ULTIMATE RESOLUTION OF SOLEIL X-RAY PINHOLE CAMERA

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Abstract

During the SOLEIL Storage Ring commissioning, the beam emittances have been measured with an X-ray pinhole camera. As a result of the excellent alignment of the ring magnets, the vertical beam size is smaller than expected. It prompted an effort for improving the initial resolution of the instrument. Selecting the harder X-ray part of the radiation spectrum seems the key element leading to better resolutions. However it requires a more sensitive CCD camera. Recently, the machine has been tuned up to a very low coupling (~1‰) and the usual quadratic addition of the individual resolutions (pinhole geometry, diffraction, CCD) did not fit the measurements. A better analysis using the "Synchrotron Radiation Wavefront" (SRW) code shows that the actual resolution limit due to the pinhole itself is twice better than expected and as a consequence, resolutions in the 4 µm range are achievable even for medium energy machines like SOLEIL.

INTRODUCTION

A pinhole camera, based on the ESRF design [1] is installed at a location with a low dispersion value of 1.8 cm. The rms beam sizes at that place are theoretically 40.5 µm in the horizontal plane and 23.8 µm in the vertical plane for 1% coupling. Beam size measurements show a 3.7 nm.rad horizontal emittance (as expected) and a machine coupling below 0.5%. For monitoring the coupling down to 0.1 % we need to accurately measure an 8 µm beam size, which requires a resolution in the 5 µm range. This paper reports on the evaluation of the ultimate resolution the present instrument can achieve.

At a fixed wavelength, there is an optimum pinhole size that can be evaluated with Fraunhofer diffraction formula. By inserting a tapered piece of copper in the photon beam path, we can select a higher part of the spectrum at the cost of the photon count on the CCD camera. The radiation spectrum that creates the visible photons arriving on the CCD can be computed. Then, the Point Spread Function (PSF) of the geometric and the diffraction contributions of the pinhole, can be added quadratically in order to evaluate the optimum pinhole size and the resolution. However, the optimum resolution occurs in a region where the Fraunhofer diffraction formula is not really valid. A better way consists in simulating the propagation of the actual X-ray wave front from its source up to the scintillator, this is done with the SRW code [2].

MONITOR DESCRIPTION

The instrument set-up is shown in figure 1. The X-ray beam comes out of a bending magnet from a source point 3.8° downstream of the magnet entrance. The photon beam exits the Storage Ring vacuum through a cooled aluminum slit-window assembly machined out of an aluminium-stainless steel flange. The 1 mm wide slot has a 0.22 mrad horizontal aperture. It limits the radiation power that exits the window to 17 W at most. A tapered copper block acts as a filter-attenuator. Its thickness along the beam path can be set from 0 up to about 15 mm. The pinhole, like that of the ESRF [1], is made of tungsten plates and one can choose between 3x3=9 rectangular holes of different horizontal and vertical sizes. The pinhole assembly is remotely moveable with four degrees of freedom. It is located 4.36 m from the source point. A transparent cadmium tungstate (CdWO4) scintillator is located 5.7 m downstream of the pinhole. The photo electric absorption of the X-ray energy in the crystal is converted in visible light emitted omnidirectionally along the X-ray path. This scintillator has been the ESRF choice. More recently after testing different materials DIAMOND adopted it too. The imaging system with two CCD cameras is protected by a thick lead wall. One camera has a field wide enough to see the whole scintillator (8x10 mm); the other with an optic of better quality and greater magnification measures accurately the beam sizes. The Al window, the pinhole assembly and the camera housing are aligned on the 3.8º direction of the synchrotron radiation fan.

An image analyser calculates the beam size several times per second.

MONITOR RESOLUTION

Simplified theoretical model

From the geometry shown in figure 1, a point source of light illuminating a rectangular hole at a distance d, will project a rectangular spot of light on the scintillator. The size of that spot is a (D+d)/d, where "a" is the hole width and D its distance to the scintillator. The camera geometric magnification is D/d, and the corresponding Full Width Half Maximum (FWHM) of the point spread function (PSF) at the source is:

$$Wg_{FWHM} = a\,(D+d)/D \qquad (1)$$

This formula shows the PSF improving with smaller holes. This is true as long as the effect of diffraction is negligible, for $a >> 2\,\sqrt{(\lambda d)}$.

For very small holes the PSF is dominated by the diffraction. Its FWHM width is:

$$Wdiff_{FWHM} = 1.10\ 10^{-6}\ d/(a*E) \qquad (2)$$

where E is the photon energy in eV; the other dimensions are in meter.

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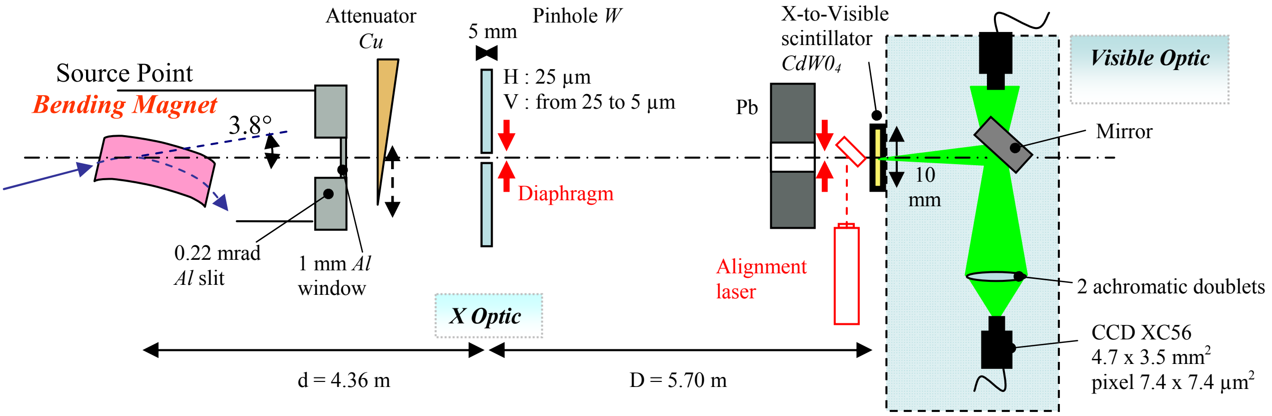

Figure 1: Pinhole Camera set-up

There are several reasons to express the PSF width in terms of the FWHM instead of the usual standard deviation of a gaussian fit to the actual function: i) the full width at half maximum is well defined and does not depend on the type of fit performed, ii) the FWHM value can be retrieved from the SRW data output, and iii) the experimental results can also be expressed in this way, without any approximation problem.

For the sake of simplicity, we can add quadratically the geometric and the diffraction widths of the pinhole PSFs. It is an approximation since the operation is valid only for gaussian distributions. Let's mention that the complete PSF also includes the scintillator and the CCD camera PSFs. The scintillator is transparent and there should be no significant secondary scattering of the visible photons inside the crystal as long it does not darken with time. The resolution of the CCD camera has been carefully measured; it amounts to 3.7 µm. It can be made negligible by increasing the optical magnification. Then, we are left with the geometric and the diffraction PSFs for our search of the ultimate resolution.

Effective X-ray spectrum

For calculating the PSF width we need the effective radiation spectrum that yields the visible photons collected on the CCD. The spectrum is that of the photon beam, attenuated by the 1 mm of the aluminum window, 6 m of air, the filter-attenuator in copper, and the scintillator conversion efficiency. The CdWO4 conversion efficiency is proportional to its X-ray photo-absorption [3]. The NIST web site [4] provides the data needed for all these materials.

The filtering applied to the synchrotron radiation for several copper thicknesses and the intensity of the visible light on the CCD expected for these thicknesses, are shown in figure 2a and 2b. To each spectrum corresponds a mean energy that can be applied to formula (2). The result of the quadratic combination of formula 1 and 2 for several thicknesses of copper is shown in figure 3.

The exposition time of the XC56 Sony camera can be controlled up to 0.5 second. With an optical magnification of 2.6 and an f# of about 10, such a camera enabled to measure beam sizes at 200 mA with up to 3 mm of copper. Figure 3 predicts the FWHM resolution would get down to 14.6 µm (~6.25 µm rms) with a 6 µm optimum pinhole size for that thickness.

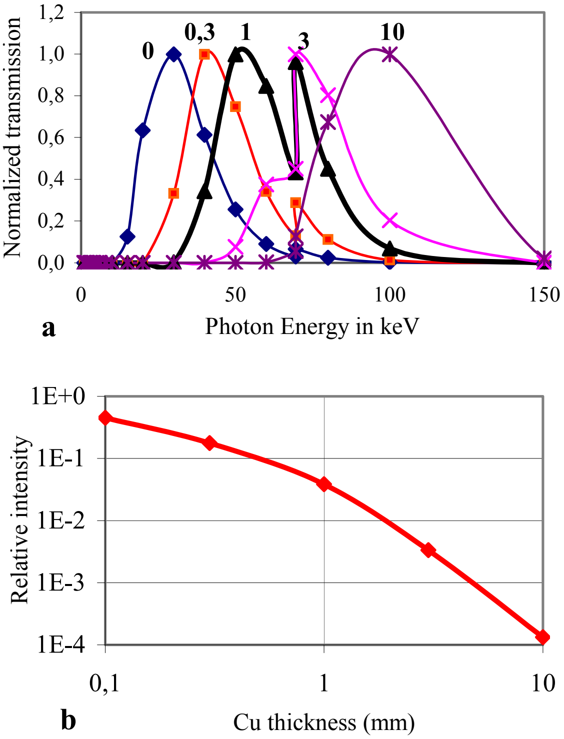

Figure 2: a) Normalized transmission spectra for several copper thicknesses (in mm). b) Relative intensity of the visible light collected on the CCD versus copper thickness. No copper is the reference.

Actual beam size measurements

After optimizing the machine coupling and with 20 mA in the Storage Ring, the vertical spot size on the scintillator was measured at 26 µm FWHM with a 10 µm hole and 0.3 mm of copper. Taking into account the instrument geometric magnification of 1.31, it translates into a 19.8 µm FWHM beam size. It is quite surprising since with that copper thickness, figure 3 (second curve from the bottom) predicts that same value for the 10 µm pinhole resolution alone.

A problem arises when we want to fit narrow vertical beam profiles to a gaussian distribution: the base is wide, only the top half resembles a gaussian. Actually, the relevant information is contained in the top half of the beam profile. The image analyzer fits the top half after bringing the base to the background level, away from the beam spot. The FWHM of the gaussian fit and that of the vertical beam profile are near equal. Then, we consider the rms width of a beam profile or the resolution of a PSF is that of the gaussian.

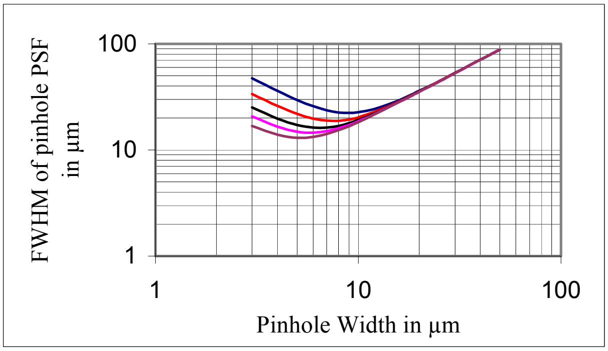

Figure 3: FWHM of pinhole PSF via the quadratic addition of the geometry and diffraction contributions. The five mean energies of fig.2a spectra have been used for the computation.

Simulation with the SRW code

SRW [2] is a wave optics simulation code that can take the actual wave front of the light emitted by a filament like source in the bending magnet and propagate it through the hole, up to the scintillator. With the proper spectrum as an input, SRW can calculate the PSF on the scintillator (fig. 4). The FWHM of the PSF versus the pinhole size is shown in fig.5. One can observe that its minima are about twice smaller than previously anticipated. They all occur with pinhole widths comprised between 10 and 15 µm instead of the 6 to 10 µm expected range. If we neglect the instrument resolution, the 19.8 µm FWHM previously measured corresponds to a 4.7 pm.rad vertical emittance and to a coupling less than 0.13 %. A camera ten times more sensitive should allow increasing the visible optic magnification by a factor of 3 which would make the CCD resolution negligible (1.3 µm rms). Then, a 3.5 µm rms global resolution is achievable.

Looking at the graph shown in fig. 4, one can see that the gauss-like criterion applies to the black curve which is the most interesting one since it features the minimum width. Then we can interchangeably use the rms or FWHM values linked by the relation:

$$W_{rms} = W_{FWHM} / 2.355 \quad (3)$$

CONCLUSION

The experience confirms the results of the SRW computation code. SOLEIL X-Ray pinhole camera equipped with a simple CCD camera already achieves a resolution in the 5 µm rms range and a machine coupling less than 0.13 % has been measured. A more sensitive camera is on order. It should bring the instrument performance to 3.5 µm which is much better than has ever been expected.

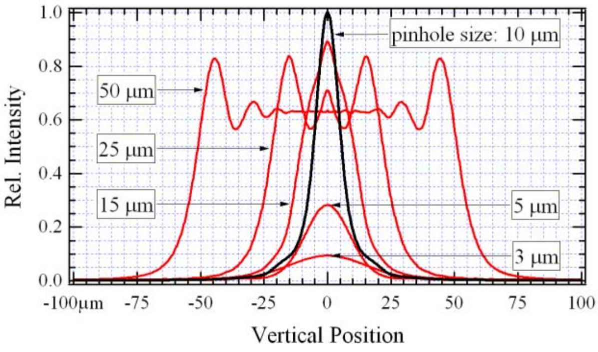

Figure 4: PSF on the scintillator from SRW for several hole sizes with 1 mm of copper.

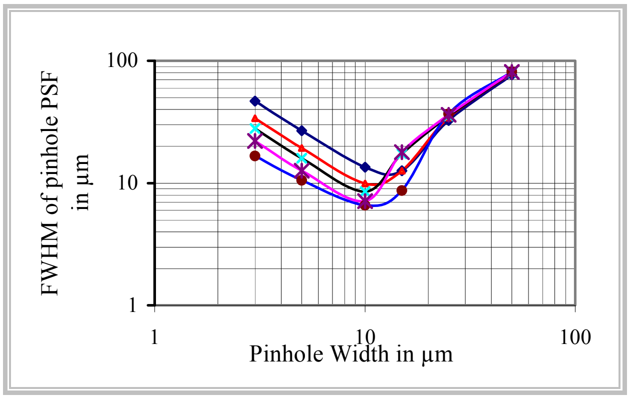

Figure 5: FWHM of pinhole PSFs obtained with SRW. The five curves correspond to the five spectra of fig.2a

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