SECTION IV

BEAM DYNAMICS
(continued)

Particle Accelerators, 1990, Vol. 28, pp. 1–9
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DYNAMIC APERTURE MEASUREMENT ON ALADDIN

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Abstract The sextupole-induced non-linear transverse beam dynamics in the synchrotron radiation storage ring Aladdin is studied. Specifically, the dynamic aperture is measured as function of the sextupole strength. The results agree reasonably well with computer simulations.

INTRODUCTION

In an electron (or positron) storage ring for synchrotron radiation, to obtain a low emittance beam, very strong horizontal transverse focusing is provided. This then necessitates very strong sextupoles to reduce the magnitude of the chromaticities to sufficiently small values to contain the desired momentum spread. The strong non-linear sextupole field tends to limit the dynamic aperture. It is therefore desireable to check and confirm the validity of computer simulations of dynamic apertures by comparing the results with measurements on an operating storage ring.

The Aladdin in the Synchrotron Radiation Center of the University of Wisconsin is a 1-GeV electron storage ring which can store a single beam bunch with current up to 10mA. A maximum of 15 bunches can be stored when used for synchrotron radiation experiments. Figure 1 shows a layout of the 4-sectored lattice.

For this study we chose the energy of 800 MeV as a compromise between long beam life-time at high energy and the ease of manipulating a soft beam at low energy. The relevant parameters of Aladdin at 800 MeV are given in Table I.

TABLE I Aladdin Parameters at 800 MeV

Energy	800 MeV
Circumference	88.9 m
Revolution period	0.30 μsec
Betatron tunes	ν_x=7.14 (h), ν_y=7.23 (v)
Emittance	0.10 π mm-mrad
Max. horizontal rms beam width	0.84 mm
RF harmonic number	15
RMS beam bunch length	87 mm (0.29 nsec)
Synchrotron radition energy loss per turn	17.4 keV
Synchrotron radition damping time	26.6 msec (89000 rev.)

EXPERIMENTAL ARRANGEMENT

For the sextupole induced dynamic aperture studies we proceed as follows:

1. Sextupole fields of desired harmonic amplitudes and phases are produced by powering eight sextupole magnets SF1, SF4, SF7, SF10, and SD1, SD4, SD7, SD10. The SF's and SD's are located at high horizontal and vertical β respectively. They exist in the Aladdin ring as spare chromaticity sextupoles.
2. A single-bunch stored beam is kicked in a transverse plane (horizontal in this case) by a fast kicker placed at a high horizontal β location as shown in Fig. 1.

3. The horizontal and vertical displacements and slopes of the beam bunch are measured every revolution by two horizontal and two vertical beam position monitors (BPM's). The existing stripline BPM's in the ring are used for this purpose. So far, however, we have only four digitizing channels. Since two channels are required for each BPM, only two BPM's can be read at a given time.
4. To reduce the dynamic aperture to smaller than the physical aperture so that it can be measured by beam kicking, one must operate close to sextupole induced third order resonances and use the harmonic sextupole magnets to strongly excite the relevant resonances.

Dynamic aperture studies are being carried out also on the Tevatron at Fermilab.[1] It is interesting to note that although Aladdin and Tevatron are drastically different in energy and size, the relativistic parameter γ, the total charge per beam bunch, the horizontal beam width and the beam pipe radius of the two machines are not too far apart. An electron machine has the advantage that after each transverse kick, the beam is restored by synchrotron radiation damping in less than a second and is ready to be used over again. During the few thousand revolutions when measurements are made, synchrotron damping is quite negligible.

Hardware Description

The kicker magnet has the conventional design -- a window frame ferrite core with a single turn coil. It is pulsed from a length of delay line through thyratron switching. This gives a total pulse length of ~350 nsec with a flat top of ~150 nsec.

The four stripline electrode signals from two BPM's are stretched using hot carrier diodes and LC single-section filters to ~50 nsec for digitizing. A four channel ADC digital oscilloscope is used for digitizing, storage and display. The ADC is clocked by a signal derived from the Aladdin rf synthesizer (Fig. 2) and is triggered by the kicker magnet trigger. Synchronization is achieved by appropriate delays so that the stretched beam signal is a maximum.

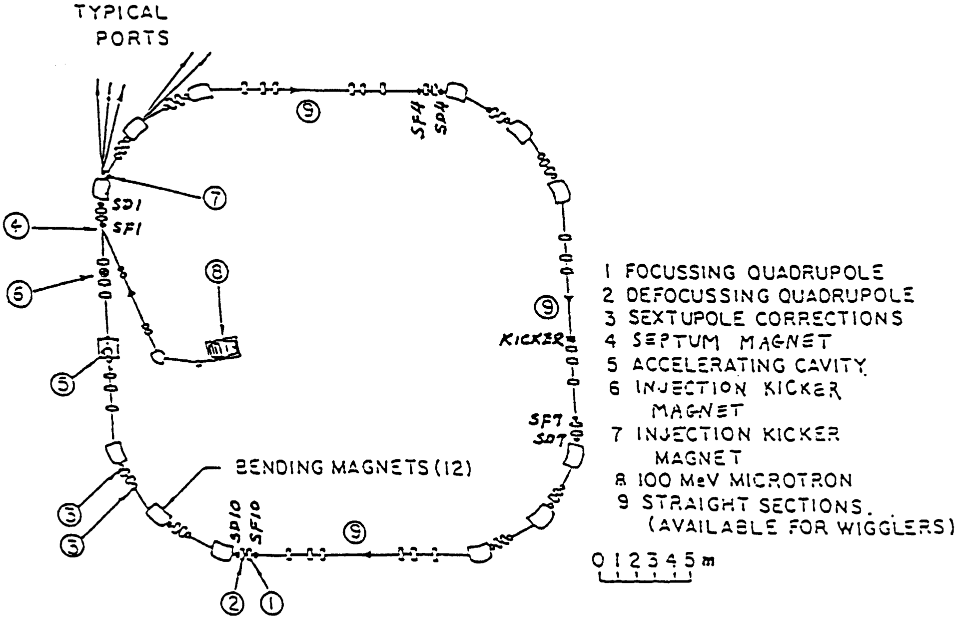

FIGURE 1 Layout of Aladdin showing locations of the kicker and the eight resonance driving sextupole magnets.

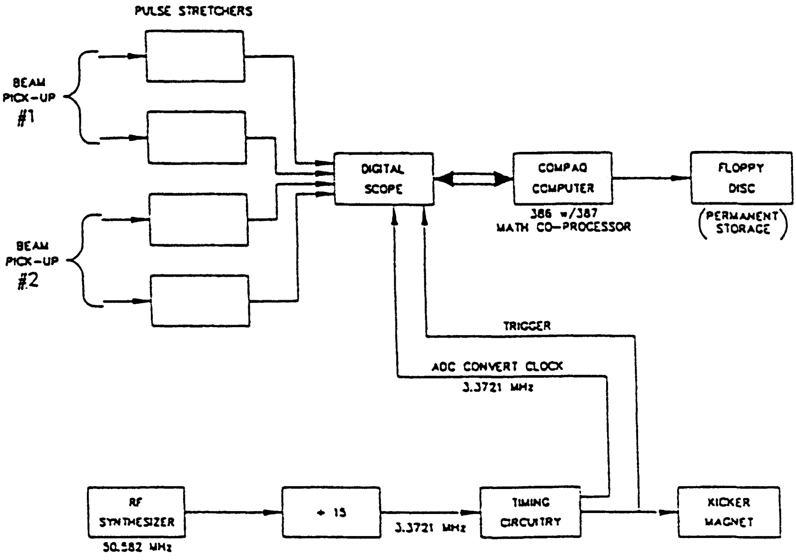

FIGURE 2 Block diagram of the timing and data acquisition, processing and storage circuitry.

The signals from a pair of right (R) and left (L) stripline electrodes of a BPM are first normalized to give the BPM reading (R-L)/(R+L). The displacement x of the beam is then obtained from the BPM reading through a non-linear relation.

Measurement Procedure

The sextupole-induced resonances that are easily reached from the nominal tunes of ν_x=7.14 and ν_y=7.23 are the single degree-of-freedom resonances $3\nu_x$=22 and $3\nu_y$=22, the difference coupled resonance $2\nu_y-\nu_x$=7 and the sum coupled resonance $2\nu_y+\nu_x$=22. Before performing kicked beam measurements the following preparatory adjustments and measurements are made.

1. The operating tunes are set close to the desired resonance(s) by adjusting the quadrupoles. Tune adjustment is a standard procedure on Aladdin. The tunes are measured by the rf knock-out technique to better than three decimal-place accuracy.
2. Closed orbit distortions are corrected by using steering dipoles. On Aladdin this operation is totally automatized. Closed orbit distortions are reduced to less than 30 μm rms in a few iterations.
3. Sizeable error sextupole fields exist in the Aladdin ring. The harmonics which drive the relevant resonances are first compensated to zero. A pair of diametrically opposite sextupoles when powered in the (+ −) polarities give all odd harmonics and when powered in the (+ +) polarities give the even harmonics. A second pair separately from the first by approximately $90^0/3$ phase is used to rotate the phase. The strengths of the two pairs are adjusted manually in a two-parameter optimization search until no effect can be observed on the beam in passing through or even sitting on the resonance. This is then the zero-point for measuring the excitation.
4. The chromaticity is adjusted to be close to zero. A small positive chromaticity is retained to avoid the head-tail instability. A program is being written for the control computer to do this automatically. But so far this is done manually by

measuring the tunes at different settings of the rf frequency. The chromaticity sextupoles have a 4-fold symmetry around the ring and therefore do not contribute to either the 7th or the 22nd harmonics which excite the resonances involved.

After these preparatory adjustments are made the beam bunch is kicked at specified amplitude and phase. The digitized signals from two BPM's (four stripline electrodes) are recorded for 4000 revolutions. The BPM signals can be plotted against turn number or can be processed to give the normalized phase space map. A beam loss is indication that the beam is kicked onto either a dynamic or a physical aperture. The amplitude of the kick gives then a measure of the aperture.

Measurement Results and Discussions

So far, we have explored only the effects of the horizontal resonance $3\nu_x=22$. To drive this resonance we used the diametrically opposite sextupole pairs SF4-SF10 and SD4-SD10 which are approximately 22^0 horizontal betatron phase apart. To produce the even 22nd harmonic the sextupoles in a pair are powered in the same polarity and, whenever convenient, at the same current.

Figures 3a and 3b show the typical plots of the data obtained. The kick amplitude is small. Figure 3a gives the beam displacement x as function of the turn number n and Fig. 3b gives the normalized phase map (x,p_x) both at the location of the upstream BPM. Figure 4 gives the phase map obtained by computer simulation. The agreement is clearly quite good. The apparent damping of the oscillation is only a result of the decoherence of the rather large phase area occupied by the beam.

Some phase maps at large kick amplitudes such as the one shown in Fig. 5 are rather difficult to interpret quantitatively, although the 3-lobed feature is typical of a third order resonance. Equally complex phase plots are also obtained in computer simulation as shown in Fig. 6. In Fig. 7 the beam is kicked close to the outer stable fixed point.

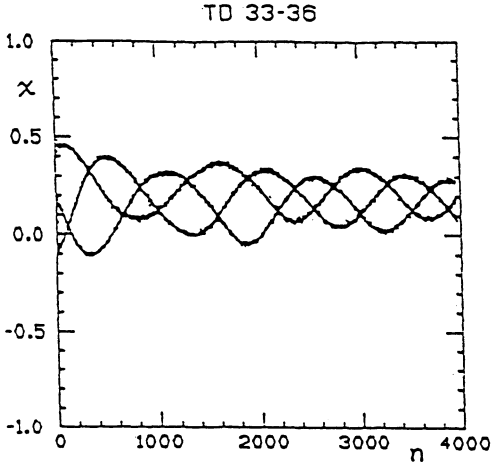

FIGURE 3 (a) Typical beam position vs. turn number plot (x,n).

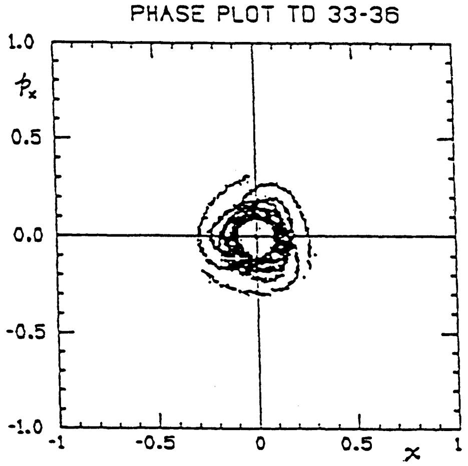

FIGURE 3 (b) Corresponding normalized phase space map (x,p_x).

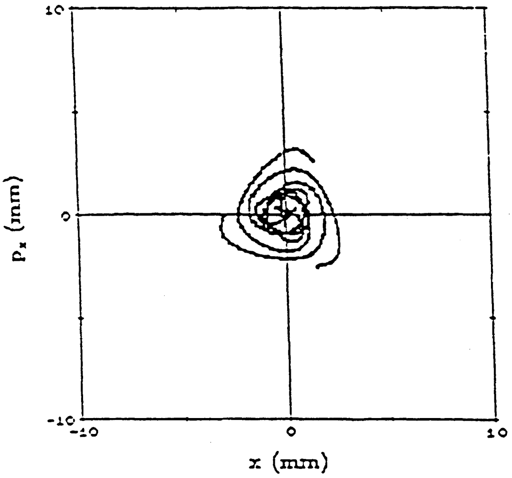

FIGURE 4 Phase space map obtained from computer simulation.

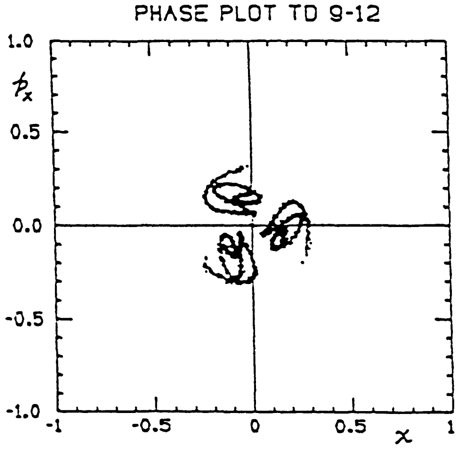

FIGURE 5 A complex measured phase space map showing the 3-lobed resonance structure.

The most important data obtained are those of the dynamic apertures at different excitations of the resonance. We define a 10% beam-loss dynamic aperture by the amplitude of the kick for which 10% of the beam is lost. This is obtained by keeping the sextupole strengths fixed and slowly increasing the kicker strength with each kick until the kick causes a 10% beam loss. The results are plotted in Fig. 8. Also plotted is the dynamic aperture obtained by computer simulation. The simulated dynamic aperture is given by the amplitude of a particle which strays outside a specified computer field in 500 revolutions. Considering the difference in definition we see that the agreement between measurement and simulation is really not bad. This gives us confidence in the computer simulation.

Next we want to study the effects of coupling resonances. For this we have added four more ADC channels and are modifying the kicker so that it can be rolled to kick the beam in both horizontal and vertical directions.

ACKNOWLEDGMENT

We want to thank D. Huber and E. Rowe of the Synchrotron Radiation Center for the use of Aladdin and for their valuable advice, and University of Wisconsin graduate students I. Hsu and J. Liu for helpful discussions and computer runs.

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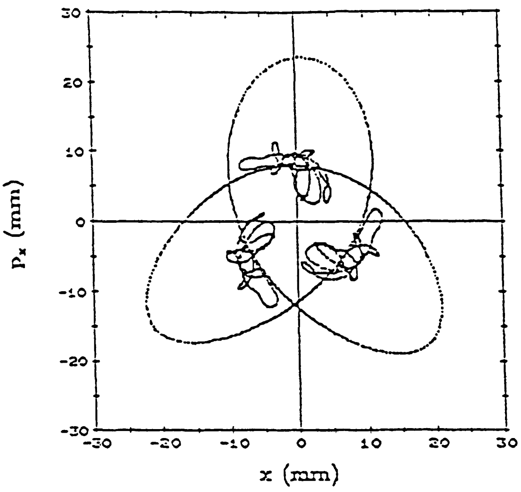

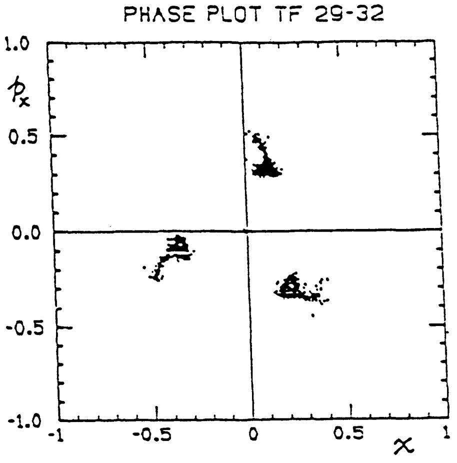

FIGURE 6 A similarly complex simulated phase space map with the separatrices shown superposed.

FIGURE 7 The phase space map when the beam is kicked near to the outer stable fixed point.

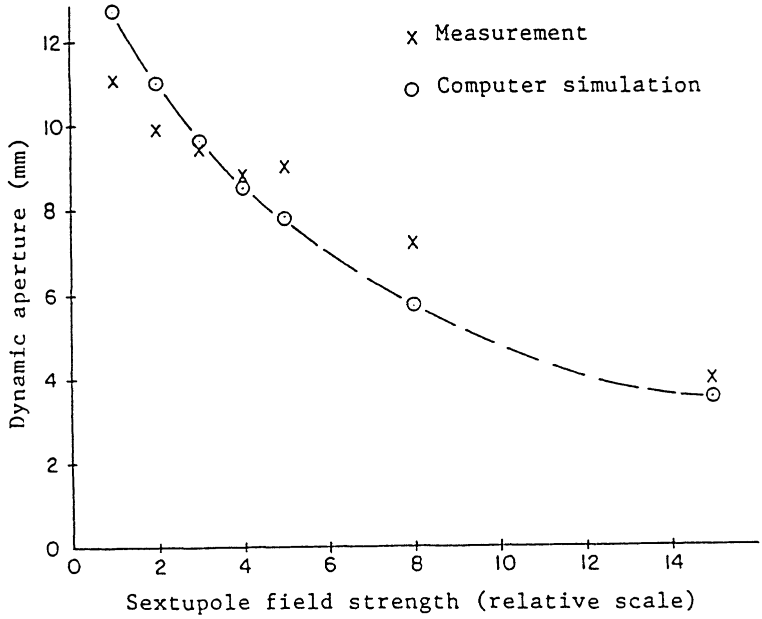

FIGURE 8 The 10% beam-loss dynamic aperture vs. the resonance exciting sextupole strength and the 500-turn loss single particle dynamic aperture obtained by computer simulation.