IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

PERFORMANCE OF THE CERN ISR AT 31.4 GEV

Claude Fischer, Patrick Jacquiot, Jean-Pierre Koutchouk, François Lemeilleur, Dewi Lewis, Stephen Myers, Dirk Neet, Hugh O'Hanlon, Thys Risselada and Lucien Vos*

Summary

Due to the recent improvements in phase displacement acceleration, operating techniques and beam diagnostics, considerable progress has been achieved in operating the ISR at the maximum energy of 31.4 GeV (this centre of mass energy corresponds to a 2 TeV fixed target machine). High intensity stacks are stored at 26.6 GeV before acceleration by phase displacement to 31.4 GeV. At this energy up to 34 Amps are obtained with corresponding initial luminosities of $2.10^{31}cm^{-2}s^{-1}$ per intersection and $4.3\ 10^{31}cm^{-2}s^{-1}$ in a low-β intersection. Due to the long beam lifetime, physics data taking may be performed over periods of 60 hours. The principle of phase displacement and the associated beam phenomena are discussed together with the control of the magnetic machine and the mutual interaction of the two beams. The operational technique is described and it is shown that the present day performance of the ISR at 31.4 GeV is comparable to the previous performance (1977) at 26.6 GeV. Consequently, in 1978 about 90% of the time requested for physics data collection was at 31.4 GeV.

1. Introduction

During the period 1971 to 1977 the ISR operated primarily at 26.6 GeV which is the optimum ejection energy of the injector synchrotron CPS. Early acceleration tests in 1972 had demonstrated that the magnetic field precision could be maintained up to a maximum energy of 31.4 GeV, the limit being set by the main power supplies. Improvements in stacking techniques[1] and the introduction of new equipment have permitted stable circulating currents of 36 Amps to be stacked at 26.6 GeV. Parallel development of acceleration by phase displacement has enabled such high intensity stacks to be accelerated to 31.4 GeV with only a few per cent loss in beam current.

2. Principle of Acceleration by Phase Displacement

By this technique[2], a stacked beam is accelerated stepwise in small energy increments (i.e. 0.025 GeV). Each increment corresponds to the passage of a train of 30 empty buckets through the coasting beam, and is referred to as "a sweep". The buckets generated by the normal stacking RF system pass from high to low momentum and ideally the step increase in momentum is:

$$\overline{\Delta p} = \frac{\bar{p}}{\beta\gamma}\ \frac{A_b}{2\pi} \qquad (1)$$

where A_b is the total bucket area, which is a function of the RF phase angle ϕ_s and $\sqrt{V_{RF}}$.

The beam is maintained in the centre of the vacuum chamber by simultaneously increasing the main bending field during each RF sweep. Variations in the machine tune, chromaticity and closed orbit due to magnetic saturation and increased beam momentum are corrected at the same time. A typical acceleration requires some 200 sweeps and simultaneous control of both the RF system and magnet systems is performed by the control computers[3].

3. Effects of Modulation on the Bucket Area

The longitudinal efficiency of phase displacement acceleration may be quantified by three main parameters: the relative beam intensity loss per sweep (ΔI/I), the increase in rms momentum width per sweep ($\overline{\delta p_{rms}}$), and the amount of acceleration per sweep ($\overline{\Delta p}$) (see equation 1). In the ideal case of a perfect RF system and constant bucket parameters throughout the sweep ΔI/I is zero, and

$$(\delta p_{rms}) = \frac{\Gamma}{\alpha(\Gamma)}\ \overline{\Delta p} \qquad (2)$$

where α(Γ) is the ratio of the area of a moving to a stationary bucket, and $\Gamma = \sin\phi_s$.

In practice, variations are produced in the bucket area parameters due to :

a) RF "noise". Unwanted frequency modulation (noise) on the accelerating frequency causes variations of ϕ_s and hence A_b. When this modulation frequency is of the same order as the synchrotron frequency for small amplitudes, some particles penetrate the separatrix of the RF bucket, spiral towards the centre of the bucket before spiralling outwards again[4]. However, some particles, which are still trapped inside the RF bucket, are unavoidably lost against the inner aperture limit as the RF bucket reaches the end of the frequency sweep. Intensity losses have been reduced to very low levels by the use of special low noise RF control electronics, thus eliminating the need for a phase lock system on the empty buckets.

b) Space charge effects. The longitudinal density modulation produced by the sweeping empty buckets generates ac image currents which flow in the vacuum chamber and RF cavities. The resulting electric fields change the RF bucket area. This change depends on the local longitudinal density at the position of the moving empty bucket in the stack. The beam loading compensation system for the RF cavities[6] has been adjusted so as to reduce the beam loss per sweep (ΔI/I) by a factor of two. The total loss per sweep ΔI/I has been reduced, due to the above mentioned mechanisms, to about 0.01%.

c) γ_T variation with Δp/p. Measurements[5] in the ISR have shown that $\Delta\gamma_T/\gamma_T = -\Delta p/p$; this momentum dependence causes all bucket parameters, related to γ_T, to change as the bucket is swept through the stack. It has been shown that[4] for low Γ values, a significant increase in the momentum blow-up per sweep (δp_{rms}) results from this dependence of γ_T on Δp/p.

4. Variation of stack position and density distribution

Due to the difficulties in evaluating and controlling the RF bucket area during a sweep, a mismatch between the increase in beam momentum and the magnetic field changes does occur. The resultant displacement of the stack position is corrected by executing only an RF sweep (stack moves outward) or only a power supply increment (stack moves inward). The average displacement in each case is about 1.5 mm. The momentum blow-up (δp_{rms}) changes the density profile of the stack and consequently the incoherent space charge effect due to image forces. This requires a regular correction of the tune values in the stack. Furthermore, during the phase displacement process itself, the stack is split into two parts by the sweeping RF bucket; this effect results in small transient changes of the tune and chromaticity and requires extra horizontal aperture.

* CERN, Geneva, Switzerland

0018-9499/79/0600-3155$00.75 © 1979 IEEE

5. The Magnetic Machine

The ELSA[1] working line is employed because of the large tune spread available for transverse stability and also because it is free of non linear resonances of order less than 7. This working line permits the addition of the low-β section[7] in one intersection which is applied at 26 GeV and progressively adjusted during acceleration to 31.4 GeV. Additional tuning quadrupoles have been used so as to leave the poleface windings with a greater flexibility in correcting for magnetic saturation and incoherent space charge effects. Systematic cycling of most magnetic elements is performed prior to injection. Since tune values on the high momentum side are close to the integer resonance, the closed orbit becomes extremely sensitive to small magnetic errors. Both the working lines and the closed orbits were measured and corrected for each 1 GeV step in an initial experiment. Interpolation between settings at these fixed energies is performed for each magnetic element and for every phase displacement sweep.

6. Control of the vertical transverse emittance

In a machine with horizontal crossings, careful control of the vertical beam height is required to produce maximum luminosity. During the acceleration process, the transverse motion of the protons may be affected by machine, coasting beam-beam, and overlap knock-out[8] resonances. The effects of machine and beam-beam resonances are further increased by the motion of the particles around the empty buckets and by the transient tune change due to the stepwise nature of phase displacement acceleration.

Single beam effects (machine and single beam overlap knock-out) have not been found to be harmful.

The presence of a beam in the second ring can provoke strong resonance excitation:

(i) Coasting beam-beam resonances increase the vertical betatron amplitudes of the particles which are accelerated across these resonances and result mainly in proton losses on the vertical aperture limits, i.e. dump block and collimators[9]. This accounts for 80 per cent of the losses per sweep. With vertical separation of the beams in the intersections, this beam-beam effect can be reduced by 50%.

(ii) Two beam overlap knock-out results from the interaction of the longitudinally modulated beam on the coasting beam in all intersection regions; due to the RF frequency swing, the resonances traverse the complete stack, causing an increase in the vertical beam height of typically 20%.

The conditions required for overlap knock-out are such that dipolar and higher order resonances are expected to be excited. For large beam separation in one intersection, the excitation function of the dipolar resonance is maximum whilst it is small for higher order overlap knock-out and coasting beam-beam resonances. (Fig. 1). Therefore, the requirements for simultaneous minimisation of the current loss per sweep and of the vertical beam height cannot be met simply. Development is in progress to compensate for the dipolar resonance either by suitable beam separation in all intersecting regions, taking into account the irregular phase advance between the intersections due to the low-β insertion, or by active damping.

7. Operational Techniques

Stacking at 26.6 GeV is performed in a manner similar to that described in a previous paper[1] except that

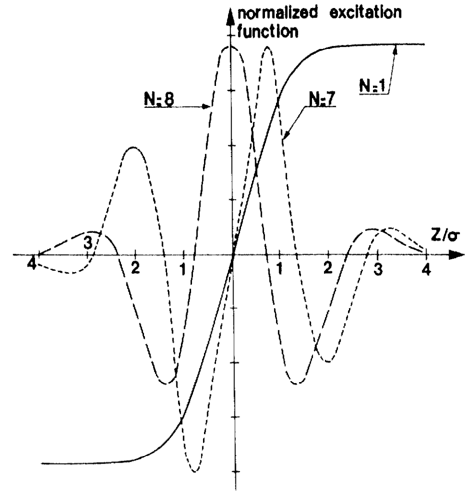

Fig. 1 Normalised Beam-Beam Resonance Excitation Function for one Intersection

improvements in the vacuum system and in operational procedures have permitted stacks of up to 36 Amps to be made. These improvements have equally enabled these high intensity currents to be stacked more efficiently, and reliably. The new approach to magnet cycling has improved the reproducibility of the magnetic machine, in particular with respect to the horizontal closed orbit, which governs the available aperture during acceleration. The 36A stack at 26 GeV would ideally be built with a momentum spread of 3% (with an average width of 60 mm and a density of 0.6 A/mm). In practice, a somewhat lower current is stacked (Fig. 2) in order to ensure a safety margin against transverse instability and to avoid problems during acceleration. The density during stacking is controlled by regulating the intensity of the injected beam pulses by vertical scraping. After stacking, the withdrawal of the injection kicker magnets allows the stack to be centered in the vacuum chamber at 26.6 GeV, thus increasing the available horizontal aperture for phase displacement acceleration.

Acceleration of the first stack takes place with no beam circulating in the other ring and the total current loss during this acceleration is only around 3% (Fig. 3). Prior to the acceleration of the second stack, a small test stack of around 5 A at 26 GeV is made in the second ring. Both beams are then steered vertically so as to define the zero beam separation in the intersections. From this reference position the beams are separated vertically by 3 to 5σ (where σ is the rms beam height, i.e. σ ≃ 1.2 mm) so as to reduce all higher order resonance excitation. This separation is maintained during the stacking and acceleration of the second beam and beam loss is reduced to around 7% in this way. The vertical positions for optimum beam-beam collision are restored before permitting physics data taking.

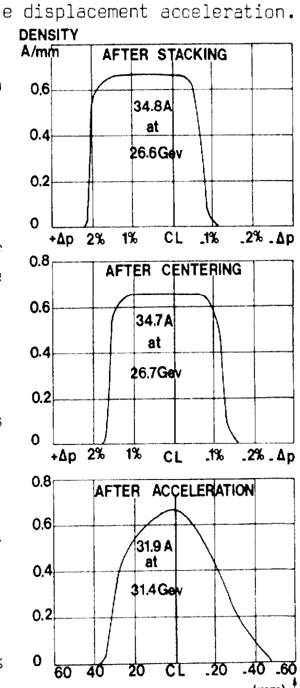

Fig. 2 Stack Profile before and after Acceleration

During the actual acceleration process, advantage may be taken of the ac component produced in the coasting beam by the sweeping empty RF buckets. From beam pick-ups, signals are obtained which indicate the stack position, the closed orbit distortion, the stack density profile and if the beam is subjected to weak transverse excitation the tune values in the stack may also be determined[10]. Based on this information, corrections are applied to the machine tune and the closed orbit whenever variations exceed prescribed limits. A system of beam loss ionization chambers is triggered on every RF sweep and the examination of the resulting beam loss pattern and its timing can indicate the source of the beam loss, e.g. inner/outer aperture limit, resonance excitation, RF noise etc. Finally, signals of the natural Schottky noise[11] are used to measure the stack density profile (Fig. 2) of the coasting beam and also the tune values at the edges of the stack.

8. Performance for physics data-taking

During physics data-taking periods, the betatron amplitudes of the particles are continuously growing due to the high order machine and coasting beam-beam resonance excitation, intra beam scattering and to a lesser extent collisions with the residual gas. Power supply fluctuations may also be transmitted onto the beams. The result is that interventions are necessary at 2-5 hour intervals, during which the beam "halo" is removed by thin foil scrapers. A comprehensive collimator system[9] limits background in the intersections during these interventions and during stable beam periods. Furthermore, adjustment of tune and closed orbits is possible in order to minimise background levels for experimenters.

The improvements in ISR luminosity performance at 31.4 GeV since 1977 are shown in Fig. 3. Table 1 shows further data on runs for physics.

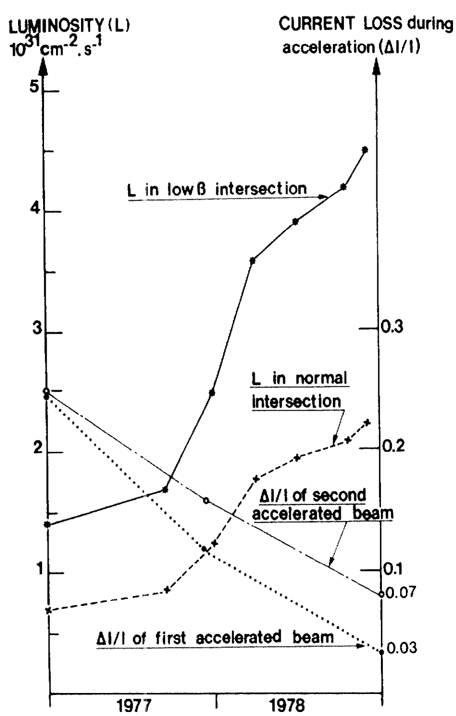

Fig. 3 : Luminosity performance and reduction of acceleration losses

Table 1 : Representative data of 31 GeV runs for physics
Initial current : 25-34 A, Initial Luminosity see Fig. 3
Average effective beam height = 4.3 mm
Loss in luminosity : 0.65% per hour
Beam current loss rate : 0.02% per hour
Setting up, filling and acceleration time : 8-12 hours
Data taking time : 50-60 hours.

9. Conclusion

The ISR are currently operated close to the long-term vacuum and transverse stability limits; developments to the relevant systems are in progress and combined with improved exploitation of the control system and with new diagnostics[12], will provide the capability to obtain 40 A of circulating beam current at 31.4 GeV.

10. Acknowledgements

This paper summarises the achievements of all the staff of the ISR Division. We should like to thank the operations technicians for their competent support in the realisation of the 31.4 GeV running program.

11. References

1. C. Fischer et al.: "Operation of the CERN-ISR for High Luminosity" IEEE Trans. Nucl. Sci. NS-24, no. 3 pp 1515-1517, 1977.

2. E. Ciapala, S. Myers, C. Wyss: "Phase displacement acceleration of high intensity stacks in the CERN-ISR", IEE Trans. Nucl. Sci. NS-24, No. 3, pp 1431-1433, 1977.

3. E. Ciapala, R. Keyser, S. Myers: "The CERN ISR Control Scheme for Acceleration by Phase Displacement", this Conference (D-29).

4. S. Myers, E. Peschardt: "The Efficiency of Acceleration by Phase Displacement in the Presence of RF Noise", this Conference (F-25).

5. E. Ciapala, A. Hofmann, S. Myers: "The Variation of γ_T with $\Delta p/p$ in the CERN ISR", this Conference (M-28).

6. H. Frischholz, W. Schnell: "Compensation of beam loading in the ISR RF cavities", IEEE Trans. Nucl. Sci. NS-24, No. 3, pp 1683-1685, 1977.

7. J.P. Gourber, E. Keil, S. Pichler: "The first high luminosity insertion in the ISR", IEEE Trans Nucl. Sci. NS-22, No. 3, pp 1419-1422, 1975.

8. J.P. Gourber et al.: "Overlap knock-out resonances in the CERN ISR", IEEE Trans. Nucl. Sci. NS-24, no. 3, pp 1405-1407, 1977.

9. T. Risselada et al.: "The ISR Collimator System", this Conference (J-41).

10. D. Kemp, E. Peschardt, A. Vaughan: "On line Q-measurement during phase displacement acceleration", this Conference (E-31).

11. J. Borer et al: "Non destructive diagnostics of coasting beams with Schottky noise", IXth Conf. on High Energy Accelerators, SLAC, 1974.

12. J. Borer et al.: "Information from beam response to longitudinal and transverse excitation", this Conference (D-32).