Progress on Systems Code and Revision of Previous Results

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What's New Since June ARIES Meeting

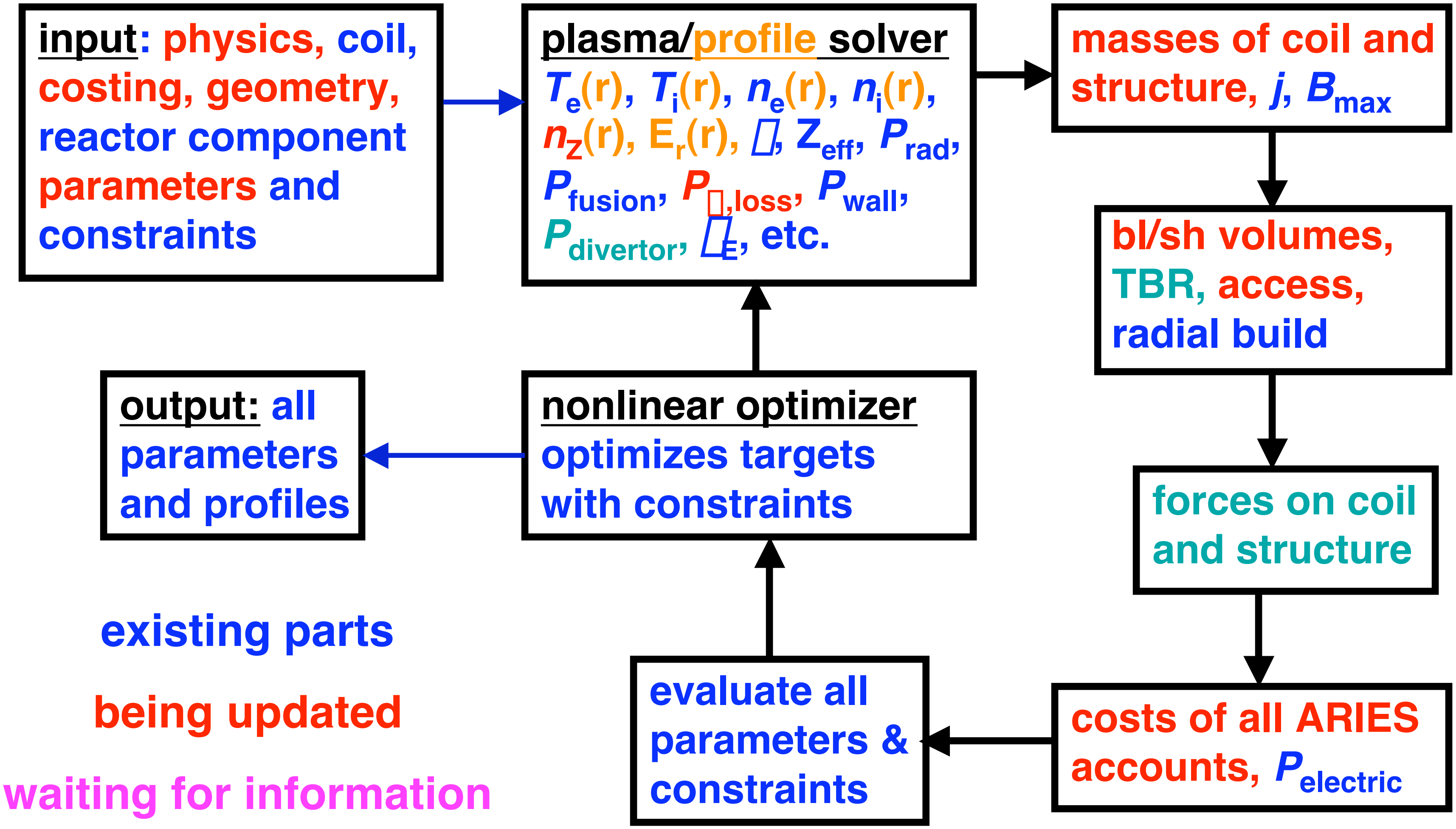
- **Progress on Systems/Optimization Code**
  - changes required and progress to date
  - issues and next steps
- **Revisions to 1-D POPCON calculations**
  - corrected He calculation
  - edge $T(r)$ and $n(r)$ pedestals; profile and sensitivity studies
- **Additional 0-D calculations**
  - examined two $A_{\square}$ cases for NCSX and extended scaling with $\langle p_{wall} \rangle$ for all cases
- **Comments on LHD reactor systems study**

Systems Code

- **Purpose: integrate coil and plasma geometry, reactor constraints and costing**
- **Starting point -- last (mis)used in SPPS study**
  - code written for tokamaks, revised for helical-coil stellarators (rotating ellipse, calculated B_{max} interpolating from database)
  - has ~ 7400 lines of code, highly interconnected
  - written ~15 years ago and last used ~10 years ago on computer platforms using math routines that no longer exist
- **Changes needed even for *relative* comparisons**
  - incorporate modular coil geometry (main components)
  - update physics & engineering (scaling, profiles, limits)
  - consistent treatment of impurities and edge
  - new models for blankets, shields, coils, structure
  - new costing for main components (waiting for numbers)
  - updated costing of other cost accounts (need consultation)
  - incorporation of maintenance periods

blue -- (partly) done, black -- in progress, red -- information needed

MHHOPT Reactor Optimization Code



existing parts

being updated

waiting for information

can update

no plans to use

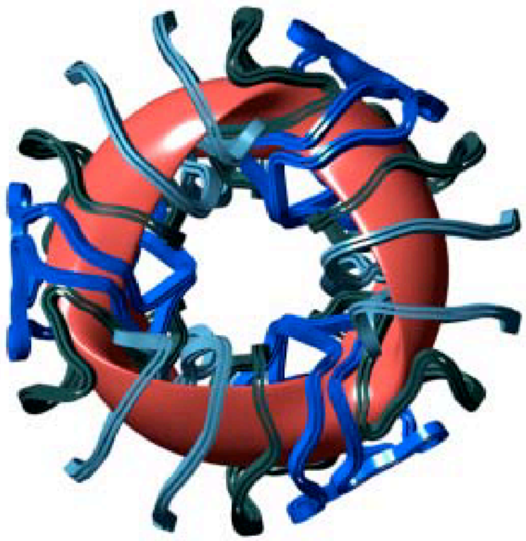
Systems Optimization Code

- **Minimizes core cost or size or COE with constraints for a particular plasma and coil geometry using a nonlinear constrained optimizer**
- **Iterates on a number of optimization variables**
  - **plasma: $<T_i>$, $<n_e>$, H-ISS95; coils: width/depth of coils**
  - **reactor variables: B_0, $<R>$**
- **Large number of constraints allowed (=, <, or >)**
  - **$P_{electric}$, ignition margin, □ limit, ISS-95 multiplier, radial build, coil *j* and B_{max}, plasma-coil distance, clearance between coils, blanket and shielding thicknesses, TBR, access for divertors and maintenance, etc.**
- **Large number of fixed parameters for plasma and coil configuration, plasma profiles, transport coefficients, cost component algorithms, and engineering model parameters**
- **Calculates a large number of parameters**
  - **plasma: □, Z_{eff}, power components (radiation, □ => i, □ => e), □ losses, etc.**
  - **coils: components volumes and costs, *j*, B_{max}, forces**
  - **reactor variables: blanket volumes, TBR, neutron wall loading, divertor area, access between coils, radial build, etc.**
  - **costs: equipment cost, annual operating cost, total project cost, CoE**

Input Parameters

- **Configuration geometry**
  - **plasma aspect ratio, surface area, coil aspect ratio, closest approach aspect ratio, □$_{limit}$, □(r), ~~ripple$_{effective}$(r)~~, etc.**
- **Reactor component parameters**
  - **inside & outside shield thickness; coil width and depth**
  - **blanket thickness inside & outside, under and between coils**
  - **coil case & vacuum vessel thickness, dimensions of modular coils and VF coils; scrapeoff thickness**
  - **first wall and reflector thickness; coil to vacuum vessel gap**
  - **~~allowable nuclear heating in coil~~; $j_{max}(B)$**
  - **blanket energy multiplication**
- **Cost assumptions**
  - **modular and VF costs /kg**
  - **costs and multipliers for blanket and shield**
  - **duty factor, inflation, safety assurance**

Four Configurations Now Studied

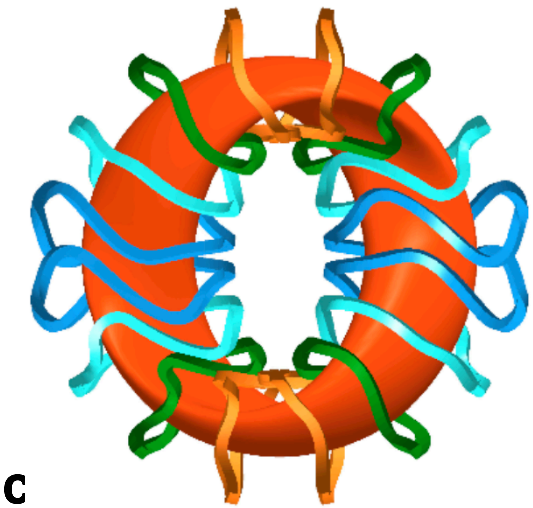


NCSX

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 $\langle R\rangle/\Delta_{min}$	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

- $\langle R_{coil}\rangle/\langle R\rangle$ constant for each case, can't change separately

Output

- **Plasma parameters and profiles**
  - $\langle R \rangle$, $\langle B_{axis} \rangle$, W_{plasma}, $\square_E$, H factors, $\langle \square \rangle$, $\square^*$, n_{Fe}/n_e, n_O/n_e, Z_{eff}
  - $\langle T \rangle$, T_{i0}, $T_{i,edge}$, T_{e0}, $T_{e,edge}$, $\cancel{\square_0/T_{e0}}$, $\langle n \rangle$, n_{i0}, n_{e0}, $\langle n \rangle/n_{Sudo}$, n_{DT}/n_e,
  - ignition margin, P_{fusion}, $P_{electric}$, $P_{neutron}$, $P_{charged}$, $P_{divertor}$, components of P_{rad} and P_{wall}, P_{loss}
- **Coil parameters**
  - modular & VF coil dimensions, currents, forces, inductance, stored energy, j, B_{max}, case thickness
- **Reactor parameters**
  - blanket area accessible and blocked, inboard and outboard shield thickness, cryostat gap, access between coils

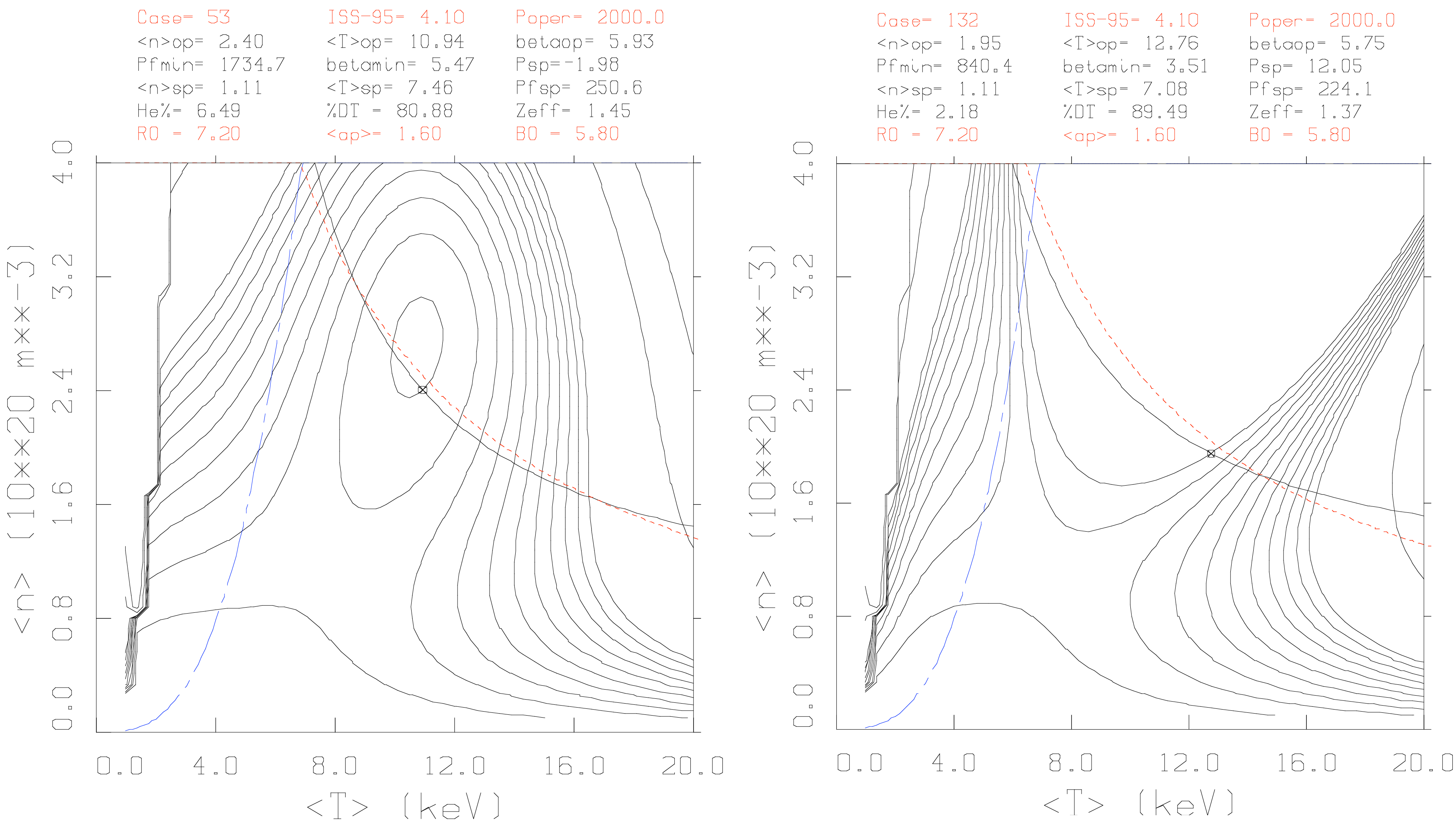
Output (cont.)

- Cost elements
  - land & structures; power supplies; impurity control; heat transport; power conversion; startup power
  - blankets & first wall; shields; modular & VF coils; structure; vacuum vessel
  - turbine plant equipment; electric plant equipment; misc. plant equipment; special materials; total direct cost
  - construction; home office; field office; owner's costs; project contingency; construction interest; construction escalation; total capital cost
  - unit direct cost; unit base cost; total unit cost; capital return; O&M costs; blanket/first wall replacement; decommissioning allowance; fuel costs; cost of electricity
- Summary of all component masses & mass utilization
- Dimensions of each element in the radial build

Revision to 1-D (POPCON) Calculations

- **Purpose of 1-D calculations:**
  - test different profiles, physics models and assumptions for incorporation into systems code
  - examine effect of assumptions on operating point
- **Corrected error in calculation of helium concentration**
  - this affected n_{DT}/n_e, P_{fusion}, etc.
  - removes earlier concern on $\tau_{He}/\tau_E < 2$ being too low (now > 6)
- **Added edge pedestals to simulate edge cooling from enhanced (neoclassical impurity) edge radiation**
  - small effect, but more consistent with large edge radiation
- **Will later update confinement scaling ISS-95 --> ISS-04**
  - small effect, but dimensionally correct and fits data better
  - $\Rightarrow$ basis for assumed H-ISS values

Effect of Correction to n_{He} Calculation

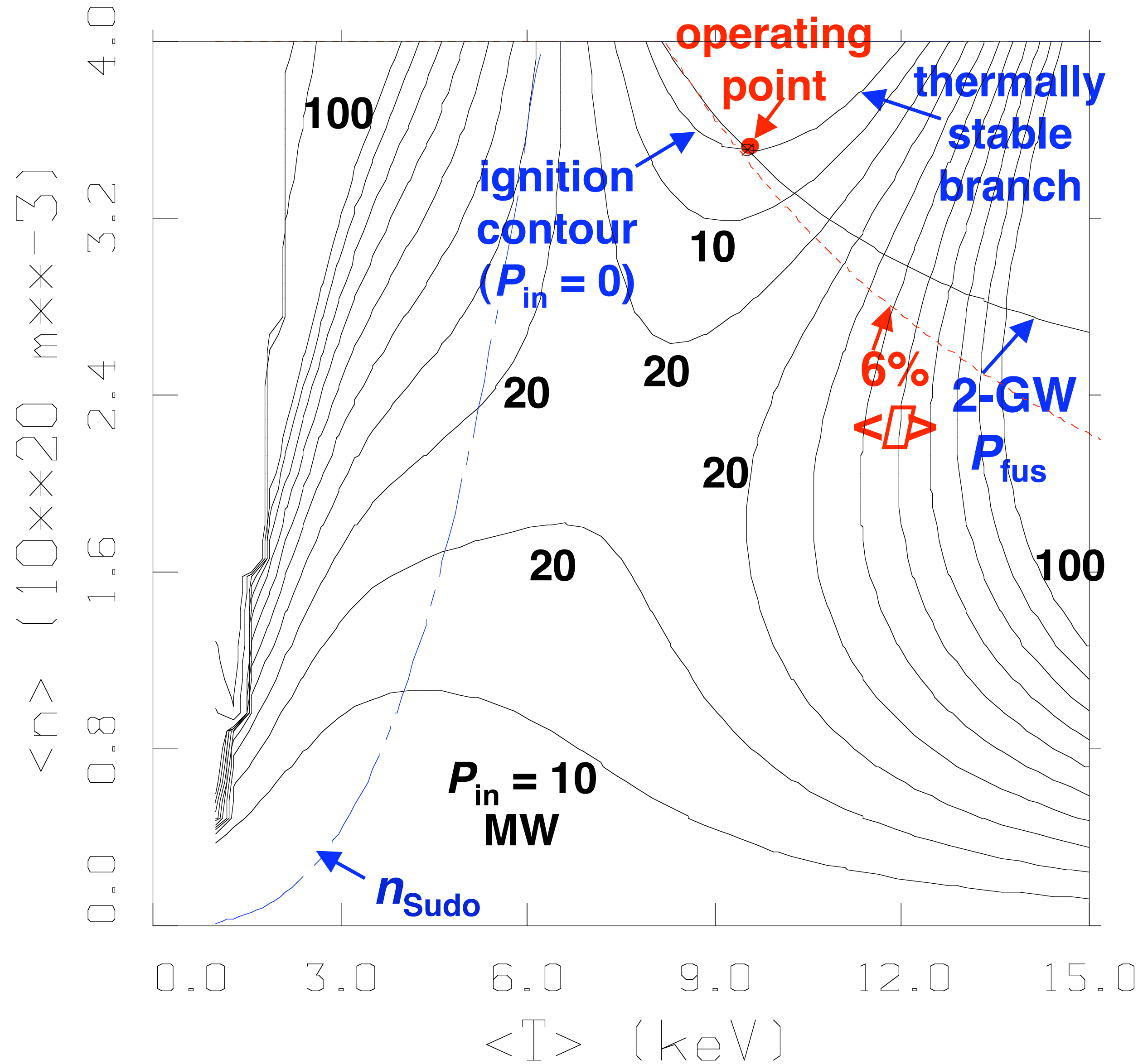


- **Previously required τ_{He}^*/τ_E <2, now > 6 OK**
- **Minimum H-ISS95 ==> 3.7 for a stable operating point**

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

H-ISS95 =

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



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

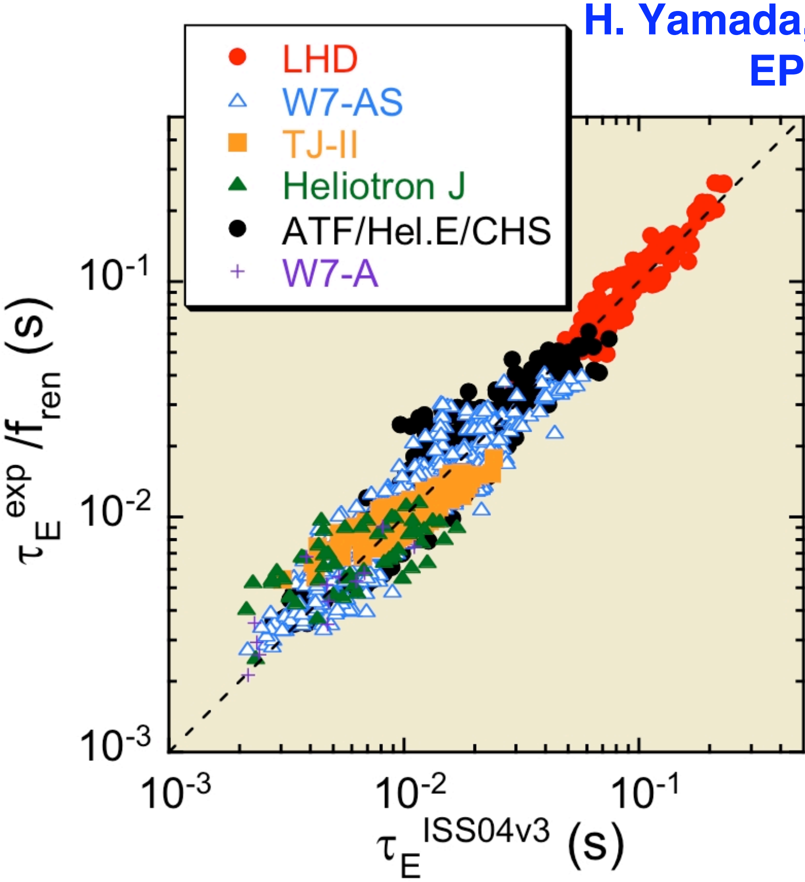
Plasma Parameters from 1-D Power Balance

	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

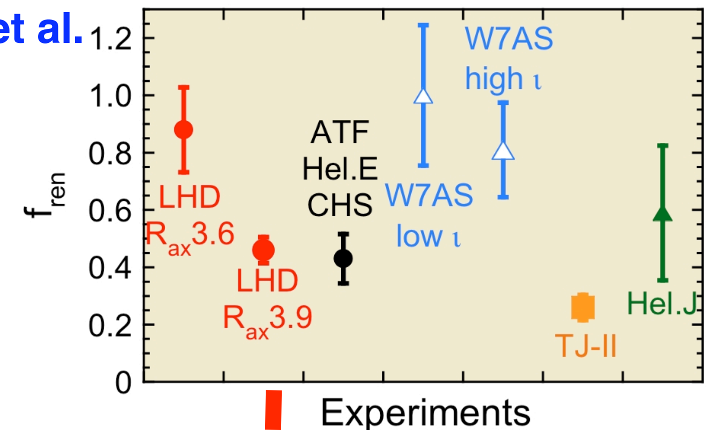
- ISS-95 of 3.75 to 4.2 is required; present stellarator experiments have up to 2.5
- ISS-2004 scaling indicates $\epsilon_{eff}^{-0.4}$ improvement, so compact stellarators should have high H-ISS values

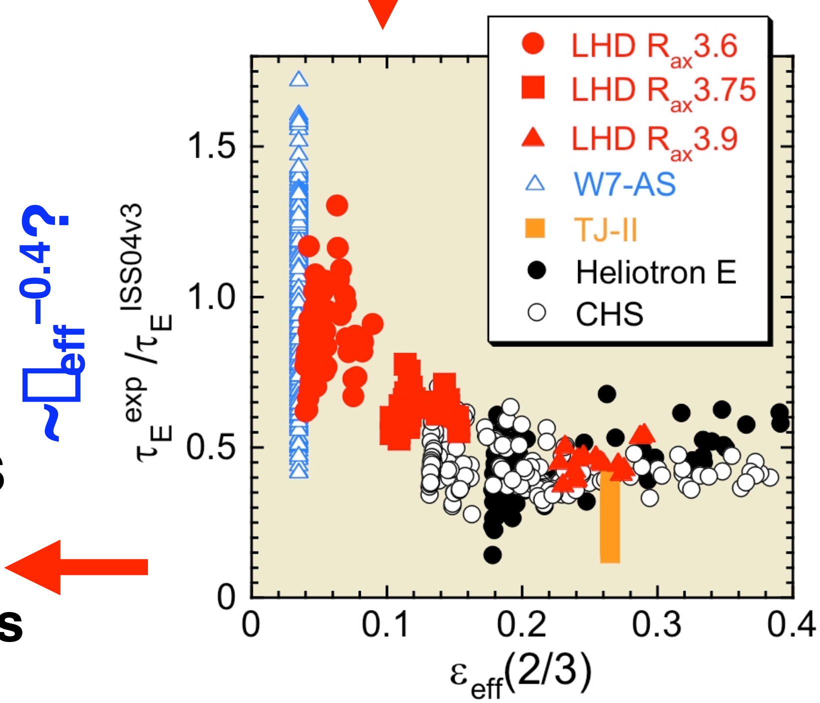
ISS-95 Confinement Scaling Is Being Updated

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



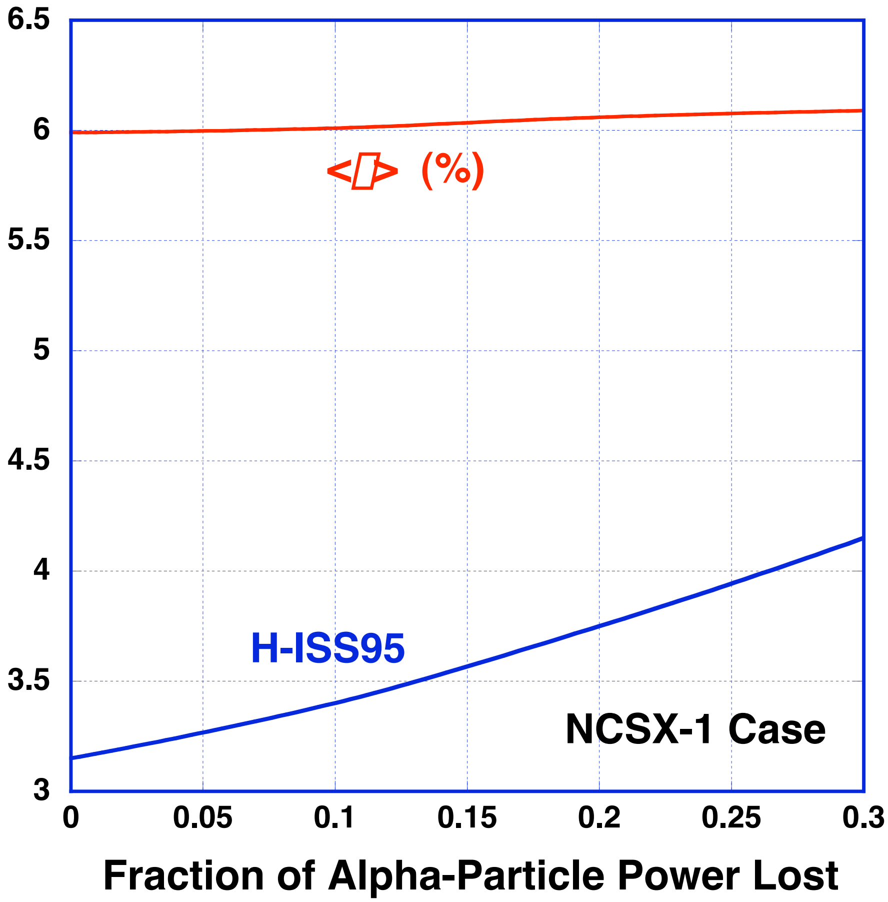
H. Yamada, J. Harris et al.
EPS 2004

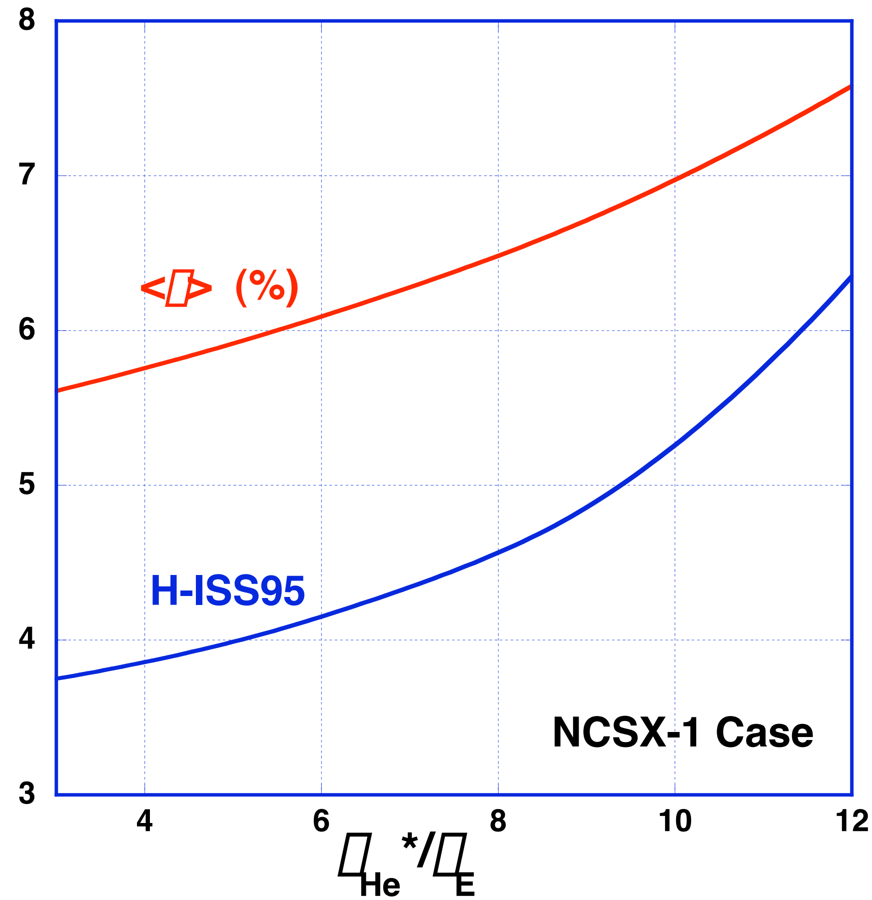




- $\tau_E \sim \varepsilon_{eff}^{-0.4}$ should give large H-ISS for low ε_{eff} NCSX configuration
- Lays basis for higher H-ISS values

H-ISS95 Is Sensitive to Some Assumptions





- Need to control alpha-particle power loss and helium recycling back into plasma -- both *divertor* issues

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

0-D (Volume-Average) Calculations

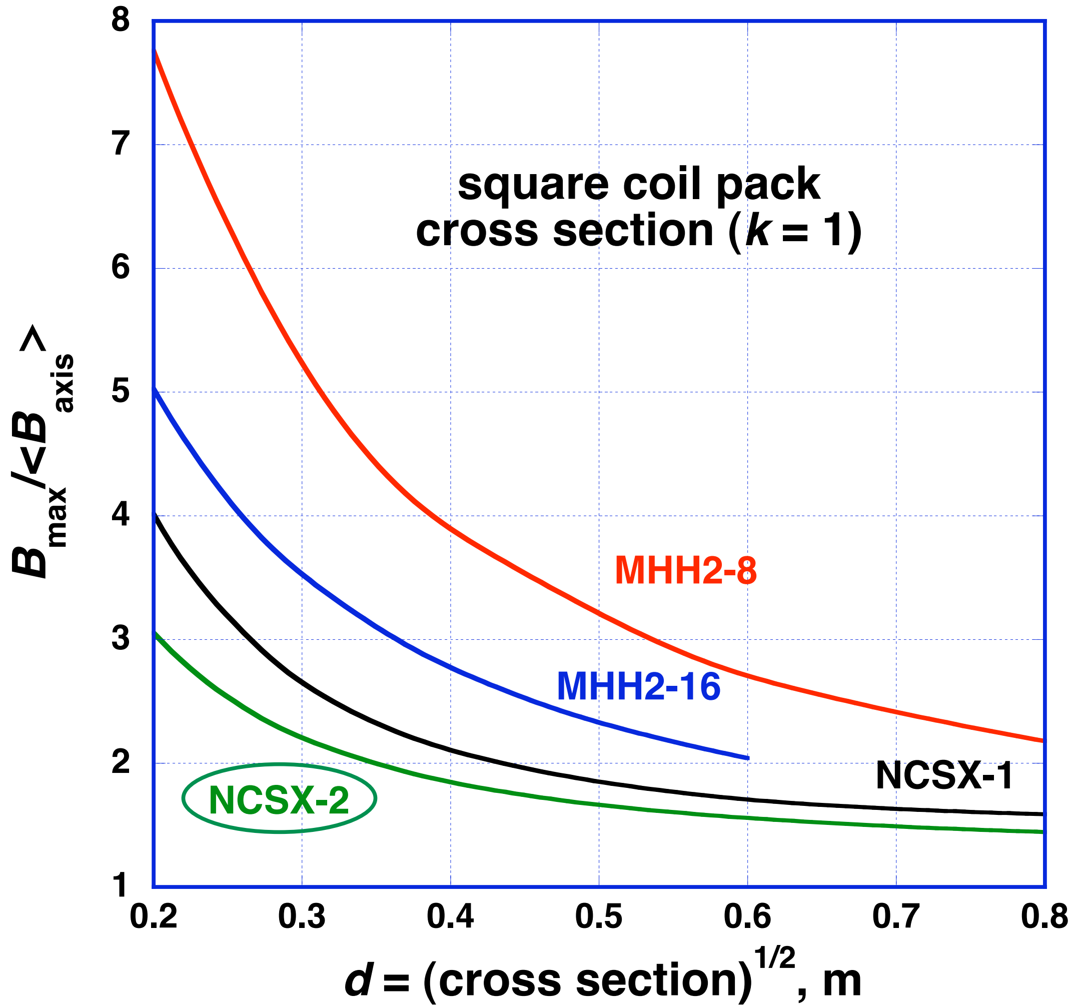
PURPOSE

- Allows analytic treatment of
  - connection between different device parameters
  - effect of different assumptions and constraints
- Validates modules needed for systems code

ADDITIONS

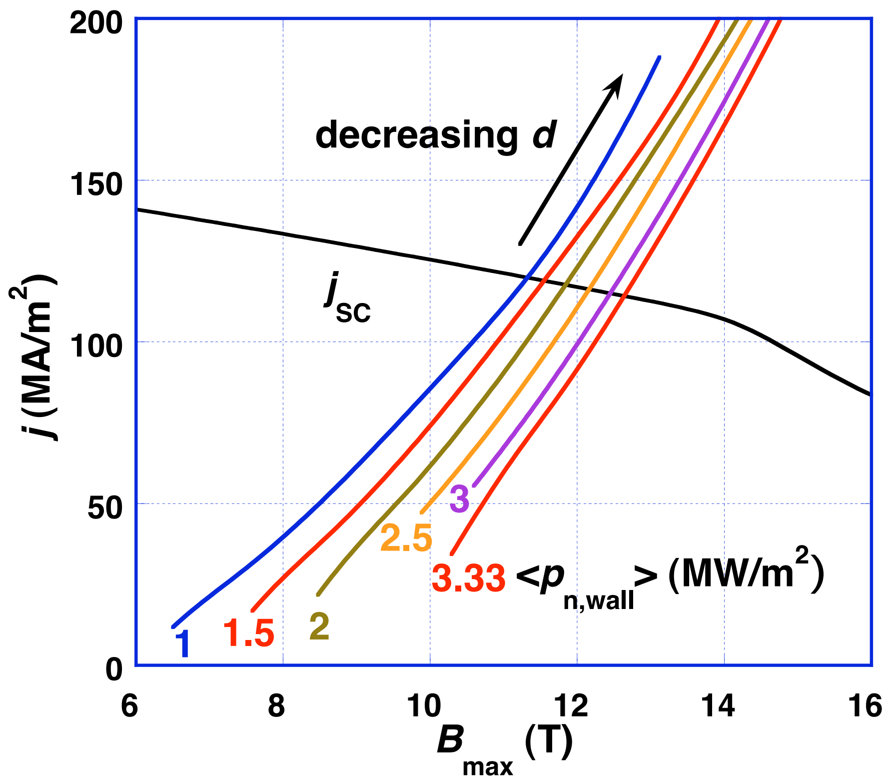
- NCSX case with different $A_{\square}$ (2/25/03 case)
- Superconducting coil constraint
- Varied p_{wall} from 1 to 3.3 MW/m^2 (assumed peak 1.5 times higher) to study variation in global parameters

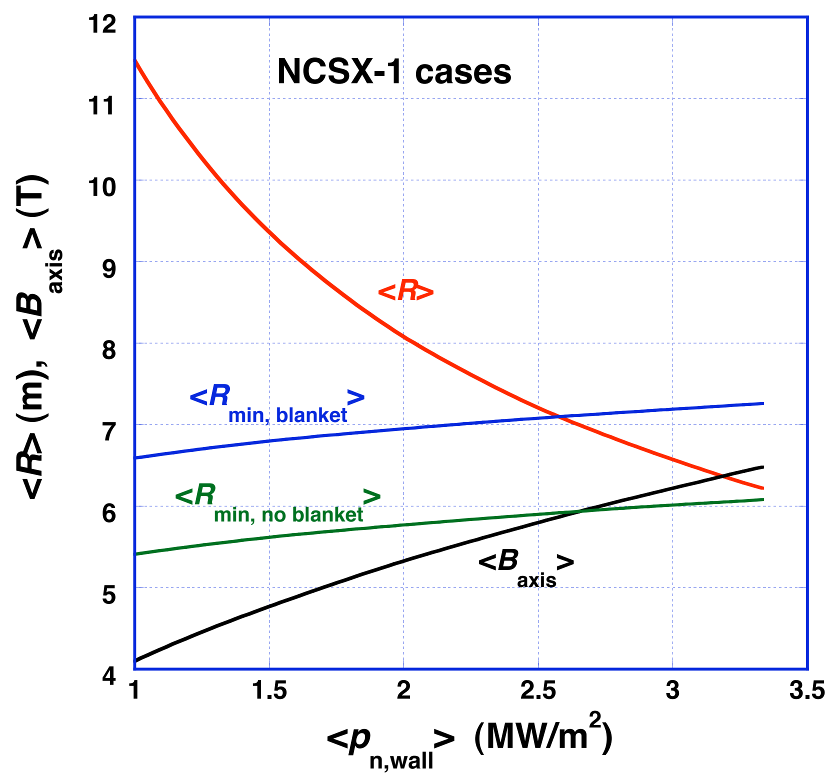
Added 2/25/03 (NCSX-2) Case



- Smaller plasma-coil spacing leads to less convoluted coils and lower $B_{max}/\langle B_{axis}\rangle$
- Minimum coil-coil separation distance determined k_{max}

NCSX-1 Values Limited to $p_{n,max}$ = 5 MW/m²





- $\langle R \rangle$ = 6.22 m, $\langle B_{axis} \rangle$ = 6.48 T, B_{max} = 12.65 T
- j_{coil} approximately constant
- $\langle R \rangle$, $\langle B_{axis} \rangle$, B_{max} & d are constrained for other cases by radial build to lower $\langle p_{n,wall} \rangle$ (2.13–2.67 MW/m²)

Scaling Relations for Reactor Parameters

- **Fusion power** *red indicates configuration-specific parameters*
  - $P_{fusion} \sim \langle \square \rangle^2 \langle B_{axis} \rangle^4 \langle R \rangle^3 / A_p$
  - $p_{n,wall}/1.5 = \langle p_{wall} \rangle = 0.8 P_{fusion} / [\langle R \rangle^2 (A_{wall}/\langle R \rangle^2)]$
- **Coil-geometry related** $sh = sh_2 + c \times \ln(\langle p_{wall} \rangle)$
  - $\langle R \rangle = A_{\square}(so + fw + bl + sh + vv + gaps + 0.5 d k^{1/2})$ *constraint*
  - $j_{coil} = I_{coil}/d^2 = \langle B_{axis} \rangle \langle R \rangle [I_{coil}/\langle B_{axis} \rangle \langle R \rangle]/d^2$
  - $j_{SC}(B_{max})$ and d, k from $B_{max}/\langle B_{axis} \rangle$
- **Cost-related (rationale for $\langle p_{wall} \rangle$ emphasis**
  - blanket, shield, vacuum vessel, coil structure ~ wall area ~ $P_{fusion}/\langle p_{n,wall} \rangle$, but $\langle p_{n,wall} \rangle$ configuration constrained
  - fw/blanket replacement ~ frequency x cost ~ $1/\langle p_{n,wall} \rangle \times P_{fusion}/\langle p_{n,wall} \rangle \sim P_{fusion}$ independent of $\langle p_{n,wall} \rangle$ but actual cost depends on specifics
  - volume of coils ~ $L_{coil} I_{coil} / j_{coil} \sim C \times P_{fusion}^{7/8} / (\langle p_{n,wall} \rangle^{5/8} \langle \square \rangle^{1/2} j_{coil})$
    $C = (L_{coil}/\langle R \rangle)(I_{coil}/\langle B_{axis} \rangle \langle R \rangle) A_p^{1/2} / (A_{wall}/\langle R \rangle^2)^{5/8}$, C/j_{coil} constant

Main Reactor Parameters from 0-D Study

	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

- **Wall (blanket, shield, structure, vacuum vessel) area smallest for NCSX-1**

⇒ chose NCSX-1 (8/1/03 case) for more detailed study

LHD Reactor Study (T. Dolan)

- Based on LHD plasma and coil configuration
- Uses port maintainence scheme and three blanket + cooling models (RAFS + Flibe, Va + Li, SiC + PBLi)
- Based on Miller's costing code with some new values
- H-ISS95 limited to 2, <□> to 4%, B_{max} = 13 T
  - consistent with LHD performance, higher $□_{eff}$ value
- Base case has R = 14.4 m, B_{axis} ~ 5.5 T, H-ISS95 = 1.7, <□> = 3%, P_{fusion} = 4.5 GW ($P_{electric}$ = 1.94 GW), $\langle p_{wall} \rangle$ = 2.1 MW/m^2, j_{coil} = 30 MA/m^2, k = 2, f_{loss} = 0.1, □ = 40%
- Studied CoE variation with T_0, n & T profiles, <□>, k, plasma-wall dist, shield-coil gap, B_{max}, $\langle p_{wall} \rangle$, $P_{electric}$

Summary

- **Progress on Systems/Optimization Code**
  - added modular coil geometry and updated physics models
  - treatment of impurities and edge and new models for blankets, shields, coils, structure in progress
  - information needed on new costing for main components and updated costing of other cost accounts
- **Revised 1-D POPCON calculations**
  - corrected He calculation
  - insensitive to profiles, edge $n(r)$ & $T(r)$ pedestals
  - more sensitive to alpha-particle losses and helium τ_p^*
- **0-D -- added 2/25 NCSX case, superconducting coil constraint, and extended scaling with $\langle p_{wall} \rangle$**
- **Examined LHD reactor systems study**