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TECHNICAL NOTE ON HIGH POWER MICROWAVE ELECTRONICS

by

John W. E. Griemsmann

Report No. PIBMRI-947-61
Contract No. AF-30(602)-2135

for

Rome Air Development Center
Air Force Systems Command
Griffiss Air Force Base
Rome, New York
October 2, 1961

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ON

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19 Pages of Text
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ABSTRACT

Progress in the build-up of a high microwave power facility culminating in a 10 megawatt peak power C-band klystron system is reported. Details are given on the design considerations for a C-band peak power enhancement device (traveling wave resonator) capable of boosting high peak powers by a large factor and making it available for use with an external load. Approaches to the microwave switching problem are discussed and progress reported on work toward a suitable switch. Results are given for a prototype low-power X-band dischargeable resonator about 1000 wavelengths long from which enhanced pulsed power was extracted by means of a fast ferrite switch. As part of a connected program of study of the interaction of high microwave power and fields with materials, work is described on the design of a test cell for subjecting materials to high power densities and the investigation of special electrodeless microwave cavities for the study of intrinsic and free surface breakdown effects.

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I. Introduction

The work in this program has been divided into three major areas: (1) the development and construction of a High Microwave Power Facility including a variety of high power microwave sources (so far entirely in the C-band frequency range); (2) effort in the direction of a C-band high power enhancement device for boosting the output peak power of the highest power source in our Facility by some 8 db, with part of this effort in the area of high power microwave engineering, components development, and testing; (3) interaction of high microwave fields and high microwave energy with dielectric media. This technical note will summarize the work progress for the 18 month period ending March 31, 1961.

II. High Power Microwave Facility

Personnel: Professor S. W. Rosenthal, E. Crimza, M. Klinger, M. Nussbaum

This facility includes a number of high power microwave sources in C-band of varying capabilities and suitable for a variety of experimental purposes.

A. One Megawatt C-band Magnetron System

(Raytheon QK632 and QK509)

This system is now in operation. It provides a C-band pulse power source of the order of one megawatt peak power in the frequency range 5250-5310 mc with a duty cycle of 0.0011. By means of a specially designed 4-port circulator and a variable impedance termination, as shown in the block diagram of Fig. 1, it is possible to smoothly vary the power into a desired load from very small values to the maximum available from the magnetron. In addition, the load (designated as "work" in the diagram) can be of any type (from a perfect match to one that is purely reactive) without harming the magnetron which is almost completely isolated from it. The system requires gas pressurization of 15 psig and can work up to pressures of 30 psig.

B. 2.5 Megawatt C-band Klystron System (Sperry SAC 214)

This system is now in operation with a 2-3 kw driver, but requires higher input from the driver to develop its rated output. At present an rf output of about one megawatt peak in the 5450-5850 mc range with a duty cycle of 0.001 is available. It is planned to use a 10 kw magnetron (now on order) to obtain the rated output and to use a ferrite circulator-variable impedance arrangement (such as shown in Fig. 1) to provide the same flexibility as in the Raytheon magnetron system. With its present driver the SAC 214 provides a high power signal source of variable power, frequency, pulse width and frequency sweeping capabilities and this is particularly suitable for probing plasmas and materials.

C. Ten Megawatt (Peak Power) C-band Klystron System

This system is under construction by the Sperry Gyroscope Company for delivery sometime in August 1961 and will be installed in the new Research and Graduate Center of the Polytechnic Institute at Farmingdale, L.I., N.Y. It will provide pulsed rf power of the order of 10 megawatts peak at a maximum pulse width of 5 microseconds or a reduced peak power of 5 megawatts at a pulse width of 10 microseconds. This system will permit the power output, frequency, pulse width, and repetition rate to be varied, and the frequency to be swept. The design of the system provides for increased flexibility and power output capabilities in the future. It is now in the process of being assembled and, after suitable testing, will be shipped to the Graduate Center for installation and completion there. A schematic of the output rf system is shown in Fig. 2.

S. W. Rosenthal

III. Power Enhancement Devices and Related Work

Personnel: Professor M. Sucher, D. Jacenko, R. Goldie, B. Ford

At the initiation of this program a power enhancement device was proposed[1] for boosting the peak pulsed power obtainable from a given primary high power source by a sizeable factor. The contemplated use of this device was at C-band frequencies in conjunction with the high power C-band klystron system. The device is essentially a dischargeable traveling wave resonator (referred to hereafter as a traveling-wave microwave "flywheel" or TWF) fed from the highest available primary source (see Fig. 3).

1. Problems Connected with the TWF

The subject of traveling wave resonators has been widely treated in the literature[2] and no detailed attempt will be made here to describe their operation. Suffice it to say that, if the resonant ring is fed with a constant amplitude rf pulse of long duration relative to the time required for the energy to travel once around the ring, there will be a build-up period in which energy from the source is partly stored in the ring in the form of a traveling wave of increasing amplitude and partly dissipated in both the terminating load and in wall (or other) losses normally associated with the one way attenuation of the ring. In the absence of obstacles or reflections from bends or other discontinuities, the ring will be resonant when its length is exactly an integral number of guide wavelengths. At optimum coupling between the source and ring, as steady state is reached, the power dissipated in the terminating load will drop to zero, the amplitude of the circulating wave in the ring will approach its maximum value, and all of the energy of the source will go toward supplying the waveguide attenuation losses of the circulating wave. For arbitrary coupling the power flow associated with this circulating wave will be M^2 times that of the primary source where, M, the steady state voltage multiplication factor, is equal to $C/(1 - T\sqrt{1 - C^2})$, C being the voltage coupling coefficient between primary and secondary arms of the coupler (always < 1) and T the voltage attenuation coefficient of the ring (also < 1). ($T = \epsilon^{-\alpha \ell}$ for a ring of length ℓ and an attenuation constant of α nepers per unit length.) At critical (or optimum) coupling $C = \sqrt{1 - T^2}$, $T = \sqrt{1 - C^2}$, and $M = 1/C$. Thus, for sufficiently small attenuation, a relatively wide pulse of microwave power from the source can be used to build up a traveling wave of much higher power level in the ring which, upon being discharged by means of a fast acting microwave switch, will yield an rf pulse of higher amplitude (though shorter duration) than that of the source for use with any desired external load. For example, it was calculated[1] that a 537 foot C-band ring using over-sized copper waveguide of about 0.58 db overall attenuation could produce a 0.55 microsecond output pulse for an 8.5 microsecond input pulse with an apparent power multiplication of 6.4 and an efficiency of about 41 percent, assuming optimum coupling and an ideal switch.

One phase of our program has therefore concentrated on design considerations for such a TWF, particularly on how to realize the necessary small attenuation for substantial power magnification with good efficiency, while meeting the problems caused by the possibility of higher mode generation in the necessarily over-sized waveguide. One report[3] deals with possible rectangular geometries, the corresponding number and types of higher modes and their control, and the spacing of higher mode resonant frequencies (for modes of the TE_{mo} type which are not easily filtered out) for a C-band TWF of the desired output pulse and power magnification. An examination was also made of how TE_{mo} type modes could be eliminated by deliberately introducing a selective loss mechanism discriminating in favor of the dominant TE_{10} mode. In addition, thought has been given to the desirability of using the TE_{01} mode in oversized circular waveguide in an effort to reduce losses and improve efficiency. This has led to the possibility of a long resonant cavity in place of a TWF as a power enhancement device.

Another aspect has been the design, construction, and operation of a 95 foot long, low power, X-band prototype TWF using oversized square waveguide as a means of becoming familiar with problems of mode control, frequency stability, tuning and switching to be encountered in the large C-band TWF.

A problem of critical importance to the ultimate success of the contemplated power enhancement devices (and also one of the most difficult) is that of an efficient, fast, high power, low loss, microwave switch. The various possibilities have been under continuous review - the use of gas discharges, ferrites, ferroelectrics, and multipactor effect. It was tentatively decided to pursue the phenomena of gas discharges as the best means of realizing a switch of the desired characteristics while keeping in mind any new promising developments along other directions as they arise. In this connection, two approaches to the switch have been adopted. One involves the building of a grid-controlled low pressure arc discharge switch tube along with a test facility for testing various switching tubes.[4] The other is to investigate the use of gaseous discharges at high or atmospheric pressure as a means of fast microwave switching.*

With regard to the directions not being pursued, such as ferrite and ferroelectric switching, the following remarks may be made. Although the use of ferrite in high power circulators has proved feasible (with cooling), the geometries required are not very favorable for fast switching, while geometries favorable for fast switching are unfavorable for operation at high power levels. Ferroelectrics, particularly the voltage sensitive types such as lend themselves to switching applications, (see Appendix II of First Quarterly Letter Report PIBMRI-853.1-60, Feasibility of Ferroelectric Phase Shifter by M. Sucher and L. Birenbaum) until recently have been too lossy for the requirements of this program. Only recently, with single crystals[5] (which however, are not yet in a form suitable for use in switching) have losses been reduced to the point where ferroelectrics may be comparable with ferrites. The multipactor (or secondary electron resonance) switch may yet prove useful[6] but, in its present state of development, is not easily held off in the face of high microwave power, so that it is preferable to use the switch in its fired state for charging up the ring and to use it in the quenched state to discharge the ring. Unfortunately, this means that a loss of some 0.3 to 0.4 db (the value obtained at S-band) is introduced by the switch, thereby severely limiting the attainable ring power magnification.

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* D. B. Schwarzkopf (private communication) has performed nanosecond switching at moderate power levels at X-band by use of a dc spark in waveguide at atmospheric pressure.

Furthermore, in the unfired state the switch (which is part of a waveguide resonant structure) has an insertion loss of about 0.5 to 0.7 db. Even if one could overcome the tendency of the switch to fire at lower than desired power levels and attempt to use it in the unfired state for charging up the ring, one is confronted by the too large insertion loss of the unfired state. It may yet be possible to overcome these difficulties by a design more closely adapted to the requirements of the ring. This matter will be pursued further.

2. Use of Oversized Waveguide for a TWF

Calculations were made of the attenuation, power magnification, power carrying capacity and possible number of propagating modes to be expected for a 500 foot long ring resonator using several different rectangular geometries. The waveguide was assumed to be copper and the calculated microwave resistivity was multiplied by 1.21 to take account of surface roughness. The results are given in Table I at several C-band frequencies. The calculated losses due to waveguide dissipation, α_w, and estimated losses due to waveguide components (such as mode filter sections and switches), α_c, are separately tabulated; two different possible values, 0.1 and 0.2 db, are used for the latter. The a dimension, usually smaller than b, is perpendicular to the TE_{10} electric field lines and determines the number of propagating TE_{mo} modes.

It is to be noted that waveguide of square cross-section generally propagates a larger number of modes than one of rectangular cross-section of the same attenuation value and, in particular, a larger number of TE_{mo} modes which are difficult to filter out if generated. The data would seem to indicate that a waveguide of the same inside dimensions as RG-(204)/U (4.875" x 9.75" or 12.38 cm x 24.76 cm), but with E field polarized perpendicular to the narrow dimension, might be a practical choice because of its availability and the manageable number of possible TE_{mo} modes (four). Filtering of the remaining modes can be simply accomplished through use of an appropriate number of metal septums perpendicular to the electric field of the TE_{10} mode. The non-conventional waveguide of 10 cm x 26.81 cm cross-section admits only three TE_{mo} modes and has comparable attenuation but requires special fabrication.

Table I

Comparison of Possible Waveguides for C-band TWF

Waveguide Type		Freq.	a	b	a_c	a_w	a_T	Apparent Power Multiplication	P_{cc}	Number of Modes			
JAN RG-( )/U	EIA WR-( )	mc	cm	cm	db	db	db		Megawatts	TE_{mo}	TE_{on}	TE_{mn}	TM_{mn}
	Non-Conv.	5850	25	25	.2	.364	.564	8.0	738	9	9	66	66
	Non-Conv.	5450	19	19	.1	.464	.564	8.0	411	7	7	34	34
	Non-Conv.	5650	10	26.81	.1	.464	.564	8.0	308	3	10	23	23
	Non-Conv.	5650	10	37.98	2	.364	.564	8.0	437	3	14	34	34
203	1150	5850	14.60	29.21	2	.345	.545	8.3	506	5	11	43	43
203	1150	5450	14.60	29.21	.2	.348	.548	8.3	484	5	10	36	36
204	975	5850	12.38	24.76	.2	.427	.627	7.4	358	4	9	30	30
204	975	5450	12.38	24.76	.2	.436	.636	7.3	358	4	9	26	26
	Non-Conv.	5850	10	26.81	.2	.460	.660	7.1	309	3	10	23	23

P_{cc} = power carrying capacity based on E_{max} = 30 kv/cm

Since filtering out the higher order TE_{mo} modes is a difficult problem, consideration was given to a method of eliminating these unwanted modes by introducing a selective loss mechanism to increase their attenuation relative to that of the dominant TE_{10} mode. Since the higher modes are closer to cut-off, the associated transverse top and side wall currents are larger than those for the TE_{10} mode. Therefore, by introducing corrugations in the top wall which increase the resistance presented to transverse top and bottom wall currents and by increasing by a large factor the sidewall rf resistance (for example, by use of nichrome) one may expect substantially to increase the attenuation of the TE_{20} and TE_{30} mode in a rectangular waveguide without unduly increasing the attenuation of the TE_{10} mode. (See Fig. 4.)

It can be shown that the attenuation due to wall losses of an empty rectangular waveguide supporting modes of the TE_{mo} variety may be written as

$$A_m = \frac{R_s}{\zeta\, b\sqrt{1 - \left(\frac{m\lambda}{2a}\right)^2}} \left\{ F_{a\ell}\left[1 - \left(\frac{m\lambda}{2a}\right)^2\right] + \left(\frac{m\lambda}{2a}\right)^2 \left(F_{at} + \frac{2b}{a} F_{bt}\right) \right\}$$

where a, b are respectively top and side wall waveguide dimensions, ζ the intrinsic impedance of free space, R_s the skin resistance of a standard metal, $F_{a\ell}$ a factor representing the skin resistance of the top and bottom walls relative to the standard for longitudinal (axial) currents, F_{at} a similar factor for the top and bottom walls for transverse currents, F_{bt} a similar factor for the side walls, m the order of the mode, and λ the free-space wavelength.

Attenuation calculations were made for square (b = a) guide and tall (b = 2a) guide at $\lambda = a/2$ (the cut-off limit for the TE_{40} mode) using $F_{a\ell} = 1$, $F_{at} = 2$, $F_{bt} = 20$. The table below compares the attenuation of the first three TE_{mo} modes of the resistive waveguide with that for a waveguide of standard metal of the same geometry. The quantity A'_m represents the attenuation A_m normalized with respect to $R_s / a\zeta$; that is, $A'_m = A_m (a\zeta)/R_s$.

Table II

Comparison of Attenuating Properties of Waveguides Using Specially Resistive and Standard Materials

	Standard Material	Resistive Material	$\frac{A'(\text{resist.})}{A'(\text{stand.})}$	Guide Geometry
A'_1	1.16	3.67	3.16	Square Guide $b = a$
A'_2	1.73	13.0	7.5	
A'_3	3.22	36.5	11.4	
A'_1	0.645	3.13	4.85	Tall Guide $b = 2a$
A'_2	1.15	12.25	10.6	
A'_3	2.46	35.3	14.3	

For square guide, the results show that the TE_{20} and TE_{30} mode attenuations are indeed increased substantially and by a larger factor than the increase in TE_{10} mode attenuation, but the latter increase is nevertheless prohibitive for our ring resonator applications. The same occurs for tall guide ($b = 2a$), but the penalty paid in the TE_{10} mode attenuation is even greater. It is interesting to note, however, that if one uses tall guide, as it is proposed to do in the long C-band TWF, and restricts oneself to the usual construction (material having equal resistivity for both axial and transverse currents in all walls), one obtains a substantially smaller TE_{10} mode attenuation as compared with square guide of the same a dimension. This advantage of tall guide may almost entirely disappear if specially resistive material is used. (Note the A'_1 value of 3.13 for tall guide as compared with 3.67 for square guide in the resistive material case.) It should also be pointed out that the attenuations for the TE_{20} and TE_{30} modes are respectively almost twice and four times that of the TE_{10} mode in the tall guide case (standard material), a more favorable ratio than for square guide. Since for small attenuations the apparent power magnification of a ring at critical coupling is essentially inversely proportional to the attenuation, the resonances of the higher modes will tend to be weaker than those of the TE_{10} mode, and in this respect, too, tall guide has an advantage over the square geometry.

An examination was also made of the relative spacing of TE_{mo} mode resonances in the 500 foot C-band ring. This spacing and the associated Q's of the resonances will determine the feasibility of obtaining a desired resonance in the TE_{10}

mode without coupling to unwanted higher order TE_{mo} modes. The case of the 10 cm x 26.81 cm waveguide was considered for a 500 foot resonant ring for a frequency range from 5450 to 5850 mc. The frequency spacing $\triangle f$ between two successive resonances of a given mode is given by the simple formula[3]

$$\triangle f = \frac{c}{s}\frac{\lambda}{\lambda_g} = \frac{v_g}{s} = \frac{1}{\tau_d}$$

where s is the length of the ring, c the velocity of light, λ the free space wavelength, λ_g the guide wavelength of the mode concerned, v_g the group velocity of the wave, and τ_d the discharge time or time required for the energy to travel once around the ring. Since guide wavelength increases as cut-off is approached, the higher order modes have more closely spaced resonances than the dominant TE_{10} mode. (As cut-off is approached the spacing becomes infinitely close.) Thus, at a frequency of 5650 mc the respective spacing of resonances for the TE_{10}, TE_{20}, TE_{30} modes is 1.76, 1.55, and 1.10 mc. Calculation of the bandwidth between points on the TE_{10} resonance curve at which the power magnification drops to one half the maximum value gives 84 kc for an attenuation of 0.564 db. The resonance curve is therefore quite narrow relative to the spacing between resonances. Furthermore, it becomes evident from a detailed examination that one may expect to find many points in the spectrum where the resonances for the two higher modes are sufficiently far from the neighboring TE_{10} resonance so as not to interfere with it and, in practice, one could always, by a slight tuning adjustment, expect to displace a particular interfering resonance away from a desired TE_{10} resonance.

Another problem is that of frequency stability of the source and dimensional stability of the ring. To keep the power magnification at 95 percent of maximum magnification (at resonance) requires a frequency stability of $\pm$ 0.01 mc in 5,650 mc which is better than 2 parts in a million. An afc system will therefore be needed, involving the injection into the ring of low power pulses in the interval between the high power pulses so as to determine departure from ring resonance frequency and accordingly to correct the driver frequency of the high power klystron feeding the ring.

3. Prototype X-band TWF

In order to anticipate some of the problems to be encountered in the proposed high power C-band microwave flywheel, such as mode control, frequency stability, internal reflections, and switching problems, a 15 foot low power prototype ring and flywheel at X-band was designed, built, and tested. The X-band frequency range was chosen because of the availability of components, test equipment, and a high speed ferrite switch. Another reason was the fact that a ring of this size could be fitted into the available laboratory space and yet contain about a thousand wavelengths and give a sufficiently long output pulse (about 0.1 microsecond) together with a reasonable amount of power magnification. About 80 feet of oversized copper guide (square guide, 2.84" inside dimension) was used, again because of availability, the remainder of the ring consisting of components and bends in RG-52/U (0.500" x 0.400") rectangular waveguide, mode filter sections in the large square guide, and tapered transitions between the square and rectangular cross sections. A schematic of the ring is shown in Fig. 5.

The key question about the operation of the ring was whether there would be undue interference from higher-order modes, since the 80 foot length of oversized waveguide could sustain at least 24 different modes above 8.4 kmc. The filter sections used in the ring (two in all) were designed to eliminate the double-subscript as well as TE_{on} modes that might be generated in the tapered transitions but were without effect on the TE_{20}, TE_{30}, and TE_{40} modes. Preliminary tests to detect any resonances due to higher modes in the oversized waveguide were made (prior to the assembly of the ring) by measuring the transmission loss between planes A-A and B-B. In the range 8.5-9.5 kmc, only six sizable resonances were detected, the strongest giving about 2.35 db of attenuation, the weakest about 1.3 db, while the normal attenuation throughout this range was only about 0.4 db, exactly the attenuation theoretically expected for the TE_{10} mode.

The waveguide was then connected in the ring configuration shown in the figure. A two-hole, nominally 10 db (actually 11.4 db at 9.3 kmc) directional coupler was used to feed the ring, and a 20 db cross-guide terminated in well matched crystal detectors was used to monitor the forward and backward wave (if any) in the resonant ring.

Original plans called for the use of a tuner in the ring to eliminate any backward wave that might be set up by unavoidable mismatches within the ring. The tuner consisted of the conventional arrangement of a short-slot hybrid, the coupled waveguides being terminated at one end by two chock-type sliding shorts. It was found that, although this arrangement was effective, it introduced excessive loss. Therefore, it was decided to tune out the reverse wave by means of a variable load (matched load preceded by slide-screw tuner) at the output end of the main arm of the feeding directional coupler. This arrangement added substantially less attenuation (estimated from separate measurement to be about 0.65 db total) and served very well to eliminate the backward wave.

Using a swept X-band oscillator (HP model 686 A) and a dual-trace oscilloscope for displaying the output of the monitoring crystals, one could observe typical resonance response curves for both forward and reverse waves. These resonances were about 9 mc apart in the neighborhood of 10 kmc, in agreement with the estimate of 950 wavelengths for the overall length. Rough measurement of the Q (about 20,000) gave good agreement with the value (24,000) calculated using a formula given by Miller[2] and based on the assumption of an over-all ring attenuation of 0.65 db and a measured coupling of 10.4 db at the test frequency.

Measurement of the apparent power magnification at 8.9 and 9.2 kmc gave 7.8 db $\pm$ 0.2 db for a coupling of 11.4 db. Upon calculation (see Ref. 1, p. 6), this corresponds to 0.65 db over-all attenuation for the ring, precisely the value calculated independently from separate measurements. The optimum magnification for the 0.65 db figure would be 8.55 db, which is also the optimum coupling value. This coupling value could also have been achieved by using a variable directional coupler made from a conventional system of three 3 db short-slot hybrids and two ganged plungers. However, the additional losses introduced by the extra lengths of line needed to accommodate this coupler into the ring would actually have resulted in a drop in magnification.

A test was made of the power build-up in the ring under pulsed conditions. For this purpose, a pulse generator of 0.02 microsecond rise-time, and a coaxial-type X-band crystal diode modulator (rise time of less than 2.5 nanoseconds) were used to modulate the rf. The build-up time for 80 percent or so of the steady-state power in the ring was measured as lying between 1.5 and 2 microseconds while calculation gave a figure of 1.4 microseconds.

Finally, tests were made on the ring with a ferrite switch inserted. (This switch and its associated circuitry is described in the Section 4 below.) The insertion loss of the switch was between 0.2 and 0.3 db and thus reduced the magnification of the ring to about 6 db. The operation of the TWF was tested with both cw and pulsed rf power. Fig. 6 shows the envelope of the rf power switched out of the ring under three different switching currents. (The time scales on the oscilloscope trace are respectively 10 mμs, 20 mμs, and 50 mμs per division in Fig. 6 a, b, and c, with switching currents of 120, 55, and 38 amperes respectively.) The duration of the output pulse appears to have been about 0.110 microseconds and the rise time of the pulse, as observed on the scope (Tektronix 545 A), ranged from about 20 mμs at the lowest switching current to about 10 mμs or less at the highest switching current. The rf power used was in the milliwatt range.

It should be mentioned that the existence of interfering higher mode resonances at a number of frequencies could be detected by the distortion that coupling to such a resonance produced in the resonance curve of the TE_{10} mode. This type of distortion differed from that which ordinarily occurred as a result of a backward wave resonance set up by reflecting discontinuities in the ring in that it could not be reduced or eliminated by the available tuning arrangement. It might have been possible to reduce this type of distortion or to decouple the resonances through a tuning element in the oversized waveguide but no provision had been made for this and so this method was not tried. Instead, the ring was operated at frequencies where this type of interference did not occur

4. Fast Ferrite X-band Microwave Switch

The ferrite switch used in the prototype X-band TWF is actually a switching circulator[7] developed at the Microwave Research Institute. It consists of a folded magic-tee, two parallel sections of ferrite-loaded waveguide having a differential phase shift of 90 degrees, and a short-slot hybrid as shown in Fig. 7. Each ferrite section is in the form of a narrow-rectangular tube through which runs a wire which carried the pulsed current creating the magnetic field which switches the magnetization of the ferrite. The two ferrite sections simultaneously undergo a reversal of magnetization when a pulse of current of sufficient magnitude and proper polarity is passed through the wires. This results in a reversal in sign of the differential phase shift and a corresponding reversal of the sense of circulator action. Milli-microsecond switching of the circulator requires rather large currents to be switched rapidly. The rise time for the microwave switching is essentially the same as that of the switching current (for the range of currents tried) and this depends basically on the ratio of inductance L to resistance R in the dc circuit. The lower limit on L is ultimately set by the quantity of ferrite material used in the microwave circuit, but R can be made sufficiently large to give reasonably short switching times. This is accomplished by use of a dc current source whose impedance is large relative to the effective resistance of the single turn of wire producing the switching magnetic field.

The current source used with the ferrite switch was actually a 300 foot length of RG-8/U cable of 50 ohms characteristic impedance, open circuited at its far end and having its outer conductor at the near end connected to the dc winding of the ferrite cores. The cable is short-circuited through this winding via a 5C22 thyratron tube (T_1) in response to an appropriate trigger pulse at the grid of the tube. (See Fig. 8a.) The current waveform, consisting of two pulses of opposite polarity in immediate succession, is shown in Fig. 8b. A peaking capacitor (not shown) is used at the input of the cable to improve the rise time. A more complete description of this circuit is given in Reference 8.

5. Fast High Power C-band Microwave Switch

As part of the C-band TWF power enhancement program work on a fast microwave switch has been in progress with the aim of realizing the following specifications:

switching time:	$<$ 30 nanoseconds (3×10^{-8} sec)
microwave holdoff power:	$>$ 1 megawatt (peak)
arc losses:	$<$ 0.25 db
isolation*:	$>$ 40 db
cold insertion loss:	$<$ 0.1 db

The type of switch under development is essentially a microwave thyratron (referred to as a low-pressure arc-discharge gaseous shutter). A schematic showing the essentials of the switch construction is shown in Fig. 9. The switching action is performed by the rapid ionization of the low pressure gas filling the rectangular waveguide section and the creation of a sufficiently high electron density so as to convert the ionized gas into a medium that is incapable of propagating electromagnetic energy at the operating frequency.[4] Thus, the permittivity of the gas becomes negative, and the discharge region exhibits the properties of a beyond cut-off waveguide which in turn causes the incident wave to be almost completely reflected. The rectangular waveguide itself, suitably perforated, serves also as the control grid for the gas-filled thyratron.

The work on this switch has progressed to the point where the grid aperture dimensions for satisfactory operation of the tube have been determined. Simulated tubes, using different hole sizes for the grid apertures, were fabricated and tested. It was found that the best operation was obtained with 1/8" diameter holes. When the tube was filled with hydrogen at 0.7 mm of Hg pressure, the anode holdoff voltage was as high as 20 kv and the peak current 225 amperes. The corresponding grid trigger voltage was as low as 50 volts. The electron density for the physical area of cathode used at the above current was estimated to be approximately $2 \times 10^{13}/cm^3$ as compared with the required value of $5 \times 10^{11}/cm^3$ for C-band microwave switching. Microsecond pulses at 1000 pps were used in the tests.

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*This is defined as 10 log (P_{in}/P_{trans}) where P_{in} is the incident power and P_{trans} the power transmitted past the switch in the fired condition.

The construction of a high power test facility for testing arc-discharge switch tubes has been included as part of the switch tube development program (see Fig. 10). This facility is fully described in Reference 4 and will be useful both for testing switch tubes as well as waveguide pressure windows.

M. Sucher

IV. Interaction of High Microwave Power and Fields with Materials

Personnel: Professor H. Farber, J. Brogan, V. Nanda, E. Moley, E. Malloy, and N. Poley

During the period covered by this note this group has been primarily engaged in developing suitable techniques and equipment required in the study of the interaction of high power and high fields with various materials. The objectives included the design of a special "sway back" section for subjecting materials to high power densities and the investigation of special "electrodeless microwave cavities" for the study of intrinsic and possible free surface breakdown effects. Because of the importance of the "microwave switch", as indicated earlier in this report, and because of the experience of this group with discharges, the relatively high pressure, d. c. triggered rf discharge is also being worked on within this group.

The efforts of the group are concentrated currently on three phases. These are:

1. to study thermal failure (due to microwave fields);
2. to determine the mechanism and the characteristics of a dc triggered microwave spark gap and;
3. to develop a suitable microwave test cell for measuring the intrinsic electric strength of dielectric materials (solids and liquids).

Phase I: Thermal Breakdown of Dielectric Materials at Microwave Frequencies

The two most probable methods for the breakdown of dielectric materials at microwave frequencies are breakdown due to discharges in gas voids in the material and thermal breakdown due to the dielectric heating of the material. Since the electric fields within the void are greater than in the dielectric material, (for small cylindrical voids which are coaxial with the electric field the field in the void is increased by a factor equal to the dielectric constant) breakdown occurs at relatively low microwave peak fields and, consequently, for pulse conditions at low average power levels.

The breakdown in the dielectric is usually characterized by one or more narrow, localized channels through the material although the bulk of the material may not be affected.

For thermal failure at microwave frequencies appreciably higher average powers are needed. However, the required fields are far below the intrinsic electric strengths of the dielectric materials. The thermal failure is characterized by the destruction or decomposition of the bulk material near the regions where the electric field is high.

A "swayback" section of waveguide (Fig. 11) was designed for use as the dielectric test cell. The height of the waveguide was decreased in the center section by a factor of 29 which results in an equal increase in power density and an increase in field strength by a factor of 5.4. The length of the tapered section in the initial unit was 1 1/2 guide wavelengths. However, this unit had a high insertion VSWR and another section was designed and constructed with a 3 1/2 wavelength taper. Although the VSWR was decreased the minimum VSWR was 2.0. By increasing the gap height by a factor of 2 it was possible to attain an insertion VSWR of 1.05 at 5.3 Gc (which corresponds to the output frequency of the available magnetron). The resultant power density increase in the tapered section is 14.5 times. With a short circuit termination the apparent increase in power density is 58. The microwave circuit in which this cell is used is described in reference 4.

Phase II: A DC Triggered Microwave Spark Gap

Triggered spark gaps have been used as dc protective devices and switches. In general these are spark gaps which are maintained at voltages which are 50-90 percent of the breakdown strength of the spark gap. When a trigger voltage is applied between one of the gap electrodes and an auxiliary electrode a discharge develops in the spark gap. The specific mechanism or mechanisms which occur are not fully understood but the time delay for developing the discharge has been shown to be a function of the trigger voltage, the hold-off voltage across the spark gap, and to a lesser degree the geometry of the spark gap and auxiliary electrode.

Schwartzkopf* has demonstrated that for moderate microwave powers it is possible to construct a switch which is capable of switching within a few nanoseconds.

The objective of this phase is to study the discharge parameters which may relate to the speed of switching, the microwave power capacity and the insertion losses before and after switching. The results of the study should lead to an understanding of the mechanism of the switch and indicate how to design a switch for a given microwave power

* Private communication

A microwave spark gap has been designed and constructed (Fig. 12 a). The dc trigger will be applied using a standard automotive spark plug. A dc test jig (Fig. 12 c) has also been constructed to determine the dc characteristics of the trigger electrode. An impulse generator has been assembled using the modulator section of an airborne radar unit (APS/2). Impulses of 15 kv with 0.01 μ sec rise may be obtained from this unit.

The initially proposed theory for the time delay dependence of the switch is related to the results of impulse breakdown of air. It has been shown that the time for breakdown is related to the overvoltage ratio of the applied impulse. The overvoltage is defined as the ratio of the voltage at which the air breaks down for the impulse to the minimum dc voltage at which air breaks down. Thus for a ratio of 1 the time for breakdown is several microseconds whereas for a ratio of 2 it is several nanoseconds.

The initial studies will determine if a linear superposition of the dc trigger voltage and the microwave field would have the same time delay as the equivalent impulse voltage. Another discharge parameter that may affect switching times is photo-ionization. There are some triggered spark gaps which depend solely on photo-ionization rather than a triggering spark. However, the hold-off voltage must be within 5-10 percent of the breakdown voltage in order to obtain switching action. For the discharge triggered gap, the hold-off voltage may be in the range of 50-90 percent of the breakdown voltage and the higher the voltage the faster the switching action.

Phase III: Microwave Test Cell for Intrinsic Breakdown Studies

The intrinsic electric strength of dielectric materials is so high that the electric fields required for breakdown approach the fields required for electron field emission from the electrodes. Field emission would modify the measured value of the electric strength. Although electrodes (or their equivalent) are necessary for establishing static electric fields it is possible to establish high frequency electromagnetic fields without electrode surfaces. (For this discussion an electrode surface is considered to be a metal surface or electric charge at which a normal electric field is terminated.) Thus the initial study has been to determine the feasibility of obtaining high electric fields which may be capable of breaking down dielectrics but do not terminate on metallic surfaces.

Several methods have been used to obtain higher electric fields than exist in standard transmission lines. These include:

a) A transmission line terminated by a short circuit will have regions where, the field is twice that of a transmission line terminated in its characteristic impedance.

b) Decreasing the waveguide size may increase the field by a factor of 5-10 times; e.g., decreasing the height of a rectangular waveguide operating in the H_{01} mode by a factor of 30-100 times would increase the field by a factor of 5.5 to 10 times.

c) A traveling wave resonator could increase the electric field by a factor of 3 to 6 times although it is very sensitive to small losses in the system.

d) Resonant cavities have been used to obtain increases in field strength by factors ranging from 9 to 3000 times.

e) Combinations of the above procedures may also be used to obtain high electric fields.

The optimum procedure for developing the electric fields required for intrinsic breakdown is the one using the resonant cavities. (The cavity could be used with the traveling wave resonator.) However, to obtain very high field gains one generally uses an operating mode where the electric field is normal to the bounding metal walls.

An analysis was made of the cylindrical cavity resonating in the H_{011} mode where the electric field is parallel to metal surfaces. For a frequency of 5 Gc with 1 megawatt input the maximum field would be 0.2 Mv/cm, or 25 megawatts input power would be required to attain a field of 1 Mv/cm. Previously measured values for the electric strength of polyethylene report a value of 7 Mv/cm which would require an input of 1250 Mw if the Q of the cavity were to remain 5000 with the dielectric sample in it.

A limited survey is planned of other possible cavities to determine if a modification of the geometry would give appreciably greater electric field gains and still retain the desired field configuration.

The proposed program for the following periods is as follows:

Phase I: The immediate program is to carry out measurements of the thermal breakdown of several dielectric materials. It is anticipated that these measurements will permit determining the parameters (of the dielectric and of the microwave field) which influence thermal breakdown. Consideration is also being given for the design of suitable test cells for studying the behavior of metals interacting with very high microwave fields.

Phase II: The program for this phase is to determine the parameters of the dc triggered microwave spark gap which influence the switching time and the insertion losses of the switch. The overall objective is to understand the mechanisms of the switch and to design a high power switch with the following specifications:

1) capable of handling the power developed in the microwave flywheel;
2) less than 0. 1 db insertion loss prior to switching;
3) less than 1 db insertion loss during switching into the circuit;
4) switching time less than 10 nanoseconds.

Phase III: The immediate program will be to continue the present study to determine the feasibility of designing an electrodeless microwave fast cell for studying intrinsic breakdown of dielectric media. Subsequent work will be to study the intrinsic strength of materials (solids and liquids) in order to obtain a better understanding of the structure of these materials.

H. Farber

V. Conclusions

By virtue of tests on the prototype X-band low power flywheel and calculations on the modal stability, a microwave flywheel of the type indicated appears to be realizable if a high power switch of appropriate type can be developed.

In the future, major experimental effort will be devoted to the development of a microwave switch including the dc induced microwave discharge at atmospheric pressure and the thyratron type of switch. The state of development of the multipactor switch will be closely followed.

The cavity type flywheel will be considered in more detail particularly with regard to methods of coupling and type of switching components.

Under the investigation of the interaction of high power with materials, specific dielectrics will be tested in the swayback cell for thermal failure at increased power densities. Further consideration will be given to the question of realizing intrinsic breakdown in electrodeless cavities.

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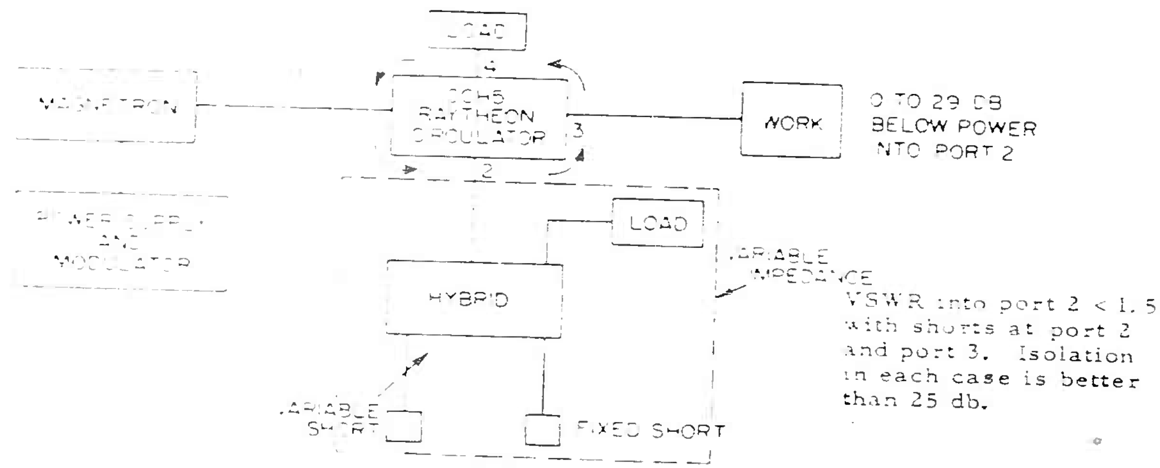


FIG. 1

MRI- 18374

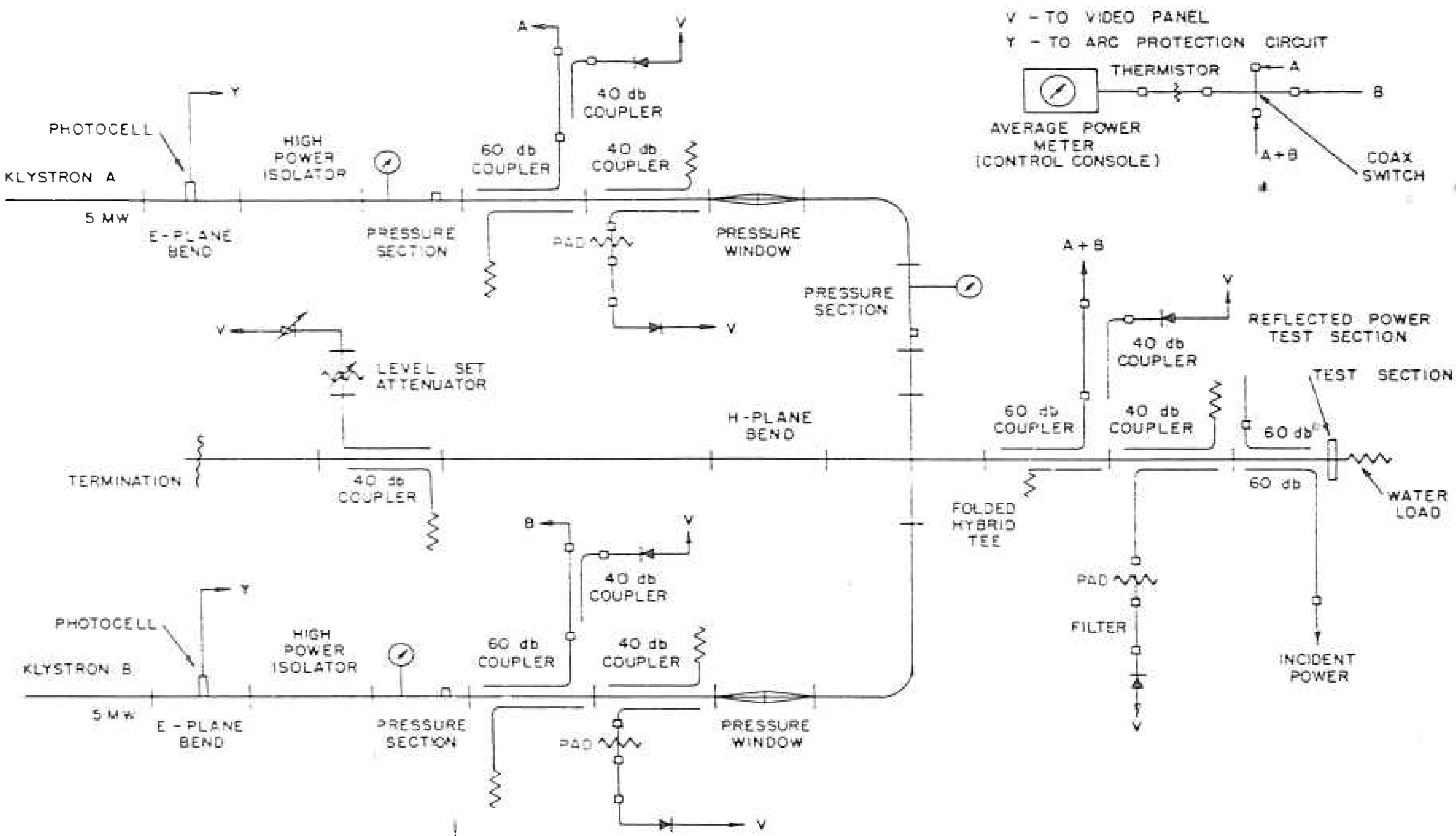


FIG. 2 RF OUTPUT CIRCUIT

MRI - 18354

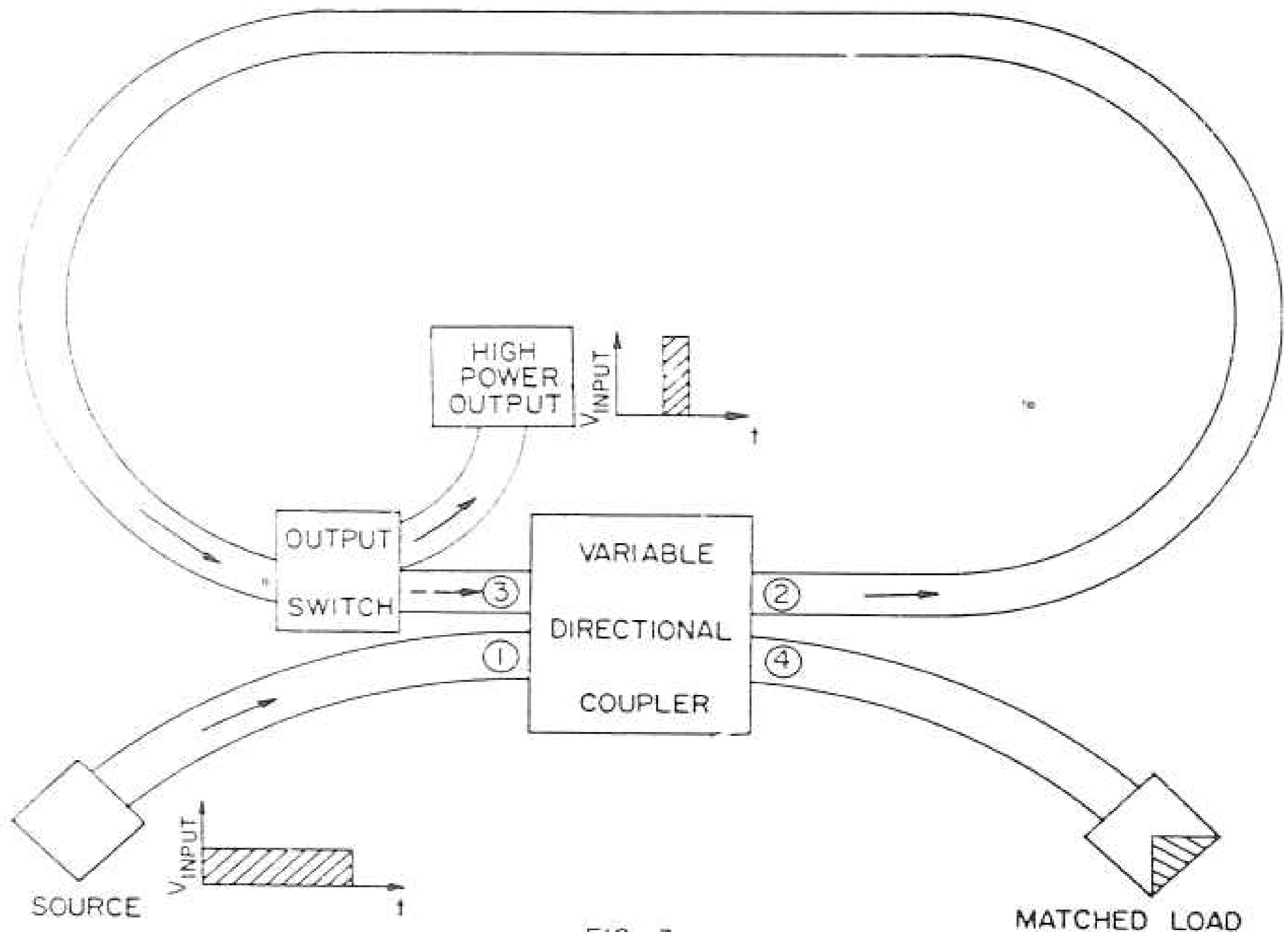


FIG. 3

MRI-18372

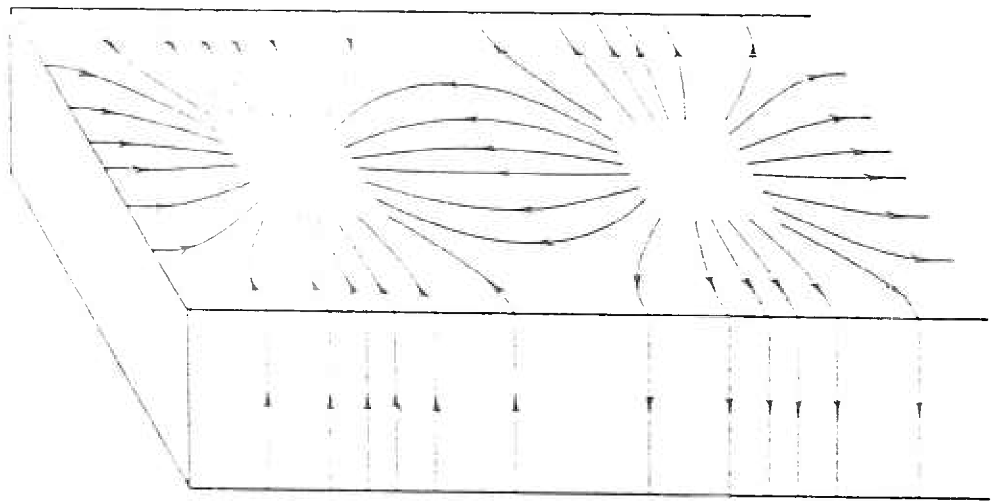


FIG 4 CURRENT FLOW IN WALLS OF RECTANGULAR GUIDE WITH TE_{10} MODE

MRI-18370

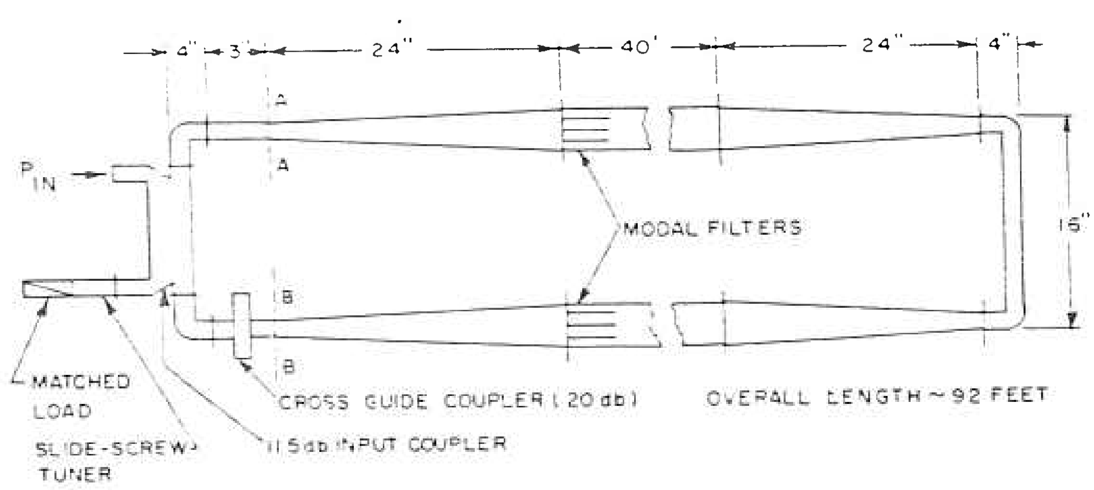

4"
3'
24"
40'
24"
4"
A
A
B
B
P IN
MODAL FILTERS
16"
MATCHED LOAD
SLIDE-SCREW TUNER
11.5db INPUT COUPLER
CROSS GUIDE COUPLER (20 db)
OVERALL LENGTH ~ 92 FEET

FIG. 5

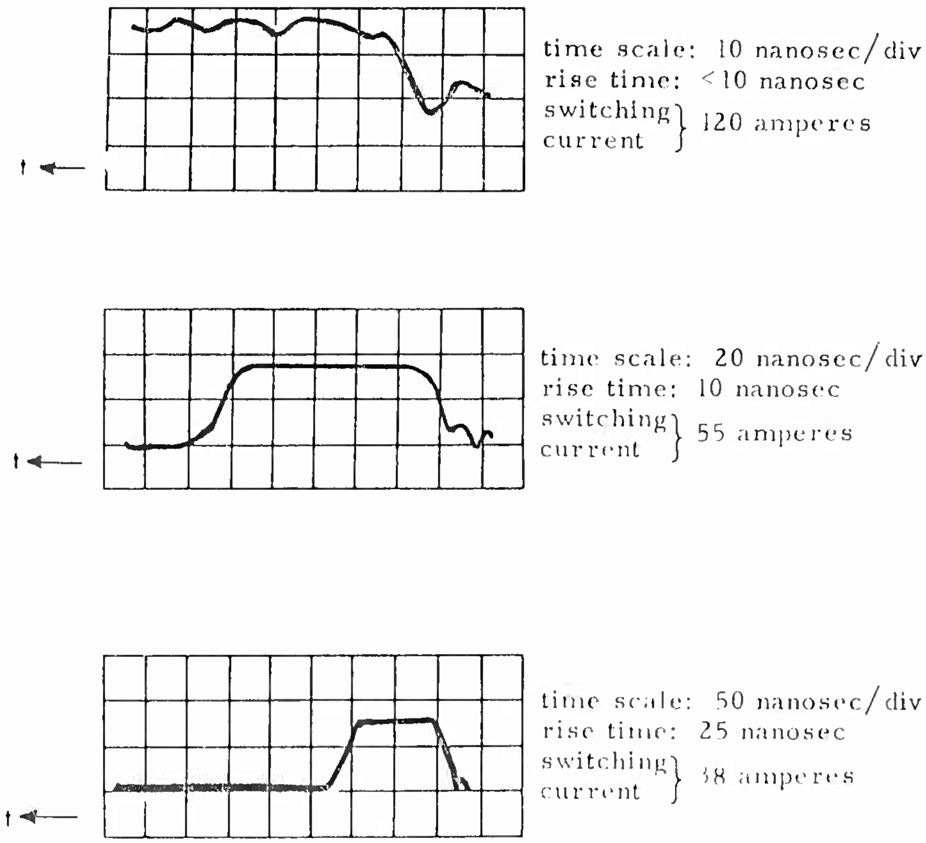


FIG. 6

General Legend: RF Envelope of Prototype X-Band Ring Output Pulse Using Ferrite Switch

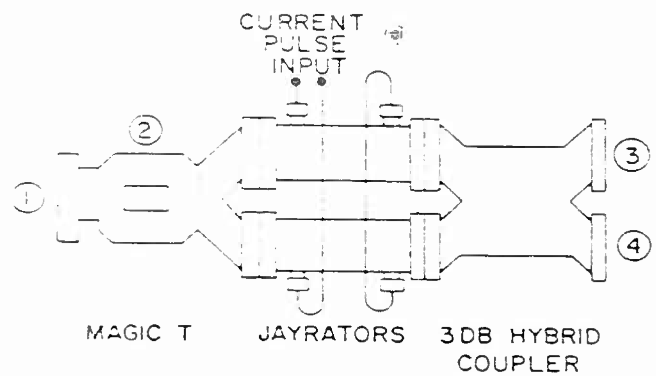
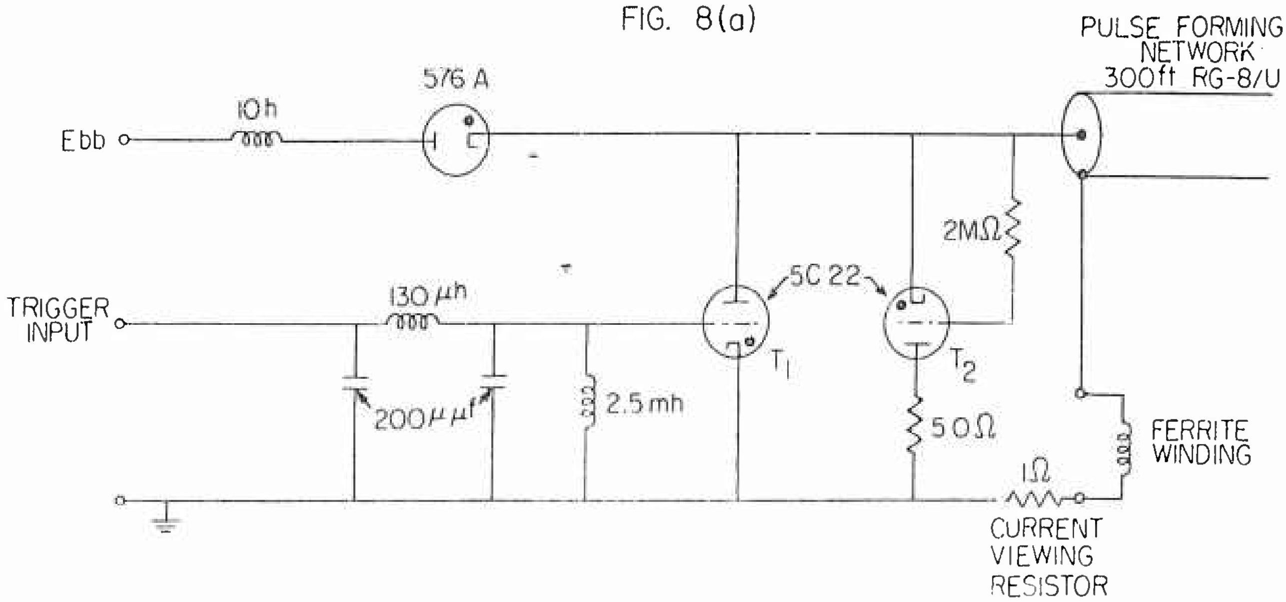


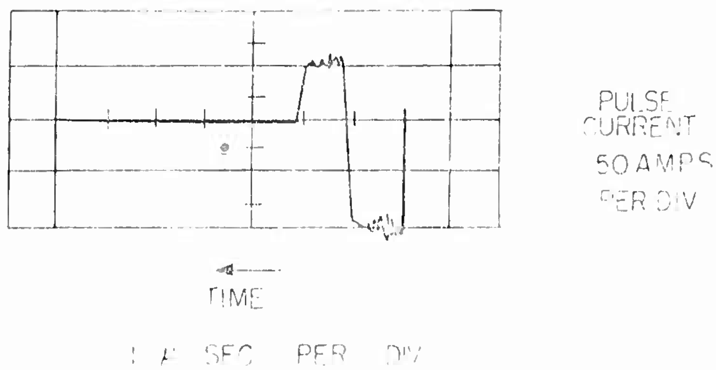
FIG. 7

MRI-17512

FIG. 8(a)



FERRITE CURRENT
SCHEMATIC OF PULSE GENERATOR



ACTUAL CURRENT WAVEFORM
(POLARITY INVERTED)

FIG. 8(b)

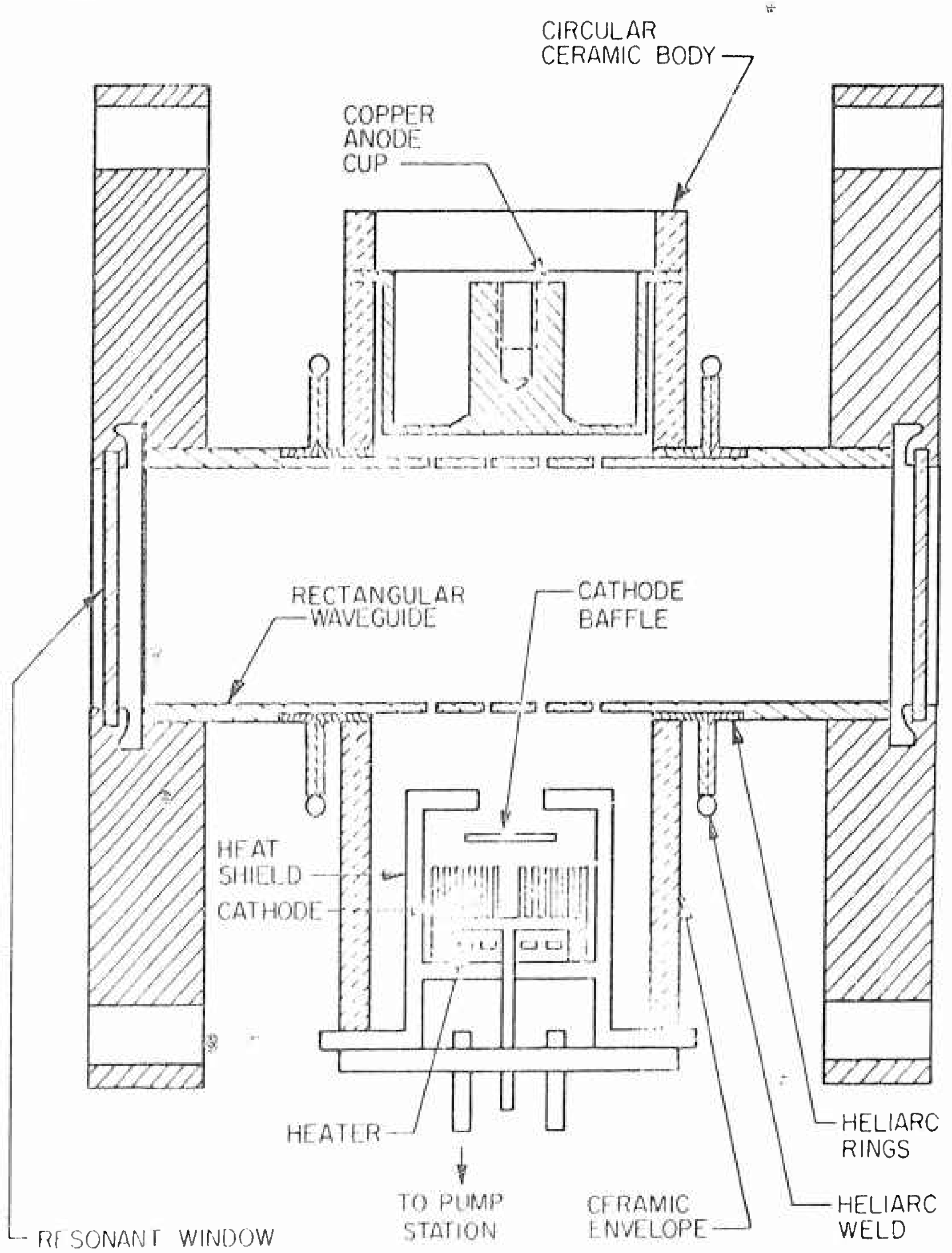


FIG 9 LOW-PRESSURE ARC-DISCHARGE GASEOUS SHUTTER

MRI-18375

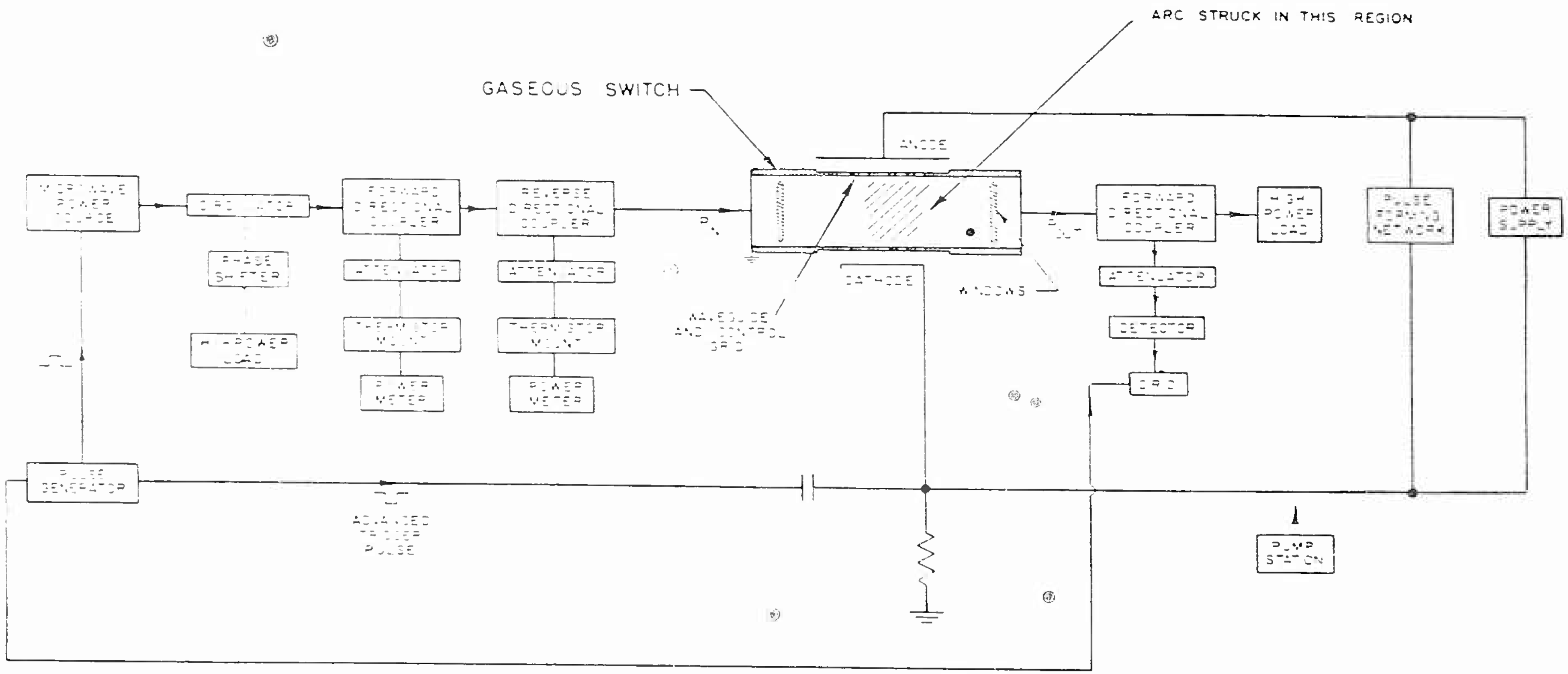


FIG 10 HIGH POWER TEST FACILITY

MRI - 18371

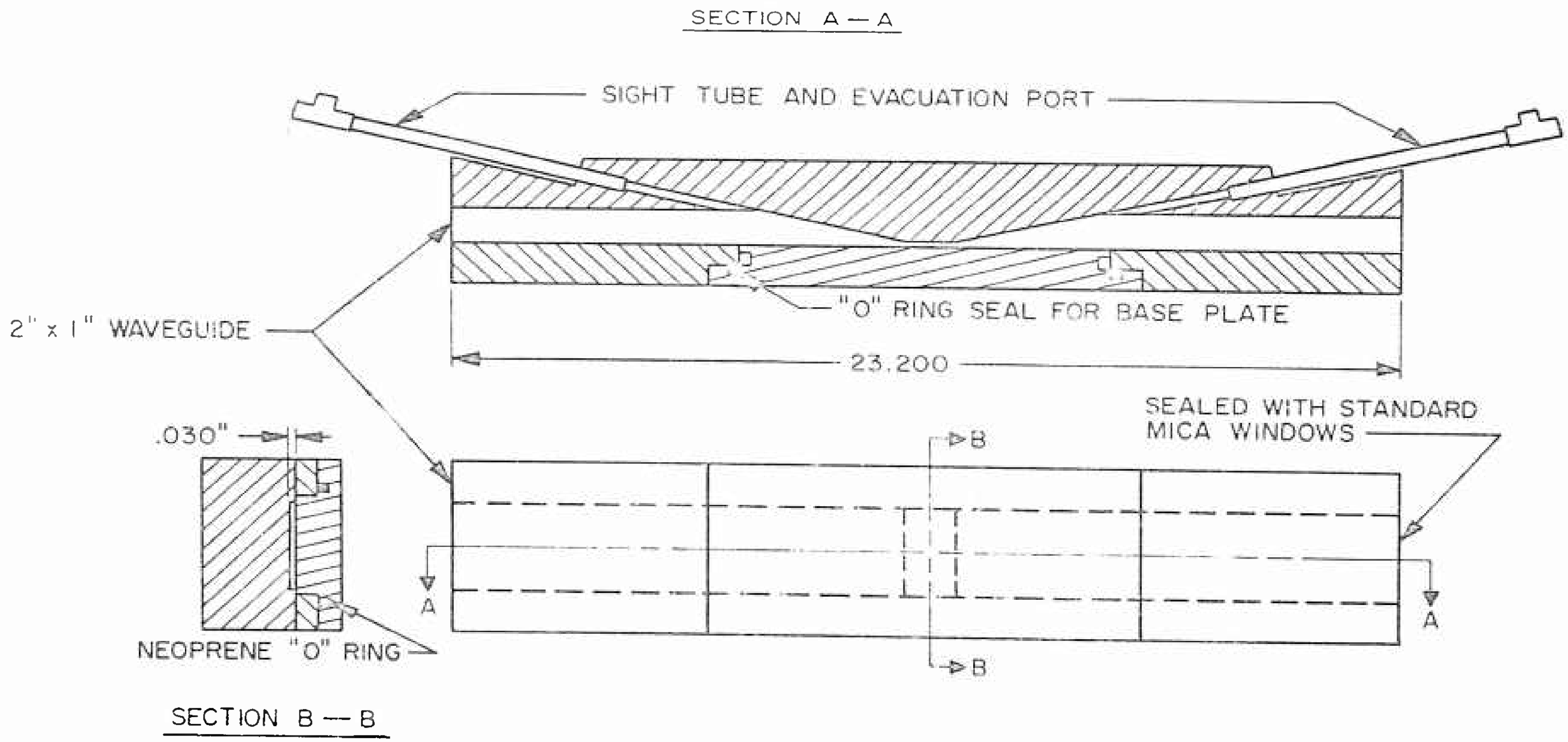
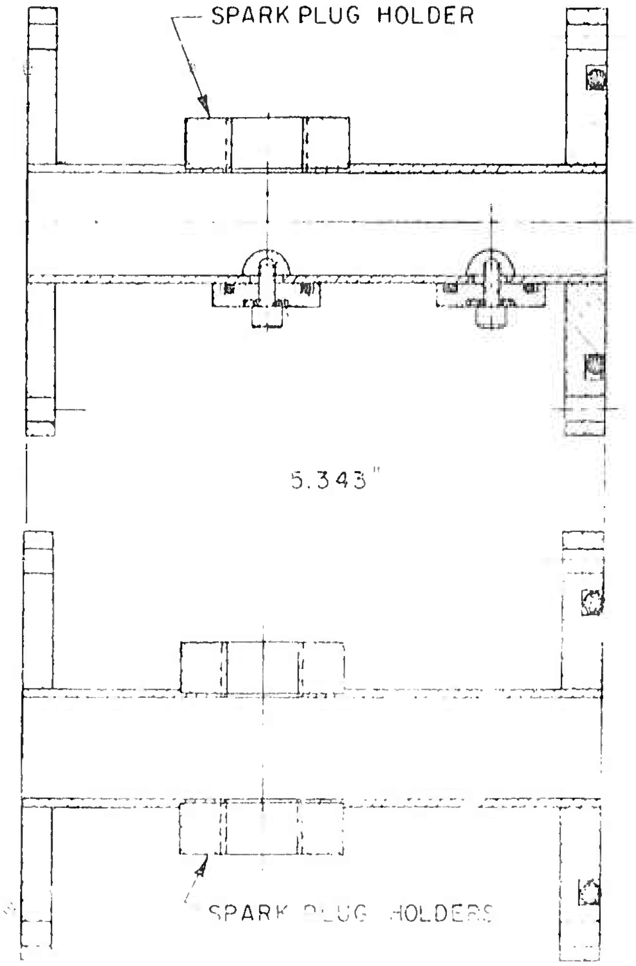


FIG. 11

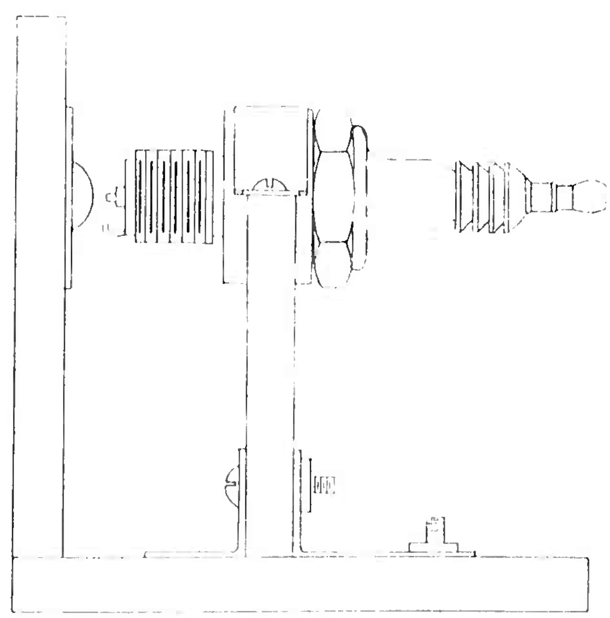
MRI — 18139



(a)

(b)

(a),(b) - EXPERIMENTAL SPARK GAPS



(c)

Fig. 12

MRI-18227

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