Optical layouts for large infrared beamline opening angles

Th. Moreno 1, H. Westfahl 2, R. de Oliveira Freitas 2, Y. Petroff 2 and P. Dumas 1

1- SOLEIL Synchrotron, BP 48, L’Orme des Merisiers, 91192 Gif Sur Yvette Cedex (France)
2- LNLS, Caixa Postal 6192 CEP 13083-970, Campinas – Brazil
E-mail: moreno@synchrotron-soleil.fr

Abstract. The number of infrared beamlines at synchrotron facilities is expending worldwide. Due to the long wavelength of the radiation in the infrared region, the optimum collection of the emitted photons requires large opening angles, both vertically and horizontally (order of few tens of mrad). Most of the infrared beamlines use toroid shaped mirrors, or elliptical mirror to conjointly focus both the vertical and the horizontal source emission. However, such optical set ups produce distorted images due to the optical aberrations produced by the depth and the circular shape of the source. In this article, we propose a new optical layout consisting in two optimized shape mirrors, focusing independently the vertical and the horizontal source emission, and providing low aberration beams for large horizontal apertures. The setup has been used to design the new LNLS Brazilian synchrotron Infrared beamline.

1. Introduction

Infrared radiation is widely used in research and industry to analyse and characterize solid and gas samples through spectroscopy (FTIR-Fourier transform infrared spectroscopy) and micro-spectroscopy (µ-FTIR). The latter technique provides high spatial resolutions which allows one to generate chemical images of components distribution across samples /1, 2/ while spectroscopy mainly allows one to identify and study matters by measuring their rotational and vibrational structures /3/.

The use of a synchrotron beam is exploited to provide much higher bright beam, for improved spatial resolution and for the higher flux in the far-infrared region /4/. Synchrotron infrared radiation is produced when electron bunches cross the magnetic guide field of bending magnets following circular trajectories. The intensity is then proportional to the horizontal source aperture, which is often large (several tens of mrad), resulting in an elongated photons source. Because they are easier to implement and align, most of the infrared beamlines use combination of plane and toroidal (elliptical) shape mirrors to both redirect and focus the vertical and the horizontal source emission outside the beamline frontend. Often the beam, then, is collimated thanks to cylindrical or parabolic mirrors, and propagates towards the FTIR spectrometer, in order to be coupled in. However, such an optimal set up generates distorted images due to the optical aberrations produced by both the toroid mirror and the circular shape of the source. This results in a non-optimum coupling of the photons emitted by the source with the infrared spectrometer and microscope. In this article, we propose a new optical layout consisting in two optimized shape mirrors, focusing independently the vertical and the horizontal source emission, and providing low aberration beams for large horizontal apertures. The setup has been used to design the new LNLS Infrared beamline /5/. Although infrared emission is transversally coherent, optical beam properties such as intensity, size and divergence can be accurately represented using ray-tracing (including the source diffraction limit), which has been used in this article for all the reported simulations and optical optimizations /6/.
2. Typical IR optical layout

The aim of a typical optical set up of an infrared synchrotron beamline is to deliver a well-defined beam shape, with most of the photons emitted by the source, to the experimental end-stations. Because of the large horizontal source aperture, the beam must be first focused at the vicinity of an IR transparent window (generally of CVD diamond-type). Consequently, the optical layout is always made in two stages: a first group of optics redirects and focus the beam outside the frontend and a second one propagates the beam (preferentially collimated) to the end stations as shown on Fig.1.

![Figure 1: Typical optical diagram of an infrared beamline](image)

The first optic is, in almost all the existing beamline, a plane mirror, often slotted on its center in order to let the hard X-ray components of the emission, which are concentrated in the synchrotron orbit, pass through the mirror without been absorbed. In the focusing stage, a toroid /7/ or ellipsoid /8/ shaped mirror is used to conjointly focus both the vertical and the horizontal source emission outside the frontend. The second optical stage is mainly made of two cylindrical or parabolic mirrors in crossed KB (Kirkpatrick – Baez) configuration used in order to collimate the vertical and the horizontal beam components. Such an optical diagram, with a single focusing optic (the second one in Fig.1) gives acceptable results for horizontal beamline aperture no larger than 40 mrad /7/. For larger horizontal apertures, strong aberrations occur, resulting from the depth and the circular shape of the source. In a first step, we have adapted the optical scheme of Fig. 1 to the planned IR beamline at LNLS (Brazil). This beamline attend to use an opening horizontal angle of 80 mrad, in order to increase the photon flux emitted. Table 1 summarizes its main source parameters.

| Machine parameters | $E_0 = 1.37$ GeV, $I_0 = 0.1$ A |
|--------------------|----------------------------------|
| Bending magnet     | $B = 1.67$ T                     |
| Electron beam size | $400 \times 80$ µm$^2$ RMS (H×V) |
| Photon divergence  | $80 \times 40$ mrad$^2$ tot (H×V) |

Table 1: LNLS IR source parameters

All mirrors are oriented at 45° and supposed to be fully reflective (they are usually metallic). The distance between the source and the first focal plane (outside the tunnel wall) is 5.867 m. Due to the necessary beam deviation in vertical and horizontal planes, the first two mirrors (plane and toroidal respectively) and the focal plane are located in our simulations respectively at 2.5, 3.1 m and 6.467 m from the source (optical distance). The beam properties have been simulated along the beamline at the wavelength of $\lambda = 10$ µm using ray tracing and taking into account the diffraction limit. Fig.2a (top left) gives the image of the beam on the focal plane. Fig.2b (top right) displays the divergence of the beam at the focal plane, while Fig.2c (bottom left) and 2d (bottom right) show the image of the beam at the exit of the last mirror (7.348 m from the source) and 2 m after the last mirror, respectively. As expected, the beamline aperture of 80 mrad is too large to produce undistorted images with the optical layout proposed, and the resulting beam images and divergences exhibit COMA aberrations due to the toroid surface of mirror M$_2$ and the depth and the circular shape of the source. Table 2 gives the corresponding beam sizes and divergences values.
3. Optimized IR optical layout

As shown in the previous section, the main aberrations originate from the source shape. The source depth generates vertical aberrations while the circular source shape resulting of the electrons trajectory produces horizontal COMA aberrations. We propose to suppress the vertical and the horizontal aberration components separately with two adapted optical shapes. The source depth aberrations will be solved by using a conical shape mirror in tangential reflection while the circular source shape will be compensate through a long cylindrical mirror in order to remove the COMA aberrations. Consequently, a pair of conical and cylindrical mirrors, both working in tangential configuration, replaces the toroid mirror of Fig.1.

Fig.3 gives the optical layout proposed for the infrared beamline at LNLS. The toroid mirror of Fig.1 has been replaced by a M2 conical mirror with radii varying between 4.922 and 5.019 m and positioned at 3.1 m from the source, followed by a cylindrical M3 mirror with a radius of 4.986 m and positioned at 3.7 m from the source (Fig.3).

Because the position of the M1 flat mirror and the focal plane were initially imposed, the M3 mirror cannot be placed in the optimum position to remove completely the COMA aberrations of the source emission. Consequently, the resulting vertical beam divergence remains significant (see table 2). Due to the close distance between the focal plane and the vertical collimating M3, this mirror must have a parabolic shape (with radii ranging from 1.083 – 1.682 m) unlike the horizontal one (M6) that can be cylindrical (with a radius of 2.444 m).

We have simulated, at the wavelength of $\lambda = 10 \, \mu m$, the beam properties of the beamline for a source aperture of $80 \times 40 \, \text{mrad (HxV)}$. Fig.4a (top left) gives the image of the beam on the focal plane (7.067 m from the source). Fig.4b (top right) shows the divergence of the beam at that position. Fig.4c (bottom left) and 4d (bottom right) show the image of the beam at the exit of the last mirror (7.948 m from the source) and 2 m after the last mirror, respectively. Because of the orientation of the M3 mirror, the resulting beam images and divergence (Fig.4b to Fig.4d) are tilted by 90° with respect to...
the previous layout (Fig.2). Table 2 compares the properties of the beam between the typical and proposed optical layouts. We can see that, thanks to the conical shape mirror $M_2$, the new optical layout strongly remove the horizontal beam aberrations. Nevertheless, the vertical beam divergence remains non-negligible due to the fact that the cylindrical $M_3$ mirror cannot be placed in the best position to remove the COMA aberrations of the electrons trajectory.

Figure 4: Ray-tracing simulations @ $\lambda = 10 \mu m$ with the optimized optical layout: a) beam size on the focal plane, b) beam divergence after the last mirror ($M_6$), c) and d) beam image at the exit of the last mirror and 2 m after.

|                      | Size (mm) @ focal plane | divergence (mrad) after $M_6$ |
|----------------------|-------------------------|-------------------------------|
| Usual layout (Fig.1) | 2.2x0.7 FWHM            | 2.2x1.4 FWHM                  |
|                      | 4.5x3.4 @ 99%           | 4.6x7.0 @ 99%                 |
| Optimized layout (Fig.3) | 0.3x1.2 FWHM          | 0.4x2.5 FWHM                  |
|                      | 0.7x2.6 @ 99%           | 0.8x5.2 @ 99%                 |

Table 2: Comparison of the beam properties (HxV) produced by the two optical layouts

4. Conclusion

We have presented a new optical layout for infrared synchrotron beamlines consisting in two optimized shape mirrors, focusing independently the vertical and the horizontal source emission, and providing low aberration beams for large horizontal apertures. The setup has been adapted to the new Infrared beamline at LNLS. The resulting beam has a Gaussian divergence of 0.4x2.5 mrad FWHM (HxV) with low aberrations. This new optical layout can be easily adapted to existing IR beamlines.

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