Lower Hybrid Current Profile Control Studies in Alcator C-Mod

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Advanced Tokamak Workshop
March 9-11, 1999

Motivation

- Quasi-steady state operation at the β-limit is achievable with RF current drive in C-Mod
  - $t_{\rm pulse} \simeq (5-7)$ s @ $B_0 \simeq (4-5)$ T
  - $t_{\rm pulse}/\tau_{\rm L/R} \simeq 2$ @ $T_{\rm e}(0) \simeq 5$ keV

- Increased β-limits due to plasma shaping ($\kappa_{\rm x} \lesssim 1.8,\ \delta_{\rm x} \lesssim 0.8$)

- Full RF current drive with effective current profile control and high bootstrap current fraction ($f_{\rm BS}$) is possible:
  - Compact size ($R_0 = 0.67$ m)
  - (4–8) MW of (40–80) MHz RF power for ICRH
  - 3 MW of 4.6 GHz LHCD power

Role of Lower Hybrid Current Drive in Advanced Tokamak Physics Experiments in C-Mod

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- Efficient off-axis ($r/a \gtrsim 0.5$) current generation with $\eta_{\rm CD} \simeq 0.1 - 0.15$ (10^{20} A/W/m^2) allows:
  - → Access to second stability regime as $q(\psi) > 2$
  - → Access to enhanced confinement modes as $q(\psi)$ becomes non-monotonic and local magnetic shear is reduced

- Expect rapid thermalization of fast electron tail for $\epsilon_{\rm F} \simeq 50$ keV and $n_{\rm e} \simeq 1 - 1.5 \times 10^{20}$ m^{-3}

Overview of Numerical Models

- Current drive and MHD equilibrium code - ACCOME (MIT - JAERI - LLNL)
  - Noncircular MHD solver (SELENE)
  - Non-inductive current density source terms

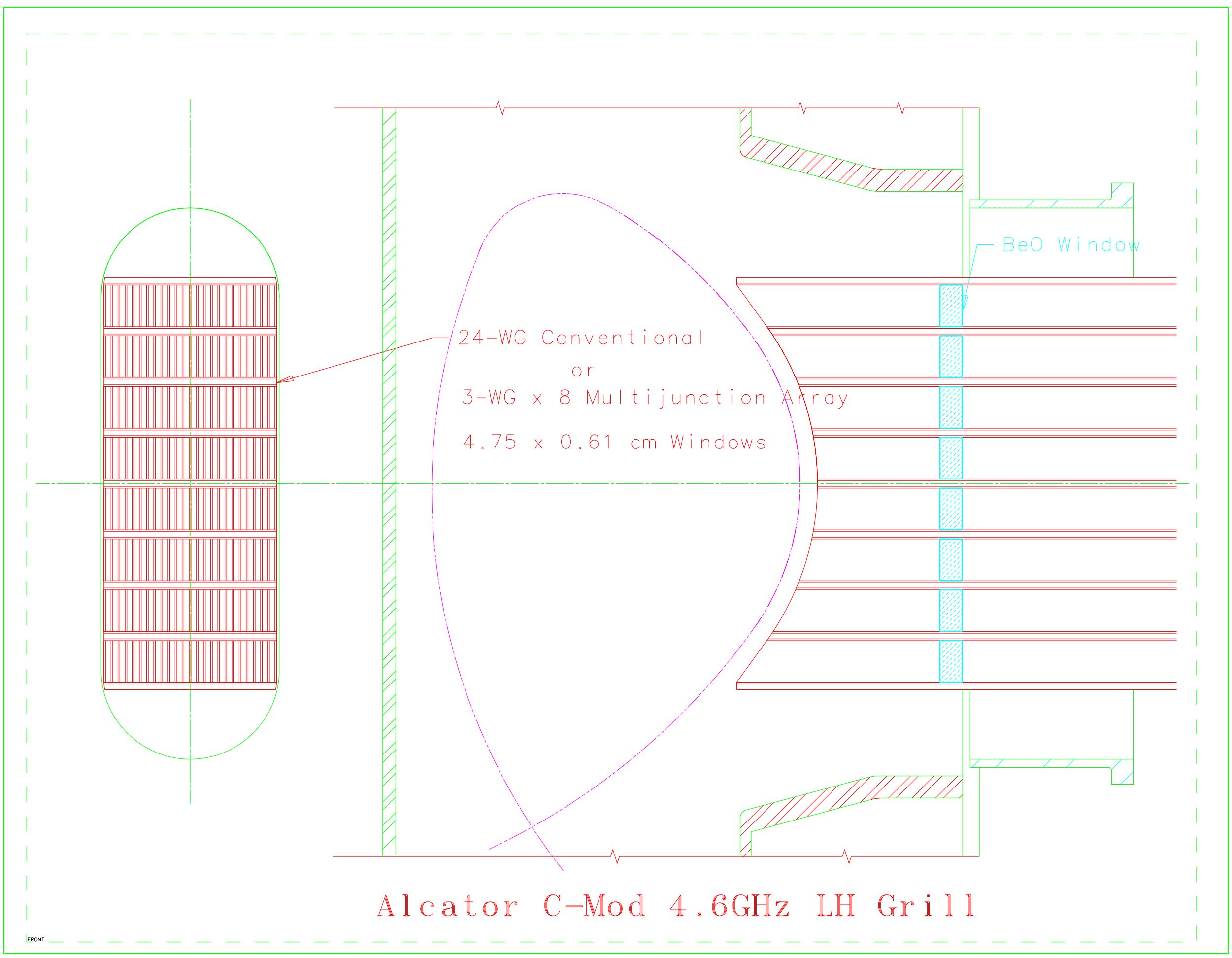
    Lower hybrid current drive (LHCD)

    ICRF fast wave current drive (FWCD)

    Bootstrap current
  - Pressure profiles are assumed in model - no transport
- Current drive modules iterate with MHD solver to obtain self-consistent MHD equilibrium
- Equilibria from ACCOME are analyzed for ideal stability:
  - JSOLVER / PEST II - (PPPL)
  - CAXE / KINX - (Keldysh Institute)

Lower Hybrid Grill - 24 Waveguides
Conceptual Design

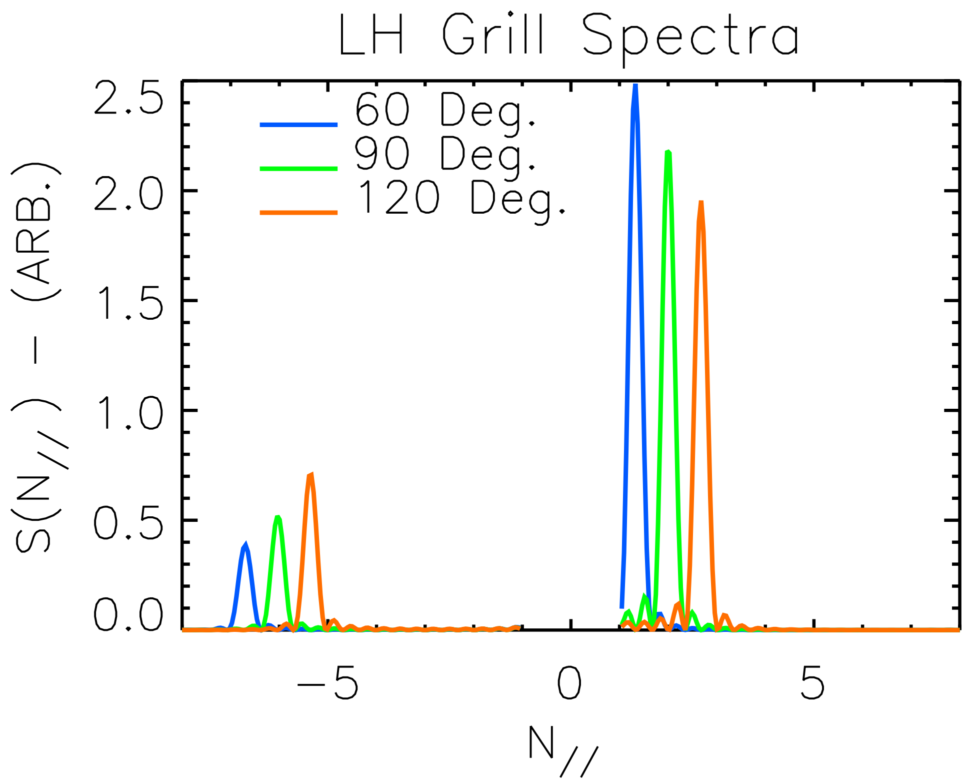
$$f_0 = 4.6 \text{ GHz}$$



Lower Hybrid Grill Spectra - 24 Waveguides

$f_0 = 4.6$ GHz, (4.755 cm $\times$ 0.61 cm) Windows

(0.2 cm Wall Thickness)



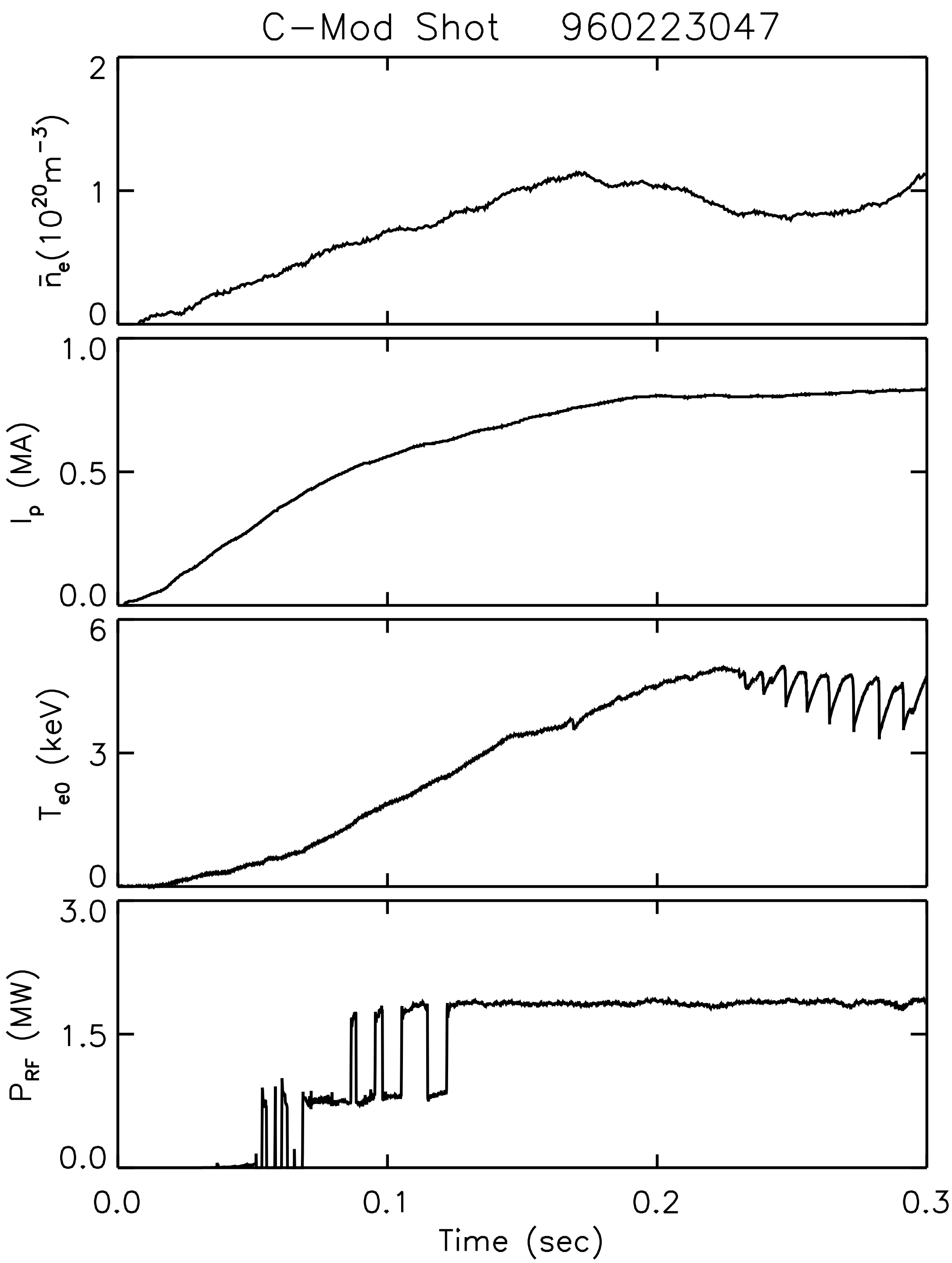
Grill Spectra calculated using a LH coupling code (M. Brambilla).

Summary of Operating Scenarios

	Start Up		β-Limit	
$H_{\mathrm{ITER-89P}}$	1.0	1.0	2.50	2.50
P_{ICH}(MW)	2.0	4.0	5.0	5.0
β_{N}	1.3	1.6	2.9	3.0
I_{p}(MA)	0.69	0.84	0.98	0.81
f_{bs}	0.41	0.45	0.70	0.74
P_{LH}(MW)	3.0	3.0	2.4	3.0

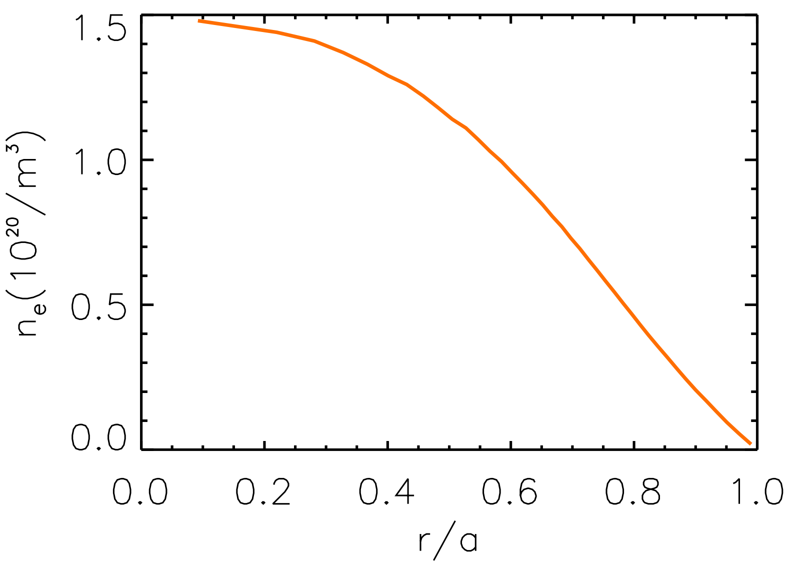
Start Up Modelled Using C-Mod Data for Current Ramp Plus High Power ICRH

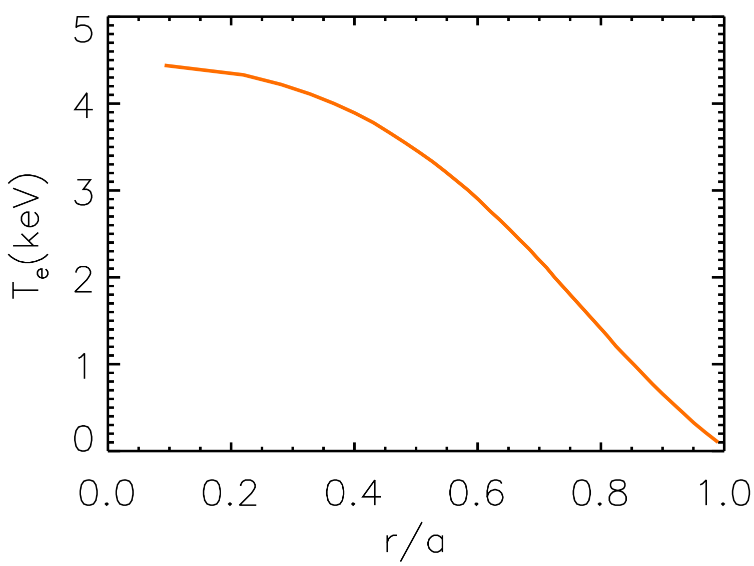
D(H) at $B_0 = 5.3$ T, $f_0 = 80$ MHz



Plasma Profiles for Start Up with Reverse Shear

$n_{\mathrm{e}}(0) = 1.5 \times 10^{20}\ \mathrm{m}^{-3} \quad T_{\mathrm{e}}(0) = 4.5\ \mathrm{keV} \quad B_0 = 4.4\ \mathrm{T}$





$p(\psi) = p(0)(1-\psi)^2 \qquad H_{\mathrm{ITER-89}} \simeq 1.0$

$n(\psi) = n(0)(1-\psi) \qquad P_{\mathrm{ICRF}} \simeq 2.0\ \mathrm{MW}$

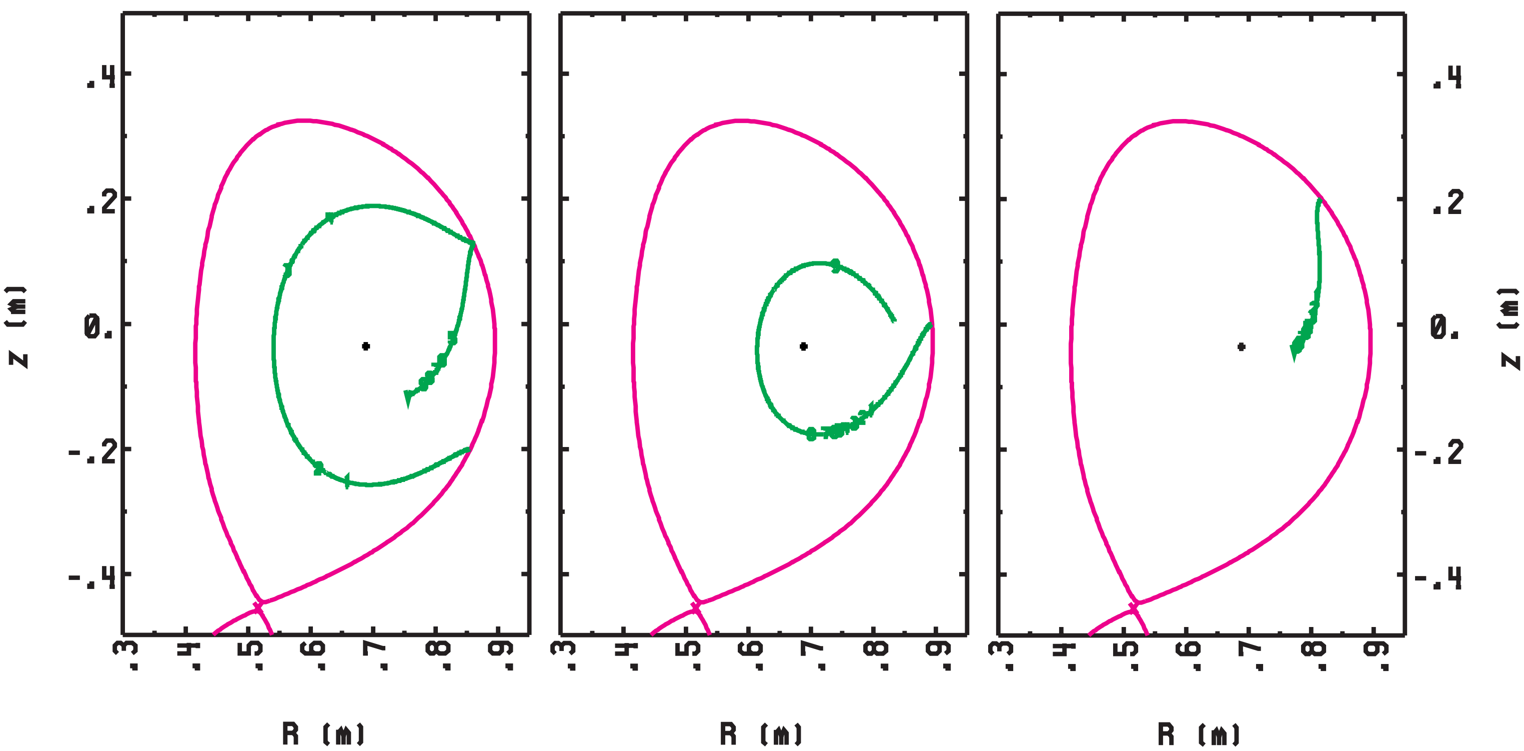
$T(\psi) = T(0)(1-\psi)$

C-Mod Start Up with Reverse Shear - ($\beta_N = 1.3$)

$n_e(0) = 1.5 \times 10^{20}$ m^{-3}, $T_e(0) = 4.5$ keV

$P_{ICRF} \simeq 2.0$ MW $H_{ITER-89} \simeq 1.0$

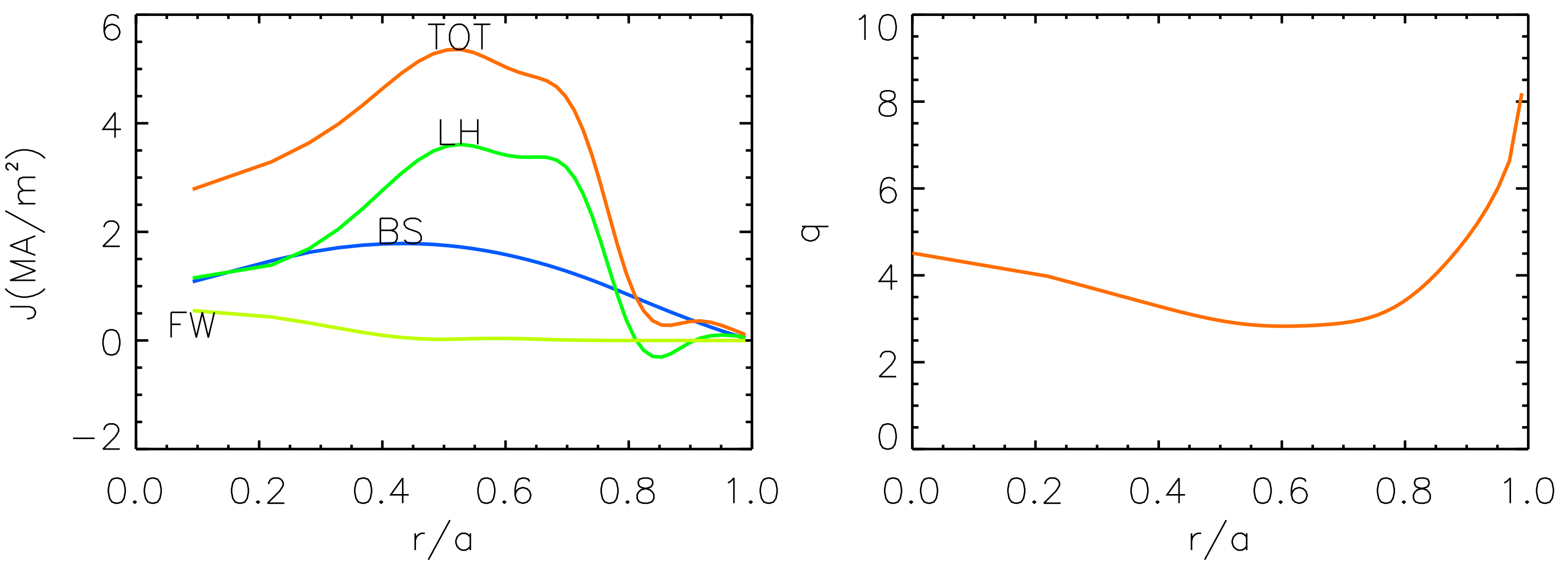
Lower Hybrid Ray Trajectories ($n_{\|}^{0} = 2.75$)



C-Mod Start Up with Reverse Shear - ($\beta_N = 1.3$)

$n_e(0) = 1.5 \times 10^{20}\ \mathrm{m}^{-3}, \quad T_e(0) = 4.5\ \mathrm{keV}$

$P_{ICRF} \simeq 2.0\ \mathrm{MW} \quad H_{ITER-89} \simeq 1.0$



$I_p = 0.69\ \mathrm{MA} \quad (f_{BS} = 0.41)$

$I_{LH} = 0.39\ \mathrm{MA}$

$P_{LH} = 3\ \mathrm{MW}\ (n_{\parallel}^0 = 2.75)$

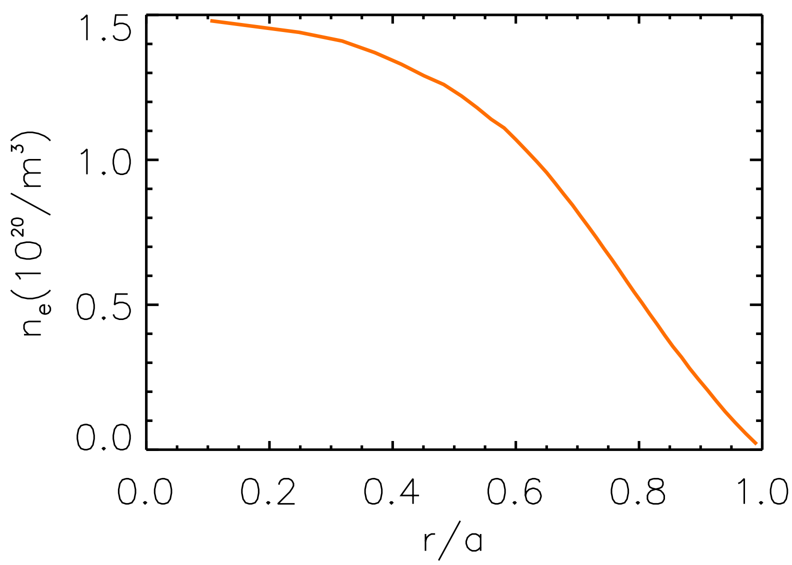
$q_0 = 4.47 \quad q_{min} = 2.83$

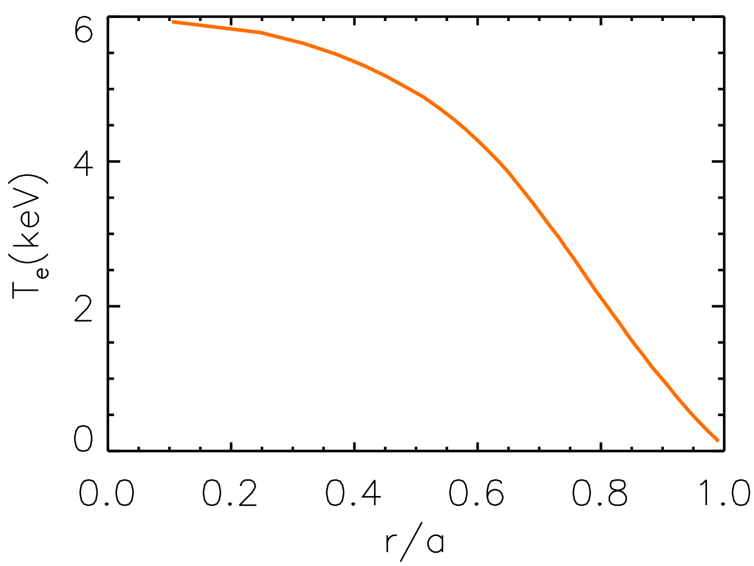
$\beta_t = 0.88\%$

$p(0)/ < p >= 3.17$

Plasma Profiles for Start Up with Reverse Shear

$n_e(0) = 1.5 \times 10^{20}\ \mathrm{m}^{-3} \quad T_e(0) = 6.0\ \mathrm{keV} \quad B_0 = 4.4\ \mathrm{T}$





$p(\psi) = p(0)(1-\psi)^2 \qquad H_{\mathrm{ITER-89}} \simeq 1.0 - 1.5$

$n(\psi) = n(0)(1-\psi) \qquad P_{\mathrm{ICRF}} \simeq 4.0\ \mathrm{MW}$

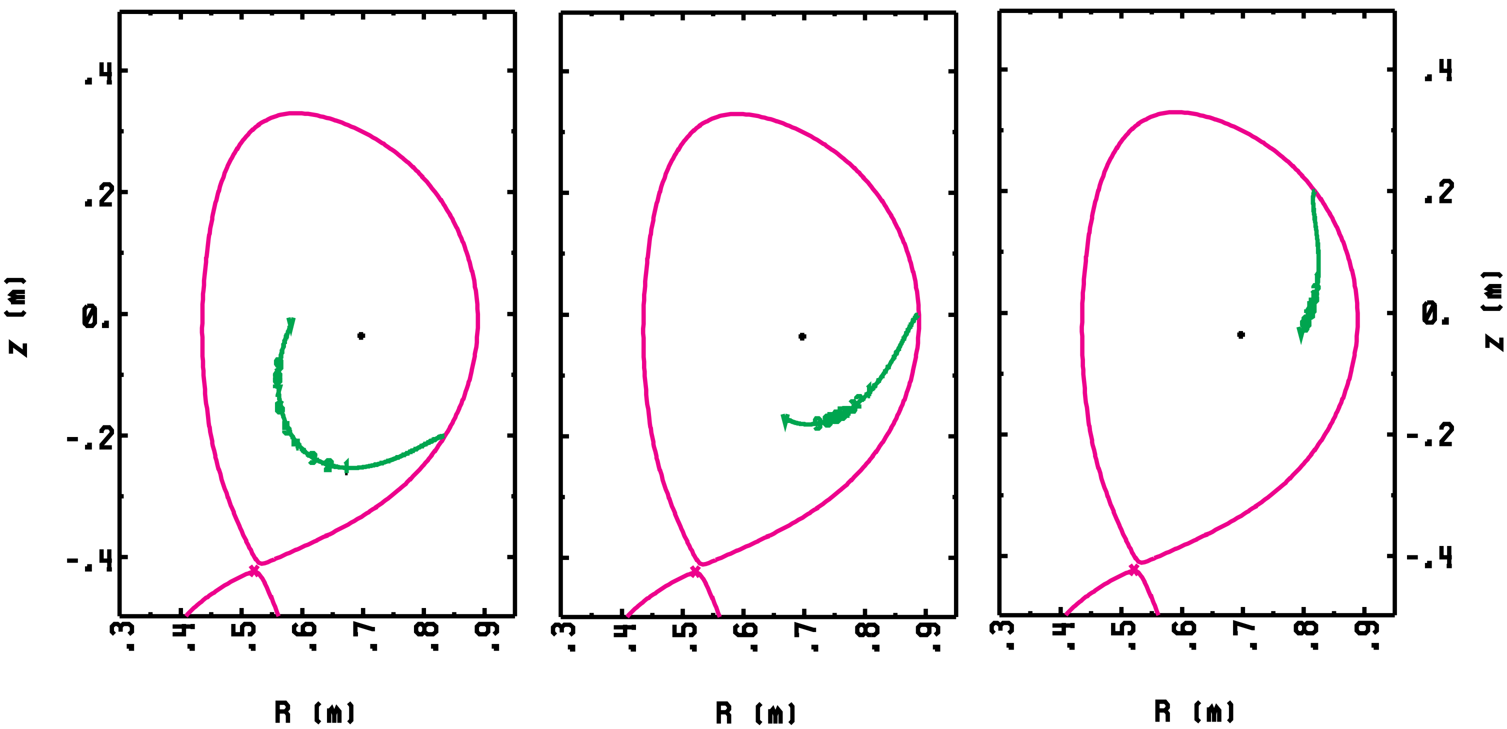
$T(\psi) = T(0)(1-\psi)$

C-Mod Start Up with Reverse Shear - ($\beta_{\mathrm{N}} = 1.6$)

$n_{\mathrm{e}}(0) = 1.5 \times 10^{20}\ \mathrm{m}^{-3}, \quad T_{\mathrm{e}}(0) = 6.0\ \mathrm{keV}$

$P_{\mathrm{ICRF}} \simeq 4.0\ \mathrm{MW} \quad H_{\mathrm{ITER-89}} \simeq 1.0 - 1.5$

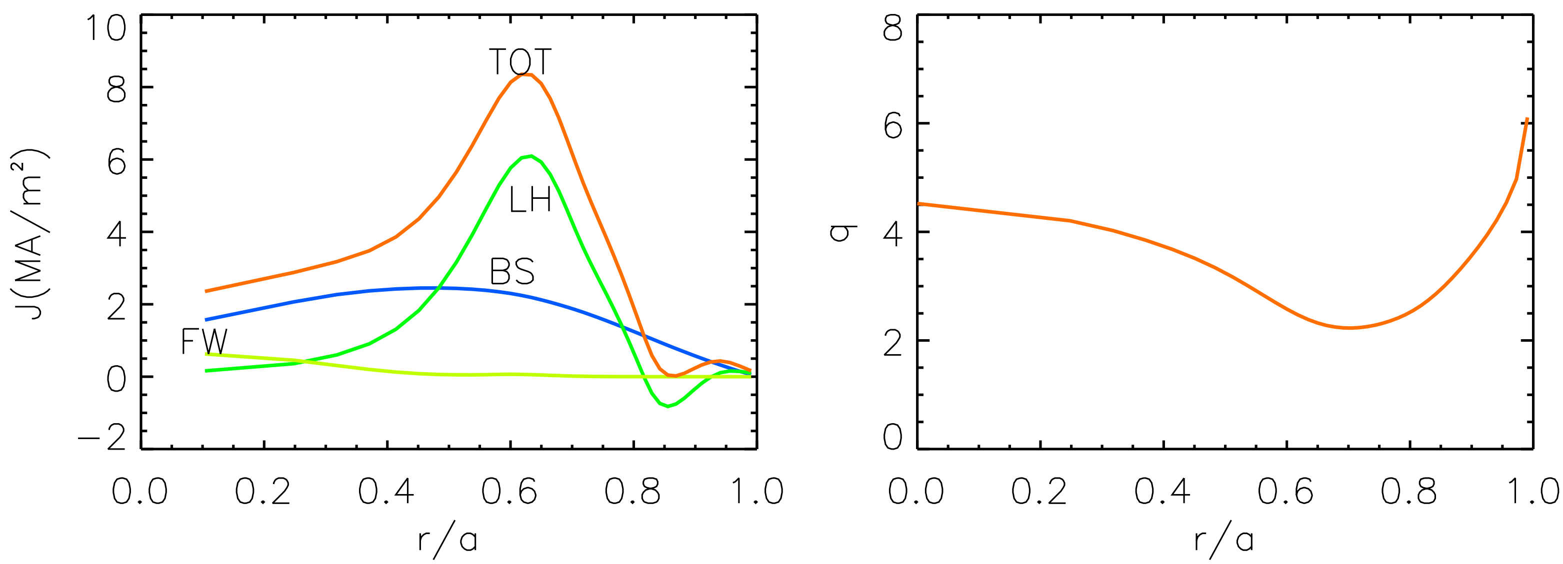
Lower Hybrid Ray Trajectories ($n_{\parallel}^{0} = 2.75$)



C-Mod Start Up with Reverse Shear - ($\beta_N = 1.6$)

$n_e(0) = 1.5 \times 10^{20}$ m^{-3}, $T_e(0) = 6.0$ keV

$P_{ICRF} \simeq 4.0$ MW $H_{ITER-89} \simeq 1.0 - 1.5$



$I_p = 0.84$ MA $(f_{BS} = 0.45)$

$I_{LH} = 0.45$ MA

$P_{LH} = 3$ MW $(n^0_{\|} = 2.75)$

$q_0 = 4.49$ $q_{min} = 2.23$

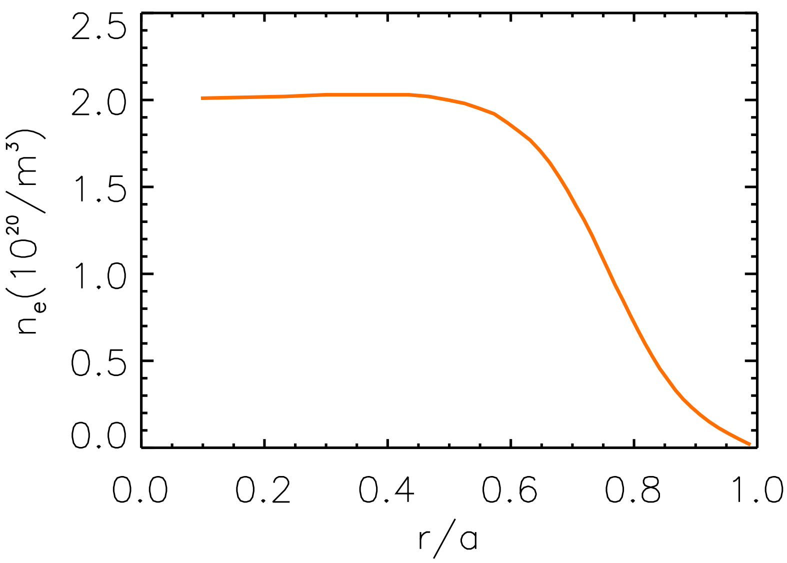
$\beta_t = 1.33\%$

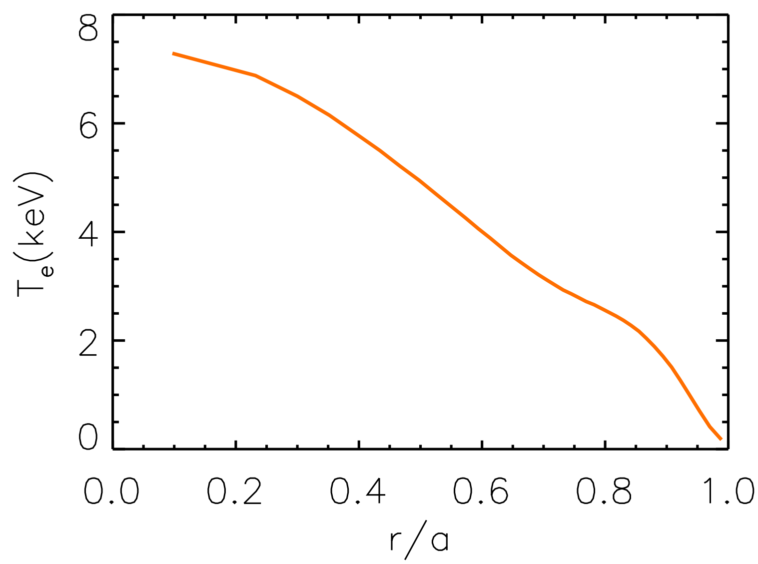
$p(0)/ < p >= 2.81$

Plasma Profiles for Reverse Shear Near the β-limit

$n_{\rm e}(0) = 2.0 \times 10^{20}\ {\rm m}^{-3} \quad T_{\rm e}(0) = 7.5\ {\rm keV} \quad B_0 = 4.0\ {\rm T}$

Plasma Profiles Simulate a Transport Barrier





$$p(\psi) = p(0)(1-\psi)^2 \qquad H_{\rm ITER-89} \simeq 2.5$$

$$n(\psi) = p(\psi)/T(\psi) \qquad P_{\rm ICRF} \simeq 5.0\ {\rm MW}$$

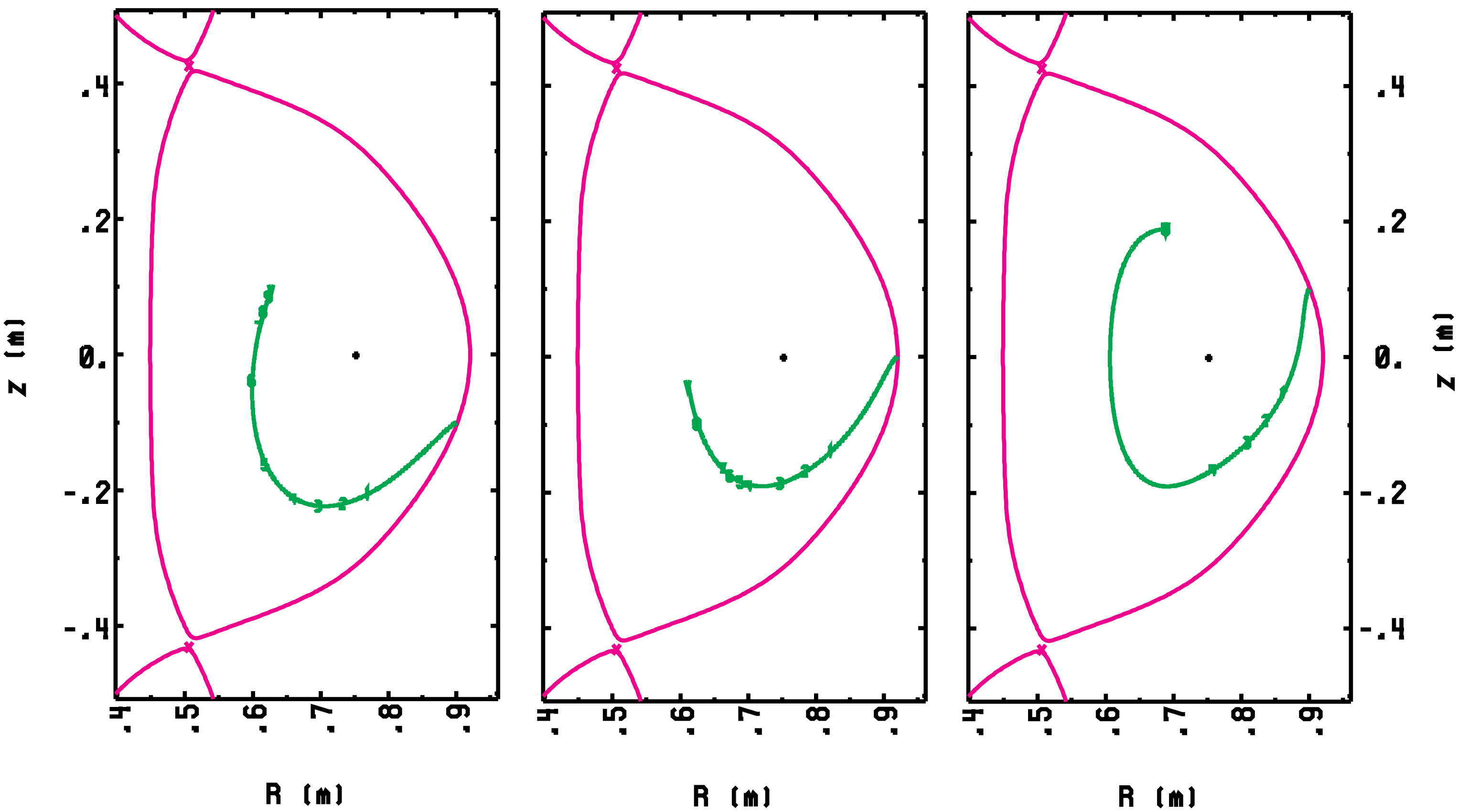
$$T(\psi) = T(0)[\tfrac{2}{3}(1-\psi)^{5/2} + \tfrac{1}{3}(1-\psi^8)^{3/2}]$$

Reverse Shear Mode Near the β-limit ($\beta_N = 3.0$)

$n_e(0) = 2.0 \times 10^{20}$ m^{-3}, $T_e(0) = 7.5$ keV

$P_{ICRF} \simeq 5.0$ MW $H_{ITER-89} \simeq 2.5$

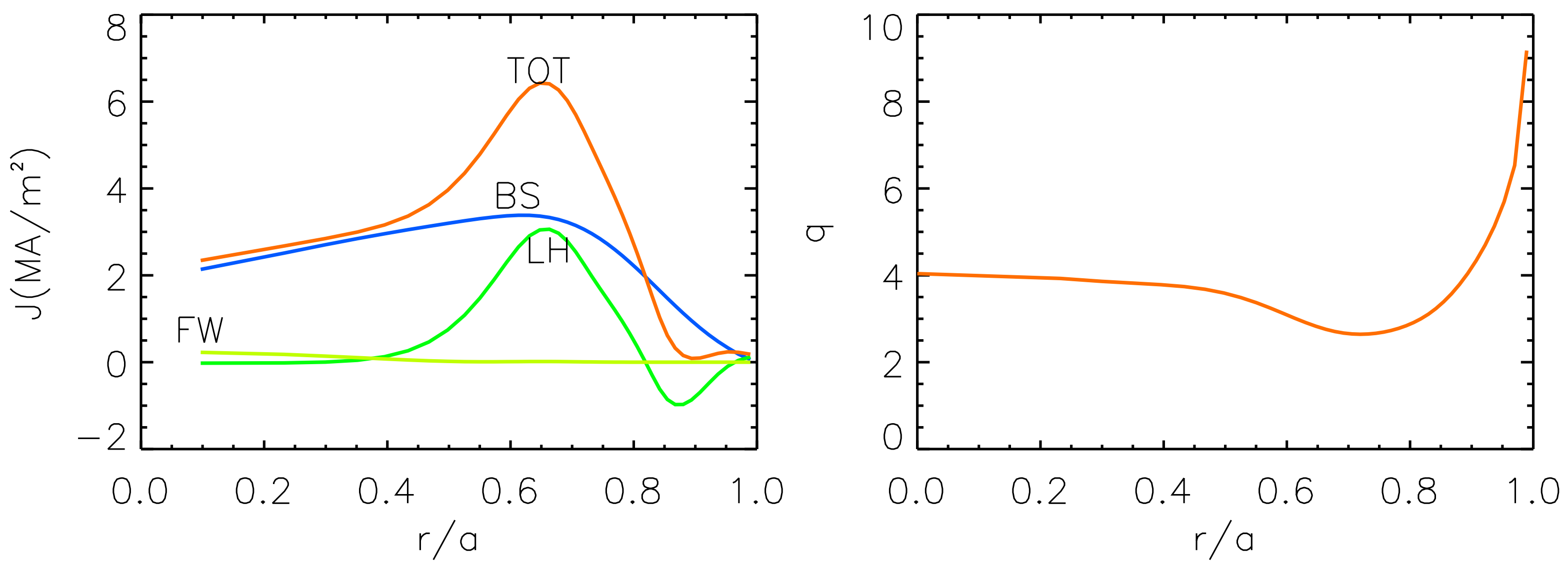
Lower Hybrid Ray Trajectories ($n_{\parallel}^0 = 2.75$)



Reverse Shear Mode Near the β-limit ($\beta_N = 3.0$)

$n_e(0) = 2.0 \times 10^{20}\ m^{-3}, \quad T_e(0) = 7.5$ keV

$P_{ICRF} \simeq 5.0$ MW $\quad H_{ITER-89} \simeq 2.5$



$I_p = 0.81$ MA $\quad (f_{BS} = 0.74)$

$I_{LH} = 0.19$ MA

$P_{LH} = 3$ MW $(n_{\|}^0 = 3.00)$

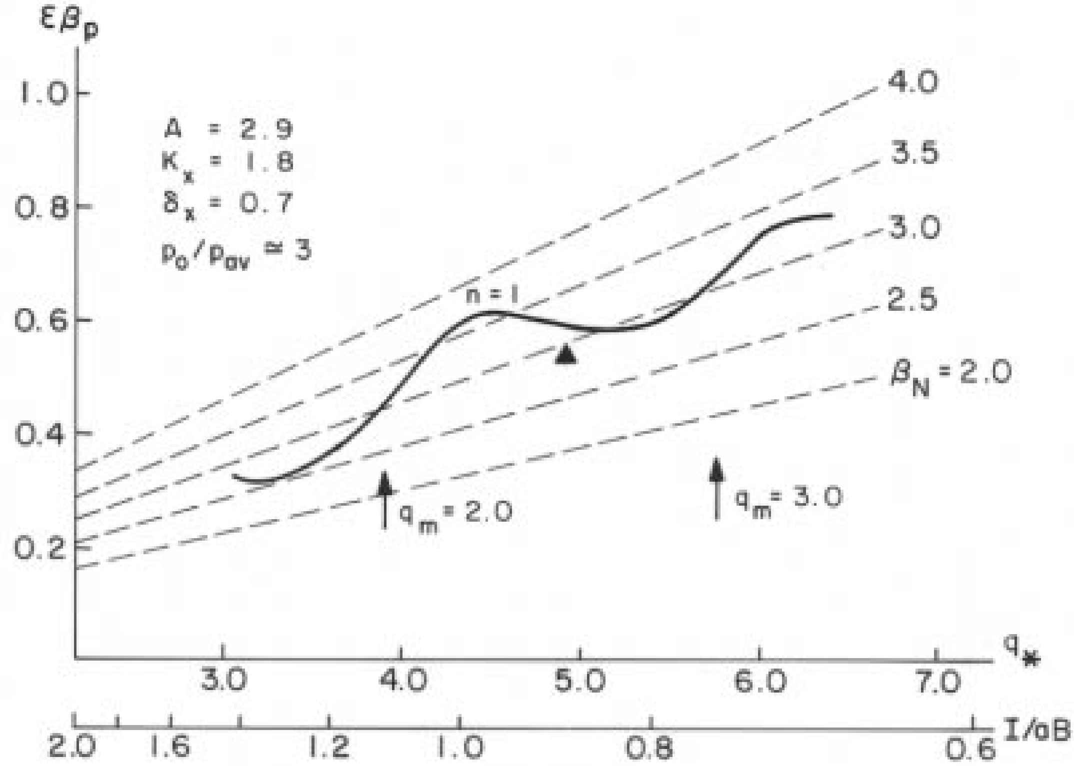
$q_0 = 3.95 \quad q_{min} = 2.65$

$\beta_t = 2.60\%$

$p(0)/ < p >= 2.90$

Ideal MHD Stability Analysis Using PEST-II

Analyze ACCOME equilibrium at $\beta_{\mathrm{N}} \simeq 3.0$



- Results with $r_{\mathrm{wall}} = \infty$

  $\beta_{\mathrm{N_{crit}}} \simeq 3.7 \rightarrow$ set by $n = 1$ external kink mode

- Results with $r_{\mathrm{wall}} = 1.3\ a$

  $\beta_{\mathrm{N_{crit}}} \simeq 4.5 - 5.0 \rightarrow$ set by $n = 3$ external mode

Time Dependent Modelling

(Work in Progress)

- Use TRANSP to simulate LH current profile control in experimental discharge with I_{p} ramp plus ICRH.

  ICRH $\Longrightarrow$ FPPRF module

  LHCD $\Longrightarrow$ LSC Code (D. Ignat)

- **Goals:**

  Show that off-axis LHCD can be used to sustain a RS discharge with $q(\psi) > 2$.

  Study sensitivity of LHCD profile to changes in $n_{\mathrm{e}}(r,t)$, $T_{\mathrm{e}}(r,t)$, $T_{\mathrm{i}}(r,t)$.

  Use $\chi_{\mathrm{e}}(r,t)$ from previous TRANSP analysis of a C-Mod shot to predict $T_{\mathrm{e}}(r,t)$ in presence of LH electron heating.

TRANSP / LSC Modellling Set-Up

- $I_{\rm p}$ ramped up from 200 kA to 800 kA
- ICRF heating of bulk plasma:

  $B_0 = 5.3$ T $\quad f_0 = 80$ MHz

  D(H) - (95%:5%)

- Lower hybrid Current Drive

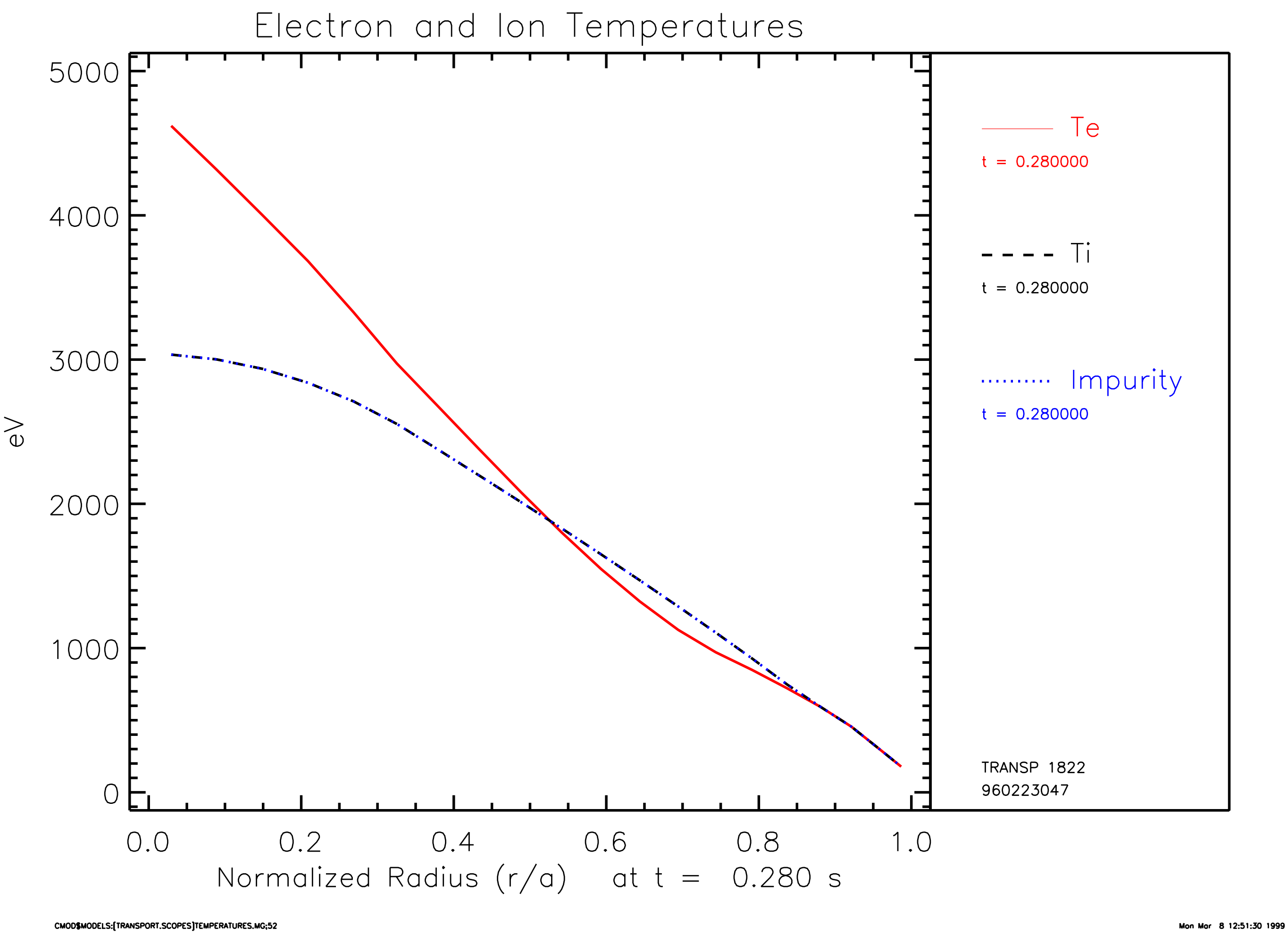
  $f_0 = 4.6$ GHz $\quad P_{\rm LH} = 2.7$ MW

  "Compound" Lower Hybrid Spectrum

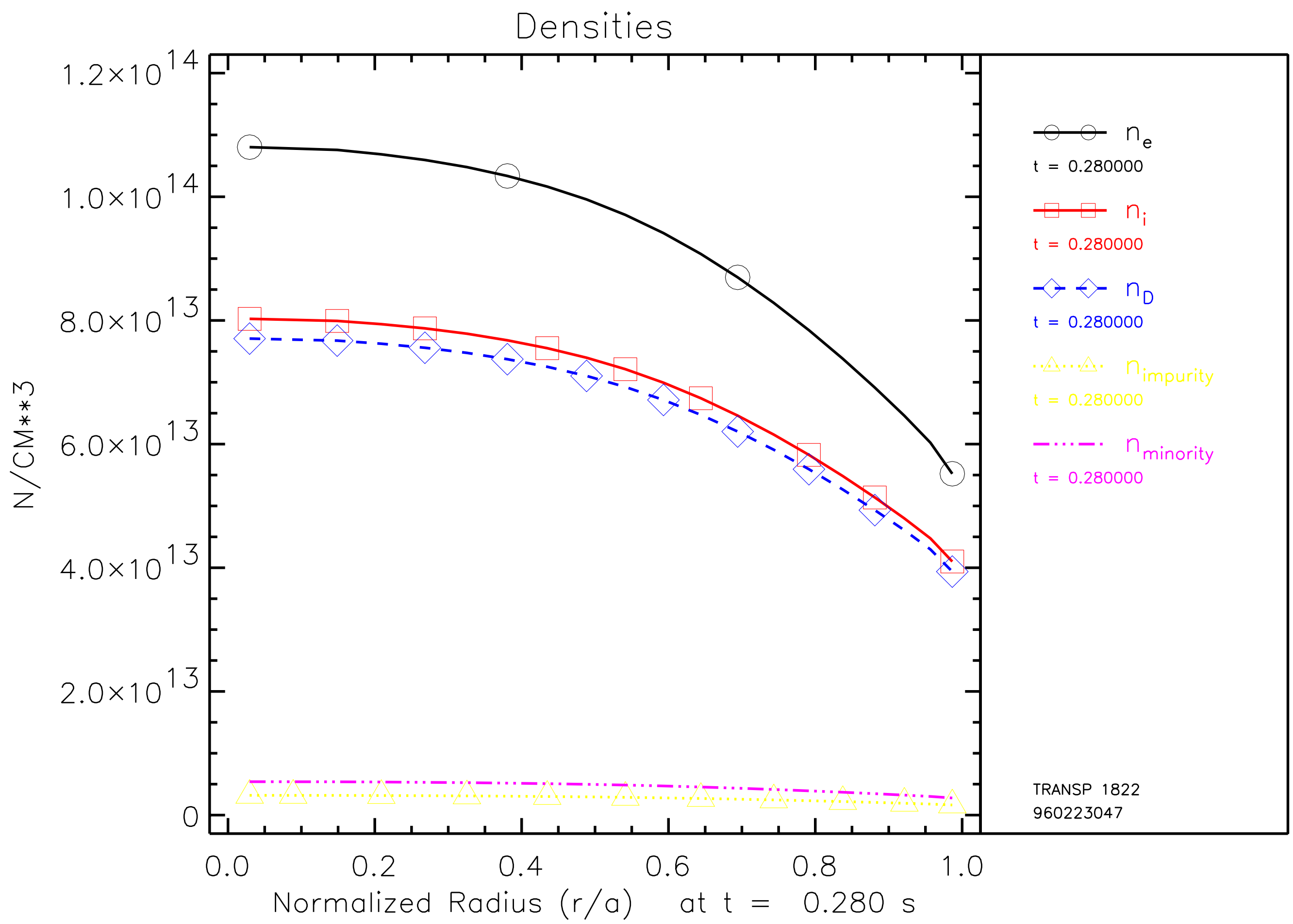
  $\rightarrow$ $P_{\rm LH}(n_{||} = 2.75) = 2.25$ MW

  $\rightarrow$ $P_{\rm LH}(n_{||} = 4.00) = 0.45$ MW

Experimental Temperature Profiles Used in TRANSP / LSC Analysis



Experimental Density Profiles
Used in TRANSP / LSC Analysis

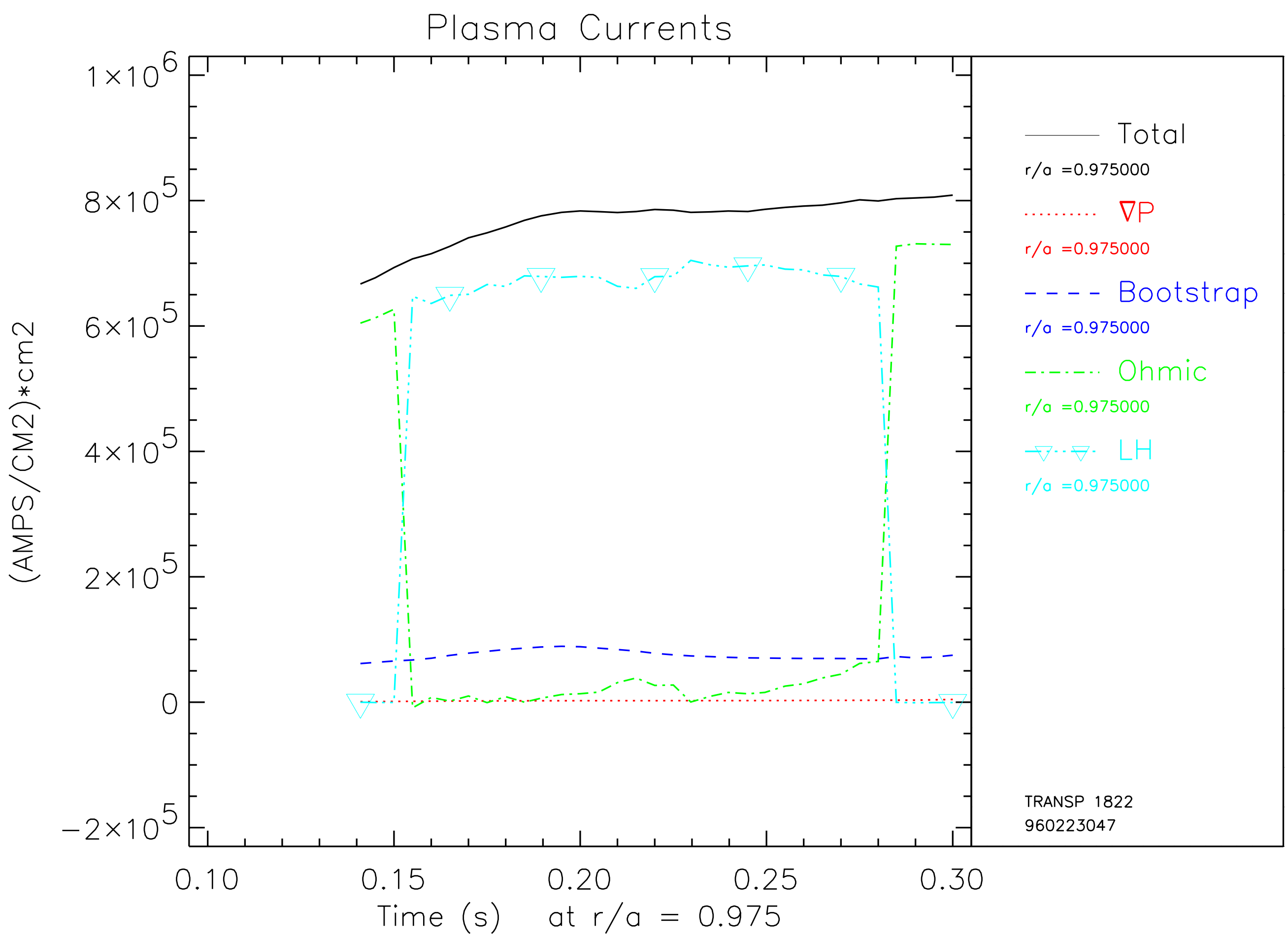


CMOD$MODELS:[TRANSPORT.SCOPES]DENSITIES.MG;29

Mon Mar 8 12:48:39 1999

TRANSP / LSC Modelling - Time Evolution of Currents

$P_{\rm LH} = 2.7$ MW $\quad f_0 = 4.6$ GHz



CMOD$MODELS:[TRANSPORT.SCOPES]CURRENTS.MG;20

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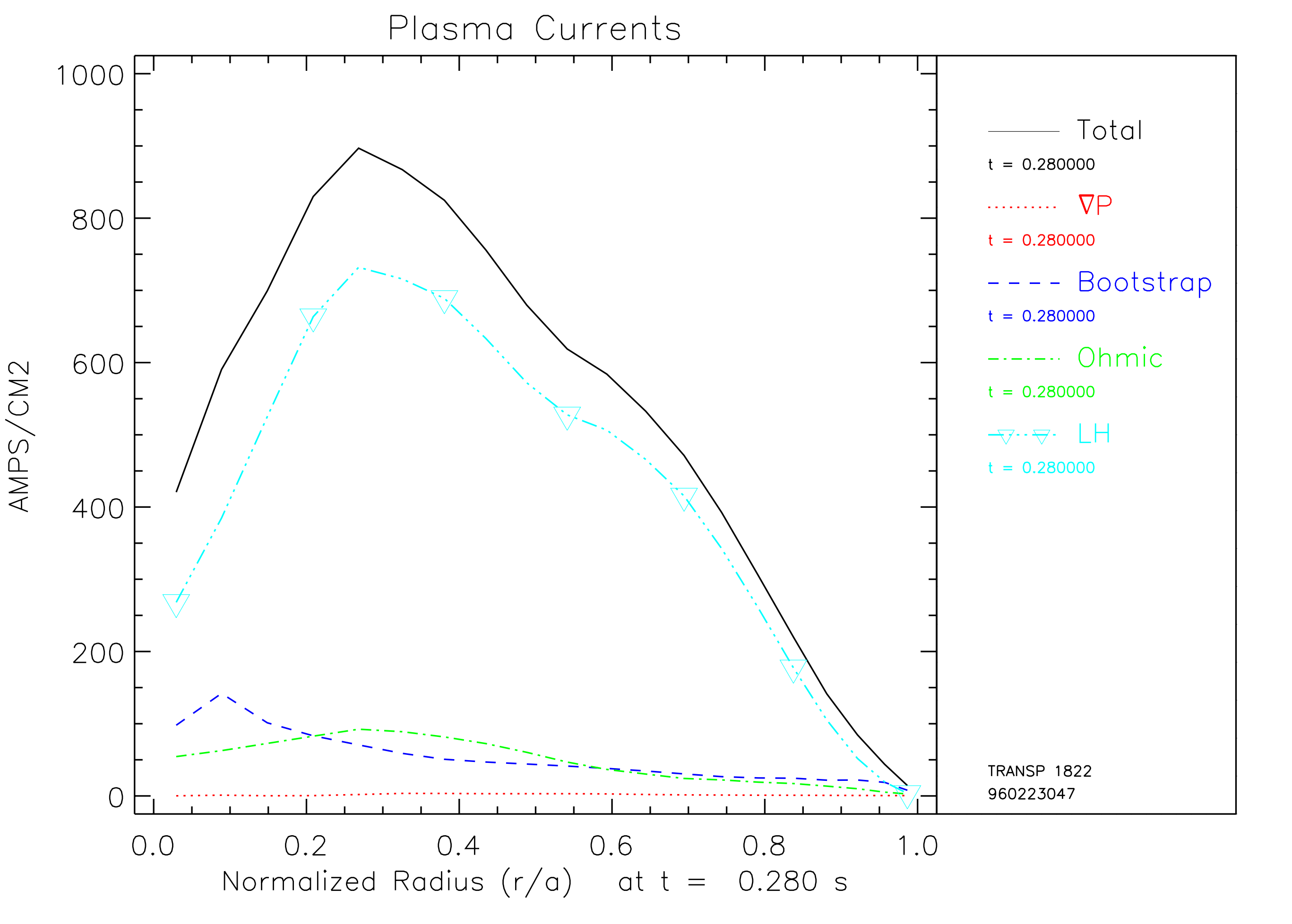
TRANSP / LSC Modelling - Current Density Profiles at 0.28 s

$P_{\rm LH} = 2.7$ MW $\quad f_0 = 4.6$ GHz



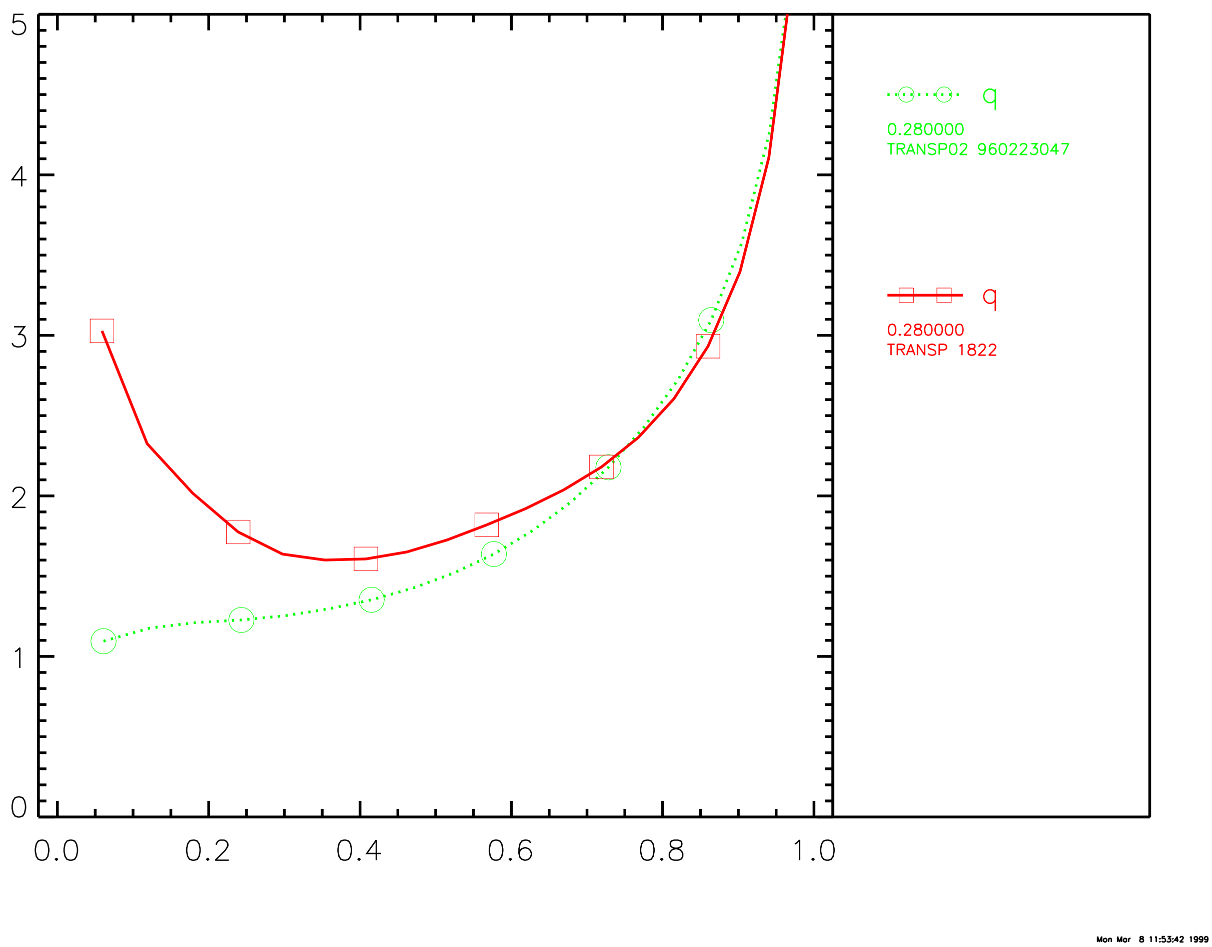
$I_{\rm LH} = 660$ kA

$I_{\rm BS} = 70$ kA

$I_{\rm OH} = 70$ kA

TRANSP / LSC Modelling -
Q-Profiles at 0.28 s

$P_{\rm LH} = 2.7$ MW $\quad f_0 = 4.6$ GHz



Solid Curve $\Longrightarrow$ OH Ramp + ICRF + LHCD

Dotted Curve $\Longrightarrow$ OH Ramp + ICRF Only

Time Dependent Modelling - Future Work

- Use $\chi_{\rm e}(r,t)$ from TRANSP shot analysis to **predict** $T_{\rm e}(r,t)$ with OH ramp plus ICRF plus LHCD.

- Simulate an ITB by assuming:

$$\chi_{\rm i}(r,t) = \chi_{\rm i}^{\rm NEO}, \quad r \le r(q_{\rm min})$$
$$\chi_{\rm i}(r,t) = \chi_{\rm i}^{\rm ANAL}, \quad r > r(q_{\rm min})$$

ICRF Heating Scenarios for Advanced Tokamak Operation in Alcator C-Mod

- D(H) @ (4.0 T & 60 MHz)

  (H) – minority heating on-axis

- $D(2\Omega_{^3\mathrm{He}})$ @ (4.0 T & 80 MHz)

  $(2\Omega_{^3\mathrm{He}})$ – heating on-axis

- D(H) @ (4.4 T, 60 & 80 MHz)

  (H) – minority heating off-axis
  $[r/a \simeq (0.35 - 0.45)]$

Conclusions

- Stationary (time) and time dependent modelling of lower hybrid current drive in Alcator C-Mod indicates that it is a promising technique for off-axis current profile control.

- Reversed shear current density profiles can be maintained using 3 MW of off-axis LHCD power as the plasma evolves from start up ($\beta_\mathrm{N} \simeq 1.0$).

- Strong plasma shaping in C-Mod has been found to result in increased ideal MHD β-limits relative to circular and elliptical plasmas.

- Time dependent modelling using TRANSP & LSC is now underway to determine the sensitivity of the LHRF current drive physics and system design to changes in plasma density and electron temperature.