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# Quadrupole Shunt Experiments at SPEAR*

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**Abstract.** As part of a program to align and stabilize the SPEAR storage ring, a switchable shunt resistor was installed on each quadrupole to bypass a small percentage of the magnet current. The impact of a quadrupole shunt is to move the electron beam orbit in proportion to the off-axis beam position at the quadrupole, and to shift the betatron tune. Initially, quadrupole shunts in SPEAR were used to position the electron beam in the center of the quadrupoles. This provided readback offsets for nearby beam position monitors, and helped to steer the photon beams with low-amplitude corrector currents. The shunt-induced tune shift measurements were then processed in MAD to derive a lattice model.

## INTRODUCTION

In order to improve electron beam stability in SPEAR, the storage ring and photon beam lines were re-aligned in 1995 (1). After the alignment, however, the electronic offset of the beam position monitors (BPMs) were still unknown, and beam steering remained difficult. To locate the BPM centers, we made use of an old but effective beam steering method that is now used widely, and installed a shunt circuit on each quadrupole (2-7). Since a shunted quadrupole deflects the beam when the orbit passes off-axis through it, the shunt can be used to center the beam in the quadrupoles.

The steering procedure involves a few simple steps. In the first step, we center the beam in quadrupoles located at each end of an insertion device straight section (see Fig. 1). With the beam centered, the offset values can be determined for BPMs located in the straight section. In some cases, the BPM offsets were up to 6 mm. These values were entered into the database for use by the orbit correction program. By using the BPMs as steering fiducials, the beam could then be centered at any time without re-activating the shunts. The shunt-induced tune shifts were also numerically processed to derive a lattice model. As a result, initial machine commissioning, and orbit adjustments after each fill have become routine. This paper reports on three aspects of the quadrupole shunt work at SPEAR: shunt circuit design, beam centering, and lattice diagnostics.

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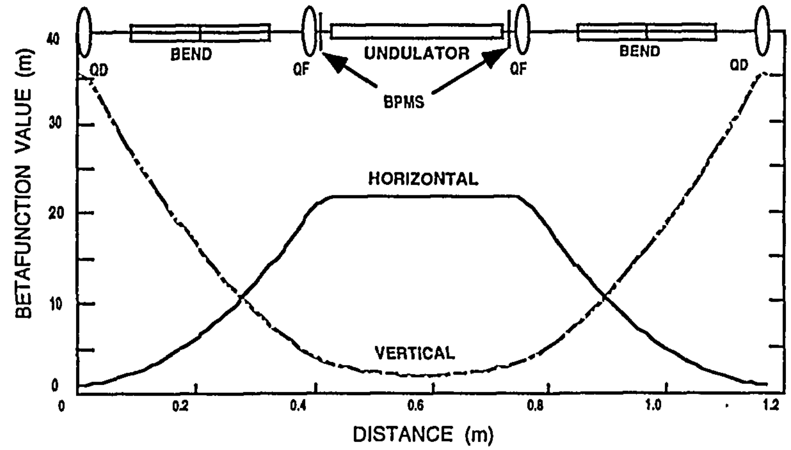


**FIGURE 1.** Betatron functions in SPEAR insertion device cells.

## SHUNT CIRCUIT DESIGN

The design goal for the shunt circuits in SPEAR was to produce the maximum orbit shift and a betatron tune shift of order 0.01, but with the shunt resistor power load not to exceed 250W. In addition, high tolerance resistors were needed for accurate β–function measurements, and the driving circuit needed to switch the shunts at up to a 10Hz rate. These criteria led to an optically isolated FET switch design with 250W, 1% power resistors mounted on water-cooled copper plates. Depending on the quadrupole family, the resistor impedances range from 0.1-0.3Ω, and they bypass 1-3% of the supply current to the individual quadrupoles. A multiplexer activates each FET switch separately in either AC or DC mode, and reads back the bypass current. A schematic circuit diagram for a shunt is shown in Fig. 2.

To estimate the resolution for centering the beam in a quadrupole, one can take the orbit kick 'θ' from each shunt as proportional to the change in focusing strength and proportional to the beam offset in the quadrupole,

$$\theta \propto c\,(\Delta k\, L)\, x_q \qquad (1)$$

where 'c' is a proportionality constant, $\Delta k\, L(m^{-1})$ is the change in the integrated quadrupole strength, and $x_q$ is the beam offset relative to the magnetic center of the quadrupole. The closed orbit perturbation Δx (suppressing the phase factor) is then

$$\Delta x \propto \theta\sqrt{\beta_k \beta_o} \qquad (2)$$

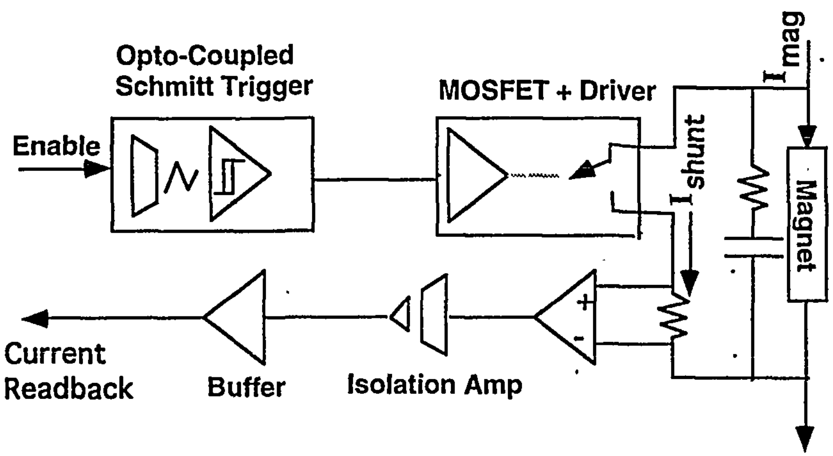


FIGURE 2. Circuit schematic for quadrupole shunt in SPEAR.

with $\beta_k$ and $\beta_o$ the β-function values evaluated at the kick and observation points, respectively. Substituting Eq. (1) into Eq. (2) yields the orbit offset $x_q$ that can be detected for a specific BPM processor resolution,

$$x_q \propto \frac{\Delta x}{c\Delta k\, L\sqrt{\beta_k\beta_o}} \qquad (3)$$

Equation (3) shows the factors that contribute to high resolution beam centering measurements: good BPM processor resolution (small $\Delta x$), a large shunt-induced value for $\Delta k$ L, and large β–functions. The fractional betatron tunes enter through the proportionality constant 'c'. The ratio $x_q/\Delta x$ for BPMs in the beam line regions (where most SPEAR BPMs are located) and in the lattice matching cells (where β–functions are highest) are listed in Table 1 for each quadrupole family. Also listed are the sensitivities for the largest beam motion at one of the 9 photon beam monitors, depending on phase.

The relative ability to resolve the electron beam offset in the different quadrupole types is found by multiplying the value listed in Table 1 by the

Table 1. Ratios of (orbit offset)/(orbit shift) for quadrupole shunts in SPEAR

| | x(arc) | y(arc) | x(max) | y(max) | y(photon) |
|---|---|---|---|---|---|
| Q2 | 10 | 90 | 6 | 21 | 7.4 |
| Q1 | 52 | 40 | 31 | 9 | 3.3 |
| QFA | 8 | 30 | 5 | 7 | 2.5 |
| QDA | 47 | 32 | 28 | 7 | 2.5 |
| QFB | 8 | 55 | 5 | 13 | 4.5 |
| QF | 8 | 56 | 5 | 13 | 4.6 |
| QD | 46 | 30 | 27 | 7 | 2.5 |

(arbitrary units)



resolution of the BPM processor. The resolution for horizontally centering in a QF quadrupole, for example, is about a factor of 3 higher than the vertical resolution. As a result, we often center the beam vertically in the QD quadrupoles (higher β–function) to obtain the vertical BPM offsets in the straight sections.

The resolution is also better at the photon BPMs because the effective 'β–function' values at these locations are typically a few hundred meters. The photon BPMs also have the advantage that the position resolution is about 1 μm, and the signal is available continuously.

## BEAM CENTERING (DC)

In general, algorithms exist for steering the beam through the center of many quadrupoles simultaneously (6). These algorithms require a matrix of derivatives,

$$S_{ij} = \frac{\Delta(\text{orbit shift from shunt})_i}{\Delta(\text{corrector})_j} \qquad (4)$$

evaluated for each quadrupole shunt 'i' and each corrector 'j'. To correct a particular electron beam orbit, one measures the orbit shift induced by each shunt and multiplies by the 'inverse' matrix $S^{-1}$ to calculate the corrector pattern that best centers the beam in the quadrupoles (6). This matrix inversion technique, although elegant and global in extent, requires either a relatively accurate lattice model or a lengthy data acquisition process to generate the S-matrix.

Alternatively, our approach has been to find BPM offsets once the beam is centered in the quadrupoles at the ends of a straight section. With this technique, we minimize errors incurred if the orbit passes through a quadrupole at an angle. The sources of BPM calibration error are reduced to quadrupole alignment errors, the discrepancy between the mechanical and magnetic centers of a quadrupole, and the BPM processor resolution.

Two different DC shunt methods have been used at SPEAR to center the beam in quadrupoles. The first method is to sweep the beam through the quadrupole, and record both the shunt-induced orbit perturbation and absolute orbit as a function of beam position. As shown in Fig. 3a, the horizontal center of a QF quadrupole can be determined to within about 50 μm. Although the sweep method yields good resolution for a single quadrupole, it is difficult to center the beam in two quadrupoles simultaneously with this method.

The second method is a derivative-based algorithm outlined in Table 2. Similar to the matrix inversion technique, we measure the effect of a closed bump

Table 2. Algorithm for centering beam in SPEAR quadrupoles

I. Measure orbit shift from shunt.
II. Apply closed bump over quadrupole.
III. Re-measure orbit shift from shunt.
IV. Form derivative $\frac{(\text{step III - step I})}{\text{step II}}$.
V. Calculate requisite bump amplitude, apply bump to center beam.

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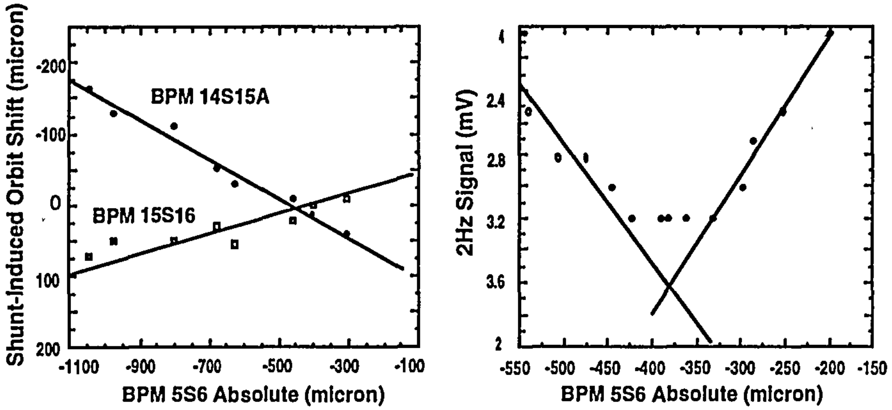



**FIGURE 3a,b.** Orbit perturbation as a function of beam position read back at BPM.

or a single corrector on the shunt induced orbit shift. The *change* in the orbit shift (numerator of the derivative in step IV of Table 2) can include any figure of merit: for example, rms orbit shift, peak orbit shift, or the entire orbit shift.

We typically form the inner product of the orbit shift induced by the shunt with the vector formed for the numerator of the derivative computed in step IV. Appropriately normalized, this 'projection' of the orbit shift yields the bump amplitude needed to center the beam. Repeated applications of the orbit adjustment 'servos' the beam into position. Although this method is not as accurate as the sweep method, it efficiently centers the beam in two quadrupoles simultaneously.

## BEAM CENTERING (AC)

Centering the beam vertically in the QF quadrupoles can be difficult because the QF magnets have small vertical β–functions. To improve resolution, the shunts are driven with a square wave of up to 10Hz (AC), and the motion synchronously detected at the photon beam BPMs. Similar examples of 'lock-in' detection can be found at LEP (5).

As shown in Fig. 3b, we can easily position the orbit in a quadrupole to minimize the signal power at the excitation frequency. After centering the beam with the AC technique, however, we found that the application of the shunt in the DC mode can cause a detectable orbit shift. The discrepancy between the two techniques can give a different value for the beam position at the quadrupole center by up to 500 μm.

The source of the different measurements was traced back to the impact of the load modulation on the power supply output. This effect is shown in Fig. 4, where we plot beam position as a function of time. Each time the FET shunt switch changes state, the load modulation makes the power supply regulator overshoot before it settles to the steady state. As a result, the excitation frequency can be detected even when the beam is centered in the quadrupole. The minimum of the spectral line amplitude occurs when the AC component of the shunt-induced orbit shift best cancels the AC component of the power supply current spikes.



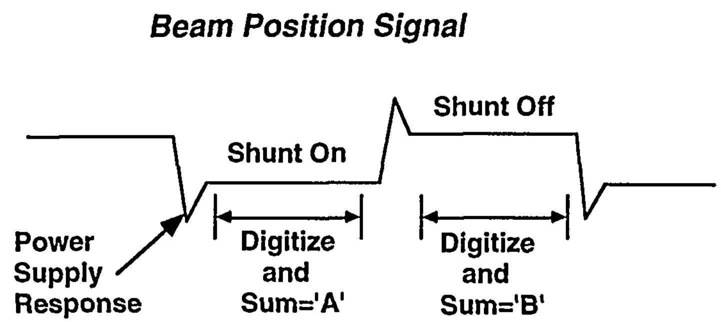



**FIGURE 4.** Impact of supply regulation on beam position signal.

To suppress the current spike effect, the analysis can be made on the component of the signal in the interval between spikes. Referring to Fig. 4, the beam offset is proportional to the difference between the signal evaluated during sample interval 'A' (shunt on) and during interval 'B' (shunt off). By processing on these components of the signal, the beam can be accurately centered in the quadrupoles.

## LATTICE DIAGNOSTICS

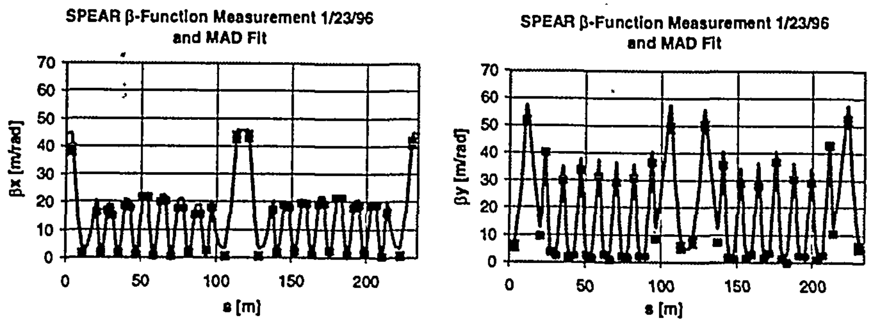
Individual quadrupole magnet shunts allow the measurement of the β-functions <β> in each plane, averaged across the length of the quadrupole, i. e.,

$$\langle\beta\rangle = \frac{4\pi\Delta\nu}{\Delta k\, L} \quad (5)$$

Here, Δν is the observed change in betatron tune caused by the change in the integrated quadrupole strength, Δk L, due to the shunt activation.

In SPEAR, the shunts allow the measurement of β-functions at 50 different locations in each plane around ring. This information is sufficient to perform a numerical analysis to find the sources of deviation between the design lattice and the actual lattice; it also allows calibration of the ratio Δk/ΔI for each of the 7 quadrupole families. Using the MAD accelerator design code (8), the 7 quadrupole strengths, k, were fitted to minimize the rms difference between the measured and model β–functions, and the measured and model betatron tunes.

The fitting procedure was applied to the operational configuration as well as to a bare lattice, i.e. a lattice without insertion devices. The MAD model includes the measured quadrupole positions as obtained from a global magnet survey. Before the shunt dependent tune shift data was collected, the electron orbit was centered in the shunted quadrupole. Otherwise the shunt would shift the global closed orbit, and non-linear elements such as the sextupoles would add errors to the measurement.




**Figures 5a,b.** Horizontal and Vertical β-Function measurements in SPEAR.

For the MAD fitting routine, the measured β-function values are converted from quadrupole average, $<\beta>$, to quadrupole center values, $\beta_c$, via

$$\frac{<\beta>}{\beta_c} = \frac{1}{L\beta_c}\int_{-L/2}^{L/2} (R_{11}(s)\beta_c - 2R_{11}(s)R_{12}(s)\alpha_c + R_{12}(s)^2\gamma_c)ds \quad (6)$$

where $\alpha_c = \frac{-1}{2}\beta'(s{=}c)$, $\gamma_c = \frac{\alpha_c^2+1}{\beta_c}$, and $R_{ij}$ are elements of the quadrupole transfer matrix. The evaluation of the integral gives:

$$\frac{<\beta>}{\beta_c} = \frac{1}{2\sqrt{k}\,L}\Big[\big(\sqrt{k}\,L + \sin(\sqrt{k}\,L)\big) + \frac{(\alpha_c^2+1)}{k\beta_c^2}\big(\sqrt{k}\,L - \sin(\sqrt{k}\,L)\big)\Big] \quad (7)$$

for the focusing plane, and $\sin(\sqrt{k}\,L)$ becomes $\sinh(\sqrt{k}\,L)$ with the second term changing sign for the defocusing plane. The second term in the bracket is much smaller than the first term and the values for $\alpha_c$ and $\beta_c$ can be taken as the initial model values in very good approximation.

The strength-to-current ratio, i.e. the ratio of the average quadrupole strength to its excitation current is not well known in SPEAR. The shunt based analysis allows us to calibrate these factors, and provides information about individual quadrupoles within the families. To determine the strength-to-current ratios, a self-consistent iterative method is used, which re-calculates the average β–function from the measured shunt current and from the observed tune shifts. The fitting is done iteratively using β-function data based on the strength-to-current ratios from the previous fit, and converges quickly.

Using the updated calibration factors, new quadrupole excitation currents can be predicted to achieve the desired β-functions in the machine. The method was applied in several iterations to significantly reduce the difference between the



measured and predicted β-functions. Figures 5a and 5b show the result of a fit (solid line) to the measured β–functions (square dots) for SPEAR. The error bars are based on statistical analysis of errors incurred in the data acquisition process. The residual deviations are due to variations within the quadrupole families, most notably the SPEAR QD quadrupoles which have been mechanically modified (part of the iron core was removed) to provide space for photon beam exit ports. These modifications reduced the on-axis gradient by about 1.2-1.5%. This effect has not yet been considered in the shunt data analysis.

## SUMMARY

Following a re-alignment of SPEAR, we were able to use quadrupole shunts to measure horizontal BPM offset values in the straight sections. These measurements quickly led to an electron beam orbit with steered photon beams. Further application of the shunts improved the orbit in both planes throughout the storage ring. To improve resolution of beam position in quadrupoles, the shunts are modulated in an AC mode. The AC measurement system will be incorporated into a fast algorithm to automatically servo the beam position to the quadrupole center. Finally, shunt measurements to identify and correct modulations in the β–functions have proven successful. In the future, we plan to analyze the BPM readings to determine and correct individual quadrupole misalignments, and to identify the dispersion component of the orbit.

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