EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

CERN-ISR-BOM-OP-RF/77-13

PHASE DISPLACEMENT ACCELERATION OF HIGH INTENSITY STACKS

IN THE CERN ISR

by

E. Ciapala, S. Myers, C. Wyss

Presented at the 1977 Particle Accelerator Conference

Chicago, March 16-18, 1977

Geneva, Switzerland

March 1977

PHASE DISPLACEMENT ACCELERATION OF HIGH INTENSITY STACKS IN THE CERN ISR

E. Ciapala, S. Myers, C. Wyss

CERN
Geneva, Switzerland

Summary

In the ISR high intensity stacks of more than 25 A are accelerated by phase displacement from 26.6 to 31.4 GeV/c. Phase displacement is the only known means of accelerating stacks of such large momentum spread ($\Delta p/p = 3\%$) with the existing low power RF system. Acceleration in this way may produce loss of intensity due to RF and power supply magnet noise, momentum blow-up of the stack, closed orbit and working line variations, and changes in the RF bucket size while traversing the stack. The existing instrumentation allows close control of all relevant parameters during acceleration and has resulted in reducing the intensity losses to as little as 10%. In this way, luminosities significantly in excess of the ISR design luminosity are achieved in an operational way, making 31.4 GeV/c one of the standard ISR momenta for physics data taking and giving an equivalent momentum of greater than 2,000 GeV/c when related to stationary target machines.

1. Introduction

The maximum operational momentum for the I.S.R. injector (the C.P.S.) is 26 GeV/c whereas the I.S.R. has a top momentum of 31.4 GeV/c. Consequently acceleration of beams between 26 and 31 GeV/c must be performed within the I.S.R. itself. Present maximum longitudinal phase plane densities in the stacks would allow only around 1.4 Ampères to be rebunched by the existing R.F. system. In fact, in the early stages of development rebunched beams were accelerated¹ to 31 GeV/c. However, due to the severe limitation on maximum intensity (0.5 A was reached at 31 GeV/c) and luminosity, the technique of phase displacement acceleration was adopted².

Phase displacement acceleration of high intensity stacks from 26.6 to 31.4 GeV/c in the I.S.R. takes around 200 sweeps of empty R.F. buckets through the stack. During each accelerating sweep the main bending field is increased so as to maintain the stack position constant and the machine magnetic properties are adjusted in order to compensate for variations in the tune values across the stack and to correct deviations in the closed orbits.

The recent introduction of new working lines with space charge compensation, closer control of the closed orbits, continuous control of the R.F. parameters and the stack position, and phase lock onto the empty buckets has produced intensities of more than 21 Amps and luminosities of more than $8 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$ at 31 GeV/c. This has resulted in an ever-increasing physics demand for operation at 31.4 GeV/c even though the luminosity is somewhat lower than what can be attained at 26.6 GeV/c.

2. R.F. Parameters

When empty buckets are passed through a coasting stack from high to low momentum, the momentum of the whole stack is increased by

$$\Delta p_{SW} = \frac{m_0 c}{2\pi} A_b = 6.383 \frac{m_0 c}{2\pi} \alpha(\Gamma) \sqrt{\frac{V_{RF}}{E_0 h \eta}} \quad (1)$$

where $\alpha(\Gamma)$ is the ratio of the area of the moving bucket to a stationary bucket. The R.F. system of the I.S.R. has a maximum voltage of 20 kV, consequently the minimum required number of passages is around 140 for acceleration from 26 to 31 GeV/c. However, until recently the passage of such large R.F. buckets through high density stacks produced severe beam loading on the R.F. cavities. The existing cavity amplifiers were unable to provide sufficient current and the correct cavity voltage could not be maintained. This problem has recently been eliminated by a beam loading compensation³ system which supplies additional current pulses, dependent on the stack longitudinal density, to each of the 7 cavities via a separate amplifier for each cavity. Before this system became operational a voltage of 12 kV was used, which required around 200 R.F. sweeps through the stack.

The sweeping of empty buckets through a stack also causes the momentum spread of the stack to increase⁴, i.e.

$$\langle (\Delta p)_{i+1}^2 \rangle = \langle (\Delta p)_i^2 \rangle + (\delta p_{rms})_i^2$$

where $\delta p_{rms} = \Gamma \frac{m_0 c A_b}{2\pi \alpha(\Gamma)}$, $\Gamma = \sin \phi_s$, A_b = bucket area.

Consequently during phase displacement acceleration the momentum spread of the stack is increased. In a fixed aperture machine the fractional stack momentum spread ($\frac{\Delta p}{p}$) or the average stack radial width ($\Delta r = \frac{R}{\gamma^2} \frac{\Delta p}{p}$) is a more meaningful parameter. The r.m.s. value of the average stack width is given by

$$(\Delta r_{rms})_{i+1} = (\Delta r_{rms})_i \frac{p_{i+1}}{p_i} \sqrt{1 + \left(\frac{\alpha \Gamma A_b}{2\pi \beta \gamma \alpha(\Gamma) \Delta r_{rms} p_i} \right)^2} \quad (2)$$

where i refers to the sweep number.

The evolution of the stack width has been computed for various values of Γ and is plotted in Fig. 1 for a typical full aperture I.S.R. stack.

Fig. 1 Evolution of stack width during acceleration

Also shown are some measured values obtained from longitudinal Schottky scans during acceleration with $\Gamma = 0.1$. For suitably low values of Γ the computed stack width is

seen to decrease. Also for lower beam intensities the measured results for $\Gamma = 0.1$ are also in good agreement with those calculated. However, this is not the case for very high stack intensities where a considerable blow-up of the radial width occurs during acceleration. Fortunately this blow-up has not caused intensity losses since the extra aperture freed by the retraction of the injection system has been sufficiently large to accommodate the increased beam width. The blow-up may be due to a longitudinal instability which occurs during sweeping of stacks with very high longitudinal phase plane density. This problem is still under study, particularly in connection with phase displacement acceleration to higher energies in future machines.

During acceleration by phase displacement, particle losses occur on each accelerating sweep for the following reasons.

- (i) Due to its required tune spread the stack crosses non-linear resonances which provoke losses (see section 3).
- (ii) Particles which diffuse into the sweeping buckets are decelerated to the inner aperture limitation and lost. The diffusion of particles into the "empty" buckets may be caused by magnetic noise produced by ripple on power supplies or by noise on the R.F. system itself. Tests have shown that a small additional amount of low frequency noise injected onto the frequency program causes a relatively high increase in the current losses per sweep. Recently the R.F. losses have been reduced by a factor of around 4 by the use of phase lock onto the empty buckets. With this system the difference signal between the beam phase and the noisy cavity phase is fed back into the frequency control system and hence reduces the phase noise on the cavities.

3. Working Line Control

Working line control is essential during the acceleration process in order to avoid beam losses due to resonances and transverse coherent instabilities arising from local reductions in the chromaticity.

When non-linear resonances are excited either by magnetic imperfections or by beam-beam effects, an increase in the amplitude of the betatron oscillations and some particle loss may result. These losses are much larger when the coasting beam is traversed by empty R.F. buckets due to the resulting momentum modulation. Experience in the I.S.R. has shown that in order to produce acceptable background conditions for data taking only resonances of order eight and above can be allowed in the stack. This same criterion also produces negligible particle losses when accelerating by phase displacement.

It is also important to ensure that the chromaticity throughout the stack is higher than the threshold⁵ for transverse instability. If this criterion is violated then total loss of the stack will result. The main reasons for variations in the tune values are :

- (i) Saturation of the main magnet. The tune variations which result from magnetic saturation are compensated for by the pole face winding system, local sextupoles and newly installed local quadrupoles. The sextupoles and quadrupoles are excited in such a way as to reduce the loading on the pole face windings.

- (ii) Incoherent Space Charge Tune Shift. The tune shift due to image forces is dependent on the longitudinal density distribution of the stack and its momentum. These effects are compensated dynamically during stacking at 26 GeV/c by appropriate excitation of the pole face windings⁶. However, during acceleration by phase displacement the stack density distribution changes due to the repeated sweeps by the empty buckets. This effect and to a lesser extent the effect of current losses can change significantly the required tune compensation. For this reason the density distribution of the stack is measured at regular intervals during acceleration and the compensating tune shift is applied.

4. Closed Orbit Control

The observed increase in the closed orbit distortion during acceleration may be explained by fluctuations in the bending and focussing power due to differences in weight between the main magnetic units. The extreme orbits, both outer and inner are the worst affected because of magnetic saturation across the gap aperture. When working with tune values far from the integer (e.g. 8.63) the increase in orbit distortion is not large enough to produce current losses during acceleration because of the increased aperture after retraction of the injection system. In this case orbit corrections are not performed during acceleration but only when the top momentum is reached. However, with the now standard high intensity working line (ELSA) where the maximum tune values are $Q_H = 8.955$ $Q_V = 8.935$ (fig. 2) the orbits must be continuously corrected during acceleration because of the orbit distortion produced by tune values so close to the integer.

Fig. 2 Tune diagram

The 31.4 GeV/c ELSA working line has only recently been made possible by the installation of new quadrupoles⁸ which allow the loading to be taken off the pole face windings. This working line is still being developed.

5. System of Control

As previously stated phase displacement acceleration from 26.6 to 31.4 GeV/c necessitates around 200 sweeps of empty R.F. buckets through the stack while simultaneously correcting the working line and increasing the main bending field. The whole operation is now performed automatically by the I.S.R. control computer in the following way.

Before each accelerating sweep the resulting momentum increment (equation 1) and hence the required power supply changes are calculated. The start of the R.F. sweep is then triggered and simultaneously the calculated increments are added to the power supplies at a rate compatible with the acceleration rate. In this way the main bending field is increased at approximately the same rate as the stack is accelerated and the working line is maintained constant. Small working line changes caused by variations of the stack density distribution may also be applied using a standard technique (see section 3).

During each sweep the frequency (R.F.) at which the empty buckets reach the stack is measured. This frequency is converted into an average radial position and is used by the operator for fine control on the position of the stack top.

During each sweep the closed orbits may also be measured inside the stack by processing the 'negative bunch' signal produced by the empty buckets. Orbit corrections can also be calculated and applied by the computer using standard techniques.

Fig. 3 ISR performance at 31 GeV/c

Figure 3 shows the performance evolution of acceleration to 31.4 GeV/c over the past 4 years. The maximum luminosity of $8.0 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$ may still be improved upon even though this value is already high enough for some physics groups around the I.S.R.

Conclusions

The acceleration by phase displacement of high intensity stacks from 26.6 to 31.4 GeV/c in the I.S.R. is now completely operational. The steady improvement in understanding and the implementation of many new techniques has allowed, at 31.4 GeV/c, current intensities in excess of the I.S.R. design current, (20 A at 26 GeV/c) and luminosities twice as high as the design value ($4 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$ at 26 GeV/c). With the availability of such high luminosity, 31.4 GeV/c operation has in 1977 become as much in demand as the I.S.R. "standard" high momentum of 26 GeV/c. The availability of new quadrupoles will for the future allow operation on a higher intensity working line (ELSA). In conjunction with phase lock onto the empty buckets this will allow operation at 31.4 GeV/c with even high luminosities.

Acknowledgements

Sincere thanks are due to R. Keyser who programmed the computer control and to J.P. Gourber, H.G. Hereward, A. Hofmann and W. Schnell for many helpful discussions.

References

1. S. Hansen, K.N. Henrichsen, and M.J. de Jonge, CERN ISR-MA-RF/73-9, Feb. 1973.
2. K.N. Henrichsen and M.J. de Jonge, CERN ISR/Rf/MA/74-21, April 1974.
3. H. Frischholz and W. Schnell, (to be presented to this Conference).
4. E.W. Messerschmid, CERN ISR-RF/72-28, August 1972.
5. B. Zotter and W. Schnell, CERN-ISR-GS-RF/76-26.
6. P.J. Bryant et al, CERN-ISR-BOM/75-54.
7. J. Borer - private communication.
8. C. Wyss (report to be published).