MAXIMAL BOOTSTRAP CURRENT TOKAMAK EQUILIBRIA IN THE FIRST STABILITY REGIME

by

David A. Ehst and Kenneth Evans, Jr.

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ABSTRACT

A series of tokamak equilibria are studied in order to identify characteristics which may maximize the proportion of toroidal current naturally provided by the bootstrap effect. These plasmas are typical of high field reactors considered by the ARIES [Advanced Reactor Innovation and Evaluation Study] collaboration and are assumed to have rather flat density profiles and broad pressure profiles. With the use of noninductive current drive to provide the seed current it is possible to operate with $q_{axis} \approx 2.0$; this results in a (bootstrap-assisted) current drive power of $P_{CD}^B = 117$ MW and a figure of merit $\gamma^B = 1.12$ for a reference reactor with $T_e \approx 21$ keV. For the reference reactor $P_f = 2880$ MW so $Q = 24$. Without the bootstrap effect the absorbed current drive power would be $P_{CD} = 285$ MW, so $r \equiv 1 - (\gamma/\gamma^B) = 0.59$.

1. Introduction

Detailed comparisons of steady-state and pulsed, ohmic burn cycles for tokamak reactors have shown there is a minimum current drive efficiency needed to permit economical operation in the steady state. In terms of the normalized efficiency, $\gamma \equiv \bar{n}_e I_O R_O / P_{CD}$, where P_{CD} is the auxiliary power absorbed in the plasma, it was found [1] that $\gamma \gtrsim 0.4$ ($10^{20} \text{ A-m}^{-2}\text{-W}^{-1}$) is needed to make steady state more attractive than pulsed operation. Unfortunately, calculations of MHD equilibria in the first stability regime, generated by rf current drive alone [2], have yielded somewhat disappointing results: although $\gamma \approx 0.4$ looks possible, it may be difficult to increase the value much more.

Recently, however, there has been experimental evidence that the neoclassical bootstrap current spontaneously arises in tokamak experiments. This is most encouraging because it reduces the amount of auxiliary power needed to maintain a reactor plasma in equilibrium. With the bootstrap effect, the absorbed power, P_{CD}^B , is smaller, and the effective figure of merit, $\gamma^B \equiv \bar{n}_e R_O I_O / P_{CD}^B$, is larger than without the bootstrap effect. A survey of reactor equilibria [3] recently revealed that $\gamma^B > 1.0$ is possible under certain conditions, especially when peaked density profiles occur in the plasma. Correspondingly, the fraction of the current provided by the bootstrap effect, approximately $\Gamma \equiv 1 - (\gamma/\gamma^B)$, can exceed 50% and be as large as 90%.

The ARIES effort to design a high-field, first-regime (low beta) reactor highlighted the concern that reactor-sized plasmas will be difficult to fuel near the magnetic axis, and this will lead to quite flat density profiles. Based on previous work [3] we would expect the bootstrap effect to contribute only a small fraction ($\Gamma \lesssim 0.3$) of the equilibrium current for low poloidal beta plasmas under these conditions. The purpose of the present communication is to demonstrate that even with flat densities it is possible to have $\Gamma \gtrsim 0.5$ in a high field reactor. The guiding principle in our study is that raising the axis safety factor, q_a , should reduce the toroidal current density, j_t , at the magnetic axis. Since most of the noninductive current drive power is absorbed near the axis to provide the seed current, the greatest savings in auxiliary power should be achieved by operating at large values of q_a .

2. Equilibria with $q_a > 1.0$

There is increasing evidence that long pulse tokamak operation at $q_a > 1.0$ is possible with noninductive current drive. ASDEX experiments [4] with lower hybrid current drive (LHCD) provided a clear demonstration of stable operation with $q_a \approx 1.3$. Similarly, on Versator II LHCD provided $q_a \approx 4.4$ [5], and these discharges proved to be very quiescent even though the poloidal beta was very large -- $\beta_I/A \approx 1.2$, where A denotes the aspect ratio. Low current operation of DIIID has been maintained by neutral beam current drive (NBCD), and these experiments [6] also resulted in high poloidal beta operation, $\beta_I/A \approx 1.4$; magnetic diagnostics suggest $q_a > 1.0$ for these discharges [7]. On typical DIIID shots the bootstrap effect is found to supply $\sim 5\text{--}7\%$ of the total equilibrium current.

Theoretical studies further increase our confidence that equilibria with large q_a can be stable at the modest beta values of the first stability regime. A particular example was studied which is similar to the bootstrap equilibria discussed in the following sections. This test case has $A = 6.0$, a mild elongation, $\kappa = 1.3$, and a small triangularity, $d = 0.25$. The pressure profile has the functional form considered below, $p(\psi) = p_0 \tilde{\psi}^\alpha$, where $\alpha = 1.4$ and $\tilde{\psi}$ is the normalized poloidal flux function which is one at the axis and zero at the edge. When $q_a = 1.25$, and for a boundary safety factor $q_b = 2.15$, this equilibrium was stable to all ballooning modes ($N_{\text{crit}} \rightarrow \infty$) and to $n=1$ kinks with a conducting wall at 0.3-0.4 times the minor radius, with $\beta_t = 0.05$ and $\beta_I/A = 0.63$. The normalized ratio of beta to toroidal current is given by $g \equiv \beta_t a B_0/I_0 = 0.0744$, which is roughly twice the conventional Troyon value, $g_T \approx 0.03$. Presumably, operation at lower beta, e.g., $\beta_t = 0.02$ and $g = 0.03$, would provide even better stability.

3. Fixed Plasma Parameters for Equilibrium Survey

For this study we set $A = 6.0$, $\kappa = 2.25$, and $d = 0.5$. This geometry was selected after preliminary considerations of a high-field reactor by the ARIES group. The large κ simplifies the design of a double-null poloidal divertor, although feedback stabilization of the axisymmetric mode is problematic. While the optimum geometry for this reactor is not presently settled, we expect that the choice among these parameters is not crucial to the current drive/bootstrap results.

The equilibrium pressure profile in a reactor is difficult to predict. Early numerical studies [8] of kink and ballooning modes clearly demonstrated enhanced stability for $p(\psi) \sim \tilde{\psi}^\alpha$ as α is reduced from 2.0 to 1.4 to 1.2. Broad pressure ($\alpha = 1.2$) is thus desirable to achieve maximum MHD stability (largest value of g). Initial transport calculations for ARIES [9] indicated, however, that the pressure could be quite peaked due to the central alpha heating. Nevertheless, it is plausible that such peaked profiles will not appear, as temperature gradient (kinetic) instabilities will tend to flatten the temperature profile.

The profile argument is as follows. Central fueling is believed to be extremely difficult at reactor temperatures with line average densities $\geq 2 \times 10^{20} \text{ m}^{-2}$. Conventional fueling techniques such as pellet injection will not penetrate far, even with pellet velocities $\geq 10 \text{ km/s}$. If we follow the ARIES high-field reactor philosophy of using relatively proven plasma physics ("ITER physics"), we conclude that the electron density profile, $n_e(\psi) = n_{e0} \tilde{\psi}^{\alpha_n}$, is fairly flat. Simulations for ARIES [9] suggest $\alpha_n \leq 0.1$, and ITER guidelines are presently $\alpha_n \approx 0.5$. For the present study we select

$$\alpha_n = 0.3.$$

The temperature profile is assumed to be $T(\psi) \sim \tilde{\psi}^{\alpha_T}$, and the logarithmic ratio of temperature and density gradients is then $\eta = d(\ln T)/d(\ln n) = \alpha_T/\alpha_n$. A large body of theory suggests that drift waves can be driven unstable when $\eta \geq 2$ for either electrons or ions in the confined plasma. The resulting turbulence will enhance thermal transport, and presumably the instabilities will saturate at some value of η greater than two. We select

$$\alpha_T = 0.9$$

for our present study. This results in $\eta = 3.0$ and has $\alpha_n + \alpha_T = \alpha = 1.2$. [More elaborate profiles could be investigated in the future; for example, flatter pressure profiles can be represented by $p(\psi) \sim p_0 [1 - (1-\tilde{\psi})^{\alpha_1}]^{\alpha_2}$. We may wish to defer such studies until more reliable transport code predictions are provided, however.]

We have computed a variety of equilibria (with different safety factors), for the specified geometry and pressure profiles. The remaining quantity which we have fixed in these calculations is the normalized ratio of beta to current. We have selected $g = 0.030$. This is a conservative beta limit; ITER guidelines specify $g = 0.030-0.033$ for steady state operation.

4. Equilibrium Options: Variation with q_a

Noninductive current drive may truly provide an opportunity to control the current profile and safety factor. Unlike with ohmic current drive, there is no apparent constraint forcing q_a to the vicinity of unity. Since stability does not appear to deteriorate with moderate increases of q_a , we can investigate the benefit of large q_a equilibria to the problem of noninductive current drive. We do constrain $q(\psi)$ to monotonic, however, to avoid double tearing mode instabilities.

The MHD equilibrium candidates are modelled with a diamagnetism function $F(\psi) \equiv R B_t$ with $F(\psi) = F_b (1 - \delta \tilde{\psi}^{\alpha_F})^{1/2}$. For a fixed geometry ($A=6$, $\kappa=2.25$, $d=0.5$), pressure profile ($\alpha=1.2$), and $q_a (= 1.0)$ a matrix of equilibria at different β_t and q_b values is created by varying the diamagnetism variables δ and α_F . Figure 1 plots the locus of numerous equilibria which were found. The total toroidal current for a 2-D MHD equilibrium is not a simple function of q_b , since the toroidal current density profile $j_t(R, Z)$ varies with β_t . In the figure we point out that equilibria with $\beta_t \leq 0.041$ are all paramagnetic and have $g = \beta_t$ a $B_0/I_0 < 0.030$. The circles at $\beta_t \geq 0.058$ denote equilibria with $g > 0.030$. The triangles (and, in general, the "forbidden" region around $\beta_t = 0.04$ with $q_b \geq 3$) are beyond the convergence limit of the code; these limiting equilibria feature surface current density gradients which are very large.

For our purposes we concentrate on the sequence in Figure 1 labelled by $\alpha_F = 1.2$. Each point in the sequence is scaled to a new equilibrium with $g \equiv 0.030$ by an appropriate increase of q_a [10]. The resulting set of equilibria, all with $g = 0.030$ but different q_a values, is given in Table I.

Table I quantifies the benefits of raising q_a . Referring to the table, we note as q_a increases and β_t decreases that the equilibrium current decreases significantly. If the very large toroidal field ($B_0 \geq 15$ T) can be

provided, then the lowest β_t equilibria in the sequence are most attractive from the point of view of steady-state current drive. Also evident is a reduction in the toroidal current density at the magnetic axis, $j_{ta} \equiv j_t(R_{mag}, 0)$, as q_a increases. Figures 2 and 3 show that this reduction in j_{ta} is associated with a change in the current density profile; at the largest q_a (highest poloidal beta) the current density maximizes further away from the magnetic axis (where the pressure profile peaks). Additional advantages of large q_a equilibria are the increase of Shafranov poloidal beta, β_I , and the slight increase in the pressure peaking in configuration space, given by the ratio of peak to average pressure, $p_0/\bar{p}$. In Ref. 3 it was shown that the bootstrap fraction ($\approx \Gamma$) is proportional to the factor $(p_0/\bar{p}) \beta_I$.

5. Reference High Field Reactor

We will proceed to the current drive calculation by concentrating on a single equilibrium. We select the case with $q_a=1.808$, $q_b=4.88$, and $\beta_t=0.0225$. This has the profiles given in Fig. 3 and Fig. 4. Poloidal flux and constant toroidal current density contours are shown in Figs. 5 and 6. The corresponding density and temperature profiles in the midplane are shown in Figs. 7 and 8. The intermediate step facing us, now that the equilibrium has been chosen, is to select the proper average density, temperatures, major radius, and magnetic field to enhance the steady state reactor performance. These variables and the current drive calculation must be consistent with confinement and the plasma power balance. We accomplish the power balance calculation by using the 2-D flux surface distribution (Fig. 5) in the TRAC II code, which averages the power balance over ten flux surfaces.

Several constraints occur for the power balance:

- a. neutron wall load (average) $\equiv W_n \approx 5.0 \text{ MW} \cdot \text{m}^{-2}$
- b. fusion power $P_f \approx 2700 \text{ MW}$

These two constraints, which stem from economic considerations, lead us to select a major radius $R_0 = 6.0 \text{ m}$ for our tokamak geometry.

- c. maximum field at TF coil $B_M \leq 24$ T

Invariably current drive power, P_{CD} , is reduced by operating at the highest $\bar{T}_e$, which ultimately forces us to design for the highest toroidal field which can be created.

d. $\bar{n}_e = 2 \times 10^{20} \text{ m}^{-3}$

The divertor, used for impurity control, requires $n_e \geq 1.5 \times 10^{20} \text{ m}^{-3}$ at the midplane of the divertor flux surface. This forces the average density to be somewhat larger. However, operational experience with tokamaks indicates there is an upper limit to $\bar{n}_e$ which must be imposed in order to avoid disruptions. In the absence of auxiliary heating, the Murakami and Greenwald density limits are both below $2 \times 10^{20} \text{ m}^{-3}$. However, auxiliary heating increases the $\bar{n}_e$ limit, and we presently assume $\sim 2 \times 10^{20} \text{ m}^{-3}$ is achievable.

- e. $Z_{\text{eff}} = 1.5$
f. confinement

The power balance includes additional heat input (P_{aux}) due to the absorbed current drive power, so the plasma is always subignited. This permits smaller electron energy confinement time, τ_e , than is needed for pure ignition. However, τ_e should be approximately consistent with the predictions of various scaling laws.

A reference reactor which meets our requirements is presented in Table II. The auxiliary heating, P_{aux} , which is specified as an input to the calculation, anticipates the results of the current drive calculation. The results are relatively insensitive to the actual value of P_{aux} chosen -- $\bar{n}_e$ and temperatures are roughly constant for $100 \text{ MW} \leq P_{\text{aux}} \leq 200 \text{ MW}$. P_{aux} mostly affects the required electron energy confinement time. For the reference design the neoclassical ion energy confinement time is $\tau_{\text{NC}} = 75$ s. The neo-Alcator confinement time is $\tau_{\text{NA}} = 23$ s; the Odajima-Shimomura offset - linear scaling predicts L mode global confinement to be $\tau_{\text{OS}} = 0.42$ s, while Kaye-Big scaling predicts $\tau_{\text{KB}} = 0.35$ s. Thus, divertor operation with H mode factors of ~ 2 - 3 may be needed to achieve this particular power balance.

The parameters most relevant to current drive calculations are the temperatures, electron density, and total current. The field strength B_0 will have an influence on the wave frequencies chosen for current drive. These values, from Table II, are used in the next section.

6. Current Drive with High Frequency Fast Waves

The central current density required for our equilibrium is provided by fast waves at frequencies well above the fundamental cyclotron frequencies (~ 100 MHz for deuterium), and ion power absorption will be found to be negligible. Near the surface a small amount of lower hybrid wave power is provided at a frequency $f = 8$ GHz, which is adequately high to avoid damping on nonthermal alphas.

First the current drive problem is solved in the absence of any bootstrap contribution. The calculation is standard [2] and can be accomplished by the following idealized power spectrum:

	$P = 13.9 \text{ MW @ } n_i = 3.2$
$f = 8.0 \text{ GHz (LH)}$	$P = 16.9 \text{ MW @ } n_i = 2.2$
	$P = 14.3 \text{ MW @ } n_i = 1.8$
$f = 2.45 \text{ GHz (FW)}$	$P = 145 \text{ MW @ } n_i = 2.0$
$f = 0.80 \text{ GHz (FW)}$	$P = 94.9 \text{ MW @ } n_i = 2.5$

The total power is $P_{CD} = 285 \text{ MW}$, which results in $\gamma = 0.46$ for $\bar{n}_e = 2.1 \times 10^{20} \text{ m}^{-3}$, $I_0 = 10.6 \text{ MA}$, and $R_0 = 6.0 \text{ m}$ at $T_e = 22 \text{ keV}$ and $Z_{eff} = 1.5$. [By comparison the formula in Ref. 2 would predict $\gamma = 0.42$, although the formula was derived for equilibria with $q_a=1.0$, $\alpha=1.4$, and $\alpha_n=1.1$ (peaked density profiles).]

The current drive calculation is next performed including the bootstrap terms [3]. Figure 9a displays the important functions in this problem. The solid curve is $\langle j_{\parallel} B \rangle / \langle B^2 \rangle$ required for our equilibrium, where $\langle \rangle$ denotes the

flux surface average and $j_{||}$ is the component of current flowing along the field line. Note that $\langle j_{||} B \rangle$ peaks at the magnetic axis ($\tilde{\psi} = 1$) even though j_t peaks off axis (Fig. 3). The bootstrap contribution to $\langle j_{||} B \rangle$ is the chain-dashed curve, $H(\psi) = \langle j_{||}^B B \rangle / \langle B^2 \rangle$. H is substantial and provides nearly all the required $\langle j_{||} B \rangle$ near the plasma surface ($\tilde{\psi} = 0$). Near the axis the plasma is in the plateau regime and H is very small, so the remaining portion of $\langle j_{||} B \rangle$ must be provided by the wave-driven currents. This complementary function, $G(\psi) = \langle j_{||}^{RF} B \rangle / \langle B^2 \rangle$, can be produced by three waves (dashed curves in Fig. 9a):

$$f = 8.0 \text{ GHz (LH)} \quad P = 11.4 \text{ MW @ } n_{||} = 3.2$$

$$f = 2.45 \text{ GHz (FW)} \quad P = 33.0 \text{ MW @ } n_{||} = 2.0$$

$$f = 0.80 \text{ GHz (FW)} \quad P = 72.4 \text{ MW @ } n_{||} = 2.5$$

The ray-tracing, current drive and equilibrium calculations are iterated, and the stated solution is found to be numerically stable with $j_t(R,0)$ and $q(R,0)$ as given in Fig. 9. The slight nonmonotonic behavior of $q(\psi)$ is believed to be only a cosmetic blemish; better $q(\psi)$ tailoring is numerically possible by using many more rays in the power spectrum in order to more smoothly illuminate the plasma near the magnetic axis.

Compared to the former current drive calculation, much less external power is needed to create this equilibrium with its large bootstrap current -- $P_{CD}^B = 117 \text{ MW}$ -- and the bootstrap-aided figure of merit is larger, $\gamma^B = 1.12$.

Thus, for the equilibrium considered we find there is a large bootstrap fraction, $r = 1 - (\gamma/\gamma^B) = 0.59$. This value of r , incidentally, is not much different from the value predicted by the formula in Ref. 3, although the calculations in the reference were for equilibria with $q_a = 1.1$. We would also expect approximately the same r if neutral beam current drive were used.

7. Conclusions

Thanks to "free" current generation provided by the bootstrap effect we find $r \gtrsim 0.5$ is possible even in a reactor with rather flat density profiles. This is possible if the noninductive seed current is used to generate a high poloidal beta equilibrium with $q_a \approx 2.0$. The resulting high-field reactor has $Q \approx 24$.

Future studies should evaluate variations of r with α_n , especially considering $\alpha_n \leq 0.2$. A systematic evaluation of r vs. q_a (e.g., for Table I) would be desirable; and flatter pressure functions could be explored with the possibility of increasing q_a and r still further. Finally, the MHD stability of large q_a equilibria needs to be quantified.

Acknowledgement

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Table I
Equilibrium Sequence with q_a Variation

$A=6.0$, $\kappa=2.25$, $d=0.25$, $\alpha=1.2$, $R_0=6.0$ m, $\alpha_F=1.2$
Toroidal current and B_0 are adjusted so $\beta_t^2 B_0^4 = \text{constant}$;
 $g = \beta_t a B_0 / I_0 = 0.030$ (m - T - MA⁻¹)

Well Depth δ	q_a	q_b	β_t %	B_0 (T)	I_0 (MA)	j_{ta} (MA-m ⁻²)	β_I	$p_0/\bar{p}$
.0324	1.073	2.21	4.48	10.1	15.0	2.85	1.44	2.41
.0364	1.242	2.67	3.75	11.0	13.8	2.72	1.71	2.44
.0381	1.438	3.34	3.11	12.1	12.4	2.52	2.10	2.45
.0366	1.616	4.00	2.63	13.1	11.6	2.40	2.43	2.47
.0350	1.808	4.88	2.25	14.2	10.6	2.34	2.88	2.52
.0317	2.070	6.35	1.82	15.8	9.6	2.22	3.52	2.56

Table II
High Field Reactor Reference Parameters

Parameter	Variable	Units	Value
aspect ratio	A		6.0
elongation	κ		2.25
triangularity	d		0.5
pressure profile exponent	α		1.2
diamagnetism exponent	α_F		1.2
well depth	δ		0.0350
axis safety factor	q_a		1.808
boundary safety factor (limiter)	q_b		4.88
cylindrical safety factor	q_*		4.37
volume average toroidal beta	β_t		0.0225
r.m.s. beta	β_*		0.0280
Shafranov poloidal beta	β_I		2.87
peak to average pressure ratio	$p_o/\bar{p}$		2.52
magnetic axis fractional shift	$(R_{mag} - R_o)/a$		0.157
"Troyon" ratio	g		0.030
major radius	R_o	m	6.0
minor radius	a	m	1.0
inboard scrapeoff	Δ_V^i	m	0.10
inboard blanket plus shield	$\Delta_{B/S}^i$	m	1.25
plasma volume	V_p	m ³	253.0
first wall area	A_w	m ²	~430.0
blanket energy multiplication	M_B		1.25
thermal power conversion efficiency	η_{th}		0.40
current driver efficiency	η_{FW}		0.65

Table II
High Field Reactor Reference Parameters
(continued)

Parameter	Variable	Units	Value
density profile exponent	α_n		0.3
temperature profile exponent	α_T		0.9
$d \ln T_e / d \ln n_e$	η_e		3.0
minimum electron collisionality	ν_{*e}		0.026
minimum ion collisionality	ν_{*i}		0.011
fusion power	P_f	MW	2880.
alpha power	P_a	MW	576.
neutron power	P_n	MW	2304.
auxiliary heating (electrons)	P_{aux}	MW	~ 120.
neutron average wall load	W_n	MW-m ⁻²	5.36
plasma power density	p_f	MW-m ⁻³	11.4
volume average electron temperature	$\bar{T}_e$	keV	22.0
peak electron temperature	T_{eo}	keV	44.6
average ion temperature	$\bar{T}_i$	10 ²⁰ m ⁻³	20.2
average electron density	$\bar{n}_e$	10 ²⁰ m ⁻³	2.09
peak electron density	n_{eo}	10 ²⁰ m ⁻³	2.80
effective ion charge (light impurities)	Z_{eff}		1.5
fuel density (50% DT) average	$\bar{n}_{DT}$	10 ²⁰ m ⁻³	1.70
required electron energy confinement	τ_e	s	1.12
required ion energy confinement	τ_i	s	0.71
peak pressure	p_o	MPa	4.53
vacuum toroidal field on axis	B_o	T	14.2
maximum field, at TFC	B_M	T	23.2
plasma toroidal current	I_o	MA	10.6
toroidal current density at magnetic axis	j_{ta}	MA-m ⁻²	2.34

Table II
High Field Reactor Reference Parameters
(continued)

Parameter	Variable	Units	Value
thermal power ($P_\alpha + P_{aux} + M_B \cdot P_n$)	P_{th}	MW	3576.
gross electric ($\eta_{th} \cdot P_{th}$)	P_g	MW	1430.
current drive, electric power ($P_{aux} \cdot \eta_{FW}^{-1}$)	P_{CD}^e	MW	185.
net electric ($P_g - 0.06 \cdot P_g - P_{CD}^e$)	P_{net}	MW	1160.
plasma power multiplication (P_f/P_{aux})	Q		24.
net thermal efficiency	P_{net}/P_{th}		0.32

Figure 1. Equilibria with $p \sim \tilde{\psi}^\alpha$ and $F \sim [1 - \delta \tilde{\psi}^{\alpha_F}]$.

Figure 2. Equilibrium with $q_a=1.07$, $\beta_t=0.045$, $I=15.0$ MA, and $\beta_I=1.44$ with $B_0=10.1$ T.

Figure 3. Equilibrium with $q_a=1.81$, $\beta_t=0.023$, $I=10.6$ MA, and $\beta_I=2.88$ with $B_0=14.2$ T.

Figure 4. Same equilibrium as in Figure 3.

Figure 5. Poloidal flux contours for reference reactor.

Figure 6. Contours of constant toroidal current density for reference reactor.

Figure 7. Normalized density for reference reactor: $n_e/n_{eo} = \tilde{\psi}^{0.3}$.

Figure 8. Normalized temperature for reference reactor: $T_e/T_{eo} = \tilde{\psi}^{0.9}$.

Figure 9

Equilibrium with fast-wave seed current and bootstrap contribution: a) chain dashed curve is H , dashed is wave-driven G (3 rays), dotted is $G+H$, and solid is target $\langle j_t \rangle$ to be reproduced; b) $j_t(R,0)$; c) ray trajectories; d) $q(R,0)$

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