iFCX: Fast Contrast X-ray imaging

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The iFCX (Fast Contrast X-Ray Imaging) project of a new LNF unit "XLab Frascati" (http://www.lnf.infn.it/xlab/index.html) aims in X-ray high resolution imaging studies based on the use of polycapillary optical elements. The main scope is to design a prototype unit for new imaging technique to investigate low contrast and fast developing processes in the energy range of 5÷30 keV (from soft to hard X-rays). For 2012 we have realized two desktop testing layouts: one for high resolution imaging analysis of static biological samples, while another one - for X-ray imaging of the engine fuel sprays.

1 Introduction

As known, one of the main properties of X-rays is the permeability into the matter that can be exploited for X-Imaging (mainly X-ray microscopy), the technique in a wide use at scientific and industrial centers, at hospitals, etc. The advanced X-ray imaging instrument, known as X-ray computed tomography, is a non-destructive analysis technique to evaluate the inner structure of investigated objects with extremely high spatial resolution . A rapid development of SR laboratories has induced essential improvement in dedicated optical components resulting in strong increment of a spatial resolution, rising up to several tens of nanometers of sample penetration range. Nowadays, X-ray microscopy is a unique tool to complement existing imaging techniques such as light and electron microscopies. The tomographic images are achieved by mathematical reconstruction of sample projections; such projections are represented by the intensity data (matrixes) of transmitted X-rays through the object.

A major number of papers dedicated to high resolution X-ray tomography is principally obtained at SR centers. However, SR procedure requires long time planned experiments, moreover, the SR research is rather expensive and can be performed just at a fixed number of facilities. Obviously, it complicates any SR study. Additionally to various procedure difficulties we have to take into account another factor; typically, any SR probe is characterized by high exposition dose on a studied sample that followed by direct consequence of a rapid degradation of biological samples.

On the contrary, conventional X-ray tubes are worldwide distributed. Optimized combination of X-ray tubes and optical elements, such as, for instance, polycapillary lens, can provide an equipment with intense photon flux probes necessary to realize a proper layout for high resolution X-Imaging. Moreover, a specific design can result in a compact and portable X-ray instrument for "in situ" studies . In this context a prototype of X-ray microscope based on polycapillary semi lens has been designed in our laboratory.

As a result we have shown first results on polycapillary lens ability as an optical device for high resolution tomography. The tomography slices instrumentally obtained (registered by the detector) allowed the image reconstruction by the projection frames realized via the OCTOPUS (inCT Co.) code . Successfully, supported by the AMIRA rendering software

2 Activity in 2012

2.1 X-ray μ-tomography of organic samples

The X-ray tomography test bench is composed of a radiation source, an Oxford Apogee 5000 tube (Cu Kα), with a source spot of about 50×50 μm^2 and power of 50 W, a Photonic Science CCD (FDI 1:1.61) with a pixel resolution of 10.4×10.4 μm^2 and a Newport micrometer positioner $xyz\theta$ (Fig. 1).

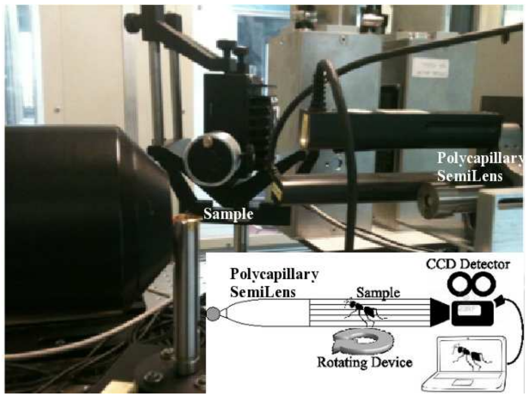

Figure 1: Tomography prototype for biological sample. To obtain a quasi-parallel beam we have used a polycapillary semilens as schematically shown.

To obtain a rather small radiation divergence, which allows getting a very small blurring effect, we have used a polycapillary semilens. Any lens is characterized by a residual divergence responsible for the resolution graduation. If one supposes that the sample dimension ΔX_0 is reproduced at the detector as ΔX, then the effect can be estimated as $|\Delta X_0 - \Delta X_0| \propto l\Delta\theta$, where l is the distance from the sample to the detector. To reach the higher resolution it becomes necessary either to use the optics with the small residual divergence, or to place the sample as close as possible to the detector. Since the used semilens had a residual divergence of 1.5 mrad and the sample was placed about 15 mm from the detector because of the physical dimensions of the stage rotation, the minimum allowed resolution was about 15 μm (comparable with the CCD resolution).

The first 3D image reconstruction we performed on a biological sample, namely, on an ant. The CCD exposure time was 250 ms, enough to avoid the CCD saturation. The sample was positioned on the $xyz\theta$ micro-positioner and step rotated by 0.5 degrees per image, for a total of 720 projection images: the rotation velocity was 0.5 deg/s for a total exposition time of 720 s. To reduce the noise effects a background subtraction has been preformed by the image acquisition software ("Image-Pro Express").

The reconstruction work is separated in two stages: the conversion of the projection images into the slice images (Octopus code) and the rendering process (Amira code). The results of image rendering carried out by highlighting the sample inner parts, central nervous system and mandibular glands (brown areas) are shown in Fig. 2. The X-ray tomography permits a 3-dimensional vision of the ant head and body structure: the biological sample "is seen" through all the planes and it is possible to enter in the investigated body volume and to resolve the projections on a single information plane.

Due to the fact that, an ant exoskeleton has made by hard surface, a second reconstruction was done for a flower bud. Such kind of a sample is perfect to test qualitatively and to obtain quantitatively the information on the prototype of soft-biological matter. In Fig. 3, a 3D reconstruction with a corner cube cut is shown. The onion-geometry of all biological layers is clearly seen.

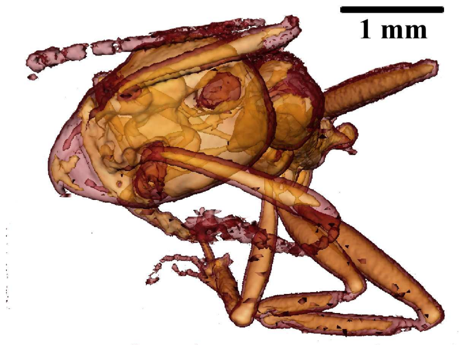

Figure 2: Rendered image of an ant. The brown areas represent the sample inner structure making evident the nervous system as well.

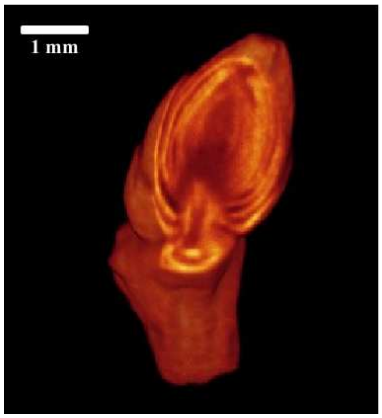

Figure 3: X-ray micro Tomography of a flower bud. The experimental setup is based on polycapillary semilens with 1.4 mrad residual divergence and the power source of 22 W. To obtain this 3D image, 720 images on 360° with an exposition time of 250 ms/image for a total exposition time of 12 minutes were registered and analyzed.

2.2 X-ray μ-tomography of fuel sprays

Additionally to our studies on biological objects, one of the main topics of the project iFCX (gr. V - INFN) is to investigate the fast processes involving low absorption samples. Within this project a few years ago the XLab Frascati LNF has started the collaboration with the Istituto Motori CNR aiming to study the fuel injection processes through the X-Imaging technique.

Attempts to analyze the fuel density distributions inside transient high-density fuel sprays by X-ray based techniques have been carried out in several laboratories around the world. Obviously, SR facilities are mainly adopted for such research due to high SR intensity and its pulsed nature. X-radiation penetrates the dense part of a fuel spray because of its weak interaction with the hydrocarbon chain, and, hence, useful information is provided from the emerging radiation. Time-resolved X-ray both radiography and tomography have been used to elucidate three-dimensional structures both for gasoline and diesel sprays in close-nozzle high-dense optically-impenetrable regions allowing quantitative data on fuel densities, jet structure and morphology, induced shock waves, droplet ruptures, etc. Typically, all these works used of pulsed high-brilliant sources like SR. As known, they overcome the initial limits of X-ray tube sources , and are characterized by continuous in both time and energy radiation spectra, by their monochromaticity, by pulsed time-structure and high time resolution. On the contrary, this sources have, as above said, the intrinsic limitations of high costs, beamlines with dedicated instrumentation, as well as poor duty cycles. The table-top Tomography prototype designed within our collaboration can overcome these problems, Fig. 4. Evidently, our prototype, revealed rather high ability to perform X-imaging studies, is intended as a preliminary instrument to be advanced in the future.

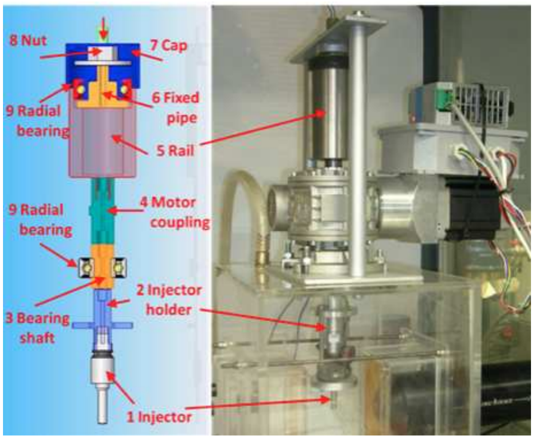

Figure 4: Fuel-tight high-pressure rotating system: schematic sketch on the left and photo on the right: 1 - the injector; 2 - the injector holder; 3 - the bearing shaft; 4 - the motor coupling; 5 - the rail; 6 - the fixed pipe; 7 - the cap; 8 - the nut; 9 - the radial bearing.

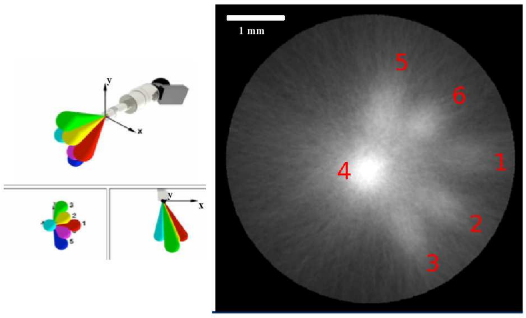

Figure 5: (On the right an axial slice of the GDI 6 jets tomography reconstruction after the Octopus processing is shown, while in the left there are 3D spatial schemes of the GDI injections.

The CCD detector has been synchronized via external trigger with the fuel injection event. Its acquisition time is defined by enabling TTL pulse duration. At this stage the temporal resolution has not been pursued. A time resolution of the system is achievable by reducing the duration of the enabling pulse and synchronizing it at different time from the start of the injection. On the contrary, the signals reduce in intensity, and highest repetition rates are necessary with the unavoidable problems of fuel deposits and fog. The best compromise between the detector intensity and the number of acquisitions should be found. Likewise for the space resolution, slits or spatial windows can be adopted to reduce the focused area of the spray.

Fig. 5 reports an axial tomography slide of a six-hole GDI spray at 12.0 MPa injection pressure and 3.0 ms in duration. The X-radiography of the spray has been carried out with an injector rotation of 360°, step 1° with the images stored and processed off-line.

To realize the setup for GDI injector tomography, a homemade rotating device has been designed and successfully tested at high pressure. The system allows a controlled trip, 360° rotation and 0.1° precision step, of the injector body working at pressures up to 20 MPa. The challenge has been to realize the coupling between the fixed and the rotating parts at high pressure, preventing fuel loss. The device has been designed as an assembly of several components in order to quickly change parts without compromise the system set-up (for the device details see).

Ideal projections for the tomography reconstructions are the images free of noise. In practice, this is never the case due to the statistical nature of the measurements, as repetitions and ensemble averages do not warranty identical conditions at the same spatial and temporal coordinates. However, low noise is present only in measures of static and unanimated objects. On the contrary, sprays are not in this set, but constituted by periodic events of evolving objects (droplets, ligaments, bulks) that changes continuously shape and thermodynamic conditions during their life-time. By this way, it is necessary to find a threshold of number of images to average in order to lose all the informations. As a starting point, at each angle the resulting picture is a sum of 48 images, 12 bit resolution with the detector acquisition as long as the spray duration. The huge noise on the outline could destroy the sinogram constructions. To minimize the stray signals (caused from the deposition of the drop-let on the Kapton sheets and residual fog) and the injector precession mode during the rotation, acquisition of back-ground images have been carried out per each measurement point. Background subtraction, intensity stretching, low-pass filtering and contrast enhancing have been applied to process the images.

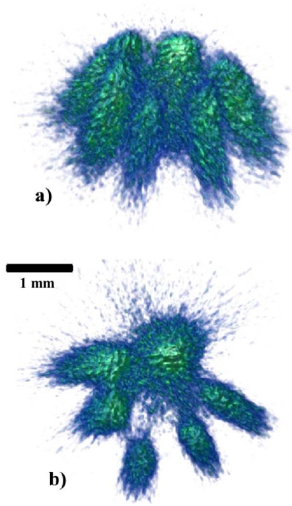

Figure 6: Tomography pictures, in pseudocolors, of the six hole GDI spray.

At this stage, we didn't define both local densities of the fuel and droplet diameter or parcel structures. Due to the geometry of the injector, in Fig. 5, the fourth jet is much intense than the others, even if the fuel density is equal for all jets. In this way , a normalization function for that jet should give us the information of the droplet size and the density.

Figs. 6a and 6b show 3D reconstruction of the axial tomography results of the six-jet spray structure, as obtained from the sinograms. The field of view of the object is limited to the part immediately downstream the nozzle tip, typically a few millimeters. Fig. 6a reports a sight from the top (injector body) while, on the right, a lateral view is shown. Fig. 6b shows clearly the footprint of the spray, viewing positions and propagating directions of the six jets. No interferences of squirts occur at these locations; the fuel delivered from the different holes propagates in an independent way and the profiles appear distinct.

3 Conclusions

During 2012 we prospected polycapillary lenses and the possibility to use them in combination with conventional sources for portable tomography instruments with a resolution about 10 μm with a radiation exposition less than 15 min using a low power X-ray source.

In particular we have shown, as preliminary results, static biological samples, both for axial tomography and for 3D reconstruction. As a second step, we have studied a GDI injector, mounted on a high-pressure rotating device, with a $\Delta\theta < 0.1^\circ$ angular resolution, that explored at 12 MPa injection pressure in a vented pirex chamber. Good reconstructions of the spray structure have been obtained for the six-hole injector with recognition of positions and propagation directions of the six jets. Vision of fuel density and parcel number are possible everywhere inside the spray implying a potential powerful tool to characterize events time-evolving, non-repetitive and at complex flu-dynamic structure.