SLAC-PUB-5409
January 1991
(A)

Radio frequency pulse compression experiments at SLAC*

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1. INTRODUCTION

Proposed future positron-electron linear colliders[1] would be capable of investigating fundamental processes of interest in the 0.5–5 TeV beam-energy range. At the SLAC Linear Collider (SLC) gradient of about 20 MV/m this would imply prohibitive lengths of about 50–250 kilometers per linac. We can reduce the length by increasing the gradient but this implies high peak power, on the order of 400- to 1000-MW at X-Band. One possible way to generate high peak power is to generate a relatively long pulse at a relatively low power and compress it into a shorter pulse with higher peak power. It is possible to compress before DC to RF conversion, as is done using magnetic switching for induction linacs, or after DC to RF conversion, as is done for the SLC. Using RF pulse compression it is possible to boost the 50- to 100-MW output that has already been obtained from high-power X-Band klystrons to the levels required by the linear colliders. In this note only radio frequency pulse compression (RFPC) is considered.

The advantages of RFPC are:

1. Generally the higher the power the harder it is to increase it further. This is not the case with RFPC because the control elements operates at low power.

2. With RFPC we can alternate between low power un-compressed pulses and high power compressed pulses by turning the modulation off and on. It is much more difficult to design tubes that function both at low and high peak power levels.

3. RFPC may have lower capital, maintenance and replacement costs per watt of peak power.

4. For a given compression ratio, the cost of RFPC is independent of pulse energy or peak power.

Three methods of RF pulse compression that are in use or have been proposed at SLAC will be reported on. The SLAC Energy Development (SLED),[2] where RF energy is stored in cavities; the Resonant Line SLED (RELS),[3] where the energy is stored in long resonant lines; and the Binary Pulse Compressor (BPC),where the energy is stored in traveling wave delay lines.

2. SLAC ENERGY DEVELOPMENT

In the SLED method of RF pulse compression, two high Q resonators store energy from an RF source for a relatively long time interval (typically 3–5 μsec). Triggered by a reversal in RF phase, this stored energy is then released during a much shorter interval equal to the filling time of the accelerating structure. A SLED energy storage network at a typical klystron station at SLAC is shown in Fig. 1.

The SLED gain is obtained as follows.[2] We equate the power into the cavity to the power dissipated plus the rate of energy buildup in the cavity, and obtain the differential equation that relates the field emitted from the cavity coupling aperture into the input waveguide to the incident field. The solution is

* Work supported by Department of Energy contract DE–AC03–76SF00515.

Presented at the SPIE's Symposium on High Power Lasers, Los Angeles, CA, January 20–25, 1991.

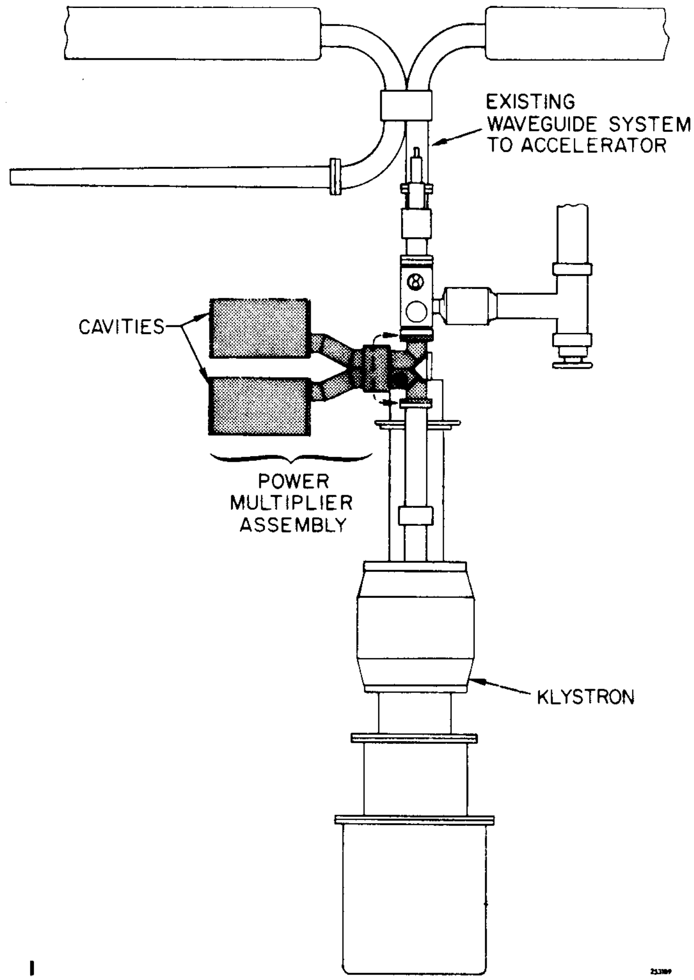

Fig. 1. SLED energy storage network at a typical klystron station at SLAC.

$$E_e(t) = E_{ef} - [E_{ef} - E_{ei}]e^{-t/T_c} \quad .$$

Here E_e is the emitted field, E_{ei} is the emitted field at time $t = 0$, and

$$E_{ef} = E_e(\infty) = \alpha E_i \quad , \qquad \alpha = 2/(1 + Q_e/Q_o) \quad , \qquad T_c = \alpha Q_e/\omega \quad ,$$

where Q_o and Q_e are the unloaded and the external Qs of the cavities. The reflected field is

$$E_r = E_e - E_i \quad .$$

For $Q_e/Q_o \ll 1$, the steady state emitted field $E_{ef}(\infty) \approx 2E_i$. If, after reaching steady state, we reverse the phase of the klystron input we have

$$E_r = E_{ef} + E_i \quad .$$

For $\alpha = 2$ this becomes $E_r = 3E_i$, an instantaneous power gain of 9.

The shape of the output pulse is, however, a sharply decaying exponential which causes a decrease in effective power gain. The other sources of loss are reflections during charging, energy left in the cavities at the end of the pulse, and energy loss inside the cavities. The SLED waveforms are shown in Fig. 2.

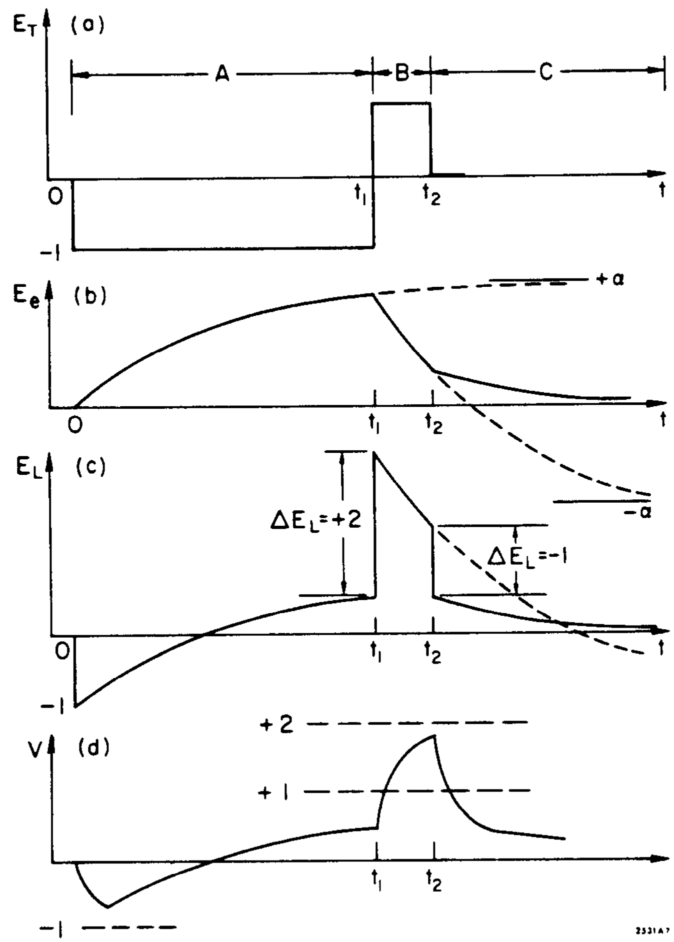

Fig. 2. SLED waveforms.

To characterize a RFPC system, define

T_k	input pulse length
T_p	output pulse length
C_f	compression factor
P_k	input pulse peak power
P_g	effective power gain
η_{pc}	compression efficiency
E_a	accelerating electric field

They are related

$$C_f = \frac{T_k}{T_p} \quad , \qquad P_g = \frac{E_a^2 \text{ (with RFPC)}}{E_a^2 \text{ (without RFPC)}} \quad , \qquad \eta_{pc} = \frac{P_g/P_k}{C_f} \quad .$$

Except for a flat top output pulse, P_g/P_k does not, generally, equal the ratio of output pulse energy to input pulse energy.

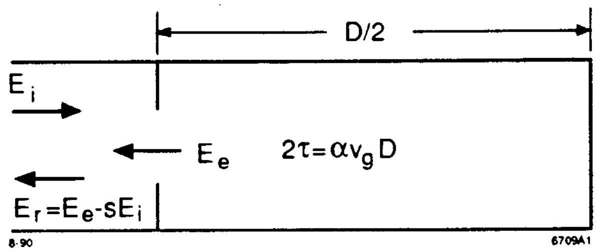

Fig. 3. Resonant line.

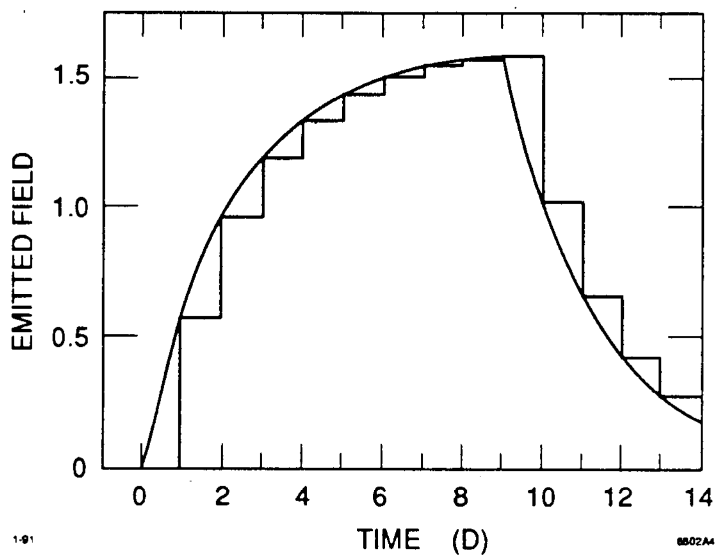

Fig. 4. RELS emitted field during charging and discharging.

Presently at SLAC we compress a 60 MW, 3.5 μs klystron output pulse into a 160 MW, 0.82 μs accelerator input pulse. A peak power gain on the order of three and a compression efficiency on the order of 60% are typically attained. Presently SLED is also used at DESY (Hamburg, Germany), IHEP (Bejing, China) CERN (Geneva, Switzerland), and at INP (Novosibirsk, USSR).

3. RESONANT LINE SLED

In RELS, the two cavities are replaced by two lengths of resonant line, forming a Resonant Line SLED. Because the speed of EM waves is finite, the emitted field changes in discrete steps, with widths equal to the time it takes for a wave to transit down and back the length of the resonant line. Most importantly, this results in a flat top output pulse. Because of this, and because the use of long low loss TE_{01} mode lines reduces the losses, RELS efficiency is greater than that of SLED.

A resonant line, shown in Fig. 3, is a transmission line terminated in a short circuit and connected to an input transmission line via a coupling network. The distance between the coupling network and the short must be an integral multiple of half guide wavelengths, and the round-trip time delay, D, between the coupling network and the short equals the desired output pulse length. After turning on an incident field of amplitude E_i, the emitted field during the first round trip time is zero.

$$E_e(0) = 0 \quad .$$

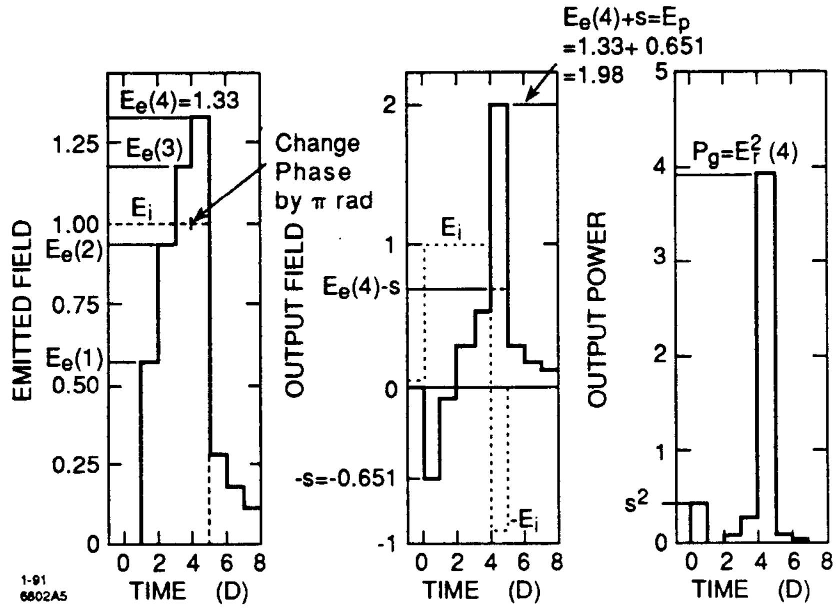

Fig. 5. Emitted field, reverse field and reverse power.

After nD time intervals it is given by

$$E_e(n) = E_i(1-s^2)e^{-2\tau}[1 + se^{-2\tau} + s^2e^{-4\tau} + \ldots + s^{(n-1)}e^{-(n-1)2\tau}]$$

$$n = 1, 2, 3\ldots \quad .$$

$$E_e(n) = E_i\frac{(1-s^2)e^{-2\tau}}{1-se^{-2\tau}}[1 - s^n e^{-n2\tau}] = E_{ef}[1 - s^n e^{-n2\tau}]$$

$$n = 0, 1, 2, 3\ldots \quad .$$

Let $s \equiv e^{\ln s}$, and let t_n be the beginning of each D interval, $t_n = nD$. Then we can express the emitted field as a function of time in units of D

$$E_e(n) = E_{ef}[1 - e^{-n(2\tau - \ln s)}] = E_{ef}[1 - e^{-(t_n/D)(2\tau - \ln s)}] \quad .$$

We generalize to the case in which $E_e = E_{ei}$ at $t_n = 0$,

$$E_e(t_n) = E_{ef} - [E_{ef} - E_{ei}]e^{-(t_n/D)(2\tau - \ln s)} \quad .$$

The emitted field during charging and discharging is shown in Fig. 4.

Using superposition, the reverse field is

$$E_r(n) = E_e(n) - E_i s \quad .$$

Let the input pulse width be $T_k = n_o D$. We reverse the phase one round trip time before the end of the pulse at $t_n = (n_o - 1)D$ and we have

$$E_r(n_o - 1) \equiv E_p = E_e(n_o - 1) + E_i s \quad .$$

E_p is constant for a duration D and is the field amplitude of the output pulse. For a given n_o, s can be varied to maximize E_p. The power gain, compression factor and compression efficiency are:

$$P_g = E_p^2 \quad , \qquad C_f \equiv T_k/D = n_o \quad , \qquad \eta_{pc} = \frac{P_g}{n_o} \quad .$$

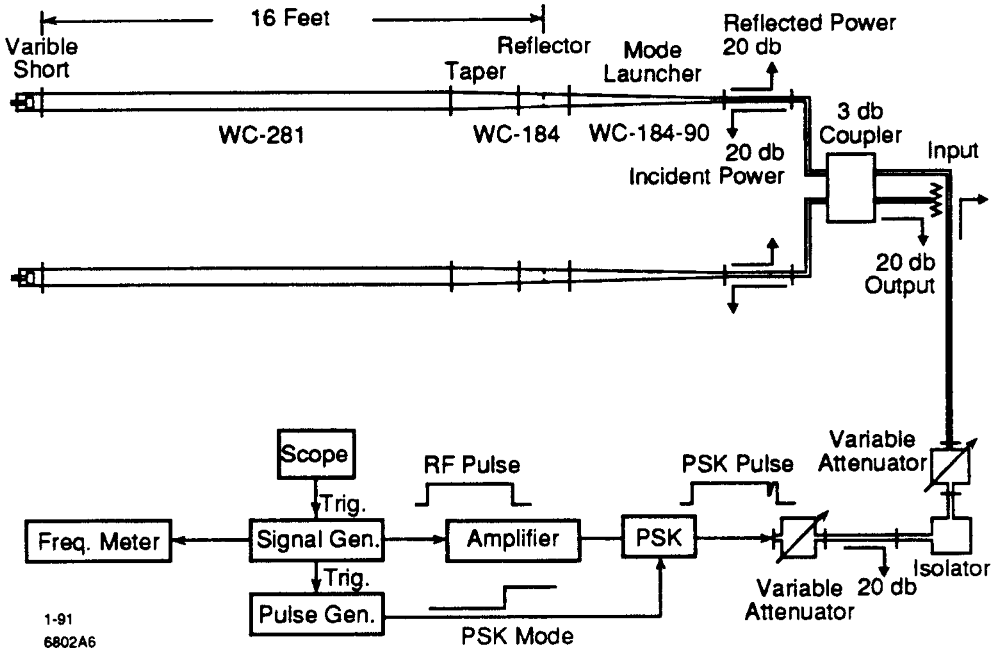

Fig. 6. Low power experimental RELS system.

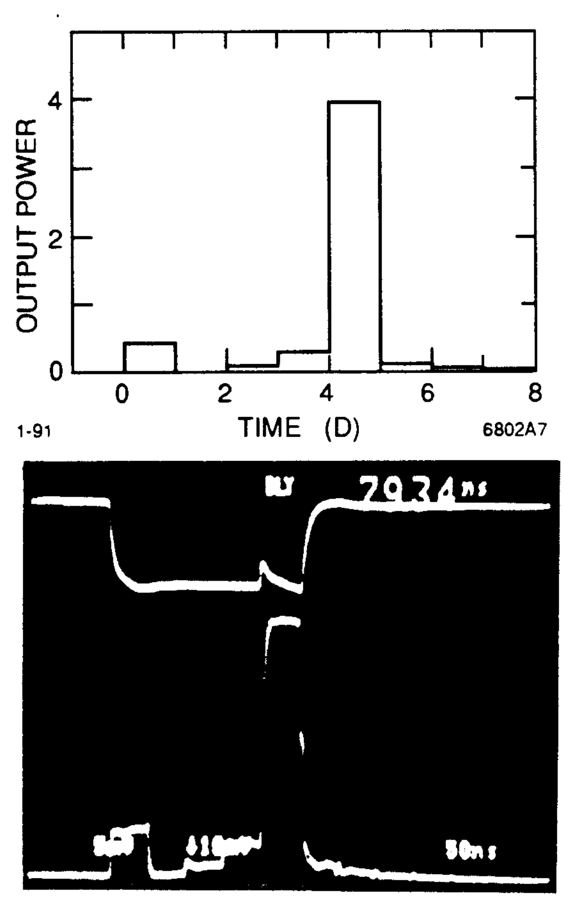

Fig. 7. Predicted waveform and an oscillogram of the experimentally obtained waveform.

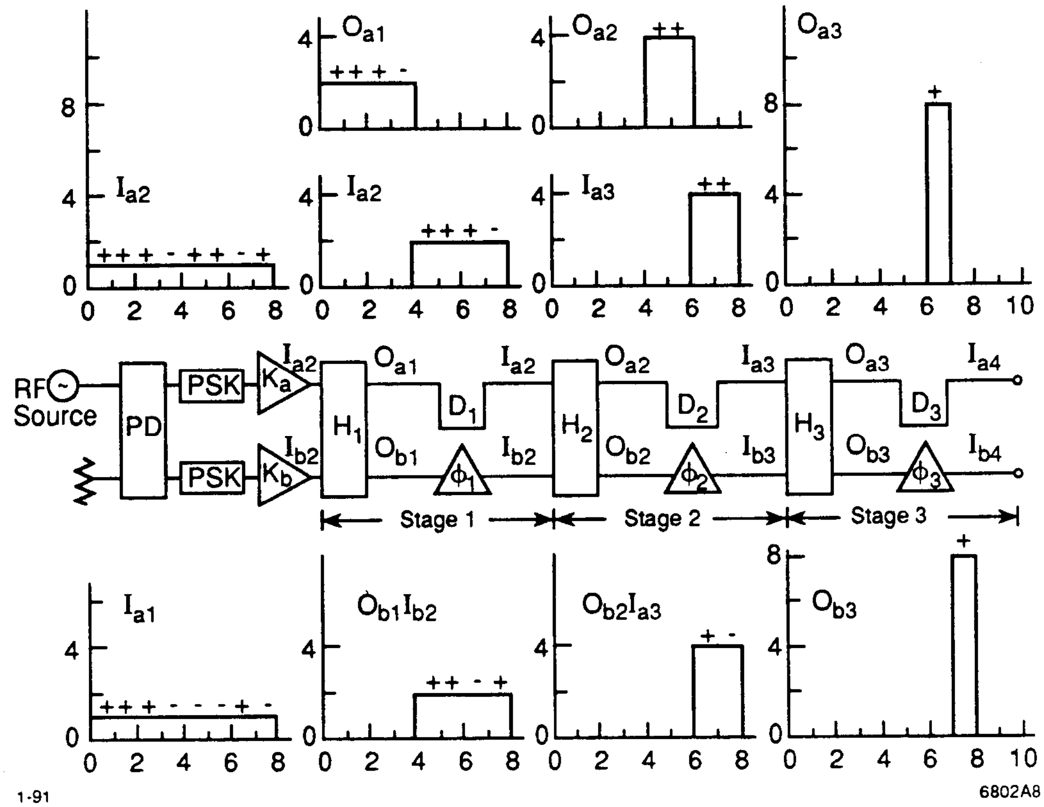

Fig. 8. 3-Stage BPC.

Figure 5 shows the emitted field, the reverse field, and the reverse power as a function of time in units of D for a 5 unit pulse. The phase is reversed after 4 time units and the reverse field goes from $E_e(4) - s = 0.682$ to $E_e(4) + s = 1.98$, for the value of s that optimizes the output power, $s = 0.65$. The output power is the square of E_r. The power gain is 4 and the efficiency is 80%. Note that s can be determined from $s = \sqrt{P_r(1)/P_i}$.

A low power experimental RELS system, shown in Fig. 6, was set up to verify the theoretical predictions. This was accomplished as indicated in Fig. 7, which shows the predicted waveform and an oscillogram of the experimentally obtained waveform. A high power RELS system, capeable of producing peak powers in the order of 500 MW, is under design.

4. BINARY PULSE COMPRESSION

As with SLED and RELS, the BPC modulation takes place at the low level input drive to the klystron amplifier, while the compression itself takes place at high power levels. But, unlike SLED and RELS, there are no reflection losses during charging. As with RELS, the dissipation loss is minimized by using as energy storing elements overmoded TE_{01} circular guides. In this mode losses decrease as the 3/2 power of frequency for a fixed guide diameter and as the cube of the diameter for a fixed frequency. In our experiment at 11.4 GHz, the guide inside diameter is 2.81 inch and the loss is 1.1 dB per microsecond of time delay. The system will be driven by a 100 MW klystron now being tested at SLAC.[5]

The basic component of the BPC is a 4 port, 3 dB coupler with one of its ports connected to a delay line. Two pulses, each twice as wide as the delay line fill time, are applied to the two isolated ports of the coupler. During the first half of the input pulse, the relative phase of the inputs is such that all power exits the port connected to the delay line and, is therefore, delayed by half the input pulse width. At the beginning of the second half of the input

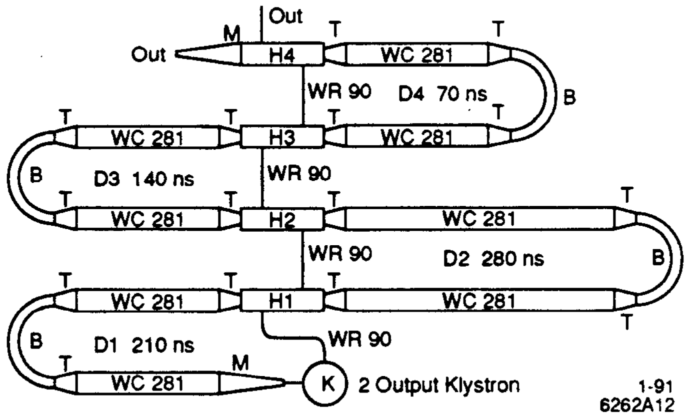

Fig. 9. Physical layout of high power single source 3-stage BPC.

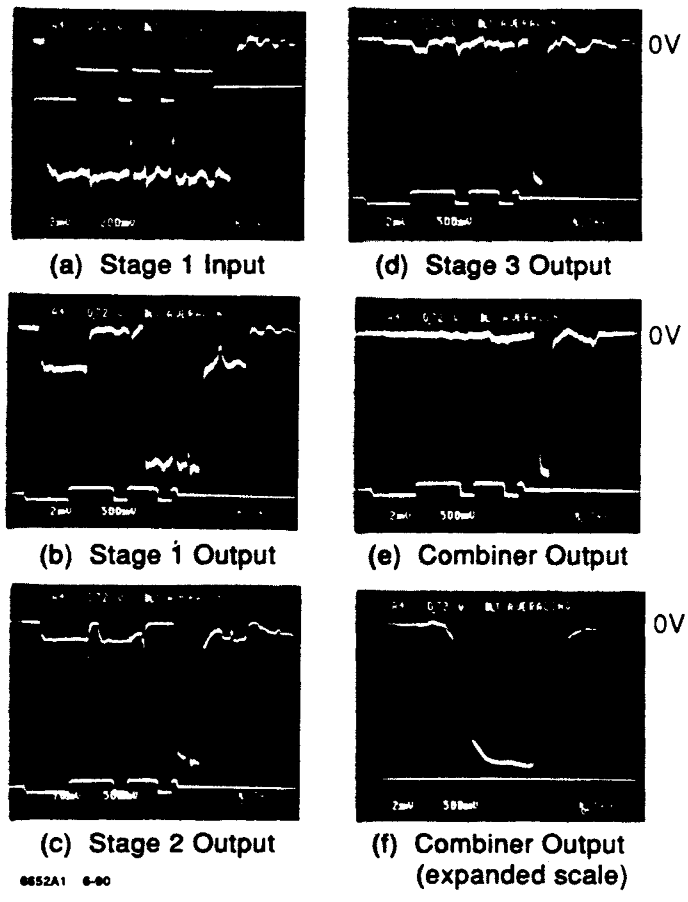

Fig. 10. High power single source 3-stage BPC outputs.

pulse, the relative phase of the inputs is reversed causing all the power to exit the other port. Thus we have two output pulses, each half as wide and twice the power of each input pulse.

BPC stages can be cascaded.[4] Thus, generally, a BPC consists of a series of stages, each stage consists of a 4-port 3 dB hybrid with one port followed by a delay line. The last delay equals the duration of the compressed

Table 1. Power gains and compression efficiencies.

Stage	Power Gain (Compression Efficiency)		
	Ideal	Expected	Measured
1	2	1.77 (88%)	1.75 (88%)
2	2	1.81 (90%)	1.79 (90%)
3	2	1.85 (93%)	1.75 (88%)
1–3	8	5.91 (74%)	5.47 (68%)

pulse. Each additional delay toward the BEC input is double the previous delay. The two input pulses to the BEC are divided into 2^n equal bins. The length of each bin is the length of the compressed pulse. Each bin is coded with either a zero or 180° phase shift. Consequently the output pulse length is divided by 2^n and, ideally, the power is multiplied by 2^n, where n is the number of stages. A 3-stage BPC is shown in Fig. 8.

The BPC also works with a single source.[6] But, in that case, the two input pulses are created by modulating a longer than $C_f T_p$ single source pulse. This pulse is then divided into two pulses which are shifted with respect to each other with an additional delay line. The region of the pulses which overlap in time has a width $C_f T_p$ and in this region the pulses have the correct phase modulation. For a 2-stage BPC the single source delay line length is T_p and for a 3-stage it is $3T_p$.

Because at this time we have only one klystron available, our high power test were performed with a single source BPC. The single source 3-stage BPC network is shown in Fig. 9 and is described in detail in Ref. 7. The outputs are shown in Fig. 10. The expected and measured gains of each stage are shown in Table 1. The input pulse is 770 ns and the output pulse is 70 ns. At present, the maximum compressed pulse peak power is 60 MW, limited by the maximum klystron output, at 770 ns, of 12 MW.

5. CONCLUSION

Three methods of RFPC have been considered. The first, SLED, is useful for providing high peak power to S-band accelerators where RELS and BPC are not suitable because the filling time of the accelerator sections approach 1 μs and hence the energy storing delay lines would be prohibitively long. For example, using RELS or the BPC at SLAC would require a minimum 800 ns delay line (about 800 ft) with about a 30 cm line diameter for reasonable loss. The SLED system is being used at high energy physics laboratories all over the world which have S-band accelerators. Future colliders require X-band frequencies and above, where both the RELS and the BPC are practical. The BPC can be, theoretically, 100% efficient. It is more complicated than RELS and, for the same compression factor, requires several times the totanl length of delay lines. A high power 3-stage BPC has been tested at 11.4 GHz. With a 770 ns, 12 MW input pulse, a 70 ns, 60 MW output pulse was achieved. When two X-Band klystrons become available, the binary pulse compressor will be reconfigured to utilize both of these high-power sources. If each klystron produces 100-MW, we expect 550-MW compressed pulses at each Stage-3 output, and1000-MW compressed pulses after combining to a single output. For 550 MW, peak surface fields in the hybrid slots and in the WR90 guides are estimated to be only 80 MV/m, well below the expected threshold for breakdown.

6. REFERENCES

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