Radially Resolved Measurements of "q" on the ATC Tokamak

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ABSTRACT

This paper describes a new technique for directly measuring the safety factor, or q , profile in a tokamak. A tightly collimated neutral beam capable of injecting ~ 100 mA of 30 keV deuterium atoms was mounted on the ATC tokamak. By proper tangential aiming of the beam a strong concentration of circulating fast ions was created at a chosen plasma minor radius. By examining the orbits of these ions with a multi-sight-line charge exchange detector, it was possible to measure the shifts of the orbits off of magnetic surfaces, and thereby to make local measurements of q . This experiment showed that when q on axis reached unity, strong internal turbulence began, and further lowering of q at the outer edge of the plasma did not lower $q(0)$. A second result was that the measured $q(0)$ was ~ 1.8 times larger than the $q(0)$ deduced from the $T_e(r)$ profile, assuming Z_{eff} to be independent of minor radius. This suggests a significant peaking of Z_{eff} on axis in ATC.

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I. MOTIVATION

One of the most important quantities that needs to be measured in order to have a complete understanding of a tokamak discharge is the radial profile of the toroidal current. The power inflow from the ohmic heating circuit is given by $\eta j^2(r)$, and in many theoretical models the thermal conductivity which carries the power out again is largely determined by $\vec{B}_\theta$, which is in turn governed by $j(r)$. In addition, the MHD stability of a toroidal pinch is mainly determined by the radial profile of the plasma current. Thus it is clearly very important to know $j(r)$, and it is surprising that there has not been a direct measurement of it, except in extremely small tokamak devices into which magnetic probes could be inserted.^{1,2}

The typical means of estimating the current profile in large devices has been to assume that $\vec{E}_\phi$ is independent of r , and to take the electrical conductivity to be proportional to $T_e^{3/2}$. Then, taking into account small neoclassical corrections to the usual Spitzer conductivity,³ one deduces $j(r)$. This process neglects the radial variation of Z_{eff} , as well as any non-classical contribution to the plasma resistivity. On the ST tokamak, considerable effort was expended in trying to evaluate the importance of these effects. Because of the imprecision of spectroscopic methods of measuring the impurity content of a plasma, it was never possible, in a "standard" discharge, to verify that all of the resistive anomaly above the Spitzer value was due to impurities. Typically, the spectroscopic measurement

was somewhat lower than the resistance anomaly measure of Z_{eff} on ST,⁴ as well as on ATC.⁵ On ORMAK, the discrepancy has occasionally been much worse,⁶ being more than a factor of 2 in some discharges. On the other hand, on TFR⁷ the agreement is quite good, and on ST, in a series of relatively clean high density helium discharges, the resistivity Z_{eff} was close to 2,⁸ indicating near classical resistivity. In clean high density hydrogen discharges in Alcator⁹ the resistivity also appears to be classical.

If we assume that the enhanced resistivity over the $Z=1$ case in typical "dirty" tokamak discharges is solely due to impurities, we are still left with a question as to whether Z_{eff} is radially uniform. Attempts have been made to measure $Z_{\text{eff}}(r)$ from radial profiles of the X-ray "target", or enhancement over hydrogenic bremsstrahlung. The resulting Z_{eff} is model dependent, largely determined by which radiating species is assumed to be dominant. On ORMAK, for instance, depending on whether one assumes the dominant radiation comes from oxygen or from iron recombination radiation, one can deduce a peaked or hollow Z_{eff} profile.¹⁰ On ST it was possible to determine that Z_{eff} was flat over the inner half of the discharge,¹¹ but only with factor of 2 uncertainties. A similar experiment on T-4,¹² however, reported significant peaking of Z_{eff} on axis. A second possible check on $Z_{\text{eff}}(r)$ is to compare the radial location of the nodes of the soft X-ray fluctuations, measured in a number of tokamak experiments, to the rational surface

locations calculated assuming $Z_{\text{eff}}(r) = \text{const.}$ This is complicated by the problem of Abel inverting the soft X-ray signal, and since the theory is not complete and no positive mode identification has been made, there is also no guarantee that the fluctuation nodes are located exactly at rational surfaces. With these caveats, however, the measurement does give q at one or two discrete points in discharges which display $n=1/m=1$ and/or $n=1/m=2$ soft X-ray fluctuations.

Comparisons have been made between this measurement and the calculation of $q(r)$ from $T_e^{3/2}(r)$ on a number of tokamaks. On ST¹³ and TFR¹⁴ the calculated $q=1$ surface is in good agreement with the location of the nodes of the $n=1/m=1$ fluctuations and of the $n=0/m=0$ sawtooth. On ATC¹⁵ the calculated $q=1$ surface is shifted significantly outward from the $n=1/m=1$ fluctuations. On ORMAK¹⁶ the $n=1/m=1$ fluctuations are sometimes observed when q on axis is calculated to be greater than 1, although the calculated $q=2$ location and observed $n=1/m=2$ fluctuations are in good agreement.

Given this variety of agreement and disagreement between the X-ray fluctuation location of rational surfaces and the $J \propto T_e^{3/2}$ assumption, it is clear that an independent direct method of measuring q is desirable. This is particularly true if one wishes to measure radial energy flow in the absence of MHD fluctuations, or if one wants to study MHD stability, and so measure $q(r)$ in both stable and unstable discharges.

An attempt was made in 1973¹⁷ to measure the poloidal magnetic field in ST using harmonic generation at the upper hybrid layer induced by an incoming wave reaching resonance. The polarization of the reflected wave gives the inclination of the total magnetic field. Unfortunately, the accuracy of the measurement was inadequate to give a check of the assumption $j \propto T_e^{3/2}$. A number of other techniques have been suggested, such as observing the cyclotron line splitting of scattered CO₂ laser radiation^{18,19} and, most recently, detecting line radiation from He⁺ captured from a He⁰ beam injected vertically into the plasma.²⁰ This is closely related to another suggestion²¹ of using a vertically injected H₂⁰ beam, which is captured as H₂⁺, and then detecting the molecular dissociation product, H⁰, emerging from the plasma. All of these techniques, however, suffer from the fact that they measure the total magnetic field, and the poloidal component, of necessity, goes to zero at the magnetic axis, where we are especially interested in knowing $q = rR_T/R_O B_\theta$.

The attractiveness of using fast ion orbits to determine the current profile, $j(r)$, is that for $v_{||}/v \approx 1$, these orbits exhibit a shift from the magnetic surfaces, $\Delta = qv/\Omega_C$, which is proportional to q , rather than B_θ , and is therefore measureable right at the magnetic axis. A number of authors have suggested techniques for using fast ion orbits to determine $j(r)$.

G. E. Guest²² proposed a method whereby a collimated neutral beam would be fired into the plasma, and a fast neutral detector would be aimed into the torus at the same angle. If the poloidal field

and injection energy are such that the beam aims at the stagnation axis, i.e., at $R_0 + qv/\Omega_c$, then the detected signal should be maximized, since neutrals ionized near the beam tangency are confined to a narrow tube around the stagnation axis. Having located this maximum in parameter space, one can deduce q . The present approach is a generalization of this to the case where the detector does not aim at the same radius as the injector, and so examines other orbits than the stagnation orbit. By injecting onto orbits that have small but finite extent, the requirements for beam collimation are greatly reduced, and by examining orbits other than the stagnation orbit one may measure $q(r)$ across the plasma without varying the beam voltage severely.

The opposite extreme from looking solely at stagnation orbits was proposed by J. A. Rome and H. P. Eubank.²³ In this scheme a broad neutral beam is counter-injected into the plasma, so the neutrals ionized near the outside are lost on unconfined orbits which strike the limiter. By looking with a charge-exchange analyzer one then finds the outermost confined orbit, and by varying the injection voltage this orbit can be scanned across the plasma, so $q(r)$ may be deduced. Unfortunately, to see $q(r=0)$ one needs an orbit which connects the magnetic axis with the limiter, so $\Delta = a/2$. For realistic current profiles, this implies an extremely high energy (~ 150 keV for ATC), and indeed, for strongly peaked current profiles, the energy is so great that the orbit pinches (or "bananas") inside the plasma,

even for $v_{||}/v = -1$. Then the outermost confined orbit is not determined by the intersection with the inner limiter, but by the more complicated pinch criterion²⁴ and so q cannot be determined from a simple orbit shift model.

II. APPARATUS

In order to measure orbit shifts of the order of 2-4 cm near the axis of ATC, an extremely narrowly collimated neutral beam was needed, and as high an energy as possible was desired. At the time of the planning of this experiment, the neutral beam development group at the Lawrence Berkeley Laboratory had begun experimenting with a 4-grid ion extraction system capable of operating at up to 40 keV in conjunction with their "10-Amp." ion source.²⁵ Although the resulting beam was larger than required for our experiment, we had available power supplies that could be modified for this application, and the beam divergence was low enough that moderate collimation could provide a Gaussian beam shape with an RMS height of ± 1.6 cm and RMS width of ± 0.5 cm, at a point deep inside the ATC plasma. The equivalent current in this beam was on the order of 100 mA.

The beam was mounted on the ATC apparatus as shown in Figure 1. Two collimators 1 cm wide $\times$ 3 cm high were placed in the beam line at 65 cm and 145 cm from the extraction grids. Typically the distance from the extraction grids to the tangency point in the plasma was 235 cm. The beam was capable of being swung so that the tangency radius varied from 86 cm to 70 cm.

The vacuum system and beam line were borrowed from a previous ATC injection heating experiment.²⁶

Extremely severe constraints were placed on the combined beam and electronics performance by the need to observe only recently injected ions. The measurement involves the injection of a stream of neutrals, but the accumulation of ions slowing down in the plasma is uninteresting for this experiment: it is only the most recently injected orbits that are of interest (see Technique). For this reason, a neutral particle detector with an energy bandwidth of 1.6% was employed to look at outgoing neutrals. This evidently constrained the high voltage regulation on the neutral beam to be better than 1%. Due to the presence of energy diffusion, however, even this narrow band-width does not guarantee that observed ions have been injected within a time shorter than 1-2 msec. In order to only view recently injected ions, the neutral beam acceleration supply was gated on and off at ~ 3000 Hz, still maintaining better than 1% regulation during the on periods. The current rise time at each pulse was < 50 μ sec. Modulation of the same frequency and phase in the neutral particle detector signal could only be due to particles spending less than 300 μ sec in the plasma. This time period was chosen because for typical parameters it corresponded to $\Delta t \leq \tau_{90}/200$, and therefore $\langle \Delta v_{\parallel}/v \rangle \leq 0.005$, which is a nearly negligible amount of scattering. In addition, the modulation frequency was neither so high that the signal was lost in the particle statistics noise, nor so low that the packet

of observed modulation had too few oscillations. The excellent transient response of the LBL neutral beam, combined with the efforts of the PPPL Power Electronics section made this novel arrangement possible.

The neutral particle detector used for this experiment was somewhat more elaborate than necessary, since four separate sight-lines were needed for other experiments using this same apparatus²⁷ while only one was needed for this experiment. However, the presence of the other channels made certain measurements easier. The detector is shown in fig. 2. It is a mild extension beyond the usual detector system used for ion temperature measurements on tokamaks. For purposes of cleanliness in the tokamak and to avoid high voltage breakdown in the detector, helium, rather than the more usual nitrogen gas was used in the stripping cell. The four-channel system involved four 3 mm diameter entrances and four 3 mm diameter exits from the stripping cell, which put a heavy gas load on the pumping system. Two freon-baffled 6" oil diffusion pumps brought the base pressure down to 2×10^{-7} T in the detector, comparable to the ATC base pressure, while the gauge pressure in the region forward of the stripping cell, with gas flow, was $\sim 1 \times 10^{-5}$ T. The parts of the vacuum system out of the ATC toroidal field were constructed of 3/8" soft iron which provided magnetic shielding. The ATC stray poloidal field was ~ 50 G, which was measured to be reduced to < 4 G inside the detector. The stripping cell was filled to a relatively high pressure of $\sim 10^{-2}$ T and its length was 14.4 cm resulting in a near-equilibrium stripping cell.

Angular scattering is negligible for energies in the multi-keV range,³⁹ which is why we chose to use a thicker cell in this experiment than is usually employed in ion temperature measurements.

The four separate sight-lines were electrostatically analyzed by a single 90° cylindrical plate energy selector. The larger radius plate was constructed with a meshed slot to permit protons and neutral particles to pass through into the back region of the detector. The fact that all four sight-lines could not be perpendicular to the entrance aperture of the energy analyzer caused a systematic variation in the selected energy less than the error caused by the difficulty of locating the plates accurately in three dimensions.

The energy selection and band-widths of the four sight-lines were checked with a small (~ 10 nA) 35 keV proton beam, in order to duplicate the reflective effects of the actual measured particles. The bandwidths were found to be 1.6%, comparing well with the design value of 1.5%, and the energy selection varied across sight-lines by less than 1%.

The detectors employed were multi-channel-plate electron multipliers arranged in series pairs.²⁹ These plates were purchased from Mullard in the form of specially cut 4 mm × 4 mm squares, and mounted in kiln fired lava holders. The detectors were chosen for their high current capability and low cost as compared with channel electron multipliers. The plates were run with -1 to -1.8 kV cathode potential, -20 V anode, with collector plate at ground. There was no inter-plate acceleration voltage.

The proton beam was used to demonstrate that the detectors responded linearly to input current up to a collector current of 10% of the steady drain current, which determined our operating range for the detectors.

The collector currents from the detectors fed into high input impedance ($10^6 \Omega$) amplifiers with bandwidths of 200 kHz and 0.1 V/nA gain. The amplifiers were used to drive coaxial lines to the ATC control room, and signals were displayed on a storage oscilloscope and photographed. In future, more automated versions of this experiment, computer data acquisition and analysis will be desirable.

III. TECHNIQUE

In order to perform this experiment one first needs various alignments. Because the 4-channel detector's sight-lines are solely determined by mechanical geometry, they can be aligned relative to the tokamak center-line with good precision. This was done using various plumb lines and straight edges. A similar procedure, however, is impossible with a neutral beam. The geometrical center of the beam spot is not determined solely by the apertures, although, of course, they constrain the peak to be within a certain small range. The beam spot center is also determined by the precise alignment of the extraction system, where a mil of misalignment can steer the beam by 1° .

Fortunately, however, the beam can be aligned relative to the detector by a simple procedure. The tokamak vacuum vessel is filled to a pressure of $\sim 2 \times 10^{-5}$ T with D_2^0 , and the toroidal

field energized. Then when the neutral beam is fired into the gas, a fraction of the beam is collisionally stripped and circulates the torus. As it circulates, however, charge-exchange reactions take place and energetic neutral atoms are flung out tangentially. Because angular scattering is negligibly small for one toroidal passage at these energies, the atoms come out at precisely the same angle (or tangency radius) at which they were injected. Thus by looking for neutral atoms at E_{inj} and swinging the detector, one may determine the beam aiming and profile. The tokamak vertical field may be adjusted to cancel the vertical curvature $\vec{B}$ drift at the tangency point, or it may be turned off to avoid any small effects due to different cancellation at different radii.

As it turns out, this relative calibration between the injector and detector alignments is all that is necessary, since the absolute calibration of the detector's alignment would only be useful if the plasma position itself were known to high accuracy, which it is not. The ATC plasma position measurement system consists of a number of small multi-turn magnetic loops arranged so as to measure the plasma current's poloidal field at various locations.³⁰ The contributions to $\vec{B}_\theta$ from the ohmic heating (OH) and vertical stabilizing field (SF) circuits are cancelled by signals from Rogowski loops around the input leads of each circuit. The OH and SF induced eddy currents in the machine structure are small except during start-up and rapid adiabatic compression, and the eddy currents induced by the slow variation of the plasma current or its slow change in position

should be negligible. The accuracy of placement and alignment of the probes, however, is such that while an accurate relative measurement of plasma position is possible, the absolute location is only known to ± 1 cm. This excludes the possibility of measuring the shape of a single high-energy orbit in the tokamak, and thereby deducing q . We had previously proposed³¹ continuously ramping the injection and detection energies over a wide range, and by using a number of detectors, see the shifts of many orbits at different energies. Then by comparing the relative shifts of orbits at different energies, one could deduce q . Ramping the neutral beam would have been a formidable technical task, and fortunately another approach presented itself.

Because of the presence of molecular ions in the arc plasma of the ion source, a fraction of the extracted current is in the form of D_2^+ and D_3^+ . In the neutralizer many of the molecular ions are broken up, and the resulting atomic ions are neutralized. Some of the molecular ions are neutralized and not dissociated, however, so five separate species of deuterium neutrals are emitted in the beam: D^0 at E_{inj} , $E_{inj}/2$, and $E_{inj}/3$, as well as D_2^0 at E_{inj} and at $2E_{inj}/3$, the last coming from partially dissociated D_3^+ . Berkner et al.³² have estimated the molecular neutral power at the full energy to be $\sim 1/3$ of the atomic neutral power at $E_{inj}/2$, and the molecular neutral power at $2E_{inj}/3$ to be $\sim 1/2$ of the atomic neutral power at $E_{inj}/3$. The atomic neutrals emitted from the neutralizer are trapped in the plasma by charge-exchange, ion impact ionization, and electron impact

ionization. The molecular neutrals are trapped by electron ionization, with³³

$$\frac{\langle \sigma_{ei} v_e \rangle}{v_b} = 4 \times 10^{-16} \text{ cm}^2 \text{ for } T_e = 800 \text{ eV}$$

$$E_b = 30 \text{ keV}$$

and by charge-exchange, $\sigma_{cx} = 8 \times 10^{-16} \text{ cm}^2$.³²

Thus after a short period of co-injection there are ion orbits in the plasma as shown in fig. 3. In this figure, for simplicity, only the orbits of ions created at the injector tangency radius are included. As the atomic ions circulate, they suffer charge-exchange reactions and fast neutrals are emitted tangentially from the plasma. The cross section for ion impact dissociation of the molecular ions is not well known, but the D_2^+ ions are at least dissociated by electron impact with³⁴

$$\frac{\langle \sigma_{de} v_e \rangle}{v_b} = 5 \times 10^{-16} \text{ cm}^2$$

so that the circulating current is reduced by at least a factor of ~ 50 for each turn around the torus. The total outflux of dissociation neutrals at $E_{inj}/2$ is still quite high, however, because essentially no molecular ions remain in the plasma long enough to scatter out of the detector's viewing angle or slow down out of its narrow bandwidth.

One can imagine scanning a neutral particle analyzer sight-line across the various orbits, and so measuring the orbit shift vs. ion momentum, at five distinct momenta. A plot then of orbit shift vs. $(mE)^{1/2}$ gives q , since

$$\Delta = \frac{q(2mE)^{1/2}c}{eB_T}$$

It is not a simple matter, however, to scan the sight-line of a charge-exchange detector over a finite angle in a time ≈ 10 msec. The alternative used here is to slowly move the plasma during a 10 msec period, and record the plasma position when the orbit of an ion of a given momentum just connects the injector and detector tangency points (fig. 4). This can be simply reduced to a plot of Δ vs. $(mE)^{1/2}$. One possible objection to this technique is that it may disturb the magnetic structure which we wish to measure. Experimentally, it was found that q at the plasma surface changed no more during slow decompression ($R = 76 \rightarrow 81$ cm in 10 msec) than during the equivalent period of normal operation. In addition to this, the X-ray or magnetic fluctuations that happened to be taking place, in most cases, continued unchanged through the slow decompression. A second objection to this technique has to do with a rather complex geometrical question. By modulating the neutral beam and looking for modulation in the fast neutral flux, we detect only recently injected ions. To see the interesting inner edge of the $v_{||}/v = 1$ drift surfaces, we must look through their outer edges, and a significant neutral flux emanates from there. But because

particles need to pitch angle scatter to be seen from these locations, the time modulation is washed out, even for $\Delta v_{||}/v$ as small as 0.04. The problem arises, however, even for completely unscattered orbits, as to whether the maximum signal will be obtained by having the detector sight-line precisely tangent to the orbit arising from the tangency point of the center-line of the injected beam.

In order to study this problem, a Monte-Carlo program was written to calculate the injected distribution of fast ions starting from the actual beam profile, and also to calculate the sensitivity of the detector to particles in the plasma with a given pitch angle and drift surface minor radius, taking into account the finite sizes of the neutral beam and of the detector acceptance cone. The result of this calculation for various detector aimings is shown in fig. 5. The peak of the sensitivity does indeed arise from having the center of the detector viewing angle tangent to the orbit which passes through the injector's tangency center.

An example of the experimental data is shown in fig. 6. The envelope of the modulation has a shape similar to fig. 5, confirming our analysis. A further confirmation is the fact that the modulated neutral flux from dissociated molecular ions has the same envelope as that of the neutrals due to atomic ions.

IV. ANALYSIS

In figure 7, we show the data and analysis from a typical run. The abscissa represents the plasma position (as measured by the magnetic loops) which was required to place an ion orbit tangent to both the injector and detector sight-lines, and the ordinate gives the particle momentum as $(mE)^{1/2}$, with E in keV, and M in A. M. U. The dots are the experimental data showing the plasma position which results in the maximum modulated signal. To zero order in r/R , and assuming q independent of r , one may simply draw a straight line through the points to deduce q . Doing this, one discovers that regularly the largest orbit shifts fall below the best fit straight line.

This results from curvature in the data which is due to the radial profile of q ; the orbits with the highest momenta sample a section of the plasma removed slightly from the magnetic axis, so they experience a higher q and have larger orbit shifts. An attempt was made therefore to fit the data with two parameters, $q(0)$ and a radial profile parameter. Unfortunately, there was too much scatter, and the curvature was too small to determine the radial profile parameter with any accuracy. Because the curvature is so small in most cases, it makes a small contribution to the deduced q , and thus an approximate method to estimate the curvature allows us to nearly eliminate the systematic error in $q(0)$ caused by the presence of a q profile.

In order to do this, we need an estimate of $q(r)$ near the axis. Using a common model, we take

$$J \propto [1 - (r/a)^2]^x$$

$$x = q(a)/q(0) - 1$$

and using the known q at the limiter, deduce $q(r)$ and therefore $\Delta(r)$ as a function of $q(0)$. Because in most experiments we have concentrated on measuring $q(0)$, we may ignore the non-concentricity of the flux surfaces which is small (< 2 mm for $r < 7$ cm) near the magnetic axis. Then it is a straightforward project to calculate the required plasma major radius to connect the injector and detector tangencies with an orbit of a given momentum. This is the smooth curve in figure 7. $q(0)$ is then varied to give the least square fit to the experimental data. The detector tangency location and magnetic loop radial position measurements must be relatively calibrated also, and this is managed by adjusting a correction factor to give the best fit over many separate q measurements. This, in essence, fixes the y intercept of the fit curve.

The systematic effects of the uncertainty in the calibration of the position measurement, of the assumption of concentric flux surfaces, and of the given $j(r)$ profile contribute an error to the $q(0)$ measurements ≈ 0.07 . The random error associated with the difficulty of finding the peak of the modulated neutral flux introduces an error of the order of ~ 0.05 - 0.10 , depending on plasma conditions. At the highest electron densities the central

neutral density in ATC is low, so the combination of reduced beam penetration, reduced target for charge-exchange, and lowered fast ion velocity space density due to a decreased τ_s , results in a small signal and therefore reduced accuracy. Similar arguments show that high plasma densities reduce the molecular ion flux. Since high densities and small orbit shifts correlate unavoidably with high currents, the measurement was least accurate at the top end of the ATC operating range. Thus most experiments were concentrated at somewhat lower than usual toroidal fields and plasma currents. At the very highest currents and densities the modulated flux could disappear altogether. This suggests that the identical experiment mounted on a significantly larger device would not be effective. Modifications, however, can be made in both the injection and detection systems to improve their efficiency and make this measurement feasible in next-generation tokamak devices.

V. RESULTS AND DISCUSSION

Because of the limited running time available on ATC, the decision was made to concentrate on measuring the central q value under various conditions. In principle the measurement of q is always easier at larger radii because the orbit shift is greater, and the neutral density is higher. Usually the detector channel tangent to the largest major radius was aligned with the injector, and the other three channels therefore viewed orbits with 4 cm, 8 cm, and 12 cm diameters. In order to use all of these, however, in a single shot, an inconveniently large

excursion of the plasma was necessary. In some cases, nevertheless, this was tried, and the results were qualitatively in agreement with our understanding of the orbits. A case which was quantitatively analyzed gave results consistent with the $j(r)$ model determined by measuring q on axis.

The results of two scans of $q(0)$ while varying $q(a)$ are shown in figures 8 and 9. In the first scan, the toroidal field was kept fixed, and the plasma current was adjusted to change q at the limiter. The plasma current was varied to find the point where sawtooth oscillations first appeared in the soft X-ray signal viewed horizontally through the plasma central chord. In that case the X-ray signal showed a characteristic rapid rise which suddenly leveled off into the sawtooth oscillation. Although we were looking through the plasma center and so were insensitive to $m=1$ perturbations, the sawteeth typically are accompanied by $n=1/m=1$ fluctuations centered about the supposed $q=1$ surface.¹⁵ We did not in this experiment measure the radius of the $q=1$ surface, but the fast ion measurement strongly suggests that the sawtooth oscillation begins as soon as the $q=1$ surface appears in the plasma. We may exclude the possibility that a $q(0) < 0.9$ is required to begin the process.

In the second scan, the plasma current was held fixed, and the toroidal field was varied in order to vary $q(a)$. In this case we were able to proceed to lower $q(a)$'s and obtain good measurements. The lower limit of the run was determined by the advent of major plasma disruptions for $q(a) < 3$. At the

two higher toroidal fields no magnetic or soft X-ray oscillations were present. However, in the lower $q(a)$ cases, soft X-ray sawtooth oscillations were present on some of the discharges, and $n=1/m=2$ magnetic perturbations were seen on others. Often early in time the $n=1/m=2$ oscillations were present, then they were followed by sawtooth oscillations during the q measurement. This is a characteristic of magnetically active tokamak discharges, that they may switch between $n=1/m=2$ dominated states, which tend to have low energy confinement times and broad low electron temperature profiles, and sawtooth dominated states which display peaked electron temperature profiles and longer confinement times. Electron temperature and density profiles unfortunately were not available for this scan.

The lowest $q(a)$ case in this run is particularly interesting. It is the only case of all the measurements where the assumed current profile was clearly incorrect. The orbit shifts, instead of exhibiting the curvature characteristic of a q profile, fell nearly on the straight line corresponding to $q=1$. This is strong confirmation of the hypothesis that magnetic fluctuations within the plasma prevent the Kruskal-Schafraanov limit from being exceeded.

In the first of the two q scans, (fig. 8) a number of laser measurements are available. Plotted in the same graph are the laser deduced $q(0)$'s, both including and neglecting the neo-classical correction to $J \propto T_e^{3/2}$, but always assuming $Z_{\text{eff}}(r) = \text{const}$. The discrepancy between the measured and calculated $q(0)$ is a factor of 1.8 ± 0.5 . This indicates that

$Z_{\text{eff}}(0)/\langle Z_{\text{eff}} \rangle_{\text{laser}} = 2.0 \pm 0.5$, taking into account the non-linearity of electrical resistivity with respect to Z_{eff} . The large error in the measurement comes predominantly from the difficulty of calculating $q(0)$ accurately from the laser data. A similar analysis has been performed on the basis of X-ray fluctuation data,¹⁵ also giving a central Z_{eff} about 2 times greater than the average. These results will be further discussed and analyzed in conjunction with a $Z_{\text{eff}}(r)$ measurement performed on ATC with this same apparatus, to be described elsewhere. In general, however, the results suggest that thermal transport and impurity transport processes that vary slowly with changing parameters govern the current profile when $q(0) > 1$, but that as the plasma current is raised beyond this point, suddenly oscillations near the magnetic axis affect the current distribution. This may occur either directly through perturbations of the magnetic structure or indirectly by affecting thermal transport. In addition, the results show that a naive $j \propto T_e^{3/2}$ model is inadequate to describe the current distribution in a tokamak which has a significant impurity content, and so detailed studies of MHD stability or of thermal transport in such devices will require direct measurements of $q(r)$.

The author wishes to thank Drs. H. P. Eubank and H. P. Furth for their aid and encouragement in the development and execution of this experiment; Drs. R. R. Smith and C. C. Daughney for their collaboration in running the X-ray and Thomson scattering diagnostics and in interpreting the results, and also the Neutral Beam technical group headed by Edward Ryan, and the ATC technical group headed by Robert Shoemaker for their assistance in the construction and operation of this experiment.

Work supported by the United States Department of Energy
Contract No. EY-76-C-02-3073.

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Fig. 1. Apparatus for injecting a highly collimated neutral beam into ATC.

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SCHEMATIC DRAWING OF DETECTOR

Fig. 2. Four sight-line fast neutral particle an

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 Fig. 3. Co-injected orbits for the three species of atoms and two species of molecules emitted by the neutral beam.

Fig. 4. Schematic of technique to measure orbit shifts by moving the plasma slowly.

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Fig. 5. Calculated flux vs. detector aiming, injector aimed at 83 cm, drift axis at 80 cm.

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Fig. 6. Fast neutral signal at E_{inj} and $E_{inj}/2$ as the plasma is slowly moved during an injection pulse.

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ATC ORBIT SHIFTS

Fig. 7. Location of the plasma for maximum modulated flux

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Constant Current Scan

$I_p = 50 \text{ kA}$, $B_T = 8-15 \text{ kg}$