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RF PULSE COMPRESSION AND ALTERNATIVE RF SOURCES FOR LINEAR COLLIDERS*

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ABSTRACT

Future linear colliders will require a very high peak power per meter of accelerating structure at a relatively high frequency—greater than 10 GHz—but at a relatively short pulse length—less than 100 ns. One technique for generating the required peak power is to use a more or less conventional microwave power source, which produces power at a pulse length typically on the order of 1 μs, together with RF pulse compression. Some parameters are given for a Binary Power Multiplier (BPM) pulse compression system operating at 17.1 GHz with an output pulse length of 60 ns. The peak power gain for a three stage system is estimated to be 6.6 (82% compression efficiency). Some possible long-pulse microwave sources which—when coupled with such a pulse compression system—would be suitable for driving a linear collider are briefly discussed.

1. INTRODUCTION

The peak power requirement for a recent TLC design[1] is 586 MW/m at a frequency of 17.1 GHz and a pulse length (equal to the structure filling time) of 60 ns. The relativistic klystron[2] is capable of producing sufficient peak power at this pulse length to power several meters of structure. More conventional microwave power sources operating at beam voltages of 500 kV or less could be expected to produce at most about 100 MW at this frequency. However, the natural pulse length for such sources, using conventional or near-conventional modulator technology, is on the order of 1–2μs. If a one microsecond pulse could be compressed to 62 ns by some technique, the gain factor in peak power would be $G = 16\ \eta_c$, where η_c is the compression efficiency. Thus, a 100 MW source coupled with pulse compression at 80% efficiency would produce 1.3 GW, which is comparable to the power to be expected from a relativistic klystron. In the next section we take a brief look at the capabilities and limitations of RF pulse compression.

2. PULSE COMPRESSION SYSTEMS

A number of pulse compression methods have been proposed and a few have been experimentally tested. The SLED scheme, for example, is in routine operation at SLAC. However, the peak power gain for SLED is limited to about a factor of three for a reasonable compression efficiency, and the system delivers a strongly time-varying output waveform. Energy storage cavities which are pumped up slowly by a relatively low power source with a long pulse length, and then dumped rapidly using a high power plasma switch, have also been proposed. However, the technological problems of a suitable switch have not been solved, and again the output waveform is highly nonuniform.

A pulse compression system with a potentially high peak-power gain, which gives a flat output waveform, is the Binary Power Multiplier (BPM) suggested by Z. D. Farkas[3]. The system uses a series of over-moded waveguide delay lines as low-loss energy storage elements, and 3 dB directional couplers—triggered by a pattern of phase reversals—as switching elements. It is important to note that in this pulse compression scheme two high power amplifiers and one set of delay lines are required for each BPM system. The phase reversal pattern is imposed at a low RF power level on the input drive to the amplifiers. The RF components used in a BPM system (3 dB directional couplers, transitions from rectangular to circular guide, 180° turn-arounds and right angle bends) must be carefully designed to avoid mode conversion. The theory of the BPM method is given in Ref. 3, and some initial experimental results on a prototype system (which did not, however, use all low-loss components) are reported in Ref. 4.

Let us look at a 17 GHz n-stage BPM system designed to compress an input pulse of $2^n \times 60$ ns to an output of 60 ns. Each stage compresses the pulse length by a factor of two and increases the peak power by a factor of $2\eta_n$, where η_n is the compression efficiency of the n^{th} stage. To calculate the compression efficiency, we assume a loss of 0.18 dB (transmission efficiency $\eta = 0.96$) per stage for a coupler and turn-around. The delay-line loss at 17 GHz for standard 2.81 inch I.D. copper pipe is .06 dB/100 ns (transmission efficiency of 0.99/60 ns). The length of line per 60 ns is 17.1 m ($v_g/c = 0.95$). The delay line lengths and efficiencies are given in Table I. Two efficiency figures are given for each stage. The top figures give the component and total efficiencies for that particular stage. The bottom figures give the cumulative efficiencies for all stages up to and including the n^{th} stage. Thus, a complete system of either one, two, three or four stages would have a net efficiency of 0.95, 0.89, 0.82 and 0.73, respectively.

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Table I. BPM Pulse Compression System at 17.14 GHz with 60 ns output pulse length

Stage Number	0	1	2	3	4
Delay time (ns)	0	60	120	240	480
Line length (m)	0	17	34	68	137
Efficiencies:					
η_{coup}	—	0.96 0.96	0.96 0.92	0.96 0.89	0.96 0.85
η_{line}	—	0.99 0.99	0.98 0.97	0.96 0.93	0.92 0.86
η_n	1.00	0.95	0.94	0.92	0.88
η_{cum}	1.00	0.95	0.89	0.82	0.73
RF Source:					
T_k (ns)	60	120	240	480	960
$P_K/feed$ (MW)	938	493	263	143	80

Note that the coupler and delay line losses are equal in the third stage. The cumulative losses due to the couplers and delay lines are approximately equal in a four-stage system. The pulse length required from the RF source is given by T_k. The peak source power per feed, P_k, is given for Palmer's TLC design parameters:[1] peak accelerating gradient, 186 MV/m; RF power per meter, 586 MW; distance between feeds, 1.60 m.

It is useful to note that a BPM system can be programmed to deliver more than one output pulse per RF source pulse. For example, suppose a three stage system is desired, which would nominally require a 480 ns source pulse. It may be more convenient and more efficient to design a modulator-source combination which delivers 3×480 ns ≈ 1.5 μs. The BPM phasing pattern is then simply repeated three times in succession, giving three 60 ns output pulses spaced 480 ns apart. The disadvantage is that the effective repetition rate of the collider is reduced by a factor of three; for example, from 360 Hz to 120 Hz in the TLC design in question[1]. This, in turn, reduces the effectiveness of feedback in controlling emittance growth due to the high-frequency component of magnet jitter from ground motion. However, the 120 Hz rate may still be acceptable. This multipulse scheme also has implications for the damping rings, but the necessary design modifications are acceptable[5] if the number of output pulses per klystron pulse is not too large.

Assembly of components for a low-loss 11.4 GHz BPM prototype system, which will compress 320 ns to 40 ns in three stages, is now underway at SLAC. The experiment will test the insertion loss of components (couplers, delay lines, 180° turn-arounds and transitions), the overall power gain of the system, and effects due to mode conversion and dispersion. Initial measurements at low power will be reported[6] early next year. The expected compression efficiency is 80% to 85%, giving a peak power gain of 6.5 to 7.0. The next step will be to make the system vacuum tight, so that it can be tested at high power.

In order to test a BPM compression system, accelerating structures and other RF components at a frequency and power level of interest for a linear collider, an appropriate near-term high-power RF source is needed. A 100 MW, 11.4 GHz klystron is under design[7] at SLAC which meets this need. The tube operates at 440 kV, and uses a combination of electrostatic and magnetic beam compression to achieve a high compression ratio and a reasonable cathode loading. K. Eppley[8] has simulated the dynamics of this tube, and finds an efficiency of 43% using a double-gap output cavity. Diode tests on the tube will begin early in 1989.

Some other possible microwave sources which can be used together with RF pulse compression to power a linear collider are discussed in the next section.

3. ALTERNATIVE RF SOURCES

By "alternative" we mean RF power sources which produce moderate peak power levels at a pulse length on the order of one microsecond, as opposed to very high peak power devices such as relativistic klystrons which operate at a much shorter pulse length equal to the structure filling time. Alternative sources can be driven by modulators using presently existing technology, and must be followed by several stages of RF pulse compression.

An example of such an alternative RF source, mentioned in the previous section, is the 100 MW, 11.4 GHz klystron now under design at SLAC. This power level is probably close to the limit that can be produced at this frequency using conventional klystron technology and a beam voltage less than 500 kV. It is well known that the efficiency of a klystron depends on the perveance, defined as $K = I_0/V_0^{3/2}$, where I_0 is the beam current and V_0 the beam voltage. A typical plot of efficiency (defined as the RF output power divided by the beam power I_0V_0) as a function of perveance is given in Ref. 9. The efficiency typically falls below 50% at a perveance of about $2\times10^{-6}A/V^{3/2}$. This fact alone limits the output power of a klystron to about 180 MW, independent of frequency, if it is to have reasonable efficiency at a beam voltage less than 500 kV. However, at shorter wavelengths cathode loading imposes an additional constraint. The cathode area is related to the beam cross-section area by the area compression ratio R_A. In turn, the beam area cannot exceed about $\pi(\lambda/8)^2$ if the coupling to the rf gaps is to be adequate. The output power for an efficiency η greater than about 50% is therefore

$$P \approx (\lambda/8)^2 R_A I_A V_0 \eta \ , \tag{1}$$

where I_A is the cathode loading in A/cm^2. Choosing $I_A = 10A/cm^2$ (reasonable but not conservative), $R = 200$ (probably near the upper limit), $V_0 = 400$ kV and $\eta = 50\%$, we have

$$P(MW) \approx 20\,[\lambda(cm)]^2 \ . \tag{2}$$

Thus at 17 GHz we can expect at most about 60 MW from such a "pushed technology" klystron.

A number of devices have been suggested which get around the λ^2 scaling in Eq. (2). The gyroklystron, for example, employs an annular beam with a thickness which scales with wavelength, but a circumference which to first order can be independent of wavelength. The area of the beam, and hence the power output, then scales roughly in proportion to λ. Thus, the gyroklystron is more suited to the production of high power at high frequencies than the klystron. As an example, a gyroklystron is being developed at the University of Maryland which will produce 40 MW at 10 GHz. It is estimated that the device could be scaled to produce 110 MW at 17.1 GHz.[10)]

Strip beam, or sheet beam, tubes are another class of device which can get around the λ^2 scaling law that round beam tubes must follow. Consider, for example, a sheet beam of width w and thickness t. To couple to the RF circuit, the thickness must be a fraction of the wavelength, say $t \approx \lambda/5$. Thus the power output of a sheet beam device is roughly

$$P \approx 0.2\lambda w R_t I_A V_0 \eta \quad . \qquad (3)$$

Here, R_t is the transverse beam compression ratio (ratio of cathode width to beam thickness). We take R_t to be 10, although detailed gain design calculations are needed to determine a realistic limit. Again, take $I_A = 10A/cm^2, V_0 =$ 400 kV and $\eta = 0.5$. Equation (3) then gives

$$P(MW) \approx 4\,[\lambda(cm)]\,[w(cm)] \quad . \qquad (4)$$

At 17 GHz such a sheet beam device with a width of 25 cm would produce 175 MW.

The perveance of sheet beam devices is also an important consideration. Longitudinal and transverse space charge effects in a sheet beam depend on the perveance per square K_s, defined terms of the current in the beam per square, I_s, as

$$K_s = I_s/V_0^{3/2} \approx I_A R_t (\lambda/5)^2 V_0^{-3/2} \quad . \qquad (5)$$

For $I_A = 10A/cm^2, R_t = 10, V_0 = 400$ kV and $\lambda = 1.76$ cm (17 GHz), $K_s = 0.05$. Space charge effects are relatively small at this low a perveance. In fact, a sheet beam device with the same output power as a round beam device has a perveance per square which is lower than the round beam perveance by a ratio on the order of $\lambda/5w$. These concepts also apply to annular beams, where w is the circumference of the beam.

The design of a sheet beam X-band (11.4 GHz) klystron has been considered by Eppley, Herrmannsfeldt and Miller.[11] The device, shown in Fig. 1, uses permanent magnets with alternating polarity to focus the beam (wiggler focusing). The tube was not actually built, but in simulations it produced an output power of 2 MW per centimeter of beam width at a beam voltage of 200 kV with an efficiency of about 50%. The perveance per square was about 0.1 $\times 10^{-6}$. The calculations indicated that the output power could be raised above 10 MW/cm at somewhat higher voltage and perveance with no loss in efficiency, giving an output power of 250 MW for a 25 cm wide beam. A number of problems with the sheet beam klystron concept need more detailed investigation, in particular the design of suitable RF cavities and potential feedback between cavities which can result from construction asymmetries.

It is possible to envision a variety of other sheet beam devices, for example sheet beam traveling wave tubes. The concept of a deflection modulated sheet beam device also looks interesting. Such a device is based on the interaction of the beam with the transverse beam-breakup mode. The tube can use discrete cavities to amplify the deflection (the Deflectron), or a continuous periodic structure (the Deflection Wave Amplifier). All sheet beam devices could in principle also be constructed as annular beam devices.

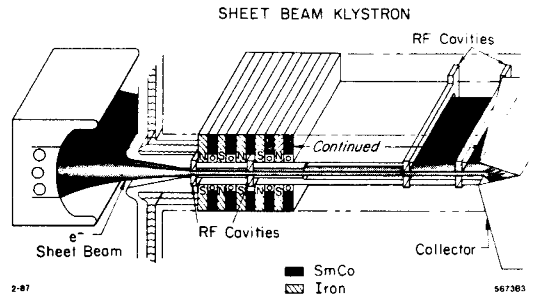

Fig. 1. Sheet beam X-band klystron.[11)]

To obtain high output power at a relatively low voltage from a linear beam device, it is clear that the beam cross section area must be increased so that in one dimension it becomes large compared to the RF wavelength. Only a few relatively simple possibilities for such extended beam area devices have been considered in this brief survey. More exotic concepts using annular or sheet beams have been proposed, such as the Gigatron[12]. Crossed-field amplifiers, which inherently operate at a high perveance (microperveance on the order of ten), have not been discussed. It has recently been suggested[13] that such devices are capable of being scaled to high power levels. In conclusion, there are a number of potential RF sources which can be used in conjunction with RF pulse compression to power a high gradient linear collider. The difficult problems are not so much in concept as in the detailed engineering and development needed to advance the technology on a reasonable time scale.

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