ACCELERATION BY PHASE DISPLACEMENT IN THE ISR

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Summary

Acceleration by phase displacement is used in the ISR to accelerate stacked protons from 26 GeV/c to 31.4 GeV/c. In the phase displacement process empty RF buckets are moved through the stack from higher to lower momentum which results in a shift of the stacked beam towards higher momentum. The total momentum shift is determined by the available RF voltage, the stable phase angle ϕ_s and the number of passages of the empty buckets through the stack. The stable phase angle ϕ_s should be as small as the time and RF noise permit, in order to reduce the dilution of longitudinal phase space density inherent in the process. One of the main difficulties encountered was the synchronisation of the magnetic field adjustments and the RF system. Twenty-six power supplies are adjusted simultaneously by the control computer in order to keep the betatron frequencies constant during the acceleration. To reduce losses resulting from beam-beam effects, the betatron frequency band used must be free of resonances and the beams have to be separated in the intersections during acceleration.

Introduction

The first attempts to accelerate stacked protons in the ISR to 31.4 GeV/c were made by means of re-bunching. The available RF voltage, however, limits the total current that can be accelerated to 31.4 GeV/c to about 1A[1]. In order to overcome this limitation the method of phase displacement acceleration has been developed. This method is at present operational and currently used in the ISR for preparation of colliding beams for physics experiments at 31 GeV/c.

Beam currents of up to 6A have been accelerated by this method. The highest luminosity so far achieved has been 0.36 10^{30}cm^{-2}sec^{-1}, but a luminosity of 10^{30} cm^{-2}sec^{-1} seems well within reach.

Phase displacement acceleration

Large stacks can be accelerated or decelerated with a medium power radio frequency system by means of "phase displacement". In this process the frequency of the radio frequency system is modulated in such a way that empty RF buckets are generated which are carried all the way through the stack repetitively. The change in momentum which the stack experiences when an empty bucket is carried through is however accompanied by a reduction in the longitudinal phase-space density, which is the main disadvantage of the process.

The choice of the RF parameters - stable phase angle, sin ϕ_s, and RF voltage V - for the phase displacement process is a compromise between an acceptable density reduction and the total time spent during the process.

The density reduction, which can be described by the root mean square momentum spread - δp_{rms} - introduced in the stack by the passage of n empty buckets, is given by

$$\delta p_{rms} = \sin \phi_s \cdot \delta p_o(p,V)\sqrt{n} \qquad (1)$$

where $2\pi\delta p_o(p,V)$ is the area of the stationary bucket that would be generated by the actual RF voltage V at $\sin \phi_s = 0$. This relationship, which was derived theoretically[2] and studied with a computer simulation[3], has been verified experimentally and good agreement has been found, as can be seen from Fig. 1.

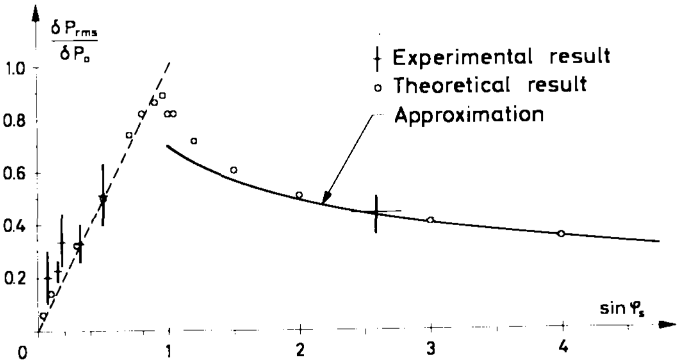

Fig. 1. Normalised r.m.s. momentum spread as function of sin ϕ_s.

The time t spent by one passage of an empty bucket through the stack is given by

$$t = \frac{s\Delta p}{\dot{p}} = \frac{s\Delta p\cdot 2\pi R\cdot m_o c}{V\sin\phi_s} \qquad (2)$$

where Δp is the width of the stack in momentum at the beginning of the process and $\dot{p}$ is the rate of change of momentum of the empty bucket, which is independent of p when sin ϕ_s and V are kept constant during the process.

The safety factor s has to be introduced since the total momentum bite traversed by the empty buckets should always be considerably bigger than the width of the stack in order to allow for the growth in Δp inherent in the process and to avoid additional density reduction due to switching transients, which occur when the RF voltage is switched on and off at the beginning and the end of the empty bucket sweeps.

The total number of passages n required to change the average momentum of a stack from p_1 to $p_2 (p_2 > p_1)$ is given by

$$n = \frac{p_2-p_1}{\delta p_o(p,V)\cdot\alpha(\sin\phi_s)} \qquad (3)$$

with $\alpha(\sin\phi_s)$ the bucket area parameter.

Combining (1) and (3) one finds

$$\delta p_{rms} = \frac{\sin\phi_s}{\sqrt{\alpha(\sin\phi_s)}}\cdot\sqrt{p_2-p_1}\cdot\sqrt{\delta p_o(p,V)} \qquad (4)$$

which shows a strong dependence of δp_{rms} on the choice of $\sin\phi_s$ and a weak influence of the voltage V since δp_o is proportional to $\sqrt{V}$. The dependence of δp_{rms} on momentum p is also very weak when p is well above transition energy.

To minimize time and density reduction the highest possible RF voltage should be used together with the lowest value of $\sin\phi_s$ which seems practical from the point of view of the total time spent.

The working line

The band covered by the tune in the stack is shown in Fig. 2. This working line is similar to the line frequently used for the preparation of medium intensity stacks for physics.

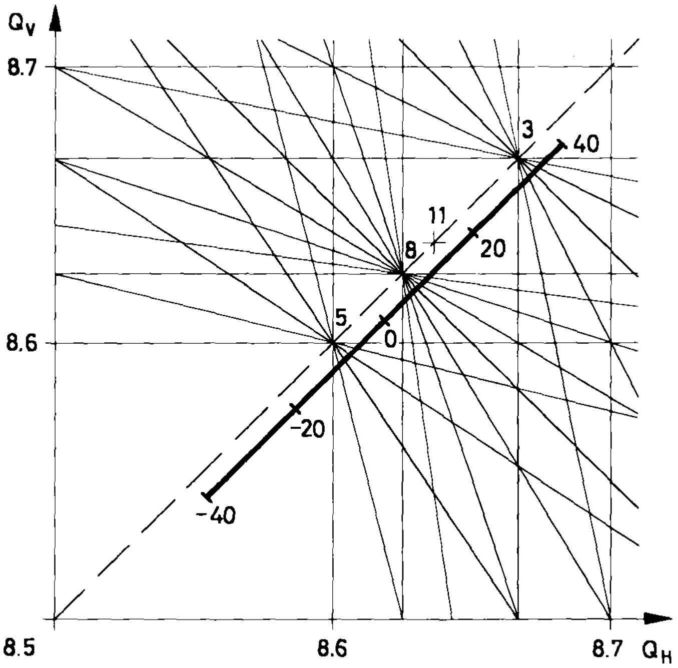

Fig. 2. The working line used for the phase displacement acceleration.

The chosen region provides 35 mm of radial space, free of resonances of an order lower than 8. Space-charge effects limit the region slightly but no compensation has been necessary hitherto. The series of 8th order resonances, $nQ_V + (8-n)Q_H = 69$, and the series of 11th order resonances, $mQ_V + (11-m)Q_H = 95$, are those of the lowest order present.

Beam loss due to the excitation of these resonances is not observed during the normal operation of the ISR. However, during the acceleration process these resonances are excited much more strongly, especially by beam-beam effects[4] when a beam is present in the other ring.

Furthermore the resonances will move slightly relative to the stack because of the imperfections when tuning the magnet. This movement can cause serious beam losses depending directly on the precision in controlling the magnetic field distribution.

Tuning the magnet

The configuration of the magnetic field is kept proportional to the beam momentum at central orbit over the full energy range by the excitation of the pole-face windings, the focussing and defocussing magnet units, as well as the excitation of the localized sextupole lenses[5]. The corrections are highly non-linear due to the saturation in the magnet core.
An example of the distribution of the pole-face winding currents as function of radial position and momentum is shown in Fig. 3.

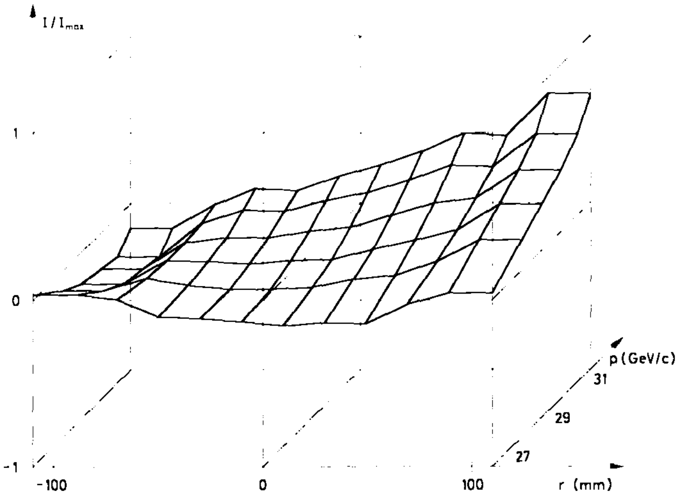

Fig. 3. Normalized currents in the pole-face windings of the focussing magnet units as function of radial position and momentum.

The resulting compensation of the magnetic field gradient is shown in Fig. 4.

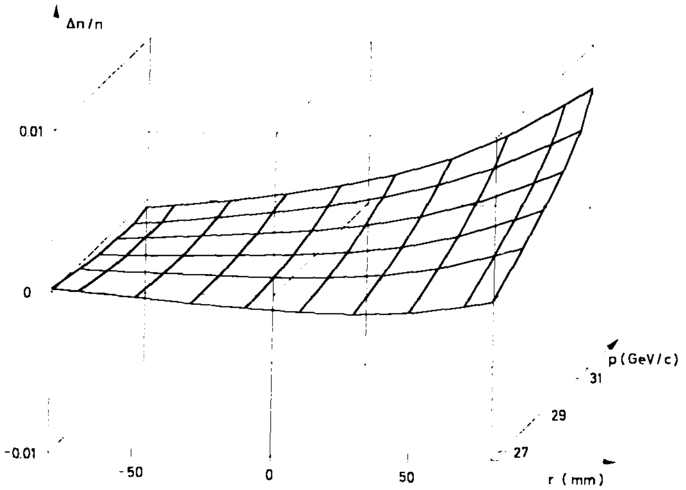

Fig. 4. Normalized field-gradient compensation as a function of radial position and momentum.

The working lines were measured and adjusted for six different values of beam momentum. To establish working lines at intermediate beam momenta linear interpolation is used.

Application of the phase displacement acceleration in the ISR

In the ISR the phase displacement method of acceleration is used to accelerate stacked proton beams from 26.5 GeV/c to 31.4 GeV/c.

The maximum voltage that can be generated by the ISR RF system is 20 kV which, however, cannot be used due to severe beam loading of the RF cavities. This beam loading is the result of the modulation of the stack by the empty buckets carried through, which results in induced voltages, equivalent to what would be induced by about 1A beam current, on the cavity gap. At present 12 kV is used which has proved to be a safe value.

The safety factor s has been chosen so that the total momentum bite travelled by the empty bucket is approximately three times the initial stack width.

The value of sin ϕ_s has been set to 0.1 which yields a total time for the acceleration process of about 20 minutes which is acceptable for routine operations. The bucket area for 12 kV RF voltage and sin ϕ_s = 0.1 is 0.168 ($\Delta p/m_oc$, ϕ_{RF}) at 26 GeV/c and increases to 0.177 ($\Delta p/m_0c$, ϕ_{RF}) at 31 GeV/c. A total of 184 empty bucket traversals is required to change the average momentum from 26.5 to 31.4 GeV/c. In Fig. 5 the RF empty bucket scans are shown at the beginning and at the end of a typical acceleration process, whereby an initial stack of 11.9A gave 6.2A at 31.4 GeV/c.

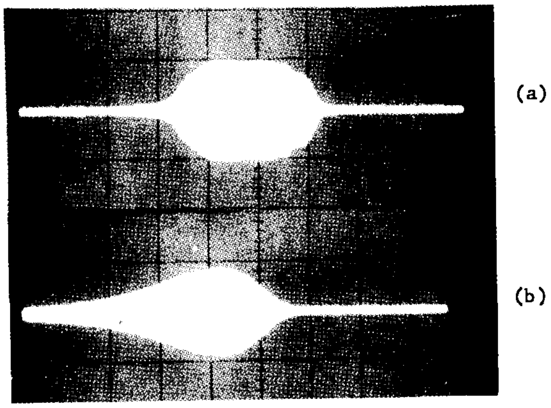

Fig. 5. Empty bucket signal induced on p.u. station

(a) initial 11.9A stack at 26.5 GeV/c
(b) 6A stack at 31 GeV/c after phase displacement

The acceleration process is at present performed under complete computer control. Main field and pole-face winding currents are changed in small steps, derived by linear interpolation from the currents measured at six different momenta. The magnitude of the steps is such that the increase in central orbit momentum due to main field change and one empty-bucket traversal are identical. The current changes in all power supplies and the empty-bucket sweep are initialized at the same time by the computer.

Synchronization of main field adjustments and RF system is guaranteed since field changes can only be applied when a signal, indicating the end of the empty bucket sweep, has been received by the computer.

The matching between empty bucket sweeps and field changes is, however, still not perfect since the variation of the bucket area as function of momentum has up till now not yet been taken into account.

Current losses during the acceleration process

During the acceleration process a considerable amount - typically between 40 and 50% - of the current stacked at 26 GeV/c is lost, which makes the process less efficient than would be expected from the density reduction described above.

The current losses seem to depend on both density and/or intensity, since the losses are always much bigger at the beginning of the acceleration process than towards the end (see Fig. 6).

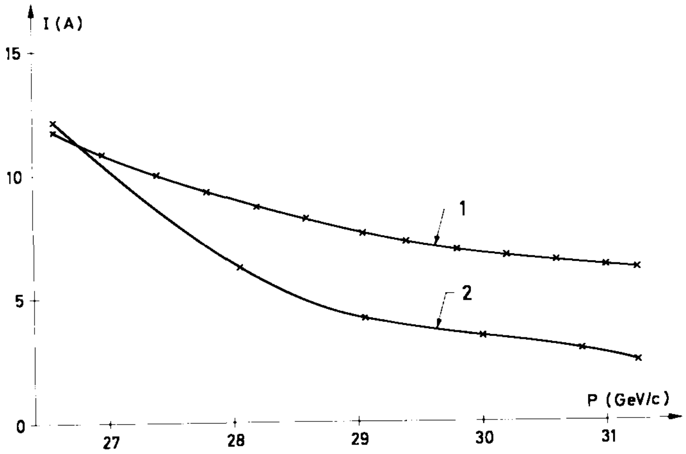

Fig. 6. Current as function of momentum

(1) single ring acceleration
(2) acceleration in presence of a stack

Several sources can be evoked for these current losses.

(a) Current loss due to RF noise

Due to noise in the RF system, which modulates both the phase and the amplitude of the RF voltage, particles are collected in the buckets when passing through the stack. If a significant number of particles is collected in the buckets, a bunched-beam-like signal should be observed on the pick-up stations as the bucket emerges from the stack. A signal of this nature can indeed be observed on a sufficiently sensitive pick-up. The particles collected in the buckets are most likely to be found near the sepatrix and since sin ϕ_s = 0.1 the bunching factor of the particles in the bucket will be small. The peak value of the signal induced on the pick-up stations, together with the low bunching factor, indicates that a total number of particles is trapped in the buckets corresponding to approximately 10 mA, which shows that RF noise is only partially responsible for the heavy current losses during the acceleration.

The number of particles collected in the bucket is a function of the density in the stack and the time the bucket spent in the stack. The RF noise is thus setting a lower limit to the value of sin ϕ_s. When sin ϕ_s is lowered to minimize δp_{rms} more time will be spent per empty bucket passage and the current loss due to particles trapped in the bucket will thus increase.

(b) Current losses due to non-linear resonance excitations

When an empty bucket moves through a stack heavy current losses occur even when the magnetic field is kept constant. These losses can be as high as 200 mA for a single empty bucket sweep through a stack which only contains relatively high order - 8th and 11th - resonances.

The reasons for these types of losses are the following: The presence of an empty bucket in the stack influences the particle trajectories and particles on orbits near the non-linear resonances are moved into the resonances and lost. Furthermore, the moving bucket does modulate the space charge detuning and as a consequence the resonances are not kept at the same position during the empty bucket sweep.

During the actual phase displacement the movements of the stack due to imperfect synchronisation between the RF system and magnetic field changes add to the losses.

The increase in momentum spread inherent in the process also contributes to the current losses since particles are moved into the 3rd and 5th order resonances which are the boundaries of our present "resonance free" region.

The relative strength of the different loss mechanisms is at present unknown and will be studied in the future.

The beam losses due to non-linear resonances are very much enhanced by beam-beam effects. Only about 1A of beam current is left after acceleration to 31 GeV/c if a beam of 5A is circulating in the other ring (see Fig. 5, curve 2). These losses are biggest in the region of the 8th order resonances. When separating the beam vertically by 10 mm in all the intersections, these losses can be avoided.

That the empty bucket in the stack is at the origin of the heavy current losses has been very clearly demonstrated by the beam-beam effect mentioned above, which appears during acceleration much more strongly than during normal stacking.

Acknowledgements

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