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Informal Report

INTERSECTING STORAGE ACCELERATOR NOTES

INJECTION INTO ISABELLE AFTER ACCELERATION
ON THE FUNDAMENTAL FREQUENCY IN THE AGS

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Abstract

Acceleration on the fundamental frequency in the AGS is suggested in order to form a single bunch in that machine. The bunch can be further compressed after acceleration by the use of the existing twelfth harmonic rf system. The procedure allows for azimuthal stacking of 90 AGS pulses in ISABELLE.

1. Introduction

The box car type stacking method, first suggested by Blewett¹ and adopted in the Preliminary Design Study² for injection into ISABELLE suffers from the disadvantage of involving adiabatic debunching in the AGS after acceleration, before rebunching it into a single bunch. The small energy spread that would exist at the end of the debunching process enhances longitudinal instabilities. Also, adiabatic debunching implies going down to extremely low voltages (~ a few volts) on the rf cavities, whereby beam loading effects become rather serious. Furthermore, a longitudinal phase space dilution factor of about 5 is introduced by the beam gymnastics connected with this method.

It is the purpose of this note to suggest a modified "Grey Book" injection method. By capturing and accelerating the beam in the AGS on the first harmonic frequency, a single bunch would be formed right after injection and maintained from then on. At the end of the acceleration cycle, the bunch would be further compressed azimuthally by adiabatic bunching by the existing 12th harmonic rf system. It would thereafter be transferred and matched into rf buckets in ISABELLE. The procedure, which allows for stacking of 90 AGS pulses into ISABELLE, avoids the difficulties of the "Grey Book" scheme.

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1. J. P. Blewett, BNL Accelerator Dept. Report AADD-169 (CRISP 71-6), 1971. See also E. D. Courant, CRISP 71-5, 1971.
 2. 200-GeV Intersecting Storage Accelerators, ISABELLE, A Preliminary Design Study, BNL 16716, 1972.

2. Acceleration on the Fundamental Frequency in the AGS

The choice of rf parameters required for acceleration on the fundamental frequency in the AGS was aimed at producing a single bunch whose angular length was equal to the total angular length of the 12 bunches in the Grey Book scheme. Assuming the same total longitudinal phase space area, the momentum spread of the single bunch would be that of the 12 bunches in the Grey Book.

The momentum spread of a bunch is given by:

$$\frac{\Delta p}{p} = \left(\frac{v_s}{\eta} \frac{S_B}{\pi R p} \right)^{\frac{1}{2}},$$

where S_B is the invariant longitudinal phase space area of the bunch, v_s equals

$$\left(\frac{h e V \cos \varphi_s \eta}{2 \pi E} \right)^{\frac{1}{2}}$$

and

$$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_{tr}^2}.$$

Here h is the harmonic number,
 V is the peak rf voltage per turn,
 φ_s is the synchronous phase,
 E is the total energy,
 R is the radius of the machine.

Noting that $S_B = S_t/h$, where S_t is the total longitudinal phase space area, one can easily see that

$$\frac{\Delta p}{p} = \left(\frac{e V \cos \varphi_s}{h \eta 2 \pi E} \right)^{\frac{1}{2}} \left(\frac{S_t}{\pi R p} \right)^{\frac{1}{2}} \quad (1)$$

Going from one rf system with harmonic number h_1 to another rf system with harmonic number h_2 , one can obtain the same momentum spread provided that:

$$\frac{v_1}{h_1} \cos (\varphi_s)_1 = \frac{v_2}{h_2} \cos (\varphi_s)_2,$$

where V_1 , $(\varphi_s)_1$ and V_2 , $(\varphi_s)_2$ are the peak voltages and synchronous phases of the two rf systems.* Therefore, using a first harmonic rf system with a peak voltage per turn equal to one-twelfth of that in the existing AGS rf system and keeping the same synchronous phase one gets a single bunch which at 30 GeV has an angular length of $\pm 10^\circ$ and $\Delta p/p \pm 6 \times 10^{-4}$. The time required to accelerate from 200 MeV to 30 GeV would accordingly increase from 0.5 to 6 sec.

A shorter acceleration time could be achieved by going to a smaller synchronous phase and increasing the voltage to a practical limit imposed by the low frequency rf system. Adopting a peak voltage per turn of 50 keV, a synchronous phase of 120° is required in order to maintain the ratio $V \cos \varphi_s/h$. However, for this choice of values for V and φ_s , the rf bucket will not be sufficiently large to contain the beam at and near injection. One would start out accelerating at a higher synchronous phase of $\sim 135^\circ$ and as the bucket grows with acceleration, φ_s could be reduced slowly. $\varphi_s = 120^\circ$ can be reached for $\gamma \sim 2.4$. The time required to accelerate from $\gamma_i = 2.4$ to $\gamma_f = 32$ is given by

$$T = \frac{(\gamma_f - \gamma_i) M_0 c^2}{V \sin \varphi_s} \cdot T_{\text{rev}}$$

With

$$\begin{aligned} V &= 50 \text{ keV} \\ \varphi_s &= 120^\circ \\ T_{\text{rev}} &\sim 2.67 \times 10^{-6} \text{ sec} \end{aligned}$$

one obtains $T \sim 1.7 \text{ sec}.$

The first part of the acceleration cycle is $\sim 0.15 \text{ sec}.$ Allowing time

* This also holds for the momentum spread at transition.³⁻⁵ Furthermore, the space charge parameter defined as the ratio of the space charge defocusing force to the rf focusing force is governed by the combination of parameters

$$\frac{V \cos \varphi_s}{h} \cdot (\cot \varphi_s)^{\frac{1}{2}}$$

at transition.⁵

3. E. D. Courant and H. S. Snyder, Ann. Phys. 3, 1 (1968).
4. J. C. Herrera, Particle Accelerators 3, 49 (1972).
5. H. G. Hereward, CERN Report MPS/DL Int. 66-3 (1966).

for capturing the beam, a total acceleration time becomes ~ 2 sec. With the presently used magnet fall time of 0.5 sec, the entire AGS cycle would take 2.5 sec.

The average magnet power resulting from such an AGS cycle is ~ 3.3 MW, well below the maximum limit of 9 MW. The change in stored energy is also less than 50% of its allowed value.

3. Adiabatic Bunching on the Twelfth Harmonic Frequency

After acceleration, the single AGS bunch will be sufficiently small azimuthally to fit into one of the 12 buckets of the presently used rf system. One can then use this system to further compress the bunch azimuthally. Switching from one rf system to another in the same ring, one can maintain a matched beam provided that

$$h_1 V_1 \cos(\varphi_s)_1 = h_2 V_2 \cos(\varphi_s)_2$$

With

$$\begin{aligned} h_1 &= 1 \\ V_1 &= 50 \text{ kV} \\ (\varphi_s)_1 &= 120^\circ \\ h_2 &= 12 \\ (\varphi_s)_2 &= 180^\circ \end{aligned}$$

one obtains $V_2 = 2.1$ keV. Hence, the bunch would be captured in one of the 12 stationary buckets with an initial voltage per turn of 2.1 keV. The voltage would be raised slowly to its maximum value of 360 keV. This will result in a compression factor of $\sim (180)^{\frac{1}{2}} = 3.7$. The beam parameters after the adiabatic bunching process would be $\Delta\theta$ (angular length) $= \pm 2.7^\circ$ and $\Delta p/p = \pm 2.2 \times 10^{-3}$.

The adiabatic bunching time is given by⁶

$$T_B = \frac{(\tau_s)_2}{\alpha} \left[\left(\frac{V_2}{V_1} \right)^{\frac{1}{2}} - 1 \right],$$

6. C. G. Lilliequist and K. R. Symon, Report MURA 491 (1959).

where V_1 is the initial voltage,

V_2 is the final voltage,

$(\tau_s)_2$ is the period of the synchrotron oscillations at the final voltage.

α is a parameter that describes the degree of adiabaticity of the process. It is given by

$$\alpha = \frac{\frac{dA}{A}}{\frac{dt}{\tau_s}},$$

where A is the bucket area.

Results from numerical experiments show that bunching with minimal phase space dilution can be done if $\alpha \leq 3$.

Using $\alpha = 3$, $V_2 = 360$ kV, $V_1 = 2.1$ keV, and

$$(\tau_s)_2 = \frac{2\pi R}{c} \left(\frac{2\pi E}{h_2 V_2} \right)^{\frac{1}{2}},$$

where $R = 128$ m, $c = 3 \times 10^8$ m/sec, $E = 30$ GeV, $h_2 = 12$ and $\eta = 0.013$, one gets $T_B = 20$ msec.

In practice, it might be difficult to go down as low as 2.1 keV on the 12th harmonic system. It is believed that with some effort, a minimum controllable voltage of 8 keV could be achieved. In order to keep the beam matched, one would have to take the following procedure:

1) Increase ϕ_s at the end of the acceleration cycle so that $\cos \phi_s$ will change from 0.5 to 1.

2) Lower the frequency of the 12th harmonic system so that it corresponds to $h_2 = 6$ and adiabatically bunch while raising the voltage from 8 to 16 keV. When $V_2 = 16$ keV is reached, make a frequency jump corresponding to a change in the harmonic number from $h_2 = 6$ for $h_2 = 12$ and at the same time go back to $V_2 = 8$ keV.

3) Increase the voltage adiabatically from 8 to 360 keV.

The first step in this procedure would add another 20 msec to the adiabatic bunching time.

4. Transfer and Stacking into ISABELLE

Ejection from the AGS and injection into ISABELLE would be accomplished as outlined in the Grey Book, i.e., by the use of septum magnets and kickers. ISABELLE could be operated on the 90th harmonic which means that the rf frequency there would be ~ 11.1 MHz.

The AGS bunches would occupy an rf phase angle of $\pm 82^\circ$ in the buckets of such an rf system. In order to obtain a match, the following relation has to hold between AGS and ISABELLE parameters:

$$\frac{h_{\text{AGS}}}{R_{\text{AGS}}^2} \frac{V_{\text{AGS}}}{\eta_{\text{AGS}}} = \frac{h_{\text{ISA}}}{R_{\text{ISA}}^2} \frac{V_{\text{ISA}}}{\eta_{\text{ISA}}} .$$

With given

$$\begin{aligned} h_{\text{AGS}} &= 12 \\ V_{\text{AGS}} &= 360 \text{ kV} \\ \eta_{\text{AGS}} &= 0.013 \\ h_{\text{ISA}} &= 90 \\ \eta_{\text{ISA}} &= 0.002 \\ \frac{R_{\text{ISA}}}{R_{\text{AGS}}} &= 3 \end{aligned}$$

one can calculate the required voltage in ISABELLE and one gets $V_{\text{ISA}} = 55$ kV, assuming stationary buckets. However, the holding voltage is only 13 keV. Going to a moving bucket, one can comfortably choose $\phi_s = 170^\circ$. For such a synchronous phase, the bunch will still be well inside the bucket and the acceleration will be 9.35 keV/turn. It will take 2.7 min to accelerate from 30 to 200 GeV.

Ninety AGS pulses could be stacked in ISABELLE, the stacking time being ~ 4 minutes. Assuming an intensity of 2×10^{13} protons per AGS pulse, a total charge of 1.8×10^{15} protons or 36 A circulating current could be stored in each ring. The Grey Book specification of 15 A circulating current could be met with 8.3×10^{12} protons per AGS pulse.

5. First Harmonic AGS Rf System

The AGS fundamental frequency system would have to operate between 210 and 375 kHz. The required 50 kV peak voltage per turn would be divided up on 6 gaps with ~ 8 kV per gap. These gaps could be paired off into three rf stations, each of which would occupy a 10 ft straight section in the AGS.

6. Comparison to Other Injection Schemes

The injection scheme described here should be compared to the energy stacking scheme presently used at the ISR⁷ and to the single (12th harmonic) bunch extraction and compaction method most recently proposed by Blewett and Cottingham.⁸ The comparison will be made on a general basis rather than on the grounds of specifically chosen parameters.

Maximum Intensity

The maximum intensity that one can store in ISABELLE will be the product of the maximum number of stored AGS pulses, $N_{\max}$, and the intensity of each AGS pulse. $N_{\max}$ will vary from one injection scheme to the other.

In the energy stacking (ISR) scheme, $N_{\max}$ is theoretically unlimited, while in the Blewett-Cottingham injection method, $N_{\max}$ is determined by the phase spread of the individual AGS bunches. Taking the Grey Book value of ± 10 rf degrees one gets $N_{\max} = 65$.

In the injection scheme described in this report, the time between adjacent bunches in ISABELLE has to be at least equal to the rise time of the injection kicker. Hence, $N_{\max} (\tau_K + \tau_B) = T_{\text{rev}}^{\text{ISA}}$, where τ_K is the rise time of the kicker, τ_B is the time corresponding to the phase spread of a bunch, and $T_{\text{rev}}^{\text{ISA}}$ is the revolution time in ISABELLE.

With $\tau_K = 50$ nsec (which is half the rise time of the kickers used presently at BNL and CERN), $\tau_B = 40$ nsec (equivalent to $\pm 2.72^\circ$ angular length after adiabatic bunching in the AGS), and $T_{\text{rev}}^{\text{ISA}} = 8$ μ sec, one obtains $N_{\max} = 90$.

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7. E. Keil and A. M. Sessler, BNL Accelerator Dept. Report CRISP 72-74, 1972. See also M. Month, CRISP 72-89, in press.
 8. J. P. Blewett and J. G. Cottingham, BNL Accelerator Dept. Report AADD-195 (CRISP 72-93), 1972.

The values of $N_{\max}$ for the different injection methods are summarized together with other parameters in Table I.

ISABELLE Charging Time

The time it takes to charge each of the ISABELLE rings, $T_{\text{ch}}^{\text{ISA}}$, is given by $T_{\text{ch}}^{\text{ISA}} \approx N_{\text{AGS}} (T_{\text{acc}}^{\text{AGS}} + T_{\text{st}}^{\text{ISA}})$, where $T_{\text{acc}}^{\text{AGS}}$ is the period of the acceleration cycle in the AGS (the adiabatic bunching time has been neglected), and $T_{\text{st}}^{\text{ISA}}$ is the stacking time per AGS pulse in ISABELLE. These times are summarized in Table I, together with $N_{\max}$ and f_D , the longitudinal phase space dilution factor.

TABLE I

Method	$T_{\text{acc}}^{\text{AGS}}$ (sec)	$T_{\text{st}}^{\text{ISA}}$ (sec)	$T_{\text{acc}}^{\text{AGS}} + T_{\text{st}}^{\text{ISA}}$ (sec)	$N_{\max}^*$	f_D
Energy stacking (ISR)	1	~ 3	~ 4	Unlimited	~ 2
Blewett-Cottingham	1	Negligible	~ 1	65	~ 1
Present work	2.5	Negligible	~ 2.5	90	~ 1

* Aperture limitations are not taken into account.

Momentum Spread at 200 GeV

The minimum momentum spread that can be achieved after adiabatic debunching at 200 GeV will only depend on the phase space dilution factor, f_D , connected with the particular mode of injection and stacking. Assuming that adiabatic debunching can be done after acceleration in ISABELLE, the total final momentum spread will be

$$\Delta p = \frac{N_{\text{AGS}} \cdot S_T \cdot f_D}{C_{\text{ISA}}},$$

where N_{AGS} is the number of AGS pulses stacked in ISABELLE, S_T is the total invariant longitudinal phase space in the AGS at 30 GeV, and C_{ISA} is the ISABELLE circumference. With $S_T = 12 \times 0.35 \text{ eV sec} = 4.2 \text{ eV sec}$, $C_{\text{ISA}} = 2400 \text{ m}$, this corresponds to

$$\frac{\Delta p}{p} = 0.125 \times 10^{-5} \cdot f_D \cdot N_{\text{AGS}}.$$

However, such a small momentum spread will probably be detrimental from the point of view of longitudinal instabilities and the beam might very well have

to be kept bunched or nonadiabatically debunched (by suddenly turning off the rf voltage).

For a bunched beam, the momentum spread is according to (1)

$$\frac{\Delta p}{p} = \left(\frac{eV}{h\eta 2\pi E} \right)^{\frac{1}{2}} \left(\frac{N_{\text{AGS}} \cdot S_T \cdot f_D}{\pi R p} \right)^{\frac{1}{2}}$$

where only V , h and f_D vary from one injection scheme to another. Here V is the voltage corresponding to the final stationary buckets. The parameters h and f_D are inherent in the injection scheme. Hence, by proper choice of V , any desired momentum spread can be achieved in all three schemes.

Momentum Spread at 30 GeV

During injection into ISABELLE, the momentum spread is determined by the final momentum spread in the AGS. This momentum spread will be highest ($\pm 2.2 \times 10^{-3}$) using the injection method described in this report because additional bunching takes place after acceleration in the AGS. In both other schemes, partial debunching is suggested in order to match into ISABELLE rf buckets, resulting in a momentum spread smaller than $\pm 6 \times 10^{-4}$. In the energy stacking scheme, further debunching takes place in the parking orbit, leading to even smaller momentum spreads. This could lead to longitudinal instabilities.

Injection Straight Sections

Specially designed injection straight sections are required for the energy stacking method only.

Possible Modulation of Linac Beam

The 200-MeV linac could be chopped at the AGS frequency at injection leading to increased capture efficiency in the AGS and reduced beam loading in the linac. With the AGS operating on the fundamental frequency the required modification of the linac would be particularly simple. The author is indebted to K. Batchelor for suggesting this idea.

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