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EXPERIMENTAL MEASUREMENTS OF THE ION CYCLOTRON ANTENNAS' COUPLING AND RF CHARACTERISTICS*

D. J. Hoffman
F. W. Baity
W. R. Becraft†
J. B. O. Caughman‡
T. L. Owens**

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831

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ABSTRACT

Ion cyclotron resonance heating (ICRH) is expected to become the dominant contributor to the supplemental heating needs of plasmas in future toroidal devices. The severity of the environments that will be imposed on the ICRH antennas by the plasma in such devices requires the investigation of different approaches to providing adequate life and reliability in addition to the necessary coupling. This work, which is part of the National Ion Cyclotron Heating Program, addresses these issues.

The rf coupling capabilities and characteristics of various antennas have been measured. The tested antenna configurations include the simple loop antenna operated at resonant lengths as used on Alcator-C, the cavity antenna proposed for Doublet III-D and the resonant double loop, asymmetric resonant double loop, and U-slot antennas.

Models of the voltage, magnetic fields outside the structure, and current have been correlated with the measurements made on these antennas. From these measurements and from typical observations of ICRH coupling in tokamaks, we are studying power and frequency limitations on each antenna and the causes of the limitations. A comparison of the technology, performance, and power limitations of each type of antenna is presented.

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†General Electric Company, Schenectady, NY 12345.
‡Summer student, University of Illinois, Urbana, IL 61801.
**McDonnell Douglas Astronautics Company.

INTRODUCTION

Ion cyclotron resonance heating (ICRH) has been one of the more successful means of heating plasmas in fusion experiments. At the core of its success is the antenna. The antenna must be able to meet plasma-imposed requirements while delivering substantial power to the plasma. Present experiments have a combined total power available of 1–5 MW,* while near-term experiments will require 10–50 MW.* The practicalities of port size and number of available ports make it necessary to maximize the power conveyed through each antenna. To date, 0.1–0.8 MW per antenna has been achieved;* 1–5 MW is needed for the next devices. The purpose of this paper is to present ways to meet this power requirement while coping with a number of constraints and uncertainties. Our analyses and experiments have been restricted to the inductively coupled class of antennas—the short loop, the long loop, the cavity, the resonant double loop, the asymmetric resonant double loop, and the U-slot antennas.

THE CONSTRAINTS

The constraints for putting power into the plasma can be nominally described as frequency, polarization, plasma impedance, plasma erosion, and port size. The frequency is usually a multiple of the ion cyclotron frequency. For 2- to 5-T machines and hydrogen or deuterium, the range is 20–100 MHz. A more restricted, typical range for a machine like Doublet III-D (DIII-D) is 40–65 MHz.* The best frequency is a matter of experimentation, so we treat this tunability range as a requirement for near-term devices. With the exception of ion Bernstein waves, the polarization of the wave has a large toroidal component of the magnetic field. The optimum $k_\parallel$ and $k_\perp$ have been calculated and are being experimentally verified.* However, the exact spectrum needed is not known except that the parallel wavelength should not be very short. In our analysis, variations in sidewall placement and multiple antenna placement could be used to control the wave number for each antenna; therefore, the analysis does not differentiate between antennas on the basis of polarization.

There is a strong interaction between power handling capabilities, plasma impedance, and antenna proximity to the plasma (implying antenna erosion).* Typically, 1 to 2 Ω per meter of current strap has been observed with antennas removed 2 to 5 cm from the plasma edge. Plasma loading is typically low enough to require the antenna to be placed close to the plasma. This means that the antennas are exposed to severe plasma conditions and may also result in undesired impurity injection. To minimize antenna damage, it is desirable to retract the antenna. However, since the rf fields (and therefore the impedance) are dramatically reduced by backing the antenna away from the plasma, a trade-off must be made. Antennas that can cope with low plasma impedances yet still operate effectively over a wide range of impedances are preferred.

The last constraint is the port size. Machines such as Tore-Supra, DIII-D, and the Tokamak Fusion Test Reactor (TFTR) have ports on the order of 60 by 70 cm, by 74 cm, and 35 by 50 cm, respectively. We consider antennas that can fit in the smallest of these ports and have the potential of launching over 5 MW.

ANTENNA DESCRIPTION

The simple (short) loop has been widely used to heat plasmas. Its total length is short compared to the free-space wavelength and can be represented schematically by an inductor and plasma load resistance in series (Fig. 1). Notably, it is not matched at the feedpoint.

An extension of the simple loop is the long loop (Fig. 2), as used on Alcator-C.* The circuit representation must be a distributed circuit since it is long compared to a wavelength. It can be operated in a $\lambda/4$ or $\lambda/2$ mode where the input impedance is L/Cr or r, respectively. Like the loop, it requires matching.

The next antenna is the cavity antenna (Fig. 3), as proposed for use on DIII-D. By means of a tuning capacitor and appropriate feedpoint, it is matched at the feedpoint for a certain load resistance.

The fourth and fifth antennas are closely related to each other. Figure 4 shows a resonant double loop (RDL) and the asymmetric RDL (ARDL). It is matched at the feedpoint (over both a frequency and a load range) by adjusting two capacitors.

The last antenna is the U-slot antenna (Fig. 5).* It, too, is matched over a load and frequency range by tuning two capacitors.

DATA AND DISCUSSIONS

The magnetic coupling of the two loop antennas has been plotted in Fig. 6. The difference between the loops is that there is variation in B_Z along the current strap in the case of the long loop. Because of the absence of sidewalls, the actual magnitude of field per unit current is greater than that of the remaining four antennas. This is directly correlated with loading measurements (Fig. 7) and with the observed higher inductance.

The remaining four antenna profiles are characterized by the cavity profiles (Fig. 8). The proximity of the sidewalls to the current strap serves to define the mode spectrum and to reduce magnetic fields away from the antenna by a sidewall-current strap quadrupole effect (Fig. 9). Again, loading is 100% correlated with this effect. However, for comparison purposes, the field values at typical plasma distances are the most relevant ones to consider. The cavity antennas typically generated 50% to 80% of the magnetic flux per unit current per unit inductance of the loop at a distance of 7 cm.

The remaining limitations are mainly those of voltage, current, and capacitor on the power (Table I). All of the antennas have the same current limitation. For example, for a given load, the current required is $\sqrt{p/r}$. The current must go through at least one of the capacitors in antennas 3–6. The high current must go through the vacuum feedthrough on the simple loop or the long loop operated in a $\lambda/2$ mode. Since up to 2500 A may be needed, some development is required. The typical capacitor current limit is 500 A for these capacitor sizes,* and the feedthroughs have only been tested to ~700 A cw. However, the solution to each problem is the same—add cooling to the feedthrough or to the capacitor's "fingers."

The feedpoint imposes a slight constraint on the cavity and ARDL antennas. Because the physical size of the input coax will be at least 3.125 in. and the total size is less than 20 in., the feedpoint alpha must be practically bound between $0.3 < \alpha < 0.7$ The value of the feedpoint is actually integral to the matching at various loads in the cavity. This is essentially fixed at antenna fabrication, and therefore, the cavity will require a tuning stub to handle the variation in plasma loading. However, the voltages and currents from the feedpoint back through the matching equipment are still substantially reduced (as shown in Table I).

The real differences in the antennas can be seen in the maximum voltages and the capacitance values. To illustrate the point, we have ascertained power limits for an antenna ~50 cm long in a cavity-like box. The maximum voltage allowed was assumed to be 60 kV peak. All antennas were given the same inductance of 100 nh. Figures 10 through 14 show these power limits as a function of plasma loading. For the ARDL, α was fixed at 0.675. The capacitors were appropriately adjusted on the matched antennas. The simple loop and cavity (same length for each) had the same power versus loading curve and were optimal in the range from 1 to 5 Ω. Below ~1 Ω, 1 MW per antenna was not achievable, depending on frequency. These antennas could cover the range from 40 to 80 MHz. Above 5 Ω, the cavity current distribution changes such that the current in the inductive leg of the main current strap is substantially different from that in the capacitive leg. For low loads, the RDL cuts voltages in half and therefore allows four times the power of the cavity. Matching conditions change this at higher loads (~2 Ω), but the RDL clearly can operate at the same power per antenna in a lower load range (1/4 to 5/4 Ω) than the cavity. The asymmetrically fed RDL has the widest range of all. For 40 MHz it has a range from 0.1 to 7 Ω; at 80 MHz, 0.8 to 20 Ω. Loads above these upper limits are inaccessible due to capacitance requirements. The U-slot's disadvantage is easily seen in Fig. 14. It can match from 1 to 10 Ω at 40 MHz, but cannot match at 80 MHz because of the last constraint—capacitance.

The values of capacitance required for antennas 3 through 6 are shown in Figs. 15 through 18. The frequency chosen is 55 MHz. The cavity needs values ~84 pf over the whole lead range. The RDL and ARDL change with load. Practically, an upper bound of 1000 pf was assumed. This puts a limit on the upper load range achievable (and the power per antenna). The ARDL, though, has achievable values of 200–1000 pf over the ultrawide load range. Finally, the U-slot has very divergent capacitances. The most serious is the series capacitance requirement, which is as low as 5 pf. In practice, the actual required capacitance at the low end was ~2x. However, it is quite difficult to control any capacitance to less than 20 pf. This precludes operation of the U-slot at 80 MHz for this antenna inductance.

The systems' maximum voltage location may play a role in the achievable voltage. In antennas 3 through 6, all voltages are behind the Faraday shield in a shieldable environment. However, the dc magnetic fields provide a conduction path to ground if breakdown occurs. In antennas 1 and 2, the high-voltage points are either at the feedthrough or close to the plasma. These differences will adjust the maximum power per antenna shown in Figs. 10 through 13.

It is favorable to be able to handle the most power at the lowest load. This allows one to retract the antenna from the tough plasma environment if loading is very good and if ultrahigh power per antenna is not needed. The advantage can be lost if the antenna losses are significant; typically, we measured 0.01–0.02 Ω on our structures. Thus, even 0.5 Ω of loading is sufficient for efficient coupling. The ARDL can handle the lowest and the highest loads of any of the antennas. The factor of 50 load range can enable it to cope with the plasma uncertainties best.

CONCLUSIONS

The state of the art in antenna applications currently relies most heavily on the simple loop. This presents advantages for simplicity of use. However, the simple loop is the worst candidate for power transmission because of its large voltage located at the feedthrough. Of the matched antennas, the U-slot has the least utility because the prohibitively small capacitances preclude higher-frequency (<55-MHz) operation for the 100-nh antennas. The cavity antenna offers the first significant improvement over the simple loop. While it cannot match all loads, the rf transmission system voltages are reduced because of the partial matching. Practically, it is suitable for coupling over a 1- to 5-Ω load range through the entire 40- to 80-MHz frequency range. On pure voltage limits, it has the same power capacity as the loop; however, its configuration relocates the difficult voltages to a region where they can be sustained more easily. Therefore, it is quite possible for a cavity antenna to have a higher voltage rating than the simple loop. The ARDL and RDL configurations offer considerably more power per antenna than the others. Also, they are matched for different loads and frequencies. They do require current capacity to be improved to three to five times that of typically available commercial capacitors. The RDL power rating is typically two to three times that of other loops. In the 55-MHz range, it offers good power coupling at 1/4 to 5/4 Ω, but matching is not possible at a certain upper load. However, the ARDL offers resolution to the problem with an ultrawide load range. Power is typically three times that of the loop. These power limits offer the freedom to retract the antenna and work at lower power or to insert fully and operate at power densities greater than 3 kW/cm^2, rivaling any waveguide power density.

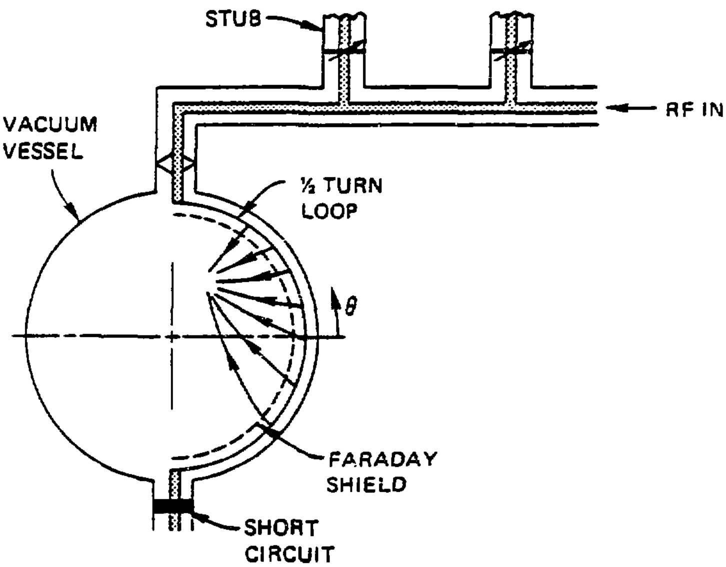
Table I. Antenna parameters

	Antenna type					
	Simple loop	Long loop	Cavity	RDL	ARDL	U-slot
V_{max}	$[r^2 + (\omega L)^2]^{1/2}\left(\frac{P}{r}\right)^{1/2}$	$\frac{Z_c^2}{r}\left(\frac{P}{r}\right)^{1/2}$	$[r^2 + (\omega L)^2]^{1/2}\left(\frac{P}{r}\right)^{1/2}$	$\left\{\frac{\omega L}{2} + \left[2\left(Z_0 - \frac{r}{2}\right)\frac{r}{4}\right]^{1/2}\right\}\left(\frac{P}{r}\right)^{1/2}$	[a]	$[r^2 + (\omega L)^2]^{1/2}\left(\frac{P}{r}\right)^{1/2}$
$V_{feedpoint}$	$[r^2 + (\omega L)^2]^{1/2}\left(\frac{P}{r}\right)^{1/2}$	Varies	$\alpha\omega L\left(\frac{P}{r}\right)^{1/2}$	$(PZ_0)^{1/2}$	$(PZ_0)^{1/2}$	$(PZ_0)^{1/2}$
I_{max}	$\left(\frac{P}{r}\right)^{1/2}$	$\left(\frac{P}{r}\right)^{1/2}$	$\left(\frac{P}{r}\right)^{1/2}$	$\left(\frac{P}{r}\right)^{1/2}$	$\left(\frac{P}{r}\right)^{1/2}$	$\left(\frac{P}{r}\right)^{1/2}$
$C_1(C_s)$			$\frac{1}{\omega^2 L}$	$\left\{\omega^2 L + \left[2\left(Z_0 - \frac{r}{2}\right)\frac{r}{4}\right]^{1/2}\right\}^{-1}\frac{1}{\omega}$	[a]	$\frac{1}{\omega}\left(\frac{Z_0}{r}\left[r^2 + (\omega L)^2\right]\right)^{1/2} - r^2$
$C_2(C_P)$				$\left\{\left(\frac{\omega^2 L}{2} - \left[2\left(Z_0 - \frac{r}{2}\right)\frac{r}{4}\right]^{1/2}\right)\omega\right\}^{-1}$	[a]	$\frac{1}{\omega}\left[r^2 + (\omega L)^2\left(\omega L - \left(\frac{r}{Z_0}\left[r^2 + (\omega L)^2\right]r^2\right)^{1/2}\right)^{-1}\right]$
α			$\left(\frac{rZ_0}{\omega L}\right)^{1/2}$	0.5	Varies	

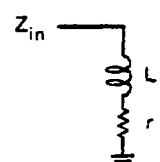
[a] Must be determined computationally.

ORNL–DWG 83-2302A FED

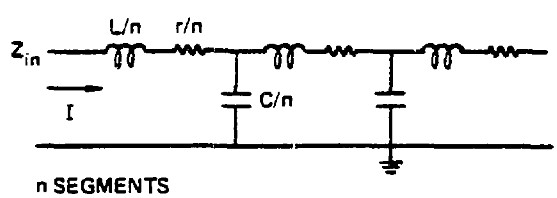
LOOP ANTENNA



SIMPLE LOOP CIRCUIT

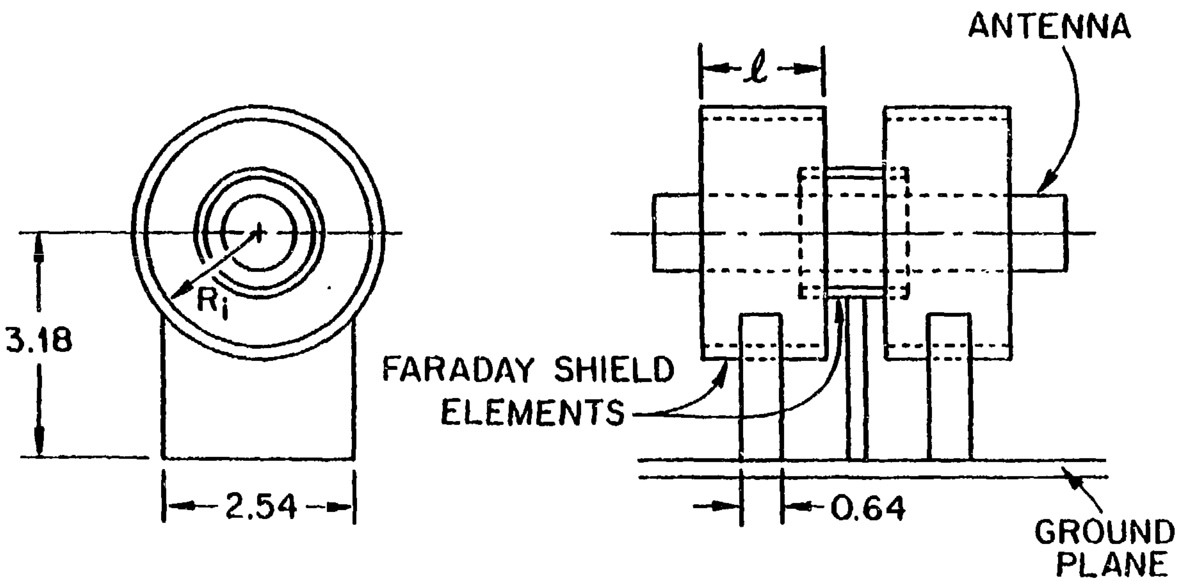


LONG LOOP CIRCUIT



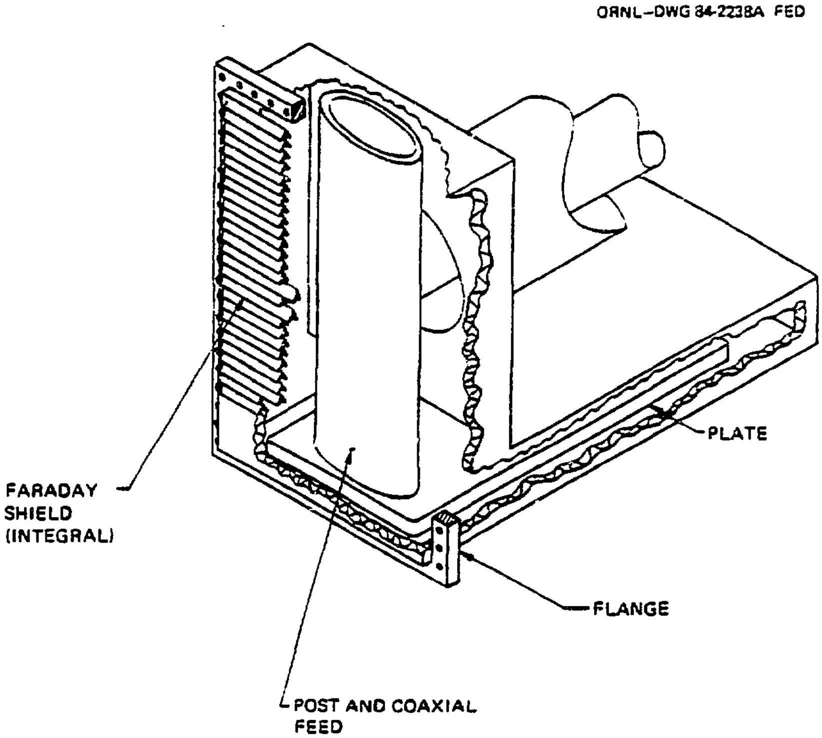
ALCATOR–C FARADAY SHIELD CONFIGURATION

ORNL-DWG 85-2289 FED

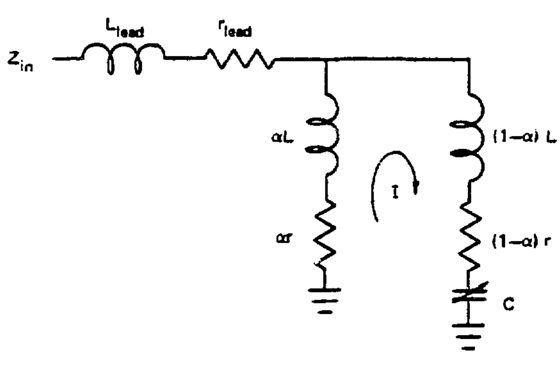


DIMENSIONS IN cm

CAVITY ANTENNA

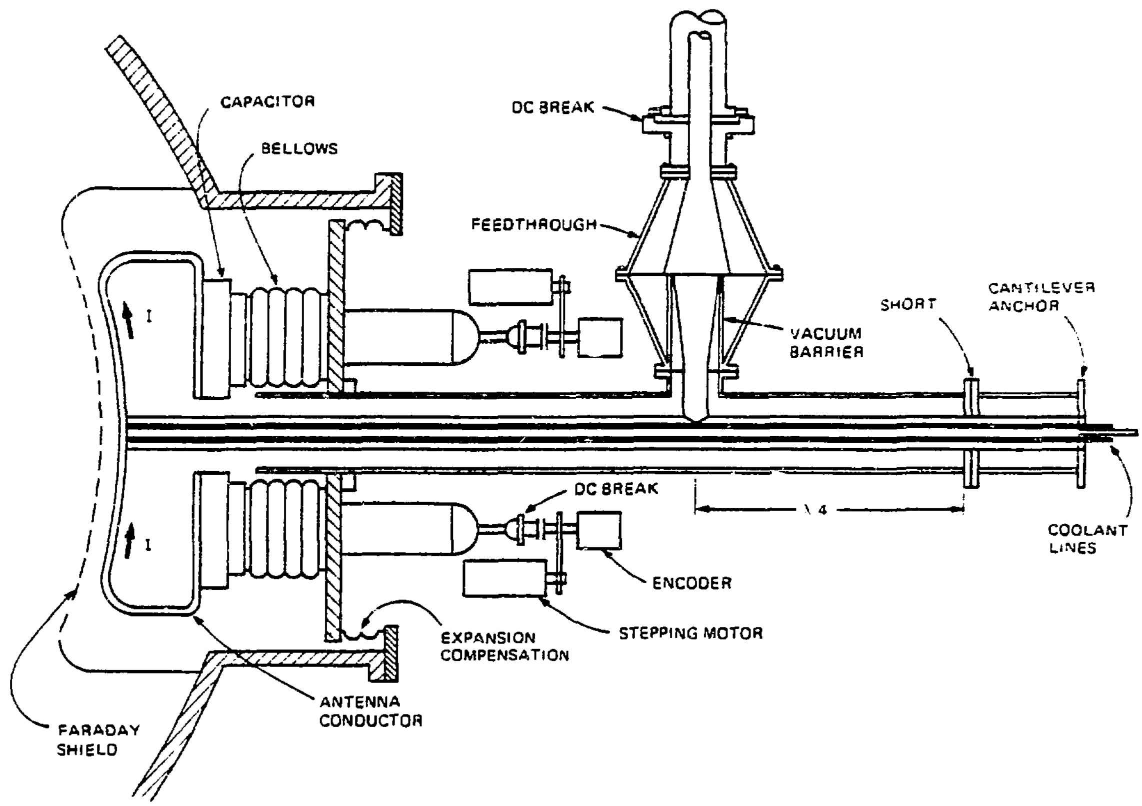


CAVITY CIRCUIT

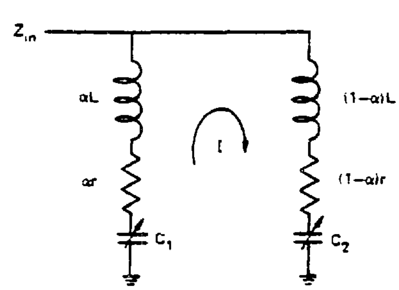


RESONANT DOUBLE LOOP (SIMPLE OR ASYMMETRIC)

ORNL-DWG 85-2278A FED



RDL AND ARDL CIRCUIT



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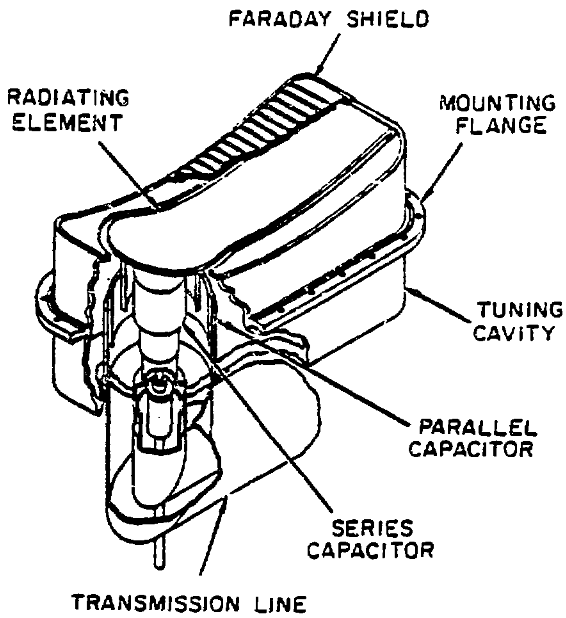
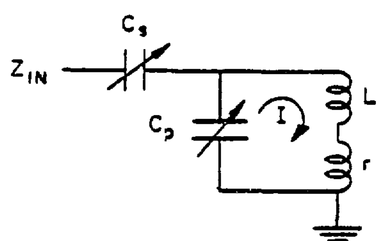
INTEGRALLY TUNABLE U–SLOT LAUNCHER
AND FEED STRUCTURE

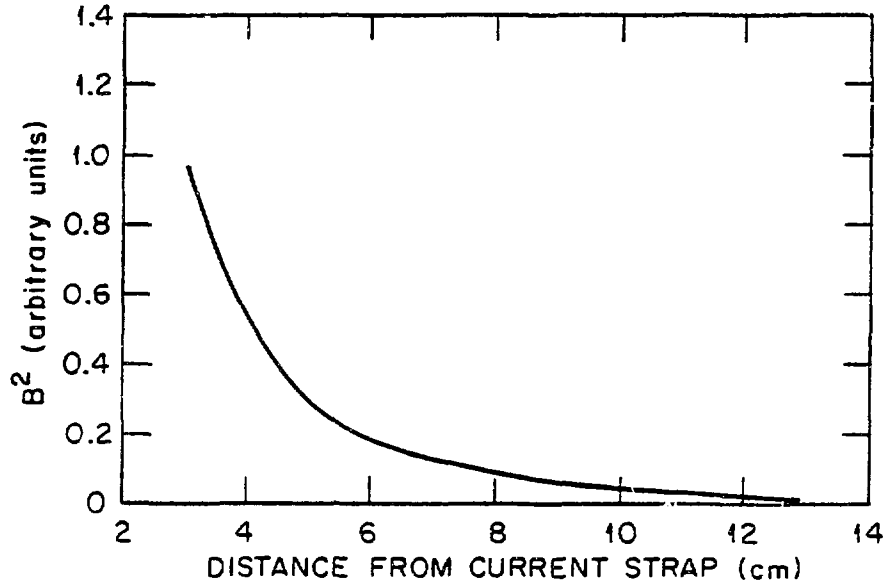


U–SLOT CIRCUIT

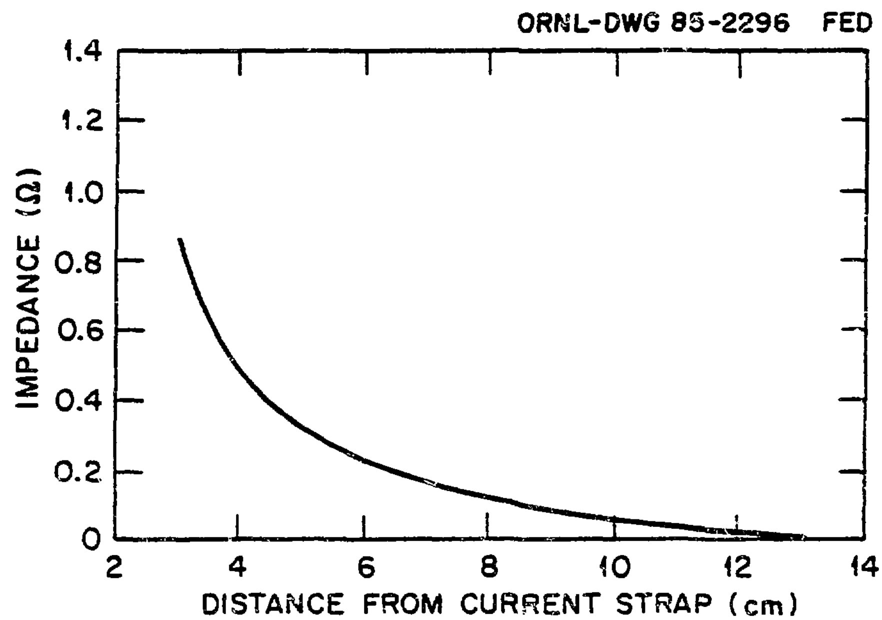


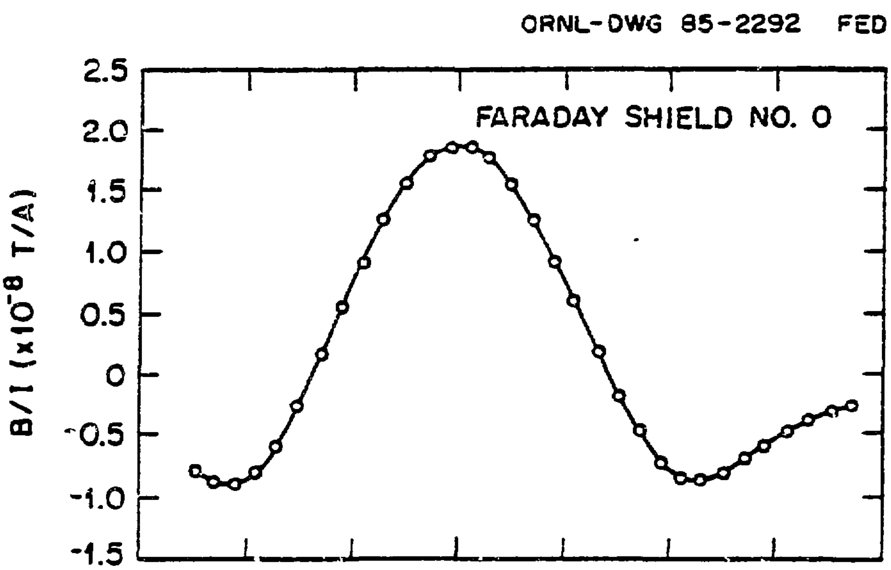
MAGNETIC FIELD AS A FUNCTION OF DISTANCE FROM ANTENNA

ORNL-DWG 85-2297 FED

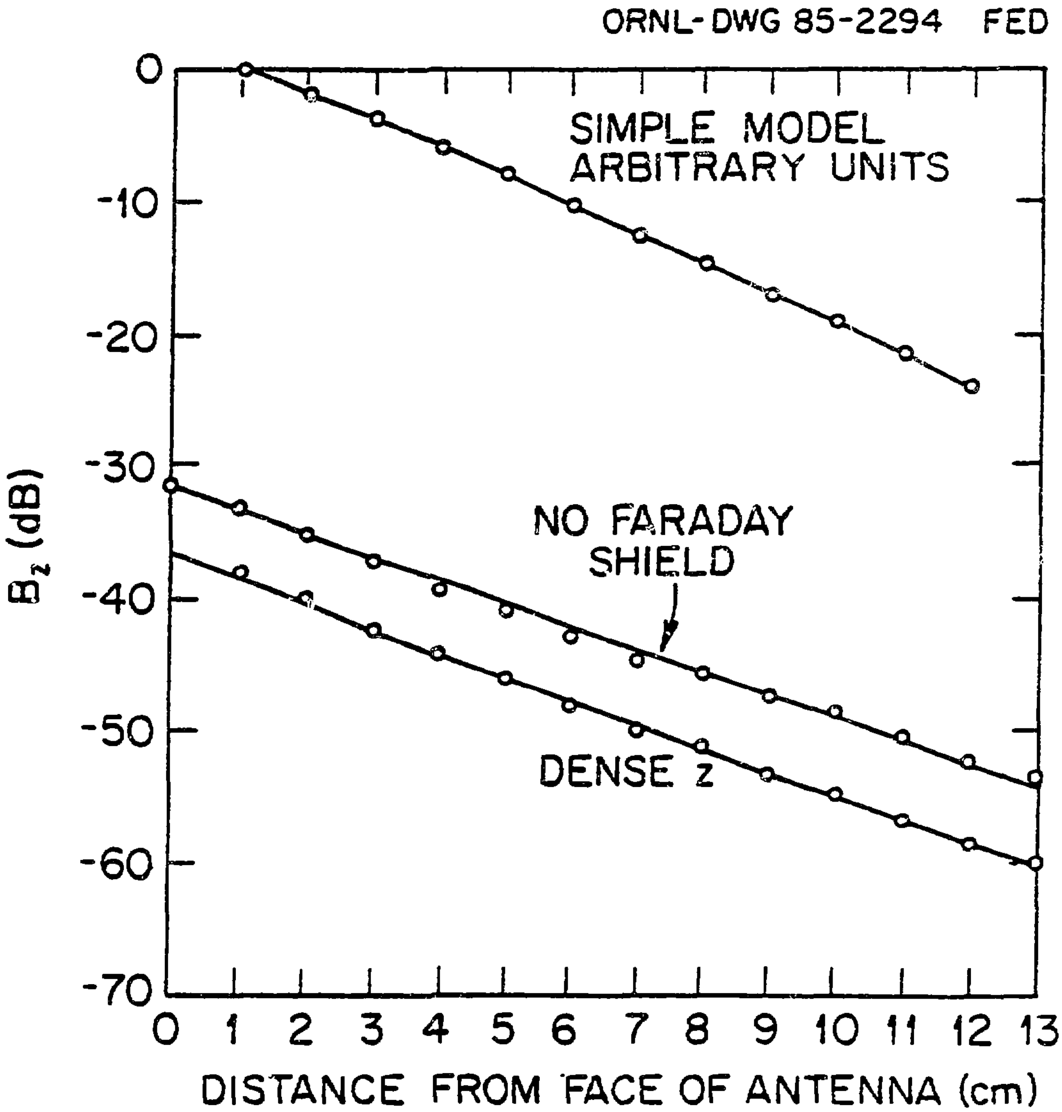


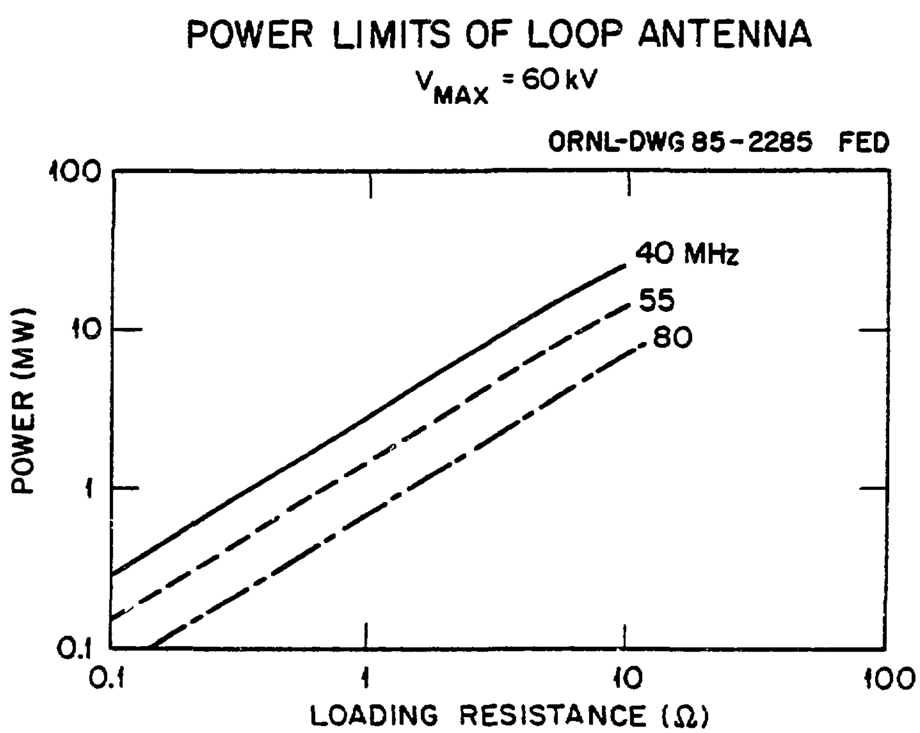
COUPLED POWER vs DISTANCE BETWEEN ANTENNA AND LOAD




ORNL-DWG 85-2292 FED
FARADAY SHIELD NO. 0
B/I (x10^{-8} T/A)
2.5
2.0
1.5
1.0
0.5
0
-0.5
-1.0
-1.5

DECAY OF THE RF MAGNETIC FIELD AWAY FROM THE ANTENNA

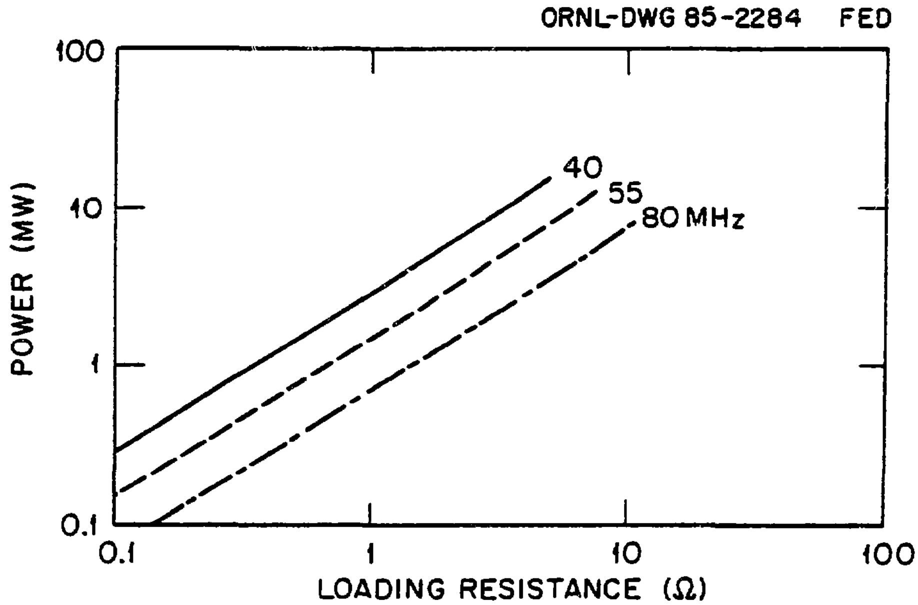




POWER LIMITS OF LOOP ANTENNA
V MAX = 60 kV
ORNL-DWG 85-2285 FED
100
10
1
0.1
POWER (MW)
40 MHz
55
80
0.1
1
10
100
LOADING RESISTANCE (Ω)

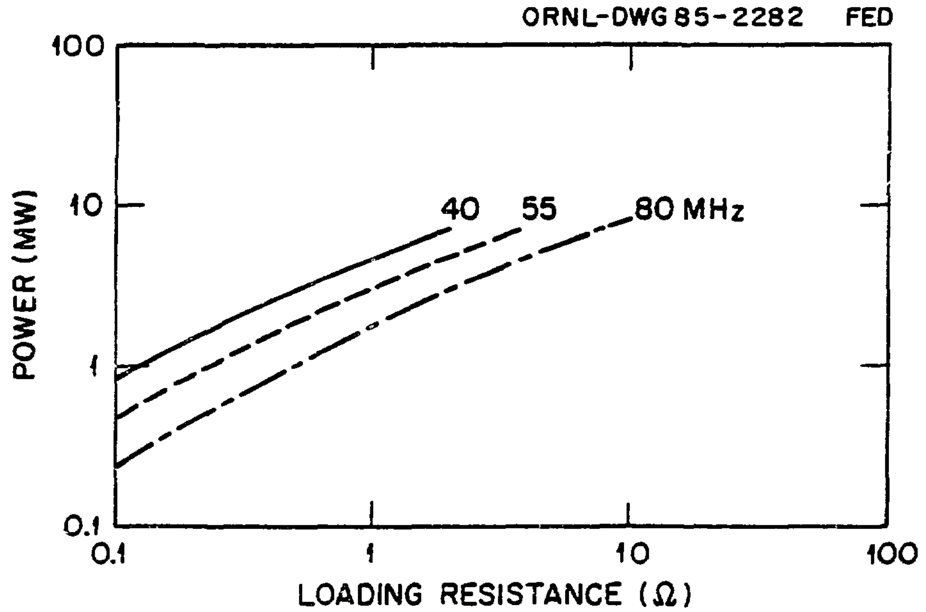
POWER LIMITS OF CAVITY

V_{MAX} = 60 kV



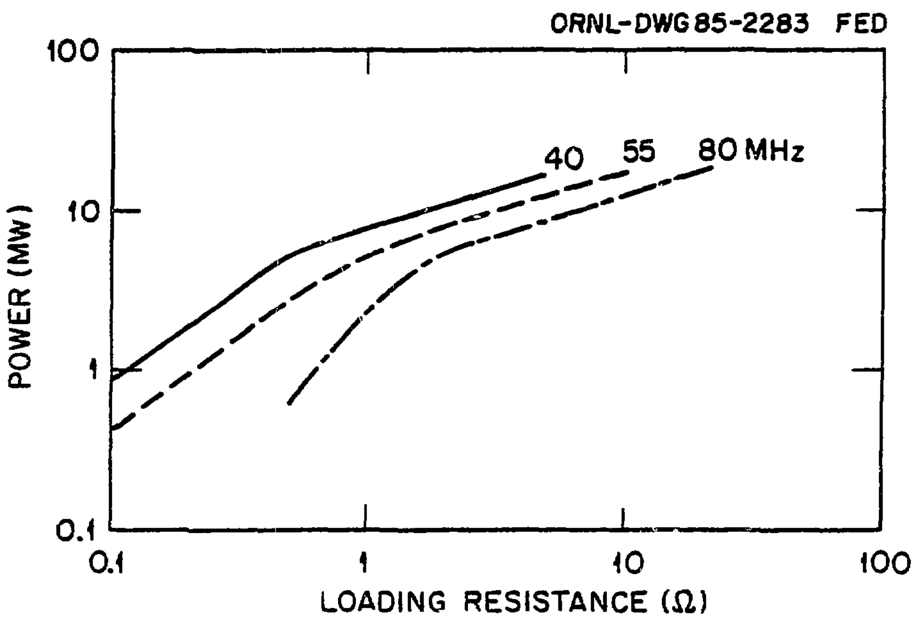
POWER LIMITS OF THE RDL

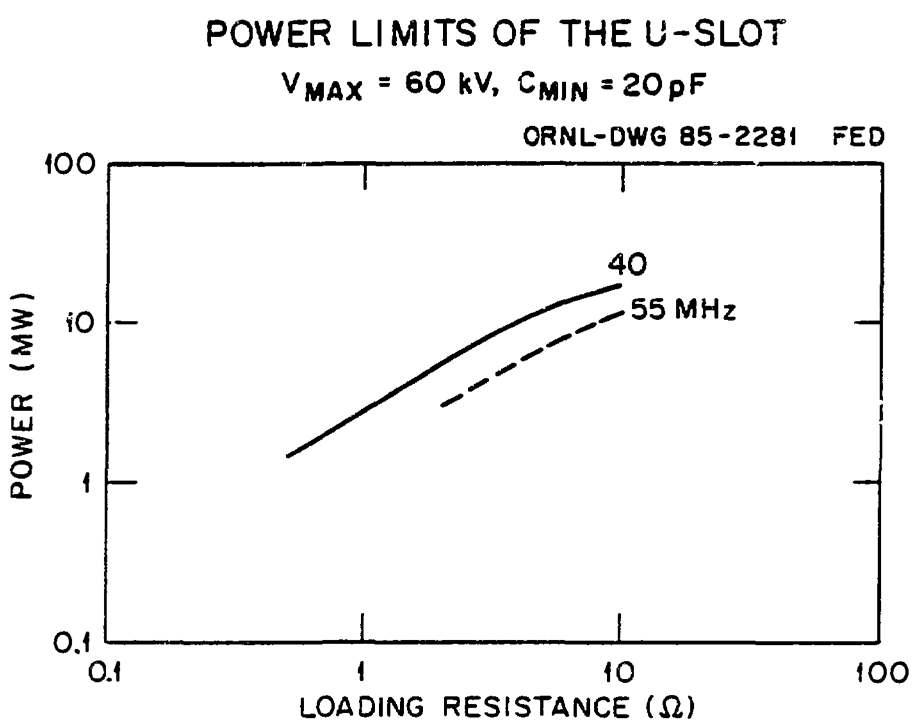
$V_{MAX} = 60$ kV



POWER LIMITS OF ARDL

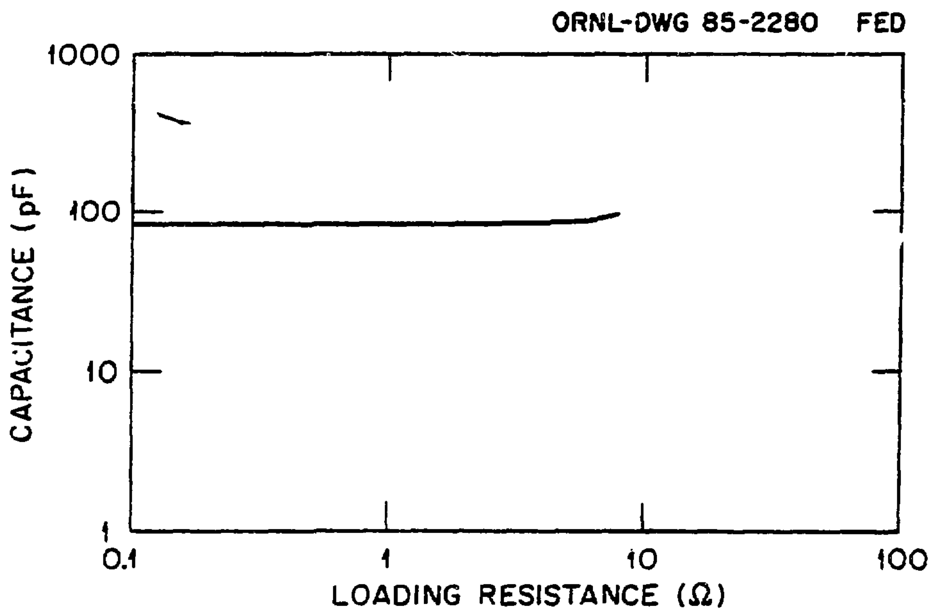
V_{MAX} = 60 kV, α = 0.675

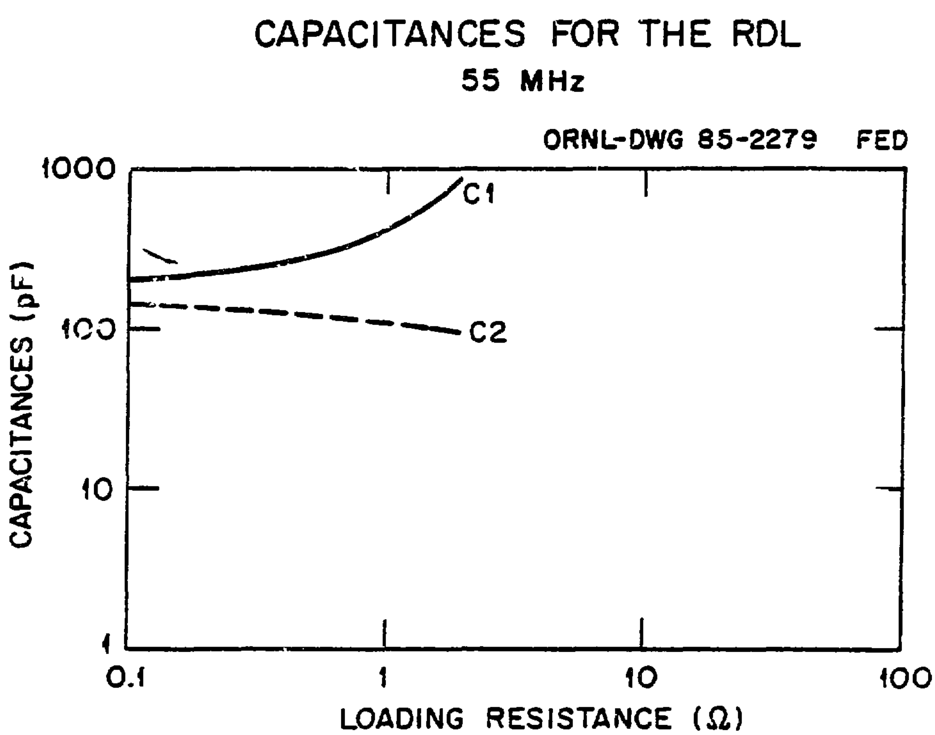




POWER LIMITS OF THE U-SLOT
VMAX = 60 kV, CMIN = 20 pF
ORNL-DWG 85-2281 FED
100
10
1
0.1
POWER (MW)
40
55 MHz
0.1
1
10
100
LOADING RESISTANCE (Ω)

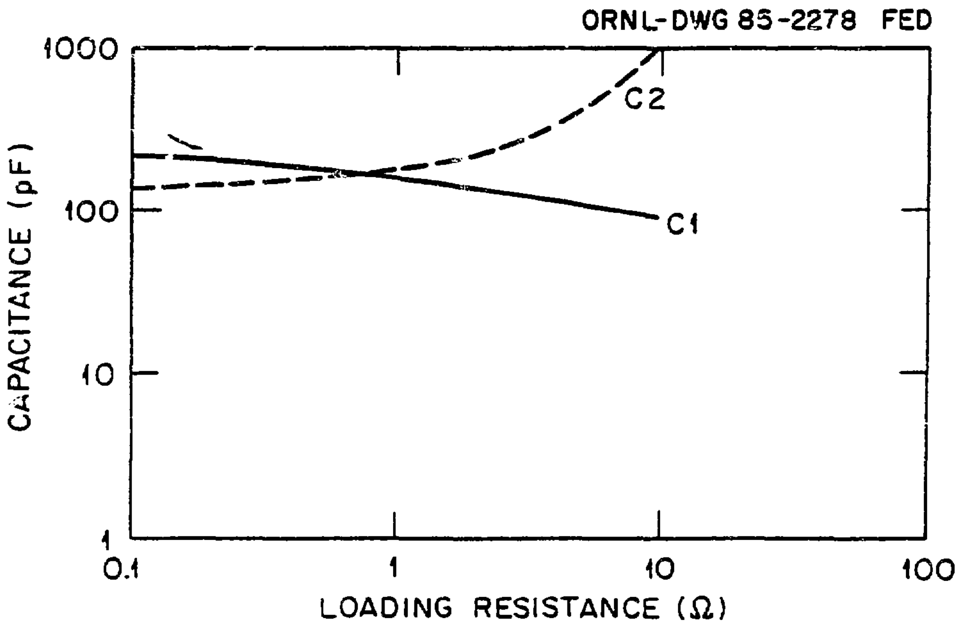
CAPACITANCE FOR THE CAVITY
55 MHz




CAPACITANCES FOR THE RDL
55 MHz
ORNL-DWG 85-2279 FED
1000
100
10
1
C1
C2
CAPACITANCES (pF)
0.1
1
10
100
LOADING RESISTANCE (Ω)

CAPACITANCES FOR THE ARDL

55 MHz



CAPACITANCES FOR THE U-SLOT
55 MHz