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ABSTRACT

It is shown that in tokamak plasmas sustained by RF current drive, the contribution of the suprathermal RF driven electron population to the poloidal beta (β_p) can be substantial if the total current is comparable to the Alfven critical current, $I_A = \frac{4\pi mc}{\mu_o e} \frac{v}{c}\gamma$. Equilibria with values of $\epsilon\beta_p$ up to approximately 1.2 were obtained, and no equilibrium or gross stability limits were observed.

Instability of ideal MHD ballooning modes is believed to limit the maximum achievable β in tokamaks.[1] Increases in the achievable β would remove a significant design constraint in tokamak D-T fusion reactors, make advanced fuel reactors feasible, and ease the confinement required for reaching ignition. To investigate the high β regime of tokamak operation various experiments have been carried out either by heating of the bulk Maxwellian component of the plasma[2-6] or by forming an anisotropic $(P_\perp > P_\parallel)$ energetic electron component by means of electron cyclotron heating.[7] In these experiments the maximum values of poloidal beta ranged up to $\beta_p = 0.8/\epsilon$ where ϵ is the inverse aspect ratio, a/R_o. In the present paper we report results in which the anisotropic plasma pressure $(P_\parallel > P_\perp)$ is produced primarily by an energetic electron component generated and sustained by lower-hybrid RF current drive.

The poloidal beta of a plasma with anisotropic pressure, such as those produced by RF current drive, may be written as[8] $\beta_p = \frac{1}{2}\bar{P}_{\varphi\varphi}/(B_a^2/2\mu_o) + \frac{1}{4}\bar{P}_{\perp\perp}/(B_a^2/2\mu_o)$ where $P_{\varphi\varphi} = m_e f_e v_\varphi^2$, $P_{\perp\perp} = m_e f_e v_\perp^2$, $B_a = \mu_o I/(2\pi a)$, and the overbar indicates both integration over velocity space and volume average. The contribution of the RF produced electron tail to the pressure can be evaluated for a model of the RF driven electron tail consisting of a flat plateau with a perpendicular temperature T_o.[9] The tail distribution function is $f_t(v_\parallel, v_\perp) = f_o \exp(-mv_\perp^2/2T_o)$ for $v_1 < v_\parallel < v_2$ and $f_t = 0$ otherwise. The upper velocity limit, v_2, is equal to the highest parallel phase velocity component of the RF spectrum,[9] and typically $v_1 \cong 4(T_e/m)^{1/2}$. With $\int f_t d^3v = n_t(r)$, the tail density, the poloidal beta as defined above can be evaluated as

$$\beta_p = \frac{4}{3} \left(1 + 3 \left[\frac{T_o}{m_e v_2^2} \right] \right) \frac{I_A}{I_{RF}} \qquad (1)$$

with the approximations $v_1/v_2 \ll 1$, and $v_2^2/c^2 \ll 1$. We have also defined I_A as the Alfven current,[10] $I_A = 17\text{kA}\gamma v_2/c$ where γ is the usual relativistic factor evaluated at $v=v_2$. Equation 1 indicates that the poloidal beta of the RF driven tail is inversely proportional to I_{RF}, thus the high β_p regime may be reached when $I_{RF} \cong I_A$ for an RF current driven plasma.[11]

In the Versator II tokamak $R_o = 0.405$m, $a_L = 0.13$m, and $\epsilon = a_L/R_o = 0.32$, and the plasma is sustained by lower-hybrid current drive at a frequency of 800 MHz. In the present experiments, RF current drive was initiated during the current decay phase following the opening of the ohmic heating transformer circuit. The current was then maintained by RF drive for a time greater than the L/R time of the plasma (5-10 msec typically) with vanishing inductive loop voltage. For the example shown in Fig. 1, β_p^* ($=\beta_p+l_i/2$, where $l_i=(\pi a^2 B_a^2)^{-1}\int_0^{2\pi}\int_0^a r dr d\theta\ B_p^2$), as obtained from equilibrium measurements,[8,12,13] rose linearly during the current decay phase from an initial value of 1.6 to a maximum value of 5.1. β_p^* was initially maintained at a steady level of $\beta_p^* = 5.1$, then after a 4 msec quiescent period, a loss of energetic electrons occured, as indicated by a burst of hard x-ray emission at t=27msec. At this time β_p^* abruptly decreased by 12%, to $\beta_p^* = 4.4$. This electron loss burst occured irregularly and is believed to be caused by the Parail-Pogutse[14] microinstability of the anisotropic electron population. Subsequently, the discharge was maintained for the duration of the RF pulse without further relaxations or decreases in β_p^*. Interestingly, an increase in the energetic electron flux to the limiter (see the hard x-ray signal in Fig. 1) was generally observed during the rise of β_p^*, along with a rise in the loop voltage. The flux then decreased during the current flattop. This behavior was a repeatable characteristic of these experiments. In the following we will be concerned with the equilibrium properties of the steady-state RF driven phase of these plasmas.

An independent indication that high poloidal beta equilibria were indeed obtained comes from the outward equilibrium shift of the magnetic axis at high $\epsilon\beta_p$[15] which produces an observable outward shift of the density profile. The total outward shift of the centroid of the density profile, Δ_N, relative to its initial position at low β_p ($\beta_p^* < 1.0$) is plotted in Fig. 2 against β_p^*. Also plotted in Fig. 2 is the theoretical prediction for the shift of the magnetic axis at high $\epsilon\beta_p$,[15] and the results of MHD equilibrium code simulations. (In order to obtain β_p^* from β_p in the theory of Ref. 15, $l_i/2 = 1.0$ was taken.) The outward shift of the density profile peak appears to agree well with the equilibrium shift of the magnetic axis, within the experimental uncertainty.

A further confirmation of the outward shift was found in the hard x-ray emission profile of the energetic electron population. The major radial profile of the x-ray bremsstrahlung emission was measured with a collimated NaI(Tl) crystal detector and pulse height spectrometer. The detector viewed along a vertical chord into a recessed vacuum port viewing dump so that stray x-rays from the walls and limiter were eliminated. The pulse height system collected counts during the RF driven flattop (see Fig. 1). The number of x-ray counts detected in the energy range of 15-100keV is plotted in Fig.3 against the major radius. The centroid of the profile was found to be shifted outward to R=0.43m from the geometric center R_o=0.405m. The width of the profile at the one e-fold decay point was W_{HXR}=0.10m $\pm$0.015m.

To obtain β_p from β_p^* a value for $l_i/2$ is needed. Using the width of the x-ray profile as an approximation to the width of the RF current profile l_i can be calculated. Modelling the current profile as $J=J_o\exp(-r^2/\lambda_J^2)$ where r is the minor radius coordinate, and λ_J is the Gaussian width, the internal inductance can be written as $l_i \cong 0.55+2\ln(a_L/\lambda_J)$. Taking $\lambda_J=W_{HXR}/2$ =0.05m, the value of $l_i/2$ is 1.2. With β_p^*=4.4 during the x-ray gate period, the value of $\epsilon\beta_p$ is ≅1.0, and at the highest β_p^* (= 5.1) $\epsilon\beta_p \cong 1.2$. Owing to the large values of β_p^* obtained here, the value of β_p is relatively insensitive to errors in $l_i/2$, for example, even a 30% error in λ_J would only produce an 8% error in the value of β_p. The central value of q ($=B_\varphi r/B_p R$) can also be calculated from the Gaussian current profile model, $q_o \cong 2\pi B_o \lambda_J^2/(\mu_o R_o I_{RF})$. For a width λ_J =0.05 m, I_{RF}= 5kA, and B_o=0.7T, q_o is 4.4. Hence for the case shown in Fig. 1 the current profile modeling indicates $q_o > 1$, and in this case the value of q_{cyl} ($=\epsilon B_\varphi/B_a$) =29.

A test of the validity of Eq. 1 is provided by the scaling of β_p with the RF current and toroidal field. The values of β_p^* attained during the RF driven flattop are shown in Fig. 4 as a function of I_{RF}. The data indicates that β_p approximately follows an I_{RF}^{-1} scaling and increases with increasing B_φ. Evaluating Eq. 1 with $v_2=1.9\times10^8$ m/sec, for B_φ=0.7 T, and $v_2=2.13\times10^8$ m/sec for B_φ=0.9T (where we have used the lower-hybrid wave accessibility criterion[16] to calculate v_2), and taking $l_i/2$ = 1.0 gives the solid curves plotted in Fig. 4. Here we have also used the prediction for the tail perpendicular temperature T_o in Ref. 9, $2T_o/mv_2^2 \cong 0.1$. Although there may be some variation of l_i with current, taking the prediction of Eq. 1 for β_p and $l_i/2=1$ yields generally good quantitative agreement with the data for β_p^*.

Ideal MHD theory predicts stable access to the second stability regime of high toroidal mode number (n) ballooning modes if q_o can be raised sufficiently.[17,18] As suggested by the present experiment, this may be achievable with RF current drive. To assess the predictions of ideal MHD equilibrium and stability theory, modeling was done using the Princeton PEST code.[19] The simple Troyon formula[20] for kink/ballooning mode instability cannot validly be used here since it was obtained with optimized pressure profiles and $q_o \cong 1$, conditions that are not well satisfied in this experiment. Equilibria which best modelled the experiments had approximately circular plasma boundaries, elongation 0.9-1.0, and were found to be stable to high n ballooning modes at the highest $\epsilon\beta_p$ ($\cong 1.2$). A stable transition to the second stability region[17,18] was found when $q_o > 8$ and $0.3 < \epsilon\beta_p < 0.4$, for sufficiently narrow (but realistic) pressure profiles. Here we define the transition as the most unstable or least stable value of $\epsilon\beta_p$. For lower q_o or wider pressure profiles, an unstable range of $\epsilon\beta_p$ exists for high n modes, but at higher $\epsilon\beta_p$ these modes restabilize. It may be that the enhanced losses of energetic electrons seen in this experiment during the ramp up of $\epsilon\beta_p$ are due to such instability activity. For $q_o \cong 4.4$ (as estimated above for the present experiment) these modes restabilized above $\epsilon\beta_p \cong 0.8$. However, if the current profile is narrower than the x-ray profile, then q_o could be lower, which would expand the unstable region. Stability of anisotropic pressure ($P_\parallel > P_\perp$)

equilibria was also calculated,[21] and these equilibria were also found to be stable. If indeed $q_o \cong 4.4$ in Versator II, as inferred from the x-ray profiles, then the theoretical modeling suggests that Versator is beyond the critical $\epsilon\beta_p$ needed for transition to the second stability region.

In conclusion, these experiments show that RF current drive can be used to produce high poloidal beta plasmas ($\epsilon\beta_p \gtrsim 1$) with the pressure and current supplied by the RF driven energetic electron component. Magnetic measurements indicate that an equilibrium limit was not encountered as β_p was increased from its initial value in the ohmic inductive phase to its maximum during the RF driven flattop phase, and equilibria with $\epsilon\beta_p$ ranging up to 1.2 were produced, with the transition to second stability at $\epsilon\beta_p \cong 0.4$ and $q_o = 4$. Recent experiments reported in Ref. 22 obtained $\epsilon\beta_p \cong 1.1$ in neutral beam current driven plasmas. Owing to differences in the profiles and geometry, the transition to second stability was shifted to higher $\epsilon\beta_p$ ($\cong 1$) placing that experiment in the transition region. It should be pointed out that it may be possible to use the technique of entering the second stable regime initially at low current and high q_o to reach stable equilibria at higher β and current. Specifically, once high $\epsilon\beta_p$ is reached, one could raise the plasma pressure and current keeping the pressure proportional to I^2, thus raising β at fixed $\epsilon\beta_p$. Further, for plasmas deep within the second stability regime, one could reduce q_o and q_{cyl} while maintaining stability.

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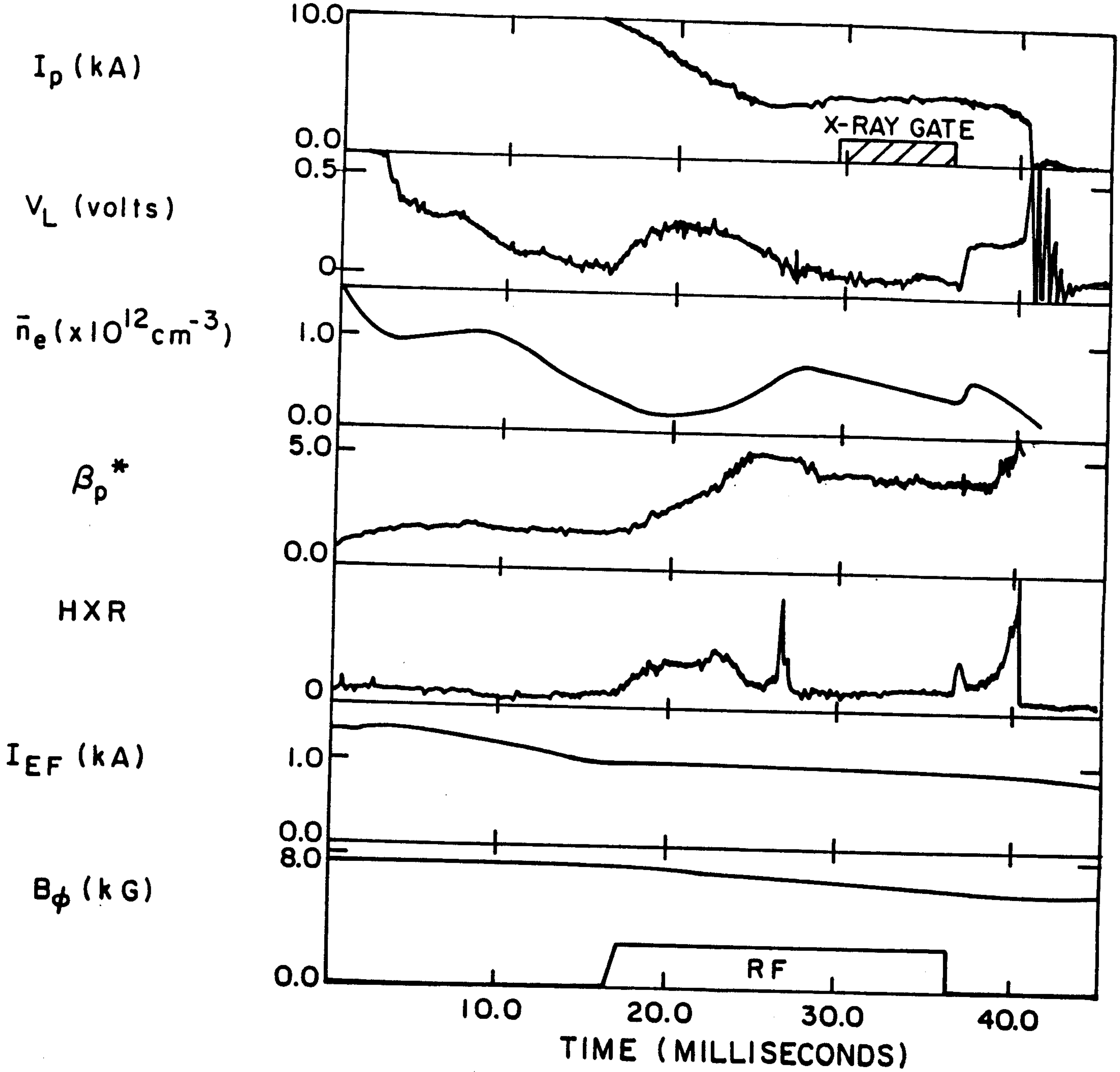
FIGURE CAPTIONS

Fig. 1 Time history of plasma current, loop voltage, density, $\beta_p^*(=\beta_p+l_i/2)$, hard x-ray emission, equilibrium field current, and toroidal field for a typical RF current driven plasma with high β_p^*.

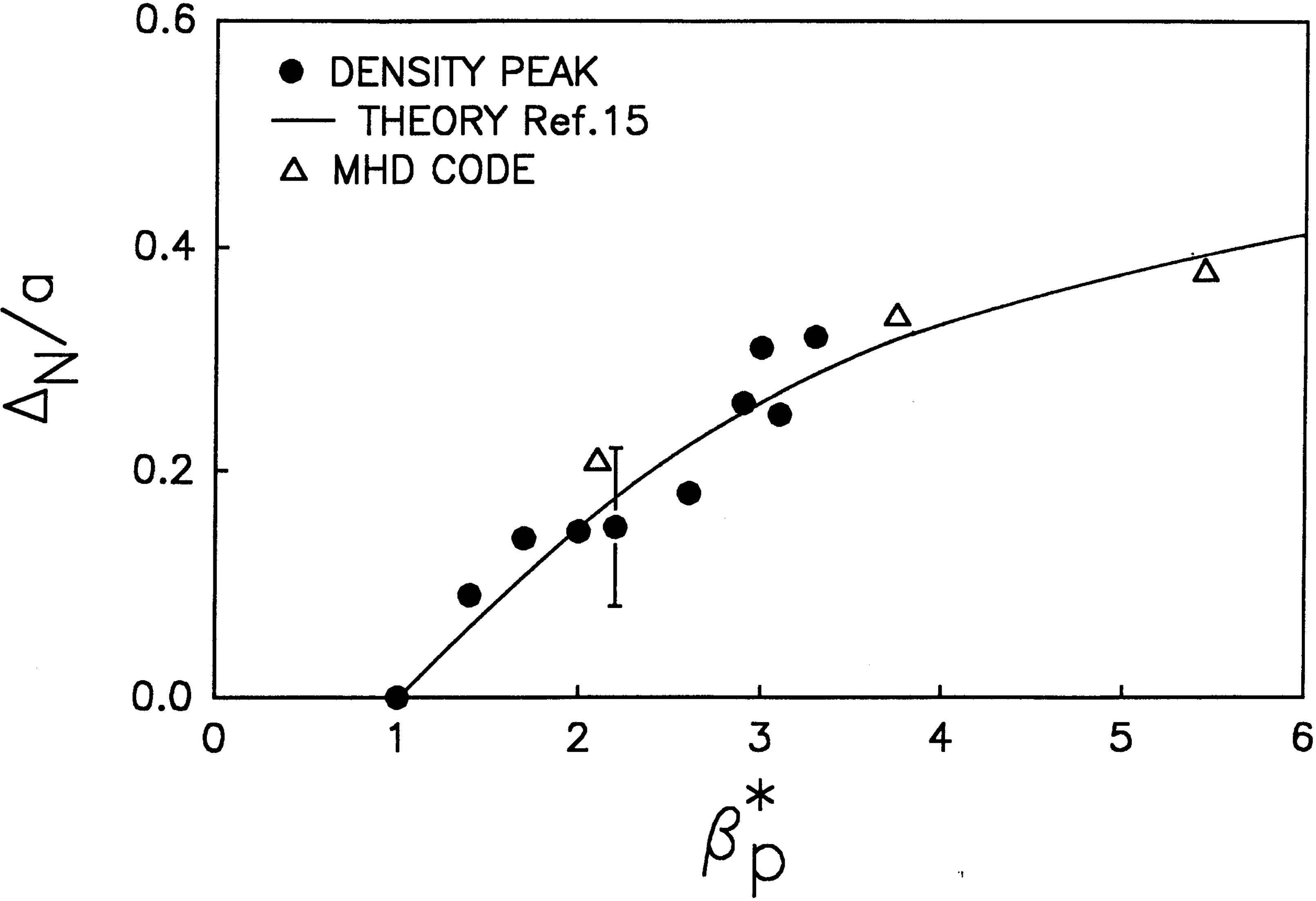
Fig. 2 Comparison between the outward shift of the density profile peak, Δ_N, with the MHD theory prediction of the magnetic axis shift at high β_p^*.

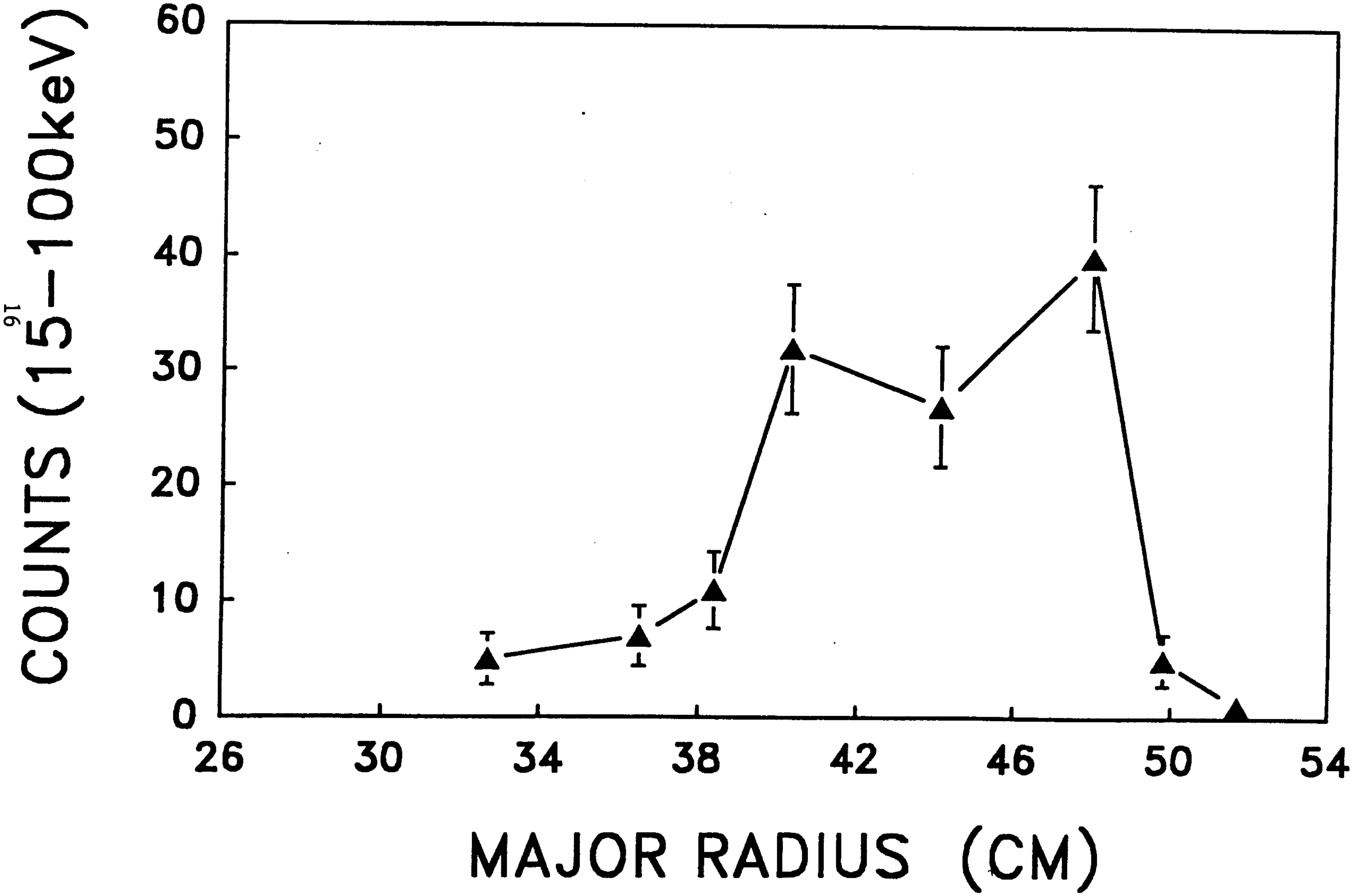
Fig. 3 Radial profile of hard x-ray emission in the energy range 15-100keV for the equilibrium in Fig. 1. The limiters were at R_o = 0.27m and 0.53m, and R_o =0.405m.

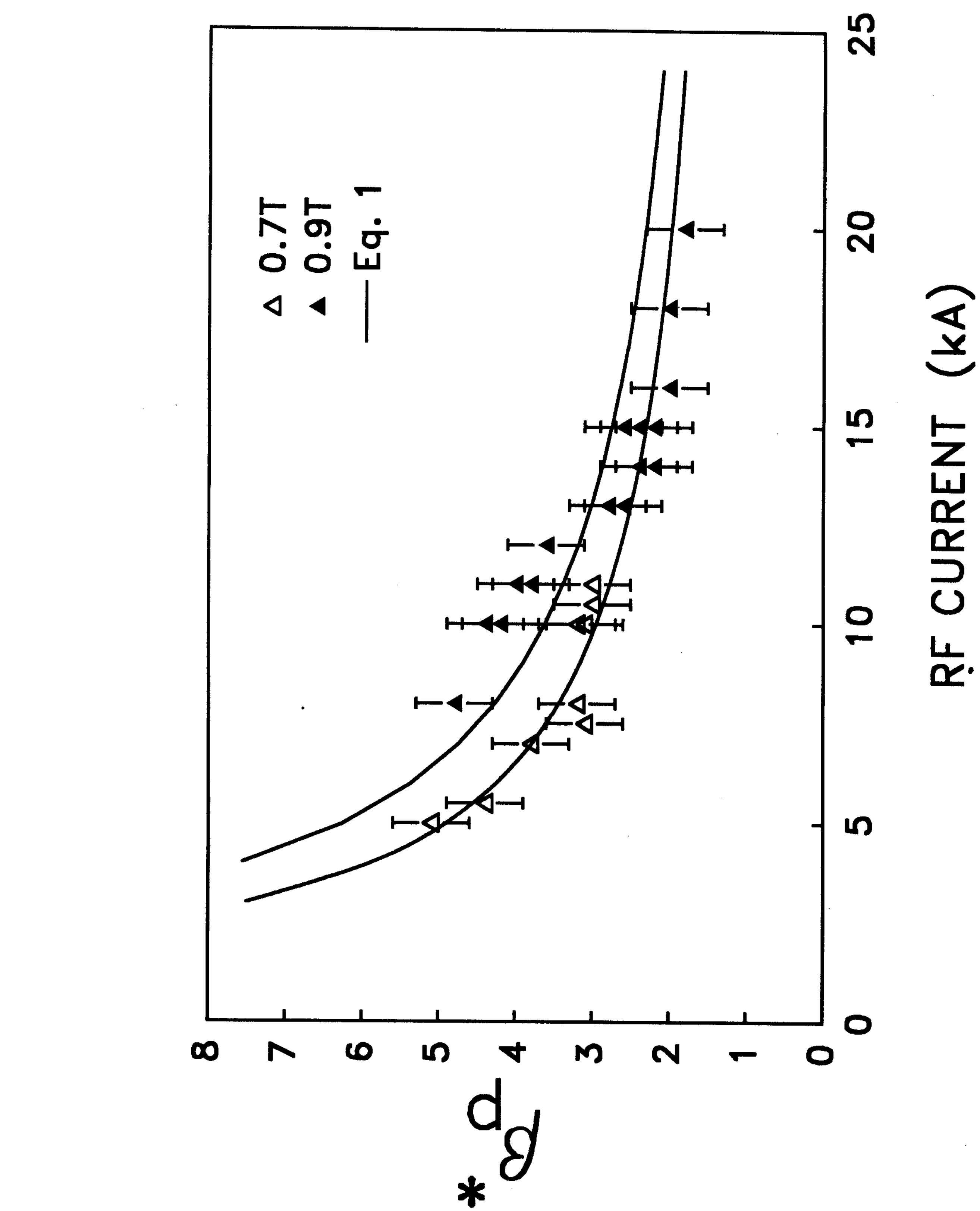
Fig. 4 Comparison of RF driven equilibrium values of β_p^* with the prediction of Eq. 1. B_φ=0.9T for the upper curve and B_φ=0.7T for the lower curve.



I_p (kA)
V_L (volts)
$\bar{n}_e$ ($\times 10^{12}$ cm^{-3})
β_p^*
HXR
I_{EF} (kA)
B_ϕ (kG)
10.0
0.0
X-RAY GATE
0.5
0
1.0
0.0
5.0
0.0
0
1.0
0.0
8.0
0.0
RF
10.0
20.0
30.0
40.0
TIME (MILLISECONDS)


DENSITY PEAK
THEORY Ref.15
MHD CODE
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
Δ_N/a
β_p^*


COUNTS (15–100keV)
0
10
20
30
40
50
60
26
30
34
38
42
46
50
54
MAJOR RADIUS (CM)


0.7T
0.9T
Eq. 1
RF CURRENT (kA)
0
5
10
15
20
25
0
1
2
3
4
5
6
7
8