Observation of a Fast Beta Collapse during High Poloidal-Beta Discharges in JT-60

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A nondisruptive β-limiting phenomenon in a large tokamak under a large bootstrap current fraction, up to ~80% of the plasma current, is described; $\beta=$(plasma pressure)/(magnetic pressure). During long-pulse neutral-beam-heated discharges in the JT-60 tokamak, it occurs at $\beta_p \sim 3$, leading to a limit of the normalized β lower than the Troyon limit. The MHD feature is characterized by a large-amplitude partial relaxation with a fast growth time. A hollow current profile evolution in the high-β_p regime plays an essential role in the MHD stability, analysis of which shows that the ideal $n=1$ kink-ballooning modes can be unstable just before the collapse.

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In nuclear fusion research, the high-β_p regime in tokamak operation is potentially of much interest as it may offer an alternative route to the development of an ignition device in which the requirement for external sources of noninductive current drive is very much reduced [1-3]. Here, the poloidal beta is defined as $\beta_p = 2\mu_0\langle p\rangle/B_p^2$, where $\langle p\rangle$ is the volume-averaged plasma pressure and B_p is the averaged poloidal field at the plasma circumference. While the discharges can be sustained in principle with much lower driven currents than are generally considered necessary, the stability of high-pressure discharges in a large tokamak under a large bootstrap current fraction is crucially important to determine whether such a reactor scenario is feasible. Actually, a long-pulse heating experiment is indispensable to investigate the current profile evolution and its effects on the stability. However, tokamak experiments have so far poorly addressed the subject. This Letter describes a β-limiting phenomenon associated with the stability of high-β_p plasmas carrying a large bootstrap current fraction in a large tokamak.

In JT-60, high-β_p experiments have been carried out in a sawtooth-free regime utilizing high-power neutral-beam heating for a long pulse duration up to ~5 s, in which a fast internal disruption, unlike a sawtooth collapse, has been observed. A significant reduction of the stored energy by (20-30)% is followed by a collapse. It limited the attainable normalized β in the discharges to much lower values than the Troyon limit. It has been dubbed the "β_p collapse" since the events occur for high-β_p discharges at $\beta_p \sim 3$ and the mechanisms appear to be closely related to the β_p in terms of the bootstrap current fraction and the MHD stability. Note that the long heating duration as compared to the field diffusion time scale allows the minimal value in the q profile ($q_{\min}$) to be sufficiently higher than unity in the core plasma.

Various attempts to extend the β values have been carried out in tokamaks and have encountered a variety of β-limiting phenomena: for instance, soft β collapses for high toroidal-beta (β_t) experiments in PBX-M [4], DIII-D [5], and JET [6]; β_p saturation for high-β_p experiments in ASDEX [7] and PBX-M [4]; and a disruptive β limit at $\beta_p \sim 2$ for supershot experiments in TFTR [8]. Pressure-driven high-n ballooning modes [9], resistive ballooning modes [10], or external kink modes [11] have been dealt with to explain the β limits. Most recently, high-β_p experiments in TFTR and DIII-D have almost reached equilibrium $\varepsilon\beta_p$ limits of 1.5 and 1.8, respectively [12]. Nevertheless, the β_p collapse observed in JT-60 is clearly different from any other β-limiting phenomenon reported before and may not be explained by those MHD modes.

The hydrogen plasmas in JT-60 were operated in the range of plasma current $I_p = 0.3$-1.2 MA with a lower single-null divertor configuration having a high aspect ratio of 4.5, a major radius of $R_p = 2.9$ m, a minor radius of $a = 0.65$ m, an ellipticity of $\kappa = 1.3$, toroidal fields of $B_t = 4.0$ or 4.5 T, and a discharge pulse length of 10 s. Neutral hydrogen beams with high power up to $P_{\rm NB} \sim 21$ MW and beam energy of ~65 keV were injected for 3-5 s from nearly balanced perpendicular angles. The diamagnetic β_p values ($\beta_p^{\rm dia}$) were determined by magnetic measurements. The noncircular cross section of the configuration allows us to separate the equilibrium β_p ($\beta_p^{\rm eq}$) and the internal inductance (l_i) from the Shafranov Λ [13]. MHD observations were obtained using a 30-channel soft-x-ray array with a spatial resolution of 3.5 cm and a digitizing time of 40 μs. Profile measurements were carried out as follows: the ion temperature (T_i) by an eight-channel charge exchange recombination spectrometer (CXRS) with a time resolution of 50 ms; the electron temperature (T_e) by an eight-channel Thomson scattering system and a Michelson interferometer for electron cyclotron emission (ECE) with a time resolution of ~25 ms; the line electron density and the Faraday rotation angle by far-infrared laser interferometers and polarimeters, respectively, with two vertical chords; and the electron density (n_e) by the Thomson scattering. The plasmas discussed here are characterized by the hot-ion mode features with enhanced confinement [14]. The experimental parameters are $T_i(0) \lesssim 12$ keV, $T_e(0) \lesssim 6$ keV, $n_e(0) \lesssim 6\times10^{19}$ m^{-3}, the global energy confinement time $\tau_E \lesssim 50$ ms, the effective charge number $Z_{\rm eff} \sim 2$-4, the electron collisionality $\nu_{*e} \gtrsim 0.1$, and the ion col-

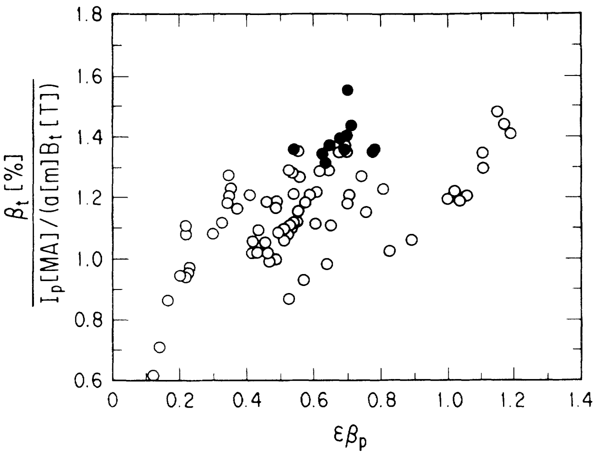

FIG. 1. Normalized β as a function of $\varepsilon\beta_p$. Solid circles indicate the data just before β_p collapses.

lisionality $\nu_{*i} \gtrsim 0.01$.

For the high-β_p discharges in JT-60, the normalized β defined as $g = \beta_t[\%]/(I_p[\mathrm{MA}]/aB_t)$ as a function of $\varepsilon\beta_p$ is shown in Fig. 1. The β_p values reached 5.0 (or $\varepsilon\beta_p \sim 1.2$) at $q^* \sim 17$ without disruptions; β_p is calculated from $\beta_p = (\beta_p^{\mathrm{dia}} + 2\beta_p^{\mathrm{eq}})/3$ and the cylindrical equivalent safety factor q^* is defined as $q^* = 5(1+\kappa^2)a^2B_t/2R_pI_p[\mathrm{MA}]$. The discharges with $q^* \sim 10$ encountered β_p collapses at $\varepsilon\beta_p \sim 0.7$ or $\beta_p \sim 3$ in excess of $g \sim 1.3$, substantially below the Troyon limit ($g \sim 3.5$) [15]. The ratio of perpendicular to parallel pressure just before a collapse is evaluated to be $P_\perp/P_\parallel \sim 1.1$, so the plasma pressure is almost isotropic.

Temporal evolutions of the diamagnetic stored energy for a couple of high-β_p discharges are shown in Fig. 2: *A*, β_p collapses observed with $P_{\mathrm{NB}} \sim 18$ MW for 4.0-9.0 s; *B*, no β_p collapse observed with $P_{\mathrm{NB}} \sim 21$ MW for 4.0-7.0 s. As shown for *A*, a β limit is designated by the repetitive β_p collapses at $\beta_p \sim 3$. Different processes approaching $\beta_p \sim 3$ are also seen in these discharges. For *A*, the stored energy spontaneously increases with some confinement improvement and falls by $\sim 30\%$ due to the collapse at $\beta_p \sim 3$. Increases in the ion and electron temperatures and the toroidal rotation velocity at the center were also observed on CXRS and ECE, accompanying the increasing stored energy. For *B*, β_p reaches ~ 3 and is sustained in a quasi steady state without β_p collapse, while continuous $m=2$ activity occurs with confinement degradation from 6.1 s. As shown here, the β_p collapses have been observed during beam injection at ~ 3-4 s after the beginning of beam injection for most cases, and so the field diffusion process may be associated with its occurrence.

The MHD activities related to the β_p collapse have been studied in detail. The MHD mode analysis for the continuous low-m ($m \leq 3$) modes usually observed during the long beam pulse may provide current profile information and the location of the collapse. Using the soft-x-ray signals, the poloidal mode number (m) and the mode location can be evaluated from a simulation of soft x rays assuming magnetic islands [16] and from the radial dependence of soft-x-ray fluctuations, respectively. The results are shown in Fig. 3(a). The discharge encounters the β_p collapse at $t = 7.53$ s during constant beam power. From these observations we infer the following: (1) Current profile broadening develops on a resistive field diffusion time scale. (2) Improvement in the confinement is initiated with the change of the dominant mode from $m=2$ to $m=3$ at $t \sim 6.5$ s. (3) An increase in the bootstrap current fraction enhances the current profile broadening. (4) Disappearance of the $m=2$ mode implies a $q_{\min}$ value close to and above 2 after $t \sim 7.0$ s. After this, the $m=3$ activity is the only clue regarding the current profile, but disappears or is not observable for ~ 100 ms just before the collapse. Then the β_p collapse occurs near the location of the $m=3$ mode, whose inversion radius is shown by open circles. So, one may postulate the following: The increasing bootstrap current fraction causes a hollow current profile with a magnetic pitch minimum closely below the $q=3$ surface, and the discharge encounters a stability boundary as discussed later. The temporal evolution of $\bar{B}_z$ from Faraday rotation measurements [17] clearly indicates that the current profile broadening is enhanced from $t \sim 6.0$ s when the $m=2$ activity begins to decrease. While the overall current profile can slowly evolve on a resistive skin time scale of $\tau_R \sim 2$ s at $r/a \sim 0.5$ just before the collapse, where $T_e(0) \sim 4.3$ keV, $\tau_E \sim 52$ ms, and $Z_{\mathrm{eff}} \sim 3.8$, a faster change of the current profile can be expected near the axis.

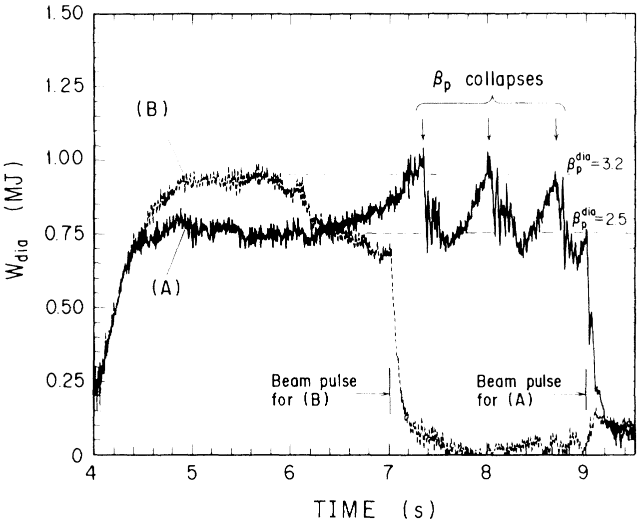

FIG. 2. Wave forms of the diamagnetic stored energy (W_{dia}) for high-β_p discharges with $I_p = 0.5$ MA and $B_t = 4.5$ T. *A*, with β_p collapses; *B*, without β_p collapse.

As shown in Fig. 3(a), repetitive partial collapses with small amplitudes are also observed to be located near the $m=2$ mode and subsequently near the $m=3$ mode. The

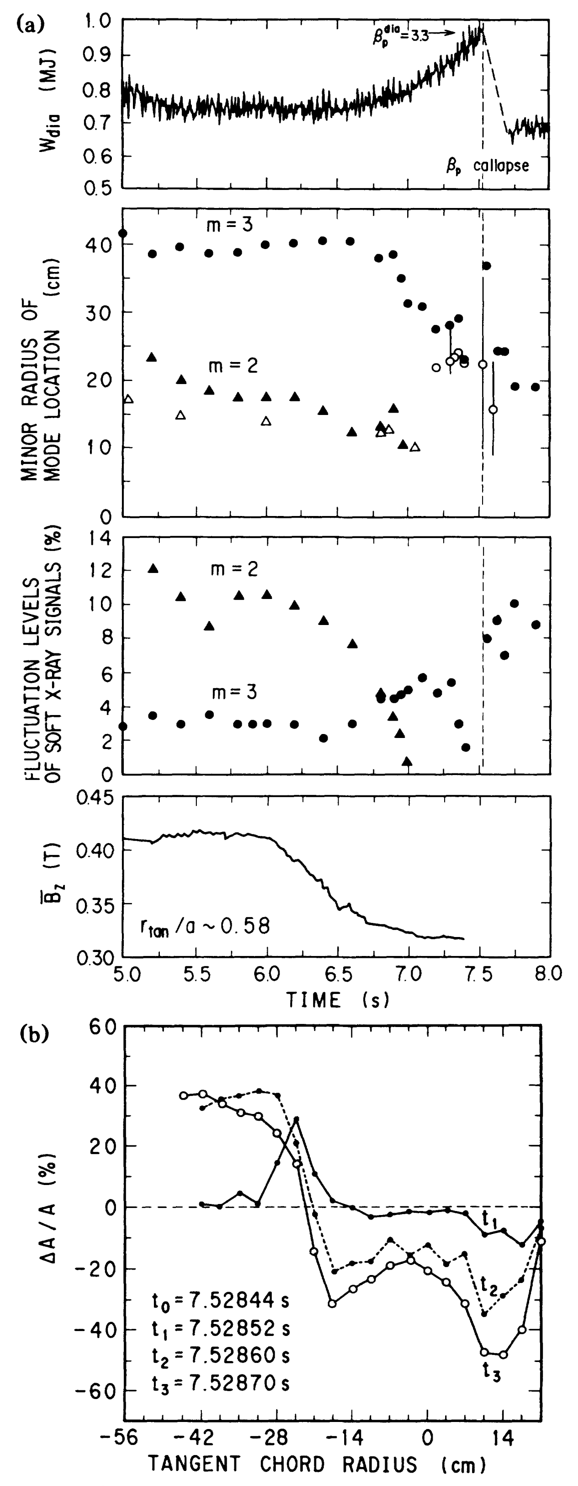

FIG. 3. (a) Time evolutions of W_{dia}, the locations of $m=2$ and $m=3$ modes (solid symbols) and the inversion radii at collapses (open symbols) from soft-x-ray emissions, and $\bar{B}_z$ at $r_{\text{tan}}/a \sim 0.58$ from Faraday rotation measurements for a typical high-β_p discharge with $I_p = 0.5$ MA, $B_t = 4.5$ T, and $P_{\text{NB}} \sim 18$ MW. (b) Soft-x-ray fluctuation levels as a function of the tangent chord radius during the β_p collapse; 80 μs (t_1), 160 μs (t_2), and 260 μs (t_3) from the soft-x-ray profile at $t = t_0$ just before the β_p collapse.

typical mixing regions inferred from soft x rays are indicated by the bars, showing that the β_p collapse causes a much larger mixing region than the small collapses do. The radial dependences of soft-x-ray fluctuation levels at different times in the β_p collapse shown in Fig. 3(b) indicate that the β_p collapse is a large-amplitude partial relaxation with a fast growth time (~ 100 μs). From the inversion radius and the $m=3$ mode location, the probable mode rational surface associated with the β_p collapse is inferred to be the $q=3$ surface.

Bootstrap current analysis has been carried out to investigate the q profile evolution preceding the β_p collapse. The high-β_p plasmas have a significant fraction of beam components with as much as half of the β_p value. So, in the bootstrap current analysis, friction and viscous forces of fast ions are calculated under the assumption of isotropic energy distribution and small banana size, employing a Monte Carlo method to evaluate the birth profile of fast ions [18]. The numerical code developed to investigate neutral-beam-driven currents, Ohmic currents, and bootstrap currents is consistent with the MHD equilibrium [19]. The experimental validity of this model calculation has been previously reported [13,20].

In order to deal with the effects of electric-field diffusion during the long beam pulse, a 1.5-dimension time-dependent transport analysis has been carried out for the high-β_b discharges. As shown in Fig. 4(a), the

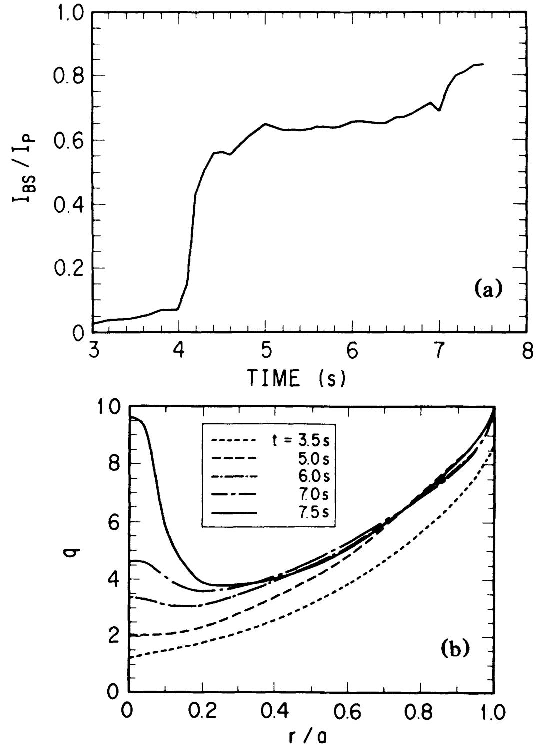

FIG. 4. (a) Time evolution of the calculated bootstrap current fraction to the plasma current (I_{BS}/I_p) during the beam injection up to the β_p collapse. (b) The calculated q profiles at $t = 3.5$, 5.0, 6.0, 7.0, and 7.5 s.

bootstrap current fraction for the discharge of Fig. 3 reaches ~80% of the total plasma current just before the β_p collapse, in which the fast-ion-driven components are evaluated to be ~25% of the bootstrap currents. The evolution of the calculated q profile before the β_p collapse is shown in Fig. 4(b). The results indicate that the current profile becomes dramatically hollowed with a very high axis q value owing to the decrease of the Ohmic currents. The q_{min} value just before the collapse is calculated to be 3.8, which is larger by as much as unity than that inferred from MHD observations. The calculated internal inductance l_i decreases from 1.2 to 0.7 during beam injection, while the magnetic measurements indicate that the l_i value decreases from 1.2 to 0.9. So the q_{min} value might be overestimated in this calculation. At present, the calculated q profiles are not consistent with the MHD observations, while the calculated resistive loop voltage is in good agreement with the measured loop voltage. However, the inclusion of the effect of reconnections driven by tearing modes on the bootstrap current profile as discussed by Boozer [21] in the bootstrap current analysis may reduce the discrepancy.

It should be remarked that in the β_p collapse we observe the following: no β saturation and no precursor oscillation just before the collapse, a fast growth time, and an event locality probably near the $q=3$ surface. The history of the q-profile evolution, that q_{min} gradually increases as it approaches the $q=3$ surface, also provides an important clue to the mode identification. From the observations, the ideal low-n kink-ballooning mode is inferred to be a most likely candidate as the initial trigger preceding any MHD instability associated with the β_p collapse, rather than the resistive pressure-driven modes, the double-tearing modes, or the ideal high-n ballooning modes. Using the ERATO-J code, MHD stability analysis for ideal $n=1$ kink-ballooning modes has been carried out with q profiles assumed to have changed from monotonic to hollow [13,22]. The stability boundary at $q_{\text{min}} \sim 3$ is found to be significantly reduced down to $\beta_p \sim 3$ due to the presence of a magnetic pitch minimum where the magnetic shear stabilizing effects are lost. The radial profiles of different Fourier components indicate that the internal $m=3$, $n=1$ mode is most dominant around the $q=3$ surface, accompanied by significant mode couplings. An experimental trajectory of the β_p value as a function of q_{min} inferred from the mode analysis is in reasonable agreement with the ideal kink-ballooning analysis.

In conclusion, a fast β collapse, dubbed the β_p collapse, has been first revealed in the JT-60 high-β_p regime at $\beta_p \sim 3$ under a large bootstrap current fraction of up to ~80%, and it leads to a limit of the normalized β lower than the Troyon limit. The MHD features associated with the β_p collapse are consistent with the ideal $n=1$ kink-ballooning stability analysis for a hollow current profile. While there were no direct measurements of such a hollow current profile, the MHD observations, the bootstrap current calculations, and the stability analysis strongly suggest such formation before the β_p collapse. The experimental evidence of the β_p collapse must have a significant impact against the high-β_p reactor scenario in which both large bootstrap current fraction and high normalized β are required for steady-state tokamak operation. However, the dependence of the current profile on β limits suggests that it will be possible to attain high normalized β discharges in the high-β_p regime in future tokamaks with current-drive mechanisms for central current profile control.

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[17] $\bar{B}_z$ is calculated from $\int n_e B_z dl / \int n_e dl$; the values of $\int n_e B_z dl$ and $\int n_e dl$ integrated along the vertical chord with a normalized tangent chord radius $r_{\tan}/a \sim 0.58$ are obtained by polarimetry (Faraday rotation measurement) and interferometry, respectively. The $\bar{B}_z$ is sensitive to the amount of currents within $r/a \sim 0.58$.

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