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6 MeV storage ring dedicated to hard X-ray imaging and far-infrared spectroscopy

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Abstract. The tabletop storage ring, 6 MeV MIRRORCLE, is dedicated to hard X-ray imaging as well as far-infrared (FIR) spectroscopy. In spite of low electron energy, the 6 MeV MIRRORCLE generates hard X-rays ranging from 10 keV up to its electron energy and milliwatt order sub-millimetre range FIR rays. Bremsstrahlung is the mechanism for the hard X-ray generation. Images produced with 11× geometrical magnification display a sharply enhanced edge effect when generated using a 25 mm rod electron target. Bright far-infrared is generated in the same way using a conventional synchrotron light source, but with MIRRORCLE the spectral flux is found to be ∼1000 times greater than that of a standard thermal source. Partially coherent enhancement is observed in the case of FIR output.

Keywords. Low-energy storage ring; X-ray imaging; far-infrared spectroscopy; coherence enhancement.

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1. Introduction

A synchrotron radiation source is known for its fine spatial resolution and phase-contrast imaging as well as for its highly brilliant infrared spectroscopy [1–4]. A far-IR laser by a tabletop synchrotron was proposed by Yamada in 1989 [5]. This tabletop synchrotron has laid the foundation for the low energy storage rings ‘MIRRORCLE’ [6,7], which are now the world’s smallest storage rings. The MIRRORCLEs are unique owing to the following properties: an electron energy lower than 20 MeV, a storage-ring orbit radius as small as 8 cm (for the 1 and 4 MeV types) and 15 cm (for the 6 and 20 MeV types), a stored ampere-order beam current circulating in a full circular electron orbit of radius 15 cm and compact magnet yoke diameters of 35 cm (for the 1 and 4 MeV types), 60 cm (for the 6 MeV type) and 80 cm (for the 20 MeV type). In spite of low electron energy, the MIRRORCLE generates hard X-rays ranging from 10 keV up to its electron energy, milliwatt order and sub-millimetre range far-infrared (FIR) rays and 0.1 W order extreme ultraviolet (EUV) and soft X-rays.

A target in the circulating electrons produces X-rays by the method of bremsstrahlung. The X-ray spectral distribution in the low-energy region can be tuned by changing the material and the thickness of the target. It is demonstrated that 6 MeV MIRRORCLE provides tremendous improvement in medical imaging capability. It is inherently suitable for hard X-ray imaging because of its magnified projection X-ray imaging, micrometre-size X-ray source point, wide radiation emission angle, X-ray spectrum ranging from 10 keV to 6 MeV, natural refraction contrast imaging and high flux output. We have already observed 11× magnified images with millimetre size targets. Our next goal will be 100× to 1000× magnification with a sub-micrometre target.

Bright far-infrared is generated in the same way as by a conventional synchrotron light source, but with MIRRORCLE the spectral flux is found to be ∼1000 times greater than that of a standard thermal source. A circular mirror around the electron orbit collects and accumulates infrared synchrotron radiation. For this reason it is also known as photon storage ring (PhSR) [5]. MIRRORCLE FIR beamline is equipped with a Michelson-type FTIR for covering a spectral range of 10–7800 cm^{-1}. Due to a large beam current, PhSR-mirror system, a large dynamic aperture and small ring energy, it can deliver a bright flux of photons in the FIR/THz region.

2. Experimental results and discussion

2.1 *Medical diagnosis*

We have observed magnified X-ray imaging of a 25 cm thick human chest phantom, consisting of a human lung, ribs and a number of knots imitating a tumour made of urethane of diameter 8 mm. The target was a 25 mm diameter, 0.5 mm thick Cu rod placed in the beam direction. Figure 1 indicates a simple experimental set-up of this observation. The source point, specimen and imaging device are aligned. The distances between the X-ray source point and the sample (L1) and the sample and the imaging device (L2) are adjustable from 0.25 m to 5 m (room size limit). The magnification can easily be changed by changing the ratio L1/L2 from 1 to 12. The imaging plate (Fuji Film, model FCR-XG1) has a pixel size of 150 mm.

Figure 2a represents the contacted image, figure 2b the 5× magnified image and figure 2c the 11× magnified image. The X-ray source–specimen distance L1 was set at 0.45 m for the 11× magnification. The knots, ribs and a number of vessels are clearly seen. The characteristics of a refraction contrast image are clearly shown at the bone and tumour edges. Vessels are soft tissues but are visible because of the phase contrast. In a conventional X-ray tube for medical use, it is impossible to distinguish the tumour in the precise shape. An 11× magnification is impossible using a conventional X-ray tube because of increased penumbral blur caused by the millimetre-order target. A millimetre-size tumour should be clearly visible because the 8 mm knots in figures 2b and 2c are identifiable by their shape. Magnified imaging has been previously available only for small and thin objects [8,9], but the magnified imaging of large objects, e.g. humans,

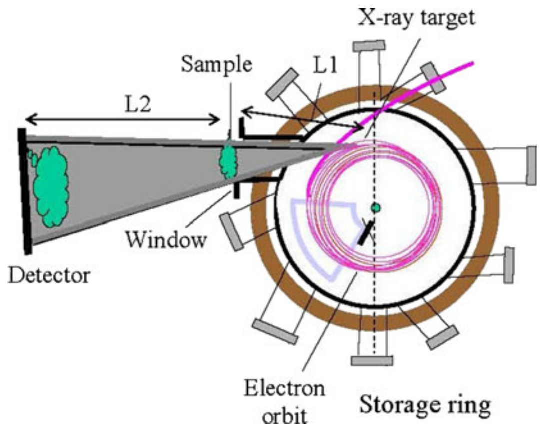

Figure 1. Experimental arrangement for the magnified X-ray imaging. The magnification rate is determined by L1 (the distance between the X-ray source and the sample) and L2 (the distance between the specimen and the detector).

has become practical with MIRRORCLE. Magnified phase contrast is the key to this fine imaging.

2.2 *Absolute photon flux*

We obtained the absolute spectral photon flux of MIRRORCLE using a reference photon source. The reference source was a 1500 K black-body internal source of FTIR. The measured photon flux of MIRRORCLE was almost 1000 times higher than that of the thermal source at the FIR/THz region (figure 3). The photon flux measured in the present work was also compared with that of other FIR beamlines at different SR sources, and it was observed that the photon flux of MIRRORCLE in the THz region is comparable with

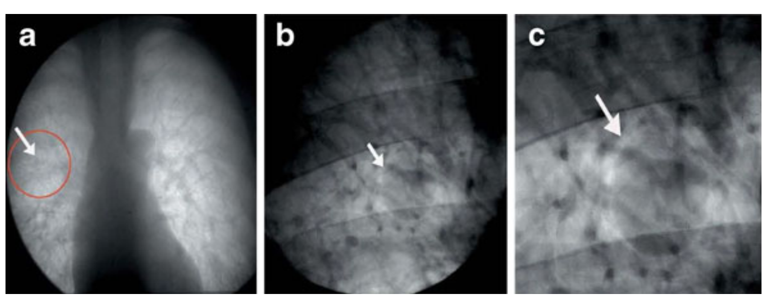

Figure 2. Medical diagnosis of a chest phantom recorded using MIRRORCLE-6X: (**a**) contacted X-ray image, (**b**) 5× magnified X-ray image and (**c**) 11× magnified X-ray image.

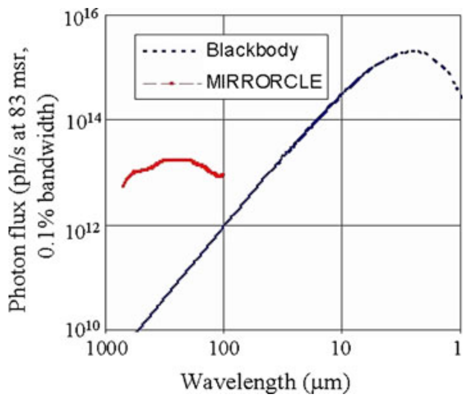

Figure 3. Spectral photon flux from MIRRORCLE and a typical thermal source (a black-body at 1500 K). The synchrotron radiation provides a much higher flux than that of the thermal source in the FIR/THz region.

that of UVSOR-II [10] and NSLS [11] sources. We conclude that this is due to the wide acceptance angle and the high beam current of MIRRORCLE.

2.3 *PhSR FIR output*

The FIR intensity was measured using a cooled Si bolometer with and without PhSR. FIR intensity measured without the PhSR was simply linear with I, where I is the injector beam current, but for the case with PhSR it was proportional to $I^{1.8}$ (figure 4). This super-linearity indicates the highly coherent nature of the PhSR FIR radiation. There are two reasons for this partially coherent phenomenon. First, due to circular mirror, interference effects of stored SR photons and the electron beam should appear. Secondly, due to very

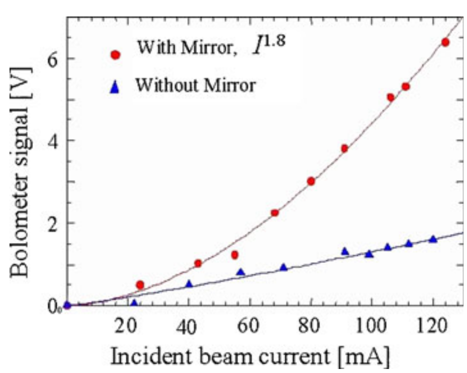

Figure 4. Beam current I dependence of FIR intensity. The dependence is $I^{1.8}$ with the PhSR circular mirror indicating highly coherent nature of PhSR FIR radiation.

small (∼0.2%) energy spread of the injector microtron, the individual bunch radial width is less than 1 mm in both vertical and horizontal directions. So, radial size less than 1 mm may generate partial space coherence.

3. Conclusions

It is demonstrated that 6 MeV MIRRORCLE provides tremendous improvement in medical imaging capability. It is inherently suitable for hard X-ray imaging owing to its magnified projection X-ray imaging, micrometre-size X-ray source point, wide radiation emission angle, X-ray spectrum ranging from 10 keV to 6 MeV, natural refraction contrast imaging and high flux output. We have already observed 11× magnified images with 1 mm size targets. Our next goal will be 100× to 1000× magnification with a submicrometre target. On the other hand, due to a large beam current, PhSR-mirror system, a large dynamic aperture and small ring energy, it can deliver a bright flux of photons in the FIR/THz region. We believe that, due to these entire novel features MIRRORCLE will provide us with a new opportunity to perform various kinds of experiments useful for broadband reflection and far-infrared spectroscopy.

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