ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOPT031

RENOVATION OF THE SR BEAM PROFILE MONITORS WITH NOVEL POLYCRYSTALLINE DIAMOND MIRRORS AT THE SuperKEKB ACCELERATOR

G. Mitsuka*, T. Mitsuhashi, H. Ikeda, KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Abstract

Synchrotron radiation (SR) beam profile monitors are fundamental to performing the stable beam operation of SuperKEKB. To suppress thermal deformation of SR extraction mirrors, a long-standing issue in SR monitors, we developed platinum-coated diamond mirrors in 2019. The diamond mirrors were made with an optical-quality polycrystalline-diamond substrate with extremely high thermal conductivity and have a size of 20 mm (W) × 30 mm (H) × 1.2 mm (D). We found surface flatness better than $\lambda/5$ in optical testing with a laser interferometer. The diamond mirrors have been installed in HER and LER in the 2020 summer and 2021 summer, respectively. Though irradiation for a year at the beam current greater than 1050 mA, we found no significant deformation of the diamond mirrors.

INTRODUCTION

Synchrotron radiations produced from the 5 mrad bends are emitted into the 23 m away extraction mirrors in each of the straight sections of the positron Low Energy Ring (LER) and the electron High Energy Ring (HER). Table 1 summarizes the source bend parameters in SuperKEKB. SR visible lights reflected by the extraction mirrors are further relayed 30 m into the corresponding optics hut above ground. SR beam profile monitors, such as interferometers and streak cameras, are located in each optics hut. For the use of the SR visible lights, thermal deformation of the extraction mirrors has been a long-standing problem not only at the preceding KEKB collider [1] but also at many synchrotron radiation facilities. Thermal deformation of the beryllium extraction mirrors at KEKB was so significant that one needed real-time measurements and complicated compensations of the distortion to correct for the beam-current dependence of the measured beam size.

Table 1: SR Source Parameters in LER and HER at SuperKEKB

Parameters	**LER**	**HER**
Energy (GeV)	4	7
Current (A)	3.6	2.6
Bending radius (m)	177.4	580
SR power (W/mrad)	72	149

Since the beginning of SuperKEKB, we have used the single-crystalline diamond mirrors to deal with even higher SR heat loads expected due to twice the beam currents than KEKB [2]. Single-crystalline diamond has extremely high heat conductivity and a lower thermal expansion coefficient than beryllium. As presented in Ref. [2], we found the thermal deformation of the first generation diamond mirrors seemed satisfactory below 900 mA, horizontally < 1 % and vertically < 4 % compared with that at zero current. However, at the designed current 2.6 A in HER, the deformation was expected to increase up to 2.5 % and 10 % and come to require unwanted compensations as we did in KEKB. In addition to the current-dependent tilt, we found some initial deformation along the horizontal direction: a cylindrically-curved surface with the cylindrical axis in the vertical direction.

To further suppress the thermal deformation of SR extraction mirrors, we developed the second-generation diamond mirrors in 2019. Hereafter, we see the design and construction of platinum-coated polycrystalline-diamond mirrors and current-dependent deformation measurements by a Hartmann test using a square array screen.

POLYCRYSTALLINE DIAMOND MIRRORS

Single-crystalline diamond mirrors previously used in SuperKEKB in 2016-2019 showed the thermal deformation of a few percent levels at < 900 mA relative to that at zero current. Though we did not yet analyze it in detail, the initial surface flatness was roughly a level of λ. These two rather unsatisfactory performances were caused by, primarily the structure consisting of six 10 mm × 10 mm single-crystalline sections fused at each edge, and second a thinner diamond substrate of 0.5 mm [2].

On the other hand, we made a new diamond mirror (20 mm (W) × 31 mm (H)) based on a polycrystalline diamond substrate having no connected subsection. A single substrate should improve surface flatness. The polycrystalline diamond we use in SuperKEKB has thermal conductivity 1800 W/mK at 300 K which is comparable to that of a polycrystalline diamond 2000 W/mK. Also, we changed the surface coating material to platinum which had 20 % higher reflective coefficient at < 500 nm than the gold used in the previous mirrors.

MIRROR HOLDER

The mirror holder is a water-cooled split cylinder of copper. The right panel of Fig. 1 shows the mirror mounted in water-cooled copper holder. The holder grips the mirror on one edge only to minimize applying extraneous strain to the mirror surface due to the thermal deformation of the copper holder itself. The use of copper enables good heat-sinking contact with the portion of the mirror surface gripped within

* gaku.mitsuka@kek.jp

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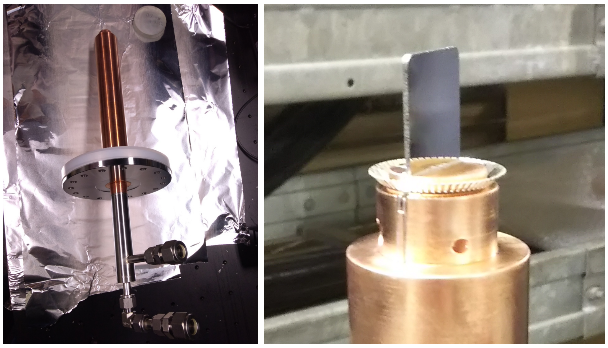

Figure 1: Left: The mirror holder consisting of a water-cooled split cylinder of copper. Right: Mirror mounted in water-cooled copper holder.

the split (about 8 mm from the lower edge). The mirror gripper mechanism was improved compared with the old holder; we inserted the 0.5 mm-thick indium sheet permitting a more 'tender' grip than a direct grip by copper only. Indium has a melting point 157 °C which is well above the expected diamond temperature at full-operation current.

INTERFEROMETRIC OPTICAL TESTING

Before installing the mirrors into the SuperKEKB tunnel, we performed two types of quality assurance testing; the first and second test is to check the mirror flatness before and after gripping it by the mirror holder, respectively. We performed the first test using the Fizeau interferometer Olympus KIF-201 (the left panel of Fig. 2). As shown in the top and bottom panels of Fig. 3, we obtained satisfactory results: the flatness of $\sim \lambda/4$ on the almost entire mirror surface and better than $\sim \lambda/5$ at the one half of the mirror. Next, we performed the second test using the laser interferometer shown in the right panel of Fig. 2 for the mirror gripped by the holder. Although we initially expected worse flatness because it was tightened from both sides by the mirror holder, we got comparable results with the first test.

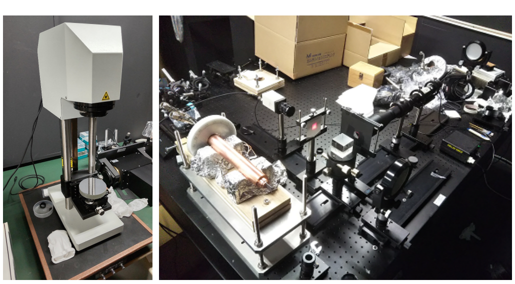

Figure 2: Interferometers used for quality assurance testing. Left: Fizeau interferometers Olympus KIF-201. Right: Interferometer setup using a He-Ne laser.

MEASUREMENTS FOR SURFACE DEFORMATION

The polycrystalline diamond mirrors were installed in the HER and LER SR extraction chambers in the 2020 summer and 2021 summer, respectively. Alignments of the extraction mirrors were performed along the SR beam axes to have a helium-neon laser beam transmitted correctly from the extraction chamber to the optical hut on the ground floor.

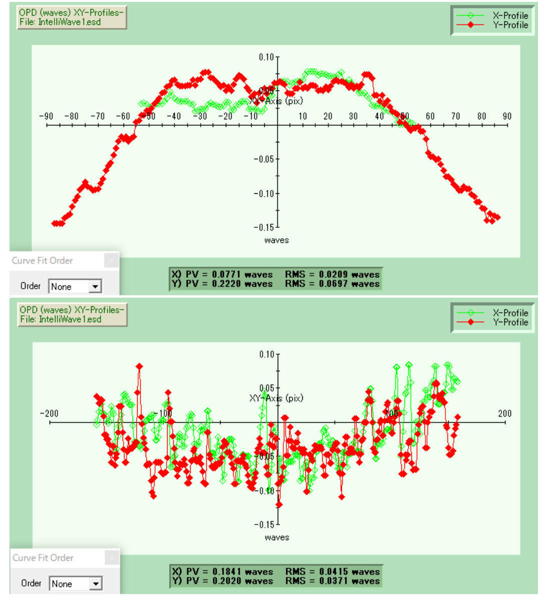

Figure 3: The mirror surface flatness. Top: the result obtained in the first test. Bottom: the result obtained in the second test.

After completing the laser-based SR beam axes alignment, we tested the mirror distortion using the SR beams. The actual rays reflected by a deformed mirror run along different optics paths than the ideal rays. To measure differences in optics paths, we apply a Hartmann test using a square array screen in which the SR beam going through the array screen holes makes blight Hartmann spots on a screen in the optics hut upstairs. The actual rays differently hit blight spots on a screen from those of the ideal rays.

The square array screen used at SuperKEKB follows that used at KEKB (the top panel of Fig. 4) that consists of a 10×10-hole square array screen where the hole diameter is 2 mm the separation of holes is 5 mm. The square array screen on a remotely movable stage is mounted 0.7 m downstream of the extraction mirror.

With measurements of the Hartmann spots' position shifts and intervals between peak positions, we can reconstruct initial and possibly current-dependent mirror deformations. The bottom panel of Fig. 4 shows an example of screen measurements using a commercial CMOS camera. Here the horizontal and vertical coordinates are rotated 90°, so the mirror bottom and top are on the vertically positive and negative sides, respectively.

Figure 5 shows the positions of a set of measured peaks of the Hartmann spots where the beam currents in LER range from 50 mA to 1050 mA. To be discussed later, hole separation distances seem equal for each, indicating well flatness of the mirror surface. As the beam current increases, the peak positions shift uniformly to the lower left. This

13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand JACoW Publishing
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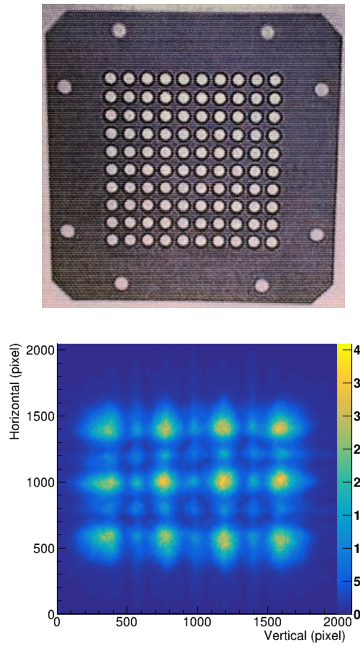

Figure 4: Top: A square array screen. Bottom: Measurement for Hartmann spots produced by the square array screen.

shift most likely comes from a tilt of the mirror holder due to its heat deformation.

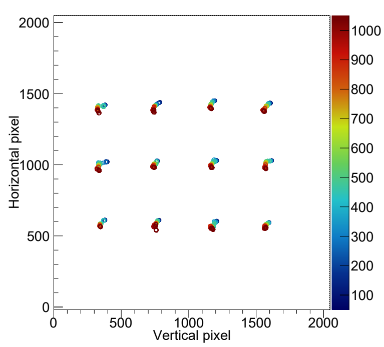

Figure 5: Pinhole image peaks measured at the beam current ranging from 50 mA to 1050 mA in LER.

Figure 6 indicates the mirror surface deformation at each beam current rainging from 50 mA to 1050 mA. As expected from the first panel (50 mA), we infer that the mirror has some initial deformation which is slightly tilting back (away from the irradiated side) perpendicular to the plane of the mirror. Although in the measurements at > 300 mA some levels of current-dependent deformation are found, the Peak-to-Valley is about $\lambda/4$ which is comparable with the interferometric optical testing in the optics hut. More sophisticated data taking and analysis will be our next task to conclude this current-dependent tendency.

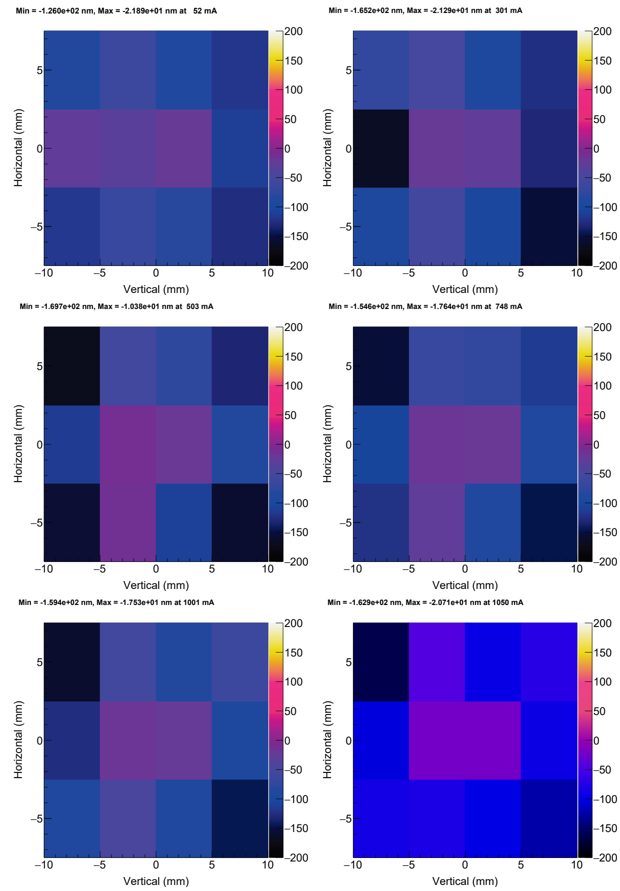

Figure 6: Mirror surface deformation in LER at the beam current ranging from 50 mA (top left), 300 mA (top right), 500 mA (middle left), 750 mA (middle right), 1000 mA (bottom left), and 1050 mA (bottom right).

ACKNOWLEDGEMENTS

The authors thank M. Arinaga of the Accelerator Laboratory at KEK for performing heat transfer simulations in a diamond mirror and copper-made mirror holder.

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