

**Enhancing coherent flux by using two-step X-ray focusing**

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**Abstract**

The undulator source of the Coherence Beamline P10 at the new synchrotron PETRA III is located at the low-beta section and has an asymmetric shape such that horizontal size is six times larger than the vertical one. In order to match the spekle size to the detector pixel one has to shape the x-ray beam by square slit. Since the coherence length in horizontal plane is six times smaller than a coherence length in vertival plane, the use of square slite leads to a significant loss of coherent photon flux. It is especially the case when one uses such a slit to illuminate x-ray focusing optics. At the P10 beamline the x-ray focusing lens changer based on beryllium compound refractive lenses (CRL) is used to obtain microfocused x-ray beam at a sample position. It is proposed to enhance the coherent flux of a focused beam by implementing the two-step X-ray focusing. This means the additional CRL changer will be used for pre-focusing in the vertical direction thus producing a secondary source which in turn will be focused by a second CRL changer on a sample position.

The aim of the reported work was to write a program for calculating the best CRL combination and beam parameters for the two-step x-ray focusing setup at the P10 beamline.

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**1 Introduction**

* 1. **Motivation**

The P10 beamline at the new synchrotron PETRA III has the low-beta source which has an asymmetric shape shown schematically in Figure 1.1.

Gv = 14.1 µm

Gh = 84.6 µm = 6 Gv

Figure 1.1: The low-beta source (G) of the P10 beamline

P10 is a coherent beamline, and one of the important value in the coherent technique is the transverse coherent length of the source which is



(1)

where is the X-ray wavelength, s2s is the source to sample distance and G is the source size. Because the horizontal size of the source is 6 times larger than the vertical size, and via the formula (1), the transverse coherent length () at the sample will have the vertical size 6 times larger than the horizontal size as shown in figure 1.2.



Figure 1.2: the coherent beam of the source

In addition, the speckle size on the detector (pixel size) will also be mentioned in the coherent technique which is:



(2)

Where is the X-ray wavelength, s2d is the source to detector distance and slit size is the slit size before detector. In this case, the speckle has a square shape (light blue area in figure 1.3a). Therefore, the coherent beam must be made to a square one to match the speckle. And the simplest way is using the slit (blue area in figure 1.3a), but many loss of the coherent beam (red area figure 1.3a) will be occurred since the slit blocked them. Therefore, two-step focusing (figure 1.3b) will be used to reduce loss of the coherent beam, also enhance the coherent flux. Furthermore, it can make a round shape of the coherent beam (green area in figure 1.3b) which mostly be matched to the square shape of the speckle on the detector.

(b)

(a)

Figure 1.3: schematics of the making the coherent beam to be matched to the speckle by using the slit (a), and two-step focusing (b)

* 1. **Two-step X-ray focusing by Two Compound Refractive Lenses (By Michael Spung, DESY)**

The goal of the two-step focusing is to make the round-shape coherent beam at the sample. Since the vertical size of the coherent beam at the sample is 6 times larger than the horizontal one. Therefore, there must be a pre-focusing lens (CRL1) in the vertical direction as shown in figure 1.4 to focus the primary source in vertical direction to be the secondary source of the following lens (CRL2). With this way, the round coherent beam can be made, and a relation between two focusing lenses is achieved as:

(3)

Where g2v  is the secondary source to second lens distance, M1 is Magnification power of the pre-focusing lens, Gh is horizontal source size, Gv is vertical source size, a is primary to secondary source size, and b2v is second lens to sample distance. In addition, the lenses which are used in this focusing are **C**ompound **R**efractive **L**enses or **CRL**.

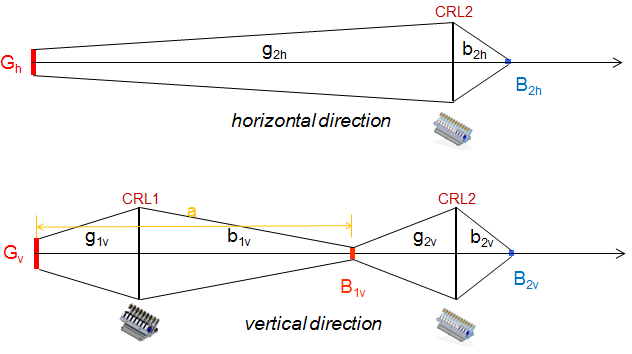
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Figure 1.4: schematic of the Two-step X-ray focusing

**2 Theory**

**2.1 Refraction of X-ray**

The index of refraction for X-rays in condensed matter can be written as follows:



(4)

where  is the refractive decrement of the order of 10-6:

****

(5)

where Na is Avogadro’s number, r0 is the classical electron radius, 𝞴 is the photon wavelength, is the density of the lens material, z is the atomic number of the lens material, and A is the atomic mass of the lens material and the absorption coefficient:

(6)

****

is characterised by the linear absorption coefficient µ. Both δ and β are energy dependent, which is the cause of a large number of complications [1].

X-rays in condensed matter have weak refraction n (the real part of is very close to one) and strong absorption. For this reason for a long time focusing lenses for X-rays were considered to be impossible to create. However, refraction of X-rays is not quite zero, and absorption is not quite infinite, so it is possible to create such a lens [1]. The first such lenses where created at Aachen University and made of beryllium, boron, aluminium and silicon [2].

**2.2 Refractive X-ray lenses**

Since the real part of n is less than one, a focusing lens would have a concave form rather that a convex one, as is the case for visible light. The first type of refractive X-ray lenses had cylinder and crossed-cylinder symmetry [3]. A system of such lenses was basically a row of holes with 1 mm diameter, drilled in a block of aluminium [2]. The focal length was about a metre, and focal spot size was several micrometres long. The material between the holes absorbed the beam [3]. In order to get such a short focal distance the radius of curvature R of the holes had to be small – 1 mm or less [1]. In the thin lens approximation the focal length for such a system would be equal to



(6)

where N is the number of lenses in the system [1].

Due to the fact that in order to focus the beam a large number of holes had to be drilled in a row, such a system is called a compound refractive lens (CRL), see Figure 2.1 [3].

Because of absorption, the absorption region d (see Figure 2.1) has to be kept small (in our case 30 µm), and the number of lenses – limited.

****

Figure 2.1: A diagram showing how the CRL with a spherical profile focuses X-ray: *a*, simple concave lens – a cylindrical hole in the material; *b*, a CRL consisting of N cylindrical holes placed close together in a row along the optical axis. In the second case the focal length is N times shorter than in the case with only one lens. R is the radius of the holes, d is the distance between the holes, λ is the X-ray wavelength, and F is the focal distance for the lens system, assuming that the falling beam is parallel. Figure from [6].

However, these cylindrical lenses were found to have strong spherical aberration. This problem was solved when new lenses were introduced. They are different from the old ones in that they have a parabolic profile and rotational symmetry around the optical axis, focus in both directions and have no spherical aberration due to their parabolic nature, see Figure 2.2 [3]. For parabolic lenses, R in the formula for the focal length is the radius of curvature at the tip of the parabola (see Figures 2.3 and 2.4) [4]. The length of the parabolic CRL system is equal to the following:

****

(7)

where 2R0 is a parameter that can be chosen independently of the radius of curvature R (which is not the case for lenses with a spherical profile), and d is the thickness of the lens between two closest points of adjacent parabolas, see Figure 2.5 [4]. 2R0 determines the point where transmission falls by 1⁄e times.

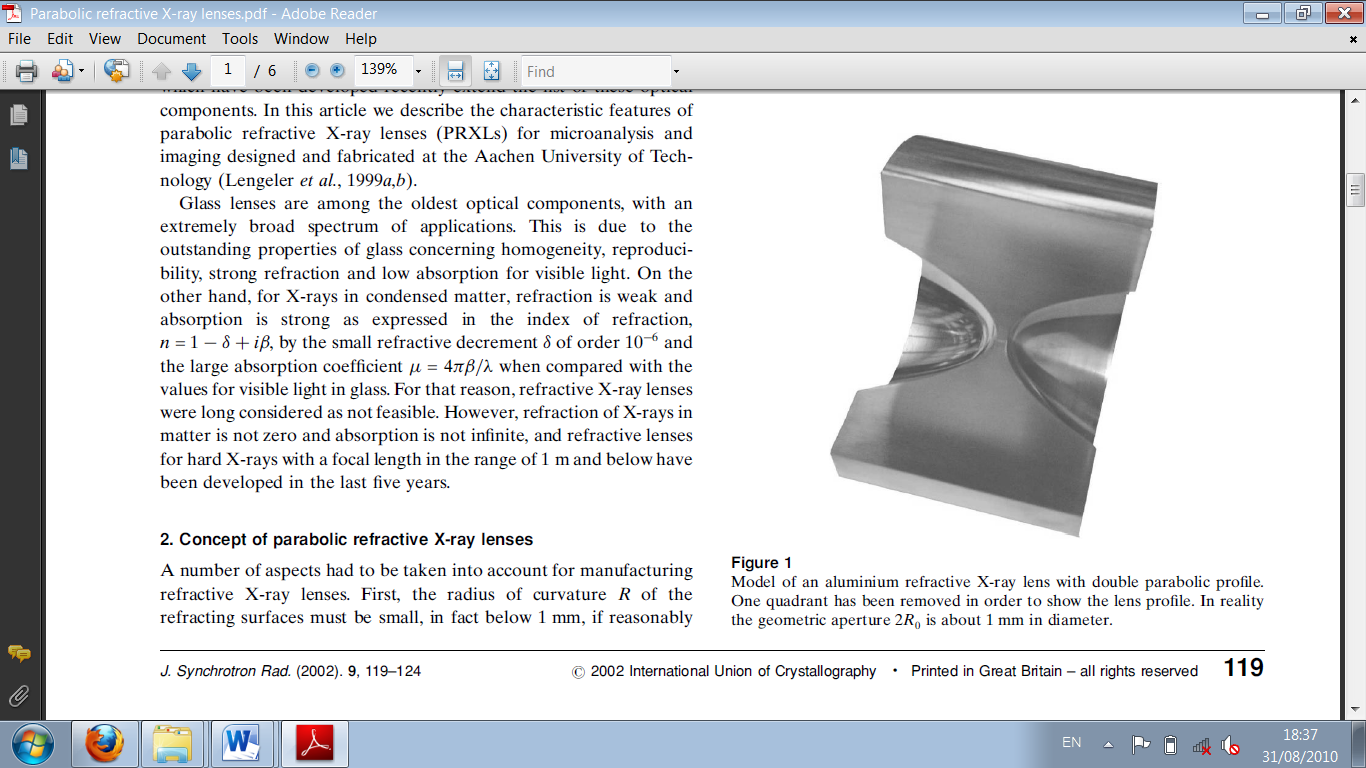
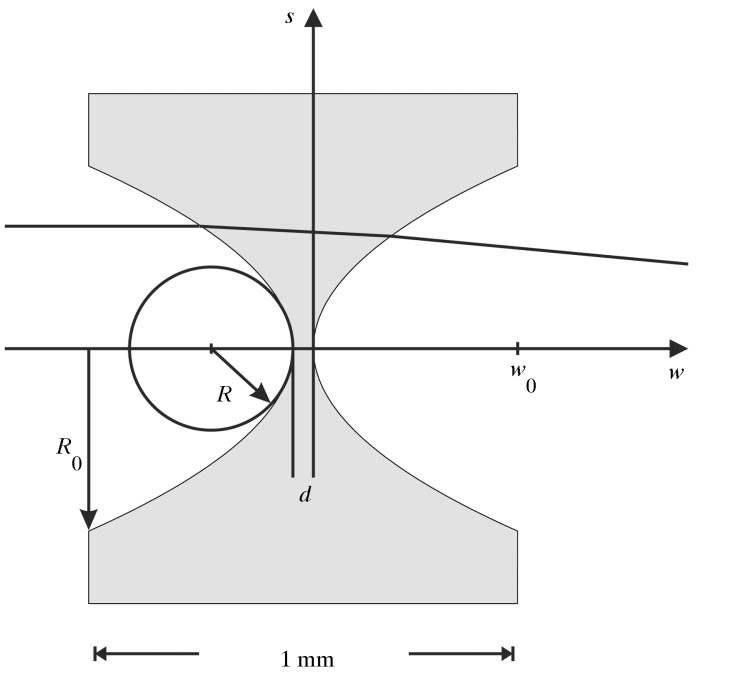
****Today the fabrication technique had improved enough that it is possible to create parabolic refractive lenses with different radii of curvature.

Figure 2.2: A model of a parabolic refractive lens. One quadrant of the lens has been removed in order to show the lens profile. Figure from [1].

Figure 2.3: A schematic diagram showing the principles of X-ray focusing by a single lens with a parabolic profile. R is the radius of curvature and 2R0 is the aperture. Figure from [3].

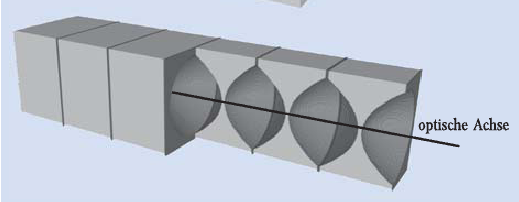
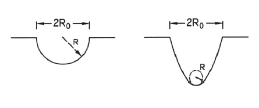
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Figure 2.4: Cross-section of a spherical refractive lens and a parabolic one. R is the radius of curvature and 2R0 is the aperture. Figure from [1].

Figure 2.5: A schematic diagram showing the row of individual lenses with a parabolic profile stacked together to form a CRL (Schmahl et all, 2001)

**2.3 Transmission and gain of refractive X-ray lenses**

The gain of a CRL is defined as the ratio of the intensity in the focal spot to the intensity behind a pinhole of the size of the focal spot without a lens [2]. The gain of a lens system depends strongly on the choice of the lens material [2]. In order to reach a high gain, materials with a small mass absorption coefficient µ ⁄ ρ must be chosen [2]. This coefficient is proportional to Z2 ⁄ E3, where Z is the atomic number and E is the photon energy, so only low Z materials must be used for creating high-gain CRLs [2]. Even for hard X-rays, only materials of light elements such as lithium, beryllium, boron, carbon, and aluminium can be used to create focusing X-ray lenses [1]. Moreover, homogeneous materials are preferred because small angle scattering must be minimized [2].

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Figure 2.6: The mass absorption coefficient µ ⁄ ρ for lithium, beryllium, boron, carbon, and nickel. The photoabsorption coefficient τ ⁄ ρ is shown for beryllium and aluminium. Figure from [3].

The photoabsorption of a lens system increases proportionally with Z3 so again, only low Z materials should be used for lens creation. Another effect that can contribute to the mass absorption coefficient at high photon energies for light elements is the Compton scattering [4]. Photons that are Compton scattered do not take part in the formation of the image, thus this effect limits the effectiveness of the X-ray lenses. Moreover, the Compton scattered photons form a background image in the detector that lessens the signal-to-background ratio for the lens image [2]. Figure 2.6 shows the mass absorption and the photoabsorption coefficients for some common elements.

The transmission of a CRL with a parabolic profile and rotational symmetry is



(8)

where



(9)

and the gain is given by



(10)

where hv and hh is the horizontal and vertical image size [4].

At first glance lithium appears to be the best material to use for the creation of CRLs, but it turns out that it is highly reactive and oxidizes easily, and is therefore quite difficult to handle. While both beryllium and aluminum are used for the creation of parabolic lenses, beryllium is considered to be best for focusing X-rays with energies between 10 and 40 keV because of its low atomic number (Z=4), as opposed to aluminum (Z=13) [2]. The imaging properties of beryllium lenses are considered to be far better than the imaging properties of aluminum lenses. Experiments have shown that not only is the transmission increased in the case of beryllium lenses, but also the effective aperture, which determines the diffraction limit. This leads to an increase of the lateral resolution and of the field of view. In addition, beryllium lenses are found to be more transparent than aluminum for lower X-ray energies, and therefore can be used for focusing X-rays at energies as low as 2 keV [5].

**2.4 Optics calculation**

To calculate some optics values, CRL can also use some formulas of the fundamental optics. The formulas are shown below:



(12)

(11)

Where fCRL is focal length of CRL, g is object distance (source to CRL distance), b is image distance (CRL to focused beam distance), B is image size (focused beam size), and G is object size (source size).

But each Refractive lens in CRL still has some thickness, so the focal length of CRL must be corrected before, the corrected focal length of CRL is:



(12)

where L is the total thickness of all lenses in the CRL, and is equal to:

(13)

L = F0 \* N

where F0 is the thickness of each lens, and N is the number of lenses in the CRL

**3 Infrastructure**

**3.1 Two CRL in P10**

The CRL2 has already been set in the P10 beamline at the 85.5 m position of the beamline and can be moved in the range of 14.70 cm from its normal position. Furthermore, CRL1 is planned to be set at the 43.0 m position of the beamline and can be moved in the range of 50 cm from its normal position. The two CRL’s positions are shown in figure 3.1.

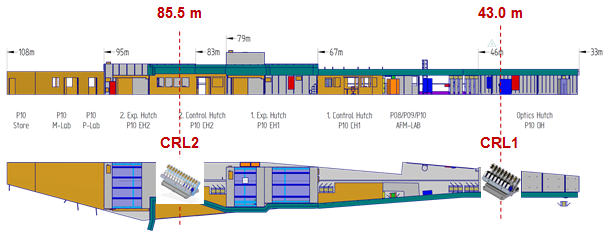


Figure 3.1: schematic of P10 beamline and two CRL’s positions

**3.2 Two CRL Profiles**

The CRL1 and CRL2 consist of stacks which have particular lenses (see at the lower left side of figure 3.2). By the way, CRL1 has only 1D focusing lenses in vertical direction since it is the vertical pre-focusing lens, and CRL2 has both 1D in the first four stacks and 2D in the following stacks. Since each CRL can combine its stacks to be a particular one, so there are 64 and 4,096 combinations possible in the CRL1 and CRL2, respectively. The profile of CRL1 and CRL2 is displayed in the table below.

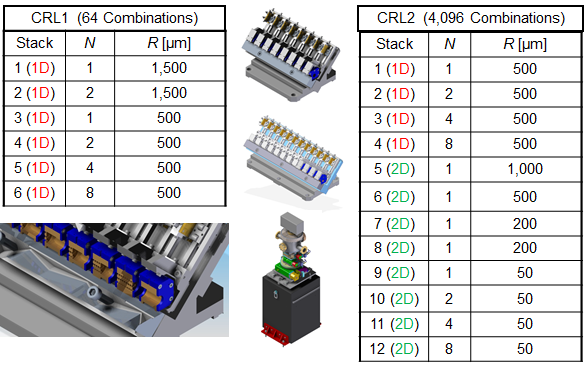


Figure 3.2: summary of the two CRL profiles

**4 Program**

The program is made by Spyder in Python(x,y) 2.6.2.0. The objective of program is to calculate and find the best combination of CRL1 and CRL2 in particular case which enhance the coherent flux and make the round shape of the coherent beam at the sample. The program is separated to be CRL1 one and CRL2 one for independently use.

**4.1 CRL1 Program**

The CRL1 program process is explained by following flow-chart diagram;

Start

EX-ray & Primary to Secondary source distance

Read Absorption Coefficient & Calculate necessary constant (δBe, b1v\_goal)

+

Create each combination profile

Calculate Secondary source profile (b1, B1v)

1

1

Secondary source is in the supposed position?

(b1v\_goal to b1 distance

≤ 50 cm?)

+

no

yes

Correct Secondary source profile & Calculate Transmission & Gain

Better combination?

More transmission  
More Gain  
Less used stacks

+

no

yes

Keep the combination profile

2

2

+

Last Combination?

no

yes

Best combination profile

End

**4.2 CRL2 Program**

The CRL2 program process is explained by following flow-chart diagram;

Start

EX-ray, Primary to Secondary source distance, & Goal CRL2 to sample distance

Read Absorption Coefficient & Calculate necessary constant

(δBe, b1v, B1v, g2v, g2h,b2\_goal)

1

1

+

Create each combination profile

Calculate Final beam profile

(b2, B2v, B2h)

Final beam is in the supposed position?

(b2goal to b2 distance

≤ 14.70 cm?)

+

no

yes

Correct Secondary source profile & Calculate Transmission & Gain

Better combination?

More transmission  
More Gain  
Less used stacks

2

+

yes

no

2

Keep the combination profile

Last Combination?

no

+

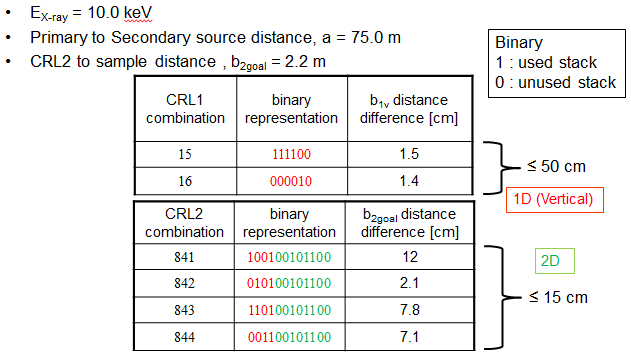
yes

Best combination profile

End

**4.3 Result**

An example of the result from the program is showed below.



The tables show only combinations of the CRL1/CRL2 which made the secondary source/final source located in the range CRL1/CRL2 can be moved. Finally, the program will display the best combination of the CRL1/CRL2. In this case, they will be;

**CRL1**

Best combination Number: 16

Number of used stacks: 1

Binary representation of best combination : 0 0 0 0 1 0

Distance correction for the best CRL combination: 1.2 cm

Vertical focused beam size: 26.4 µm

Transmission of CRL : 96.5%

Gain of flux density of CRL: 160

**CRL2**

Best combination Number: 841

Number of used stacks: 5

Binary representation of best CRL combination : 1 0 0 1 0 0 1 0 1 1 0 0

Distance correction for the best CRL combination: 9.8 mm

Vertical focused beam size: 3.38 µm

Horizontal focused beam size: 1.77 µm

Transmission of CRL : 82.5%

Gain of flux density of CRL: 2.80e+5

**5 Summary**

Two-step X-ray focusing by Compound Refractive Lenses is possible to enhance the coherent flux of the coherent beam at the sample and also make the round shape which is matched to the speckle of the detector. Furthermore, the written program is available to calculate the best combination of the two focusing lenses in each particular case.

**6 Acknowledgements**

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