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TIMING STABILIZATION FOR THE SLC ELECTRON SOURCE[*]

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Abstract

The timing stability required for the SLC electron source is determined by the energy acceptance of the electron damping ring. The jitter requirements for the gun pulse itself are somewhat mitigated by the subsequent bunching process. The design of the system by which a gun pulse stability of $\sigma \sim 20$ ps is achieved is described, and experiments to measure the resulting energy stability under various bunching conditions are discussed.

1. Introduction

The SLC electron source provides a 1.2 GeV beam for injection into one of the two damping rings[1]. The energy acceptance of the north damping ring has been measured to be ± 1%. The acceptance of the south ring is expected to be similar. Either ring could be used for damping the electron bunches. The limited energy acceptance places constraints on both the drift and the jitter in the energy of the injected electron beam. This paper discusses the manner in which the energy of the injected beam is controlled to meet the requirements of the damping rings, with emphasis on the energy jitter.

The SLC thermionic electron source and injector are fully described elsewhere[2]. They are shown schematically in Fig. 1. The electron pulse from the gun is first bunched and then accelerated by the S-band RF (2856 MHz) field fed to the accelerating sections by a series of pulsed high-power klystrons. The energy of the injected beam is determined by the phase of the five unSLEDed klystrons in Sector 0 and the six SLEDed klystrons[3] in Sector 1. Normally the phases of all but the first klystron are adjusted to be identical relative to the electron beam, and then the phase of the beam relative to the resultant accelerating RF is adjusted for the desired operating conditions. Since the energy of a particle varies as $\cos\theta$, where θ is the angle between the particle and the negative crest of the resultant RF, placing the centroid of an electron bunch at $\theta = 0°$ might be expected to minimize the energy spread due to the finite length of the electron bunch. However, because wakefields trailing behind the head of a bunch reduce the accelerating field available to the tail, a short bunch of high intensity must be positioned several degrees ahead of the crest of the composite accelerating RF in order to minimize the resultant energy spread[1]. The length of the accelerated bunch is typically about 25° FWHM.

If $E = E_o$ is the energy of a single particle riding on the crest of the RF ($\theta = 0°$), then the energy jitter, $\delta e_j \equiv \delta E/E_o$ is given by

$$\delta e_j = \tan\theta\, \delta\theta_j, \qquad (1)$$

where $\delta\theta_j$ is the jitter in the RF phase relative to the beam position. Consequently the deleterious effects of $\delta\theta_j$ grow as θ is increased. Typically θ is set to about 10°.

Changes in phase relative to the beam can be the result of a shift in the RF or a shift in the timing of the electron bunch itself. First we summarize the status of the former.

2. RF Phase Stability

The program to stabilize the RF phase has been described elsewhere[4]. The result of this effort is that $\delta\theta_j$ for a sector RF drive line is typically no more than 0.04° (σ) so that the 0.1° to 0.2° (σ) phase jitter measured at each klystron output is largely incoherrent. Since the composite RMS RF phase jitter is no more than 0.1° (σ), then by Eq. (1) the resulting δe_j for $\theta = 10°$ should be no more than 0.03% (σ), which is well below the desired limit.

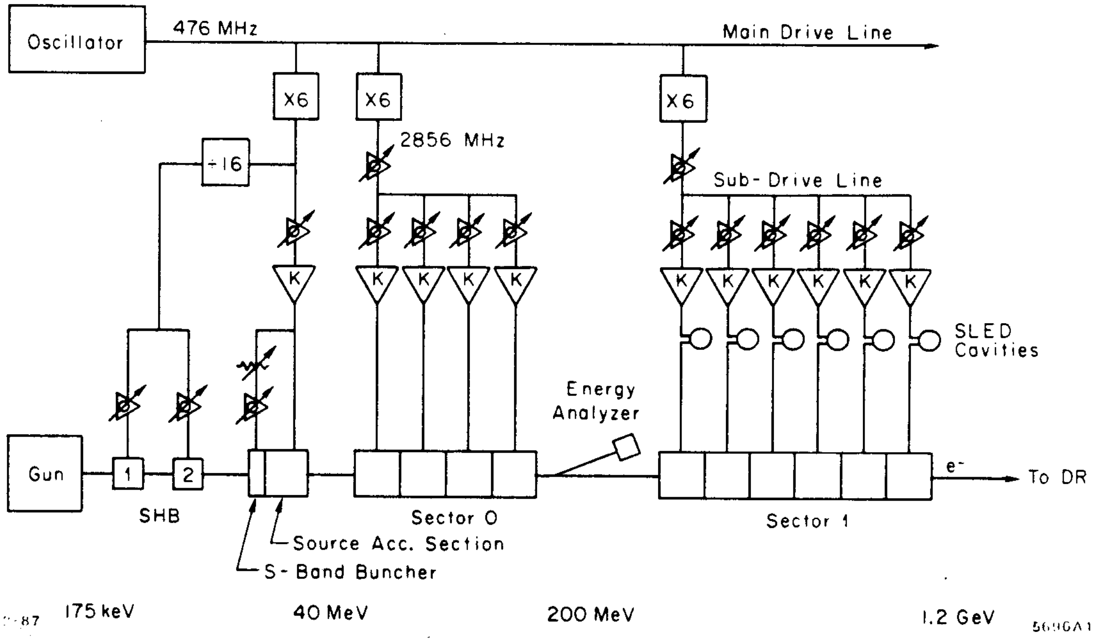

Fig. 1. Schematic drawing of the SLC thermionic gun and injector. Abbreviations used are DR for damping ring, K for klystron, and SHB for sub-harmonic buncher. In Sector 0, each klystron fills a single 3-m accelerating section, while in Sector 1 there are 4 sections per klystron.

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3. Source Timing Stability

Within the first few centimeters of the source RF accelerating section the electrons become fully relativistic and subsequently do not change their timing relative to a speed–of–light signal. However, before becoming relativistic the beam is susceptible to timing changes of several origins. These will now be described.

A fast pulser located immediately behind the cathode of the gun produces an electron pulse of up to 12 A in a 2 to 3 ns pulse (FWHM). The gun voltage is typically 175 kV. The electron bunch length is first reduced by a factor of at least five by two pulsed RF cavities operating at the 16th subharmonic of the primary 2856 MHz accelerating RF, and then further compressed by another factor of at least five in the first four cells ($v_p = 0.75c$) of the source accelerating section. The RF for this S–band buncher, though derived from the same klystron that powers the remainder of the section, has separate phase and amplitude controls. The bunch is then compressed by a final factor of about two in the remainder of the section ($v_p = c$) while being accelerated to ~ 40 MeV. The overall bunch compression ratio[5] is on the order of 75. (The initial gun pulse is deliberately made wide to maximize the charge in the final bunch; however, this practice results in some degradation in the capture efficiency.)

From this summary of the bunching process, three potential sources of jitter in the timing of the accelerated electron pulse can be identified: RF phase jitter in the source bunchers; trigger timing jitter; and gun pulser instability. The RF phase jitter is minimal, as indicated earlier. Of the three applicable triggers for the gun pulser and the buncher RF systems, the latter are not critical since the RF pulses are quite long and fairly flat in amplitude. The stability of the pulser trigger and of the pulser itself constitute the remainder of this discussion.

The fast pulser for the SLC thermionic gun has been described in an earlier paper[6]. Two planar triodes are used in a two–stage fast amplifier to produce the required current pulse. The design of the pulser circuit has taken advantage of the inherent stability of these microwave tubes. The input tube in the fast amplifier is driven by an avalanche transistor pulser. Generally the gun pulser itself is expected to be stable to within a few 10's of ps and no difference has ever been detected between the jitter at the input and at the output of the pulser.

The basic timing trigger for the gun pulser is a NIM level trigger derived from the SLC timing system[7]. A Camac crate, located just outside the gun no–access area contains a PDU[8] (Pulse Delay Unit) which places on the crate's upper backplane timing signals that are synchronized in the PDU to the accelerating RF (in this case to 119 MHz, the 24th subharmonic of the accelerating RF). These triggers may have their timing changed in increments of the period of the synchronizing RF and may be assigned or de–assigned to any combination of SLC beams by the SLC operators through the VAX–based SLC computer control system without any loss of timing stability. These NIM level triggers have a timing stability of at least $\sigma = 20$ ps, which is the practical limit commercially available instrumentation can measure.

The design problem from the outset has been to place this timing signal on the gun high voltage deck without loss of stability. Several generations of fiber optic links have been used, the original link introducing a jitter of several hundred ps. While it is possible to place a CW RF signal on the high voltage deck where the trigger can be resynchronized, an improved link was eventually developed with the required stability for transmitting the trigger.

The fiber optic link is shown schematically in Fig. 2. The link utilizes about 10 m of a 100–μ graded–index fiber optic cable. The receiver on the high voltage deck is an avalanche photodiode (RCA 30904E) whose bias level is carefully adjusted to give the highest possible gain below the noise threshold. (This adjustment results in significantly less than maximum gain.) To minimize drift in the gain, a zener diode with the same temperature coefficient as the avalanche diode is chosen to provide the bias.

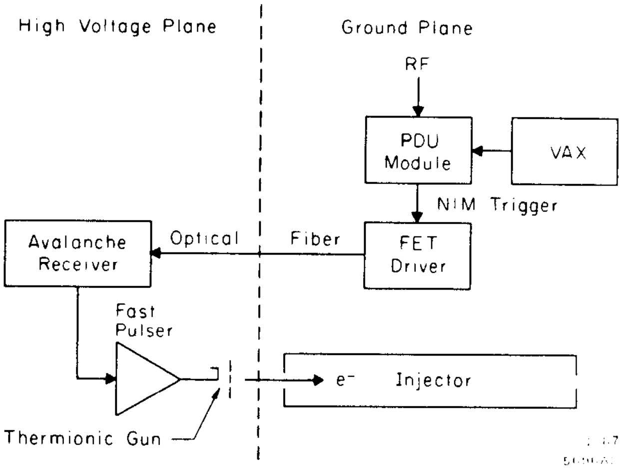

Fig. 2. Schematic diagram of the fiber optic link.

The transmitter on the ground plane consists of a FET with two bi–polar transistors driving a fast LED (Motorola MFOE1202). Since the gain of the avalanche receiver is limited by the signal–to–noise adjustment described above, the light amplitude must be especially high to produce a fast risetime at the receiver. The drive current for the LED is nominally limited to about 600 mA by the lead inductance of the circuit. By increasing the drive voltage, the effect of this lead inductance has been reduced sufficiently to produce a drive current of 2 A.

Although less than 1 V is required to trigger the gun pulser, the receiver card contains a pulse amplifier which produces a 5 V trigger for the gun pulser.

With this final design of the link, no timing jitter can be detected in the output of the gun above the $\sigma = 20$ ps threshold of the measuring instrumentation (in this case a Tektronix 7834 Sampling Scope with a 30 ps risetime sampling head). But of course at $\theta = 10^\circ$, an energy change of 1% is produced when the timing of the *accelerated* gun pulse shifts by only 3 ps. Fortunately the timing jitter at the gun output is mediated by the bunching process itself.

4. Experimental Limits of Source Timing Jitter

As a first approximation the bunching process reduces the source timing jitter by the bunch compression ratio, which as stated earlier is about 75 for the SLC source. Computer simulations indicate the effective compression ratio, R, for the timing jitter should be very large (approaching infinity) for optimum bunching conditions, but the absolute value of R could be as low as 1 for unfavorable bunching conditions[9].

To determine whether or not the gun timing jitter contributes to the observed energy jitter, a more elaborate measurement of the gun timing jitter has been devised that utilizes the linac itself as the measuring instrument. For this measurement the beam is energy analyzed at the end of Sector 0. The energy as a function of the gun trigger timing is measured. The gun trigger timing at the input to the fiber optic transmitter is changed in steps of a few ps with a trombone having a maximum range of about 1 ns. The timing changes are measured with a scale, the trombone being separately calibrated. A vidicon camera is used to view the beam hitting a fluorescent screen in air at the end of the analyzer where the dispersion is well known. The video is digitized in 2–dimensions using an SLC computer control program facility to determine both the centroid position and the width of the energy spectrum[10]. A data set is shown in

Fig. 3 where the abscissa is the change in the gun trigger timing, $\Delta t'$, produced with the trombone and the ordinate is the resulting energy change, Δe, measured at the end of Sector 0. A least squares linear fit to the data is shown, the slope of which is $s = \Delta e / \Delta t' = -2 \times 10^{-5}$ ps^{-1}. If the effective compression ratio is defined as $R \equiv \Delta t' / \Delta t$, where the primed t refers to the gun trigger time, then

$$R = \frac{\frac{d\theta}{dt} \tan \theta}{s}. \tag{2}$$

We determine θ for the conditions of a given measurement by noting the change in the phase of the Sector 0 RF drive (the source RF has a separate drive line) required to maximize the beam energy. Since θ was measured to be $\sim 14°$ for the data of Fig. 3, the average value of R under these bunching conditions is found by Eq. (2) to be about 200. This value of R should be considered a lower limit since as t' is changed in the direction of the best bunching (which in this case is at $t' = 150$ ps), the instantaneous slope, de/dt', appears to approach zero. In fact separate measurements clearly indicate that for $t' \leq 150$ ps, de/dt' changes sign. While for the best bunching R is typically very large, by deliberately misadjusting the bunching, values of R as low as 50 have been measured.

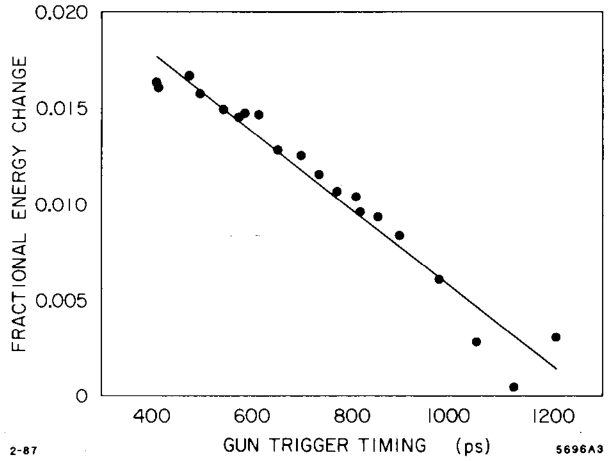

Fig. 3. Observed energy change at the end of Sector 0 as a function of timing changes introduce in the electron gun trigger circuit. The origin is arbitrary for both scales. Relative to the scale shown, the best bunching is at a gun timing of 150 ps. The slope of the linear fit is is -2×10^{-5} ps^{-1}.

Having measured R, we can also measure the energy jitter for the same bunching conditions. Then an upper limit on the gun timing jitter, $\delta t'_j$, will be

$$\delta t'_j \leq \frac{\delta e_j R}{\tan \theta \frac{d\theta}{dt}}. \tag{3}$$

The energy jitter measured at the end of Sector 0 for various bunching conditions is shown in Table 1. Since $R \geq 200$ for all of these measurements of δe_j, the value of $\delta t'_j$ calculated from Eq. (3) is in all cases greater than the directly measured upper limit of $\sigma = 20$ ps. Consequently it appears the gun timing jitter is responsible for no more than a small portion of the energy jitter observed at the end of Sector 0.

The RF phase jitter in Table 1 is calculated using Eq. (1) on the assumption that all the observed energy jitter is due to RF phase jitter. It is noted that these calculated values of $\delta\theta_j$ have about the same magnitude as the RF phase jitter that can be measured directly. Thus it also appears that for the bunching conditions under which the energy jitter in Table 1 has been measured, the energy jitter is predominately due to RF phase jitter.

For the electron beam to be injected comfortably into one of the damping rings, the energy drift and jitter should be no more than $\sigma = 0.08\%$, which is approximately 1/10th the energy acceptance of the ring. This criteria has been met. Any residual drift in the beam energy is reduced to the level of 0.05% by an energy feedback loop[11] that makes use of the final klystron in Sector 1. The energy jitter at the end of Sector 1 is typically less than 0.05%, which is consistent with the gun timing jitter and RF phase jitter measurements reported here.

Table 1. Timing and phase jitter calculated from measured energy jitter

Measured		Calculated	
θ (deg)	δe_j σ (%)	$\delta t'_j$ σ (ps)	$\delta\theta_j$ σ (deg)
14	0.065	28	0.14
17	0.110	40	0.20
21	0.125	38	0.19

5. Conclusion

The gun timing jitter now has a measured limit of $\sigma \leq 20$ ps. For typical SLC electron source bunching conditions, this timing jitter results in an energy jitter in the accelerated injection beam that is less than 1/10th the energy acceptance of the damping rings.

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