Mid-term plan for 32-ID Upgrade

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Proposal: To install a second insertion device in 32-ID, optimized for ultra-high-speed imaging.

Introduction

The APS is currently leading in the development of high-resolution (μm-scale) x-ray imaging with sub-μs temporal resolution. The source parameters (flux, repetition rate, energy range) make the APS a vastly superior facility for ultra-high-speed x-ray imaging compared to others (X/Z pinch, fs-laser-based sources, or lab-based flash generators). Although fs-laser-based x-ray sources have significantly shorter x-ray pulses, for full-field μm-level resolution imaging, a 100 ps pulse is more than sufficient. For example, sound waves in solids are in the 1000 m/s range, which translates into a 0.1 μm motion in 100 ps, which is 10X smaller than our spatial resolution.

Currently, at 32-ID, the ultra-high-speed imaging experiments are performed using white beam, in conjunction with 2 mechanical beam choppers: (1) a 5-10 ms opening time heat load shutter and (2) a 10 μs opening time high speed shutter. A camera with very fast electronic shutter (500 ns) is used to capture the x-ray pulse. The millisecond shutter is a solenoid activated cooled copper block, which serves to reduce the heat load on subsequent equipment and sample. Although in theory the camera can be shuttered to capture a single x-ray pulse, in practice, this is not successful because the electronic shutter closure is only 99% efficient. Thus, the residual accumulated light from the scintillator during the opening of the millisecond shutter will overcome the actual signal from a single bunch. For this reason, the high-speed chopper with 10 μs opening is needed; it significantly reduces (1000X) the residual unwanted background. With our present set-up (using 5X objectives) the no-sample CCD pixel count rate from a single electron bunch (16 mA during the singlet-hybrid mode) is ~ 200 with a dark count of ~ 55. Thus, the actual counts are only ~ 150 per pixel with no sample. Assuming the signal-to-noise is approximately the square root of the counts, this gives S/N ~ 12, which is 5-10X smaller than a typical imaging set-up using 12-14 bit detectors.

32-ID currently has the standard APS 3.3 cm undulator A and all the sub-μs imaging experiments have been performed using the above set-up with the 12.9 keV first undulator A harmonic at 30 mm gap. Although one would have a higher 12.9 keV photon flux (factor of 2.3X) by going to the third harmonic at 11 mm gap, there are two reasons why that is NOT done. The first reason is the heat load. The current choppers cannot handle the high heat loads. The second reason is that at closed gaps, the higher harmonics become very intense. These higher harmonics will dramatically reduce the image contrast because they have negligible interaction with the sample, but will still be detected by the scintillator (although with lower efficiency). We note that for imaging experiments, the use of a mirror to reject the higher harmonics is not feasible because the imperfections on the mirror will impart a lot of structure into the beam. Such structure cannot be subtracted out in phase contrast imaging; unlike a simple amplitude variation, one cannot easily reconstruct the distorted phase. Furthermore, at such short exposures, the beam is not steady and thus, even a less-than-perfect correction is not possible.

Scientific motivation

High-speed imaging with visible light is a well-established technique. However, visible light techniques have severe limitations due to reflection, refraction and multiple scattering. Furthermore, visible light does not have the penetrating ability of x-rays. Synchrotron ultra-high-speed x-ray imaging is the only technique that is capable of imaging inside optically opaque systems with μm-spatial and sub-μs-temporal resolutions. The scientific applications of this technique are:

- High-speed fluid flow and sprays: Most high-speed fluid flows involve cavitation and breakup and are thus opaque to visible light. As a result, most experimental studies have been limited to parts of the fluid system that is observable by visible light, such as the leading edge of the spray or the very edges. Furthermore, in many of these cases, the information is only qualitative in nature. Because these systems are usually non-linear and highly complex, numerical simulations are used extensively to study them. However, without any real experimental data to verify these simulations or their assumptions, these simulations cannot be validated. At 32-ID, we have used this technique to look at: (1) diesel sprays, (2) bio-fuel sprays, (3) effect of nozzle design on sprays [Wang et al, 2008], (4) coaxial water sprays [Wang et al, 2006], (5) jet breakup mechanisms [Wang, in print], and (6) cavitation in flow through a Venturi channel.

- Granular materials: The dynamics of granular materials (fluid-like in a macroscopic sense, but solid-like in a microscopic sense) is not well understood. A recent publication [Royer et al, 2005] demonstrates the potential of using x-ray imaging to elucidate the behavior of granular materials under impact. The spatial and temporal resolutions of that study are, respectively, about 10-1000X poorer than what can be achieved at 32-ID. The ability to look below the surface of granular materials with μm and μs-level resolutions will greatly add to our understanding on the behavior of complex materials.

- Non-equilibrium fluid singularities: Far-from-equilibrium behavior is one of the least understood areas of physics. This technique was recently used to look at the scaling laws in coalescence [Fezzaa et al. 2008] and pinching-off [manuscript in review] of water droplets.

- Dynamics of material failure: Several years ago, in collaboration with personnel from LLNL, we attempted to look at void formation in a thin aluminum disk upon impact from a 'ballistic flyer'. However, at that time we were only able to image with a 500 ns exposure, which was insufficient. The addition of this new insertion device would enable us to study the damage to thin materials upon ballistic impact. This type of work is of relevance to areas of transportation safety and security. Currently, there are no other techniques that can directly image failure dynamics.

The above highlight the types of science that have been attempted at 32-ID since the development of our ultra-high-speed imaging technique. We expect that there are many other applications. The current users of the ultra-high speed imaging technique are 32-ID include:

1. Prof. Ming-Chia Lai (Wayne State)/Jin Wang (XSD): diesel/bio-fuel sprays.

2. Alexandre Vabre (CNRS, France)/Olivier Coutier (Toulouse, France): cavitation in Venturi tubes.

3. Kamel Fezzaa (XSD): catastrophic deformations in liquids and granular materials.

4. Paul Michelli (Illinois Tool Works): water sprays.

5. David Hung (Visteon): effect of injectors on sprays.

The addition of an optimized insertion device is crucial for these experiments. Currently, single-electron bunch imaging is *barely feasible* with a non-absorbing sample such as a liquid spray. In order to extend the technique to absorbing samples, a significant increase in the flux is necessary.

Enabling technology and infrastructure

We propose to install a second insertion device, optimized for ultra-high-speed imaging, into the 32-ID straight section. This will be an addition to the current standard APS 3.3 cm undulator A. The requirements of the new insertion device are:

1. Significant increase in flux (photons/mm^2) in the 12-15 keV range
2. Significant reduction in higher harmonics
3. Significant reduction in heat load

Essentially, we would like a 'single-line' undulator. One version of such a device is installed at the ESRF ID-9 for the time-resolved program. We would like the ability to operate BOTH insertion devices simultaneously to increase the photon flux. This may or may not require modifications to the front-end. The ID group at the APS have started to look into the possibilities of such a device and their preliminary studies suggest that an APPLE-II type helical undulator might be appropriate. The calculations show that such a device would yield 4X the useful x-ray flux on the sample (12-15 keV range), compared to our current set-up, with significantly lower higher harmonic content.

References:

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