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EXPERIMENTAL ACHIEVEMENT OF TOROIDAL BETA BEYOND THAT PREDICTED BY "TROYON" SCALING

by
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EXPERIMENTAL ACHIEVEMENT OF TOROIDAL BETA BEYOND THAT PREDICTED BY "TROYON" SCALING

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Abstract. Tokamak experiments have made substantial progress toward improving the experimentally achievable beta limit beyond that predicted by Troyon scaling, β_{Troyon} (%) = 2.8 I/aB MA/m/T. These advances in achievable beta have come about from the modification of the plasma profiles, primarily the current density profile, and the utilization of stabilizing conducting structures. Both theory and experiment have shown that the beta limit increases with peaked current density profiles, high ℓ_i, and broad pressure profiles; scaling of the beta limit β_{max} (%)= 4 ℓ_i I/aB has been proposed. Experiments in DIII–D, TFTR, and JT–60U have all confirmed the increase of β with ℓ_i, using high powered heating and negative current ramps to increase ℓ_i. It is recognized that high ℓ_i is difficult to maintain at high β_N in steady-state conditions as a consequence of the profile of the bootstrap current: β is limited by low *n* external kinks. Profiles with a negative central shear and high edge current density have been proposed that are stable to the low n external kinks provided there is a stabilizing influence from a resistive wall. Experiments from PBX–M and DIII–D provide evidence that wall stabilization is effective and recent experiments at DIII–D have resulted in β_T = 12.5% and β_N = 4.3 at ℓ_i = 0.72 and q_{95} = 2.5; conditions that are expected to have a lower beta limit in the absence of wall stabilization.

INTRODUCTION

A viable tokamak reactor requires both sufficient energy confinement time, τ_E, for ignition margin and sufficient volume average toroidal beta, β_T (%) = 100 μ_0 $\langle p \rangle / B_T^2$, for adequate fusion power density. Both τ_E and the maximum β_T have been shown to increase with increasing plasma current, Ip so that conservative scalings lead to reactor designs with very high plasma current, large size, and high capital cost. More compact and economically attractive tokamak reactor scenarios are realized if confinement enhancement over L–mode scaling [1], $H = \tau_E / \tau_E^{ITER-89P} > 1$, and high normalized beta $\beta_N = \beta_T/(Ip/aB)$ %-m-T/MA can be simultaneously obtained [2]. These reactor studies have shown that the largest impact on fusion reactor designs in reducing both the capital cost and the net cost of electricity is increasing β_N, especially if $H > 2.5$, a value now often exceeded in tokamak experiments [3]. In these experimentally achieved high confinement regimes, performance is no longer limited by transport or heating power, but instead by stability at high β [4]. In addition there are many advantages to steady state operation of a tokamak reactor [5,6]. Efficient steady-state reactors require a large fraction of the total current to be provided by the bootstrap current, which in turn requires high poloidal β, $\beta_P = \mu_0\langle p\rangle / B_p^2$. The bootstrap driven current fraction is $f_{BS} = I_{BS}/I_P \cong (0.3\text{–}0.6)\sqrt{\varepsilon}\,\beta_P$, with the coefficient depending on the details of the profiles. The need for both high β_P and high β_T leads to high β_N, since

$$\beta_T\,\beta_P = \beta_N^2\,(1 + \kappa^2)/8 \qquad (1)$$

where κ is the plasma elongation.

There has been significant progress demonstrating high β_T and high β_N operation, and in developing a physics understanding of the limits. There has been excellent cooperation and synergism amongst the theorists and the experimentalists working toward understanding the limitations to the plasma pressure in a tokamak. Early theoretical work by Wesson [7] and Troyon [8] led to a simple and eloquent scaling of the expected beta limit in a tokamak, commonly referred to Troyon scaling:

$$\beta_T^{max}\ (\%) = C_\beta\, I_P/aB\ (\mathrm{MA/m/T}). \qquad (2)$$

Many other theorists completed similar scaling studies, and found the same overall relationship, but with different values of the scaling coefficient C_β depending on the details of the plasma profile assumptions, and the instabilities considered. The value found by Troyon is 2.8 (%-m-T/MA). Armed with this simple scaling, and sufficient neutral injection heating power, experimentalists soon confirmed this basic scaling [6]. More recently, there have been a number of experiments which have obtained values of β_T substantially above that predicted by Troyon. Values of β_N greater than 6%-m-T/MA have been obtained experimentally (we will use β_N to designate normalized beta, irrespective of any consideration of stability limits, experimental or theoretical; and C_β to indicate a scaling relation).

In this paper we will review these experimental results with β_N substantially above that predicted by Troyon and compare the results with some of the theory and code calculations. In the next section we will discuss high β_N operation in the context of modifying the current density profile and pressure profile. In Section 2, we will also discuss the consistency of high β_N operation with near steady-state profiles. In Section 3, we will discuss high β_T and β_N in the context of wall stabilization and plasma rotation. We will provide some conclusion and outstanding issues in Section 4. The division of Sections 2 and 3 is motivated by the discussion by Troyon [8], where he suggested that the β limit might be improved by optimization of the pressure profile and by wall stabilization.

IMPACT OF THE PRESSURE PROFILE AND THE CURRENT DENSITY PROFILE ON HIGH β_N OPERATION

The scaling relation given by Eq. (2) with C_β = 3.5 %-m-T/MA adequately represented the experimental data through approximately 1988. However, over the past several years, many experiments have obtained β_N values significantly above 3.5%-m-T/MA. This high β_N is illustrated in a summary of high beta results from a number of experiments in Fig. 1. Notice that DIII–D, PBX–M, JT–60U, and TFTR experiments have all exceeded $\beta_N = 3.5$. Although these experimental results differ significantly from Troyon's prediction, there has been no claim that the ideal stability limits predicted by theory have been exceeded. Most of the difference between the experimental results shown in Fig. 1 and "Troyon scaling" can be attributed to details in the current density and/or pressure profile. The experimental β limit increases with peaking of the current density profile, or increasing internal inductance, $\ell_i = 1/B_{Pa}^2 \int dv\, B_p^2$, where Bp is the poloidal field and B_{Pa} is the average poloidal field at the plasma surface, $B_{Pa} = \mu_0\, I_P/C_{Pa}$. Initial high β_N results were obtained in DIII–D [9] and PBX–M in 1989 [10]. Up until this time, there was not a sufficiently large set of data with β values significantly different from that predicted by Troyon scaling, and not sufficiently detailed measurements to evaluate the dependence of the limit on any other global variable. The strong shaping of the plasma cross section in PBX–M and DIII–D allows the ready determination of β_T and ℓ_i from equilibrium reconstruction [11]. With the ready availability of the current profile parameter, ℓ_i, and motivated by simple theory [12] and some early stability code calculations [9,13], researchers compared the scaling of the β limit with and without including ℓ_i and proposed that the scaling [14]

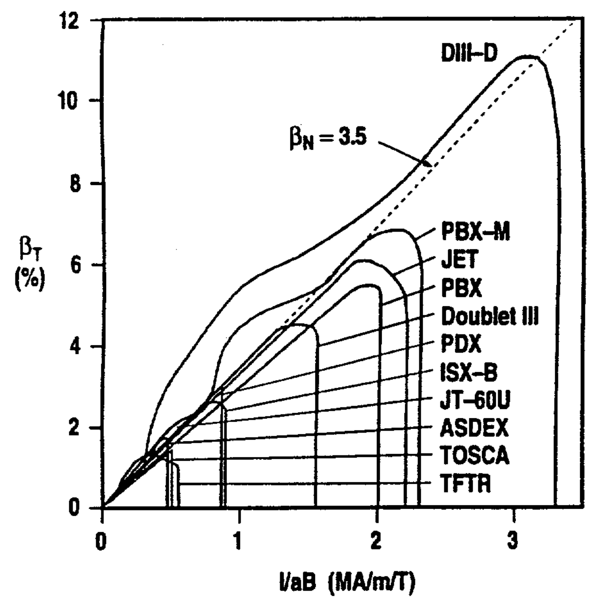

Fig. 1. Comparison of experimentally observed beta limits and Troyon scaling, showing the operational envelopes for a number of tokamaks. Data compiled September 1993. All experimental data was well represented by the dashed line, β_T = 3.5 I/aB, through 1988 [6].

$$\beta_T^{max} (\%) \leq 4\ \ell_i\ Ip/aB\ (MA/m/T)\ . \quad (3)$$

better represented the experimental data. A comparison between the scalings is shown in Fig. 2. Although this scaling looks promising, more detailed experiments were necessary to confirm the dependence of β_T^{max} on ℓ_i

The increase of β with ℓ_i is a very robust result and has been demonstrated in several tokamak experiments using transient current profile control techniques. One can increase ℓ_i transiently by rapidly decreasing the magnitude of the plasma current. This technique has been used to increase the achievable β_N and evaluate its dependence on ℓ_i in DIII–D, TFTR and JT–60U. The temporal evolution of typical DIII–D example is shown in Fig. 3(a). The value of ℓ_i at the highest β_N is altered by varying the current ramp rate and the timing of the maximum injection power with respect to the current ramp. Figure 3(b) shows the temporal evolution of a TFTR [15] current ramp discharge. In the TFTR discharges, the value of ℓ_i at the highest β_N is altered by varying the total change in plasma current $\left(I_p^{final}/I_p^{initial}\right)$, and by adjusting the beam power timing with respect to the current ramp. The use of different current ramp rates was used in JT–60 U [16] to vary the ℓ_i of the target discharges as shown in Fig. 3(c) In Fig. 3(b), the time dependent stability boundary to n=1 modes calculated by PEST is shown, and it is seen that disruption or β collapse occurs at the calculated boundary. The scaling results of the above three experiments are shown in Figs. 4(a–c) [16–18] respectively. It is seen that β_N increases with ℓ_i in all three cases, and in DIII–D, a maximum β_N of greater than 6%-m-T/MA was obtained. In Fig. 4(a), the maximum beta stable to ideal ballooning modes is shown

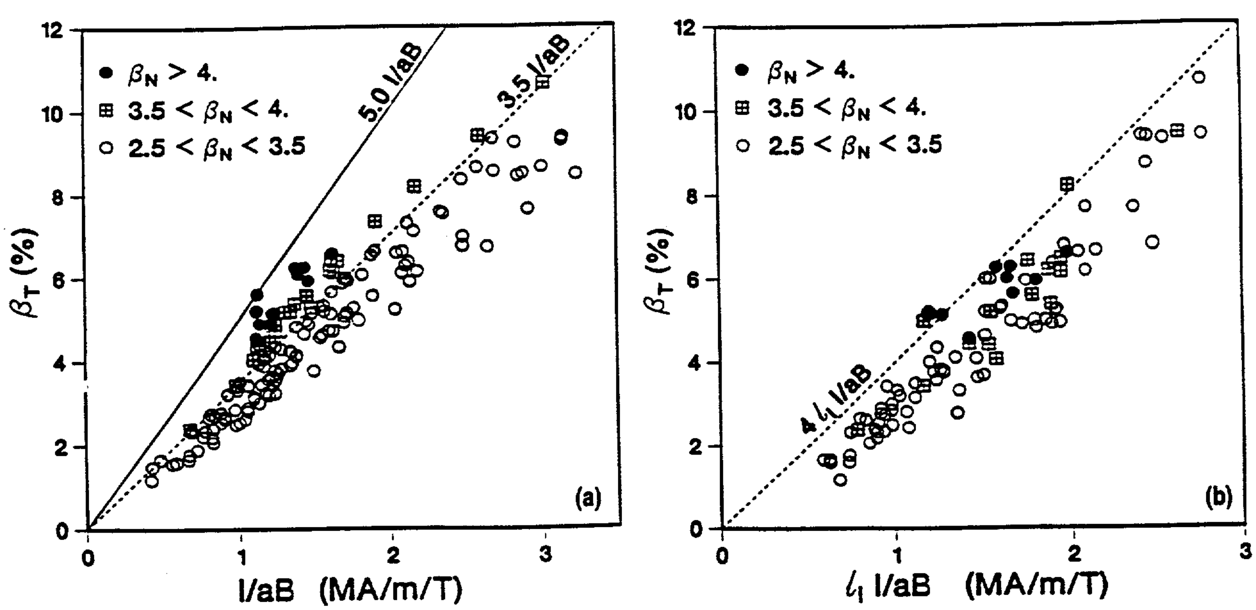

Fig. 2. Comparison of DIII–D high beta results to two scaling relations (a) Troyon (I/aB) (b) inclusion of internal inductance, (ℓ_i I/aB). Data shown represents the highest value of β_T obtained at each value of I_p and B_T. Highest β_T at each condition does not necessarily represent a β-limit. Data through 1990.

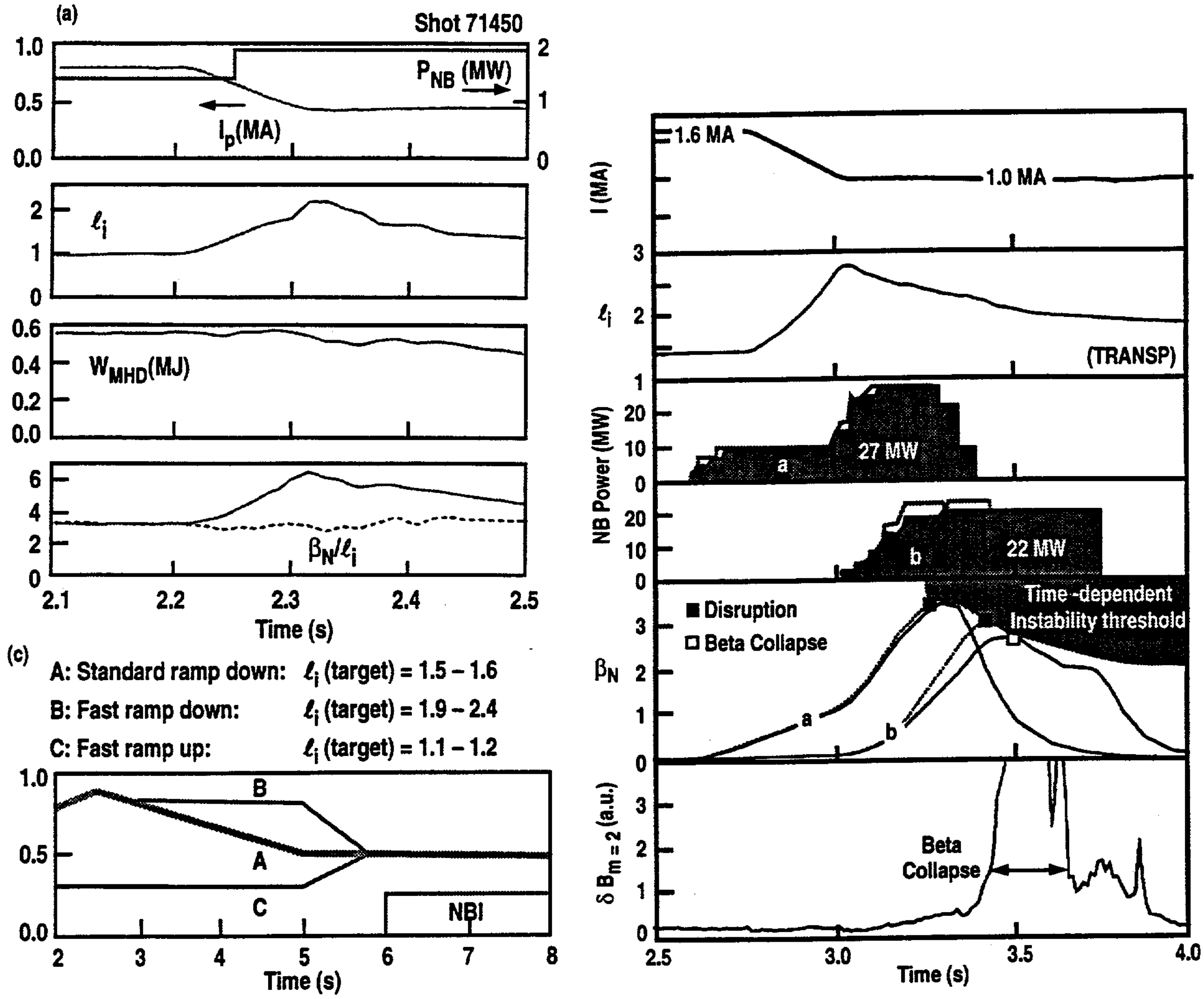

Fig. 3. Temporal evolution of negative current ramp discharges illustrating the operational scenario to obtain a variation in ℓ_i and high β_N for (a) DIII–D, (b) TFTR, and (c) JT–60U.

(obtained by determining the pressure gradient at each flux surface that is marginally stable to ideal ballooning). The experimental value lies below the maximum ballooning stable value, but both increase with increasing ℓ_i, illustrating agreement between theory and experiment.

Insight into the dependence of β_T^{max} on the current profile can be easily gained by estimating the ballooning limit in the large aspect ratio circular limit. Following the procedure outlined by Wesson [7], with $\alpha = 0.6$ S, where α is the reduced pressure gradient, $\alpha = 2\,\mu_0\,R\,q^2/B_T^2\,dp/dr$ and S is the magnetic shear parameter, $S = r/q\,dq/dr$; the Wesson ballooning beta limit is given by:

$$\beta_{WS} \equiv 0.6\,\varepsilon \int_0^1 x^3 \int dq/dx \;\; 1/q^3\,dx \quad (4)$$

and ℓ_i is given by ;

$$\ell_i = 1/2 + q_a^2 \int_0^1 x^4\,dq/dx \;\; 1/q^3\,dx. \quad (5)$$

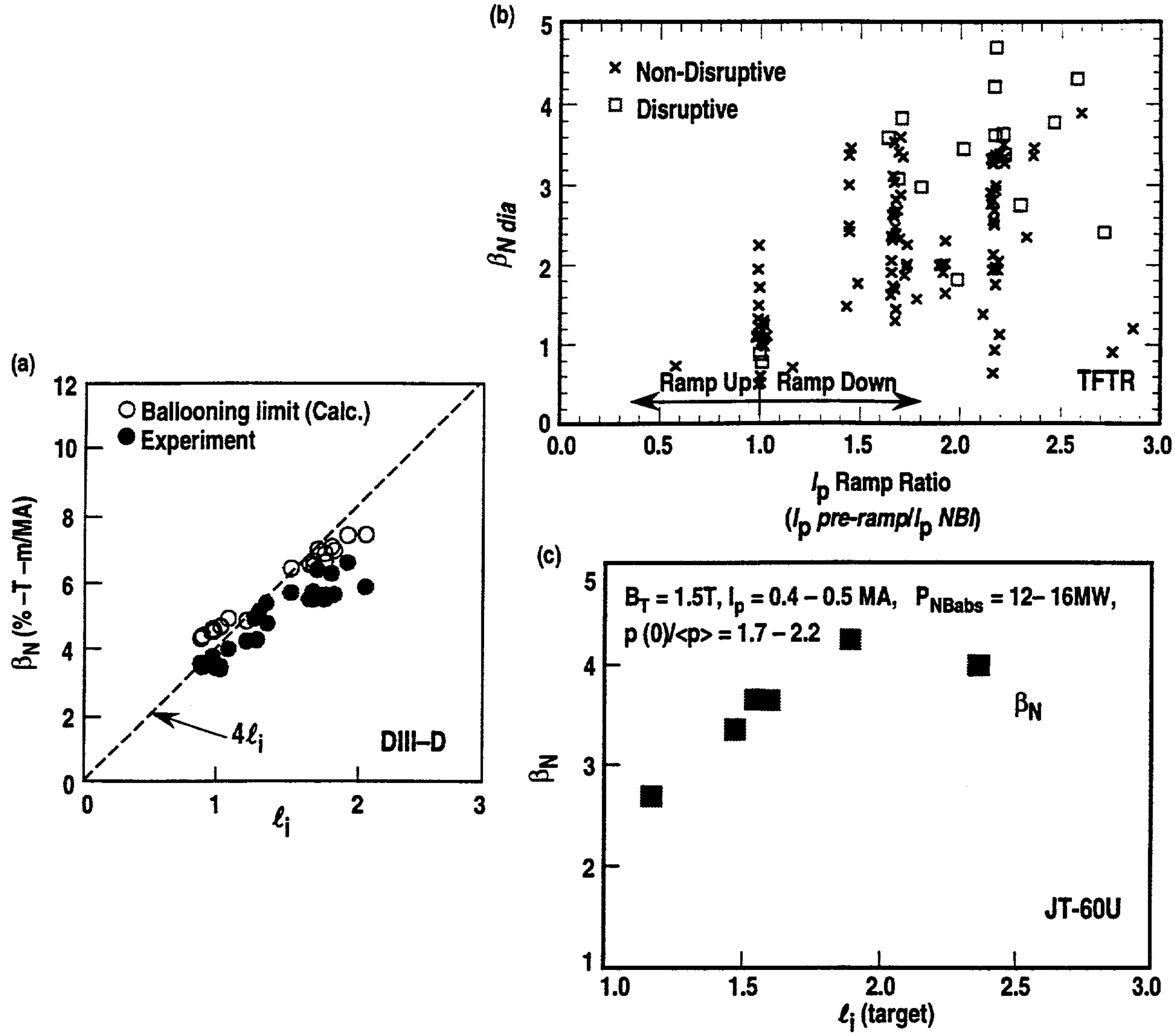

Fig. 4. Dependence of β_N on ℓ_i for three experiments: (a) DIII–D, (b) TFTR, (c) JT–60U. The ratio of the pre-ramp to post-ramp current in TFTR is roughly proportional to ℓ_i.

x is the reduced radial coordinate, x = r/a. From Eq. (4) and Eq. (5), one can obtain

$$\beta_{WS} \approx 1/q_a \, (\ell_i - 1/2) \, \varepsilon/q_a \ , \tag{6}$$

and using $5 \, \varepsilon/q_a = I_P \, (MA)/a \, (m) \, B_T \, (T)$ in this configuration, we obtain

$$\beta_{WS} \, (\%) \approx 20/q_S \ (\ell_i - 1/2) \, I_P \, (MA)/a \, (m) \, B_T \, (T) \ . \tag{7}$$

Detailed code calculations have shown Eq. (7) to be nearly exact for the infinite aspect ratio limit. Using the calculated q profile from a TFTR discharge, Kesner [19] has used Eq. (4) directly and found good agreement between the observed beta collapse and the experimental β exceeding β_{WS}. The empirical scaling of Eq. (3) and the simple ballooning estimate given in Eq. (7) show β_N increasing with ℓ_i. However, this simple estimate exhibits a stronger dependence on ℓ_i than is observed in the experiment: This is explained in the differences in the details of the q profiles and the important differences resulting from the effects of finite aspect ratio, the axis shift and plasma shaping [12].

It is surprising that high ℓ_i from the negative current ramp discharges consistently, in several different experiments, gives higher β_T than the lower ℓ_i counterparts, especially since the β limit is known to depend on the pressure profile. There are two possible reasons for the uniformity of this result. The first reason may be that marginally stable ballooning modes readjust the pressure profile to a more favorable profile. The experimental pressure gradient is close to that marginally stable to ballooning over much of the discharge, as shown for a β_N = 4.3 discharge in Fig 5 [9]: in this case, the n = 1 kink limit is calculated to be above that of the ballooning limit [18]. The outer 2/3 of TFTR current ramped discharges are also near the marginal ballooning limit. In such cases, it is likely that high n ballooning modes could result in modification of the pressure profile, without causing catastrophic loss of plasma energy. The second reason may be the change in the background transport from the current ramp leads to a more favorable pressure profile for increasing β_N. The energy confinement also increases with increasing ℓ_i: the transport is reduced in the outer region where the magnetic shear is increased as a consequence of the negative current ramp [19]. The reduction in the transport is observed in cases where β_T is much less than the calculated stability limit. This reduced outer transport naturally results in broader pressure profiles, which are more favorable for stability at high β_T.

Broad pressure profiles as well as high ℓ_i are necessary to achieve high β_N. To show this the stability boundary was calculated for a target discharge, with three different pressure profiles. The plasma size and shape, the toroidal field, the total plasma current, and the axial safety factor, q(0), were all held constant. Equilibria were generated for each of the three pressure profiles, varying the total β_T and ℓ_i independently. Stability against the n=1 ideal kink was calculated using the code GATO, and the stability boundary was mapped out as shown in Fig. 6 [6,13]. There are several key features shown in this figure: 1) at low ℓ_i, the stability boundary is similar for all three pressure profiles, and high β_N is not accessible, 2) as the pressure profile becomes broader, the β limit increases, and the broadest pressure profile has access to high β_N at high ℓ_i, 3) the boundary at high ℓ_i is limited by internal modes and do not require a conducting wall for stabilization. The boundary at low ℓ_i is determined by external kinks and is susceptible to wall stabilization: the calculation shown has an ideal conducting wall at r_w/a = 1.5. It should also be noted that the stability boundary with the most peaked pressure profile is limited by internal and global n = 1 modes over the majority of the range of ℓ_i. This calculation was carried out for the specific equilibria conditions and the conclusions depend somewhat on these conditions. However similar calculations have been carried out elsewhere with significantly different geometry and assumptions [20], and the general conclusions drawn were the same.

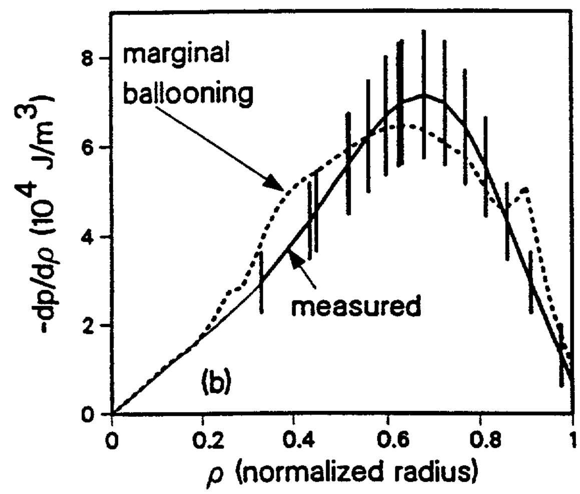

Fig. 5. Comparison of the measured pressure gradient to that marginally stable to ideal ballooning for a DIII–D double-null divertor discharge. The peak experimental β_N for this discharge is β_N = 4.3%-m-T/MA; the value everywhere marginally stable to ideal ballooning is β_N^{ball} = 4.6%-m-T/MA.

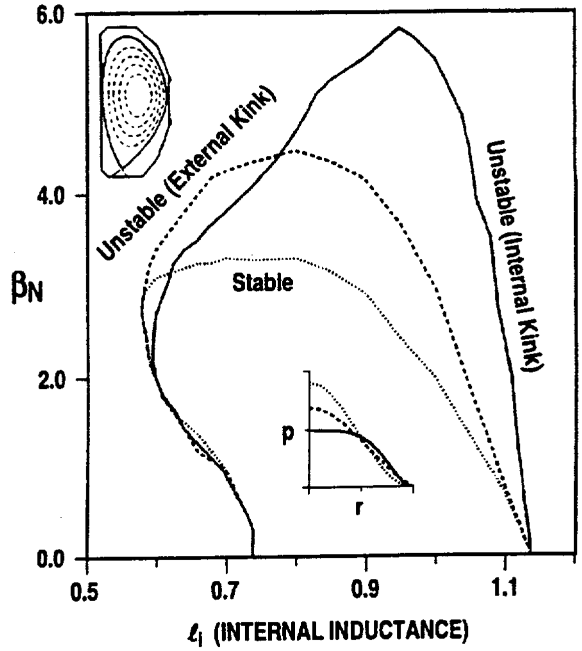

Fig. 6. Dependence of the calculated n=1 kink β-limit on the current density profile ℓ_i; and the pressure profile. The three pressure profiles are shown as an inset and the pressure gradients are given by: solid $P'(\psi)$ = 1-5/8 ψ; dotted, $P'(\psi)$ = 1–ψ. The stability was calculated for a single-null divertor shown as inset, q ~ 3.1 and a conducting wall was assumed at $r_{w/a}$ = 1.5.

A combination of high ℓ_i produced by current ramps and broad pressure profiles produced by tailoring the neutral beam power deposition has been used in JT–60U to increase the achievable β_N [16]. High ℓ_i is obtained by the negative current ramps as depicted in Fig. 3(c). To broaden the pressure profile, the plasma shape and position with respect to beam injection were adjusted to give off-axis deposition and produce a broad fast particle pressure. In addition, conditions for the H–mode were maintained to obtain a higher edge pressure gradient. The resulting pressure profile for the high β_N discharge is shown in Fig. 7(a) and for comparison the profile for a high β_P case is shown in Fig. 7(b). The maximum β_N obtained for the two cases shown are 4.2 and 2.5%-m-T/MA respectively, illustrating the benefit of the broad pressure profile.

All of the high β_N discharges thus far discussed have been relatively short in duration. The short duration is a consequence of the transient nature of the current profile control technique, the negative current ramp. It is important to ask if these high ℓ_i discharges can be maintained in steady-state conditions. It easily calculated that the bootstrap current, unavoidable at high β_T, significantly reduces the value of ℓ_i that is accessible in steady state, and furthermore results in current density near the boundary which is in general destabilizng to low n kinks.

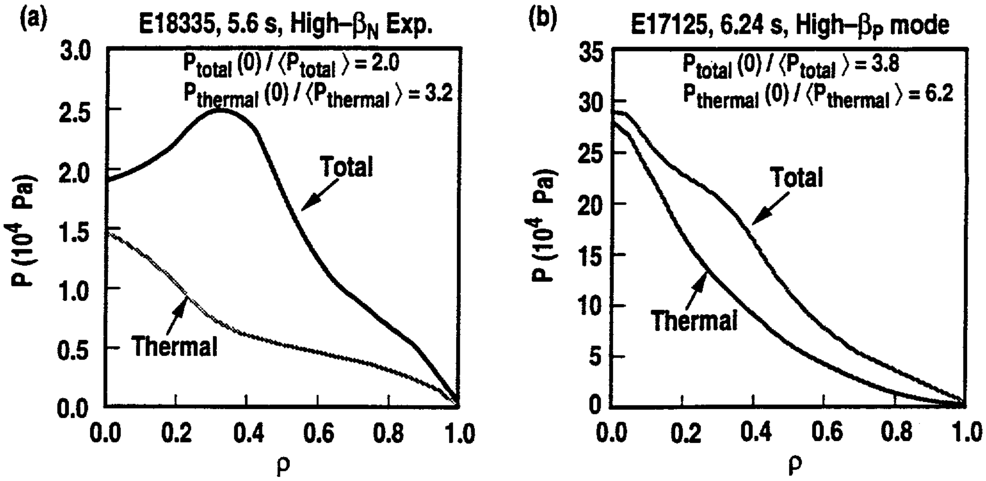

Fig. 7. Comparison of the pressure profiles between a high β_N discharge (a) and a high β_p (b) discharge in JT–60U.

A simple illustrative calculation shows the effect of the bootstrap current on the expected β limit. Again we follow Wesson and assume the cylindrical approximation. From Wesson,

$$-\,dp/dx \approx 0.6\,\varepsilon\; 1/(2\,\mu_0)\,(B_T/q)^2\, x/q\; dq/dx \quad , \tag{8}$$

from Bickerton [21],

$$J_{BS} \approx C_{BS}\; \sqrt{\varepsilon/a}\sqrt{x/B_p}\;(-dp/dx) \quad , \tag{9}$$

where C_{BS} is a constant of order unity, and using the definition of q, Ampere's Law in cylindrical coordinates is

$$J(x) = \langle J\rangle\, q_a\, 1/q(x)\,[1 - S(x)/2] \quad . \tag{10}$$

For simplicity, let us consider a "top hat" current density profile as did Wesson, but the current density in the outer region will be non zero, $q = 1$ for $x < x_0$, and $q = q_a\, x^\gamma$ for $x > x_0$. In this way, we are modeling a core current that is driven by some external means and estimating an outer current driven only by the bootstrap. Now setting $J(a) = J_{BS}$, we can solve for the bootstrap current density, the magnetic shear and the pressure gradient, all self-consistently, assuming the pressure gradient is that given by marginal stability to ballooning. We find,

$$\gamma = S(a) = 2/(1 + 0.3/\sqrt{\varepsilon}\; C_{BS}) \quad . \tag{12}$$

Again for simplicity, we choose $\sqrt{\varepsilon} = 0.3$ and obtain $\gamma = 1$. The resultant maximum β_T is then

$$\beta_T^{max}\,(\%) = 6\; I_P\,(MA)/a\,(m)/B_T\,(T)\;[2/q_a\,(1 - 1/q_a)] \quad . \tag{13}$$

This indicates a considerable reduction in the attainable β_T. Notice at $q_a \approx 5$, the β_N is limited to 2.4%-m-T/MA, a value not very different, (perhaps somewhat larger) than observed in long pulse high β experiments with significant bootstrap. This simple example shows why experiments that have tried to significantly extend the high β_N phase following the current ramp down have not met with success and beta collapse's at $\beta_N \approx 1.4$ have been observed at higher q.

High values of β_N have been obtained at high ℓ_i, up to greater than 6%-m-T/MA. But these high values have only been obtained transiently. It appears that high β_N at high ℓ_i is inconsistent with long pulse or steady-state operation as a consequence of the bootstrap current. Although $\beta_N = 5$ has been obtained at $\ell_i = 1.2$ in a DIII–D double-null divertor discharge, stability calculations indicate a stabilizing influence of the conducting wall is necessary to obtain agreement with the theory.

WALL STABILIZATION AND PLASMA ROTATION

There has been a substantial effort in trying to identify steady-state scenarios with high bootstrap fraction and high β_N that are stable to low-n modes without wall stabilization [5,22,23]. Attractive scenarios have been identified with wall stabilization [14,15]. It has long been recognized that a close fitting ideal conducting wall provides stability to low n ideal and resistive modes. However, the ideal modes again become unstable as the walls become resistive. New theory indicates that plasma rotation in the presence of a resistive wall can provide stabilization. As a consequence of the identified steady-state scenarios, the new theory, and previous experimental indications of the favorable stabilizing influence of a resistive wall, attention has recently been given to stabilization of low n modes with a resistive wall.

There has long been experimental evidence of the stabilizing influence of a resistive wall. In DIII–D discharges, the experimentally observed β_T values exceed the values calculated without wall stabilization, and are in general agreement with the code calculations if a conducting wall is included at the location of the DIII–D vacuum vessel [24]. Similarly, a conducting wall was necessary to obtain better agreement between PBX–M experimental high β_T values and the ideal code predictions, see Fig 8 [25]. And the highest β_N (>4%-m-T/MA) and β_T (6.8%) values were obtained after conducting plates were added to PBX (PBX–M). In addition the growth rate of the modes is observed to decrease as conducting plates are moved closer to the plasma in HBT-EP [26]. However, in these earlier results, the gain, in β_N with the wall compared to without wall stabilization were not sufficiently great, and the details of the pressure profiles and the current density profiles were not sufficiently well known, to rule out the possibility that the difference between the calculated and measured β limits could not be accounted for in the profiles.

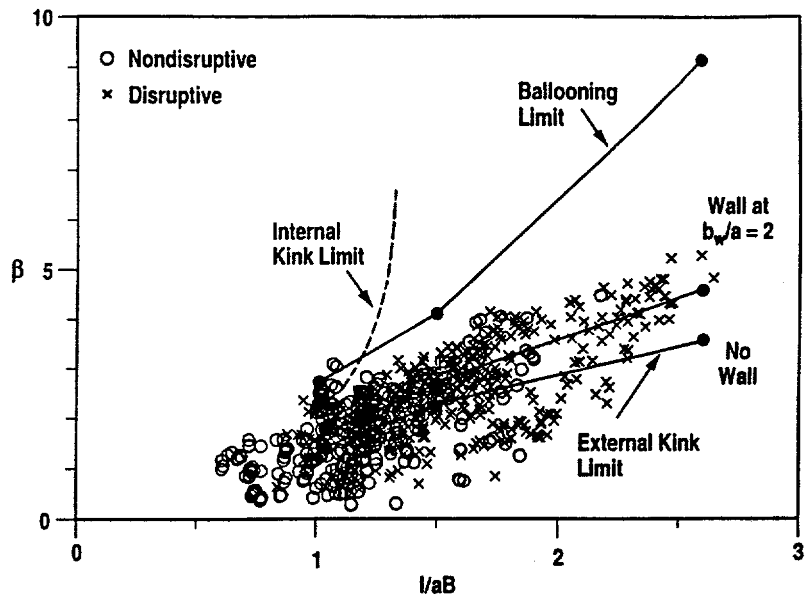

Fig. 8. Operating range of high beta discharges in PBX compared to calculated stability limits, including the ideal n=1 external kink limit with a conducting wall at twice the plasma minor radius and without a wall.

With much improved profile measurements, especially the measurement of the q profile with the Motional Stark Effect (MSE) diagnostic, an experiment was recently carried out on DIII–D to try to better evaluate the stabilizing influence of the resistive wall and attempt to achieve high β_N under discharge conditions where the ideal limit without the wall would be substantially lower [22,27]. Theory and code calculations indicate that low ℓ_i discharges are especially susceptible to low n edge kinks and therefore the gain from wall stabilization is expected to be significant: This same conclusion would be drawn from Eq. (3). To maintain the low ℓ_i target, the discharge is heated very early in the discharge with neutral beam injection. In addition, near parallel injection was used preferentially to maximize toroidal rotation. A typical discharge evolution is shown in Fig. 9. Using this technique to obtain low ℓ_i, high β_N was obtained: $\beta_N = 4.3$, $\beta_T = 12.5\%$ $\ell_i = 0.71$, and $q_{95} = 2.5$

The high β_N results are summarized in Fig. 10. The large solid points represent the recent data. A number of discharges were obtained with β_N significantly greater than 4 ℓ_i. We obtained a discharge at higher q_{95} with $q(0) > 1$ to make the ideal stability analysis possible [instability is almost always found with $q(0) < 1$ independent of β]. The effect of rotation and wall stabilization on stability is seen more clearly by looking at the detail of the termination of this discharge [27]; $q(0) > 1$ and $\beta_N = 3.7$: see Fig. 11. Ideal stability analysis has been completed for this discharge using equilibria reconstructed with the measured pressure profile and the measured q profile from MSE measurements. The highest stable beta against low n kink modes with no wall stabilization is $\beta_N = 2.8\%$-m-T/MA. This analysis indicates that a 30% gain in the stability limit is provided by the wall. Higher beta is prevented by the appearance of TAE modes which result in a loss of heating efficiency. A rotating

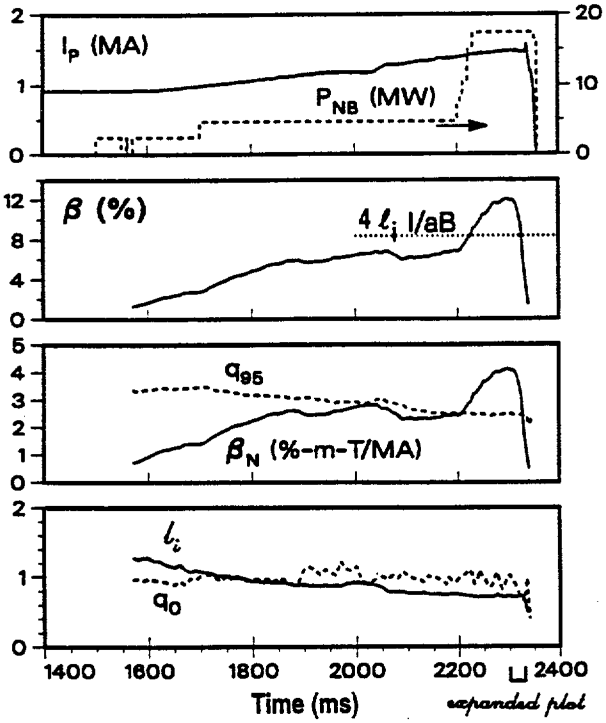

Fig. 9 Temporal evolution of high β_T, (B_T = 12.5%) high β_N (β_N = 0.13) discharge in DIII–D. Early beam injection during the current ramp maintains low ℓ_i, $\ell_i \sim 0.71$.

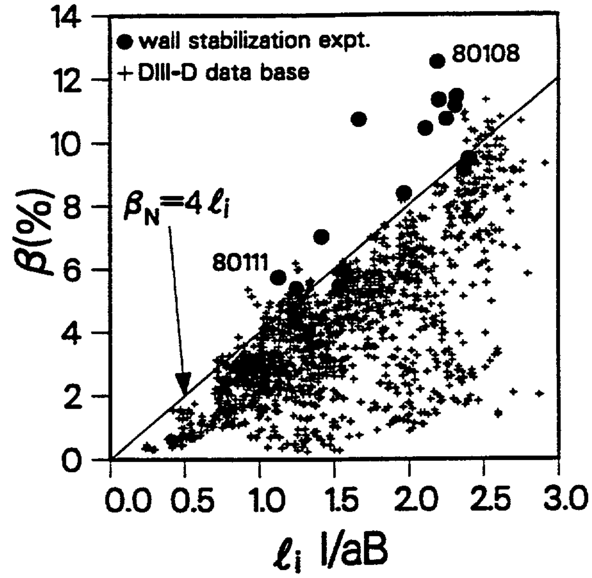

Fig. 10. Comparison of recent DIII–D discharges designed to maximize the gain from a close fitting wall to previous scaling.

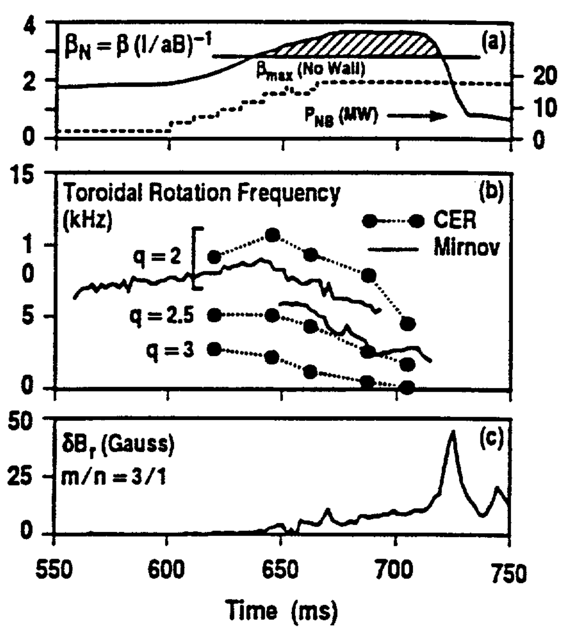

Fig. 11. Impact of plasma rotation on low n-stability in DIII–D, temporal evolution of discharge 80111 showing normalized beta, β_N, neutral beam injection power P_{NB}, rotation frequencies at several rational surfaces determined from magnetic (Mirnov) oscillations and CER spectroscopy, and δB_r of nonrotating m/n=3/1 mode determined from saddle loops.

m/n=5/2 mode is observed during the discharge; starting before the high beta phase. Approximately 10 ms prior to the plasma termination, a nonrotating m/n=3/1 mode begins to grow very rapidly, while the m/n=5/2 mode continues to rotate. The growth rate of the 3/1 mode is $\gamma = (6\ \mathrm{ms})^{-1}$ consistent with the expectation for a resistive wall mode. At the time the m/n=3/1 mode begins to grow rapidly, the measured rotation (from charge exchange recombination measurements) becomes zero. The expectation is that if the rotation could be maintained significantly different than zero at the 3/1 surface, higher beta could be obtained.

Wall stabilization looks promising as a means to increase β_N and β_T. However, as with the current profile modification, the high beta phase to date in these discharges is transient. All the discharges do suffer a beta collapse and/or disruption. The termination always involves a non rotating n=1 mode, which very often grows on a time scale comparable to the wall time. It is extremely difficult to keep the mode rotating, either because of the drag of rotating modes interacting with the resistive wall or the loss of momentum from the plasma due to collective particle effects.

DISCUSSION

Significant progress has been made in the recent years in developing a better understanding of the beta limit physics and using that understanding to obtain values of β substantially above those predicted by Troyon. We have obtained β_N values of greater than 6%-m-T/MA at high ℓ_i with negative current ramps, and β_N up to 4.3%-m-T/MA has been achieved by taking advantage of wall stabilization at low ℓ_i. A change to the beta limit scaling has been proposed to include the major effect of the current profile: β_T^{max} (%) = 4 ℓ_i Ip/aB (MA/m/T). It is important to emphasis that the basic scaling proposed by Troyon and others still holds, plasma beta still increases with normalized current, and the highest values of beta are obtained at the lowest q and highest I/aB that are obtainable.

The major challenge remaining is to develop high β_N operational scenarios consistent with near steady-state profiles. To date all the very high β_N discharges have remained at high β for fairly short times: $t_{DUR} \gg t_{MHD}$ (ideal MHD time scale), $t_{DUR} \gg t_{RWALL}$ (resistive wall penetration time), $t_{DUR} \geq \tau_E$, but $t_{DUR} < t_{ST}$ (sawtooth period), $t_{DUR} \ll t_{JDIF}$ (current diffusion time). Near term goals should include maintaining reliable high β operation for several sawtooth periods because $q \leq 1$ is calculated to have a deleterious effect on stability near the β limit, and $q \leq 1$ and the m/n=2/1 instability are observed to play a role in many high β discharge terminations. Even ohmically driven pulsed tokamak reactors are expected to have pulse lengths longer than the current diffusion time, so high β operation with fully penetrated current profiles must be demonstrated. It appears that operating with very peaked current density profiles at high β_N will be extremely difficult as a consequence of the bootstrap current.

Very high β_N at high ℓ_i with negative current ramps has not yet been obtained in strongly shaped discharges. Numerical calculations indicate that the expected dependence on ℓ_i should be less than is observed in the more circular shapes. This expectation should be evaluated experimentally.

In addition to the dependence of β on ℓ_i, the β limit is also expected to depend on other details of the profiles. These include: dependence on q(0), dependence on edge current density, and dependence on the edge pressure gradient. Does $q(0) < 1$ reduce the achievable β? Does raising q(0) above 2 or 2.5 increase the β limit? There are indications that the edge bootstrap current and edge pressure gradient observed in H–mode and VH–mode are destabilizing at high β. Several inverted q profiles have been identified that promise stable high β_N operation with a resistive wall that is roughly consistent with the expected bootstrap current. Can these profiles be controlled to maintain sufficient stability margin with proven current drive schemes? Can the resulting instabilities be sufficient localized to the edge, such that they regulate the edge gradients without too adversely impacting confinement or the global stability? Are there ways to control the edge pressure gradient (and thus also the edge current density) to maintain stable operation?

Stabilization by a resistive wall appears very promising for achieving high β_N in near steady-state conditions, for example inverted q profiles or the second stable core VH–mode [5,22,23]. However, for the resistive wall to provide the stability margin, the plasma rotation (mode rotation) must be maintained or active feedback schemes must be developed for the slowly growing resistive wall mode. There is much theory, code, and experimental work to be completed in this area.

The biggest experimental challenge is to lengthen the duration of the high β_N phase of the discharge, and evaluate means to maintain the plasma and mode rotation. In the high β DIII–D discharges, why do the existing plasmas always seem to end with a non-rotating mode? Is this an example of the resistive wall mode? Can this mode be avoided with sufficient plasma rotation? Both experiment and theory must evaluate the effect of the plasma to wall distance on the stabilizing effect. From theory, we need to know what magnitude of rotation is necessary and what rotation profile or $E\times B$ rotation profile is necessary. How much momentum input is required to provide the necessary rotation? We also need to evaluate in more detail the stabilizing effect of non-axisymmetric stabilizing structures including where and how close to place them. There is much experimental and theoretical work now underway in this area and we should expect new results and understanding soon.

Although we have not addressed the affect of plasma shape directly, shaping is expected to play a role in achieving steady state high β_T. There is no reason to expect the effect of details of the plasma profiles and the plasma shape to be separable. We should not expect aspects of the profile that are favorable for stability for a given plasma shape and aspect ratio to necessarily to hold for another configuration . Theoretical calculations have shown that the range in current profiles that are stable to both ballooning (especially second regime access) and the low n kinks becomes much broader in shaped plasmas. For example, negative central shear scenarios with a zero in the magnetic shear off axis are expected to be unstable to internal kinks (infernal modes) in weakly shaped plasmas. Thus we expect high β_N steady state scenarios to require strong shaping. This expectation needs to be evaluated both theoretically and experimentally.

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