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THERMAL PERFORMANCE OF DIAMOND SR EXTRACTION MIRRORS FOR SuperKEKB

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Abstract

The SuperKEKB accelerator is a high-current, low-emittance upgrade to the KEKB double ring collider. The beryllium extraction mirrors used for the synchrotron radiation (SR) monitors at KEKB suffered from heat distortion due to incident SR, leading to systematic changes in magnification with beam current, and necessitating continuous monitoring and compensation of such distortions in order to correctly measure the beam sizes. To minimize such mirror distortions, quasi-monocrystalline chemical-vapor deposition (CVD) diamond mirrors have been designed and installed at SuperKEKB. Diamond has a very high heat conductance and a low thermal expansion coefficient. With such mirrors it is hoped to reduce the beam current-dependent magnification to the level of a few percent at SuperKEKB. Preliminary measurements of mirror distortion during SuperKEKB commissioning show very promising results with regard to thermal performance, though full beam currents have not yet been stored in the SuperKEKB rings. Measurements of the thermal deformation of the diamond mirrors will be presented in this paper, along with a description of the design of the mirrors and their mounts, and issues encountered during commissioning.

INTRODUCTION

Table 1: SR Source Parameters at KEKB and SuperKEKB

Parameter	KEKB		SuperKEKB	
	LER	HER	LER	HER
Energy (GeV)	3.5	8	4	7
Current (A)	2	1.4	3.6	2.6
Bending radius (m)	85.7	580	177.4	580
SR Power (W/mrad)	48	136	72	149

Visible-range SR monitors have been installed at SuperKEKB in both the 4 GeV positron Low Energy Ring (LER) and the 7 GeV electron High Energy Ring (HER). The SR monitors at SuperKEKB use source bends in the same locations as at KEKB, the 5 mrad "weak bends" heading into the Fuji (LER) and Oho (HER) straight sections. The source bend parameters are shown in Table 1.

Heat deformation of the beryllium extraction mirrors was a very significant problem at KEKB, requiring complicated measures to measure and compensate for the distortion in real time in order to correct the beam-current dependence on the measured beam size [1]. Because the SR heat loads will be even higher at SuperKEKB, we have been pursuing the use of mirrors made of diamond, which has higher heat conductivity and lower thermal expansion coefficient than those of beryllium. Previous simulations have suggested that in the ideal case of a continuously monocrystalline mirror, the effective magnification changes due to thermal distortion as a result of absorbed incident SR power can be kept to the level of a few percent at the full design beam currents of SuperKEKB [2].

MIRROR AND HOLDER

The mirrors designed for SuperKEKB are made of CVD diamond, made by Cornes Technology and EDP Corporation. Each mirror is 20 mm wide x 30 mm tall, consisting of six 10 mm x 10 mm monocrystalline sections fused together, with a reflective surface made of 3 μm of gold. The thickness of the diamond substrate of each mirror is 0.5 mm. One of the mirrors is shown in Figure 1.

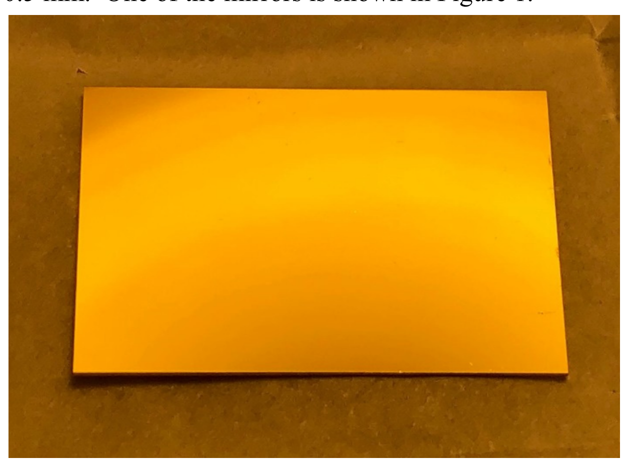

Figure 1: A 20 mm x 30 mm x 0.5 mm diamond mirror, consisting of six 10 mm x 10 mm monocrystals fused together, with 3 μm Au reflective coating. The light intensity pattern seen on the mirror surface comes from the reflector of the lamp used to illuminate it.

The mirror holder is a water-cooled split cylinder of soft copper, which grips the mirror on one edge only in order to

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minimize the application of extraneous strain on the surface of the mirror due to thermal deformation of the copper holder itself. The use of soft copper permits a good heat-sinking contact with the portion of the mirror surface gripped within the split (about 6 mm from the lower edge). The holder with mirror installed is shown in Figure 2.

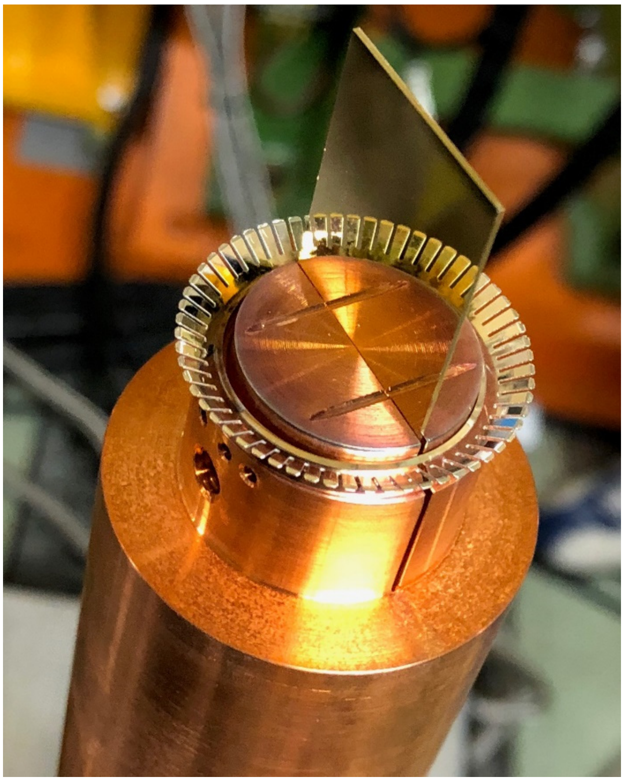

Figure 2: Mirror mounted in water-cooled soft copper holder.

The mirror and holder are located in an antechamber away from the beam, to minimize impedance and trapped-mode heating. Figure 3 shows the mirror mounted inside the antechamber of the SR extraction chamber. The mirror is mounted at a 45-degree angle with respect to the beam, with an extraction window located directly across from the mirror, in the wall of the other antechamber, on the opposite side of the electron or positron beam from the mirror.

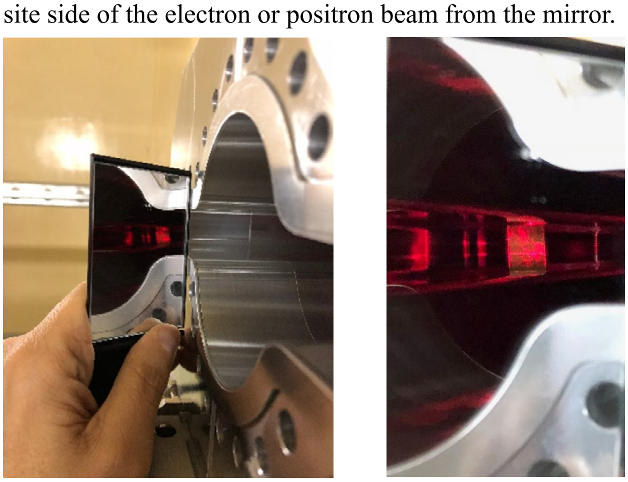

Figure 3: Mirror mounted in antechamber of extraction chamber, illuminated by helium-neon alignment laser. Left: View from the entrance of the extraction chamber. Right: Close-up of the reflection in the hand-held mirror seen at left. The mirror is the right-most illuminated rectangle in the right-hand image.

The height of the antechamber is 24 mm. The extraction chamber is located about 20 meters from the source point in each ring, with about another 40 meters of light path after that to reach the corresponding optics hut above ground. SR interferometers [3,4] and a streak camera are located in each optics hut.

PINHOLE MASK MEASUREMENTS

Mirror distortion measurements were made by the use of a pinhole mask array. The pinhole arrays used at SuperKEKB were also used at KEKB -- for further details, see [1]. The pinhole array is mounted just outside the extraction chamber on a remotely movable stage so that it can be moved out of the way for normal operation.

For measurements, the mask is moved into the path of the SR beam reflected from the extraction mirror, and its projection is observed in the optics hut upstairs. Deformities in the mirror surface cause the observed pinhole images to shift position. One of the pinhole arrays is shown in Figure 4.

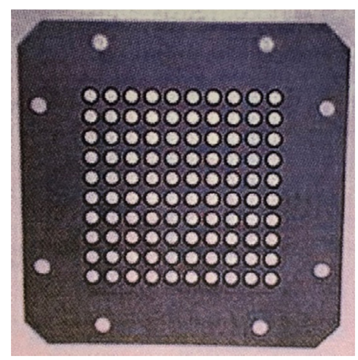

Figure 4: Pinhole array mask used for mirror deformation measurements.

Mirror Tilt and Static Deformation

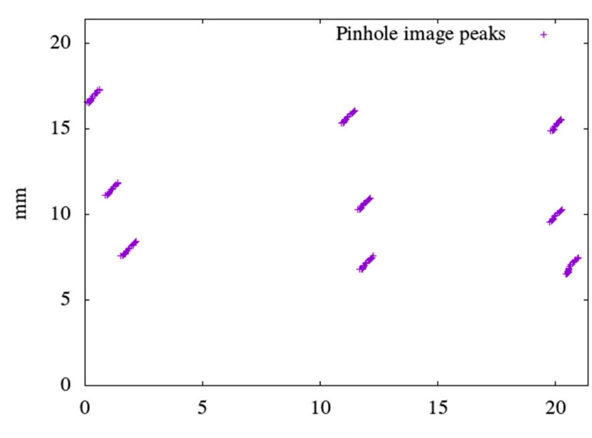

Figure 5: Pinhole image peaks measured at a range of beam currents in HER. As beam current increases, each peak position shifts upward and to the right.

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The positions of a set of measured peaks of the pinhole images for the HER mirror are shown in Figure 5, for a range of beam currents from 90.6 to 900 mA. As beam current increases, the peaks shift uniformly to the upper right at a 45 degree angle. This indicates that the mirror and/or holder is tilting slightly back (away from the illuminated side of the mirror) perpendicular to the plane of the mirror. The degree of tilt in going from 90.6 mA to 900 mA is 92 microradians. This corresponds to a total tilt of 295 microradians in going from 0 mA to the full SuperKEKB design current of 2.6 A, which is an acceptable amount.

In addition to the current-dependent tilt, some static deformation can be seen, as reflected in deviations of pinhole image peaks from the regular square spacing of the pinhole mask itself. Most notably, while the average spacing in the vertical direction is close to what would be expected from simple geometric projection, in the horizontal it is significantly larger, suggesting a cylindrically-curved surface with the cylindrical axis in the vertical direction. There are further local irregularities visible in addition. The manufacturer reports that they have improved their polishing technique since this initial batch of mirrors, and we are consulting with them to produce a new set of mirrors with improved flatness and rigidity for installation in the next year.

The LER mirror showed a much larger beam current-dependent shift than that of the HER, but almost entirely in the vertical direction, indicating that the entire chamber is tilting downwards at the upstream end, perhaps due to a loose footing. The magnitude of the shift prevented getting good current-dependence measurements for the LER. The heat load is larger for the HER, so HER measurements should cover the range of distortion experienced in the LER as well. The LER anchor footing is being improved for the fall 2019 run.

Deformation vs Current

While in principle a fixed mirror distortion can still be used for SR interferometer measurements once measured and corrected for, a current-dependent one is much more troublesome to deal with, requiring constant measurement and correction.

For a pinhole separation D, distance from source R, and wavelength λ, the size σ of a Gaussian beam is given by:

$$\sigma = \frac{\lambda R}{\pi D}\sqrt{\frac{1}{2}ln\left(\frac{1}{\gamma}\right)}, \tag{1}$$

where γ is the visibility of the interference pattern produced by the interferometer [4]. Inverting the above, γ is dependent on Dσ, so if the slit separation unknowingly changes from D to D^*, then the apparent measured beam size changes to $\sigma^* = (D^*/D)\sigma$, where s is the true beam size. Thus the relative change in magnification when using an SR interferometer is given by the relative change in effective interferometer slit separation, which corresponds to the inverse relative change in pinhole image separation as measured using the pinhole mask. Accordingly, we measured the change in distance between the most widely separated pairs of pinhole projections in both the horizontal and vertical directions in order to evaluate the change in magnification.

In the horizontal direction, three pairs of pinhole images were used at the upper, middle and lower parts of the mirror. Their separations are shown plotted in Figure 6. The linearly-fitted trends indicate that from 0 to 900 mA, the magnification changes by 0.6%, 0.2% and 0.9%, respectively (average 0.6%). At the full design current for the HER of 2.6 A, these extrapolate to 1.6%, 0.6% and 2.5%, respectively, for an average of 1.6%.

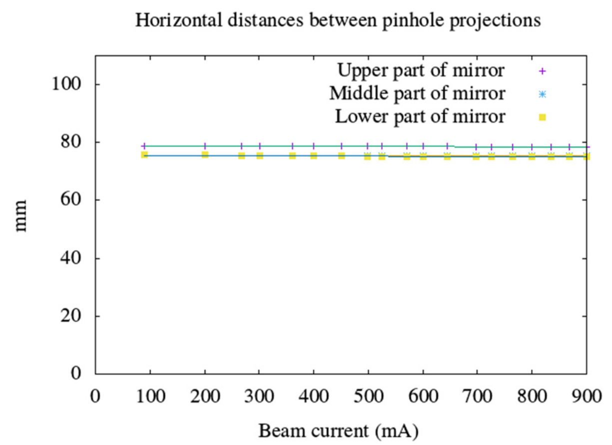

Figure 6: Distances between horizontally-separated pinhole image peaks as a function of beam current in HER.

In the vertical direction, three pairs of pinhole images were used at the upstream, middle and downstream parts of the mirror. Their separations are shown plotted in Figure 7. From 0 to 900 mA, the fitted trends indicate magnification changes of 3.6%, 0.5% and 0.9%, respectively (average 1.7%). At full design current, these extrapolate to 10%, 1.5% and 2.5%, respectively, with an average of 5%.

For the LER, as mentioned above, the incident SR power load at the full design current of 3.6 A is lower than that of the HER at its full design current (see Table 1), so the magnification changes should be correspondingly lower.

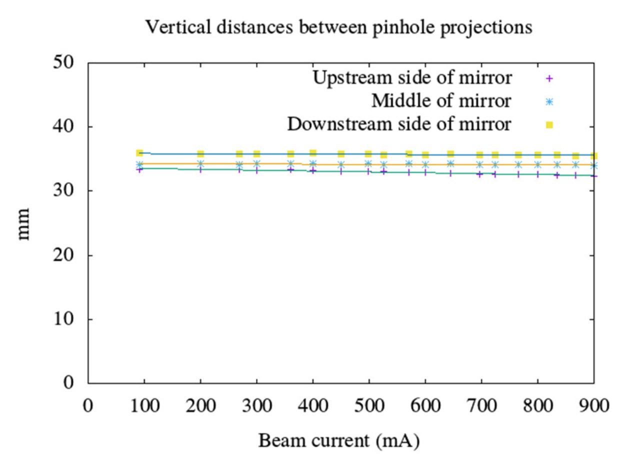

Figure 7: Distances between vertically-separated pinhole image peaks as a function of beam current in HER.

These changes in magnification are satisfactory for our purposes at SuperKEKB. Nevertheless, in the next version

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of the mirrors we may increase the thickness of the diamond substrate, which may improve the rigidity of the mirrors.

CONCLUSION

The thermal deformation of the first generation of diamond mirrors at SuperKEKB has been measured during beam commissioning at beam currents up to 900 mA in the HER. At the full design beam current of 2.6 A in the HER, the extrapolated deformation in the horizontal direction corresponds to a change in magnification of 0.6% to 2.5%, depending on location on the mirror, with an average of 1.6%. In the vertical direction, the change in magnification extrapolates to 1.5% to 10%, average 5%, at the full design current. The changes in the LER mirror should be smaller, due to lower incident SR power heat load.

This thermal performance seems quite satisfactory. Some issues of mirror flatness and uniformity remain, and we are working with the diamond manufacturing company to address these issues for the next version of the mirrors, and possibly further improve the rigidity of the mirrors, with a hope to install and test the next generation of mirrors at SuperKEKB in the next year.

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