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New Developments in RF Power Sources*

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Abstract

The most challenging rf source requirements for high-energy accelerators presently being studied or designed come from the various electron-positron linear collider studies. All of these studies except TESLA (the superconducting entry in the field) have specified rf sources with much higher peak powers than any existing tubes at comparable high frequencies. While circular machines do not, in general, require high peak power, the very high luminosity electron-positron rings presently being designed as *B* factories require prodigious total average rf power. In this age of energy conservation, this puts a high priority on high efficiency for the rf sources. Both modulating anodes and depressed collectors are being investigated in the quest for high efficiency at varying output powers.

1. INTRODUCTION

Recent progress in radiofrequency (rf) sources has been evolutionary rather than revolutionary. There have been no great breakthroughs, no startling innovations, nothing comparable to the discovery of strong focusing or the invention of the FEL, that I am aware of. Rather, the period has been characterized by steady progress towards higher powers and higher efficiencies. UHF klystrons [1] for storage rings are now available with 1.3 MW of CW power and an efficiency of 65%. Almost all tubes are designed with the aid of two- and/or three-dimensional PIC codes such as MASK, CONDOR, MAGIC, or FCI [2]. Klystrons intended for linear colliders have achieved peak powers on the order of 100 MW for short pulses at X-band and above. A microwave FEL has achieved 1 gigawatt at a 1 cm wavelength (quite a number of years ago). There is a lot of research activity at a number of universities and laboratories on various "gyro" devices producing tens of megawatts at a number of frequencies above 10 GHz. I won't discuss a number of ultra high power, high frequency rf sources like the vircator and the phase-locked relativistic magnetrons, which I view as having little or no chance of generating what I would call "accelerator grade rf." I hope this will not offend anyone.

2. CW AND LONG PULSE AMPLIFIERS

The 1.3 MW, 352 MHz, CW klystron for LEP II is a Philips YK 1353. It has a modulating anode to control the current and was designed to avoid beam interception all the way from 2 amps to a maximum design current of 22.4 amps. It has greater than 60% efficiency when operating between .7 MW and 1.3 MW. One of the interesting features of this tube, I think, is that it was designed by Philips HFPT in Hamburg, Germany, using the gun design program EGUN written by Herrmannsfeldt at SLAC, and using the code FCI written by Shintake at KEK to study the interaction between the beam and the microwave fields.

For CW and high duty factor high power amplifiers efficiency is an important issue. Most UHF klystrons used in storage rings achieve efficiencies between 60 and 70% when run at saturation. When it is necessary to run them well into the linear region in order to have some headroom for a feedback system, the efficiency suffers. This is the case for the klystrons for the high luminosity *B* factories presently being designed. One possible way to regain some of the lost efficiency in this operating mode is the depressed collector: an old idea whose time may be coming soon. Depressed collectors got a bad reputation because they had a nasty tendency to cause oscillations by reflecting electrons back toward the input cavities. However, with modern PIC code running on fast computers it is possible to design multistage depressed collectors which return no electrons over a wide range of operating conditions. E. W. McCune of Varian Associates has reported on one of these designs [3].

3. LINEAR COLLIDERS

The greatest motivator for R&D in rf power sources in recent years has been the linear collider. This is because of the very challenging requirements for the rf for linear colliders and the expectation that the rf system will dominate the cost of TeV linear colliders. As is well known, for a given gradient, the stored energy in the accelerator structure scales as the rf wavelength λ squared. This has pushed a number of the designs toward higher frequency: 10 to 30 GHz. This is not the only reasonable strategy. If one scales the length of the collider as $\lambda^{1/2}$, the peak rf power required becomes independent of λ, and the stored energy varies as $\lambda^{3/2}$, as does the filling time. If the beam pulse train length is also scaled as $\lambda^{3/2}$, and the average beam current during the beam pulse train is independent of wavelength, then the rf to beam efficiency is independent of wavelength. To keep the average power constant, one would like to scale the pulse repetition rate as $\lambda^{-3/2}$, but repetition rates below 50 or 100 pps, make it hard to correct for seismic motion (unless the pulse is so long that the correction can be done within the pulse, as in the case of TESLA's 1 msec pulse). The result is that the parameter sets for collider studies with lower frequency rf tend to have higher beam power, which allows larger beam spots at the collision point, and eases tolerances in the final focus and emittance.

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This is certainly not intended to cover the very complicated subject of linear collider scaling, but rather to point out that reasonable rf system parameters can be chosen for linear colliders operating over a wide range of frequencies. Indeed, there are major linear collider studies at frequencies all the way from 1.3 GHz (TESLA, the superconducting entry) to 30 GHz (CLIC, the two beam collider proposal at CERN). The AC power requirements for these proposed colliders span just slightly more than a factor of 2.

A second very basic choice which must be made about the rf system is whether to use discrete rf sources, each powering a few meters of accelerator, or to build a Two Beam Accelerator in which a high-current bunched relativistic rf drive beam travels parallel to the main collider beam. The advantage of the discrete sources is that they make possible a drive system which is completely modular and which can be meaningfully tested by testing a few modules. While the Two-Beam-Accelerator may have modular components, for example the power extraction structures and the reacceleration modules, the drive beam dynamics are not modular, but rather cumulative. It is a long extrapolation from a few meters to about 10 kilometers.

At 3 GHz and below the choice is easy: klystrons adequate for the presently contemplated next step after SLC look quite straight forward. An R&D klystron for SLC produced 150 MW at 2856 MHz [4], the peak power required for the proposed DESY S-band linear collider, in the mid 1980s. Their pulse length was only 1 μsec, but it is a small extrapolation to the 150 MW, 2.8 μsec pulse required for the DESY proposal. The standard SLC klystron runs well at 100 MW for 1 μsec pulses. On the other hand, the rf source requirements for the linear collider proposals above 10 GHz are daunting.

Of the six major linear collider design studies (VLEPP in Russia; CLIC at CERN; TESLA, the Superconducting Linear Collider; NLC at SLAC, JLC in Japan, and the DESY S-Band Collider), five have selected klystrons as the rf source. The single exception, CLIC, is a two beam accelerator in which the rf drive system may reasonably be described as an ultra-relativistic klystron with traveling wave output structures. One might attribute this dominance by the klystron to the natural conservatism of the established large accelerator laboratories conducting these design studies. While conservatism may play a role, I would suggest that the choice of klystrons is reasonable for the next generation linear collider. Klystrons can have a number of desirable characteristics: 1) High gain (commonly on the order of 60 dB; the VLEPP design goal is 80 dB); 2) High efficiency is possible; 3) Good isolation between the input and the output; 4) Good stability which gives clean rf output, relatively free from parasitic oscillations—what we might term "accelerator grade rf;" 5) Relatively simple beam dynamics; 6) pretty good axisymmetry, so that 2-D simulations are fairly accurate. The principal disadvantage of klystrons for high frequency, ultra high power applications is their susceptibility to damage from beam interception and high voltage arcs.

For linear collider applications, it appears that single pulse heating is a more serious problem than average power. The energy in the beam in a single pulse is enough to melt copper. In this situation it is the current density, not the power density, in the beam which causes the problem. Since the stopping distance of the electrons varies roughly linearly with beam voltage, the energy deposited and the volume in which it is deposited both vary linearly with beam voltage, so the temperature rise is roughly independent of voltage. In this situation there are three strategies for avoiding beam damage: 1) Design with low perveance, $k = I/V^{3/2}$—this helps because low perveance klystrons achieve higher efficiencies, and because for constant efficiency the current varies as $k^{2/5}$; 2) Design the gun and beam focusing carefully to avoid beam interception (this is easier with low perveance) except in the collector where the beam is defocused; 3) Install special beam halo collimators which have a high melting point and high specific heat per unit mass—beryllium is good except for its toxicity. The first strategy helps avoid beam interception damage but exacerbates two other problems, gun arcs and high power rf arcing in the output structure.

The peak voltage across the output circuit of a klystron as seen by a synchronous particle must be roughly equal to the DC beam voltage. Thus, the low perveance (i.e. low current, high voltage) strategy exacerbates the problem of rf arcs in the output circuit. The obvious solution is to use extended interaction output circuits—either traveling wave or standing wave multiple cell structures. Of course with n cells there are n modes (a continuum of modes in the traveling wave case) in any passband, any of which may produce an oscillation, so the stability picture becomes more complicated.

3.1 Sheet Beam Klystrons

Anything that reduces the space charge forces on the beam and the space charge potential depression can improve efficiency. Making the beam a thin sheet, either flat or annular, can make a big difference. Sheet beam klystrons can achieve "anomalously high" efficiencies with high total perveance and power. When the width w of the beam is much greater than its thickness t, it is appropriate to think of the "perveance per square" of dimension t. The sheet beam geometry permits a high total current with greatly reduced space charge forces and current density. The price one must pay for this is that TE modes down to very low frequencies propagate readily in the drift tube and may cause instabilities unless careful remedies such as lossy or broadband reactive filters are used. A design study by Duly Research [5] indicates that, if the stability problem is solved, a 200 MW X-band sheet beam klystron suitable for NLC stage II can be built with a voltage of 300 or 400 kV with current densities which will not melt copper. The study concludes that for constant w the as λ, rather than as λ^2 as in round beam tubes.

3.2 X-Band Klystron Development

In the course of the X-band klystron development at SLAC we have observed melting clearly caused by beam interception, cavity damage from rf breakdown, melted copper from undetermined cause, rf window failure, catastrophic gun arcs which damaged the guns so that high voltage processing could not regain full voltage operation, and a dipole mode instability. But, while the progress has not been monotonic, we have learned from each failure and moved in the direction of better, more stable, longer pulse operation. Klystron XL-1 (X for X-band, L for 50 MW) has achieved stable 50 MW operation with a 1.5 μsec pulse at 60 pps. We are very close to a having a satisfactory klystron for our test accelerator. The Test Accelerator tubes will have performance suitable for the Stage I operation of NLC, but will have copper electromagnet focusing, which would significantly increase the power consumption of NLC. Our klystron department hopes to then develop a periodic permanent magnet (PPM) version of this tube. XL-1 has a 3-cell, π-mode, disk-loaded, standing wave output structure. A 4-cell, π/2-mode, traveling wave output has also been designed and will be tested soon. The simulation predicts an efficiency of 54% for the traveling wave version. We do not see a clear advantage for either the standing wave or the traveling wave. The choice of which type of output to use in the long run will depend on performance testing including efficiency, stability, resistance to damage from beam interception, and rf arcs. We are now convinced that a single gap output is not viable for these tubes and are putting all our effort into extended interaction output structures. It would also work to have several independent single gap resonant output cavities with the outputs combined externally. Indeed, klystron XC-6 produced a total of 80 MW for 800 ns from two independent resonant output cavities, arguably the best performance from any of SLAC developmental klystrons. However, unless we run into problems with both the traveling wave and the standing wave extended interaction structures, we do not intend to build any more tubes with multiple independent output cavities.

The final planned improvement is to add an intercepting grid so that the klystron becomes its own switch tube in a "hard tube" modulator. This will significantly improve the cost and efficiency of the overall system, since the modulator becomes just a DC power supply. The price one pays for this is that the klystron gun must hold off the full DC Voltage. The gridded gun will have a coated oxide cathode, rather than a dispenser cathode. Guns with intercepting grids and dispenser cathodes are plagued with dark current because of the higher operating temperature and greater rate of emitter evaporation from the surface characteristic of dispenser cathodes.

At KEK, the klystron XB72-k has achieved 80 MW for a short pulse (50 nsec). This tube has a single non-reentrant output cavity. By eliminating the nose cones on the cavity they have reduced the peak electric field on the surface substantially. They hope by this technique to avoid the need for an extended interaction output structure. I suspect they will find that the output cavity will arc when operating with a long pulse. The design pulse length is 600 nsec.

The klystron for VLEPP is the most ambitious of the three X-band klystrons. It is a grid controlled, PPM focused klystron designed to run at 1 MV and 300 amps, 150 MW with a 700 nsec pulse length. It has a 14 cell traveling wave output structure, and is designed to have 80 dB (!!) gain. While such high gain is commonly believed to guarantee instabilities caused by retrograde orbits, Balakin argues convincingly that the PPM focusing will strongly defocus the electrons accelerated back toward the input, because they are always considerably lower in energy. The performance is strongly limited by dipole mode instabilities (called Beam Break Up in accelerators) which limits the current to less than half the design current and limits the power to about 60 MW at full design pulse length. The high gain does increase the length of the tube and number of gain cavities, and thus exacerbates the problem of the dipole modes. The approach on this tube has been to build it with all the desired features—grid, PPM focusing, 80 dB gain—right from the start, and then try to solve the problems that occur. The approach being taken at SLAC now is to design the minimal tube—diode gun, electromagnetic solenoid, 50 MW output power—and then add one upgrade after each version works well. There is no way of knowing which approach will get to the final product faster and cheaper. The triode gun for the VLEPP klystron has a non-intercepting grid with 37 round apertures aligned with the orbits of 37 microbeams from 37 oxide microcathodes on the surface of a single metal substrate. The high voltage insulator is segmented into ten pieces with nine intermediate electrodes, in order to withstand 1 MV DC. In order to avoid grid emission, the grid is a massive (6 mm thick) copper structure that improves conduction cooling.

3.3 Windows

Windows are one of the major problem areas for discrete sources. With thousands of discrete rf sources on a linear collider it is essential that it be possible to preprocess the sources to full performance, and to replace them without interrupting operation. This implies that the sources are built with rf output windows or bakeable valves. At both SLAC and KEK a number of window failures have hampered progress toward higher power and longer pulses. A number of clever ideas have surfaced to help solve the window problem, several of which are old ideas. The most common window design for high-power short-pulse klystrons of the type used on electron linacs is a round ceramic window in a pillbox-shaped section of waveguide. The propagating mode in the short section of round guide is the TE_{11}, but because the section of round guide is short, there are also a number of evanescent modes which raise the peak fields at the window. This design also has longitudinal electric fields at the surface of the ceramic, which can cause multipactor between the ceramic and the step to rectangular guide, or single surface multipactor on the ceramic.

The first improvement which a number of groups have taken is to replace the step transition from rectangular to round waveguide with a long taper. The VLEPP group has proposed adding the waveguide equivalent to the quarterwave plate to convert the linearly polarized TE_{11} to a circularly polarized TE_{11}. The circularly polarized wave would transmit twice as much power with the same peak fields. As far as I know this idea has not been tested to see if it actually increases the power handling capability of a window, but it seems that it should. A second clever idea proposed (perhaps resurrected is more correct, since I understand it is an old idea) is the "traveling wave window." The idea is to match the upstream surface of the ceramic from upstream and to match the down stream surface with matching elements down stream. When this is done the wave *inside* the ceramic is a pure traveling wave, and there is no peak field enhancement from a standing wave. We have tested this idea in our X-band resonant ring, and it appears to improve window performance. For thin windows it is actually possible to do better than the "traveling wave" window by creating a standing wave which enhances the magnetic field and diminishes the electric field within the window.

A third clever window idea from Russia is to make a many-hole 100% (0 dB) coupler between two waveguides and put a small ceramic window in each hole. A final brute force approach is to reduce the fields by making the windows bigger. This approach is not without risk, since as the window gets bigger, the density of modes trapped in the ceramic increases, and it gets harder to find a comfortable place to operate which is well removed from the frequencies of modes trapped in the window.

At SLAC we have gone to windows in the TE_{01} mode in round guide. We feel this mode is superior because it has no electric field line terminating on the sharp edge of the braze fillet. Arcs originating at this point in TE_{11} windows appear to be one of the common modes of failure. *We have had several failures of the TE_{01} windows.* Our next klystron will have a "traveling wave" TE_{01} window, which tested very well in the resonant ring. Since we want to use the TE_{01} mode in round guide to transfer the power from the klystron to the SLED II rf pulse compressor, and from there to the accelerator, in order to dramatically reduce propagation losses, the use of a TE_{01} windows seems natural, and requires no extra mode converters.

KEK [6] has done considerable work studying the optimum thickness of the titanium nitride coating on the windows. This coating lowers the secondary emission coefficient of the surface, and thus suppresses multipactor. They have also found that Hot Isostactic Pressure (HIP) processing of the window ceramic improves performance.

Despite all the work on windows it is not obvious that the problem is solved. Getting satisfactory windows is a problem common to all large linear accelerators using discrete rf power sources. Isolating the vacuum of the rf power source from the vacuum of the high energy linac may not be so important for two beam accelerators if the rf source (i.e. drive beam) vacuum is of adequately high quality, as it probably must be to perform well. Segmenting the common vacuum system longitudinally with vacuum isolation valves in each beam line at appropriate intervals in locations where there are no rf fields is probably the most reasonable approach. The question of vacuum isolation for repair work on one segment of a two beam accelerator raises another important related question for any two beam accelerator: is there a way of detuning one section to reduce the rf generated in that section by an arbitrary amount to prevent arcing in one region from disabling the whole accelerator, and to permit reprocessing of one segment while production running the rest of the accelerator. The ability to do both of these is very important for the efficient operation of any large linear accelerator.

While a number of us feel that the discrete klystron (with single cavity or traveling wave (TW) or resonant extended-interaction output structures) is the leading candidate for the rf power source for the next generation linear colliders, there are certainly plenty of other promising candidates. Among these, I would include flat beam klystron, multibeam klystrons, ultra high current annular beam relativistic klystrons, gyroklystrons and gyro-TW-klystrons, relativistic TWTs, gyrocon and magnecon, and finally Two Beam Accelerators using either the FEL or klystron extraction mechanism. Of the discrete sources, perhaps the gyro-klystron work at University of Maryland [7] has reached the most advanced state for application to linear colliders. They have achieved 29 MW with an efficiency of 27% with a narrow pulse, and 21 MW with an efficiency of 21% for 1 μsec at 19.7 GHz with a second harmonic gyroklystron Their fundamental mode gyroklystrons have produced 24–27 MW of output power at 9.85 GHz for 1 μs at up to 33% efficiency. I say most advanced even though there are a number of other sources which have higher power at similar frequencies, because they have produced stable, moderately rectangular pulses with a *gun* whose cathode type has demonstrated long life at high repetition rates. It is of concern that the magnetic field, voltage, and spin factor a are critical enough that they get a triangular pulse when they tune for maximum output. They have to detune to get a moderately rectangular pulse.

3.4 Intense Relativistic Klystrons

Several groups are working on relativistic klystrons with intense beams which utilize a principle originally proposed by Friedman [8] in which the rf modulation of the beam occurs through switching by the virtual cathode mechanism rather than velocity modulation followed by a drift. Fazio et al. [9] are following in Friedman's footsteps but are using 1 μs pulses and hope to reach repetition rates of 100 Hz. They have produced triangular pulses with a peak power of 375 MW and a base width of 1 μs at 1.3 GHz. R. B. Miller et al. [10] have built what they call a Super-

Reltron. The bunching in this device occurs in a three-cell side-coupled structure (two on-axis cells and one coupling cell) which oscillates due to its intrinsic feedback when the 100 kV beam passes through it. The low energy bunched beam is then post accelerated to about 1 MeV, which "freezes the bunching." The energy is then extracted as rf power in one or more decelerating gaps. The best performance is 700 MW at L-band in a 500 ns pulse with a total rf energy of 250 joules and a peak electronic efficiency of 45%.

3.5 Two Beam Accelerators

Several two beam accelerator systems have been proposed and are being studied theoretically and experimentally. Wang [11] and Sessler have reported on a 3-D, time dependent simulation of a well bunched beam passing through an array of nine standing-wave FELs with a reacceleration cell after each, in a 17 GHz two beam accelerator. The average power is about 150 MW per cavity with a total fluctuation from FEL to FEL of about +/- 10%. The beam pulse length is 100 ns, and the output power waveform from the first FEL cavity is an almost perfect duplicate of the current wave form. By the ninth cavity the rf pulse has shortened by 7 or 8 ns, and the leading edge is rounded for an additional 20 ns. They do not report any phase sensitivity to beam parameters, but in an earlier article Sessler [12] reports that for a standing wave FEL with somewhat different parameters, a 1% increase in the beam energy creates a synchrotron oscillation which causes a 2.3 radian peak to peak phase oscillation along the 40 meters of wiggler. This would seem to set a peak to peak energy jitter tolerance of about 0.1%, which sounds like a rather challenging (but probably not impossible) requirement for the induction cells accelerating the drive beam. Wurtele, Whittum, and Sessler [13] derive expressions for this phase oscillation. The phase oscillation for the FEL differs from the Relativistic Klystron only by the factor of $(1 + a_w^2/2)$. For either, the phase jitter varies as $(1/\gamma^2)(\partial\gamma/\gamma)$. However, as they point out, the FEL beam energy is constrained by the FEL resonance condition to be low for a microwave FEL with reasonable wiggler parameters, while the Relativistic Klystron beam energy is a free parameter. Raising the beam energy by a factor of 3 changes this energy jitter tolerance by an order of magnitude: from challenging to comfortable. It should also be noted that the high sensitivity of the FEL phase to beam energy seems to apply only to the leading edge of the beam pulse, because a 4% droop in the beam energy during the pulse had almost no effect on the phase of the microwave output.

At Lawrence Livermore National Laboratory they have successfully performed a relativistic klystron reacceleration experiment [14] in which they extracted about 60 MW of 11.4 GHz power from a 5 MeV beam in each of three disk-loaded traveling-wave output structures and reaccelerated in two interleaved induction cells. The microwave amplitude and phase waveforms look quite good. They are proposing powering an 1 TeV linear collider with 50 relativistic klystrons (beam energy = 10 MeV) each having 150 extraction structures (one every two meters) interleaved with induction acceleration modules.

Lastly, I would like to mention a very encouraging result: at the CERN CLIC Test Facility they have successfully generated 40 MW of 30 GHz power and used it to accelerate a beam in one of their 30 GHz accelerator structures in a Proof of Principle demonstration of the two beam accelerator concept to be used for their proposed linear collider, CLIC. The beam is generated in an S-band rf gun with a photocathode excited by a picosecond pulse train laser with a 3 GHz micropulse repetition rate. The beam is accelerated in a three-meter S-band linac section, passes through a 30 GHz traveling wave extraction structure, is bent through 180 degrees by a beam transport trombone, and then is reaccelerated in a 30 GHz traveling wave accelerator. The extraction structure used was one of their 30-cm-long accelerator structures. The gradient in the extraction structure was 80 MeV/m (their design gradient for acceleration) and about 70 MeV/m in the reacceleration structure. No rf breakdown was observed during this test—no rf processing appeared to be required!

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