High resolution Imaging based on X-ray Holography

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Abstract

Up to now standard X-ray imaging technologies, rely primarily on the amplitude properties of the incident radiation, and do not depend on its phase. This is unchanged since Röntgen's discovery [1] that the intensity of an X-ray beam, as measured by the exposure on a film or an equivalent X-ray detection device, was related to the relative transmission properties of an object. However, the new imaging techniques, which have been emerged, depend on the phase of the X-rays as well as the amplitude. Phase becomes important when the beam is coherent and the imaging system is sensitive to interference phenomena. Significant new advances have been made in coherent optic theory and techniques which now promise phase information in medical and material imaging.

1 X-RAY HOLOGRAPHY ON ATOMIC SCALE

In accordance to optical holography one of these new imaging techniques works on interference phenomena between a scattered wave front (with the origin of scatter sources in a sample of interest) and an undisturbed reference wave field. The basic working principle is that of the so-called 'in line holography', which was suggested first by the Hungarian physicist Gabor in 1947 [2]. In combination with X-rays this modality enable either imaging on an atomic scale or imaging of structures in the (sub-) micrometer range with the so called 'phase contrast' approach, which will be described later.

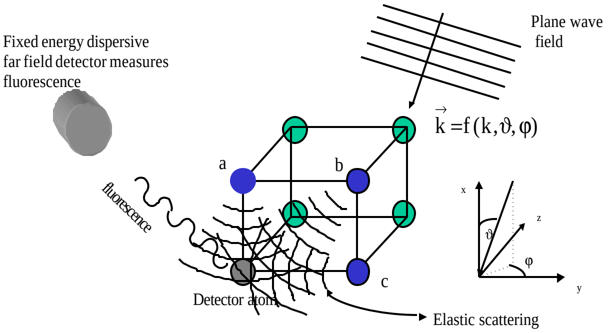

Figure 1: Set up for multi energy X-ray holography.

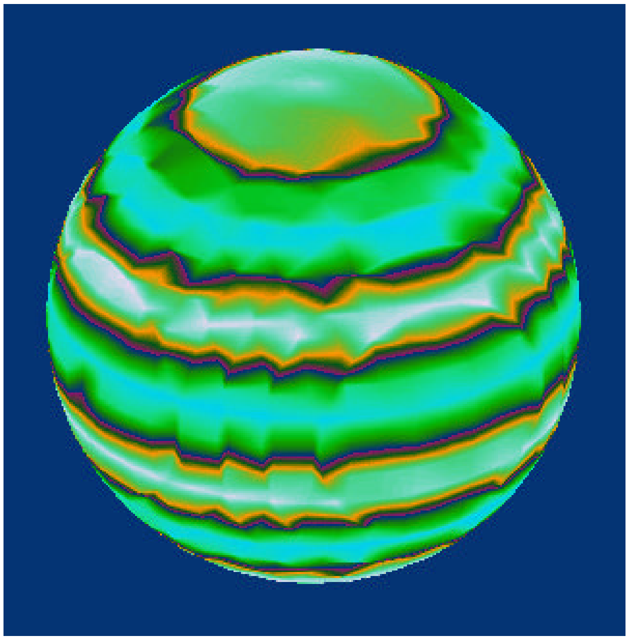

Figure 2: Measured hologram of a germanium bulk crystal.

That X-ray holography is possible on a atomic scale was proven recently by three research groups [3] [4] [5] who obtained for the first time holographic images of atoms in the bulk of crystals. One of these techniques called “Multi energy X-ray holography (MEXH)” (figure 1) was suggested and successfully performed by T.Gog et al [4,6,7]. The set up is different from that of optical holography but the basic working principle is the same: A plane wave field (reference wave) impinges on the object of interest. The energy is set slightly above the binding energy of the k-shell electrons of the material of interest. In this fashion photo-electric absorption and subsequently the emission of a fluorescence photon is possible. At the same time the interaction between the X-rays and matter might be also elastic scattering with the atoms **a,b,c** as depicted in figure 1. These atoms are sources of spherical waves that interfere with the reference wave at the position of a so called ‘detector atom’. In case all the waves add up at this position a photo-electric absorption and subsequently the emission of a fluorescence photon is possible, which then can be detected with a far field detector. If the scattered waves add up to zero at the

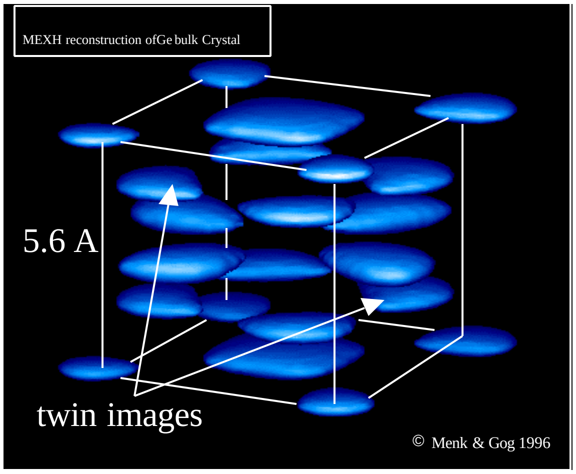

Figure 3: First image of the atomic structure of a germanium bulk crystal as reconstructed using MEXH

position of the detector atom clearly no fluorescence occurs. The interference conditions depend on the direction and the energy of the incident radiation. The final hologram is then obtained by scanning the hemisphere and recording the amount of fluorescence with a far field detector (figure 2) for each single position. A sophisticated data processing allows the reconstruction of the electron density and thus the position of the atoms in real space at a latter time as shown in figure 3, in which the three dimensional reconstruction of a Germanium unit cell is shown. The remaining artifacts, such as the flat shape of the atoms, might be removed by utilizing more sophisticated filtering methods. Twin images, however, as also visible in the reconstruction of figure no 3, seem to be unavoidable.

2 MEDICAL IMAGING

Ever since the very first medical image was taken with X-rays in 1895 by Röntgen the basic imaging setup has not changed. Typically it consists of a X-ray source, a slit system in order to define the field of view and a detection device. The object of interest normally stays in contact with the detection device (figure 4). During the exposure X-rays penetrate the object and are attenuated according to

$$I = I_0 \cdot e^{\int_{-\infty}^{\infty} \mu_{total} \cdot \rho(z) \cdot dz} \qquad (1)$$

Here I_0 is the intensity before the object and I is the recorded intensity on the detection device, μ_{total} is the mass absorption coefficient and ρ the density of the object.

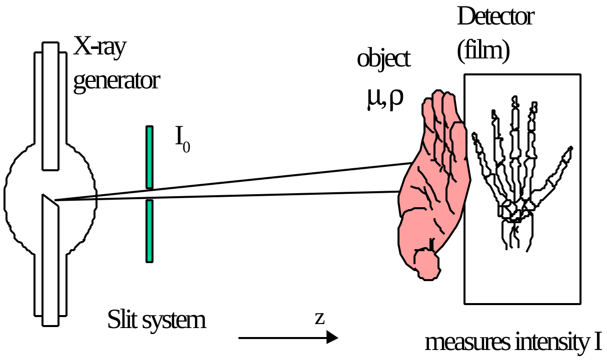

Figure 4: Standard set up in radiography

The phase information, however, has not yet been exploited. Neither was scattering (e.g. due to refraction) considered to be useful. In fact using this kind of set up, scattering causes image disturbance such as blurring and contrast reduction for small details.

3 REFRACTION AND PHASE CONTRAST IMAGING

When an X-ray crosses a boundary between media with different refraction indices n_1 and n_2 the beam is deviated from its original direction. Especially for curved boundaries the deviation can be large and is in the range of $10^{-6} - 10^{-7}$ rad even for a small difference in the refraction indices n_1-n_2 of about 10^{-2} [8],[9]. Note that the cross section for refraction drops only with the square of the energy.

Let's suppose a small cylindrical object with the refraction index n_2 embedded in a material with a refraction index of n_1 (figure 5) which is penetrated by a plane wave field.

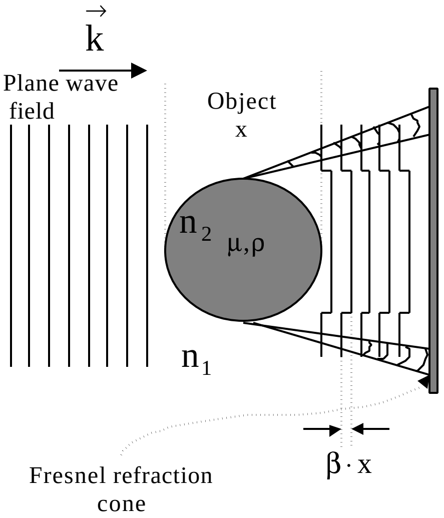

Figure 5: Descriptions see text.

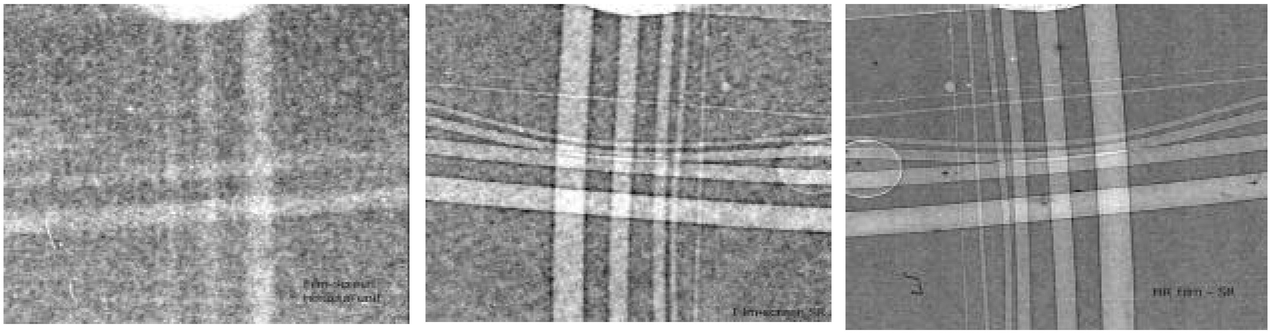

Figure 6: Images of a fiber phantom taken at SYRMEP. Left: normal radiography, middle: low dose phase contrast, right: high dose, high-resolution phase contrast [11].

The plane wave is only disturbed in the vicinity of this object and especially on the boundary of the two media where the refracted beam is emitted in a cone. Behind the object a phase shift of $\beta \cdot x$ occurs. Since the plane wave (reference wave) as well as the refracted wave (scattered wave) are of the same source they interfere. Whether this interference can be resolved by the detector is strongly dependent on the source characteristics and the distances source-object, object – detector. Under certain conditions the interference between the reference wave and the scattered wave can be detected by the detector system as shown by Snirgirev et al [10] and Wilkins et al [11]. For a line scan geometry where the object and the detection device are moved through a fixed beam it is just a matter of the right distance and the right speed ratio. The object and the detector move simultaneously but with slightly different velocities for a spherical wave analysis. In this fashion it is possible to obtain almost artifact free interference fringes as variation of intensity on the detector and which are the hologram of the object. This technique is called Phase Contrast Imaging (PhC).

At first high resolution films were utilized as the detection device delivering tremendous results (figure 6) but with the cost of high dose. It was shown later by DiMichele et al [16] that phase contrast imaging can be exploited for medical imaging which has very strict dose requirements.

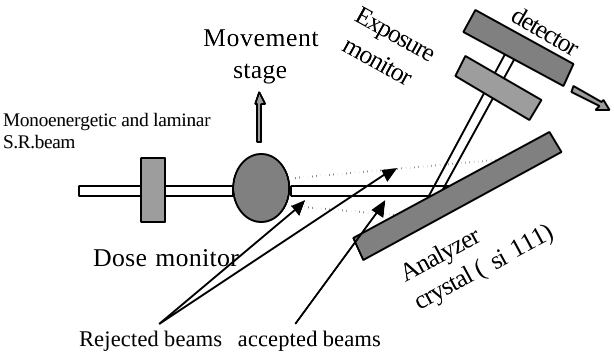

Figure 7: Set-up with a crystal analyzer.

Utilizing a film screen system such as that used in clinical mammography it was possible to obtain phase contrast images with doses comparable to clinical mammography but with superior image quality. The potential of this technique is emphasized by radiographs shown in figure 6. The fibers shown there are almost transparent for normal radiographic techniques at an energy of about 17 keV (left image) but produce images of high contrast when the Phase Contrast Imaging technique is employed.

4 DIFFRACTION ENHANCED IMAGING

Even if interference is not visible the scattering in this angular range can be exploited as shown first by Produrets et al [13], Somenkov et al [14] and Beliavesky et al [15]. By means of an analyzer crystal placed between the object and the detection device it is possible to convert the angular distribution of the refracted beams into intensity changes on the detector (figure 7). This is due to the fact that a crystal has a very narrow angular acceptance (approximately some µ radian) for X-rays of certain energy. For monoenergetic radiation only those beams are reflected whose angles with respect to the surface of the crystal are in a certain range around the Bragg angle. The reflectivity as a function of the Bragg angle – also known as a rocking curve- is shown in figure 8 for a Si (111) crystal and an X-ray energy of 20 keV. If the analyzer crystal is perfectly aligned with respect to the direction of the incident wave (and its energy) then only those rays that are within the FWHM of the rocking curve are reflected onto the detector and subsequently form the image. Beams refracted at higher angles however, are rejected. In this configuration the analyzer crystal serves as a perfect slit with almost no contributions from refracted rays.

As an example of the tremendously improved image quality a radiograph of an entire mouse is shown in figure 9. This image was taken at a photon energy of 20 keV. With a well defined contribution of scattering even small

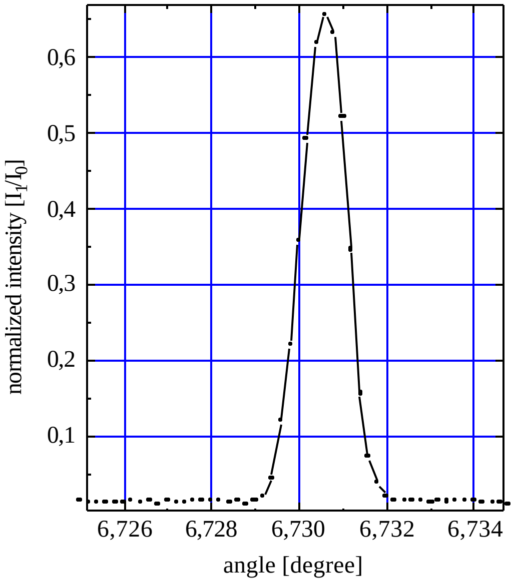

Figure 8: Rocking curve of the analyzer crystal (Si 111 for an X-ray energy of 20 keV) measured at the SYRMEP beamline at Sincrotrone Trieste.

details such as the fur of a mouse can be visualized as demonstrated in this post mortem image taken at the SYRMEP beam line at Elettra. Note, the mouse was found by chance in the vicinity of the laboratory and not killed for the purpose of imaging. The visibility of the lungs is due to refraction that occurs at the boundary of the lung spheres and subsequently at the water – air transition. Beyond simple scatter rejection, a crystal analyzer reveals another more sophisticated feature when detuned (e.g. moved to the slope of the rocking curve). In this fashion, a well defined amount of the scattered /refracted radiation contributes to the image recorded by the detector. The image can be now considered as a mixture of two components only - namely a pure absorption and a pure refracted part. Initially the weight of both components is unknown. If, however, two images are recorded- one with the analyzer crystal detuned to smaller angles and the other with the analyzer detuned to higher angles- then the weight of the two unknown components can be found by a simple matrix inversion on a pixel basis. This technique is called ‘Diffraction Enhanced Imaging“ (D.E.I.) and was first suggested and proven by Chapman et al [15] and shows tremendously improved image quality when compared to a normal radiography (figure 10). Shown here on the left and in the middle are a pure refraction image and a pure absorption image of a

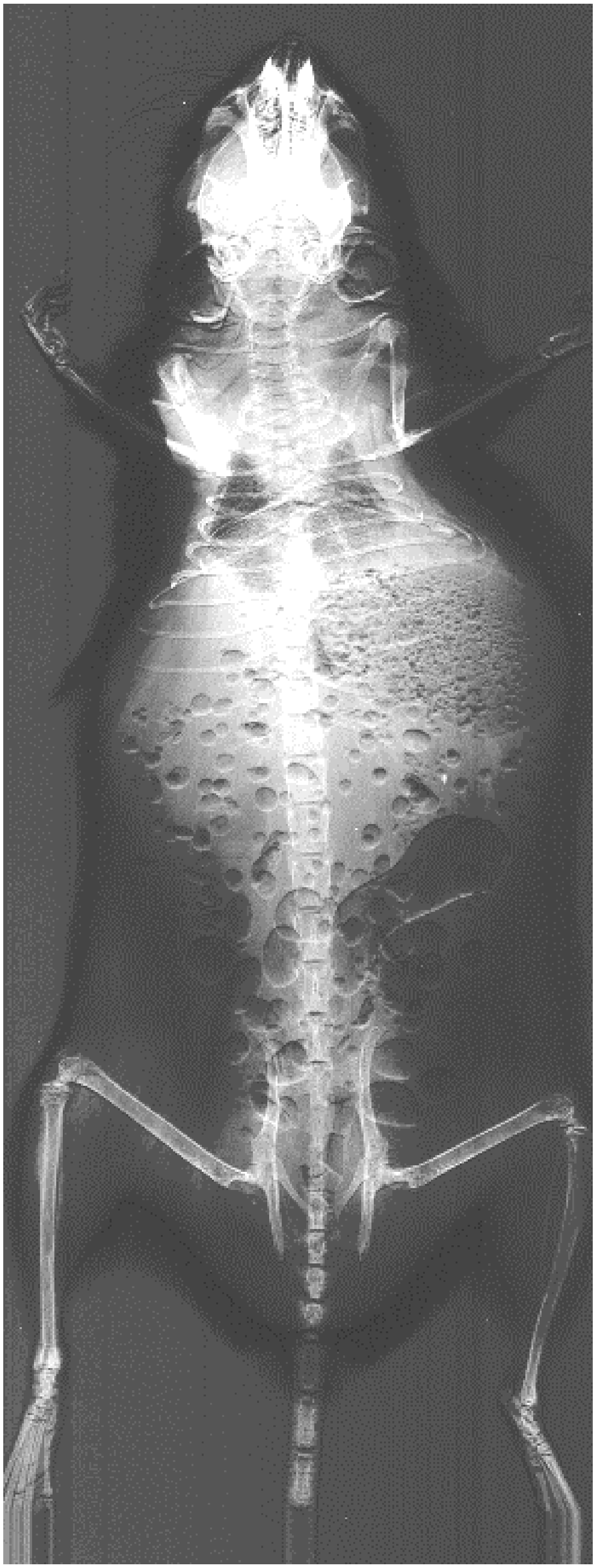

Figure 9: Post mortem radiography of a mouse take at the SYRMEP beamline at Elettra at 20 keV. The mouse was found already dead in the vicinity of the laboratory.

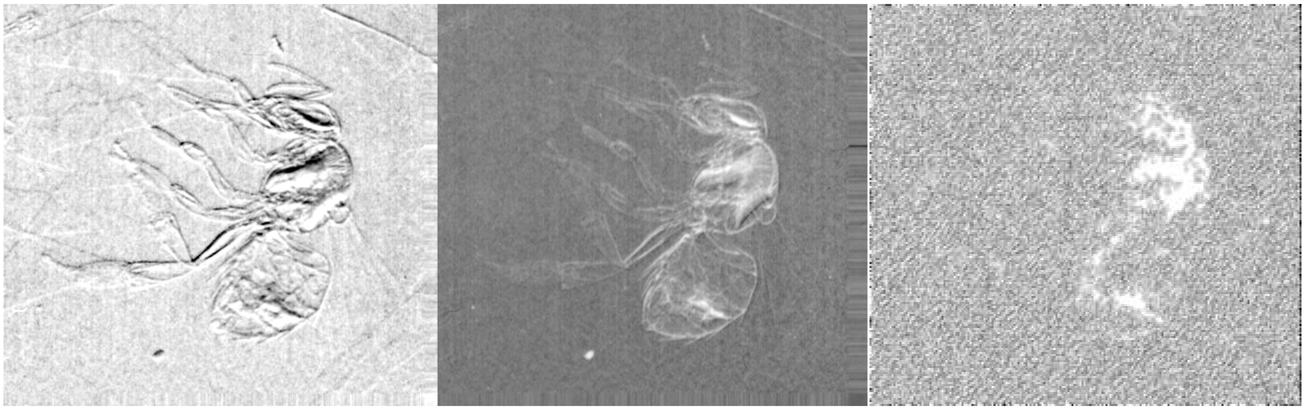

Figure 10:Description see text

bee, respectively, which were calculated from two images obtained on two different slopes of the rocking curve. The energy was set to 20 keV in order to compare these images to a standard transmission radiography of the same bee taken with a clinical mammographic unit at the same dose (right image).

5 SUMMARY AND PROSPECTIVES

It was shown that new imaging modalities with X-rays deliver superior image quality and even enable imaging on an atomic scale. Recently PhC as well as D.E.I were successfully implemented in feasibility studies for X-ray mammography with synchrotron radiation showing improved image quality and higher sensitivity for early breast cancer detection than conventional mammography. Another medical application already proven is micro tomography on bone-cartilage interfaces. For full exploitation of these techniques in a clinical environment, however, some basic research has still to be carried out.

X-ray holography could play a key role in the determination of complex protein structures. Although holograms on diluted samples were already obtained also this technology stands at its beginning.

6 ACKNOWLEDGMENT

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