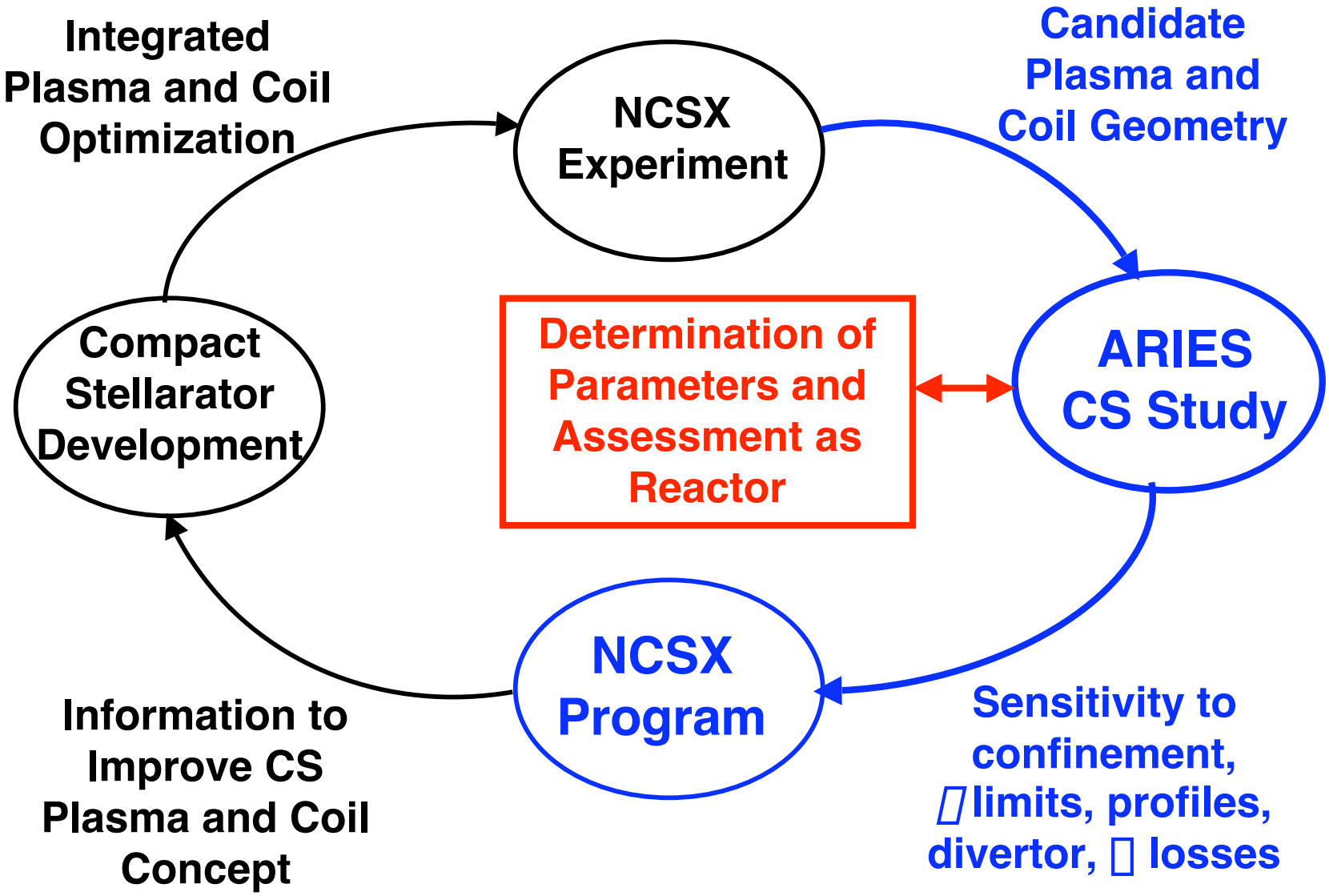
# ARIES Compact Stellarator Reactor Study and Connection to NCSX Program

J. F. Lyon, ORNL
for ARIES team

NCSX PAC Meeting July 13, 2004

# Interaction between ARIES & NCSX Programs



# ARIES Compact Stellarator Reactor Study

- 3-4 year study to explore attractiveness of compact stellarators as reactors
- 3 configurations studied thus far
  - "NCSX-R" with $R/a$ = 4.4, but modular coils have larger $R/\Delta_{min}$
  - "MHH2" with tokamak-like shear, $R/a$ = 2.7 and 3.75
- ARIES reactor assessment covers multiple aspects
  - configuration exploration
  - parameter determination and cost optimization
  - blanket/shield models, superconducting coil design
  - maintenance, heat removal, safety, etc.

# Motivation for a CS Reactor Study

- **German HSR with *R/a* = 10.5 had *R* = 24 m (now 18-22 m)**
  - **estimated CoE ~1.6 x tokamak reactor?**
- **ARIES SPPS (~1994) reduced reactor size and cost**
  - **based on Garabedian's 4-field-period "MHH4" with *R/a* = 8**
  - ***R* = 14 m due to smaller *R/a* and $R/\Delta_{min}$**
  - **estimated CoE same as ARIES-IV tokamak reactor**
  - **but configuration was *not* optimized, physics analyses weak**
- **New optimized compact stellarators have *R/a* < 4.5**
  - **more developed physics basis, does smaller *R/a* has the potential for smaller *R* and lower CoE?**
  - **NCSX provides most developed configuration for ARIES case**
  - **ARIES study can point out reactor-critical issues that need to be resolved in a compact stellarator experiment**

# Parameter Determination Integrates Plasma/Coil Geometry and Reactor Constraints

## Plasma & Coil Geometry

- Shape of last closed flux surface and $\langle R_{axis}\rangle/\langle a_{plasma}\rangle$, $\beta$ 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**

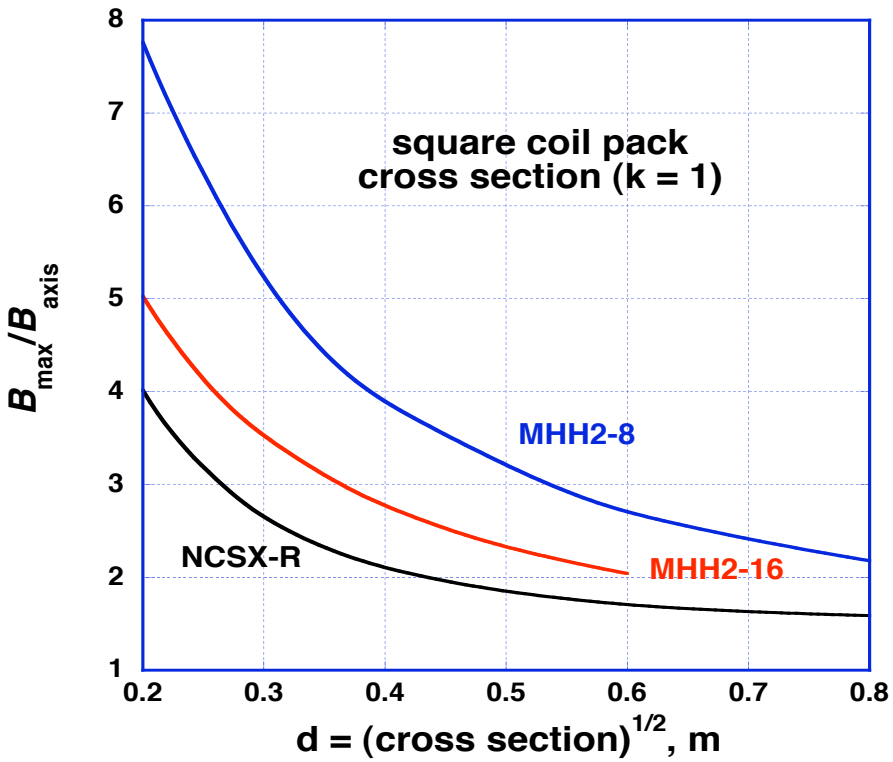
# Staged Approach in Defining Parameters

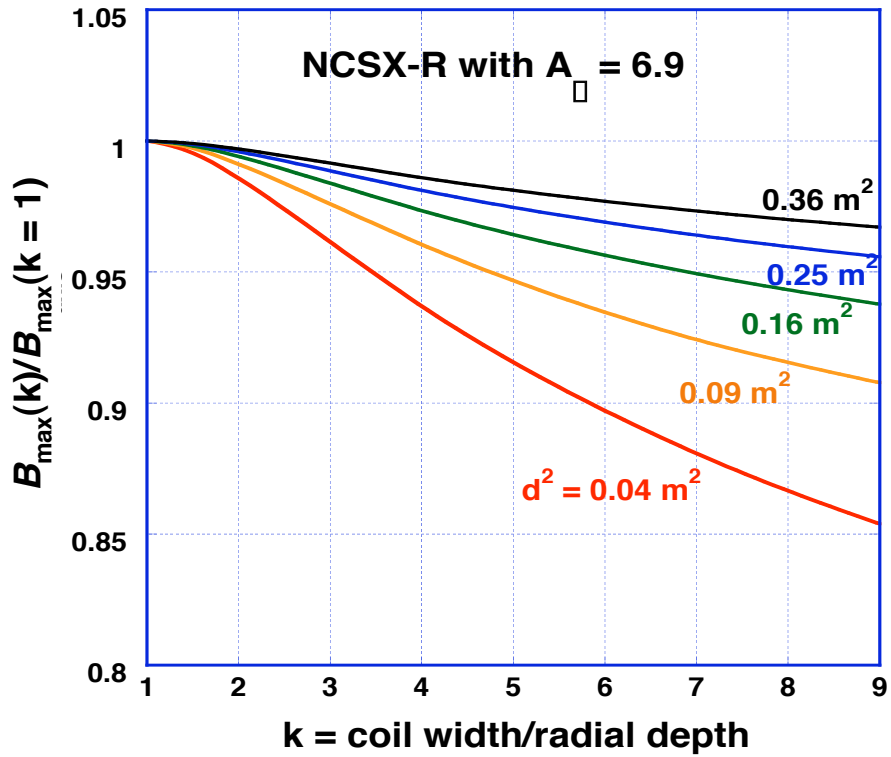
- **0-D scoping study determines device parameters**
  - calculates $\langle R_{axis} \rangle$, $\langle B_{axis} \rangle$, $\langle \beta \rangle$, $\langle p_{n,wall} \rangle$, $B_{max}$, $j_{coil}$, etc. subject to limits and constraints
- **1-D power balance determines plasma parameters and path 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, electric field and power balance
  - calculates reactor component and operating costs
- **Examine sensitivity to models, assumptions & constraints at each stage**

# Example of 0-D Approach

- **e.g., fix max. neutron wall loading $p_{n,wall}$ at 5 MW/m$^2$**
  - **peaking factor = 2 (1.5?) → use $\langle p_{n,wall} \rangle$ = 2.5 MW/m$^2$**
    - **also examined $\langle p_{n,wall} \rangle$ = 2 and 3 MW/m$^2$ as limits**
  - **$\langle p_{wall} \rangle$ = 2.5 MW/m$^2$ → wall area = 640 m$^2$ for $P_{fusion}$ = 2 GW**
    - **$\langle R \rangle$ = 7.20 m for NCSX-R vs. $\langle R \rangle$ = 14 m for SPPS!**
    - $\langle R \rangle$ = 5.70 m for 8-coil MHH2, 6.78 m for 16-coil MHH2
    - **cost of main reactor components (blanket, shield, structure) same for all 3 cases since cost ~ wall area**
    - **correction for coil and blanket replacement costs**
- **Chose $\langle \beta \rangle$ = 6%; also examined 4% as pessimistic limit**
  - no credible instability model for $\beta$ limit; equilibrium better
  - **$B_{axis}$ = 5.80 T for NCSX-R for $P_{fusion}$ = 2 GW**
  - $B_{axis}$ = 5.36 T for 8-coil MHH2, 5.54 T for 16-coil MHH2
- **$B_{max}$ on coil depends on coil cross section**

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

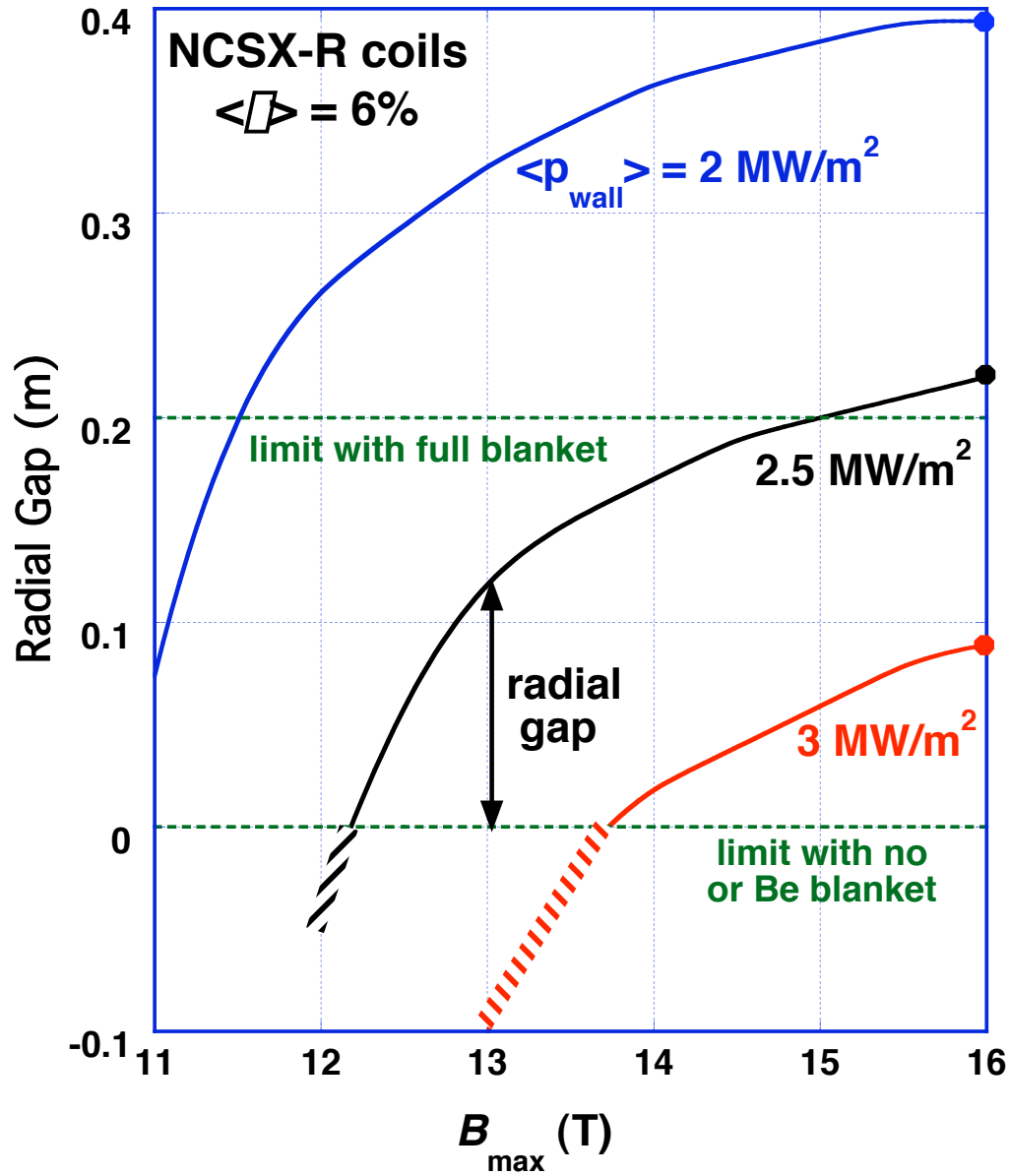



- coil pack area $d^2$, toroidal elongation k, and coil-coil separation distance (determines $k_{max}$)

# Radial Space Available Constrains $B_{max}$

- **Radial gap is the extra space between the removable blanket and the fixed shield/coil structure**
- Lower $B_{max}$ is obtained with larger coil pack size ==> smaller gap
- **Use $B_{max}$ = 16 T (lowest cost) where allowed**
- Better to revise coil winding surface



# Variation with $<p_{wall}>$, $\beta$, Configuration

| Coil Configuration | $<p_{n,wall}>$ (MW/m$^2$) | $<R>$ (m) | $B_{axis}$ (T), 4% $\beta$ | $B_{axis}$ (T), 6% $\beta$ |
|---|---|---|---|---|
| NCSX-R | 2 | 8.07 | 6.53 | 5.33 |
| | **2.5** | **7.20** | **7.11** | **5.80** |
| | 3 | 6.57 | ----- | 6.22 |
| MHH2 (8) | 2 | 6.40 | 6.02 | 4.92 |
| | **2.5** | **5.70** | **6.56** | **5.36** |
| | 3 | ------ | ----- | ----- |
| MHH2 (16) | 2 | 7.60 | 6.23 | 5.09 |
| | **2.5** | **6.78** | **6.79** | **5.54** |
| | 3 | 6.18 | ----- | 5.94 |

- **Successful in reducing reactor size ($<R>$) by factor ~ 2! (need to verify with 1-D and systems/cost optimization study)**
- Set $B_{max}$ = 16 T

# 0-D Parameter Determination Is Limited

- **0-D reactor parameter determination only involved <$R$>, <$a$>, <$B_{axis}$>, <$p_{n,wall}$>, <$\kappa$> and coil cross section**
- **Want to minimize the CoE: 2 components of interest**
  - **initial construction costs, mostly area-related: blanket, shield, structure -- min. area => max. $p_{n,wall}$**
    - **coil costs: min. $d^2$, not same scaling as above components**
  - **operating costs (blanket replacement) -- long life => min. $p_{n,wall}$**
  - **need systems code analysis to optimize costs**
- **Need 1-D power balance (POPCON) analysis to determine plasma (and device parameters), involves**
  - density and temperature radial profile shapes
  - impurity levels and profiles
    - effect on radiation losses and $\kappa$
  - alpha-particle losses, confinement model (H-ISS95)
  - ignition contours and startup paths

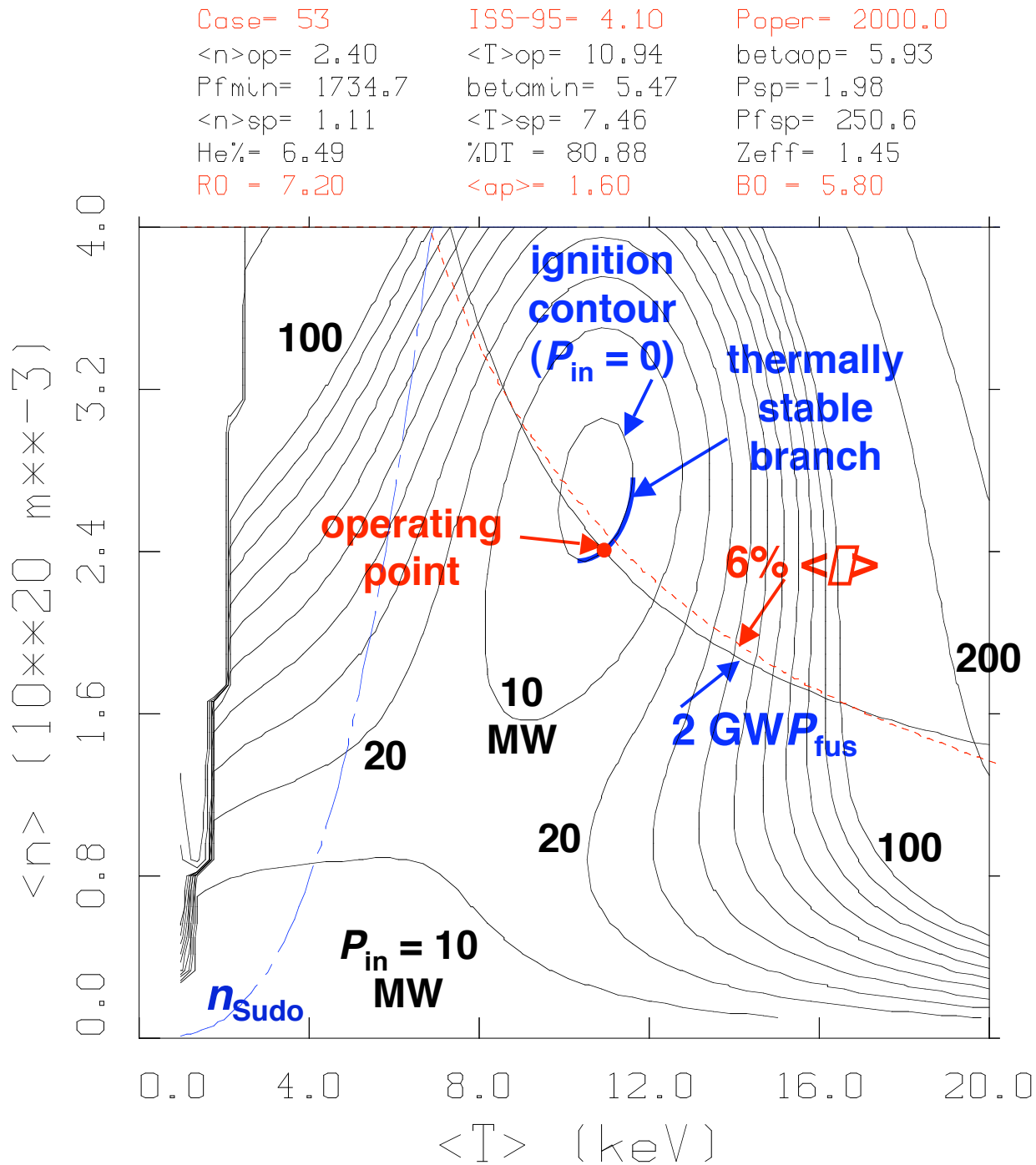
# Determination of Plasma Parameters

- **Too many variables, need to make some parameter assumptions**
  - **choose H-ISS95 < 5 (twice present maximum experimental value)**
    - **assuming improvements due to quasi-symmetry and experience**
  - choose impurity levels: 1% C and 0.01% Fe (OK?)
  - 30% alpha-particle losses **(a better case is being developed)**
  - **choose $\tau_{He}/\tau_E$ = 2: too low?, $f_{He}$ too high ($f_{DT}$ too low) for higher values, no operating point**
- **Choose profile shapes**
  - **choose hollow $n_e$(r) with center/peak = 0.8 (right choice?)**
  - **choose neoclassical impurity profiles $n_Z \sim n_e^Z$**
  - **choose $T \sim$ parabolic$^{1.5}$, but not consistent with radiation**
    - need better transport model ($\chi$, $E_r$) to determine self-consistent $T_e$(r), $T_i$(r)
    - full 1-D model with self-consistent $E_r$ and radiation is in the systems code (later step)
- **Test sensitivity to these assumptions**

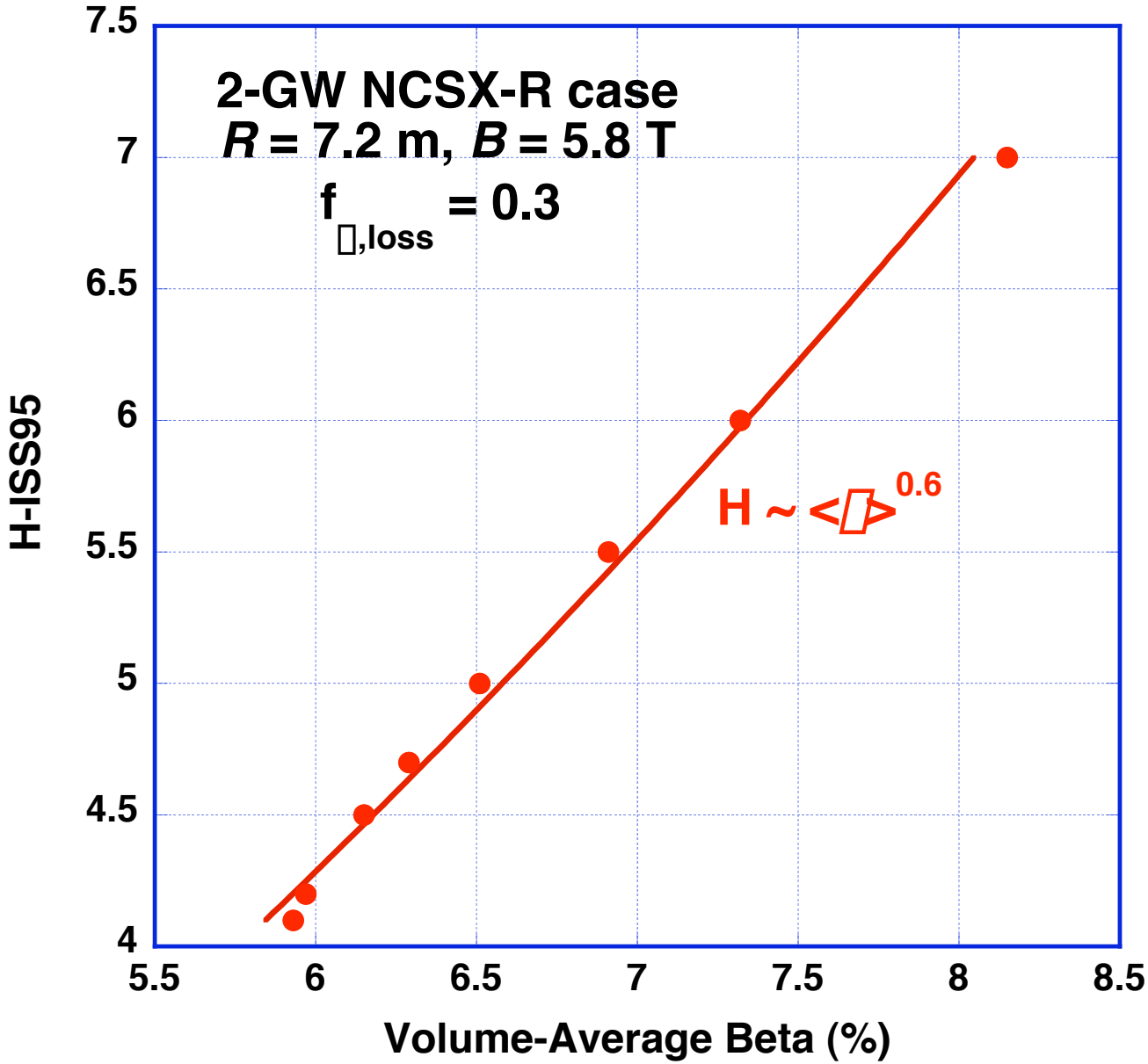
# Treatment of Impurities

- **Impurities reduce $P_{fusion}$ through reduced $n_{DT}^2$ and reduced $T_e$ (hence $T_i$) through radiative power loss**
  - **requires larger *B*, H-ISS95 or *R* to compensate**
- **Use carbon for low Z & iron for high Z and standard coronal model:** line radiation and electron-ion recombination
- **Use neoclassical impurity transport model**
  - $n_Z(r) = n_e(r) \times \langle f_Z \rangle (n_e/n_{e0})^Z [T_e/T_{e0}]^{-Z/5}$
  - ignore $[T_e/T_{e0}]^{-Z/5}$ term because it probably is not applicable in stellarators
  - $n_e(r)$ is hollow for regime of interest in stellarators ==> $n_Z(r)$ peaked near edge

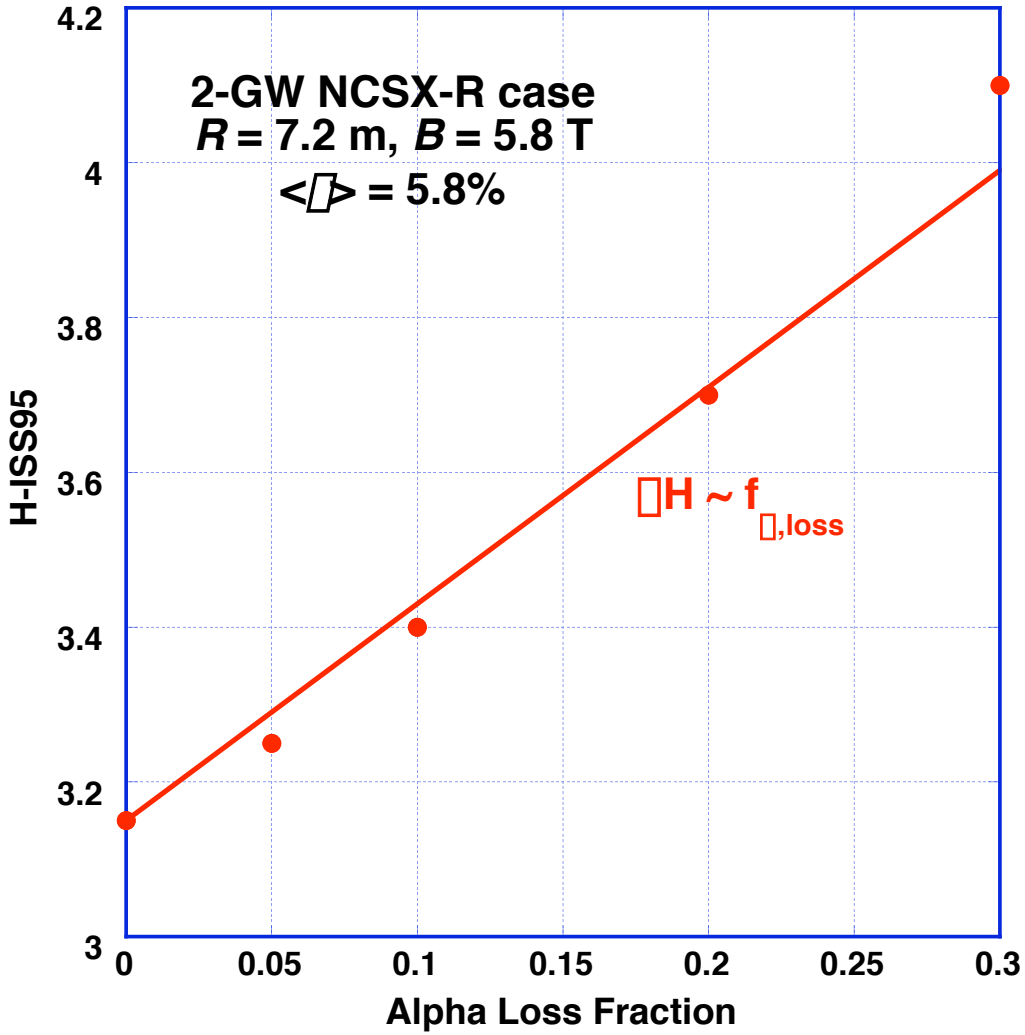
**An NCSX-R example**



# H-ISS95 Required Increases with <β>



# H-ISS95 Required Increases with $f_{\alpha,loss}$

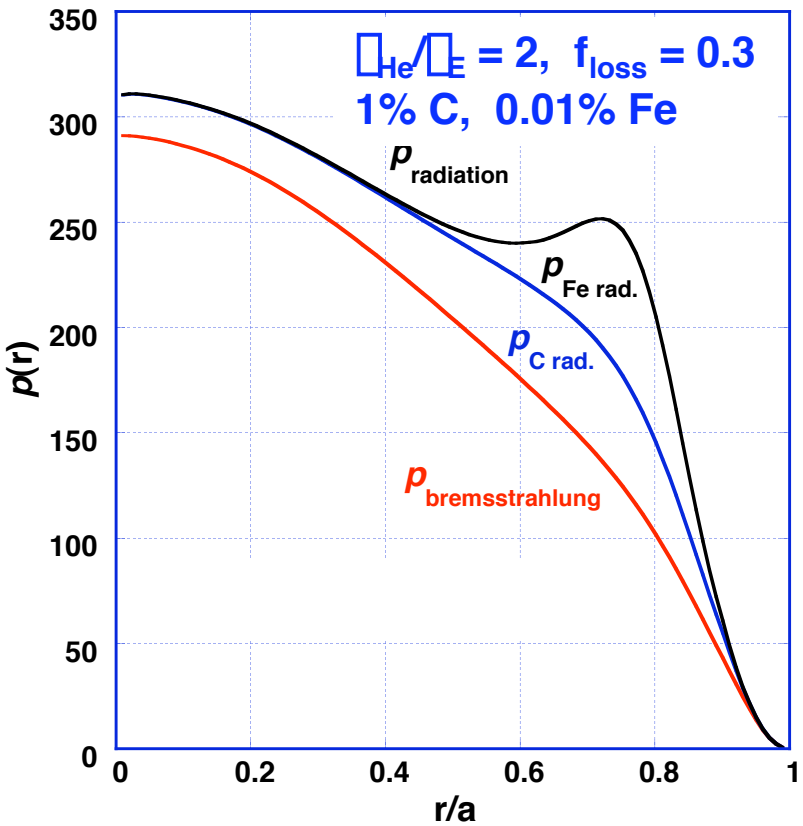


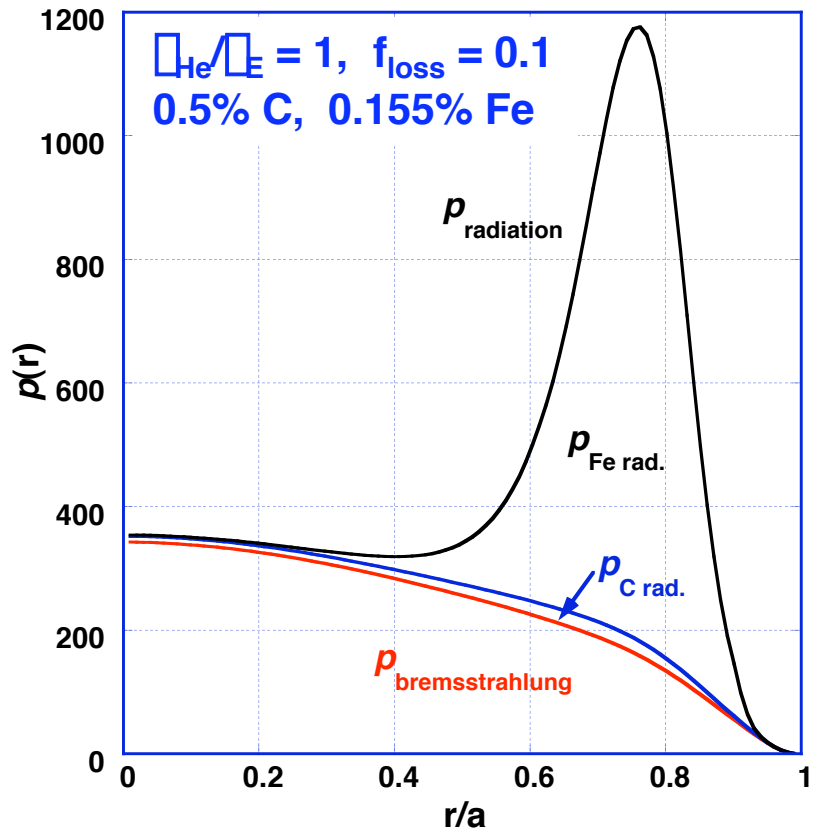

QA configurations with $f_{loss}$ < 10% are being developed

**Useful to reduce wall particle power flux (including α loss)**

- if $\langle p_{n,wall} \rangle$ ~3 MW/m$^2$ ($\langle p_{p,wall} \rangle$ ~ 0.75 MW/m$^2$) & divertor ~10% of wall area), then $\langle p_{divertor} \rangle$ is ~ 7.5 MW/m$^2$ and peak values much higher
- increasing power radiated to the wall can alleviate divertor problem

# $P_{radiated}$ Can Be Increased




- **$P_{\alpha \Rightarrow e}$ = 171 MW, $P_{rad}$ = 69 MW**
  **17% of $P_\alpha$, 40% of $P_e$**
  $P_{rad,H}$ = 50 MW, $P_{rad,C}$ = 11.6 MW
  $P_{rad,Fe}$ = 7.5 MW

- **$P_{\alpha \Rightarrow e}$ = 220 MW, $P_{rad}$ = 175 MW**
  **44% of $P_\alpha$, 80% of $P_e$**
  $P_{rad,H}$ = 63 MW, $P_{rad,C}$ = 5.3 MW
  $P_{rad,Fe}$ = 107 MW

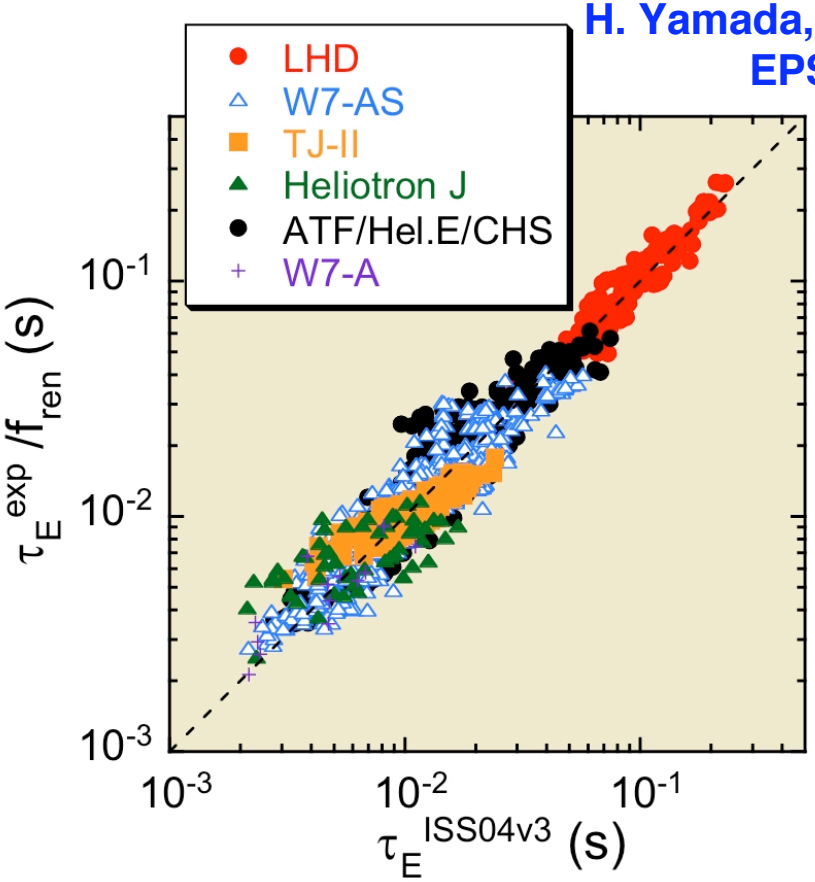
# Reactor-Relevant Issues for NCSX #1

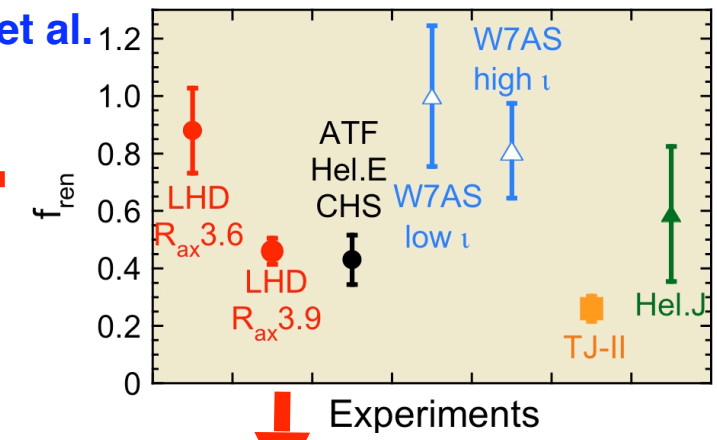
- **Density and temperature profiles are assumed**
  - **What are reasonable transport coefficients (D, $\chi$)? ambipolar electric field? bootstrap current?**
  - **Is neoclassical impurity model OK? Is *n*(r) hollow?**
- **Required confinement multiplier (H-ISS95 ~ 4) is calculated**
  - **How does confinement scale with plasma and configuration parameters?**
  - **Does quasi-symmetry, smaller $\iota_{eff}$ and reduced flow damping lead to improved confinement?**

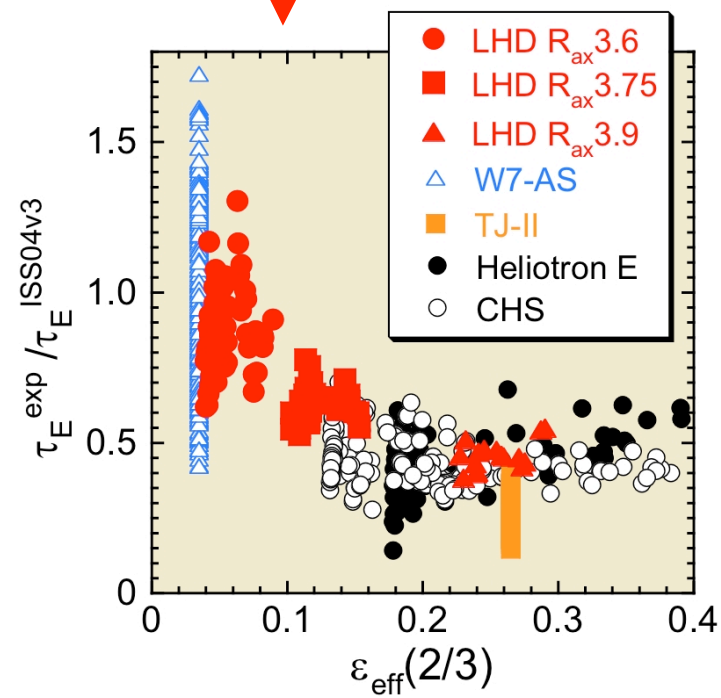
# ISS-95 Confinement Scaling Updated

$$\tau_E^{ISS04v3} = 0.148 a^{2.33} R^{0.64} P^{-0.61} \bar{n}_e^{0.55} B^{0.85} \iota_{2/3}^{0.41} \qquad \rho_{Bohm} \rho^{*-0.90} \beta^{-0.14} \nu_b^{*-0.01}$$

**H. Yamada, J. Harris et al.**
**EPS 2004**




$\sim \varepsilon_{eff}^{-0.4}$?

- **Determine $\tau_E$ increase with lower $\varepsilon_{eff}$ in NCSX**

# Reactor-Relevant Issues for NCSX #2

- $\beta$ limit is assumed -- no credible model exists
  - What are actual $\beta$ limits and their dependence on configuration parameters?
- Disruptions are ignored
  - Can disruptions be avoided?
- Power density to the divertor is very high
  - Can power density on the divertor be reduced? (larger footprint?, fixed magnetic islands?)
  - Can radiated power to the wall be increased?
- Alpha-particle losses are high at present
  - What are energetic ion losses? Can they be reduced?

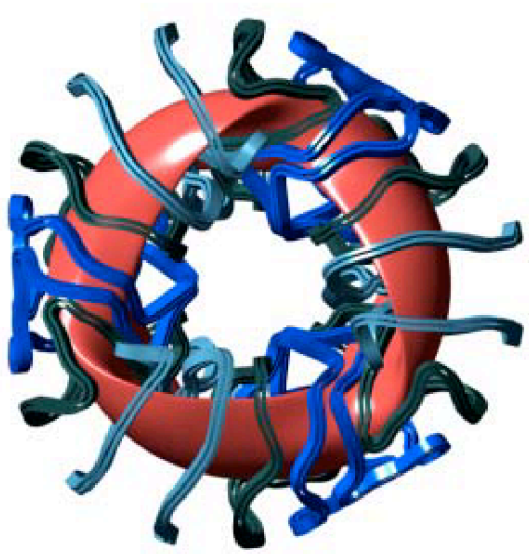
# Summary

- 3-4 year ARIES study is underway to explore compact stellarators for their reactor potential
- Study involves concept exploration + physics, engineering and cost optimizations
- Parameter determination involves all the optimization components
- Initial results lead to factor ~2 smaller stellarator reactors, closer to tokamaks in size (lower CoE?)
  - no need for current drive or disruption protection
- Study points up uncertainties in reactor physics assumptions that NCSX can help clarify

# Backup

# Three Configurations Have Been Studied

| | NCSX-R | MHH2 (8) | MHH2 (16) |
|---|---|---|---|
| Plasma-coil aspect ratio $A_{\square} = \langle R \rangle / \square_{min}$ | 5.90 | 5.52 | 4.91 |
| Min. coil-coil aspect ratio $A_{c\text{-}c} = \langle R \rangle / (c\text{-}c)_{min}$ | 10.1 | 13.3 | 7.63 |
| Plasma aspect ratio $A_p = \langle R \rangle / \langle a \rangle$ | 4.50 | 3.75 | 2.70 |
| Rotational transform $\square_{ave}$, shear $(\square_a - \square_0)/\square_{ave}$ | 0.5, 0.6 stell shear | 0.45, –0.22 tokamak shear | |
| Surface figure of merit $A_{\square}^2/A_p$ | 7.74 | 8.13 | 8.93 |



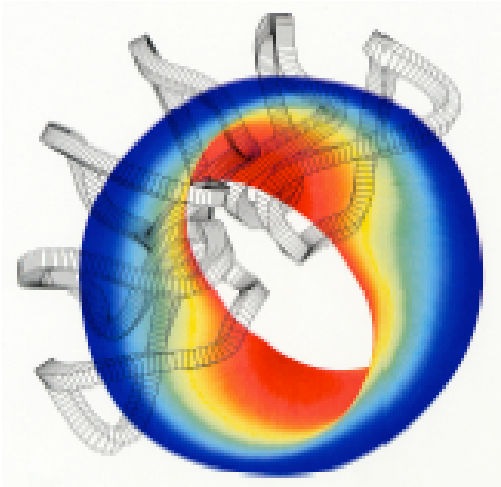
**"NCSX"**

sector (end) access

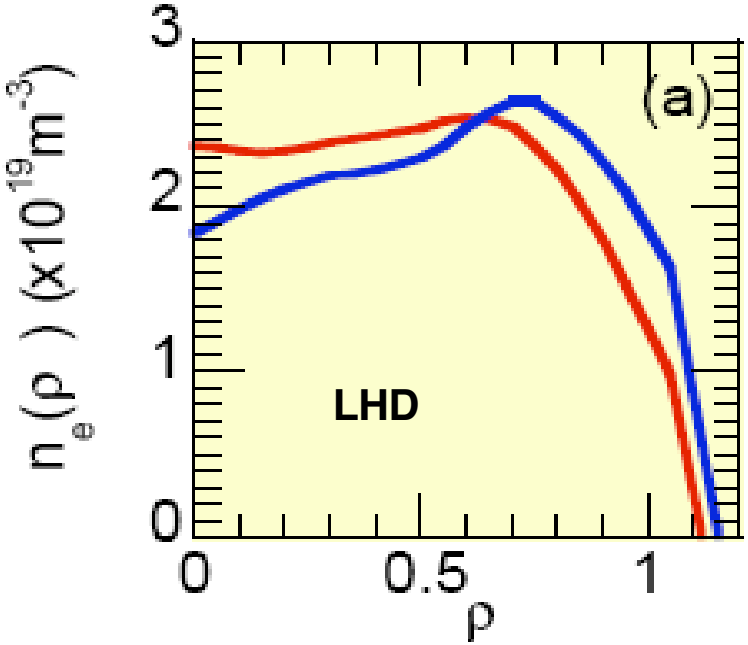
**MHH2**

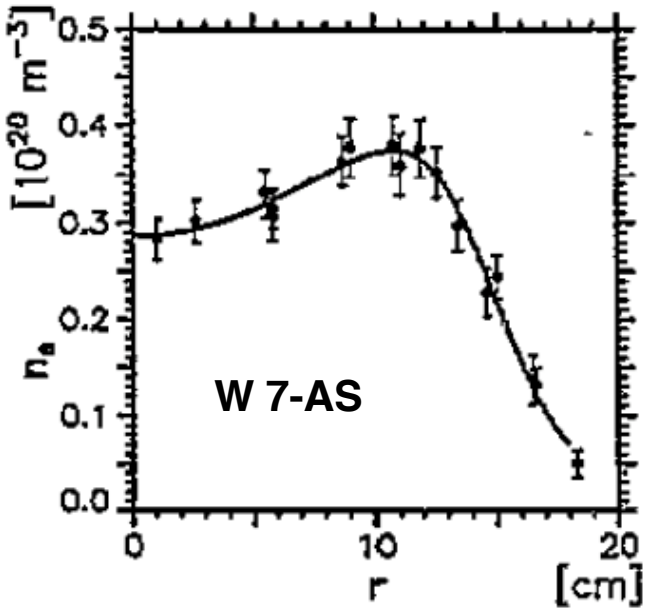
access through ports

both quasi-axisymmetric



# $n_e$(r) Hollow in Stellarators at Low $\nu^*$




$P_{NBI}$ = 1 MW, $T_i(0)$ = 1.3 keV

ECH, $T_e(0)$ = 1.5 keV

$P_{NBI}$ = 6.5 MW, $T_i(0)$ = 1.9 keV (more hollow at lower collisionality)

- Even flat *n*(r) in W 7-AS produces impurity profiles peaked near the edge
- Assume *n*(r) slightly hollow and $T_{e,i}$(r) peaked on axis