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THE CERN ISR COLLIMATOR SYSTEM

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Summary

Each ring of the ISR is equipped with a collimator system consisting of 10 movable, remotely controlled, blocks inside the vacuum system. One vertical and one horizontal collimator at the same azimuth limit the beam size during all machine operations. These primary collimators are followed at $\pi/2$, π and $3\pi/2$ betatron phase advance by secondary collimators, which intercept the high energy protons scattered at small angles from the surface of the primary collimators by Coulomb forces. This system makes it possible to limit the beam dimensions without scattering protons into the intersections downstream of the collimators. Considerable improvement has been achieved in background and induced radioactivity conditions in all physics intersections. The properties of different metals with respect to collimation, temperature rise and ultrahigh vacuum compatibility are discussed.

1. Introduction

At the ISR the high energy physics experiments are installed in 6 out of the 8 intersections, with sensitive detectors close to the vacuum chamber, and are, therefore, sensitive to (i) radioactivity induced during filling periods, and (ii) to background caused by loss of protons from circulating beams during physics periods.

Due to controlled beam loss during the stacking process (shaving and scraping) for every Amp stacked, one Amp is lost in the machine. From circulating beams 10^7 to 10^8 protons are lost per second during physics runs.

Obviously, the losses of these large numbers of protons have to be concentrated in an area well away from the physics experiments. In the early years of the ISR the beam size was limited by the internal dump absorber block in the vertical plane, and by thin foil scrapers in the horizontal plane[1]. It soon became clear that this was insufficient, as a large number of protons escaped from these aperture limitations, without being absorbed.

In 1974 a solution of placing vertical collimators downstream of the dump block was successfully tested. However, this was insufficient to cover the experiments in all intersections simultaneously and a study of a complete collimator system was undertaken.

A first set of horizontal collimators was installed in 1976, improving the protection of the most critical physics intersections. The system will be completed in March 1979, and is expected to protect the entire machine, the induced radioactivity and losses from circulating beams being concentrated in a small area around the location of the internal beam dump in each ring.

2. Theory of outscattering

At the ISR protons are lost during filling periods mainly by scraping with thin foil scrapers[1]. The internal dump absorber block, approximately 1/4 betatron wavelength downstream of the scrapers, is placed against the beam to absorb protons scattered by the scraper blade, and to limit the beam size in the vertical plane. In this case the protons strike the block less than 3 mm away from the edge (Fig. 1 a and b). In the case of protons lost from stable beams, where slow mechanisms are involved (intra-beam scattering, resonance excitation, collisions with residual gas), the distances to the edge are even smaller than 30 µm (Fig. 1c).

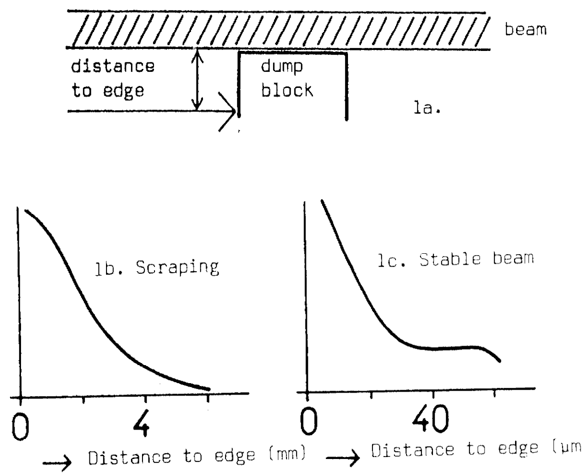

Fig. 1 Particle distribution (used in calculations)

These superficial impacts on the titanium block permit a significant part of the incoming protons to be scattered out of the block by multiple Coulomb scattering, without having any nuclear interaction with the nuclei in the block which would either stop the protons or scatter them with very large angle and momentum errors.

The angle and momentum errors resulting from non-nuclear interactions only (Coulomb scattering and ionisation) are so small that the larger part of the Coulomb scattered protons can actually circulate over some distance and be lost elsewhere around the machine. Experience has shown that they can be extremely harmful to the high energy physics experiments, either as direct background or by inducing radioactivity in the intersection vacuum chambers.

The conclusion was that with these superficial impacts, one single collimator (in this case the dump block) is not sufficient to stop protons with a high enough efficiency. In each plane the "primary" collimator has to be followed by "secondary" collimators.

Computer calculations[2] were carried out on outscattering from blocks of different metals. The outscattering probability, the mean path length inside the block before outscattering occurs, and the mean outscattering angle have been computed for an ideal flat block of infinite length parallel to a 26 GeV proton beam, in the two cases of "scraping" and "stable beam". The results are summarised in Table I.

The calculated outscattering probabilities are minimum values and can only be obtained if the block is perfectly flat and at least as long as the calculated "mean path" for the particular metal. This allows a first selection of suitable collimator metals, which should have a low out-scattering probability and a short mean path (the available space is often limited). In this respect tungsten and molybdenum are the most attractive candidates.

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Metal	Outscattering Probability (%)	Mean Path (mm)	Mean Angle (mrad)
SCRAPING :			
Copper	1.0	235	4.5
Steel	1.2	267	4.2
Tungsten	1.3	159	7.2
Molybdenum	1.4	200	5.4
Titanium	2.5	422	3.4
STABLE BEAM :			
Copper	37	49	1.1
Steel	38	53	1.1
Tungsten	38	32	1.8
Molybdenum	39	47	1.3
Titanium	42	76	0.9

Table I. Computer calculation of outscattering properties of metals suitable for collimation for the input distributions shown in Fig. 1

3. Collimator system required for the ISR

The momentum spread of an ISR circulating beam is 3%, requiring an average horizontal aperture of about 60 mm, whereas the average vertical beam height is only 6 mm. To limit the beam size in both planes 3 primary collimator blocks are therefore required: 2 horizontal (inner + outer) and 1 vertical. As each of these blocks scatters in both planes, it is important that all primary collimators be located at the same azimuth. In this way, they can be backed up by one and the same system of secondary collimators.

Due to the betatron oscillations angle errors are transformed into position errors at π/2 and 3π/2 phase advance. Momentum errors become horizontal position errors at π phase advance, due to the shift in radial equilibrium orbit (Fig. 2). In the scraping case the momentum loss in the block is of the order of 1% for 26 GeV protons, as around 1 MeV is lost per mm due to ionisation.

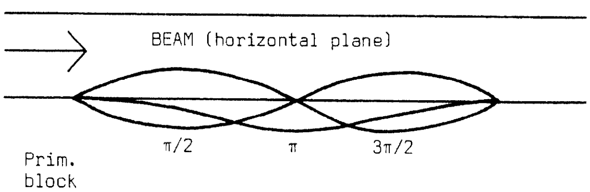

Fig. 2 Scattering from primary block

The average angle and momentum errors result in position errors of several cm. A secondary block, placed at one of the above mentioned phase advance locations close to the beam will then be hit by protons escaping from the primary block at large distances from the edge. The probability of outscattering from the secondary block is therefore negligeable.

Secondary horizontal collimators are required at both sides of the beam (inner/outer) at π/2 and 3π/2 downstream of the primary collimator, whereas in the vertical plane only one double upper/lower collimator at π/2 is sufficient. The momentum error collimator at π is only required in the horizontal plane, at the inside (low momentum side) of the beam. A complete collimator system consists thus of 7 blocks in the horizontal plane and 3 in the vertical plane per ring. An additional vertical collimator is mounted in front of the new ISR dump block[4].

The highest efficiency is obtained when the secondary collimators are positioned close to the circulating beam. It is essential that they do not actually touch the circulating beam, otherwise they would become a primary scatterer. A typical collimation curve is shown in fig. 3, representing the proton losses in the first intersection downstream of the collimator system, versus the lateral position of the π/2 collimator. The position range over which the maximum efficiency is obtained is only a few mm wide, which means that the collimators have to be positioned with a precision better than 1 mm with respect to the beam.

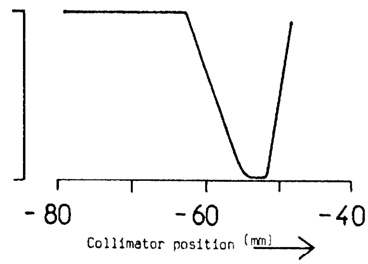

Fig. 3 Proton losses in first intersection downstream vs. position of horizontal collimator at π

The ideal azimuths as defined above are not available in the ISR. The actual locations are a compromise and the phase advances are slightly different from the ideal ones. This is shown in betatron phase space plots, where the acceptance of the vacuum chamber over 1 turn, the acceptance of the collimator system, and the beam emittance are plotted. A collimator block figures as a straight line, of which the slope corresponds to the betatron phase of the collimator location, and the distance to the origin represents the normalised distance of the block to the centre of the beam.

Ideally, a horizontal collimator system of 4 blocks at π/2 intervals figures as a square, but for reasons mentioned above, the square may be distorted.

The fact that the acceptance of the collimator system lies entirely inside the acceptance of the vacuum chamber means that the chamber is completely protected. In addition to protection against outscattering from the primary collimator, the system provides also protection against injection errors with any phase and against accidental changes of the closed orbit. A phase space plot of the ISR collimator system, valid for the currently used magnetic machine, is shown in Fig. 4.

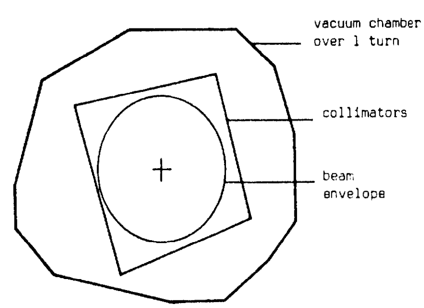

Fig. 4 Betatron phase space plot of ISR horizontal collimator system valid for the injection orbit

4. Blocks and Controls

The blocks are mounted inside the ultra high vacuum chamber. As the design is constrained by the available space, two types of collimators are installed :

a) a sufficiently long block in straight sections between magnets. For vertical collimators a 300 mm long block can be mounted in this space, and 270 mm in the horizontal plane. (Fig. 5).

b) a much shorter block installed through a pumping port at the end of a main magnet vacuum chamber. In this case a block of only 130 mm mounted on a 500 mm long arm can be accommodated. This length is adequate only for secondary collimators.

All primary blocks have a length greater than 270 mm.

Choice of metal. The first (vertical) blocks installed were made of stainless steel. For the horizontal secondary collimators, including the short 130 mm blocks, tungsten was chosen for its short absorption length, given the limited space.

The primary collimators, which were the last ones to be installed, will carry the heaviest thermal load. As sufficient available space could be found at these locations, the absorption length is not critical and the metal was chosen for its vacuum properties. Molybdenum is preferred to tungsten for two reasons : the outgassing rate is about a magnitude lower, and the heat capacity is 50% larger for the same volume. Additional cooling of the primary molybdenum blocks is not necessary. The temperature of the primary blocks is monitored with thermocouples. A maximum temperature rise of 50°C is estimated to be compatible with the ISR ultra-high vacuum. Experience shows that during normal filling periods this value is not exceeded.

Controls. The blocks are moved by stepping motors and their position is monitored by resolvers. The system has been designed for computer control via CAMAC, with a simplified but complete manual back-up facility. The maximum displacement speed has been set to 6 mm/s, with proper acceleration and deceleration cycles. The blocks can be moved in 5 µm steps under computer control or manually in 40 µm increments. Resolvers are used to measure the position with a precision better than 20 µm over a 50 mm stroke. Multiplexed controls are used, resulting in minimum cost for cables and electronics.

The displacements are interlocked with a beam loss detector, to avoid beam loss and damage to the collimator block surface.

5. Operational Use

The collimator blocks have to be positioned with high precision with respect to the circulating beam. During the set-up the optimum positions of the inner horizontal and of the vertical blocks are derived from a closed orbit measurement made with a single pulse on the injection orbit. A computer program, using harmonic analysis and interpolation, calculates the position of the beam centre and the beam size at each collimator and positions the blocks at a pre-set distance from the beam envelope. The blocks are kept at these positions during the entire filling period.

During stable beam periods, when the orbits are generally not known precisely, the collimator positions are optimised manually, using the background signals from scintillator counters in the intersections.

The optimum positions depend on the actual beam size, and may have to be adjusted occasionally.

The small step size (5 µm) permits collimator fine adjustments at any time, without risk of causing large background splashes which could damage the wire chambers in the physics experiments.

6. Results

The vertical secondary collimators have been in use since 1974, and have reduced backgrounds by as much as a factor of 20 during stable beam periods, particularly in the intersection downstream of the dump block in each ring, where very sensitive experiments are located. They are, however, less efficient during injection, due to the eccentric position of the injected beam in the vacuum chamber. The horizontal $\pi/2$ collimators, installed in 1977, have reduced the losses during the injection and stacking cycle in the intersections downstream of the dump block by a factor 10 to 20 (Fig. 3). However, it was often not possible to protect the other physics intersections with the same efficiency. It is expected that with the complete system, all intersections will be equally protected.

Dosimeter results[3] show that since the installation of the horizontal collimators, the integrated proton losses around the rings have decreased, except in the region of the collimator system, dedicated to this purpose.

7. Acknowledgements

We are indebted to F. LeNormand for the vacuum tests of the tungsten and molybdenum blocks. The proposal to install vertical collimators in 1974 was made by K. Potter and S. Turner. The collimators were designed and built by J. Genest and A. Maurer. The electronic equipment was built by I. Barnett, A. Marchand, H. Kropf and J-M. Vouillot, and the computer control software by P. Martucci.

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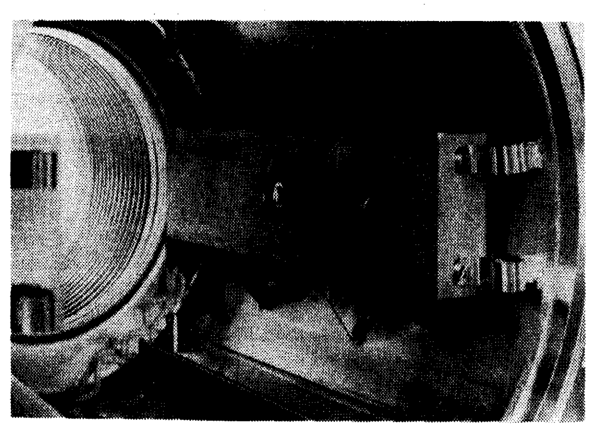

Fig. 5 Horizontal Collimator Block