High Bootstrap Fraction Scenarios without Conducting Walls

J. J. Ramos in collaboration with P. T. Bonoli

Plasma Science and Fusion Center
MIT

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"ADVANCED TOKAMAK" CONCEPT

* STEADY STATE.

* NON-INDUCTIVE CURRENT WITH EXTERNAL CONTROL OF ITS PROFILE.

* HIGH β_P AND f_{BS}.

* HOLLOW q-PROFILE, $q_{min} > 2$.

* MACROSCOPIC STABILITY AGAINST ALL ($n \neq 0$) MHD MODES WITHOUT CONDUCTING WALLS.

TOPICS:

(1) GEOMETRY AND PROFILE OPTIMIZATION.

(2) SELF-CONSISTENT SIMULATION OF CURRENT DRIVE AND CURRENT PROFILE CONTROL.

(3) SIMULATION OF TRANSPORT BARRIER PRESSURE PROFILES.

(1), (2): P.T. Bonoli et al., Plasma Phys. Contr. Fusion 39, 22 (1997).

M. Porkolab et al., in Fusion Energy 1998 (IAEA, Vienna 1999) p. 1267

J. J. Ramos, GA workshops (1999)

(1) GEOMETRY AND PROFILE OPTIMIZATION

* FIXED BOUNDARY EQUILIBRIA WITH ANALYTIC BOUNDARY SHAPE.

* SMOOTH, ANALYTIC $\langle j \rangle(\psi)$, $n(\psi)$ AND $T(\psi)$ PROFILES.

* NUMERICAL SIMULATIONS WITH J-SOLVER AND PEST-II CODES

OPTIMIZED PROFILES FOR HIGH f_{bs}

$A = 3.0$

$\kappa = 1.8$

$\delta = 0.5$

$I/aB = 1.09$ MA/mT

$q_0 = 3.4$

$q_{min} = 2.2$

$q_a = 6.1$

$\beta_p = 1.5$

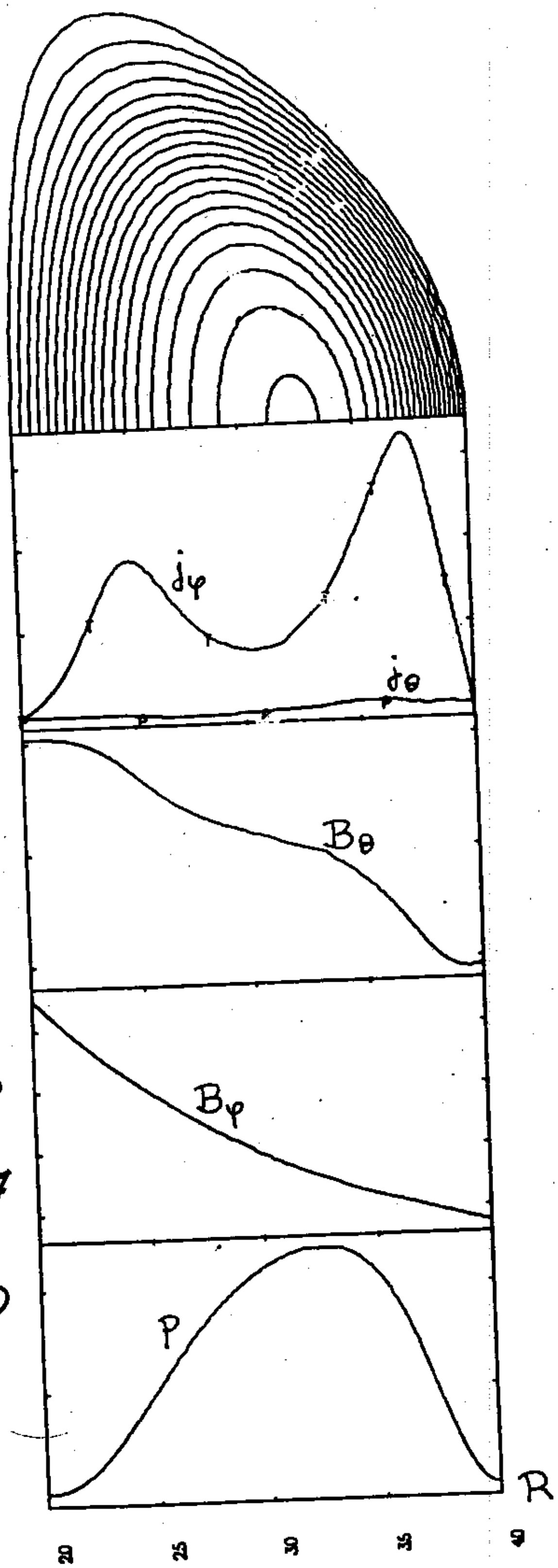
$\beta_N = 3.1$

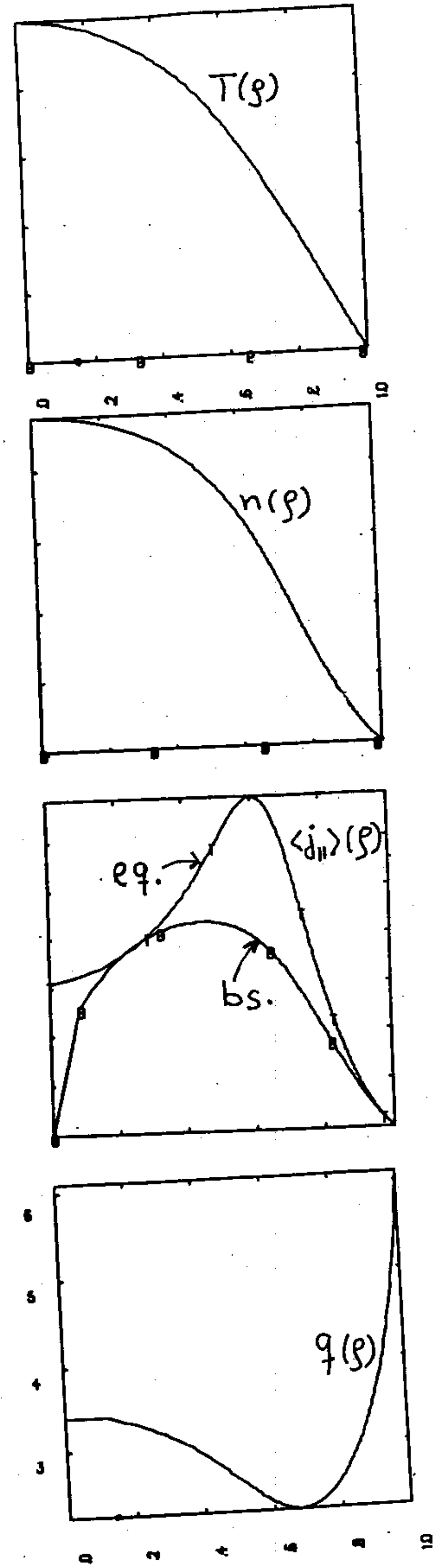
$\beta = 3.4\%$

$p_0/p_{av} = 2.8$

$l_i = 0.77$

$f_{bs} = 0.70$





(2) SELF-CONSISTENT SIMULATION OF CURRENT DRIVE

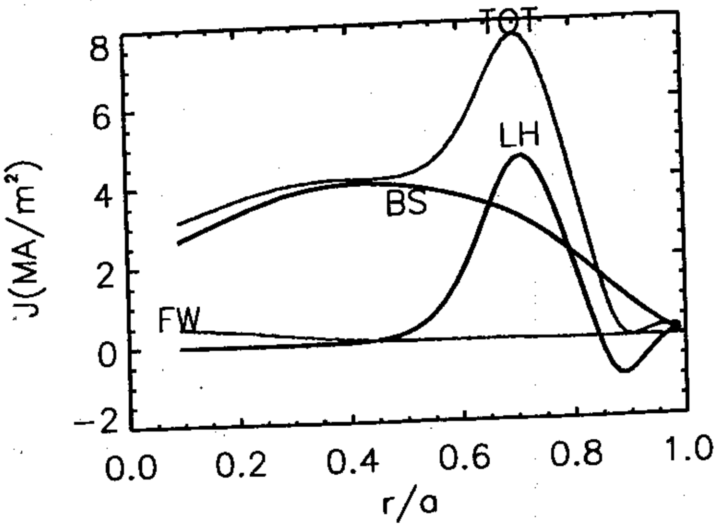
* FREE BOUNDARY EQUILIBRIA WITH REALISTIC P.F. COIL SET.

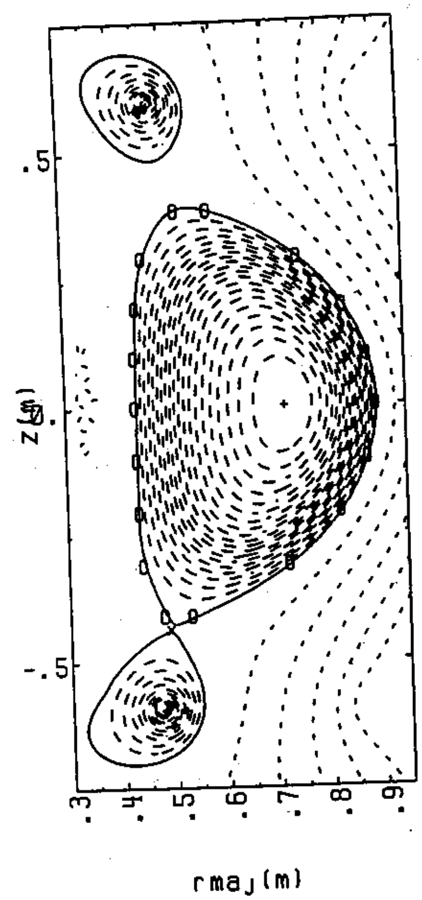
* SMOOTH, ANALYTIC $n(\psi)$ AND $T(\psi)$ PROFILES FROM PREVIOUS OPTIMIZATION

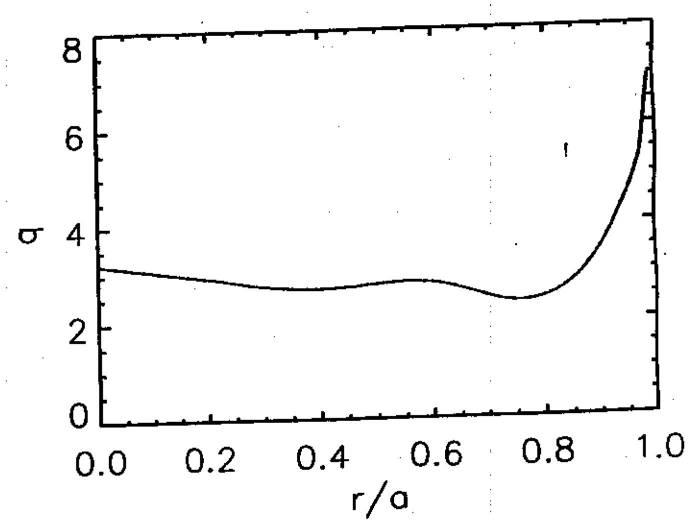
* SELF-CONSISTENT EVALUATION OF $\langle j \rangle(\psi)$ PROFILE INCLUDING BOOTSTRAP, LOWER-HYBRID AND NEUTRAL BEAM CURRENT DRIVE

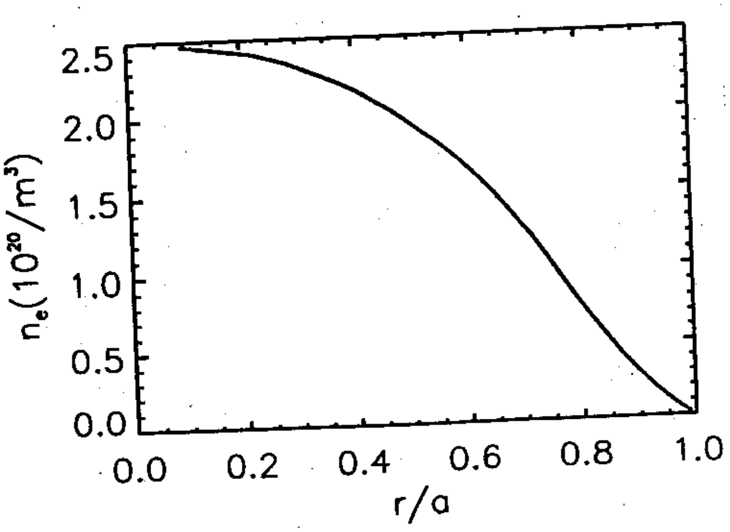
* NUMERICAL ANALYSIS WITH ACCOME, CAXE AND KINX CODES

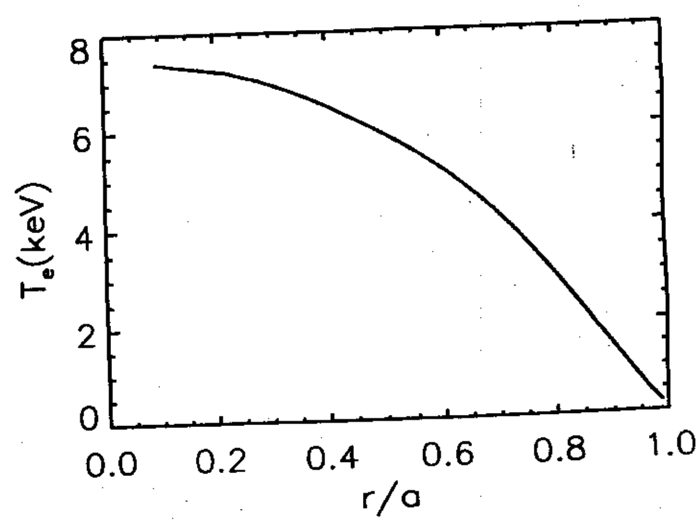
ALCATOR C-MOD "A.T." EQUILIBRIUM











ACCOME RESULTS OF ALCATOR-C-MOD "ADVANCED TOKAMAK" EQUILIBRIUM.

$n_e(0) = 2.5 \times 10^{20}\ \mathrm{m}^{-3}$ $T_e(0) = 7.5$ keV $B_0 = 4.0$ T

$p(\psi) = p(0)(1-\psi)^2$

$T(\psi) = T(0)[0.7\ (1-\psi)^{3/2} + 0.3(1-\psi^4)]$

$n(\psi) = p(\psi)/T(\psi)$

$H_{\mathrm{ITER-89}} \simeq 2.5$

$P_{\mathrm{ICRF}} \simeq 5.0$ MW

$I_p = 0.98$ MA $f_{BS} = 0.70$

$I_{LH} = 0.28$ MA

$P_{LH} = 2.4$ MW $(n_\parallel^0 = 2.75)$

$q_0 = 3.20$ $q_{min} = 2.39$

$\beta_t = 3.13\%$ $\beta_N = 2.9$

$p(0)/ <p> = 3.01$

STABILITY DIAGRAM AFTER ALCATOR C-MOD "A.T." EQUILIBRIUM

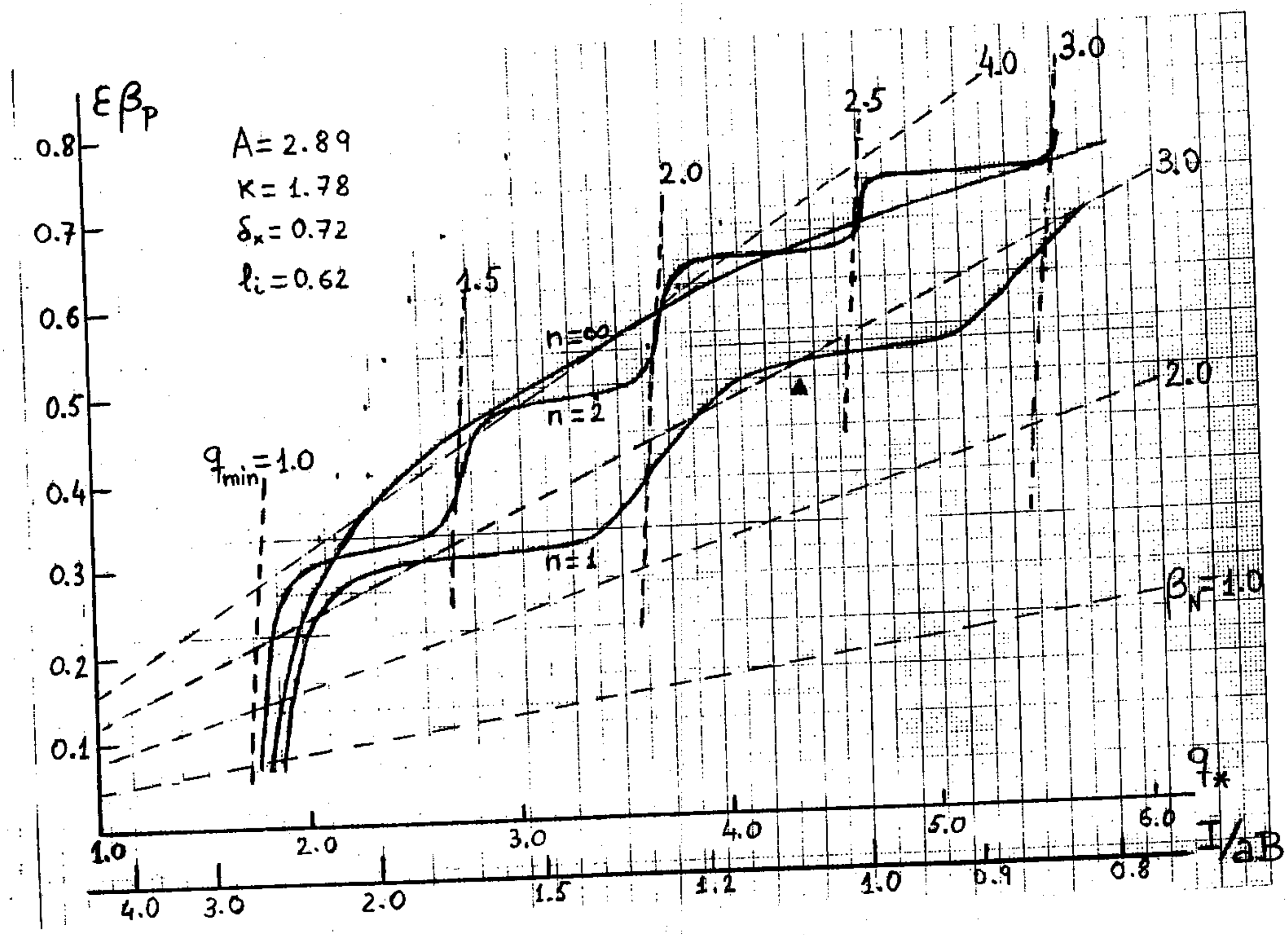
TWO-PARAMETER SET OF EQUILIBRIA TO SPAN A β vs I SPACE, OBTAINED BY SCALING THE PRESSURE AND CURRENT PROFILES ACCORDING TO:

$$\frac{dp}{d\psi} \longrightarrow \lambda \frac{dp}{d\psi}$$

$$F\frac{dF}{d\psi} \rightarrow F\frac{dF}{d\psi} + R_*^2(\lambda)(1-\lambda)\frac{dp}{d\psi}$$

$$F^2(\psi) \longrightarrow F^2(\psi) + \mu$$

where $R_*(\lambda)$ is adjusted to maintain a constant l_i throughout.



▲ : ALCATOR C-MOD "A.T." EQUILIBRIUM

$$\beta_p \equiv \frac{4\pi^2 a^2 P_{avg}}{\mu_0 I^2}(1+\kappa^2)$$

$$q_* \equiv \frac{2\pi R_0 B_0}{\mu_0 I}\left(\frac{1}{2\pi}\oint_a \frac{dl_p}{R}\right)^2$$

(3) SIMULATION OF TRANSPORT BARRIERS

* SAME APPROACH AND TOOLS AS IN CURRENT DRIVE SIMULATION.

* ANALYTIC $n(\psi)$ AND $T(\psi)$ PROFILES WITH INTERNAL AND EDGE BARRIER FEATURES.

ISSUES:

- SUSTAINEMENT OF FAVORABLE CURRENT PROFILES AFTER ENHANCED BOOTSTRAP CONTRIBUTIONS AT THE BARRIERS

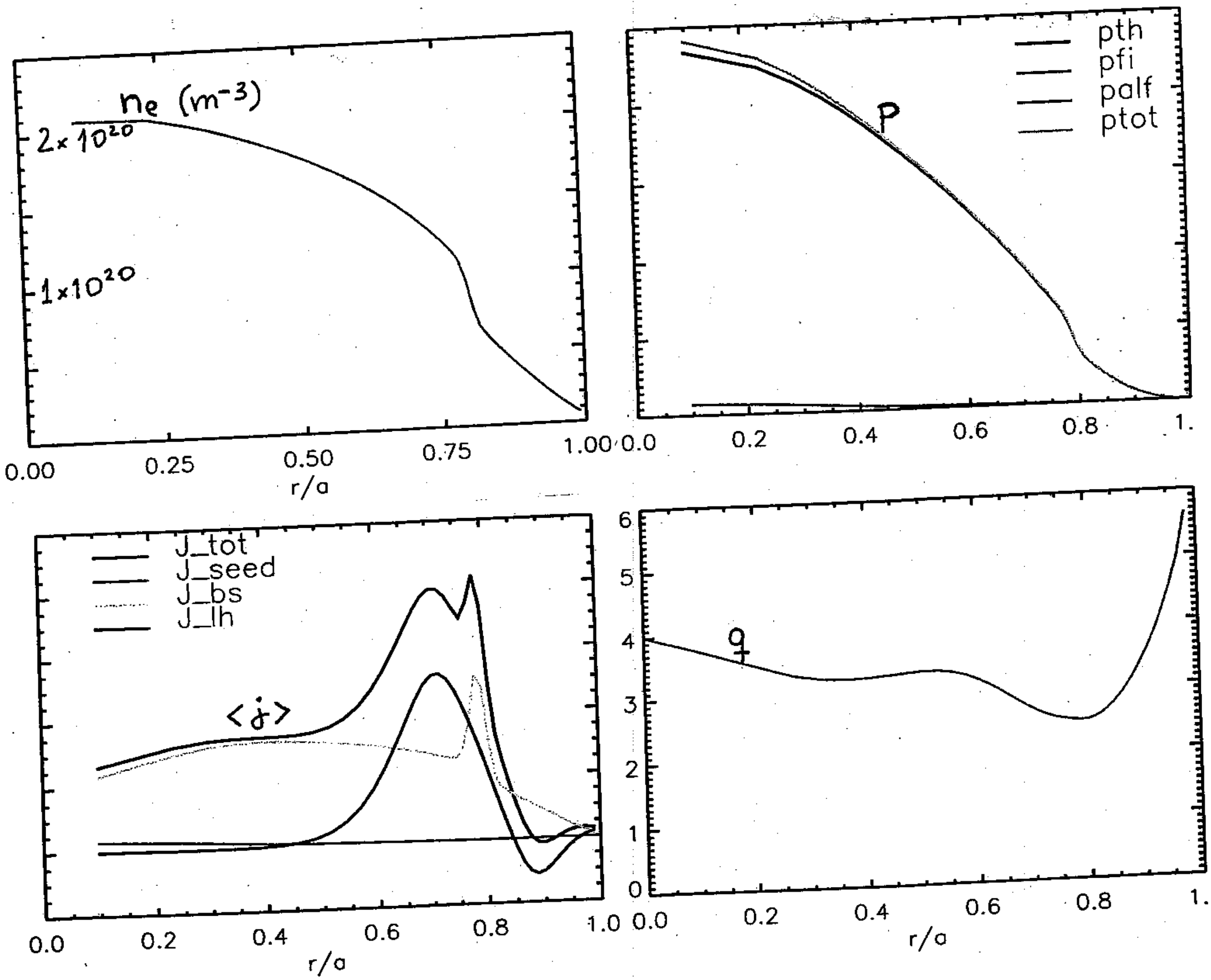
- MHD STABILITY WITH THE MODIFIED $p(\psi)$ PROFILE.

TWO ALCATOR C-MOD SIMULATIONS:

A: INTERNAL DENSITY BARRIER AT THE MAGNETIC SHEAR REVERSAL LOCATION. L-MODE EDGE PROFILES.

B: INTERNAL BARRIER AT THE MAGNETIC SHEAR REVERSAL LOCATION AND EDGE BARRIER TO SIMULATE H-MODE PROFILES.

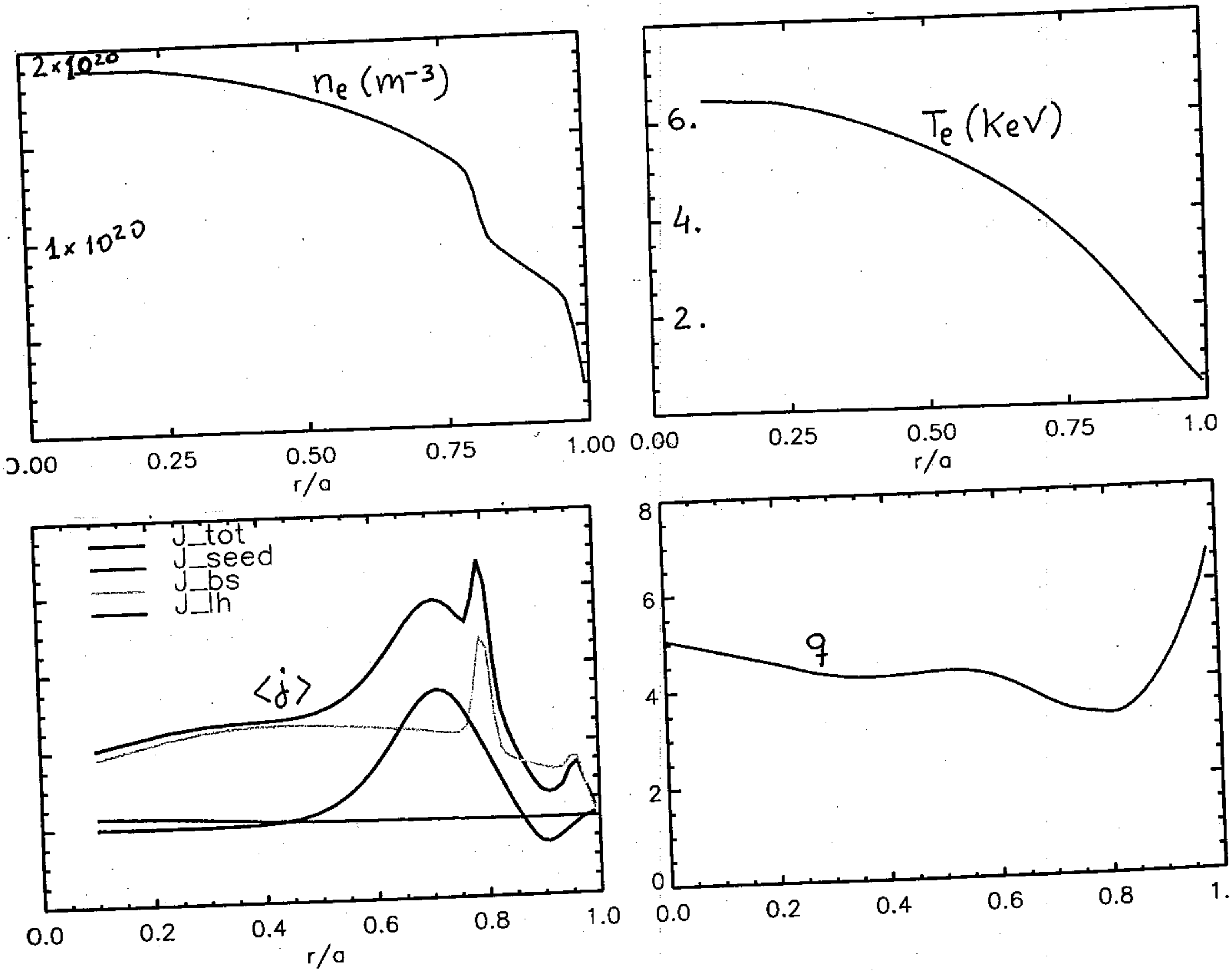
STABLE EQUILIBRIUM WITH INTERNAL TRANSPORT BARRIER



$B_0 = 4.0$ T $\quad I = 0.944$ MA $\quad f_{bs} = 0.68$

$P_{LH} = 3.0$ MW $\quad \beta_N = 2.9 \quad \beta = 2.97\%$

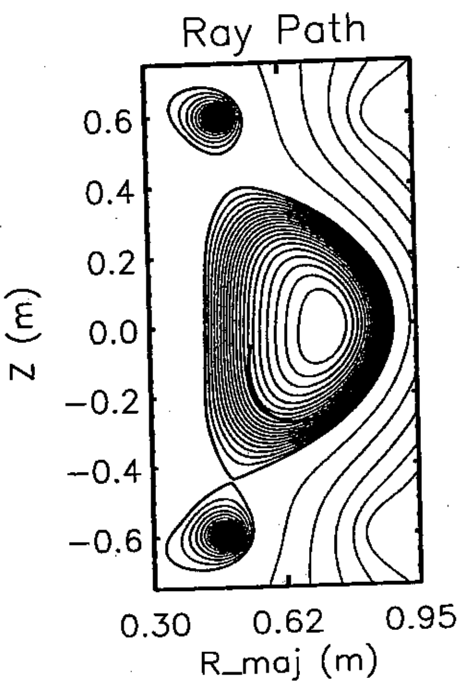
STABLE EQUILIBRIUM WITH INTERNAL AND EDGE BARRIERS

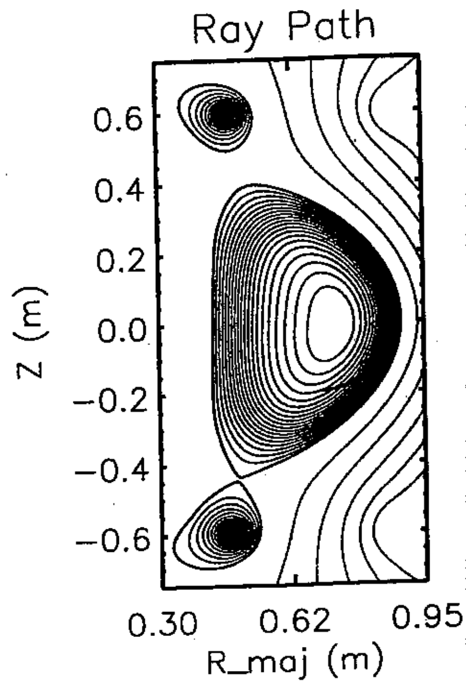


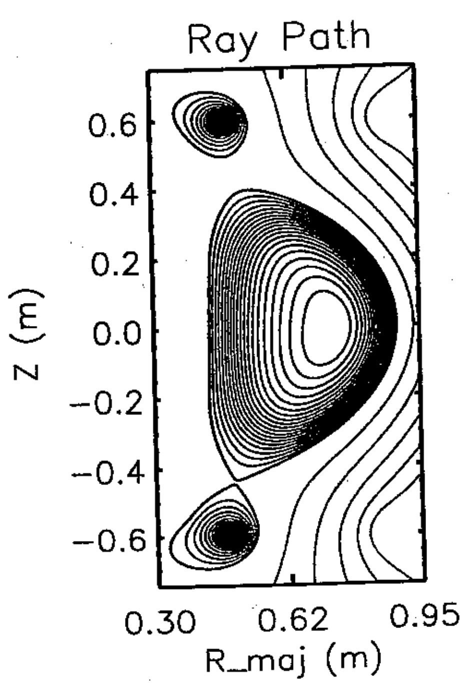
$B_0 = 4.0$ T $\quad I = 0.862$ MA $\quad f_{bs} = 0.70$

$P_{LH} = 3.0$ MW $\quad \beta_N = 2.9 \quad \beta = 2.7\%$

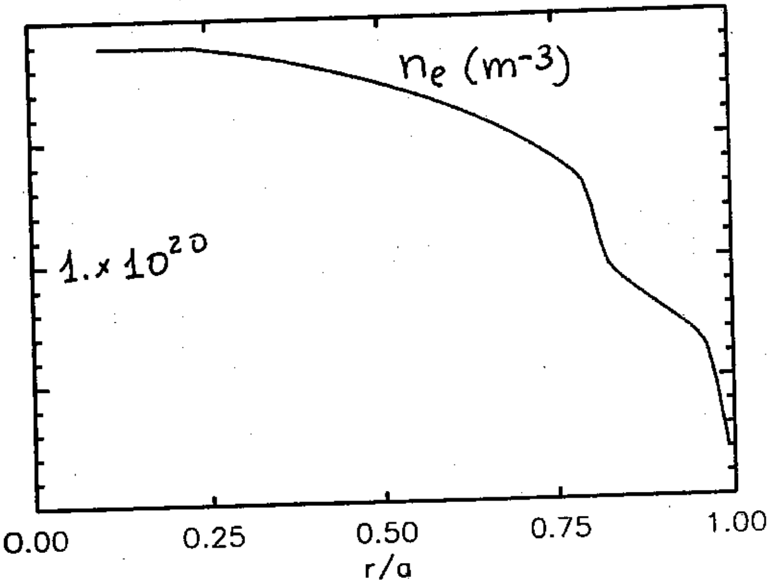
POLOIDAL PROJECTION OF L-H RAY TRAJECTORIES





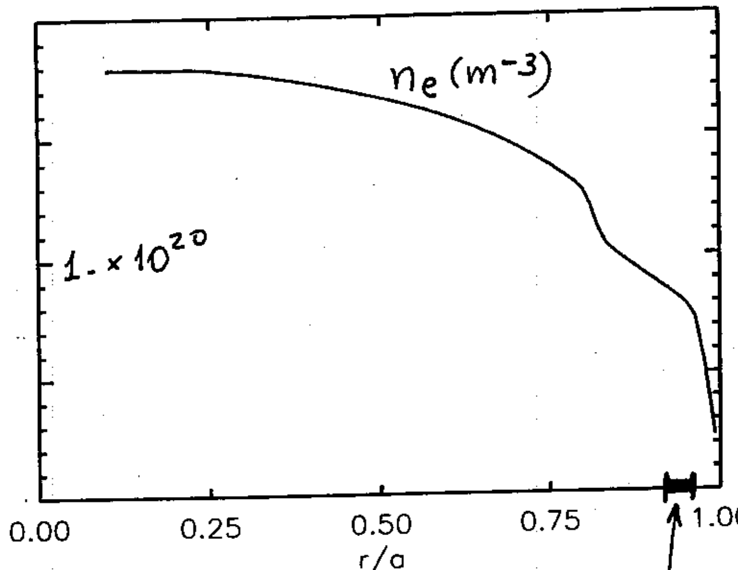


A STEEPER EDGE PEDESTAL YIELDS BALLOONING INSTABILITY



$\beta_N = 2.9$

STABLE



$\beta_N = 2.8$

$n = \infty$ UNSTABLE

SUMMARY OF TRANSPORT BARRIER SIMULATION RESULTS FOR ALCATOR C-MOD

1. CONTROL OF FAVORABLE CURRENT PROFILES IS MAINTAINED WITH ONLY A MODERATE INCREASE OF LOWER-HYBRID POWER (FROM 2.4 MW TO 3.0 MW).

2. VERY GOOD L-H WAVE ACCESSIBILITY AND ABSORPTION STILL FOUND IN THE PRESENCE OF AN H-MODE-LIKE EDGE BARRIER.

3. THE CONSIDERED TRANSPORT BARRIERS RESULT IN NO DEGRADATION OF THE BETA LIMIT (SET BY THE $n=1$ EXTERNAL MODE AT $\beta_N \simeq 2.9$) OR THE BOOTSTRAP CURRENT FRACTION ($f_{bs} \simeq 0.70$).

4. THE HEIGHT OF THE H-MODE EDGE PEDESTAL IS LIMITED BY THE $n=\infty$ BALLOONING INSTABILITY THRESHOLD.