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"SLIP-STACKING": A NEW METHOD OF MOMENTUM-STACKING

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I. Introduction

A new method of momentum-stacking, with several advantages for injection into the Main Ring and into the Energy Doubler, is proposed. The method uses the different revolution frequencies of two beams of different momenta, as follows. First, part of the circumference of a ring is filled with beam in the usual manner, leaving a gap for later injection of additional beam. Then the beam is accelerated or decelerated to a slightly different momentum, adiabatically debunched, and left to coast on a stacking orbit. Next, additional beam is injected into the azimuthal gap in the coasting beam and held at the injection momentum in stationary RF buckets. The momentum difference between the two beams is chosen so that by the time the injector is ready to inject more beam, the difference in revolution frequencies of the two beams has caused one beam to "slip under" the other azimuthally. Thus the gap into which beam is injected has reappeared. When two beams of equal length have been created, the bunched beam is ac(de)celerated and deposited adjacent to the coasting beam in momentum. If greed sets in, the process can be repeated. Finally the coasting beam is recaptured adiabatically by the RF and accelerated in the usual manner.

This method has two major advantages over other momentum-stacking methods for Fermilab accelerators. First, no modifications to injection systems are required. Second, the momentum difference between injected and stacked beam is smaller, allowing both to fit into the available apertures in the Main Ring and the Energy Doubler.

The requirements and limitations can be summarized as follows. The cycle time and beam length of the injector must be short compared to those of the destination ring. The momentum difference between the two beams must fit into the available aperture. The momentum spread of the stack must be small enough so that the coasting beam does not lengthen too much. The RF required to hold, decelerate, and debunch the injected beam must not disturb the stack too much. Finally, the machine must be able to accelerate the beam in the face of higher intensity (space charge limit, instabilities) and perhaps greater longitudinal emittance (available RF, losses at transition energy).

The rest of this document addresses some of these questions for the particular cases of injecting from the Booster to the Main Ring and from the Main Ring to the Energy Doubler.

II. Discussion

The fractional momentum difference $\Delta p/p$ required to cause azimuthal slippage $\Delta\theta$ or length slippage Δs in a ring of circumference C and revolution frequency f_{rev} during one injector cycle time T_{cyc} is given by

$$\frac{\Delta p}{p} = \frac{1}{\eta}\left(\frac{\Delta\theta}{\theta}\right),$$

where

$$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_t^2},$$

$$\Delta\theta = 2\pi\,\Delta s/C,$$

$$\theta = 2\pi f_{rev} T_{cyc}$$

Substituting, we find that

$$\frac{\Delta p}{p} = \frac{\Delta s}{\eta C f_{rev} T_{cyc}}$$

For injection from Booster to Main Ring, I assume slippage by one Booster batch length per Booster cycle. For injection from Main Ring to Energy Doubler, I assume that four Booster batch lengths will be injected simultaneously with a 2 second cycle time, and so require slippage by four Booster batch lengths. The results are $\Delta p/p$ = 0.292% for Booster to Main Ring injection, and 0.113% for Main Ring to Energy Doubler injection. For comparison, previous momentum-stacking schemes into the Main Ring required a momentum separation of almost one percent(1) or 0.47%.(2) Old measurements found Main Ring momentum acceptances (full width at half maximum) of 0.44% to 0.66% at 8 GeV.(3)

Conventional momentum-stacking requires enough radial aperture to accommodate the horizontal betatron oscillation amplitudes and momentum spreads of both beams, separated by a shutter or septum. Obviously no such requirements apply to the new method. The momentum dispersion function is typically 3 meters in the Main Ring, with a maximum of 5.85 meters. The momentum difference of 0.292% then corresponds to a radial separation of typically 8.76 mm between the two beam centroids in Main Ring, with a maximum separation of 17.1 mm. If the Energy Doubler lattice is not too different, typical radial separations of 3.4 mm can be expected, with a maximum of 6.6 mm.

The coasting stack will start to spread azimuthally due to its own momentum spread as soon as the RF is no longer holding it in place. The stack momentum spread would be simply related to the original longitudinal emittance of the beam if there were no dilution during the RF gymnastics. The longitudinal emittance of the Booster beam depends on its intensity and on other complicated factors. A typical value at moderate intensity is about 0.06 eV-sec, corresponding to $\Delta p/p = \pm 1.8E-4$. Even assuming moderate 50% dilution, this is only about 10% of the momentum difference between bunched and coasting beam. Thus the ends of the stack will migrate into the gap by 10% of a Booster batch length per Booster cycle. If this turns out to be a problem, there is a possible solution: the stack can be held in place azimuthally by a small RF system.(4)

Presently, the Main Ring RF system runs at about 1 MeV/turn during injection. The corresponding half-height of the bucket is $\Delta p/p = 0.26\%$. This is uncomfortably close to the edge of the stack. So it would be nice to turn down the RF voltage at injection. But the voltage is determined by matching to the shape of the Booster bunch, which in turn is governed by the Booster RF. Turning down the Booster RF makes it more difficult to phase-lock for synchronous transfer from Booster to Main Ring. So ultimately a better phase-lock system may be required. But for now, turning down the Main Ring RF and living with the mismatch might be necessary.

The synchrotron frequency at injection is about 600 Hz. However, it is necessary to reduce the voltage during the stacking process in order to debunch adiabatically, thereby also reducing the synchrotron frequency. In this note I assume that the process of decelerating, stacking, and reestablishing a stationary bucket at the injection momentum can be accomplished in two Booster cycles, a time long compared to the synchrotron period.

Injection for the Main Ring fixed-target program then would proceed as follows:

1) Inject 11 or 12 Booster batches into stationary buckets in the normal fashion.

2) Decelerate, adiabatically debunch, and deposit this beam on the stacking orbit during two Booster cycles. Inhibit one Booster batch during the RF gymnastics.

3) Inject 13 more Booster batches into the azimuthal gap.

4) Decelerate, adiabatically debunch, and deposit this beam next to the previously stacked beam.

5) Recapture the stack adiabatically and accelerate in the usual fashion.

For production of antiprotons, it should be possible to superimpose two or more individual Booster batches into a beam of Booster batch length without lengthening the Main Ring cycle time very much. Whether the antiproton collection rate would thereby be enhanced depends on several factors: the longitudinal emittance of the Main Ring beam, target heating, the available stochastic cooling power, etc.

For the Energy Doubler fixed target program, the following injection scheme could be used:

1) Inject and stack a beam of eight Booster batch lengths.

2) Inject three cycles of four Booster batch lengths each into the azimuthal gap.

3) Debunch and stack the bunched beam next to the coasting beam.

4) Recapture the stack adiabatically and accelerate.

Each of these Main Ring beams, in turn, could have been formed by momentum-stacking from the Booster. The Energy Doubler filling time for four Main Ring cycles would be about ten seconds; the total number of Booster batches injected in this example is forty.

Clearly the potential intensity gains are large. Whether the potential can be realized depends on several factors. In the Main Ring, we may already be close to the incoherent space-charge limit or to other intensity-dependent instabilities. It may be difficult to accelerate through transition with the longitudinal emittance resulting from the stacking process. However, the emittances of the Booster beam in all three planes grow rapidly with intensity,(5) so it is possible that stacking beams of moderate intensity may produce a brighter beam. The real payoff may occur in injecting into the Energy Doubler, where the above limitations do not apply.

The required RF gymnastics can be accomplished by a separate low-level RF system without disturbing the existing system. Construction of this separate system will be greatly facilitated if MRRF spare modules can be used. The feasibility of producing more than 13 consecutive Booster batches was examined some time ago when Rol Johnson was in charge of the Booster and no fundamental limitations were found. However an upper limit of 13 batches is presently imposed in several places in hardware and software; these limits must be found and removed. It seems

relatively easy to inhibit the Booster beam for one cycle in the middle of many; I have not yet looked into how easy it is to inhibit the Main Ring injection kicker for one cycle in the middle.

Simulations of the RF stacking process are presently getting underway. However there is really no substitute for a careful, well-planned trial of the method during dedicated accelerator study time. The scheme seems promising enough that preparations for such a trial should commence immediately with high priority, and testing with beam should occur as soon as preparations are complete. Of course, initial tests would be carried out at modest intensity with a total of 13 or fewer Booster batches.

III. Acknowledgements

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IV. References

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