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Observation of new branch of Toroidal Alfvén Eigenmodes in TFTR

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Experimental observations are presented of a new branch of the toroidal Alfvén eigenmode spectrum during ICRF heating of plasmas on TFTR. The identification of the second branch is based largely on direct measurements of the toroidal mode numbers of the toroidal Alfvén Eigenmodes, and by the differences in the time evolution of the frequency spectrum between the new branch and the original toroidal Alfvén eigenmodes as reported by Taylor et al. Phys. Fluids B 5 2437 (1993). The new branch has so far only been observed in relatively low edge q (=4-4.5) plasmas .

Introduction

In this paper are reported observations of a new branch of toroidicity induced Alfvén Eigenmode (TAE) activity observed in ICRF heated plasmas. This new branch appears in higher plasma current, lower edge q plasmas [q(a)≈4-4.5] with H-minority Ion Cyclotron Range of Frequency (ICRF) heating. The modes are generally at a lower frequency than the global TAE mode which has previously been discussed [1,2]. This lower frequency branch of the TAE modes, (labeled LTAE) have multiple peaks in the frequency spectrum corresponding to independent modes as was seen for the original, higher frequency branch (now labeled HTAE). The modes in the LTAE branch have a range in the toroidal mode numbers similar to those for the HTAE, based on direct measurements with a toroidal array of Mirnov coils[3]. Comparison of the Mirnov coil data to the data from the microwave reflectometer show that LTAE modes evolve from the core localized mode discussed by Nazikian et al [4]. Recently, TAE modes which are strongly localized within the q=1 surface have been predicted from numerical simulations[5]. The core-localized TAE modes are theoretically predicted to have a higher frequency than the global TAE modes, but the experimentally observed rapid drop in frequency coupled with the apparent decentralization of the mode have not yet been explained.

Characteristics of the lower TAE mode branch

A typical time evolution of the Mirnov spectrum during high power ICRF H-minority heating is shown in Fig. 1. The data is displayed as a contour plot of the spectrogram. To aid in interpretation of the figure, the contour range has been chosen to emphasize the dominant modes and curves have been added to illustrate the trajectory of the modes in the lower frequency group. The data is from a 1.7 MA, 3 Tesla plasma heated with 6.6MW of fundamental H-minority ion heating power. The RF power, line average density, stored energy in the tail and the envelope of the TAE amplitude are shown in Figure 2. The tail energy is determined from the diamagnetic measurement of the perpendicular component of the plasma energy and the magnetic measurement of L ($\equiv 2\beta_{||} + \beta_{\perp}/2 + l_i/2$). ICRF injection starts at 2.5sec and the TAE modes appear about 700 msecs later. For this data set, the TAE onset occurred when the energy in the fast ion tail reached about 100kJ, with a similar threshold for the LTAE and HTAE modes.

There are at least four distinct modes present in each branch, corresponding to each of the peaks in the frequency spectrum. The n numbers are determined for each of these modes at the three time points indicated by the horizontal dashed lines. The n numbers are indicated in the figure and range from 5-8 in each branch. The modes are easily divided, by their time history, into two groups. The higher frequency group (HTAE) is of the type reported on earlier [1,2] which was observed in lower current plasmas and which consists of peaks with n increasing monotonically as the frequency increases. The peaks are almost evenly spaced, the spacing becomes somewhat closer for the higher frequency, higher n peaks. Unlike the upper group, the frequency for each of the peaks in the lower group evolves much more independently from the others. All peaks in the lower group show a characteristic rapid drop in frequency shortly after the appearance of the mode. The high n number modes appear first, and are thus generally at lower frequency (the opposite ordering from that seen for the HTAE modes). Later in the evolution, the order of the peaks often inverts, or the peaks coalesce. These characteristic differences in the behavior of the two groups of modes, together with the overlap of observed mode numbers, strongly suggest that these modes are clearly distinct. As the toroidal mode numbers (and at times the mode frequency) are the same, it must be that the radial eigenstructure of the modes is different.

The modes in the lower group (LTAE's) typically are first measurable on the Mirnov coils at frequencies about or slightly higher than the frequencies of the upper group. They appear to evolve from the core localized modes [4,5], visible only in the data from the microwave reflectometer viewing the center of the plasma ($r/a \approx 0.1$). This can be seen in Figures 3a and 3b where spectrograms of Mirnov and reflectometer data are compared. Again, lines have been superimposed on the two spectrograms tracing the path of the individual modes in time and frequency. The parameters of this shot, shown in Figure 4, were similar to that shown in Figures 1 and 2. An interesting aspect of this data is that when the mode amplitude falls in the reflectometer data, the modes appear in the Mirnov coil data. As the Mirnov coils are outside the plasma, this suggests that while the LTAE's evolve from the core-localized modes they are strongly coupled to the higher m (larger minor radius) components later in time, and thus visible in the Mirnov data.

The most striking feature of the LTAE modes is the rapid drop in frequency at the onset of each mode. This drop is not due to changes in the plasma density which is directly measured to be unchanging, nor is it likely due to changes in the plasma rotation as the HTAE's show little change in frequency. The change in mode frequency might also be due to a change in the plasma pressure. As the plasma pressure increases, the mode frequency tends to drop in the gap. However, in some, but not all cases, the global plasma b is nearly constant during the period of rapid frequency change of the LTAE's. This suggests that this is not the solution, however, the local pressure, which is not measured on TFTR, may be changing.

A slow evolution of the central q profile could affect the mode frequency indirectly in several ways. Using the local expression for the TAE frequency as an approximation, the frequency is inversely proportional to the q at the mode location and thus the 10-15% drop in mode frequency between 3.25 and 3.4 seconds in Figure 3 might be superficially attributed to a 10-15% drop in central q. However, as the q drops, the core localized modes will tend to move outward in minor radius. This would have two opposing effects on the mode frequency. Firstly, the mode would move to a region of lower density; thus a drop in central q would tend to raise the frequency of modes with otherwise the same poloidal mode structure. Secondly, as the gap moved outward in minor radius, the gap would tend to broaden due to the change in aspect ratio, this would allow the mode frequency to be lower. These effects are probably small, and not sufficient to explain the observed change in frequency.

A more plausible model for the frequency drop of the LTAE modes due to evolution of the q profile is that as the q profile evolves, the TAE gap opens up radially, allowing the initially core localized mode to become more strongly coupled to higher m components, located at larger minor radii. As the characteristic frequency of the TAE modes tends to be lower at larger minor radii (Figure 5), it is reasonable to expect the mode frequency to drop and the signal level on the Mirnov coils to increase. The problem with this explanation is that the radial profile of the gap center frequency is typically highest in the plasma core, dropping towards the plasma edge. Thus the drop in central q from continued current diffusion would tend to close the gap, forcing the mode to become more localized in the core. In Figure 5 the TAE frequency profile is calculated using $f_{TAE} = V_{Alfvén}/4\pi qR$. As the plasma consists primarily of deuterium and He^4, with the dominant impurity being carbon, the Alfvén velocity is calculated from the electron density assuming 2 AMU/electron. The profile of the electron density and the q profile as calculated with a time-independent code are shown in Figure 5. The calculation of the q profile becomes unreliable within $r/a \approx 0.4$ due to the assumption that the current is in equilibrium, and uncertainties in the temperature and impurity profiles.

The change in mode frequency may also be due to changes in plasma parameters which are not measured. In addition to lack of direct measurements of the q profile evolution in these plasmas, no direct measurements of the fast ion energy distribution or radial profile evolution are available. It is possible that the appearance of the TAE modes, which have been demonstrated to cause fast ion loss, are affecting these parameters. Thus, the changes in frequency could be due to changes in the fast ion population demographics.

The HTAE modes are more sensitive to core conditions suggesting that the modes are core localized. The lower branch of TAE modes have so far only been observed in low q(a) ($\approx$4) plasmas, i.e., plasmas with relatively large mixing radius. This stability dependence on the edge q, or radius of the q=1 surface suggests that the modes are core localized. While both groups of modes are strongly affected by sawteeth, as can be seen at 3.7s in Figure 1, the upper group survives the sawtooth crash, while the lower group disappears. The drop in frequency of the upper group following the sawtooth crash, on a slow time scale (10's of msecs) may reflect the evolution of the density profile following the crash. This would indicate the HTAE are radially localized outside the sawtooth mixing radius.

The ICRF driven TAE modes recently observed on JT-60 have a superficial resemblance to the LTAE modes discussed here[6]. However, the indirect identification of the toroidal mode numbers on JT-60 by a Doppler shift technique results in an inverse ordering of the mode numbers compared to those directly measured for the TFTR data. That is on JT-60, the lowest toroidal mode numbers appeared first, with the modes appearing in an ascending sequence of toroidal mode numbers. On TFTR, the highest toroidal mode number becomes unstable first, with subsequent modes having lower n's. Thus, the ordering of the toroidal mode numbers is consistent with that seen on TFTR for the HTAE modes. The frequency evolution of the modes on JT-60 is more similar in appearance to the TFTR LTAE modes.

Poloidal Structure

The TAE modes are theoretically expected to have strong coupling of multiple poloidal mode structures for each toroidal mode number. For the Mirnov diagnostic which is limited to measurements outside of the plasma, the multiple modes make it difficult to determine anything meaningful about the poloidal mode numbers of the modes. However, it is possible to determine the mode amplitude variation in the poloidal direction. The TAE modes of both branches are found to be strongly ballooning as is shown in Figure 6. This suggests that neither branch is of the frequency down-shifted kTAE branch, which is expected to be anti-ballooning [7].

Summary

The new branch of TAE activity reported here, the LTAE, has not, as yet been simulated theoretically. The modes in the new branch have apparently the same toroidal mode numbers and, at times, the same frequencies as the originally observed TAE modes (HTAE's), but are independent. The modes originate as the core localized TAE modes first predicted theoretically and then observed experimentally. They evolve to become more global and their frequency drops significantly. This observation is of fundamental importance as it is the first evidence of a new branch of TAE activity not yet predicted theoretically, thus with unknown implications for ITER and other future reactor devices.

Acknowledgments

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Bibliography

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[7] H L Berk (Private Communication Sept 1994)

Figure captions

Figure 1 Contour plot of the spectrogram for shot 74330. The data is the time derivative of the magnetic fluctuations and has not been corrected for the frequency response of the system. Shot # 74330, Ip=1.7MA, B=3T, q(a)=4, PRF = 6.6MW.

Figure 2 The time history of the ICRF power input, the estimated energy in the fast ion tail, the semi-empirical scaling for the TAE frequency and the magnetic fluctuation amplitude for the same shot as Fig. 1.

Figure 3a Contour plot of the spectrogram of edge magnetic fluctuations during a plasma with H-minority ICRF heating. Shot # 67630, Ip=1.8MA, B=3.3T, q(a)=4, PRF = 11.2MW.

Figure 3b Contour plot of the spectrogram of core density fluctuations measured with a microwave reflectometer.

Figure 4 Time evolution of the plasma current, ICRF heating power, estimated fast ion tail energy and semi-empirical scaling for the TAE frequency during the plasma shot of Figure 3.

Figure 5 Profiles of the electron density, q and the local TAE frequency calculated from SNAP data for shot 67630.

Figure 6 Poloidal variation of the TAE amplitudes for the upper and lower groups of TAE modes for the shot in Figs. 1 and 2. The distance from the circle is the mode amplitude.

Figure 1

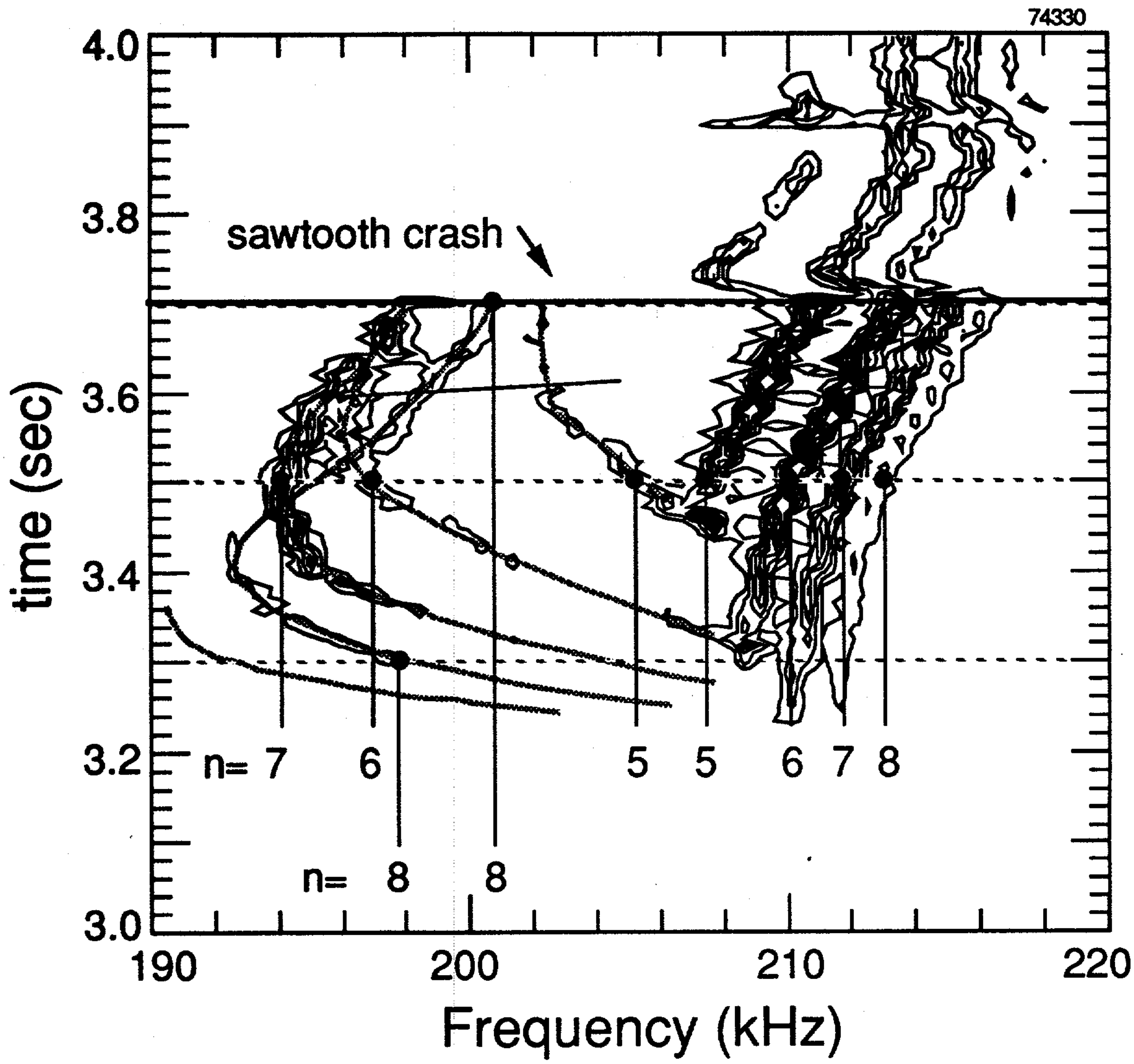
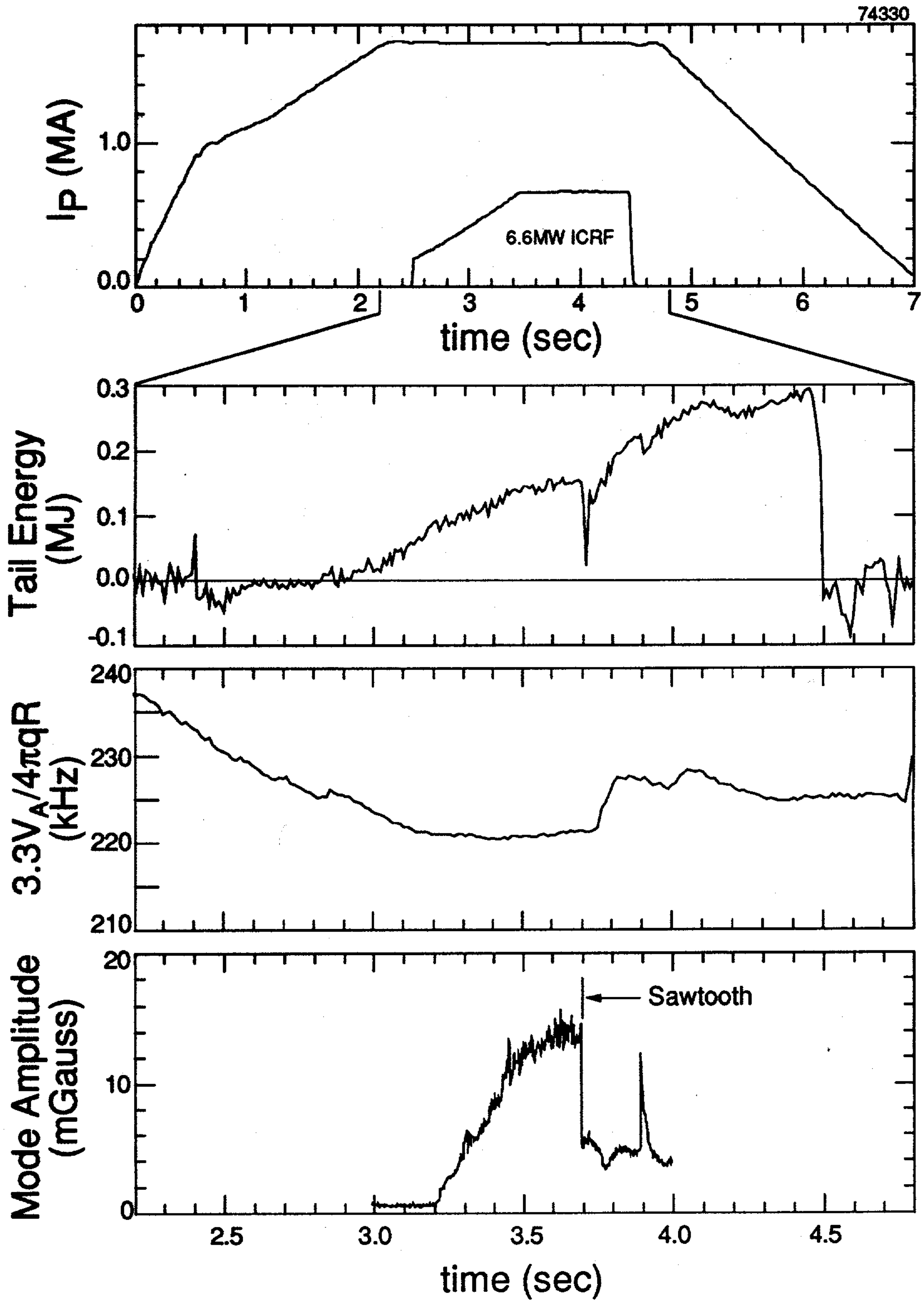

74330
4.0
3.8
3.6
3.4
3.2
3.0
time (sec)
sawtooth crash
n= 7
6
5
5
6
7
8
n=
8
8
190
200
210
220
Frequency (kHz)

Figure 2



74330
Ip (MA)
1.0
0.0
6.6MW ICRF
0
1
2
3
4
5
6
7
time (sec)
Tail Energy (MJ)
0.3
0.2
0.1
0.0
-0.1
3.3VA/4πqR (kHz)
240
230
220
210
Mode Amplitude (mGauss)
20
10
0
Sawtooth
2.5
3.0
3.5
4.0
4.5
time (sec)

Figure 3a

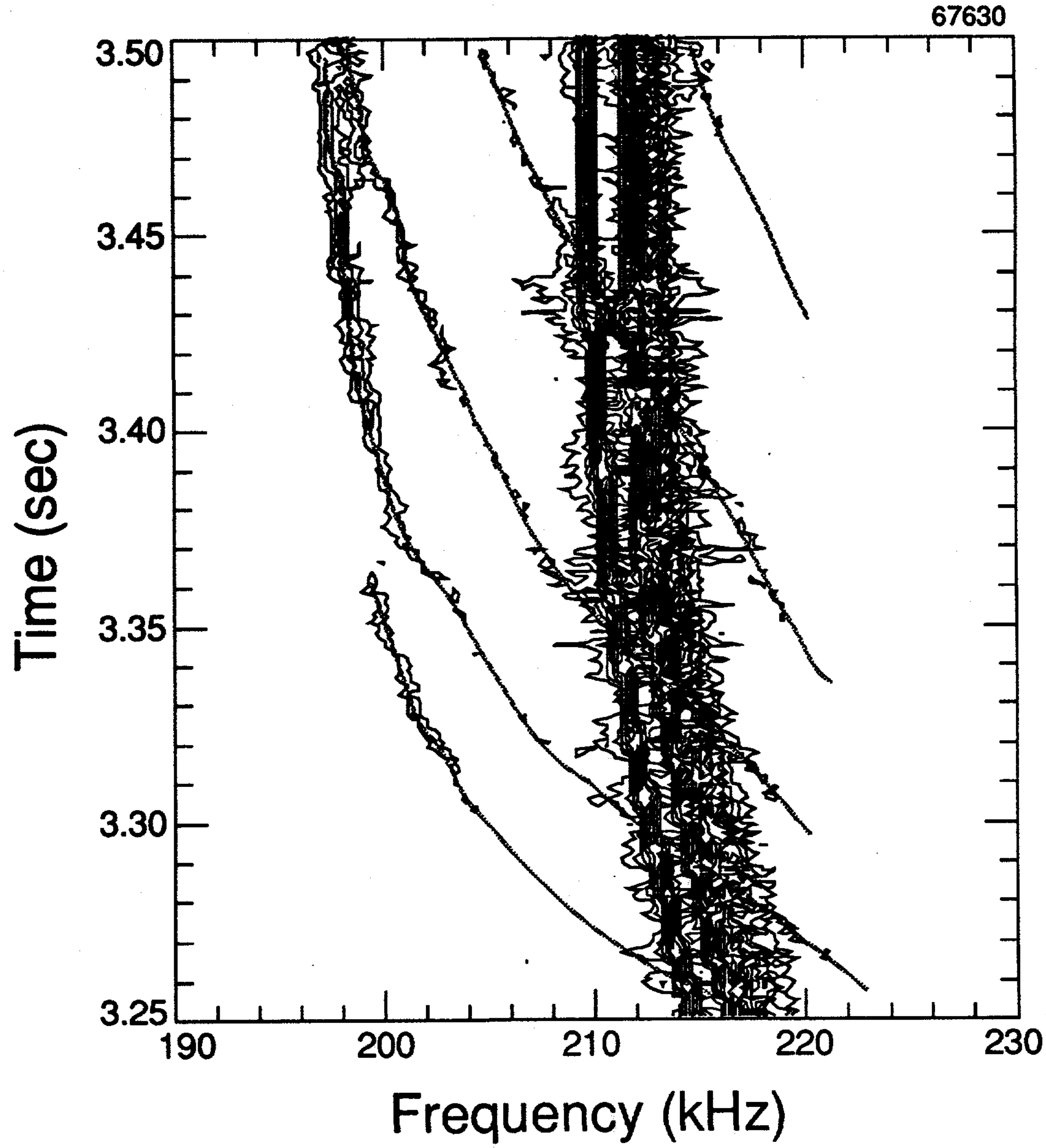
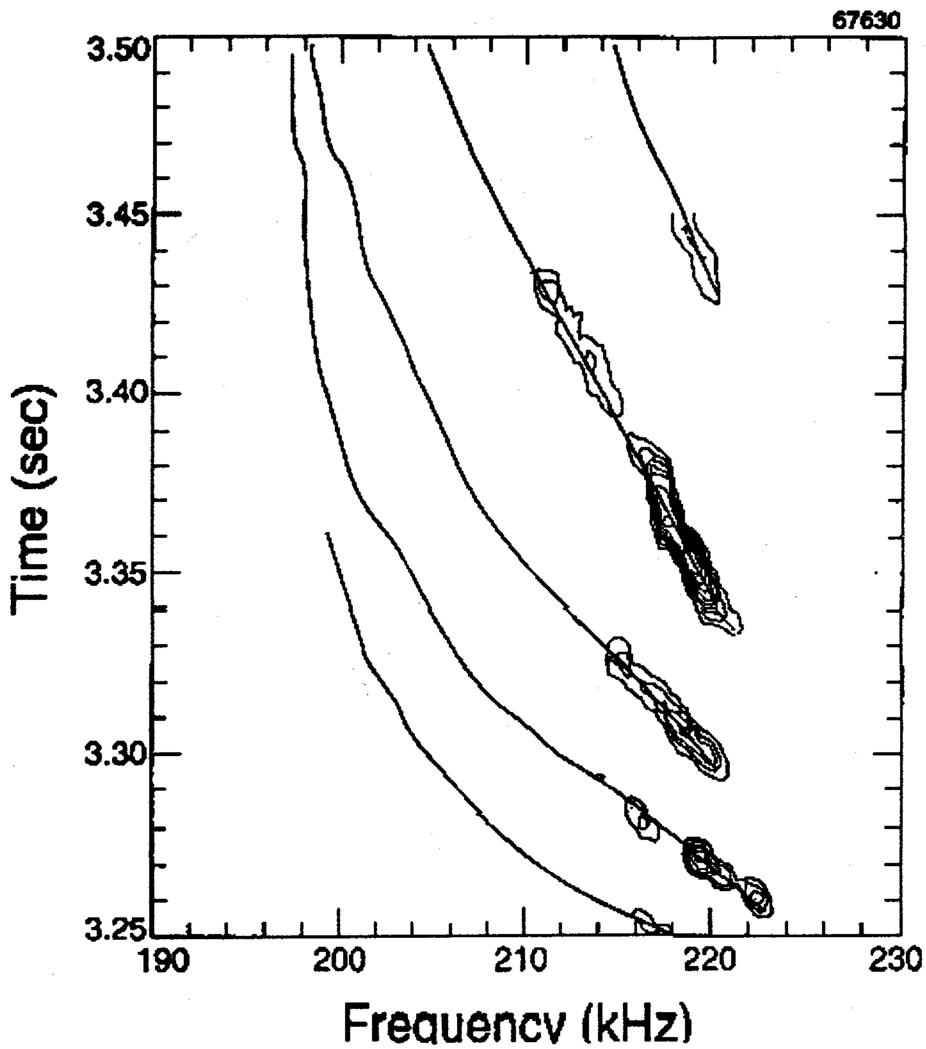

67630
3.50
3.45
3.40
3.35
3.30
3.25
Time (sec)
190
200
210
220
230
Frequency (kHz)

Figure 3b



67630
3.50
3.45
3.40
3.35
3.30
3.25
Time (sec)
190
200
210
220
230
Frequency (kHz)

Figure 4

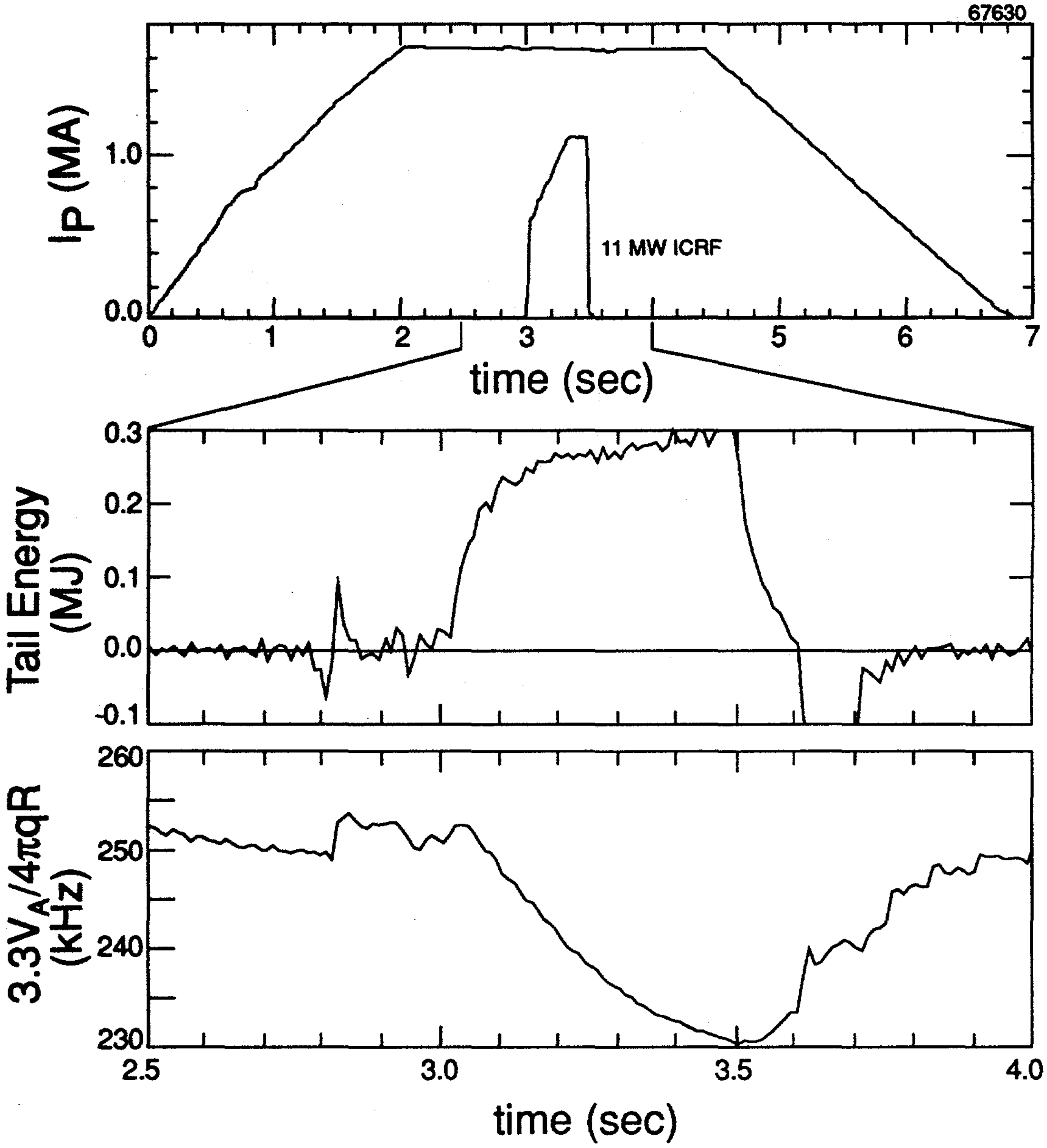

67630
IP (MA)
1.0
0.0
0
1
2
3
5
6
7
11 MW ICRF
time (sec)
Tail Energy (MJ)
0.3
0.2
0.1
0.0
-0.1
3.3VA/4πqR (kHz)
260
250
240
230
2.5
3.0
3.5
4.0
time (sec)

Figure 5

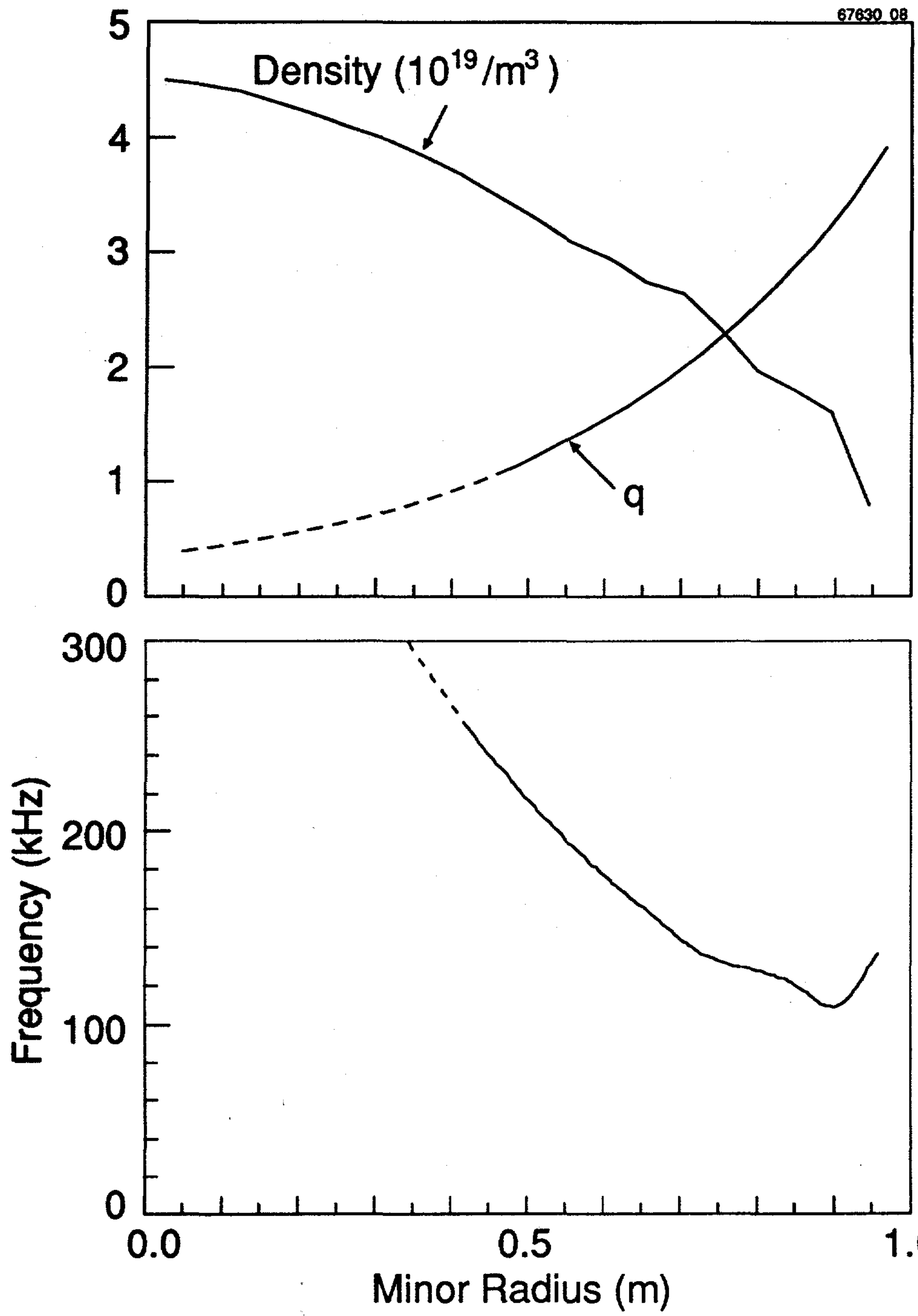

67630.08
Density ($10^{19}/m^3$)
q
5
4
3
2
1
0
300
200
100
0
Frequency (kHz)
0.0
0.5
1.0
Minor Radius (m)

Figure 6