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The new X-ray imaging and biomedical application beamline BL13HB at SSRF

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Abstract

A new X-ray imaging and biomedical application beamline (BL13HB) has been implemented at the Shanghai Radiation Synchrotron Facility (SSRF) as an upgrade to the old X-ray imaging and biomedical application beamline (BL13W1). This is part of the Phase II construction project of the SSRF. The BL13HB is dedicated to 2D and 3D static and dynamic X-ray imaging, with a field of view of up to 48.5 × 5.2 mm2 and spatial resolution as high as 0.8 m. A super-bending magnet is used as the X-ray source in BL13HB, which has a maximum magnetic field of 2.293 T. The energy range of monochromatic X-ray photons from a double-multiplayer monochromator was 8-40 keV, and the white beam mode was provided on the beamline for dynamic X-ray imaging and dynamic X-ray micro-CT. While maintaining the previous experimental setup of BL13W1, new equipment was added to the beamline experimental station. The beamline is equipped with different sets of X-ray imaging detectors for several experimental methods such as micro-CT, dynamic micro-CT, and pair distribution function (PDF). The experimental station of BL13HB is designed specifically for various in situ dynamic experiments, and BL13HB has been open to users since June 2021.

Full Text

Preamble

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A new X-ray imaging and biomedical application beamline (BL13HB) has been implemented at the Shanghai Synchrotron Radiation Facility (SSRF) as an upgrade to the previous X-ray imaging and biomedical application beamline (BL13W1). This upgrade is part of the SSRF Phase II construction project. BL13HB is dedicated to 2D and 3D static and dynamic X-ray imaging, offering a field of view up to 48.5 × 5.2 mm^2 and spatial resolution as high as 0.8 m. The beamline utilizes a super-bending magnet as its X-ray source, with a maximum magnetic field of 2.293 T. The energy range of monochromatic X-ray photons from a double-multilayer monochromator spans 8–40 keV, and a white beam mode is also provided for dynamic X-ray imaging and dynamic X-ray micro-CT. While maintaining the previous experimental setup of BL13W1, new equipment has been added to the beamline experimental station. The beamline is equipped with different sets of X-ray imaging detectors for various experimental methods including micro-CT, dynamic micro-CT, and pair distribution function (PDF) analysis. The experimental station of BL13HB is specifically designed for diverse in situ dynamic experiments, and the beamline has been open to users since June 2021.

Keywords: X-ray imaging, dynamic micro-CT, Shanghai Synchrotron Radiation Facility

I. Introduction

The Shanghai Synchrotron Radiation Facility (SSRF) is a third-generation synchrotron light source featuring a 3.5-GeV storage ring that will have more than 30 beamlines in service upon completion of the Phase II construction project. The previous X-ray imaging and biomedical applications beamline (BL13W1) was one of the first beamlines constructed at SSRF, focusing primarily on the development and application of X-ray phase contrast imaging, micro-computed tomography (CT), and other X-ray imaging methods and processing techniques. With photon energies ranging from 8 to 72.5 keV, BL13W1 has served users in various research fields including materials science, biomedical science, paleontology, physics, chemistry, environmental science, and industrial applications since its opening in May 2009. During its more than ten years of operation, numerous papers have been published based on data collected at the beamline, and detailed introductions to BL13W1, methodology development, and user research achievements are available in references [1-4].

As part of the SSRF Phase II construction project, BL13W1 needed to be relocated to accommodate the construction of BL13U, and is being replaced by the new X-ray imaging and biomedical application beamline BL13HB. This paper introduces the beamline design, experimental station, methodology development, and user research results for BL13HB at SSRF. Due to limitations imposed by the neighboring BL13SSW beamline, the previous beamline layout of BL13W1 could not be duplicated. A bending magnet light source and double multilayer monochromator were selected for BL13HB to achieve high photon flux density. A double multilayer monochromator is used instead of a double crystal monochromator, and the white beam mode is also provided to compensate for the loss of photon flux density from the super-bending magnet source, replacing the wiggler source. With an energy range of 8–40 keV and newly added equipment, BL13HB can meet most BL13W1 user demands. Construction of BL13HB was completed in June 2021, and the beamline has been open to users since then, accessed through the sharing service platform of the Chinese Academy of Sciences Large Research Infrastructure Program. This paper discusses the beamline characteristics and methodology development of BL13HB and introduces typical user experimental results from various research fields.

II. The Beamline Characteristics

A. The Super Bending Magnet Source

Given the limited straight-section resources at SSRF, a super-bending magnet light source was employed to meet the scientific goals and requirements of BL13HB. Compared with the wiggler source used in BL13W1, the photon flux is significantly reduced by a factor of 10. To compensate for this loss, a double multilayer monochromator was selected for BL13HB, as discussed in detail in the following sections. The X-ray light source of BL13HB is a super bending magnet with a magnetic field strength of 2.293 T and a bending radius of 5.09 m. Within the energy range of 8–40 keV, the maximum photon flux occurs at approximately 15 keV, which is also the critical energy. Throughout this energy range, the photon flux at each energy point exceeds 1×10^{13} phs/s/0.1%BW, meeting most X-ray imaging experimental requirements for energy range, photon flux, and beam size. The divergence angle is determined by both the beam and optical component sizes. Based on SSRF storage ring parameters, the divergence angle of BL13HB is set to $1.6\times0.3 mrad^{2}$. The simulation result of the spectral flux curve using XOP software is shown in Fig 1 [Figure 1: see original paper]. The phs/s/0.1%BW. The detailed technical specifications of BL13HB are listed in Table 1 .

B. Beamline Optics

Several factors must be considered when designing an X-ray imaging beamline, including energy range, beam size, photon flux density, and spatial coherence. To ensure high photon flux density at the sample position, the distance between the sample and beam source must be as short as possible. The experimental hutch of BL13HB is located 28–34.8 m downstream of the light source, with two optical hutches and two experimental hutches on the beamline. The layout of BL13HB is shown schematically in Fig 2 [Figure 2: see original paper]. The optical hutch comprises two sets of beam slits, two sets of filters, a double multilayer monochromator (DMM), a fluorescent screen, two sets of beryllium windows, and other necessary safety measures. The experimental hutch contains X-ray detectors with different resolutions, sample stages, and other equipment.

Double Multilayer Monochromator. A monochromator is a key component of beamline optics that determines the energy resolution, photon flux, and beam size. Currently, double-multilayer monochromators have been applied to various X-ray imaging beamlines, such as ID19 at ESRF, 2-BM at APS, and TOMCAT at SLS. The BL13HB monochromator is positioned 21 m from the beam source. BL13HB features a double-multilayer monochromator designed with two sets of multilayers fitted for different X-ray energy ranges. Excessive thermal load causes crystal deformation, which can lead to loss of photon flux and beam size reduction. To maintain stable operation, a gravity water cooling system is employed in the double multilayer monochromator to minimize vibration disturbance. The schematic design of the DMM at Beamline BL13HB is shown in Fig 3 [Figure 3: see original paper].

Ru/C and W/Si multilayer structures were selected for their smooth surfaces and stability. Ru/C and W/Si multilayer strips were deposited side by side on the Si crystal substrate along the incident X-ray beam direction. The second Si crystal mirror can be moved in the Y-axis direction to switch the energy range. To achieve higher X-ray photon flux, the Ru/C multilayer is used for 8–20 keV and the W/Si multilayer for 20–40 keV, as the Ru/C multilayer shows higher reflectivity in the lower energy range while the W/Si multilayer shows higher reflectivity in the higher energy range. The first Si crystal mirror can be removed from the beam path to switch to white-beam mode, enabling high-temporal-resolution X-ray imaging. The height difference between the white and monochromatic beam is 12.5 mm, corresponding to the height difference between the two crystals of the DMM. The parameters of the double multilayer monochromator of BL13HB, chosen based on simulation results with XOP software to optimize beam performance, are listed in Table 2 .

Filters and Be Windows. The total power generated by the BL13HB source is approximately 172 W, which is too high for a water-cooled DMM. Therefore, filters must be installed to absorb low-energy X-ray photons and reduce the beamline thermal load to improve beamline optics performance. Two sets of filters are installed in the BL13HB optical hutch. The first set of glassy carbon SIGRADUR filters reduces the heat load on the downstream Be window and the double multilayer monochromator in the optical hutch. Glassy carbon was chosen for its high purity, isotropy, high-temperature resistance, and high surface quality. BL13HB offers a white beam mode that eliminates low-range energy X-rays during white beam imaging experiments; therefore, a second set of aluminum filters is installed to absorb lower energy X-rays in high X-ray energy mode. Different combinations of Al filters can be used for different energy ranges. Both sides of all filters are polished to maintain good spatial coherence of the beamline.

Be windows with high thermal conductivity are used to preserve the vacuum environment of the storage ring and prevent contamination from the first set of glassy carbon filters to the downstream double-multilayer monochromator. Two sets of self-developed water-cooled Be windows are installed: one at the entrance of the optical hutch (19.7 m in front of the DMM) to isolate the storage ring vacuum chamber, and the other at the end of the optical hutch (27.4 m from the light source) to isolate the beamline optics from the surrounding atmosphere.

Slits and Fluorescent Screen. Two high-purity tantalum (99.98%) slit systems are installed in the BL13HB beamline optics: one before the DMM and one after. The white beam slit is located 18 m from the light source, restricting the beam divergence angle and absorbing surplus thermal load. It reduces the angle from 2.0$×0.3*mrad*^{2}$ to 1.6$×0.3*mrad*^{2}$. The beam angle decreases as energy increases; therefore, the vertical slit size of the white beam is restricted by the X-ray energy. The second slit system is located after the DMM, 24.8 m from the light source, controlling the beam size of incident X-rays into the experimental hutch. A water-cooled fluorescent screen is positioned 23.5 m from the light source, comprising a fluorescent target, lenses, and a CCD camera. It enables real-time remote observation of beam size and position for beam alignment testing. The fluorescent screen is controlled by a driving device and can be moved in and out of the beam path.

C. Experimental Hutch

Attenuating filters, an ionization chamber, and a shutter are placed on a platform at the front end of the experimental hutch. The attenuating filters comprise several Al filters of different thicknesses (1–10 mm). By applying different combinations of these Al filters, attenuation of the X-ray beam can be achieved to meet diverse photon flux requirements. The ionization chamber monitors X-ray intensities in the experimental hutch, and the shutter is used during white beam mode experiments and other high-time-resolution experiments to limit exposure time and reduce thermal load on sensitive samples and X-ray detectors. An overview of the BL13HB experimental hutch is shown in Fig 4 [Figure 4: see original paper].

X-ray Imaging Detectors. BL13HB is equipped with several sets of X-ray detectors designed for different X-ray imaging experiments, which will be discussed in the next section. The detailed models and specifications are listed in Table 3 . For fast X-ray imaging measurements, a PCO.dimax HS4 camera coupled with an Optique Peter White Beam microscope is used. The microscope system has three sets of lenses at different magnifications (2×, 5×, and 10×). Its numerical apertures are 0.15, 0.3, and 0.4, which are twice those of commercial lenses, and its coupling efficiency is four times that of commercial lenses. This system is suitable for fast dynamic micro-CT measurements with a frame rate up to 2277 fps. Different sample-detector distances can be obtained by moving the detectors. BL13HB is also equipped with two flat-panel detectors, Perkin Elmer 1621N and Mar345, for X-ray diffraction and pair distribution function measurements. Table 3 lists all current X-ray detector models and apparatus parameters of BL13HB.

Sample Stages. The high-precision sample stages of BL13HB, controlled by computer, comprise one set of Kohzu 5-axis sample stage and two sets of 7-axis sample stages with a maximum rotation speed of 20°/s. The 5-axis sample stage is designed specifically for in situ CT experiments and has a maximum load capacity of 20 kg. In situ equipment such as tensile and heating devices can be easily fitted to the adaptor on top. The 7-axis sample stages are mainly used for high spatial resolution CT imaging experiments and can bear a 3.7-kg load. A 6-axis UR robot is installed to speed up the sample changing process, specially added to meet large-batch sample measurement requirements. All sample stages are placed on stable test platforms to isolate vibration disturbances, with numerous M6 screw holes in the platform for additional guide rail and equipment installation. The sample stages are shown in Fig 6 [Figure 6: see original paper].

D. Control and Data-Acquisition System

Using a graphical user interface, BL13HB users can easily adjust X-ray energy, slit sizes, and sample positions to acquire desired experimental settings. Moreover, the working status of beamline optics, such as DMM positions, angles, and vacuum readings, are stored and displayed in real time. The data acquisition system at BL13HB was developed for CT and other X-ray imaging experiments, combining control of sample stages, detectors, shutters, and Al filters with a user-friendly graphical interface. For example, CT experimental settings such as projection number, flat number, and exposure time can be easily set, and real-time images can be reviewed during measurements. Data processing of BL13HB imaging measurements primarily includes CT image reconstruction. The PITRE software, developed by BL13HB staff, is provided at the beamline for CT slice data processing. Other 3D visualization software such as Amira and VG Studio is installed at the beamline user office.

III. Typical Experimental Methods and Applications of BL13HB

This section introduces notable method developments and user publications based on the X-ray imaging methodology and experimental setup of BL13HB.

A. Micro-CT

Laboratory-based X-ray micro-CT is often used to image samples in static states. The principle of micro-CT is simple: by recording projections of rotating samples and reconstructing them, three-dimensional (3D) structure visualization is realized. Although commercial products can perform micro-CT experiments, synchrotron radiation provides a coherent high-flux X-ray source that enables high-resolution and fast micro-CT experiments. With the addition of white beam mode to BL13HB and the high-speed frame rate of the camera systems, fast micro-CT experiments are also available.

B. Dynamic Micro-CT

Dynamic micro-CT is a powerful tool for investigating real-time dynamic behavior of materials at the microscale because it offers both 3D spatial and temporal resolutions in a nondestructive manner. It can reconstruct three-dimensional images from 2D radiographs and segment 3D images for visualization and quantification analysis. Dynamic micro-CT via synchrotron X-ray source has been widely applied across science and engineering disciplines. On BL13HB, a dynamic micro-CT system is set up with X-ray imaging detectors with pixel sizes ranging from 0.61 m to 3.1 m. With high-flux white beam X-rays, achieved by removing the monochromator crystal from the beam path, a typical dynamic micro-CT can achieve a temporal resolution of 5 Hz, compared to 2 Hz for the previous BL13W1. Coupled with the in situ sample stages of BL13HB, the dynamic micro-CT method has been applied to investigate in situ processes such as dendrite morphology of alloys [19], liquid water transport in microporous layers [20], liquid structure transition [21], and structural gaps between pellets in artificial dissolution media [22].

C. Pair Distribution Function

The pair distribution function (PDF) has been widely used for the last 20 years, although the technique's origins can be traced back to the 1910s when the Debye scattering equation was proposed [23]. Recently, this technique has been applied in various research areas [24]. The high energy and high flux beams of synchrotron radiation X-rays enable a high reciprocal area (Qmax\$ $20^{\{-1\}) and high spatial resolution. By applying both Bragg and diffuse scattering signals, PDF becomes a powerful tool for detecti}$ 1}\$ in BL13HB. Equipped with flat-panel detectors such as Perkin Elmer 1621N and Mar345, BL13HB is suitable for X-ray PDF experiments on disordered systems such as glass and liquid, and nanosystems such as bulk amorphous carbon [25].

IV. Beamline Characteristic Testing Results for BL13HB

This section discusses the BL13HB beamline characteristic testing results, with detailed results listed in Table 4 .

Energy Range. Co, Mo, and CeO_2 near-edge absorption measurements were performed to verify that BL13HB met the designed energy range of 8–40 keV and to calibrate the X-ray energy. Two ionization chambers were placed at the front end of the experimental hutch with standard samples positioned between them. With DMM switched to Ru/C mode, Fig 7 [Figure 7: see original paper] shows the absorption curves of Co and Mo at the tested energy points. The theoretical K-edge energies for Co and Mo are 7.709 and 19.995 keV, respectively. DMM was then switched to W/Si mode, and Fig 8 [Figure 8: see original paper] shows the absorption curves of Mo and CeO_2. The theoretical K-edge energies for Mo and Ce are 19.995 and 40.443 keV, respectively. The measured energy range of BL13HB is 7.7–40.4 keV, demonstrating that the energy range exceeds the designed specification of 8–40 keV.

Beam Size. For X-ray imaging applications, a large beam size is critical for applications in biomedicine, materials science, and paleontology. The beam size of BL13HB is determined by the DMM length and X-ray energy. In the same DMM mode, the vertical size of the X-ray beam decreases as energy increases. With X-ray energy set to 20 keV under Ru/C DMM mode, an X-ray CCD camera with 13-µm pixel size recorded the beam images. The vertical and horizontal profiles are shown in Figs 9(a) and 9(b), respectively. By calculation, the beam size at 15 keV energy is 48.5 mm × 5.2 mm, as shown in Fig 9 [Figure 9: see original paper].

Energy Resolution. Energy resolution was measured using a Si(111) analytical crystal. With DMM switched to W/Si mode and X-ray energy set to 20 keV, the rocking curve obtained at 20 keV is shown in Fig 10 [Figure 10: see original paper]. Using the relation $\Delta E/E \quad \Delta \quad \times \cot$, where Δ is the FWHM of the rocking curve and   is the Bragg angle, the energy resolution at 20 keV was calculated to be 2.3%, meeting the designed specification of 3%.

Photon Flux Density. To measure the photon flux density of BL13HB, an ionization chamber was placed at the entrance of the experimental hutch to record current intensity, and a Hamamatsu X-ray imaging detector recorded the beam size. Using the equation I_0 = (photon flux) × ($_0$/ E), the photons at each energy point were calculated, where I_0 is the ionization chamber current, $_0$ is the average ionization energy for air,   is the ionization chamber efficiency, and E is the X-ray energy. Fig 11 [Figure 11: see original paper] shows the photon density distribution of BL13HB at a storage ring current of 300 mA. By integrating over the full range of 8–40 keV, the white beam photon flux density was calculated to be 2.7$×10^{13}$ phs/s/mm^2.

Spatial Resolution. To test the spatial resolution capability of BL13HB, the JIMA RT RC-02B X-ray resolution test pattern was used. Energy was set to 15 keV in Ru/C mode, ideal for the tungsten filaments in the test pattern. A Hamamatsu X-ray detector with 0.325-µm pixel size recorded the projection image of the test pattern with an exposure time of 200 ms. The test result is shown in Fig 12 [Figure 12: see original paper], where the 0.8-µm target line can be clearly distinguished.

Dynamic Micro-CT Tests. Dynamic micro-CT in white beam mode was performed to investigate the expansion process of foaming glue. Foaming materials were injected and mixed in a thin plastic tube placed on a high-speed rotating sample stage, where they instantly and freely expanded. The data acquisition speed of the white-beam X-ray imaging detector was set to 2000 fps, and the rotational speed of the sample stage was 900°/s. A complete set of CT data was acquired every 200 ms, with a total of 8800 projections obtained during the measurement, including 22 complete CT datasets. The processed 3D images of the evolved expansion process are shown in Figs 13(a) and 13(b), clearly displaying bubble evolution. The 2D projection pictures show that the temporal resolution is 0.5 ms, as shown in Fig 13 [Figure 13: see original paper].

Pair Distribution Function. A typical PDF experimental setup is shown in Fig 14 [Figure 14: see original paper], comprising an adjustable beam slit, lead panel, sample stage, and Perkin Elmer XRD 1621 detector. Beam slits and lead panels block ambient scattered X-ray beams. The beam slit can be adjusted automatically or manually for collimation. Pure CeO_2 and Si powders are normally used to calibrate sample-to-detector distances. PDF results for commercially purchased CeO_2 indicated that the Q value for PDF experiments in BL13HB reached 20 $Å^{-1}$, as shown in Fig 15 [Figure 15: see original paper].

V. Applications

This section presents typical experimental and published results for BL13HB users from various research areas.

Environmental Science. Air-dried soil aggregates were placed in a plastic tube on a rotation sample stage for micro-CT measurements to study soil structures. X-ray scanning energy was set to 30 keV. A micro-CT experiment was performed using a Hamamatsu X-ray detector with 3.25-µm pixel size, with a projection field of view of 2048 × 2048 pixels. A complete CT dataset with 900 projections was obtained, and slice reconstruction was performed using PITRE software provided at the beamline. Fig 16 [Figure 16: see original paper] shows pore structures at the aggregate scale. Some cracks and larger pores were observed within aggregates collected from 0–10 cm topsoil depth (Fig 16a). Aggregates from 10–20 cm depth exhibited completely different pore morphologies, with numerous small pores but no larger pores observed (Fig 16b) [26].

Material Science. The *Strombus gigas* shell is a lightweight, high-strength, high-toughness biocomposite. In-depth exploration of its internal microstructural characteristics and corresponding strengthening and toughening mechanisms is significant for designing high-performance composite materials. In situ tensile loading experiments based on CT phase-contrast imaging were conducted with X-ray energy set at 18 keV and X-ray CCD camera resolution of 0.33 m/pixel. As shown in Fig. 17d [Figure 17: see original paper], the upper part of the loading device was a loading platform enabling high-precision loading. During in situ X-ray CT measurements, the sample was loaded in 0.5- m steps. CT datasets were collected when loading displacement reached 5 m or when cracks appeared in projection images. This process was repeated until sample fracture. Projection images were collected continuously by the CCD camera with 1-s exposure time and image acquisition frequency of 1 frame/0.5 s. Internal 3D cracks in the *S. gigas* shell at a certain loading state are shown in Fig. 13e [Figure 17: see original paper] [27].

Biology. Contrast agents are typically used to improve image contrast for in vivo X-ray imaging of vessels and angiomatous tissue. For traditional X-ray imaging methods, high-quality images of microvessels in vivo are challenging due to intermittent flows, short circulation times of contrast agents, and nonrigid motions of adjacent tissues. Live mice were used as animal models to verify the proposed moving contrast X-ray imaging method (MCXI). During MCXI measurements, 180 L of iodine was injected into internal carotid arteries at 133.3 L/s. A PCO X-ray CCD camera was placed approximately 65 cm from the objects, with recording sequence set to 100 frames/s and exposure time of 10 ms per frame. Using reconstructed images of the dynamic signal from the entire perfusion process, MCXI can achieve complete imaging of contrast agent trajectories in blood vessels. Figure 18 [Figure 18: see original paper] shows experimental results of intact vasculature imaging using MCXI, including (a) entire vasculature, (b) arteries, (c) capillary images with insufficient resolution, and (d) veins. The results demonstrate successful separate imaging of arterial and venous vascular systems in vivo, eliminating mutual interference between different microvascular systems [28].

Pharmaceuticals. Defining and visualizing the three-dimensional (3D) structures of pharmaceuticals is extremely important for illustrating the behavior and underlying mechanisms of drug delivery systems. The mechanism of drug release from complex-structured dosage forms has not been investigated for most solid 3D structures. CT images of osmotic pump tablets were acquired at 18 keV X-ray energy. The detailed in situ structures of bilayer osmotic tablets are shown in Fig 19 [Figure 19: see original paper]. NaCl crystals were observed in the push layer, creating osmotic pressure and facilitating water absorption. Two types of coating layers were identified: an inner semipermeable membrane and an outer dense protective layer. The three-dimensional microstructures of the tablets were revealed by X-ray micro-CT imaging and could be utilized for further analysis [29].

Nanoparticles. Fe_3O_4 magnetite nanoparticles of different sizes were investigated using the pair distribution function method at BL13HB. Measurements were obtained for 8-nm nanoparticles at ambient pressure with X-ray energy of 40.433 keV. After Fourier transformation of the total scattering data, the PDF in real space was obtained. The measured PDF for the 8-nm sample was compared to the calculated PDF for ordered normal spinel in Fig 20 [Figure 20: see original paper]. The PDF calculated using the disordered spinel model showed the best agreement with the experimental PDF, supporting the bond length of a general spinel structure but with a disordered spinel structure rather than an ordered normal spinel structure [30].

V. Summary

After ten years of user operation, biomedical and materials science applications on the BL13W1 beamline have demonstrated remarkable achievements, serving research fields including pharmaceuticals, environmental science, materials science, and industrial applications. BL13W1 has been replaced and upgraded by the new beamline BL13HB as part of the SSRF Phase II construction. A bending magnet with a 2.293-T light source and double multilayer monochromator were implemented in BL13HB to achieve high photon flux density. The new beamline provides both white and monochromatic X-ray beams. With an energy range of 8–40 keV and new features including upgraded X-ray detector systems and sample stages, BL13HB can meet most BL13W1 user demands. The new beamline achieves higher temporal and spatial resolutions: for fast dynamic CT measurements, the CT frequency can reach 5 Hz and the 2D time resolution is 0.5 ms.

The new X-ray imaging and biomedical applications beamline at SSRF is a powerful platform for research in materials science, biomedical science, paleontology, and industrial applications. With these new features, BL13HB is equipped with different detector sets for experiments such as micro-CT, in situ dynamic micro-CT, and PDF methods, and is now open to users.

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