RF POWER SOURCES FOR 1990 AND BEYOND*

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Summary

This paper will discuss the types of devices and system architectures that show promise in providing rf power sources for future space requirements. It will extrapolate these solutions to accelerators that are now being planned for construction and commissioning in the 1990s and will suggest technological advantages of using SDI-developed rf systems. Finally, the present state of the various SDI-sponsored high-powered rf-development programs will be reviewed.

Overview

For the past 25 years, most accelerators have been driven by rf sources previously developed for radar or high-power broadcast systems. The workhorse of accelerator rf power sources has been the klystron for frequencies above 400 MHz with the gridded tube being used below that frequency. Magnetrons have been used for single-structure electron accelerators.

The Strategic Defense Initiative (SDI) requirement to determine if it is feasible to place a Neutral Particle Beam (NPB) accelerator or a Free-Electron Laser (FEL) in space has placed an unprecedented demand on rf sources for compactness, light weight, and efficiency as well as other parameters. Table I is a set of typical NPB parameters. The FEL parameters are no less stringent.

TABLE I

NPB RF POWER REQUIREMENTS

Frequency	UHF (425 MHz typical)
Peak output power	20 to 100 MW
Pulse length	milliseconds
Duty	1% to cw
Weight ratio (amplifier)	0.3 g/W (1.5 kW/lb)
Volume ratio (amplifier)	15 w/cu in.
Efficiency (amplifier)	> 50%
Reliability	0.9999

In the past, a single section of rf accelerator structure was usually of the appropriate length to be driven by a single rf power source, and the sources were sized as large as possible to keep the number of parts low. The Spallation Neutron Source (SNQ) project proposal[1] suggested the use of many, relatively small rf sources driving individual cavities. Multiple drives into a single cavity have been used on the FMIT system at Los Alamos,[2] and the HILAC at Berkeley.[3] Because of very stringent reliability considerations and the desirability to package the rf in manageable sizes, the prospect of using multiple sources for each accelerator section is attractive for the SDI application. The ideal peak power output per amplifier package appears to be between 500 and 1000 kW. This scheme has the added advantage of being able to add or subtract power modules as the accelerator requirements change.

Solid-State Amplifier Systems

One of the most promising technologies for solving the problems associated with SDI rf systems is the solid-state amplifier. Two recent systems have been developed for radar applications[4, 5] with power levels that are applicable for the accelerator system designer. One of these systems was tested into a resonant cavity with excellent results.[6]

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The typical solid-state amplifier is made up of modules, or books, as some companies call them. Figure 1 shows a typical 2.5 kW module with the new version, which uses 1986 technology. Each module contains 8 to 10 transistors and delivers about 2.5- to 3.0-kW peak power. The modules are also self-contained in that they have their own power conditioning, preamplifier, and output combiner.

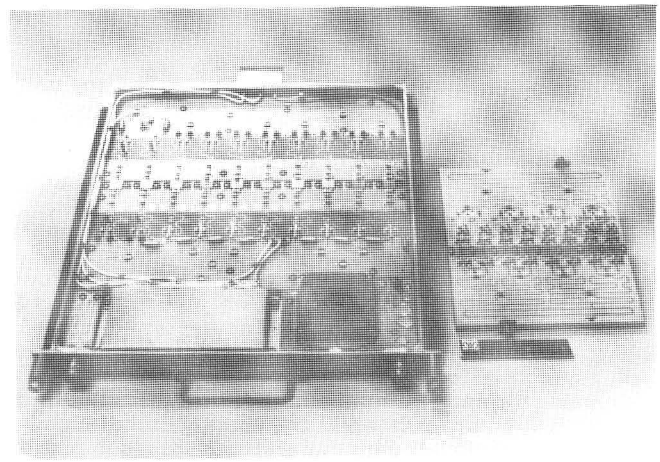

Fig. 1. The 2.5-kW solid-state amplifier modules showing reduction in size using new technology.

Many modules are combined to develop the final output power. Some manufacturers use a Wilkinson combining scheme and others use a radial combining scheme. Figure 2 shows a 32-way radial combiner with a cw power output at 200 MHz of 2 kW. In principal, a solid-state amplifier could be built at any power level if the designer were willing to use enough combiner stages.

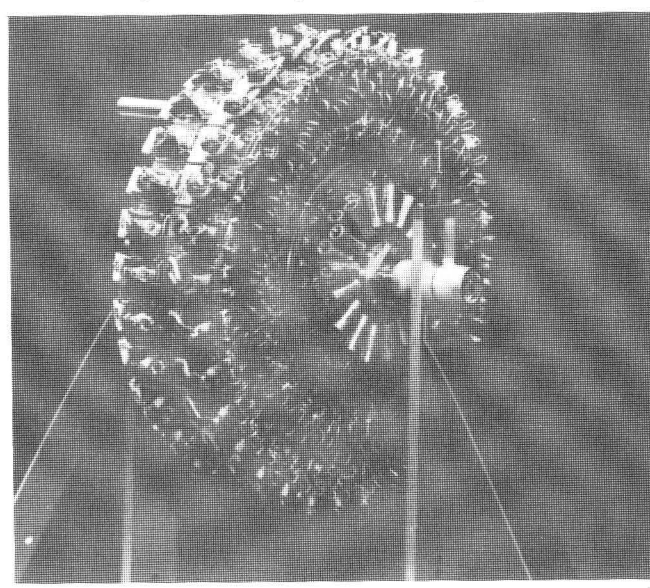

Fig. 2. A 32-way radial combiner.

The heart of the solid-state amplifier is the high-power, microwave transistor. There are three generic types of transistor that are used in high-power microwave amplifiers. The most commonly used type is the silicon bipolar transistor. The silicon FET is also used, and the newest device is the static induction transistor or SIT.[7] Table II is a comparison of the three transistor types. A 425-MHz frequency, a 1-ms pulse length and a 10% duty is assumed.

TABLE II

COMPARISON OF TRANSISTOR PARAMETERS

Parameter	Silicon Bipolar	Silicon FET	SIT
Supply voltage	40 V	40 V	100 V
Efficiency	70%	70%	67%
Power out	350 W	300	100 W
Power gain	10 dB	10 dB	6 dB

Figure 3 shows the power-handling capabilities of each type of device as a function of calendar time. A pulsed condition is used for the bipolar transistor. The FET and SIT are cw devices. As can be seen, the curves are still on a rapid slope upward. If the improvement continues as indicated by the progress to date, 0.2 to 0.3 g/w for solid-state amplifiers appears achievable in the next 2 to 3 years. This means that a 1-MW power system, operating from a 40-V source would weigh 660 lbs and have a volume of 38 cu ft, a package of 3 by 3 by 4.5 ft. The anticipated efficiency, defined as source power to rf output power, is 60%. Unfortunately, the present cost of such a system is 5 to 8 dollars per peak watt but should improve substantially during the next 3 to 5 years.

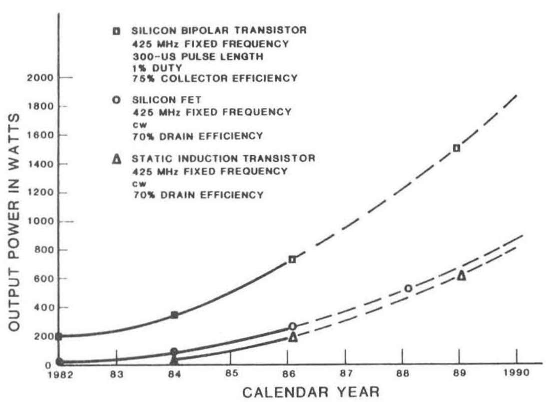

Fig. 3. Output power versus calendar year for microwave power transistors.

Another issue that must be addressed in the use of solid-state amplifiers is potential radiation damage. Tests done on typical bipolar transistors at Sandia Laboratory,[8] indicate that large neutron doses cause degradation in gain and efficiency.

Tube Amplifier Systems

Historically, tubes have been the device chosen when megawatts of rf power have been required. Above 400 MHz, the workhorse has been the klystron operating at several MW peak power with crossed field devices entering the picture at powers up to 2 MW. Frequencies below 400 MHz have generally been the exclusive domain of the gridded tube. More recently, emission-gated devices such as the Klystrode[9] and the lasertron[10] appear promising as power sources for the 1990's at UHF and low L-band frequencies.

Very little will be said about klystrons. They are mature devices with well-understood operating parameters. They are readily available at beam efficiencies of 50 to 60%. Klystrons can be operated at any pulse length from a few microseconds to cw. Their role in space-based accelerator applications is doubtful because the klystron size at UHF frequencies is prohibitive.

Gridded tubes operate well at UHF frequencies and show promise as space-based, low-duty-factor accelerator drivers because of their compact size. This size reduction is especially true when use of distributed amplifiers is anticipated. These tubes operate at 50 to 60% beam efficiency and have 20-dB gain. Gridded tubes do have a pulse-length limitation. Typically, as the pulse length increases, the peak-power capability decreases, and extrapolation to cw service appears unlikely. For example, one tetrode has an advertised output power of 2 MW at a duty of 0.4% and a pulse length of 13 μs. The output power falls to 275 kW when the duty is raised to 6% and the pulse length increased to 2 ms. A typical gridded power tube is shown in Fig. 4. The tube must be housed in an external, resonant cavity.

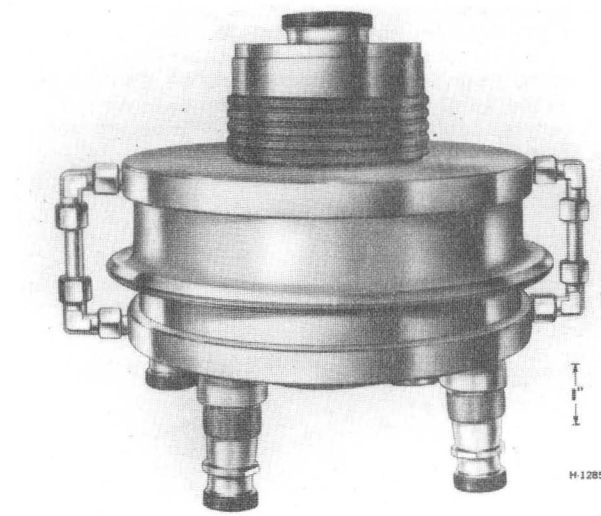

Fig. 4. UHF tetrode power tube.

Los Alamos has recently developed a cavity amplifier at 425 MHz that uses several planar triodes operating in parallel in the same output cavity.[11] The tube arrangement is shown in Fig. 5. The output stage operates at 60% efficiency and 13-dB gain. The output power using nine planar triodes is 150 kW at 60-μs pulse length. Again, this system is pulse-length and duty-cycle limited. The system is very cost effective, however, with the entire system, including power supplies and pre-amplifiers, costing less than $2.00 per watt.

Magnetrons have been used as accelerator drivers where the accelerator consisted of a single section. A magnetron operating at 2.5 MW has been used successfully by several companies as an rf power source in medical and radiographic accelerators. Unfortunately, the capability to combine two or more magnetrons with sufficient phase stability to drive the high-Q accelerator structure has not been successful. Recent work at Varian-Beverly[12] shows promise of a solution to this problem by injection locking two magnetrons. Magnetrons are cost effective, can be operated at a few megawatts, and do

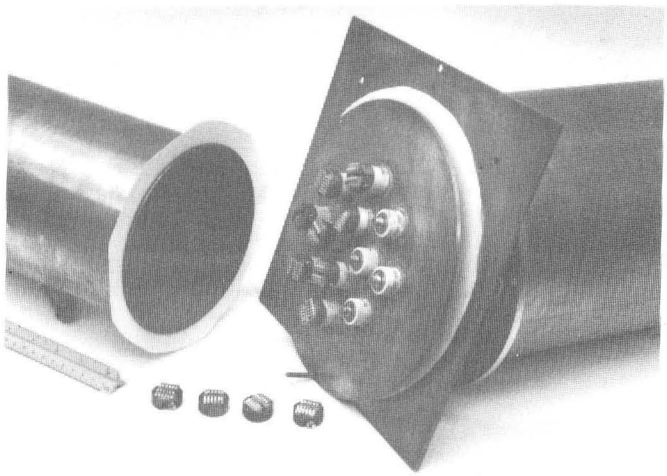

Fig. 5. Multiple planar triode cavity amplifier.

not require a preamplifier chain. They do, however, have average-power and pulse-length limitations. For example, the magnetron cited above is limited to a duty cycle of 0.1%.

The gain structure of the conventional crossed-field amplifier does not provide isolation between the input and the output of the tube. This deficiency makes the device very susceptible to variations in rf load. Because an accelerator cavity presents such a high VSWR during the fill time and reflects most of the stored energy back to the source after the pulse, the crossed-field amplifier could not be stably run without using expensive circulators, which are large and have an adverse effect on system efficiency. For this reason, and because of the experience at Chalk River and at LAMPF, accelerator designers have avoided using the crossed-field amplifier.

During the past few months Raytheon has been testing a new crossed-field amplifier that is cathode driven. This technique solves the isolation problem between the input and output circuit in that the new device has greater than 30 dB isolation between these two ports. SDI is presently funding a project with Raytheon to test and characterize this device into a resonant load. The present tube operates at S-band at 1.25-MW output power, 60% efficiency and weighs 70 lb. It has 24-dB gain. This is an exciting possibility for space applications because of the low weight and volume factors.

A relatively new device, the emission-gated amplifier tube, has been developed during the past few years. Two tube types have resulted: the lasertron[10] and the Klystrode.[9] In both of these devices, the beam is bunched at the required rf frequency as it is emitted from the cathode. The beam is then passed through a klystron-type output cavity where the power is extracted in the conventional way. The big advantage to this type of device is the elimination of the interaction space required in the conventional klystron, which enables the tube to be much shorter for a given frequency than a conventional klystron.

Eimac has developed the Klystrode, which has a triode input section and a conventional klystron output section. A cross section of the tube is shown in Fig. 6. The grid is coupled to a resonant cavity that is driven at the appropriate frequency. This scheme causes a bunched beam to be emitted from the cathode.

Eimac has proposed on a pulsed Klystrode at 425 MHz with an output power of 500 kW. The pulse length is 350 µs at 1% duty, and the tube will have a gain of about 20 dB. This tube will have at least 70% beam efficiency at

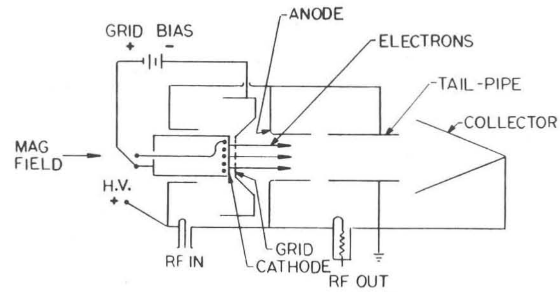

Fig. 6. Klystrode cross-section schematic

85 kV and will weigh slightly over 100 lbs, with the magnet.

The lasertron is being worked on at several places including Varian, SLAC, Orsay, and Los Alamos. The basic idea is the same as the Klystrode except that the cathode is pulsed by a laser beam. The lasertron requires a photoemissive cathode as well as the added complexity of a laser with enough power to activitate the cathode, but does have the potential for operating at higher frequencies and faster pulse rise times than the Klystrode because of the elimination of the capacities associated with the grid.

Conclusions

During the past 18 months, the SDI requirements to place a NPB accelerator in space has put tremendous emphasis on small, lightweight, highly efficient, high-power rf sources. The development of solid-state rf systems makes distributed amplifiers or individual cavity drivers practical. Such systems also hold promise of excellent reliability, elimination of high voltage and its associated floor-space requirements, and inexpensive repair bills.

The SDI requirements have also caused a renewal of interest in small, compact tubes. The Klystrode shows promise, as does the cathode-driven crossed-field amplifier and phase-locked magnetrons. These requirements have also caused a new look to be taken at an old friend, the direct coupled cavity/amplifier, using multiple triodes or a single, tetrode tube.

The bottom line for the linear accelerator designer is cost, both initial and operational, efficiency, and size. The potential for using rf sources that are smaller and that require less power-conditioning equipment means less floor space and a substantial initial cost savings. The potential operating cost savings will be significant when better reliability is considered. An improvement in overall efficiency of 15 to 20% translates to a power-bill savings of the same amount.

The on-going developments for rf power sources for SDI applications should be carefully watched during the next 3 to 5 years to determine the feasibility for space-based applications. There will undoubtedly be several developments that could have major impact on present accelerator upgrades and new accelerator designs.

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