# HIGH RESOLUTION X-RAY IMAGING BY PORTABLE SYNCHROTRON RADIATION SOURCE "MIRRORCLE-6X"

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**Abstract:** MIRRORCLE-6X is a portable synchrotron composed of a 6-MeV microtron injector, and a 60cm outer diameter exactly circular synchrotron ring made of a normal conducting magnet. The injection is performed at 400 Hz repetitions by 100 mA injector peaks current, which lead to 3A accumulated peak current. X-rays are generated by a collision of the relativistic electron beam and a small target placed inside the beam. The generated X-ray flux is comparable to that of 8-Gev synchrotron light source. The few μmϕ cross-section target placed in the central orbit defines the X-ray emitter size and the extremely fine resolution of the edge enhanced image. The image field is 30 cm wide at 4m distances from the source point. Since this X-ray flux is dominated by high-energy components, ranging from 30keV to 6 MeV, this machine provides highest quality non-destructive testing of heavy constructions. Due to the phase contrast effect, however, this machine also enables imaging of soft tissues. Therefore, MIRRORCLE-6X opens up new frontiers of X-ray imaging in medical and industrial fields.

**Introduction:** Since brilliant X-ray beam has been realized by the synchrotron radiation (SR) sources, it turned out to be a major tool at the frontier of material and life sciences. Synchrotron radiation has led to many innovations in these fields. The construction of huge facilities such as SPring-8 [1] was the trend in the 20th century. Its industrial and medical applications are, however, quite limited by its size of 10 to 100 m width or 100 to 1000 m circumference, and also by its cost of 15 MUS$ for the smallest one. To generate 100 keV hard X-rays it requires at least 100 MUS$ and a few GeV synchrotron. Recently, big efforts are made on down sizing the light source. Scientists expect that powerful portable X-ray source will change the paradigm of X-ray business and open up totally new research fields that were impossible before.

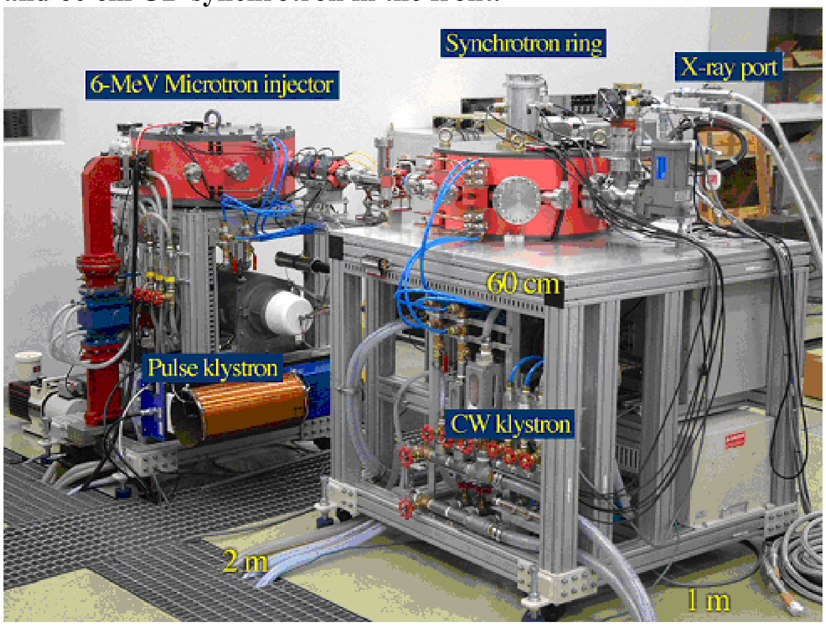
Many progresses on the laser-plasma [2] and laser-Compton X-ray sources [3] have been made. A unique approach given by Yamada [4-9] at Ritsumeikan University is the portable synchrotrons named MIRRORCLE. Electron energy as low as 6-MeV and electron orbit diameter as small as 15cm are achieved using normal conducting magnet. X-rays are generated by the small peace of target placed inside the electron orbit. The quality of the generated X-ray beam by this machine, using novel method, exceeds that of GeV synchrotrons in many regards. The X-ray source spot size is the order of micrometer that is much smaller than 20μm of the largest SR source, the covered X-ray energy range is from few keV to 6 MeV that is much wider than 1keV to 1MeV of the largest SR, the radiation angle of 85 mrad is much wider compared to 0.1 mrad of SR, and the total X-ray flux of $10^9$ photons/s, 0.1% band is larger than $10^8$ of SR sources, although the brilliance of $10^{11}$ (=photons/s, mrad2, mm2, 0.1% band) is lower than $10^{15}$ of SR sources. Magnified images have been obtained up to 10 times without distortion because of the extremely small emitter size. When we discuss the degree of coherence, the size of the emitter spot is the most important factor. MIRRORCLE gives one order higher degree of coherence compared to SR sources.

This machine provides excellent X-ray imaging, as well as highest quality non-destructive testing and novel medical diagnostics. Hard X-ray microscope is realized at up to 10 times magnification.

In this paper, we describe the properties of the 6 MeV version of MIRRORCLE, namely MIRRORCLE-6X that is the most recently developed smallest synchrotron in collaboration with Photon Production Lab. Ltd. [8]

**Results:** Yamada proposed novel x-ray source based on a low energy tabletop synchrotron [10] and demonstrated its brilliant x-ray production by using MIRRORCLE-20 [6, 7], which is a 20 MeV synchrotron having 15 cm orbit radius, and 1.2 m outer diameter (OD) magnet. Photon Production Lab. Ltd. commercialised this novel source and developed even smaller synchrotron MIRRORCLE-6X [9], which is the 6 MeV version, containing 60 cm OD magnet as shown in Fig. 1.

**Fig. 1 An overview of MIRRORCLE-6X, which is composed of the 6-MeV microtron injector in the back and 60 cm OD synchrotron in the front.**

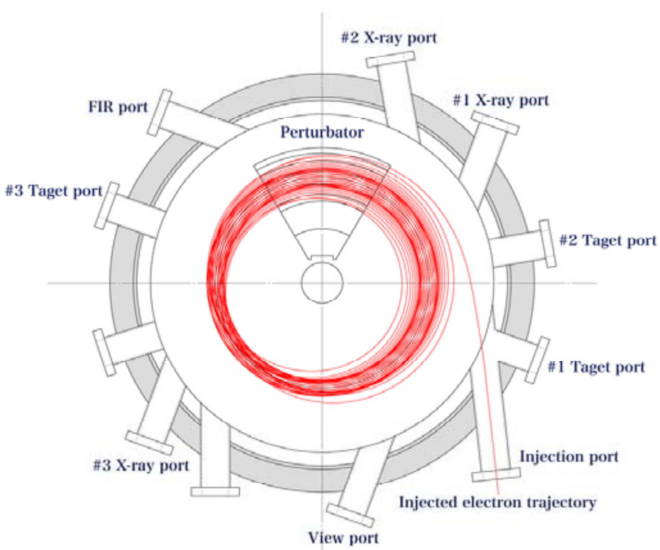



MIRRORCLE-6X specifications are listed in Table 1. The 6-MeV microtron is of the type, which has a $LaB_6$ electron emitter inside the single cell-accelerating cavity. The electrons are extracted directory by the RF field. Because of this scheme, we are able to apply strong magnetic field, by the small, 60 cm outer diameter magnet. The RF source is a powerful pulse klystron that utilizes multi-beam with 30 kV low anode voltages. The output power is 5 MW at peak, 5 kW on average, with 45 % efficiency, and 80×30 cm compact body. The operating frequency is 2.45 GHz. The synchrotron is made of one peace of cylindrical normal conducting magnet with 60 cm OD. The 1/2-integer resonance injection [11,12] is selected to provide stronger vertical focusing power compared to the 2/3-integer resonance used for MIRRORCLE-20 [4,5], which is suitable for minimizing the energy dispersion. To introduce the 1/2-integer resonance injection scheme the horizontal n-value of the magnet field is set at 0.72 over 50 mm in radial direction around the central orbit. The expected beam size is less than mm in vertical, and 10 mm in horizontal. The perturbator triggering the 1/2-integer resonance, is one-turn air core magnet, which produces ±0.42 T× mm magnetic field at ±30 mm from the central orbit.

**Table 1. Specifications of MIRRORCLE-6X. The resent results are shown in red.**

| | Storage Ring type、Electron E=6MeV<br>Injector=100mA、Repetition=400Hz |
|---|---|
| Radiation schme | Collision with target nucleus |
| Radiation Angle | 85mrad |
| Spectrum | White 1keV～6MeV |
| Time structure | Pulse width 100ns～10ms<br>Repetition:2.45GHz Current:50A/pulse |
| Intensity | 0.4(0.006)Gy／PULSE（200ns） |
| Imaging time | 1(100)pulse（200ns(250ms)）／flame(576cm$^2$) |
| Average Power | 160(2.4)Gy/s |
| Brilliance | 2.5E+13(11) 光子/s/mrad$^2$/mm$^2$/0.1% λ at 30keV |
| Total Photons | 5.5E+11(9)photons/s/0.1% λ at 30keV |

**Fig. 2. Schematic configuration of MIRRORCLE-6X, and its simulated beam trajectory. MIRRORCLE-6X has 3 X-ray ports.**

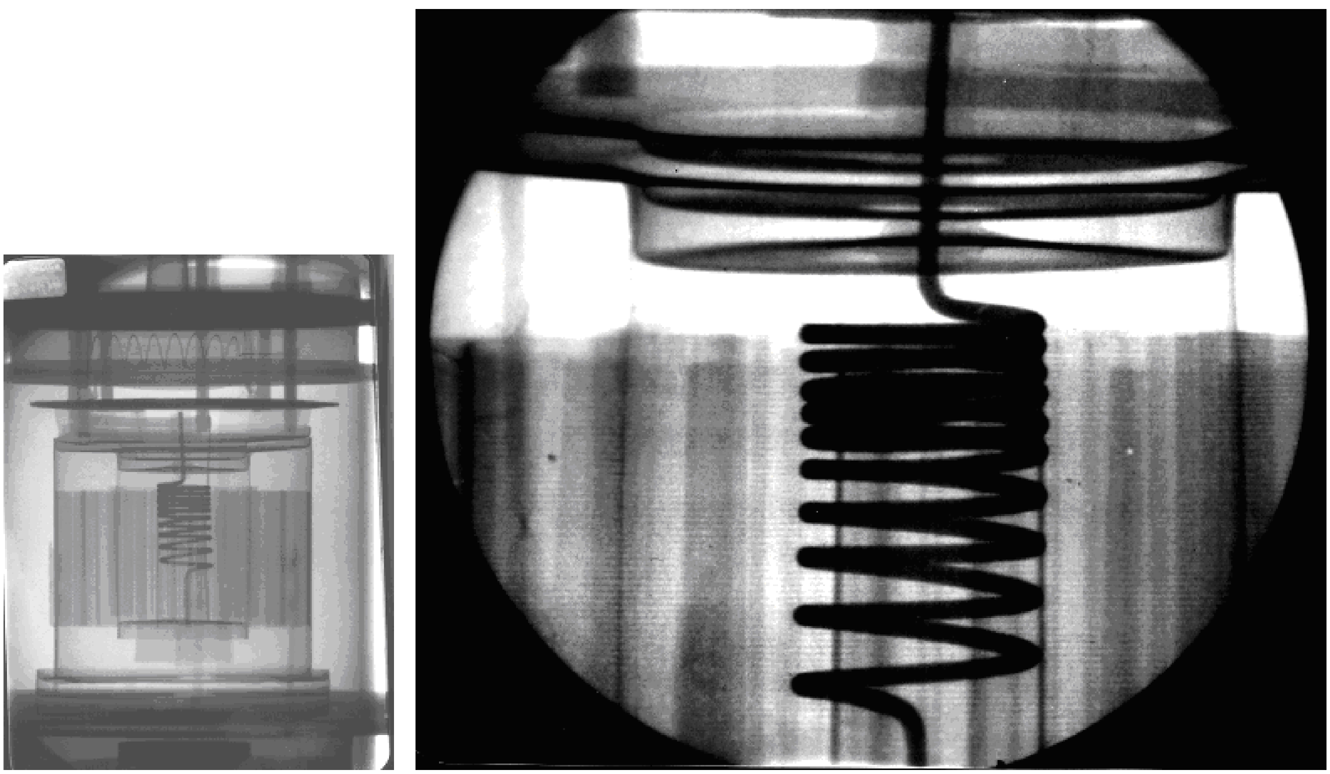



MIRORCLE-6X accommodates 3 x-ray beam ports as seen in Fig. 2. The beam trajectory is illustrated in red colour. Each port is assigned to X-ray crystallography, X-ray microscope, X-ray fluorescent analysis, and X-ray imaging. The X-ray microscope and X-ray crystallography beam line is equipped with a focusing element made of multi-layered set of 8, concentrically aligned, cylindrical mirrors.

In Table 1 are listed the specifications of MIRRORCLE-6X X-ray beam. We measured the integrated DOSE by calibrated ion chamber. The brilliance and the total flux are the theoretical values, and they are consistent with measurements made by NaI scintillator with correction of the lifetime. We keep the injection continuously at 400Hz with 100mA injector peak current. Our injection scheme enables injection without disturbing the circulating beam. We can increase the X-ray intensity, as much as user requests, by increasing the beam injector current and the repetition. So far, heating up of the target is not observed at this beam current. We assume that the target is thin enough, for the primarily and secondary electrons and the generated soft X-rays, to escape from the target as predicted by Yamada [10]. The radiation angle, which is defined by the kinematics, of electron and target atom, is 85 mrad.

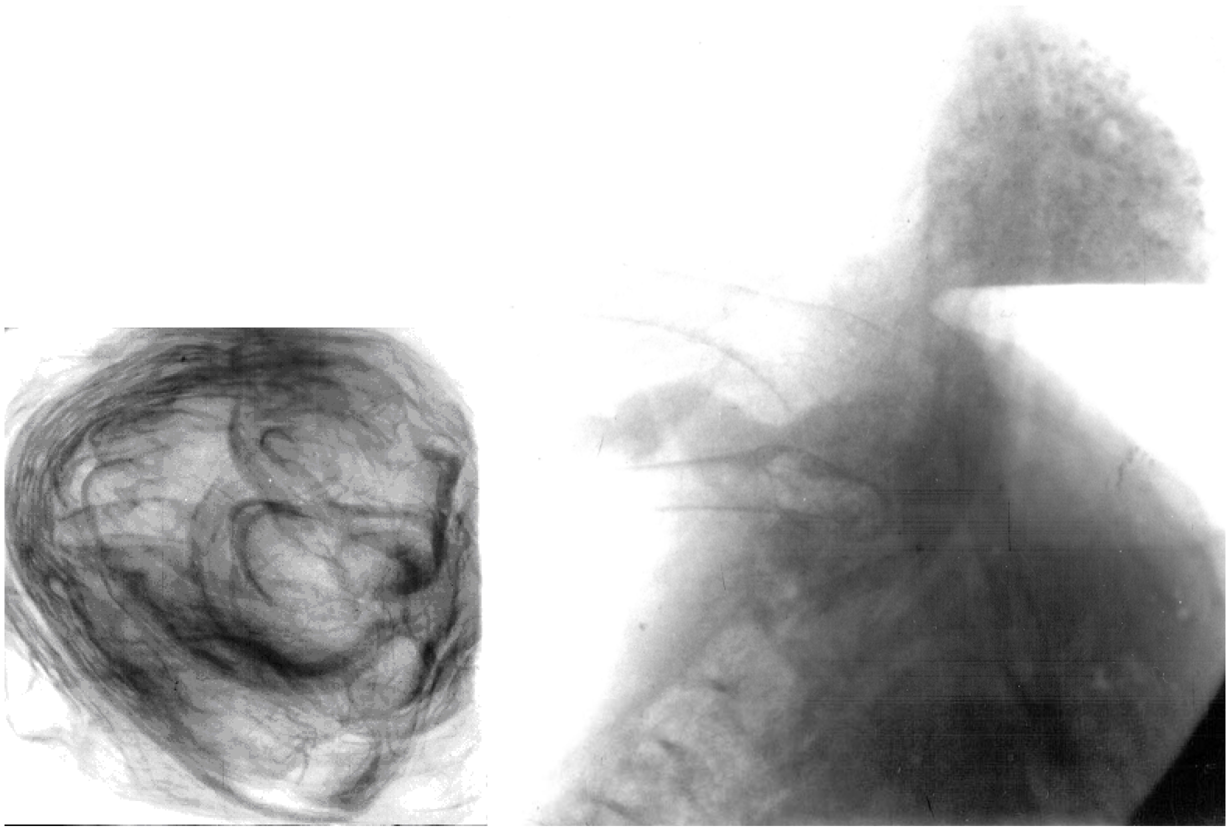
The X-ray image obtained by MIRRORCLE-6X represents the most extraordinary features of this machine. The image of the 20 cm long vacuum tube (made of 5mm thick ceramics tube and 3 mm thick metal flame) is obtained in 0.3 sec at 2 m distance from the source point as shown in Fig. 3(a). Fuji super HRS-30 medical film together with image intensifier screen HR-8 is used in this case. Fig. 3(b) is 4.4 times magnified picture obtained by placing the imaging device 4.4 times further from the source point, in regards to the sample. These demonstrate that the total X-ray flux is stronger than that of SR, since SR image is obtained in 0.1 seconds for only a few cm wide samples. The X-ray beam is dominated by the hard components higher than 30keV. The spatial resolution is of the order of micron, as seen from the spacing of 0.1mmϕ filaments of this picture. The X-ray beam is uniformly spread over 85 mrad angles. The quality of the picture is similar to the image obtained by SR, but the field is much wider.

**Fig. 3. Non-destructive testing of 20 cm long cylatron vacuum tube performed utilizing MIRRORCLE-6X. (a) contact image, and (b) 4.4 times magnified image obtained by placing the imaging device far from the sample.**



Another extraordinary image is shown in Fig. 4(a) and (b). These are images of 10 cm wide lettuce, and a part of 20cm long chicken body. The soft tissues are seen by the hard X-rays. The above images are of transmission type, and not of absorption type, because X-ray energy is very high. We understand that these are phase contrast images [13] usually obtained by SR. The coherent power of our X-ray beam is as high as that of SR sources. In this image we observe density difference, but not atomic number difference. Chicken has a complex body. We see its sandbag, wings, bronchus, feathers, blood cells, lungs, heart and others without additional imaging aids such as beryllium or iodine. Bones are transparent and heart and bronchus is seen in black.

**Fig. 4. X-ray images of lettuce (left) and chicken (right) obtained by MIRRORCLE-6X. Soft tissues are observed by the hard X-ray of more than 50 keV. Due to the very small emitter size, phase contrast images are observed.**

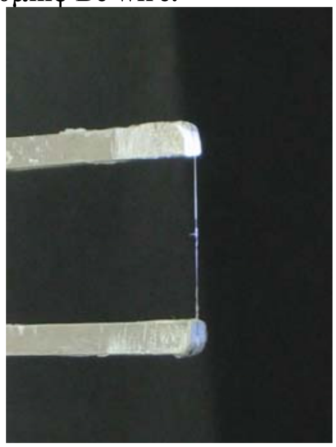


**Discussion:** In MIRRORCLE-6X, X-rays are produced by inelastic collision of circulating relativistic electrons and a tiny target placed in the central electron orbit [10]. The observed brilliance of hard x-rays is comparable to that of SR. This novel source is unique by its few μm X-ray source size, high efficiency electron to X-ray conversion rate, and broadband X-ray spectrum from few KeV up to the energy of injected electrons.

We can easily explain the advances of this X-ray source from its emission mechanism. Firstly, synchrotron light is a kind of bremsstrahlung generated by the magnetic force, while in the MIRRORCLE, X-rays are generated by the atomic force of the target. In both cases, X-rays are emitted from the incident relativistic electron itself, and not from the atomic electrons. Consequently, the divergence of X-ray emission is defined by the kinematics, $1/\gamma$, in which the electron energy $\gamma$ is normalized by the electron rest mass energy. 6MeV electron gives 85 mrad spread X-ray that is suitable for imaging of large object, while 8GeV gives 0.06 mrad that is good for material science.

The X-ray source spot size is the most important parameter to define the X-ray beam characteristics. In the conventional SR source, it is determined by the electron beam size. The electron beam dynamics of storage rings is, thus, a very important subject for designing the storage ring. This is the reason why the modern storage ring is made with huge circumference without using super conducting magnets. The large magnetic force gives perturbation in the radial direction to the electron beam, which increases the beam size. Also, the low energy electron is unsuitable for this perturbation, because of its small relativistic mass. The 8-GeV storage ring has about 20μm vertical X-ray source size. In horizontal direction, X-rays are emitted from the whole arc of the electron trajectory, which has the size of the bending magnet.

**Figure 5. X-ray target placed in the electron orbit of MIRRORCLE-6X. The 0.1 mm long and 10 μmϕ cross-section W wire is fixed in the middle of 50μmϕ Be wire.**



In the case of MIRRORCLE, however, the source size is determined by the target size. We use, for instance, a 10μmϕ cross-section target regarding to the beam direction as seen in Fig. 5. In this case 0.1 mm long (in the direction of beam) Tungsten wire is fixed on the 50μmϕ Beryllium wire (perpendicular to the beam direction). From this tiny target are emitted X-rays comparable to that of SR source. The problem of heating or melting target never occurs because all electrons pass through the target almost without heating it.

The brilliance $\Psi$ is introduced for SR source as follows:

$\Psi = photons/s, mA, mrad^2, mm^2, 0.1\% band\ of \lambda$ .

The brilliance is the number of photons divided by the source cross-section, and radiating solid angle ($mrad^2$). Sub-micron ϕ target will enhance the brilliance 10 thousand times compared to 10μmϕ cross-section target.

The inelastic scattering cross section is the order of $1.3 \times 10^{-27} m^2$. The photon number produced by one electron in one turn is only $7 \times 10^{-5}$. The average energy loss in single collision is 50 keV. Therefore, electrons are quite transparent with respect to this tiny target but they are re-circulating in MIRRORCLE at 0.3 GHz. The number of circulating electrons is $10^{13}$. As a result of these reasons, we can produce brilliant X-rays. The electron energy is quite effectively converted to the X-ray energy. According to Yamada's theory [10], the brilliance reaches $10^9$, and the flux reaches $10^{11}$ photons/s, 0.1% band when 100mA peak current is injected at 400 Hz repetitions.

To describe correctly the characteristics of MIRROCLE X-ray beam, we propose the notation "macro-peak brilliance", since the MIRRORCLE beam is more like pulse beam having 10 μs pulse width and 400 repetitions, which is different from the CW SR beam. The macro-peak brilliance of MIRRORCLE-6X is $2.5 \times 10^{12}$ photons.

The small source spot guarantees achieving of superior spatial resolution of imaging, and obtaining of magnified image. Introducing a condenser mirror enables to focus the X-ray beam to the size of the source point. In this case, the photon density is $2.5 \times 10^{14}/mm^2$, and the peak photon density is $6 \times 10^{16}/mm^2$. These values are comparable to those of SR sources.

**Conclusions:** Since Roentgen has discovered X-ray, X-ray imaging has been a very valuable tool for human society, but not many progresses on the X-ray source itself have been made. MIRROCLE-6X is a compact and very powerful new type X-ray source in comparison with synchrotron light sources, and conventional X-ray tubes. This machine is based on a portable synchrotron, different from the conventional synchrotron, and the X-ray tube. X-ray images produced by its extremely small X-ray source spot (a few microns) of this machine are characterised by a superior image quality. The spatial resolution naturally reaches the order of micron, because of its small source spot size. Magnified images were obtained by setting imaging devices downstream far from samples. These images are of transmission type, and not from absorption type, and are produced by its high energy X-rays. Soft tissues are also seen due to the edge enhancement resulted by X-ray scattering and diffraction. Conventional synchrotron light sources opened the novel imaging technology called phase contrast, which is realized by highly parallel beam, but the divergence is small and limits the size of specimens to be observed. MIRRROCLE-6X provides imaging field as large as 30cm without distorting the spatial resolution and uniformity. Also, the amount of absorbed radiation [14] is 10 times smaller compared to that of ordinary X-ray tube imaging, because the high energy dominated X-rays of MIRRORCLE are absorbed less. In conclusion, we believe that we have provided a new type of powerful X-ray source, which promises a new era of non-destructive testing. Furthermore, X-ray microscope with nano-scale resolution, due to its nano-scale target, is not just a dream.

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