THE KLYSTRON - AN ULTRA HIGH POWER RF ENERGY SOURCE

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Summary

Each large particle accelerator which has been developed over the past years has been designed to yield information which was previously unavailable. Much of the design criteria depended upon the r.f. energy source available. This paper discusses the r.f. energy sources presently available. An extension is made to higher power tubes and the associated problems are discussed in detail.

Introduction

As the energy level of particle accelerators has increased over the past ten years, the demands for correspondingly higher power r.f. energy sources has also increased. Present day requirements ask for power levels to 30 Mw peak and up to 150 Kw of average r.f. power. Requirements may include being able to operate at short pulse lengths on the order of 2.5 μsec or up to pulse lengths of 500 to 1000 μsec. In addition, requirements are being discussed for CW operation at very high average powers. As accelerators get larger and require more sections, there is an increasing demand for phase stability as well as for high gain to make phase adjustment problems less complicated.

To date, nearly all of the high power accelerators being built or proposed that operate at frequencies above 400 MHz are using or are planning to use high power klystrons as their r.f. energy sources. In general, because of the relatively large size of the klystron, the large bulk of material makes cooling of the device simple. If the tube is carefully designed, a high power klystron is also a very stable device. In general one does not expect a klystron to have oscillations under pulse conditions on the voltage rise and fall time. Although the power may vary somewhat, one does not expect a klystron to oscillate as the load VSWR varies. In addition, the klystron has very predictable phase characteristics with relation to beam voltage. One is also able to vary the gain from 35 to 60 db by adding or subtracting gain stages which consist of a cavity and drift tube length.

Tubes Presently Available

Table I is a summary of present high power klystrons used in accelerators. No all klystrons are listed in Table I. Only those high power klystrons which represent present day state of the art for use in accelerator work are listed. Several significant items are to be noted from the parameters listed in this table. First, most of the high power klystron activity appears at 1300 MHz or at 2856 MHz. There has been little accelerator activity requiring klystrons at UHF frequencies between 400 and 1000 MHz, although several tubes exist in the lower portion of this frequency range and operate at relatively high power. Perhaps this is partly due to the problems of operating klystrons in the UHF frequency range due to the large size which is required. Tubes operating at 30 MW in the 400 megacycle region are up to 15' in length and a horizontal mounting is often advisable.

The second significant item to be noted in Table I is the 3 experimental tubes of the SLAC variety which have been run under varying conditions. These tubes were run under the conditions noted to determine the useability of the SLAC klystron. The Litton experimental tube was run at 200 KV using a 26 μsec video pulse. There was no evidence of any deterioration of tube performance. A SLAC experimental klystron was run to 300 KV at 2.5 μsec pulse length and achieved 40 Mw of output power. Once again, there was no evidence of deterioration at this voltage and power level. A tube was run by Lincoln Laboratory to 425 KV with a very short pulse length. There was evidence of cathode limitation at 375 KV. Although these special tests pushed the SLAC type tube to its limits, it is capable of operating in many other modes than that presently being used.

The third significant item to be noted is that most of the tubes listed operate at relatively short pulse lengths. The exception to this is the tube for the proposed Los Alamos accelerator. This tube operates at pulse lengths of 500 to 1000 μsecs and has a modulating anode. Because of modulator switch tube limitations nearly all long pulse klystrons have a modulating anode to aid in ease of modulator design.

Future Tubes

It is a matter of historical fact that each new accelerator of any major proportions tries to develop the capability of doing something new in the area of particle physics. With this requirement for a machine capable of doing things which no other particle accelerator can do, comes additional requirements on the r.f. energy source for improved performance. This improved performance may be in terms of higher peak power, higher average power, longer or shorter pulse length, increased stability or higher gain. From Table I it can be seen that tubes are presently available to the order of 30 megawatts of peak power and to 150 kW of average power. It is also apparent that tubes are available at pulse lengths from 0.2μ sec to 1000 μ sec. Although not listed in Table I, CW tubes are also available should this be desirable. Stability values presently available are best represented by the SLAC tube. The logical question which comes from this review is, "What might be available in high power klystrons over the next five years?"

Probably the most interest lies in higher peak and average powers. To illustrate the problems involved let us look at a tube capable of 50 Mw peak power and 500 Kw of average power. We will first discuss the problems associated with 50 Mw of peak power.

If one assumes a perveance of 2.0×10^{-6} and an efficiency of 50%, it is necessary to run the 50 Mw tube at 300 KV and 330 amps. If one assumes only 40% efficiency, the present readily quoted figure, the beam voltage becomes 330 KV and the peak beam current 380 amps for the same perveance and power level. Two cathode problems immediately arise at such voltages and current levels - voltage breakdown between cathode and anode and current loading of the cathode head.

The maximum voltage which is obtainable on a normal convergent cathode is given[1] by Equation (1). This equation holds between 25 and 300 KV. The factor k(2) is equal to 3×10^{-6}, 4×10^{-6}, or 6×10^{-6} for dc, long pulse or short pulse operation respectively.

$$V_{max} = k_2 L^{0.8} \quad (1)$$

L is equal to d/n where d is the cathode anode spacing and n is a number which is normally between 2 and 3. If one expands this basic formula to take into account space charge wave theory and beam formation, one finds a maximum beam power limitation of approximately 1 Mw per square centimeter of cathode area. Thus, a 50 Mw tube must have at least 100 square centimeters of cathode area. This is easily achievable in tubes operating at L-band and lower.

The other important consideration is current loading on the cathode head. Figure I shows the allowable current loading on an oxide coated cathode head as a function of time and as a function of temperature in the case of the impregnated cathode. It is to be noted from these curves that as the required pulse length increases the current density for an oxide head decreases towards the limiting value of approximately 250 ma/cm^2. The curve shown for the impregnated cathode is a limiting curve and depends on cathode temperature as a limiting value rather than pulse length. It is true that somewhat higher values of current can be achieved at short pulse lengths.

One of the critical problem areas in achieving 50 Mw output power is oscillation problems associated with the 300 to 330 KV beam voltage. As the voltage increases, experience has shown that problems arise with oscillations at third and fourth harmonic frequencies. When one looks at the number of resonances at third and fourth harmonics and the way they rapidly change with cavity dimensions, one finds that it is very difficult to achieve a buncher cavity in a high power klystron which does not have some impedance at these harmonics. In addition, the klystron drift tubes can propagate. However, the fact that the application is fixed frequency helps in the solution of these problems.

To date several tubes have been built by different manufacturers which operate in the 200 to 300 kW average power range. It is conceivable that 500 kW could be achieved in a single tube at either the UHF or L-band frequencies. A problem which must be solved in achieving 500 kW of average output power is to make a collector of reasonable size which is capable of dissipating approximately 1.25 MW of average power. A rather significant achievement in average power has been reported by one manufacturer[2] who has achieved an average output power of 210 kW at low X-band frequencies. This required a collector with a dissipation capability of 2.5 MW.

It is also important to consider drift tube dissipation at the 500 kW level. If the tube has 10% beam interception under r.f. conditions, this is 100 kW and is an impractical number. It will be necessary, in order to decrease the drift tube dissipation, to make a tube which has very good beam dynamics and in which the drift tube dissipation is considerably less than this 10% figure. In summary, it will probably be easier to achieve a 500 kW average power tube than it will to achieve a 50 MW peak power tube.

The practicality of being able to build a high power klystron with 50% efficiency appears to be a realistic goal. This is easier to achieve in a fixed frequency tube than it is in a tube which has to cover a wide range of frequencies either instantaneously or by cavity tuning. Two significant areas have been explored in the hopes of enhancing efficiency. The most promising of these areas is the use of an extended interaction output circuit. This consists of 2 to 5 closely coupled klystron cavities which comprise the output circuit. It appears that the addition of an extended interaction output circuit on a properly designed klystron will enhance the efficiency between 5 and 10%. A klystron using an extended interaction circuit has been reported which achieved 60% efficiency.[2]

A typical technique which is used on low power tubes to enhance efficiency is collector depression. The practical use of collector depression in high power klystrons appears to be unrealistic because of the necessity to depress to approximately 50% of beam voltage to achieve a significant enhancement of the efficiency. For a tube operating in the 200 to 300 KV range, this means that the entire collector would have to be immersed in oil. Thus, the physical limitations of collector depression for efficiency seem to rule this device out. In addition, high power klystrons with 50 db gain are very susceptible to oscillations. An excellent feedback mechanism is to return electrons from the collector back down the drift tube in a high power klystron. This would certainly happen if the collector was depressed which further complicates its use.

Perhaps one of the most important factors to consider in the enhancement of efficiency is to build klystrons with the best beam dynamics which one is able to incorporate. It is very important to have the magnetic field properly matched to the beam. If this is the case, scalloping is minimized. As one designs new klystrons, it is also important to keep in mind that the higher the perveance, the more difficult it is to contain the beam because of high space charge. As the perveance of a beam is increased, the beam tends to become more hollow because of spherical aberrations in the gun area and edge loading of the cathode head.

All of these problems are compounded by trying to make a cathode which is too highly convergent. Figure 2 is a curve showing cathode head area as a function of tube frequency for cathodes with a 10:1 area convergence ratio and 20:1 area convergence ratio. Above 2000 MHz the criteria for beam size was the cutoff frequency of the 2nd harmonic in the drift tube. Below 2000 MHz the criteria was that γb could not be less than 0. 4 at 300 KV. A 10:1 area convergence ratio in the cathode is a conservative figure A 20:1 convergence ratio is a realizable figure, but it does cause some hollowness in the beam.

Using Figure 2 it is possible, once an operating frequency has been determined, to determine the available peak current and thus the maximum operating beam power for a given frequency .

One of the significant requirements in proposed accelerators is to have longer pulse length tubes available. Several things must be kept in mind when requiring increased pulse lengths. Each additional microsecond of pulse length increases the possibility of oscillation or arcing by some amount. It has already been discussed and shown in Figure 1 that cathode limitations are caused by increasing the pulse length. As the pulse length is increased, impregnated cathodes certainly enhance the possibility of successful operation. The basic characteristic which enables one to get longer pulse lengths with smaller cathodes using impregnated cathodes is the ability of the impregnated cathode to run at higher current densities and extreme pulse lengths which approach CW condition.

Four basic types of focusing are available for high power klystrons. They are electromagnet, permanent magnet, periodic permanent magnet and electrostatic focusing. The electromagnet has been used longer than any other type of focusing for high power klystrons. It has the obvious advantage of flexibility and interchangeability as far as tubes of a given type are concerned. It does have the drawback that there is continual power dissipation from this type of system. In most cases, it is necessary to interlock the high voltage to the electromagnet in case of loss of magnet current.

The newest focusing scheme to be used on high power tubes is the use of a permanent magnet. With the advent of new magnetic material, it has become practical to build high power klystrons with a single permanent magnet to focus the beam. However, these magnets do represent hazards to personnel and equipment since they have an extremely strong external field. It also is necessary to run such devices on completely non magnetic tanks. Pulse transformers and viewing circuitry must be removed from the tube itself by approximately 3'. The permanent magnet also suffers from the lack of adjustment flexibility but it does represent a power savings for large multiple installations. Presently, permanent fields of 1100 gauss have been achieved over approximately 21".

Periodic permanent magnets have been discussed for use in high power klystrons and have been used in low to medium power klystrons. Perhaps the biggest problem in using periodic permanent magnets in high power klystrons is the physical one which requires the pole piece to be close to the beam and magnetic material to have a relatively small inner diameter. The fact that the klystron cavities are relatively large as well as the necessity of breaks in the magnetic material and pole pieces for structure supports, tuner rods or cooling lines present magnetic difficulties. In addition, it is desirable to have the periodicity of the magnetic field coincide with the position of the klystron cavities. In most klystron designs, however, it is undesirable to have all cavities the same distance apart. Thus a further problem is presented. It is not anticipated that in the near future there will be considerable strides made in the area of periodic permanent magnet focusing at high power levels.

One of the newest devices available is the klystron using electrostatic focusing. So far voltages on the order of 90 KV have been focused by electrostatic means. Once again, the lenses forming the electrostatic focusing system are periodic and require evenly spaced cavities. In addition, because the beam must have uniform current density to have successful electrostatic focusing, most tubes built today have relatively low perveance. It is anticipated that over the next few years considerable strides will be made in the area of successful electrostatic focusing of higher perveance tubes which will bring the peak and average power availability up into the area of interest.

Significant strides have been made during the past few years in developing output windows which are capable of the powers discussed in this paper. Specifically, windows have been built which reliably handle in excess of 300 kW of average power and in excess of 30 MW of peak power. Since the advent of using a coating on high power tube windows to reduce single surface multipactor, considerable reliability has been achieved in high power tubes. If one talks about windows to handle 500 kW of average power, careful consideration must be given to the technique of cooling the window. It seems that peak power capabilities of 50 MW are achievable providing very careful consideration is given to window fabrication which reduces the possibility of high voltage breakdown in the window area. Perhaps the most promising window type which is available today is the block window which was first used in high power CW klystrons. These windows have good bandwidth, excellent average power handling capabilities and should be adaptable to high peak powers. They have the added advantage that they are mechanically rugged.

In summary, it may be noted that the present state of the art in high power klystrons, appears to be approximately 30 MW peak power and 300 kW average power. Pulse lengths varying from 0.2 µsec to 1000 µsec are presently available.

In the next five to ten years, one may look toward development of high power klystrons up to 50 MW and 500 kW of average power in the frequency ranges below S-band. Pulse lengths from very short to very long will range through these peak and average powers. One may expect to see more use of permanent magnet focusing in high power klystrons for multi-tube installations. It is not felt that electrostatic focusing will be available in the tens of megawatts range in the near future. One can also look toward designing of modulators which need only provide sufficient power for a klystron operating at 50% efficiency. Of these achievable goals, the most difficult one to achieve will be the 50 MW goal because of its associated r.f. breakdown problems, high voltage breakdown problems and the oscillation problems associated with operating at extremely high voltages. In all probability the goal of 50 MW peak power and 500 kW average power will not be achieved in a single step but rather in small steps and these only with some difficulty.

REFERENCES

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TABLE I

PRESENT KLYSTRON USAGE

Frequency MHz	Peak Power Mw	Average Power kW	Pulse Length µsec	Gain db	Beam Voltage Kv	User
800	1.25	150	1000	50	75	Los Alamos
1300	20	30	10	45	225	Argonne
1300	30	75	4	45	290	Oakridge
2856	21	20	2.5	50	250	SLAC
2856	11.0	1.7	26	50	200	Litton Experimental
2856	100	1.0	0.2	60	420	Lincoln Lab Experimental
2856	42	6.3	2.5	50	300	SLAC Experimental
2856	4	80	16	45	130	MIT

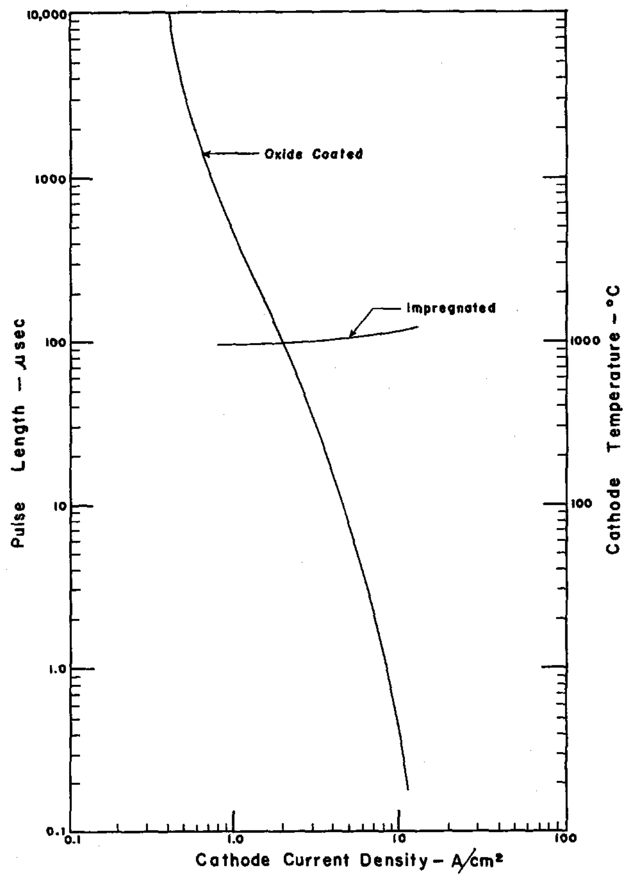

Fig. 1. Cathode current loading.

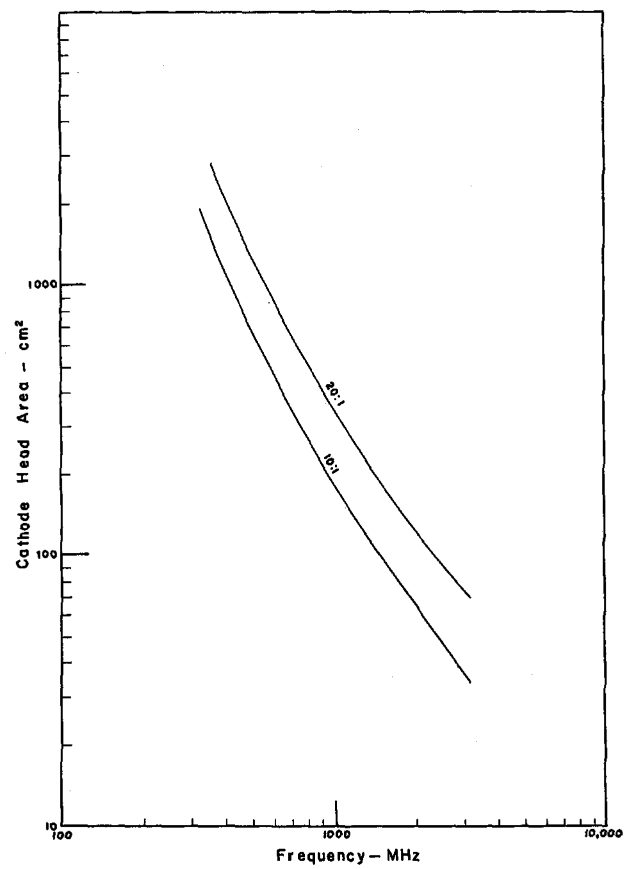

Fig. 2. Cathode convergence.