Transport and Machine Size

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Some plasma parameters are determined by physics goals (e.g., β, ν^*), but how do other plasma parameters vary as R_o and B_o are changed.

What part of the parameter space is placed off limits by neoclassical transport?

- Want low ν^* for reactor relevance (collisionless bootstrap and neoclassical χ).

  At fixed β, ν^*, P_{heat} where is H_{ISS-95} minimized?

  At fixed β, ν^*, P_{heat} where is $H_{ITER-89P}$ minimized?
- Disadvantage of low ν^* is that it requires $H_{ISS-95} \geq 2$.

- $\tau_{E\ ISS-95}$ is maximized at high density, so

  Where is H_{ISS-95} minimized if $n_e = n_{Sudo}$ is used instead of fixing ν^* ?
- Disadvantage of $H_{ISS-95} \sim 1$ is very high ν^*.

Methodology

Assume fixed density and temperature profile shapes.

Plasma parameters are then related by simple expressions:

$$\beta \propto n \langle T \rangle / B_o^2$$

$$\nu^* \propto n R_o / \langle T \rangle^2 \propto n^3 R_o \beta$$

$$\tau_E \propto n \langle T \rangle R_o^3 / P_{heat} \propto \beta B_o^2 R_o^3 / P_{heat}$$

$$H_{ISS\text{-}95} \propto \beta B_o^2 R_o^3 / (\tau_{E\ ISS\text{-}95} P_{heat})$$

- Add constraints (e.g., fixed β, $\nu^*(a/2)$, P_{heat}), solve for independent variables.

Spot check the fixed profile assumption:
Predict new temperature profiles at selected locations in the (R_o, B_o) plane.
Look for boundary of the neoclassically accessible region

H Scalings

For fixed ν^*, density $\propto (\nu^* \beta^2 B_o^4/R_o)^{1/3}$

$H_{ISS\text{-}95} \propto \beta^{0.66} B_o^{0.49} R_o^{0.31}/\nu^{*0.17}(P_{heat})^{0.41}$; $H_{ISS\text{-}95}$ is held constant if $B_o \propto R_o^{-0.63}$

$H_{ITER\text{-}89P} \propto \beta^{0.93} B_o^{0.82} R_o^{0.68}/\nu^{*0.03}(P_{heat})^{0.50}$; $H_{ITER\text{-}89P}$ is held constant if $B_o \propto R_o^{-0.83}$

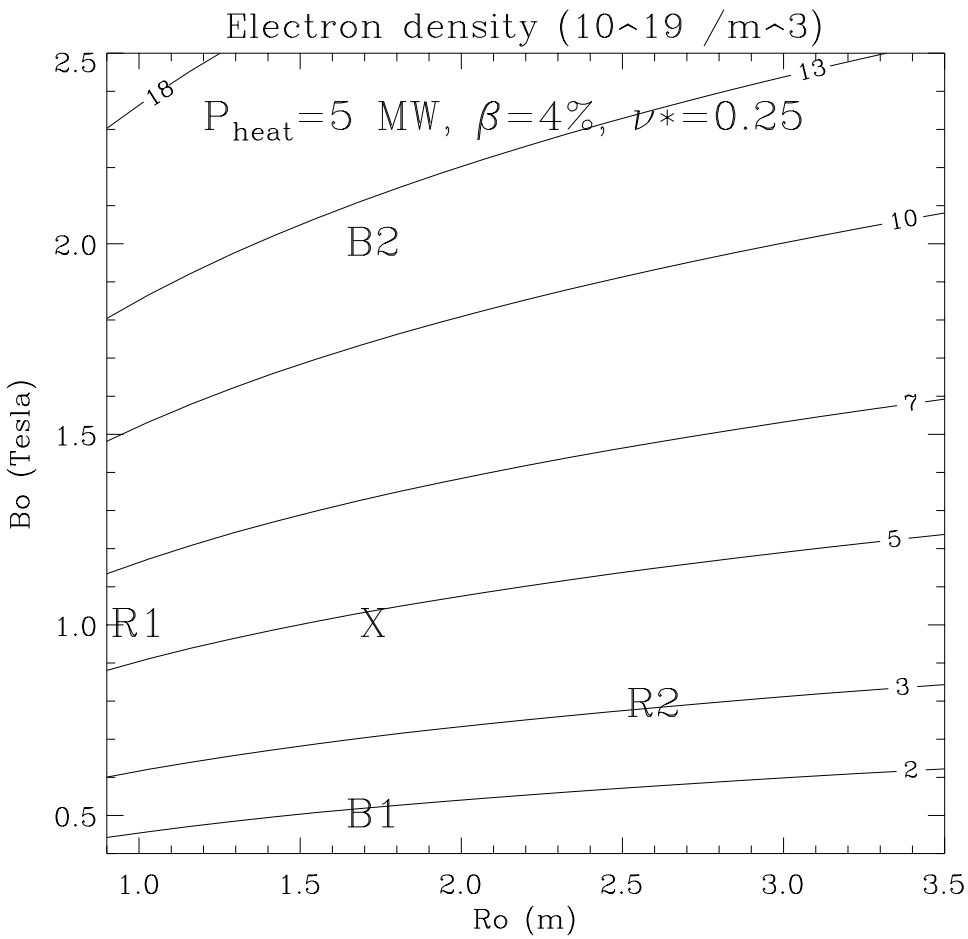
$H_{ITER\text{-}93H} \propto \beta^{0.89} B_o^{0.39} R_o^{0.21}/\nu^{*0.06}(P_{heat})^{0.30}$; $H_{ITER\text{-}93H}$ is held constant if $B_o \propto R_o^{-0.54}$

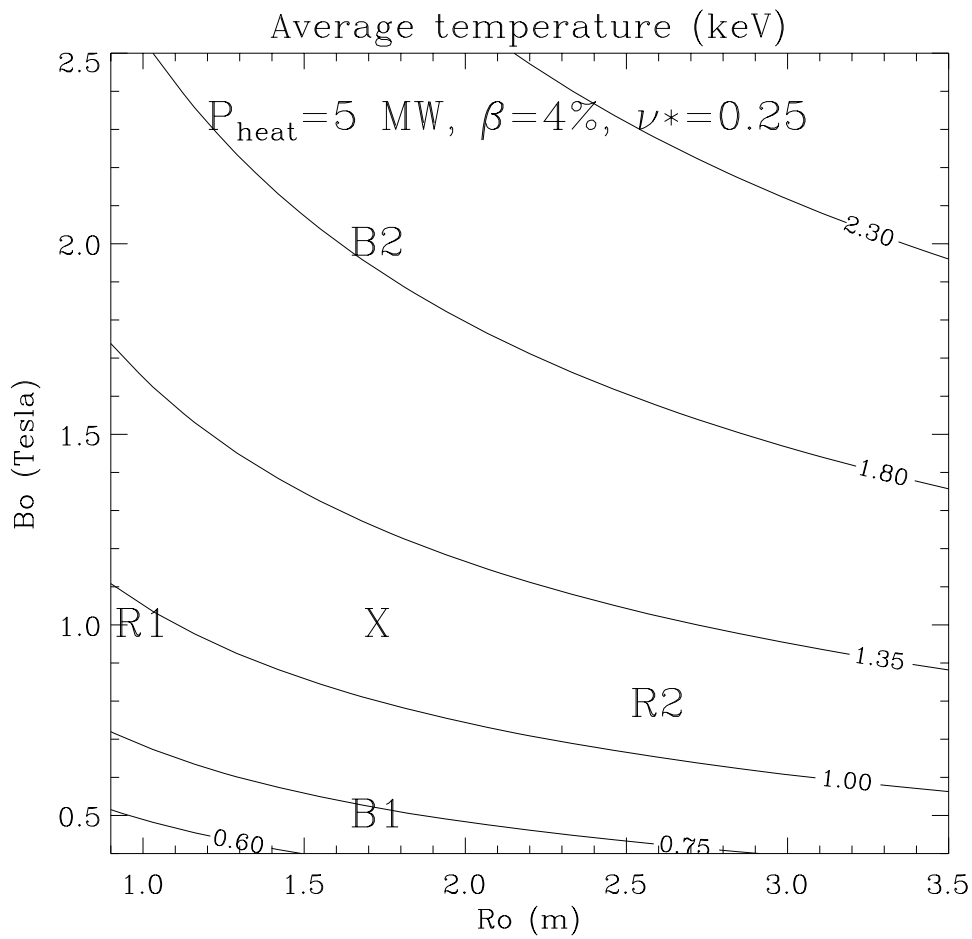
For density = Sudo limit $\propto (P_{heat} B_o/R_o^3)^{1/2}$

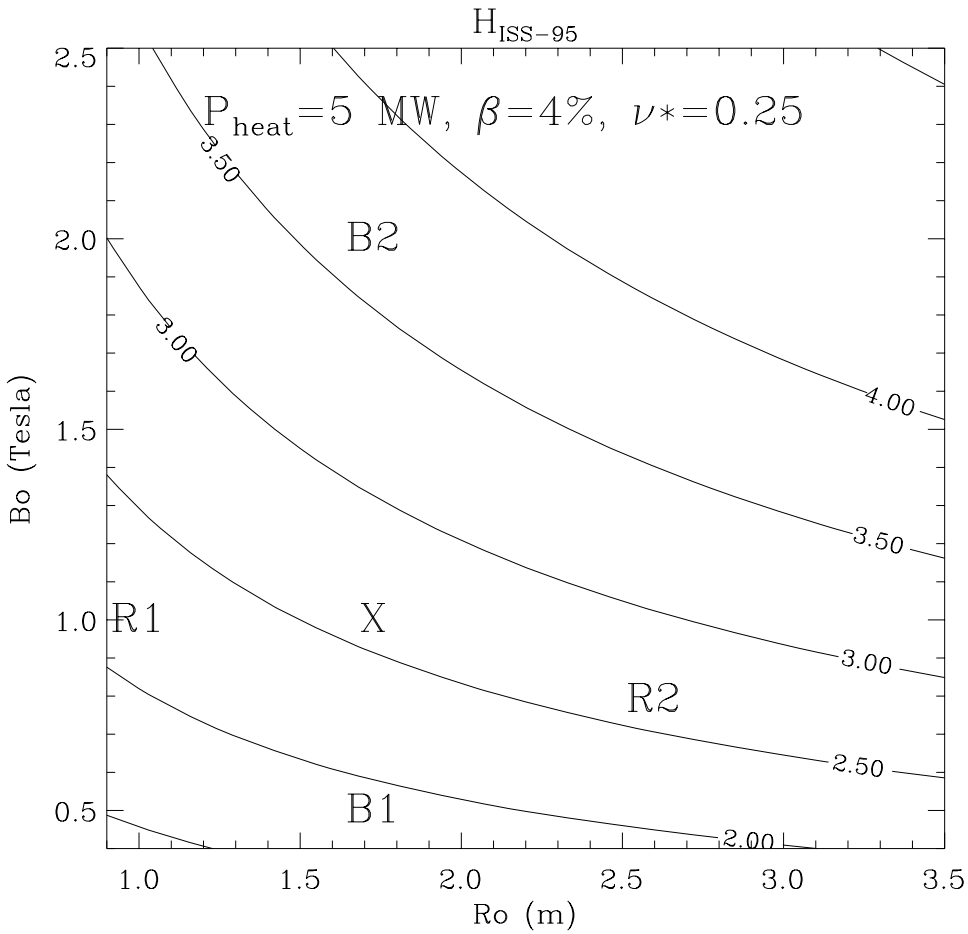
$H_{ISS\text{-}95} \propto \beta B_o^{0.915} R_o^{0.905} / (P_{heat})^{0.665}$; $H_{ISS\text{-}95}$ is held constant if $B_o \propto R_o^{-0.99}$

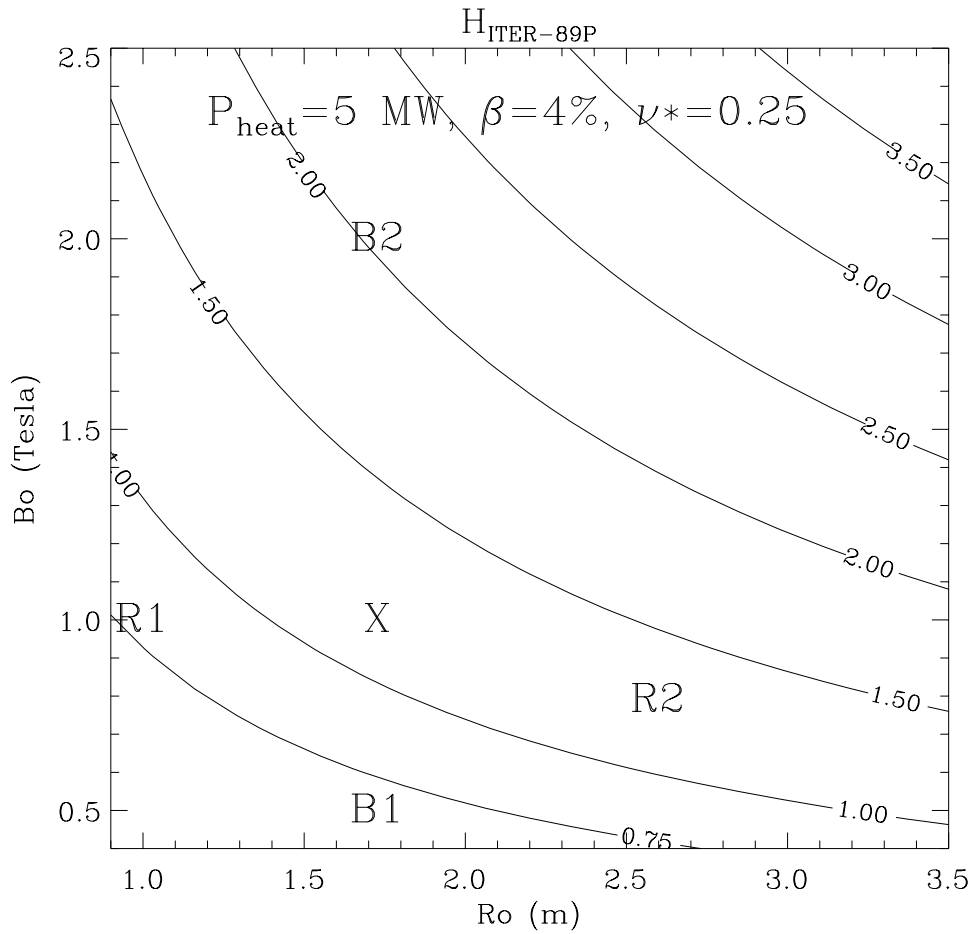
$H_{ITER\text{-}89P} \propto \beta B_o^{0.90} R_o^{0.80} / (P_{heat})^{0.55}$; $H_{ITER\text{-}89P}$ is held constant if $B_o \propto R_o^{-0.89}$

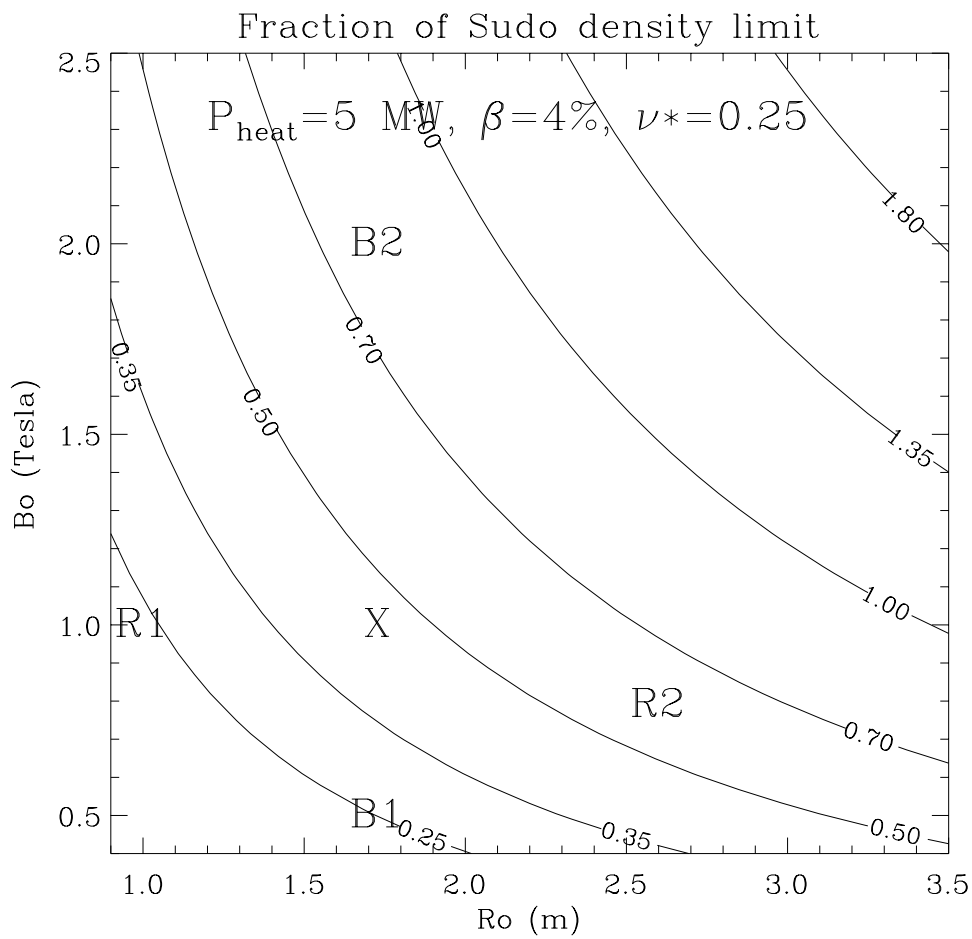
$H_{ITER\text{-}93H} \propto \beta B_o^{0.535} R_o^{0.405} / (P_{heat})^{0.385}$; $H_{ITER\text{-}93H}$ is held constant if $B_o \propto R_o^{--0.76}$

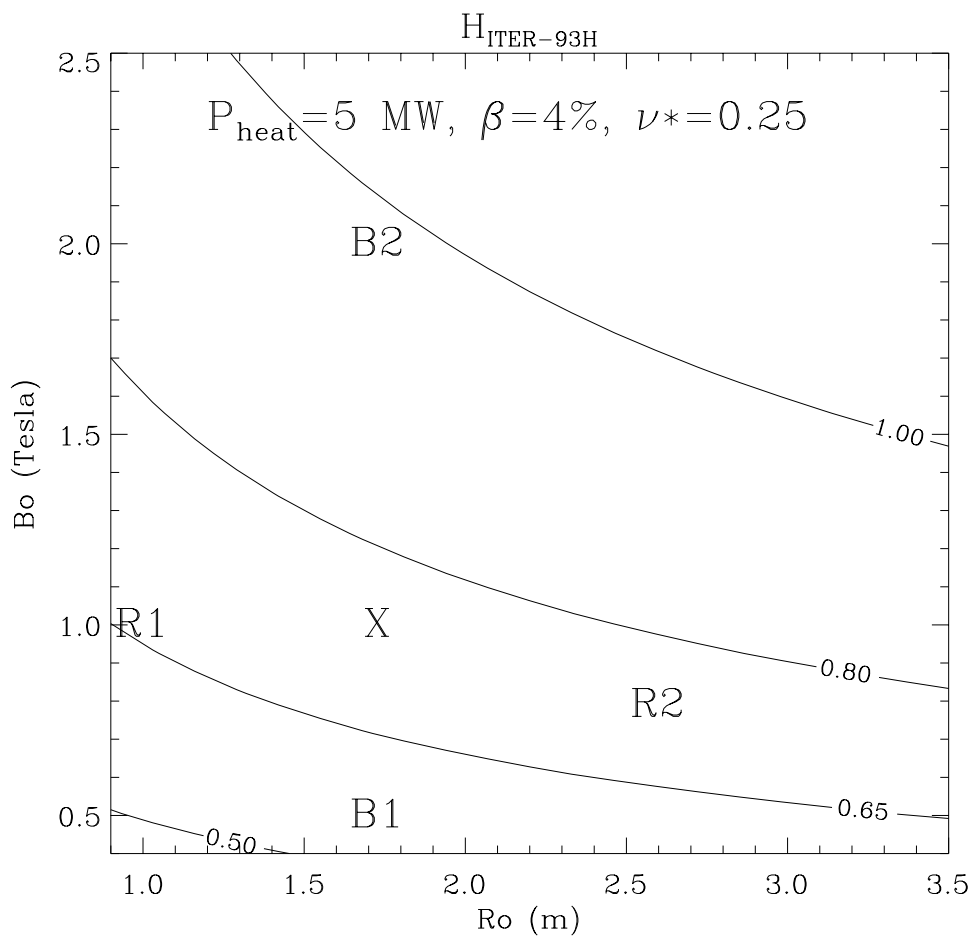

Electron density (10^19 /m^3)
P heat=5 MW, β=4%, ν*=0.25
18
13
10
7
5
3
2
B2
R1
X
R2
B1
Bo (Tesla)
Ro (m)
2.5
2.0
1.5
1.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

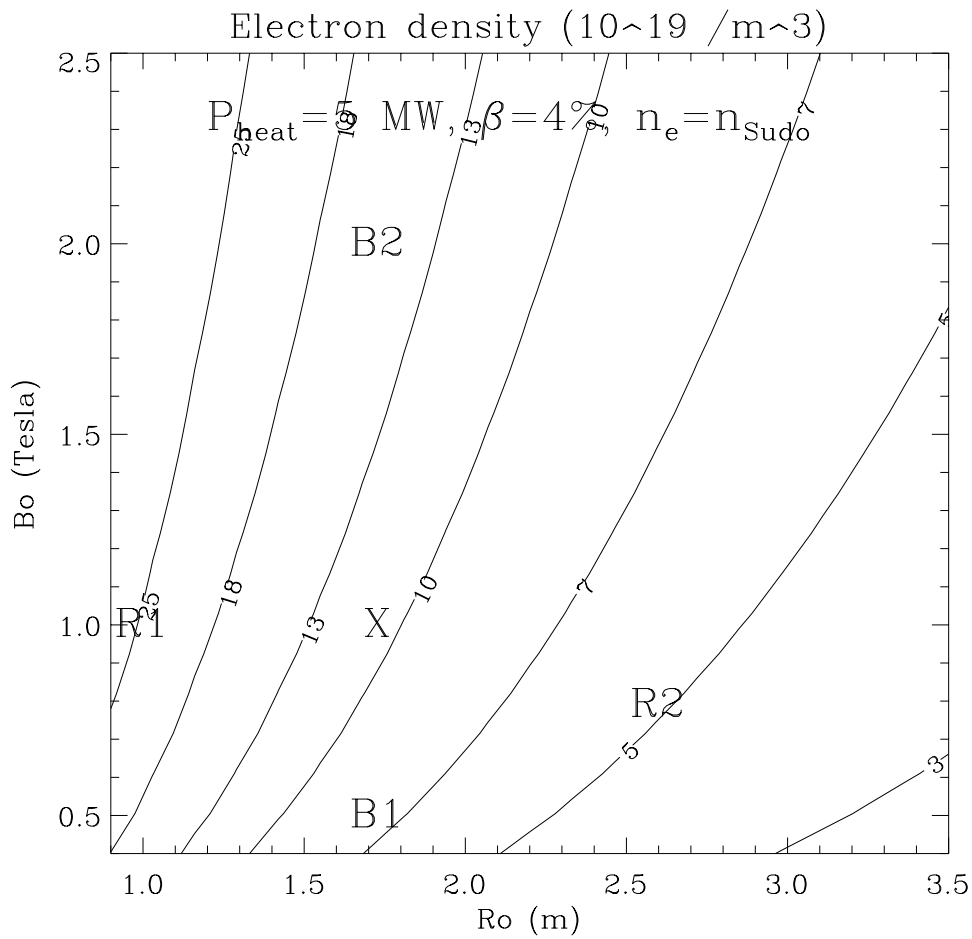

Average temperature (keV)
P heat=5 MW, β=4%, ν*=0.25
2.30
1.80
1.35
1.00
0.75
0.60
B2
R1
X
R2
B1
Bo (Tesla)
Ro (m)
2.5
2.0
1.5
1.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

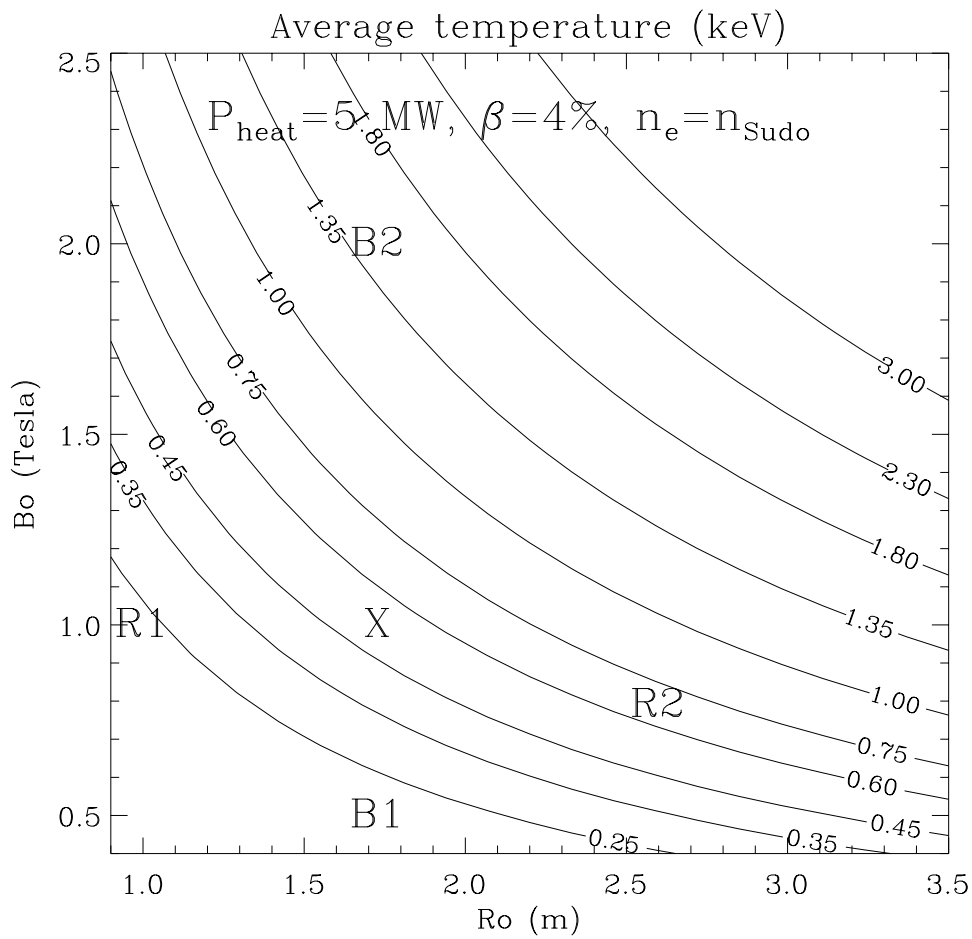

H_ISS-95
P_heat=5 MW, β=4%, ν*=0.25
B2
R1
X
R2
B1
4.00
3.50
3.00
2.50
2.00
Bo (Tesla)
Ro (m)

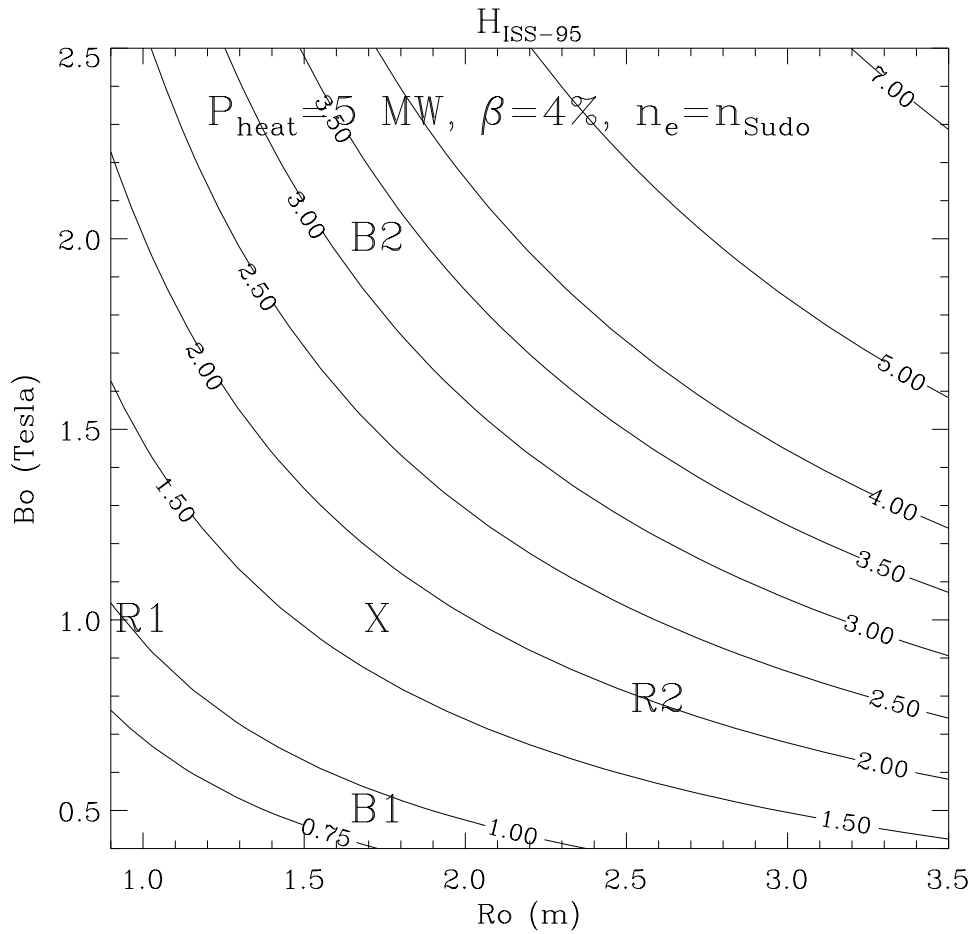

H_ITER-89P
P_heat=5 MW, β=4%, ν*=0.25
B2
R1
X
R2
B1
3.50
3.00
2.50
2.00
1.50
1.00
0.75
Bo (Tesla)
Ro (m)

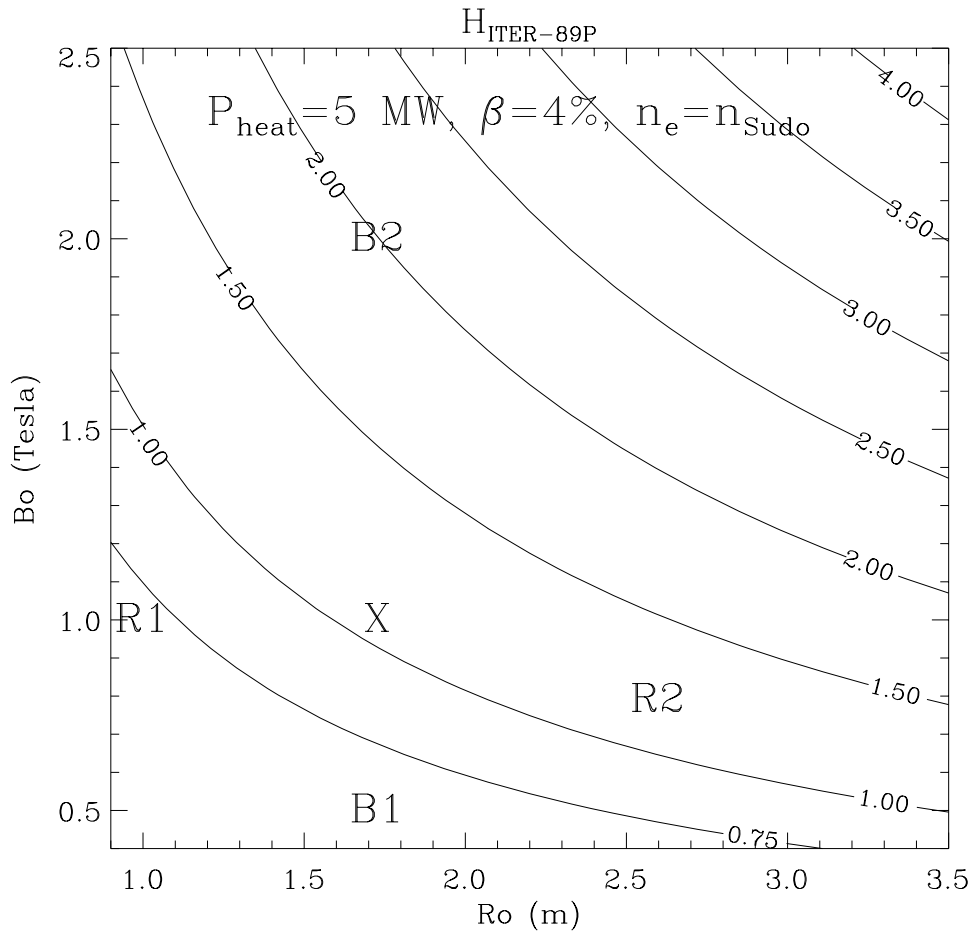

Fraction of Sudo density limit
P heat =5 MW, β=4%, ν*=0.25
B2
R1
X
R2
B1
0.35
0.50
0.70
1.00
1.35
1.80
0.25
0.35
0.50
0.70
1.00
Bo (Tesla)
Ro (m)
2.5
2.0
1.5
1.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

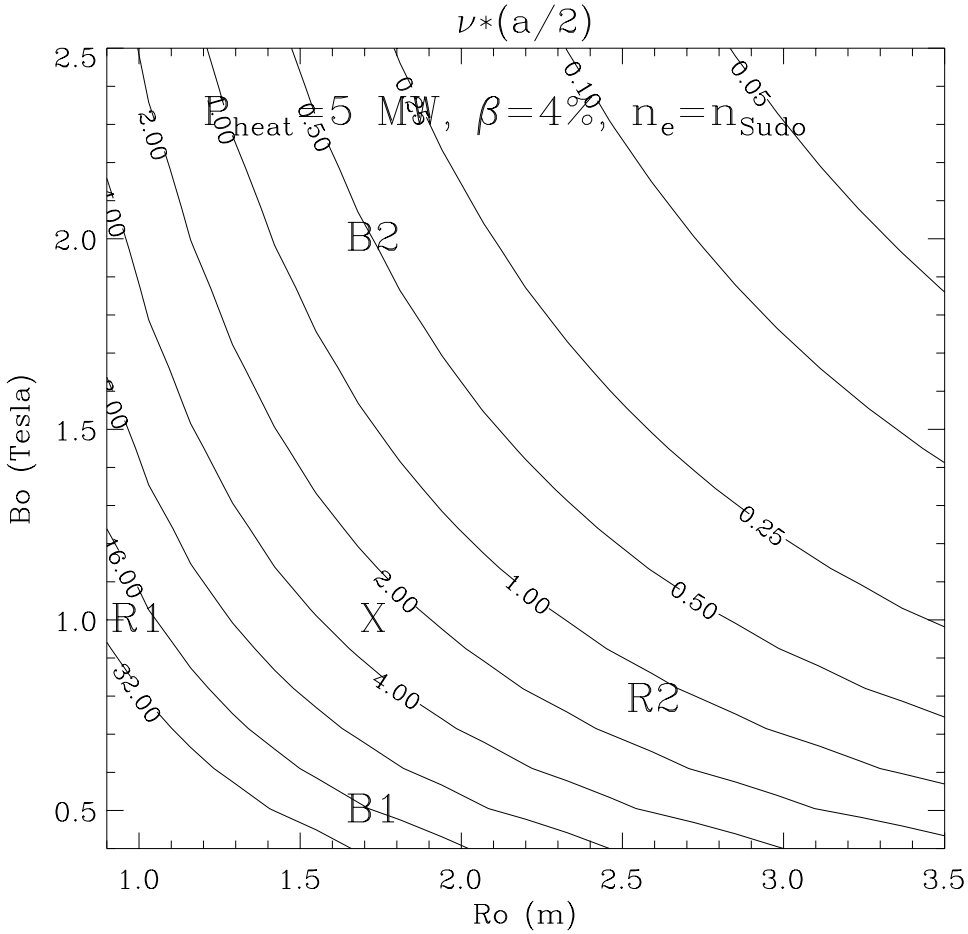

H ITER−93H
P heat =5 MW, β=4%, ν*=0.25
B2
R1
X
R2
B1
1.00
0.80
0.65
0.50
Bo (Tesla)
Ro (m)
2.5
2.0
1.5
1.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

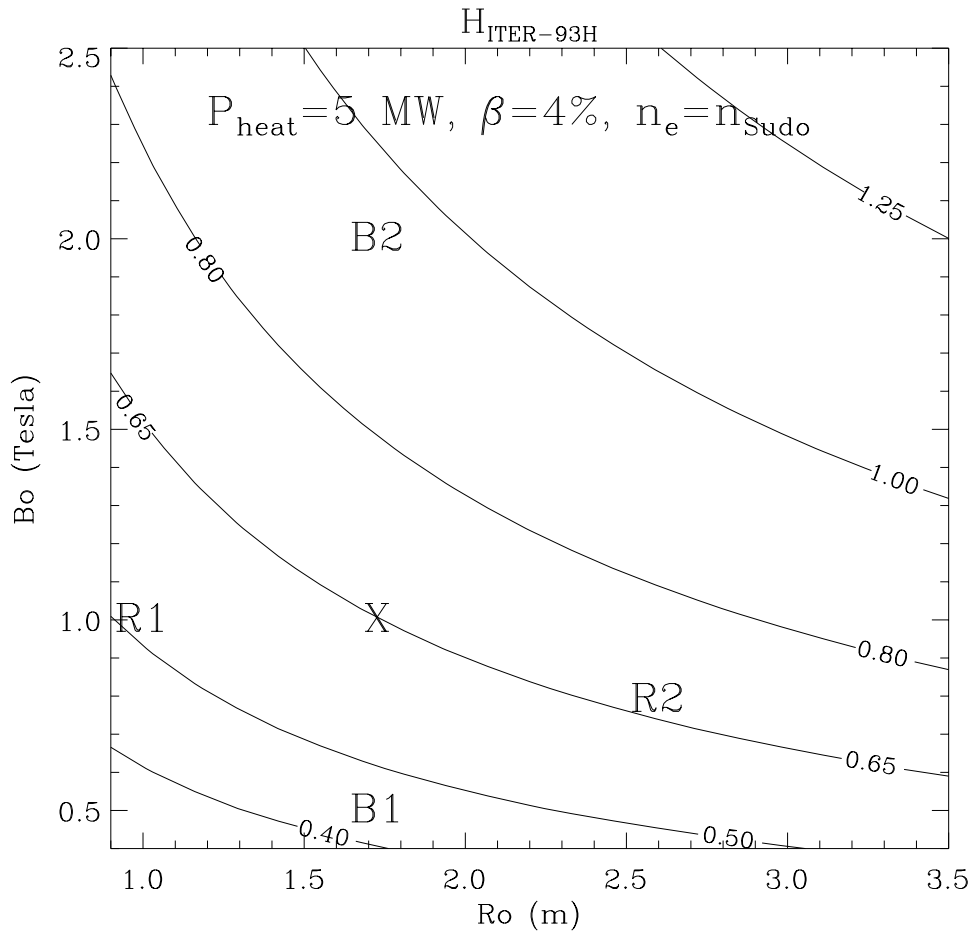

Electron density (10^19 /m^3)
P_heat=5 MW, β=4%, n_e=n_Sudo
B2
R1
X
R2
B1
25
18
13
10
7
5
3
Bo (Tesla)
Ro (m)


Average temperature (keV)
P_heat=5 MW, β=4%, n_e=n_Sudo
B2
R1
X
R2
B1
3.00
2.30
1.80
1.35
1.00
0.75
0.60
0.45
0.35
0.25
Bo (Tesla)
Ro (m)


H_ISS-95
P_heat=5 MW, β=4%, n_e=n_Sudo
B2
X
R1
R2
B1
7.00
5.00
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.75
Bo (Tesla)
Ro (m)

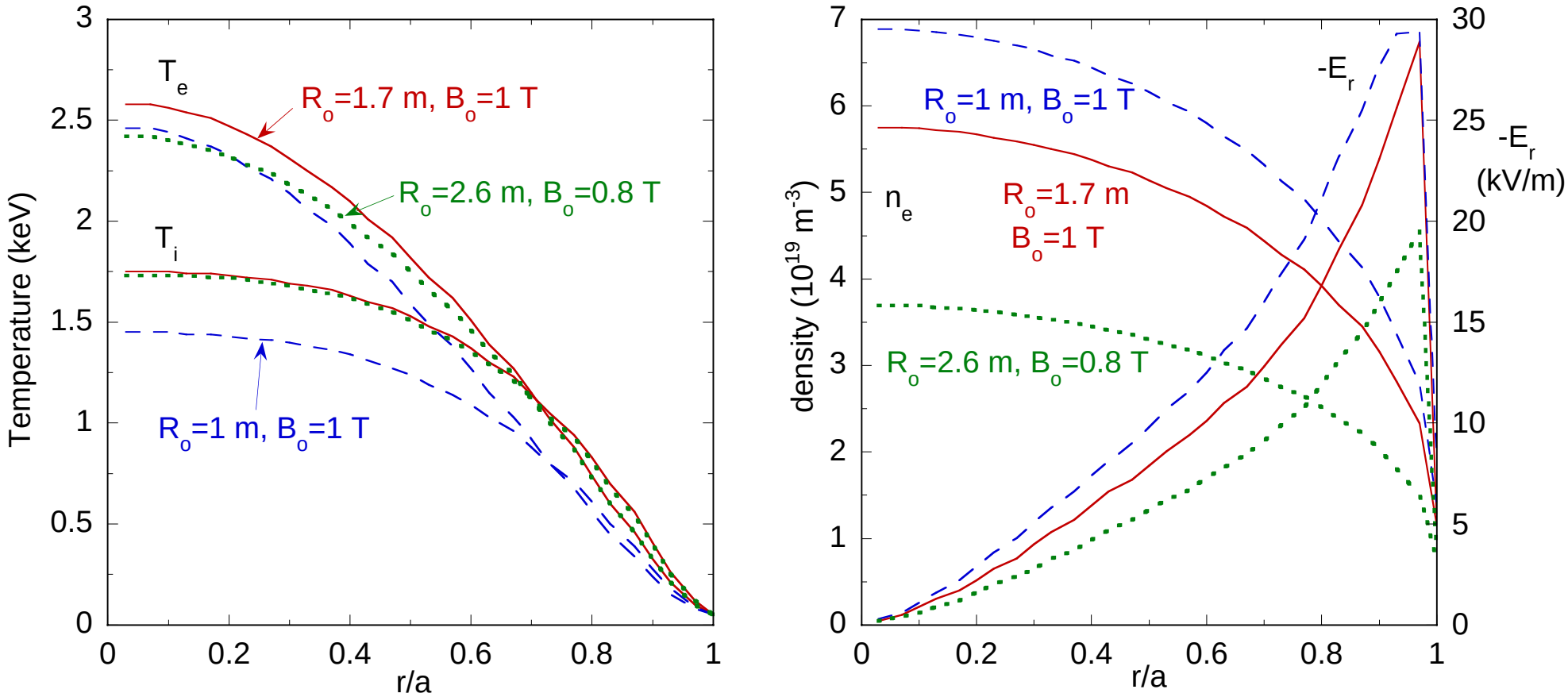

H_ITER-89P
P_heat=5 MW, β=4%, n_e=n_Sudo
B2
X
R1
R2
B1
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.75
Bo (Tesla)
Ro (m)


ν*(a/2)
P_heat=5 MW, β=4%, n_e=n_Sudo
B2
R1
X
R2
B1
2.00
1.00
0.50
0.25
0.10
0.05
4.00
8.00
16.00
32.00
Bo (Tesla)
Ro (m)


H_ITER-93H
P_heat=5 MW, β=4%, n_e=n_Sudo
B2
R1
X
R2
B1
1.25
1.00
0.80
0.65
0.50
0.40
Bo (Tesla)
Ro (m)

Temperature profile shapes preserved in size scan

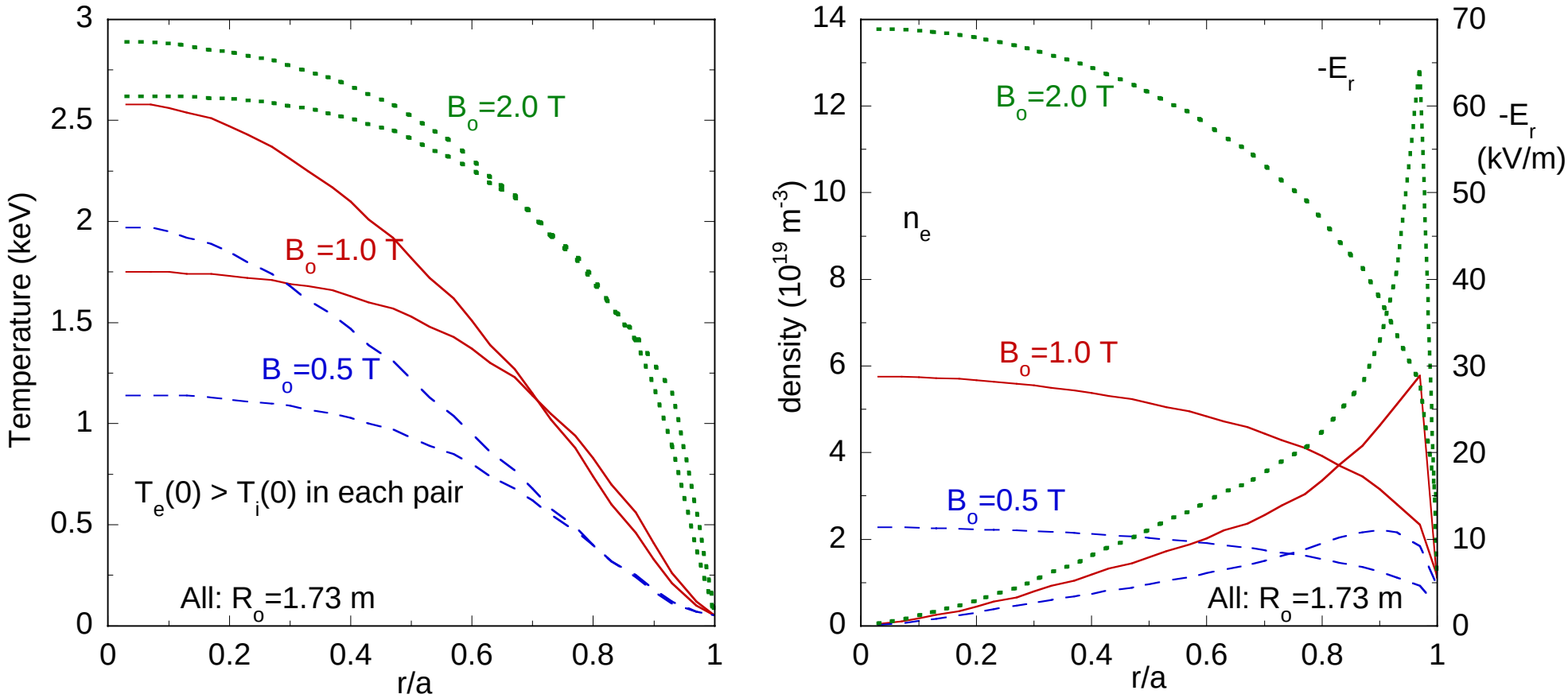
$\langle\beta\rangle$=4%, P_{heat}=5 MW, $\nu^*(a/2)$=0.25



Temperature profile shapes change in B_o scan

$<\beta>=4\%$, $P_{heat}=5$ MW, $\nu^*(a/2)=0.25$

Neoclassical χ limits β to $\leq 4\%$ at $B_o = 2T$



Summary

- For fixed ν^*, density $\propto (\nu^* \beta^2 B_o^4/R_o)^{1/3}$

$H_{ISS\text{-}95} \propto \beta^{0.66} B_o^{0.49} R_o^{0.31}/\nu^{*0.17}(P_{heat})^{0.41}$; $H_{ISS\text{-}95}$ is held constant if $B_o \propto R_o^{-0.63}$

$H_{ITER\text{-}89P} \propto \beta^{0.93} B_o^{0.82} R_o^{0.68}/\nu^{*0.03}(P_{heat})^{0.50}$; $H_{ITER\text{-}89P}$ is held constant if $B_o \propto R_o^{-0.83}$

- With P_{heat} = 5 MW, reaching β = 4% and ν^* = 0.25 requires $H_{ISS\text{-}95} \geq 2$. Maximum $H_{ISS\text{-}95}$ in LHD and W7-AS is ~2.0–2.4.

- Raising density and lowering R_o to reduce $H_{ISS\text{-}95}$ to ~ 1 raises $\nu^* >> 1$.

- Neoclassical χ limits β to $\leq$ 4% at B_o=2T, R_o=1.73 m, P_{heat}=5 MW.
  Helical neoclassical transport becomes significant in the outer third of the minor radius because helical ripple transport has stronger temperature dependence than symmetric neoclassical transport.
  Temperature profile flattenned in core by symmetric neoclassical transport.

Next Steps

- Include temperature predictions in scans over the (R_o,B_o) plane.
- Vary the density profile shape.
- Use other tokamak transport models (add Culham and Mixed Shear).