LONGITUDINAL PHASE SPACE COMPUTER SIMULATION OF IUCF COOLER RING MULTITURN STACKING INJECTION

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An electron cooled synchrotron/storage ring with internal gas target for nuclear physics experiments has been built at the Indiana University Cyclotron Facility. The cooler ring uses the existing cyclotrons as its injector. Since the beam intensity available from the cyclotrons is about 2 μA and the polarized beam intensity is an order of magnitude less, multiturn injection accumulation is needed to achieve the desired luminosity. The electron cooled storage ring offers a special advantage in that the number of stacks is not limited by the ratio of ring acceptance and injector emmitance due to the usual incompressibility of the phase space flow. This paper discusses the longitudinal phase space computer simulation of multiturn rf stacking injection and the preliminary experimental results of stacking at IUCF.

Both the kicker magnet injection and the striping loop injection methods are used for the cooler ring. 350 μA of proton beam has been successfully stacked in the cooler ring with striping and electron cooling. The striping injection, however, does not work with the polarized beam and has other restrictions. The longitudinal rf stacking injection was therefore proposed to raise the beam intensity. The following is a brief description of the principle of operation:

The injected cyclotron beam burst has a small time spread (about 0.4 ns typical) but a relatively larger momentum spread of 0.06 % dp/p. It is injected into the cooler ring by a pair of kicker magnets and captured by a phase matched rf bucket. Inside the rf bucket, the beam undergoes a longitudinal phase space rotation for a quarter of synchrotron oscillation period, reducing its momentum spread to about 0.002% dp/p at the cost of a small phase spread. The rf bucket is then quickly shrunk to keep the rotated beam structure. After this, with the guiding magnetic field unchanged, this low momentum spread beam is decelerated by a small rf bucket to a transverse orbit sufficiently away from the injection orbit before the next kicker injection. Electron cooling energy is set adjacent to this transverse orbit and, while rf continues to bring more and more bunches of beam to the orbit, the electron cooling force gradually cools the particles into a very low emmitence beam.

A quantitative study of this longitudinal phase space beam manipulation method is necessary to determine the basic rf control parameters. Effects such as oscillatory ripples on the cooling stack orbit due to the debunching rf voltage, finite slew rate of rf modulations and compromised choices of bucket height, debunching linearity and deceleration speed need to be considered. For this purpose, a longitudinal phase space computer simulation program was introduced by Robert E. Pollock at IUCF and research on rf stacking with varied rf parameters was carried on by the author.

The equations of general longitudinal motions are:

$$d(\phi - \phi_r)/dt = h\omega - \omega_r \qquad (1)$$

$$dp/dt = -(eV/2\pi R) \sin(\phi - \phi_r) \qquad (2)$$

where
ω_r is the ring rf frequency;
ω is the particle fundamental revolution frequency;
h is the ring harmonic number;
$2\pi R$ is the ring circumference;
ϕ_r is the rf phase;
ϕ is the particle phase;
$\phi - \phi_r$ is the effective rf phase seen by the particle.

Since $d\phi_r/dt = 0$ except for a phase transition in the stacking process, we can approximate the first equation by:

$$d\phi/dt = h\omega - \omega_r. \qquad (1')$$

For the second equation, we expand about a given momentum p and use the relation

$$\Delta f/f = \eta \, \Delta p/p \qquad (3)$$

to reformat it in terms of frequency, where $\eta = (1/\gamma^2 - 1/\gamma_t^2)$ is treated as a constant for our problem.

This leads to:

$$d(\Delta hf)/dt = -f_s^2 \sin(\phi - \phi_r) \qquad (2')$$

where $f_s^2 = f^2 \, (heV\eta \, / \, 2\pi\beta^2\gamma m_o c^2)$ is the synchrotron oscillation frequency squared for near synchronous particles.

Integrating equations (1') and (2') using second order symplectic method, we can track and study particle motions under rf field force.

Introduced on a Macintosh computer, the code was revised to run on a VAX computer to take advantage of its speed to gather a greater number of data. On the other hand, the personal computers' easy access to graphics continued to interest us to make animated graphics simulation of the stacking process that could be visually interpreted at a reasonable calculation speed. The graphics simulation results presented in this paper were obtained from IBM PC computers or compatibles using Borland International's Turbo Pascal.

In the following figures, the horizontal axis is the particle phase ϕ and the vertical axis is deviation Δhf from the ring harmonic rf frequency at injection in unit of debunching synchrotron oscillation frequency f_s. Six to seven particles corresponding to the injector momentum spread are placed on the initial orbit.

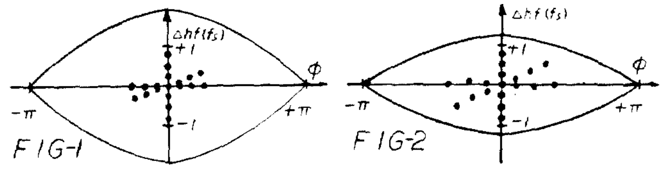

Fig-1 and Fig-2: The injected particles are represented by seven dots on the vertical axis. The size of the stationary debunching rf bucket is shown. Two snapshots thereafter track the synchrotron rotation of the particles. With appropriately chosen debunching parameters, the initial frequency spread that corresponds to injection momentum spread is transformed to a phase spread. Non-linearity effect intrinsic with the equation of motion is obvious when the debunching rf bucket is too

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small or the rf amplitude turn-off is too slow, as indicated by the slight "S" shape of the debunched beam in Fig-2. This needs to be avoided since it leads to phase space dilution and increases the momentum spread of the debunched beam.

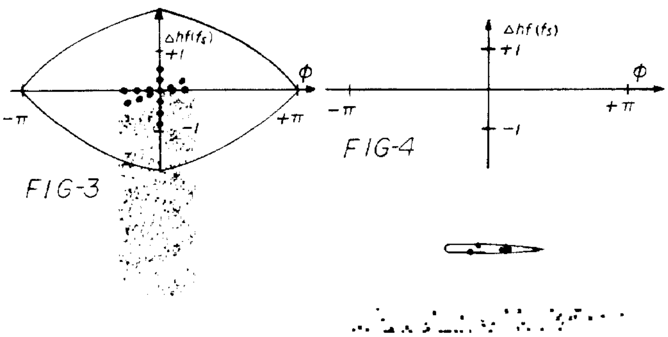

Fig-3: During deceleration with a small rf bucket, the synchronous beam phase shifts significantly with respect to rf phase and the beam bunch length $\Delta\phi$ for stable motion becomes much shorter. Therefore, it is important to compensate the phase shift with a corresponding rf phase shift. The dotted lines tracing the phase motion of the decelerated particles study the effects of rf amplitude, phase shift and frequency sweeping rate during deceleration.

Fig-4: With minimized debunching rf agitation and time integral of cooling force, the beam particles start to accumulate on the cooled band as indicated by the dense number of particles on the frequency corresponding to the electron cooling energy. In the middle of the picture, six more representative particles are being decelerated in a much reduced moving bucket into the lower momentum transverse orbit near the cooling band.

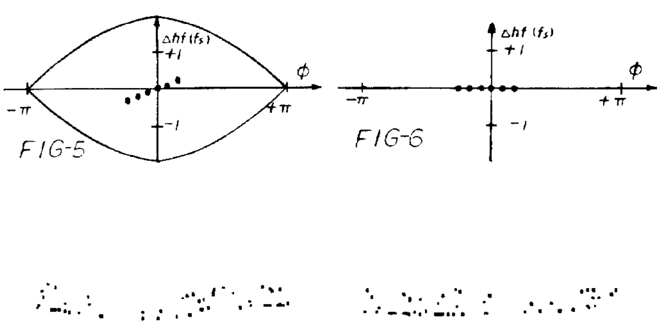

Fig-5 and Fig-6: The heating effect of the high amplitude debunching rf is illustrated by the warping of the beam particles at or near the cooling band in Fig-5. This effect, which involves oscillatory motion, can be minimized by letting the oscillation undergo near an integer number of periods and return the phase close to the initial value. With properly chosen rf on-time at debunching voltage, the agitating effect shown in Fig-5 undoes itself once the debunching rf is over as shown in Fig-6. Since the rf time durations required to rotate the beam and to minimize the heating effect on the cooled stack are different, an additional rf on-time at the debunching voltage before the kicker injection, called precursor period, is added.

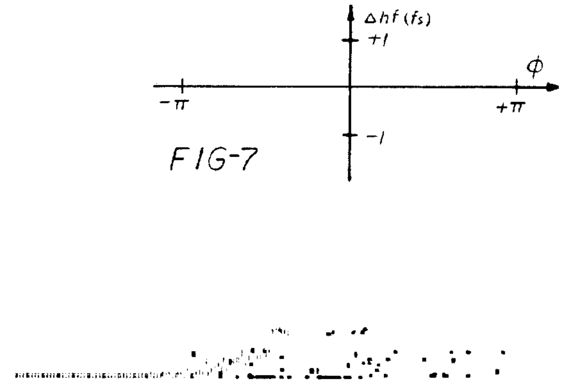

Fig-7: Successfully stacked cooled band occurs soon with optimized stacking parameters. A histogram consisting of small vertical bars on the lower left corner shows the particle momentum spread at the end of the program execution. Each vertical bar represents a particle being stacked and its vertical axis is the same as that of the rest of the picture. The horizontal position of the histogram represents the arrival sequence of the stacked particles, with the earliest particles on the left and the latest particles on the right. It is shown that all but the latest 7 injections have been cooled.

Based on the computer simulation, rf and control design parameters were specified and hardware and software for the rf stacking operation have been developed. For example, the rf amplitude control servo loop was designed with a dynamic range of 40 dB and response time less than 10 μs without overshooting. The following is a brief description of the status of the IUCF cooler rf stack injection project.

Due to the time engineering development takes, we have had about only 10 hours of stacking beam test experience with the basic electronics functional at the time of this writing. A 120 MeV polarized proton stacking test run was conducted recently and some interesting photos and plots were copied from the run log book. The simulation program generated a set of basic control parameters for us to start with. The initial effort was concentrated on seeing that the first turn of the kicker injected beam could be moved sufficiently away by rf deceleration and survive the second kicker fire that brought in the next turn of injection. When this was verified, we proceeded with more turns of injections.

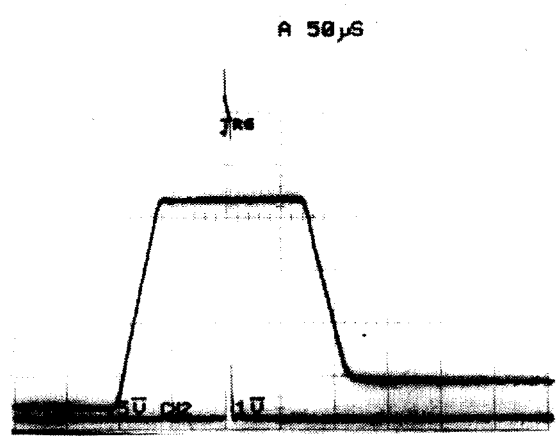

Fig-8: The rf amplitude control is matched with the kicker firing (the center spike). In the precursor period before the kicker injection, the rf cavity voltage rises in 40 μs from about 0 to 1330 volts and flattops for 65 μs. After the kicker firing the cavity voltage lasts for another 65 μs and then rolls down to a small voltage in 40 μs to debunch the beam.

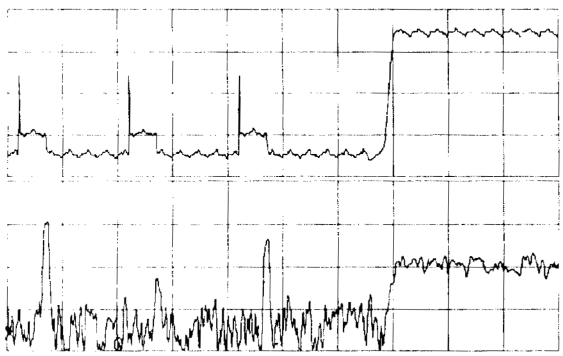

Fig-9: The double trace storage scope picture shows our test procedure. The top trace is the rf amplitude. The spikes correspond to the precursor and debunching rf amplitude. The following small step is the period when the rf cavity frequency is lowered and the injected beam is decelerated. The rf is then turned off to let the frequency and phase return to the injection value. After several cycles, the rf is turned on at the stack frequency to adiabatically capture the stacked beam into rf buckets for viewing. The time scale of the scope is 50 ms/div. The injection repetition rate was mainly restricted by the kicker electronics dissipation limit at the time. According to the computer simulation, 50 injections per second rate is possible.

The lower trace is the video output of a spectrum analyzer monitoring the wall gap beam monitor signal. The spectrum analyzer is tuned at the stack frequency. The spikes correspond to the decelerated beam just before losing the rf structure. The final step is the signal from cooled stack recaptured by rf.

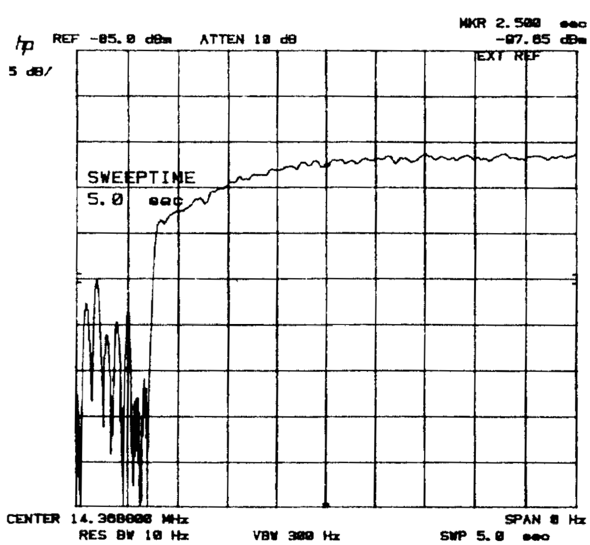

Fig-10: The spectrum analyzer plot shows that after seven injections, there is a gain of intensity. The slow rising pattern of intensity and the long beam life are a demonstration of the beam being successfully cooled.

Summary: The computer simulation is very helpful to gain a quantitative understanding of rf stacking and is instrumental in specifying software and hardware parameters. Transverse effects are not included in the simulation and will be optimized in the future beam tests.

During the 120 MeV polarized proton test, about 50 nA of beam was stacked and cooled with six turn injections. This reflected a gain of two from the kicker injected intensity at the time. Significant beam loss was incurred during injection and deceleration due to the lack of time to do any optimization. The steady growth of intensity with more turns of injection was not observed. This was an indication that the stacked beam could only survive a limited number of kicker firings. Better matched kickers will minimize the transverse heating during injection in our future runs.

Acknowledgements:

The author wishes to thank Professor Robert E. Pollock for introducing the rf stack computer simulation program and directing author's stacking research project.

References:

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