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FAST-WAVE ION-CYCLOTRON HEATING IN THE PRINCETON LARGE TORUS

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ABSTRACT

Recent experimental results for ICRF heating in PLT are presented. For the two-ion regime in D-H or D-^{3}He plasmas minority H and ^{3}He ions are found to absorb the rf power and transfer it to the deuterons and electrons in accordance with Fokker-Planck theory. The deuteron heating rate is ~3 eV × 10^{13} cm^{-3}/kW for H and ~6 eV × 10^{13} cm^{-3}/kW for ^{3}He minorities. Neutron fluxes of ~3 × 10^{11} sec^{-1} corresponding to a $T_d \sim 2$ keV ($\Delta T_d \sim 1.2$ keV) have been produced with $P_{rf} \approx 620$ kW at $\bar{n}_e \approx 2.9 \times 10^{13}$ cm^{-3}. Neutron energy spectra and mass sensitive charge exchange spectra indicate Maxwellian deuteron distributions. In addition, D-^{3}He fusion reaction rates $\gtrsim 10^{12}$ sec^{-1} have been produced by the energetic ^{3}He ions. For the second harmonic regime, initial heating results for an H plasma at $P_{rf} \approx 140$ kW are consistent with the Fokker-Planck theory and the bulk heating rate is comparable to that of D heating in the D-H minority regime.

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1. INTRODUCTION

Fast wave heating in the ion cyclotron range of frequencies (ICRF) is being investigated in the Princeton Large Torus (PLT) to evaluate its potential for heating reactor-scale toroidal plasmas. Two basic heating regimes are of primary interest: the two-ion and second harmonic regimes. In both cases energetic ion distributions are produced which can be well confined in PLT at higher current levels thereby facilitating efficient ion heating with minimal impurity influx. With proper control of the excited wave spectrum using multiple antennae, the rf power can be deposited in the plasma core which minimizes heating of poorly confined ions near the plasma surface [1].

Half-turn loop antennae are being used to excite waves from the low field side of the PLT plasma in keeping with the expectation that low field excitation will be employed in a reactor in order to facilitate loop or waveguide antenna design. The waves then propagate to the damping zone in the core of the plasma and in the case of sufficiently weak damping, form poloidal eigenmodes dominated by $m = 0, \pm 1$ poloidal mode numbers, and for still weaker damping, toroidal eigenmodes may exist.

For the results to be presented, wave excitation has been at $f = 24.6$ MHz and $f = 42$ MHz. The lower frequency is suitable for the two-ion regime [D-H, $B_\phi \approx 16$-32 kG; D-^{3}He, $B_\phi \approx 24$-32 kG] and the higher frequency for both the two-ion regime [D-H, $B_\phi \approx 28$-32 kG] and the second harmonic regime [H, $B_\phi \approx 14$ kG; ^{3}He, $B_\phi \approx 21$ kG].

2. TWO-ION REGIME

In a plasma having two-ion species, the ion-ion hybrid region is located between the fundamental resonance layers of the individual ion species, and it can strongly affect the wave damping and rf power distribution among the ions and electrons [2,3]. For sufficiently small minority ion concentrations, most of the wave power is predicted to couple directly to the minority ions. However, when the minority concentration is sufficiently large, fast waves incident from the low-field side can be partially reflected and those incident from the high-field side can be partially mode converted to ion Bernstein waves. Depending on the $k_\parallel$ spectrum, the mode converted wave can lead to direct electron heating through Landau damping in addition to direct ion heating of both ion species. However, for low field excitation, much of the wave power which is reflected can be coupled directly to the minority ions when their cyclotron layer is on the low-field side of the cutoff layer [4].

2.1 H and ^{3}He Minority Ions

Considerable attention has been given to the case of direct minority damping in PLT [4-6] where the minority fundamental resonance is at a lower magnetic field than for the majority; specifically H and ^{3}He minorities in deuterium. For the minority H case, the measured proton energy distribution has been found to be consistent with Fokker-Planck theory [7] including hydrogen charge exchange [5] and with wave absorption dominated by the minority species. Perpendicularly charge-exchanged protons have been detected for energies up to 80 keV, demonstrating the expected improvement in energetic ion confinement for PLT. Also, the proton distribution has been found to be approximately isotropic up to ~25 keV as determined by angle-scanning charge exchange measurements.

The rf energy is transferred via the protons to the deuterons and electrons through ion and electron drag, respectively. Deuterium charge-exchange distributions are found to be Maxwellian, indicating that second harmonic deuteron heating is negligible. Deuteron heating via an H minority has been observed at the rate of ~3 eV × 10^{13} cm^{-3}/kW as indicated in Fig. 1 [e.g., $T_e(0)$ = 600→1200 eV for $\bar{n}_e = 2 \times 10^{13}$ cm^{-3} with P_{rf} = 350 kW]. Significant electron heating has been observed as well, the level depending strongly on the impurity radiation from the plasma. Indeed, the radial power balance indicates that approximately half of the rf power can be given to the electrons and subsequently lost via radiation in agreement with bolometry and spectroscopic measurements [4].

The introduction of ^{3}He serves to further test the heating characteristics and to permit operation with the 24.6 MHz source at higher magnetic fields and plasma currents for improved confinement. The power deposition into a ^{3}He minority is similar to that for a hydrogen minority with the added feature that the deuterium second harmonic layer is no longer degenerate with the ^{3}He fundamental layer. According to Fokker-Planck theory [7], for a given rf power, electron density, and density attributable to minority ions, the ^{3}He distribution is more strongly coupled to the bulk ions than for the proton minority case since there are fewer ^{3}He particles with energies above the critical energy where electron drag dominates. In addition, ^{3}He charge exchange losses are negligible. Thus the efficiency of deuterium heating should be considerably improved. In fact, the deuterium heating rate is approximately doubled to ~ 6 eV $\times$ 10^{13} cm^{-3}/kW as shown in Fig. 1.

At the highest rf power ($\sim$600 kW), the thermonuclear neutron flux is increased by more than a factor of 100 to $\sim 3 \times 10^{11}$ n/sec while T_d increases by $\sim$1.2 keV to give T_d approaching $\sim$2 keV in comparison to a T_e of $\sim$1.2-1.4 keV (Fig. 2). Collimated neutron energy spectral measurements in the direction of the plasma current [8] reveal that the 2.45 MeV d-d reaction energy is unshifted, indicating the reacting deuteron pairs have a negligible directed velocity. Moreover, the width of the neutron emission peak is consistent with the expected Doppler width for a 2 keV plasma which implies no significant deuteron tail is present. The mass sensitive perpendicular charge exchange spectrum also indicates a Maxwellian deuterium population and $T_d \sim 2$ keV. The neutron emissivity has been found to be toroidally uniform from activation measurements of In foils [^{115}In (n,n') ^{115m}In $(\underrightarrow{4.5\ h})$ In^{115}] placed on the PLT vacuum vessel. This result indicates that local excitation and trapping of energetic deuterons near the antennae is negligible.

Due to the low cross-section for ^{3}He charge exchange, direct measurement of the ^{3}He energy distribution has not proven to be practicable. However, indirect evidence of the production of an rf driven energetic distribution has been obtained by detecting $d(^{3}He,p)\alpha$ reactions using two separate diagnostic techniques. First, activation of titanium samples by energetic protons (threshold > 5 MeV) has been observed by measuring the presence of ^{48}V produced by $^{48}Ti\ (p,n)\ ^{48}V \xrightarrow{(16d)} {}^{48}Ti$ reactions followed by decay. Secondly, time resolved measurements of the 14.7 MeV proton emission have been obtained with a silicon surface barrier detector located in the horizontal midplane just outside the plasma limiter boundary (Fig. 3). A stainless steel foil 0.3 mm thick has been used to limit detection to protons with energies greater than ~10 MeV and the detector has been calibrated using deuterium neutral beam injection into a plasma containing deuterium and ^{3}He.

As indicated in the case of Fig. 3, the energetic proton emission can be considerably greater than the neutron emission when energetic ^{3}He is produced. A d-^{3}He reaction rate of $\sim 1\text{-}2 \times 10^{12}$ sec^{-1} has been observed at $P_{rf} \sim 300$ kW, indicating a reaction weighted average energy in the range of 50-60 keV. Furthermore, this rate implies a fusion energy multiplication $Q_{d\text{-}^{3}He} \sim 2 \times 10^{-5}$ which is within a factor of five of the $Q_{d\text{-}d}$ obtained with 2.5 MW $D^{o} \rightarrow D^{+}$ neutral beam injection on PLT [9]. The neutral beam neutron emission level is $\sim 10^{3}$ times larger than for the rf heating case, indicating the attractiveness of the ^{3}He minority regime for advanced fuel reactors.

2.2 D Minority Ions

For a D minority in an H or ^{3}He plasma the minority fundamental resonance is at a higher magnetic field than for the majority. Also, the majority fundamental resonance can be placed outside the plasma when the minority resonance is near the plasma axis. Thus the penetration of fast waves from the low field side to the vicinity of the minority resonance can be impeded both by two-ion hybrid mode conversion (with the associated cutoff) and the usual slow wave mode conversion encountered in the surface of the plasma when the frequency is less than the majority cyclotron frequency. That there is such an impediment is clear as revealed in Fig. 4. The neutron emission and deuteron tail formation by the rf exhibits a rapid onset with respect to a relatively small change in D concentration. It is suspected that the dominant effect is due to the transition from the two-ion mode conversion (without neutron production) to the direct damping case (with neutron production). In any case, the lack of significant neutron production in the case where mode conversion is predicted to occur shows that deuterium tail production can be negligible in contrast to the H minority case which exhibits strong proton tail production well into the predicted mode conversion regime.

2.3 Two Ions with Comparable Concentrations

Even for 50/50 D-H mixtures, strong proton heating is observed when the magnetic field is adjusted so that the plasma center is at or between the hydrogen fundamental and the two-ion hybrid layers. Deuteron heating remains consistent with ion-ion coupling with the protons with no significant direct deuteron heating being indicated. However, electron heating is observed over this magnetic field range even when the energetic proton component is small. This suggests the occurrence of electron Landau damping either directly or via mode conversion. Some of these results are in apparent diagreement with previously published wave deposition models for the 50/50 case [2,3].

3. SECOND HARMONIC REGIME

Initial heating results for the second harmonic regime have been obtained in hydrogen with a single coil excited at f = 42 MHz. An ion energy distribution consistent with Fokker-Planck theory [10] has been observed out to ~60 keV as shown in Fig 5. The bulk heating estimated between 1.5 keV and 5 keV is sizeable even at moderate power levels as indicated. Note that even this conservative estimate of the energy added to the hydrogen ions gives a heating rate of ~3.5 eV × 10^{13} cm^{-3}/kW which is comparable to that achieved in the D-H two-ion regime (Fig. 1). The results clearly show that the ion distribution does not run away but exhibits a distribution similar to the minority heating regime except that the bulk population is increased and the tail population decreased, consistent with the complete Fokker-Planck theory including large Larmor orbit effects.

Mode tracking appears not to be essential for the second harmonic regime in PLT. The loading exhibits moderate to low Q modes which provide adequate coupling throughout the rf pulse. This result can be attributed to the influence of the ion Bernstein wave on the second harmonic damping in a fashion similar to that at the two-ion hybrid layer. The theory indicates that the damping for the conditions of Fig. 5 should be 1 [illegible] of that predicted for direct minority damping in the two-ion D-H regime with the same plasma temperatures and electron density.

4. CONCLUSIONS

The PLT ICRF heating results for both the two-ion heating and the pure second harmonic heating regimes indicate efficient heating. These results are predicted to scale favorably to higher power and to higher density conditions, and the prospects for utilizing ICRF heating in next generation devices (TFTR, etc.) and ultimately in reactors are very promising. Based on the current experimental results, several scenarios using two-ion heating and second or higher harmonic heating in future devices have been developed theoretically with emphasis directed towards regimes where waveguide (cavity) excitation is feasible. The various possibilities can be classified into heating of two-ion component plasmas and of three-ion component plasmas.

In T-D or D-^{3}He mixture plasmas, loop antennae will be required if fundamental cyclotron heating of one species is employed. However, for second harmonic heating of D or ^{3}He, the excitation frequency is sufficiently high so that waveguide coupling is possible (B_ϕ = 50 kG, $2\omega_{cd}$ = 76 MHz, $2\omega_{c^3He}$ = 100 MHz). Third harmonic heating of deuterium for reactor plasma parameters is found to exhibit wave absorption comparable to the present PLT second harmonic hydrogen case and affords the possibility for further reduction of the size of the coupling structure.

The minority heating regime can also be used in future devices via small admixtures of H and/or ^{3}He in D-T or D-^{3}He plasmas. In these cases, fundamental and second harmonic heating of H is possible with waveguides whereas second harmonic heating of the ^{3}He minority will likely be required for waveguide excitation. Finally, the T-D-^{3}He regimes are of particular interest in light of the large 14.7 MeV proton reactivity in the rf driven plasma. With adequate confinement of these protons in a reactor, the rf power can be used to provide efficient burning of the ^{3}He and possibly permit the alternative D-^{3}He fuel cycle to be employed with a considerable reduction in neutron activation.

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FIGURE CAPTIONS

Fig. 1. Deuteron temperature increase as a function of rf power normalized to the electron density. The rf power ranges from ~30 to 600 kW over densities from $\bar{n}_e \sim 1.0$ to 4.5×10^{13} cm^{-3}. Heating is via ion-ion coupling with minority H or ^3He ions. (803893)

Fig. 2. Neutron emission and derived deuterium temperature for the ^3He minority case: P_{rf} ≈ [illegible] kW, $\bar{n}_e \approx 2.9 \times 10^{13}$ cm^{-3}, $\eta_{^3He}$ ≈ 5%. The shaded region indicates the duration of the rf excitation. Inset shows high resolution neutron energy spectrum with the expected Doppler width of a 2 keV plasma. (803908)

Fig. 3. 14.7 MeV proton emission from d(^3He,p)α reactions in a deuterium plasma with ^3He minority; P_{rf} ≈ 180 kW, $\bar{n}_e \approx 1.5 \times 10^{13}$ cm^{-3}, $\eta_{^3He} \approx 10\%$. The detected emission is strongly peaked at the toroidal field placing the ^3He fundamental resonance layer ~10 cm out from the vessel axis. (803906)

Fig. 4. Neutron emission from H-D plasmas with deuterium minority concentrations of 10% (●) and 5% (I). The rf power (~450 kW) and the electron density ($\bar{n}_e = 5 \times 10^{13}$ cm^{-3}) have been kept constant for the two cases. (803907)

Fig. 5. Charge exchange measurement of the proton distribution produced by second harmonic heating of a hydrogen plasma (f = 42 MHz, B_ϕ = 14 kG, $\bar{n}_e \approx 1.7 \times 10^{13}$ cm^{-3}, $P_{rf} \approx$ 140 kW) and the time evolution of the bulk hydrogen temperature (for the 1.5-5 keV energy range). Both mass sensitive ⊥ charge exchange (●) and angle scanning near ⊥ charge exchange (Δ) data are shown. (803913)

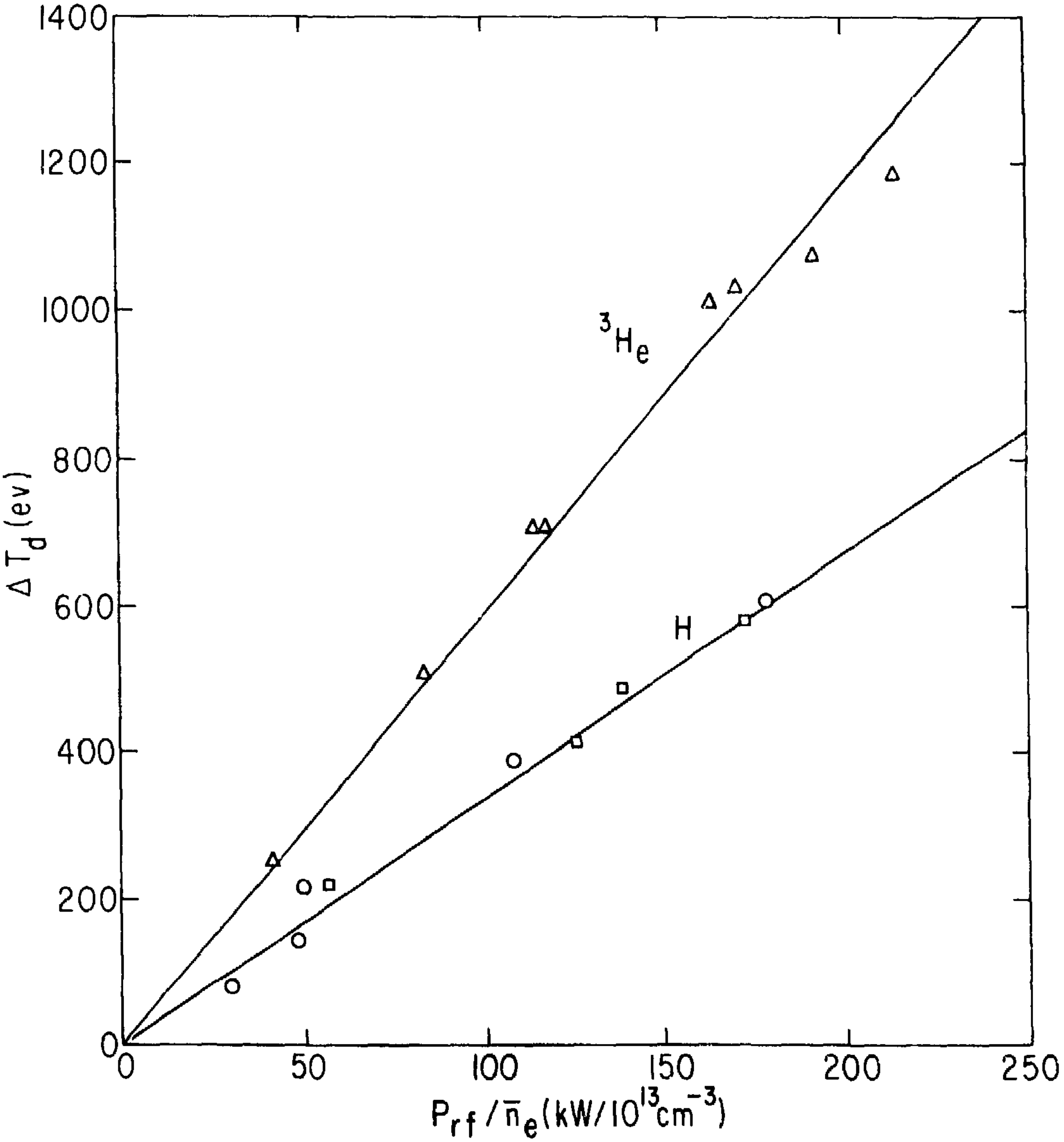


Fig. 1. (PPPL-803893)

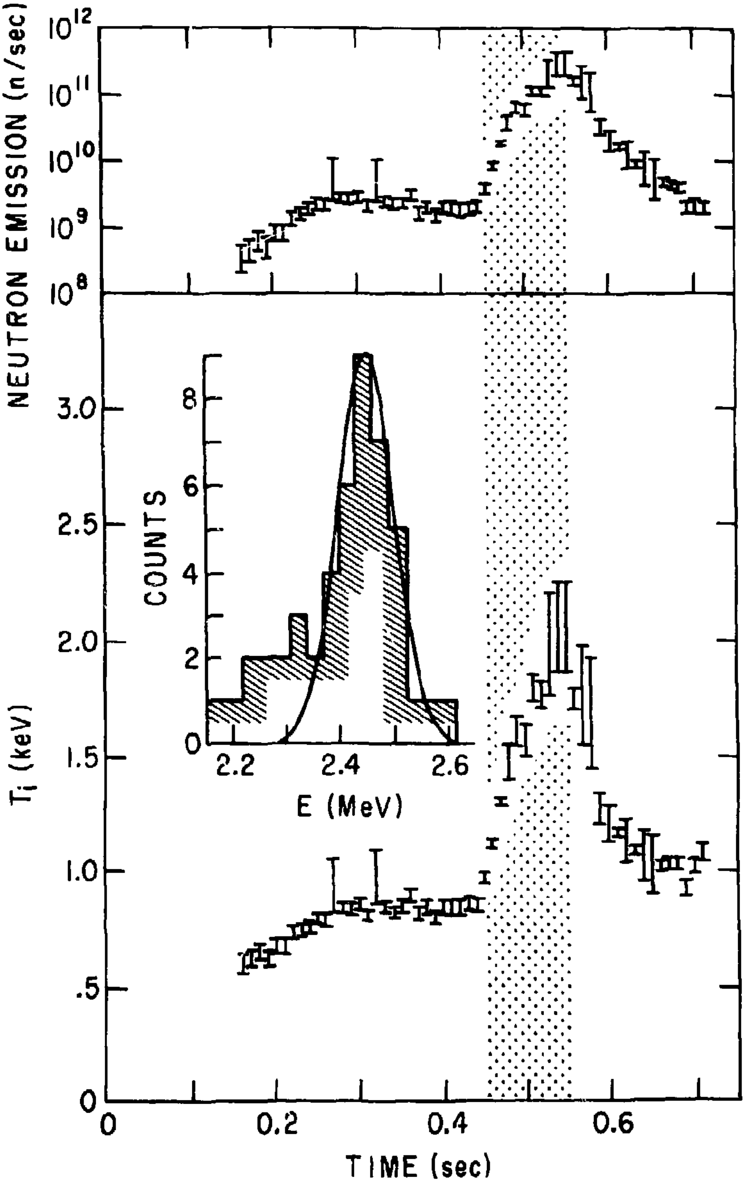
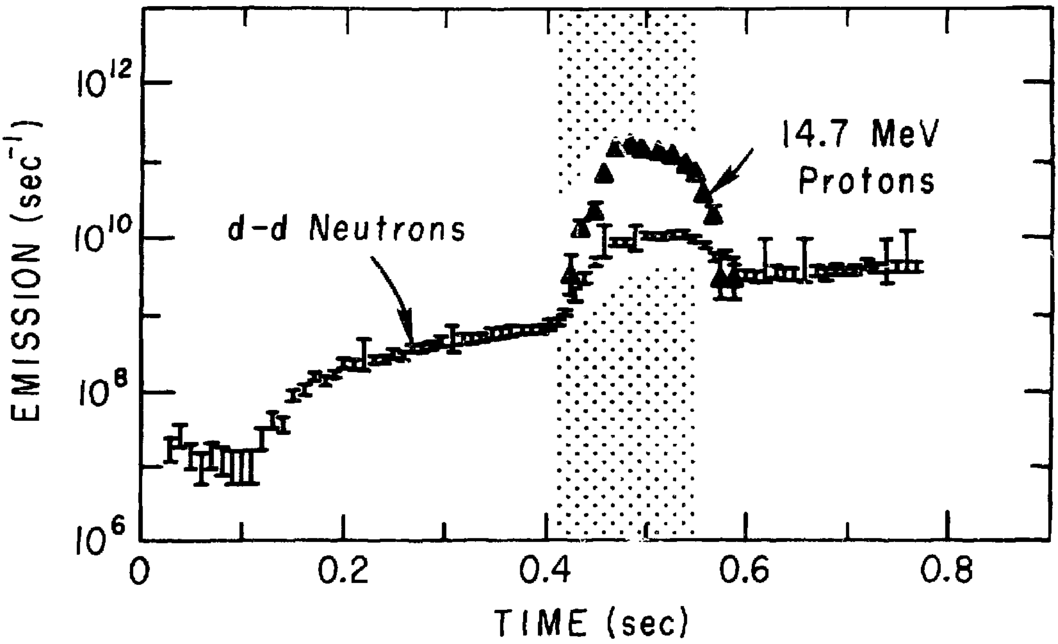


Fig. 2. (PPPL-803908)



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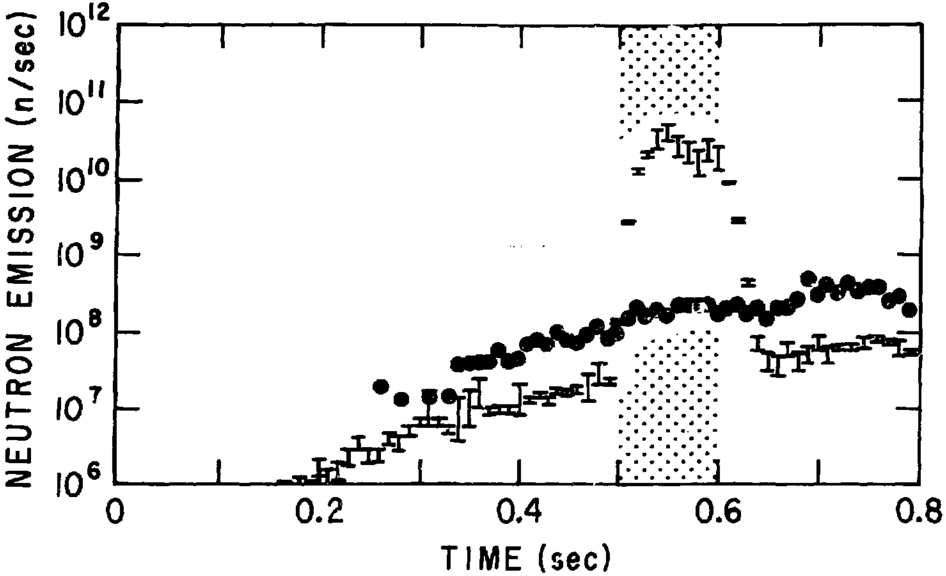

Fig. 4. (PPPL-803907)

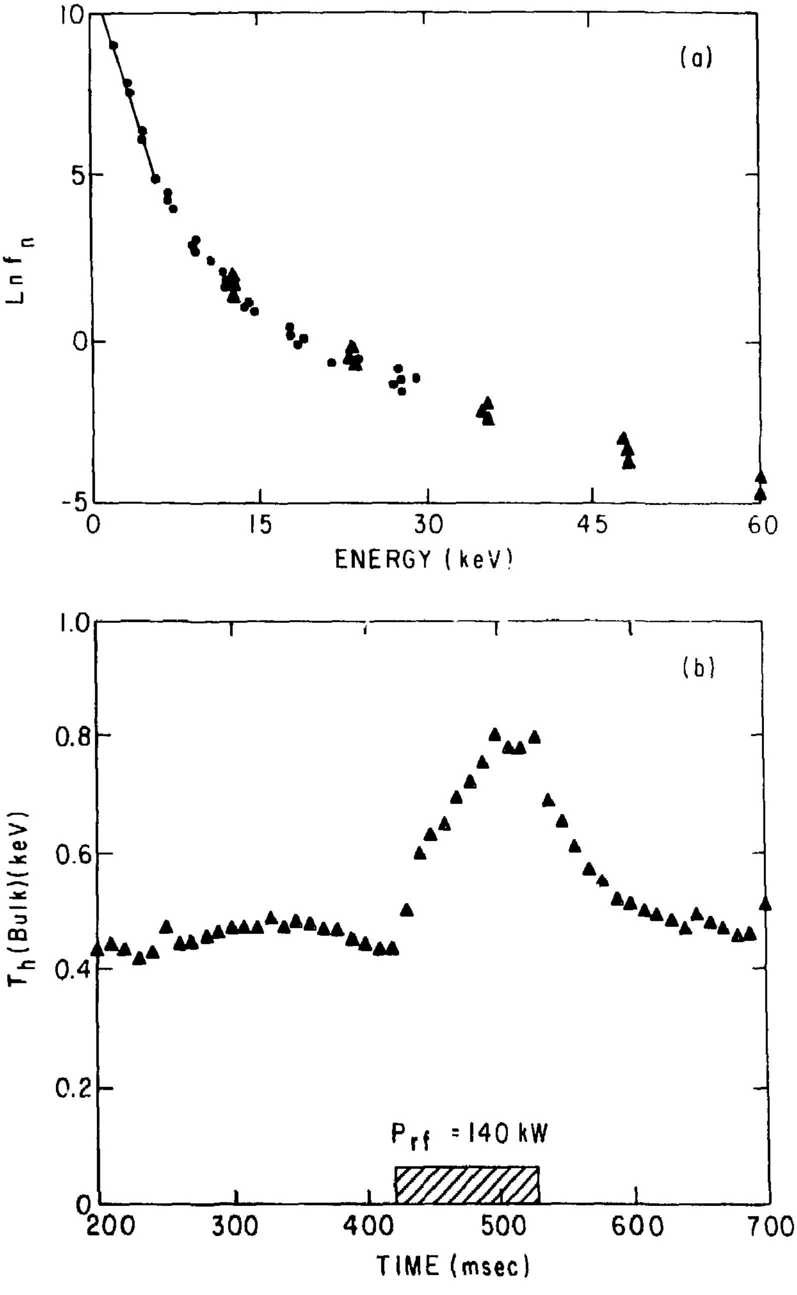

Fig. 5. (PPPL-803913)