© 1973 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

EXTENSION OF THE CERN ISR ENERGY BY ACCELERATION OF STACKED BEAMS

S. Hansen, K.N. Henrichsen, M. de Jonge
CERN
Geneva, Switzerland

Summary

The proton beams in the CERN Intersecting Storage Rings (ISR) have been accelerated to achieve colliding beams at 31.4 GeV/c, equivalent to a momentum of above 2000 GeV/c if a conventional accelerator with a stationary target were used. High density stacks were made at 26.5 GeV/c from which a part was rebunched with the maximum available RF voltage. The rebunched beam was kept near central orbit while the magnetic field was gradually increased to its maximum value. The major problem was to keep the betatron oscillation frequencies unchanged while changing the magnetic field thus avoiding any blow-up of the beam due to resonances. The corrections of the highly non-linear saturation effects of the main magnet were achieved by a computer controlled tuning of the field by excitation of the poleface windings and sextupole lenses. Closed orbit corrections were applied throughout the acceleration. Colliding beams with currents above 0.5 A were obtained.

1. Magnetic Field Requirements

1.1 Working Line

The requirements for distribution of betatron oscillation frequencies (working line) for accelerated beams in the ISR differ from those for normal operation with stacked beams. Due to the narrow momentum distribution of the rebunched beam, only a small space in the Q_V/Q_H stability diagram is needed during the acceleration itself. On the other hand, this space must be completely free of excited resonances because of the tuning of the magnet during the acceleration. Furthermore, the stacking at maximum intensity requires a large Q-spread. This demand will, however, cause low Q-spreads near the injection orbit. The alternative to the consequent difficult RF trapping would be the blow-up of the beam by stacking through a resonance. The location of the working line in the Q_V/Q_H stability diagram is shown in Figure 1. This line was chosen mainly because it was near to the conditions of the uncorrected magnet, thus making the initial saturation corrections relatively simple. Furthermore, it had already proved successful for low beam currents during the early days of ISR operation.

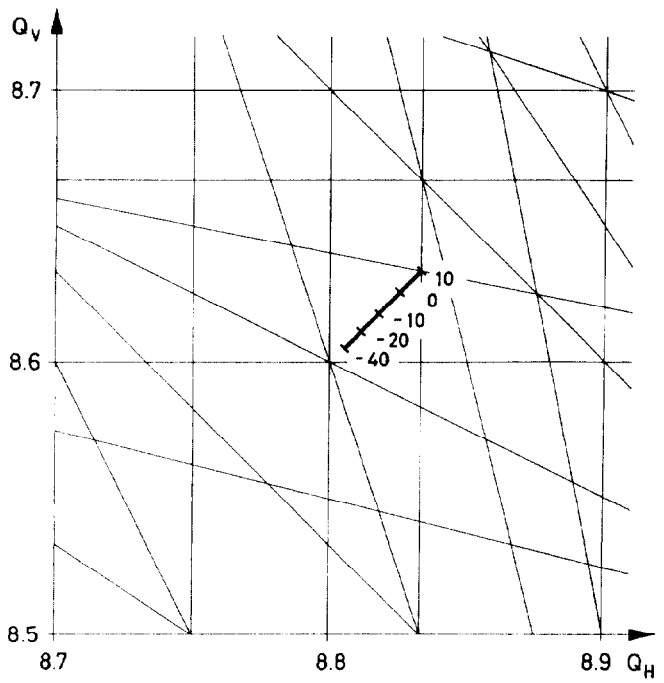


Figure 1. Working Line in the Q_V/Q_H Stability Diagram

1.2 Tuning of the Main Magnet

The highly non-linear magnetic saturation effects were compensated by excitation of the poleface windings. The total of 24 independent current circuits distributed on the poles of the magnet makes very precise corrections possible.

The initial current settings were based on the results of the systematic magnetic measurements, performed during the construction of the ISR. Further tuning was done according to measurements of Q-values at different energies by the application of multipole corrections using the poleface windings. A table of the necessary current settings at six different beam momenta between 26.5 and 31.4 GeV/c was determined in the following way: a single pulse was placed circulating at central orbit where it was kept bunched and accelerated by simultaneous adjustments of the main power supply, the auxiliary power supplies and the applied radio frequency. At each of the particle momentum values, the beam was displaced to different radial positions by the radio frequency and the corresponding Q-values were measured. The wanted betatron frequency distribution was then obtained by the application of multipole corrections.

1.3 Closed Orbit Corrections

Horizontal closed orbit corrections were applied during the acceleration by excitation of the orbit correction windings according to precalculated values.

The resulting closed orbits were measured. At 31.4 GeV/c, the peak-to-peak values were about 16 mm for both rings. This distortion was acceptable due to the narrow beam width.

2. Rebunching the Stacked Beam

To rebunch the stacked beam, the following method was used. A stack was made with highest possible density with the chosen working line. The width in momentum Δp of the stack was made large compared to the width in momentum $\Delta p'$ of the rebunching RF buckets. The RF frequency was adjusted to coincide with the central part of the stack and the RF voltage was switched on abruptly so that RF buckets were formed in the middle of the stack.

By making $\Delta p > \Delta p'$, no great precision in the frequency adjustment was required and no adiabatic turn-on of RF voltage was needed. The rebunching operation can be performed with the existing RF system. The dis-

advantage of this method is that the non-rebunched part of the stack is lost when the magnetic field is changed.

When the beam was kept bunched without phase lock, the bunch structure disappeared rapidly when the magnetic field was changed. Thus in order to accelerate the rebunched beam to higher momenta, phase lock must be used. The phase lock can be switched on in two ways, either simultaneously with the RF voltage or when bunches have been formed. The best results were obtained when phase lock was switched on at the same moment as the RF voltage. The presence of the buckets in the stack modulates the stack sufficiently to create a signal large enough for the phase lock to lock in.

With phase lock the beam can be kept bunched without any noticeable change in the bunch structure (see Figure 2) for more than one hour. This provides ample time for the acceleration from 26.5 to 31.4 GeV/c.

The total current that can be rebunched, I_{tot}, is a function of the bucket area used for the rebunching, the PS bunch area, the overall efficiency of the ISR and the current injected from the PS:

$$I_{tot} = \frac{3}{2} \cdot \frac{A_{reb}}{A_{ps}} \cdot \eta \cdot \bar{I}_{ps}$$

where

A_{reb} = area of rebunching bucket
A_{ps} = area of injected bunch
η = overall ISR efficiency defined as the ratio of phase space density in the stack and at injection
$\bar{I}_{ps}$ = average current injected per pulse from the PS during the stacking process.

The factor 3/2 originates from the circumference ratio ISR - PS and is only applicable when stacking is done with the suppressed bucket scheme.

The area of the rebunching bucket has an upper limit determined by the maximum RF voltage available, typically 20 kV, which yields a bucket area of 0.27 ($\Delta p/m_o c$, ϕ_{RF}) at 26.5 GeV/c.

Given the PS bunch area of 10^{-2} ($\Delta p/m_o c$, ϕ_{RF}) the overall ISR efficiency of about 50 % and an average current $\bar{I}_{ps} \approx 70$ mA, the total current that theoretically can be rebunched is found to be $I_{tot} = 1.4$ A.

The actual amount of rebunched current is difficult to measure, since the magnetic field changes required to remove the non-rebunched part of the stack also create losses of protons from the buckets.

The present maximum rebunched current is estimated to be around 850 mA. The difference between theoretical and practical value of the rebunched current is probably due to

a) the optimum density cannot be made with the working line used at present,

b) transients during the switching on of the RF voltage and phase lock as well as the changes in magnetic field reduce the longitudinal phase plane density.

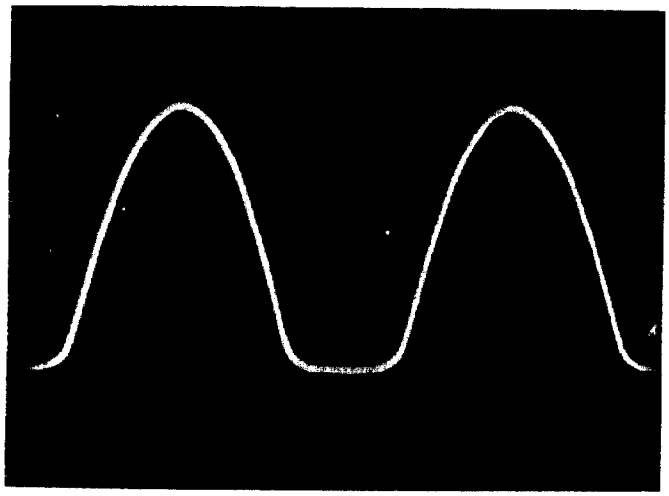


Figure 2. Bunches at 31.4 GeV/c, Ring 2, 505 mA

3. Acceleration

The change of RF frequency required to keep the beam in the centre of the vacuum chamber during the increase of magnetic field was made manually. The main magnet power supply was also adjusted manually, current steps of 1 °/oo of full scale each second being found sufficiently small and yet convenient to handle.

The auxiliary power supplies (about 35 in total for each ring) were changed simultaneously and according to a table of current settings by the ISR control computer. The basic difficulty of the acceleration process was the synchronization of magnetic and RF adjustments. If these are not properly timed, considerable losses of current occur.

During the acceleration from 26.5 to 31.4 GeV/c, typically about 10 % of the rebunched beam was lost. A 15 % reduction of the effective beam height was observed during the acceleration.

The technique of the acceleration is now being improved by computer control of the main magnet power supply and automatic adjustment of RF frequency.

4. Colliding Beams at 31.4 GeV/c

Physics experiments at 31.4 GeV/c have taken place during three runs for a total of 42 hours. Highest luminosity of 5×10^{27} $cm^{-2}s^{-1}$ was reached over a period of 16 hours. The beam loss rate was less than 2 ppm/min.

Acknowledgements

The authors are indebted to B. Autin for calculating the closed orbit corrections, to J. Borer for the measurements of the closed orbits, to P. Brown for his assistance in the Q-measurements and to R. Keyser for programming the control computer.