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Displaced Bunch Synchrotron Oscillation Echoes in Accelerators

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It has recently been pointed out that the echo effect, known for many years in such diverse branches of physics as nuclear magnetic resonance, plasma physics and laser physics, has a counterpart in transverse accelerator beam dynamics.[1,2] In this note, we wish to point out that the echo phenomenon may be elicited as well in longitudinal accelerator bunch dynamics, and suggest a plausible scenario for demonstrating it at the Indiana University Cyclotron Facility (IUCF) Cooler Ring.

The longitudinal echo effect operates in virtually perfect analogy with the transverse echo phenomenon described in References 1 and 2, which we now very briefly review. As is well known, a beam which is kicked off the closed orbit proceeds to undergo spiral filamentation (decoherence) in phase space in the presence of nonlinear components in the magnetic field, such as octupoles. Once the beam has thoroughly decohered, a quadrupole pulse can initiate a partial, transient reversal of that decoherence, with the partial recoherence, or echo, reaching its transient peak value the same number of turns after the quadrupole pulse as that pulse followed after the occurrence of the initial kick off the closed orbit. In the longitudinal case, a bunch which is "kicked" (*e.g.*, phase shifted) away from the center of the bucket also undergoes spiral filamentation in the phase space (at least if the feedback system is disabled) because the pendulum-like restoring force which gives rise to synchrotron oscillations is inherently nonlinear. In precise analogy with the transverse situation, once the bunch has thoroughly decohered, an RF voltage pulse can initiate a partial, transient recoherence echo, which peaks the same amount of time after the RF voltage pulse as that pulse followed after the initial displacement of the bunch from the center of the bucket. Since an RF voltage pulse in longitudinal bunch dynamics is closely analogous to a quadrupole pulse in transverse beam dynamics, it is not surprising that the normalized phase space portraits of the evolution of a longitudinal bunch synchrotron oscillation echo are essentially indistinguishable from those of a transverse beam betatron oscillation echo, examples of which are displayed in Reference 2.

We have used the longitudinal tracking code ESME[3] to try to simulate the occurrence of echoes in the IUCF Cooler Ring. Conveniently, this low-energy proton storage ring is frequently run at harmonic number unity, *i.e.*, just a single bucket, which contains the lone bunch. Much less conveniently, this bunch is normally injected into the ring in the presence of electron cooling, which stabilizes the beam, but ensures that it is space-charge dominated. Even if the electron cooling is subsequently switched off, it turns out that a space-charge dominated bunch decoheres at best only extremely slowly after displacement from the center of the bucket. Figure 1a shows the phase space portrait of a typical 45 MeV IUCF Cooler Ring bunch (whose parameters are discussed in more detail in the next paragraph) which has just been displaced 40° in phase from the center of the bucket.

With the effects of space charge suppressed, Figure 1b shows the same bunch after 140 ms, at which point the spiral filamentation is well advanced. In Figure 1c, however, the effects of space charge have been taken into account, and after the same 140 ms, we see that there is only a slight amount of filamentation. Figure 1d shows the complete decoherence history of these two cases for the first 140 ms in terms of the bunch centroid's synchrotron oscillation amplitude *i.e.*, the centroid's simple harmonic oscillator invariant) versus time. The reluctance of the case with space charge taken into account to manifest evidence of decoherence is striking. It is obviously difficult to demonstrate a recoherence echo under circumstances in which space charge effects inhibit decoherence to begin with!

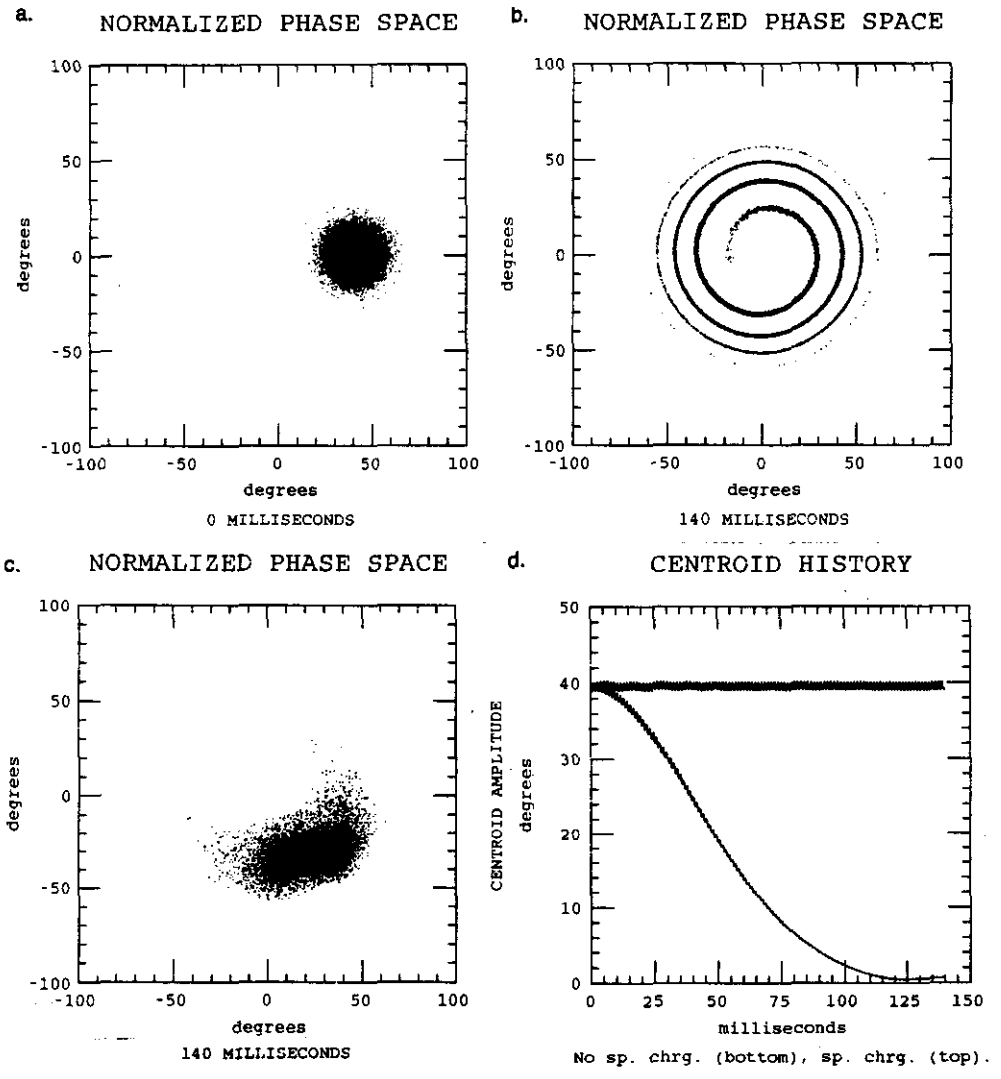

Figure 1. (a) Phase space portrait of 6.3° rms length Gaussian bunch at 0 ms, launched at 45 MeV with a 40° centroid displacement. (b) Same bunch after 140 ms, not including the effects of space charge. (c) Same as (b), but with space charge effects (bunch contains 3×10^8 protons) included. (d) Centroid synchrotron oscillation amplitude history of the bunch, the lower curve being that without the effects of space charge, and the upper curve including the space charge effects.

To remedy this state of affairs, it is suggested that a low intensity bunch be injected into the Cooler Ring without benefit of electron cooling, and then promptly accelerated to 400 MeV in order to obtain a stable beam. A coasting bunch of 3×10^6 protons at 400 MeV (instead of the 3×10^8 protons at 45 MeV typically used in conjunction with electron cooled injection) provides slightly more than 1 μA of beam current, enough to permit the phase detector to satisfactorily track the synchrotron oscillations of the bunch centroid. The rms bunch length would be made about twice that typically used at 45 MeV with cooled injection, namely 12° instead of 6.3°, and the rms transverse beam size could be expected to be about 3.4 mm rather than 0.7 mm (within a beam pipe which averages about 51 mm in diameter). The much smaller total charge of the bunch, its greater length and transverse size, and its higher energy all act to reduce the space charge effect. Since the synchrotron tune tends to decrease at the higher energy, and along with it, the effective (non-linearity induced) synchrotron tune spread which produces decoherence, we proceed to partially counteract this by increasing the RF voltage to its highest presently practical value of 400 volts, instead of the 95 volts typically used at 45 MeV. Some additional relevant parameters for the IUCF Cooler Ring are its transition gamma of 4.85 and its circumference of 86.82 m.

Under the above conditions, the bunch is well decohered about 90 ms after being displaced 40° in phase from the center of the bucket—see Figure 2a. At this point, the RF voltage is decreased from 400 volts to 200 volts for 0.081 ms (200 turns), after which it is restored to its former 400 volt value, thus producing the (negative, in this instance) RF voltage pulse which is supposed to initiate the echo. Figure 2b shows the elliptical deformation of the phase space spiral produced by this pulse. Decoherence of this elliptically deformed spiral leads, by 140 ms after the phase displacement, to the formation of the distinctive phase reversal tips mentioned in Reference 2, as seen in Figure 2c. The confluence of these tips around 180 ms, as shown in Figure 2d, comprises the echo's peak. Figure 3a displays the complete history of the echo in terms of the bunch centroid's synchrotron oscillation amplitude versus time. Figure 3b is the same as Figure 3a, except that the space charge effects have been suppressed—we see very little difference between these two cases, indicating that the measures detailed above to minimize space charge influence have been successful. It is hoped that an echo experiment along these lines can be carried out during the summer of 1993 at the IUCF Cooler Ring.

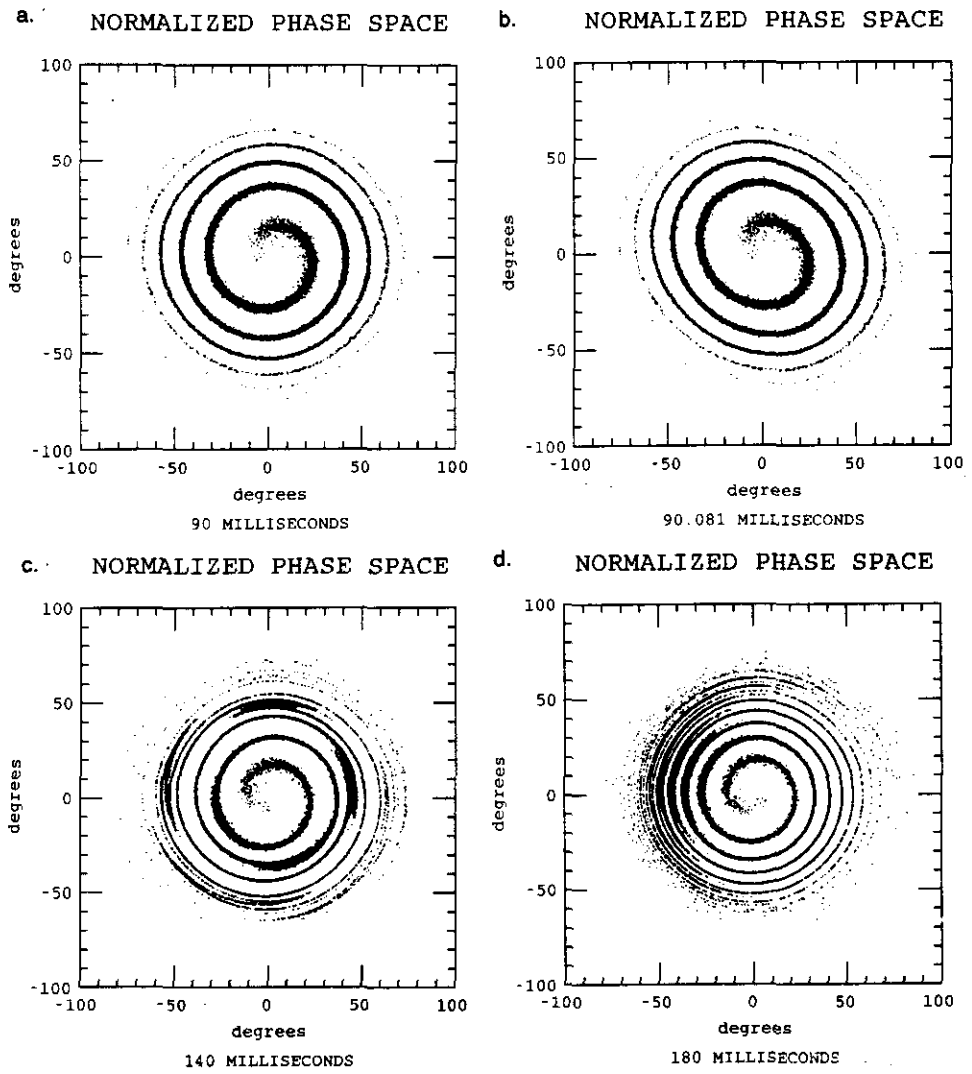

Figure 2. (a) Phase space portrait at 90 ms of a decohered bunch of 3×10^6 protons, which was launched at 0 ms at 400 MeV as a Gaussian of 12° rms length, with a 40° centroid displacement. (b) Same decohered bunch, now elliptically deformed by the negative RF voltage pulse (RF voltage was decreased from 400 volts to to 200 volts for 0.081 ms, and then restored to 400 volts). (c) Same bunch at 140 ms; it has now formed distinct, sharp phase reversal tips. (d) Confluence of the phase reversal tips at 180 ms, very near the peak of the echo phenomenon.

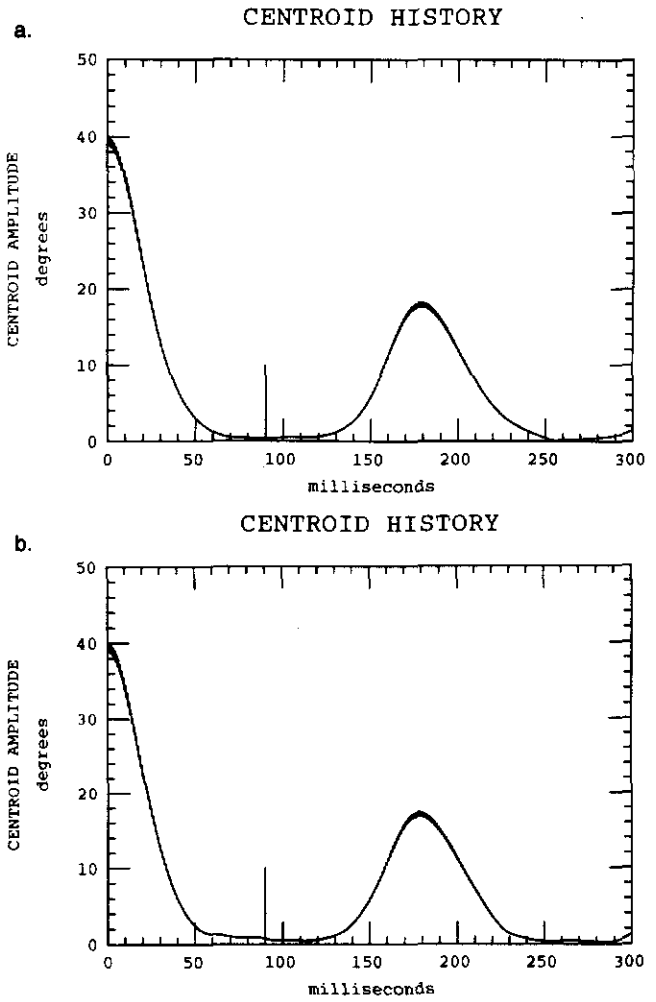

Figure 3. (a) Centroid synchrotron oscillation amplitude history of the echo which has been depicted in Figure 2 by means of selected successive phase space snapshots. Long vertical bar locates the time (90 ms) of the negative RF voltage pulse. (b) Same echo history, but with space charge effects not included.

REFERENCES

1. G. Stupakov, "Echo Effect in Hadron Colliders", SSCL Report 579, July, 1992.
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3. S. Stahl and J. MacLachlan, "User's Guide to ESME v. 7.1", Fermilab TM–1650, February, 1990.