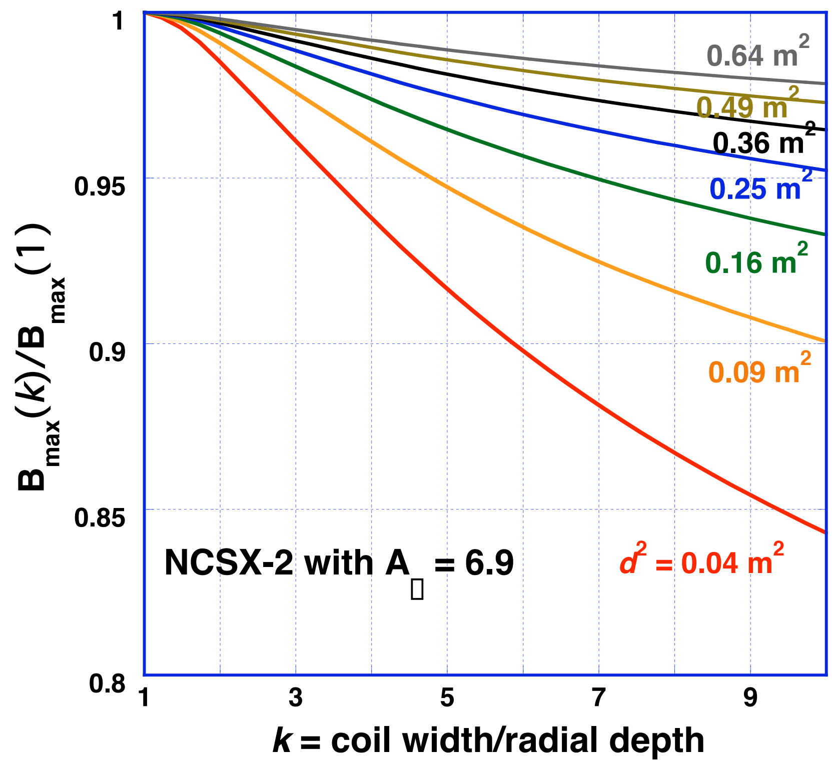
- **Fix maximum neutron wall loading $p_{n,wall}$ at 5 MW/m^2**
  - **peaking factor =1.5 → $\langle p_{n,wall} \rangle$ = 3.3 MW/m^2**
- **Maximize $\langle p_{wall} \rangle$ subject to $j_{SC}(B_{max})$ and radial build constraints**
  - **blanket, shield, structure, vacuum vessel ~ wall area ~ $1/\langle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

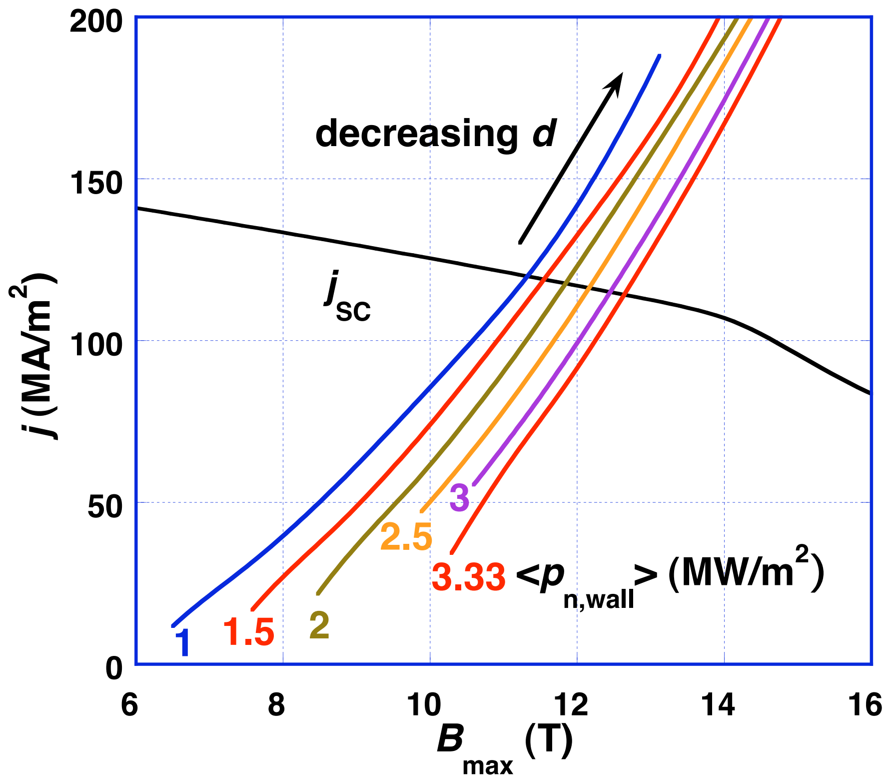
B_{max}/B_{axis} Depends on Coil Cross Section

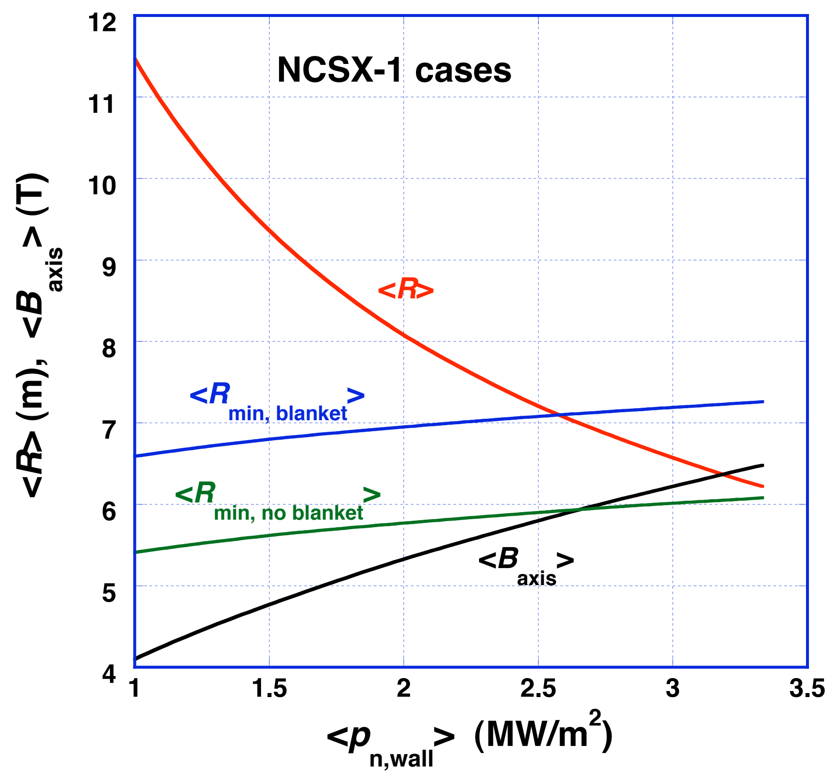




- Larger plasma-coil spacings lead to more convoluted coils and higher $B_{max}/\langle B_{axis}\rangle$
- Minimum coil-coil separation distance determines k_{max}

Parameters Depend on Neutron Wall Power





- **The NCSX-1 values are determined by $p_{n,max}$ = 5 MW/m^2**
  - **$\langle R \rangle$ = 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**

0-D Study Gives Main Reactor Parameters

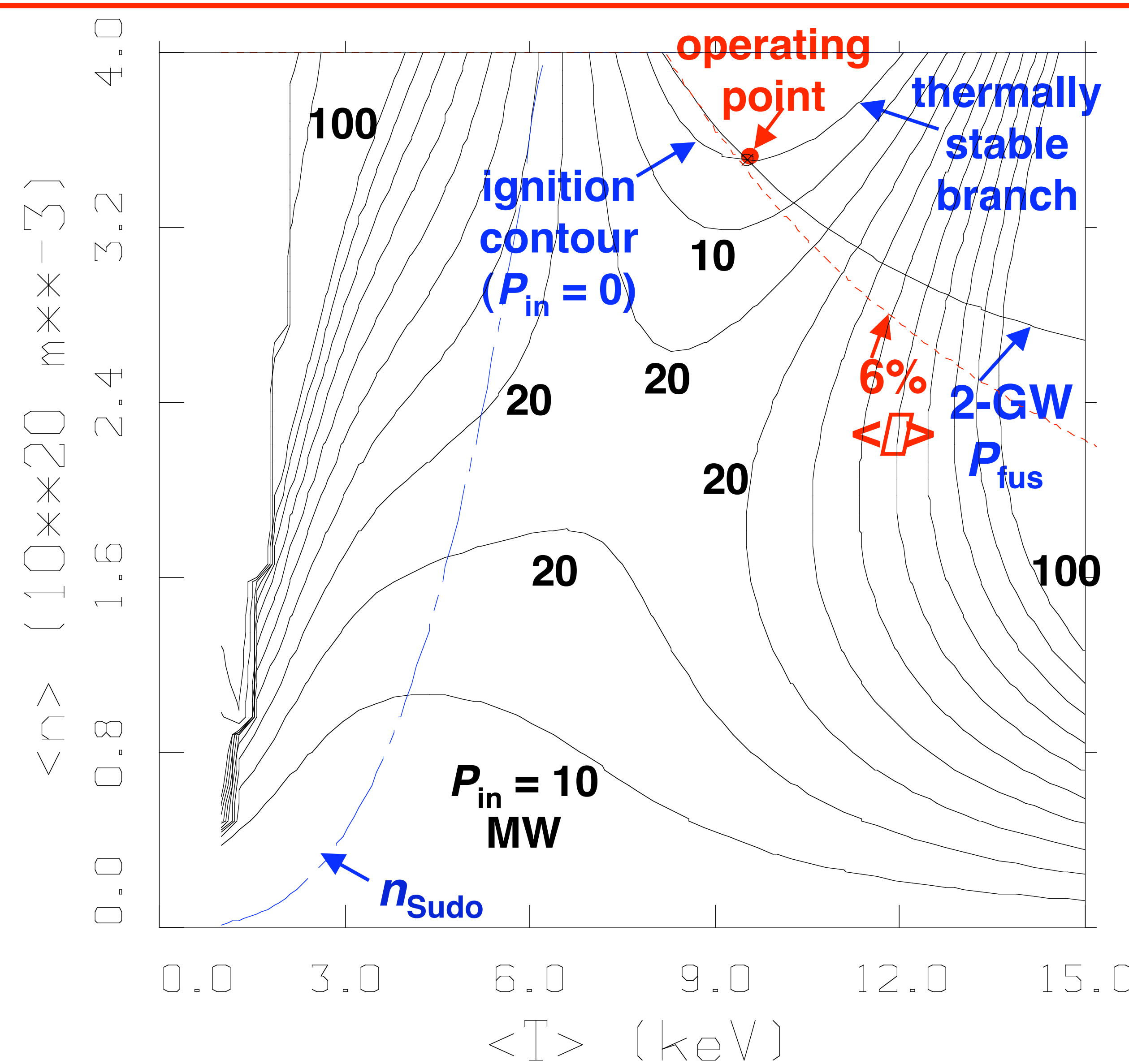
	NCSX-1	NCSX-2	MHH2-8	MHH2-16
$\langle p_{n,wall} \rangle$ (MW/m^2)	3.33	2.67	2.13	2.4
$\langle R \rangle$ (m)	6.22	6.93	6.19	6.93
$\langle a \rangle$ (m)	1.38	1.54	2.29	1.85
$\langle B_{axis} \rangle$ (T)	6.48	5.98	5.04	5.46
B_{max} (T)	12.65	10.9	14.9	15.2
j_{coil} (MA/m^2)	114	119	93	93
k_{max}	3.30	5.0	2.78	1.87
coil width (m)	0.598	0.719	0.791	0.502
coil depth (m)	0.181	0.144	0.286	0.268
radial gap (m)	0.026	0.012	0.007	0.005
Coil volume (m^3)	60.3	63.4	61.4	60.3
Wall area (m^2)	480	600	750	667

- Successful in reducing reactor size ($\langle R \rangle$) by factor ~ 2!
- Wall (blanket, shield, structure, vacuum vessel) area smallest for NCSX-1 ==> choose for more detailed study

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 =

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



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

1-D Power Balance Gives Plasma Parameters

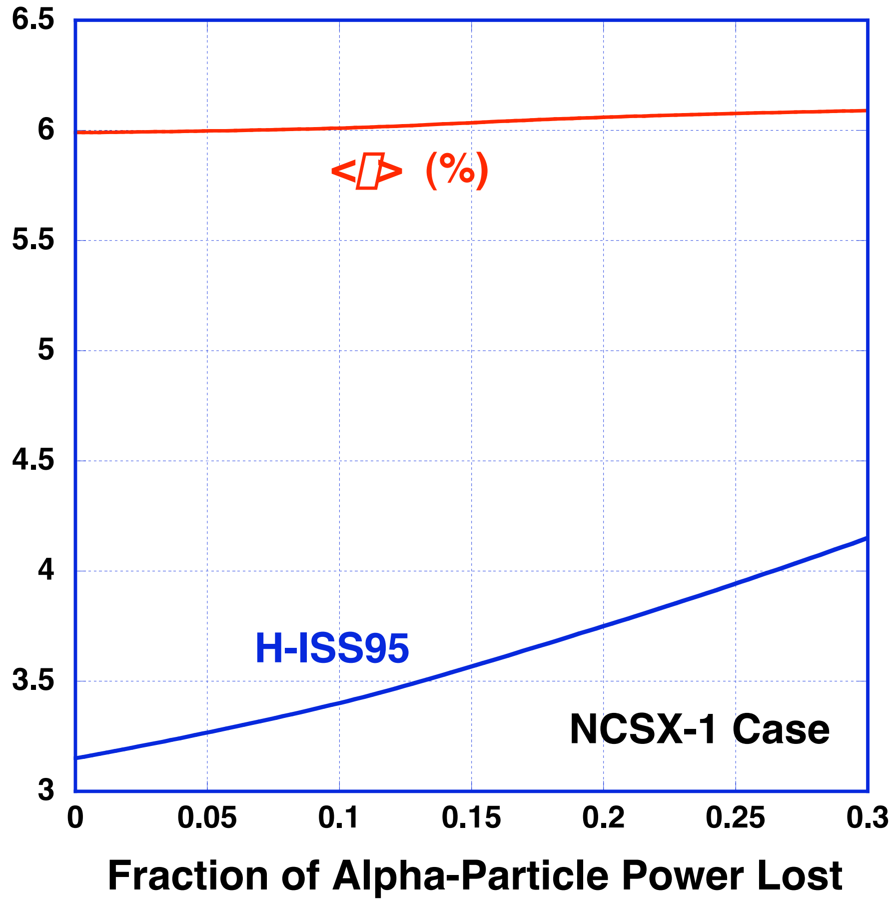
	NCSX-1	NCSX-2	MHH2-8	MHH2-16
$\langle R \rangle$ (m)	6.22	6.93	6.19	6.93
$\langle a \rangle$ (m)	1.38	1.54	2.29	1.85
$\langle B_{axis} \rangle$ (T)	6.48	5.98	5.04	5.46
H-ISS95	4.15	4.20	3.75	4.10
$\langle n \rangle$ (10^{20} m^{-3})	3.51	2.89	2.05	2.43
f_{DT}	0.841	0.837	0.837	0.839
f_{He}	0.049	0.051	0.051	0.050
$\langle T \rangle$ (keV)	9.52	9.89	9.92	9.74
$\langle \beta \rangle$ (%)	6.09	6.12	6.13	6.09

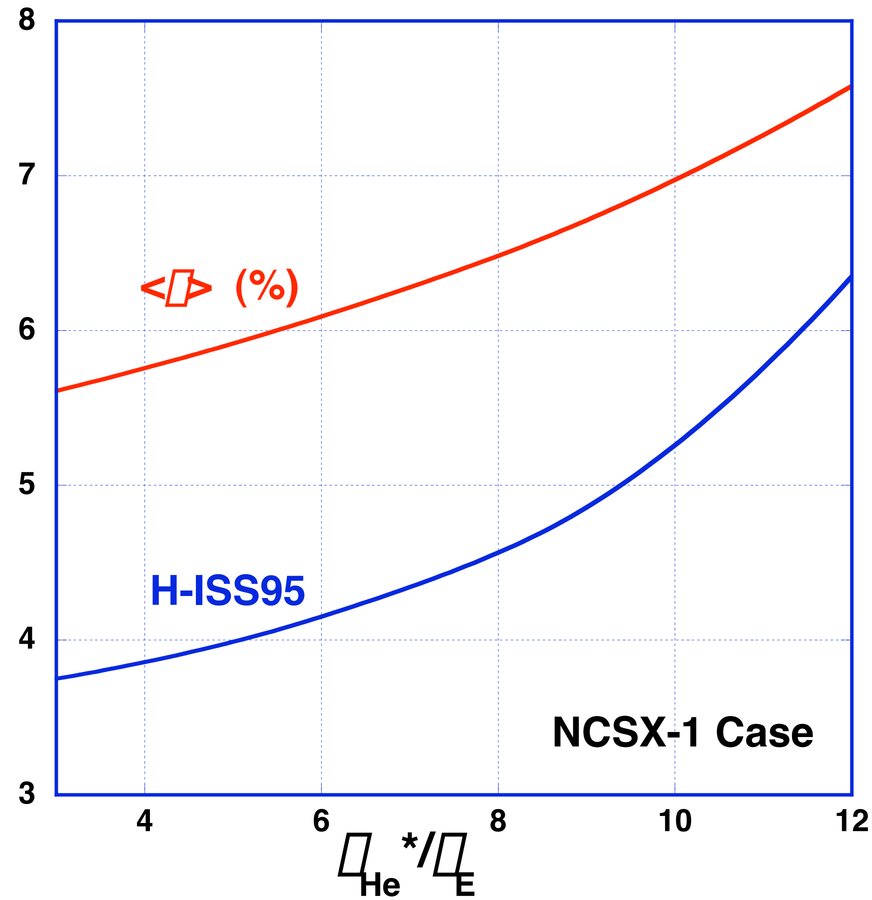
- **ISS-95 confinement improvement factor of 3.75 to 4.2 is required; present stellarator experiments have up to 2.5**
- **ISS-2004 scaling indicates $\epsilon_{eff}^{-0.4}$ improvement, so compact stellarators with very low ϵ_{eff} should have high H-ISS values**

Parameters Insensitive to Profile Assumptions

Variation	$\langle n \rangle$ 10^{20} 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

H-ISS95 Sensitive to Parameter Assumptions





Next Steps

- **Practical coil configurations need to be developed for some newer plasma configurations that have the 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**
  - assumed plasma temperature profiles are not consistent with high edge radiation losses and need to be calculated self-consistently
  - optimum tradeoff between high $p_{n,wall}$ for smaller R and lower $p_{n,wall}$ for longer periods between maintenance needs to be determined

Summary

- **Parameter determination integrates plasma & coil geometry with physics & engineering constraints and assumptions**
- **Initial results lead to factor ~2 smaller stellarator reactors (<*R*> = 6–7 m), closer to tokamaks in size**
- **Results are relatively insensitive to assumptions**
- **Next step is to refine results with the 1-D systems/ cost optimization code**