Experiments in which the powers of two SLAC klystrons were combined and fed into a resonant cavity pulse-compression system (SLED) are described. Pulse powers up to 65 MW into SLED were reached. The corresponding instantaneous peak power out of SLED was 390 MW. After normal initial aging, no persistent RF breakdown problems were encountered. X-radiation at the SLED cavities was generally less than 400 mR/hr after aging.

Theoretical relationship between x-radiation intensity and RF electric field strength is discussed.

The SLED pulse-compression system has been developed to achieve the goal of increasing the energy of the electron and positron bunches produced by the two-mile accelerator to be increased to 50 GeV. The preferred option for achieving this goal is to develop 50 MW, 5 μs pulsed klystron amplifiers to drive the accelerator sections through the installed SLED pulse compression system. The pursuit of this option gives rise to concern about the possibility of RF breakdown occurring anywhere in the waveguide system. For this reason, system tests with incident peak powers in the 50 MW range have been made before the completion of the first prototype 50 MW klystron. The power level was achieved by combining the outputs of two adjacent 36 MW klystrons in phase.

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Introduction

The SLAC Linear Collider (SLC) project requires the energy of the electron and positron bunches produced by the two-mile accelerator to be increased to 50 GeV. The preferred option for achieving this goal is to develop 50 MW, 5 μs pulsed klystron amplifiers to drive the accelerator sections through the installed SLED pulse compression system. The pursuit of this option gives rise to concern about the possibility of RF breakdown occurring anywhere in the waveguide system. For this reason, system tests with incident peak powers in the 50 MW range have been made before the completion of the first prototype 50 MW klystron. The power level was achieved by combining the outputs of two adjacent 36 MW klystrons in phase.

The Experimental Station

Figure 1 shows schematically the experimental configuration. The drive to two adjacent klystrons was derived from a single subdrive line coupler as shown, using a common level-set attenuator A1 and a common automatic protection attenuator P. Attenuators A2 were used to adjust the klystrons individually for different saturation characteristics. The sector automatic phasing system was modified to phase-lock continuously the outputs of the two klystrons. Unbalance at the phasing system bridge generated an error signal which caused phase-shifter P1 to move to restore balance. The balance point (and hence the phase relationship of the two high-power inputs to the combiner hybrid) could be adjusted by means of phase-shifter P2 which was set to minimize the power into the load arm of the combiner hybrid. Klystron fault conditions (over-voltage, over-current, poor wave-guide vacuum, high reflected RF power) were summed in a common protection unit, so that a fault associated with either tube caused triggers to be withheld from both modulators. In addition, combiner hybrid load-arm power in excess of a predetermined level was treated as a common fault by the same protection system. Following long-established logic, withholding of triggers for a few seconds caused the common protection attenuator P to run in, removing drive from both klystrons. The gain and phase characteristics of the two tubes were sufficiently well-matched that no problems with combiner hybrid load-arm power were experienced for any setting of P or A1.

The combined output of the two klystrons was fed into the SLED (SLAC Energy Development) cavity assembly at the station selected for the experiment. This installation (which was entirely typical of the SLED installations at all other stations on the SLAC accelerator) was in turn connected to the standard waveguide network feeding four accelerator sections.

The SLED pulse-compression system has been described in detail elsewhere. However, it may be convenient to review very briefly the operating principle.

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Peak Powers Achieved at 2856 MHz

All of the waveguide couplers shown in Fig. 1 were carefully calibrated before installation. Using these couplers (with low-pass filters to eliminate harmonic power), it was possible to make reasonably self-consistent sets of power readings. For instance, the maximum output powers of the two klystrons were measured to be 35.8 MW and 33.9 MW respectively. The maximum combiner hybrid load arm power was 4.3 MW and the maximum power transmitted to the SLED cavities was measured at 65.2 MW. Assuming the theoretical SLED gain of 7.8 dB indicates that a maximum peak power of 390 MW was transmitted to the accelerator network.

Figure 2 shows some typical power vs time waveforms. Note that the actual pulse width at half-maximum was approximately 5.4 µs. The peaks at each end of the pulse into the combiner load are due to imperfect synchronization of the two klystron RF pulses. This is caused by the ten-meter physical separation between the two tubes.

Generally, RF breakdown in the system was not a problem provided the rate of power increase was low enough to keep the waveguide vacuum better than 10⁻⁶ Torr. The waveguide valve which precedes the SLED assembly contains a knife-edged piston which, in the closed position, is pressed against an indium-filled seat.

It was expected that this valve would cause breakdown problems but this was not found to be the case.

Breakdown was detected by monitoring the rectified RF waveforms at the various coupler ports in the system (Fig. 1), and also by surveying for x-radiation.

X-Radiation Measurements

Some earlier measurements on stations running in the SLED mode with 5 µs klystron pulses had indicated that the SLED cavities when the incident power was raised to 50 MW and beyond. Figure 3 summarizes the radiation levels actually experienced at the experimental station. All measurements were made with a survey meter calibrated against a standard source. The meter was supported with its ion chamber in contact with both SLED cavities. The radiation data are plotted against (RF power)⁻¹/₂ which is proportional to the inverse of the electric field in the cavities. The actual peak power incident upon the SLED cavities from the combiner is also shown. It can be seen in curve (a) that the initial levels ranged up to 2 R/hr at 65 MW incident power and 180 pps. However, the radiation decreased with aging. After many days of running the station under varying conditions of power, repetition rate and time of SLED phase-reversal (PSK), the radiation had dropped by a factor of five (curve b). The radiation is primarily a function of the instantaneous electric field in the cavities. As such, it is proportional to not only the incident power level but also to the time allowed for the cavities to charge and to the precision of tuning to cavity resonance (curve c). Curves 3(a,b,c) are for 5.4 µs pulse-length.

Fig. 2. Experimental RF and x-radiation waveforms.

![Fig. 2. Experimental RF and x-radiation waveforms.](image)
particularly in conjunction with niobium cavities for RF with emission from sharp whiskers. Others consider resonant tunneling or surface charging of impurity inclusions (or insulating microparticles) on the surface. All of these theories have in common some variant of the Fowler-Nordheim theory which leads to a count-rate \( R \) of the simplified form

\[
R \sim A E^n \exp \left( -\frac{1}{KE} \right)
\]

where \( A \) and \( K \) are constants which depend upon the surface conditions and cavity configuration, \( E \) is the accelerating electric field (proportional to \( \nu P \)) and \( n \) is an exponent on the order of 7.5 to 1. In the case of SLED operation, \( E \) is a known function of time. Choosing \( n = 7.5 \) as in Ref. 2, an attempt was made to see if a set of self-consistent constants \( A \) and \( K \) could be found which would corroborate the data of Fig. 3.

In what follows, it is assumed that the fields which accelerate the electrons producing x-rays (not necessarily those which cause the electrons to be emitted) are the SLED fields in the cavities. These are of different forms depending upon whether the PSK is used or not. Letting \( \alpha = (28)/\beta \) where \( \beta \) is the cavity coupling coefficient, and normalizing all times \( \tau \) to the cavity filling time \( T_C \) (=1.67 us), we obtain:

PSK used:

\[
E(\tau) = \alpha P \left[ 1 - e^{-\tau/\tau_f} \right] \quad \text{and} \quad E(\tau) = \alpha P \left[ 1 - e^{-\tau/\tau_f} \right] e^{-(\tau_1-\tau)}/T_f
\]

(Charging Time)

(Discharging Time)

where \( \tau_f \) is the normalized PSK time filling the accelerator section, \( t_p/T_c \)

PSK not used:

\[
E(\tau) = \alpha P \left[ 1 - e^{-\tau/\tau_f} \right] \quad \text{and} \quad E(\tau) = \alpha P \left[ 1 - e^{-\tau/\tau_f} \right] e^{-(\tau_1-\tau)}/T_f
\]

(Charging Time)

(Discharging Time)

where \( \tau_f \) is the normalized pulse length \( t_p/T_c \)

The radiation count-rate is then simply given by inserting the expressions for \( E(\tau) \) into the expression:

\[
R = A \int E^{7.5} (\tau) \exp \left( -\frac{1}{KE(\tau)} \right) d\tau
\]

where the limits of integration are shown above. Using this expression, we obtain good agreement with Fig. 3 curves (b) and (c) for \( A = 2.768 \times 10^{-3} \) and \( K = 0.042 \) (PSK used). The initial levels shown in the curve (a) are obtained for \( A = 13.327 \times 10^{-5} \) and \( K = 0.042 \). Thus the surface conditions before "clean-up" were roughly 4.8 times more emitting. It is interesting to note that the calculation shows that the radiation gives up by a factor of 1.7 when PSK is not used. This was corroborated experimentally. It then turns out that when PSK was not used, cleaning up the cavity was greatly accelerated. It may be noted in conclusion that, taking into account the 4-way power division between the SLED output and each 3 m accelerator section, plus the 0.5 dB waveguide feed loss, an instantaneous peak power of 87 MW was achieved into each accelerator section, corresponding to a maximum accelerating field of 65 MV/m. The peak radiation field was thus on the order of 130 MV/m.

References

