Nuclear Instruments and Methods in Physics Research A309 (1991) 581-584
North-Holland

NUCLEAR
INSTRUMENTS
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IN PHYSICS
RESEARCH
Section A

Discussion and improvement of the SX-700 beamline

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Received 16 November 1990 and in revised form 14 June 1991

We analyze and compare the existing designs of SX-700 beamline in this article and describe a new version of the SX-700 beamline in which we make some improvements on SX-700 designs mentioned before [1-4]. The new design uses a plane elliptical pre-mirror which deflects the SR beam vertically to compress the SR source onto the entrance slit and uses an ellipsoidal mirror to focus the monochromatized light. By proper selection of design parameters, the beamline produces non-astigmatic and nearly aberration free images like the improved SX-700 beamline by Nyholm et al. [4]. But our design has the following advantages: (1) our plane elliptical pre-mirror is much smaller, (2) an entrance slit is put in the beamline, and (3) the beamline is suitable to be installed at high energy electron storage rings.

1. Introduction

The field of soft X-ray monochromator beamlines is very significant. There have been various kinds of designs by many authors. The typical existing systems are: (1) toroidal grating monochromator (TGM), (2) extended-range grasshopper mounting of Rowland circle (ERG), (3) another kind of spherical grating monochromator (SEM) by C.T. Chen, (4) the plane grating monochromator (PGM). Every system has its own features: TGM may get high resolution and photon flux, but its serious astigmatic coma, especially at short wavelengths, limits its resolution. In addition the high quality toroidal grating is very difficult to make. The Rowland circle mounting (ERG) has comparatively high resolution with spherical grating, but it is not easy to realize accurate wavelength scanning kinematically, and its Colding mirror usually leads to photon flux reduction as its carbon layer covering grows, which is caused by high SR power load on it. Non-Rowland circle spherical grating system (SEM) by Chen has been reported in some articles [6,7]. Its resolution entirely depends upon the vertical size of source. This simple design with a minimum of optical components should give a very high optical efficiency. But each of the spherical gratings can only cover a quite narrow wavelength range, so more gratings than other designs have to be installed to cover a certain wavelength range and its spot size at sample varies a lot since the exit slit has to be moved for about 700 mm during scanning. In the family of PGM, there is a well-known system which was called SX-700 [1] by H. Petersen, which was used at DESY/F41 in Hamburg with the ingenious GLEISPIEMO by C. Kunz and later another improved form called FLIPPER at DORIS. It only uses one or two simple plane gratings to cover a very wide wavelength range. At present the Zeiss company can provide the commercial SX-700 UHV X-ray monochromator for the spectral range from 5.25 eV to 2300 eV. Furthermore the system has more effective suppression of higher orders than other non-plane grating monochromators. The main disadvantage is that there is a aspheric optical element in the monochromator, of which the manufacturing accuracy is a crucial factor to attain high resolution. The modified SX-700 by Nyholm et al. [5] used a plane elliptical pre-mirror which focuses the SR source horizontally onto the sample and a plane elliptical post-mirror which focuses the dispersed light vertically onto the exit slit in order to avoid aberration caused by difference in meridian and sagittal object distance of the ellipsoidal mirror in the original SX-700 design by Petersen [1-4], and at the same time increasing the horizontal acceptance of SR. But the mirror is very large (1100 mm) even for the use at the low energy ring, and it will result in more serious trouble to be used with a high energy storage ring for its limited source–mirror distance. None of the above mentioned instruments has an entrance slit.

In our design, as shown in fig. 1, the monochromator is similar to the design of Petersen which consists of a plane pre-mirror, a plane grating and an ellipsoidal mirror. But we use an entrance slit and use a plane elliptical pre-mirror mirror M1 in order to compress SR source onto the entrance slit vertically. By proper selection of design parameters, we can eliminate the astigmatism of the ellipsoidal mirror occurring in the design of Petersen. Since M1 reflects light vertically, we only need a small size of it (50×35 mm^2 in our case), and the distance from source to mirror M1 can be larger to be applicable for a high energy storage ring, which will not result in a too large M1. Also we use an entrance slit in the beamline, which makes it possible to attain the aberration-limited resolution of the monochromator by using a small enough slit width and reduces the effect on resolution caused by SR source drift. In our design the manufacturing accuracy of the ellipsoidal mirror also has a big effect on the spectral resolution of the monochromator. According to the recent information [9], Zeiss company made an ellipsoidal mirror with 0.9 arc sec slope error successfully and used it in their SX-700 monochromator. If we use such a good ellipsoidal mirror we will get quite an ideal instrument possibly.

2. Design principle

In our design the optical system consists of a plane elliptical premirror M1, an entrance slit S1, a plane pre-mirror M2, two plane gratings with 1200 lines/mm, 400 lines/mm, an ellipsoidal mirror M3 and an exit slit S2. The sample is put at a distance of 100 mm behind the exit slit. Our SR source size is 0.7×1.64 mm^2 (FWHM) in GPLS operation mode, having a comparatively large vertical size. The beamline will accept a 0.25×5 mrad^2 SR beam. The pre-mirror M1 focuses the SR source onto the entrance slit with a demagnification of 10 in the vertical plane, compressing SR source onto the entrance slit. The motion and mechanic principle of our monochromator are similar to SX-700 design by Petersen. The wavelength scanning is then realized by rotating the plane mirror around an axis mounted outside the mirror surface and rotating the grating in such a way as to direct the SR beam onto the plane grating and to keep the ratio $\cos\alpha/\cos\beta$ (α, β means incident and diffraction angle respectively) of the plane grating constant. We take the constant equal to 2.25, as Petersen did. Using the equation for defocus-free performance with the above condition, we can get a wavelength-independent fixed monochromatic virtual source at distance r' behind the grating

$$r' = -r \times 2.25^2, \qquad (1)$$

in which r and r' are the object and virtual image distance of the grating respectively. In order to make the ellipsoidal mirror M3 image stigmatically we make the distance from SR source to plane grating equal to r', i.e. the ellipsoidal mirror M3 will have the same meridian and sagittal object distance. And finally the M3 focuses the monochromatized SR beam onto the exit slit of the monochromator horizontally and vertically. Only a very small coma and astigmatic coma are preserved in the system, and the image quality is quite good. On the other hand, because of its 50 mm length obtained by calculation, the pre-mirror M1 and its chamber will be much easier to manufacture than in the design by Nyholm. Furthermore, we use an entrance slit in our design.

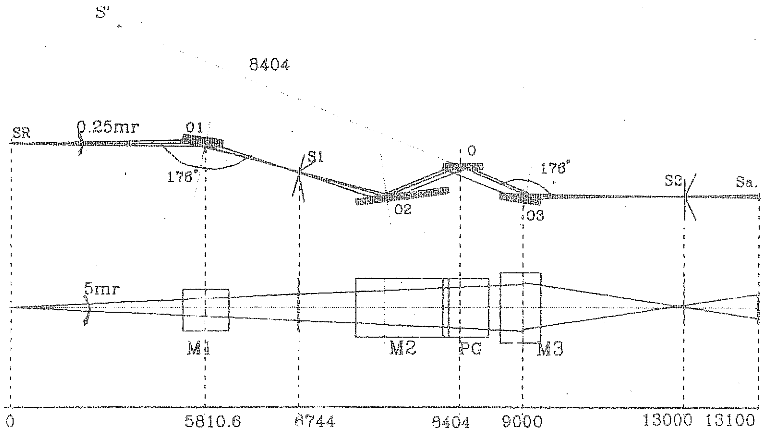

Fig. 1. The optical design of our SX-700 beamline.

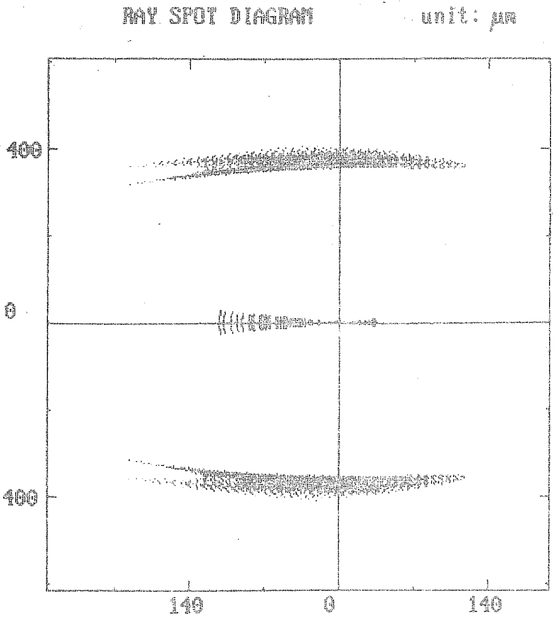

Fig. 2. Spot diagram at exit slit, λ at 400 eV plane grating, 1200 lines/mm, SR size 0.7×1.64 mm^2 (taking 3×3 points).

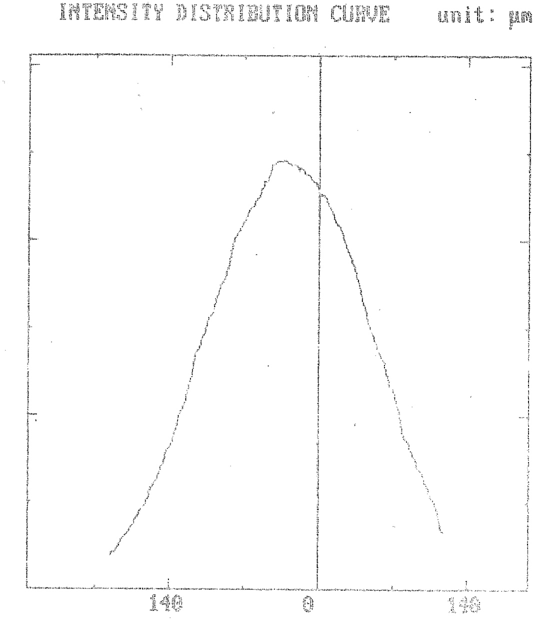

Fig. 3. Intensity curve at exit slit, parameter as shown fig. 2, exit-slit width 158 μm.

For different SR source sizes we can adjust the design parameters. We can reduce the demagnification ratio of M1 to improve the image quality if we have a smaller vertical size of SR source. We only have to satisfy the condition mentioned above, i.e. to make the distance from SR source to the plane grating equal to the virtual image distance of the grating. If we have a quite different horizontal source size, we can adjust the exit focus length of M3 to retain a comparatively small spot size at the sample. In our design we only use two plane gratings with 1200 lines/mm and 400 lines/mm which are interchangeable with each other under vacuum and a plane pre-mirror M2 of 600 mm length, so we can realize a wavelength scanning from 10 Å to more than 1000 Å. If we increase the size of the plane mirror or the number of gratings, we can extend the working wavelength range just as the Zeiss company did.

3. Ray-tracing analysis

To analyze the image quality of the system and to evaluate its resolution we make some calculations with our ray-tracing program. Using the optical parameters from table 1, and the system parameters in fig. 1, we get a spot diagram at the exit slit at a photon energy of 400 eV with the entrance slit width large enough (> 158 μm) not to shade the rays, as shown in fig. 2. Its geometrical ray distribution curve with exit-slit width 158 μm is shown in fig. 3. From the result of our calculation, the FWHM value W_s of the ray distribu-

Table 1
Grating and mirror parameters (unit of length: mm)

Element			Parameter [a]	Volume	Coating	Groove density	Spectral range
Grating	G1	plane		100×50×15	Au	1200 lines/mm	10–320 Å
	G2	plane				400 lines/mm	40–1280 Å
Pre-mirror	M1	plane-ellip. cylinder	$A = 3372.0$ $B = 67.7$	50×35×10	Au		10–1280 Å
	M2	plane		600×55×40	Au		10–1280 Å
Post-mirror	M3	ellipsoidal	$A = 6500.0$ $B = 209.4$	240×60×30	Au		10–1280 Å

[a] A: half long-axis length of ellipse, and B: half short-axis length of ellipse.

tion is 190 μm. Actually the image width caused by the source size is at least 158 μm, and the aberration widening is only about 30 μm. If we can get a high quality ellipsoidal mirror M3, e.g. its slope error σ_{se} as low as 1 arc sec, then the imaging broadening due to σ_{se} is

$$W_{se} = \frac{\pi}{180} \frac{2\sigma_{se}}{3600} r'_3, \qquad (2)$$

where r'_3 is the exit focus length of M3. So the value of W_{se} is 38 μm. We estimate the resolution $\Delta\lambda$ according to the formula

$$\Delta\lambda = \left(W_{sy}^2 + W_{se}^2\right)^{1/2} \frac{\cos\beta}{mNr_3}, \qquad (3)$$

in which m, N and β mean the diffraction order, groove density and diffraction angle of the grating respectively. If we take the entrance and exit slit to be 50 μm, we get $\Delta\lambda = 0.018$ Å. If the slit width is 10 μm then $\Delta\lambda = 0.01$ Å, i.e. we can get a resolving power of about 3000. The spot size at the sample will be 1.0 × 2.0 mm^2 or so.

4. Discussion

From the analysis above we know that the manufacturing accuracy of the ellipsoidal mirror M3 is still a key factor in our design, and the mirror needed is 220 mm long according to table 1. If its slope error is larger than 2 arc sec, or the source size is not so large, it will become a more prominent factor of affecting resolution.

Our design incorporates the main features of the SX-700 by other authors, i.e. making use of the focusing condition of the plane grating in the primary SX-700 monochromator to cover a wide soft X-ray wavelength range with simple plane gratings and get more effective suppressing of higher orders, which are also the common points of different designs. But we eliminate astigmatism in the SX-700 of Petersen with a small pre-mirror M1 increasing the brilliance at the sample, and we put an entrance slit in the beamline, which will give great convenience for experimentalists.

Acknowledgements

The author wish to acknowledge Dr. H. Petersen for his good suggesions and for making some calculations about the design to check our results.

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