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MULTIPLE EXTRACTION CAVITIES FOR HIGH POWER KLYSTRONS*

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ABSTRACT

The design, performance, and comparison with 2-D computer simulations of an X-band high power klystron amplifier utilizing an output circuit consisting of two uncoupled output cavities are described. It is shown that good efficiency, low RF gap gradient, relatively uniform power extraction from each cavity, and freedom from oscillations due to extraneous modes can be achieved. The change in phase relative to the RF input for the two extraction cavities is relatively small within a frequency bandwidth of the order of 1%, and when the beam voltage or drive power is varied over a moderate range. For narrow band applications where the combining of the separate outputs is desired, good combining efficiency is possible. The number of extraction cavities can be extended to obtain still higher peak powers.

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I. INTRODUCTION

Much effort has been devoted in recent years to the generation of huge amounts of microwave power for both military and high energy physics applications. Gigawatts of single-shot pulsed power at short pulse length have been achieved [1]. At S-band and 1 μs pulse width, 150 MW of RF power at 60 pps were reported in 1985 [2]. Hundreds of MW at X-Band at about 50 ns pulse width, using induction accelerators, have been reported [3]. Several laboratories, viz., KEK in Japan, INP in Novosibirsk, the University of Maryland and SLAC in the U.S., are engaged in developing power sources between 100 to 120 MW at 1 μs pulse length, repetitively pulsed, for 2.1 to 2.6 cm wavelength operation.

With the exception of the gyroklystron, whose interaction circuit dimensions can be made much larger than the operating wavelength, a problem common among many of the approaches being pursued is the extremely high RF gradient in the output circuit, which presents an obstacle to long-pulse operation. RF breakdown is a function of frequency and pulse duration. RF breakdown in accelerating structures has been studied extensively [4]. However, experimental data on RF breakdown in high-power microwave tubes are scarce. The presence of a high density electron beam traveling through the interaction gaps of the output structure in these devices adds to the severity of the problem. When the RF pulse is short, the breakdown threshold can be very high (greater than 2 MV/cm) as demonstrated by experimental devices already made.

The problem gets more difficult when the pulse width is increased. Attempts to solve this high peak-power, repetitive, long-pulse problem involved some sort of extended interaction mechanism, whether for the traveling wave or the standing wave type circuit. Some success has been achieved, but the problem is not yet completely solved. For example, in coupled standing-wave circuits, when the number of cells is increased, it is very difficult to achieve the appropriate values for the amplitude and phase of the impedance of each cell such that the resulting RF gap voltage is reasonably uniform for all cells, with the result that some cells generate very little power (hence, are not really utilized) and others generate too much, thus creating a condition for possible breakdown [5]. Low efficiency, or oscillations due to negative beam loading conductance of extraneous modes, are other problems faced.

This paper presents an alternate solution to these problems, a solution which is simple in concept and relatively easy to implement. Instead of having the cells of an extended interaction circuit coupled together, either through irises in the common walls or through the beam aperture, we separate the cells so that they become independent extraction cavities, each capable of being tuned and loaded appropriately to remove equal portions of power from the beam. In this way, one can avoid many of the problems mentioned above. Actually, this idea is not new or unique. The relativistic klystron two beam accelerator [6] utilizes this concept and carries it even further. In this device, RF power is extracted from the low-energy, high-current accelerator at various locations and fed into the high-energy, low-current accelerator. The energy of the high-current beam is alternately decelerated by conversion to RF power, and then replenished by re-acceleration with induction linacs.

In the following sections, the design and operation of an output circuit consisting of two uncoupled extraction cavities for an X-band 100 MW klystron are described. It will also be shown that the number of extraction cavities can be further extended to obtain still higher total output power, or to obtain further reduction in RF gap gradient at the same output level.

II. OUTPUT CIRCUIT WITH TWO UNCOUPLED EXTRACTION CAVITIES

A. Design considerations

The objective is to design the output system so that an equal amount of power is extracted efficiently from each cavity, and that the resulting RF gap gradients are sufficiently low as not to cause breakdown. This means that the electron beam must remain well-bunched as it delivers a portion of its power to the electromagnetic wave and traverses on to the second extraction cavity. This is accomplished by inductively detuning the first cavity by an optimum amount, loading each cavity appropriately for efficient power transfer, and developing equal and safe levels of RF gap voltages. These requirements can be readily met because the cavities are separate and independent. They do not interfere with each other, as is the case with coupled cells.

The optimization of the pertinent parameters was done with a 2-1/2 dimensional computer code CONDOR [7]. The operating wavelength of this amplifier is around 2.6 cm and the peak power output is nominally 100 MW at 1 μs pulse length, 60 pps. The beam voltage is 440 KV, beam current 540 A. A schematic of the output circuit is shown in Fig. 1.

The output cavities are separated by about 280° (i.e., $\omega L/v_e = 4.88$ radians). The first cavity is detuned inductively, whereas the second cavity is tuned to the signal frequency. Each output cavity is loaded by two output waveguides, symmetrically located, with approximately the same Q_{ext}. For a cavity with a given R/Q, the value of Q_{ext} is determined by the requirements for optimum impedance. The dimensions for the waveguide coupling irises are determined by experimental trial-and-error method, although they may be obtained by 3–D computer calculations [8]. In cold test, a swept signal is sent into one waveguide, while the other waveguide is terminated. The resulting VSWR-versus-frequency curve provides information to determine the Q_{ext} value.

Each waveguide has a pillbox-type ceramic output window. The use of two output waveguides for each cavity makes the electromagnetic field more symmetrical and reduces the power handling requirement of the output windows which can be limitations to the achievement of long-pulse, high-peak power operation.

The radius of the cavity drift tube nose is made rather large so as to minimize the RF gradient. An estimate of the maximum surface electric field on the cavity nose tip is 385 KV/cm at the saturated power output level of 90 MW. This is based on the CONDOR-calculated axial RF cavity voltage of 332 KV at saturation. This value of voltage, together with the SUPERFISH-calculated axial voltage, and the corresponding maximum surface electric field for this cavity (see Fig. 2), gives us the above estimate. From previous experimental evidence, this value of RF gradient should be within safe limits for 1 μs pulse-width operation. A photograph of the completed device is shown in Fig. 3.

B. Experimental results and comparison with computer simulation

Figure 4 shows a measured and calculated transfer characteristic. It shows a measured output power of 87 MW, with a saturated efficiency of 36.5% and saturated gain of 58.3 dB. We see that the agreement between experiment and computer simulation was remarkably close. The difference in saturation efficiency was 1.3 percentage points and the difference in saturation gain was 2 dB. It is also significant that, with appropriate RF drive, the output from each one of the four output waveguides is nearly equal, as shown in Table 1, indicating that one of our important design objectives, viz., equal power distribution, was actually achieved.

Figure 5 shows the output pulse shapes from each of the four waveguides. Figure 6 shows performance as a function of frequency, with a few computed points to show reasonable agreement. Figure 7 is a plot of output power as a function of beam voltage with saturation drive. The output system has a total of four ports. Depending on the application, each port can either be fed to the load individually, or each pair of outputs from each cavity can be combined and then fed to the load, or the combined outputs from each cavity can be again combined into a single port. The phase of the output with respect to the RF input is the same for the two output waveguides of each cavity, but this phase is different between the two output cavities. A natural question arises as to what effect this phase difference would have when all the ports are combined into one and either the RF drive or the beam voltage or signal frequency is varied. Tables 2 through 4 show the computed amplitude and phase characteristics and combining efficiency as functions of RF drive, beam voltage and signal frequency.

It can be seen that the phase difference between the two output cavities does change very little under the conditions studied (about 18 degrees at most). If the initial phase difference (i.e., $\Delta\theta_0$) is compensated for by making the length of one arm of the final combiner slightly different, then the RF drive, or beam voltage, or signal frequency can be varied over a certain range with little effect on the combining efficiency. Taking into account both the amplitude and phase deviations, less than 3% of the total power is wasted in the fourth arm of the magic-T combiner over the range studied.

The output powers shown in Figs. 4, 6, and 7 are the sum totals of the individual outputs.

III. EXTENSION TO FOUR EXTRACTION CAVITIES

In the case where a still longer pulse width or higher peak power is required, it may be necessary to reduce the RF gap gradient further in order to avoid breakdown. To meet these situations, the number of extraction cavities can be increased.

Following is an example of a CONDOR simulation result for an output circuit with four uncoupled extraction cavities. The operating frequency, beam voltage, beam current, etc., are the same as those used for the 2-cavity case above. Figure 8 shows the electron position diagram, with the locations of the interaction gaps shown by the symbol P. Figure 9 is a curve of dc and RF current versus distance. We see that the beam remains bunched quite well as it traverses through the various gaps, as indicated by the high level of RF current. The calculated RF gap voltages and output powers from each cavity are shown in Table 5. We see that the output powers are within 10% of each other. The maximum surface electric field on the cavity nose tip is now reduced to 269 KV/cm for a total power output of 106 MW. The output cavity design parameters are listed below.

Output gap position (m)	0.257	0.274	0.291	0.308
Fractional detuning	0.060	0.060	0.060	0.0
R/Q on axis (Ω)	100	100	100	100
Q_{ext}	10	10	10	10

IV. SUMMARY AND CONCLUSIONS

Output circuits consisting of multiple uncoupled extraction cavities offer a viable alternate solution to the problem of generating repetitively-pulsed high peak powers for relatively long pulse width at high frequencies. Conceptually, they are simple and straight forward. Experimentally, it has been demonstrated that the electron beam can remain bunched as it progresses through the various extraction gaps. Since the cavities are separated and independent, they can be tailored individually to satisfy a particular requirement while being free of many of the problems that exist in coupled systems. The efficiency of 36% reported here is not the best that can be done. By further refinements in design, an efficiency of 45%

for X-band, 100 MW level is quite reachable, as indicated by computer simulations. These simulations have proven to be a useful and reliable tool for modeling interaction configurations such as those reported here.

A disadvantage of this scheme for applications where the output powers need to be combined lies in the added complexity involved. For two extraction cavities where the excursions in operating parameters are not too large, this problem is minimal. However, because the output phases change more rapidly with variations in operating parameters, a four-cavity extraction system is more suitable for operation with fixed frequency, voltage, and RF drive. With fixed parameters, the differences in output phase need to be compensated for only once, and the separate outputs can then be combined efficiently. On the other hand, if high power phase shifters are installed in the output system, the fixed-parameter restriction can be eased.

ACKNOWLEDGMENT

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Table 1. Waveguide outputs.

Waveguide	Cavity	Output (MW)
a	1	21.91
b	1	20.68
c	2	21.61
d	2	22.36
Total output power		86.56

4 Output W.G's. and 4 Output Windows

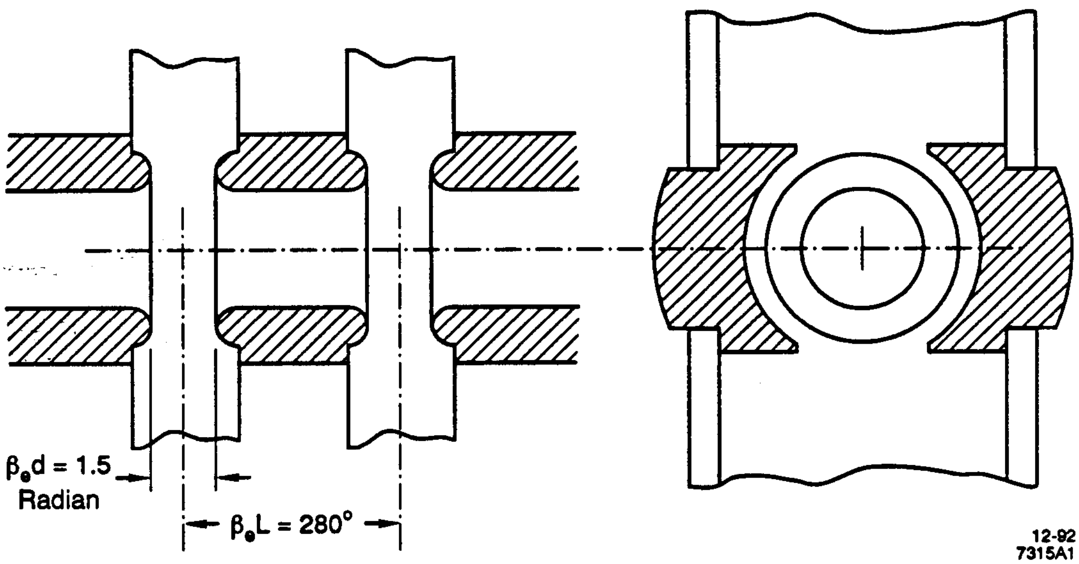
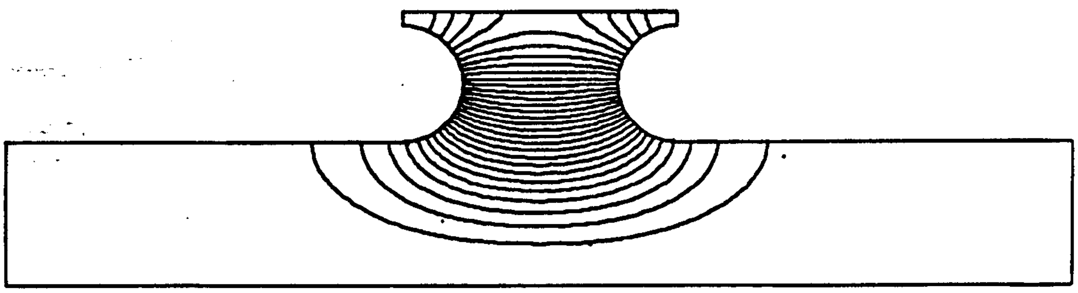


Fig. 1

Integral (abs(E(z))dz) = 6.9265 x 10^4 V
Maximum Electric Field on Boundary = 7.996 MV/m



12-92 7315A2

Fig. 2

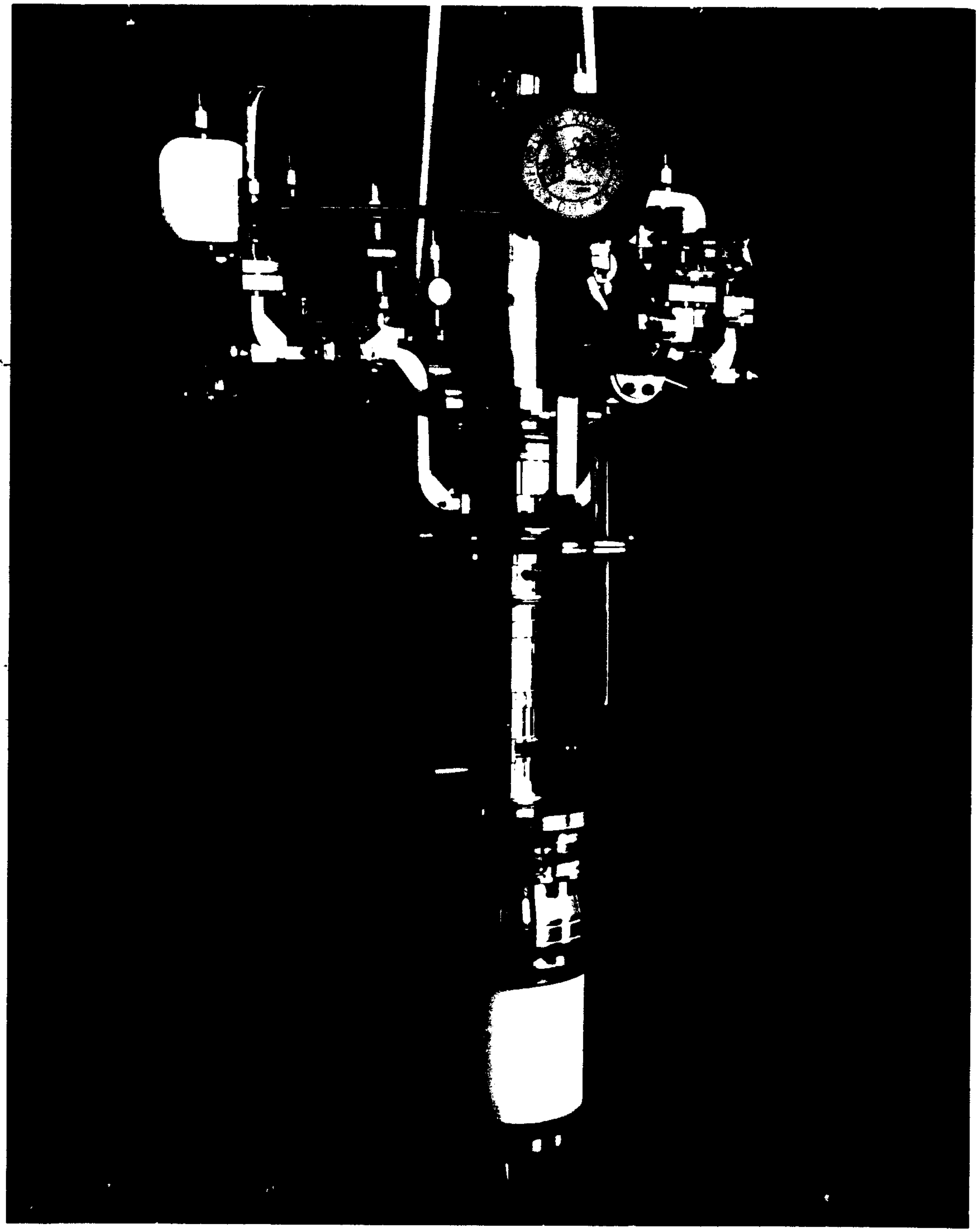


Fig. 3

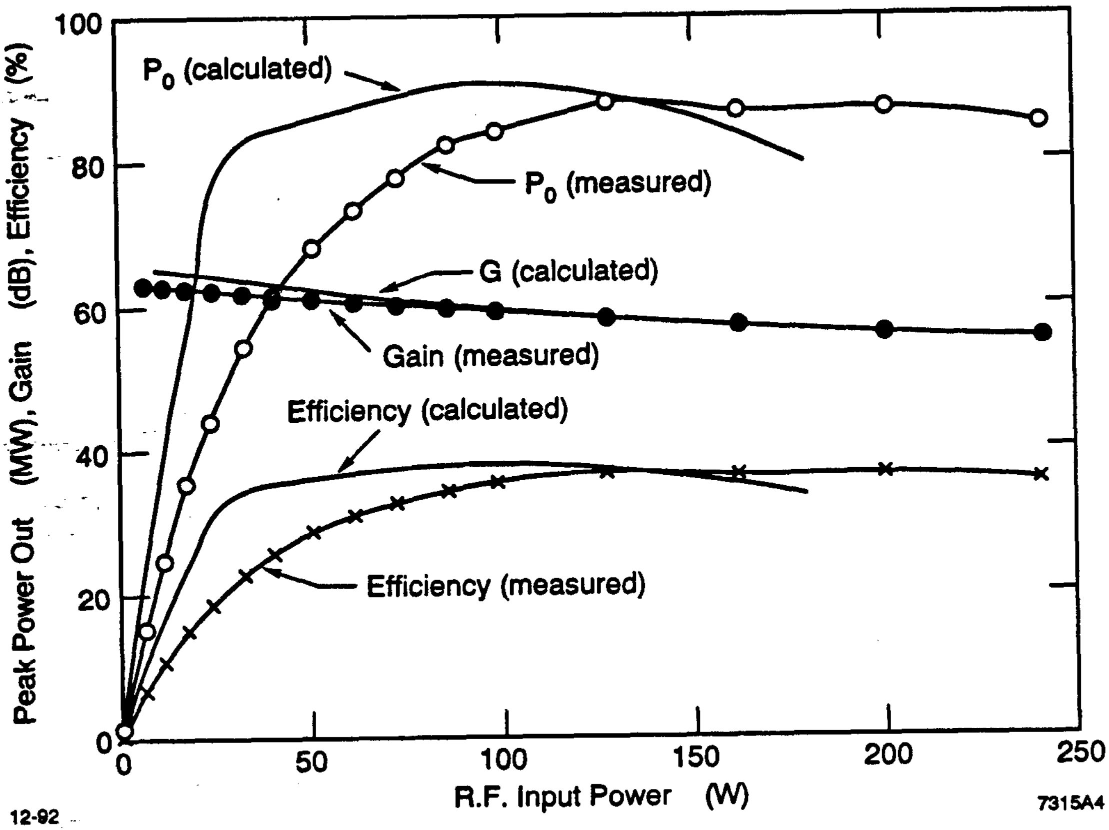

100
80
60
40
20
0
Peak Power Out (MW), Gain (dB), Efficiency (%)
P_0 (calculated)
P_0 (measured)
G (calculated)
Gain (measured)
Efficiency (calculated)
Efficiency (measured)
0
50
100
150
200
250
R.F. Input Power (W)
12-92
7315A4

Fig. 4

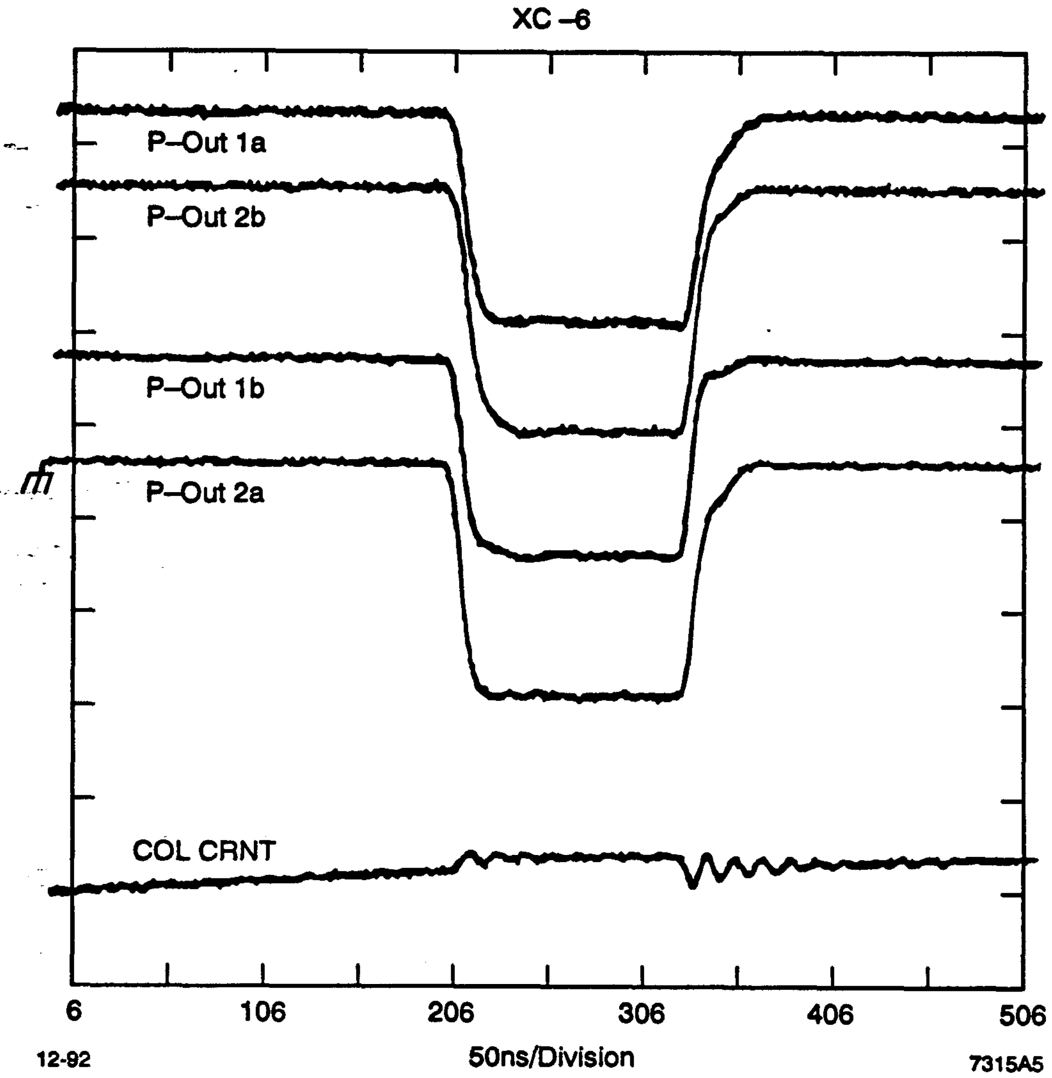
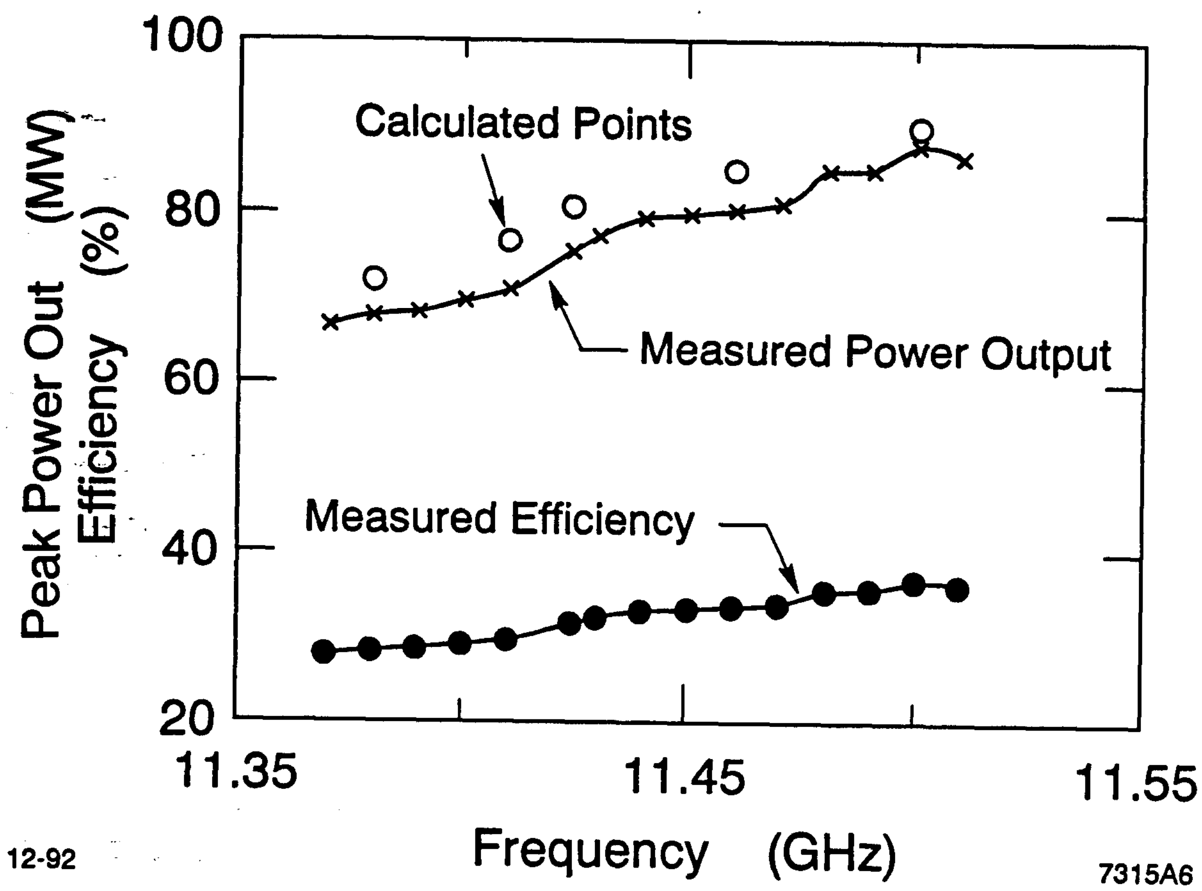

XC –6
P–Out 1a
P–Out 2b
P–Out 1b
P–Out 2a
COL CRNT
6
106
206
306
406
506
12-92
50ns/Division
7315A5

Fig. 5



100
80
60
40
20
Peak Power Out (MW)
Efficiency (%)
Calculated Points
Measured Power Output
Measured Efficiency
11.35
11.45
11.55
Frequency (GHz)
12-92
7315A6

Fig. 6

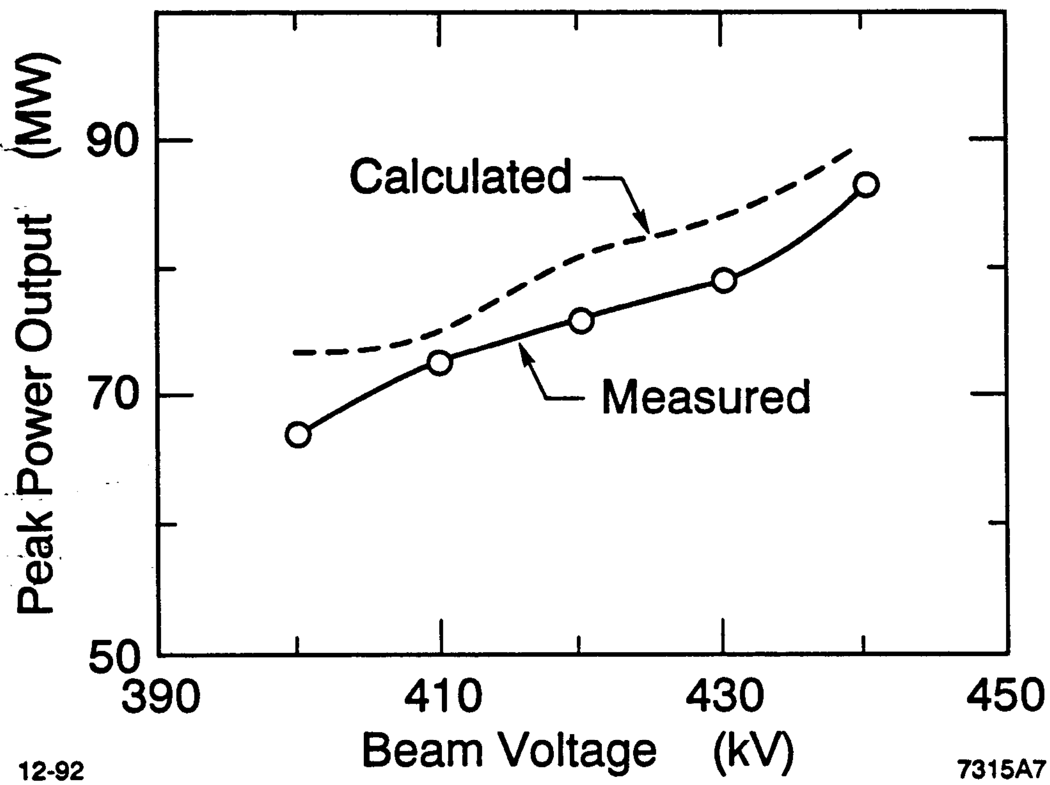

Peak Power Output (MW)
90
70
50
390
410
430
450
Beam Voltage (kV)
Calculated
Measured
12-92
7315A7

Fig. 7

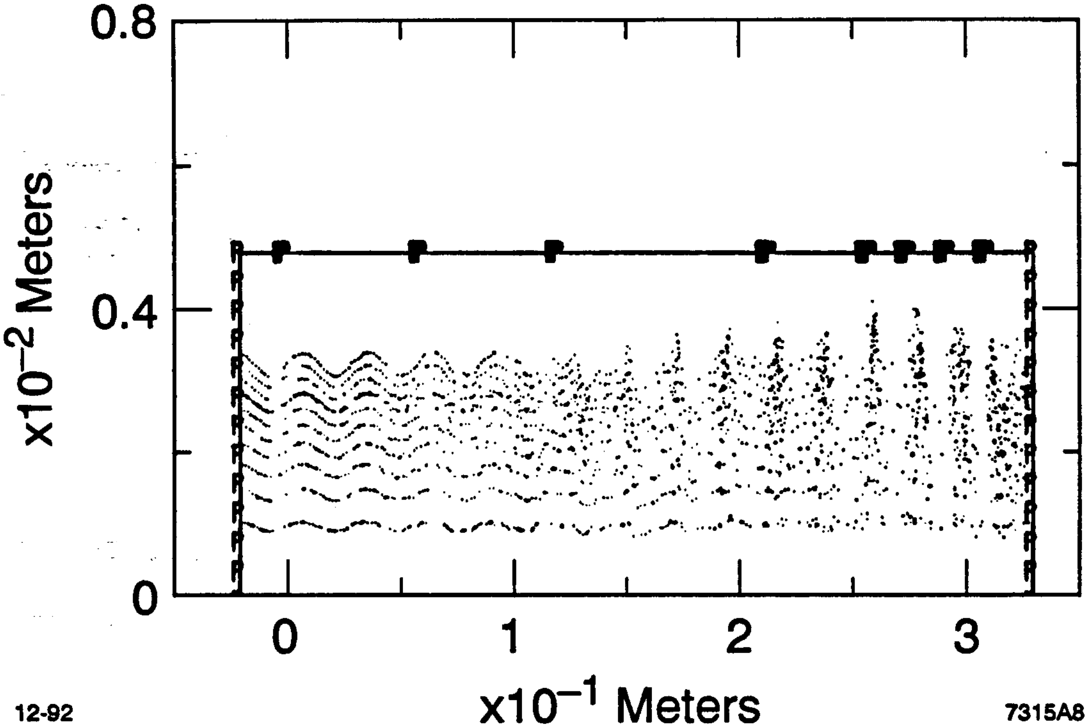
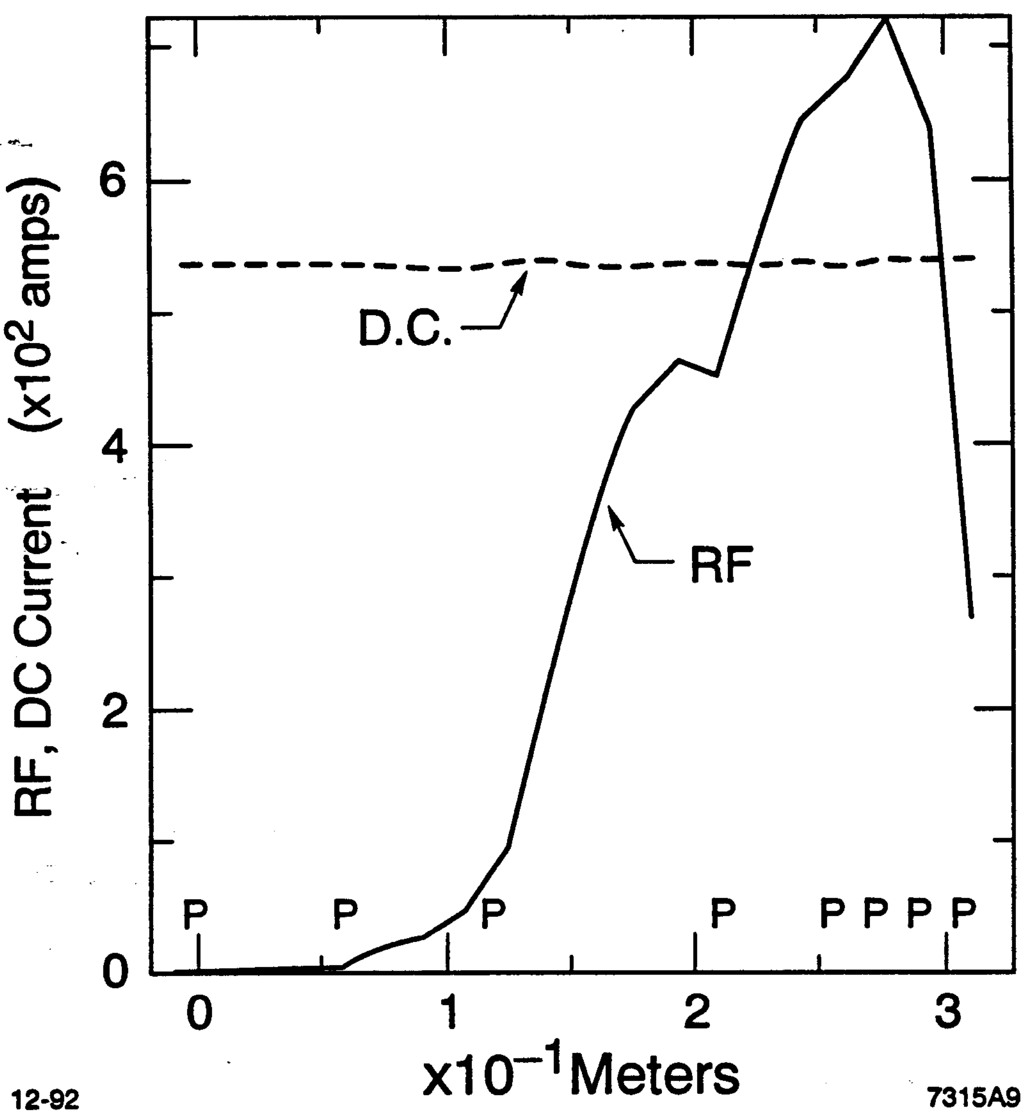


Fig. 8



RF, DC Current (x10^2 amps)
6
4
2
0
D.C.
RF
P P P P P P P P
0
1
2
3
x10^{-1}Meters
12-92
7315A9

Fig. 9