X-ray imaging using Synchrotron radiation.

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I. INTRODUCTION

X-ray imaging is a relatively new technique. A considerably part of knowledge in this field follow from work made in visible optics or elektron microscopy. An overview of the principles and methodology of X-ray image acquisition in 0D, 1D, 2D, and 3D will be given with the emphasis on the specificities of synchrotron radiation.

One possible way to look at the current trends in x-ray imaging with synchrotron radiation is to say that the development is carried out in two distinct directions which necessarily meet once in a while, but still both require a separate research. The two directions can be identified as the improvement of temporal and spatial resolution. What are the motivations and where are the real limitations in these two research directions? The aim of the tutorial is to be able to give some answers to this question.

The overal outline of the tutorial will follow the layout of this letter.

II. PRINCIPLES OF SYNCHROTRON BASED X-RAY IMAGING

It follows from the relativistic electrons properties that the divergence of the x-ray beam emerging from a synchrotron source is extremely low. As a consequence we speak about parallel beam imaging in contrary to laboratory x-ray experiments where by the nature of its generation the fan- or cone-beam geometry is usually the case. The parallel beam has many advantages for tomography, such as easy and artifact free reconstruction. The high brilliance of the source also results in a much higher number of useful photons at the level of the detector. The beam angular divergence is typically $0.1-1\,\mu$rad demonstrating the important difference in this value when looking at a usual laboratory source divergence which emits over half space.

The unique properties of the x-rays emerging from an instrument such as one of the numerous operational and planned 3rd generations synchrotrons allow to develop and implement state-of-art instruments, a tool for applications that can hardly be addressed elsewhere with the same resolution (in many senses of the word).

The spatial resolution with laboratory x-ray sources has achieved remarkable results in the last decade. Commercially available systems routinely offer spatial resolutions close to a few micrometers. Very recently even sub-micrometer resolution laboratory systems are reported. The image quality is however often poor when imaging real materials. In this work we also address sub-micrometer resolution in tomography with 3rd generation synchrotron radiation x-ray beams that do offer additional possibilities to those used in laboratory setups.

Using laboratory sources, the acquisition time for a complete tomographic set at a resolution of few micrometers is of the order of hours. At synchrotron sources the situation is far better because of the available high flux of x-ray photons.

When an X-ray beam impinges on a sample, part of it can be absorbed (mainly photoelectric effect), scattered or reflected.

The attenuation of the X-rays of the initial intensity I_0 in a material of thickness z is expressed by the *Beer-Lambert law* with boundary condition $I(z=0)=I_0$

$$I(z) = I_o e^{-\mu z} \tag{1}$$

μ is referred to as the linear attenuation coefficient.

The complex refractive index can be expressed as:

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

When instead of the intensity we regard the wave function in the media traveling a distance Δz , where $k=\frac{2\pi}{\lambda}$ is the wave vector we can write $e^{i(1-\delta)k\Delta z}.e^{-\beta k\Delta z}$ where $\beta=\frac{\mu}{2k}$, it becomes clear that the δ is responsible for the phase shift $\varphi=-\frac{2\pi}{\lambda}\int\delta dz$ and β for the amplitude attenuation. Both factors will be present in imaging, but one important advantage of synchrotron sources is the possibility to use both factors selectively. How and why to do this selection will also be discussed in detail.

III. TOMOGRAPHY

It is a big step from radiography (2D imaging) to tomography (3D imaging).

Tomographic techniques are nowadays employed using several complementary probes including x-rays. The first ever tomographic images were obtained in 1957 by Bartolomew and Casagrande [1]. Cormack and Hounsfield [4] got a Nobel price in medicine in 1979 for their work with computed axial tomography.

We can say that the utilization of x-rays was in the 20th century the most important trigger of the developments in tomography. This fact is due to the property of x-rays to go through the studied sample without being completely absorbed or scattered. It allows to obtain an image of the cross section of a sample from projection data. The projections consist in this case of line integrals of the complex refractive index $n(x,y,z)$.

IV. IMAGING WITH A PARTIALLY COHERENT SOURCE

Perhaps the most spectacular difference in imaging performed with a synchrotron beam compared to laboratory sources is the interference effects resulting from the spatial coherence properties of the x-ray radiation. Coherent radiation comes from a point source, which is not the case in practice, since the dimension of the source is not infinitely small. We say therefore that the radiation is partially coherent.

The *coherence* is the property of a signal or data set in which the phase of the constituents is measurable and plays a significant role in the way in which several signals or data combine. This term is also used to characterize radiation in two distinct respects. The first is the *longitudinal (temporal) coherence* which is related to the monochromacity of the source.

The *transverse coherence* is related to the source size and its distance. Depending on the source of radiation that is used in a given imaging system we can consider two limiting cases: the spatially coherent and the incoherent case. One way of defining our system is to say that it is incoherent if the transverse coherence length is much smaller than the resolution of the images we acquire. Changing from coherent to incoherent illumination changes the blurring process substantially. A coherent imaging system has an abrupt cut-off in the frequency domain, which results in “ringing” around edges. Incoherent illumination produces a smooth drop-off in the frequency domain which blurs edges gradually.

The inverse problem in phase contrast imaging consists in finding the phase and the amplitude of the object from the available information which is the measured intensity. This is not a trivial problem. Several alternatives to retrieve the information from phase contrast images are to be reviewed.

If the imaging system is designed to record the Fresnel diffraction pattern on the detector, then there are various approaches to approximate the forward problem in order to be able to retrieve the phase. They are generally either be based on the *Transport of intensity equation* [3] or the *Contrast transfer function* [2]. If the diffraction pattern is in the Fraunhofer regime, the iterative methods are the most performant, as reviewed in [7].

V. SPECIAL IMAGING TECHNIQUES

Changing the parallel geometry of a synchrotron beam in order to take advantage of both the geometric magnification and high monochromatic flux appears to be a very promising direction towards nano-imaging. Using Fresnel zone plates as objective lens and keeping the x-ray energy below 7 keV has brought resolutions approximately 100 nm [6, 9]. One step forward is to combine x-ray microscopy with tomography to access the bulk properties of materials at similar precision using highly penetrating hard x-ray radiation [5, 8].

Numerous other techniques are merging today. We will shortly look at these 3D techniques: coherent diffraction imaging, analyzer based imaging, fluorescence tomography, laminography, difraction contrast tomography.

VI. APPLICATIONS

Two principal applications will be selected to demonstrate the two aspects of imaging as stated in the introduction. The first is the liquid foams; a system which requires fast image acquisition eventually real time imaging.

Scientists know a great deal about the individual bubbles in foams and how they "talk" to one another through simple friction. But when many bubbles clump together to form a foam, the resulting material exhibits a host of unexpected properties and behaviors. Liquid foams, for instance, are composed of roughly 95 percent gas and 5 percent liquid, yet they tend to be far more rigid than their components. This is due to a phenomenon called jamming. Because the bubbles are so tightly packed, when a foam is pressed down, the bubbles can’t hop around one another. The more the bubbles are jammed together, the greater the pressure inside them grows and, consequently, the more they take on the characteristics of a solid.

The biggest challenge facing scientists is to create predictive models of foam rheology, or just simply coarsening that is, the way it flows or evolves over time. As foams age, gravity drains their liquid downward, and smaller bubbles are absorbed by larger ones, a process called coarsening. But until quite recently our understanding of this process has been limited to 2D foams by the inherent difficulties of studying such an ephemeral material in three dimensions.

The spatial distribution and shape of particles in Near nano-structured or ultrafine-grain materials is the second selected application demonstrating the need for submicrometer spatial resolution. These materials are defined as materials having grain sizes whose linear dimensions are in the range of $100\,nm$ to $1\,\mu m$. The physical properties of these materials are potentially superior to those of their coarse-grained counterparts. This potential superiority results from the reduced size or dimensionality of the near nanometer-sized grains as well as from the numerous interfaces between adjacent grains resulting in large volume fraction of grain boundaries. It is of high technological importance to study the bulk of these materials in different conditions.

Further examples in the field of biology, medicine, paleonthology and other fields will be shortly mentioned.

[1] R N Bartholomew and R M Casagrande. Measuring solids concentration in fluidized system by gamma-ray absorption. *Industrial and Engineering Chemistry*, 49(3):428–431, 1957.

[2] P Cloetens, W Ludwig, J Baruchel, D Van Dyck, J Van Landuyt, J-P Guigay, and M Schlenker. Holotomography: Quantitative phase tomography with micrometer resolution using hard synchrotron radiation x rays. *Appl. Phys. Lett.*, 75:2912–2914, 1999.

[3] T E Gureyev, A Pogany, D M Paganin, and S W Wilkins. Linear algorithms for phase retrieval in the fresnel region. *Optics Communications*, 231:53–70, 2004.

[4] G N Hounsfield. A method of and apparatus for examination of a body by radiation such as x-ray or gamma radiation. Patent specification 1283915, The Patent Office, 1972.

[5] R Mokso, P Cloetens, E Maire, W Ludwig, and J Y Buffiere. Nanoscale hard x-ray tomography with Kirkpatrick-Baez mirrors. *Appl. Phys. Lett.*, 90:144104, 2007.

[6] U Neuhausler, G Schneider, W Ludwig, M A Meyer, E Zschech, and D Hambach. X-ray microscopy in zernike phase contras mode at 4 kev photon energy with 60 nm resolution. *J. Phys. D - Appl. Phys.*, 36(10A):79–82, 2003.

[7] I K Robinson and J W Miao. Three-diemnsional coherent x-ray diffraction microscopy. *MRS Bulletin*, 29(3):177–181, 2004.

[8] C S Schroer, P Cloetens, M Rivers, A Snigirev, A Takeuchi, and W Yun. High-resolution 3d imaging microscopy using hard x-rays. *MRS Bulletin*, 29(3):157–164, 2004.

[9] H S Youn and S W Jung. Observations of a human hair shaft with an x-ray microscope. *Phys. Med. Biol.*, 50(22):5417–5420, 2005.