Discharges with Safety Factor, q, < 1 in a Noncircular Tokamak

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Characteristics of plasmas in Tokapole II (a noncircular poloidal divertor tokamak) with directly measured q as low as 0.4 are discussed. This is a q regime bounded by well studied $q > 1$ tokamaks and $q \approx 0.1$ reversed-field pinches. After q drops below 1, soft-x-ray sawtooth oscillations begin. During the oscillations the central q values remain stationary and below 1, while a small oscillation in the edge q values near $q = 1$ is observed.

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All tokamaks operated to date seem to be limited to safety factor $q(0) \approx 1$ at the plasma center by internal disruptions, which appear as sawtooth oscillations on soft-x-ray (SXR) detectors.[1] This instability is thought to be the result of a resistive tearing mode with poloidal and toroidal mode numbers $m = n = 1$ which occurs when the $q = 1$ surface enters a region of nonzero current density gradient, j'. q profiles, which have generally been inferred from fits to magnetohydrodynamic (MHD) equilibrium codes, typically oscillate between 0.8–0.9 and 1.0 during a sawtooth.

In Tokapole II,[2] a noncircular tokamak with a four-node poloidal divertor, flat j and q profiles are observed with the bulk of the plasma, including the center, as low as $q \approx 0.4$. SXR sawtooth oscillations accompany the low-q discharges. Concomitant with these oscillations we observe a fluctuation in the q values near the $q = 1$ surface while the central q values remain below 1. This low-q state might be viewed as intermediate between two well-studied stable regions, $q > 1$ tokamaks and the family of $q \approx 0.1$ tori[3] such as reversed-field pinches and spheromaks. In this Letter we report observations of the stability properties of these low-q discharges.

Four inductively driven, toroidal, copper rings, inside the 50-cm major radius vacuum chamber, provide plasma shaping for either dee, inverse dee, or square plasmas[4] (Fig. 1). For these low-q experiments, $T_e \approx 80$ eV, $T_i \approx 25$ eV, $I_{\text{plasma}} \approx 25$ kA, $I_{\text{rings}} \approx 250$ kA, $Z_{\text{eff}} \approx 3$, and $B_{\text{toroidal}} \approx 3$ kG (Fig. 2). Limiter plates can be inserted into the plasma to prevent plasma current flow in the region beyond the separatrix. In addition to spectroscopic and interferometric diagnostics, $\frac{1}{8}$-in.-diam magnetic probes can be inserted into the plasma without serious effect. When magnetic probes are used, shots are rejected which show more than 10% changes in the current or B_{poloidal} (separatrix) or which show significant changes in the shape, frequency, or amplitude of the sawteeth. The poloidal magnetic flux plot [Fig. 1(b)] is obtained directly from the magnetic field measurements. From the flux plot, $q(\psi) = d\varphi/d\psi$ (where φ is the toroidal flux and ψ is the poloidal flux) is determined. $q \rightarrow \infty$ at the divertor separatrix since $B_{\text{pol}} \rightarrow 0$ near the poloidal field nulls (Fig. 1).

Discharges with q_{min}, the value of q on the magnetic axis at the current peak, between 0.4

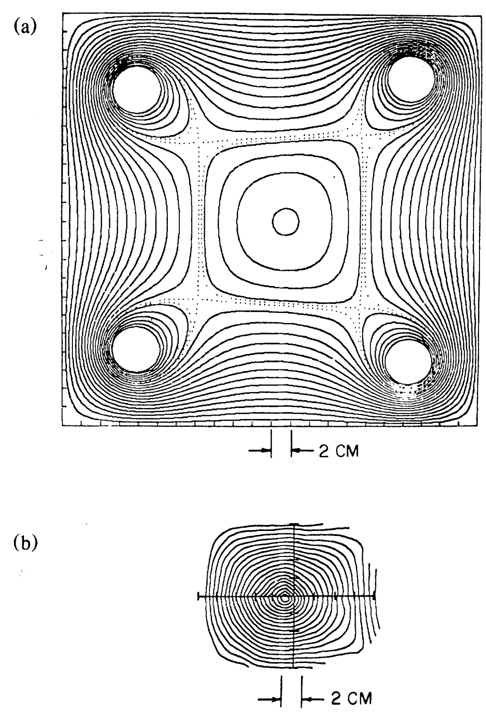

FIG. 1. (a) Theoretical flux plot generated numerically from the Grad-Shafronov equation. The dotted lines represent the separatrices which encircle the plasma and one or more of the divertor coils; the outer boundary represents the conducting wall. (b) Experimental flux plot generated directly from magnetic probe measurements.

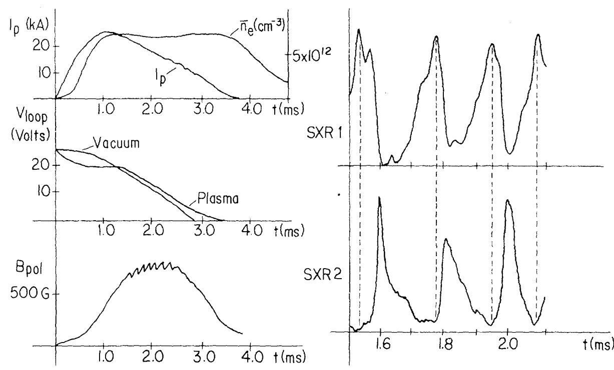

FIG. 2. Typical parameters for low-q discharges. The SXR signals are shown in expanded time scale. SXR1 is the central-chord signal and SXR2 is the signal from the separatrix region that shows the sawtooth inversion. The line-averaged density includes both the central tokamak and scrape-off regions.

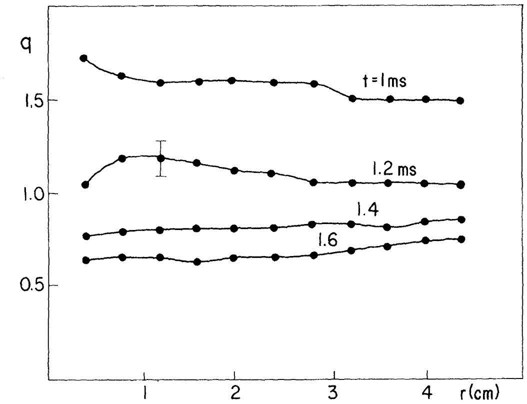

FIG. 3. Approach of the q profiles to the low-q state. q is plotted vs the distance from the magnetic axis along the midplane, for a case where q reaches 0.6.

and 1.0 were observed with variation in I_P and B_T near the typical values of 25 kA and 3 kG. No correlation between the plasma cross-section shape and $q_{\min}$ was found. The smallest $q_{\min}$ obtainable for a given B_T was not reproducible although all cases showed similar MHD activity. Figure 3 shows the time evolution of the q profiles for a case where q reaches 0.6. The factors that determine the particular value of $q_{\min}$ for $B_{\text{toroidal}} \approx 3$ kG are unknown.

Sawtooth oscillations in SXR and magnetic probe signals, with poloidal and toroidal mode numbers $m=n=0$, accompany all discharges studied. In most cases q is not clamped to 1 by the sawteeth. The SXR sawteeth are seen to invert near, but somewhat inside, the $q=1$ surface as determined from the magnetic data. The time of the first rapid decrease in the central-chord SXR signal occurs 50–350 μs after the time when q passes through 1 and 50–350 μs before q reaches $q_{\min}$.

The time dependence of q during a sawtooth period was measured. Surprisingly, the central q did not rise to 1 on the falling edge of the sawtooth but remained near $q_{\min}$. An oscillation in q, localized to the outer region near the separatrix and increasing with r, was observed (Fig. 4). This feature repeats with successive sawteeth.

Sinusoidal oscillations accompanying the sawteeth are sometimes observed both on the magnetic and, more rarely, on the SXR detectors; however, they differ from the growing sinusoidal $m=1$, $n=1$ "precursor" oscillations seen in other tokamaks, and thought to be the result of a helical magnetic island associated with the tearing mode. In Tokapole II the oscillations do not always grow in amplitude during the increasing stage of the sawtooth. Mode-number measurements have not given reproducible results; often many modes seem to be present.

The inner magnetic surfaces show a small motion accompanying the sawteeth. This motion appears to be a bulk shift of the equilibrium, possibly in response to the profile changes near the separatrix, rather than a direct effect of the instability on the magnetic surfaces. The SXR signals, however, imply that the electron tempera-

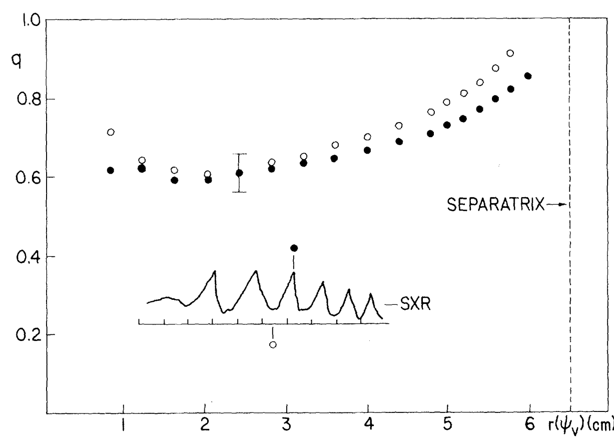

FIG. 4. Time dependence of the q spatial profile during a sawtooth period. The points corresponding to the sawtooth valley are plotted relative to the minor radius along the midplane, while those for the peak are plotted for the same values of poloidal flux as the valley regardless of the actual radius. An error bar is shown which represents the possible offset of both curves. The possible error in the relative values of peak and valley q values is estimated to be 25% of the error shown.

ture is indeed oscillating near the center. Electron-temperature profiles, inferred from SXR data, indicate that T_e remains relatively flat out to the sawtooth inversion radius during all phases of the sawtooth oscillations. This suggests that the central T_e oscillation could result from the coupling of the poorly confined central region ($\tau_E = 50-100\ \mu s$) to the edge where the instability provides a thermal short circuit.

Theoretical understanding of the stability of these discharges is not yet well established. The bulk of the plasma is a very-low-shear region with $q<1$. The destabilizing influence of j' on tearing modes is localized to the very-high-shear, noncircular edge region near the separatrix where $q \to \infty$.

The experimental observation that the central q values remain relatively stationary and significantly below 1 during the sawtooth oscillation might be viewed as a modification of Kadomtsev's[6] picture of the internal disruption. According to this heuristic model, the resistive tearing mode allows the growth of a helical magnetic island at the $q=1$ surface by the reconnection of flux perpendicular to a helical strip resonant with the island. This flux is conserved in such a way that a given amount of helical flux within the $q=1$ surface reconnects with an equal amount outside the $q=1$ surface. In the model applied to most tokamaks the reconnection and subsequent island growth extend inwards to the original magnetic axis, and thus must also extend outside the $q=1$ surface the distance necessary to reconnect to the corresponding helical flux surfaces. This results in a final axisymmetric state in which $q>1$ everywhere.

In Tokapole II, since the $q=1$ surface is very near the separatrix, there is not enough helical flux between the $q=1$ surface and the separatrix to reconnect all the flux within the $q=1$ surface. A plot of the helical flux for a purely $m=n=1$ mode, $\chi = \psi - \varphi$, where ψ is the poloidal flux and φ is the toroidal flux, is shown in Fig. 5 extrapolated to the separatrix. Since the null surface of the magnetic island is helical, reconnection may be unable to proceed into the topologically different region beyond the separatrix where the flux that would be reconnected is locked to the axisymmetric structure of the divertor coils. Limiting the reconnection to within the separatrix would cause the island to saturate at a width determined by the amount of helical flux that originally exists between the $q=1$ surface and the separatrix, leaving the central flux surfaces and q values

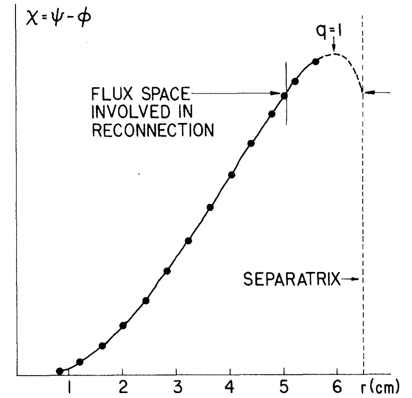

FIG. 5. The helical flux χ for a low-q Tokapole II discharge before reconnection. The region of helical flux space which would be involved in the reconnection if the island did not extend beyond the separatrix is shown.

unaffected.

The ability to reach these low q values and not be clamped to $q \approx 1$ is presumably related to the flat j profile and/or the noncircular separatrix.[6] As is shown in Fig. 3, the q profile approaches the low-q state with a flat profile. This suggests that there is insufficient current-density gradient for the growth of the tearing mode until the $q=1$ surface reaches the edge region, at which time the central q values are quite low. This view is consistent with the fact that the time of the first sawtooth falling edge usually does not occur until significantly after q goes through 1.

In conclusion, even though minor disruptions occur in discharges with the central q as low as 0.4, the magnetic surfaces and q values are unaffected near the center. The SXR sawteeth are associated with an oscillation in q which is localized to the edge region near the $q=1$ surface.

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Spatially Resolved Measurements of Fully Ionized Low-Z Impurities in the PDX Tokamak

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Fully ionized oxygen and carbon in PDX plasmas are detected via charge-exchange recombination reactions between the impurities and hydrogen atoms from a low-power neutral beam. The C^{6+} and O^{8+} ions are observed out to radii beyond the limiter, which is in contrast to expectations based on coronal equilibrium but consistent with a simple diffusive transport model. Central values of $Z_{\rm eff}$ obtained with these measurements agree with values obtained from plasma resistivity and visible bremsstrahlung measurements.

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Low-Z elements such as carbon and oxygen are usually the most abundant impurities in tokamak plasmas. At the central electron temperatures in present large tokamaks ($T_e \sim 1$ to 2 keV), these atoms are fully ionized in the plasma core, and their detection with conventional spectroscopic observations is not possible. The inference of central low-Z impurity behavior from observations of lower-charge-state emissions from the plasma edge region will become increasingly uncertain as T_e increases to 5 keV and above in the next generation of tokamak devices, such as the tokamak fusion test reactor (TFTR). Thus, direct detection of these fully stripped impurities is necessary.

Since an impurity ion is left in an excited state following charge-exchange recombination between the ion and a hydrogen atom, the process

$$H^0 + Z^{+q} \rightarrow H^+ + (Z^{q-1})^* \qquad (1)$$

is useful for detecting the presence of the ion Z^{+q} (with charge q) by observing the subsequent photon emission from the excited product of the reaction described in Eq. (1). The cross sections for these processes are large ($\sim 10^{15}$ cm^{-2}), resulting in high emissivities with only a moderate neutral hydrogen density.

Spectral-line excitation from this process was observed during neutral-beam heating in the ORMAK[1] and ISX-B[2] tokamaks. In addition to perturbing the plasma, high-power neutral-beam heating introduces enough H^0 into the discharge to change the ionization distribution of the impurities themselves.[3,4] It is thus desirable to employ a nonperturbing source of neutrals to induce the reaction [Eq. (1)] as was done in the T-4 and T-10 tokamaks.[5,6] A similar approach has been used on the poloidal divertor experiment (PDX) tokomak and is reported here.

The experimental apparatus for the measurements on PDX includes a highly collimated diagnostic neutral beam (DNB)[7] which provides neutrals in the field of view of an absolutely calibrated grazing incidence spectrometer (Fig. 1). The beam can be scanned across the plasma midplane. The neutral hydrogen atoms had a primary energy of 25 keV and a total injected power of 4 to 11 kW. Typical column densities along the line of sight of the spectrometer were 10^8 to 10^9 cm^{-2}, which results in line intensities on the order of 10^{12} to 10^{13} photons/cm^2 s sr. The neutral-beam cross section full width at half maximum was 12 cm high and 5 cm wide, while the spatial resolution of the spectrometer in the vertical direction was 2 cm.

The PDX tokamak was run with graphite rail limiters for these experiments; the divertor was not activated. The plasma major radius was 147 cm and the limiter radius was 30 cm. The plasma current was 250 kA, the line-averaged elec-