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IMPLEMENTATION OF NONINTERCEPTING ENERGY SPREAD MONITORS*

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Abstract

Stripline beam position monitors (BPMs), located in regions of large dispersion, are being used to monitor the relative energy spread of beams injected into the SLC damping rings. Several BPMs have been configured so that the quadrupole moment as well as the dipole moment (beam position) information is generated in hardware. The dipole moment is subtracted in quadrature from the quadrupole moment to produce a signal which is related to the beam width but which is independent of the beam position. Data reduction and averaging is accomplished in the control system microprocessors. Additional data handling occurs in the host computer. Beam width signals from the devices are used in conjunction with RF phase adjustments to minimize the energy spread of the beams. A computer controlled feedback loop has been developed to oversee the process of energy spread manipulation.

Introduction

The energy spread of bunches accelerated through the SLC injector[1] must be less than the 2% full width acceptance of the damping rings. Because of longitudinal wakefields,[2] the energy spread of each bunch, σ_ϵ, depends upon the charge in the bunch, N, the bunch length, σ_z, and the phase, ϕ, at which the bunch is accelerated on the RF. Figure 1 illustrates the variation of σ_ϵ on phase at the end of the injector for $\sigma_z = 2$ mm and for $\sigma_z = 3$ mm. A bunch population of $N = 5 \times 10^{10}$ particles per bunch has been used for Fig. 1. Figure 2 shows the phase offset in the injector which minimizes σ_ϵ as a function of bunch current, for several different values of σ_z. Electron bunches generated in the injector have a σ_z of 2 to 2.5 mm. Positron bunch lengths should be about 3.0 mm but recent measurements have shown that $\sigma_z \geq 4.5$ mm for the positrons transported to the injector.

Stripline beam position monitors (BPMs) located in regions of large dispersion are being used to monitor the relative energy spread of the bunches injected into the SLC damping rings. In each of the transport lines (LTRs) leading to the north and south damping rings from the end of the injector, several BPMs have been configured so that the quadrupole moment as well as the dipole moments are measured on a pulse to pulse, bunch by bunch basis. Because of the multiplexing of the BPMs to the electronics, reading of every pulse is not possible, nor is it possible to monitor more than one electron bunch on a particular beam pulse. Quadrature subtraction of the dipole contribution to the quadrupole moment and data averaging is performed in the local microprocessor. The reduced beam width data along with the beam position information is transmitted to the central control system computer for further analysis. A feedback process has been developed wherein the central computer monitors the energy spread and varies the injector RF phase to minimize σ_ϵ.

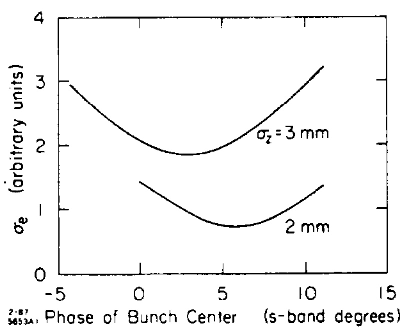

Fig. 1. The energy spread for a particular bunch length and current depends upon the phase of the bunch with respect to the crest of the accelerating wave. For the cases shown, $N = 5 \times 10^{10}$ particles per bunch.

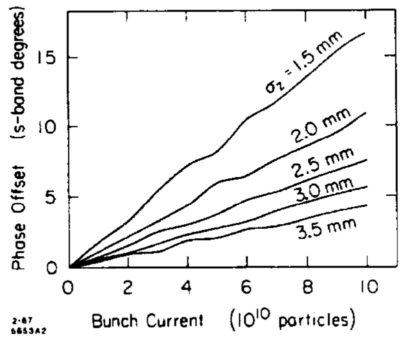

Fig. 2. The phase offset required to minimize the energy spread depends upon both the bunch length and the charge in the bunch.

Beam Width Monitors

The most common use of stripline beam position monitors in the SLC is to measure transverse beam position (dipole moment). Stripline monitors can also be used as beam width monitors (BWMs) to measure the beam size (quadrupole moment),[3] from which the energy spread is inferred. Figure 3 illustrates the wiring used to measure both the dipole and quadrupole moments from a single monitor, using standard SLC BPM hardware.[4] Beam signals from the four strips (N=North, T=Top, S=South, and B=Bottom) are first divided using power splitters.[5] One of the outputs from each of the splitters is connected to an SLC BPM electronics module to produce the usual difference signals ($N-S$ and $T-B$) which are proportional to the beam position, $\langle x \rangle$ and $\langle y \rangle$:

$$\langle x \rangle = a_1 \frac{N-S}{T+B+N+S} \tag{1a}$$

$$\langle y \rangle = a_1 \frac{T-B}{T+B+N+S} \tag{1b}$$

wherein a_1 is a scaling constant, dependent on the monitor geometry. To generate the quadrupole moment, the N and S signals and the T and B signals are first summed in a hybrid junction.[6] The $N+S$ and $T+B$ sum signals are then connected to an SLC BPM module which performs the $(N+S)-(T+B)$ subtraction which is proportional to the beam quadrupole moment, Q:

$$Q = a_2 \frac{(N+S)-(T+B)}{T+B+N+S} \tag{2}$$

wherein a_2 is a different scaling constant, also dependent on the monitor geometry. Inverters at the output of the hybrids are necessary to produce the proper polarity required by the BPM module.

The control system local microprocessor normalizes the differences by the overall sum signals, $T+B+N+S$, subtracts offsets, and multiplies the signals by appropriate scaling factors. In addition to accumulating signal averages, the microprocessor also subtracts the dipole moments in quadrature from the quadrupole moment before transmitting the information to the host computer.

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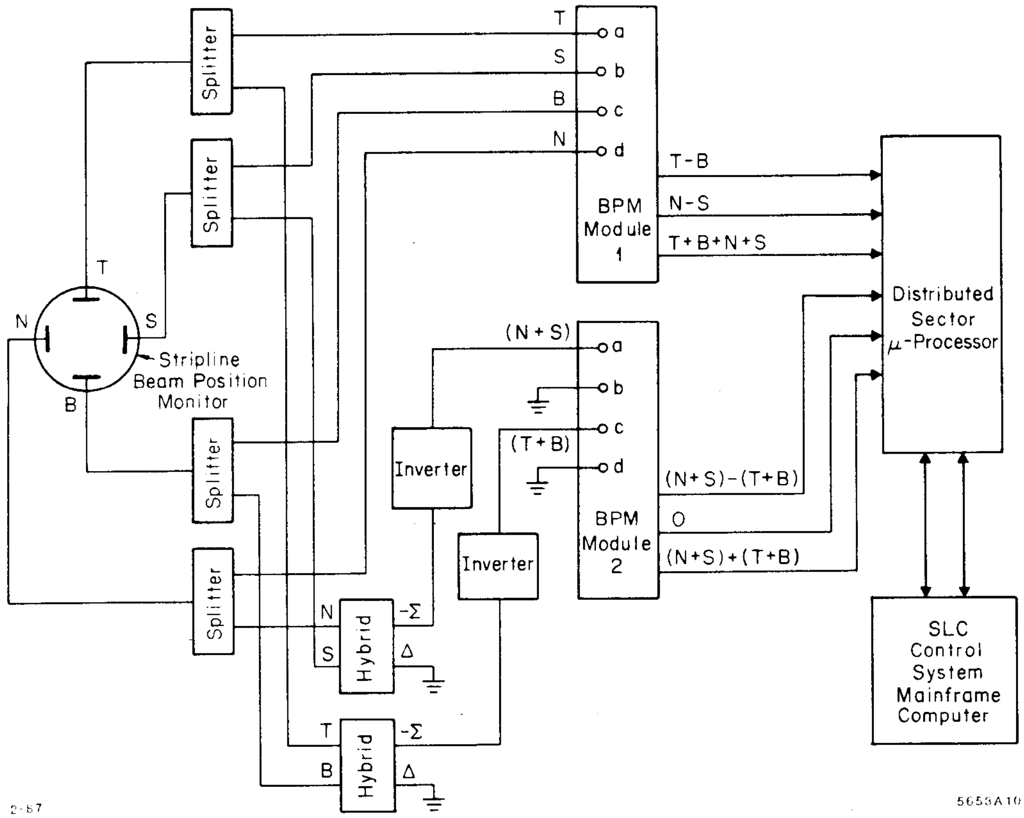

Fig. 3. Signals from a single stripline monitor are processed using 2 standard SLC BPM electronic modules to produce both dipole and quadrupole moment signals. The dipole dependencies are subtracted from the quadrupole moment in the control system μ-processor. User interface to the data collection and handling is accomplished via the central SLC control system computer.

Energy Spread Algorithm

The BWMs measure a signal, Q, which is proportional to the quadrupole moment of the beam:

$$Q \propto (\sigma_x^2 - \sigma_y^2 + \langle x \rangle^2 - \langle y \rangle^2) \ . \qquad (3)$$

In Eq. (3) σ_x and σ_y are the horizontal and vertical beam sizes; $\langle x \rangle$ and $\langle y \rangle$ are the horizontal and vertical beam positions. For an energy spread of σ_ϵ, the horizontal beam size at a location with horizontal dispersion, D_x, is given as

$$\sigma_x^2 = \epsilon_x \beta_x + D_x^2 \sigma_\epsilon^2 \equiv \sigma_{\beta x}^2 + D_x^2 \sigma_\epsilon^2 \qquad (4)$$

wherein ϵ_x is the horizontal beam emittance; β_x is the corresponding β function value; and $\sigma_{\beta x}$ is the horizontal beam size in the absence of any energy spread.

Beam centroid contributions to Q, $\langle x \rangle^2$ and $\langle y \rangle^2$, are subtracted in a local microprocessor during signal processing to yield the quantity P:

$$P \equiv Q - A(\langle x \rangle^2 - \langle y \rangle^2) \propto (D_x^2 \sigma_\epsilon^2 + \sigma_{\beta x}^2 - \sigma_y^2) \ . \qquad (5)$$

Beam positions are measured in the same stripline monitor as is used to determine Q. The value of A is determined empirically to null changes in P with respect to beam position variation.

From Eq. (5), it is seen that minimization of σ_ϵ is accomplished by minimizing P. This reduction is accomplished by varying the phase of the accelerating RF. Two BPMs in each of the LTRs are presently being used to monitor the beam energy spread. Table 1 lists the expected values of P for $\sigma_\epsilon = 0\%$ and for $\sigma_\epsilon = 1\%$, using the SLC design values for dispersion and beam size at the locations of the installed BWMs.

Table 1. Expected Parameters: $P = (D_x^2 \sigma_\epsilon^2 + \sigma_{\beta x}^2 - \sigma_y^2)$

Location	D_x (m)	σ_x (mm)	σ_y (mm)	$P(\sigma_\epsilon = 0\%)$ (mm²)	$P(\sigma_\epsilon = 1\%)$ (mm²)
NLTR:BPM 134[a]	0.357	0.692	0.633	0.08	12.82
NLTR:BPM 164[a]	0.693	1.070	0.449	0.94	48.97
SLTR:BPM 135[b]	0.362	5.713	5.167	5.94	19.05
SLTR:BPM 255[b]	0.506	4.264	2.929	9.60	35.21

(a) $\gamma\epsilon_x^- = \gamma\epsilon_y^- = 15 \times 10^{-5}$ m-rad for electrons.
(b) $\gamma\epsilon_x^+ = \gamma\epsilon_y^+ = 1000 \times 10^{-5}$ m-rad for positrons.

Figure 4 shows the measured Q signal from a BWM installed in the north LTR as the horizontal beam position is varied. This data was acquired by setting A from Eq. (5) equal to zero in the microprocessor software. As expected, Q exhibits a quadratic dependence on $\langle x \rangle$. The curvature of the Q versus $\langle x \rangle$ data is equivalent to A. Figure 5 shows the P signal, for a value of $A = 0.35$. In Fig. 5, it is seen that the dependence of P on $\langle x \rangle$ is essentially nulled. Similar data has been acquired in the vertical plane which shows that the proper value of A to null vertical beam position dependence is the same as for the horizontal plane, as is expected.

Figure 6 shows the change in P as the phase of the accelerating RF is varied with respect to the beam. A parabola has been fit to the data to determine the phase setting, $\phi_{\min}$, which minimizes P. The values of $\phi_{\min}$ found with the BWMs are the same which are found by using a TV screen, located in a dispersed region near the BWMs, to minimize the horizontal spot size with respect to RF phase. In order to make a reliable determination of $\phi_{\min}$, it is necessary to average the P data at each phase setting for several ($\sim$ 10) beam pulses. In Fig. 6, two sets of 10 pulse averages were acquired for each phase value. The error bars in the data represent the RMS scatter of the measurements.

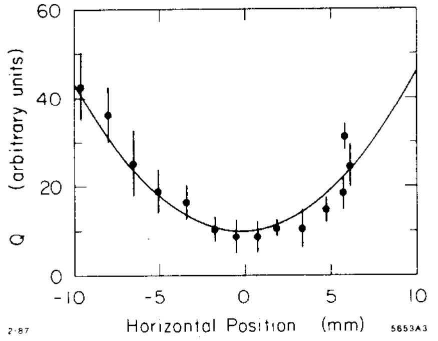

Fig. 4. $Q \propto (\epsilon_x \beta_x + D_x^2 \sigma_\epsilon^2 - \sigma_y^2 + \langle x \rangle^2 - \langle y \rangle^2)$ measured in NLTR BWM 164 as $\langle x \rangle$ is varied while everything else is held constant. The fit to the data is $Q_{\rm fit} = b(\langle x \rangle - c)^2 + d$ where $b = 0.3464$, $c = -0.2244$ mm, $d = 9.9187$.

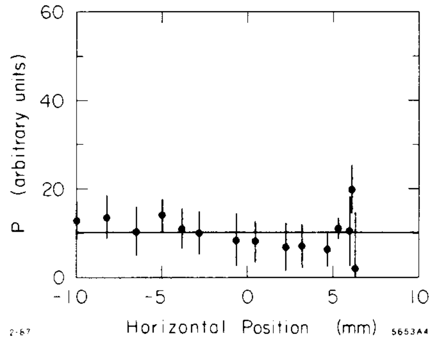

Fig. 5. $P = Q - A\langle x \rangle^2$ measured in NLTR BWM 164 as the horizontal position is varied. $A = 0.35$ is chosen to minimize the dependence of P on $\langle x \rangle$. $P_{\rm fit} = 10.194 \pm 4.152$.

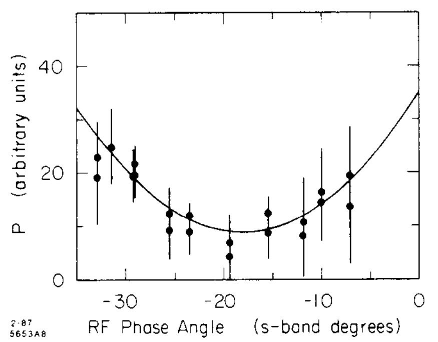

Fig. 6. $P = Q - 0.35(\langle x \rangle^2 - \langle y \rangle^2)$ measured in NLTR BWM 164 as the phase of the accelerating RF is varied to change σ_ϵ of the beam. $P_{\rm fit} = b(\phi - c)^2 + d$ with $b = 0.0810$, $c = -18.007^0$, $d = 8.916$. $\phi = -18.007^0$ is the phase setting which minimizes σ_ϵ.

Computer Feedback

A program has been developed whereby the central computer uses the BWMs to minimize the beam energy spread at the end of the SLC injector. This program has been incorporated into the slow, feedback process.[7,8] Upon scheduling, the program measures the current value of P and notes the current setting of the RF phase. Next, the phase is varied from -6^0 to $+6^0$ from the present phase setting in 10 steps. The average value of P is measured at each step. In addition, the beam energy is stabilized[9] with respect to phase changes with both a feedforward and a feedback algorithm. Once the P versus phase data has been collected, a parabola is fit to the data to determine $\phi_{\rm min}$. This new value for the phase is then set into the system along with the proper change to beam energy. Since there are two BWMs available in each LTR, the value of $\phi_{\rm min}$ is presently taken as the arithmetic mean of the $\phi_{\rm min}$ determined from individual monitors.

Figure 7 illustrates the results of 16 successive iterations of the energy spread minimization software. This data was acquired over a period of about an hour. In the event that the $\phi_{\rm min}$ fit predicts a phase value which is beyond the swept range, the phase is set to the appropriate extreme of the actual sweep and the loop is rescheduled. When the fit quality is below a specified acceptance tolerance, the phase is returned to the initial value.

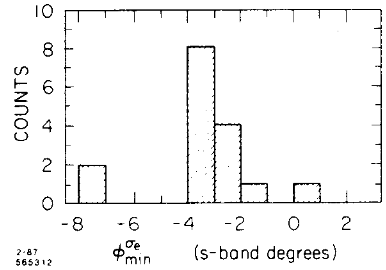

Fig. 7. Results of the $\phi_{\rm min}$ determining software for 16 trials of the σ_ϵ minimization software. This data was collected over a period of about 60 minutes.

Status

BWM hardware has been developed and installed to allow nonintercepting measurements of the energy spread of bunches at the exit of SLC injector. Two sets of BWM electronics have been installed and tested in the north LTR for monitoring of electrons. Three sets of BWM electronics have been placed in the south LTR for monitoring of positrons; the hardware in the south LTR has been tested using electrons. The BWM signals are somewhat noisier than originally hoped. The noise arises from both the low signal levels and the fact that the Q data is measured on different beam pulses than the position data. This latter difficulty is a consequence of the particular scheme being employed in the LTRs which multiplexes a large number of stripline monitors into a few BPM electronics modules. The noisiness, however, is overcome through data averaging. Additional BWM hardware has been installed in the transport lines leading from the damping rings to the linac for energy spread monitoring of the damped beams.

A computer program has been developed to permit automated minimization of the energy spread. This routine has been tested successfully and has been incorporated into the control system feedback process. Routine operation of the loop is not presently required because of the stability of the beams presently being injected into the LTRs. It is anticipated that the automated energy spread minimization software will become necessary as the beam currents and repetition rates are increased for full SLC operation later this spring.

Acknowledgments

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