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On controlling gravitational distortions in long synchrotron x-ray mirrors

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ABSTRACT

X-ray mirrors for synchrotron radiation beamlines must have low roughness and small figure errors to preserve source brilliance. Gravitationally-induced slope errors can be particularly detrimental for large vertically-deflecting mirrors on ultra-high brilliance third-generation beamlines. Although mirror support can greatly reduce gravitational distortions, in some cases mirror support can complicate dynamic bending. We discuss techniques for controlling gravitational distortions with particular emphasis on removing gravitational distortions from simple bendable mirrors. We also show that in beamlines with parallel mirrors, gravitation induced slope errors can be canceled through the mirror pair; gravitation induced slope errors of the first mirror can be canceled by matching slope errors with opposite signs on the second mirror.

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1. INTRODUCTION

The development of ultra-brilliant third-generation synchrotron sources places extreme demands on the surface roughness and figure error requirements for x-ray mirrors. For example, at third generation storage rings the vertical x-ray divergence has a standard deviation, σ_V', on the order of tens of microradians or less, whereas at second generation sources the vertical x-ray divergence has a σ_V' on the order of hundreds of microradians. The small vertical divergence of third generation sources places extreme demands on the mirror figure and roughness. For example as shown in Fig. 1, with a source of 5 μrad RMS vertical divergence, the brilliance from a mirror begins to seriously degrade when the RMS slope errors exceed 1-2 μrad.

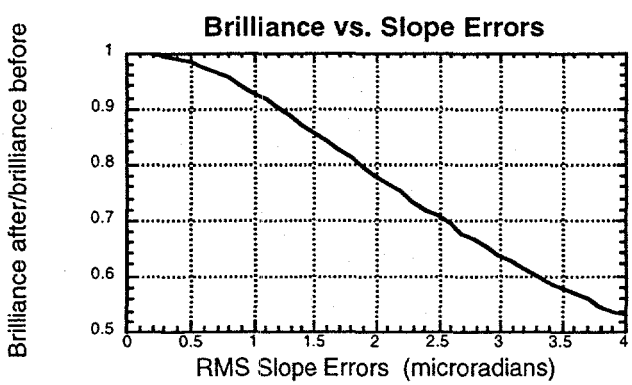

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Fig. 1 Decreased x-ray brilliance for a vertically scattering x-ray mirror as a function of the longitudinal RMS slope errors for an undulator beam with an intrinsic vertical RMS divergence of 5 μrad.

The requirement of ultra-low-figure-error x-ray mirrors is further complicated by the roughly four times larger distances between the source and the first optics of third generation beamlines compared to second generation beamlines; mirrors for third generation sources must have an order of magnitude lower figure errors than second generation mirrors to preserve brilliance but must have nearly the same length. One solution, which reduces the need for low-figure-error mirrors, is the use of mirrors which deflect in the plane of the x-ray ring (horizontally). The three times larger horizontal divergence means that the mirror figure

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errors can be about three times larger before beam brilliance is degraded.[1] Also gravitational sag has almost no effect on the mirror figure in the horizontal scattering geometry, and horizontal scattering introduces virtually no beam degradation in the vertical plane. However horizontal deflecting mirrors must also be three times longer than vertical deflecting mirrors which challenges mirror technology for glancing angle mirrors designed to reflect high energy x-rays.

For flat mirrors or for mirrors with fixed radii, distortions introduced by gravitational sag can be greatly reduced by making thick mirrors and by holding the mirror so as to minimize gravitational distortions. Schemes for making stiff mirrors and for holding mirrors to reduce gravitational sag have been discussed by Howells and Lunt.[2] For an end supported mirror the deflection at the center of the mirror is given by,[2]

$$\Delta y = \frac{-5mL^4}{32wh^3Y} \tag{1}$$

Here Y is the modulus of elasticity, m is the mass-per-unit-length, w is the mirror width, h is the mirror thickness and L is the mirror length. Mirror sag rapidly increases as mirror length increases and as mirror thickness decreases. As an example consider a 80 mm thick Si mirror which is 800 mm long. If the mirror is supported on the ends, a flat mirror will distort due to gravitation to a shape as illustrated in Fig. 2a. The unacceptably large gravitational distortions can be greatly reduced by supporting the mirror at an intermediate position. For example, Howells and Lunt[2] have described the performance of a simple mirror with different support locations. Minimum slope errors occur for $d=L/\sqrt{3}$. Here L is the mirror length and d is the distance between the supports. As shown in Fig. 2b, the gravitational slope errors, for the same mirror, with optimal support are very small. However the use of support structures away from the ends of the mirror can complicate bending mechanisms and may not be acceptable for bendable mirrors.

We discuss means to reduce gravitational sag for bendable mirrors. With bendable mirrors the thickness of the mirror may be limited by materials availability, by the allowable stress limit of the mirror material or by the strength of the bending mechanism.

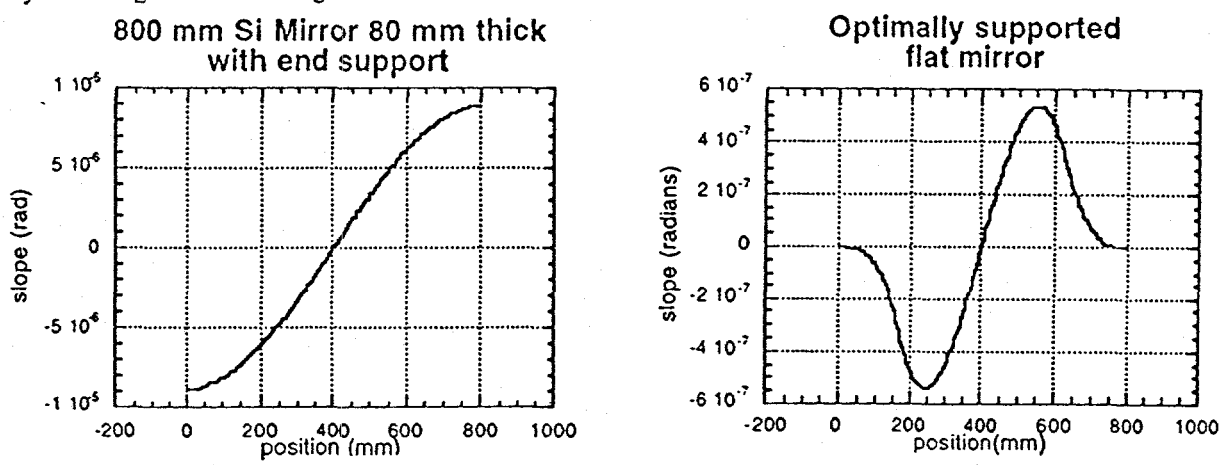


Fig. 2 (a) Silicon 800 mm long mirror with end support shows large gravitationally induced slope errors even when 80 mm thick. (b) Same mirror with two support points centered on the mirror and separated by $d=L/\sqrt{3}$ where L is the mirror length.

2. MINIMIZING GRAVITATION SAG IN BENDABLE MIRRORS

Counter bending

As discussed above, the simplist means to reduce gravitational sag in bendable mirrors is to make stiff mirrors. For a given material, stiffness increases as the cube of the mirror thickness, h^3, but bending becomes more difficult. If thickness is limited, the next simplest means to reduce gravitational sag in

bendable mirrors is by counter bending the mirror. As shown in Fig. 3a and 3b, counter bending with a cylindrical bending mechanism can remove most of the slope errors introduced by gravitational sag. For example with an 800 mm long by 80 mm thick Si or ultra-low-expansion glass (ULE) mirror, the maximum counter-bent slope errors are within 1 μrad over a mirror aperture of at least 700 mm. The distribution of slope errors has a standard deviation of less than 0.2μrad over the central 700 mm of the Si mirror, and less than 0.25μrad over the central 700 mm of the ULE mirror. With a thin mirror however counter bending may not be sufficient. As shown in Fig. 4, a 800 mm long by 40 mm thick ULE mirror cannot maintain sub-μrad figure errors through counter bending alone. The distribution of slopes for the 800 mm long by 40 mm thick ULE mirror has a standard deviation of 1μrad over the central 700 mm of the mirror. Far worse performance will result from very thin mirrors (e.g. float glass).

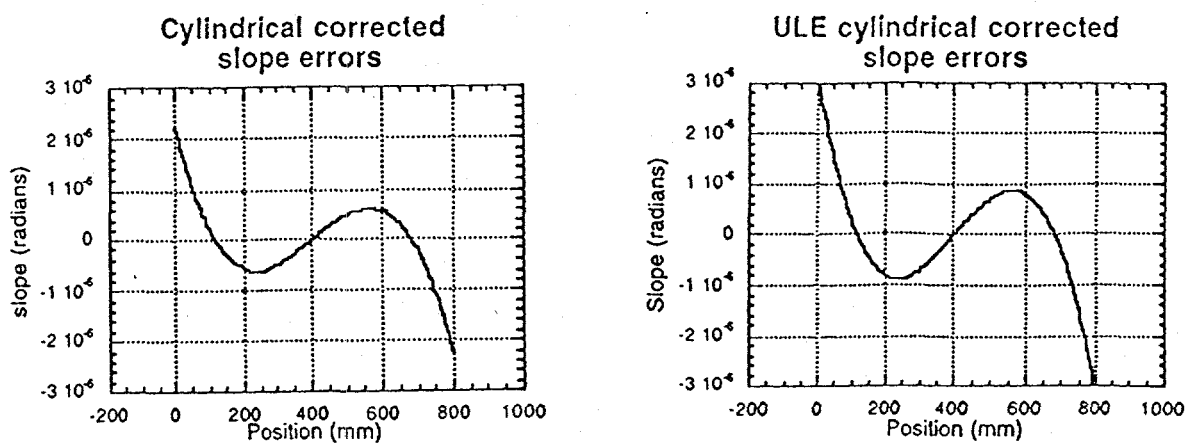


Fig. 3 (a) Slope errors for an 800 mm long by 80 mm thick Si mirror which is end supported and then reverse bent with a cylindrical bending mechanism to counteract the effects of gravity. (b) Slope errors for a ULE mirror with the same 800 mm by 80 mm dimensions.

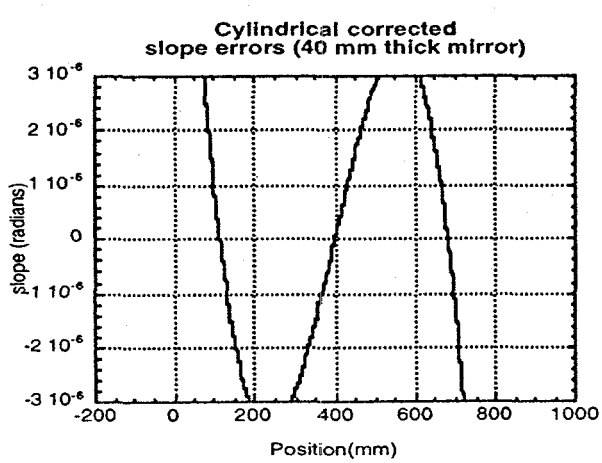


Fig. 4 ULE mirror 40 mm thick x 800 mm long after cylindrical correction to remove gravitational sag. The cylindrical correction cannot compensate for gravitational sag. Substantial beam brilliance loss will result from the gravitational sag.

Spring Support

Another simple way to reduce the gravitational sag distortions is to support the mirror along its length with springs which float the mirror. Even a single centrally located spring can significantly reduce the maximum slope errors. For example as shown in Fig. 5a with a single central spring supporting half the mirror weight, the slope errors are reduced by an order of magnitude. For uniformly distributed springs, best performance occurs when the mirror weight is divided evenly between the springs. If a mirror of weight W is supported by n springs, which evenly divide the mirror into n+1 segments, the springs should apply a force W/(n+1). Multiple springs can be used to further refine the slope and can provide some compensation for residual slope errors left from manufacturing. With three springs the maximum slope error is reduced an additional order of magnitude (Fig. 5b).The maximum deflection of the center of the mirror during bending depends on the mechanism used to bend the mirror and the radius of curvature. For a simply supported mirror with a minimum radii of 1 km and a length of 1m, the deflection at the center is ~125 μm. If the springs are designed to achieve the required force with a macroscopic deflection of at least 10 mm then the total change in the spring applied forces varies less than ~1% as the mirror is bent.

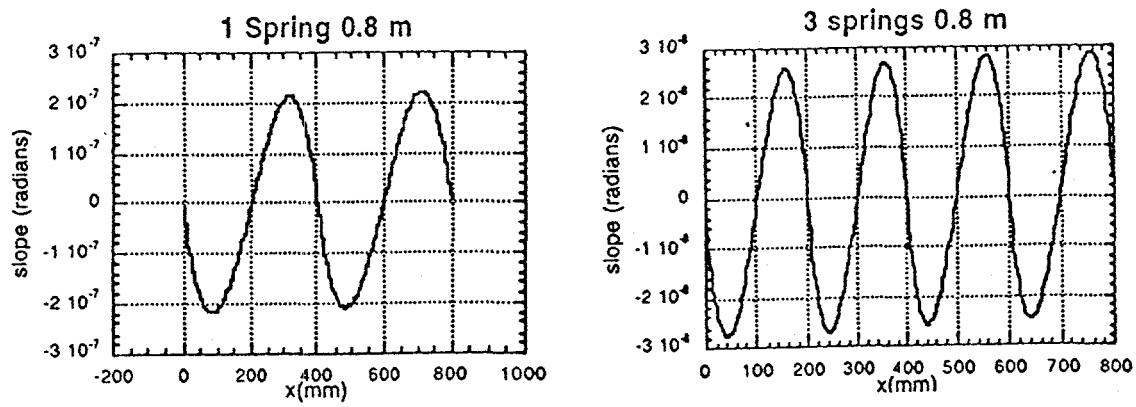


Fig. 5 (a) Slope errors of a Si, end supported 0.8 m 0.08x0.08 m^2 mirror with a single spring in the center. (b) Slope errors of a Si, end supported 0.8 m 0.08x0.08 m^2 mirror with three equally spaced springs.

Spring loading changes on the order of 10% are within the required range for the corrected mirror slope errors as shown in the comparison between Fig. 5b and Fig. 6. Springs have previously been used on an x-ray mirror at beamline X14 (NSLS) to compensate for gravitational sag.[3] No problems with vibration were ever observed.

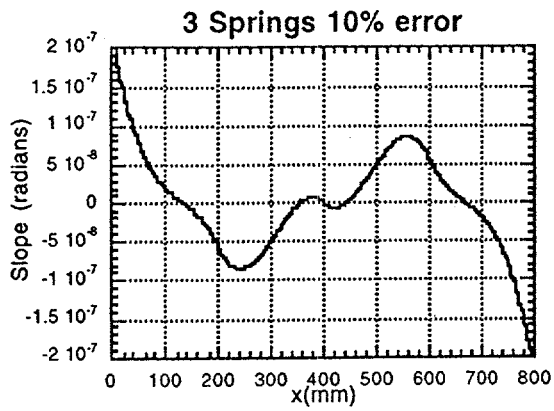
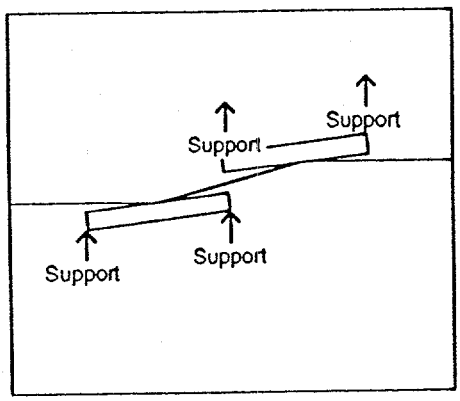


Fig 6. Slope errors for an end supported, 800 mm long by 80 mm thick Si mirror with three springs but with the springs 10% away from the optimized forces. We note that deviations of less than 0.1% are anticipated in the applied spring forces due to deflection of the mirror from bending.

Compensating gravitational sags

In some cases, where matched nondispersive mirror pairs are used, gravitational sag error may naturally cancel. For example the two mirrors shown in Fig. 7a naturally cancel their slope errors if they are similarly supported and if they are not too far apart; the first mirrors sag makes it concave with respect to the incident radiation and the second mirrors sag makes it convex. Because each ray strikes the two mirrors at nearly the same position along the mirror(when well aligned), the focusing/defocusing of the mirrors nearly cancels out. Complete cancellation is difficult because of the x-ray beam has a small divergence, and because the first mirror introduces a divergence which spreads even a collimated beam before it strikes the second mirror. Excellent cancellation is however possible as shown in Fig. 7b. Here there is a 1 m separation between the two mirrors but the gravitational sag errors are not exactly canceled because of beam spreading between the two mirrors. This spreading can be controlled by collimating the x-ray beam with the first mirror. However even without beam collimation, the cumulative slope errors for two matched mirrors



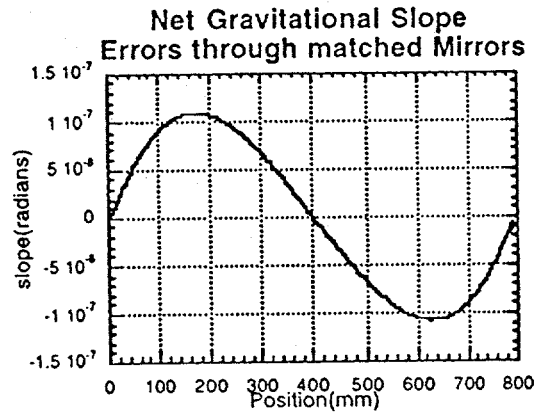


Fig. 7 (a) Nondispersive mirror pair. (b) Cumulative slope errors through two gravitationally sagging mirrors. The rough slope results from round off errors and illustrates the small errors associated with this geometry. A uniform bending moment applied to the second mirror will achieve nearly ideal focusing for modest demagnifications.

is small compared to the divergence of the x-ray beam. The net effect of matched mirrors from gravitational sag should be negligible. The main challenge is holding the mirrors in such a way that the upward and downward mirrors sag identically (but reflect from opposite sides relative to the sag).

Matched nondispersive mirrors not only compensate for gravitational sag, but allow the mirror critical angle to be adjusted with only a small change in the exit beam height. Matched nondispersive mirrors are planned for several beamlines including the UNI-Cat beamline at the APS.

3. CONCLUSION

Gravitational sag, which contributes to loss of brilliance, can be controlled by using stiff mirrors, by counter bending, by supporting with springs and by cancelling focusing/defocusing with matched mirror pairs. For cases where it may be difficult or impossible to produce thick mirrors, counter bending can reduce the max-to-minimum slope errors by more than an order of magnitude. Further reduction in slope errors can be accomplished by spring support. Spring support allows bending with gravitational sag errors reduced by 1-2 orders of magnitude. The precision of the spring support required is not high.

4. ACKNOWLEDGMENTS

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