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OPERATION OF THE CERN-ISR FOR HIGH LUMINOSITY

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Summary

The CERN Intersecting Storage Rings are routinely operated at 26 GeV/c for physics experiments with proton beam intensities greater than 25 Amps and luminosities greater than $2.10^{31} cm^{-2} sec^{-1}$. Six out of eight intersection regions are used concurrently for colliding beam physics experiments. Each experiment is sensitive to background caused by protons lost from the stacked beams and locally induced radiation. Operational techniques for each of the essential processes involved in establishing stable beam conditions are reviewed and methods of maintaining minimal beam loss rates and the control of background in individual intersections throughout the beam lifetime of about 40 hours are presented.

Introduction

Since the first proton-proton colliding beam physics programme started at the I.S.R. in early 1971, there has been a persistent demand for running at the highest luminosity possible consistent with low background from proton losses through beam gas collisions, or from collisions of the protons in the beam halo with the vacuum chamber and/or other aperture limits.

In the I.S.R., the beam-beam interaction rate, luminosity, in each intersection is $L = k\ I_1 I_2 / h_{eff}$ where $I_1 I_2$ are the beam intensities (Ampères) in each ring respectively and h_{eff} is the effective height of the two beams' interaction diamond.

Within the intensity limits imposed by the vacuum and resistive wall instability criteria, maximum luminosity is attained by exploiting the full I.S.R. stacking aperture ($\Delta p/p = 3\% \simeq 60$ mm) and the high longitudinal phase plane density available from the CPS - CERN Proton Synchrotron - injector. This requires that closed orbit distortions and transverse emittances are minimal and the stack longitudinal density is rigorously controlled. Shaving, which reduces the injected beam's vertical emittance and intensity, is used as a means of regulating the density of a stack and results in a small effective height of the colliding beams.

Six hours are allocated to the preparation, set-up and filling of both rings for physics runs that are scheduled to use stable beams for periods of up to 40 hours. At the beginning of the stable beam period it is essential to have the beams correctly aligned so that the luminosity is maximised in all intersections, that the stacks have the correct tune over their full width and that there is sufficient clearance from the stacks extrema to the vacuum chamber limits to permit increase of the stack dimensions due to resonances, intra-beam and gas scattering etc. As the stack ages, the halo of the beam reaches the aperture limitations and the resulting background distribution has to be controlled.

Luminosity decreases at an average rate of ~1%/hour during high intensity runs, being mainly due to the rate of increase of the effective height of the two beams; the normal intensity loss rate, which is dependent upon many factors, the most important being the presence of low order resonances in the stack, power supply fluctuations etc., is typically < 300 ppm/hour.

Injection

Injection into the I.S.R. commences with a check-out of the beam transfer trajectories and the circulating beam orbit. 3 bunches (out of the 20 in the CPS) are used so that the risk of contamination caused by beam loss is low and the other CPS users can continue their programme. 100% injection efficiency is achieved by computer control of the injected beam trajectory to make it coincident with the equilibrium injection orbit of the I.S.R. This is achieved in both planes using only seven pulses and at the same time measuring the distortion of the equilibrium closed orbit. From the latter, corrections can be calculated and, if necessary, applied before proceeding with repetitive injection. Fine correction of the injection errors is left until both the closed orbits and the working line (tune) have been checked and, when necessary, adjusted. Complete correction of the injection error is an essential part of the setting-up since errors in the radial plane reduce the stacking space available and errors in the vertical plane are manifest as increased beam height, which reduces the luminosity proportionately. The injection optimisation process is completed by using a program of small steering adjustments on the injected beam to minimise the measured resultant betatron oscillation whilst it is still coherent. An injection error feedback damping system is used to eliminate any residual errors; particularly any pulse to pulse deviations of power supplies and ejection conditions that may occur. It has been shown that over a period of many months, the CPS beam transverse emittance is constant. Following this, 20 bunches from the CPS are used for all subsequent operations at an intensity of 300.10^{10} protons per pulse.

Working Line and Closed Orbit

In the I.S.R. the tune, or Q, values across the aperture are known as the working line and a special working line, called ELSA, has been developed (Fig. 1) for use with high luminosity physics beams. Because of the large tune spread this line provides inherent transverse stability for the coasting beam. In the stacked beam region there are no low order resonances ($n \leq 7$) that can cause unacceptable beam losses and background. Another feature is the distance from the line to the coupling resonance ($Q_V - Q_H = 0$) providing absence of mutual coupling between horizontal and vertical betatron motion thus ensuring that small vertical beam heights are conserved. All these permit a good safety margin when making adjustments to the tune and tune spread of a stacked beam.

During the first trials with the ELSA working line, the effect known as overlap knock-out was identified. This is due to the injected bunched beams' high frequency components being the same as those of the transverse betatron frequencies of the stacked beam and is manifested by the increase of the transverse emittances in the outer part of the stack resulting in loss of intensity and an increased effective beam height. Bunched beams can cause this effect on a stack in the same ring or in the other ring due to the beam-beam forces at the intersections. Operationally, this effect has been eliminated by making a temporary shift of the working line for the stacking period and by using a special r.f. acceleration programme to increase the bunch length at injection and thereby eliminates the harmful harmonics from the bunched beam frequency spectrum.

The detuning effect produced by the image forces of the stacked beam on itself must be compensated during stacking high intensity beams to maintain the correct tune and chromaticity throughout the stack. An on-line computer program calculates the space charge induced incoherent tune shift from the measured longitudinal density distribution of the stack; the latter being derived from computer analysis of the beam's longitudinal Schottky signal. Tune shifts, necessary to correct the working line across the full aperture, are calculated and applied after each 3A increase in beam intensity. There are ten Q-parameters dealt with in this program and the application of the correction is made by synchronous adjustments of the currents in the poleface windings.

Precision measurement and control of the working line is required through all phases of operation. Via the control computer the Q-meter, which uses single pulses anywhere in the aperture, the Q-diagram meter, which by the r.f. knock-out technique measures the Q in a stacked beam and the transverse Schottky device, which is a non-destructive means of determining the Q-values at stack extrema or at features, are all regularly used.

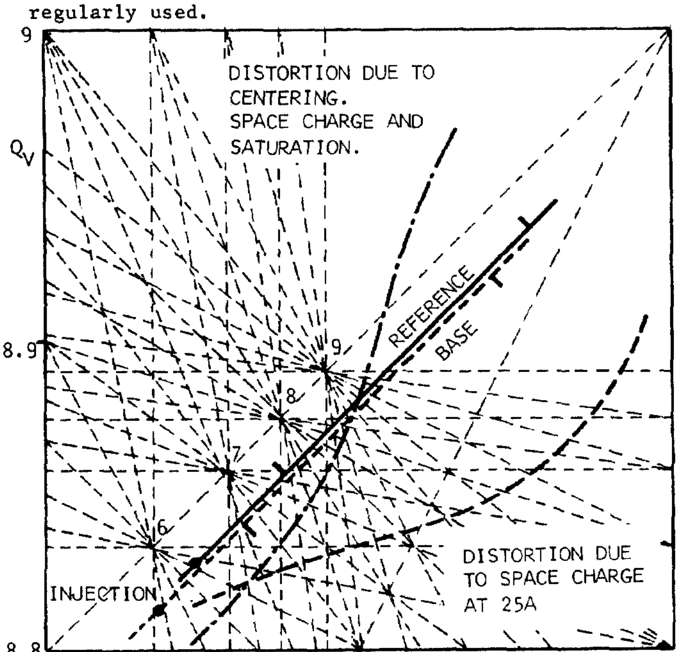

Fig. 1

Fig. 1 shows the ELSA working region. The reference line is that used for the stable beams, the base line for stacking. It is necessary to use the base line so that the beam blow-up effects of overlap knock-out at Q values > 8.930 can be avoided. The base line covers the 7th order resonances, which, although not important during stacking, have to be avoided during the stable beams period. For comparison, the space-charge distorted line is shown for a 25A stack on ELSA. In practice this does not develop since the compensation program is applied at each 3A increase of intensity during the stacking. Also shown is the distortion to the reference line resulting from displacing a 25 Amp stack in the aperture from +40; -20 to +30; -30 average mm.

Distortions of the closed orbit have to be rigorously controlled to ensure maximum aperture for the stack and its halo, to minimise the risk of contaminating the experimental physics regions and to maintain the beam colliding head-on. A quantitive measure of this distortion is made for each set-up using the 53 pick-up stations in each ring. Computer programs use this information, together with working line parameters to determine the location and excitation required of the minimal number of dipolar correcting elements. Since the closed orbit distortion is dependent on the tune across the aperture it is not possible to obtain one correction that is uniform for all orbits. This is the case when using the ELSA working line due to the proximity of the integer resonance and several cycles of measurement and correction are necessary to establish minimal distortion of the horizontal closed orbits in the stack and injection regions. Vertical orbits require special attention since it is imperative to make the two beams collide head-on over the complete, horizontal stack widths.

Stacked Beam Intensity

The two principal limits to the stacked beam intensity in the I.S.R. are the maximum current that can be tolerated for vacuum stability and the resistive wall coherent transverse stability limit. The former is well defined in machine development periods both for the short and long (> 10 hours) vacuum stability limits. During stacking the factors that influence the transverse stability limit, viz. longitudinal phase plane density, the chromaticity, and the stack's aspect ratio, have to be controlled at regular intervals. A dynamic feedback system is used to damp inherently unstable, low frequency modes due to the high transverse impedance at these low frequencies, and the compensation program maintains the correct tune and chromaticity for each part of the stack.

The high longitudinal phase plane density available from the CPS and the flexibility of the I.S.R. stacking programmes, permits optimisation of, stacking parameters for longitudinal density control, number of stacked pulses, filling time and the degree of shaving. Shaving, i.e. reduction of the injected beam intensity by diminishing the vertical emittance with a scraper was first used as a way of filling the I.S.R. with small effective height beams. In this way, the maximum luminosity was achieved with intensities less than the current vacuum limit. Shaving is still employed though the reasons have increased. Shaving the injected beam to a predetermined dimension gives a degree of control of the effective height of the stacked beam, and shaving to a controlled intensity gives a flexible means of regulating the stack density without resorting to changing CPS intensity and/or I.S.R. stacking parameters in mid-stack. In this process all protons with large vertical betatron amplitudes are removed. These contribute little to the total luminosity but, if allowed to remain in the stack, would be the primary source of background due to their proximity to the vacuum chamber.

Controlled reduction of the injected bunched beam intensity by shaving is also used to minimise the longitudinal emittance blow-up caused by the intensity dependent high frequency instability. The effects of this instability are further diminished by repetitive stacking to make a dilute pre-stack to shield the stacked pulses during the critical debunching phase. This shielding effect of the pre-stack also reduces the space-charge effect on the r.f. bucket facilitating precise control of the stacking parameters and resulting stack density.

Using these techniques, it is possible to establish, early in the filling process, the longitudinal density which can be achieved, the required shaving level, the minimum number of pulses required to fill the stack aperture with beams of minimal vertical emittance.

Stable Beam Conditions

After the stacking has been completed, the base working line is measured with the Q-diagram meter or by making density markers in the stack which are visible on both the longitudinal and transverse Schottky scans, thus providing the means for deducing the Q for several horizontal positions in the stack. With this measurement all accumulated errors, including the influence of the beam in the other ring can be taken into account when calculating the Q-shift necessary to change the tune of the stack to that of the reference line.

Following the removal of the injection apparatus the stack is centred in the horizontal aperture (~10 mm). This is done by increasing the main bending magnets' field at a slow rate and synchronously changing the poleface winding currents to maintain the stack tune against the detuning influence of the new stack position relative to the vacuum chamber wall. Centering gives added clearance for halo as well as placing the interaction diamond in the centre of the intersection region's detector geometry.

During stable beam periods, the beam decay rates would, if uniformly distributed, give 10^5–10^6 lost protons per sec. per 10 metre length of the machine and produce a background rate comparable to that of the beam-beam rate at an intersection. A system of standard scintillation telescopes is installed in each intersection so that a uniform assessment of the background conditions can be made, and are necessary for monitoring the consequences of machine adjustments.

Whenever a particular intersection region is subjected to very high background rates during stable beam periods, it is often possible to improve their conditions by steering the beam so that the halo is deflected away from the intersection concerned and onto a less sensitive area of the machine. To do this, there is a facility for measuring the orbit in the stack and programs for making local radial or vertical bumps (position or position and angle) at various points of the machine's azimuth. A complete measure of the closed orbit in the stack is essential to this manipulation so that the bump chosen is optimal and will not be detrimental to another intersection region.

Concentrating beam losses in discrete areas of the machine is the object of using the 2 metre long dump block as the vertical aperture limit and the system of scrapers and collimators that are used to define aperture occupied by the beam and its halo.

Scrapers (and shavers) are thin foils that intercept the coasting beam or its halo and, by multiple scattering, cause it to blow-up, predominantly in the vertical plane, to reach the dump block aperture limit.

Since the dump block is not a perfect absorber for small amplitude incident protons and since the scrapers scatter a significant amount, ~5%, to the horizontal aperture limits it has become necessary to install a system of collimators in the vertical and horizontal apertures. Although primarily foreseen to control the limit of the stable beam's halo, these devices are all useful during the setting up and filling phases to limit the risk of excessive induced radiation around the machine.

Ion chambers are located at azimuthal positions where the horizontal betatron amplitudes are large as well as in the intersection regions. These are used to measure the magnitude and location of beam losses as well as the efficiency of collimation. The large dynamic range of ion chambers makes them suitable for all phases of operation, set-up, filling and stable beams.

During the lifetime of a high intensity stacked beam it is sometimes necessary to correct the tune of the machine; this is the case whenever there has been a significant beam loss or the normal beam loss rate produces unacceptable background conditions. The latter occurs when the stack crosses low order non-linear resonances (≤ 7) and/or approaches the second order coupling resonance which through increase of the vertical height, which also diminishes the luminosity.

The luminosity depends upon the relative vertical alignment of the two beams at the crossing point. Steering is done in steps in all intersections at the same time to find the positions where the luminosity is maximum. A system of scintillation counter telescopes, in a standard configuration in each intersection, is used to count the beam-beam interaction rate and the corresponding background event rate for each step. From this, the beam positions for maximum luminosity and low backgrounds are set.

Stacked beam dimensions are measured using beam probes and the sodium curtain beam profile monitor. Whenever part of a stack (or halo) reaches the aperture limits and results in high background conditions, the beam has to be cleaned-up by using the scrapers in a selective way. This is normally required following any machine adjustment or perturbation.

Correlation of background and beam loss rates with 18 kV supply net work perturbations, power supply instabilities etc. is done with a 2 x 6 channel magnetic tape recorder; very fast (< 100 μsec) beam losses are monitored with a transient recorder.

Control Computer

All aspects of operating the I.S.R. are now realised via the Argus 500 control computer and more than 150 programs are regularly employed. Fixed head discs hold 400 programs and over over 1,200 data files. The operating system provides multiprogramming for 5 user levels, one being allocated to logging and alarm-scanning programs. Four terminals, combined with graphical displays, printers and copiers, are installed so that up to four programs called by operators may run in parallel. Each terminal has a set of program request buttons, to which a list of frequently used commands may be associated: over a hundred strings of such commands are held in the disc store. Thus, many standard operations can be performed rapidly with minimal use of the keyboards.

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