SINGLE BUNCH RADIATION LOSS STUDIES AT SLAC*

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Abstract

The experiments described in this paper have been prompted by interest in the radiation loss of relativistic electron rings passing through periodic structures. In these experiments, single bunches of electrons with intensities up to 10^9 particles per bunch are accelerated through the SLAC three-kilometer accelerator and their energy spectrum is analyzed. Although only a limited number of measurements have been conducted to date, some broad conclusions can be drawn: (a) The radiation loss for a single bunch of 10^9 electrons traversing ~86, 000 cavities of the accelerator is of the order of 38 MeV. (b) Between 900 MeV and 19 GeV, the radiation loss seems to be independent of energy and (c) The dependence of radiation loss on charge in the bunch appears to be linear. The paper also describes the instrumentation and equipment used to generate single bunches. Additional experiments are being planned during 1971 and 1972 which should further refine the results presented here.

1. ERA and SLAC

In 1968, one experiment was done at SLAC which demonstrated that the small energy losses associated with a single bunch of electrons traversing the SLAC accelerator could indeed be measured with some degree of accuracy. With the feasibility of measurements established, some discussion followed between LRL and SLAC as to whether measurements conducted at SLAC would be applicable to the problem of electron ring radiation loss as the ring passed through an accelerating structure. Indeed there is a major difference between the bunch interaction at SLAC and the electron ring interaction: at SLAC, the longitudinal bunch size remains constant in the laboratory frame while in an ERA the longitudinal ring size remains constant in the electron frame while it goes to zero in the lab frame as its energy increases. In late 1970, calculations made at LRL[1] predicted that the radiation losses for the two models would be similar and that the experiments described herein would be very worthwhile.

During this same period, E. Keil[2] at CERN, was developing a new computer modal analysis of the energy loss process for bunches of electrons traversing cavities. Keil programmed the SLAC interaction parameters into his model and calculated the energy losses to be expected for single bunches in the two-mile machine.[3] So far, his computer results and the SLAC experimental results have been in very good agreement. The results of Keil's work will be published separately in the near future.

2. SLAC Accelerator and Instrumentation

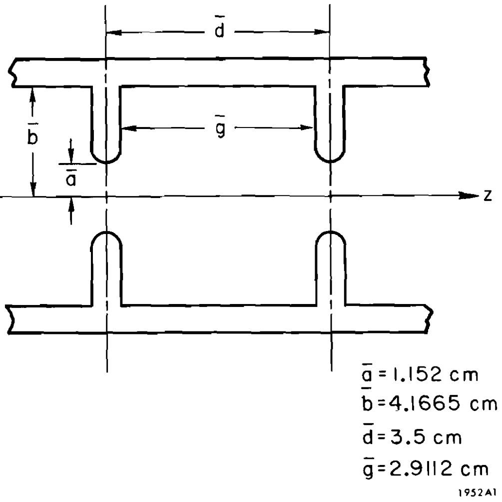

FIG. 1--SLAC average cavity dimensions.

The SLAC accelerator consists of 960 three-meter long constant-gradient sections. Each section contains 86 cavities of slowly varying dimensions. The dimensions shown in Fig. 1 are averages computed by Keil. For calculation purposes, the accelerator is assumed to be made up of 86, 000 of these average cavities. Depending on how many of them are excited, beams with energies from 500 MeV up to 20 GeV can be generated and transported through the beam switchyard. The energy profiles used in the experiments are shown in Fig. 2. The beam is initially accelerated by as many cavities as are necessary to produce the desired beam energy, and then is allowed to drift through the remaining length of the accelerator. Some of the experiments in the low energy ranges were conducted in a spectrometer at the 2 kilometer point of the accelerator.

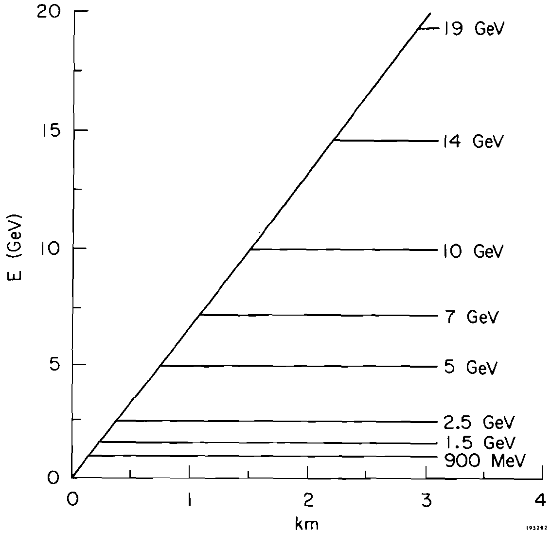

FIG. 2--Energy versus distance.

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The main requirements for making single bunch radiation loss measurements are that the accelerator be stable in energy and that the energy spectrum be available on a pulse-to-pulse basis. For this purpose one must have very fast energy analysis, pickup and recording instruments to observe energy variations as the bunch intensity is varied. Figure 3 shows the principal elements of this system when experiments are conducted in the full 3 km accelerator mode. The instrumentation for the 2 km mode is very similar. Details of the instruments are as follows:

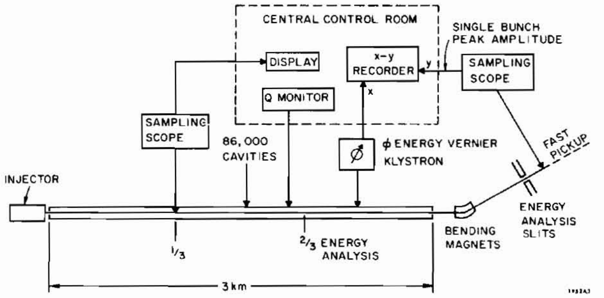


FIG. 3--Instrumentation used in single bunch radiation loss measurements.

1) Sector 10 fast pickup and sampler

   This pickup, located at the 1 km point of the machine, is used to look at the bunch structure to determine that there is indeed only one single bunch of electrons in the accelerator. A drawing of the pickup is shown in Fig. 4. The pickup has a rise time of less than 100 ps and can easily display the difference between a single bunch and two adjacent bunches on the RF in the machine (Fig. 5). The sampled output display of this monitor is repeated in the Central Control Room (CCR).

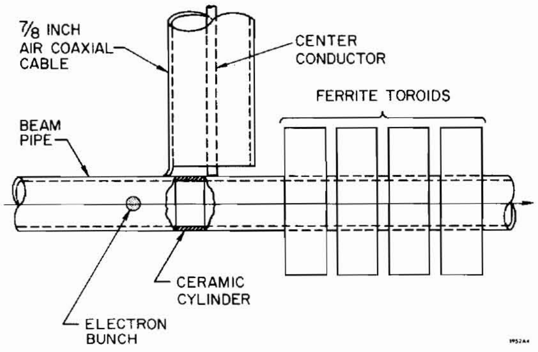
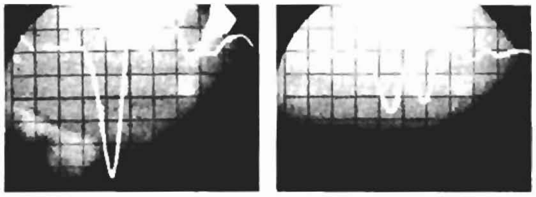


FIG. 4--Non-intercepting fast beam pickup.



200 psec/cm (SINGLE BUNCH) 200 psec/cm (TWO BUNCHES)

FIG. 5--Sampling scope displays obtained in Sector 10 with fast beam pickup.

2) Linear Q charge monitor

   The normal charge monitor system in existence on the machine4) has proven quite satisfactory for monitoring trains of single bunches spaced 150 ns apart during the normal 1.6 μs pulse of the machine. By using this system, the single bunch fast output display of the Sector 10 pickup can be calibrated in charge amplitude.

3) Energy analysis magnets and slits

   There are two beam transport-energy analysis systems in the SLAC accelerator, the A-bend and slit, and the B-bend and slit. A-bend has twice the angle (24°) of B-bend (12°) and hence has better energy analysis resolution. A-bend5) was used for all full-machine tests except for the 1968 data. Slit width openings were set from 0.5% to 0.1%, the smaller slit openings being used at the higher energies.

4) Klystron energy vernier

   To avoid a number of problems including magnet hysteresis, it has been easier to leave the energy analysis magnets and slit fixed at a single energy and to sweep the beam energy across the slit with a klystron whose phase can be remotely controlled and readout. This klystron contributes about 100 MeV to the beam when phased for maximum energy. An analog signal proportional to the phase excursions is used as the X-axis input to an X-Y recorder.

5) A-bend fast pickup and sampler

   A fast pickup similar to that shown in Fig. 4 is installed beyond the slit in A-bend. It has a much larger beam pipe aperture than the pickup installed in Sector 10, and hence has a somewhat poorer rise time. The output of this pickup is routed via high quality coaxial cable to the Data Assembly Building (DAB). This building is the closest point outside the radiation area where a sampling scope can be located. During a measurement, the sampling scope is manually adjusted to sample only at the time corresponding to the peak of the fast pickup response. The resulting d.c. output is transmitted to CCR via a low noise cable and forms the Y-input of the X-Y recorder.

6) X-Y recorder

   This recorder is the heart of the single bunch energy analysis system. The X-axis is driven by the analog output of the phase of the vernier klystron and represents relative beam energy with respect to the fixed energy defined by the A-bend. This system is first calibrated by using a 1.6 μs low intensity unchopped beam through the machine and into the A magnet-slit system. The vernier energy klystron is varied over ± 90 degrees, and the position on the X-axis is noted along with the measured center energy of the A magnet slit system. The Y-axis is proportional to the peak of the analyzed single bunch signal from the A-bend fast pickup. A typical data run consists of recording a series of X-Y traces generated by sweeping the klystron phase through about 120° about its zero energy contribution point. A characteristic X-Y plot is shown in Fig. 6. Beam charge is changed as a parameter between each trace over a range of about 10 to 1.

3. Single Bunch Beam Generation

Figure 7 is a block diagram of equipment used in the injector to generate single bunches of electrons for these experiments. The buncher and chopper systems which

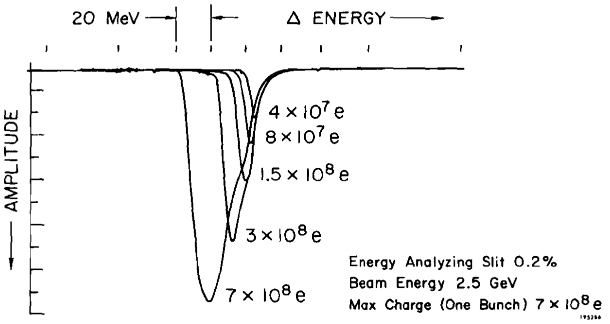


FIG. 6--X-Y plot of current amplitude as a function of energy for various values of charge in bunch.

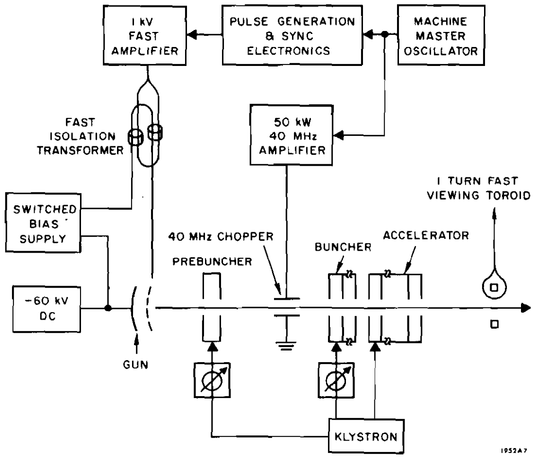


FIG. 7--Single bunch beam generation equipment.

form the 1.5 mm bunch are described in Ref 6. Since the RF wave in the accelerator ultimately shapes the single bunch of this experiment, the single bunch generation electronics is synchronized to the machine master oscillator.

3.1 Gun Drive System

Synchronized to the accelerator RF (2856 MHz), a train of 8 ns pulses spaced about 150 ns apart is generated in a fast electronics system. This train of pulses is amplified in a special fast amplifier to a level of 1 kV. By means of a transmission line type isolation transformer with fast rise time, this pulse is applied across grid-cathode gap of the gun. The gun cathode floats at a potential of -60 kV d.c. The 1 kV pulse produces gun currents from 1 to 5 amps depending on gun characteristics. A programable bias supply in series with the gun grid provides output current control. The resulting gun output pulse is less than 8 ns wide.

3.2 Bunching, Chopping, Injection

The beam pulse is initially bunched by the prebuncher into about 25 bunches. A 39.667 MHz transverse chopper then rejects all but one of these bunches (or two if improperly phased, as shown in Fig. 5). The single remaining bunch is axially compressed farther to 1.5 mm, or 5° by the traveling-wave buncher, and injected into the accelerator.

4. Experimental Results

Since September, 1968, five allotments of time have been made available on the SLAC accelerator to perform single bunch beam loading experiments. Because of the complexity of the equipment involved, an appreciable fraction of this time was spent checking out instrumentation under beam conditions. From the results that have been recorded, some broad conclusions can be drawn:

1) The radiation loss from a single bunch of 10^9 electrons traversing ~86,000 cavities of the accelerator is of the order of 38 MeV.
2) Between 900 MeV and 19 GeV, the radiation loss seems to be independent of energy within experimental errors.
3) The dependence of radiation loss on charge in the bunch appears to be linear.

Figure 8 shows a graph of results with error bars of all experiments to date. This graph is based on the experimental results given in Table I.

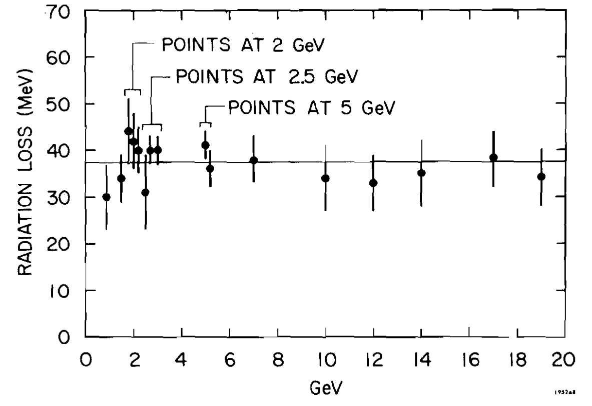


FIG. 8--Summary of single bunch radiation loss measurements normalized for 10^9 electrons.

TABLE I

Radiation Loss of Single Bunches with 10^9 Electrons

Date	Energy	Energy Change	Estimated Error ±
9/17/68	2 GeV	44 MeV	7 MeV
1/14/71	2 GeV	42 MeV	6 MeV
4/19/71	7 GeV	38 MeV	5 MeV
4/19/71	10 GeV	34 MeV	7 MeV
4/19/71	14 GeV	35 MeV	7 MeV
4/19/71	19 GeV	34 MeV	6 MeV
7/14/71	0.9 GeV	30 MeV	7 MeV
7/14/71	1.5 GeV	34 MeV	5 MeV *
7/14/71	2 GeV	40 MeV	5 MeV
7/14/71	2.5 GeV	31 MeV	8 MeV
7/15/71	2.5 GeV	40 MeV	3 MeV
7/15/71	5 GeV	41 MeV	3 MeV
8/12/71	2.5 GeV	40 MeV	3 MeV
8/12/71	5 GeV	36 MeV	4 MeV
8/12/71	12 GeV	33 MeV	6 MeV
8/12/71	17 GeV	38 MeV	6 MeV

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* Experiment done with only 2/3 of accelerator length.

The estimated errors are based on the statistical spread of several data runs for each point and the estimated inaccuracy due to calibration errors and random accelerator energy drift.

Peak attainable bunch intensity varied from 6 to 9 × 10^8 electrons and was extrapolated to the 10^9 electron figures shown above. Figure 9 gives a graph of several selected energy losses versus charge (Q) to show the linearity of this function.

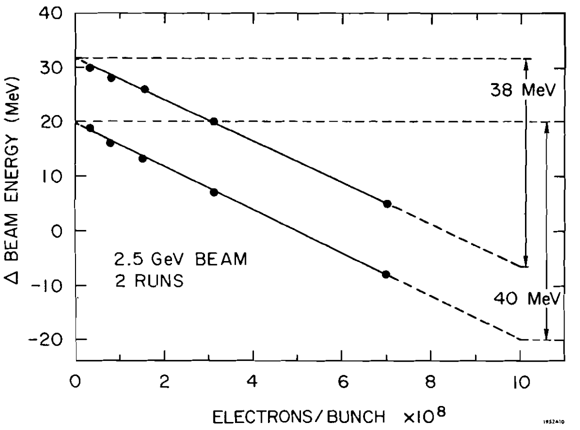

FIG. 9--Energy loss versus bunch intensity.

The first single bunch experiment (performed in September, 1968) used the energy defining slits on the B-bend of the switchyard. The slits were set for 1% transmission. An intercepting beam monitor behind the slits was used for beam observation. One bunch of 3.3×10^8 electrons was compared in energy to a similar beam of one quarter this intensity. Energy differences were measured by noting the bending magnet settings at which the edge of the energy defining slit intercepted these two beams. This difference amounted to a one half percent energy separation of the two beams. Extrapolating this result to 10^9 electrons gave an energy difference due to radiation loss of 44 MeV for a 2 GeV beam. The quality of instrumentation for this first experiment was marginal so that the error bar on the result was large.

After it was decided in 1971 to proceed with these experiments, an initial checkout run in January using the energy analysis system in the A-bend produced a measurement of 42 MeV loss for 10^9 electrons at 2 GeV. The instrumentation at that time was still marginal but by April the instrumentation described earlier in this paper became available. The April run was largely used to check out the new instrumentation and data recording techniques. A fast survey of radiation loss in the higher energy range produced the April results shown in Table I. The energy spectrum of a single bunch is affected quite dramatically by small variations in the phase with which it is injected into the accelerator. The spectrum can have either a high or low energy tail or it can be double peaked. It can vary with bunch intensity. Figure 10 shows one example of these effects. Such spectra make interpretation of the data difficult, and lead to error bars larger than might otherwise be necessary.

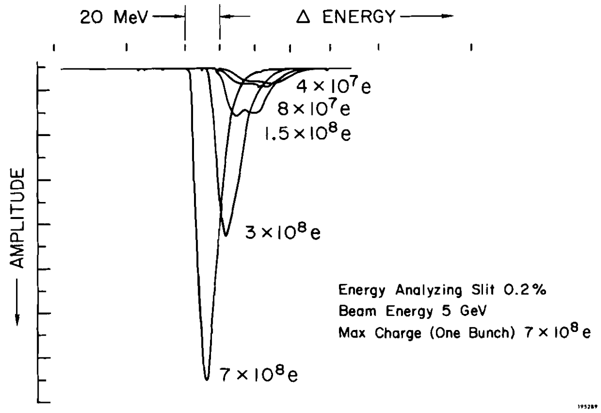

FIG. 10--X-Y plot showing double energy peak response.

During the next experimental run (July, 1971) two shifts of available beam time were used to obtain low energy data with the spectrometer located at the 2 km point. A fast intercepting beam monitor was placed behind the existing analysis foils. The size of the pickup corresponds to an 0.4% energy bite of the analyzed beam. The pickup and other instrumentation worked well, but the energy analysis magnet exhibited some hysteresis effects which were difficult to separate from the data. These results are also shown in Table I. Only 4 hours of beam time was available in the full accelerator mode, and this time was used to record data at 2.5 and 5 GeV energy points.

The last experimental run prior to publication of this paper took place in August, 1971. One full shift of beam time was used to record data at energies of 2.5, 5, 12 and 17 GeV. Energy spectrum broadening effects similar to those seen in April were in evidence, and some time was taken to explore these effects.

4. Experimental Problems and Future Work

Energy drift and jitter of the accelerator can come from a variety of causes, some of which are klystron phase and amplitude instability, drive system phase variation and accelerator temperature variation. While it takes some time to tune the accelerator to minimize these and other effects, it is possible to produce an accelerated beam that remains stable in energy for a duration long enough to record a set of data, even when the energy stability required is less than .05%. The problem of optimizing the shape of the energy spectrum and of deciding where the center of the spectrum is as the charge is varied is a more difficult one. Bunch length and population density within the bunch, along with the bunch position with respect to the accelerating field, determine the energy spectrum as seen in the data of this experiment. A bunch which rides along the machine off crest by only 2 or 3 degrees can have its energy spectrum broadened by a factor of 2. Variations in bunch length and population density, coupled with phase errors of bunch injection can combine to produce spectral distributions which have high or low energy tails, and in some cases double peaks. While these effects are not large enough to mask the radiation loss data, they do complicate the data interpretation and hence enlarge the error bars that must be assigned to the results. Further analytical work with the possibility of developing a computer model to extricate these effects from the data should improve results in future experiments.

During the latter part of 1971 and early 1972 several more data taking runs on the accelerator are planned to investigate more fully spectrum optimization techniques, and to add to the single bunch radiation loss data already on hand. It should also be possible to exceed 10^9 electrons in a bunch by means of some minor injector modifications. Keil's computer results predict measurable radiation loss change with changing longitudinal bunch size. At present it is difficult to measure the bunch size accurately in the accelerator on a short time experimental basis. If an RF deflector operating at the accelerator frequency were installed in the injector, this measurement would be possible; in addition, the bunch size of the injected beam could be chopped to dimensions smaller than 1.5 mm. Since Keil3) predicts only a 25% radiation loss increase between a 1.5 mm bunch and a 0.5 mm bunch, the overall accelerator stability and radiation loss measurement accuracy would have to be improved to reliably extract this bunch length effect from the data. The installation of the deflector is nontrivial, but a structure is on hand and a standby klystron which is otherwise unused could power it. This idea will be studied further, and if the measurement precision warrants it, such installation and measurement may be considered.

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