Poloidal Field Design and Plasma Scenarios for the Fusion Ignition Research Experiment (FIRE)

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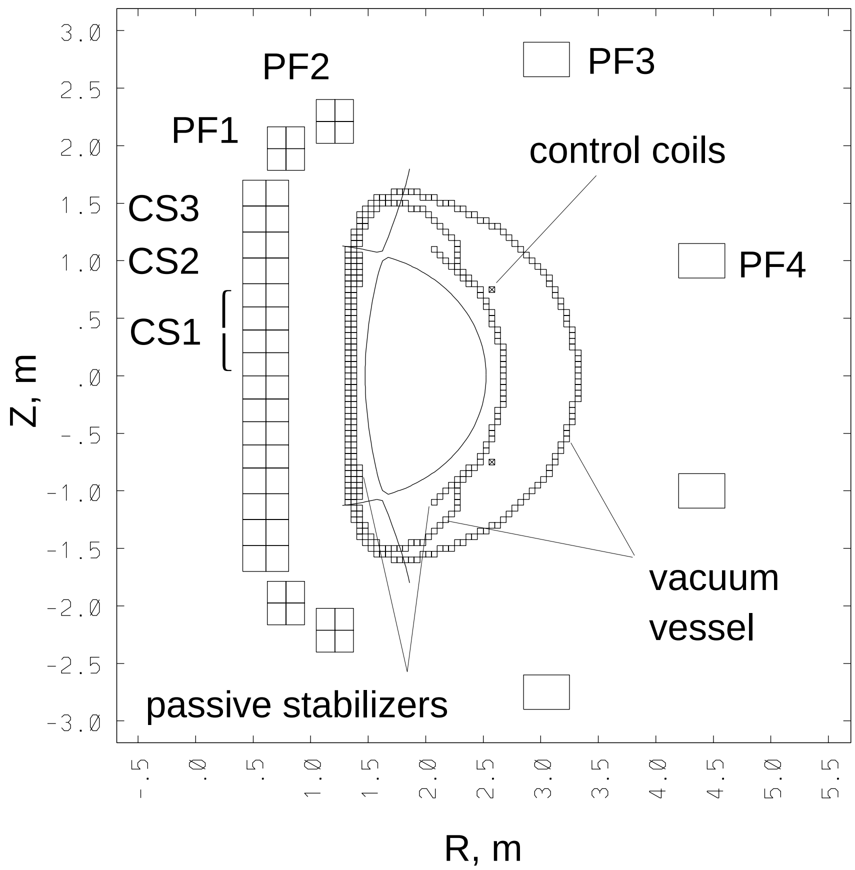
http://fire.pppl.gov

FIRE Fusion Ignition Research Experiment

Plasma Equilibrium Analysis



I_p = 6.44 MA
B_T = 10.0 T
R = 2.0 m
a = 0.525 m
κ_x = 2.0
δ_x = 0.7
l_i = 0.85
β_p = 1.20
$-16 \le \psi_{ext} \le 20$ Wb

- PF coil locations determined by functionality, interferences, and proximity to plasma

- PF coil currents are determined to provide κ_x = 2.0 δ_x = 0.7, and $q_{95} \ge 3.0$, subject to uncertainties in li, βp, and ψext

- generate equilibria at fiducial states; SOD, SOF, SOB, EOB, EOC, and EOD, with flux consumption between states determined by TSC

- heating and stresses in the PF coils provide the primary limits on coil currents, and these were combined with power supply analysis and TSC to optimize a scenario

Vertical Stability and Control

- design passive structures to slow vertical instability and provide a stability factor $f_s = 1 + \tau_g / \tau_{L/R} \geq 1.2$, and a growth time sufficiently long for feedback control

- passive stabilizers are made of 1.5 cm thick Cu, toroidally continuous on the inboard, and in saddle configuration on the outboard

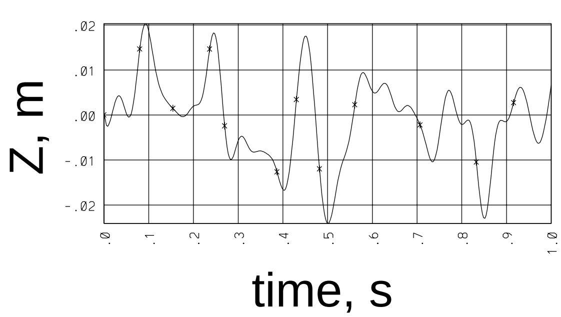
- for low pressure plasmas ($\beta_p = 0.1$), over the range $0.7 \leq l_i \leq 1.1$, the stability factor and growth time are $1.3 \leq f_s \leq 1.13$ and $43 \leq \tau_g(\text{ms}) \leq 19$

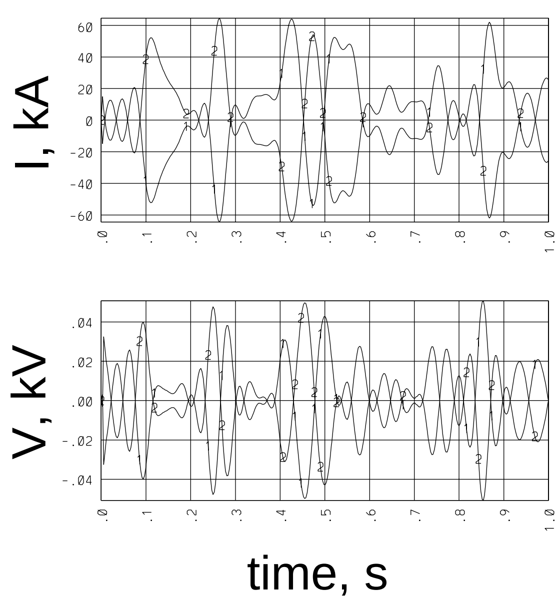
- utilize internal control coils for feedback on the plasma vertical position, located just outside the inner VV

- control simulations indicate that for random disturbances with ΔZ_{RMS} = 1 cm and step disturbances with ΔZ = 2 cm, the peak power requirement is 5-10 MVA

I_{peak} = 55-75 kA-turns

V_{peak} = 50-75 V/turn





FIRE Reference Discharge Scenario

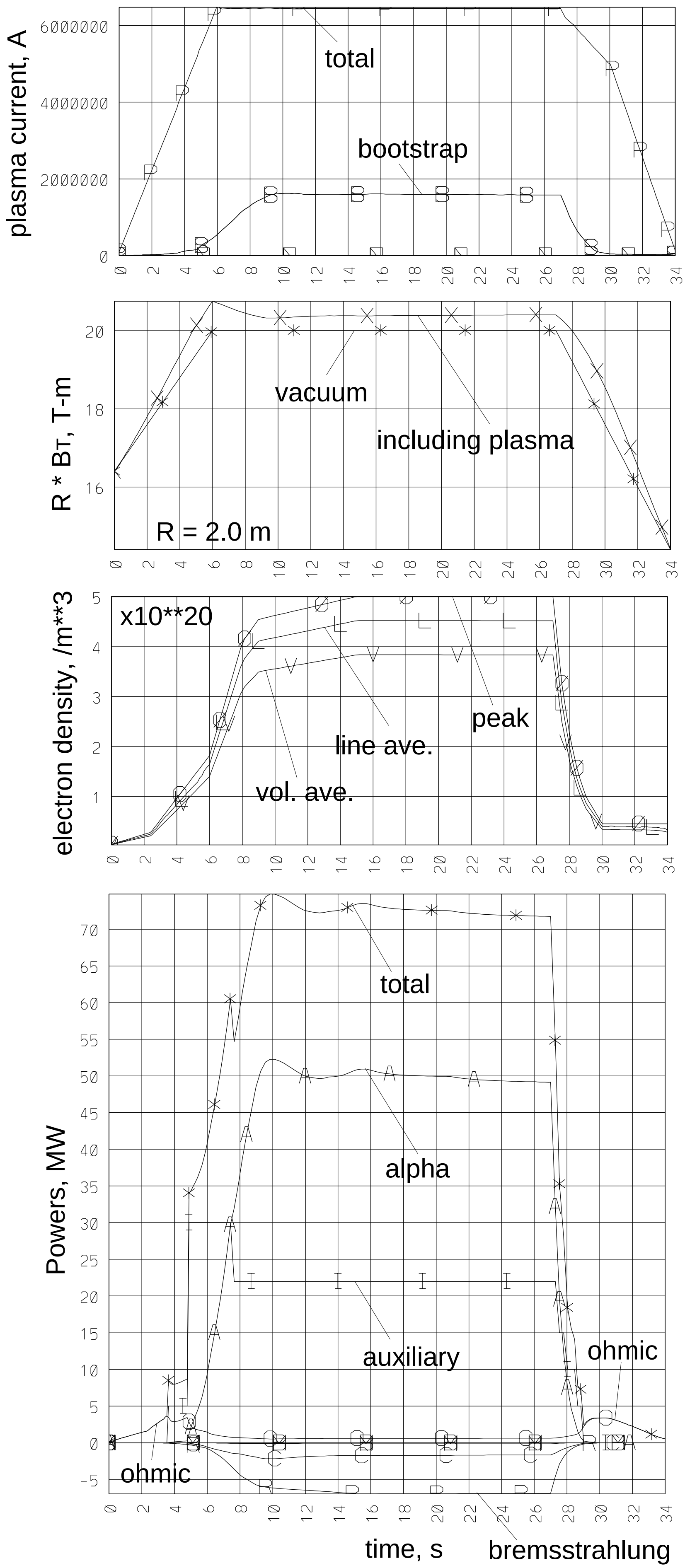
assumptions/inputs

- $n(\psi,t) = n_o(t)[\,1 - \psi^{2.0}]^{0.5} + n_b$
- $n_b = 0.3n_o$
- 3% Be impurity
- $\tau_p^* / \tau_E = 5$
- $\tau_E \approx 0.5$ s
- $T_{edge} = 500$ eV
- time averaged sawtooth
- Harris collisional bootstrap model

main plasma parameters

- $I_p = 6.44$ MA, $B_T = 10$ T
- $l_i = 0.85$, $q_{95} = 3.2$
- $\beta_p = 1.2$, $\beta = 3\%$, $\beta_N = 2.42$
- $W_{th} = 34.5$ MJ, $P_\alpha = 50$ MW
- $n_e / n_{Gr} = 0.6$
- $T_e(0)$, $T_i(0) \approx 18$-19 keV
- $f_{bs} = 25\%$
- $V_{loop} = 0.1$ V
- $Q = P_{fus}/P_{aux} = 11.4$
- $\Delta\psi$(rampup) = 31.3 V-s
  $\Delta\psi$(SOF$\rightarrow$EOB) = 2.5 V-s
- $n_e(0) = 5.0 \times 10^{**}20$ /m**3
  n_e(line) = 4.55
  $\langle n_e \rangle_v = 3.85$
- $\langle n_{He} \rangle = 0.04 \langle n_e \rangle$

FIRE Reference Discharge Scenario

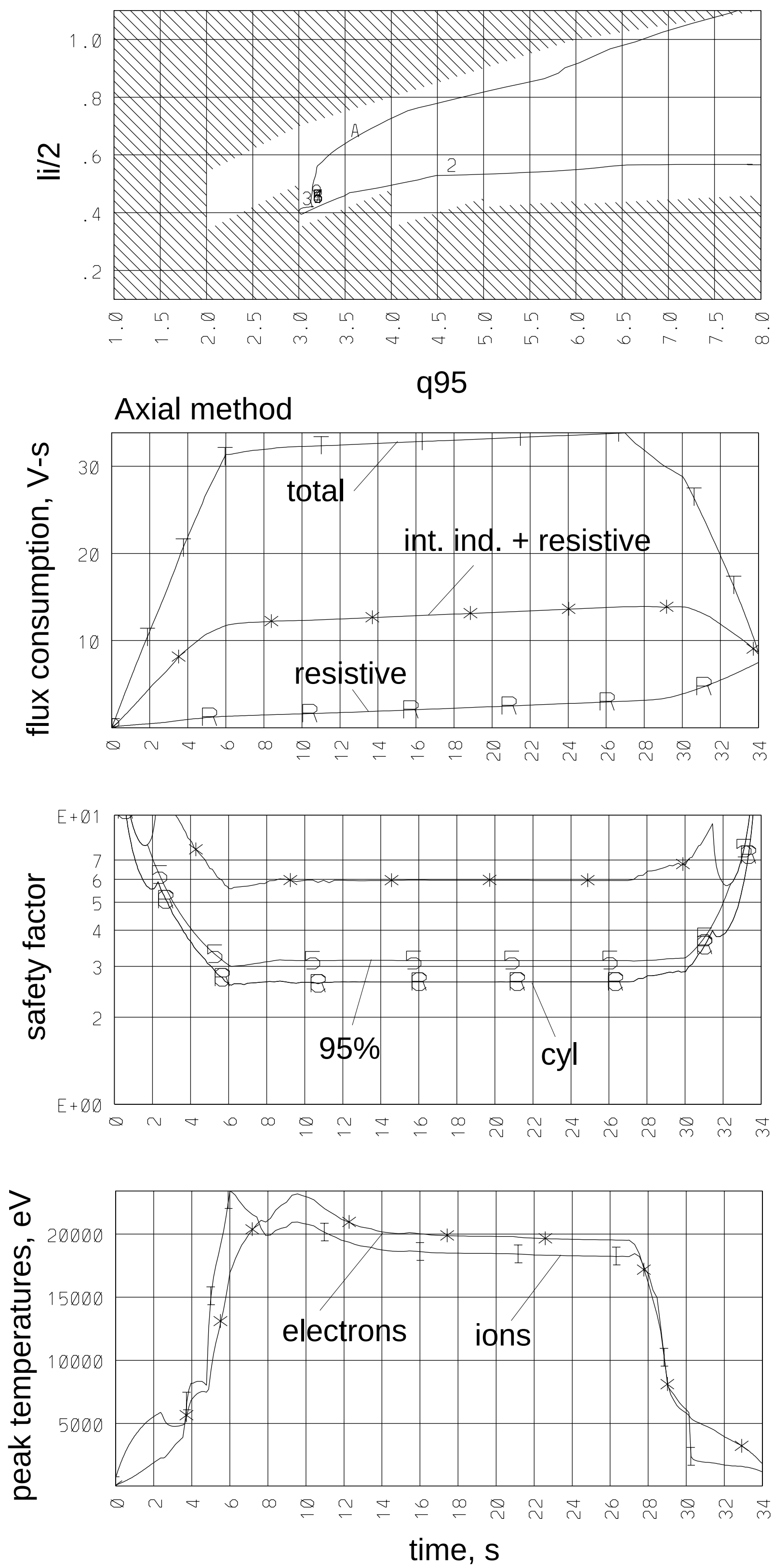


Current Rampup, t=0-6 s
I_p = 0.1→6.44 MA
B_T = 8.2→10.0 T
n_e = .05→1.8×10**20
plasma diverts at 3.2 s
30 MW heating at 4.8 s

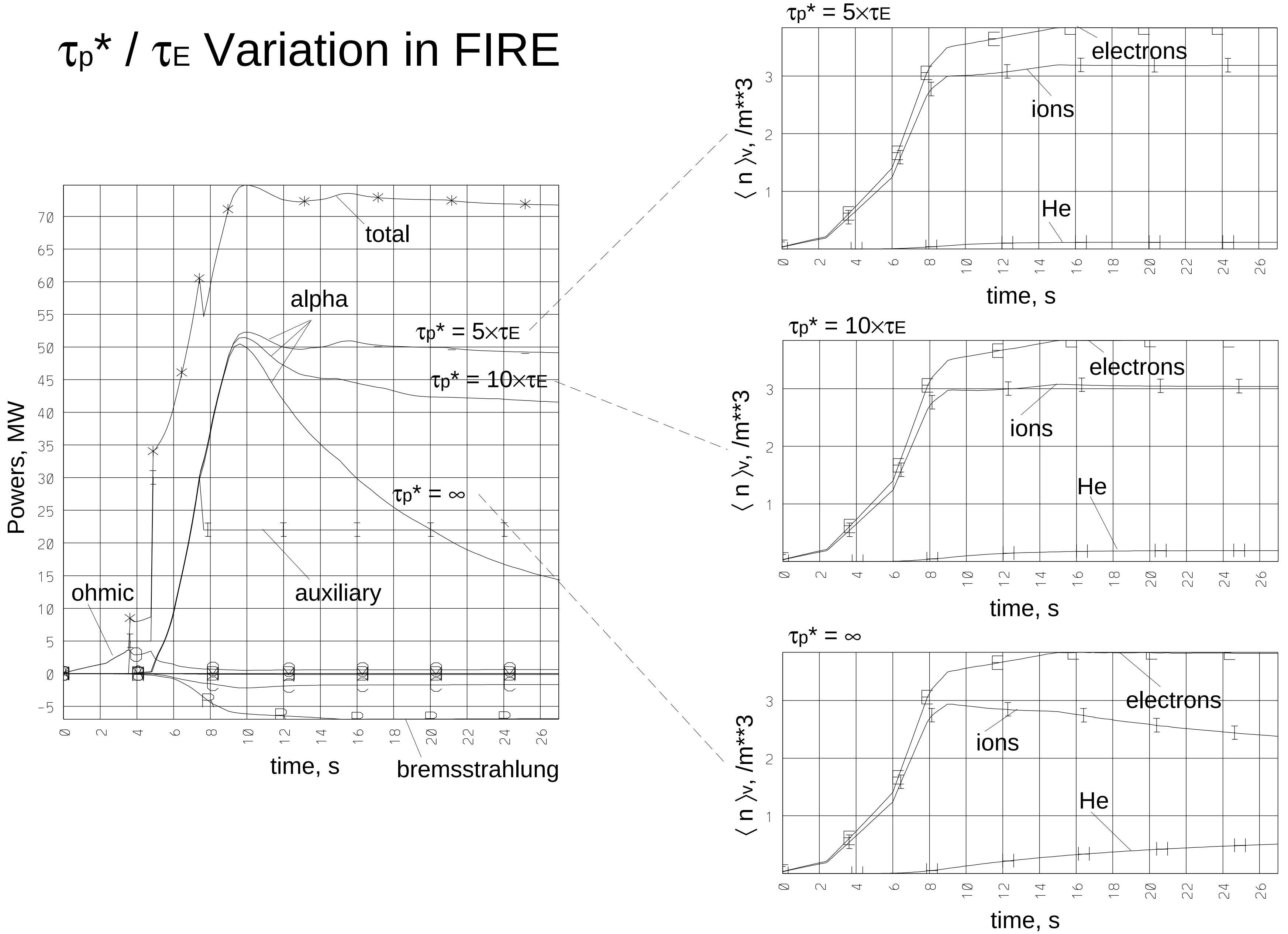
Heating to Burn and Flattop, t=6-27s
I_p and B_T fixed
n_e = 1.8→5.0×10**20
heating dropped 30→22 MW
P_α →50 MW, Q ≥ 10
$\langle n_{He} \rangle \rightarrow 4\% \langle n_e \rangle$, $Z_{eff} \rightarrow 1.4$

Burn Termination and Rampdown,
t=27-34s
stop plasma fueling
Pα drops and H→L mode
Paux is dropped 15→10→5 MW
Ip reduced to 5.0, and then 0.1 MA

FIRE Reference Discharge Scenario



τ_p^* / τ_E Variation in FIRE



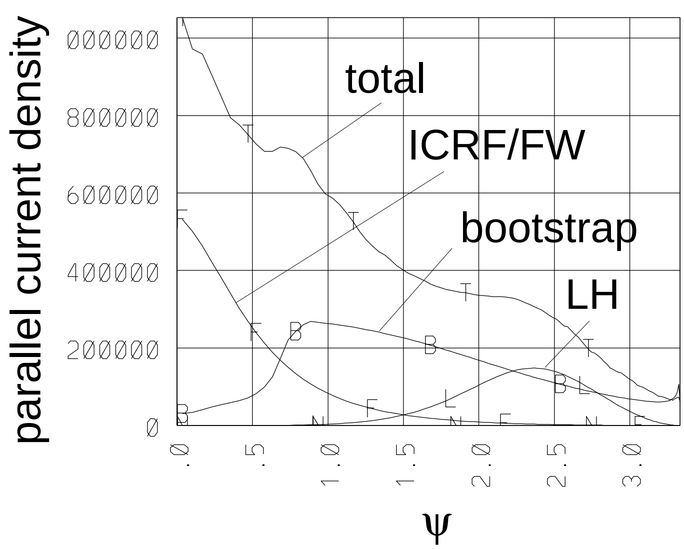
FIRE Long Pulse DD Capability

- if B_T is lowered to 4.0 T, and I_p is lowered to 2.0 MA, the pulse length reaches 250 s

- the TPX physics objectives can be achieved

- taking 14 MW of ICRF/FW
  6MW of LHCD
  $2 \times$ L-mode confinement
  $n_e(0) = 1.35 \times 10^{**}20$ /m**3
  $T_e(0) = 15$ keV

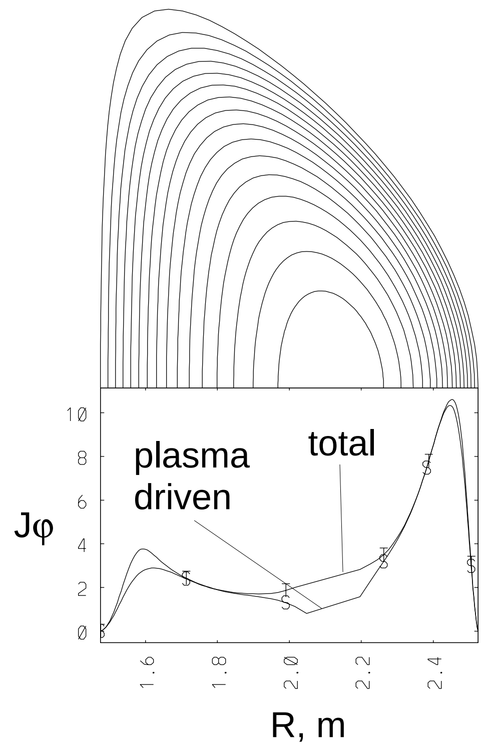
we get
I(FW) = 300 kA (phased antenna)
I(LH) = 300 kA
I(BS) = 775 kA
I(OH) = 625 kA
$V_{loop} = 0.02$ V
$\beta_N = 2.5$
$\Delta\psi$(total) = 14.6 V-s

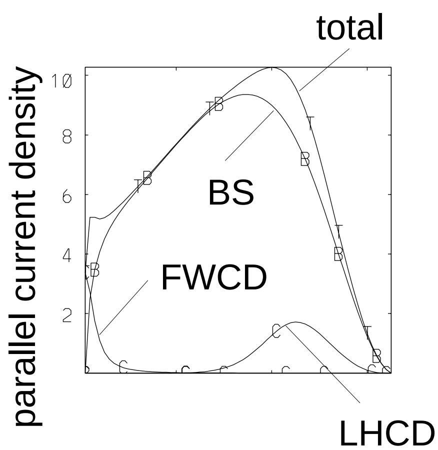


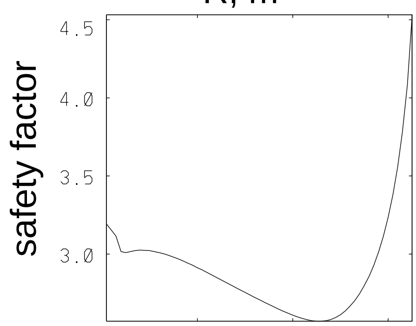
FIRE Burning AT Modes

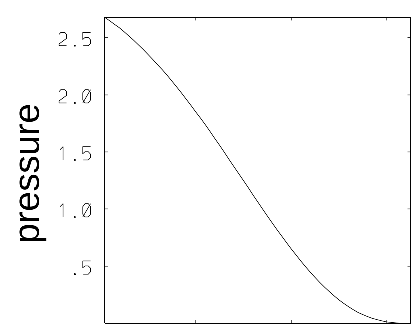
- reducing B_T to 6.75 T and I_p to 4.50 MA, a burning advanced tokamak mode with P_{fus} = 160 MW can be found

f_{bs} = 91%
I(LH) = 275 kA
I(FW) = 115 kA
$q_{axis} \approx 3.0$
q_{min} = 2.6
β_N = 4.5
n_e/n_{Gr} = 0.78
α-loss = 9.5%









- critical issues:
  - ideal MHD, kink mode
  - neoclassical tearing modes
  - alpha particle losses
  - heating/CD power
  - plasma edge compatibility
  - bootstrap current
  - achievable Q

Summary

- PF coils designed for FIRE provide the reference scenario with sufficient margin to all coil allowables to compensate plasma uncertainties

- In addition, the PF coils can provide

  – a 12 T and 7.7 MA discharge for 11 s

  – a 4 T and 2.0 MA discharge for 250 s

  – burning AT modes at reduced I_p and B_T

- the passive stabilizer design in combination with internal feedback coils provides sufficient vertical position control with reasonable power

- full discharge scenarios for FIRE

  – demonstrate Q=10 operation

  – sensitivity to plasma parameter assumptions

  – burn response/control

  – plasma current and boundary evolution, flux consumption, and feedback control

  – used in conjunction with coil heating, stress, and power supply analysis to optimize scenarios