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LINAC RF SYSTEMS - PAST PRESENT AND FUTURE

J. Ross Faulkner
Continental Electronics Mfg. Co.
P. O. Box 270879
Dallas, Texas 75227

Summary

A brief review of past linac RF system capability is presented, and a discussion of improvements made in their performance is followed by a look at near term and possible long term increases in capability.

Introduction

The linear accelerator relies on an RF field for particle acceleration as opposed to the magnetic field found in circular machines; therefore, it is only natural that the evolving linac technology has forced dramatic improvements in RF system capability.

The earliest electron linacs were built around Klystrons scavenged from military radar systems. These early Klystrons were characterized by poor efficiency, modest gain, and meager power output capability. Klystron performance has been vastly improved over the years with much of the impetus for improvement coming from the unique demands of the linac community.

As in the case of early electron linacs, the development of machines to accelerate heavier particles such as protons, resulted in the adaptation of electron devices developed for VHF/UHF radar applications to provide the necessary RF energy.

Electron Linacs

The developments at SLAC have brought about dramatic improvements in the state of the Klystron art. Peak output powers of 25 - 30 MW are now available at up to 50% efficiency in S-band. New Klystrons are soon to be available which will provide 50 MW or more peak power with high efficiency. Varian has recently developed an S-band Klystron which can deliver 500 kW CW for use on the Microtron.

The 805 MHz Klystrons developed for LAMPF are another good example of tube development brought about by the linac community´s need for higher efficiency devices. These units which brought Klystron efficiencies up to the 50% level have now been superseded by Klystrons with 60% efficiency or more.

SLAC and DESY have both provided impetus to the development of UHF Klystrons. The DESY units built by Valvo deliver 500 kW CW at 500 MHz whereas the SLAC Klystrons on PEP produce 500 kW CW at 353 MHz. CERN,through their work with Thomson-CSF and Valvo, have developed a big brother to the SLAC unit which will give 1 MW CW output at 353 MHz for use on LEP.

Varian has demonstrated Klystron feasibility down to 224 MHz with successful operation at the 3 MW peak, 375 kW average power output level.

Heavy Particle Machines

The linacs for machines such as ZGS, AGS or HILAC used large triodes which were designed back in the 1940´s and 1950´s for military pulsed power, or VHF/UHF radar applications. The ZGS and AGS operated at 200 MHz whereas the HILAC required 70 MHz RF energy. As linac technology began to develop, these old triodes were pushed harder and harder.

The RCA 6949 triode used in the 70 MHz RF system on LBL´s HILAC was subsequently chosen as the 50 MHz amplifier for the PHERMEX electron accelerator at Los Alamos in the early 1960´s. Six 3 MW RF systems were built to supply the needed RF. The PHERMEX application stressed the tubes far beyond that incurred on the HILAC and, in fact, tubes which were removed from PHERMEX because of low output power were routinely used on the HILAC successfully.

In the same time frame, the early 60´s, the highest power device available for applications between 200 and 450 MHz was the RCA 7835 triode, which was used in military UHF radar. The prototype linac RF amplifier system for this tube was delivered to ANL by Continental Electronics in 1962 for use on the ZGS injector. A power output of 3 MW was available at modest duty factor. Beginning in the early to mid 1960´s, the AGS upgrade, FNAL, LAMPF, the UNILAC, and SPS were all in the proposal stage. The three American accelerators chose the ANL amplifier as the prototype for their linac RF systems. CEMC eventually delivered 25 such systems for ANL, BNL, FNAL, and LAMPF. As was the case with PHERMEX, each step in the evolution pushed the RF equipment farther and farther. Since both operating frequency and power handling capability are strong factors in determining the size required of gridded vacuum tube RF amplifiers, the product of the two is a good figure of merit by which to measure capability. The original ANL RF amplifier provided 3 MW peak, 20 kW average at 200 MHz for a power frequency product of 4x10E12. The LAMPF units produced 3 MW peak power with a similar product of 8.5x10E13, a considerable jump in performance. The LAMPF operating conditions stress the RCA 7835 to the limit of its capability. No new device with greater capability has been developed during the 17 years since the LAMPF system was designed. This power x frequency product is still the highest found at the popular 200 MHz linac frequency.

The SPS chose to use several smaller tubes to produce each megawatt of RF, a more complex but also highly successful technique. Another major project in this time frame, the UNILAC chose a single tube approach to generate about 1 MW of Rf power at 108 MHz.

All of this improvement in RF system performance was accomplished without any development work being performed on the basic electron devices used for RF amplification. Circuit development was mainly limited to improvements in cooling capability since operational frequencies and device parameters remained unchanged.

Recent interest in CW accelerators emphasizes larger RF systems than those presently in use on the linacs around the world. Fortunately, this comes at a time when the fusion power community is also looking for RF systems capable of delivering several megawatts of CW RF power at frequencies up to 200 MHz. This is, of course, the band of interest to those desiring to accelerate protons or heavy ions.

Continental Electronics delivered the world's first multi-megawatt, single tube, CW RF system in 1974. This system, using an EIMAC 8974 tetrode, is capable of over 2 megawatts CW RF output over the range 10 - 25 MHz. It is in routine daily operation and has formed the basis for many more such amplifiers built for other linacs, such as FMIT, as well as other high power applications.

Future RF Systems

The newly proposed CW linacs could use the same RF systems that have traditionally been used on the existing pulsed linacs. The operating frequencies likely will be the same as or very close to those on existing linacs. The necessary CW power could be obtained by combining several amplifier outputs such as is done on SPS. However, even this technique would push electron devices one step farther and reduce the operating reliability accordingly. Since all these earlier systems had their beginnings in military and radar applications, an additional problem is that the old devices are becoming increasingly expensive and difficult to obtain as the number of operating sockets decline with reduced military use. Some of the older linacs such as PHERMEX and the HILAC are already instituting programs to retrofit their RF systems with more modern RF amplifiers using newer, less expensive tubes. Other facilities have begun to consider long range alternatives in the event that their present RF systems become too expensive to operate and maintain.

It would appear that present RF system capabilities yield a power x frequncy product of approximately 1x10E14 for systems using a single conventional gridded power tube. The power x frequency product is probably not as good a measure of the limit of capability in the Klystron system as it is in the case of lower frequency gridded tube amplifiers. For a conventional gridded tube to work at higher frequencies, it must be made smaller thus increasing the power density for a given power output. Almost all the pressure for CW Klystron development for linac use seems to be directed toward pushing the devices lower in frequency rather than the reverse. Consequently, as Klystrons are pushed lower in frequency, they become larger and larger decreasing the power density. The cross-over in practicality seems to occur in the 200 - 350 MHz band where gridded tubes may become too small to handle megawatts of power and where Klystrons become large, unwieldy, and expensive.

Even though a 3 MW, 224 MHz Klystron has been successfully demonstrated, the complexity, large size, and high cost make it somewhat unattractive and leave the frequency spectrum between 200 and 350 MHz somewhat a no mans land for megawatt systems. Hopefully, the concurrent interest in multi-megawatt CW RF systems on the part of both the accelerator and fusion research communities will result in an influx of money into the development of election devices and the RF systems to use them. Those of us who build RF systems and those of you who use them are limited by the output capability of the available electron devices used for amplification.

The future requirements of the fusion community indicate a need for a VHF system with a power x frequency product of 5x10E14 or greater; however, a minimum power x frequency product of 1.5-2x10E14 would suffice. This number would appear to mesh well with future linac requirements. The RF amplifier system capability already exists, and electron devices capable of delivering this power are presently under development both in Europe and in the USA. As of this writing, no larger devices are in active development.

As these systems with higher power x frequency products are developed, it will be mandatory to improve efficiency of both tube and circuit. For successful operation of new linacs such as breeders or heavy ion fusion machines, power break even is essential. Hopefully, these new systems with smaller size, better efficiency, and higher output will also provide coverage in the so-called no mans land between 200 and 350 MHz.

The most recent large RF system built for linac use was the FMIT system built by Continental Electronics. Each of these 17 units was designed to produce 600 kW CW at 80 MHz. This system will form the basis for many similar systems in the future. New versions of this amplifier system are presently under development at CEMC which will supply up to 2.25 MW of CW RF power over the band 40 - 80 MHz. Similar systems which will push the operating frequency upward to 200 MHz at reduced average power are also under consideration

New materials have been developed for tube construction. Better modeling and use of computer systems to optimize tube and circuit design have resulted in dramatic increases in capability. The RF power capability of Klystron systems is almost entirely a function of tube performance since tube and circuit are one in the integral cavity Klystron. The pyrolytic graphite grid material pioneered by Thomson-CSF and now in use by EIMAC, Siemens, EEV, and Philips makes it possible to run tube grids much hotter than those made from more conventional materials.

It may be that 1 - 3 MW CW power is all that may be expected from a single tube RF amplifier in the VHF range. Higher power would then be obtained by coupling several such amplifier as is done today on SPS. However, conceptual designs have been proposed utilizing very large modular gridded vacuum tubes with non-intercepting accelerating electrodes, capable of delivering up to 5 MW of CW power over the VHF and UHF range. These would be density modulated devices like a gridded vacuum tube as opposed to velocity modulated tubes such as klystrons. In theory, these density modulated tubes could be made to operate with efficiencies as high as 85 - 90%. So far, the largest of these tubes, called a Klystrode, by Varian, has run only a few tens of kilowatts of CW power from a single module in the 400 - 900 MHz band. Much larger modules could be grouped together in a single vacuum envelope with either integral or external cavity circuitry to theoretically form a highly efficient high power amplifier.

If improvements in the state of the Klystron art continue and efficiency of these velocity modulated devices continue to rise, then it may become feasible and cost effective to consider very large VHF Klystrons for developing up to 5 MW CW at 200 MHz. However, mere physical size alone will probably preclude use of Klystrons below 200 MHz.

Conclusion

Linac RF systems have historically been built around electron devices which were originally designed for other applications. Through improvements in efficiency and cooling, the systems designers have extracted every available watt from these devices but the evolution of linac technology has pushed them to the limit of their capability.

Future requirements from both the linac and fusion research communities foresee a need for CW RF power in large blocks where power x frequency products of 2-5x10E14 would be desirable. This capability does not now exist but perhaps a joint effort from both groups could provide the funding to support development of devices and systems to satisfy this need.