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# TFTR 60 GHz ALPHA PARTICLE COLLECTIVE THOMSON SCATTERING DIAGNOSTIC

BY

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# TFTR 60 GHz Alpha Particle Collective Thomson Scattering Diagnostic

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## ABSTRACT

A 60 GHz gyrotron collective Thomson Scattering alpha particle diagnostic has been implemented for the D-T period on TFTR. Gyrotron power of 0.1-1 kW in pulses of up to 1 second can be launched in X-mode. Efficient corrugated waveguides are used with antennaes and vacuum windows of the TFTR Microwave Scattering system. A multi-channel synchronous detector receiver system and spectrum analyzer acquire the scattered signals. A 200 Megasample/sec digitizer is used to resolve fine structure in the frequency spectrum. By scattering nearly perpendicular to the magnetic field, this experiment will take advantage of an enhancement of the scattered signal which results from the interaction of the alpha particles with plasma resonances in the lower hybrid frequency range. Significant enhancements are expected, which will make these measurements possible with gyrotron power less than 1 kW, while maintaining an acceptable signal to noise ratio. We hope to extract alpha particle density and velocity distribution functions from the data. The D and T fuel densities and temperatures may also be obtainable by measurement of the respective ion cyclotron harmonic frequencies.

## I. INTRODUCTION

Collective Thomson scattering[1,2] has been traditionally used for measuring the ion species and ion temperature in the earth's ionosphere[3,4], and in many laboratory plasmas[4-11]. The detected signal is due to the scattering of the electromagnetic radiation by the Debye cloud of electrons which effectively surround each ion. These clouds of electrons move with the ions and impart a Doppler shift to the detected scattered radiation which provides a signature of the ion velocity distribution. In tokamaks, very high power and long wavelengths are required to see the collective Thomson scattered ion feature[11]. In order to measure the much smaller (approximately 0.1 - 1%) alpha ion fraction, many proposals have relied on high power, long pulse sources using wavelengths near the plasma cut off frequencies. The large Doppler shift of the alpha particles, which are born at 3.5 MeV energy, is used to distinguish the alpha particles from other plasma ions. These ideas required extensions of the scattering theory to situations where the scattering frequency is approximately the electron plasma frequency[12,13,14]. In addition, recent scattering theory includes not only density fluctuations, but electric and magnetic field and velocity fluctuations as well. Lastly, transverse components of the dielectric tensor were also added to the theory to describe the dielectric shielding[15,16].

## II. EXPERIMENTAL ARRANGEMENT

The type of collective Thomson scattering to be implemented on TFTR differs from previous proposed experiments in that it will make use of a scattering resonance achieved when the fluctuations' wave vectors and frequencies are in the vicinity of weakly damped plasma waves. In this case, the fluctuations are near the lower hybrid frequency[17,18]. For this experiment, a 0.1 to 1 kW, modulated 60 GHz gyrotron is pulsed for up to 1 second into the TFTR plasma, and the scattered radiation is synchronously detected. A previous version of the alpha particle scattering experiment for TFTR was to have used a 200 kW gyrotron with a scattering geometry that was substantially off perpendicular from the magnetic field in order to eliminate the lower hybrid effect on the scattered spectrum and measure the full alpha particle slowing down feature.

In the present experiment, whose main components are illustrated in Figure 1, the scattering geometry will be nearly perpendicular to the magnetic field to take advantage of the lower hybrid resonance. This resonance begins at approximately the ion plasma frequency for scattering nearly perpendicular to the magnetic field. In the simulated spectrum of Figure 2, this corresponds to a scattered frequency of approximately 60.38 GHz, or a fluctuation in the plasma at approximately 380 MHz. Equivalently, this frequency corresponds to an alpha particle energy of approximately 1 MeV. As the scattering radiation within the transmitted Gaussian beam becomes less perpendiclular to the magnetic field, the lower hybrid resonance moves out to higher frequencies which corresponds to higher alpha particle energies. The alpha particle birth energy of 3.5 MeV corresponds to a scattered frequency of approximately 60.7 GHz, which is a fluctuation at approximately 700 MHz within the plasma as shown in Figure 2. This resonance will increase the scattering cross section significantly from the originally proposed experiment. The power requirement of the scattering source has been reduced by a like amount to obtain the same signal to noise performance. However, a minimum power of at least 0.1 kW is required to provide enough signal to noise performance to determine the thermal deuterium and tritium densities and velocity distributions which determine the lower frequency behavior of the scattered spectrum.

Detecting the thermal ion feature simultaneously with the higher frequency alpha particle signal will more precisely establish the alpha particle density and velocity distribution function. An absolute calibration of the scattering system would normally be required to measure the thermal ion and alpha densities. However, a relative measurement of the alpha density to the thermal deuterium and tritium densities is easily accomplished without an absolute measurement. The TFTR interferometer will be used to calibrate the thermal ion density with a knowledge of $Z_{eff}$ and ion impurity spatial distribution from the TFTR $Z_{eff}$ diagnostics.

The main disadvantage of scattering perpendicular to the magnetic field is that the lower hybrid feature may be altered by inhomogeneous plasma effects and is possibly more sensitive to a particular alpha particle energy in which the phase velocity of the lower hybrid wave is close to the alpha particle velocity. Another disadvantage is that the lower hybrid resonance is sensitive to the value of the fluctuating wave vector, $k = |k_s - k_i|$, which is determined by ray tracing. Therefore, accurate ray tracing of the Gaussian beams through the plasma is imperative to reduce the error of the resulting data analyses.

The transmitted beam will be launched in the extraordinary mode (X-mode) at approximately half the electron cyclotron harmonic frequency. The background plasma emission, which is due primarily to relativistically down-shifted electron cyclotron emission, was 25 eV on TFTR shot 55851, which is a high performance supershot typical of that expected during D-T operation. The receiver antenna will also be arranged to detect X-mode.

Plasma refraction will slightly bend the transmitted and received beams when the plasma refractive index changes significantly from unity. This occurs if the plasma density increases to the point at which the 60 GHz wave would approach the X-mode cutoff for perpendicular propagation to the magnetic field. For TFTR, the X-mode wave will be able to propagate to the core of the plasma for densities below $1.5 \times 10^{14}$ $cm^{-3}$. Refraction will become noticeable at central densities greater than approximately 6-7 x $10^{13}$ $cm^{-3}$.

The initial arrangement of the scattering diagnostic will have low loss waveguide for both the transmitter and receiver with scanning antennas which can be moved between shots. The existing scanning antennas are part of the TFTR microwave scattering diagnostic[18], which is a 60 or 70 GHz, 1.0 Watt scattering experiment that makes use of an extended interaction oscillator (EIO). Multiple plasma shots will be required to scan spatial profiles and explore possible anisotropies in the alpha particle velocity distribution.

This experiment will use three techniques to reduce the effects of stray gyrotron radiation into the receiver. First, the transmitted beam will be deposited on existing carbon tiles, which are angled to scatter the radiation toroidally. This will reduce the amount of radiation in the poloidal plane of scattering. Second, the receiver will have notch filters, which could reject up to 60 dB of unshifted gyrotron radiation. Finally, the initial receiver will be a homodyne receiver, in which a small amount of the gyrotron power will be mixed with the received radiation. The unshifted gyrotron radiation will then be from DC to several tens of Hertz, depending on the final gyrotron intrinsic linewidth, and an intermediate frequency amplifier will be used to amplify a bandwidth from 5-1500 MHz. If the stray gyrotron radiation can be reduced by the two previous methods to less than 200 mW, which is the damage threshold of the RF mixer, then the detection electronics of the receiver will not be affected by stray light. This 5-1500 MHz bandwidth will then be mixed with a 9.44 GHz oscillator, to frequency up convert the received bandwidth into the filter bank's range of operation.

## III. SIMULATED SCATTERED SPECTRUM

The calculated post-detection signal to noise ratio for a typical D-T plasma is shown in Figure 2. The post detection signal to noise calculation is $SNR_{PD}=[P_s/(P_s+P_n)]\times(BW\times t)^{1/2}$, where $P_s$ is the predetection signal power, $P_n$ is the predetection receiver and plasma background noise power, BW is the receiver channel bandwidth and t is the integration time. The predetection signal power is based on 1 kW gyrotron power, and the predetection noise power is assumed to be 25 eV. This calculation has spatially integrated the transmitter and receiver Gaussian beam patterns. Plasma refraction was not included in this calculation, and is presently being put into our computer codes. The result is expected to be similar, but the shape of the spectrum will be modified because the fluctuating wavenumber changes with refraction. A signal to noise ratio greater than 10 is desired for the data reduction to result in an error less than 5% for the alpha density, the alpha birth energy, and the slowing down distribution function critical velocity, or mean energy for a Maxwellian distribution function. For Figure 2, the highest signal to noise ratio corresponds to an alpha particle energy of approximately 1 MeV, where the signal to noise ratio is approximately 10. The spatial resolution will vary from 10 to 30 cm depending on the scattering geometry of the transmitter and receiver. For a 1 kW gyrotron, the temporal resolution for acceptable signal to noise ratios could be as short as 5 msec.

This diagnostic will also measure energetic ions produced during neutral beam and ICRF heated plasmas. In addition, thermal ions, such as the fuel D and T ions, will be measured automatically in the low frequency range of the scattered spectrum. Since the scattering will be performed perpendicular to the magnetic field, the ion cyclotron harmonics should be observable for all ion species[20,21] with a 200 Megasample/sec digitizer. The ion species can then be determined by measurement of the observed ion cyclotron frequencies which are directly proportional to the ions' charge to mass ratio. This provides the advantage of determining the densities and velocity distribution functions of all ion species simultaneously. Therefore, the deuterium and tritium fuel mixture could be observed as their ion cyclotron harmonics change in intensity and linewidth with alpha particle production. Other ion impurities may also be determined by their ion cyclotron harmonics.

## IV. PRELIMINARY DATA

During the installation period, data has been taken with the synchronous detector and the 1 Watt TFTR Microwave Scattering Diagnostic EIO transmitter, primarily to test the data recording system, and to calibrate the receiver. We were surprised to detect signals during deuterium only, neutral beam and ion cyclotron resonance frequency (ICRF) heating plasma shots. These signals are several orders of magnitude higher in energy than that expected from existing theory using Maxwellian or slowing down velocity distribution functions. The scattered frequency spectrum from plasma shot 74488 is shown in the 3-dimensional plot of Figure 3. The vertical axis is the energy of the scattered signal in Watts/Hz (Joules), as plotted against time and frequency. The neutral beams were on between 3.0 and 4.0 seconds and ICRF heating was applied between 3.2 and 4.0 seconds. The signal appears to be present even above the highest frequency channel of the filter bank. There was a notch filter in the receiver to help reject EIO radiation which was not Doppler shifted, and its 3 dB bandwidth is 200 MHz. Therefore, there was no signal in the lower frequency channels. The enhanced signals may be due to highly energetic, anisotropic and inverted velocity distributions of the deuterium, which is heated in perpendicular velocity by the ICRF heating. Other possibilities, such as deuterium fusion products, are under consideration, and theoretical effort is on-going to determine the origin of the enhanced signal.

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Figure 1. Schematic of the TFTR alpha particle scattering diagnostic.

Figure 2. Simulated scattered spectrum for a D-T TFTR plasma shot.

Figure 3. Scattered signal for TFTR plasma shot 74488 represented in a 3-dimensional plot of energy (Watts/Hz), time and frequency.

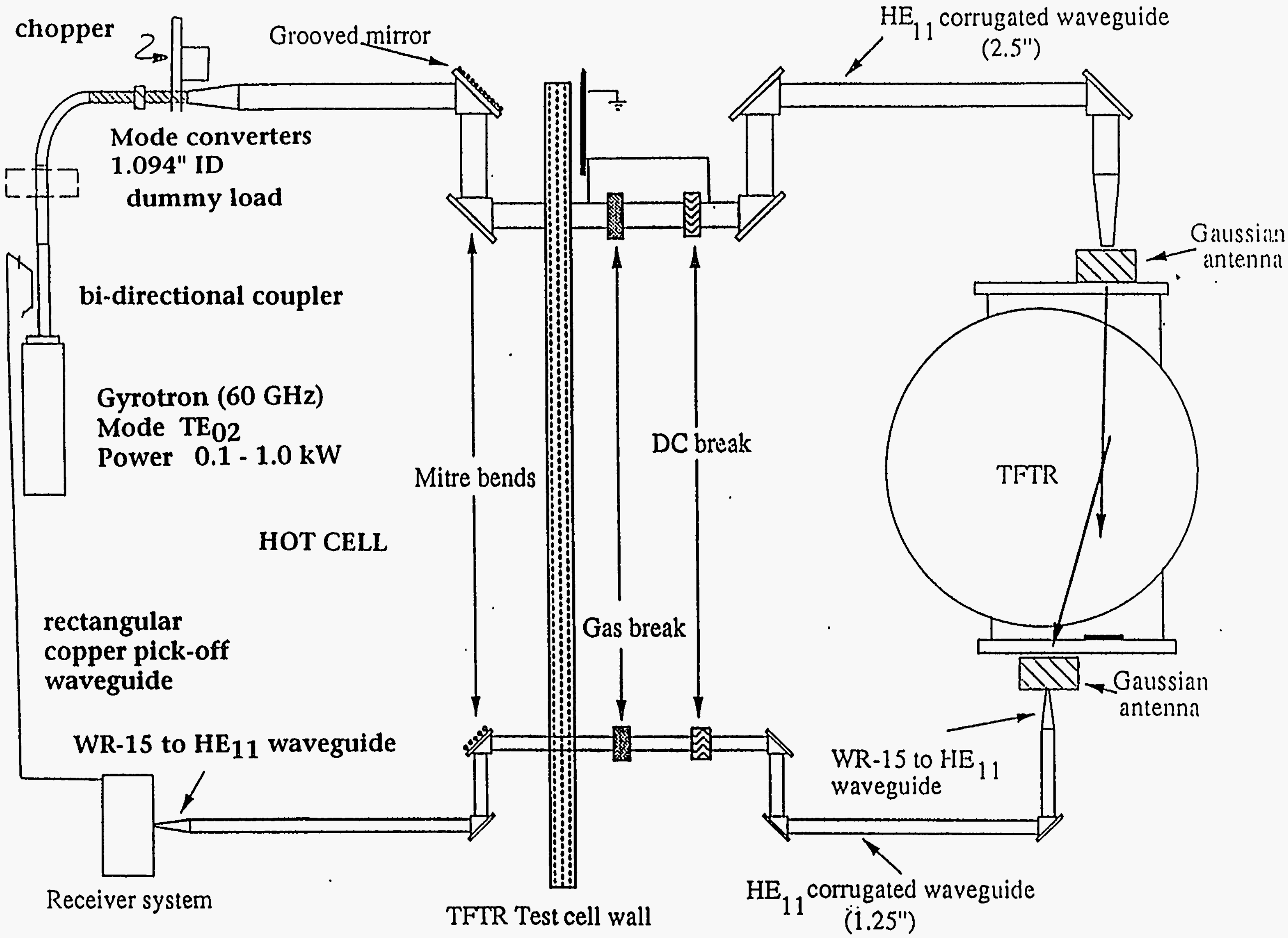

Figure 1. Schematic of the TFTR alpha particle scattering diagnostic.

Fig. 1

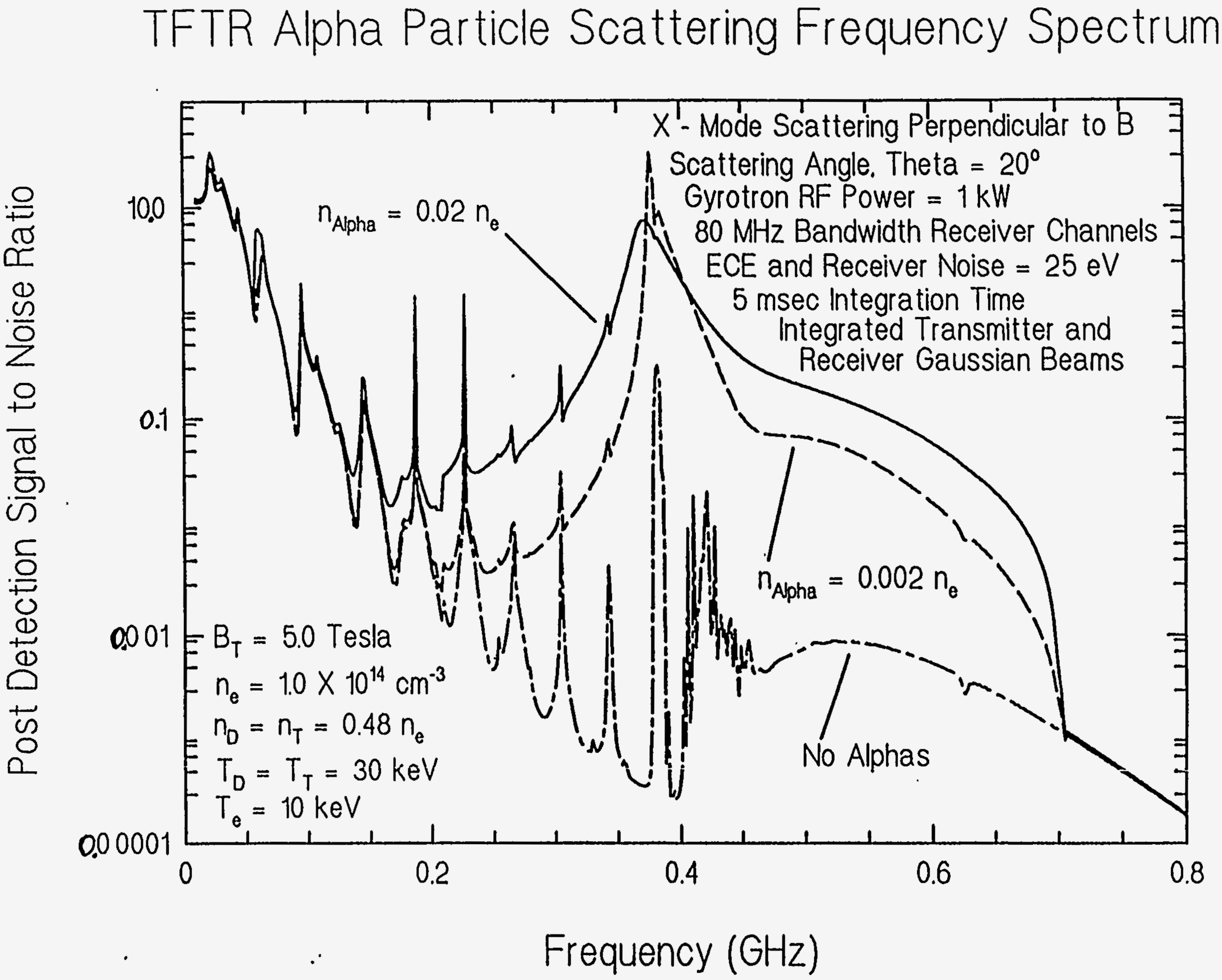
TFTR Alpha Particle Scattering Frequency Spectrum
X - Mode Scattering Perpendicular to B
Scattering Angle, Theta = 20°
Gyrotron RF Power = 1 kW
80 MHz Bandwidth Receiver Channels
ECE and Receiver Noise = 25 eV
5 msec Integration Time
Integrated Transmitter and Receiver Gaussian Beams
$n_{Alpha}$ = 0.02 $n_e$
$n_{Alpha}$ = 0.002 $n_e$
No Alphas
$B_T$ = 5.0 Tesla
$n_e$ = 1.0 X $10^{14}$ $cm^{-3}$
$n_D$ = $n_T$ = 0.48 $n_e$
$T_D$ = $T_T$ = 30 keV
$T_e$ = 10 keV
Post Detection Signal to Noise Ratio
10.0
0.1
0.001
0.00001
0
0.2
0.4
0.6
0.8
Frequency (GHz)

Fig. 2

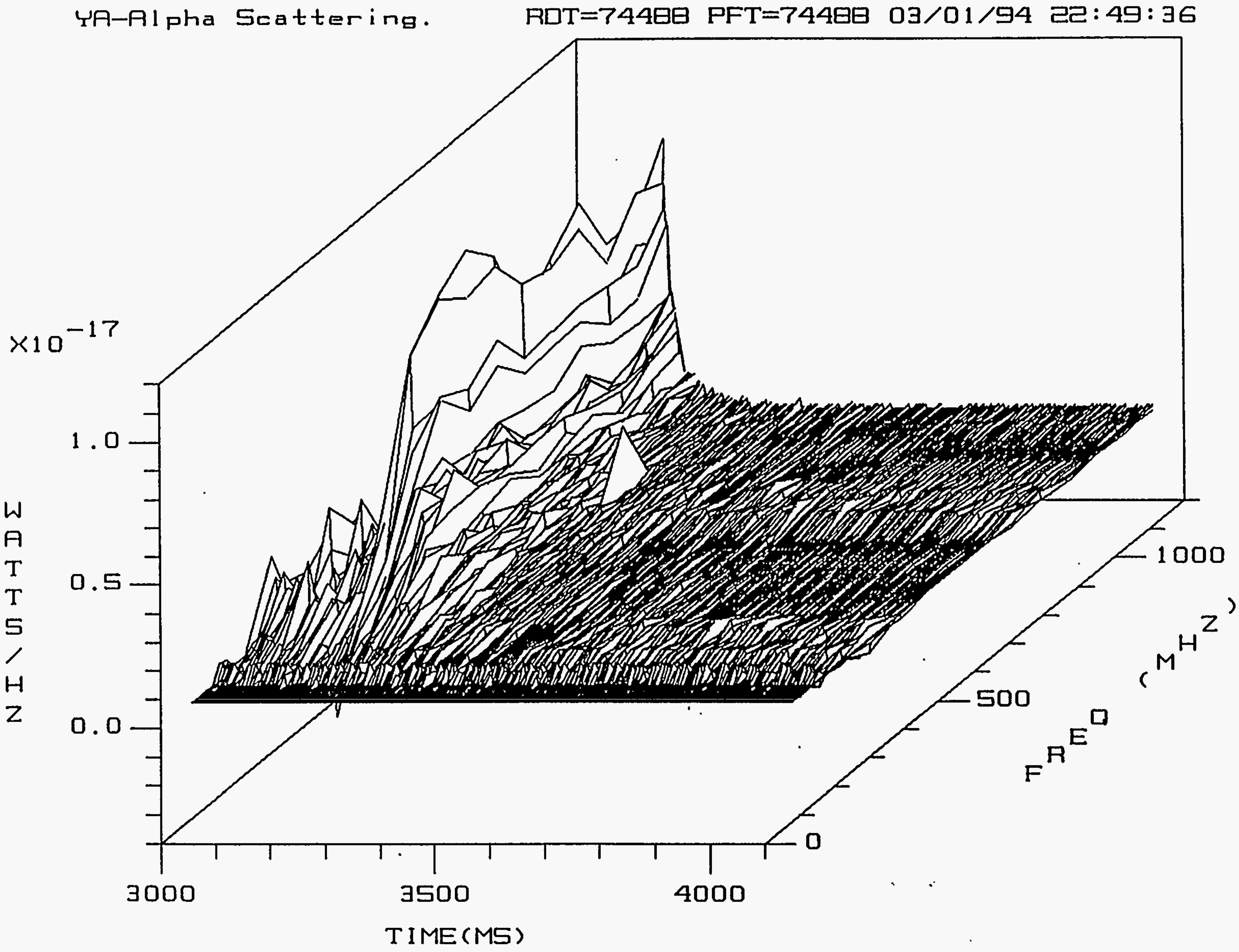
YA-Alpha Scattering.
RDT=74488 PFT=74488 03/01/94 22:49:36
X10$^{-17}$
1.0
0.5
0.0
WATTS/HZ
3000
3500
4000
TIME(MS)
0
500
1000
FREQ (MHZ)

Fig. 3

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