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The TORE SUPRA Fast Reciprocating RF Probe

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ABSTRACT

A fast reciprocating ICRF (Ion Cyclotron Range of Frequencies) probe was installed and operated on TORE SUPRA during 1992/1993. The body of the probe was originally used on the ATF experiment at ORNL. The probe was adapted for use on TORE SUPRA, and mounted on one of the two fast reciprocating probe mounts. The probe consists of two orthogonal single-turn wire loops, mounted so that one loop senses toroidal RF magnetic fields and the other senses poloidal RF magnetic fields. The probe began operation in June, 1993. The probe active area is approximately 5 cm long by 2 cm, and the reciprocating mount has a slow stroke (5 cm/sec) of 30 cm

by 2 cm, and the reciprocating mount has a slow stroke (5 cm/sec) of 30 cm and a fast stroke (1.5 m/sec) of about 10 cm. The probe was operated at distances from the plasma edge ranging from 30 cm to -5 cm (i.e., inside the last closed flux surface). The probe design, electronics, calibration, data acquisition and data processing are discussed. First data from the probe are presented as a function of ICRF power, distance from the plasma, loop orientation, and other plasma parameters. Initial data shows parametric instabilities do not play an important role for ICRF in the TORE SUPRA edge and scrape-off-layer (SOL) plasmas. Additionally it is observed that the probe signal has little or no dependence on position in the SOL/plasma edge.

I. Introduction

This new TORE SUPRA diagnostic is intended for the study of propagation and absorption of ω_{ci} waves (Ion Cyclotron Range of Frequencies--ICRF--waves) in the edge, and by inference the core, of the TORE SUPRA plasma. Figure 1 is a schematic of the diagnostic. The probe head consists of two single-turn conducting loops which measure the magnetic field created by propagation of the ω_{ci} waves. The two conducting loops are perpendicular to each other. One of the loops is also perpendicular to the toroidal magnetic field, and the other is perpendicular to the poloidal magnetic field. The diagnostic is designed to have a frequency response from 1 MHz to greater than 100 MHz. The original design was done by M. Kwon and R. Goulding (ORNL) and the original probe head was fabricated at ORNL and initially used on the ATF experiment.[1] The probe was then exported to TORE SUPRA, adapted to the TORE SUPRA mounting scheme, and mounted on one of the two existing fast reciprocating probe mounts.

When a wave with frequency greater than a few kHz is present, a signal will appear on one of the two conducting loops (or on both, depending on the direction of propagation of the wave), in accordance with Faraday's Law (integral form of the first Maxwell equation):

$$V = -d\Phi/dt$$

Where Φ is the magnetic flux, $\Phi = \bar{B} \bullet \bar{A}_p$, with $\bar{B}$ the magnetic field and $\bar{A}_p$ the area of the loop. This signal will have the same frequency as the wave, and the phase will be different by 90 degrees, plus the number of wavelengths on the coaxial conductor between the loop and the spectrum analyzers shown in Fig. 1. It is important to know that the wavelengths of interest in TORE SUPRA are much larger than the size of the probe conducting loop. For instance an 80 MHz (57 MHz is a typical ICRF frequency on TORE SUPRA, and 80 MHz is the nominal maximum) wave has a length of 3.75 meters in vacuum, and this wavelength is not reduced below 10 cm in the plasma, and much closer to 20 to 30 cm in the plasma edge. The size of the loop is only 5 cm by 2 cm. This means that there is not any ambiguity in the wave amplitude measurement, or in the phase measurement, if it is desired to make one. In addition to the frequency analyzers indicated in Fig. 1, phase and amplitude modules[2] (courtesy Princeton Plasma Physics Laboratory) were also used to track the injected ICRF amplitude. The frequency analyzers have at least initially proved more interesting and useful than the phase and amplitude modules, though for tracking of a single frequency the phase and amplitude modules would clearly be more appropriate.

The probe has been used during several months of ICRF injection on TORE SUPRA, and the results have proved very useful in investigating the edge-plasma interaction with the ICRF. The probe mechanical design, electronics, data acquisition system, calibration, and initial data analysis will be discussed below.

II. Probe Design

A. Mechanical Design

1. Probe Head

Figure 2 is a mechanical schematic of the probe head. The probe was constructed from materials suited for a high vacuum, high temperature, and severe plasma-edge environment. The coaxial feeders were stainless steel with an internal conductor insulated by Teflon insulation suitable for 200 degrees C maximum temperature. The base structure is non-magnetic stainless steel and the probe head was armored with graphite armor chevrons about 1.5 cm in radius. The graphite chevrons were separated by MACOR machinable ceramic insulators to allow penetration of the RF magnetic field, and insulation of the detector loops. A copper ring conductor at the top was used to form the upper connection for both of the single-turn loops used for detecting the RF magnetic field. Modifications for mounting on the TORE SUPRA reciprocating probe head included the new stainless base and connecting structure, and a CFC (carbon-fiber composite) shield which covered the whole structure just to the probe base. Note that the stainless base structure is adequately thick and conductive to prevent RF magnetic fields from penetrating and making the effective loop area larger than planned.

2. Probe Body

As mentioned above the probe body was constructed from non-magnetic stainless steel. The body of the probe was about 25 cm long, consistent with the design of the existing hydraulically driven fast reciprocating ram, so that the probe maximum stroke into the vacuum vessel would be 30 cm. The stainless jacketed dual coaxes connecting each of the two loops were brought down the inside of the body to the base of the probe, where they were transitioned through a commercial 9-pin connector into the similar stainless coaxes which led the signal through the length of the reciprocating mount and vacuum feed-throughs to the exterior of the tokamak. The probe reciprocating mount was allowed to move and vacuum isolated by a stainless bellows. The hydraulic system which drives the two fast probe mounts also serves to position the ICRF and lower-hybrid current-drive (LHCD) antennas. A cylindrical CFC shield covered the probe head and body. The cylindrical shield has an inner diameter equal to the diameter of the probe body and is 1 mm thick. When installed it extends from the tip of the probe head to the broadened base of the probe (about 26 cm). The purpose of the CFC shield is to prevent impurity sputtering from the stainless probe body into the SOL or edge plasmas.

3. Reciprocating Mount

The reciprocating ram (probe mount) was designed and provided by the TORE SUPRA engineering group. The ram is capable of a total slow movement (5 cm per second) of 30 cm, and a fast movement (1.5 m per second) of about 10 cm, so that the probe could be rapidly inserted from deep in the SOL into the plasma edge and retracted without thermally damaging the probe. No cooling other than radiation cooling was provided for the system. The probe was typically inserted up to 3 times during a discharge, with the insertions separated by about 2 seconds. Since TORE SUPRA is intended for steady-state plasma studies, measurements are generally only taken during periods when the plasma is deemed at least in a stationary state, so insertion every few seconds was generally adequate. The reciprocating mount was capable of insertion and retraction in a total of 200 milliseconds, and a pause of up to 100 milliseconds was programmable for the maximum-in position.

B. Electronics System

Two Hewlett Packard spectrum analyzers proved to be the most effective equipment for analyzing the probe signals. They were typically operated with a total sweep of 100 or 200 MHz in 20 to 50 milliseconds. The short sweep time was necessary in order to have a complete sweep during the pause of the probe motion inside the plasma. The resolution bandwidth, RBW, (minimum resolvable frequency difference) was typically set to about 1 MHz since otherwise the fast sweep time would have caused aliasing of the digital data acquisition system. Thus the RBW adjustment of the spectrum analyzers was used as an anti-aliasing filter. The spectrum analyzers were normally operated with a reference level of 0 dBm (1 milliwatt of power into the spectrum analyzer providing a signal of 0 dB) with 80 dB of signal displayable on the analog sweep readout. The video and sweep signals from the back of the two analyzers were led through the programmable buffer amplifiers to the analog to digital converters (ADC's) in the data-acquisition rack. The buffer amplifiers were remotely programmable through the INTEL data-acquisition microcomputer in the relay rack, with gains ranging from 0.1 to 50. They proved extremely useful in maximizing the signal to noise ratio for the spectrum analyzer sweep signals and amplitude (video) signals, which showed digitization noise from the ADC if not properly amplified.

It was necessary to have a DC break between the probe loops and the spectrum analyzers (see Fig. 1). The DC break served two purposes: it functioned as a partial equipment and personnel safety break in case of a high voltage breakdown, and it stopped any DC signal from reaching the electronics, (which were not designed to support DC signals). Several 1:1 isolation transformers from Mini-Circuits were used as the DC breaks, in conjunction with the buffer amplifiers which were also optically isolated.

The distance from the probe mount to the spectrum analyzers was about 40 meters. Unfortunately, normal 50 ohm coax shows considerable loss at frequencies exceeding 100 MHz, and since it was desired to look at injected harmonics or ICRF wave products in the plasma up to about 500 MHz, it was necessary to install low-loss dielectric 50 ohm cable. Type KX-15 cables were used for this long run. The measured loss in the cable, including connectors, ranged from approximately 1 dB at 10 MHz to 7 dB at 500 MHz for about 40 meters of cable.

C. Data Acquisition

The data acquisition system was a commercial system provided by INTEL with 80386 chips used as the local microprocessor for each data-acquisition rack. Programming was done in FORTRAN on a compiler provided by INTEL. The ADC modules plugged into a local bus in the Intel acquisition system. The modules used had a programmable acquisition rate of up to 20 kHz, with an input voltage range from -5 to +5 Volts, and a 12 bit ADC. Local storage of 1 MB was provided, and the data was continuously passed during the shot from the locally controlled acquisition unit to the central control and data acquisition system, a Nordsk-Data computer. The system was capable of accepting data continuously at about 1 kHz. For data rates higher than this the allowable length of the data-acquisition period was limited by the local random-access memory (RAM) storage. After a shot all of the acquired diagnostic data was passed to an

INGRES data base system running on a SUN workstation with 100 gigabytes of optical storage.

D. Calibration

The original magnetic calibration of the ATF magnetic probe heads is shown in Fig. 3. This calibration was accomplished using a Helmholtz coil from 0 to 30 MHz and a TFTR prototype antenna from 30 to 80 MHz, along with a Hewlett Packard network analyzer.[1] The solid line in the figure is the result of a transmission line analysis of the probe characteristics. The circuit model used for the transmission line analysis takes account of the fact that the loop was brought in and out of the torus vacuum system using two 50 Ω coax lines, as opposed to a single coax line, and the center feeds of the two coax lines were then brutally adapted to a single 50 Ω coax by connecting one of the center feeds to the shield of the high frequency KX-15 coax, and the other center feed to the center feed of the KX-15 coax. A small aluminum chassis with two incoming BNC connections and one isolated outgoing BNC connection was used for this purpose. This of course creates a mismatch which depending on frequency, causes a reflection and attenuation of the probe signal, as will be further discussed below.

The equations which describe the circuit in Fig. 4 are:

$$V_O = 2IZ_L \quad , \tag{1}$$

$$V_O = 2\frac{V_p}{Z_T}Z_L \quad , \tag{2}$$

$$V_O = 2V_pZ_L\left[(Z_L)\frac{Z_0\cos(\beta l)+iZ_L\sin(\beta l)}{Z_L\cos(\beta l)+iZ_0\sin(\beta l)}\right]^{-1}\left(A_{cal}A_{CFC}A_{15}(f)\right) \quad , \tag{3}$$

$$V_p = A_p\omega B_{rf} \quad , \tag{4}$$

$$\beta = \omega\sqrt{LC} \quad , \tag{5}$$

Where V_O is the voltage at the spectrum analyzer (equal to the voltage at the output terminals shown in Fig. 4, neglecting phase), Z_L is the impedance indicated in Fig. 4 of the stainless jacketed coaxes carrying the probe signal out of the torus, Z_O is the apparent impedance (here the apparent load impedance) of the KX-15 cable and spectrum analyzer. The impedance of the stainless jacketed coaxes is 50 ohms, the KX-15 cable is a 50 ohm cable and the spectrum analyzer is precisely matched in 50 ohms. However, the apparent impedance looking in from the center feeds of the two stainless jacketed coaxes, where they are patched to the center-feed and shield, respectively, of the KX-15 coax is only 25 ohms, since the cable appears to the two center feeds as two 50 ohm cables in parallel. The attenuation constant A_{cal} found from Fig. 3 for the probe voltage relative to a bare unshielded wire probe (again by Kwon) is 25, and the attenuation of the CFC shield A_{CFC} is estimated to be 0.707 for voltage (3 dB), since it is open at the probe end. The attenuation $A_{15}(f)$ represents the attenuation of the KX-15 cable as a function of frequency. The voltage V_p is the voltage induced in the single-turn sensor loop at the probe head as a function of the perpendicular magnetic field B_{rf} at the probe location, where ω is the RF frequency in radians and Ap is the area of the loop.

Equation (1) is derived by looking into the circuit in Fig. 4 towards the probe loop, and realizing that the voltage across the two center conductors is equal to the current times the total impedance looking into the terminals. Equation (2) then follows immediately by replacing the current with the probe loop voltage divided by the total circuit impedance. Equation (3) then follows immediately from solving the transmission line equations for the system, where the expression for the total impedance follows from the expression for the impedance of a transmission line with a load or a discontinuity (see, e.g., Durney and Johnson[4]). Equation (4) is just the integral expression of Faraday's Law for the probe loop and the incident RF magnetic field, and equation (5) just gives the inverse wavelength on the stainless jacketed transmission line where L is the inductance per meter and C is the capacitance per meter of the line (10^{-6} Henry's per meter and 0.25×10^{-10} Farads per meter respectively). The quantity l in Eq. (3) is the length of each of the two stainless jacketed coaxes and connector to the KX-15 coaxial cable (which we take to be 5.33 meters).

The power into a matched 50 ohm load (i.e., the Hewlett Packard spectrum analyzers) can then be immediately calculated from Eqn. (3), and has been calculated and plotted in Fig. 5 for an incident RF magnetic field of 1 Gauss (10^{-4} Tesla). All of the attenuation factors have been taken into account in calculating the data for Fig. 5, including the frequency dependence of the KX-15 cable attenuation. The calibration is done in dBm (received power into the analyzer relative to an RF power of 1 mW at the given frequency) since the spectrum analyzer displays received power in dBm. Thus Fig. 5 represents our best estimate of the absolute calibration of the recorded probe signal as a function of frequency. In using Fig. 5 to convert received signal to incident magnetic field, it must be remembered that a change of 2 in the magnetic field represents a change of 6 dB on the plot, since the magnetic field goes into the power equation as the square ($P = V_o^2 / R$, and V_o proportional to B_{rf}). The estimated uncertainty in this absolute calibration is the order of 5 dBm. This uncertainty is largely due to the addition of the CFC shield to the probe after the original calibration, and the change in the length of the stainless jacketed coax double-feeders from about 1 meter to 5.33 meters to adapt the probe to TORE SUPRA.

The resonances observed in Fig. 5 are just the well known effect of the wavelength in the transmission line changing as a function of frequency, thereby bringing the discontinuity into a perfect match every time the probe transmission lines are the correct number of wavelengths. This effect can also be seen in Fig. 6, where the reflection coefficient has been measured back through the system from the spectrum analyzer, in order to confirm the present analysis.

III. Data Analysis

A. Software

Most of the data analysis at TORE SUPRA is done using the MATLAB software environment, and the RF probe is no exception. A direct interface has been written to the database server, so that data can be called directly into MATLAB with a simple subroutine call. In analyzing the data, the measured scaling of the spectrum analyzer sweep voltage as a function of frequency and the video output as a function of input power at the given frequency are used to reproduce the display seen in real time on the analyzer scope.

B. Typical Data

1. Low and High Power Spectra

Figure 7 shows typical data from the loop whose area faces the toroidal direction (B_T loop) of the RF probe at a power level of 0 MW (this shows the system noise level), 1 MW, and 7 MW of injected ICRF power. Similarly Fig. 8 shows typical data from the loop whose area faces the poloidal direction (B_p loop) at power levels of 0 MW (typical noise spectrum again), 0.8 MW ICRF, and 4.8 MW of ICRF plus 2.1 MW of lower hybrid current drive (LHCD) power (3.7 GHz, doesn't normally show on the ICRF loop signal as experimentally verified on numerous occasions under no ICRF conditions).

The wild zoo of signals evident in Fig. 8c is typical of observations with the B_{pol} loop for injected ICRF power levels greater than about 3 MW. Understanding these signals will be a considerable challenge and is the subject of a current Ph.D. thesis at TORE SUPRA. A conclusion that can be immediately drawn from this data, however, is that parametric decay instabilities do not play a role in the edge of TORE SUPRA. This follows since all of the observed signals not at the injection frequency of 57 MHz or its harmonics are down by more than 40 dB from the peak at 57 MHz. Since the power being measured is in the edge plasma, and therefore is only a small fraction of the injected power to start with, this means that the power in any parametric decay wave can be totally neglected, as it will be down four orders of magnitude from some already small fraction of the injected power (i.e., 3-D ICRF codes show that the power is focussed towards the center of the machine and absorbed there). It is unlikely that more than 10% of the total power is in the edge, probably less. For 5 MW in this would mean only 50 Watts of power in the largest of the non-injected signals).

2. Signal as a Function of Probe Position

Our observations to date show no observable change in the signal level as a function of probe position in the plasma. The uncertainty in the measurement (order of 5 dB, as can be seen from Fig. 7a and 8a) is larger than any directly observable change when the probe position is rapidly changed by 10 cm during a shot. This might be statistically verified or disproved in the future by taking enough data to statistically analyze whether there is a change when the probe is moved. A level of 5 dB while not particularly large on our graphs, is nevertheless a significant change in the edge power level. It is also possible to decrease the noise level by decreasing the RBW or by increasing the sweep (integration) time of the analyzers.

IV. Discussion

The TORE SUPRA RF probe has already shown itself to be a very useful instrument, since it has ruled out at least some forms of parametric decay as suspects for edge heating of plasmas during ICRF injection. It is planned in the future to compare the edge measurements with 3-D code predictions in order to better understand ICRF propagation, and also to attempt to understand the polarization differences observed in the plasma. The probe absolute calibrations will also make it possible to estimate the amount of ICRF power directly absorbed in the edge plasma.

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Figure Captions:

Figure 1: Schematic of the TORE SUPRA RF probe.

Figure 2: Mechanical schematic of the head of the TORE SUPRA RF probe.

Figure 3: Original calibration of the TORE SUPRA RF probe. Three calibration curves (the points) and two theoretical models are shown. The solid curve is the transmission line model, whereas the dotted curve is a lumped circuit model. The curves labeled small-1 and small-2 are the two small ATF probes, one of which was mounted on TORE SUPRA.

Figure 4: Circuit schematic of the RF probe and an equivalent circuit diagram. The point where the two coaxes are terminated, before the transformer, is where the adaptation from dual coax to single coax is made. The terminals at the end of the circuit schematic is where the equivalent load of the KX-15 cable, Z_0 , occurs.

Figure 5: Total calculated absolute calibration curve for the TORE SUPRA RF probe. This curve incorporates the calibration of Fig. 4, the measured attenuation as a function of frequency of Fig. 6, and the estimated attenuation of the carbon fiber composite shield, using an effective length of 5.33 meters for each of the dual coaxes before they are adapted to the KX-15 coaxial cable. This is the expected signal

that would be shown on the spectrum analyzer for a 1 Gauss RF magnetic field.

Figure 6: Reflection coefficient of the RF probe measured from where the cable is attached to the spectrum analyzer. The cable was simply disconnected from the spectrum analyzer and attached to a network analyzer to make the measurement. The reflection coefficient is observed to have very similar resonances to Fig. 7, as expected.

Figure 7: Recorded signal from the spectrum analyzer from 10 to 210 MHz for: a) 0 MW of injected power--noise measurement; b) 1 MW of injected ICRF power; c) 7.2 MW of injected ICRF power. All three graphs are for the loop which measures toroidal RF magnetic field.

Figure 8: Recorded signal from the spectrum analyzer from 10 to 210 MHz for: a) 0 MW of injected power--noise measurement; b) 0.75 MW of injected ICRF power; c) 4.8 MW of injected ICRF power. All three graphs are for the loop which measures poloidal RF magnetic field.

ORNL-DWG 94M-3134 FED

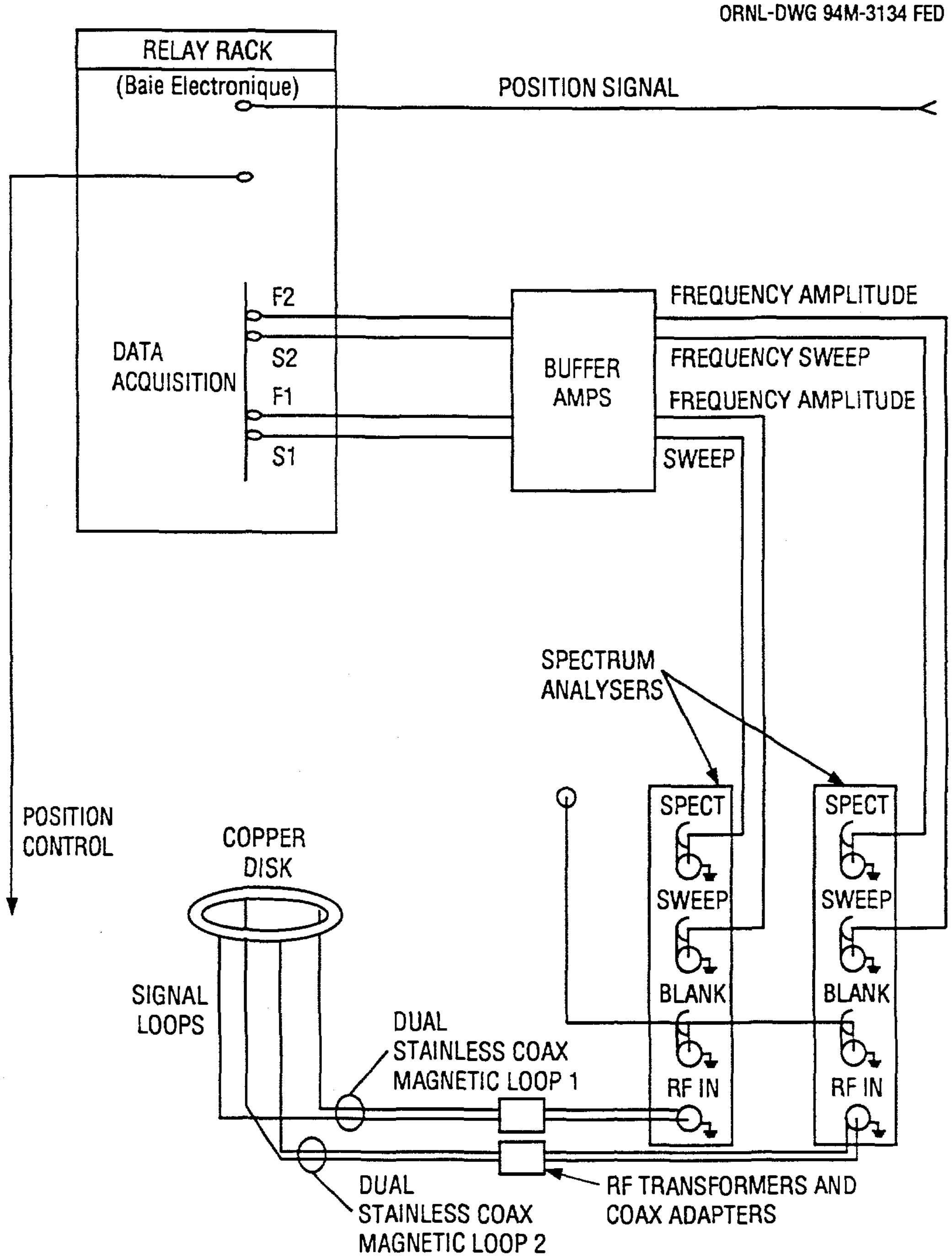

Fig. 1

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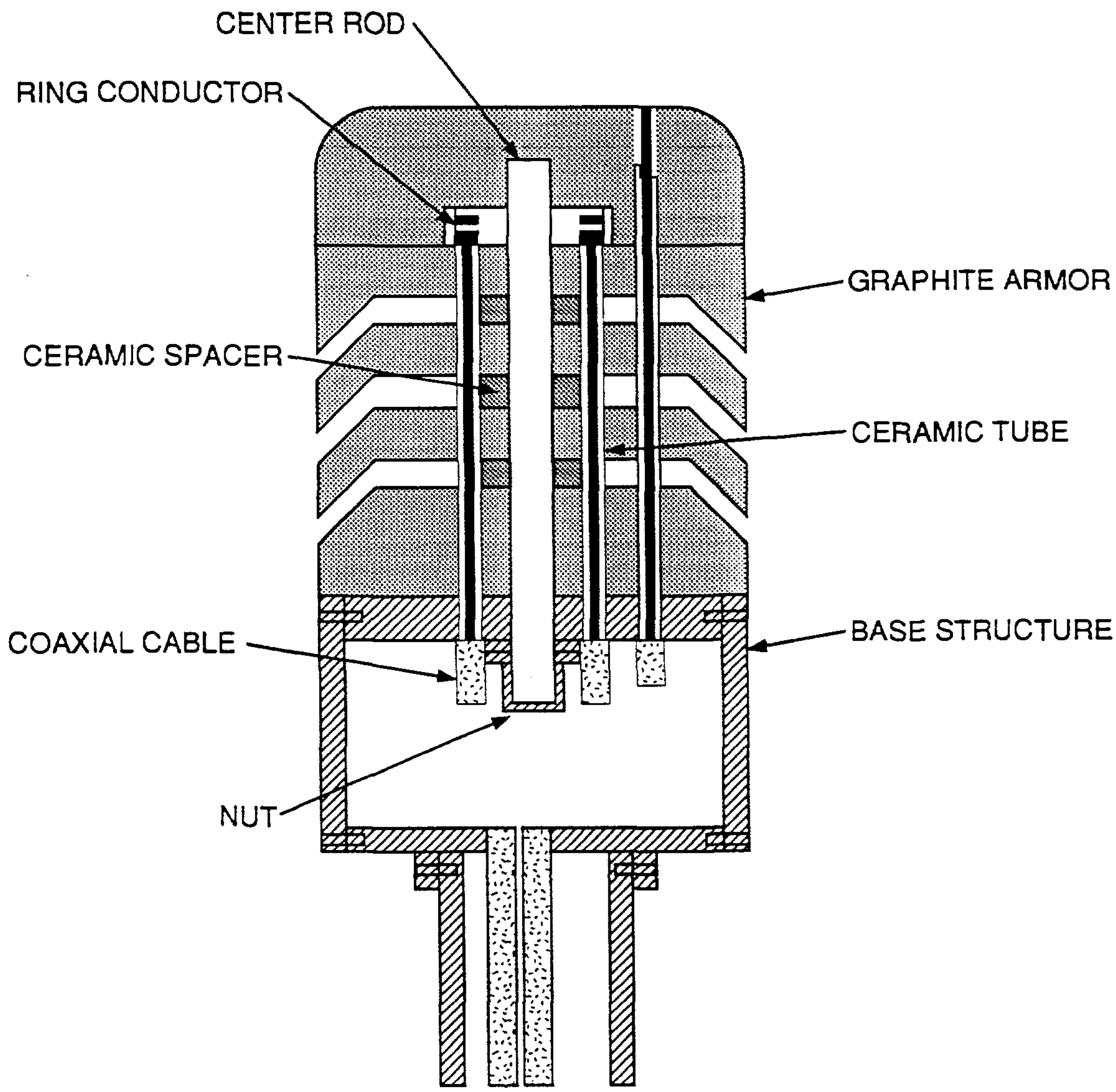

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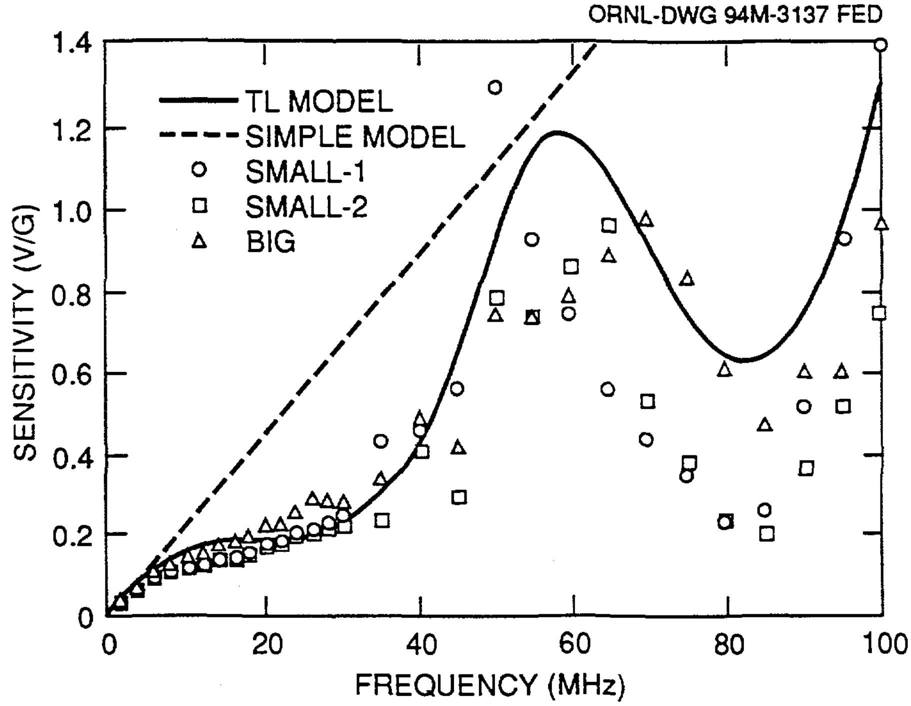

Fig 3

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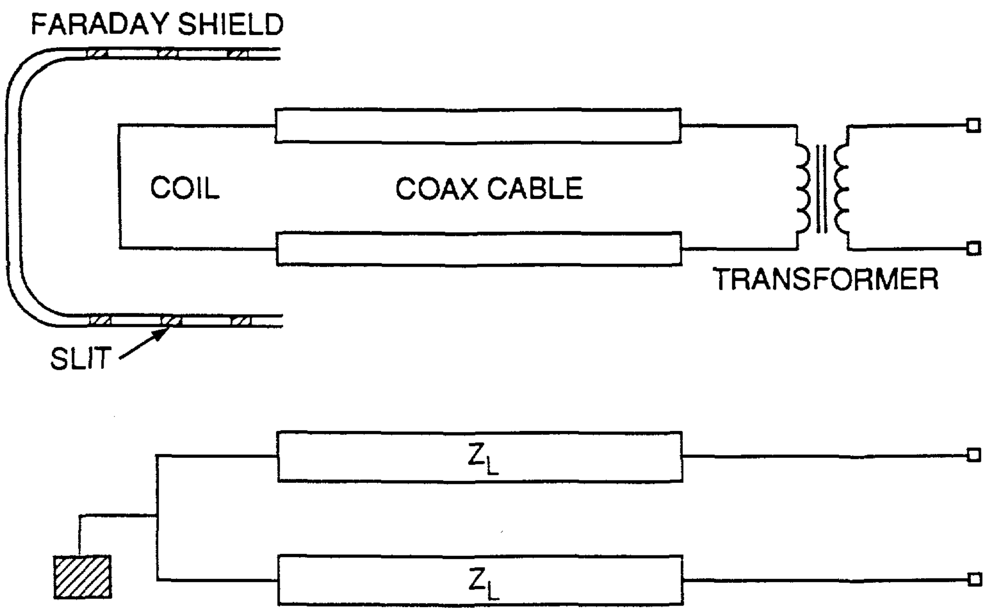

RF PROBE AND EQUIVALENT CIRCUIT DIAGRAM

Fig. –

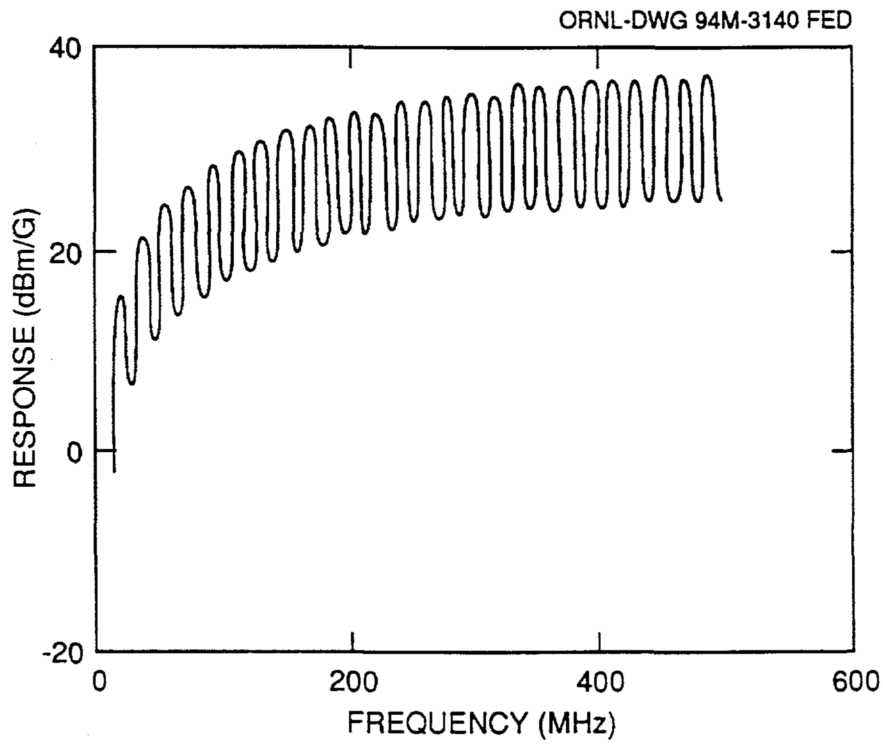
ORNL-DWG 94M-3140 FED
40
20
0
-20
RESPONSE (dBm/G)
0
200
400
600
FREQUENCY (MHz)

Fig. 5

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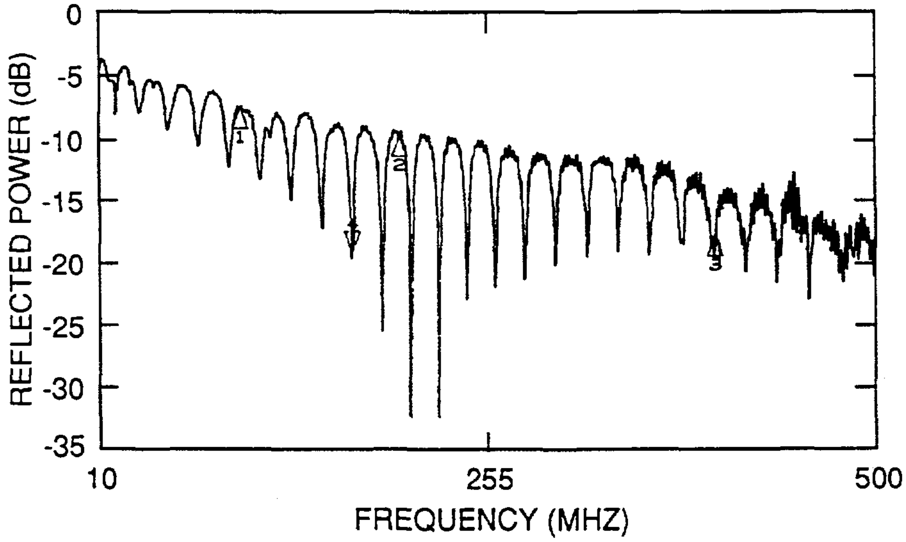

Fig

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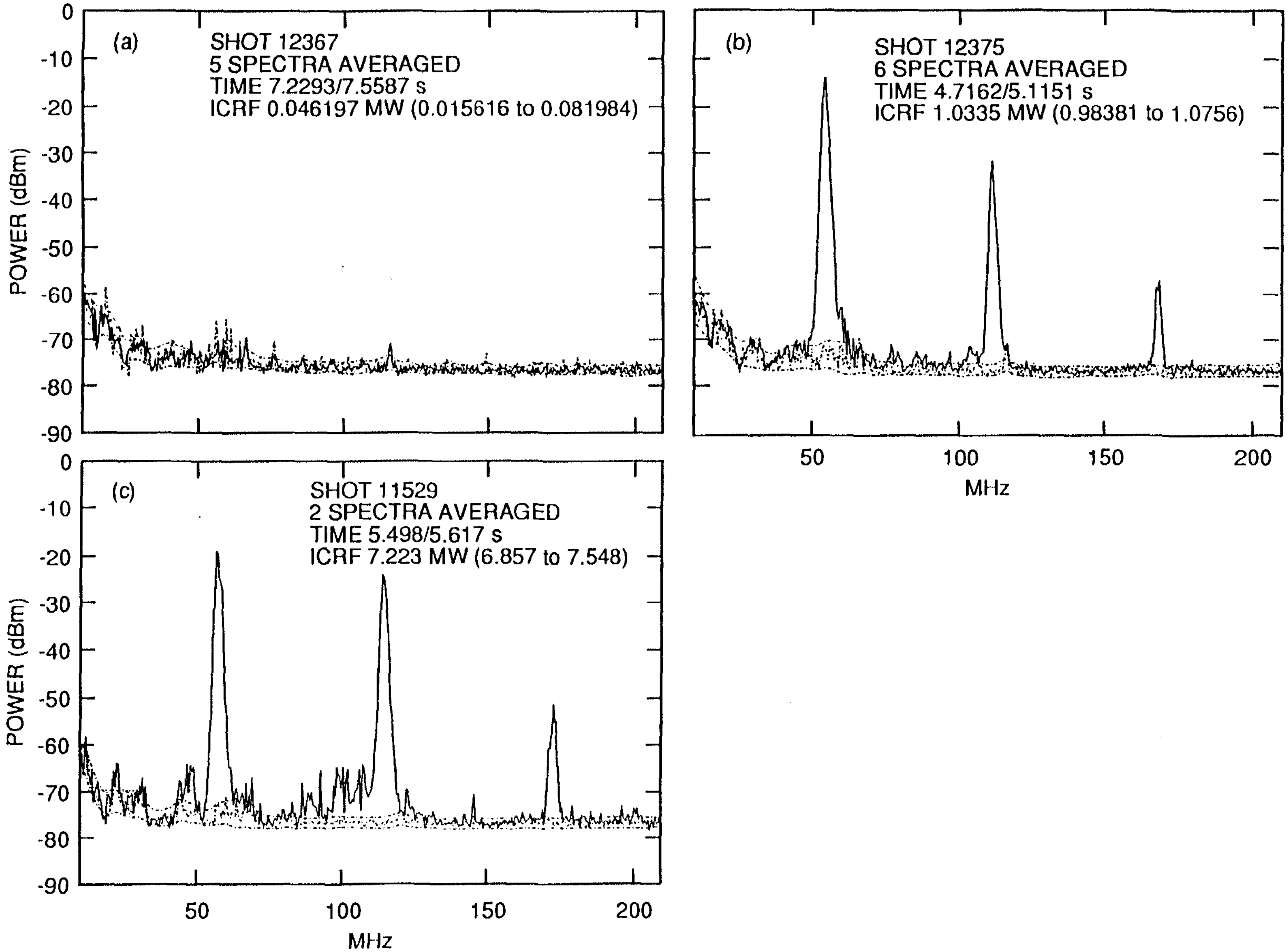

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