SLAC – PUB – 4220
March 1987
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PHASE DETECTOR AND PHASE FEEDBACK FOR A SINGLE BUNCH IN A TWO-BUNCH DAMPING RING FOR THE SLAC LINEAR COLLIDER[*]

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Abstract

The synchronous phase of a bunch of positrons or electrons being damped in a SLAC Linear Collider (SLC) damping ring is dependent on beam intensity. Injection for alternate bunches into the SLC linac from the damping rings should occur at a constant phase. A phase detector was developed allowing the measurement of phase of a single-stored bunch in the presence of a second bunch in reference to the phase of the linac. The single-bunch phase is derived from beam position monitor signals using a switching scheme to separate the two bunches circulating in each damping ring. The hardware is described including feedback loops to stabilize the extraction phase.

1. Introduction

The SLAC Linear Collider (SLC) project at SLAC uses a linear accelerator and damping rings in its task to produce both electron and positron beams for eventual collision.

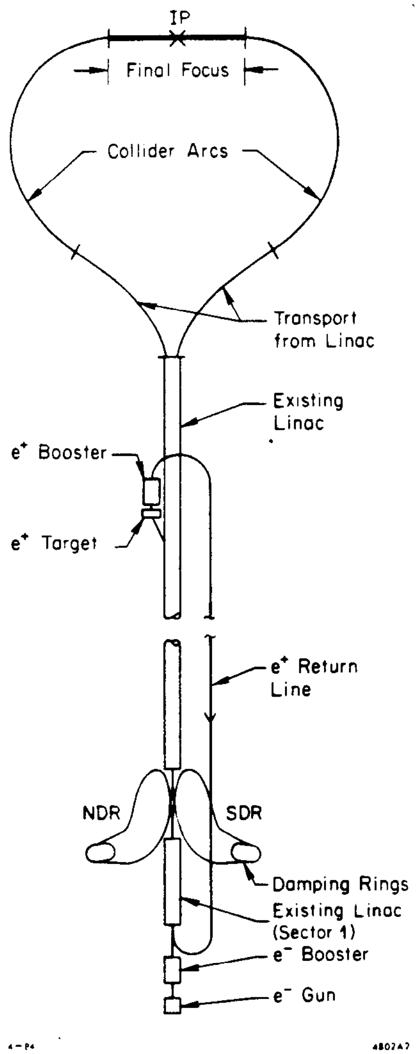

Fig. 1. SLC layout.

The main function of the damping rings is the reduction of the emittance of the beams. Two electron bunches with 5×10^{10} particles each are stored in the NDR for a minimum of 5.5 msec. At ejection time the two electron bunches are extracted together with one of two circulating positron bunches from the SDR. The three bunches are then accelerated, the positron bunch and one electron bunch to collide and the second electron bunch to make new positrons. The new positrons are returned to the injector and reinjected together with two new electron bunches.[1]

The subject of this paper deals with the phases of the electron and positron beams at extraction time from the damping rings in reference to the phase of the accelerating field in the linear accelerator.

Phase detectors to measure these phases as well as feed-back and feed-forward circuits are described.

The operating frequency of the linear accelerator is 2856 MHz and the RF system of the damping rings operates at 714 MHz, both frequencies are derived from a common master oscillator.

2. System Requirements

The S-band phases of one positron and two electron bunches being accelerated in the main accelerator during one RF pulse have to be defined to an accuracy of ±1° and a stability of ±.1°. While the beams are rotating in their respective rings, these relative phases can be measured and adjusted.

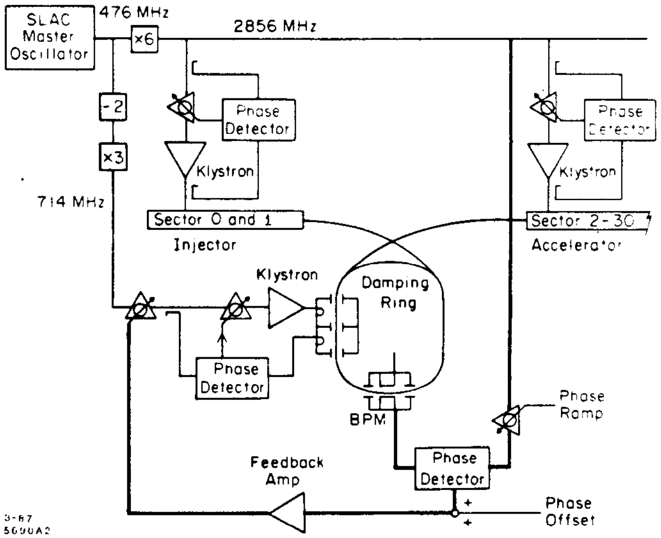

Fig. 2. System block diagram.

The phase of a beam in a damping ring is determined by the phase of the RF field in the accelerating cavities and the synchronous phase angle which the beam establishes, dependent on its loss of energy for each revolution. The energy loss is caused by synchrotron radiation and parasitic-mode losses. The synchrotron radiation depends on particle energy and geometric factors, and is held constant in the damping rings. The parasitic mode losses which are a function of beam intensity which is expected to not always be constant for SLC.

The phase change due to parasitic mode losses has been measured to 14° (714 MHz) between zero and maximum intensity[2] which translates to 56° at the accelerator frequency. A phase detector coupled with a feed-back loop controlling the phase of the damping ring drive RF can correct this phase uncertainty.

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[*] Work supported by the Department of Energy, contract DE–AC03–76SF00515.

Presented at the Particle Accelerator Conference, Washington, D.C., March 16–19, 1987

The same phase feed-back loop would also correct beam phase variations caused by phase changes in the damping ring RF system, assuming an independent phase reference is provided. The RF phase of the accelerator downstream from the damping ring is the most logical source for this reference. Both the accelerator frequency of 2856 MHz and the damping ring frequency of 714 MHz are derived in a phase stable way from a common master oscillator, and the individual power sources of the accelerator and damping ring employ phase feed-back stabilization.[3,4] However, taking a variety of error sources into account, phase variations of the order of ±16° at S-band are possible between the damping ring cavity fields and the accelerator RF.

Besides this feed-back circuit, there are two feed-forward functions the system will have to provide:

1. A phase offset up to ±20° S-band to compensate for beam loading effects of the main accelerator which depend on beam intensity.
2. A phase ramp of 100° S-band in the electron damping ring to match its path length to that of the positron damping ring. This ramp is to move the electron beams slowly during storage time and has to be reset to zero quickly during the 13 μsec when no beams are stored in the electron damping ring. A path length difference NDR and SDR of about 3 cm was measured and is to be corrected electronically.

3. Description of Selected System and Components

The phase of a beam in the damping ring is determined by the time of arrival at any point in the ring. Beam position monitors (BPM)[5] produce a pulse every time the beam passes, containing this time of arrival information, with the pulse magnitude proportional to beam position and intensity and the pulse width of approximately 40 psec, reflecting the beam length of $2\sigma_B \sim 12$ mm. A second pulse caused by reflection at the shorted end of the BPM with opposite polarity appears 254 psec later (Fig. 3).

Converting from time domain to frequency domain, the BPM signal contains harmonics of the beam revolution frequency of 8.5 MHz well into the tens of GHz with a minimum at 4 GHz caused by the second pulse reflected from the shorted end of the BPM (Fig. 4).

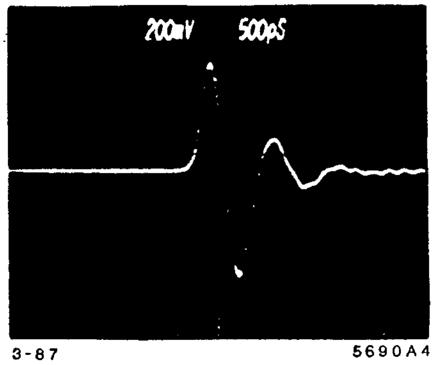

Fig. 3. Time domain display of beam position monitor pulse after 100 m coaxial cable.

If the 336th harmonic of the go-around frequency is chosen, a direct phase comparison with the accelerator frequency of 2856 MHz is possible and will yield the desired beam phase.

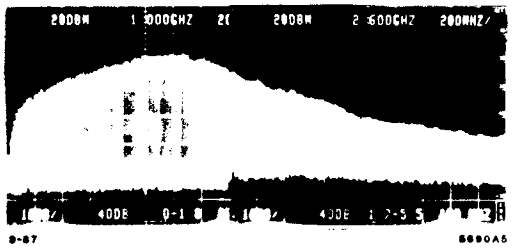

Fig. 4. Frequency domain display of beam position monitor after 100 m coaxial cable. Line at 2856 MHz used for phase detection.

Since two bunches of particles with potentially different intensity on opposite sides of each damping ring are to be stored for SLC operation, but in the case of positrons only one bunch will be extracted for acceleration at any one time, the phase of only the beam marked for extraction is of interest. The phase of one beam can be singled out by switching the BPM pulses with broadband fast switches alternately into the phase detector or an absorptive load. The switch has the following requirements.

Frequency	2-4 GHz
Rise/Fall Time	~ 10 nsec
Repetition Rate	8.5 MHz
Isolation	> 60 dB
Stable Phase During On Time	

These requirements were met by commercial switches (General Microwave, Part No. F9120H).

The conversion from time domain to frequency domain after the switch is done by a five-stage band pass filter with 20 MHz band width realized in stripline.

The requirements for the actual phase detector are high relative phase stability and accuracy over a dynamic range of at least a factor 10 in beam intensity or 20 dB. The most suitable approach was selected to be a heterodyne system with an IF of 60 MHz, limiting amplifiers at the IF frequency with minimal phase variation over the limiting range and an analog phase detection scheme at the IF frequency using mixers.

The 60 MHz IF frequency allows for potentially several MHz band-width of the phase detector but is low enough where commercial limiting amplifiers are available (Plessey, SL532C). The phase variation of the IF amplifier should be < 1° over its dynamic range of 20 dB.

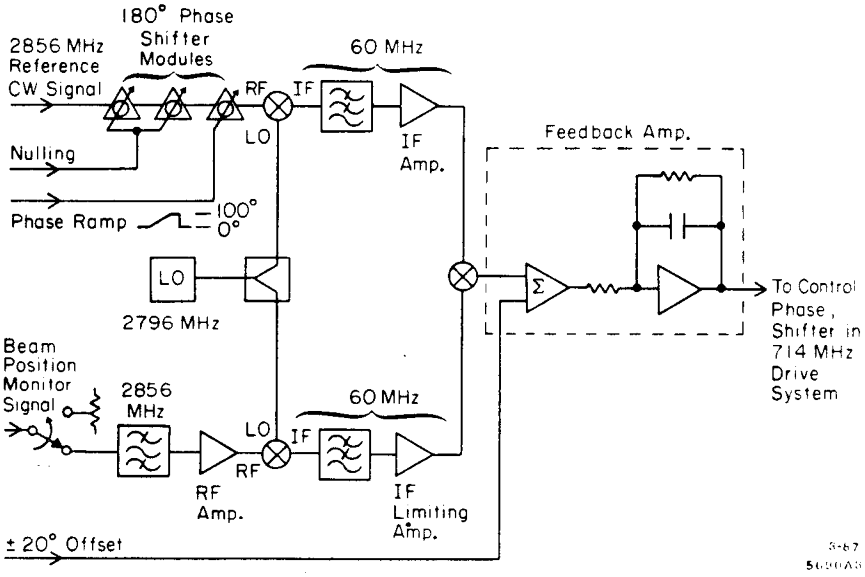

Fig. 5. Phase detector block diagram.

For the actual phase detector at the IF, digital versus analog methods were investigated. The limited rise time of digital circuits limits the phase resolution to about 5° using fast *GaAs* integrated circuits at the frequency of 60 MHz. For this reason, digital phase detection with its linear range of ±180° was not usable and analog techniques using mixers were employed. Mixers as phase detectors can be modeled as:[6]

$$V_{out} = A\cos(\phi_s - \phi_r) + V_{offset}$$

where

A = amplitude proportional to RF signal level
ϕ_s = the phase of the RF signal
ϕ_r = the phase of the RF reference
V_{offset} = a dc offset term.

A constant amplitude reference signal is assumed.

The usable dynamic range of a phase detector of this sort is approximately ±80°. The effect of the dc offset voltage is minimized by the use of a high sensitivity mixer/phase detector (Mini Circuit RPD-1) which is operated at its nominal signal levels.

The phase detector is used as a nulling detector when the feedback loop is closed, see Fig. 2. Small phase offsets can be purposely introduced, between phase detector and feedback amplifier. In the case of the 100° phase ramp, the limited dynamic range of the mixer/phase detector requires that a phase shifter in the reference line of the phase detector at 2856 MHz applies the phase ramp. The closed feedback loop will then adjust the phase of the beam accordingly by keeping the phase detector nulled.

Three 180° modules of linear electronic phase shifters[7] are combined to meet the requirement of nulling the phase detector and applying the phase ramp. The response time of these phase shifters is on the order of 50 nsec and this allows the fast resetting required after the phase ramp is applied.

The temperature of the total phase detector is stabilized at 45°C by electric heating and a control circuit. This reduces instrument sensitivity to ambient temperature changes.

In a similar way the signal and reference cables are temperature stabilized by being enclosed by water-cooled copper pipes held at constant temperature. The signal cable with a total length of about 100 m from the BPM to the phase detector is held constant to ±.5° in phase.

4. Operational Results

The limiting IF amplifier could be built with good phase response over a 20 dB signal range (Fig. 6) using three limiting stages in series. It is expandable to five stages with an increase of dynamic range to 50 dB with twice the phase error over the total range.

The sensitivity of the total phase detector to temperature was measured to 1.7° phase/1° celsius. With the temperature of the phase detector held constant to ±.1°C, the phase detector works within the allowable error.

At the writing of this report only single beams were stored in each damping ring and the two-beam operation could not be tested yet. The phase ramp feature also has not been tested.

The feedback loop has been closed with a unity gain bandwidth of 30 kHz. Figure 7 shows the open loop and closed loop phase of a beam stored for 33 msec.

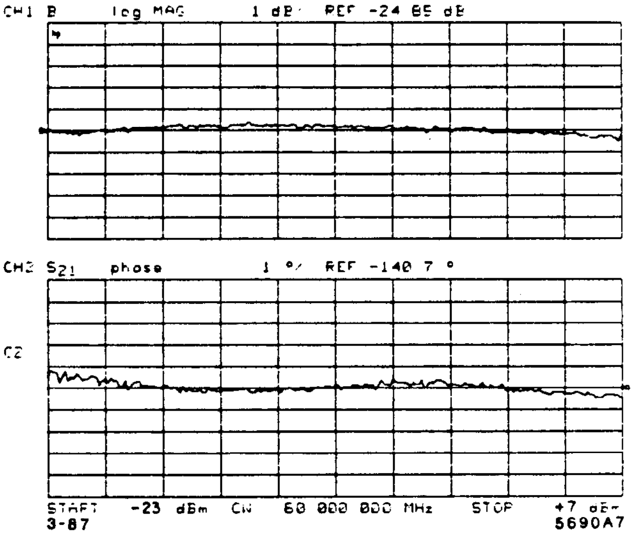

Fig. 6. Output power (top) and transmission phase (bottom) versus drive power of a three-stage 60 MHz limiting amplifier.

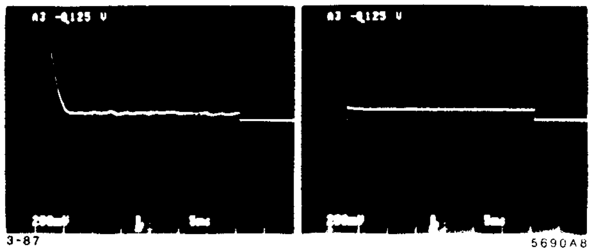

Fig. 7. Beam phase for beam stored for 33 msec as measured with the phase detector 20°/cm sensitivity. a) open loop; b) closed loop.

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