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The Long Trace Profilers

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Abstract. The Long Trace Profiler (LTP) is the most commonly employed instrument for measuring grazing incidence optics used in synchrotron radiation. This is a direct slope measurement device, able to detect root mean square slope variations of the order of 0.1 μrad. It was originally developed at the Brookhaven National Laboratory in Upton, NY, but several custom modified devices are used at laboratories around the world. In this chapter the main principles as well as various modifications are described, in order to give a general overview of what is possible with such instruments.

10.1 Introduction

In this section, we will describe the characteristics of the long trace profiler (LTP), the most commonly used instrument for measuring grazing incidence optics used in synchrotron radiation. Some features are common to all the LTPs available around the world. Many laboratories have modified their instrument according to their own particular needs or to try to improve the performance. However, the underlying principle is more or less the same and will be described here. Some variations for improving or customizing the instrument will be also highlighted.

This section together with the section on the NOM, are intended as a guideline for the choice of a particular trace profiler or its configuration, depending on the requirements and available budget.

10.2 The Long Trace Profiler

The most frequently used instrument for grazing incidence optics is the LTP. This instrument was developed at Brookhaven National Laboratories by Takacs et al. [1–4], and marketed by Continental Optical Corporation (later on by Ocean Optics [5]). It is basically a double pencil, slope-measuring interferometer, able to directly measure the slope of optical surfaces of any shape

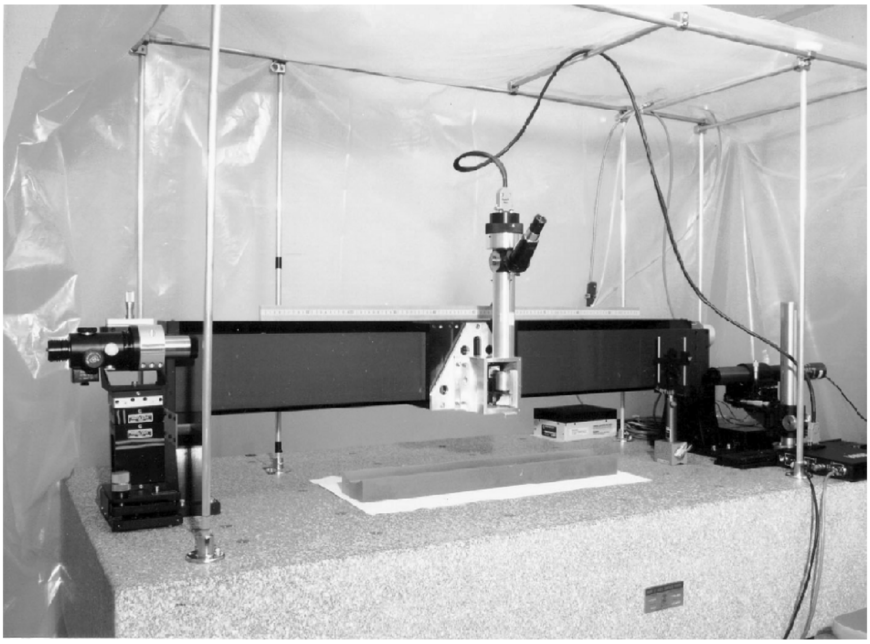

Fig. 10.1. Picture of the first LTP. The optics head moved on a ceramic bar and no reference mirror was used. Picture courtesy of Peter Takacs (Brookhaven)

up to 2 m in length (depending on the setup). Under optimum operating conditions, very precise measurements, with a repeatability better than 2 nm $P–V$ (or 0.1 µrad rms) can be made.

Figure 10.1 shows the first ever LTP to be produced. It was installed and tested at Brookhaven National Laboratory. In this set up, an optics head moved along a ceramic beam, using air–vacuum bearing pads. A linear encoder was used (as today) to determine the position of the measurement.

The most important part of the instrument is, of course, the optics head. The schematic shown in Fig. 10.2 includes some improvements to the original design. Originally light coming from a laser diode is collimated and sent to a beam splitter and corner reflectors so that two parallel, collimated, coherent beams emerge downward toward the surface under test (SUT). The beams reflected by the SUT return into the optical system, and a beam splitter directs the returning beams into the Fourier transform lens (FTL), which produces an interference pattern at the linear detector array. The interference pattern contains a sinusoidal component whose phase depends on the angle of the beam pair with respect to the optic axis, or on the phase difference between the two beams, produced by the local angle of reflection of the SUT. Therefore, the position of the sinusoidal component will directly depend on the slope of the surface at the position where the laser hits the surface.

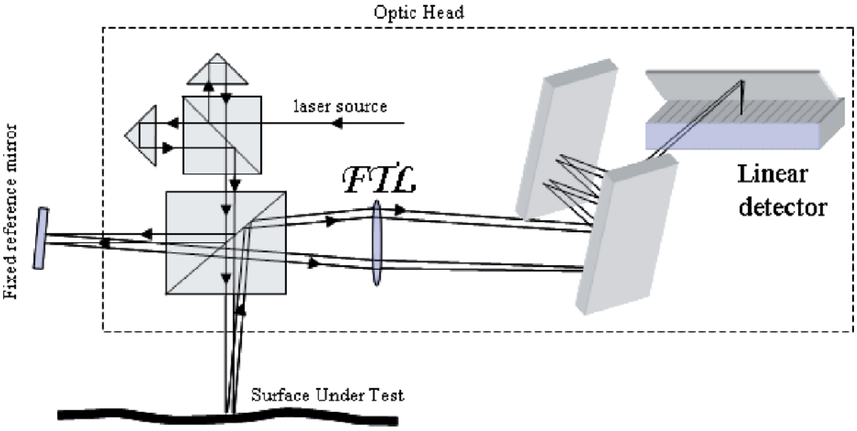

Fig. 10.2. Drawing of the optical setup for the LTP 2. The laser beam is split into two pairs of beams. One is sent to a fixed reference mirror (to compensate for the nonlinear movement of the head) and the other is sent to the SUT

In other words, the FTL converts a tilt induced in the laser beam pairs, by the mirror local slope, into a variation of the position of the interference pattern in the focal plane itself. Using a linear array detector to measure the position of the minimum of the interference pattern, one can directly measure the slope of the optic, point by point.

In principle, the measured pattern will depend only on the slope of the SUT but, in reality, it depends on a number of additional factors, like the beam pointing instability of the laser, the nonlinearity of the motion of the carriage on the ceramic bar, imperfect optics inside the optics head, random errors.

Over the years, most of these problems have been overcome. A major source of error was the imperfect movement of the optics head on the ceramic. As the beam propagation direction at the laser changes, the angle of the beam with respect to the optic axis also changes. However, if one can simultaneously measure the SUT and a fixed reference mirror, one can subtract the reference signal from that of the SUT and, apart from random noise, one can perfectly compensate for this effect. This first modification drastically improved the performance of the LTP, down to the microradian level (this is the main improvement of the LTP 2). To measure the reference mirror, the laser beam pair is divided in two by a further corner cube beam splitter. One of the two beam pairs is sent to a second mirror, rigidly mounted on one of the legs supporting the ceramic bar and the beam reflected by it is measured together with the beam reflected by the SUT.

Other sources of error include refractive index changes in the air where the beams propagate (due to air turbulence induced by sound and thermal waves), thermal instability which act on the laser as well as causing deformation of the mechanical mounting, mechanical relaxation. Several in-house modifications were necessary over the years to improve the performance of the different LTPs to meet the increasingly demanding precision requirements of mirrors in the synchrotron radiation field [6]. In the following, some of the most frequently adopted modifications will be described. In some LTPs, the solid-state laser source was substituted with a He–Ne laser tube, connected to the optics head by means of a polarization-preserving optic fiber. This is a very stable source in terms of wavelength, which is a critical requirement when the groove density variation of diffraction gratings has to be measured [7–9]. Moreover, Qian [10] suggested a different method of scanning by moving only a pentaprism. In this case the optics head is stationary and the laser is sent to the scanning pentaprism. The main advantages of such a configuration were the introduction of an angle-maintaining pentaprism (less sensitive to vibrations and to the tilting errors of the scanning translation stage), a significant weight reduction of the movable part of the interferometer (with an obvious decrease of the mechanical flexure of the scanning slide), and an easy switching between side-mounting and upward facing configurations for the SUT. Nevertheless the use of a pentaprism can reduce the precision of the profilometer since the beam has to cross it twice. In fact, an imperfect surface, in particular in terms of microroughness, introduces a phase shift between the two beams retro reflected by the SUT. This is seen as a false slope of the mirror and therefore introduces systematic errors which are not easily removed. This problem can be overcome by using a pair of superpolished mirrors mounted at 22.5° acting in the same way as the reflecting part of the pentaprism. Unfortunately these are not the only optical components along the path of the laser beam. Therefore, one of the main limitations of the LTP is the presence of systematic errors due to imperfect optics used in the profilometer.

Another important, and fundamental, hardware improvement is related to environmental condition control (mainly temperature stability and air turbulence along the laser beam path). The fundamental need is to shield completely the area where the scan is made from the external laboratory. This avoids air turbulence which introduces random noise in the measurement. In addition thermal stabilization is very important, and several solutions have been adopted with or without active temperature control. If the temperature changes during a scan, an artificial slope is introduced, resulting in an incorrect measurement of the radius of curvature of the optic. Precise thermal monitoring at different points inside this inner room or, even better, by looking at a reference mirror to be sure that no thermal effect are present is therefore mandatory if sub-microradian level of precision is required.

With such environmental control, it is possible to reach a very good level of repeatability. An example, obtained at Elettra, is plotted in Fig. 10.3, where the same mirror was measured on different days, but the measured residual slope errors differ by less than 0.04 μrad.

Another important source of error is the misalignment of the different optics present in the optics head, in particular relative to the position of the linear array detector which has to be “exactly” in the focal position of the

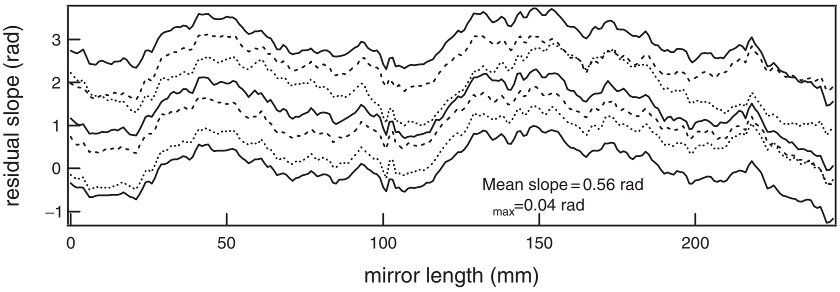

Fig. 10.3. Different measurements of a 250 mm long mirror. The measured residual slope errors differ by less than 0.04 µrad. The curves are shifted to be easily distinguished

FTL [11]. The detector must be in the focal plane of the lens with a precision better than 0.1 mm. If the beam is focused either before or after, it will impinge on the detector in a different position with respect to the focused one. This is again a systematic error that can be eliminated by proper alignment which can be performed in several ways. One of the easiest ways is to measure a mirror at different positions of the detector. Any discrepancy among the measurements means that there is a misalignment of the lens and, by trial and error, one can correct it.

A better way to calibrate an LTP, to estimate and if possible eliminate the systematic errors, is to use a calibrated reference mirror, i.e. a mirror with a well-known profile. Of course, this raises the problem of finding the real profile of the reference mirror. This can be overcome by making cross measurements at several laboratories and with different instruments.

A cross calibration measurement campaign started in 2004, among some of the major European laboratories [12], with the aim of defining a set of reference optics, of calibrating the different instruments, and of finding the limit of their performances (under the European funded action COST P7 [13]). The results and the procedure adopted in such a round robin will be described in detail in chapter 14.

10.3 Major Modifications of the Original Long Trace Profiler Design

There are a number of "homemade" LTPs in various laboratories. One of these, the NOM machine developed at Bessy, is described in detail in the chapter 11. Other designs use the pencil beam concept of Von Bieren [1] but with major modifications with respect to the original LTP solution. An example of this is the completely homemade design of the Soleil Profilometer, described below.

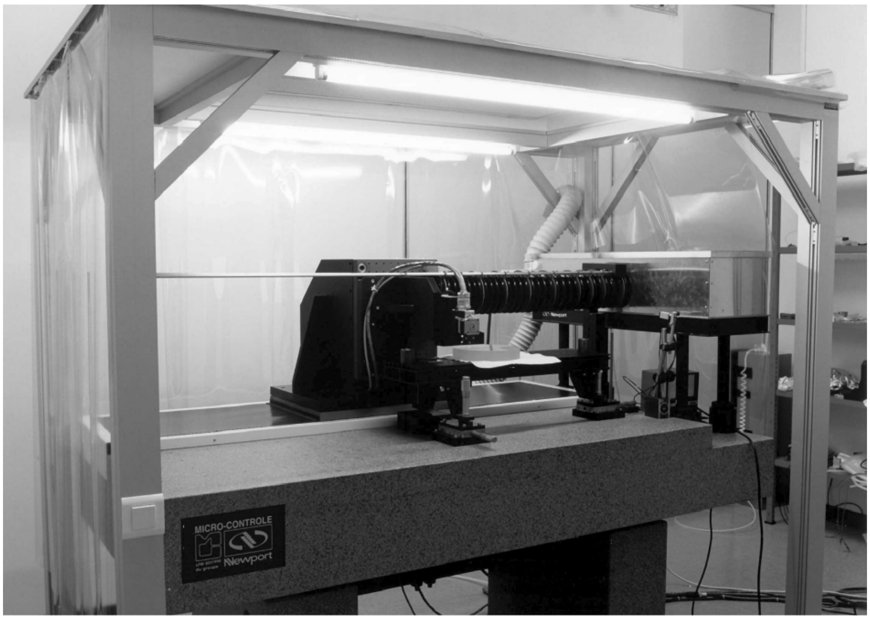

Fig. 10.4. Picture of the Soleil LTP with the environmental control enclosure

The SOLEIL LTP was constructed from a custom 1-m translation stage on air bearings powered by a linear motor (Fig. 10.4). It was designed to make "on the fly measurements." The guide surfaces of the air bearing are directly manufactured in the granite optical table. Large distances between the bearings ensure a high stability of the three angle components. Pitch, roll, and yaw errors have been measured along the whole carriage travel and are lower than 5 μrad rms. The position of the carriage is read by a Heidenhain optical encoder with 1 μm precision. The absolute accuracy has been controlled with an Hewlett-Packard interferometer and is better than 5 μm over the whole travel range. The carriage is able to support an overall weight of 45 kg.

The optics scheme is a variant of the pentaprism LTP described by Qian et al. [10] and is shown in Fig. 10.5. A fixed optical system creates a collimated light beam which is sent to the movable optical head, parallel to the motion direction. The beam is then reflected by the combination of three reflectors (mirrors or total reflection prisms) toward the SUT.

The advantage of the roof configuration of M1 and P1 is to allow a variable distance between these two elements and therefore an easy way of changing the transverse position of the measured track on the SUT without moving the latter. The prisms P1 and P2 are glued together for better stability and ease of manipulation. The stabilized beam is then reflected by the SUT and the local slope affects the return direction which is measured by the lateral position of the image spot on the CCD camera. Between the prisms and the SUT a

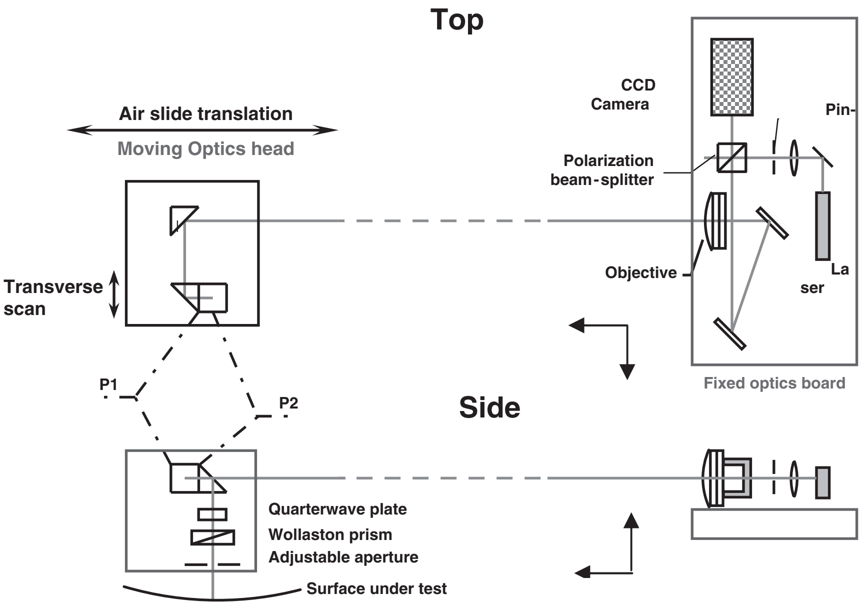

Fig. 10.5. Setup of the LTP of Soleil which was made in-house

compact polarization interferometer is inserted whose main components are a quarter wave plate and a Wollaston prism. The interferometer is completed by the polarization beam splitter which acts as a polarization filter.

The vertically polarized beam from the laser source is sent to the optics head while the horizontal component of the returning beam is sent to the camera.

The cut angle of the Wollaston prism is calculated to produce a sinusoidal fringe pattern with a period of about 2.5 mm when used in double pass (5 mm in single pass) between cross polarizers. The size of the beam is defined by an iris aperture located as close as reasonably possible to the SUT so that the probe beam size is precisely defined. The only precaution is to “clean” the beam by focusing the laser source ($\lambda = 532$ nm) on a small pinhole.

The camera is a C8040-96 Hamamatsu digital CCD camera, with 1,280 × 1,024 pixels at $6.7 \times 6.7\,\mu$m pixel pitch and integrated microlenses. A 2D detector allows the alignment of toroidal mirrors in the longitudinal direction with a precision better than 20 μrad. Objective lenses of different focal lengths can be used in the fixed optics part. A 500 mm focal length is normally used.

The Wollaston interferometer has been chosen for its ease of implementation and very high stability. In order to get a symmetrical image with a sharp central minimum on the CCD camera, the dark fringe of the Wollaston must be properly centered on the aperture. This is done by centering the Wollaston and by fine adjustment of the quarter wave plate orientation. However it can be shown that the spurious signal resulting from a slightly offset sinusoidal fringe is in quadrature with the signal resulting from the centered fringe. The depth of the image minimum is affected but its position does not change. The position of the minimum is interpolated from nine bracketing points.

In some cases, namely when measuring gratings [7–9], the SUT reflectivity will be different for polarization along or perpendicular to the track direction. In order to minimize the loss of fringe contrast in this case we use a specially cut Wollaston prism arrangement where the optical axes of the two prisms are set at 45° to the wedge direction and therefore parallel to the quarterwave plate axes, instead of being parallel and perpendicular to the wedge as it is usually constructed. Due to the symmetry, the reflected components for the two principal directions of polarization are equal and the fringe contrast is preserved. Finally the direction of the probe beam can be chosen by different arrangements of the mirrors and prisms in the moving head. By rotating P2 by 180° around the X-axis before gluing, we obtain an upward pointing stabilized beam. The actual configuration used to measure downward facing surfaces is obtained by inserting between M1 and P1 a periscope composed of two flat and parallel mirrors which brings the beam up without changing its direction. Side illumination is realized using the same principle with M1 and the following prisms in an upward pointing configuration, turned 90° around the incoming beam so that the lateral direction of the equivalent roof reflector is now along Y instead of Z.

A 500 m long instrument of the type described above is able to measure slopes in the range of about ±5 mrad corresponding to a radius of 10 m in a 100 mm long mirror [14, 15]. When this range is not enough, it is still possible to extend the measurement length by stitching a series of successive scans with different inclinations of the surface. A limited number of scans can be stitched without degrading the accuracy as they can be overlapped sufficiently.

Another important issue is to be able to measure very long mirrors, up to 2 m. With this target in mind, the European Synchrotron Radiation Facility (ESRF) constructed its own trace profiler.

The ESRF LTP is a homemade instrument. The first version was built in 1993 with the help of Takacs to measure long mirrors up to 1.5 m [3]. Many modifications have been made to the original design: the source and the detector are now separate from the moving optical head and fixed to the table (Fig. 10.6), the source is a helium–neon stabilized laser fitted to the optics head through a polarization-preserving optics fiber, a mirror assembly equivalent to a pentaprism is carried by the linear motor stage guided by the 2.5 m long ceramic beam.

The error in the linearity of the translation is optically corrected by the pentaprism. A fixed reference mirror corrects for any source instabilities. The detector is a 1,024 pixels photodiode linear array from Hamamatsu which gives a maximum measurable range of 12 mrad. Placed at the focal plane of the lens (800 mm focal lens), the sensor detects a fringe pattern intensity profile resulting from the interference of the two beams coming from the Michelson

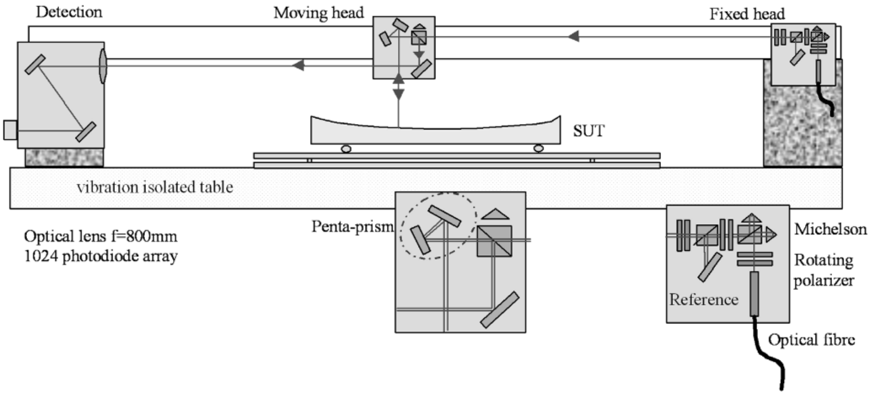

Fig. 10.6. Optical setup of the ESRF long trace profiler

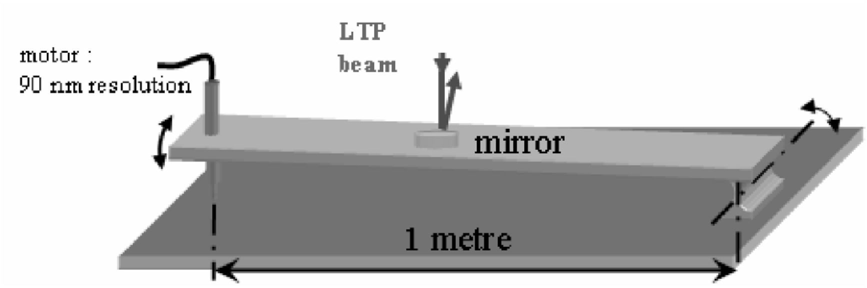

Fig. 10.7. ESRF LTP calibration setup

interferometer. The algorithm used to define its position on the detector is based on a fast Fourier transform calculation. The software has been developed using Labview® as programming language and can be easily adapted for specific needs. In the standard measurement configuration, the sample under test is reflecting upward but an optical bracket can be added to this setup if the SUT is reflecting downward.

Measurements are taken "on the fly"; the data are collected while the optical head is smoothly moving above the mirror at a constant speed of $40\,\mathrm{mm\,s^{-1}}$. The LTP is surrounded by a Plexiglas enclosure which reduces greatly the air turbulence. Measurements can be carried out faster, thus repeatability has been improved and is better than $0.05\,\mu\mathrm{rad}$ rms, while the slope accuracy on flat mirrors is better than $0.2\,\mu\mathrm{rad}$. To ensure a reliable measurement, an important issue is the determination of the calibration factor. At the ESRF a method based on the well-known wedge angle technique is used; Fig. 10.7 shows the setup used for calibration. A motor displacement of $1\,\mu\mathrm{m}$ induces a $1\,\mu\mathrm{rad}$ angular deviation. The precision achieved is $0.1\,\mu\mathrm{rad}$.

The mirror to be characterized may be integrated on a static or bending holder system. When no mechanical mounting system is provided, the mirror

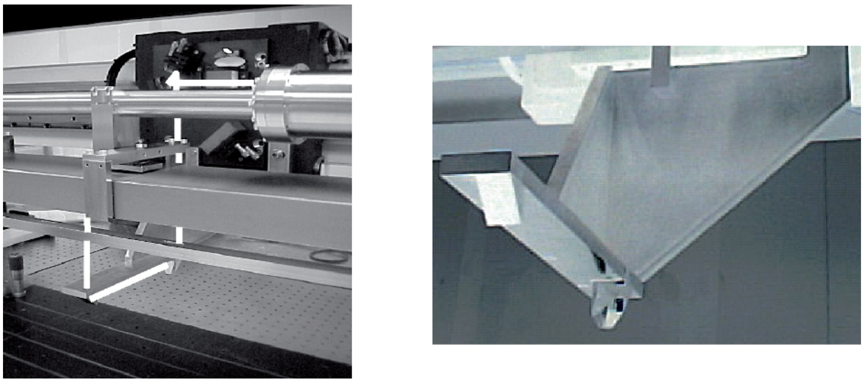

Fig. 10.8. *Left*: mirror facing down under LTP measurement – *Right*: detail of the split retro reflector

is lying with its surface facing up on three balls or two cylinders separated by a well-known distance. Thus the deformation induced by gravity can be analytically calculated and subtracted from the measurement. Gravity can have a strong influence on the slope error profile.

Nevertheless it is always preferable to measure a mirror as close as possible to its future working conditions on the beamline in terms of mounting and the X-ray beam reflecting direction. For mirrors reflecting downward an additional bracket with a split retro reflector is added to on the LTP moving head (Fig. 10.8) in order to redirect the beam toward the surface through a roof prism and a right angle prism. This combination keeps the number of reflections needed to preserve the pentaprism correction. For further details on the characteristics of this instrument, please see [16].

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