

HIGH PRECISION SCRAPERS FOR ISR LUMINOSITY MEASUREMENTS

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Summary

Two intersections of the CERN ISR have recently been equipped with beam scrapers. Controlled by computer, they permit the vertical profile of the circulating current intensity to be plotted automatically, so that the position of the centre of a beam can then be determined to within 10 microns. This has been used to calibrate the beam displacements used in the standard "Van der Meer" type luminosity measurements while the particle density profiles allow a direct evaluation of the luminosity. A description of the mechanism and the computer control system is given and some results are discussed.

1. Introduction

The usual method of determining the luminosity at the CERN ISR is by using the beam displacement method suggested by S. Van der Meer¹. The method has proved to be rather simple in operation, if somewhat lengthy, but the precision obtained depends largely on the local vertical closed orbit bumps which are used to provide the required beam separations. The accuracy needed in luminosity calibrations requires vertical displacements of the beams of one to two millimetres with a precision of 1%. The scrapers described here were designed to provide a method of determining the vertical position of a beam in an intersection to $\pm 10 \mu\text{m}$ so that the method of making the bumps could be checked and the displacements accurately calibrated. By completely destroying a beam with the scrapers, a vertical profile of the current intensity can be obtained which not only gives the beam position but also allows the vertical density profile to be calculated. From this a value for the effective height of the beams can be obtained and thus an independent calculation of the luminosity.

There are at present two scrapers of the type described in the ISR, one in intersection I5 and the other in intersection I7 where a low- β insertion² is being tested. They have thus been useful in evaluating the performance of the low- β insertion since the profiles obtained give directly the reduction in beam height achieved.

2. Construction of the Scrapers

The scraping technique used at the ISR³ relies on multiple coulomb scattering in a thin foil, which over a number of revolutions increases the betatron amplitude of the circulating protons until they fall onto the internal dump block. The foil thickness is chosen to give a suitable compromise between the scattering rate and heating in the foil. In the present application the scrapers must be in an intersection and cannot be close to, or have a definite phase relationship with, the dump block; a slow growth in amplitude is, therefore, desirable. A thickness of 0.1 mm of tantalum was chosen as this is sufficient to destroy most particles within 100 turns (300 psec) while calculations and previous experience showed that a scraping speed of

1 amp/sec would be possible without burning the foil. Two scraper blades are positioned, one above, and one below the beam (Fig. 1) with a relative precision of $\pm 10 \mu\text{m}$ and $\pm 0.2 \text{ mm}$ with reference to the horizontal plane of the machine. These tolerances are maintained in a vacuum chamber bakeable to 300°C and with a final vacuum in the 10^{-11} torr range.

Fig. 2 shows the mechanical details of the scraper designed for the ISR low- β insertion; the second scraper in intersection I5 being very similar. The scraper blade(1) consists of 20 individual 10 mm wide x 0.1 mm thick tantalum foils with their vertical edges ground to an angle of 45°. These foils are assembled side by side with a 50 μm gap between each one. In this way local expansion of a foil due to beam heating can be accommodated without distortion of the blade edge which must be straight to within 10 μm along its 200 mm length. The gaps, being at 45° to the proton beam axis, prevent protons passing unimpeded through them. A photograph of the completed blade assemblies is shown in Fig. 1.

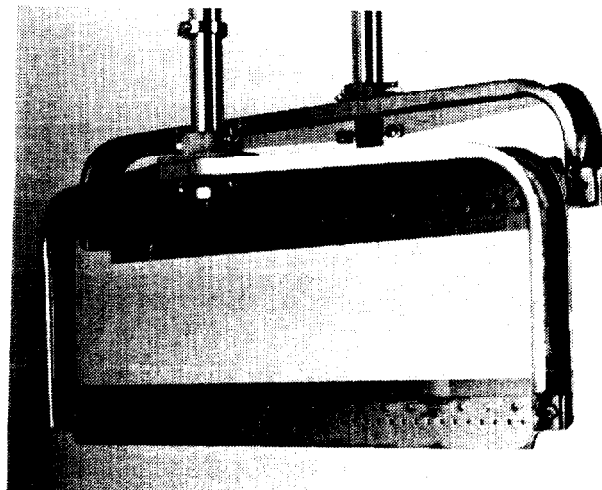


Fig. 1 Blade Assemblies for the Low- β scraper

The scraper blades are attached to frames(2) and to Stumattite insulators(3) so that the current due to protons producing secondary electron emission⁴ in the blades can be measured via the wires(4) and feed-throughs(5). By means of the arms(6) and the edge-welded stainless-steel bellows(7) the blades are attached to the carriage(8) of the displacement mechanism mounted outside the vacuum chamber flange(9). Using a ball bearing arrangement(10) to eliminate play, the carriage(8) can be moved along the guides(11) by a ball screw(12) having a precision of $\pm 10 \mu\text{m}$ in 10 cm and driven by a stepping motor(13). The displacement mechanism and hence the scraper blades can be tilted about the roller(14) using the adjusting screws(15).

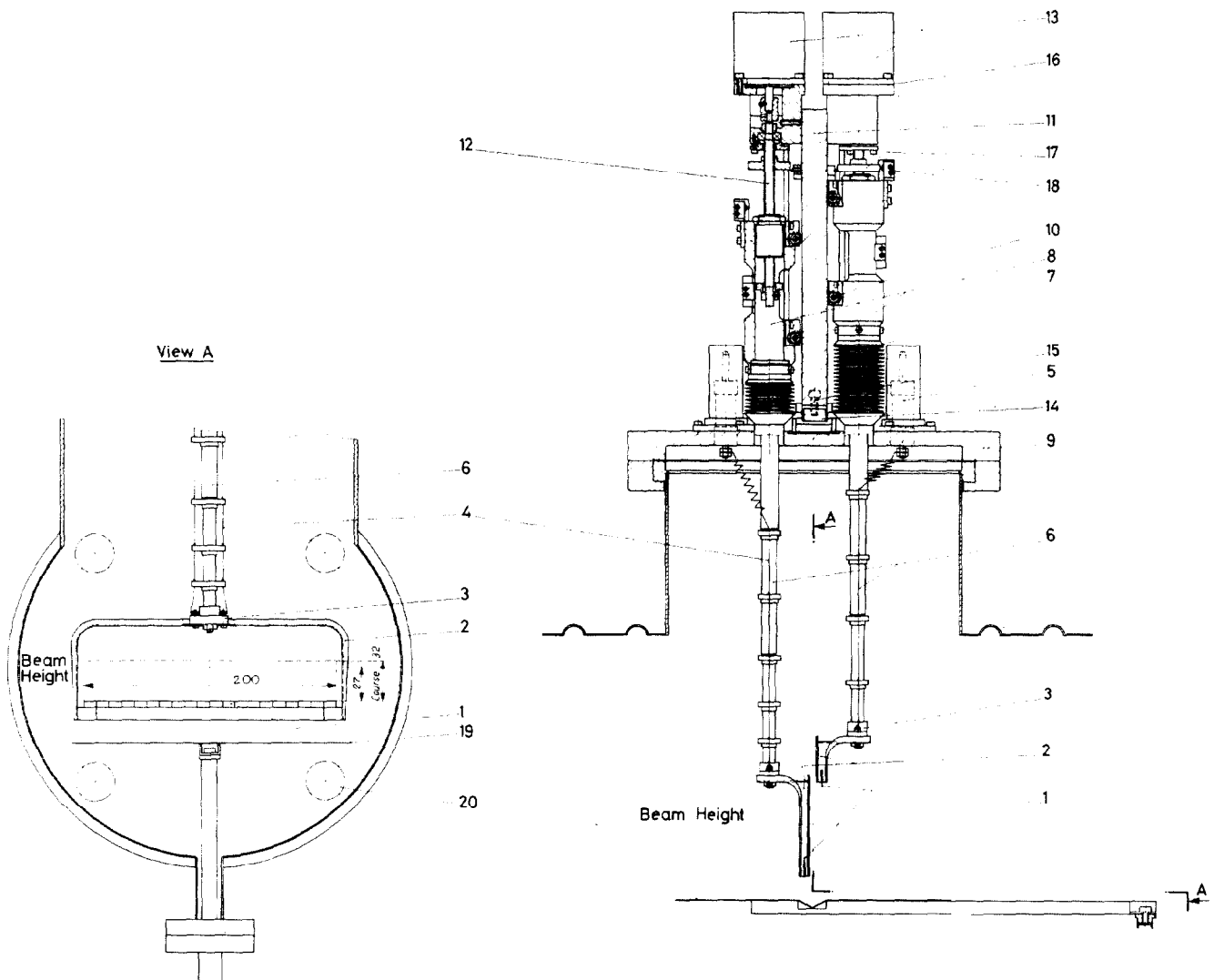


Fig. 2 Scrapper Assembly for Low- β Insertion

This allows the blades to be set horizontally to better than 0.5 mrad independently of the position of the vacuum chamber flange; an external reference plane(16) having previously been set parallel to the blades.

The stepping motor has 200 steps per revolution but each of these is divided electronically⁵ into 5 sub-steps in the form of a sinusoidal ladder. With the 2 mm pitch of the ball screw, this results in a blade movement of only 2 μ m per sub-step and has the added advantages of smoother movement than is normally associated with this type of motor together with faster acceleration and braking without losing steps. The latter point is important since the blade positions are determined by counting the steps fed to the motors using a cam(17) attached to the ball screw and a micro-switch(18) mounted on the carriage to give a fiducial position accurate to within one motor sub-step. The maximum speed of the blades is about 3 mm/sec.

Also shown in Fig. 1 is a clearing electrode(19) for removing secondary emission electrons from the scraper and forming part of the general ISR clearing

electrode system. The resistors(20) damp cavity resonances excited by the circulating beam.

3. Controls

Control of the scrapers can be carried out manually or by computer, the two main modes of operation being "Find Beam" and "Go to Set Position". In the former mode, the scraper blade advances towards the beam until the secondary electron emission current from the blade is equal to a pre-set value. The scraper then stops, records its position on a digital display and immediately retreats from the beam. In the second mode, the blade moves to a pre-determined position and by repeating this while simultaneously recording the circulating proton beam current, a vertical beam current profile can be plotted or the vertical position of the centre of the beam determined. The secondary emission facility is also used in this second mode but this time to monitor the rate at which protons are being scraped away and, if necessary, to retard blade advancement to prevent melting of the foils.

While other types of scraper⁶ have been in use in the ISR for several years, only manual operation has been possible. However, for the scrapers described here, computer control was foreseen from the outset and has resulted in a simple yet versatile system.

Each stepping motor drive system is connected to the ISR Argus computer by means of a Camac module (consisting of parallel registers for the input and output) so that simultaneous movement of the scraper blades is possible. Completion of an operation resets the drive system "busy" signal and causes the Camac module to interrupt the computer ready for the next operation.

Simplicity, reliability and speed were the main criteria upon which design of the software was based. Several control programs are available and permit, for example, partial analysis and display of information or output onto magnetic tape for off-line analysis. Several program and module error messages are incorporated, particularly those concerned with scraping away too much current, thus inhibiting further scraper movement. For additional safety, a software check limits the scraping rate to 100 mA/step.

4. Measurement of Beam Displacements

In the usual ISR luminosity calibration by the Van der Meer method, the beams are moved vertically using a beam steering program which calculates and sets the necessary currents in horizontal field magnets. The operation of this program and the precision of the displacements it gives, have been extensively checked by using the scrapers. Since the scraper measurement is naturally destructive, the measurement of a displacement requires the determination of the centres of two successively injected beams. In general single pulses of 80 mA are used. The stability of the vertical centre of successively injected pulses in the ISR has been carefully checked and found to be extremely good.

The following technique is used to find the vertical centre of a beam. Under computer control, both upper and lower scrapers are first used in the "Find Beam" mode to place them above and below the beam. The lower scraper is then advanced in discrete steps of 10 μm or more. After each step, the scraper remains stationary for 200 msec while the intensity of the circulating current is measured using the standard PIDC⁷ system. A precision of ± 0.02 mA in the value of the current is obtained in this time. The computer program thus advances the scraper at a rate of about 3 steps a second constructing a file of scraper position and remaining circulating current. After a predetermined number of steps n , the lower scraper is stopped and the upper advanced instead. The current is read after each step but the file is not continued until a significant amount of current has been removed, usually 1 mA, a further n steps are then made. The beam is completely destroyed in this manner, one scraper removing a substantial amount of current, giving a well defined edge to the beam, and the other finding that edge. A computer display of the resulting file is shown in Fig. 3. In this case there was a circulating current of 1 amp in each ring before the start of the measurement.

A value for the centre of the beam is found at each break by using a linear extrapolation of dI/dz before the break and a reflection of the opposite data points. The successive centres thus obtained at

different beam intensities typically have a spread of $\pm 5 \mu\text{m}$ for a step length of $50 \mu\text{m}$, and for beam intensities of about 100 mA. Since the whole operation takes about a minute, this spread includes the stability of the beam over this time, in addition to local errors in the driving screws. Beam stability may be the dominant effect since in the low- β insertion where the beam height is reduced by a factor of 2, the typical spread is only $\pm 2.5 \mu\text{m}$.

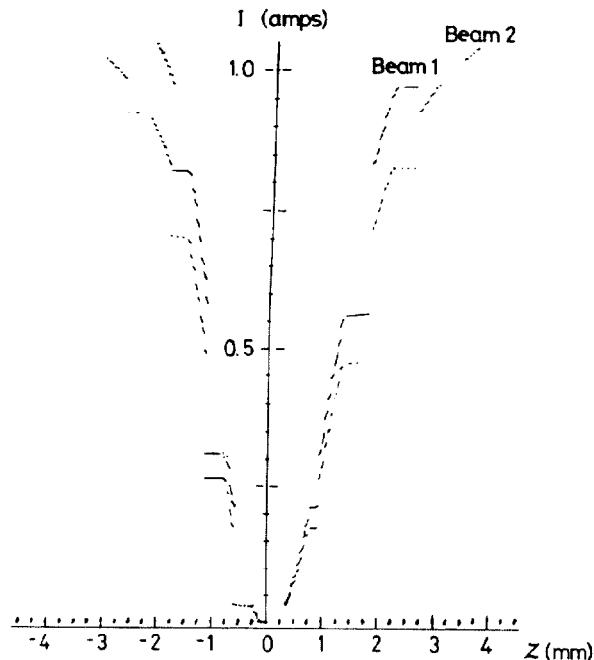


Fig. 3 : Circulating current I vs. scraper position z . The on-line computer display obtained by destroying two 22 GeV/c, 1 A beam with the scraper in intersection I7.

In measuring a beam displacement, all errors associated with alignment of the scrapers including the relative alignment of the two blades are irrelevant provided that care is taken to make all measurements with the beam at the same radial position. From the figures given above for the typical spread of results from a single scan, an error of $\pm 3 \mu\text{m}$ on a displacement of 1 mm can be deduced. The technique described was able to demonstrate clearly the effects of hysteresis in the steering magnets giving errors of only a few hundredths of a millimetre in the displacements used for luminosity calibrations.

5. Direct Determination of the ISR Luminosity

The scraper data illustrated in Fig. 3 can be used to generate a complete current profile of each beam once the beam centres have been determined. It has been shown⁸ that under the assumption of a perfectly aligned scraper and no coupling between the horizontal and vertical betatron oscillations, a current profile can be transformed into a real space density profile using :

$$\rho(z') = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{dI}{dz} \cdot \frac{dz}{\sqrt{z'^2 - z^2}} \quad (1)$$

where $\rho(z')$ is the local particle density at position z' on the vertical z axis and I is the circulating current.

This vertical density is precisely the parameter required to obtain the effective height of the beams since

$$h_{\text{eff}} = \frac{\int_{-\infty}^{\infty} \rho_1(z) dz \cdot \int_{-\infty}^{\infty} \rho_2(z) dz}{\int_{-\infty}^{\infty} \rho_1 \cdot \rho_2(z) dz} \quad (2)$$

where the subscripts refer to beams 1 and 2. The luminosity can then be obtained by substituting in the usual formula

$$L = \frac{I_1 \cdot I_2}{e^2 c h_{\text{eff}} \tan \alpha / 2} \quad (3)$$

where I_1 and I_2 are the initial circulating currents, α is the crossing angle, L is the initial luminosity and the other symbols have their usual meaning.

If equation 1 is used to transform the scraper data, the resulting density functions ρ_1 and ρ_2 are obtained on the same vertical scale since the scrapers are placed exactly at the intersection and pass through both beams simultaneously. An off-line analysis program has been written to numerically calculate the integrals of equations 1 and 2 and hence find the initial effective height.

Unfortunately, the initial assumption is rather critical as a small amount of coupling rapidly destroys the validity of equation 1⁹. The scraper scan yields the peak amplitude distribution in the vertical plane over a long time average, while the luminosity depends on the distribution of average amplitudes. In the ISR there is normally sufficient coupling to give an effective height some 10% larger than that obtained by the Van der Meer method. However, a purely empirical approach of exciting the machine's skew quadrupoles until the height of a single pulse, as measured by the scrapers, passes through a minimum, has given very promising results. A rather sharp minimum as a function of quadrupole current can be found and if the analysis is then made using the zero current point of the scraper profile as the beam centre, an approximately gaussian distribution of the density function is obtained and the calculated effective height is very close to that found by the standard methods. The analysis of the profiles of Fig. 3 gave $h_{\text{eff}} = 3.88$ to be compared with 3.94 ± 0.04 mm by the Van der Meer method.

6. Conclusion

The scrapers, their controls and the computer programs have proved to be entirely satisfactory and have adequately met the specification with regard to precision.

The technique for determining beam centres has given an accuracy considerably better than ± 0.01 mm and has allowed a detailed investigation of the techniques used to provide beam displacements in the usual method of measuring the ISR luminosity.

Profiles of the circulating current obtained with the scrapers have been of great practical use in the testing of the low- β insertion and have given values for the luminosity within a few per cent of those obtained by the Van der Meer method. A measurement of the luminosity by scraping has the disadvantage of being destructive but is potentially simple in operation and rather fast.

Acknowledgements

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