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ADAPTIVE OPTICS FOR THE LEP 2 SYNCHROTRON LIGHT MONITORS

Burtin, G.; Colchester, R.J.; Gras, J.J.; Jung, R.; Vouillot, J.M.
CERN- Geneva - CH

Abstract

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Abstract

The image obtained with the LEP synchrotron radiation telescopes deteriorates, giving multiple and deformed images, when the beam energy goes beyond 80 GeV at beam currents above 2 mA. This problem is due to the deformation of the light extracting beryllium mirror, by as little as 1 µm, and had been predicted at the design stage. To overcome this problem, several changes together with an adaptive optics set-up have been introduced. These essentially consist of a cylindrically deformable mirror to compensate the cylindrical deformation of the beryllium mirror and a movable detector to compensate the spherical deformation. Both components are continuously adjusted as a function of beam current and energy.

1. INTRODUCTION

Four Synchrotron Radiation (SR) telescopes are installed in LEP around IP8 [1]. For each particle type there are two telescopes, one of them looks at the light emitted in the first normal dipole at the exit of the experimental straight section, where the Dispersion is very small, and one is located in the arc where the Dispersion is large: Fig. 1. With the data from the two telescopes it is possible to calculate the emittances and the energy spread of the beam for both horizontal and vertical directions.

The long distance between the telescopes and the accessible area in IP8 means that the telescopes have to be self-contained units incorporating all tuning facilities by remote control.

The optical set-up, the detector and the image signal processing have been optimised during the LEP 1 running period to provide the profile measurements with best precision [2]. The achieved accuracy has been established during cross-calibration runs by comparison with the wire scanners and the luminosity detectors of the experiments. The agreement of the vertical emittances determined by the different instruments has been demonstrated to be within 0 ± 0.1nm [3].

2. THE LEP 1 SR TELESCOPES

Each telescope is mounted on a standard 3.2 m optical bench housed inside a 3.5 m stainless steel tube for stability and protection. The telescope uses a spherical mirror, with a focal length of 4 m, as imaging device. A Magnification G = 0.2 is achieved with the help of folding mirrors. Chromatic filters, polarisation selection filters and linear density filters are incorporated in the set-up to control the wavelength, the polarisation components and to match the light intensity to the detector sensitivity to give the highest dynamic range.

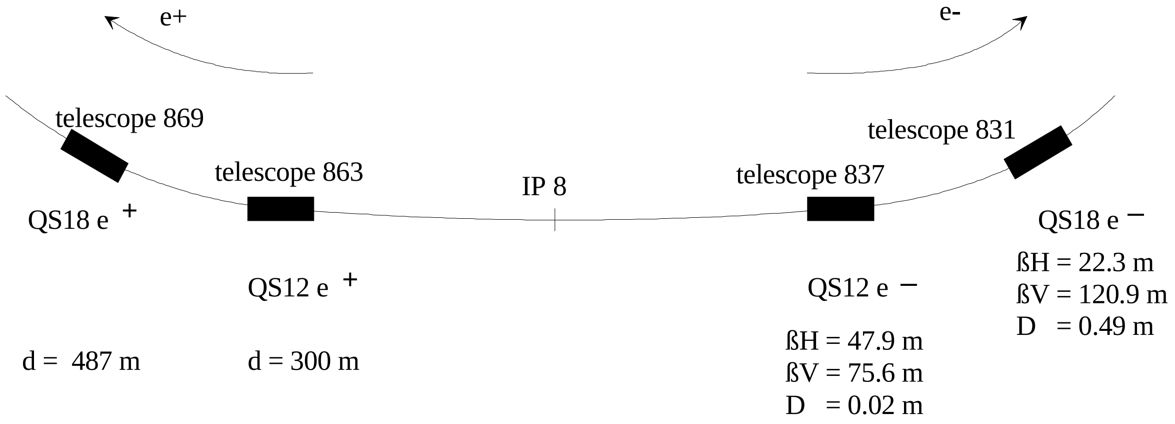

Figure 1: Layout of the Synchrotron Radiation Telescopes in LEP.

The light is extracted from the vacuum chamber by a Beryllium mirror 10 mm thick with a reflecting surface of 23 x 23 mm^2. In order to be outside the nominal LEP acceptance, this extraction mirror has to be located at 21.7 m from the SR source being measured. This mirror has been placed at an angle of 30° with respect to the vertical, mainly to reduce the material thickness presented to the energetic part of the SR, as it had been clear from the beginning that the reflecting surface would deform because of the heating due to power deposition of the SR. This effect had been estimated to deform the mirror mostly cylindrically with a curvature radius of the order of 1000 m during the LEP 1 period.

A major difficulty, due to the large bending radius of LEP of nearly 3100 m, is the precise selection of the centre of the light source and of the longitudinal acceptance along the beam path. A special set-up had to be made to solve this problem as the mechanical alignment of the telescope would not have been sufficiently precise. The principle is illustrated in Fig.2 using the horizontal phase-space defined in [4]. The origin of the phase-space is at the ideal source point of the light and the axes are the horizontal machine axis x and the trajectory angle θ with respect to this origin. In this phase-space, the beam trajectory is a parabola, the extraction mirror is defined by a skewed acceptance band, and a vertical slit located at the focal point of the spherical imaging mirror is represented by a horizontal acceptance band. As can be seen in this diagram, such a slit defines precisely the centre of the light source and the longitudinal acceptance. By moving the slit, the whole acceptance defined by the extraction mirror can be explored. It can be seen that the telescope acceptance doesn't change when the position of the beam orbit changes by as much as ± 5 mm. A slit and not an iris was chosen as the limiting horizontal aperture so as not to introduce additional diffraction in the vertical plane.

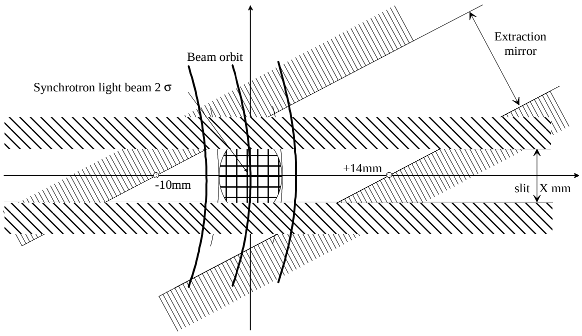

Figure 2: Telescope horizontal phase space, with beam trajectories (δx = -5, 0, +5 mm), extraction mirror and slit at the focal point of the imaging mirror.

It was assumed that a gaussian approximation of the various perturbing contributions was acceptable for the on-line deconvolution of the beam size measurement.

If w is the slit width, it has been shown that the longitudinal acceptance introduces an image broadening at the detector of the type:

$$\sigma_{LA} = k_{LA}\, w \tag{1}$$

The major optical limitation of the instrument in LEP 1 was however the diffraction. In the vertical direction, the diffraction pattern at the detector can be approximated by a gaussian with a standard deviation

$$\sigma_{DV} = k_{DV}\ \lambda^{2/3} \tag{2}$$

At the light extraction location of the telescope, the SR is a horizontal band which is limited by the light extraction mirror and afterwards by the slit having a width w. With a uniform window, it will generate a diffraction pattern, the width of which at the detector was approximated by a gaussian of standard deviation.

$$\sigma_{DH} = k_{DH}\, \lambda / w \tag{3}$$

The design aim was to minimise these effects and to be able to measure precisely and independently the remaining contributions. For both directions, the diffraction broadening of the light spot will decrease when decreasing λ, hence the smallest possible wavelength is used in routine operation, i.e. 450 nm with a normal CCD.

Using the remote control facilities, the slit position is adjusted to centre precisely the SR source at 2 m from the bending magnet entrance, then the slit width and the chromatic filters are changed to estimate the coefficients from equations (1) to (3). To be able to measure without ambiguity the various contributions, a perfectly achromatic set-up using only mirrors has been chosen for the telescope, despite its higher complexity.

The LEP 1 campaign gave the following values:

$$k_{DV} = 3.9 \pm 0.1$$
$$k_{DH} = 1.6 \pm 0.2$$
$$k_{LA} = 40 \pm 10$$

if the σ's are expressed in μm, λ in nm and w in mm.

With these corrections it was possible to measure vertical emittances smaller than 1nm to ± 0.1nm. The major contribution to the uncertainty on the emittances was however coming from the knowledge of the LEP beam optics [3].

An additional limitation comes from the vertically polarised component of the synchrotron light. The horizontal component is a single lobe containing all the information about the beam and can be imaged in the usual way onto a detector. The vertical component unfortunately has four lobes [5] which are critical for the precision of the measurement because they generate additional diffraction and define a very limited longitudinal acceptance before deforming the beam image on the detector where they generate two horizontal light spots when slightly out of focus. Even though the horizontal polarisation component contains 3/4 of the total energy, it is still beneficial to filter out the vertical polarisation component. This was however not a serious problem at LEP 1.

Two additional devices were installed for special studies: a “corona” filter attenuating the dense core to study the beam tails with a 10^5 dynamic range, and a CCD with a pulsed intensifier to investigate the behaviour of individual bunches on selected turns [6].

3. THE LEP 2 SR TELESCOPES

When the LEP energy was raised above 80 GeV, the slit position scans clearly showed that the beam image was no longer focused in the same location in H and V, pointing to the cylindrical deformation expected. At that time, a mobile camera was introduced to optimise the telescope either for the vertical or for the horizontal measurement and to confirm the validity of the slit scans. When the power was raised above 90 GeV, the effect became even more dramatic. At this level of SR power, the deterioration was visible on the beam image which became difficult to use by the control room crew: see Fig.3.

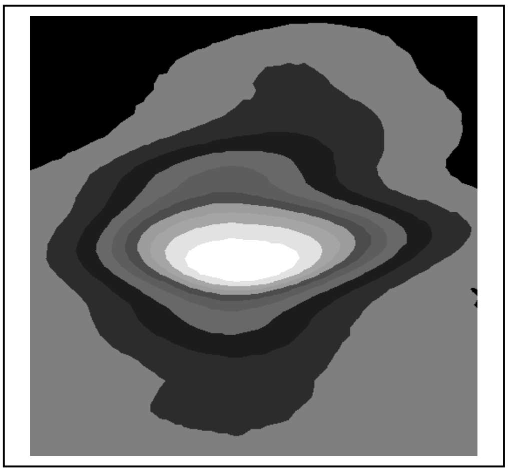

Figure 3: Beam image for a 2 mA beam at 91.5 GeV

It was clear that the performance of the telescopes was seriously compromised and needed drastic changes to the telescope set-up. As a side-effect of the energy increase, the radiation level at the telescope location increased beyond 10^3 Gray/year which even though attenuated at the CCD level, could not be reduced enough for the detector to survive a whole year of operation.

Because of this high radiation level, it was decided to suppress a number of facilities of the LEP 1 telescopes and to aim at maximum reliability rather than maximum possibilities. For that reason, the pulsed MCP detector and the corona filter were suppressed and a unique mobile CCD detector protected by heavy lead shielding was used.

The SR power generates several problems due to the deformation of the Beryllium extraction mirror.

The first effect is a small angular deformation which shifts the light source towards the entry of the bending magnet. For the QS12 telescopes, it can extend the longitudinal acceptance to the whole straight section up to the opposite QS12 telescope which results in multiple images originating from the various quadrupoles where the beam is not exactly centred. This can be corrected by decreasing the slit width from 2 mm in LEP 1 to 1 mm in LEP 2, and by adjusting the slit position.

As can be seen in Fig. 3, side lobes appear on the beam image. These lobes can be explained by the combination of the remaining vertical polarisation component of the SR and the cylindrical deformation of the Be mirror. The lobes being of smaller angular aperture than the main horizontal component, they contain enough energy to become clearly visible. The original metallic polarisation filtering [1] has been supplemented by an additional dichroic sheet polariser having an extinction ratio of 1/4000 to attenuate further these lobes. The polariser is mounted in a rotating housing to provide both maximum attenuation for normal operation and maximum transmission which is useful for optimising the tuning of the telescope. This strongly attenuates the vertical polarisation lobes and is sufficient for a good measurement of the beam sizes using a gaussian fit applied above a software defined threshold. But as the video signal is used for a TV display in the control room and because of the characteristics of the TV monitor and of the human eye, the lobes were still apparent and these “ghosts” were disturbing for the operations crew. For that reason an electronic “ghost buster” was implemented on the video signal for the comfort of the crew. It is linked to the data processing program and suppresses the video signal below the threshold defined for the fitting routine applied on the image data.

With this set-up, it was possible to measure with good precision the beam dimensions by using the two telescopes of each beam, one tuned for vertical and the other for horizontal measurements, and also having good TV observation conditions. This was acceptable for a limited time, and was useful to precisely measure the deformation of the Be mirror as a function of beam energy and intensity. It was however felt that a better correction scheme was needed in anticipation of the LEP beam energy increase towards 100 GeV with currents above 3 mA per beam when a SR power of more than 1.5 kW is expected to hit the mirror.

4. THE DEFORMABLE MIRRORS

The possibility to correct for the deformation of the Be mirror has been investigated during the LEP 1 period. As it is not possible to decrease further its deformation, the easiest scheme was to replace the first flat bending mirror by a cylindrically deformable mirror whose deformation compensates the main deformation of the Be mirror, with the possibility to introduce an additional spherical correction with the mobile camera.

A series of measurements were made at 94.5 GeV which show the evolution of the deformation of the Be mirror as a function of beam current: see Fig.4. Using deformation measurements taken at different energies, a scaling was defined to estimate the curvature radius needed at higher energies. It is estimated that the curvature radius will follow a law of the type:

$$R \sim 3600\, I_b^{-2}\, (E_b/90)^{-6} \qquad (4)$$

with the radius R in [m], the beam intensity I_b in [mA], and the beam energy E_b in [GeV].

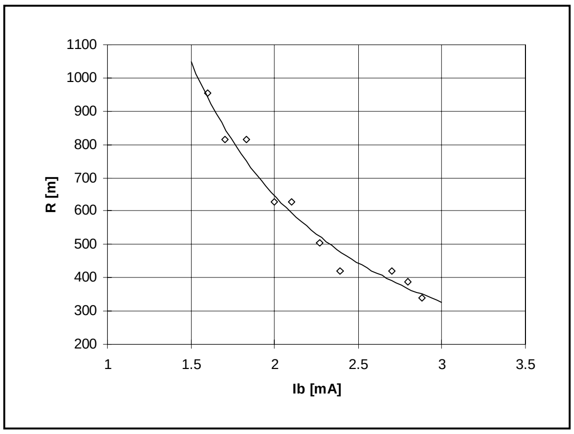

Figure 4: Curvature radius of the Be mirror as a function of beam current measured at 94.5 GeV.

As a result of a call for tenders, the most economical solution proposed was that of a U-shaped mirror deformed by a force generated by a spring compressed by a stepping motor. The motor is of the type standardised in the telescopes and can be driven by the existing multiplexed system in use in the telescopes.

The mirrors have a reflecting surface of 50x90 mm^2. One of these mirrors is shown in Fig. 5. They have been measured at the manufacturer's premises and found to have a cylindrical deformation from flat to a radius of curvature of 350 m. The deviation from a perfect cylinder is less than $\lambda/10$ over the full range. In order to have an optimum mirror lifetime, the manufacturer recommends to limit the deformation of the mirror to a curvature radius of 400 m. This limits the beam current which can be corrected to slightly less than 3 mA per beam at 94.5 GeV.

Figure 5: Detail of the U-shaped deformable mirror: the reflecting surface is towards the bottom, the force is applied at the top, on the left arm of the U by the spring-loaded piston.

The mobile camera has to be used for currents beyond 3 mA per beam. This was verified during the 1998 run and gives a correction capability of an additional 1 mA beam current, which will bring the telescopes close to the LEP limit.

For economical reasons, only the QS12 telescopes, which are the main ones, have been equipped with such mirrors. It is nevertheless important to keep the QS18 telescopes available as a back-up for the main QS12 ones and for studies on the telescope performance.

A second type of deformable mirror was designed using the original flat mirrors of 40 x 60 mm^2: see Fig. 6. In this set-up, an invar bar is cemented to the central part of the mirror the edges of which are blocked against the mirror support. The central part is pulled by a variable force generated by two springs put in tension via a cam driven by a stepping motor. A mirror of this type has been measured together with a U-shaped mirror and gave a bending radius from 1.4 km to 270 m in the bend plane with a radius varying from 1.3 km to 82 km in the perpendicular direction, which is excellent. The origin of the slight spherical shape at minimum stress is not clear, but it is easily corrected by the mobile camera. It should be possible with this mirror to reach a 2.7 mA beam current at 100 GeV before having to move the camera.

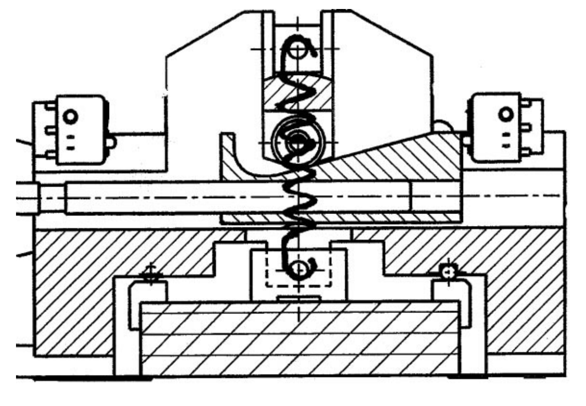

Figure 6: Drawing of the 2nd type of deformable mirror: the reflecting surface is towards the bottom, the central part of the mirror is pulled upwards by the spring which is put in tension by a piston displaced by the cam.

5. RESULTS WITH BEAM

The layout in Fig. 7 was chosen for the LEP 2 situation and implemented in the electron telescopes 837 and 831 for the 1998 run. The previously determined deformation law for the Be mirror and its compensation were refined. The telescope control software was modified so as to monitor every minute the beam energy and current and to deform accordingly the folding mirror. The dichroic polariser was fine tuned by maximising the vertical polarisation lobes and then rotated by 90° for maximum vertical polarisation attenuation. The slit position has been adjusted to centre the SR origin 2 m inside the corresponding bending magnet at top energy and the slit width adjusted to 1 mm for a longitudinal acceptance of ± 40 cm.

It was verified that under these conditions, both telescopes gave the same emittance, within the errors on the beta values.

The importance of the deformable mirrors is very well demonstrated in Fig. 8, where the same beam is imaged with and without deforming the mirror and filtering the vertical polarisation.

For the 1999 run, all telescopes have been put in the LEP 2 configuration and a campaign to re-measure the correction coefficients will be undertaken.

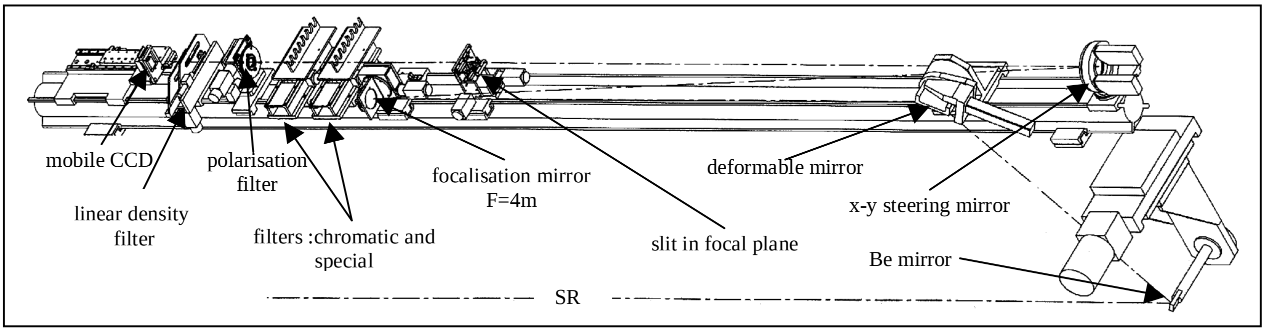

Figure 7: Layout of the SR telescope in the LEP 2 version

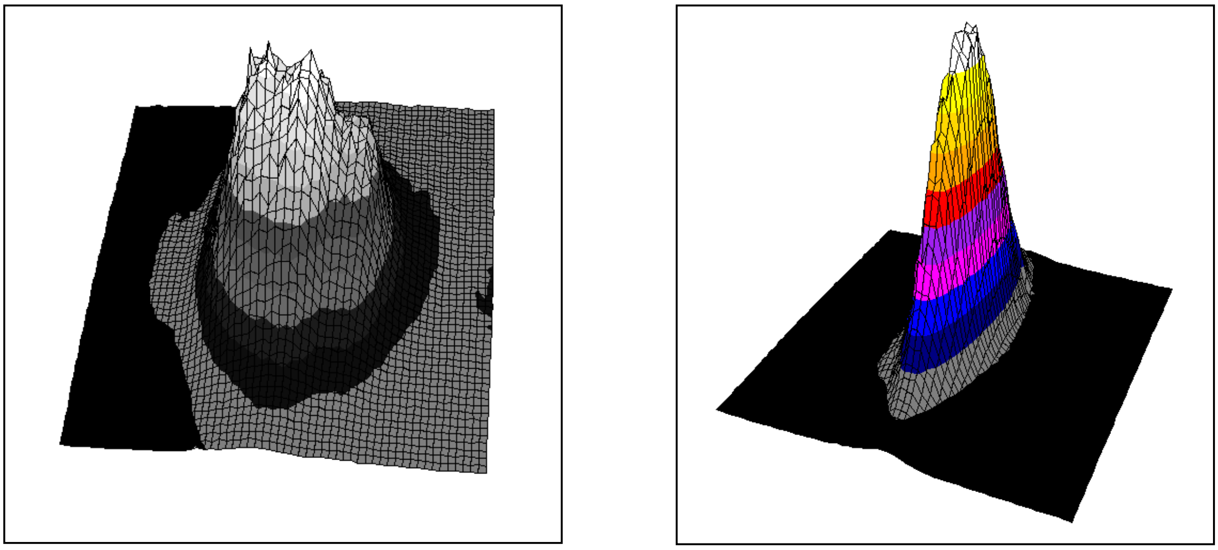

Figure 8: Left: beam imaged with the flat folding mirror and no polarisation filtering, for 2.2 mA at 94.5 GeV. Right: same beam with folding mirror set to calculated curvature and vertical polarisation attenuated.

ACKNOWLEDGEMENTS

R. Perret designed the second type of deformable mirror and provided us with the technical illustrations. His help is always much appreciated.

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