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Liquid compound refractive X-ray lens

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Abstract: We introduce the concept of a liquid compound refractive X-ray zoom lens. The lens is generated by pumping a suitable liquid lens material like water, alcohol or heated lithium through a line of nozzles each forming a jet with the cross section of lens elements. The system is housed, so there is a liquid-circulation. This lens can be used in white beam at high brilliance synchrotron sources, as radiation damages are cured by the continuous reformation of the lens. The focal length can be varied by closing nozzles, thus reducing the number of lens elements in the beam.

1. Introduction

Compound refractive X-ray lenses (CRLs) are X-ray optics useful for photon energies above about 8 keV. They consist of a large number of focusing lens elements, first described in [1] and realized by [2]. Today, they are fabricated from beryllium [3], aluminum [4], silicon [5], diamond [6], and other materials like photoresist [7–9]. The most common type of CRL consists of many identical, biconcave, parabolic lens elements, aligned along the optical axis and is used in many applications [8–11]. In some applications the geometry of the individual lens elements is varied, such as in the case of adiabatic lenses [12]. Variable aperture CRLs have been described for full field microscopy with increased field of view [8,13]. So called transfocators have been designed to tune the focal length [14–17]. In these transfocator sets of CRL elements can be removed using actuators. All of these lenses are formed out of solid state matter.

In this paper we present a new type of refractive X-ray lenses for imaging or illuminating using liquid lens elements [18]. The Liquid Compound Refractive X-ray Lens (LCRL) is formed by a number of liquid jets generated through a line of nozzles with double parabolic cross-sections. The lens system has an overall volume of only a few liters. Due to its compactness it can be easily included in different experimental setups. The adjustment of the focal length of the zoom lens can be remote controlled within seconds to adapt to changed photon energy or changed object distances. The lens can be configured for line or point focus, or even astigmatic geometry to compensate for asymmetrical source dimensions, and thereby achieve a more circular focal spot on a sample.

2. Principle and mechanical lens design

The X-ray lens is generated by pumping a suitable liquid through nozzles with a cross section like a refractive double parabolic X-ray lens. The nozzles with double-parabolic cross section can be fabricated via deep X-ray lithography followed by an electroplating step. This process provides very low sidewall roughness in the range of a few ten nanometers [19]. At KIT/IMT the nozzles can be fabricated from sulfamate nickel or hard-nickel electrolytes with a Vickers-hardness of up to 550 HV0.1 [20].

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A CRL made of equidistant and identical elements with total length L, radius of curvature in the apex of the parabola R and N lens elements has a focal length of [19,20]

$$f = \frac{R}{2\delta N} + \frac{L}{6} \tag{1}$$

The refractive index n of any material is slightly below one and commonly expressed by the decrement δ

$$n = 1 - \delta + i\beta \tag{2}$$

with β being the absorption coefficient. The decrement δ is very small, usually in the range of $\delta \approx 10^{-5} \ldots 10^{-8}$. The resulting number of lens elements and thus nozzles is in a feasible range between ten and hundred.

Suitable liquids would have to fulfill two criteria: They must have suitable optical properties and at the same time ensure that the liquid jet retains its shape as long as possible. For good optical properties they should have a high refractivity while at the same time show low X-ray absorption and therefore have a low average Z-number. In Fig. 1 the important ratio of the refractive decrement δ and the absorption coefficient β is shown for some chosen liquids in comparison to commonly used solids [21]. Possible liquids could be for example water, alcohols, alkanes, glycols or molten lithium. Figure 1 shows that lithium is a good CRL material as it is more transparent than other materials due to its low Z-number.

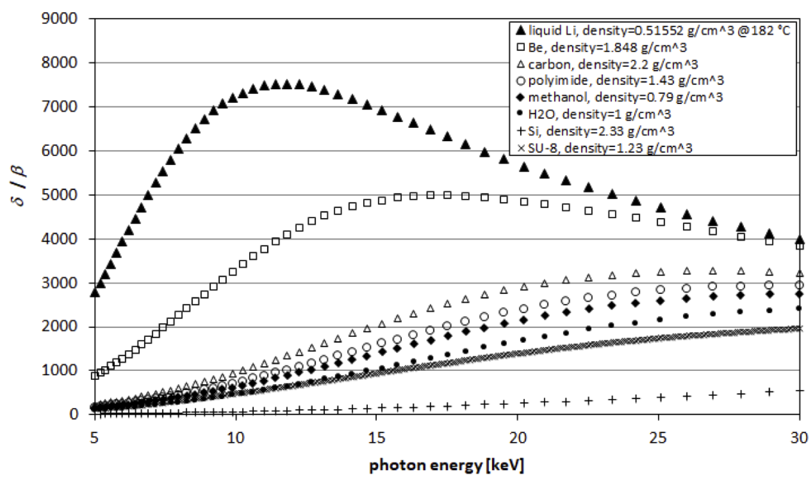

Fig. 1. Ratio delta/beta of CRL lens materials; filled markers for liquids [21].

Liquids do not show long-range order like crystals. For a CRL this is an advantage, because the CRL's material does not generate a regular diffraction pattern around the focus point. Each nozzle has got a cross section of the lens element it should form. Typically the cross section of a lens element is limited by a mirror symmetric pair of parabolas defining the refracting surfaces [2]. The nozzles are aligned on the optical axis of the lens. An X-ray beam crossing this row of liquid jets will be line focused. To get a point focus CRL, two rows of nozzles have to be arranged under 90°, see e.g. [11]. To get a low astigmatism lens, the horizontal and vertical nozzles would be arranged alternatingly (Fig. 2).

The nozzles would be mounted in the sidewall of the reservoir storing the pressurized liquid. To make the liquid circle in the system and avoid contamination of the liquid as well as of the environment, the system is housed. The housing would also contain an inert gas atmosphere or reduced gas pressure if required. The inside of the housing has to be shaped suitably to prevent

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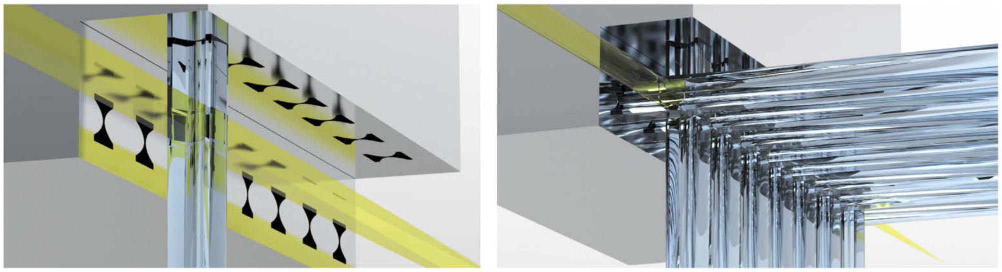

Fig. 2. Sketch of the device with the nozzles (gray box) and the CRL formed of liquid jets (blue) alternatively focusing the X-ray beam entering from the left side (yellow) in vertical and horizontal direction. Left: Only one nozzle is opened, this results in a line focus of the beam. Right: All nozzles opened, the beam (yellow) gets point focused at the right bottom side of the image.

liquid splashing back from the walls towards the CRL. A suitable pump is needed to provide the necessary pressure in the liquid and to transport the liquid back into the reservoir. In case of very high radiation load, an active cooling system might be necessary to keep the liquids temperature constant. In case of lens materials with a melting point above room temperature, a thermostat controlled heater would keep the liquid at constant working temperature. Two X-ray windows at opposite sides of the housing allow the X-ray beam to pass.

To make the system zoom-able, remote controlled actuators could move sliders inside the liquid reservoir closing individual nozzles or individual lens elements could be supplied through valves. In this way the focal length of the lens could be adjusted by using less lens elements. Astigmatic or line focus lenses would be generated by closing more or all nozzles of one focusing direction. Thus the focal length in vertical and in horizontal direction can be chosen independently. Which elements should be in or out of the beam depending on the actual experimental setup will be calculated and decided by software. Thus changing the configuration of the CRL could be done within seconds.

3. Liquid simulations

Depending mainly on the liquid pressure, surface tension, surface contact angle of the nozzle front plate, temperature and the gas pressure in front of the nozzles, but also on the flow conditions in front of the nozzles and in the nozzles themselves, the cross section of the jets will change until at a certain distance from the nozzles the jets finally form droplets. The jets can only be used as X-ray lens as long as their cross section is close to the perfect form of the optically required lenses cross section. As CRLs normally have physical entrance apertures between 100 µm to 2 mm, the useable length of the jets should be in that range. To find out if the jets keep their cross section long enough for a practical use of the lens, liquid simulations have been performed at KIT/ITS and at KIT/IMT. The simulations were done with ANSYS Fluent using the Volume of Fluid Model (VOF) and the k-ω-SST (Shear-Stress-Transport) turbulence model. To keep the beam profile of the liquid jet over a certain distance from the nozzle exit the surface tension has to be small in comparison to the liquid inertia. This means a high Weber-number

$$We_{\mathrm{l}} = \frac{\rho c {v_{\mathrm{l}}}^2}{\sigma} \tag{3}$$

is required, with ρ the density of the liquid, v_{l} the velocity of the liquid, σ the surface tension and c the characteristic length of the liquid jet cross section. High Weber-numbers can either be achieved by increasing the liquid velocity v_{l}, which can be adjusted by the pressure in the reservoir, or by reducing the surface tension σ by choosing a different liquid. On the same time the Reynolds number

$$Re = \frac{\rho c v_l}{\eta} \tag{4}$$

has to be taken into account, where η is the dynamic viscosity of the liquid. For low Reynolds numbers the liquid shows laminar flow, but once it exceeds a critical value $Re > Re_{\mathrm{crit}}$ the flow becomes turbulent, which has to be avoided to achieve a stable jet profile. Therefore, it is important to maintain a Reynolds number below the critical value while at the same time increasing the Weber number as high as possible.

The data depicted in Fig. 3 was obtained from simulations using water and methanol as liquid and aluminum as nozzle material. For the lens parameters a web (minimum distance between the two parabolic surfaces) of 40 µm has been set. Since methanol has a lower surface tension than water the jet keeps its form over a greater distance downstream the nozzle.

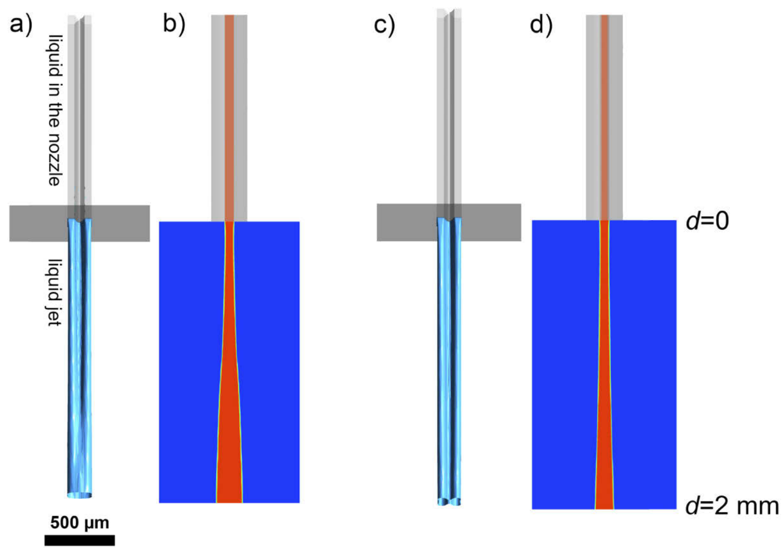

Fig. 3. Simulated jet ejected by a nozzle with double parabolic cross section with a speed of 44.5 m/s for water ($\sigma = 0.0728$ N/m, p=7.7 bar, a) and b)) and methanol ($\sigma = 0.0226$ N/m, p=5.2 bar, c) and d)) up to a distance of 2 mm from the nozzles exit. Figures b) and d) show a cross-section through the liquid at the position of minimum distance between the two parabolic surfaces.

In Fig. 4 the cross section of the methanol jet can be seen for different distances d from the nozzle exit. At $d = 0$ mm the cross section of the jet is the same as the cross section of the nozzle. With growing distance to the nozzle exit the surface tension slowly leads to a deformation of the jet. Since the lenses are arranged under 90° to achieve a point focus the cross section should be reasonably well maintained for a distance of twice the aperture size. This is the case for the two examples shown in Fig. 4. In both cases the liquid used is methanol with a velocity $v = 44.5$ m/s but the aperture and parabola radius are different. For the lens with smaller parabola radius the web constantly grows over the considered nozzle distance d. To achieve a velocity of $v = 44.5$ m/s pressures of $p = 9.1$ bar for H_2O and $p = 5.9$ bar for methanol are required.

In Fig. 5 shows that for the CRL with a parabola radius $R = 6$ µm for $d = 2$ mm the deviation from the target web $w_{\mathrm{target}} = 0.04$ mm is $\Delta w_{2\mathrm{mm}} = 0.07$ mm and therefore nearly triples the resulting web width to $w_{2\mathrm{mm}} = 0.11$ mm. For the larger parabola radius $R = 390$ µm the web contracts very fast and then stays roughly constant, reaching a deviation $\Delta w_{2\mathrm{mm}} = 0.02$ mm. For

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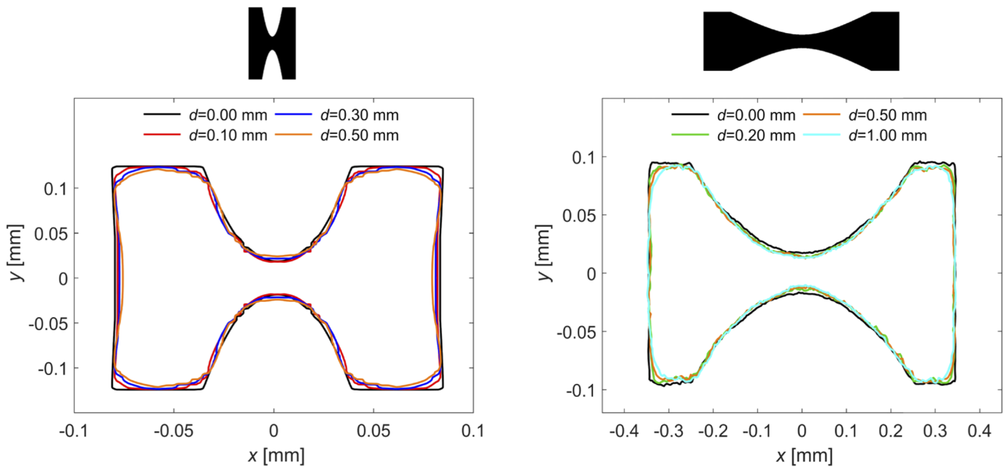

Fig. 4. Simulated deviation of the jet's cross section from the nozzle exits cross section over the distance *d* from the nozzle for methanol at a speed of 44.5 m/s and different nozzle cross sections (equal scale geometry above the diagrams). Left: Aperture = 70 µm, parabola radius = 6 µm; right: Aperture = 500 µm, parabola radius = 390 µm.

a larger parabola radius the cross section is maintained better over a longer distance and is also kept more constant. This allows for larger apertures.

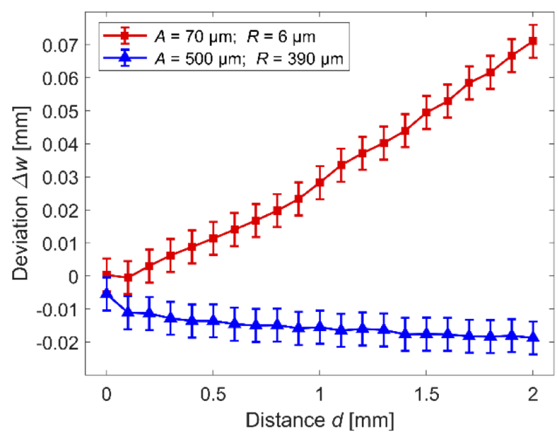

Fig. 5. Deviation from target geometry for two lenses with different parabola radius R and aperture A. The target web width in both cases is $w = 0.04$ mm.

However, for larger lenses the velocity distribution varies more (see Fig. 6), for the CRL with larger aperture the velocity in the web area is only 78% of the maximum velocity while for the CRL with smaller aperture it is 92%. This is the reason why the web distance decreases for the larger parabola radius and increasing distances d from the nozzle: Since the liquid is much slower in the web area, it begins to separate at this point. If the web is too small the jet tears and results in two separate jets. This limits the achievable aperture. Nevertheless with the right parameters a lens with good geometry fidelity can be achieved.

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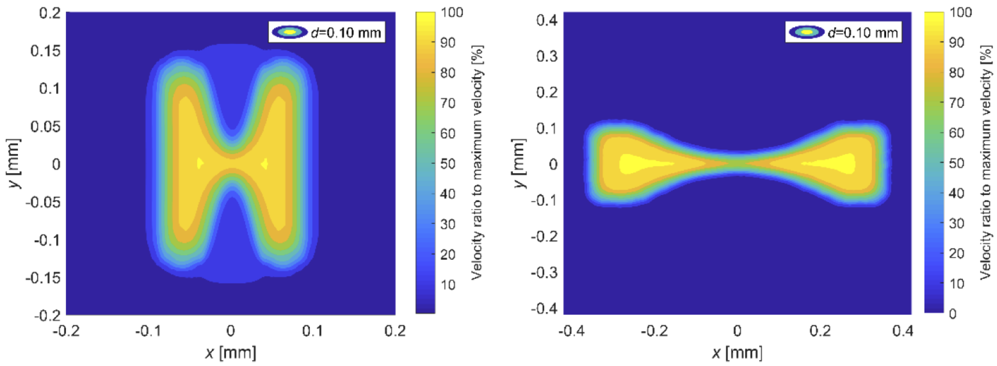

Fig. 6. Velocity distribution of the simulated liquid jet at a distance $d = 0.1$ mm downstream the nozzle exit. In both cases the starting velocity is $v = 44.5$ m/s. Left: Aperture = 70 µm, parabola radius = 6 µm; right: Aperture = 500 µm, parabola radius = 390 µm.

4. Conclusion

A liquid compound refractive X-ray lens (LCRL) formed out of a line of liquid jets has been proposed and its liquid dynamics have been simulated. The LCRL's main advantage is that any radiation damage and the heat load are washed away by the continuous reformation of the lens elements. Possible lens materials could range from water over alcohols to molten lithium. The lenses' focal length can be remote controlled and chosen separately in the horizontal and vertical direction, providing not only point focus, but also line focus or an astigmatic lens. The lens system could have a compact size with a construction volume of only a few liters, so it could easily be integrated in any experimental setup. The geometry fidelity depends mainly on the liquid material and the lens geometry. For high fidelity a large web width w and parabola radius R are preferable. They are however limited for optical reasons: the web width w only contributes to absorption and by increasing the parabola radius R the refractive power of the lenses is reduced. Taking all these factors into account, liquid simulations have shown that liquid X-ray lenses can be feasible.

These lenses could beneficially be used in all high flux applications as in white beam at synchrotron sources for collimating beams or for sample illumination. White beam widening with beam shaping optics would also be possible. The next step will be realizing a first prototype of such a system and perform optical simulations of its refractive properties.

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Disclosures

The authors declare no conflicts of interest.

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