IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983

EXPERIMENTS WITH VERY HIGH POWER RF PULSES AT SLAC*

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Summary

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

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 $\phi 1$ 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 $\phi 2$ 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.[1] However, it may be convenient to review very briefly the operating principle.

* Supported by the Department of Energy, contract DE-AC03-76SF00515.

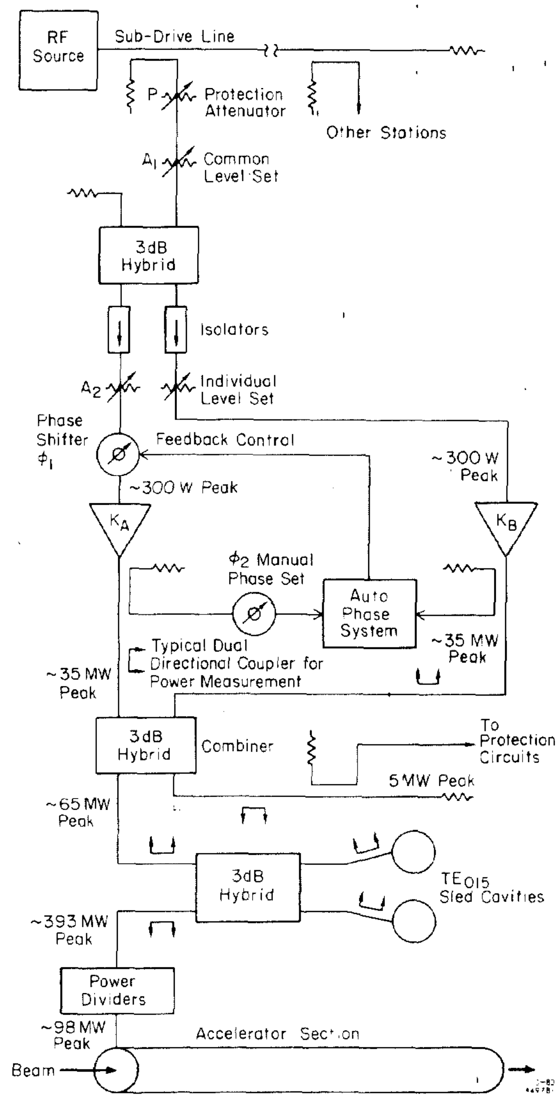

Fig. 1. The experimental configuration.

Two cylindrical copper cavities resonant at 2856 MHz in the TE_{015} mode are coupled into the waveguide running from the combiner to the accelerator, using a 3 dB hybrid coupler as shown in Fig. 1. The cavities may be detuned by the insertion of tungsten needles into high-field regions. The needles are moved by an external, motor-driven magnetic coupling system which acts on the needles through a vacuum envelope. Power from the flat-topped 5 μs RF pulse out of the combiner divides equally between the two tuned cavities, charging them exponentially with time. The 90^0 phase-shifts inherent in coupling between diagonal arms of the hybrid ensure that no power (either reflected or emitted) from the cavities returns to the combiner. One accelerator filling time (i.e., 0.8 μs) before the end of the 5 μs pulse, the phase of the RF drive to the klystrons is rapidly changed by 180^0. The RF signal reflected at the cavity coupling irises is then in phase with the RF emitted from the cavities. The two combine to produce instantaneous peak power 7.8 db greater than the incident flat-topped pulse, and the cavities discharge rapidly.

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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.

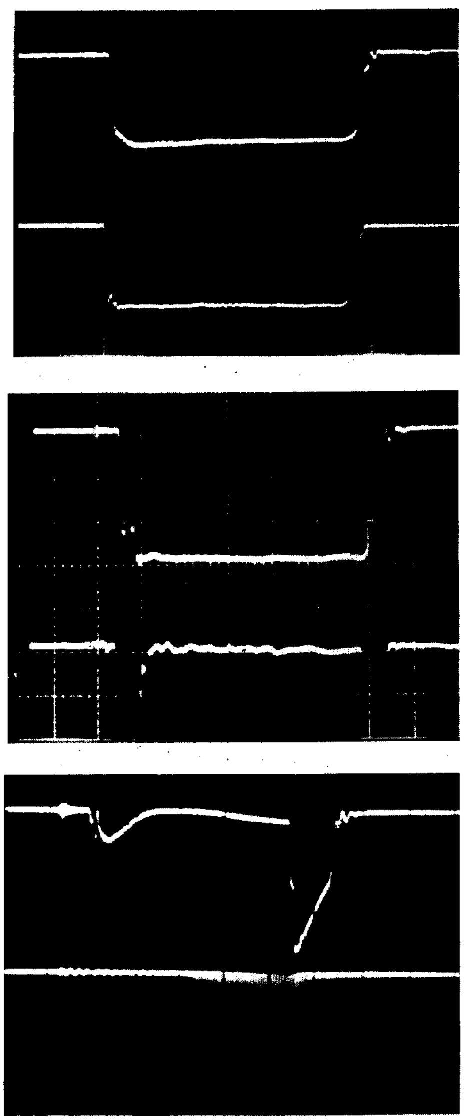
Figure 2 shows some typical power *vs* time waveforms. Note that the actual pulse width at half-maximum was approximately 5.4 μs. The peaks at each end of the pulse into the combiner load are due to imperfect synchronization of the two klystron RF pulses. This is caused by the ten-meter physical separation 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 there might be a problem with x-ray generation in 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



(a) Detected RF output pulse waveforms of two klystrons used in combiner experiment.

Sweep speed for all traces is 1 μs/cm.

(b) Upper trace is detected RF output pulse from combiner.

Lower trace is detected RF pulse into load arm of combiner. Peaks at each end are due to imperfect timing of klystron pulses at combiner, caused by physical separation.

(c) Upper trace is detected RF output waveform from SLED.

Lower trace is the output of a plastic scintillator x-ray detector.

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

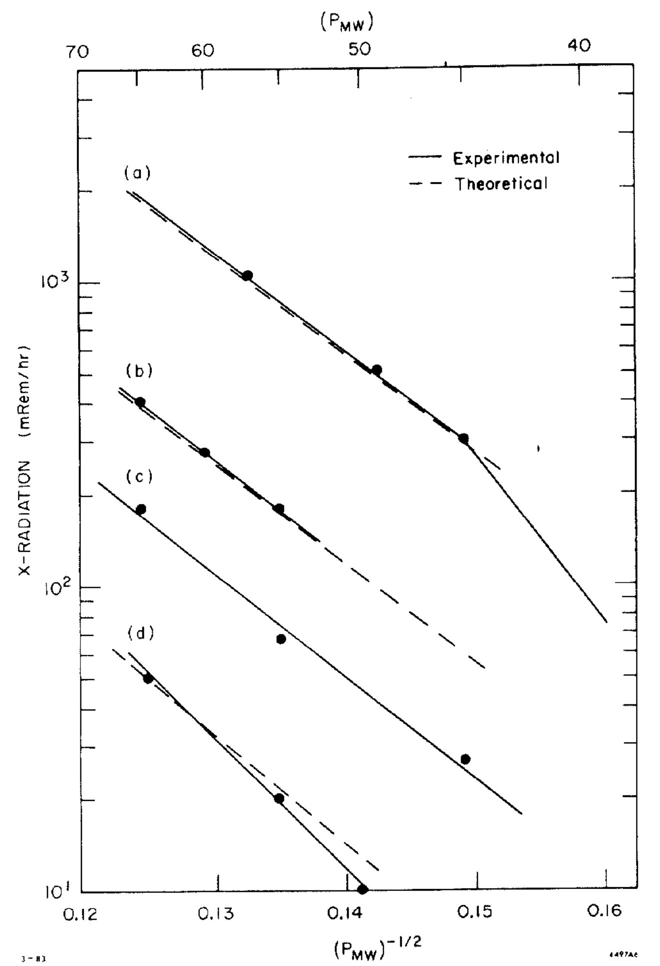


Fig. 3. Plots of x-radiation at the SLED cavities as a function of peak RF power into SLED. All data are taken with PSK phase reversal 0.8 μs before end of RF pulse.

(4.6 μs charging time) while curve 3(d) is for 3.8 μs pulse-length (3.0 μs charging time). Figure 4 is further evidence of how radiation varies with charging time and incident power level Radiation is shown as a function of PSK time (measured from the beginning of the incident RF pulse) for two incident power levels

In separate experiments nitrogen was introduced into (a) the waveguide at a point close to the SLED coupler and (b) into the upper SLED cavity. Pressure increases of two orders of magnitude produced no significant or lasting increases in the radiation levels.

The lower trace in Fig. 2(c) shows the photomultiplier output of a fast scintillator x-ray detector. It can be seen that the x-ray instensity appears to be a very strong function of the cavity fields, building up rapidly as the cavities charge and decaying much more rapidly as they discharge after the PSK phase-reversal. The theoretical dependence of x-radiation intensity (transmitted through the cavity walls) upon cavity electric field strength is discussed below.

The x-rays of up to 150 KV detected around the SLED cavities must be produced by electron field emission but the mechanism of production is not entirely understood. The TE_{015} mode in the cavities does not have fields perpendicular to the copper walls. Thus, the field-emitted electrons originate either from the coupling iris or from the adjacent rectangular waveguide coupler or they are generated by another cavity mode excited by harmonics from the klystron. Regardless of their origin, the electrons receive their acceleration from the TE_{015} fields. They are probably bent by the RF magnetic field, and then strike the cavity walls where they produce x-rays which are attenuated before they reach the radiation survey meter.

Many theories of field emission have been developed in the last few years (see for example, Refs. 2 and 3) particularly in conjunction with niobium cavities for RF superconducting accelerators. Some of the theories deal with emission from sharp whiskers. Others consider resonant tunneling or surface charging of impurity

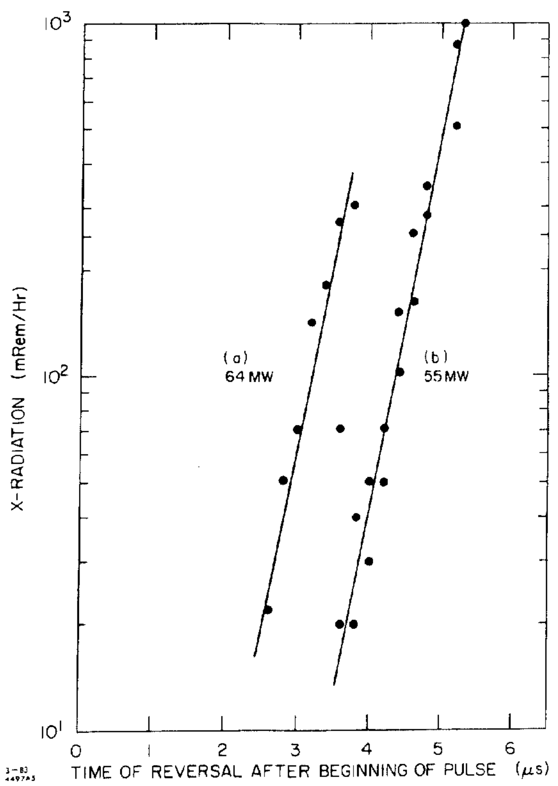


Fig. 4. Plots of x-radiation at the SLED cavities as a function of time of PSK phase reversal for two input pulse powers.

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

$$R \sim A\,E^{n} \exp\{-1/KE\}$$

where A and K are constants which depend upon the surface conditions and cavity configuration, E is the accelerating electric field (proportional to $\sqrt{P}$) and n is an exponent on the order of 7.5 ± 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 $\alpha = (2\beta)/1+\beta$ where β is the cavity coupling coefficient, and normalizing all times τ to the cavity filling time T_C (= 1.67 μs), we obtain:[1]

PSK used:

$E(\tau) = \alpha\sqrt{P}(1-e^{-\tau})$, $0 < \tau < \tau_1$ (Charging Time) where τ_1 is the normalized PSK time

and

$E(\tau) = \alpha\sqrt{P}\left[(2-e^{-\tau_1})\, e^{-(\tau-\tau_1)} - 1\right]$, $\tau_1 < \tau < \tau_1 + \tau_F$ (Discharging Time) where τ_F is the normalized filling time of the accelerator section, t_F/T_C

PSK not used:

$E(\tau) = \alpha\sqrt{F}(1-e^{-\tau})$, $0 < \tau < \tau_2$ (Charging Time) where τ_2 is the normalized pulse length t_P/T_C

and

$E(\tau) = \alpha\sqrt{P}(1-e^{-\tau_1})\, e^{-(\tau-\tau_1)}$, $\tau_2 < \tau < \infty$ (Discharging Time)

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

$$R = A \int E^{7.5}(\tau) \exp\{-1/KE(\tau)\}\, d\tau$$

where the limits of integration are shown above. Using this expression, we obtain good agreement with Fig. 3 curves (b) and (d) for $A = 2.768 \times 10^{-5}$ 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 goes up by a factor of 1.7 when PSK is not used. This was corroborated experimentally. It 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 cavity field was thus on the order of 130 MV/m.

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