DISCLAIMER

SRC Technical Notes are informal memos intended for internal communication and documentation of work in progress. These notes are not necessarily definitive and have not undergone a pre-publication review. If you rely on this note for purposes other than its intended use, you assume all risk associated with such use.
The following discussion is a result of studies undertaken to determine the feasibility of using bent glass cylinders (wide bore tubing) as the focusing element in the CXrL ES-2 beamline. Such a system is available at moderate cost from the Blackett Laboratory, London, England (1). Cylinders are available in a variety of inner bore diameters ranging from 5 mm to 150 mm in 5 mm increments.

This white-light beam-line should, ideally, accept about 35 mRad and focus it to a small spot about 6 m from the source. The grazing angle should be 2 degrees, or less, to avoid reflectivity losses of the high-energy components. It would also be desirable to have a uniform, somewhat rectangular distribution down-stream from the optimal focus that could be scanned across a sample (ie. for lithography work).

To establish a standard for comparison, a double mirror system using the familiar Kirkpatrick-Baez arrangement was studied and optimized for the given source to focus parameters. Both mirrors used were elliptical cylinders.

**SHADOW Results**

**KIRKPATRICK-BAEZ**

The first case studied was that of the familiar Kirkpatrick-Baez arrangement set up to focus the light 6 m from the source (Fig 1a). The desired 35 mRad acceptance angle requires a rather long mirror for the horizontal deflection and focusing. At 2 degrees this translates to an active optical surface of about 230 cm in length. This is visually demonstrated in Fig 1b. The second mirror must be wide enough to accept the full width of the horizontal beam, but its length is much shorter (Fig 1c) due to the narrower vertical divergence of the SR beam.

The final image of this system is a thin horizontal line (Fig 1d), the result of a system that magnifies the image in one plane, and demagnifies the image in the other plane. Switching the positions of the two mirrors (Fig 2a) will help by demagnifying the plane with the greatest width providing a more compact image (Fig 2d), however the length required of the horizontally focusing mirror increases proportionately.

Since the vertical and horizontal deflections are independent of each other and are performed by mirrors that are curved in one plane but flat in the other, the final image does not experience any curvature, even when the image plane does not coincide with the focus (Fig 3).
BENT CYLINDER – Toroidal

Toroidal mirrors provide best focusing results when used in a 1:1 configuration (Fig 4a), focusing a point source to a point image. The source to focus distance was held at 6m, to make direct comparisons with the above system easier. The toroidal mirror deflects the beam in the vertical plane, thus it can be quite compact (Fig 4b). The simplicity of the optics allows for use of overall beamline lengths from 4m on up. The image displays a diffuse tail on the side opposite the mirror(Fig 4c), typical of such toroidal systems attempting to focus a non-point source. Appropriate use of masks just upstream of the image can help eliminate the tail.

BENT CYLINDER – Ellipsoidal

For imaging of a point source, the best choice is an ellipsoidal mirror. Unlike the toroid, the ellipsoid can be used at other than 1:1 imaging, though for purposes of comparison the overall length is 6 m (Fig 5a). Like the toroid, there are limitations to what this ‘ideal’ mirror can accomplish. Since the SR source is not a point source, the image experiences distortions. In the case of the ellipsoid, the best focus possible for a SR source is the ‘butterfly’ image in Fig 5c.

BENT CYLINDER – General

Due to the compound curvature of these mirror surfaces, the image experiences a very characteristic curved distortion before and after the optimal focus (Fig 3). It is possible to eliminate this distortion by using two mirrors in such a way that the second mirror corrects for the aberrations of the first.

General Results

KIRKPATRICK-BAEZ

Advantages:

1. With a little care, the optics can be matched in such a way as to produce a fairly uniform spot.

2. Furthermore, since the vertical and horizontal focusing are independent, the image does not experience the curved ‘smiley’ aberrations introduced by toroidal and ellipsoidal optics.

Disadvantages:
1. One of the primary drawbacks to such a system is the required length of the horizontally focusing mirror. For a 2 degree grazing angle accepting 35 mRad of incoming SR light, the optical surface of the mirror must be nearly 230 cm long! Though this is not an unheard of length, it tends to eat up a lot of floor space on a 600 cm beamline, 120 cm of which is already consumed by the front-end. Fortunately, the vertically focusing mirror can be much shorter due to the smaller vertical divergence of the high energy (1000+ eV) photons, making the physical construction of this line a possibility.

2. One other optical limitation of the system is the use of a reflecting surface at right angles to the principle polarization axis of the radiation. This results in lower reflectances than a surface which is nearly parallel to the, predominantly horizontal, electric-field polarization axis.

3. In addition to the optical limitations stated above, the long mirror implies a lengthy vacuum chamber wide enough to permit room for the mirror and bending jig and provide an unobstructed path for the light. There is also the problem of procuring and coating the mirror, in addition to the need for two bending jigs, mirrors, etc.

BENT CYLINDER

If thin-walled tubing is utilized, the bending of the tube causes the outward displacement of the cylinder's wall, and results in a more ellipsoidal figure (Fig. 7). A detailed analysis of this distortion is possible, through ANSYS, but is not included in this report. The assumptions made for the basis of this project were that, the thicker the cylinder's wall, the more toroidal the final configuration. Thus the actual reflective surface is a hybrid between a toroid and an ellipsoid. To make an evaluation of the possible results, the pure toroid and pure ellipsoid extremes were studied. The actual image should be somewhat intermediate of the two extremes.

Advantages:

1. The ‘bent cylinder’ optical systems have the advantage of utilizing only one mirror to simultaneously focus in both the vertical and horizontal directions. As a result, the mirror can be much smaller if mounted to deflect the beam vertically making it much easier to consider a wider variety of enhancements and options.

2. Since all of the reflections are in only one plane, advantage can be made of the synchrotron radiation's horizontal polarization to improve reflectances.

3. The uniform 1:1 imaging of the bent cylinder system produces an image that has a tighter spot than the K-B system discussed above. It is also conceivable that the system could be used in a 1:2 overall demagnification of the image to produce an even tighter spot. However, toroidal mirrors work best near 1:1 magnifications.
Dissadvantages:

1. One of the biggest disadvantages of the bent-cylinder system is that the final image experiences distortions before and after the optimal focus. This is true of both the ellipsoidal and toroidal mirrors and is an unavoidable result of their compound curvatures. This can be compensated for by using a two mirror system, though this doubles the cost of the optics.

2. Unlike ‘float-glass’, which has an inherently smooth surface finish, the wide-bore tubing has a surface finish dependent on its extrusion conditions. The suppliers of the bent cylinder optics use a Nomarski microscope to choose tubing with smooth inner surfaces. They state that they have measured the reflectivity at 4.4 nm and found it approaches 70% of the theoretical (1). Should a smoother finish be desired any of a number of specialty optic shops could do the work with prices depending on the final surface finish required (2).

Conclusions

The use of bent cylinder optics provides a good quality image at a very reasonable cost (approximately $2800.00 for the wide-bore glass tubing and bending jig, delivered). In addition, it is compact and simple, allowing for various beamline designs incorporating additional instrumentation or optics. Some possible configurations are included in Fig. 8. Future alterations to the beamline length can be accommodated by purchasing the appropriate diameter tubing (approx. $400.00) and replacing the existing tubing. Gold vacuum deposition on these mirrors can be done at SRC without modification of existing equipment. The trade-off for all of this is an image that exhibits a curved shape at other than the optimal focus.

References

(1) Personal correspondence with R.J. Speer, 305, The Blackett Laboratory, Imperial College of Science and Technology, London, England, SW7 2BZ.

(2) Personal communications with representatives of J.A. Optics and Continental Optics.
Fig. 1 - The familiar Kirkpatrick-Baez arrangement was used as a standard for comparison. a) Optical layout of the 6 meter long line. b) Footprint of SR on first (horizontally deflecting) mirror. c) Footprint of SR on second (vertically deflecting) mirror. d) Final image at optimal focus.
Fig. 2 – Exchanging the positions of the two mirrors produces a more desirable image. 

a) Optical layout of 6 meter long line. 
b) Footprint of SR on first (vertically deflecting) mirror. 
c) Footprint of SR on the second (horizontally deflecting) mirror. 
d) Final image at optimal focus.
Fig. 3 – The shape of the image from the K-B arrangement is still rectangular in nature well past the optimal focus (in this case, 20 cm) as opposed to the curved image produced by the bent cylinder optics. a) Kirkpatrick–Baez. b) Bent cylinder.
Fig. 4 - The toroidal case of the bent cylinder. a) Optical layout of a 6 meter long line. b) Footprint of SR on the vertically deflecting toroidal mirror. c) Final image from the toroidal mirror at its optimal focus displays a ‘tail’.
Fig. 5 - The ellipsoidal case of the bent cylinder as compared to the toroidal line.  
a) Optical layout of a 6 meter long line is identical.  
b) Footprint of SR on the vertically deflecting ellipsoidal mirror.  
c) Final image from the toroidal mirror at its optimal focus showing the butterfly shape produced by a non-point source.
Fig. 6 – Double mirror system is capable of removing the curvature exhibited by the image in Fig. 3. a) Optical layout of a possible two mirror system. b) Final image at optimal focus displays fewer aberrations. c) Image downstream of optimal focus exhibits no curvature.
Fig. 7 – Bending the wide-bore glass tubing to form the major radius causes the walls to bow outward as indicated in this exaggerated drawing.
Fig. 8 – One of several options can be considered for beamline development. In this option, a cooled optical flat could be used before the bent mirror to protect it from heat-loading while a rocking optical flat could be used after the bent mirror to provide scanning capabilities.