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PROGRESS AT SLAC ON HIGH-POWER RF PULSE COMPRESSION*

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Abstract

Rf pulse compression is a technique for augmenting the peak power output of a klystron (typically 50–100 MW) to obtain the high peak power required to drive a linear collider at a high accelerating gradient (typically 200 MW/m is required for a gradient of 100 MV/m). The SLED pulse compression system, with a power gain of about 2.6, has been operational on the SLAC linac for more than a decade. Recently, a binary pulse-compression system with a power gain of about 5.2 has been tested up to an output power of 120 MW. Further high-power tests are in progress. Our current effort is focused on prototyping a so-called SLED-II pulse-compression system with a power gain of four. Overmoded TE_{01}-mode circular waveguide components, some with novel technical features, are used to reduce losses at the 11.4-GHz operating frequency.

1. SLED

The SLED system of rf pulse compression has been in use on the SLAC linac since 1982. Originally called SLAC Energy Doubler, and later modified to mean SLAC Energy Development, "SLED" is now often used as a generic name for a method of pulse compression involving the use of high-Q energy storage cavities. Energy coming from the klystron builds up in these storage cavities during the major fraction of the high-power pulse, and is released at the end of the pulse during a period equal to the filling time of the accelerating structures. The signature of SLED is that this release is triggered by a 180° phase shift in the low-level drive to the klystron. During this release time, energy coming directly from the klystron is combined with energy emitted from the storage cavities. A 3-dB directional coupler, with two identical storage cavities placed symmetrically at the output ports, acts as a circulator so that energy emitted from or reflected by the cavities is directed to the accelerator.

The theory of SLED is described in detail in Ref. [1] for a constant-gradient accelerating structure, as used in the SLAC linac. For the case of a SLED system driving a constant impedance structure, it is possible to derive an expression for the power gain G, defined as the klystron power multiplication factor that would be necessary to obtain the same accelerating gradient without SLED. The SLED power gain depends on the compression ratio R, defined as the ratio of the klystron pulse length to the structure filling time. The SLED power gain is

$$G = \left[\frac{1-\beta}{1+\beta}+\frac{2\beta}{1+\beta}\left(2-e^{-\mu}\right)\frac{e^{-v}-e^{-\tau}}{\tau-v}\,\frac{\tau}{1-e^{-\tau}}\right]^2 \quad (1)$$

where

$$\mu=\frac{(R-1)(1+\beta)}{x}, \qquad v=\frac{1+\beta}{x}, \qquad x=\frac{Q_0}{\pi f T_f}.$$

Here, β $(=Q_0/Q_{\text{ext}})$ is the cavity coupling coefficient, τ is the voltage attenuation parameter for the structure, T_f is the structure filling time, x is the unloaded time constant of the storage cavities normalized to the structure filling time, and f is the rf frequency.

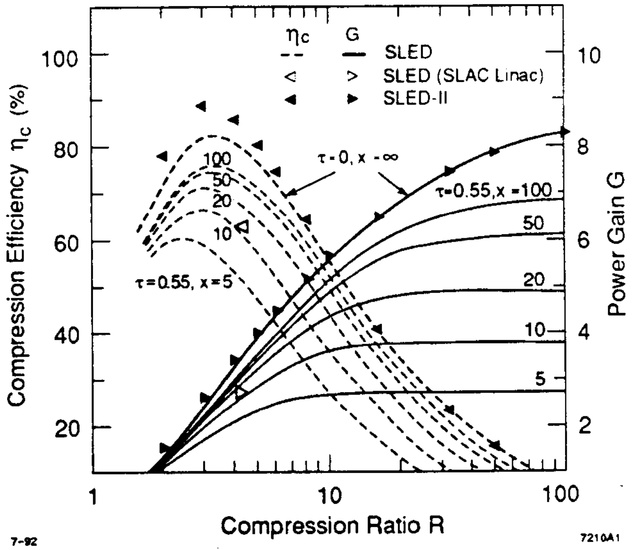

Figure 1. Power gain (solid curves) and compression efficiency (dashed curves) for a SLED rf pulse-compression system driving an accelerator structure with τ and x as indicated. The top curves show gain and efficiency for a SLED system with lossless components ($\tau = 0$, $x = \infty$). The two open triangular points show gain and efficiency for SLED as implemented in the SLAC linac. The solid triangular points are for a SLED-II system with lossless components.

Expression (1) also gives, to good approximation, the power gain for a constant-gradient structure. For each value of x and R, the maximum power gain achievable is obtained by optimizing the cavity coupling β. The maximum power gain as a function of the compression ratio R for an accelerating structure with $\tau = 0.55$ is

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shown by solid curves in Fig. 1. The corresponding compression efficiency, $\eta_c = G/R$, is shown by dashed curves. The top curves for both G and η_c give the limit on gain and efficiency for a lossless structure ($\tau = 0$) and lossless cavities ($x = \infty$). Note that in this case the maximum compression efficiency for a SLED system is 82% at a compression ratio of about three.

A major disadvantage of SLED is that the shape of the pulse delivered to the accelerator falls exponentially from a sharp initial peak by about a factor of three over the filling time of the accelerating structure. This nonuniformity also makes the SLED gain depend on the properties of the accelerating structure. This disadvantage does not apply to SLED-II, which is discussed in Section 3.

2. Binary Pulse Compression (BPC)

The BPC method of rf pulse compression, invented by Z. D. Farkas[2], can deliver a flat pulse to the accelerator with, in principle, 100% efficiency. One stage of a BPC system consists of a 3-dB directional coupler and an associated delay line having a delay time of one-half the input pulse length. One property of a 3-dB coupler is that equal rf power flowing into the two input ports can be combined to emerge from either output port, depending on the phase difference between the input ports. During the first half of the input pulse, this phase difference is chosen such that the power flows into the port connected to the delay line. The input phase difference is switched by 180° during the last half of the pulse so that the power is directed to the other output port to arrive synchronously with the power emerging from the delay line. The output power thus has twice the peak amplitude and one-half the pulse length of the input power.

The heart of the BPC concept is a clever phase coding scheme which allows, in principle, any number n of BPC stages to be added in series to give a total power gain of $G = 2^n$. This gain must, of course, be multiplied by an efficiency factor which takes into account losses in the delay lines and other components. Two klystrons are normally required to drive a BPC system. A variation of the basic BPC concept, due to P. Latham[3], allows a single klystron to drive the system using an additional delay line.

A three-stage BPC system, described in Refs. [4] and [5], was completed at SLAC in 1990. A peak output power of 120 MW was obtained[6] in 1991. This power level was limited by the available klystron power, and not by breakdown. The measured power gain was in the range 5.2–5.8. The expected gain, based on the sum of the losses measured for each of the individual components, is 6.1. The difference perhaps is due to some unexpected mode conversion or, more likely, to uncertainty in the individual component losses. The total loss is the sum of many small losses, each difficult to measure accurately, for the individual components.

The BPC system is currently in routine use at the 100-MW output power level to provide power for high-gradient tests on a 30-cell, 11.4-GHz travelling wave structure. There is a 40% power loss in the rectangular waveguide running from the output of the BPC to the test structure in a shielded bunker. The maximum operating power level attempted to date (limited by a power output considered safe for the klystron) has produced 120 MW at the output of the BPC, and 72 MW at the input to the test structure, resulting in an accelerating gradient of 85 MV/m.

The BPC system soon will be changed over from a single klystron to a two-klystron drive configuration. The overall power gain of the BPC system, taking into account klystron-to-BPC and BPC-to-bunker rectangular waveguide losses, is about 2.6. Thus the 80 MW expected from both klystrons will produce over 200 MW in the accelerator test bunker. This is sufficient to drive the 75-cm test accelerating structure, scheduled to be installed in the bunker later this year, to a gradient of about 100 MV/m.

3. SLED-II

SLED-II is a variation of the basic SLED scheme in which the two high-Q resonant cavities are replaced by lengths of low-loss delay line shorted at the far ends. The basic concept was first described by Fiebig and Schieblich[7] in 1988. A schematic layout of a SLED-II system is shown in Figure 2. In the SLED-II concept, an iris with reflection coefficient s at the input to each delay line plays a role similar to that of the coupling coefficient β in the case of a conventional SLED system. SLED-II, however, produces a flat output pulse equal in length to the down-and-back transmission time for the delay lines. The input pulse length must be an integer N times the output pulse length. The power gain for a SLED-II system with lossless components is given by

$$G = (1 + 2s - s^{N-1} - s^N)^2. \tag{2}$$

For any choice of N, the value of s can be chosen to maximize the gain. The optimum reflection coefficient is given approximately by

$$s_o \approx \left(N - \tfrac{1}{2}\right)^{-1/(N-3/2)}.$$

This expression for s_o is exact for large N, but even for $N = 3$ it will give an accurate result for the maximum gain when substituted into equation (2). The optimum power gain, and corresponding compression efficiency, are shown in Figure 1 by the solid triangular points. It is seen that the properties of SLED and SLED-II converge at large compression ratios.

Previous work at SLAC on SLED-II is described in Refs. [8] and [9]. In Ref. [9], measurements on a low-power experimental SLED-II system with a 35-ns-long output pulse are described. The measured behavior was in complete agreement with theory. A high-power SLED-II system is under construction and will be ready for high-power tests by this coming October. The output pulse

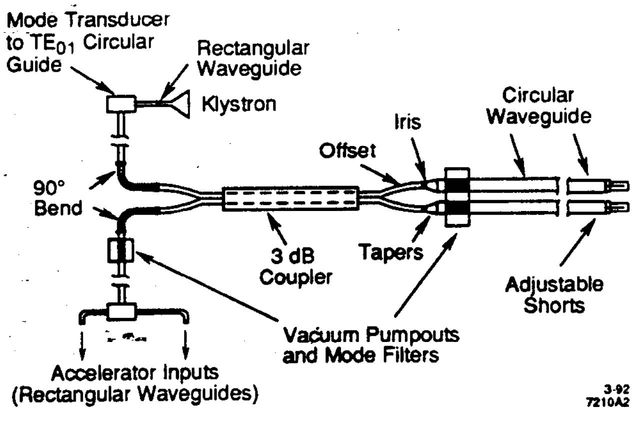

Figure 2. Schematic layout of a SLED-II pulse-compression system employing low-loss overmoded circular waveguides.

length will be about 75 ns, and a power gain of five is expected for a 900-ns-long input pulse. This system uses existing 7.14-cm-diameter delay line, and a 3-dB coupler design described in Ref. [10]. Early in 1993, construction of an upgraded SLED-II system, which uses a new 3-dB coupler design and lower-loss 12.1-cm-diameter delay line, will be completed. This pulse-compression system, operating at an output pulse length of 150 ns, will be the prototype for the NLC Test Accelerator facility being proposed at SLAC.

4. Overmoded Circular Waveguide Components

The loss in standard rectangular waveguide (WR90) at 11.4 GHz is unacceptable (0.1 dB/m). Power transmission will therefore be based on the use of circular waveguide operating in the low-loss TE$_{01}$ mode. At 11.4 GHz, the attenuation in such a transmission line of radius a is given by

$$A(\mathrm{dB/m}) = \left(\frac{0.165\,\mathrm{cm}^3}{a^3}\right)\frac{c}{v_g}$$

where

$$\frac{v_g}{c} = \sqrt{1-\frac{2.56\,\mathrm{cm}^2}{a^2}}.$$

Here, a is the guide radius in centimeters and v_g/c is the group velocity in the waveguide relative to free space. Circular guide with a diameter of 4.45 cm will be used for short-distance transmission (1% loss per 2 m), since this diameter guide can be connected directly to a 90° bend without a taper. The 7.14-cm-diameter line, now used for the BPC delay line, works well for longer-distance transmission (1% loss per 10 m), but must be tapered to 4.45-cm at a 90° bend. The delay line for the upgraded SLED-II system will use 12.1-cm-diameter circular waveguide (1% loss per 50 m or per 170 ns). Care must be taken to avoid discontinuities, dents, and kinks large enough to cause significant mode conversion.

Figure 2 shows other overmoded components needed for a SLED-II system. The electrical design of the 3-dB coupler is described in Ref. [10]. The coupler now under construction is milled in two halves from blocks of copper, which are then bolted together and enclosed in a vacuum chamber. A new coupler is under design in which the two copper blocks are assembled with input and output ports and then brazed, eliminating the need for an external vacuum chamber.

Two 90° bends made from 4.45-cm-diameter circular corrugated waveguide have been ordered from General Atomics (San Diego, CA). Mode converters are being developed by Alpha Industries, Inc. (Methuen, MA). In addition, we are working on our own in-house designs. The insertion loss for each of these components is expected to be about 2%. When the units arrive later this year, they will immediately be put to work to reduce the transmission loss from the BPC output into the structure test bunker from 40% to the order of 10%. These components also will be used for low-loss power transport between klystrons, SLED-II systems, and accelerator structures.

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