RF POWER SOURCES*

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INTRODUCTION

I am going to talk about RF power sources for accelerator applications. My approach will be with particular customers in mind. These customers are high energy physicists who use accelerators as experimental tools in the study of the nucleus of the atom, and synchrotron light sources derived from electron or positron storage rings. I will generally confine myself to electron-positron linear accelerators since the RF sources have always defined what is possible to achieve with these accelerators. A striking example of this is the development at Stanford immediately after World War II when Chodorow and Ginzton[1] set the stage for GeV electron accelerators with the development of the multi-megawatt klystron which at that time represented orders of magnitude of power capabilities above that which was available in klystron amplifiers.

Circular machines, cyclotrons, synchrotrons, etc. have usually not been limited by the RF power available and the machine builders have usually had their RF power source requirements met "off the shelf." The main challenge for the RF scientist has been then in the areas of controls. An interesting example of this is in the Conceptual Design Report of the Superconducting Super Collider (SSC) where the RF system is described in six pages of text in a 700-page report. Also, the cost of that RF system is about one-third of a percent of the project's total cost. The RF system is well within the state of the art and no new power sources need to be developed. All the intellectual effort of the system designer would be devoted to the feedback systems necessary to stabilize beams during storage and acceleration, with the main engineering challenges (and costs) being in the superconducting magnet lattice.

In sharp contrast, the next electron accelerator for high energy physics applications is the TeV linear collider. Studies of these machines are proceeding in many laboratories in the USA, Europe, the Soviet Union and Japan. All of these studies reveal that a key system which will determine the feasibility of these colliders is the RF system and, in particular, the RF power sources. In fact, many parameter studies and cost optimizations are being carried out and still it is difficult to keep the RF system cost below 50% of the total project cost.

In my presentation to this conference, I will focus on RF power sources for the next generation of linear colliders, demonstrating how the power sources developed for electron linear accelerators over the past forty years point the way to suitable sources for that application. Not surprisingly I will deal with the klystron and klystron-type interactions since Stanford University is where the klystron was invented in 1937 with the fiftieth anniversary being celebrated last year.

PRESENT STATUS

Storage Rings

Electron-positron storage rings require continuous power generally in the frequency range 50–1000 MHz. Klystrons producing over one megawatt are available for purchase from manufacturing companies at both 350 MHz and 500 MHz. These power amplifiers are high efficiency klystrons (65%) and high gain (greater than 50 dB) and are catalogue items of klystron manufacturers around the world.

The frequency of choice for storage rings dedicated to synchrotron light applications are 500 MHz and klystrons in the range 100 kW to 1200 kW are readily available for the individual requirements of these RF systems. The present day storage rings are not limited by the availability of RF power sources.

Linear Accelerators

The way of life of accelerator builders is to respond to the demands of high energy physicists for higher and higher electron and positron energies and at lower and lower costs per GeV. After World War II the chosen frequency for electron accelerators was in the S-band frequency range where significant radar developments had taken place. The klystron eventually developed for the Stanford Linear Accelerator Center was permanently magnet-focused and produced 21 MW at 250 keV beam voltage for 2.5 μsec at 360 Hz repetition rate. This served very well to produce 20 GeV beams but then, responding to the demands for higher energy, a scheme was proposed to increase the energy by compression of the RF pulse coming out of the klystron. In SLED the power from the klystron is stored in a high Q (greater than 100,000) cavity over part of the pulse and then, for the remaining part of the pulse, the power is rapidly fed into the accelerating sections for a high effective peak power level.[2] This, together with an upgrading of the SLAC klystron to above 30 MW, enabled SLAC to run close to 30 GeV for short pulses. This type of 30 MW klystrons are now readily available from tube manufacturers around the world.

The SLC program at SLAC then required a tube redesign in order to bring SLAC to greater than 50 GeV. The resulting tube which was designed and built at SLAC ran with a pulse width of 3.5 μsec giving 67 MW at 350 keV beam voltage at 180 Hz repetition rate.[3] The measured characteristics of the 5045 klystron is shown in Fig. 1 and represents the highest power, S-band, klystron for accelerator applications in large production at present. Over 300 of these klystrons have been built at SLAC with a greater of 75% production yield and lifetimes in excess of 20,000 hours.

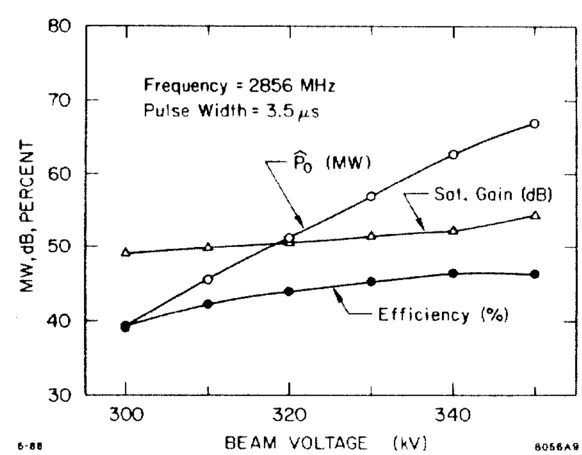

Fig. 1. Typical characteristics of production SLC klystron.

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At SLAC the limitations of these klystrons at 1 μsec pulse width (for use without SLED) was also studied. The measured characteristics of the 5045 klystron run up to higher voltages at 1 μsec is shown in Fig. 2. It was found that this production tube could operate at 415 kV at 100 MW peak power at 48% efficiency. No extensive lifetime data was taken but one tube did run for over 500 hours uninterrupted on a test stand.

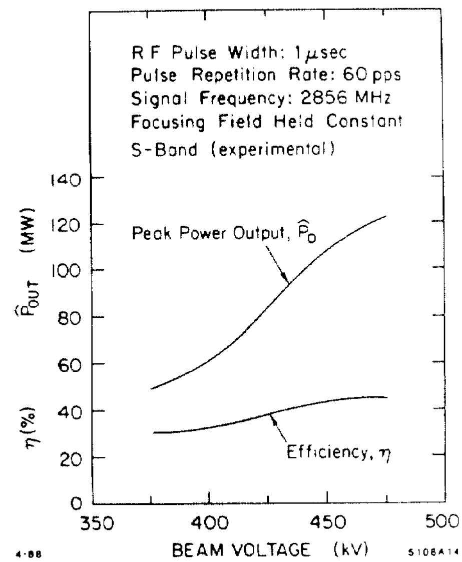

Fig. 2. Performance of production SLC klystron at beam voltages above the initial design beam voltage.

In parallel with the development of the 5045 tube for SLC, work was started for a tube to operate at 150 MW with 1 μsec.[4] The measured characteristics of this tube are shown in Fig. 3. In order to achieve the higher powers and for efficiency improvement, this tube employed a double gap in the output cavity. Although this tube was not put into production, it is likely that a successful production could have been made based on this experimental tube.

The 5045 klystron and the 150 MW klystron essentially represent the present state of the art for S-band accelerators. The next generation of linear accelerators for high energy physics looks towards higher frequencies and this is considered next.

POWER SOURCES FOR LINEAR COLLIDERS

The next generation of electron machines beyond the SLC is a linear collider in the center of mass range of the order of 1 TeV (TLC). Designs for this class of accelerator have evolved over the past few years and, since the early days of these designs, all parameters[5] and cost optimization studies have indicated that the frequency must be higher than the well-established S-band frequencies heretofore used in electron linear accelerators. The accelerating field as related to the energy dissipated in the wall losses, is more favorable as the length decreases and wavelengths between 3 cm (X-band region) and 1.5 cm are necessary to achieve reasonable "wall plug" power for the total accelerator. Because of this, about two years ago, it was decided to develop at SLAC a conventional X-band klystron to explore the peak power capabilities in that frequency range. It was decided, initially, to build a tube to operate at 330 kV and designed to achieve 30 MW at that voltage level. If that was successful, the next stage would be to proceed to 100 MW which was estimated to be the limit

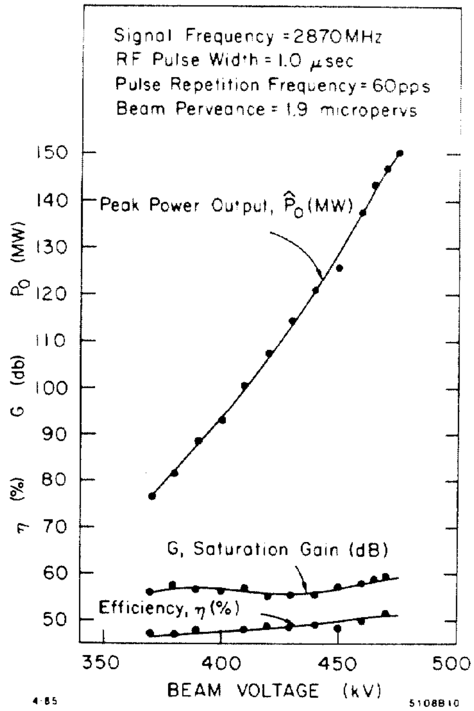

Fig. 3. Measured characteristics of experimental 150 MW klystron.

possible at 1 μsec pulse width. Figure 4 shows the performance of that tube as measured and 24 MW was achieved at 340 keV for an efficiency of 43%.

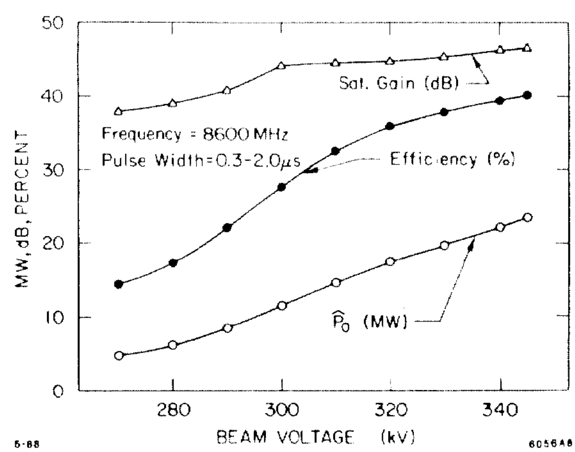

Fig. 4. Measured characteristics of experimental X-band klystron.

At about that time design studies on a TLC yielded power requirements per meter of 500 MW and higher in the frequency range 10–17 GHz with pulse widths of about 50 nsec. Short pulse widths brought us into a hitherto unexplored region of klystron performance where higher peak power might be possible. Two general approaches are possible as illustrated in Fig. 5. A long RF output pulse from a conventional klystron modulator combination could be compressed into a high peak power pulse by SLED-type techniques. A method of Z. D. Farkas utilizing a series of delay lines to store slices of the RF pulse and combine them into a single high power short pulse is an innovative extension of this SLED principle.[6] This is illustrated in Fig. 5(a). An alternate scheme is compressing the modulator pulse before it is applied to the klystron and for 50 nsec forming a megavolt-kiloampere beam in a so-called "relativistic klystron." The relativistic klystron will be considered in greater detail, but it must be emphasized other approaches are being investigated in other laboratories. Two in particular show promise: the gyroklystron at the University of Maryland[7] and work on undulating structures at Cornell University.[8]

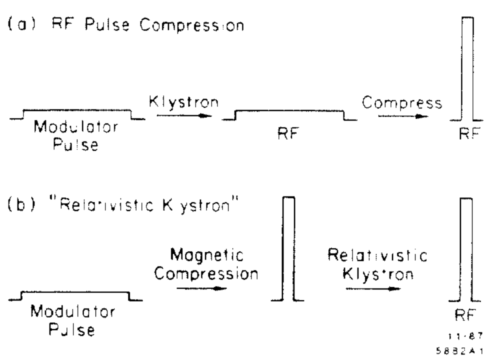

Fig. 5. a) Illustration of RF pulse compression. b) Illustration of magnetic compression.

RELATIVISTIC KLYSTRONS

A klystron is defined as a device using cavity resonators to convert an unmodulated electron beam to a bunched beam by use of velocity modulation and then to extract RF energy from that modulated beam. A relativistic klystron operates at energies where relativistic effects become significant in the bunching process. A broader definition of the relativistic klystron encompasses two-beam accelerators in which a bunched "low" energy, "high-current" beam transfers power at regular intervals to a high energy low current accelerator. Also, at regular intervals the low energy beam is reaccelerated by low frequency accelerator cavities. A significant example of this type of device is the RF power source for CLIC at CERN.[9] This proposed device would use superconducting cavities for the low energy beam. We will confine our comments to velocity modulated klystrons.

At the Lawrence Livermore National Laboratory (LLNL) there is an ongoing program using induction linear accelerators to produce high voltage high current beams.[10] Some of this work is done in collaboration with the Lawrence Berkeley Laboratory (LBL). A collaboration was started between these two laboratories and SLAC to operate a klystron with the beam of an induction linear accelerator at Livermore. As a first experiment, the X-band klystron described earlier in this paper was run with an induction accelerator beam and the experiment was designated SL-3. Essentially the cathode of this conventional X-band klystron was replaced with the induction linear accelerator. Although this klystron was designed for optimum performance at 330 keV, the experiment was performed with that klystron to confirm the fact that, at short pulse lengths, it might be impossible to achieve breakdown voltages in the klystron cavities well in excess of the 2 MV/cm which is thought to be about the limit of microsecond pulse width klystrons.

A summary of the performance of this klystron is shown in Fig. 6. Breakdown voltages well in excess of the previous limits were obtained. Since instrumentation is far from perfect at Livermore, the measured peak power outputs are ±10% in accuracy. Another difficulty in measurements at Livermore had to do with the measurement of klystron current. Since an isolated collector was not used, no measurement of body intercepted current as the beam passed through the klystron was made. Improvements are being made on future experiments and these are described in greater detail in another paper at this conference.[11] About 80 MW of peak power was obtained in 30 nsec pulses. In Fig. 7 the maximum RF field at the output gap before breakdown is calculated for this experimental tube. As expected, there is a steep rise in breakdown field as a pulse width is decreased. This confirms the expectation that much higher peak powers can be obtained from short pulse width relativistic klystrons and that peak powers in the hundreds of megawatts might be possible from a single klystron operating at the frequencies required for linear colliders.

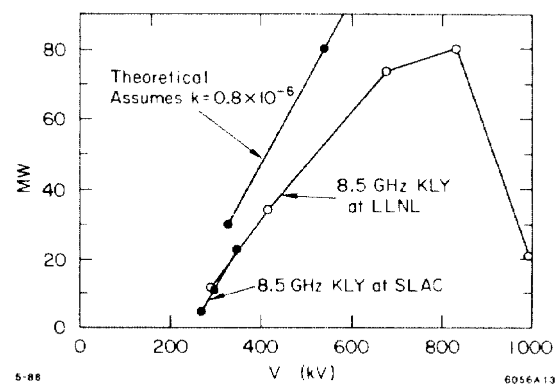

Fig. 6. Measured characteristics of relativistic X-band klystron with results with conventional cathode for comparison.

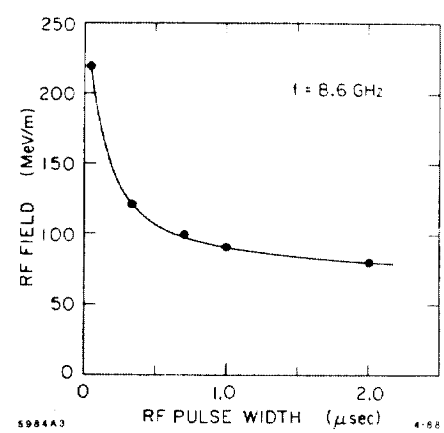

Fig. 7. Peak RF field in output cavity of X-band klystron as function of pulse width.

Two other experiments were carried out at LLNL. These are called SHARK and SL-4. SHARK is a subharmonic drive experiment shown in Fig. 8. It is a two-cavity klystron with a drive cavity at 5.7 GHz and the extraction cavity at 11.4 GHz. A summary of the output powers obtained from this experiment is shown in Fig. 9. At the highest power of 30 MW, there was a shortening of the output pulse which was due to

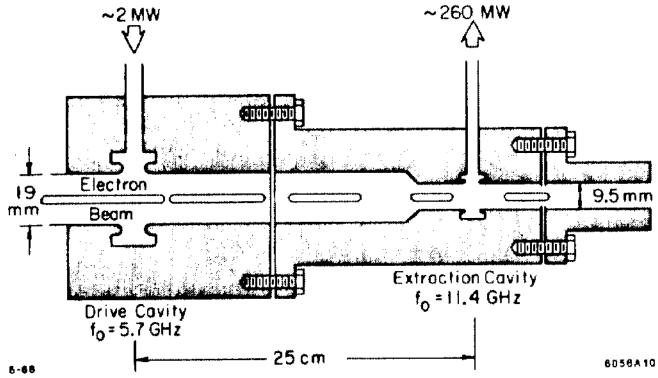

Fig. 8. Schematic of subharmonic drive experiment, SHARK.

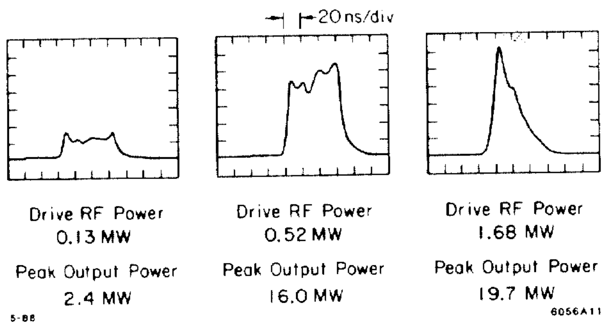

Fig. 9. SHARK RF output pulse shape for various drive powers.

some anomalous beam loading which is discussed in another paper.[11]

The next experiment consisted of a direct klystron amplifier similar to the first one, SL-3, but designed to operate with a beam voltage of 1.2 MV at 1 kA. This experiment is designated SL-4. Figure 10 shows a schematic cross section of the tube with its basic design parameters. There is high loading of the gain cavities by using lossy ceramics to decrease the rise time to less than 10 nsec. Also, because of the difficulty of focusing the 1 kA beam over long distances, it was decided to use a large drift tube diameter for the gain section and taper it down to a smaller diameter for the penultimate in output cavities, thus requiring only a short length of high-field solenoid. Figure 11 shows the typical power output pulse shape. Results from this tube is discussed in detail in the other paper at this conference.[11] The experiment produced a power output of 200 MW. The pulse shape does not follow the pulse shape of the beam current at its highest power and shows signs of anomalous loading possibly due to multipactor after 10–20 nsec. Using the values at the output cavity the maximum field at the output gap can be calculated and the value comes out to be about 300 MV/m at 200 MW. The transfer characteristics of power output versus drive is shown in Fig. 12 and it follows quite standard klystron characteristics. The gain peaks at between 300 and 600 W drive.

In an additional experiment, the output of SL-4 was fed to 25 cells (30 cm) of disk-loaded waveguide at 11.4 GHz. The 200 MW pulse was passed through the accelerator without breakdown. If this pulse could be maintained over the number of nanoseconds necessary to completely fill the structure for beam acceleration, this would correspond to accelerating fields of over 125 MV/m.

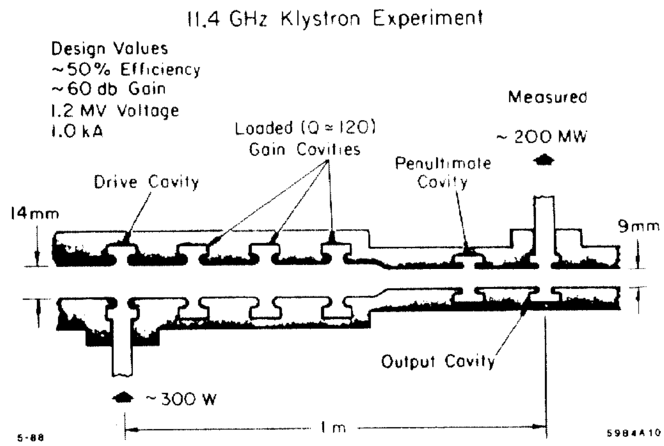

Fig. 10. Schematic of relativistic klystron, SL-4.

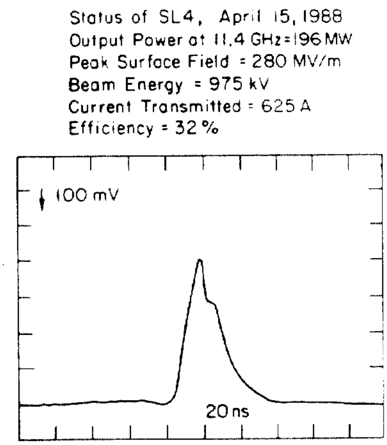

Fig. 11. Output power pulse of SL-4.

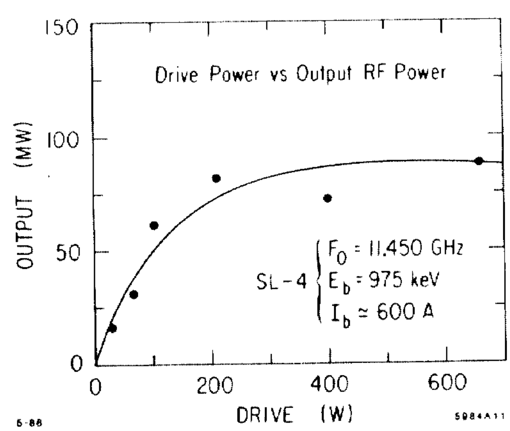

Fig. 12. Drive power versus output power of SL-4.

A summary of results is given in Fig. 13. It is possible to achieve 150 MW at S-band with 1 μsec pulses in an engineering tube and 200 MW has been achieved at X-band in very narrow pulse, but this is in a very preliminary, experimental, type of tube and the results are far from being amenable yet to tube production but are encouraging. Together with developing the relativistic klystron concept, it is necessary to carry out a program of research and development of megavolt/kiloampere beam sources that can supply suitable beams for these new type of microwave sources suitable for linear colliders. Clearly it is not practical to use these very large linear accelerators as a beam source for each of the many thousands of relativistic klystrons that would be needed for the TLC. Much effort has to go into development of suitable beam sources with this specific application in mind.

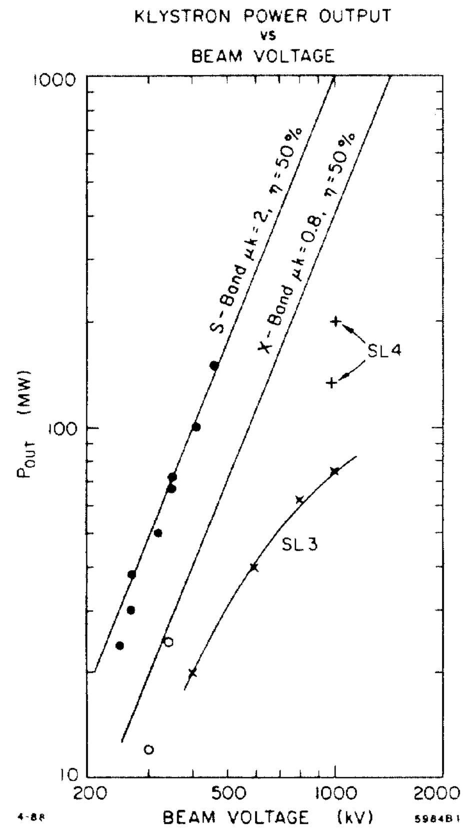

Fig. 13. Klystron power output versus beam voltages for klystrons described.

In conclusion, it has been demonstrated that the relativistic klystron is a promising RF power source for the next generation of linear colliders.

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