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by

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Abstract

The alpha particle effect on the excitation of toroidal Alfvén eigenmodes (TAE) was investigated in deuterium-tritium (d-t) plasmas in the Tokamak Fusion Test Reactor (TFTR). RF power was used to position the plasma near the instability threshold, and the alpha particle effect was inferred from the reduction of RF power threshold for TAE instability in d-t plasmas. Initial calculations indicate that the alpha particles contribute 10-30% of the total drive in a d-t plasma with 3 MW of peak fusion power.

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Collective phenomena associated with the energetic alpha particles in a d-t fusion reactor have been anticipated in the past two decades. Alfvén type instabilities[1] are expected to occur when the pressure gradient of the fast alpha particles exceeds the instability threshold. It is important to avoid these instabilities in a fusion reactor because they can eject the alpha particles before they thermalize in the plasma, thereby causing localized heating and damage of the first wall. Simulation experiments, performed recently with the energetic ions produced by neutral beam injection[2-4] and ion cyclotron range of frequency (ICRF) heating,[5,6] show that toroidal Alfvén eigenmodes[7] (TAE) can indeed be excited. The d-t plasmas in TFTR[8] provide for the first time the environment suitable for the investigation of the interaction between the alpha particles and these instabilities in reactor-relevant parameters. Up to 10.7 MW of fusion power has been produced in d-t plasmas in TFTR, with no evidence of excitation of TAE instabilities. This is because the alpha particle pressure gradient is still below the instability threshold. In this paper, we present the results of an experiment using the incremental drive technique to study the interaction between the fast alpha particles and the TAE modes.

ICRF heating of the minority hydrogen ions produces energetic protons which can assist the excitation of the TAE instability. Let γ_H and γ_α represent the growth rate of the instability due to the fast protons and alpha particles respectively. The total growth rate driven by the protons and the alpha particles is the sum of the two, i.e., $\gamma = \gamma_H + \gamma_\alpha$. By increasing the ICRF power, we can increase γ_H so that γ exceeds the damping rate and the mode becomes unstable. Let P_{dt} and P_{dd} denote the RF power threshold for TAE instabilities in d-t and d-d plasmas, respectively , and γ_d is the damping rate. At the instability threshold,

$$\gamma_H(P_{dt}) + \gamma_\alpha - \gamma_d(P_{dt}) = 0 \qquad \text{in d-t plasmas},$$

$$\gamma_H(P_{dd}) - \gamma_d(P_{dd}) = 0 \qquad \text{in d-d plasmas}.$$

Subtraction of the above equations yields:

$$\gamma_\alpha = \gamma_H(P_{dd}) - \gamma_H(P_{dt}) - \gamma_d(P_{dd}) + \gamma_d(P_{dt}) \qquad (1)$$

If d-t and d-d plasmas have similar parameters and the same damping rate for

TAE modes, Eq.(1) becomes $\gamma_\alpha = \gamma_H(P_{dd}) - \gamma_H(P_{dt})$. This means that in the regime where γ_H increases with RF power, the alpha particle effect is reflected from the fact that the RF power threshold is lower in d-t plasmas. This was observed in the TFTR experiment. Here we present these analysed data as the first experimental evidence of collective alpha particle effect in a d-t plasma.

The experiment was performed in TFTR with the following plasma parameters: plasma current Ip=1.8 MA, major radius R=2.62 m, minor radius a=0.96 m, toroidal magnetic field B_T=4.23 tesla on the magnetic axis at R=2.83 m, neutral beam power $P_b \sim 20$ MW, RF power $P_{rf} \leq 5.5$ MW, and the peak d-t fusion power is about 3 MW. The waveforms for P_b , P_{rf} and the neutron rate are shown in Fig.1. Fig.2 compares the frequency spectra of the Mirnov coil signals at various RF power levels in d-t and d-d plasmas. The bulk plasma parameters for these comparison shots are very similar. It is apparent that at the same RF power, the TAE amplitude is, with no exception, always higher in d-t plasmas. Since the frequency spectrum changes with RF power, it is difficult to make a quantitative comparison on the TAE amplitude. More peaks appear in the spectrum at higher RF power. We integrate over these peaks by choosing the instrumental frequency bandwidth broader than the frequency separation between the peaks, and we use this signal as a measure of the TAE amplitude. Its variation with RF power is plotted on Fig.2b. The RF power in these shots varies from 4.0 MW to 5.5 MW which is only a very small change compared with 25 MW of total heating power. Therefore, the bulk plasma parameters are very similar in these shots. The RF power threshold for the TAE instability in the d-t plasma is just below 4 MW, it is about 20% lower than that in similar d-d plasmas (about 5 MW). When 4.0 MW< P_{rf} < 5.0 MW, TAE modes appear only in d-t plasmas, suggesting the possibility of alpha particle effect on this instability.

The density oscillations in the plasma interior associated with the TAE modes can be detected by a three-channel microwave reflectometer[9] tuned at R=295 cm, 310 cm and 320 cm. The frequency spectra of the reflectometer data are shown in Fig.3. Maximum signal appears in the middle channel tuned at R=310 cm. Phase measurements by the toroidal coil array indicates that the dominant mode has a toroidal mode number of n=6. The density oscillation is roughly estimated to be $\delta n/n \sim 10^{-4}$. The fast ion loss rate at a probe 45^0 below the outer midplane increased by about a factor of two during the TAE activity. This probe,[10] under these conditions, detects only H-minority tail ion loss.

In the data analysis, we first assess γ_H by calculating the distribution of the RF power absorption among various charged species in the plasma. Most of the RF power (~70%) is absorbed by the minority hydrogen ions with a fundamental cyclotron resonance passing through the plasma core. Absorption by deuterium ions and alpha particles is weaker because they see the second harmonic cyclotron resonance. Tritium ions have resonance at the third harmonic frequency and the absorption is negligibly small. A few percent of RF power can go into the electrons via direct electron Landan damping of the fast wave, transit-time magnetic pumping, and mode conversion to ion Bernstein waves which are eventually damped by elctron Landau damping. Impurity ions at various charged states can also absorb RF power. However, we do not expect a significant difference in impurity absorption in d-t and d-d plasmas, both have the effective ion charge number of 3.4 . The most important quantity is the RF power that goes into the hydrogen ions which drives the TAE modes. The analysis was carried out with the FPP Fokker-Planck code,[13] the SNAP[14] and TRANSP[15] transport codes for a d-t shot (#76181) and a similar d-d shot (#76179). This calculation indicates that the fraction of RF power absorbed by the hydrogen ions is practically the same for d-d and d-t plasmas: 69% of the RF power is absorbed by the hydrogen ions in the d-t plasma, and 70% in the d-d plasma. Since the bulk plasma parameters are very similar in these two shots ($n_e(0) \sim 5 \times 10^{13}$ cm^{-3} , $T_e(0) \sim 9.5$ keV, $T_i(0) \sim 25$ keV), the minority hydrogen ions are expected to have similar initial distribution functions and their initial contribution to the TAE growth rate would be very similar until the TAE mode amplitude becomes large enough to modify the spatial distribution of the fast particles. In addition to these calculations, active charge-exchange technique[14] was also used to measure the hydrogen minority temperature in the plasma core. A lithium pellet was injected into the RF heated plasma 200 ms after the neutral beams were turned off so that the pellet could reach the plasma core. The data depicted in Fig.4 show that the hydrogen ion temperatures are very similar in d-d and d-t plasmas, just as expected from the power absorption calculation. Therefore, we conclude that γ_H is mainly determined by the RF power. It remains the same in d-d and d-t plasmas.

The next step is to evaluate the TAE damping rates. The most likely difference between the d-t and the d-d plasmas would come from the ion Landau damping[15] by the fast beam ions with $v_{\parallel} \approx V_A/3$. There was a conjecture that ion Landau damping by the deuterium beam ions is dominant in these plasmas. Replacement of tritium beams with deuterium beams would result in more deuterium beam ions in the plasma, thereby causing stronger ion Landau damping and a higher instability threshold. In order to experimentally evaluate the significance of the ion Landau damping effect due to the difference in the beam ion species, we varied the deuterium beam power and investigated its effect on the TAE instability. Shot #83044 with 5 tritium beam sources and 2 deuterium beam sources has the same fusion reaction rate as shot #83046 with 4 tritium beam sources and 4 deuterium beam sources. Since they also have the same RF power, γ_α and γ_H should be very similar. If ion Landau damping by the deuterium beam ions is the dominant damping mechanism, changing from 2 deuterium beam sources to 4 deuterium beam sources would double the deuterium beam ion density as well as the damping rate and stablize the TAE modes. This obviously did not happen. The saturated TAE amplitudes in these two shots are very similar as shown in Fig. 5 . This result proves that ion Landau damping by deuterium beam ions is not the dominant damping mechanism in the d-t plasma in this experiment.

The ion Landau damping rate can be estimated from local theory as follows:

$$\gamma_{ILD}/\omega \approx -\sqrt{\pi}\, q^2 \beta_i (1 + x^2) x^3 \exp(-x^2), \qquad x \equiv V_A/3v_i , \qquad (2)$$

where v_i is the thermal velocity of the fast ions assumed to have a Maxwellian distribution function. In d-t shots, tritium is introduced into the plasma through neutral beam injection at energies similar to the deuterium neutral beams in d-d shots. Since tritons are heavier than deuterons, they are injected at a slower velocity and give a smaller ion Landau damping rate per ion. However, TRANSP analysis shows that the pressure from the deuterium beam ions is lower than that for the tritium beams primarily because of the lighter deuteron mass and the shorter slowing down time due to electron drag. Application of Eq.(2) to d-t shot #76181 with plasma parameters at R=310 cm obtained from the TRANSP code yields $\gamma_{ILD} = -1.5\times10^4$ rad/sec. For the d-d comparison shot #76179, we obtain $\gamma_{ILD} = -1.6\times10^4$ rad/sec which is very close to that of the d-t shot.

The preceeding local analysis indicates that the reduced RF power threshold for TAE instabilities in d-t plasmas in TFTR is probably due to the alpha particles produced in the d-t fusion reaction. Further studies based on global analysis with the NOVA-K code[16] were also performed. The calculated mode frequency for the n=6 mode is 224 kHz, which is within 3% of the measured value. It was found that at 5.2 MW of RF power, the n=6 mode has $\gamma_d \sim 2.9\times10^{-2}\,\omega$, $\gamma_\alpha \sim 3\times10^{-3}\,\omega$ and $\gamma_H \sim 2.3\times10^{-2}\omega$, i.e., $\gamma_\alpha/\gamma_d \sim 10\%$. This can be compared with the result deduced from the reduction in RF power threshold for the TAE instabilities in deuterium plasmas. When TAE modes become unstable, they grow and saturate at an amplitude which increases with the initial growth rate. Specifically, if, for example, wave-particle trapping[17] is the saturation mechanism, the final amplitude is proportional to the square of the initial growth rate. Therefore, the data in Fig.2b can be used to estimate the alpha particle contribution to the instability drive. At 4.0 MW of RF power, the TAE mode amplitude in d-t plasmas is approximately a factor of seven lower than that at 5.2 MW of RF power at which the incremental drive $\Delta\gamma_H \sim 10^{-2}\omega$. The TAE amplitude in deuterium plasmas at 5.2 MW of RF power is also approximately a factor of seven lower than that in d-t plasmas at the same RF power, indicating that the alpha particle contribution is about $10^{-2}\omega$. This number is three times higher than the NOVA-K result, but is within the accuracy of these estimates. The major uncertainty is in the distribution function for the hydrogen minority ions which determines γ_H.

In summary, we have observed the first evidence of collective alpha particle effect in d-t plasmas in TFTR. This is inferred from the reduction of RF power threshold for TAE instability in d-t plasmas. At 3 MW of peak fusion power, the alpha particles contribute approximately 10-30% of the total drive. This result indicates that TAE instability is not a serious threat in the dt experiments on TFTR.

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Figure Captions

Fig. 1. Waveforms for (a). neutral beam power, (b). ICRF power, and (c). fusion neutron flux.

Fig. 2. Variation of Mirnov coil signal under different conditions: (a). d-t plasma with 5.2 MW of RF power, (b). d-t plasma with 4.5 MW of RF power, (c). d-d plasma with 5.2 MW of RF power, (d). d-d plasma with 4.5 MW of RF power, (e). TAE mode amplitude at various RF power.

Fig. 3. Power spectrum of the reflectometer signal from various locations: (a). R=295 cm, (b). R=310 cm, (c). R=320 cm. It is a d-t plasma with 5.4 MW RF power.

Fig. 4. Energy spectrum of the hydrogen minority ions heated by 5.2 MW of ICRF power in d-d and d-t plasmas.

Fig. 5. Comparison of two different d-t plasmas with 5.2 MW of RF power:
(a). TAE amplitude in a d-t plasma with 5 tritium and 2 deuterium beam sources. There was a sawtooth crash near 3.69 sec which causes a sudden change in the TAE amplitude.(b). TAE amplitude in a d-t plasma with 4 tritium and 4 deuterium beam sources, (c). Overlay of the fusion neutron flux from the above two d-t plasmas.

PPPL#95GR048

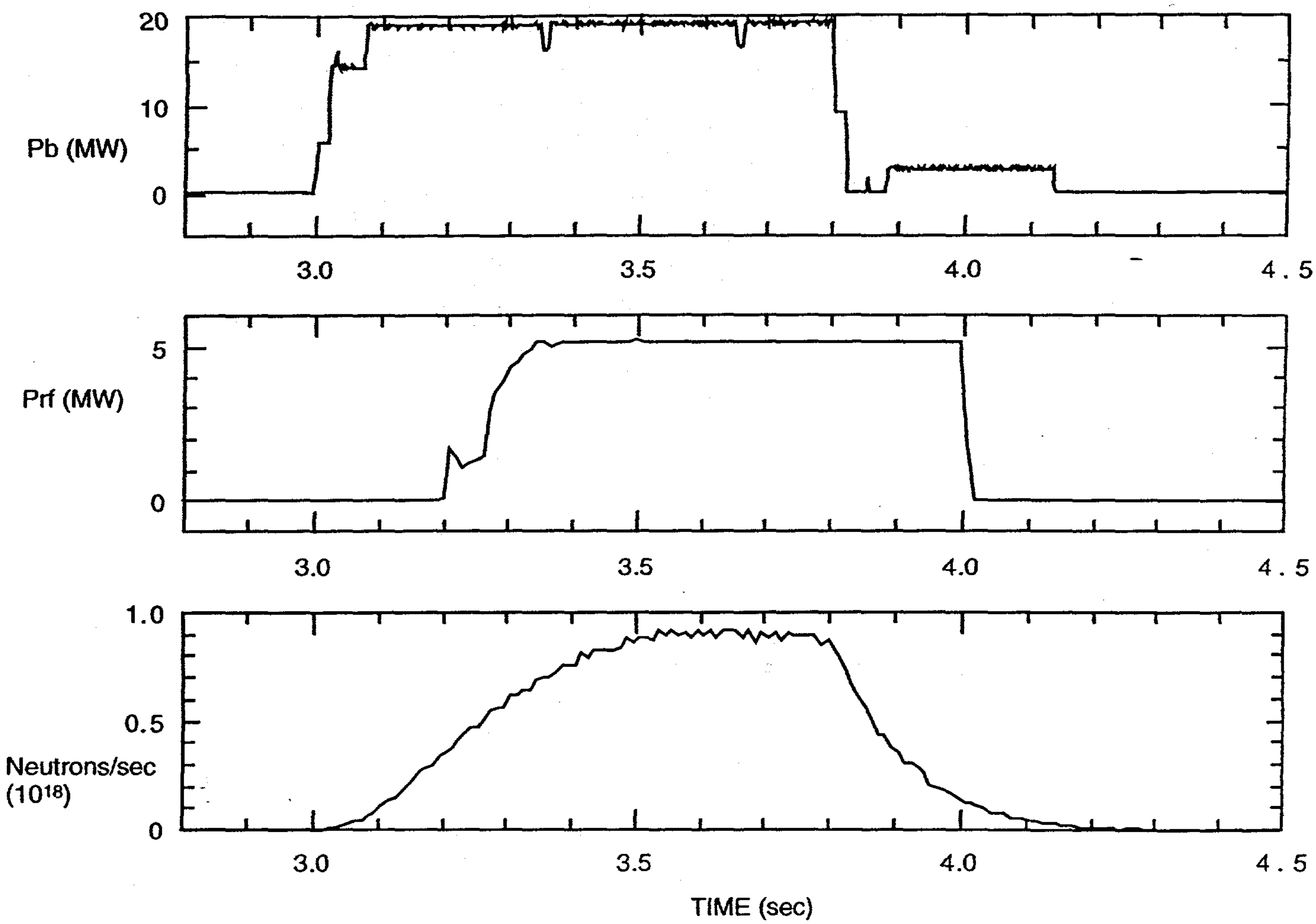


Fig. 1

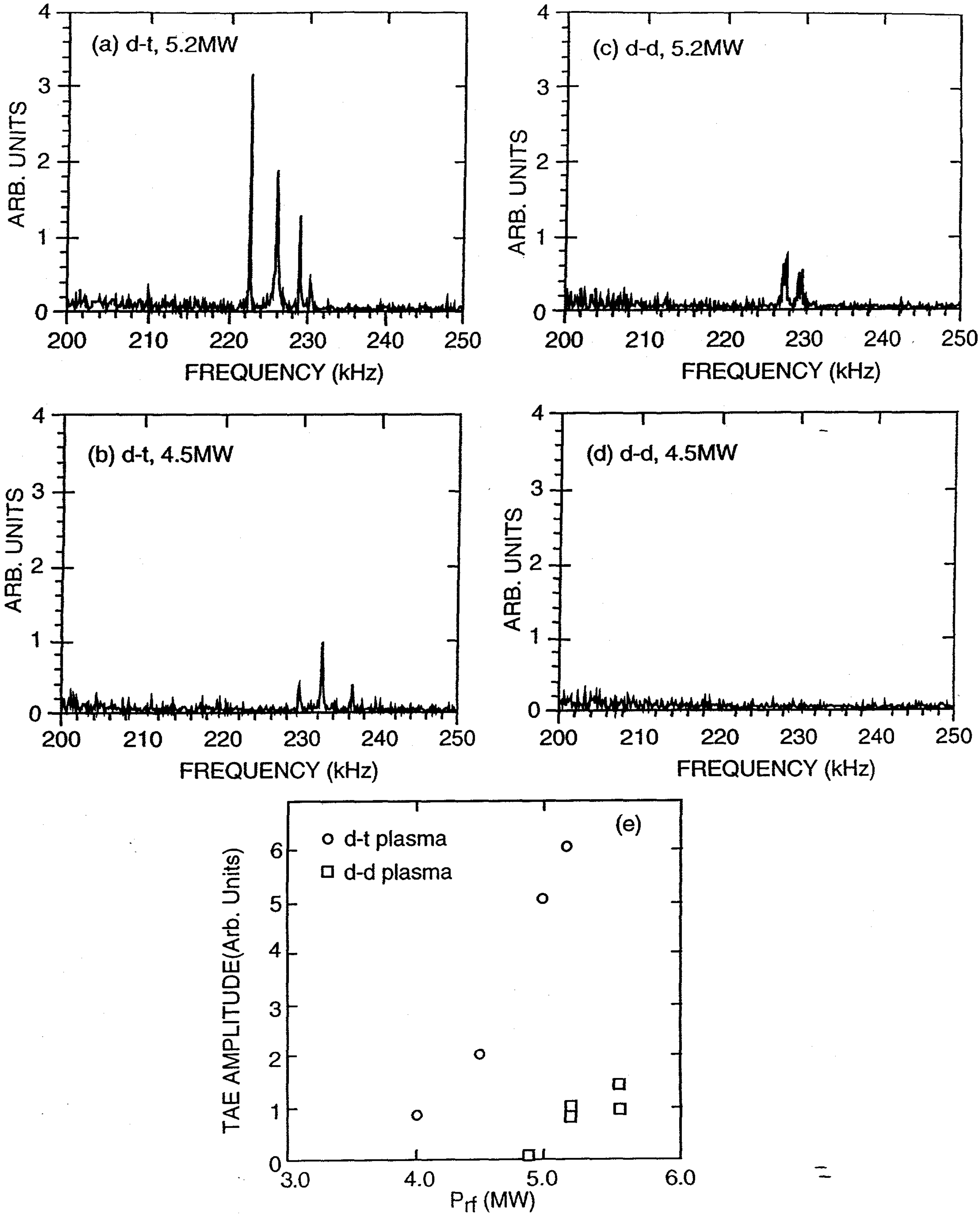

(a) d-t, 5.2MW
(c) d-d, 5.2MW
(b) d-t, 4.5MW
(d) d-d, 4.5MW
ARB. UNITS
FREQUENCY (kHz)
0
1
2
3
4
200
210
220
230
240
250
(e)
d-t plasma
d-d plasma
TAE AMPLITUDE(Arb. Units)
P_{rf} (MW)
5
6
3.0
4.0
5.0
6.0

Fig. 2

PPPL#95GR050

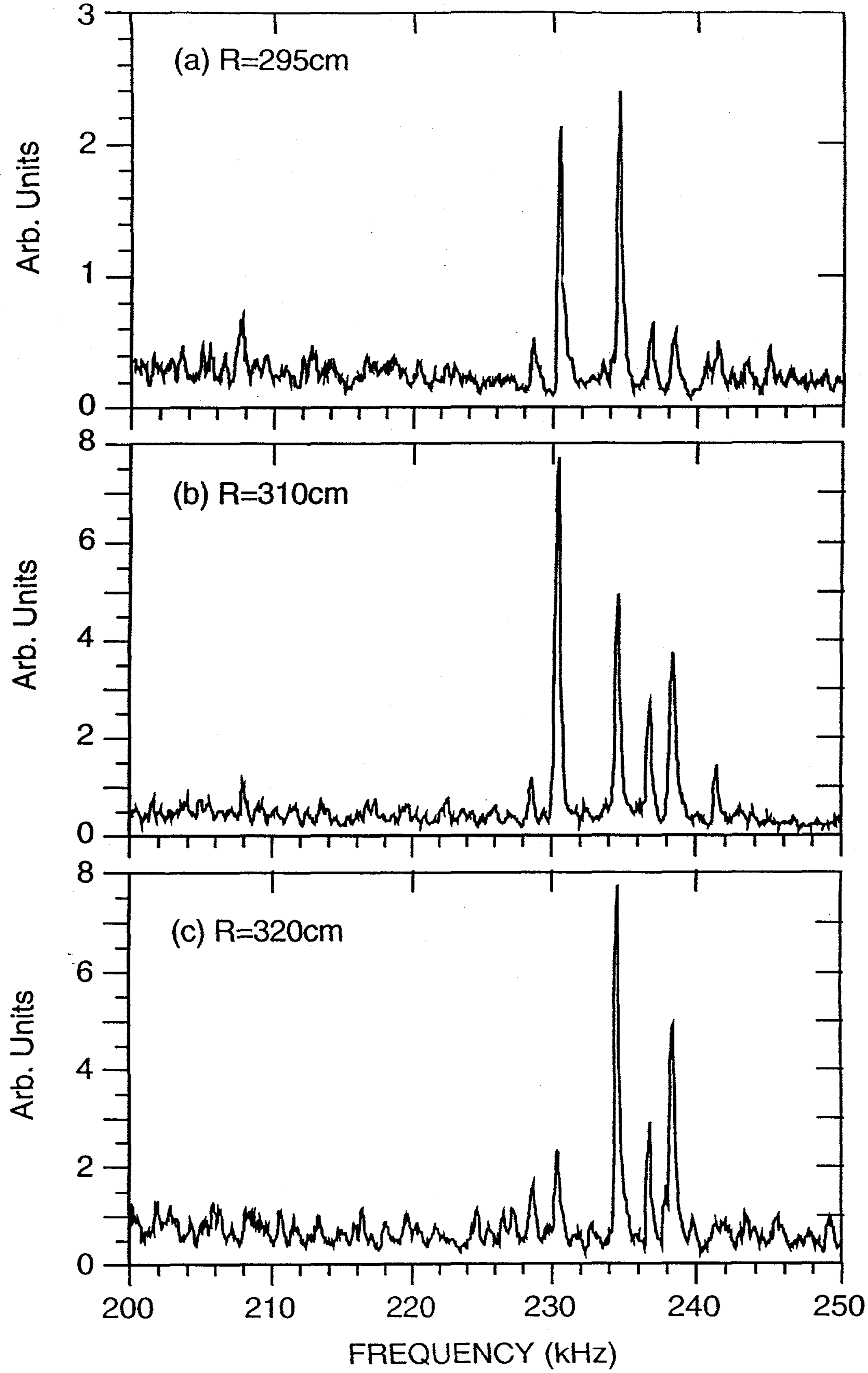
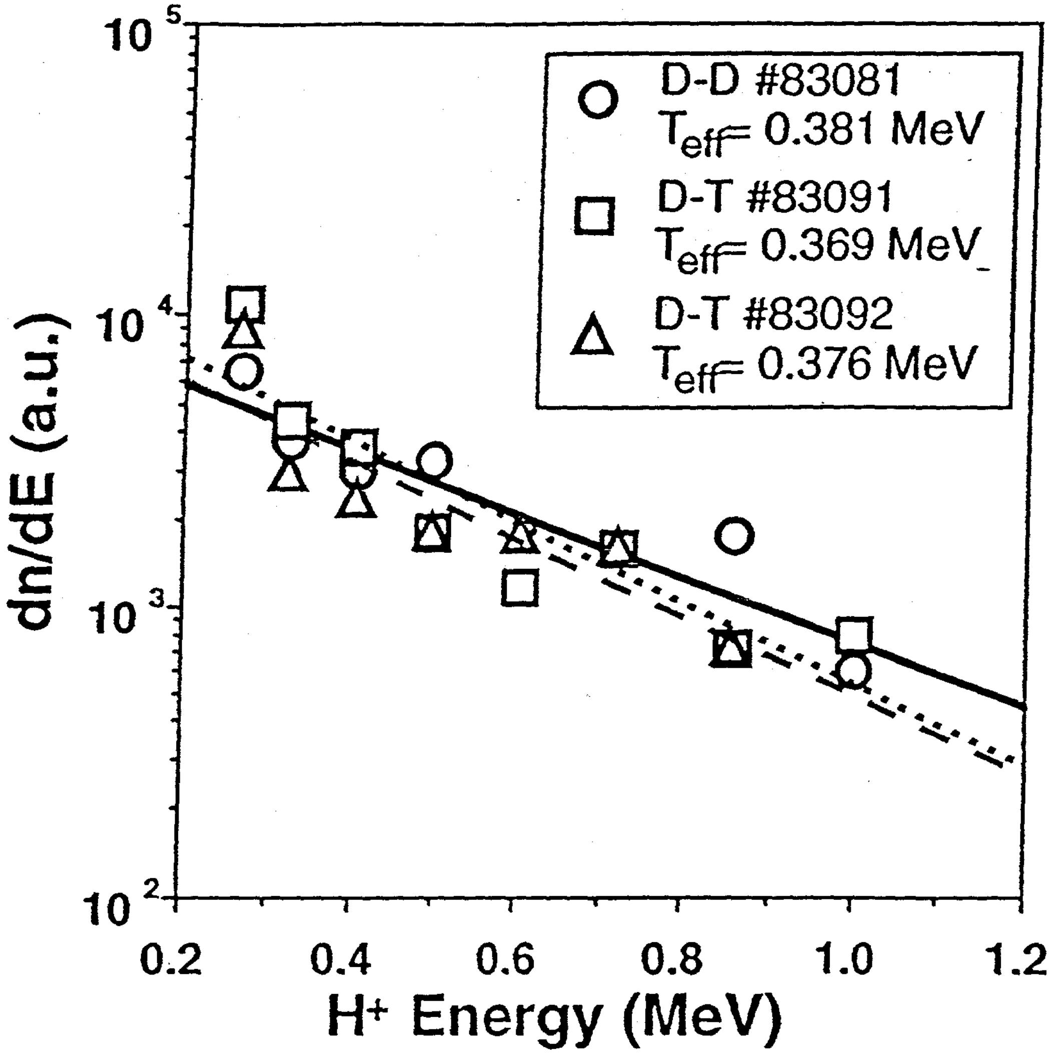


Fig. 3



D-D #83081
T_{eff}= 0.381 MeV
D-T #83091
T_{eff}= 0.369 MeV
D-T #83092
T_{eff}= 0.376 MeV
dn/dE (a.u.)
10^5
10^4
10^3
10^2
0.2
0.4
0.6
0.8
1.0
1.2
H+ Energy (MeV)

Fig. 4

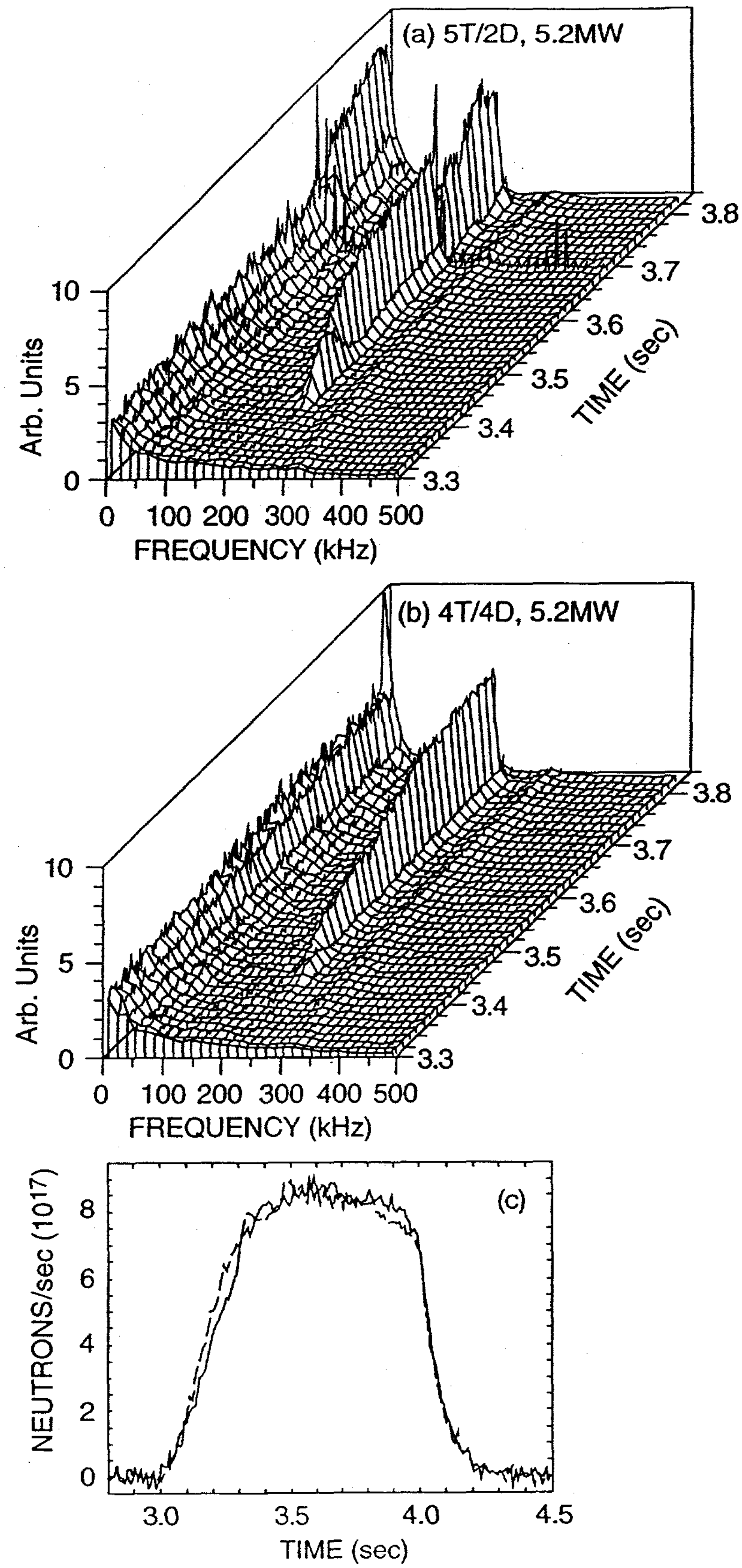

(a) 5T/2D, 5.2MW
Arb. Units
10
5
0
0 100 200 300 400 500
FREQUENCY (kHz)
3.3
3.4
3.5
3.6
3.7
3.8
TIME (sec)
(b) 4T/4D, 5.2MW
Arb. Units
10
5
0
0 100 200 300 400 500
FREQUENCY (kHz)
3.3
3.4
3.5
3.6
3.7
3.8
TIME (sec)
(c)
NEUTRONS/sec (10^17)
0
2
4
6
8
3.0
3.5
4.0
4.5
TIME (sec)

Fig. 5