BEAM DYNAMICS EXPERIMENTS AT SPEAR*

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Introduction

The single-particle properties of beams in storage rings are well understood, but high density single and colliding beams suffer from a variety of instabilities due to self-forces and interactions with their surroundings. The chief experimental problems in the study of stored beams arise from the difficulty of devising beam-diagnostic probes which do not affect the stored beams or disturb the phenomena being studied, and which give unambiguous results when different phenomena act on the probes simultaneously.

In the SPEAR electron-positron storage ring, we have apparatus and methods for measuring center-of-mass motions of our beams on all three axes, as well as motions with higher moments. The shapes of the beam bunches can also be accurately measured. We will describe the techniques we have used to study instabilities and measure operating characteristics.

Center-Of-Mass Motions

There are directional antennas (striplines) inside the vacuum envelope[1] which detect the electromagnetic field of the whole bunch. When the beam executes betatron oscillations, there is a small amplitude modulation of the signals from the striplines. We detect and measure this modulation to give us information on betatron wave numbers, line strengths and widths.

In an electron storage ring, most types of longitudinal and transverse motion damp out, with a characteristic damping time, due to synchrotron radiation. Thus, we can excite the beam transversely with external electromagnetic fields to a finite, stable amplitude in contrast with the "rf knock-out" techniques used in proton machines. Combining coherent excitation with the coherent detection referred to above allows us to measure the transverse properties of the beam in much the same way that electrical engineers measure linear networks.

Typical electrode structures, because of their small size, low capacitance and inductance, have a very poor sensitivity to betatron frequencies, which are usually in the sub-megacycle range. At SPEAR, the rotation frequency is 1.28 MHz, and the bunch length is 1 ns, thus, the frequency spectrum of a signal from a stripline has a line structure with a spacing of 1.28 MHz, extending out to $\approx$500 MHz. It is possible to observe betatron sidebands on the individual harmonic lines with a high frequency analyzer, but not with any great accuracy or ease. By using a microwave diode or a fast switching diode to detect the signal from a stripline, we convert the original spectrum, having very small amplitude at low frequencies and no dc component, to one which has a dc component and the betatron frequencies at baseband from 200-600 KHz. A simple low-pass filter blocks out the higher harmonics and their sidebands and the frequencies are scanned by a low-frequency wave analyzer of a type designed for testing communications and audio-frequency equipment.[‡] The accuracy of frequency measurement is limited only by the stability of the storage ring power supplies, as is the resolution of line widths. Excepting these effects, we can resolve betatron lines to 1 part of 10^5 of betatron frequency, and our sensitivity to transverse motion is 10^{-1}mm mA^{-1} circulating current.

The wave analyzer has an oscillator which automatically tracks the center of the receiver pass band. By connecting this oscillator to the beam excitation system and sweeping the receiver and exciter simultaneously, we observe directly resonant responses of the beam with freedom from harmonic or intermodulation responses. (Fig. 1). A similar technique has been used at the Bevatron,[2] to measure the phase response of the beam.

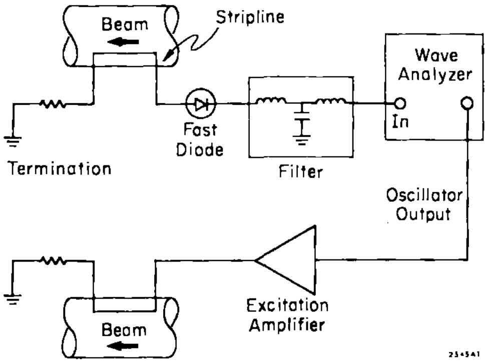

FIG. 1--The system for betatron and synchrotron-frequency response measurement. The oscillator is not used when observing self-excited lines.

We have been able to measure several rather subtle effects with this equipment, including tune shift with increasing circulating current, anomalous line-splitting at the threshold of instabilities, and coupled two-beam effects.[3]

Using only the detector system and an oscilloscope (Fig. 2) we can see the coherent damping of the beam due to large transverse kicks.[4] The incoherent damping is observed using the optical monitors, which will be discussed later.

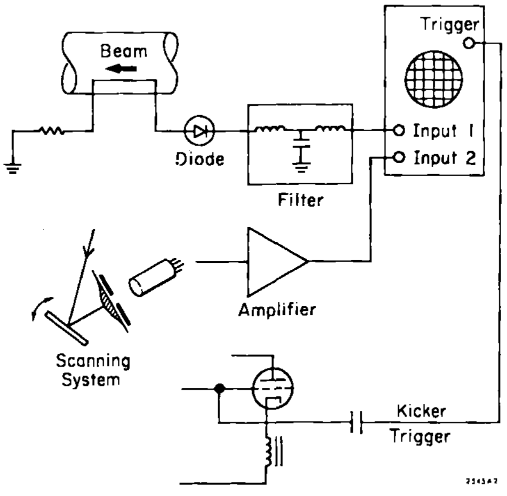

FIG. 2--Measurement of coherent and incoherent damping. The scanner system is described in Ref. 10.

Due to the dispersion (η (s)),[5] of any synchrotron, the sinusoidal energy oscillations (synchrotron oscillations) are translated into sinusoidal transverse oscillations at ω_s, the synchrotron frequency. The detector system described above for betatron oscillations picks up these oscillations as well. We can phase-modulate the rf driving voltage to our cavities

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[†] A. P. Sabersky, P. B. Wilson, H. Wiedemann, M. A. Allen, J.-E. Augustin, G. E. Fischer, R. H. Helm, M. J. Lee, M. Matera, P. L. Morton, J. M. Paterson, B. Richter.

[‡] Hewlett-Packard Mod. 3590A — sensitivity $\approx 1\mu$V.

with a voltage-controlled phase shifter.[6] Using the local oscillator of the low-frequency wave analyzer, as above, we can measure the transverse response of the beam as a function of frequency. In the linear approximation, the response of the beam is identical with an L-C-R tuned circuit about resonance frequency and the damping time due to rf system stability[7] and the active phase-feedback system[6] can be measured directly from the frequency-response curve

$$\tau_{\text{damping}} = \frac{1}{\pi \Delta f}$$

where Δf is the full width at 0.707 amplitude relative to peak response.

Longitudinal Size and Motions

Bunch length and high-order modes of bunch oscillation have been studied extensively at SPEAR.[8] The apparatus used to measure the higher modes was the same as that used to measure betatron and synchrotron oscillations.

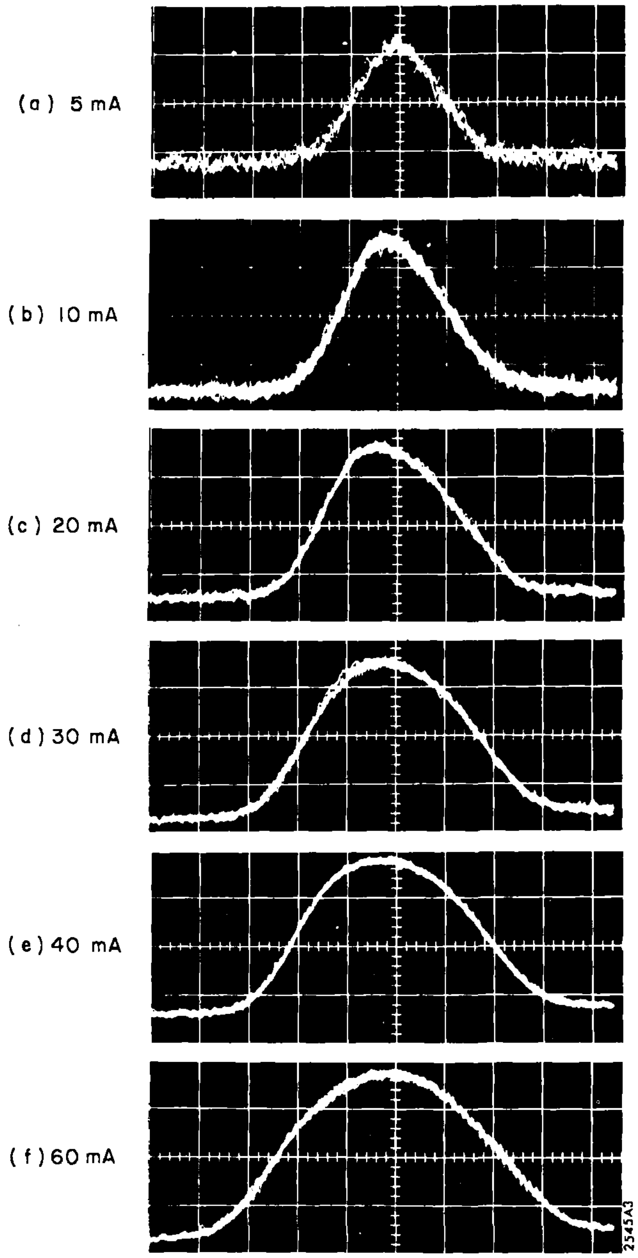

FIG. 3--Bunch shape with respect to a fixed rf time. Horizontal scale is .5 ns/division, vertical scale is amplitude.

Higher-order modes of bunch shape oscillation[9] have no amplitude-modulating frequency components at their fundamental frequency, and our system responds to them only due to the imperfectness of the detector diodes, which are peak-detecting to some degree. Higher modes have also been observed as sidebands of rotation-frequency harmonics at CEA.[10]

Bunch-length measurement methods have already been described.[11] The quality of the bunch-length data is very important in detailed studies, and there is an excellent discussion of applicable fast-pulse techniques in Ref. 12. The use of an x-y plotter to read out bunch-length traces makes a significant difference in the accuracy of the data: the absolute accuracy of bunch lengths and reproducibility is ±5%.

In order to see the distribution of current within the rf "bucket" for asymmetric bunches (Fig. 3) the sampling oscilloscope was triggered with radiofrequency taken from a pickup loop in one 51.2 MHz main cavity. This loop sampled the actual fields.

The quadrupole mode of bunch oscillation could be excited by strongly phase-modulating the rf drive to the cavities, and this mode was directly observed on the bunch length by synchronizing the oscilloscope triggers with the Q-mode excitation wave form (Fig. 4).

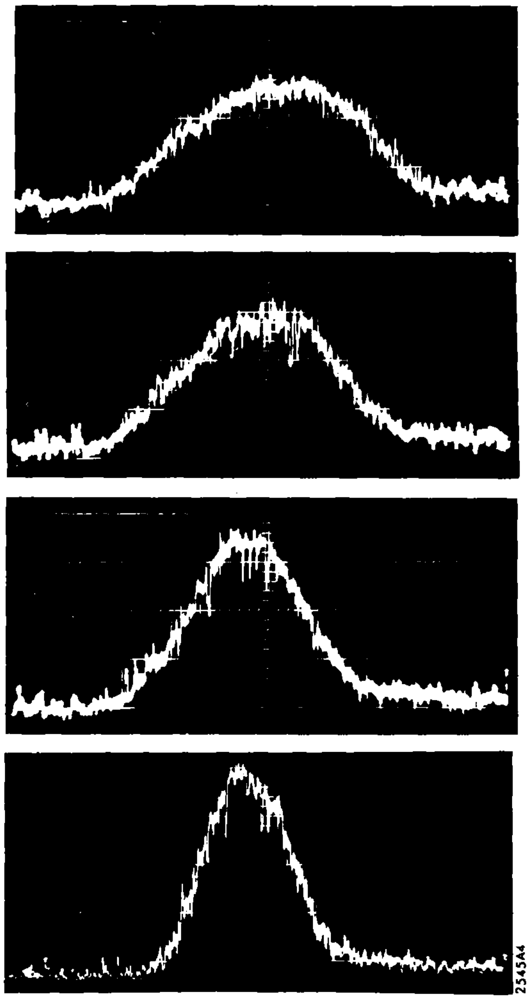

FIG. 4--Longitudinal quadrupole-mode oscillations. The horizontal scale is 1 ns/division.

Transverse Size

The optical monitors for measuring x and y transverse profile have been described in detail.[11] One modification has been the use of noise-averaging integrator (boxcar-integrator) to convert the rapidly-scanned (100 Hz), rather noisy signal into an accurate x-y tracing (Fig. 5). The reproducibility of the size measurements is ±1% and the accuracy is ±3%, limited only by errors in the calibrator system and in the construction of the optical monitors. This accuracy allows us to measure small beam-size effects such as: (1) horizontal broadening due to the excess energy spread associated with bunch lengthening, (2) shape distortions resulting from the effect of colliding beams.

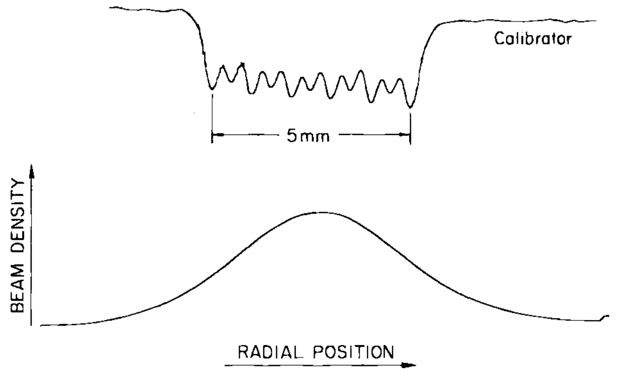

FIG. 5--A tracing of particle density versus radial position taken from the profile scanners with the scanning integrator.

The amplitude of the profile pulses is inversely proportional to the beam width for a constant beam current, thus time-resolved measurements of the pulse amplitudes can show charges in beam width. The beam profiles are scanned at 100 Hz, but this yields 200 pulses/sec, since the profile is scanned twice per cycle. This is a rapid enough rate to allow measurement of beam decoherence and damping times. For the damping time measurements, the pulses are displayed at some slow sweep rate (e.g., 10 ms full sweep) on an oscilloscope which is synchronized with the initial beam displacement, i.e., the kicker pulse.

The combination of rapid profile scans and broadband amplifiers allows us to see the first three modes of beam longitudinal-transverse motion on the horizontal profile scan. This allows us to accurately measure the amplitude of these modes with respect to the beam size.

References

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