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Informal Report

REEXAMINATION OF THE ISABELLE BOX CAR STACKING SCHEME

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ABSTRACT

Box car stacking of ISABELLE after acceleration of the fundamental frequency in the AGS is reviewed with the present ISABELLE parameters and examined with regard to longitudinal impedance requirements.

The scheme results in an impedance tolerance of $Z/n \leqslant 30\ \Omega$ compared to $Z/n \leqslant 5\ \Omega$ obtained for rf stacking. However, to meet the claimed luminosity, the AGS performance demands are increased above those assumed in the ISABELLE proposal.

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I. Introduction

It was originally proposed by Blewett[1] that ISABELLE be stacked azimuthally by debunching the AGS bunches adiabatically, rebunching the debunched beam on a first harmonic sawtooth wave form and transferring the single bunch to ISABELLE. This procedure would be repeated until the whole ISABELLE circumference was filled. Later on this scheme was modified[2] to avoid longitudinal instabilities in the AGS. It was suggested that the single AGS bunch could be obtained by accelerating on the fundamental frequency in the AGS. However, several advantages were seen in the rf stacking scheme used at the ISR, having to do with greater flexibility in beam handling and this method was adopted in the ISABELLE proposal.[3]

Recently, during the ISABELLE Summer Study,[4] it was pointed out that the longitudinal impedance tolerances in ISABELLE were extremely low, in particular during rf stacking. This is a result of the very low η-value in ISABELLE (η is the parameter describing the spread in revolution frequency for off-momentum particles).

In this paper the azimuthal stacking scheme with acceleration on the fundamental frequency in the AGS will be reviewed with the present ISABELLE parameters and examined with regard to longitudinal impedance requirements.

The reader is referred to CRISP 72-94 for a more detailed description of the scheme itself.

2. AGS Intensity

The AGS intensity required to fill ISABELLE with 6×10^{14} protons is derived in the following way: A minimum achievable kicker rise time of 35 nsec is assumed. Furthermore the longitudinal phase space density in the AGS is taken to be intensity independent and equal to that quoted in

1. J. P. Blewett, CRISP 71-6, (1971).
2. R. Chasman, CRISP 72-94, (1972).
3. "A Proposal for Construction of a Proton-Proton Storage Ring Accelerator Facility ISABELLE, BNL 18891 (May 1974).
4. E. Raka and W. Schnell, private communication, (July 1975).

the ISABELLE proposal - 0.58 × 10^{12} protons/eVsec. If N_p^{AGS} is the AGS intensity and N_B^{ISA}, N_p^{ISA} are number of bunches (or AGS pulses) and total number of particles stacked in ISABELLE one gets:

$$N_p^{AGS} \times N_B^{ISA} = N_p^{ISA} \tag{1}$$

The length of the AGS bunch, ℓ_B, can be expressed as $\ell_B = K\sqrt{S_T} = K'\sqrt{N_p^{AGS}}$, where S_T is the longitudinal phase space are and K and K′ are constants depending on rf and other machine parameters. With C_{ISA} being the circumference of ISABELLE a second equation is obtained:

$$(K'\sqrt{N_p^{AGS}} + 35 \times 10^{-9} \times c)\, N_B^{ISA} = C_{ISA} \tag{2}$$

where c is the velocity of light (assuming $\beta = 1$).

With the rf parameters quoted in CRISP 72-94 one gets from Eqs. (1) and (2):

$$N_p^{AGS} = 6 \times 10^{12}$$

$$S_T = 10.4 \text{ eVsec}$$

$$N_B^{ISA} = 100$$

Hence it will take 100 AGS pulses of 6 × 10^{12} protons each to accumulate 6 × 10^{14} protons in ISABELLE, corresponding to 10 A.

3. Acceleration of the Fundamental Frequency in the AGS

For a given total longitudinal phase space area, S_T, the phase and momentum spread of each such, $\Delta\phi$ and $\Delta p/p$ are given (assuming that all rf buckets are filled) in the linear approximation by:

$$\frac{\Delta\phi}{h} = \pm \frac{1}{h} \left(\frac{h\eta 2\pi E}{eV\cos\phi_s}\right)^{+\frac{1}{4}} \left(\frac{S_T}{\pi RP}\right)^{+\frac{1}{2}}$$

$$\frac{\Delta p}{p} = \pm \left(\frac{eV\cos\phi_s}{h\eta 2\pi E}\right)^{+\frac{1}{4}} \left(\frac{S_T}{\pi RP}\right)^{+\frac{1}{2}}$$

Here

h is the harmonic number

V is the peak rf voltage

ϕ_s is the synchronous phase

E is the total energy

p is the momentum

R is the radius of the machine

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

With V = 50 kV, h = 1 one gets during flattop at 30 GeV

$$\Delta\phi = \pm 13.7^\circ$$

$$\frac{\Delta p}{p} = \pm 1.1 \times 10^{-3}$$

4. Adiabatic Bunching on the 12th Harmonic rf System in the AGS

At 30 GeV the single bunch is just tight enough to fit into one of the buckets of the presently used 12th harmonic rf system. One can now use this system to further compress the bunch azimuthally by adiabatic bunching. Assuming a final maximum voltage of V = 400 kV one gets

$$\frac{\Delta\phi}{h} = \pm \left(\frac{400 \times 12}{50 \times 1}\right)^{-\frac{1}{4}} \times 13.7^\circ = \pm 4.4^\circ$$

$$\frac{\Delta p}{p} = \pm \left[\frac{400 \times 12}{50 \times 1}\right]^{+\frac{1}{4}} \times 1.1 \times 10^{-3} = \pm 3.4 \times 10^{-3}$$

at the end of the bunching process.

$\Delta\phi = \pm 4.4^\circ$ corresponds to a total bunch length of 19.5 m.

5. Stacking and Acceleration in ISABELLE

The AGS bunch can now be transferred and fitted into a bucket of a 100th harmonic rf system in ISABELLE. The outlined procedure can be repeated 100 times taking about 4 minutes. As was mentioned earlier, the time corresponding to the distance between back to front of adjacent bunches is ~ 35 nsec, or just long enough to allow for still manageable kickers.

The voltage required to match the bunches longitudinally in ISABELLE is derived in the following way: The phase spread of the bunch is $\pm$ 0.66 π. If matched, the bunch should occupy 75%[5] of the bucket area in this case, requiring a bucket height of

$$\left(\frac{\Delta p}{p}\right)_{\text{bucket}} = \pm \frac{3.4 \times 10^{-3}}{\sqrt{0.75}} = 3.9 \times 10^{-3}$$

But $$\left(\frac{\Delta p}{p}\right)_{\text{bucket}} = \pm \left(\frac{2eV}{\pi h \eta E}\right)^{+\frac{1}{2}}$$ for a stationary bucket and one gets

$$V = \left[\left(\frac{\Delta p}{p}\right)_{\text{bucket}}\right]^2 \times \frac{\pi h \eta E}{2e} = 82 \text{ kV}$$

with $\eta = 0.00114$.

The holding voltage corresponds to a bucket whose area equals that of the bunch and is $V_h = (0.75)^2 \times 82$ kV = 46 kV. One can then go to a moving bucket with ϕ_s such that α (ϕ_s), the moving bucket factor equals to the square root of the ratio of holding to matching voltage yielding α (ϕ_s) = 0.75, $\phi_s = 7.5^\circ$ and $\Gamma = \sin \phi_s = 0.13$[5]. This results in an acceleration per turn of 10.7 kV/turn. Acceleration to 200 GeV would take ~ 3 minutes. As will be seen later, because of bunched beam instabilities it will be advantageous to maintain a constant ratio of bunch to bucket area of approximately unity. Throughout the acceleration this can be done by decreasing V or increasing Γ or a combination of the two. The last alternative gives control over the acceleration time.

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5. F. T. Cole and P. L. Morton, UCID 10130 (1964).

6. Longitudinal Instabilities

The bunches in ISABELLE have to remain stable during stacking and acceleration. This requirement sets an upper limit to the tolerable longitudinal impedance in the ring.

Two types of longitudinal instabilities will be considered here: coasting beam type instabilities and coherent multipole oscillations of the bunches.

a) Coasting beam type instabilities

It has recently been pointed out[6,7] that one should apply coasting beam criteria to bunches for perturbations with wavelenghts and wake fields short compared to the bunch length. This criteria can be written as[8]

$$\frac{Z}{n} \leq \frac{0.7\,\pi}{2} \quad \frac{E\eta}{I_p e} \quad \left(\frac{\Delta p}{p}\right)^2_{FWHM}$$

where Z is the longitudinal coupling impedance, n is the mode number and $(\Delta p/p)_{FWHM}$ the full width, half height momentum spread. I_p is the peak current which can be expressed as $I_p = I_o P/B$ where I_o is the current averaged over one rf bucket, B is the ratio of bunch length of bunch separation and P is the ratio of averge to peak linear charge density of the bunch. During stacking in ISABELLE B = 0.66 (the value is not very different during acceleration). Assuming a parabolic distribution in longitudinal phase space one has

$$P = 1.8$$

$$\left(\frac{\Delta p}{p}\right)_{FWHM} = 0.66 \left(\frac{\Delta p}{p}\right)_{max}$$

With $\eta = 0.00114$, $I_o = 10$ A, E = 30 GeV and $(\Delta p/p)_{max} = 2 \times 3.4 \times 10^{-3}$ one obtains

$$\frac{Z}{n} \leq 27.5\ \Omega$$

An even larger value of $Z/n \leqslant 55\ \Omega$ is obtained, taking the frequently assumed parabolic line density.

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6. K. Hübner, private communication (May 1975).
7. H. Hereward, Coasting Beam Theory Applied to Bunches [to be published in Proceedings of ISABELLE Summer Study (July 1975)].

b) Bunched Beam Type Instabilities

In order that the multipole oscillations of the bunches be stable it is required[9] that

$$\frac{s}{w_{so}} > \frac{4}{\sqrt{m}} \frac{\Delta w_m}{w_{so}}$$

s is the spread in the synchrotron frequency between center and edge of the bunch (depends on the synchronous phase and the bunching factor), w_{so} is the synchrotron frequency at the center of the bunch, m is the order of the multipole and Δw_m is the coherent frequency shift for the m-type oscillation.

Neglecting contributions from conducting and resistive walls (which are indeed small) one gets from interaction with a resonant element of frequency ω:

$$\frac{\Delta w_m}{w_{so}} = 0.159 \times \frac{Z(\omega) I_o}{V\cos\phi_s} \; \frac{M}{Bh} \; D \; F_m(\omega)$$

Here M is number of bunches and Z is the shunt impedance of the resonant cavity. D and $F_m(\omega)$ are form factors. $F_m(\omega)$ has a maximum equal to $1/\sqrt{m}$ for $\omega = mM/2B \times \omega_o$, where ω_o is the revolution frequency. D, having a maximum value of unity, depends on the time between bunch centers, on ω and on Q, the quality factor, of the resonant element.

With $\cos\phi_s = 1$ (exact during stacking and approximate during acceleration) and B = 0.66 one gets $s/w_{so} = 0.25$.[9] Taking $I_o = 10$ A M = h = 100 (corresponding to time when all rf buckets are filled), V = 82 kV, D = and $F_m = 1/\sqrt{m}$ one gets for $\omega = (mM/2B)\omega_o$

$$\frac{Z}{m} \le 2150\ \Omega$$

Defining $\omega = n\omega_o$ this can be rewritten as

$$\frac{Z}{n} \le 28.4\ \Omega$$

9. F. J. Sacherer, IEEE Trans. Nucl. Sci. NS-22, Vol. 3, 825 (1973).

7. Rf System

Although a maximum voltage of 82 kV was calculated earlier in this paper, the rf system should be designed for a peak voltage of ~ 120 kV. The additional voltage is needed to compensate for the reduction in bucket size due to an inductive impedance of Z/n = 30 Ω. The frequency corresponding to h = 100 is ~ 10 MHz. Four gaps of 30 kV each are envisioned, with a total dynamic shunt impedance of ~ 1200 Ω. This is low enough to avoid bunched beam instabilities excited by Fourier components of the current other than multipoles of the rf system harmonic number. Such components will be present, especially during stacking when not all rf buckets are filled.

8. Discussion

The stacking scheme described here yields fairly reasonable longitudinal impedance tolerances of $Z/n \leq 30\ \Omega$. This ought to be compared with $Z/n \leq 5\ \Omega$ obtained with the rf stacking method, for comparable AGS intensity and longitudinal phase space density.

The impedance tolerance could be further increased by going to higher values of η. This is possible with the box car stacking scheme because of the relaxed aperture requirements inherent in this method: With the present ISABELLE lattice yielding $\eta = 0.00114$ at 30 GeV the horizontal aperture would be subdivided in the following way:

Betatron amplitude	1.3 cm
Phase oscillation amplitude $(X_p \frac{\Delta p}{p})$	1.1 cm
Sagitta	1.3 cm
Reserve	4.3 cm
	8.0 cm

Lattice calculations performed by E. Courant[10] show that $\eta = 0.0022$ at 30 GeV can be achieved with the proposed ISABELLE lattice and reduced quadrupole gradients, going to smaller betatron phase advances in the regular cells of $\Delta\Psi_x = 60^\circ$ and $\Delta\Psi_z = 75^\circ$. This results in $\beta_x^{max} = 43$ m and $X_p^{max} = 2.3$ m and

10. E. D. Courant, private communication (August 1975).

increases the maximum horizontal beam size by only 0.5 cm, still leaving 3.0 cm reserve. Both coasting beam and bunched beam longitudinal impedance tolerances would then be doubled at the expense of a similar increase in the rf voltage.

Additional advantages seen in the present scheme are lower momentum aperture requirements at injection and during acceleration (because of more efficient stacking), shorter filling time of ~ 4 min/ring and the need for only one rf system.

In addition to the lack of flexibility in beam handling (this means lack of freedom in trading AGS intensity for number of stacked AGS pulses) other drawbacks are the following: The required increase in AGS intensity to 6×10^{12} ppp might result in transverse emittances that are larger than those quoted in the ISABELLE proposal ($0.4\ \pi \times 10^{-6}$ mrad). Increased vertical emittance would reduce the luminosity and increased horizontal emittance would enlarge the interaction length. At the same time the effects of nonlinear resonances would become more serious.* Furthermore, kicker demands are increased and transverse instabilities from beam interaction with resistive walls and parasitic resonant elements may become troublesome.

Conclusion

Box car stacking after acceleration on the fundamental frequency in the AGS results in a longitudinal coupling impedance tolerance of $Z/n \leq 30\ \Omega$ in ISABELLE. This should be compared to $Z/n \leq 5\ \Omega$ obtained with rf stacking for comparable AGS intensity and longitudinal phase space density. Longitudinal impedance tolerances could be further relaxed by going to lower betatron phase advances in the normal cells resulting in higher values of η and a reduction in quadrupole gradients. The box car stacking method requires better AGS performance than that assumed in the ISABELLE proposal in order to meet the claimed luminosity. Kicker demands are increased. Possible transverse bunched beam instabilities, originating in beam interaction with resistive walls and with resonant elements will have to be investigated.

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*It should be pointed out that the impedance requirement employing rf stacking of $\frac{Z}{n} \leq 5\ \Omega$ was arrived at assuming a similar increased AGS intensity of 5×10^{12} ppp. The proposed AGS intensity of 2.5×10^{12} ppp would result in even lower values of $\frac{Z}{n}$ assuming constant longitudinal phase space density.

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