RECENT DEVELOPMENTS IN HIGH POWER VACUUM TUBE TECHNOLOGY

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Summary

There have been several recent developments in vacuum tube technology which will benefit the next generation of particle accelerators now being proposed. These improvements involve devices covering the frequency spectrum from HF through millimeter wavelengths. Significant developments involving klystrons, gyrocons, or gyratrons, at frequencies above 200 MHz are being reported elsewhere in these proceedings.

The developments in the EIMAC line of conventional gridded tubes for use at frequencies below 200 MHz will be of particular benefit to those machines which will be used to accelerate heavy particles for neutron production, heavy ion fusion, and other similar applications. While some of these developments are aimed at improving tube reliability, the main thrust of these efforts is to develop high gain gridded vacuum tubes which can deliver higher powers at better efficiencies than those available today.

This paper will describe how the use of pyrolytic graphite grid construction makes it possible to achieve the tight tolerances, close inter-element spacing, and dimensional stability necessary to produce high gain tubes capable of handling higher power per unit volume. Other new construction techniques and improved cooling methods which contribute further towards improvement in vacuum tube technology will also be discussed.

Introduction

The next generation of linear particle accelerators all appear to have one common parameter which is of keen interest to those in the business of making vacuum tubes. These proposed machines will require rf power of a scale heretofore unheard of. For example, the accelerator breeder concept would require 300-500 MW of cw rf and proposed heavy ion machines talk of thousands of megawatts. While the peak power requirements for some of these proposed machines are not dissimilar to that required by existing accelerators or large radar arrays, the combination of high peak power and high average power place new constraints on the design of amplifier tubes for these applications. The trend toward higher average power is somewhat in contradiction to the trend toward use of higher frequencies. While the use of higher rf frequencies allows for significant reduction in the size of the various accelerator components, it likewise produces a similar reduction in permissible size of the rf amplifier devices to be used. Such a reduction in size makes it necessary to handle more power per unit volume and/or unit area, in both the accelerator and in the rf amplifier device. If smaller devices can be produced which can handle high average power, then materials must be used which are capable of operating at much higher temperatures, and more efficient cooling methods must be developed. Of utmost importance, however, devices must be developed which are basically more efficient, require less cooling, and hence make better use of the available energy.

Good efficiency has always been an operational goal for accelerators if only to keep the power bill to a minimum. However, some proposed machines, such as the Accelerator Breeder or the Heavy Ion Fusion machines, depend upon this improved efficiency to achieve a break-even condition and prove their feasibility. New devices for rf amplification which address this requirement are required if these machines are indeed to be feasible.

Old Technology

In considering where the EIMAC line of gridded vacuum tubes will fit into these new particle accelerators, it would seem appropriate to draw the line between the use of these devices and those applications requiring klystrons, gyratrons, or gyrocons, at about 200 MHz. Below this frequency the last three devices become rather large and expensive to build. Above 200 MHz, it would be difficult to construct a conventional gridded device large enough to handle the required power and small enough to operate efficiently at the desired frequency.

Examination of the data on tubes currently in production and availalbe for these applications reveals that the largest gridded vacuum tube is the EIMAC X2159/8974 rated at 1.25 MW plate dissipation. However, at the present time these ratings apply only up to a frequency of 30 MHz and a de-rating factor is then applied for operation above this point. Most of this de-rating is necessary to account for the heating of the screen grid wires due to the rf current flowing in the output circuit between the screen grid and the anode. Likewise, the X2170/8973 made by EIMAC is rated for 650-kW anode dissipation to 50 MHz above which the same de-rating phenomenon occurs. In fact, for the higher frequencies in the range of 30-200 MHz, the grid dissipation will almost always be the limiting factor in the power handling capability of super-power gridded vacuum tubes. To illustrate how severely the dissipation capability of the screen grid limits the power handling capability of the tube, consider the case of the EIMAC X2170/8973 operating at 50 MHz where more than 1100 kilowatts output are obtainable while still staying under the 7.5 Kw screen dissipation rating. However, if the same tube is operated at 100 MHz only about 620 kW output is projected before the 7.5 kW screen dissipation rating is exceeded. Under the latter conditions the anode dissipation is only 300 kW. If the screen grid were more robust and able to handle more power, then the full anode dissipation of the tube could be utilized and a power output of over 1200 kW would be available from a single tube at the higher frequency.

Grids in vacuum tubes of this type are usually constructed from wires of molybdenum or tungsten which have been welded together in a "birdcage" type structure. These materials are necessary because the grid is located only a few millimeters away from a hot cathode which is operating at about 1650°C. The use of these refactory materials still permit operation of the grid wires at a maximum temperature of only about 1000°C. Both tungsten and molybdenum are fairly good emitters of both primary and secondary electrons in this type of service and measures must be taken to minimize both these phenomena. If left unchecked, the primary and secondary emissions of electrons from the grid wires will make the current division within the tube very unpredictable and somewhat uncontrolled. To reduce both these emissions, the grid wires are usually coated with a substance which helps make the wire behave as a black body radiator, lowering the temperature and reducing the primary electron emission. At the same time this coating roughens the surface of the wire to help cut down the emission of secondary electrons. The coating layer, made from platinum, carbon, zirconium, etc., is applied to the wire in a plating-sintering process which is very difficult to control and usually accounts for the sometimes wide variations in the grid currents seen between tubes of the same type. These wide variations are particularly noticeable in operating regions where the anode voltage is very near the screen grid voltage. This of course is the operating region where the highest screen grid dissipation is encountered, and if these variations are on the high side of the range the screen grid dissipation could be in a runaway condition. Clearly then, it would be desirable to use a material for grid construction which is capable of operation at nearly the same temperature as the cathode and which has a very low primary and secondary emission ratio without the need for any extra surface coating.

New Technology

An ideal material, pyrolytic graphite, is available and is being used very successfully in construction of gridded vacuum tubes. This material, a graphite formed by vapor deposition, was developed for use in spacecraft heat shields and as brake pads for large aircraft. In addition to high temperature tolerance and low secondary emission ratio, pyrolytic graphite offers several other rather significant advantages over a structure made from welded tungsten or molybdenum wires. Pyrolytic graphite has essentially a zero coefficient of expansion in the directions of interest up to 2000°C. This means that closer inter-element spacing can be achieved without concern over element movements from cold to hot conditions causing inter-element shorts. Further, since the pyrolytic graphite grids are of single plane construction rather than two plane construction made of crossed and welded wires, it is possible to close the inter-element spacing down even farther. This close spacing compensates for the higher grid currents which would normally result from the lack of primary and secondary electrons from the pyrolytic graphite. It also can result in higher gain. Another advantage of pyrolytic graphite is that the grids are cut from a precision-machined graphite cup by either sandblasting or laser cutting, resulting in a much more precise repeatable geometry than is attainable by either hand or machine winding and welding of wires into a grid. One can readily see how the use of pyrolytic graphite for a grid material enables a tube to be utilized more efficiently and pushed to its maximum ratings at the higher frequencies. In addition, it is obvious that the use of such material will enable the tube maker to produce a product with much more uniform and repeatable characteristics. To this end EIMAC has committed much of its resources to the introduction of pyrolytic graphite into its product line. Over the last 5 years, products with pyrolytic graphite have been introduced into several tube designs by EIMAC and more tubes of this type will be available in the near future. Up to the present time EIMAC has purchased the pyrolytic graphite cups from an outside source and then machined them into grids, but shortly after January 1, 1980, we will have our own operational facility for the manufacture of this unique material.

The next area to be examined is the one of basic electronic efficiency in rf amplifiers and how pyrolytic graphite can contribute to this important parameter. As in the case of grid heating due to the flow of high rf currents in the output circuits at higher frequencies, severe screen grid heating similarly occurs with the higher screen currents which flow when the anode voltage is allowed to swing very low during the rf cycle. Since the electronic efficiency of the device is dependent upon the minimum anode voltage swing, or Eb min, a big improvement can be made if the Eb min is allowed to go down near or below the screen voltage. This will result in high screen current and high screen dissipation, but a grid made of pyrolytic graphite is able to accommodate this vigorous service and thus contribute to the overall device efficiency.

There are other areas which are being investigated which should help to improve the "state of the art" in gridded vacuum tubes. As previously mentioned, the largest gridded tube in production at this time is the EIMAC X2159-/8974 rated at 1.25 MW anode dissipation. It should be possible to further extrapolate the usual "birdcage" construction used in this tube to larger structures using pyrolytic graphite instead of the welded wire construction. Pyrolytic graphite grids should have a power dissipation capability of three times that of conventional grids of the same size. However, it is felt that the limit for extrapolation would probably only yield a 1.5 to 2.0 increase in overall tube capability. If improvements of the order of 5 to 10 are to be realized in the basic power handling capability, then some alternate method of construction must be devised which will permit better dimensional control of the basic electronic package of cathode, control grid, and screen grid. Since the tube characteristics are relatively independent of the screen grid to anode spacing, the relative geometry between cathode, control grid, and screen grid controls the quality and uniformity of the electron beam, and in very large devices, such control is essential to insure uniform loading of electron bombardment on the various elements within the device. For these new applications where rf power output of 2-5 MW per device are desirable, small differences in power density can be catastrophic. Tubes are now in development at EIMAC which should achieve the required power handling capability.

New anode designs are being used which feature high velocity water cooling, utilizing swirl tubes in the water passages to achieve the necessary turbulent flow. These are very similar to the water-cooled beam stops used at ORNL for neutral beam dumps and produce anodes which are capable of handling 1000 watts per square cm or more.

Considerable effort has gone into investigation of the so-called "Tyler" technique, for efficiency enhancement. This technique which is used very successfully at low frequencies and produces final amplifier efficiencies of 90% or more in the broadcast frequency band, begins to produce diminishing returns as the frequency of operation is raised. At the higher frequencies the size of the output capacitance in the amplifier tube becomes larger and larger when compared to the capacitance in both the fundamental and third harmonic resonator circuits and acts much like an integrator, limiting the "squareness" of the anode voltage waveform, and thus the improvement in efficiency which is achieveable. Tests run at EIMAC on typical devices produced increases in amplifier efficiency of over 10% at 1 MHz, but these improvements decreased to only 2-3% at 50 MHz. It would appear that for large devices with their attendant large output capacitances the practical frequency limit for employment of such techniques would be in the range 10-20 MHz.

Other devices are being developed which feature high efficiency techniques similar to the depressed collector used for efficiency enhancement of klystrons.

Conclusion

For many years now there have been those who have forecast the demise of the low frequency gridded vacuum tube, but with the further passage of time it is apparent that the "state of the art" of such devices can keep up with the demands and a new generation of such devices is being born to meet the stringent needs of the future.

Discussion

Jaeschke, Heidelberg: How do the prolytic graphite grids behave at arc-overs? Are they more delicate mechanically and do you have any experience with that?

Faulkner: Yes, the grids are as robust, perhaps, even a little more so, than a tungsten or a molybdenum grid. They do have one disadvantage, which of course, I wasn't going to mention, and that's due to the way they're made. There is an increased chance of particulate matter, or a roughness of the surface, which might be more conducive to producing arcs. However, if an arc occurred, they're quite capable of withstanding it. Techniques are being developed now for sealing this roughness without destroying its secondary emission inhibiting capabilities to cut down on the change for these particles.

Allen, SLAC: Are there any other significant developments by other tube companies besides Eimac?

Faulkner: I'm sure that there are quite a few. A great deal of this pyrolytic graphite technique was done in France. The French government put a million dollars a year for ten years into working with pyrolytic graphite for tube developments and also Siemen's is doing quite a bit with similar material.

Stabley, RCA: The question was asked: What are other tube companies doing in other areas? Some of you might know that we at RCA have made a regulator tube for Princeton University. It's a 200,000 volt device to be used with neutral beam sources. We think we might be coming up with an rf version of this tube which might be capable of about 7 megawatts of power under cw conditions at about 50 to 100 MHz.