STUDY OF VISIBLE SYNCHROTRON RADIATION MONITOR ON SOLEIL BOOSTER

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Abstract

In the scope of SOLEIL II, the booster must also be upgraded to reduce from 130 to 5 nm · rad the emittance of the beam delivered to the ring. Control of the emittance in the booster will become crucial to ensure the nominal performance of the storage ring injection. The SOLEIL I booster is already equipped with a Visible Synchrotron Radiation Monitor (MRSV). This equipment, made of an extraction mirror and a simple optical system, was originally planned to be used only for beam presence verification but has not been used routinely for operation since the commissioning in 2005. The control and acquisition systems had to be refreshed to be usable again and allow the beam size measurement along the booster energy ramp. The extraction mirror was replaced due to unexpected degradation leading to a second spot appearing on the camera. This paper traces back the MRSV upgrades from understanding the cause of mirror degradation until mirror replacement and the first proper beam visualisation, achieved at the beginning of 2023.

INTRODUCTION

Fourth-generation synchrotron light sources are presently emerging all around the world. Those machines target ultra-low emittances, below hundred of pm.rad, enabling the delivery of photon beams with unprecedented brilliance.

In this context, the French synchrotron light source SOLEIL is planning an upgrade for the late 2020s, referred to as SOLEIL-II. The targeted emittance in the storage ring is 88 pm · rad in the horizontal plane and 35 pm · rad in the vertical plane. To reach such a low emittance, all SOLEIL's accelerators will have to be upgraded, i.e. the storage ring but also the linac and the booster. The requirements on the booster beam quality will be significantly increased, and an emittance measurement along the energy ramp in the booster will be mandatory.

This emittance measurement could be done using a Visible Synchrotron Radiation Monitor (MRSV). In order to confirm this strategy, preliminary tests are ongoing on the present SOLEIL booster, using the MRSV system installed, but barely used, since 2006.

This paper traces back the issues encountered with this diagnostic and presents the solutions considered to achieve an emittance measurement along SOLEIL's booster ramp.

MRSV DESIGN

An MRSV is an electron beam diagnostic which enables to image the synchrotron radiation emitted inside a dipole at its source point. It usually simply consists of an extraction mirror, to collect and deflect the synchrotron radiation out of the accelerator vacuum chamber, an imaging system and a camera. SOLEIL's booster MRSV setup is shown in Fig. 1. The extraction mirror is a simple Pyrex glass, silver-coated, flat mirror, mounted at 45° to deflect the synchrotron radiation in the vertical plane. The imaging system consists of three lenses allowing it to reach a magnification of 0.24. The camera is a CCD camera (Model acA1920-50gm from Basler [1]). A UHV viewport of fused silica between the extraction mirror and the first lens ensures the transition from vacuum to air.

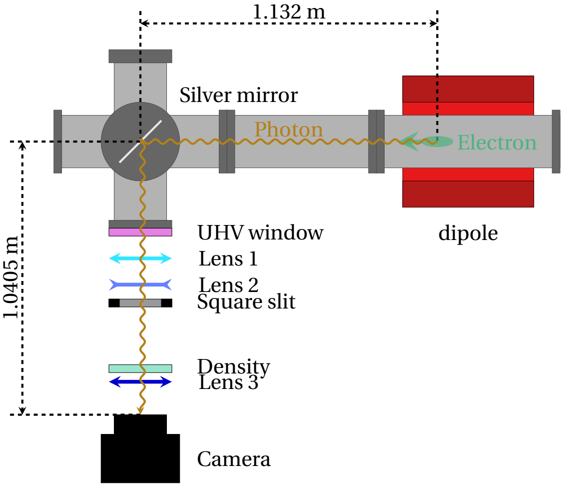

Figure 1: Experimental setup of the MRSV implemented on the booster of SOLEIL.

On many synchrotrons, MRSVs are simply used to check beam presence and its rough stability. But MRSVs can also be used to measure the electron beam size inside the source dipole [2]. In this case, the Point-Spread-Function (PSF) must be accurately considered because dipoles create a longitudinally extended source point. The PSF corresponds to the light distribution of one electron (or zero emittance and energy spread beam) in the image plane which can not be resumed to an infinitesimal point. The light distribution of the real beam (finite emittance and energy spread) results from the convolution of this PSF with the electron beam distribution at the source point magnified by the imaging system. Both the PSF and the light distribution from the whole beam in the image plane can be accurately simulated using SRW [3] as shown in Fig. 2.

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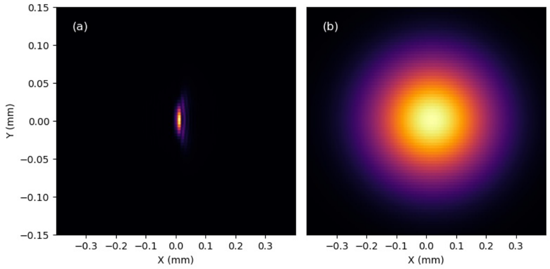

Figure 2: Simulation of the synchrotron radiation in the image plane of the booster's MRSV. (a) Single electron case, i.e. PSF, (b) Finite emittance case. Simulation with SRW at the end of the booster ramp using a beam of 2.75 GeV, 8 nC, 130 nm · rad horizontal emittance and 4.5 nm · rad vertical emittance.

Once deconvoluted from the simulated PSF, the image measured on the MRSV camera can provide the electron beam size in the image plane, allowing retrieval of the electron beam size at the source point, and finally, assuming that optics functions are known, the electron beam emittance.

MRSV ISSUE

Double Beam Observation

A few months after the commissioning of SOLEIL in 2006, the booster's MRSV monitor started to exhibit two spots, as shown in Fig. 3 (b), instead of the single one as expected from Fig. 2. However, since this MRSV was only used for beam presence verification and no major failure at ring injection was noticed, this anomaly was not thoroughly addressed, and the double spot remained for more than a decade.

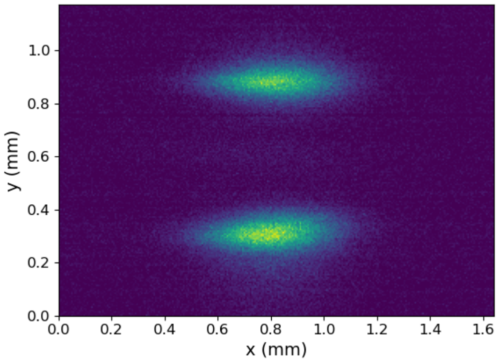

Figure 3: Image of SOLEIL's booster MRSV recorded at the end of 2022, i.e. while the double spot issue was still unsolved.

But in the scope of SOLEIL-II, since a similar system could become a key diagnostic for the booster and downstream storage ring operation, it was decided a year ago to tackle this issue.

A first series of machine studies enabled to exclude the possibility of beam instability, two orbits, or even orbit shifting, confirming that the diagnostic itself was malfunctioning. Then, the position of each component of the MRSV was carefully checked and compared with the theoretical design.

Extraction Mirror Degradation

Eventually, the guilty was found to be the extraction mirror. The inspection of this mirror through the UHV window without breaking the booster vacuum is not easy. However, it seemed that a black strip was covering part of the mirror. Following this observation, new SRW simulations were attempted, including the presence of an obstacle equivalent to the black strip that had been observed. But such an obstacle on the mirror only led to some diffraction features in the image plane, not to two spots. We therefore simply decided to replace the mirror with a new one, though exactly of the same type and geometry.

In January 2023, the extraction mirror has been dismounted. As suspected, the mirror was strongly damaged, as shown in Fig. 4, with the presence of a thick dark strip all across the mirror (at the location of the synchrotron radiation fan) and a clear iridescence besides the dark strip. The dark strip is attributed to carbon deposition. This hypothesis has been confirmed by placing the mirror for ten minutes in an O_2 plasma chamber [4] to remove all visible black traces. Iridescence is a well-known phenomenon which could be easily attributed to a strong heat-up.

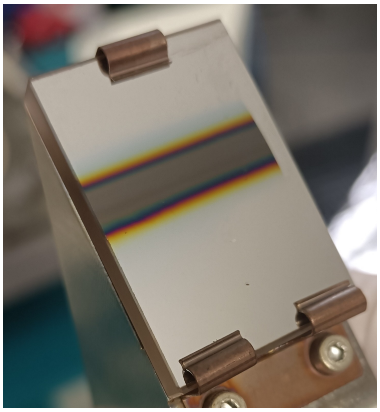

Figure 4: Picture of the booster's MRSV extraction mirror, after nearly 18 years of operation.

Once cleaned, the mirror surface was scanned using a white light interferometer (WLI [5]) at SOLEIL's surface Laboratory. This technique enabled to map the 3D surface of the mirror. As shown in Fig. 5, it clearly appeared that the mirror presented a groove, exhibiting a 5 µm deep valley all along the synchrotron radiation fan location. In addition, the upper and lower parts of the mirror, with respect to the horizontal/synchrotron radiation fan axis, were found to be tilted by an angle of roughly 1 mrad. Lastly, some drops could also be noticed, attributed to a local melting of the silver coating. The main result of this measurement is the observation of an angle between the mirror's lower and upper

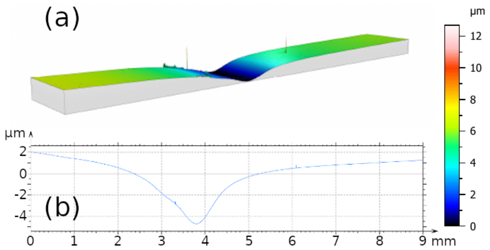

Figure 5: Results of the laser interferometry performed on the extraction mirror of the booster's MRSV after 18 years of operation. (a) 3D map of the mirror surface. (b) Mirror surface height along the vertical axis, i.e. line profile along the top image.

parts. Indeed, such an angle can induce a different pointing for the upper and lower parts of the synchrotron radiation fan (the middle part not being reflected due to the dark strip) towards the image plane, which could easily explain the double spot previously observed.

MRSV Issue Solving

Those observations indicate clearly that the synchrotron radiation has strongly damaged the extraction mirror. Due to a lack of time for a new design, a similar extraction mirror has been immediately mounted to replace the damaged one. During the following beam time at low injection rate, a nice single spot very close to the prediction was observable (Fig. 6 (a)). A survey of the MRSV image reveals that only a few weeks of operation lead to visible deformation of the MRSV spot (Fig. 6 (b)), hence a very quick degradation of the new mirror.

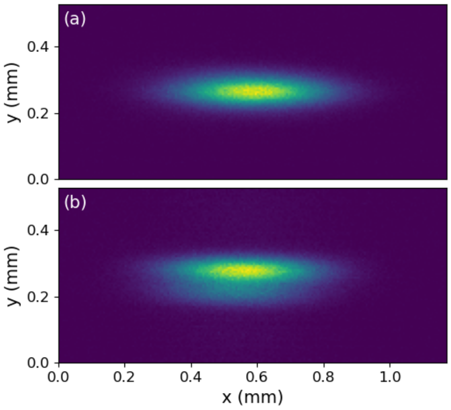

Figure 6: Image of SOLEIL's booster MRSV recorded (a) just after, (b) two weeks after, the replacement of the old extraction mirror (March 2023).

NEXT STEPS

Dark strip, iridescence and melted silver drops on the mirror were intuitively linked to an over-heat of the extraction mirror. But in the scope of SOLEIL-II, a reliable correlation between those observations and numerical thermal simulations must be established.

First, an estimation of the average power deposited on the mirror has been made relying on SRW simulations and assuming the booster to be running at 3 Hz in the higher charge mode (8 nC). The 2D average power density distribution was computed in the plane of the extraction mirror. The total average power was estimated to be ≈ 6 W, and the average power density to be $\approx 0.26\ \mathrm{W/mm^2}$. The thermo-mechanical behaviour of the extraction mirror has been simulated using the synchrotron radiation 2D power density map and a 3D modelling of both the extraction mirror and its environment in the Ansys software [6]. According to this work, the mirror surface temperature at equilibrium could reach 500°C, as shown in Fig. 7 (a). Without silver coating, this temperature could even heat up to 1000°C. Hence any defect in the mirror coating could easily lead to a local melting of the silver (silver fusion point: 961.8°C).

The reason for such high temperatures is the poor thermal conductivity of Pyrex glass ($\approx 1.2\,\mathrm{W\,m^{-1}\,K^{-1}}$). The heat load from the synchrotron radiation is locally stored by the mirror instead of dissipating within the whole mirror substrate and then through the mirror holder, finally leading to serious damage. To increase the lifetime of our extraction mirror, a first simple solution will be to change the mirror substrate material from Pyrex glass to Copper, offering a much higher thermal conductivity ($\approx 400\,\mathrm{W\,m^{-1}\,K^{-1}}$). The performances in terms of final temperature expected using such a mirror are presented in Fig. 7 (b). Thanks to a more efficient heat diffusion inside the mirror and towards its support, the final equilibrium temperature could drop down to 200°C.

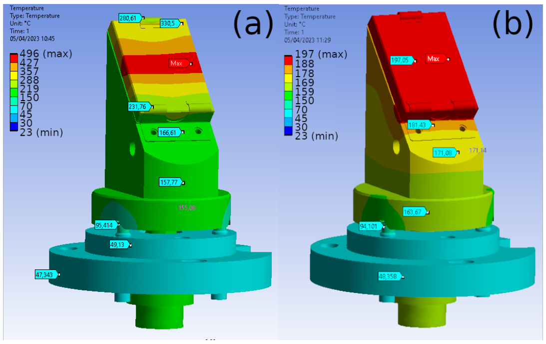

Figure 7: Surface temperature of the extraction mirror and its support simulated with Ansys using a mirror made of (a) Pyrex, i.e. actual mirror, (b) Copper, both silver coated.

Following these encouraging results, a new mirror (Copper substrate with UV-enhanced Aluminium coating) has been ordered. It has been mounted during last summer breakdown and commissioned on the 1st of September 2023. As expected, resulting image is a beam spot with similar intensity as Fig. 6 (a) in the same conditions. A regular survey is scheduled to check the presence of spot deformation (characteristic of mirror degradation) but with lower operating temperature, no degradation of the surface is expected in the future. Beam size measurement is now possible along the RF booster ramp and will hopefully be available for daily operation in the coming months.

CONCLUSION

We presented our first steps towards a future reliable beam size/emittance measurement along SOLEIL's booster energy ramp. After nearly twenty years of operation, we understood that the extraction mirror of our MRSV diagnostic was suffering a high heat load, not compatible with beam size measurement. We now expect to be able to achieve a reliable emittance measurement by the end of the year. All this work will be especially useful in the frame of the SOLEIL-II booster and associated diagnostics design.

ACKNOWLEDGEMENTS

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