Studies of NCSX and MHH2 Reactor Configurations

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What's New Since March Meeting

- Continued following a staged approach
- Focusing on highest-leverage areas
  - more accurate treatment of 16-coil MHH2 configuration; added 8-coil configuration
  - recalculated reactor parameters based on more realistic wall loading and constant □ for lower B_{max}
  - fixed problems with impurity radiation profiles
  - studied optimization of impurity radiation
  - continued to test models and assumptions for inclusion in the integrated systems code

Three Configurations Studied

	NCSX-R	MHH2 (8)	MHH2 (16)
Plasma-coil aspect ratio $A_\Delta = \langle R \rangle / \Delta_{min}$	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
Surface figure of merit A_Δ^2 / A_p	7.74	8.13	8.93

Model Assumptions

- **Blanket and shield models**
  - NCSX-R: ~10% of wall area has $\square < 1.2\ \square_{min}$
    - can have shield only in this area, full blanket elsewhere
  - MHH2: ~20% of wall area has $\square < 1.2\ \square_{min}$
    - need full blanket and shield everywhere
  - Two cases
    - (1) no shield in some areas or high Be fraction for blanket
    - (2) Laila's full blanket and shield
- **Common reference assumptions for all cases**
  - alpha-particle losses 30%; no better case yet
  - $\square_{He}/\square_E = 2$, 1% C, 0.01% Fe
  - j_{max} & B_{max} appropriate for Nb_3Sn-like conductor
    - $j_{max} = 143\ \mathrm{MA/m^2}$ for $B_{max} = 10$ T $\rightarrow$ 109 $\mathrm{MA/m^2}$ for $B_{max} = 16$ T
- **Tested sensitivity to the assumptions**

Global Determination of Reactor Parameters: $\langle R \rangle$, $\langle a \rangle$, $\langle B_{axis} \rangle$, B_{max}, coil cross section

Earlier Reactor Parameter Selection (1)

- **Minimize reactor core cost**
  - **Cost ~ blanket/shield + coils + vacuum vessel**
  - **Cost ~ surface areas, approx. ~ R^2**

□ **Minimized R for a reactor -- small d, large k**

- **$\langle R \rangle \geq A_{□}(t_{so+fw+sh+cc} + d/2k^{1/2})$**
- **Min. coil-coil dist. $R/A_{c\text{-}c} - k^{1/2}d - 2(csth) \geq 0$**
  - * $A_{□} = \langle R \rangle / □_{min}$, $d = (cw \times cd)^{1/2}$, $k =$ cw/cd
  - * $t_{so+fw+sh+cc} = t_{Laila} - 0.1$ m $= 0.95 + 0.0624\, \mathit{ln}(p_{n,wall}/2)$, csth = 1 cm

- **Maximized B_0 (minimizes □)**
  - **B_0(T) = 16 $B_0/B_{coil,max}$(d,k) /(R/8.25)   (for NCSX-R)**

Then Checked if Needed to Increase *R*

- **If $\beta > \beta_{limit}$: ($P_E \sim \beta^2 B_0^{\ 4} R^3$)**
- **If j_{coil}(MA/m^2) = 13(B_0/5.3)(R/8.25)/d^2 > 330 (or >110-135 for Nb_3Sn)**
- **Increased *R* by increasing d (increased B_0 & reduced k) but needed to keep $B_{coil,max}$ < 16 T**
  - B_{max} = (R/8.25)B_0 /{B_0/$B_{coil,max}$(d,k)}

NCSX-R Parameter Selection
(from March Meeting)

Ku's 8/1/03 coil set   0.86 shield (WC) case   Bmax = 16 T

Coil d	Coil k	R axis (m)	Max B axis	j (MA/m2)	c-c min	Wall load	Beta (%)
0.25 m	1.00	6.05	6.95	205.55	0.33	4.76	5.45
	1.78	5.89	7.18	206.96	0.23	5.01	5.31
	2.56	5.80	7.41	210.36	0.16	5.17	5.10
	4.00	**5.71**	**7.77**	**216.95**	**0.05**	**5.34**	**4.76**
0.3 m	1.00	6.20	8.15	171.64	0.30	4.54	3.82
	1.78	5.97	8.49	172.45	0.17	4.88	3.71
	2.56	**5.89**	**8.72**	**174.60**	**0.09**	**5.01**	**3.60**
0.4 m	1.00	6.43	9.83	120.88	0.22	4.21	2.48
	1.78	**6.17**	**10.29**	**121.23**	**0.06**	**4.58**	**2.42**
0.5 m	1.00	6.73	10.68	87.85	0.15	3.85	1.97
0.6 m	1.00	6.99	11.14	66.19	0.07	3.57	1.70

- **PROBLEM: had $\langle p_{wall} \rangle$ much too high and low $\langle \beta \rangle$**

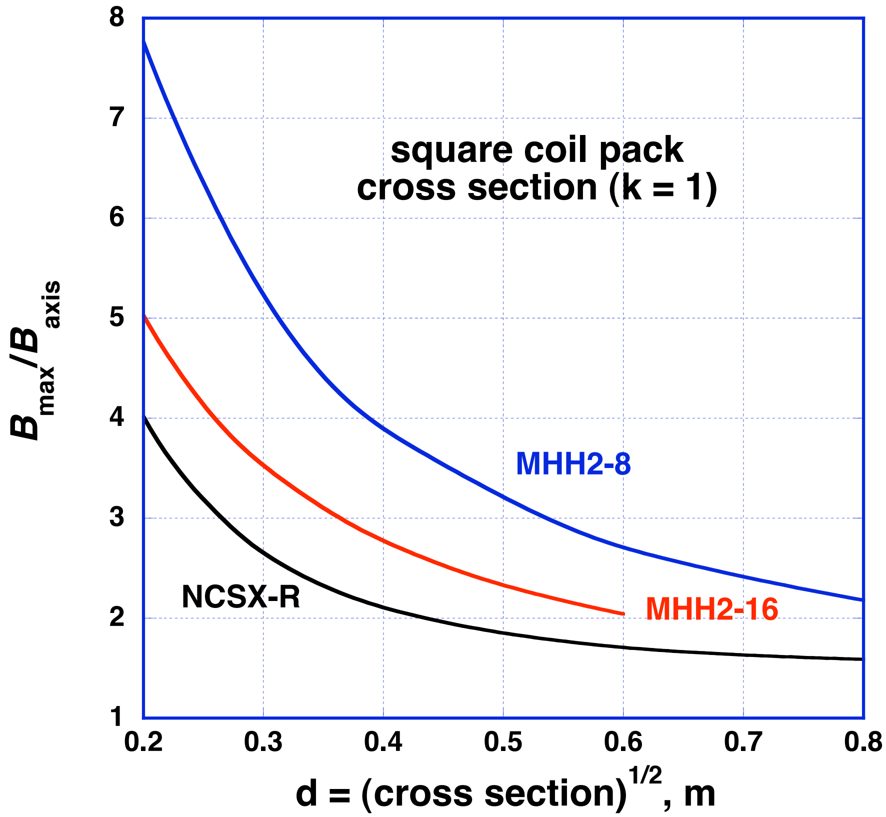
Revised Approach (1)

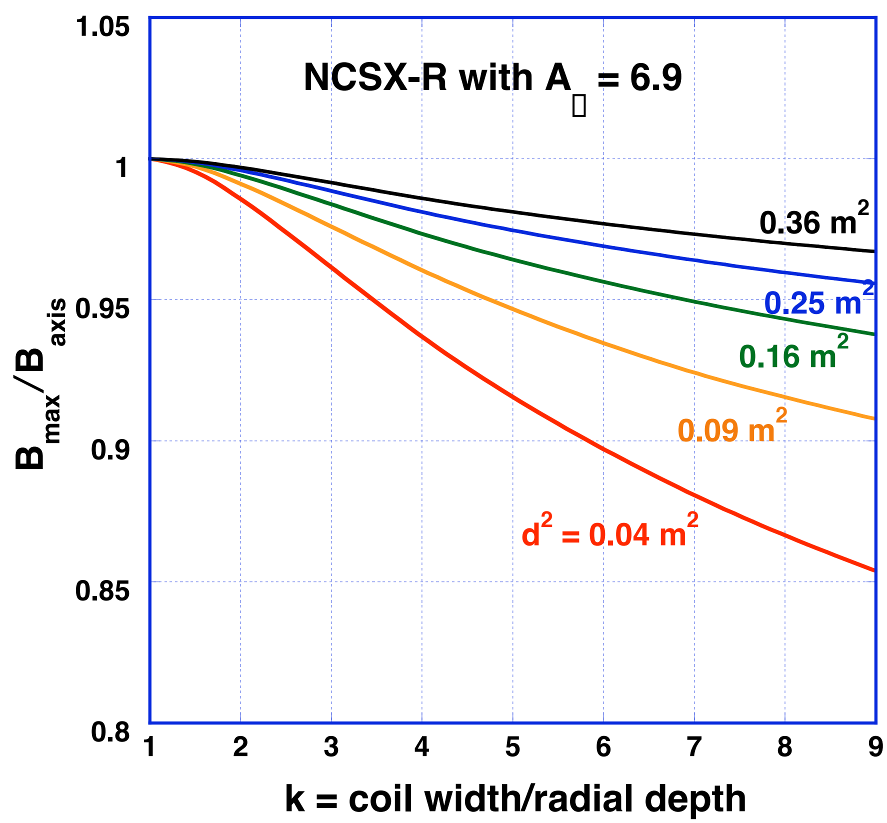
- **Fixed neutron wall loading p_{wall} at 5 MW/m^2**
  - **peaking factor ≥ 2? → used $\langle p_{\mathrm{wall}} \rangle$ = 2.5 MW/m^2**
    - **also examined $\langle p_{\mathrm{wall}} \rangle$ = 2 and 3 MW/m^2 as limits**
  - **$\langle p_{\mathrm{wall}} \rangle$ = 2.5 MW/m^2 → wall area = 640 m^2 for P_{fusion} = 2 GW**
    - **$\langle R \rangle$ = 7.20 m for NCSX-R**
    - **$\langle R \rangle$ = 5.70 m for 8-coil MHH2, 6.78 m for 16-coil MHH2**
    - **cost of reactor components (blanket, shield, structure) same for all 3 cases since cost ~ wall area**
      - **small correction for coil cross section**

Revised Approach (2)

- Chose $\langle\beta\rangle$ = 6%; also examined 4% as pessimistic limit
  - no credible instability model for β limit; equilibrium better
  - ⇒ B_{axis} = 5.80 T for NCSX-R ($P_{fusion} \sim \beta^2 B^4 R^3$ if $\sigma v \sim T^2$)
  - ⇒ B_{axis} = 5.36 T for 8-coil MHH2, 5.54 T for 16-coil MHH2
- $\langle R\rangle$, $\langle a\rangle$ and $\langle B_{axis}\rangle$ sufficient for starting physics assessments, but *not* enough for engineering assessments
- Then determined coil parameters
  - Used $\langle B_{axis}\rangle$ and Ku's B_{max}/B_{axis} calulations for different coil cross sections (d, k) to calculate B_{max}
  - B_{max} on coil depends on coil cross section and allowable gap
    - 16 T has thinnest coil depth so is least expensive, but can lead to an extra (large?) gap between blanket and shield
    - constraint eliminates some potential solutions (no gap, B_{max} > 16 T)

B_{max} Determination from B_{axis}





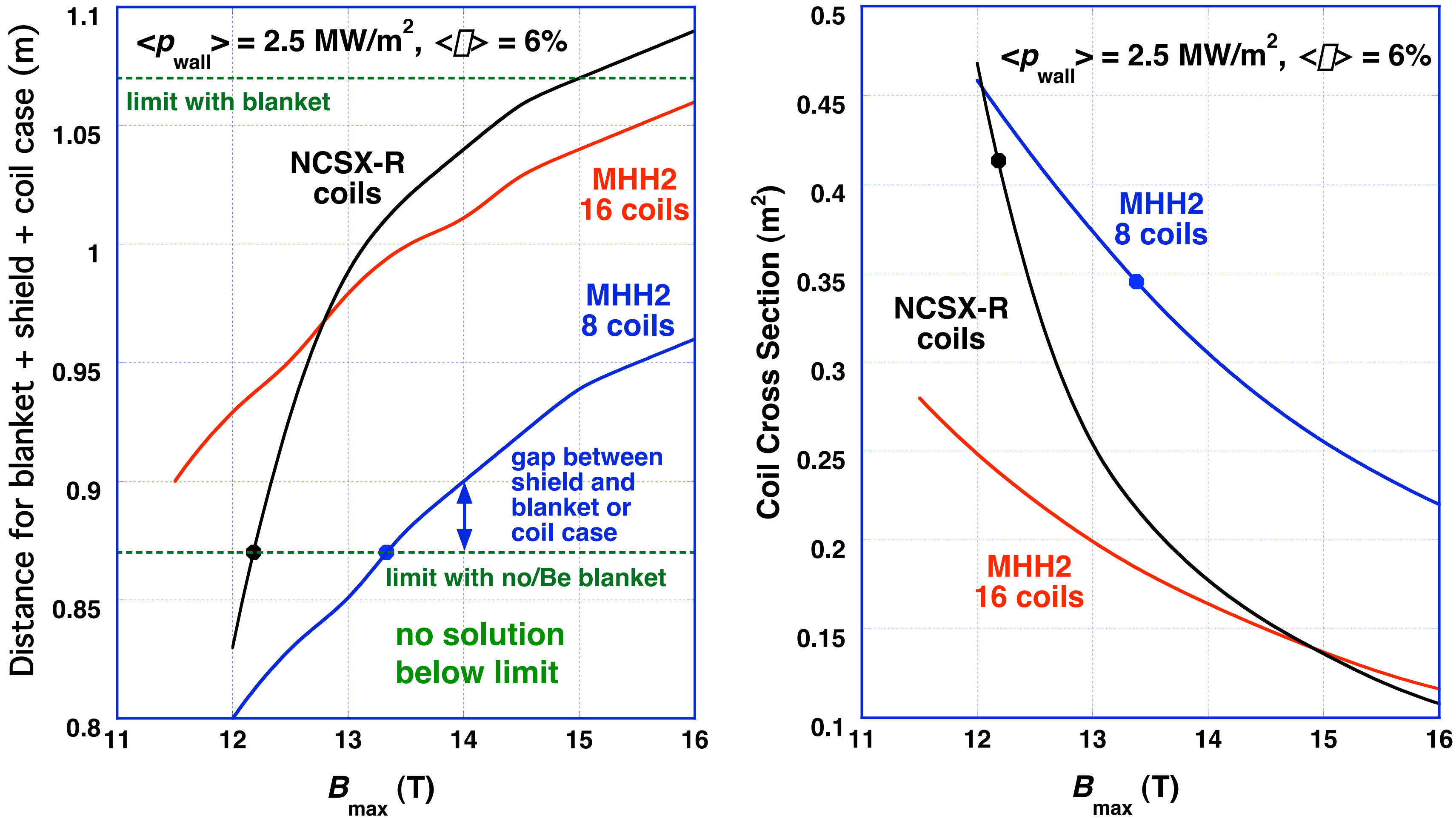
- Used Ku's B_{max}/B_0 values for square cross sections, *not* same shape as NCSX-R

- Used k dependence from 2/25/03 NCSX coil set; good approximation?

Radial Gap Issues

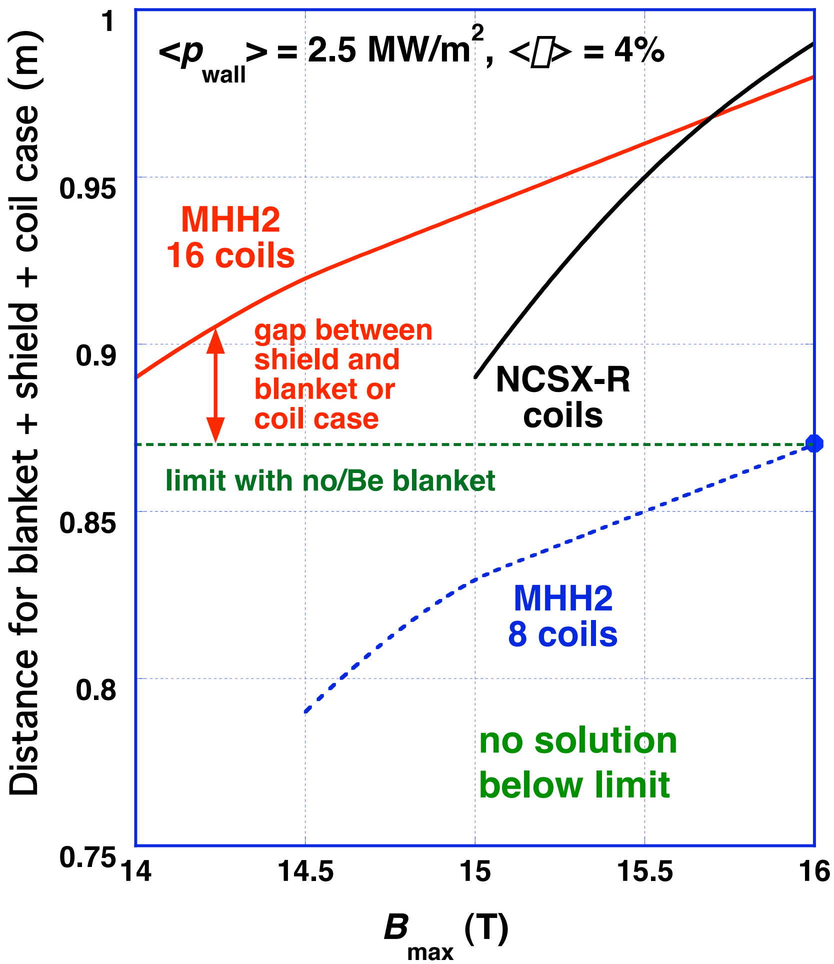
- **Choosing $\langle p_{wall} \rangle$ gives R_{wall}, $\langle R \rangle$, $R_{coil\text{-}center}$ and coil width for a given coil configuration (ratios of three *R*'s fixed)**
- **$R_{coil\text{-}center} - R_{wall}$ at $\square_{min}$ = space available for blanket (Be) + shield + coil case/structure + assembly gap + 1/2 coil depth *+ extra gap***
- **Extra gap = gap between outside of removable blanket and inside of components attached to modular coils**
  - **gap size depends on coil depth since thickness of blanket, shield and case/structure fixed**
- **Coil depth determines B_{max} (larger for smaller coil depth)**
- **Can we take advantage of extra gap for maintenance disassembly?**
- **Does extra gap present problem for support of removable blanket? Need to redo coil optimization?**

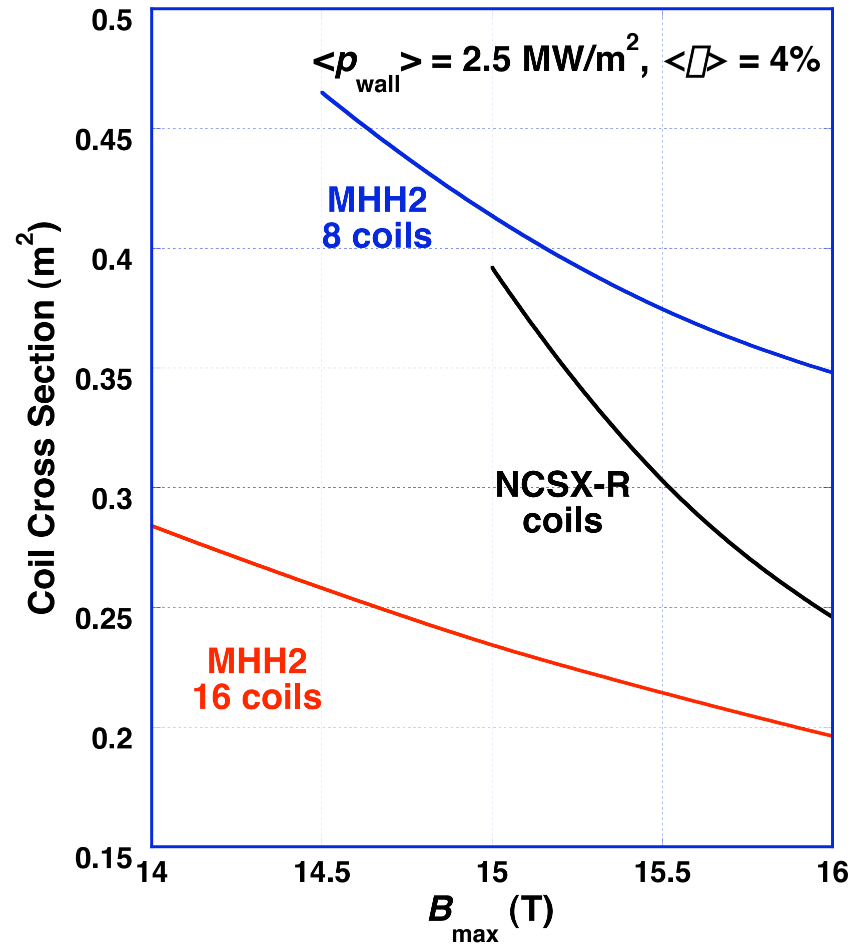
B_{max} Determination for <□> = 6%



- Tradeoff: lower B_{max} (lower forces) vs. smaller winding pack (lower cost)
- Larger gap between shield and blanket or coil case (higher B_{max}) reduces costs
- Use B_{max} for no gap or 16 T (lowest cost)? □$_{min}$ too large (A$_□$ too small)??
- These calculations do *not* affect POPCON calculations (relies on <*R*> , <B_{axis}>)

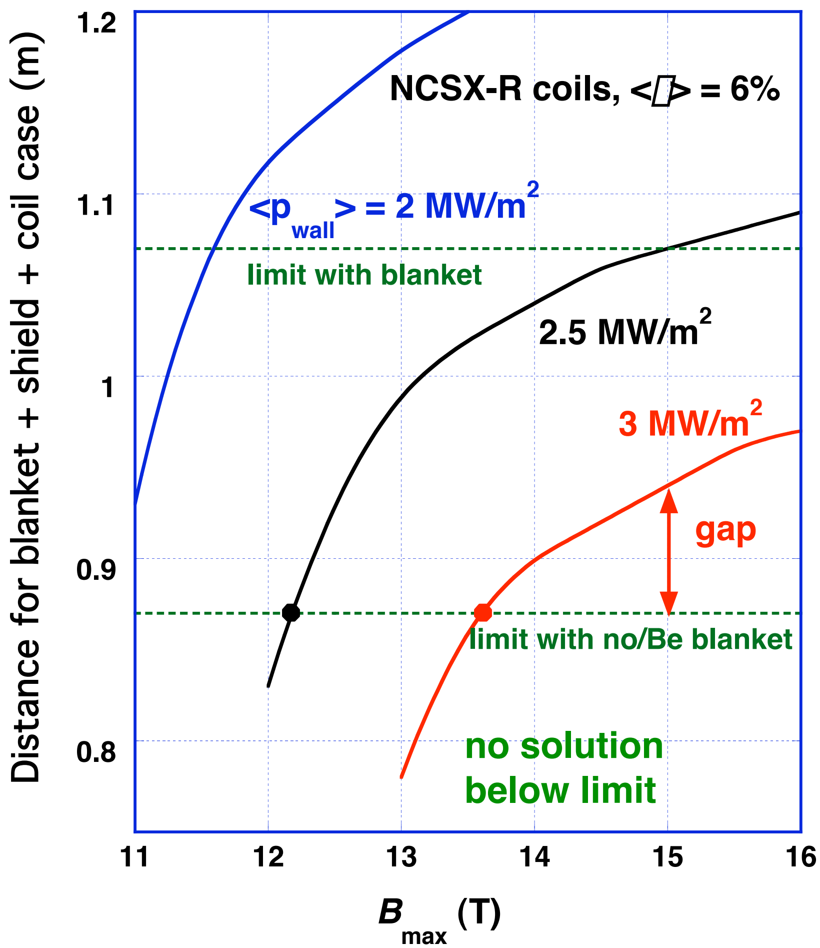
B_{max} Determination for $\langle\beta\rangle$ = 4%

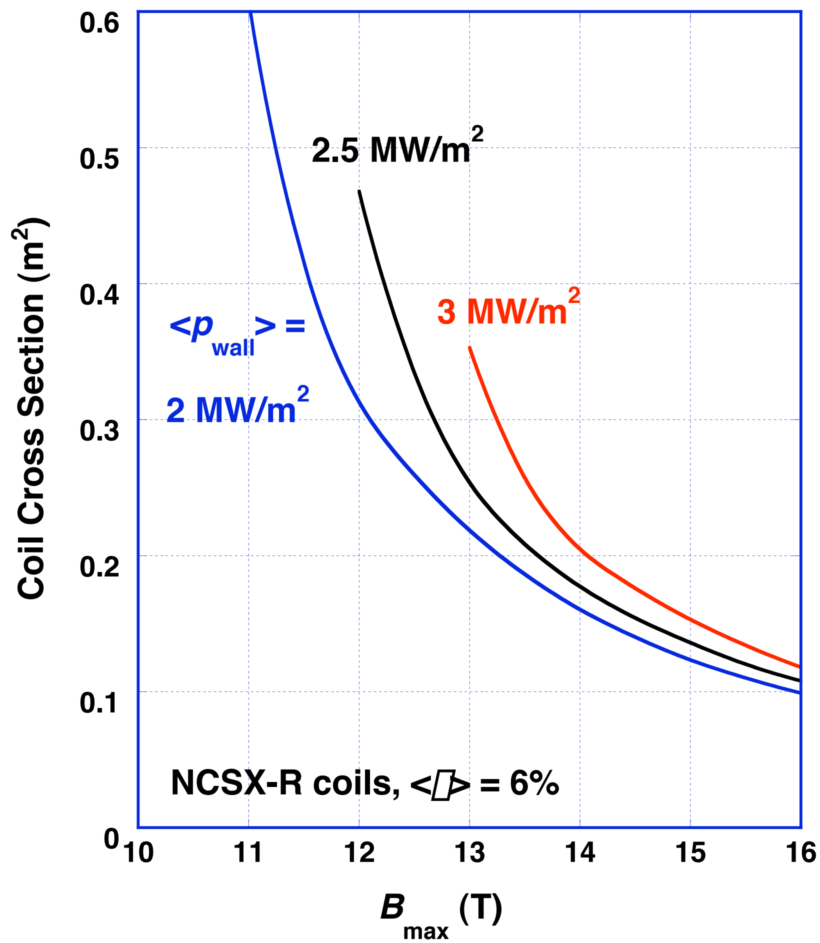




- No solution for 8-coil MHH2 for $\langle p_{wall}\rangle \geq 2.5$ MW/m^2

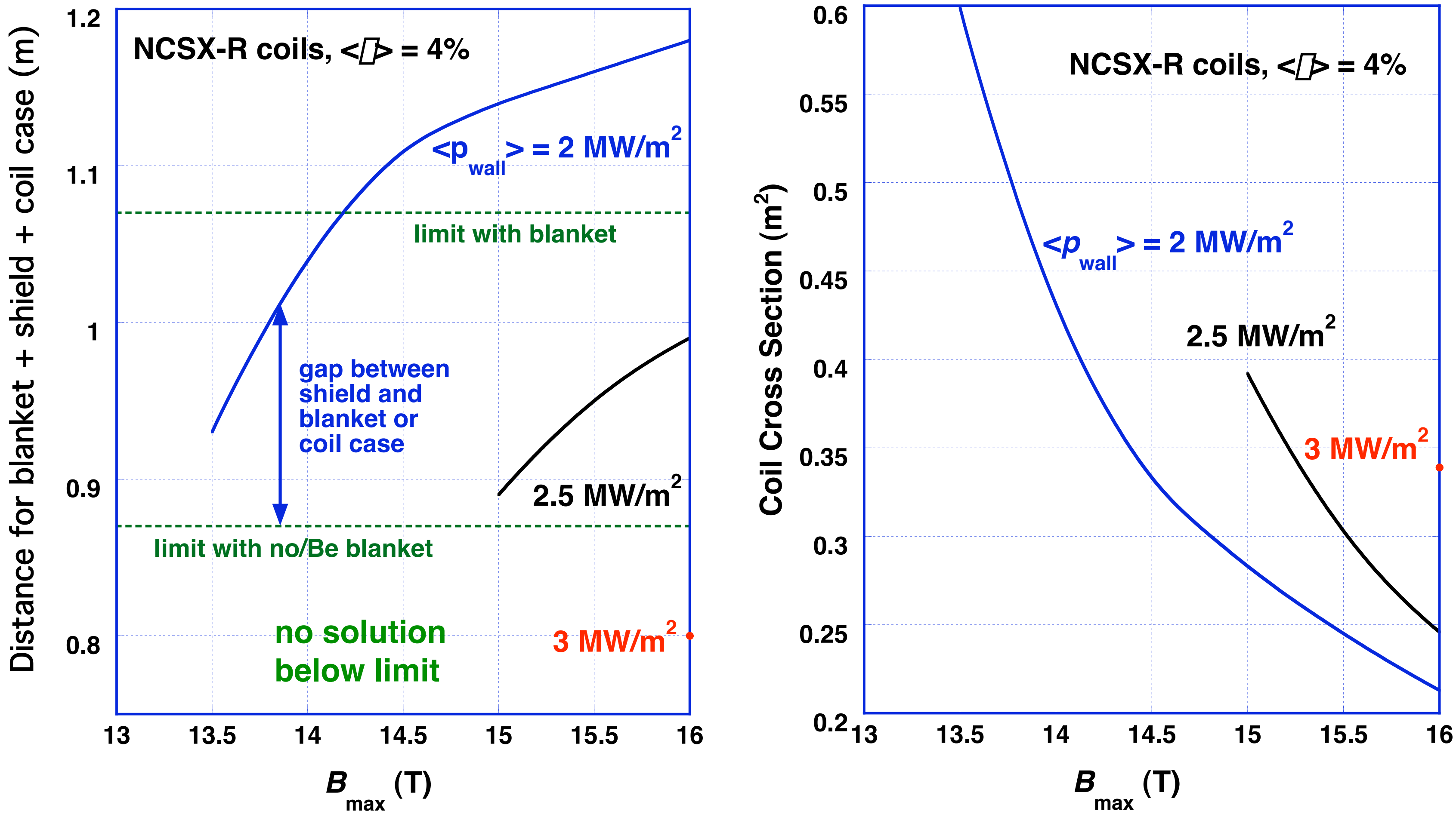
NCSX B_{max} for different p_{wall} for <β> = 6%





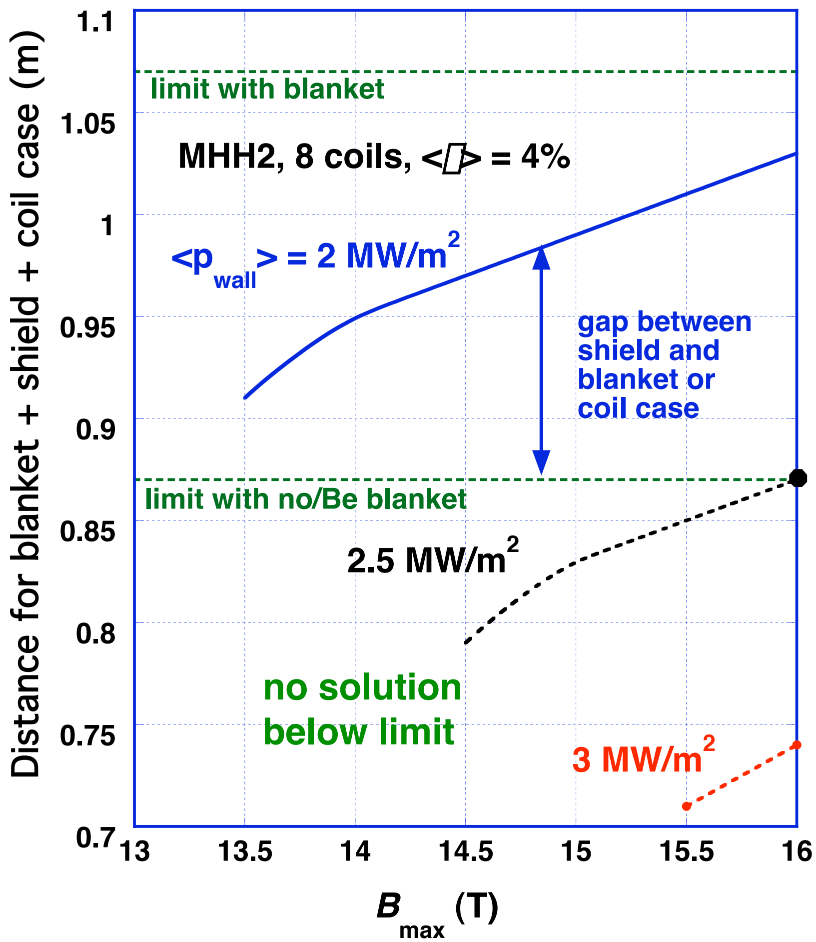
- B_{max} = 16 T for <p_{wall}> = 2 MW/m², but with gap between shield and blanket or coil case

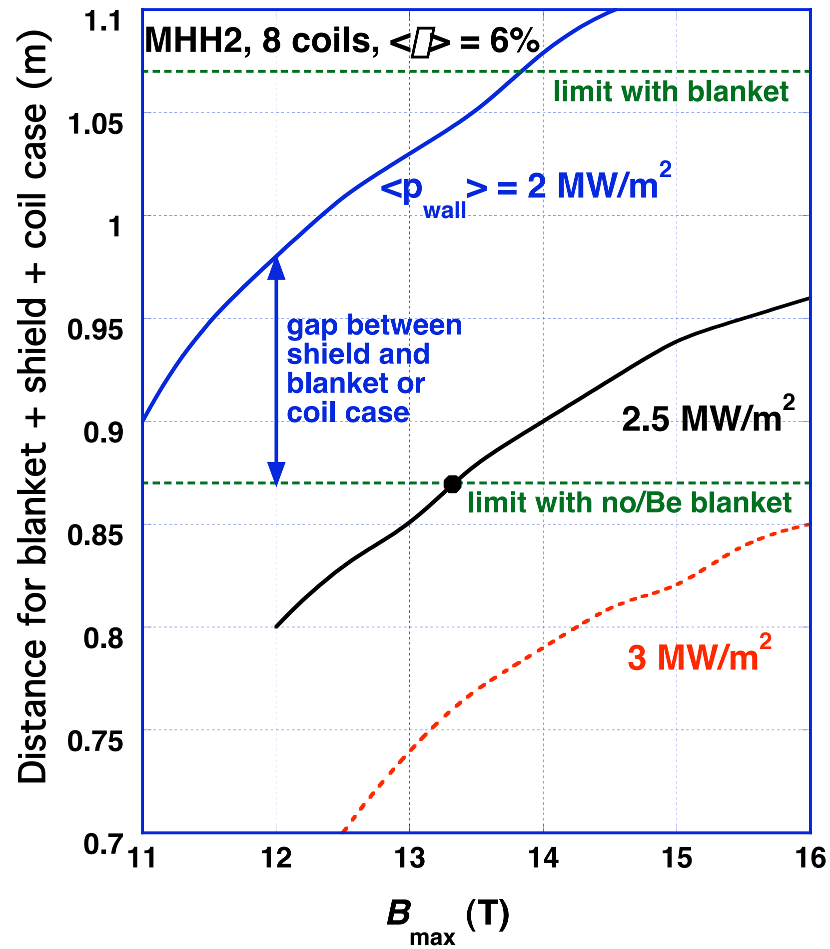
NCSX B_{max} for different p_{wall} for <□> = 4%



- No solution for $\langle p_{wall} \rangle$ = 3 MW/m^2 for calculated coil cross sections
- B_{max} = 16 T for 2.5 & 3 MW/m^2, but with gap between shield and blanket or coil case

MHH2 (8 coil) B_{max} vs p_{wall} for <β> = 4&6%





- No solution for $\langle p_{wall}\rangle$ = 3 MW/m^2 for calculated coil cross sections
- B_{max} = 16 T for 2.5 & 3 MW/m^2, but with gap between shield and blanket or coil case

Reactor Parameter Optimization

Coil Configuration	$\langle\beta\rangle$ %	$\langle R\rangle$ (m)	B_{axis} (T)	Coil width (m)	Coil depth (m)	Square coil (m)
NCSX-R		**7.20**	**5.80**	**0.70**	**0.16**	**0.33**
MHH2 (16)	**6**	**6.78**	**5.54**	**0.49**	**0.24**	**0.34**
MHH2 (8)		**5.70**	**5.36**	**0.73**	**0.30**	**0.47**
NCSX-R		7.20	7.11	0.70	0.35	0.50
MHH2 (16)	4	6.78	6.79	0.49	0.40	0.44
MHH2 (8)		5.70	6.56	0.73	0.48	-----

- $\langle p_{wall}\rangle = 2.5$ MW/m^2, set $B_{max} = 16$ T

$\langle R \rangle$ & $\langle B_{axis} \rangle$ Variation with $\langle p_{wall} \rangle$, β

Coil Configuration	$\langle p_{wall} \rangle$ (MW/m^2)	$\langle R \rangle$ (m)	B_{axis} (T), k for 4% β	B_{axis} (T), k for 6% β
NCSX-R	2	8.07	6.53 2.86	5.33 6.15
	2.5	7.20	7.11 1.97	5.80 4.49
	3	6.57	-----	6.22 3.40
MHH2 (8)	2	6.40	6.02 1.86	4.92 3.28
	2.5	5.70	6.56 1.52	5.36 2.41
	3	-----	-----	-----
MHH2 (16)	2	7.60	6.23 1.50	5.09 2.63
	2.5	6.78	6.79 1.23	5.54 2.07
	3	6.18	-----	5.94 1.71

- B_{max} and coil depth depend on coil cross section
- k = coil width / coil depth

Gap & Coil Depth Variation with $\langle p_{wall} \rangle$, ▯

Coil Configuration	$\langle p_{wall} \rangle$ (MW/m^2)	R gap (m) for 4% ▯	Coil depth, 4%	R gap for 6% ▯	Coil depth, 6%
	2	0.31	0.27	0.38	0.13
NCSX-R	2.5	0.12	0.35	0.22	0.16
	3	-----	-----	0.10	0.19
	2	0.16	0.44	0.26	0.25
MHH2 (8)	2.5	0	0.48	0.09	0.30
	3	-----	-----	-----	-----
	2	0.27	0.37	0.35	0.21
MHH2 (16)	2.5	0.11	0.40	0.19	0.24
	3	-----	-----	0.07	0.26

Coil Gaps Variation with $\langle p_{wall} \rangle$, ▯

Coil Configuration	$\langle p_{wall} \rangle$ (MW/m^2)	*R* gap (m) for 4% ▯	Coil-coil gap, 4%	*R* gap for 6% ▯	Coil-coil gap, 6%
	2	0.23	0.32	0.30	0.47
NCSX-R	2.5	0.05	0.20	0.14	0.37
	3	-----	-----	0.01	0.29
	2	0.09	0.22	0.17	0.37
MHH2 (8)	2.5	-----	-----	0.01	0.26
	3	-----	-----	-----	-----
	2	0.24	0.10	0.30	0.21
MHH2 (16)	2.5	0.09	0.05	0.14	0.15
	3	-----	-----	0.02	0.10

- Square coil cross section with B_{max} = 16 T

Comments on Extra Gap

- **Extra gap between removable blanket and components attached to modular coils exists for most coil cases**
  - **can increase $A_{□}$ (reduce $□_{min}$): bring coils closer to plasma edge, which also reduces B_{max}/B_{axis}**
  - **would require *redoing* coil optimization (unlike a tokamak)**
- **However, negative gap (no solution) exists for**
  - **MHH2 (8 coil) for $\langle p_{wall} \rangle \geq 2.5$ MW/m^2 at $\langle □ \rangle = 4\%$**
    $\langle p_{wall} \rangle = 3$ MW/m^2 at $\langle □ \rangle = 6\%$
  - **NCSX-R for $\langle p_{wall} \rangle = 2.5$ MW/m^2, $\langle □ \rangle = 4\%$**
- **How do we want to proceed?**

Issues for Further (Global) Work

- **Since reactor components (blanket, shield, structure) cost ~ $1/\langle p_{wall} \rangle$, can we allow p_{wall} locally > 5 MW/m^2?**
  - **omit or thin blanket where p_{wall} high and increase Be fraction in blanket elsewhere to compensate?**
  - □ **need to know where p_{wall} high (and area fraction), probably *not* near $\square_{min}$**
- **Is highest B_{max} the best tradeoff between B_{max} and coil cross section?**
- **Do we need to reoptimize $\square_{min}$ (new coils)?**

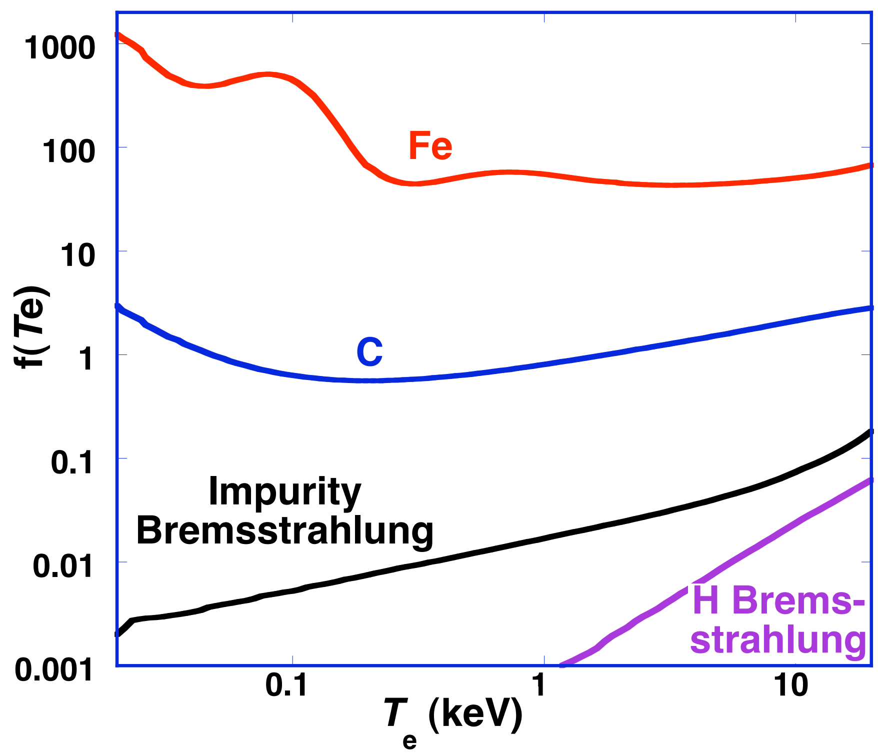
Impurity Radiation

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

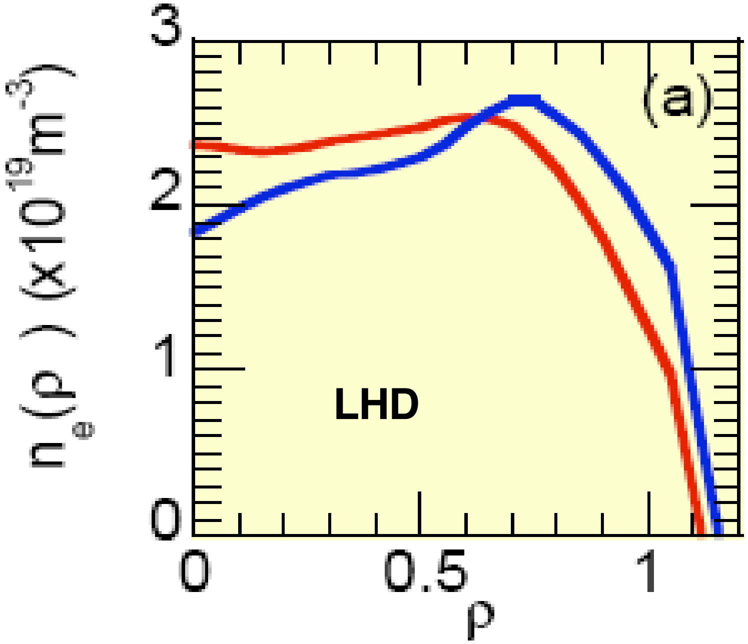
$p_{radiation} \sim n_e n_Z f(T_e)$

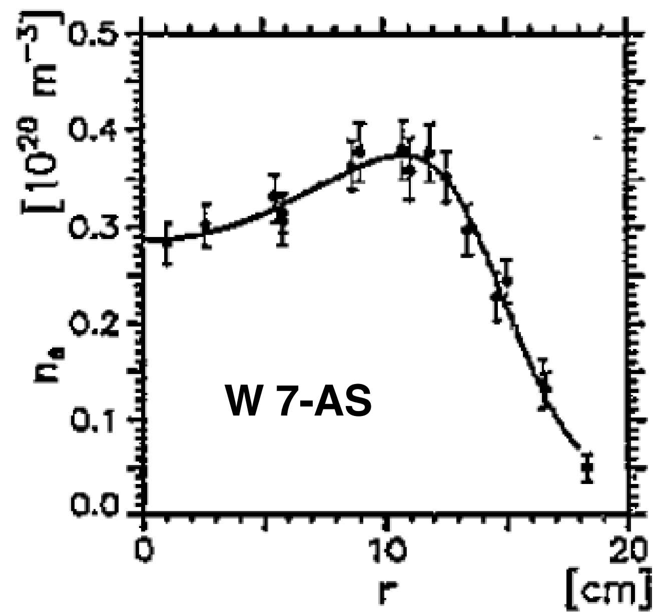


Impurity Radiation Model

- **No longer assume $n_Z(r)$ = constant x $n_e(r)$**
- **Use neoclassical impurity transport model**
  - **$n_Z(r) = n_e(r) \times \langle f_Z \rangle (n_e/n_{e0})^Z\ [T_e/T_{e0}]^{-Z/5}$**
  - **conservative approach: ignore $[T_e/T_{e0}]^{-Z/5}$ term because it probably is not applicable in stellarators**
  - □ **$n_Z(r)$ peaked near edge: $n_e(r)$ is hollow for regime of interest in stellarators**

n_e(r) Hollow in Stellarators at Low □*





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

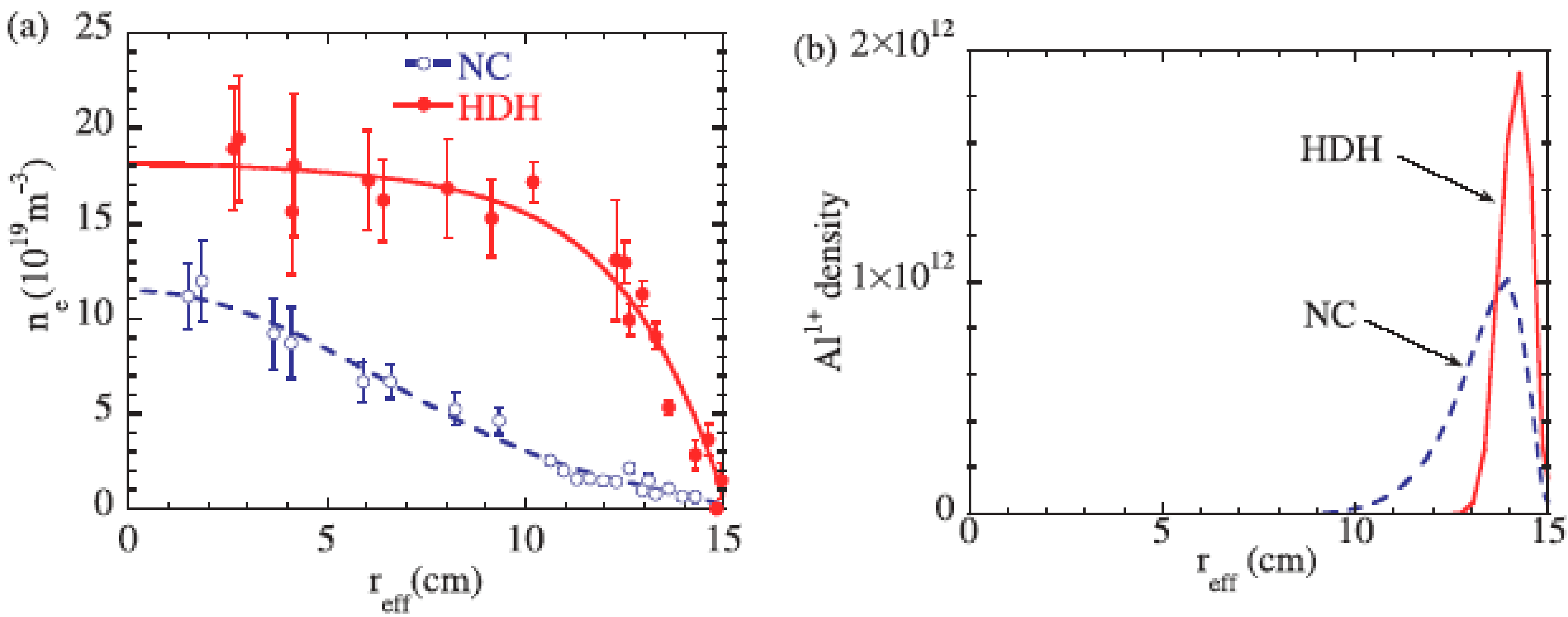
ECH, $T_e(0)$ = 1.5 keV

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

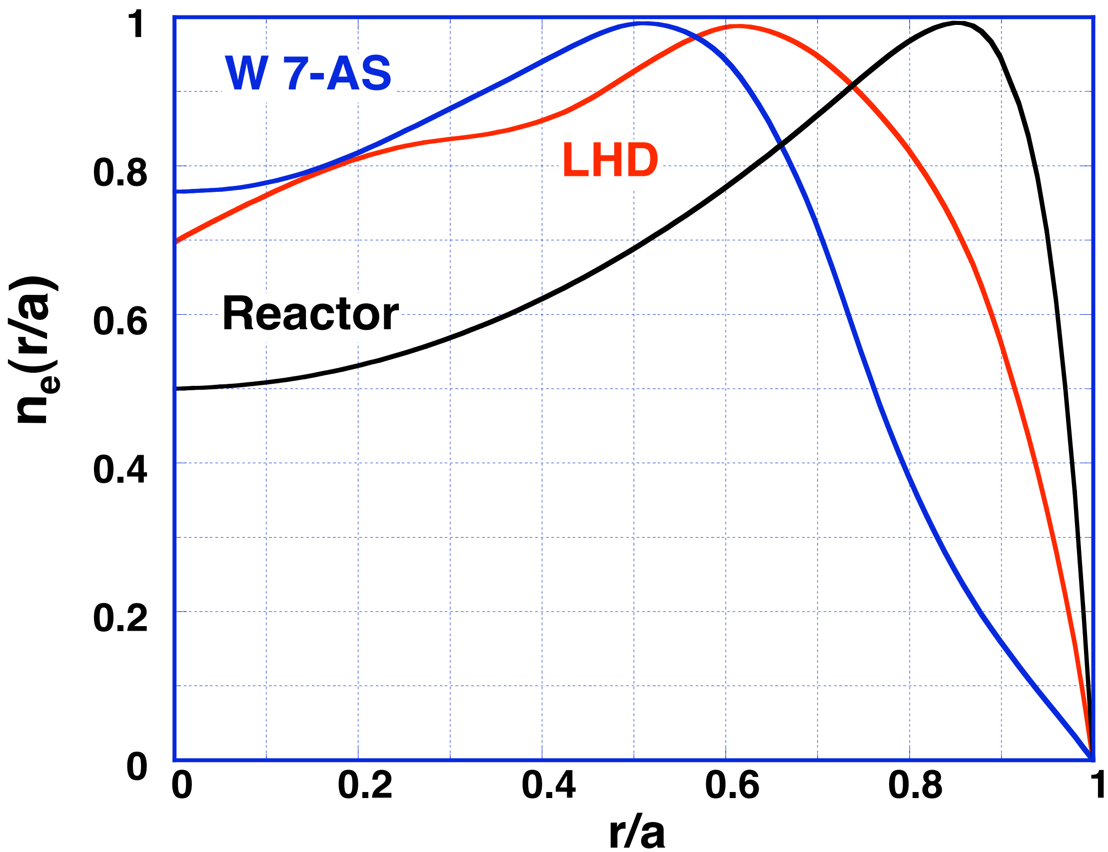
- $n_e = n_{e0}[(1 - (r/a)^{xn})(f_0 + (1 - f_0)(r/a)^2) + n_{edge}/n_{e0}]$, xn ~ 12
- Temperature profiles peaked on axis
  - $T_e = T_{e0}[(1 - (r/a)^2)^{xT} + T_{edge}/T_{e0}]$, xT ~ 1.5

Even Flat n_e(r) Produces Hollow Impurity Profiles

- **W 7-AS results at high collisionality**
  - **Calculations show more extreme impurity edge peaking at lower collisionality**

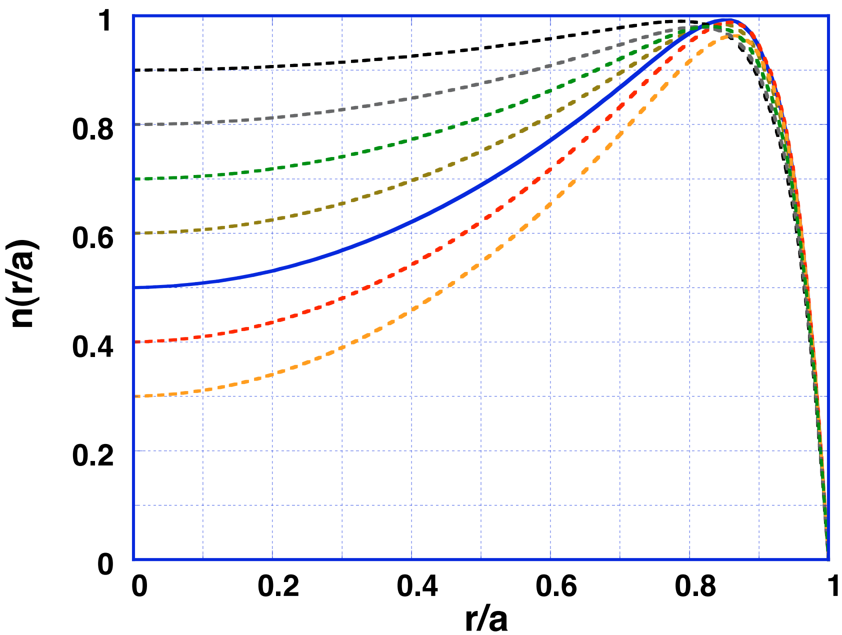


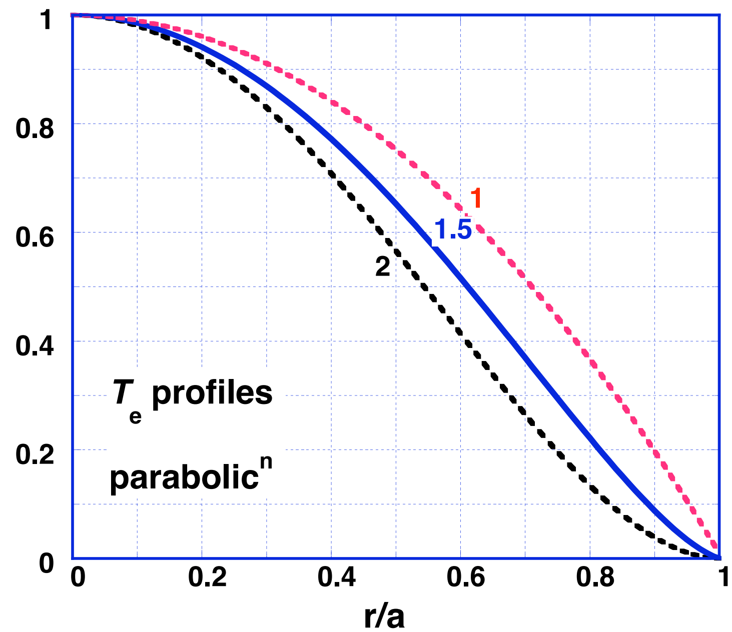
Choose Hollow n_e(r) for ARIES Calculations



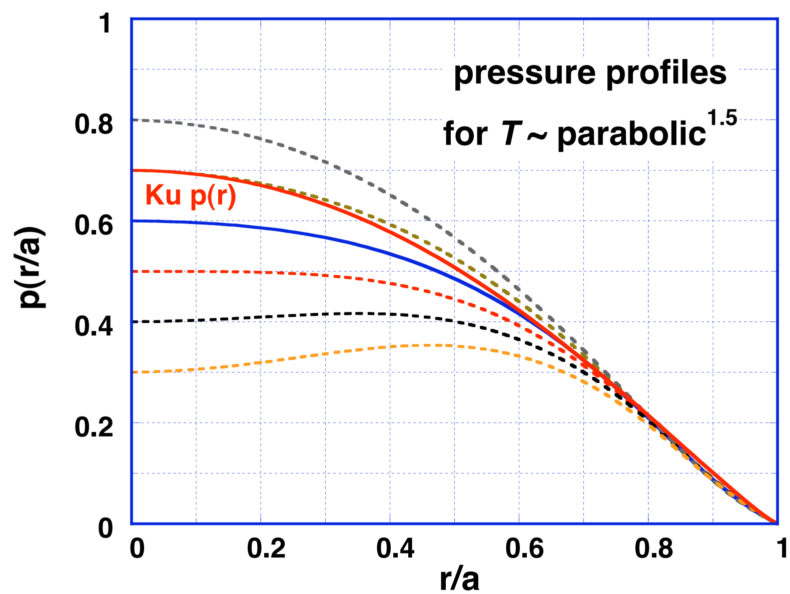
- No credible model exists to calculate n(r/a); must assume shape
- Density peak should shift out in radius and hollowness increase in a reactor
- Will test sensitivity to *n*(r/a) and peak/central ratio

Density, Temperature & Pressure Profiles

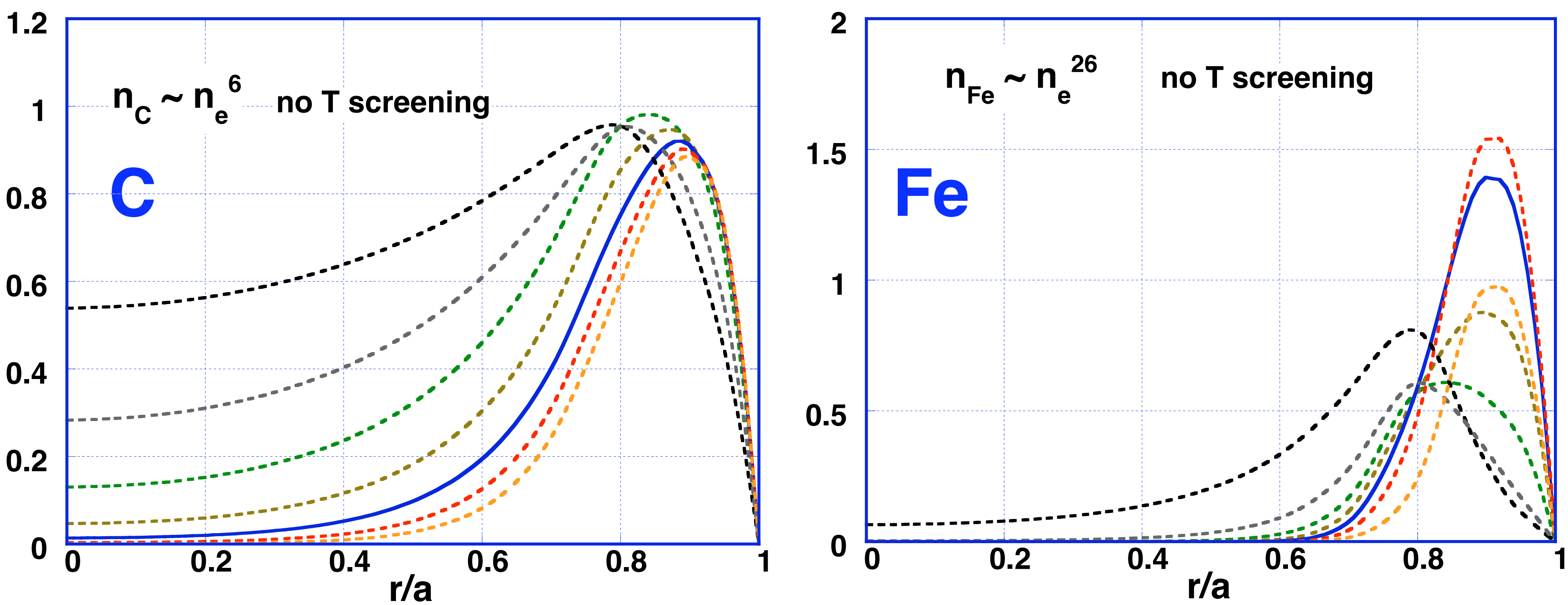




- Initially assume blue profile shapes
- Test sensitivity to profile shapes



Impurity Density Profiles



1-D Determination of Plasma Parameters: $\langle T \rangle$, $\langle n \rangle$, $\langle \square \rangle$, P_{rad}, etc. for operating point

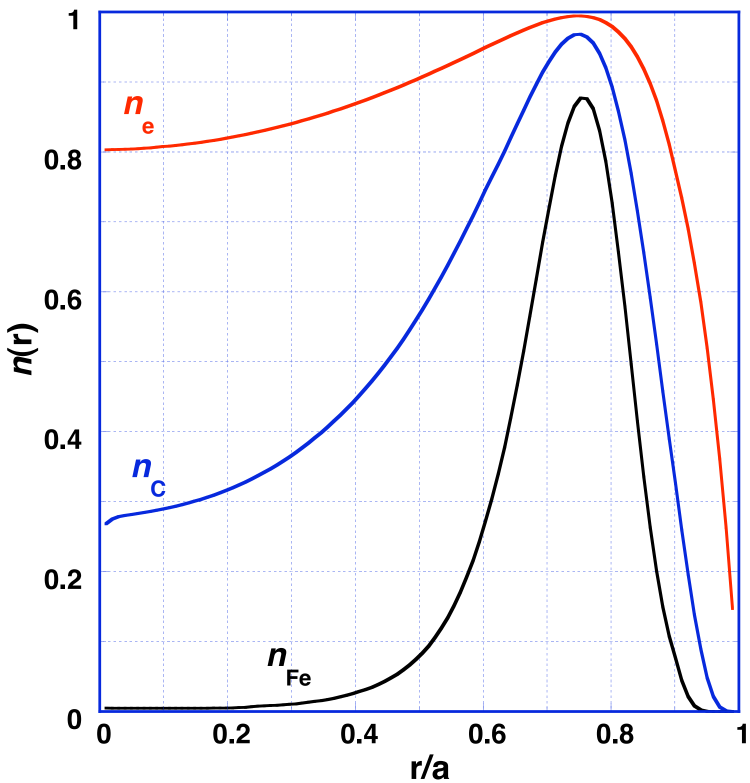
1-D Determination of Plasma Parameters

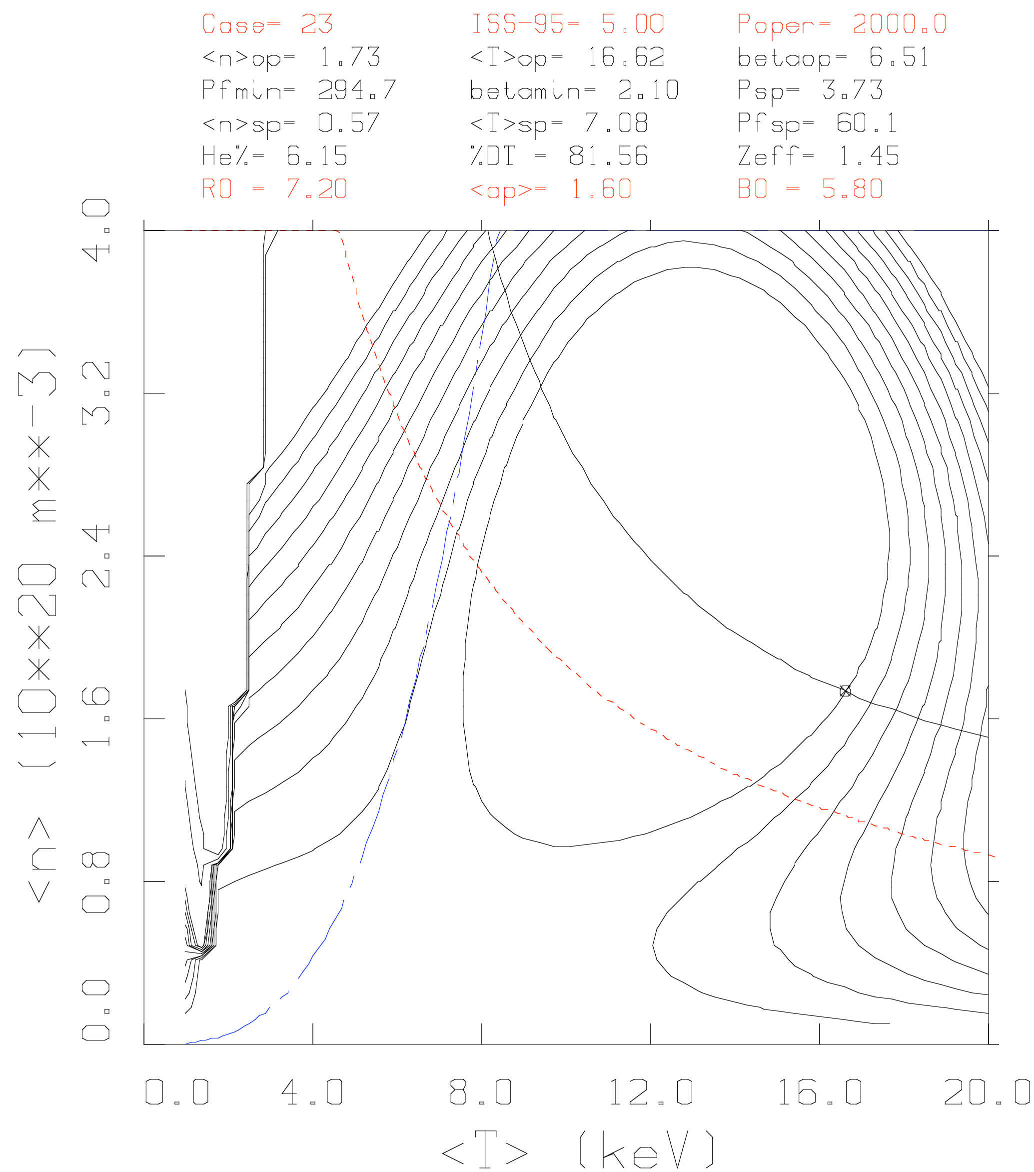
- **Global reactor parameter determination only involved $<R>$, $<a>$, $<B_{axis}>$, $<p_{wall}>$, $<\beta>$ and coil cross section; some cases may not be allowable for power balance reasons**
- **Further step, 1-D power balance (POPCON), involves**
  - **fixed density and temperature radial profile shapes**
    - **peaked or hollow; how hollow; does it matter?**
  - **impurity levels and profiles**
    - **peaked or hollow -- does it matter?**
    - **effect on radiation losses and β**
  - **alpha-particle losses, confinement model (H-ISS95)**
  - **ignition contours and startup paths**

Determination of Plasma Parameters

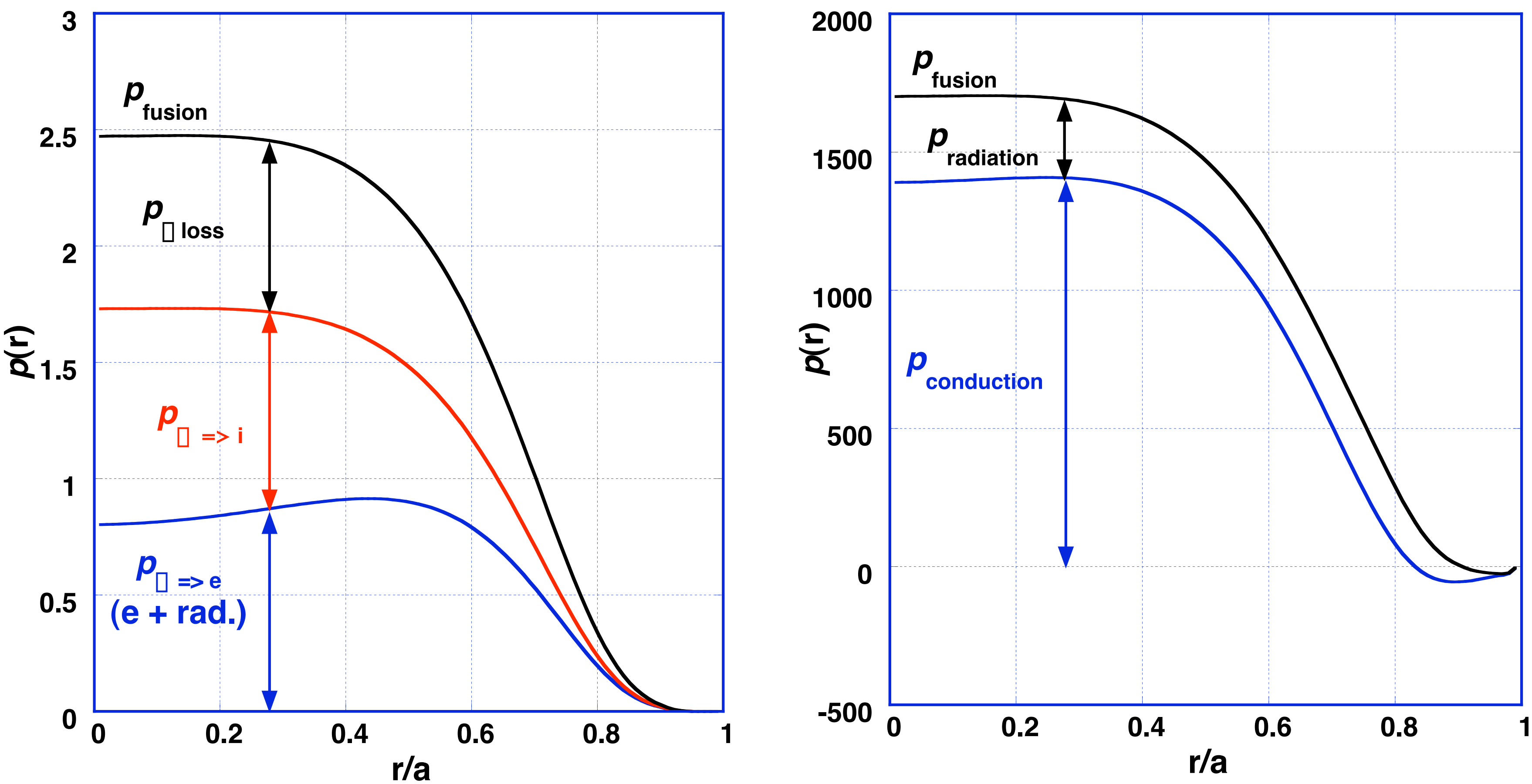
- Too many variables, need to make some parameter assumptions
  - choose H-ISS95 = 5 (twice present maximum experimental value)
    - assuming improvements due to quasi-symmetry and experience
  - choose impurity levels: 1% C and 0.01% Fe (OK?)
  - 30% alpha-particle losses (no other case yet, can do better?)
  - choose τ_{He}/τ_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 (χ, 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

Initial NCSX-R Reference Case



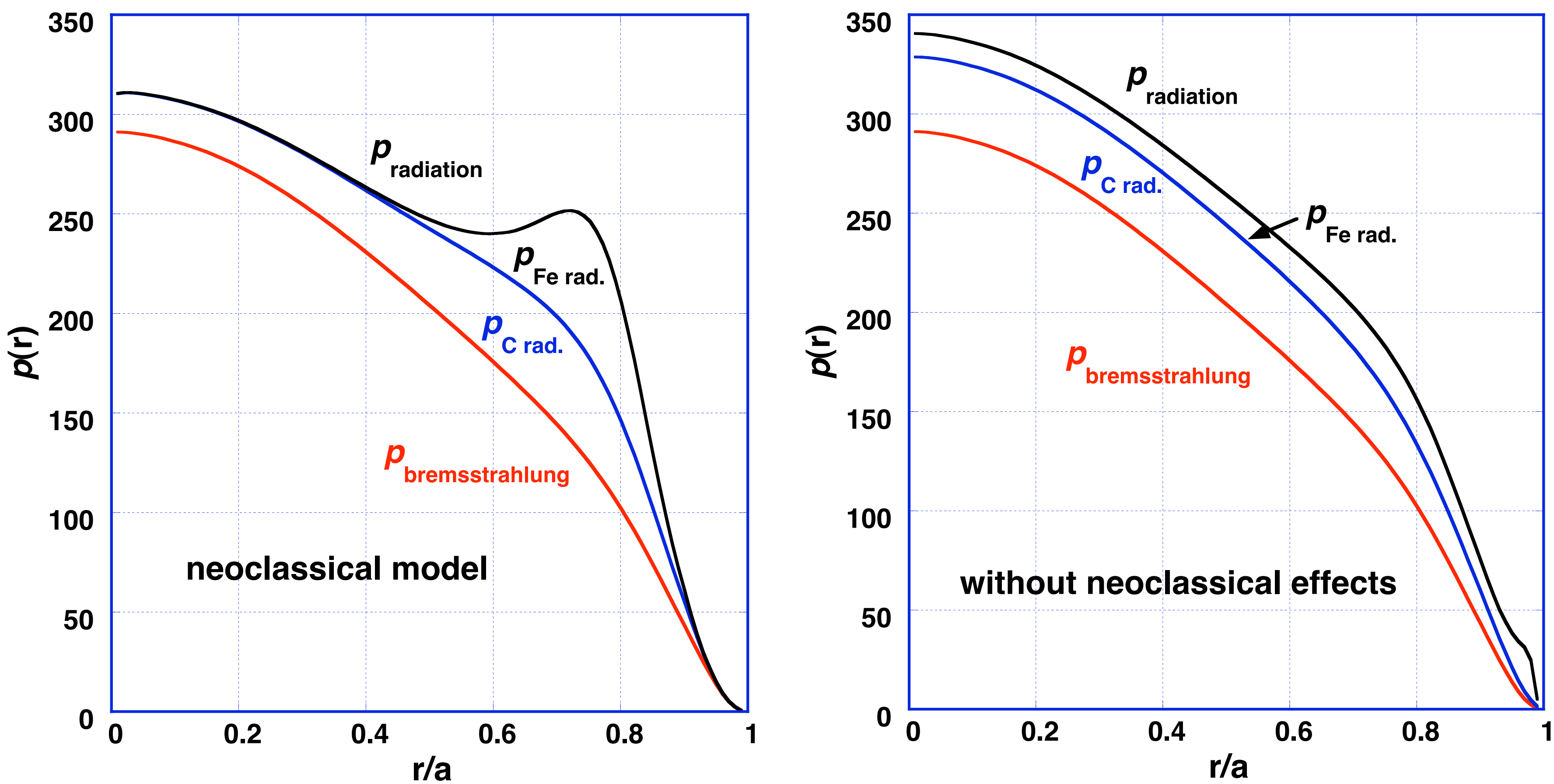


Reference Case Profiles



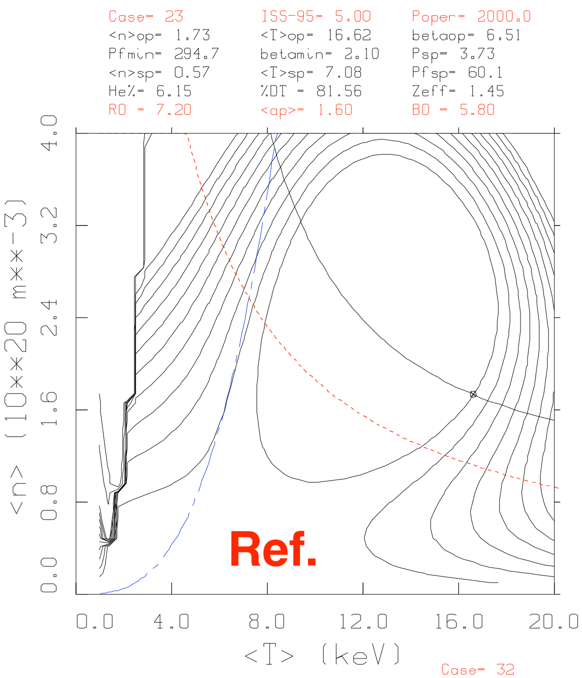
- P_{fusion} = 400 MW; $P_{\square \Rightarrow e}$ = 171 MW; P_{rad} = 69 MW
- $P_{rad,H}$ = 50 MW; $P_{rad,C}$ = 11.6 MW; $P_{rad,Fe}$ = 7.5 MW

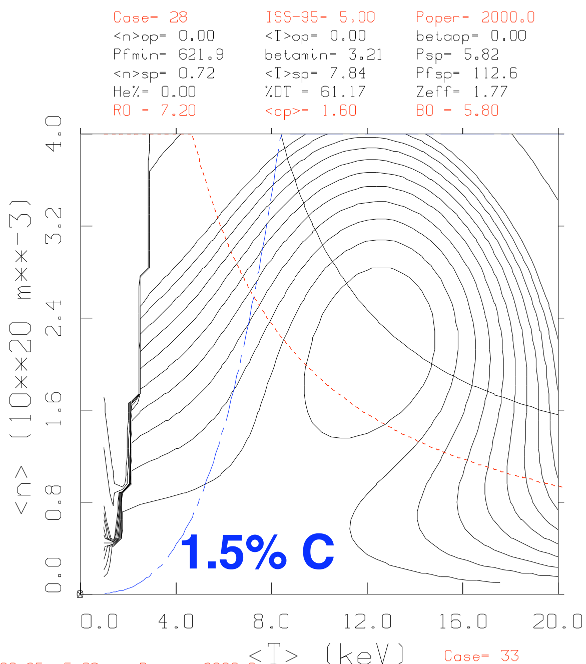
Reference Case Profiles

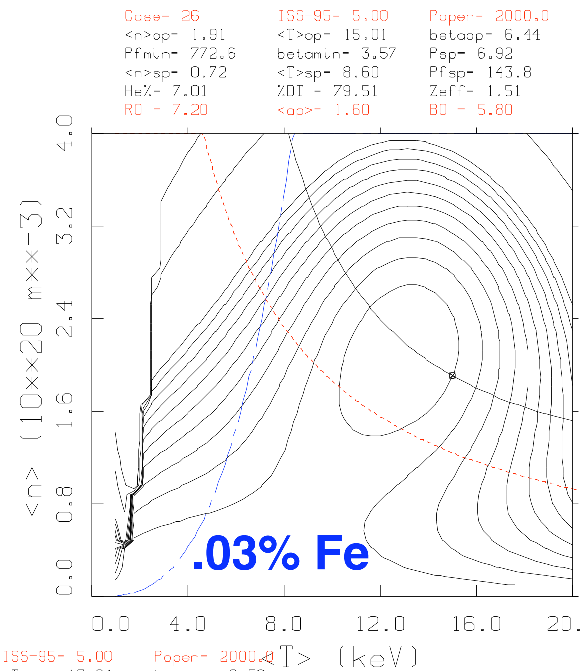


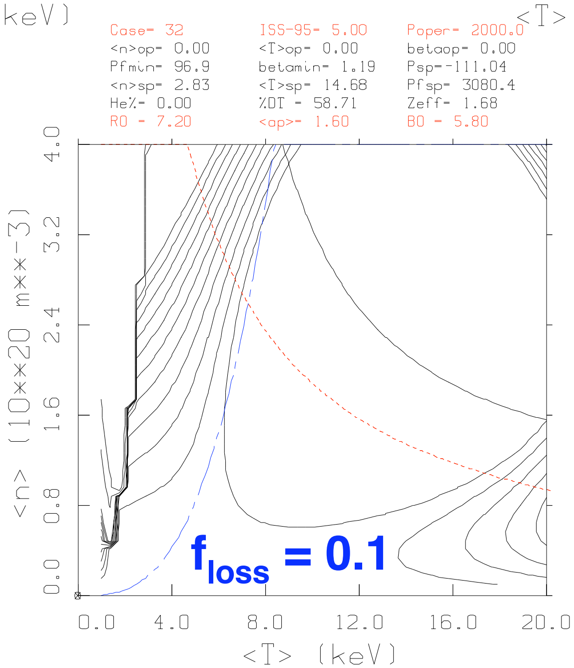
- **Incorporated impurity radiation profile in 1-D Power Balance code**
  - **volume-average impurity (C and Fe) densities kept the same**
- **Have not been able to signicantly reduce power flow to divertor by increasing power radiated to the wall (so far)**

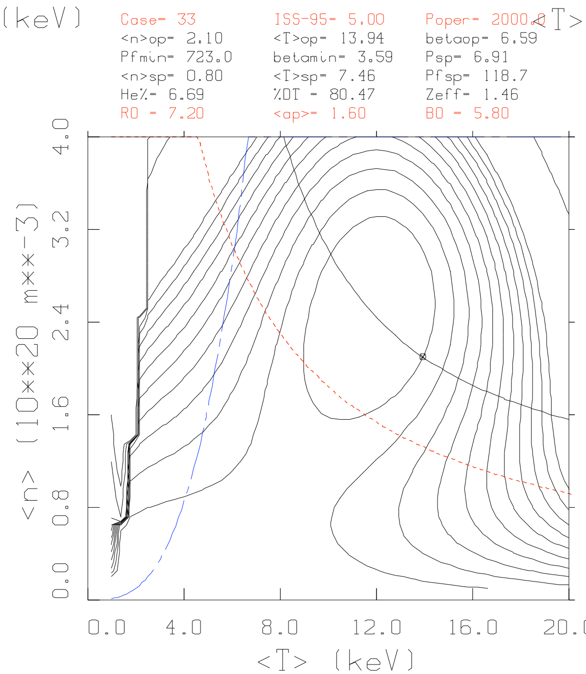
Variations from Reference Case





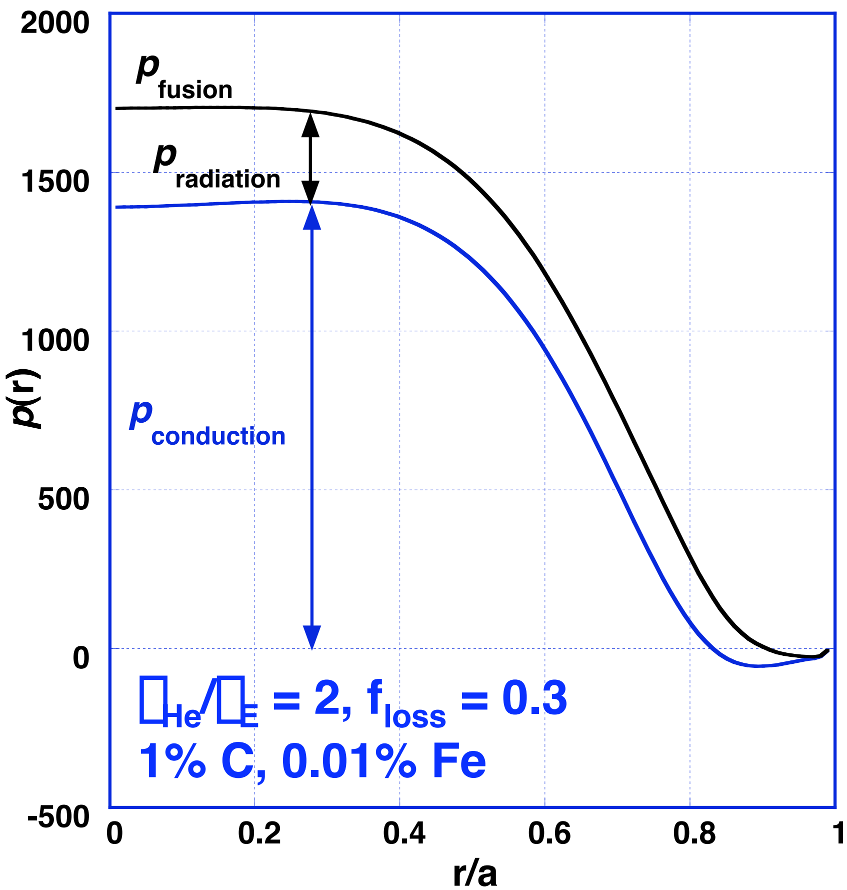


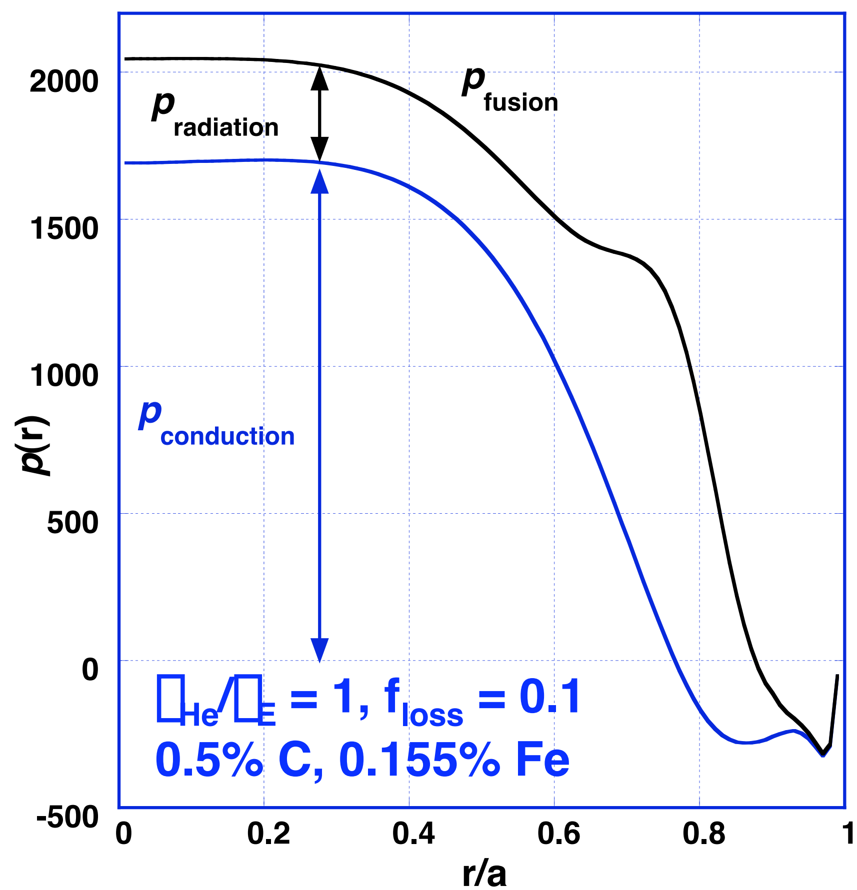




center/ peak = 0.5 instead of 0.8

Higher Fe Allows Increased Radiation

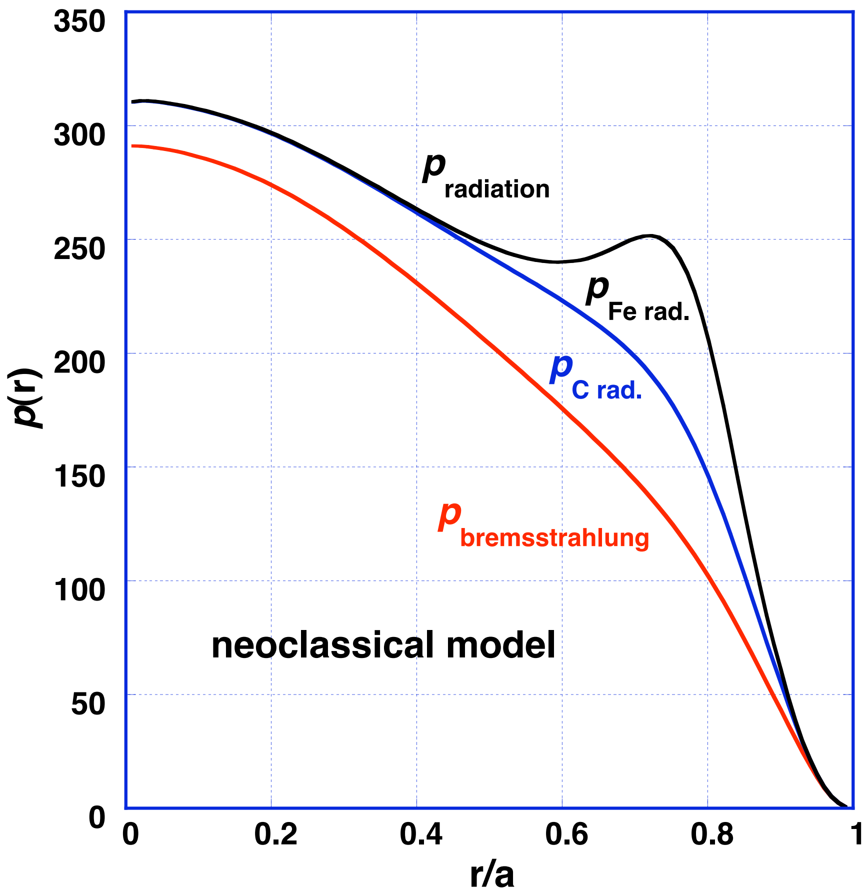


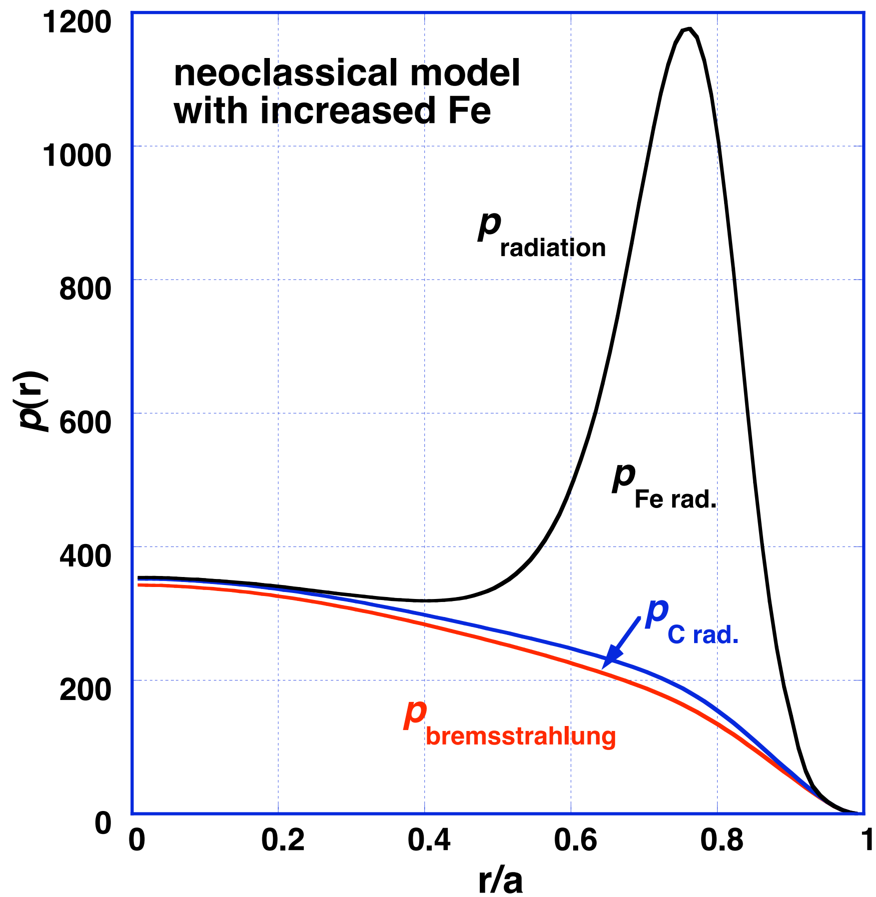


- $P_{□ => e}$ = 171 MW
- P_{loss} = 120 MW, P_{rad} = 69 MW
  17% of $P_{□}$, 40% of P_e

- $P_{□ => e}$ = 220 MW
- P_{loss} = 40 MW, P_{rad} = 175 MW
  44% of $P_{□}$, 80% of P_e

Reference Case Profiles





- $P_{rad,H}$ = 50 MW
  $P_{rad,C}$ = 11.6 MW
  $P_{rad,Fe}$ = 7.5 MW

- $P_{rad,H}$ = 63 MW
  $P_{rad,C}$ = 5.3 MW
  $P_{rad,Fe}$ = 107 MW

Next Step for 1-D Calculations

- **Choose reference cases, redo sensitivities/tradeoffs**
  - **choose reference parameters (other ARIES studies as a guide?)**
  - **repeat for other configurations**
- **Document static startup path through Cordey pass**
  - **refine saddle point calculation and ignition contour**
- **Time-dependent startup path**
  - **optimize $\langle n \rangle$ and impurity levels for reduced fusion power (commissioning) cases**
- **Extract 1-D transport code module from systems code, update and recommission**

Obtaining Information Needed for Systems Code

- Will improve rough values for blanket/shield costing as available
- Rough cost values for coil costing from Leslie
- Analytic expression for $B_{max}(d,k)/B_0$
  - need to find good fit to Ku's numbers (B^4 sensitivity)
- Testing models and assumptions with other codes before submerging in systems code
  - profile assumptions and treatment of impurities
  - $T_e(r)$ consistency with radiation profiles

Summary

- **Used more accurate treatment of 16-coil MHH2 configuration; added 8-coil configuration**
- **Recalculated reactor parameters based on more realistic wall loading and constant ▯ for lower B_{max}**
- **Studied optimization of impurity radiation**
- **Continued to test models and assumptions for inclusion in the integrated systems code**
- **Need to adopt reference assumptions and decide if we need to change coil configurations**