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INJECTION INTO THE ISA*

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Abstract

Three modes of injection into the ISA storage accelerators are discussed. The three are: 1) Energy stacking in the ISA. 2) Acceleration of 12 bunches in the AGS followed by single bunch transfer to the ISA. Application of a moving bucket technique then allows the transferred bunch to be brought closer to the bucket train circulating in the ISA. 3) Acceleration on the first harmonic in the AGS. The single bunch is then transferred directly to the ISA into a matched bucket.

1. Introduction

In the Intersecting Storage Ring Accelerators ISABELLE,[1] which have recently been proposed at Brookhaven, protons are injected from the AGS at 30 GeV and accelerated to 200 GeV. High luminosities are achieved by storing beam currents of the order of 15 A. Considering that the anticipated current in the AGS is 1.2 A and that the ISA circumference is three times the AGS circumference, $\sim$ 36 AGS pulses have to be injected to reach such an intensity.

It is proposed that the rings be filled by stacking in longitudinal phase space. This does not only reduce aperture requirements but also gives maximum luminosity if the beams in the storage rings will be coasting. In that case, assuming zero dispersion in the interaction region, the only luminosity determining beam parameter in addition to current is the transverse emittance, which will be minimum if the beam is stacked in longitudinal phase space only.

Several longitudinal stacking methods have been proposed involving either azimuthal or energy stacking. They will be described in this paper and comparison between them will be made. Considerations entering the choice of suitable criteria, by which the methods should be judged, will be briefly mentioned.

2. 30-GeV Beam Parameters in the AGS

At the end of the accelerating cycle, i.e., at flat top, in the AGS, the beam is expected to have the following longitudinal characteristics:

Number of bunches:	12
Bunch half width:	9.8° (rf degrees)
	0.82° (angular length)
Momentum half width:	5.8×10^{-4}
Distance between bunches:	67 m
Total number of particles:	2×10^{13} (1.2 A)

The rf parameters are:

Peak voltage per turn:	360 kV
Frequency:	4.45 MHz
Harmonic number:	12

3. Azimuthal Stacking

Three different azimuthal stacking methods have been proposed by which consecutive AGS bunches are stacked box-car type fashion around the ISA circumference. Both single and multiple bunch extraction in the AGS have been considered.

a) Single bunch extraction (one bunch per AGS pulse). Originally it was proposed by Blewett[2] that the 12 bunches in the AGS be bunched into a single bunch by a sawtooth oscillator operated on the fundamental frequency of the AGS. This would avoid the use of extraordinarily fast kickers needed to deposit the individual bunches right next to each other in the ISA. To minimize the width of the single bunch it was suggested that the beam be adiabatically debunched before rebunching into a single bunch takes place. However, the adiabatic debunching would result in such a small momentum spread that unreasonably low coupling impedances would be required in the AGS to avoid longitudinal instabilities.

An alternate way of forming a single bunch in the AGS is to accelerate with an rf system operating on the fundamental frequency of that machine.[3] A single bunch, whose angular length equals the total angular length of the 12 individual bunches can be obtained if the rf peak voltage per turn is one-twelfth of that used in the present 12th harmonic system (30 kV) and the synchronous phase of 150°, used with that system is maintained. The momentum spread of the single bunch equals the momentum spread of the 12 bunches under these conditions. The choice of 30 kV lengthens the acceleration cycle by a factor of 12. A shorter cycle can be achieved without changing the beam characteristics by going to 50 kV and a synchronous phase of 120°.

To be able to stack as many AGS pulses as possible into the ISA it was also proposed to further compress the beam azimuthally by the presently used 12th harmonic rf system. Taking full advantage of the voltage capacity of that system the bunch length can be reduced by a factor of 3.7 by adiabatic bunching.

The beam bunch can now be injected into the ISA, by use of rather conventional kickers, and captured in ISA rf buckets. Allowing for a kicker rise time of $\sim$ 40 nsec a maximum of 90 such bunches can be stacked in the ISA.

b) Multiple bunch extraction (12 bunches per AGS pulse). Azimuthal stacking in the ISA can also be accomplished by a method suggested by Blewett and Cottingham.[4] The 12 bunches obtained with the existing 12th harmonic rf system are extracted from the AGS at a time interval of 80 msec, allowing the use of an already developed kicker technique. The procedure can be described in the following way: A bunch from the AGS is transferred into the ISA. As soon as the kickers in the AGS and ISA recover, another bunch is extracted from the AGS and deposited in the ISA as close as possible ($\sim$ 100 nsec) to the previous bunch. By application of the moving bucket techniques suggested by Cottingham,[5] the second bunch is moved as close as is desired to the first bunch. The process is continued until all twelve bunches have been transferred. They will be held in a close sequence in the ISA by the ISA's rf system which

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is to generate a train of waves of the same length as the sequence of stacked bunches. The procedure is repeated on subsequent AGS pulses until both ISA rings are filled except for a short vacant portion after the last bunch. This unfilled region corresponds to the rise and fall time of the ISA kicker and occupies less than 3% of the ISA circumference. A maximum of 54 AGS pulses can be stacked in the ISA by this method assuming no space between adjacent bunches.

4. Energy Stacking

Energy stacking, the injection scheme presently employed in the CERN ISR, involves moving an injected beam pulse by rf acceleration across a septum into an area where the beam is parked. The septum protects the stored beam from the injection kick. This method can be adapted for the ISA in the following way[6]: With an ISA circumference three times the AGS circumference, three AGS pulses, consisting of 36 bunches, are injected into the ISA by direct transfer. The 36 bunches are captured in buckets of an rf system, operating at the 36th harmonic frequency at the ISA, and moved by acceleration from the injection orbit into the parking orbit. The entire procedure can be repeated many times with the dilution in longitudinal phase space depending on the various parameters for the stacking process - for example, the voltage turn-off time, the rate of acceleration through the stack, and the degree of penetration of the stack. In order to minimize the amount of acceleration required to park the beam stack at a suitable distance away from the injection orbit at the kicker position, the injection area has to be designed (1) with a large X_p function (~ 4 m), so that a large movement of the beam can be made with a relatively small momentum change, and (2) with a small horizontal β-function (~ 10 m), so that the amount of beam movement needed to keep the stack and injected beam separate is as small as possible. An injection insertion, fulfilling these conditions, has been designed[7] and incorporated into the ISA lattice.

5. Comparison of Methods

There are many aspects in which the different injection methods can be compared. A few of these will be mentioned here.

Qualitatively the following should be pointed out: While energy stacking and azimuthal stacking by 12 bunch extraction do not require any modification in the AGS, acceleration on the AGS fundamental frequency involves a straightforward but major engineering effort in that machine. Only energy stacking requires a specially designed injection insertion in the ISA. Such an insertion has been designed and does not seem to cause any problems regarding the lattice structure.

The amount of hardware required in the different schemes is somewhat different but comparable. All three methods require fast kickers. The single bunch extraction method calls for a new rf system in the AGS, while the energy stacking scheme needs a special rf system for acceleration into the parking orbit. The 12 bunch extraction method requires pulse excited cavities, but these would also be used for acceleration to 200 GeV.

Finally the energy stacking method possesses a certain amount of flexibility in beam handling that the other two schemes do not have. Because of the unlimited number of AGS pulses that can in principle be stacked by this method longitudinal stacking can be combined with transverse shaving to achieve high transverse beam densities needed to improve the luminosity.

Quantitatively the three methods will be compared with respect to maximum number of stacked AGS pulses, stacking time, phase space dilution and momentum spread during stacking. Although it was assumed here that 36 AGS pulses have to be stacked into each ISA ring to achieve the design current of 15 A, it is worth mentioning that higher intensities can in principle be reached with all three schemes. Alternatively, if the beam current of 1.2 A cannot be obtained in the AGS, more than 36 AGS pulses are necessary to achieve 15 A in the ISA. The following table shows the maximum number of AGS pulses that can be stacked in each ring by the different methods:

Azimuthal Stacking		Energy Stacking
One bunch extraction	12 bunch extraction	
90	54	Unlimited

The time it takes to charge the rings will be made up by the acceleration time in the AGS and the stacking time in the ISA. In the azimuthal stacking methods the time is almost completely taken up by acceleration in the AGS. In the energy stacking method additional time is taken up by stacking in the ISA. However, neither of the described methods require more than a few minutes to stack each of the ISA rings.

Experience with the energy stacking method at the ISR has shown that some longitudinal phase space dilution takes place. A dilution factor of 2 is quoted. It is not unreasonable to assume that similar dilution will take place with the azimuthal stacking methods. Specifically, if the distance between adjacent bunches in the ISA is small, some phase space dilution will be introduced by synchrotron motion in the nonlinear parts of the rf buckets.

The momentum spreads obtained during stacking, acceleration and storing will very possibly be the most important considerations in evaluating the various injection schemes. This is because to ensure damping of longitudinal instabilities the momentum spread has to be larger than a specified minimum value. For a coasting beam the following relation has to hold between the momentum spread, $\Delta p/p$, and the coupling impedance Z_k (in ohms), corresponding to the kth harmonic frequency:

$$\left| \frac{Z_k}{k} \right| \leq \frac{E}{e} \frac{\eta}{I_o} \left(\frac{\Delta p}{p} \right)^2 .$$

Here E is the total energy of the beam,

$$\eta = \frac{1}{\gamma_{tr}^2} - \frac{1}{\nu^2} ,$$

and I_o is the beam current (in amperes).

In order to get an estimate of the required momentum spread in case of a bunched beam, this formula can be used if one replaces the average current I_o with the peak current. Assuming $|Z_k/k| \sim 10\ \Omega$ and an average current of 15 A, one can calculate the momentum spread that is required by each method to suppress longitudinal instabilities during stacking. The results are shown in Table I together with anticipated momentum spreads based on 36 injected AGS pulses and a longitudinal phase space dilution factor of 2.

During acceleration and at 200 GeV the momentum spread will be determined by the rf voltage and harmonic number of the accelerating rf system. With the energy stacking method, the beam which is coasting in the parking orbit, has to be rebunched before acceleration. There are no immediate constraints in this case on the choice of the frequency of the accelerating rf system,

TABLE I

$\Delta p/p$	Azimuthal Stacking: One bunch extraction	Azimuthal Stacking: 12 bunch extraction	Energy Stacking
At beginning of stacking:			
Required $\left(\left\|\frac{Z_k}{k}\right\| = 10\ \Omega\right)$	$\pm 3.7 \times 10^{-3}$	$\pm 1.9 \times 10^{-3}$	$\pm 4.5 \times 10^{-4}$
Anticipated*	$\pm 3.1 \times 10^{-3}$	$\pm 8.1 \times 10^{-4}$	$\pm 5.4 \times 10^{-5}$
At end of stacking:			
Required $\left(\left\|\frac{Z_k}{k}\right\| = 10\ \Omega\right)$	$\pm 3.7 \times 10^{-3}$	$\pm 1.9 \times 10^{-3}$	$\pm 1.6 \times 10^{-3}$
Anticipated*	$\pm 3.1 \times 10^{-3}$	$\pm 8.1 \times 10^{-4}$	$\pm 6.4 \times 10^{-4}$

*For a bunched beam the momentum spread is multiplied by $\sqrt{2}$ for phase space dilution of 2.

which is another aspect of flexibility in the energy stacking method. In the azimuthal stacking methods the buckets of the accelerating rf system have to conform to the already existing beam bunches. Further study of longitudinal instabilities of bunched beams is required to determine the proper characteristics of the ISA accelerating rf system.

6. Summary

Three longitudinal phase space stacking methods for injecting AGS pulses into the ISA have been described. The three schemes, employing either azimuthal or energy stacking, all seem to yield satisfactory stacking times and efficiencies.

The different methods result in unequal momentum spreads during stacking. The momentum spread is smallest in the energy stacking scheme for which the tolerable coupling impedance is of the order of 1 Ω for the fundamental frequency ($k = 1$). Of course, a higher coupling impedance can be tolerated by inducing a momentum spread dilution in the beam.

During acceleration and at 200 GeV the momentum spread of the beam will be determined by the voltage and harmonic number of the ISA accelerating rf system. Further studies, exploring the conditions under which a bunched beam becomes unstable, will determine the required characteristics of this rf system. In turn, this rf system will establish definite requirements for the injection scheme.

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