NCSX, MHH2, and HSR Reactor Assessment Results

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What's New Since Dec. Meeting

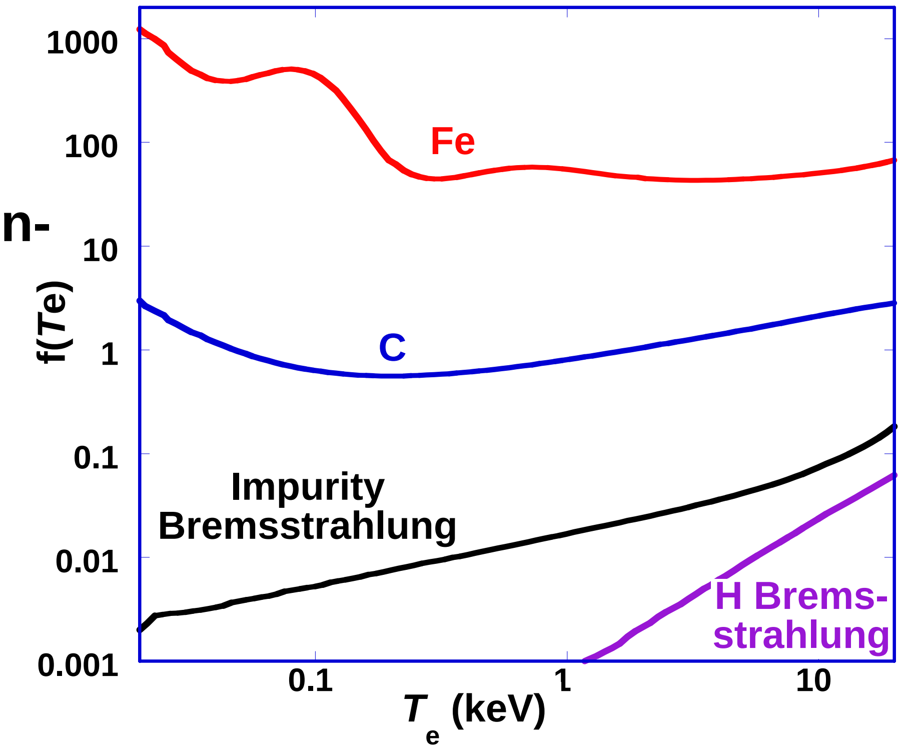
- Focused on highest-leverage areas
  - improved treatment of density & impurity profiles
  - reassessed NCSX-R and MHH2-R with high-T_c, MgB_2 (Nb_3Sn) and NbTi superconducting coils
  - reoptimized HSR according to our rules
  - testing models and assumptions for inclusion in the integrated systems code

Treatment of Impurities

- **Important to treat impurities properly**
  - **$n_e = n_{DT} + \sum Z n_Z$, 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

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



Modeling of Impurities Improved

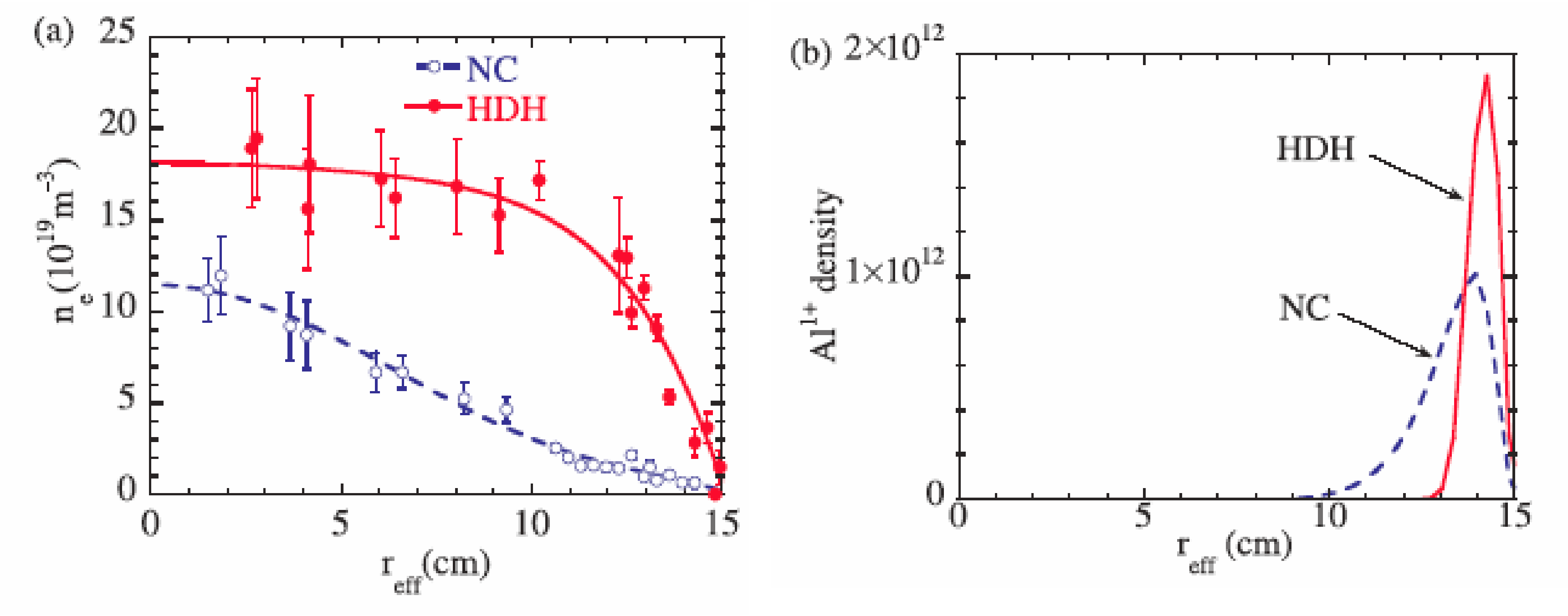
- **Earlier approach**
  - **assumed $n_C = f_C n_e$ & $n_{Fe} = f_{Fe} n_e$; f_Z = constant thruout plasma, so $n_Z(r)$ had same profile as $n_e(r)$**
- **Improved approach uses neoclassical model for impurity density profiles**
  - **$f_Z(r) \sim \langle f_Z \rangle \, (n_e/n_{e0})^Z \, [T_e/T_{e0}]^{-Z/5}$**
  - **$[T_e/T_{e0}]^{-Z/5}$ term peaks $n_Z(r)$ near the edge, but it may not be applicable in stellarators**

⇒ $n_Z(r)$ peaked at center if $n_e(r)$ peaked ignoring $[T_e/T_{e0}]^{-Z/5}$ term

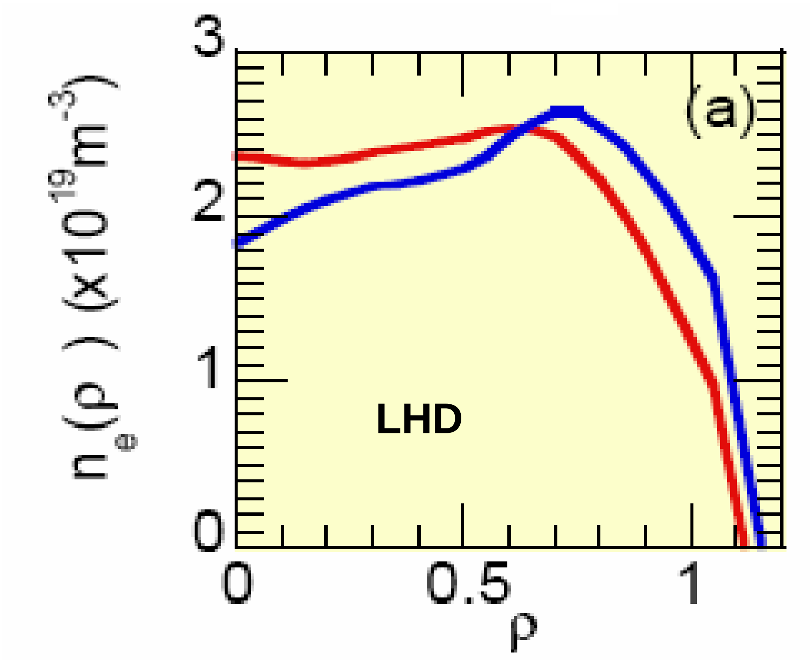
⇒ $n_Z(r)$ peaked near edge if $n_e(r)$ even slightly hollow

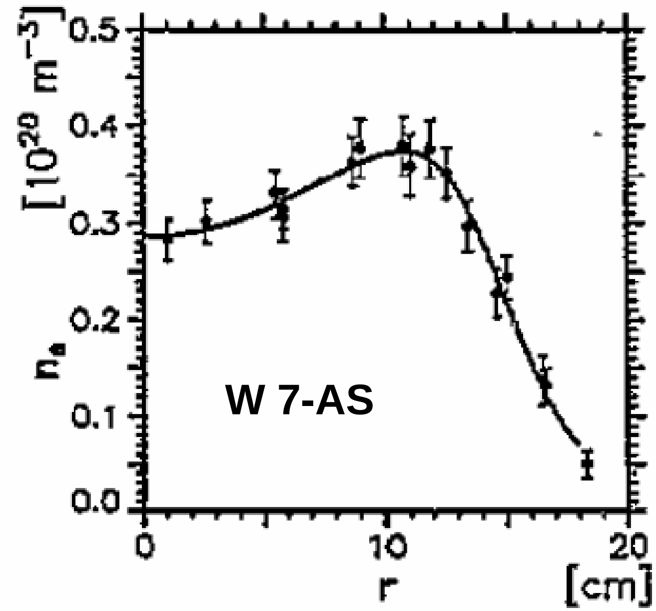
Even Flat $n_e(r)$ Produces Hollow Impurity Profiles

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



n_e(r) Hollow in Stellarators at Low ν^*





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

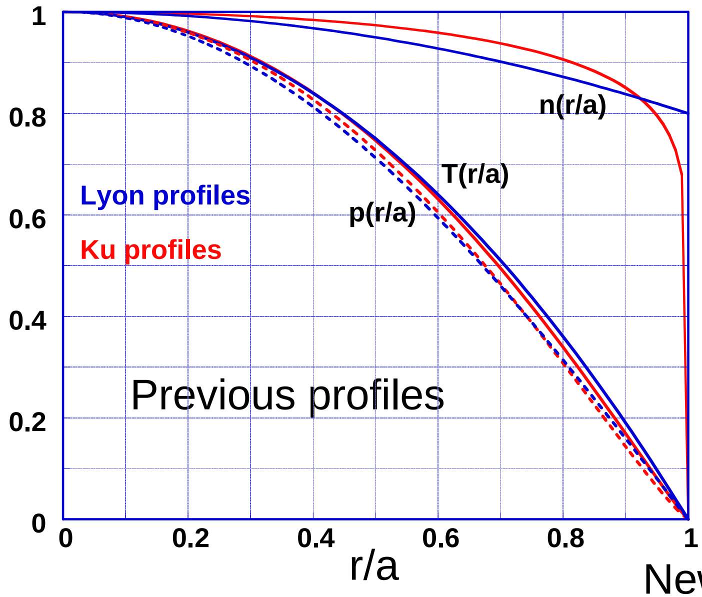
P_{NBI} = 6.5 MW, $T_i(0)$ = 1.9 keV

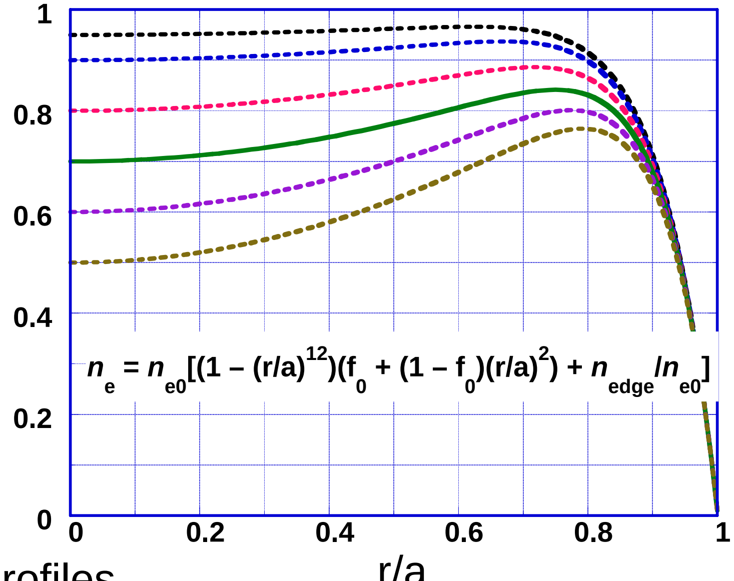
ECH, $T_e(0)$ = 1.5 keV

- **Previously used nearly flat n_e(r), T_e(r) peaked on axis**
  - $n_e = n_{e0}[\,(1 - n_{edge}/n_{e0})(1 - (r/a)^2) + n_{edge}/n_{e0}]$, $T_e = T_{e0}(1 - (r/a)^2)^{xT}$
- **Now $n_e = n_{e0}[(1 - (r/a)^{xn})(f_0 + (1 - f_0)(r/a)^2) + n_{edge}/n_{e0}]$, xn ~ 12**

  $T_e = T_{e0}[(1 - (r/a)^2)^{xT} + T_{edge}/T_{e0}]$

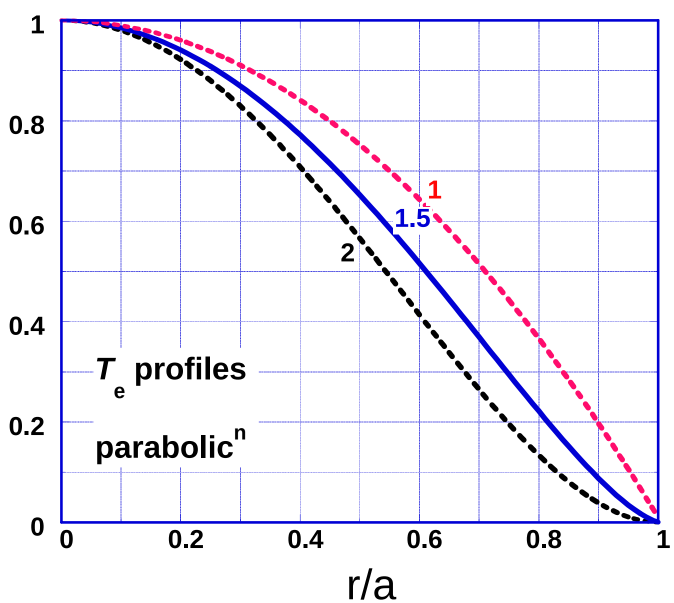
Density, Temperature & Pressure Profiles

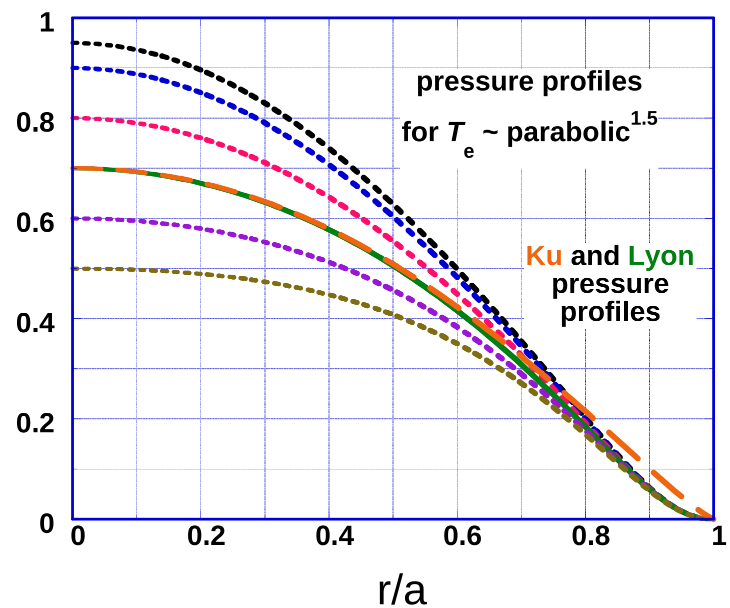




central dip
1.7%
3.9%
9.7%
17%
25%
35%

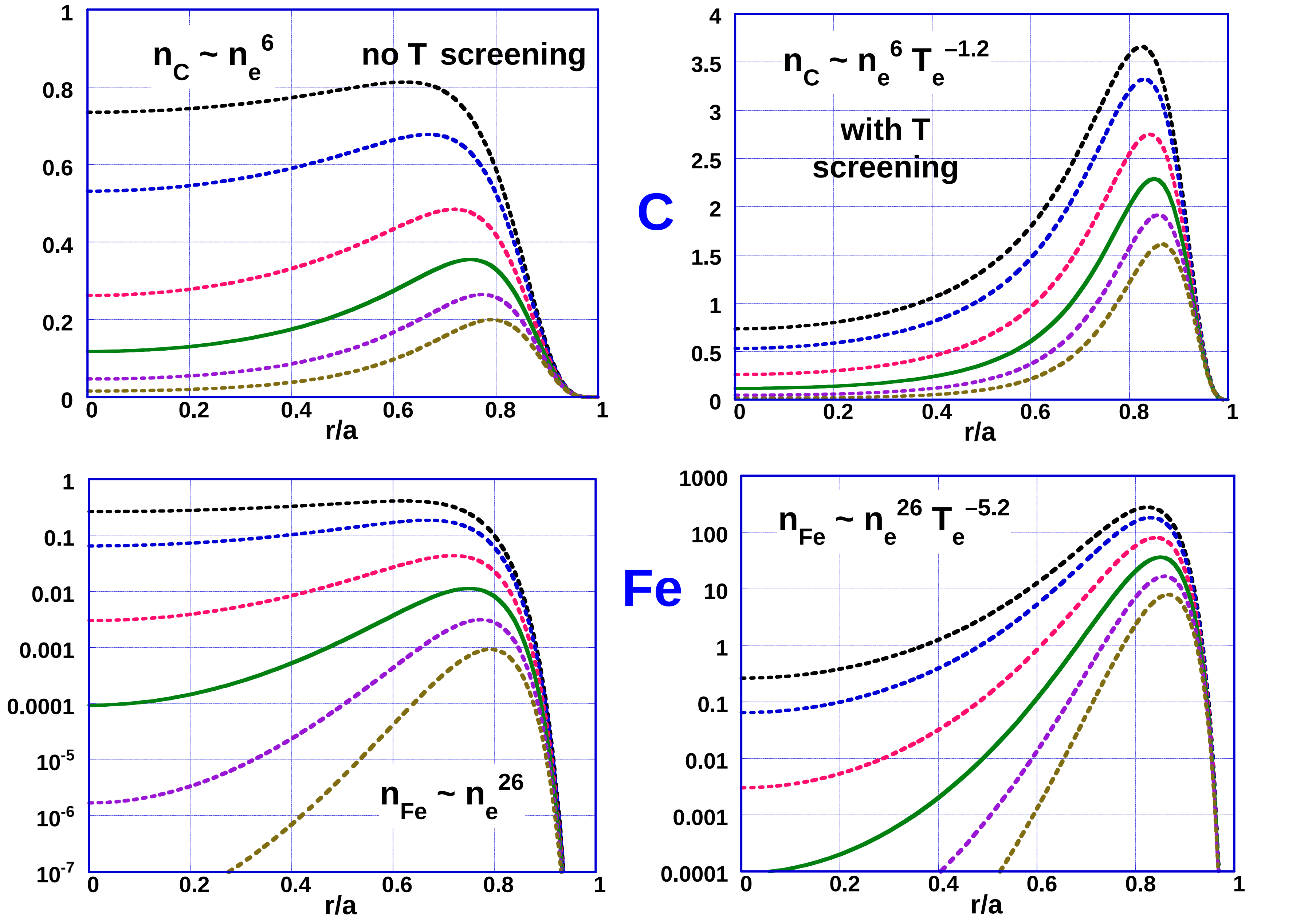
New profiles





exper.
10%
to
30%

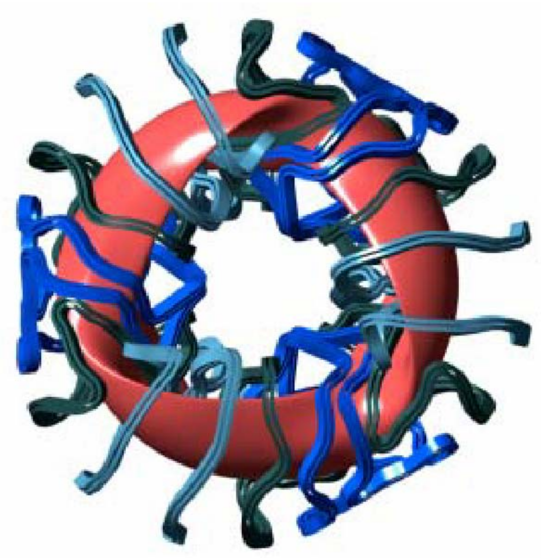
Impurity Density Profiles

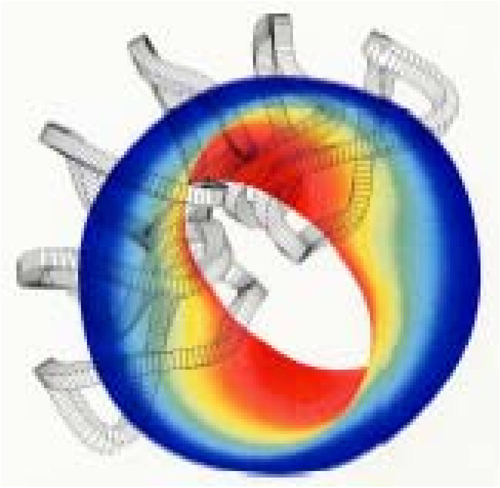


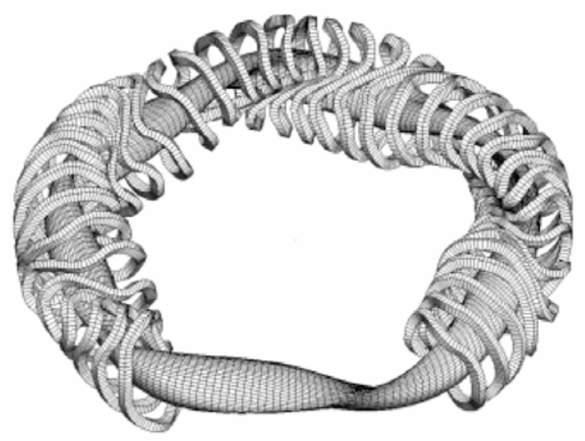
Effect of New Model on Radiation Profiles

- **Being incorporated in 1-D Power Balance code**
  - **POPCON auxiliary heating, saddle point, ignition contours**
  - **comparing effects of 3 models: constant n_Z/n_e and neoclassical models without (& with) temperature screening**
  - **volume-average impurity (C and Fe) densities the same**
  - **added impurity radiation profile and integrated power flows**
- **Purpose is to reduce power flow to divertor by maximizing power radiated to the wall consistent with reasonable confinement assumptions**
- **Status -- debugging new profile plots**

3 Stellarator Configurations Studied







- **NCSX-R**

quasi-axisymmetric
18 modular coils
ι_{ave} **= 0.5,** ι' **= 0.6**

- **MHH2-R**

quasi-axisymmetric
16 modular coils
ι_{ave} **= 0.45,** ι' **= –0.22**
tokamak shear

- **HSR**

quasi-poloidal
50 modular coils
ι_{ave} **= 0.90,** ι' **= 0.15**

- **Except for MHH2-R, these configurations have been scaled from an experiment and *not* reactor optimized**

Configuration Characterization

	NCSX-R	MHH2-R	HSR-5 (4)
Plasma-coil aspect ratio A_Δ = <*R* >/Δ_{min}	5.90	5.52	12.2 (10.3)
Min. coil-coil aspect ratio $A_{c\text{-}c}$ = <*R*>/$(c\text{-}c)_{min}$	10.1	13.3	9.8
B_0/B_{max} for *R* = 6.5 m, *d* = 0.3 m, *k* = 1	0.49	0.43	*0.5 (0.49)*
Plasma aspect ratio A_p = <*R*>/<*a*>	4.50	3.75	11.7 (8.6)
α-particle loss (%)	30	30	<*5*
$\langle\beta_{limit}\rangle$ (%): infinite-*n* to finite-*n* modes	4.1 to 6	4 to 5?	5 to ?
Surface figure of merit A_Δ^2/A_p	7.74	8.13	12.7 (12.3)

Assumptions

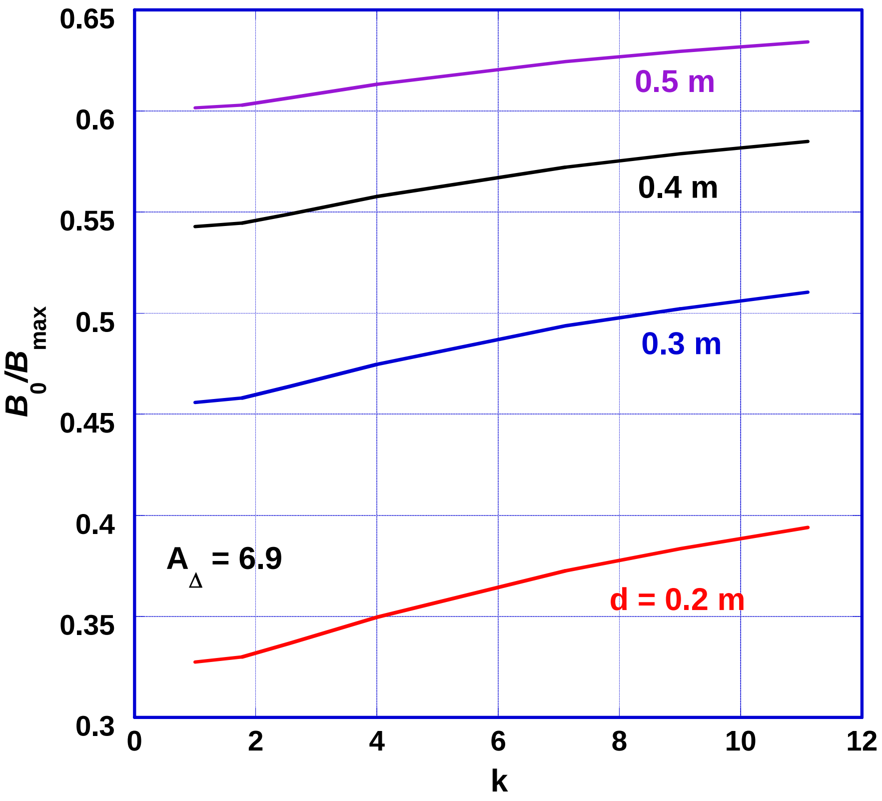
- **Blanket and shield models**
  - NCSX-R: ~10% of wall area has $\Delta < 1.2\ \Delta_{min}$
    - use shield only in this area, full blanket elsewhere
  - MHH2-R: ~20% of wall area has $\Delta < 1.2\ \Delta_{min}$; 2 cases
    - (1) full blanket and shield everywhere
    - (2) shield only there, but needs high Be fraction for blanket
  - HSR*: 5-10% of wall area has $\Delta < 1.2\ \Delta_{min}$; 2 cases
    - (1) 5 field periods using our blanket/shield approach
    - (2) 4 field periods using our blanket/shield approach
- **Common reference assumptions for all cases**
  - alpha-particle losses 30%, except ~5% for HSR
  - τ_{He}/τ_E = 6, 1% C, 0.01% Fe
  - j_{max} & B_{max} appropriate for each conductor type
- **Test sensitivity to the assumptions**

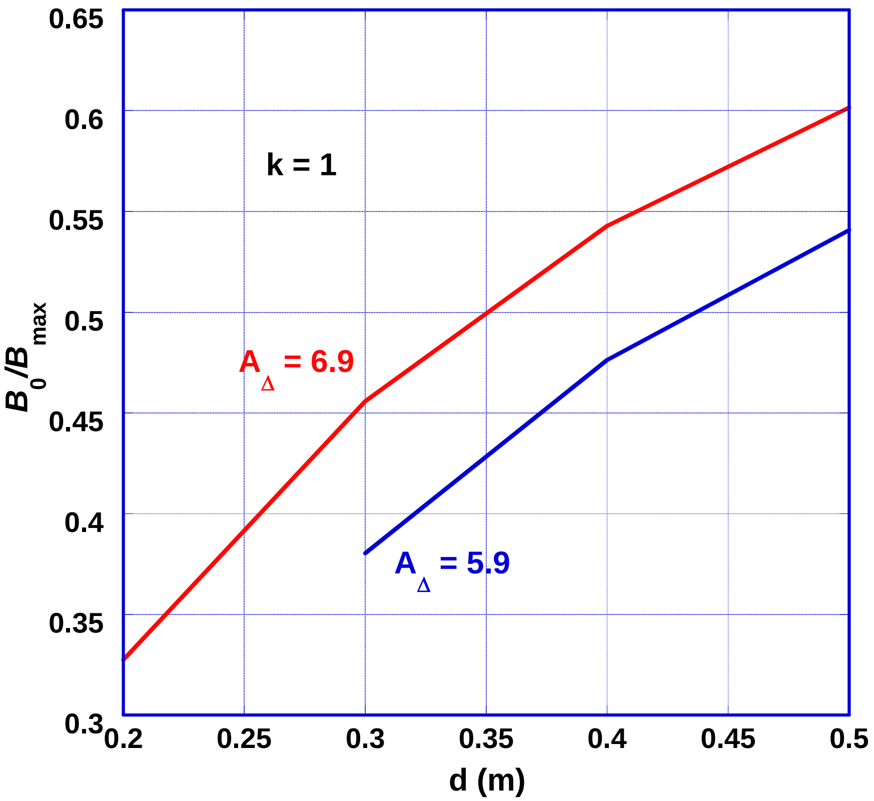
3 Choices for Superconducting Coils

- **High-temperature superconductor**
  - j_{max} = 330 MA/m^2 for B_{max} < 16 T
- **MgB_2 at 15K**
  - j_{max} = 143 MA/m^2 for B_{max} = 10 T
    to 109 MA/m^2 for B_{max} = 16 T
- **NbTi**
  - j_{max} = 150 MA/m^2 for B_{max} = 8 T (4.2K)
    to 100 MA/m^2 for B_{max} = 10 T (1.8K)

Maximum B_0 Determination

- Use B_0/B_{max}(d,k) from Ku (2/25/03 NCSX coil set)
- Normalize for each coil configuration and interpolate between d,k values





NCSX-R Parameter Selection

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 (%)	t (m)
	1.00	5.93	5.58	252.87	0.37	4.95	8.71	0.903
	1.78	5.78	5.76	254.83	0.29	5.20	8.47	0.906
0.2 m	2.56	5.71	5.96	260.05	0.23	5.34	8.08	0.907
	4.00	5.66	5.99	259.43	0.14	5.42	8.09	0.908
	7.11	5.59	6.73	287.83	0.00	5.56	6.53	0.910
	1.00	6.05	6.95	205.55	0.33	4.76	5.45	0.900
	1.78	5.89	7.18	206.96	0.23	5.01	5.31	0.903
0.25 m	2.56	5.80	7.41	210.36	0.16	5.17	5.10	0.905
	4.00	5.71	7.77	216.95	0.05	5.34	4.76	0.907
	5.53	5.68	8.00	222.55	-0.04	5.38	4.51	0.908
	7.11	5.65	8.27	228.57	-0.13	5.46	4.26	0.909
	1.00	6.20	8.15	171.64	0.30	4.54	3.82	0.897
	1.78	5.97	8.49	172.45	0.17	4.88	3.71	0.902
	2.56	5.89	8.72	174.60	0.09	5.01	3.60	0.903
0.3 m	4.00	5.78	9.10	178.75	-0.05	5.20	3.40	0.906
	7.11	5.70	9.60	186.01	-0.25	5.35	3.12	0.907
	1.00	6.43	9.83	120.88	0.22	4.21	2.48	0.893
	1.78	6.17	10.29	121.23	0.06	4.58	2.42	0.898
0.4 m	2.56	6.05	10.58	122.31	-0.06	4.76	2.35	0.900
	4.00	6.39	10.17	124.25	-0.19	4.27	2.34	0.893
	7.11	6.26	10.65	127.41	-0.47	4.44	2.20	0.896
	1.00	6.73	10.68	87.85	0.15	3.85	1.97	0.887
	1.78	6.39	11.27	88.07	-0.05	4.27	1.91	0.893
0.5 m	2.56	6.20	11.68	88.59	-0.20	4.53	1.86	0.897
	4.00	6.05	12.11	89.57	-0.42	4.76	1.80	0.900
	7.11	5.89	12.65	91.19	-0.77	5.01	1.71	0.903
	1.00	6.99	11.14	66.19	0.07	3.57	1.70	0.882
	1.78	6.58	11.86	66.31	-0.17	4.03	1.65	0.890
0.6 m	2.56	6.39	12.28	66.61	-0.35	4.27	1.61	0.893
	4.00	6.20	12.76	67.16	-0.60	4.54	1.56	0.897
	7.11	5.97	13.40	68.03	-1.03	4.88	1.49	0.902

NCSX-R Parameter Selection

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	js (MA/m2)	c-c min	Wall load	Beta (%)
	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
0.25 m	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
	1.00	6.20	8.15	171.64	0.30	4.54	3.82
0.3 m	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
	1.00	6.43	9.83	120.88	0.22	4.21	2.48
0.4 m	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

NCSX-R Cases

Minimum-R cases

B_{max} (T)	16	15	14	13	12	11	10
<*R*> (m)	5.71	5.71	5.71	5.89	6.18	6.18	6.18
$\langle B_{axis} \rangle$ (T)	7.77	7.28	6.80	7.08	7.70	7.06	6.42
$\langle \beta \rangle$ (%)	4.76	5.41	6.21	5.45	4.30	5.12	6.19
p_n MW/m^2	5.34	5.34	5.01	3.40	4.56	4.56	4.56

MgB_2 coils

B_{max} (T)	16	15	14	13	12	11	10
<*R*> (m)	6.73	6.20	6.17	6.06	6.18	6.18	6.18
$\langle B_{axis} \rangle$ (T)	10.68	9.60	9.00	8.57	7.70	7.06	6.42
$\langle \beta \rangle$ (%)	3.85	4.54	4.58	4.74	4.30	5.12	6.19
p_n MW/m^2	1.97	2.75	3.15	3.57	4.56	4.56	4.56

MHH2-R Cases

	locally no blanket 0.86 m			full blanket/shield 1.07 m		
B_{max} (T)	16	14	12	16	14	12
$\langle R \rangle$ (m)	5.90	6.01	----	6.74	6.95	----
$\langle B_{axis} \rangle$ (T)	6.52	6.31	----	5.73	5.46	----
$\langle \beta \rangle$ (%)	5.40	5.62	----	5.73	6.02	----
p_n MW/m^2	4.36	4.20	----	3.35	3.15	----

The HSR Reactor

- Based on W 7-X plasma and coil configuration
- Assumes current technology -- NbTi coil (B_{max} = 10 T)
- Uses same blanket/shield everywhere (1.2-m thick)

Case	*R* (m)	*B* (T)	<β> %	H-ISS95	p_{wall}
HSR-4	18	5	4.2	1.53	0.96

- Recalculate HSR-4 with our blanket, shield and coil models = HSR-4*

HSR-4* Cases

B_{max} (T)	16	14	12	10	HSR
<*R*> (m)	9.51	9.98	10.78	----	18.0
$\langle B_{axis} \rangle$ (T)	10.49	10.22	9.78	----	5.0
$\langle \beta \rangle$ (%)	5.93	5.82	5.66	----	4.2
p_n MW/m^2	2.93	2.67	2.29	----	0.96

Results suspect -- poor model for B_0/B_{max}(d,k)

Systems Code Status

- **Rough estimates for blanket/shield costing**
- **Rough estimates for coil costing**
- **Analytic expression for B_{max}(d,k)/B_0**
  - **need to find good fit to Ku's numbers (*B*^{4} sensitivity)**
  - **need numbers to do other configurations**
- **Testing models and assumptions with my regular codes before immersing in systems code**
  - **profile assumptions and treatment of impurities**
  - **T_e(r) consistency with radiation profiles**

Summary

- Improved treatment of n_e(r) and impurities
- Revised parameters for 3 coil types for
  - Ku's NCSX-R coil configuration
  - Garabedian's MHH2-R configuration
  - HSR-4* derived from German HSR-4
- Working on systems code models and assumptions