MAGNETRON RESEARCH AT
COLUMBIA RADIATION LABORATORY*

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Current magnetron research and development at Columbia Radiation Laboratory is principally directed towards the production of the shortest wavelengths in the millimeter region; the development of high power in the millimeter region; the development of wide range tunable tubes ; and the investigation of low field magnetron operation.

The efforts to produce short wavelengths have been along two lines - first, by conventional magnetron techniques and second, by what has come to be known as "low-field" operation. The relationship between the operating voltage and the applied magnetic field of a conventional magnetron is given by the Hartree equation

$$\frac{V}{V_o} = \frac{2B}{B_o} - 1$$

where

$$V_o = 2.52 \times 10^6 \frac{D_A^2}{n^2 \lambda^2} \text{ volts}$$

$$B_o = \frac{21,400}{(1 - \sigma^2) n \lambda} \text{ gauss}$$

V_o - characteristic voltage magnetron
B_o - characteristic magnetic field of magnetron
D_A - anode diameter
n - mode number (for π - mode $= \frac{\text{number of resonators}}{2}$)
λ - wavelength
σ - ratio of cathode diameter to anode diameter

For conventional magnetron operation the values of magnetic field usually employed lie between $2B_o$ and $3B_o$ which, according to the Hartree relationship, makes the operating voltages between $3V_o$ and $5V_o$.

Conventional Magnetrons

The conventional millimeter magnetrons are designed as scaled versions of 1.25 cm pulsed tubes developed at the laboratory during World War II. The basic anode structure which has been found to be most satisfactory for these tubes is a 22 vane rising-sun type circuit.[1] Consistently good results have been obtained at wavelengths of 3.3 mm and above. A performance chart for a 3.3 mm tube is shown in Fig. 1. At an operating point such as 10 kv and 10 peak amperes a magnetic field of 20,000 gauss is required. For maximum efficiency however a field of about 26,000 gauss is required. This value of field is about the maximum obtainable in the laboratory with the electromagnets available. Tubes such as this one have operated at 10 kw output for 100 hours with a maximum deterioration in power of about 30%. In order to avoid excessive back heating of the cathode the duty cycle is kept quite low ($\frac{1}{4}$ μs, 500 cps). A considerable effort to continue the scaling procedure to 2.5mm has been made, with quite unsatisfactory results.

Some of the important dimensions of the anodes used for the millimeter magnetrons are tabulated in Table 1. Of particular interest are the numbers for the 2.5 mm tube. One probable cause of the poor results obtained at this wavelength is the poor anode quality which is obtained with the indicated dimensions. Another serious limitation is the high magnetic field required. Since B_o is 13,000 gauss, one could expect a minimum field of 26,000 gauss to be necessary for effective operation to begin, with a significantly larger field required for efficient operation.

The possibility of producing millimeter power at a 100 kw level was investigated at 6.3 mm. The typical operating point of the 6.3 mm tube shown in the second column of Table 1 is about 15 kv and 15 pk amperes with a power output of 40 kw. To obtain 100 kw at the same efficiency requires an increase of input power by a factor of 2.5. This can be accomplished by an increase in voltage by increasing V_o by a factor of 1.6 and an increase in current by increasing the anode height by the same factor of 1.6. The scaled dimensions of the anode are shown in the last column of Table 1. The performance chart for one of the better tubes in this series is shown in Fig. 2. The 100 kw operating point is easily achieved at 20 kv and 25 peak amperes at an efficiency of 20%. (For powers above 75 kw it is necessary to pressurize the waveguide with CO_2 gas.) The duty cycle is purposely kept low to insure no damage to the glass window used on this tube. Some of the more recent tubes have been made with Alsimag #243

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windows and it has been possible to increase the duty cycle by a factor of 5. The average input power limitation is then determined by the back heating of the cathode. Several tubes have delivered 25 watts of average output power. It has also been possible to obtain 200 kw from one of these tubes.

To make successful, reproducible millimeter tubes it has been found that in addition to a high quality anode, accurate cathode centering must be maintained. Consistent results were achieved only after the incorporation of a cathode centering device on each millimeter tube. Fig. 3. The cathode stem can pivot about the braze joint to the kovar cup when pressure is applied to the ball bearings by the rotation of the tapered threaded pins. By the proper combination of pins the cathode may be moved while the tube is in operation so that maximum output at a fixed operating point is obtained. At a fixed voltage and magnetic field this occurs at a current minimum, suggesting that the optimum cathode position is in the center. Some tubes which are inoperable when first put on test can be made to operate quite efficiently when the cathode is thus centered.

The investigation of the wide range tuning possibilities of the rising sun anode structure has been concentrated at 1.25 cm. The basic scheme which has been investigated is a "crown of thorns" tuner in which pins are inserted in the large resonators only. A large amount of preliminary theoretical work has been carried out in order to investigate the effects of various choices of resonator dimensions and pin sizes, and to compare the effects of capacitive and inductive pins. The dimensions of the resonators are such that one requires a electromagnetic field calculation rather than one based upon estimates of lumped parameters. Some general features of the results are:

(1) For inductive tuning the hole and vane structure is quite superior to the conventional vane type (sector shaped) resonator (Fig. 4.) Furthermore, optimum tuning is obtained only for a judicious choice of hole size and resonator ratio. An oversized hole may have a significant capacitive region. Thus the effect of pin insertion on the inductance is partly counterbalanced (and may even be overbalanced) by an increase in capacitance.

(2) Capacitive tuning is quite superior to inductive tuning. The rising sun structure has the property that the small resonators and interaction space are almost entirely inductive, so that most of the tube capacitance is in the large resonators.

(3) The best tuning ranges are obtained with rather large resonator depth ratios. Magnetron operation, however, becomes unstable if the ratio is too large. This difficulty can be overcome by closing the ends. Since closing the ends reduces the tuning range a judicious balance is again required. Our present judgment is that it is best to leave the ends open and allow the tuning range to be restricted by the maximum useable ratio.

The most promising design which we have studied is the sector type illustrated in Fig. 4. Tuning ranges of 18% have been measured on two tubes which have been tested to date. While power is quite variable over this range, encouragement can be drawn from the fact that the power is quite high at both ends of the tuning range. The presence of unwanted resonances is being investigated at the present time.

Low Field Operation

The British work of Willshaw and coworkers showed that magnetrons with very small cathode diameters could be made to oscillate with reduced efficiences at magnetic fields about 25% of the conventional values. The anode structure they used was the same 28 resonator rising-sun structure which was used for conventional high field operation.

Since one of the limitations in obtaining conventional magnetron operation below 3 mm is the high magnetic fields required the low field approach looks promising for this wavelength region.

Many aspects of low field operation have been investigated in the wavelength range from 1.3 cm down to 1.0 cm. For this purpose a 20 vane rising-sun anode was employed. The principal characteristics of the operation of one of these tubes is shown in Fig. 5. The cathode diameter in this tube was about 2/3 normal size. This reduction in cathode diameter reduces B_0 to about 75% of its value with a normal size cathode. The vertical line at each magnetic field value shows the voltage range over which the tube oscillates. The numbers indicate the maximum power and maximum efficiency associated with each line. The solid circles are points at which the peak current is 1 ampere. The main distinction from normal operation is the fact that operation now takes place on a line below and almost parallel to the Hartree line. This is quantitatively similar to the British results. The second feature to be noted is the low value of B/B_0 at which operation begins. The actual value of field in this case, 2400 gauss, should be compared with 5000 gauss as the lowest field necessary for normal operation. Particularly similar to the British results are the facts that operation begins at voltages near V_0 and that the efficiencies are similar. A major difference is the operation over a much wider range of magnetic field than their 8%. Also only a $(\pi-1)$

mode is observed in addition to the π mode whereas they observed many more modes. One particular feature of the operation of this tube is the small range of current - only 4 amperes - as compared with the greater than 15 ampere range of normal tubes.

The dependence on operation of the following parameters was studied:

σ - the cathode-anode diameter ratio was varied from 1.7 to .63 (normal size). The maximum efficiency does not vary appreciably. However, the current range increases as does the value of magnetic field required. For next to the largest ratio used (.58) at the higher magnetic fields an abrupt change from sub-Hartree to Hartree voltages with two efficiency maxima was observed. This gives support to the view that two different types of operation are involved.

r - the ratio of resonator depths of the large to small resonators was varied from 1.9 to 2.5. The operation at the higher ratios is not quite as good as the operation at the smaller ratios. However, it is possible to obtain mode free operation at a 2.5 ratio, which is not possible with normal Hartree operation. It therefore appears that mode selection criteria for low field operation differ from those for conventional operation.

N - several 30 resonator tubes were also built. These results were much more similar to the British than were the 20 vane results. The magnetic field is further reduced due to the increase in N but the range of fields is restricted to about 10% variation. Operation takes place at fields between 1600 and 2000 gauss. The current range is however restricted to about 1 ampere.

V_o - the anode diameter of the 20 vane tube was increased to raise V_o from 3.0 to 7.9 kv. This automatically lowered the wave length to 1.0 cm from the original 1.3 cm. The efficiency of these higher voltage tubes remained the same as the lower voltage tubes, but the current range increased to as much as 15 amperes. The increased input resulted in power outputs as high as 7 kw. These results were encouraging enough to begin work at shorter wavelengths.

The high power 22 vane 6.3 mm tube whose dimensions are given in the last column of Table 1 was used to try "low field" operation at millimeter wavelengths. The anode diameter was enlarged to raise V_o from 5.1 to 8.1 kv. The wavelength was consequently reduced to 5.7 mm. The cathode anode ratio was chosen as .45, which ratio was found to yield the best results at 1 cm. The performance chart for one of these tubes (Fig. 6) shows that the efficiency and power were higher than at longer wavelengths. Also the highest efficiency was at high currents. The magnetic field was very low for such short wavelength. The figures in parenthesis after each field line value indicate the values of B/B_o. The voltage field plot for this tube (Fig. 7) shows that operation is quite normal - on or above Hartree line - exactly like a large size cathode tube. The failure of the sub-Hartree operation to scale to this wavelength is not yet understood. However, this tube is not an isolated case. Other tubes at the same wavelength with similar efficiencies and powers operating on or above the Hartree line have also been made. An extension of the same type of operation to still shorter wavelengths would eliminate the magnetic field limitation encountered with conventional magnetrons.

An anode designed for "low-field" operation at 2.6 mm has an anode diameter of .0635 in. and a vane thickness of .005 in. This should be compared with the .038 in. and .003 in. for a conventional high field anode. (Table 1) A high quality "low-field" anode has been fabricated and quite a number of tubes have been made with varying results. A power output of 3.3 kw at an efficiency of 2.5% has been the best operation to date. Several other tubes have delivered 1-2 kw at about 1% efficiency. Operation takes place at about 15,000 gauss, between 19 and 20 kv. This operation is on or above the Hartree line as was the case at 5.7 mm. However severe arcing takes place at these high voltages which limits the life of the tubes to several hours. An anode of somewhat reduced voltage (20% less) has been designed and fabricated. These lower voltage tubes are being worked on at the present time. It is hoped that more reproducible, more efficient, longer lived tubes can be made at the reduced voltage at the 2.6 mm wavelength.

References

1. Microwave Magnetrons Vol. 6 MIT Radiation Lab. Series, p. 790-1.

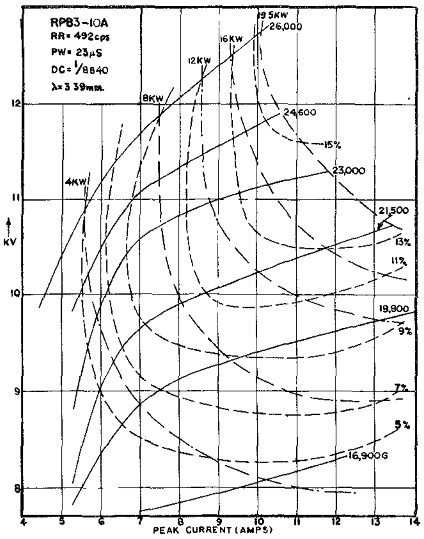

Fig. 1 - Performance chart for 3.3 mm 22 vane conventional magnetron.

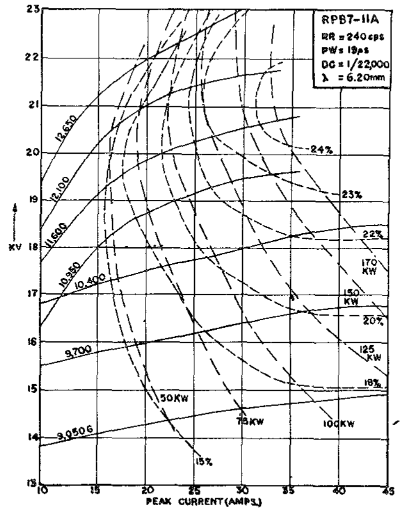

Fig. 2 - Performance chart for 6.2 mm 22 vane high power magnetron.

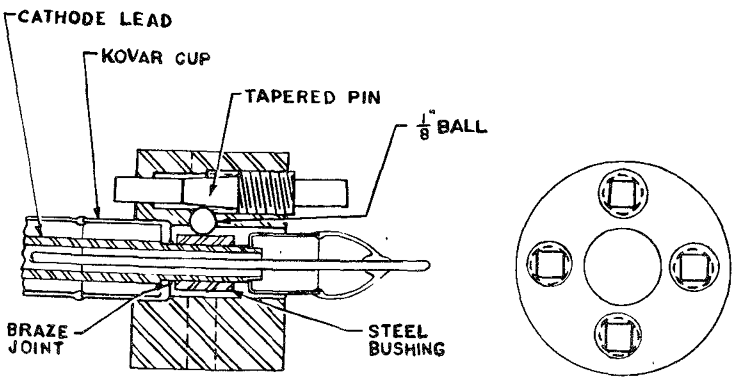

Fig. 3 - Cathode centering device.

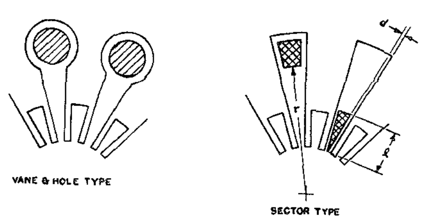

Fig. 4 - Tunable anode structures.

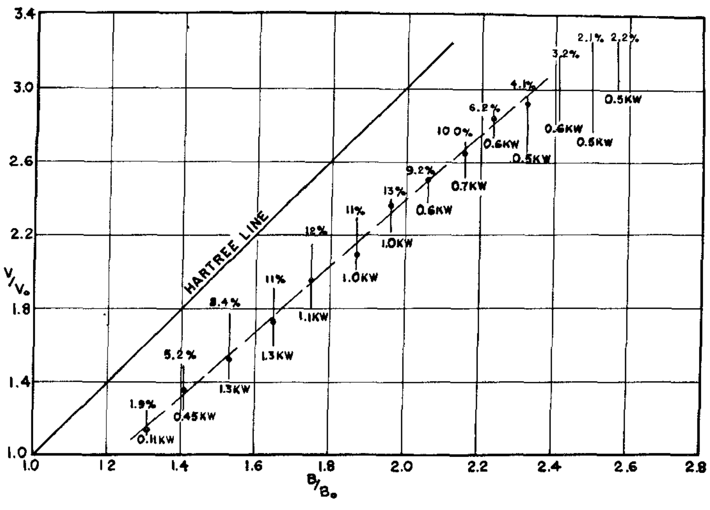

Fig. 5 - Voltage-field characteristics of 1.3 cm 20 vane "low-field" magnetron.

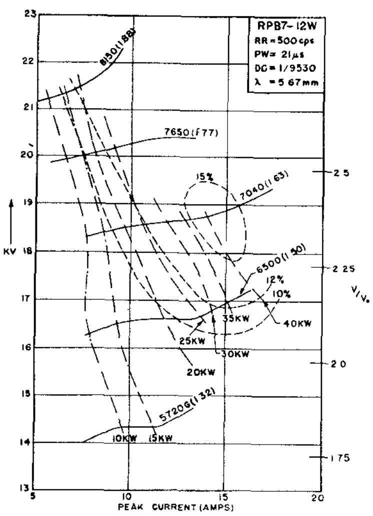

Fig. 6 - Performance chart for 5.7 mm 22 vane "low-field" magnetron.

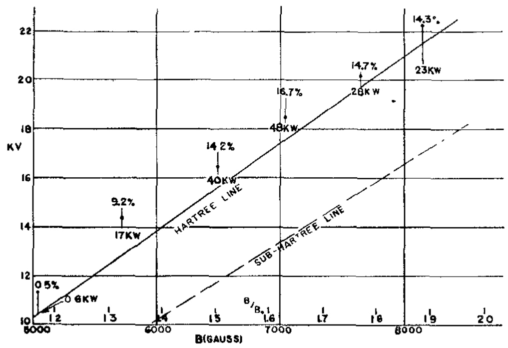

Fig. 7 - Voltage-field characteristics of 5.7 mm 22 vane "low-field" magnetron.

	1 25cm	6 3mm	4 5mm	3 3mm	2.5mm	HV 6 3mm
ANODE DIA	181	.096	.0645	050	038	.123
SMALL RES DIA.	311	165	1105	086	064	181
LARGE RES. DIA.	410	217	.148	.113	084	241
VANE THICKNESS	.0145	.0085	005	004	.003	0105
ANODE HEIGHT	.170	.120	.075	.065	.048	.200
CATHODE DIA.	.116	.062	.041	.032	.025	.077
V_0	3000	3150	3050	3000	3100	5100
H_0	2700	5200	7700	10,000	13,000	5200

Table 1 - 22-vane rising sun anodes.