CE22: NONLINEAR BEAM DYNAMICS EXPERIMENTS AT THE IUCF COOLER RING

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Nonlinear beam dynamics experiments, approved as CE22 at the IUCF Cooler Ring, have recently completed a hardware test run. A preliminary report on the Poincaré map obtained is presented. Betatron tune measurements are obtained from the FFT of the measured betatron oscillations. We have observed the fourth and the seventh order resonance islands of the Cooler Ring.

I. Introduction

The Cooler ring circumference is 86.78 m with nearly 6-fold symmetry. The horizontal and vertical betatron tunes are 3.72 and 4.72 respectively. The 95% emittance of the beam is cooled to $\ll 1\ \pi$ mm-mrad from 25 π mm-mrad at the injection. The beam lifetime is much larger than several minutes or 10^8 turns, limited by single scattering losses.

However, when the tunes of the Cooler approach the octupolar resonances, $m\nu_x + n\nu_y = integer$ with $m + n = 4$, the lifetime is reduced, where m, n are integers, and ν_x, ν_y are the horizontal and vertical betatron tunes. Fig. 1 shows the lifetime of a cooled 186 MeV proton beam vs. the betatron tunes. As the betatron tunes approach the octupole resonance, the lifetime decreases. Especially, when $\nu_x = 3.75$ and $\nu_y = 4.75$, one observes two distinct lifetimes on the current transformer, i.e. a short lifetime for the uncooled large emittance beam and a longer lifetime for the cooled beam. The dependence of lifetime on the amplitude at higher order resonances has been observed in the beam-beam experiments at SPS.

The octupole resonance in the Cooler ring may arise from the random octupole field in the dipole and quadrupole magnets or from the second order effect of the sextupoles. These weak octupole nonlinearities do not impair the machine performance; they do however provide an opportunity to study the origin and methods of correction of such resonances.

In the past, several experimental nonlinear dynamics[1-5] studies have been performed. Especially, the effect of sextupoles on the beam dynamics has been studied in detail at FNAL in the E778 experiment.[1] This experiment gave a great deal of confidence to the

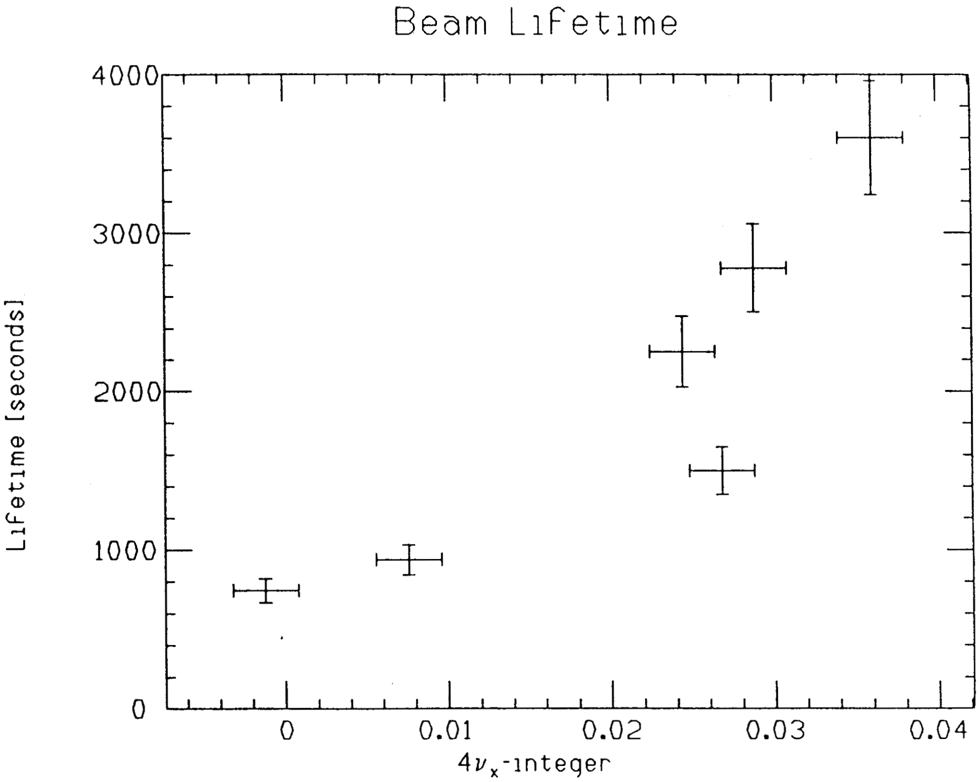

Figure 1. The cooled beam lifetime in the Cooler Ring is shown as a function of the distance from the octupole resonance line.

concept of smear. However, the nonlinear fields due to higher multipoles have not been studied. Although most accelerators are dominated by the sextupole nonlinearity, higher order multipoles do play an important role in the lifetime and diffusion process. It is therefore important to study the effect of higher nonlinear multipoles. Even more important is the issue of the correction method. Similar higher order experiments can be planned at the TEVATRON. However, considering the advantages of the Cooler beam quality and cost effectiveness of performing the experiments in a small ring, the IUCF Cooler is much better suited for beam dynamics studies.

II. Nonlinear Resonances

Particles in circular accelerators are governed by the quasi-harmonic focusing forces due to quadrupole elements. Thus particle motion in the circular accelerator is dominately linear. The phase space map exhibits the simple ellipse of the Courant-Snyder invariant. However, in the presence of weak nonlinear magnetic fields, the Hamiltonian of the particle is given by,

$$H = \frac{p_x^2}{2} + \frac{p_y^2}{2} + K_x\frac{x^2}{2} + K_y\frac{y^2}{2} + H_1(x,y), \tag{1}$$

where K_x and K_y are related to the gradient of the quadrupole magnets and where $H_1(x, y)$ is the nonlinear driving term. Most nonlinear Hamiltonians of interest in accelerator physics are *nearly* integrable. The dynamics depend critically on the operational condition of the accelerator. Such dependences provide an important window in understanding nonlinear dynamics in accelerators. There are methods to study nonlinear Hamiltonian systems, e.g. canonical perturbation theory,[6] LIE transform perturbation theory,[7,8] resonance width calculations,[9] and numerical tracking calculations.[10] These theoretical calculations, based either on perturbation or short term tracking, can be examined by experimental observation at the IUCF Cooler Ring.

Experimental studies of the nonlinear dynamics depends on the measurement of the Poincaré map derived from the difference signals of two beam position monitors separated by 90° in betatron phase advance. In the Cooler development section of this progress report, M. Ball *et al.*[12] report on the new beam tracking system at the IUCF Cooler Ring for the nonlinear beam dynamics studies.

Fig. 2 shows a preliminary example of the Poincaré map for the Cooler Ring operating near a fourth order resonance. The four different symbols in Fig. 2 represent every fourth turn in the Cooler. Four islands in the phase space can be seen clearly. Similarly, Fig. 3 shows an example of phase space plot for operation near the seventh order resonance. The total number of points ploted is about 1000 (1000 turns for Fig. 2 and 512 turns for Fig. 3). The phase space will gradually decohere due to the betatron tune spreads. Fig. 4 shows the measured betatron tune vs. the kick amplitude in millimeters. The tune shift with amplitude is fitted by the following equation,

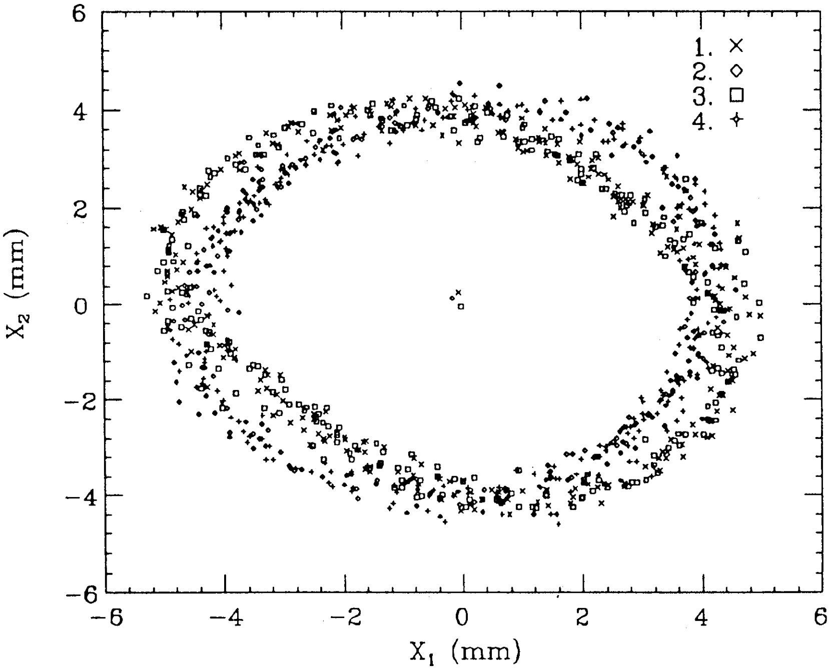

Figure 2. The phase space map of positions measured at the BPM PH14 (x_1), and PH26 (x_2), which are separated by about 90° in betatron phase. The phase space map displays fourth order resonance structure. The tune obtained from the FFT is 3.7360.

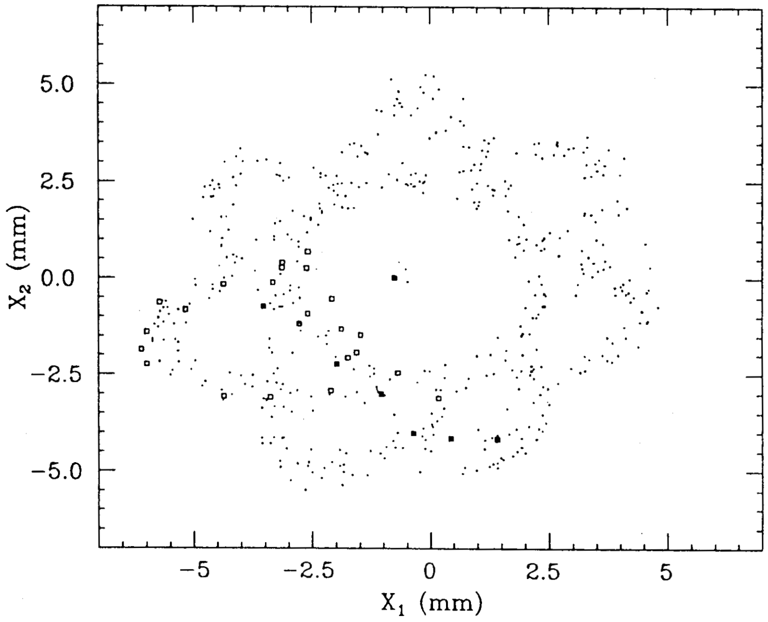

Figure 3. The phase space map at the betatron tune, obtained from FFT, of 3.72045. The 7-th order resonance is observed for the 512 turns plotted. The circles on the graph corresponds to the the phase space map every 68th turn. The tune is nearly equal to $3\frac{49}{68}$.

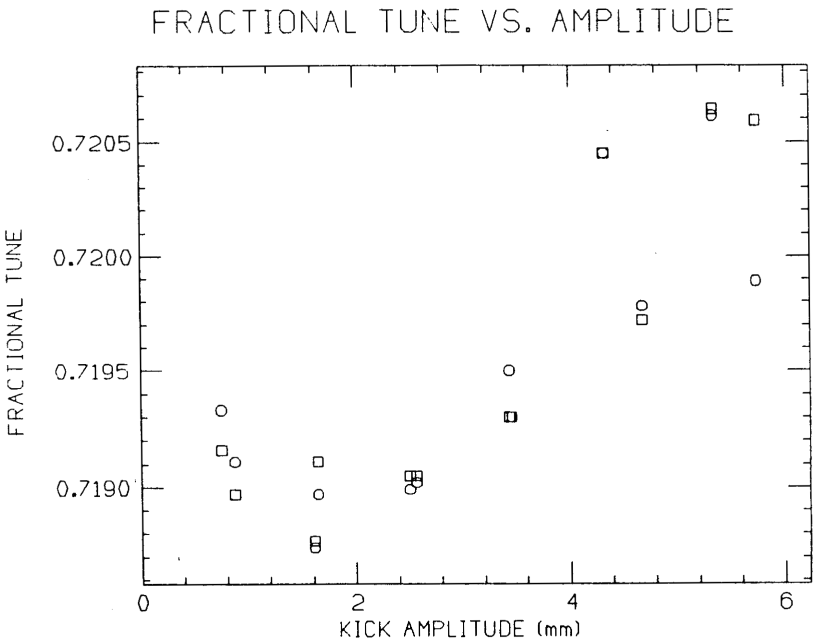

Figure 4. The betatron tune is plotted against the betatron kicked amplitude. The quadratic dependence of the tune with amplitude arise from the octupole effect of the multipoles in the Cooler Ring.

$$\nu_x = 3.7189 + 495\frac{a^2}{\beta_x}, \tag{2}$$

where a is the kick amplitude and β_x is the betatron amplitude function at the kicker location. The large dependence of the the betatron tune vs. amplitude is due mainly to possible sextupoles or higher multipoles in the Cooler Ring (during this experimental test run, chromatic sextupoles are not powered at all). By exciting the existing chromatic sextupoles in the Cooler Ring, the betatron tune shift with amplitude can be increased by a factor of 10 in comparison with the above measured tune spread amplitude, and the fourth order resonance strength can be increased by a factor of 100.

III. Conclusion

In the CE22A test run, we have successfully tested the sample and hold amplifiers, the transient recoders, and software. We have obtained preliminary Poincaré phase space maps which show interesting higher order resonance structure. Our test run indicates that some equipment modifications are required. Our next test run shall further establish the signal to noise ratio, further test the reliability of the signal processing, and explore some configurations of the sextupole setup. The betatron amplitude functions shall be measured as well.

The goals of the nonlinear experiments involve detailed phase space exploration at octupole resonance conditions, studying the effectiveness of the resonance corrections, and then the extension of these studies to higher order resonances, e.g. decapole resonances etc. Through this series of beam dynamics experiments, we hope to understand (1) detailed particle motion under the influence of high order resonances, (2) the effectiveness of resonance correction schemes, (3) the effect of dissipation vs. diffusion at the resonance condition, (4) resonance streaming and phase convection ideas, (5) the accuracy of the theoretical predictions, and (6) methods of reconstructing the invariant surface through the detailed phase space map.

1. A. Chao, *et al.*, Phys. Rev. Lett. **61**, 2752 (1988).
2. M. Cornacchia and L. Evans, Part. Accel. **19**, 125 (1986).
3. J. Gareyte, Workshop on Aperture related Limitations in Storage Rings, Lugano, (1988); L. Evans, *et al.*, The Nonlinear Dynamic Aperture Experiment in the SPS, First European Particle Accelerator Conference, Rome (1988); J. Gareyte, A. Hilaire, and F. Schmidt, Dynamic Aperture and Long Term Particle Stability in the Presence of Strong Sextupoles in the CERN SPS, Proceedings, 1989 IEEE Particle Accelerator Conference, Chicago, 1376 (1989); L. Evans, *et al.*, Beam-Beam Effect in the Strong-Strong Regime at CERN-SPS, *ibid.* 1403 (1989); and L. Evans, The Beam-Beam interaction, CERN SPS/83-38.
4. P. L. Morton *et al.*, IEEE Tran. Nucl. Sci. NS-32, 2291 (1985).
5. D. A. Edwards, R. P. Johnson, and F. Willeke, Part. Accel. **19**, 145 (1986).
6. J. Bridge *et al.*, Particle Accelerators **28**, 1 (1990).
7. R. Ruth, AIP Conf. Proc. Vol. **153**, 150 (1987); R. L. Warnock, R. D. Ruth, and K. Ecklund, IEEE Particle Accelerator Conference, Chicago, 1325 (1989).

8. A. J. Dragt, AIP Conf. Proc. Vol. **87** (1982).
9. L. Michelotti, AIP Conf. Proc. Vol. **153**, 236 (1987).
10. G. Guignard, A general treatment of resonances in accelerators, CERN 78-11, 1978.
11. Tracking codes, such as TEAPOT, RACETRACK, PATRICIA, and MARYLIE.
12. M. Ball, D. D. Caussyn, T. Ellison, B. Hamilton, N. Yoder, this report.

PRELIMINARY REPORT ON THE FEASIBILITY OF USING THE IUCF COOLER RING SYNCHROTRON AS AN ELECTRON STORAGE RING

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The IUCF Cooler Ring is a proton storage synchrotron dedicated to nuclear and particle physics research. A number of important experiments have been performed in the Cooler Ring. In recent years, electron beams in storage rings have also been widely used as an alternative probe. Having both capabilities in the same laboratory will offer great diversity in the studies of fundamental physics. Thus the adaption of the IUCF Cooler Ring to an electron synchrotron may prove to be instrumental in nuclear and particle physics research. It may also be used as a synchrotron radiation light source. Synchrotron radiation laser light from electron storage rings has been widely used in the research of basic atomic and molecular physics, condensed matter physics, material science, biological sciences, chemical science, medical science and material processing. Such a capability might reach an even broader spectrum of users at the IUCF facility. It may also be a great facility for educational purposes.

I. Introduction

The IUCF Cooler Ring is a versatile storage synchrotron. Its capability of storing and cooling light ion beams is important in the study of the proton and nuclear substructures. Alternatively, using the electron as a probe to unravel the nature of nuclear structure has also met great success. Thus studying the electron storage capability in the IUCF Cooler may be an interesting and possibly rewarding venture.

Besides the benefit of being used as a probe for nuclear and particle physics, an electron storage ring may also serve as a synchrotron radiation source. Given 1 GeV electron energy in the Cooler Ring, the critical wavelength would be in the X-ray range.