# MIRRORCLE light source demonstrating one micron resolution and clear density mapping

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## ABSTRACT

MIRRORCLE is a hard X-ray source, which is quite different from either X-ray tubes or synchrotron light sources (SLS). MIRRORCLE generates high-density photons like SLS, but the source emitter size is much smaller than SLS as well as tube. The x-ray angular distribution is much wider than that of SLS. Thus diagnosis of human body is possible. The X-ray spectrum is polychromatic and peaking around 30-200 keV, which is higher than that of SLS. The center energy is selected by changing the target material and thickness. Because of these features imaging by MIRRORCLE is advanced by the largely magnified imaging, extremely sharp edge enhancement due to the phase contrast, and one micron order spatial resolution without optical elements. Density mapping is demonstrated in a simple magnified imaging. By tomography density volume mapping is obtained.

**Keywords:** tabletop synchrotron, hard x-ray source, phase contrast, density mapping, tomography

## 1. INTRODUCTION

MIRRORCLE is an x-ray source based on a low energy storage ring [1-5]. The 4 and 1-MeV MIRRORCLE's storage ring is now 35cm outer diameter and 8cm orbit radius as seen in Fig. 1. The 4-MeV MIRRORCLE is designed for non-destructive testing of bridges, chemical and power plants and space crafts and so on. The 1-MeV MIRRORCLE is a size of x-ray tube, and is useful for medical diagnosis and X-ray microscope, which is under commissioning.

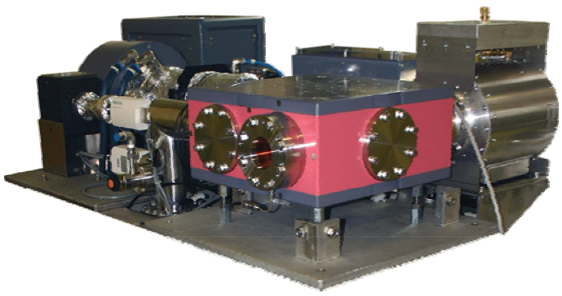



Fig. 1. Left: The 4 MeV MIRRORCLE is made of 8 cm orbit radius normal conducting storage ring as seen in pink color. Yoke is of 35 cm long rectangular shape. The injector is in the left behind, and pulse compressor is seen in the right. The total weight is 1.2 t. Right: Inside of MIRRORCLE chamber. X-ray emission from a target is demonstrated.

### 1.1 What is MIRRORCLE

MIRRORCLE is really a low energy storage ring that emits far infrared synchrotron radiation, but x-rays are generated by a target placed in the electron orbit as seen in Fig. 1 [10-12]. The accumulated beam current reaches 4A when the injector current is100mA. The measured beam size of the 20 MeV machine without target is around 2mm, damping time 10ms, and lifetime 1 minute. Injection is carried out at 400Hz repetition for the 4 MeV machine and 1k Hz for the 1 MeV machine. The designed X-ray density of the 20 MeV machine is $10^{10}$ photons/sec, mrad$^2$, 0.1%BW, while the present value is $10^8$ without synchrotron accelerator power. This value is comparable to that of x-ray tube as monochromatic x-ray beams are compared, but it should be remembered that MIRRORCLE generates polychromatic X-rays. The left figure in Fig. 2 shows the brilliance that is the value divided by the target cross section $10^{-4}$ mm$^2$ for

MIRRORCLE's. Since the angular divergence of MIRRORCLE is much wider, the total flux is much higher than that of SLS as seen in the right figure in Fig. 2. This implies that MIRRORCLE is an excellent imaging source.

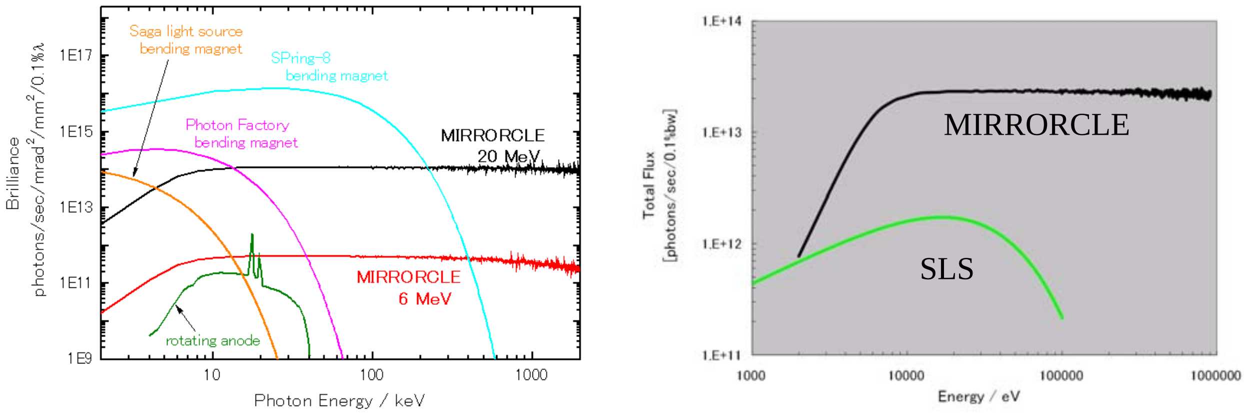
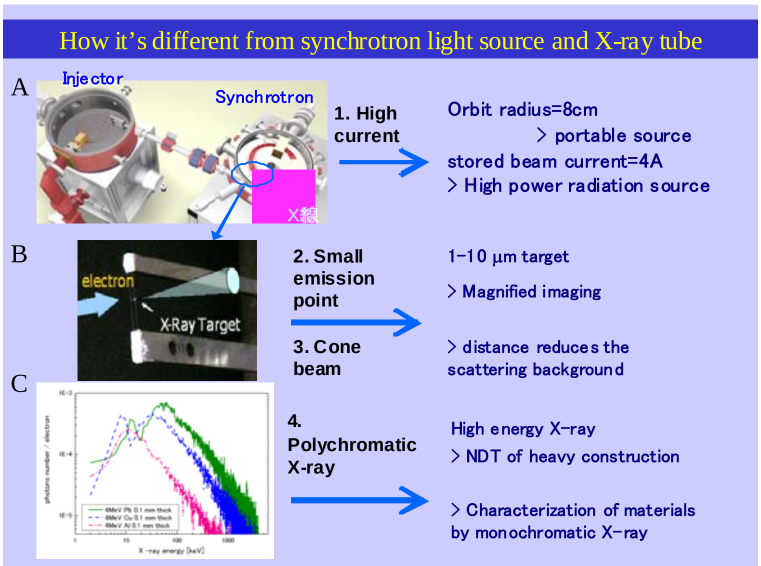



Fig. 2 Left: MIRRORCLE's Brilliance is compared with that of regular synchrotron light sources. Right: integrated photon number over $2\pi/\gamma$ in 0.1%BW., where $\gamma$ is the normalized electron energy. This is the case for 20 MeV MIRRORCLE. Currently those intensities of MIRRORCLE are one order lower.

### 1.2 How it's different from conventional SR and x-ray tube

MIRRORCLE is a synchrotron based x-ray source, but there are many differences from regular SLS and x-ray tube as summarized in Table. 1. It generates polychromatic spectrum in the range higher than 10keV up to the electron energy. We can select the central energy by the thickness and atomic number. The emission point is defined by the cross section of target in the electron beam direction as about one micron. Radiation spread over the cone defined by $1/\gamma$.

Table 1 Features of MIRRORCLE are discussed from three different aspects.



## 2. MAGINFIED IMAGING

The feature of category B in Table 1 results in the magnified imaging [6-9]. Since the image is magnified, necessary detector pixel size is less important. For instance a hundred micron pixel detector is enough to define 5 μm object as the magnification is 20. We demonstrate how resolution is improved by the target size as seen in Fig. 3.

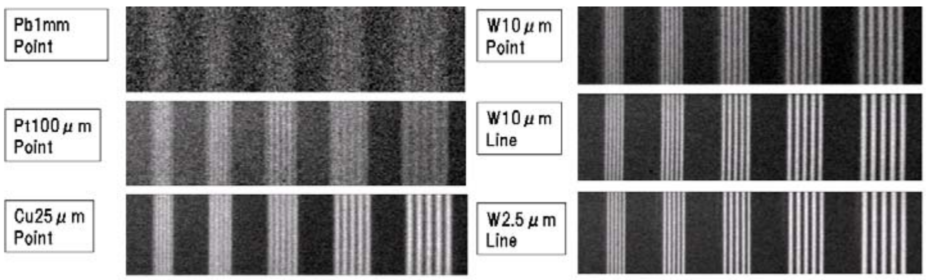



Fig. 3 an X-ray test chart is imaged by the different size targets and at 12 times magnification. Sizes and materials are indicated in the left. We see here that not only the space resolution but also the contrast is very much improved by the small target. Point and line mean point and line targets, respectively.

## 3. SIGNIFICANT PHASE CONTRAST APPEARS

Significant phase contrast appears as the target size is less than 25μm and the magnification is larger than 2 [6]. Edge is more enhanced as magnification is larger as seen in Fig. 4.

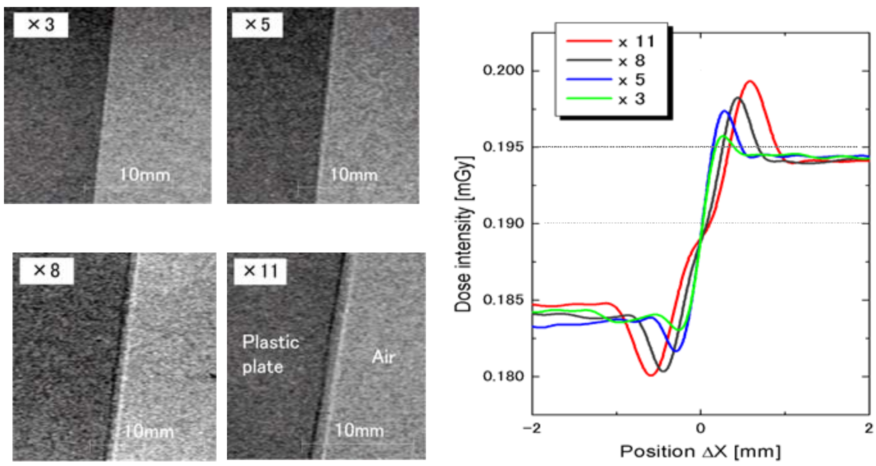



Fig. 4 the left: edge of 2mm thick plastic is imaged by MIRRORCLE. In the right, projections along the line perpendicular to the edge are shown for different magnifications. Both bright side and dark side are seen. Contrast of the edge becomes higher as magnification (indicated as x11 or so) is larger.

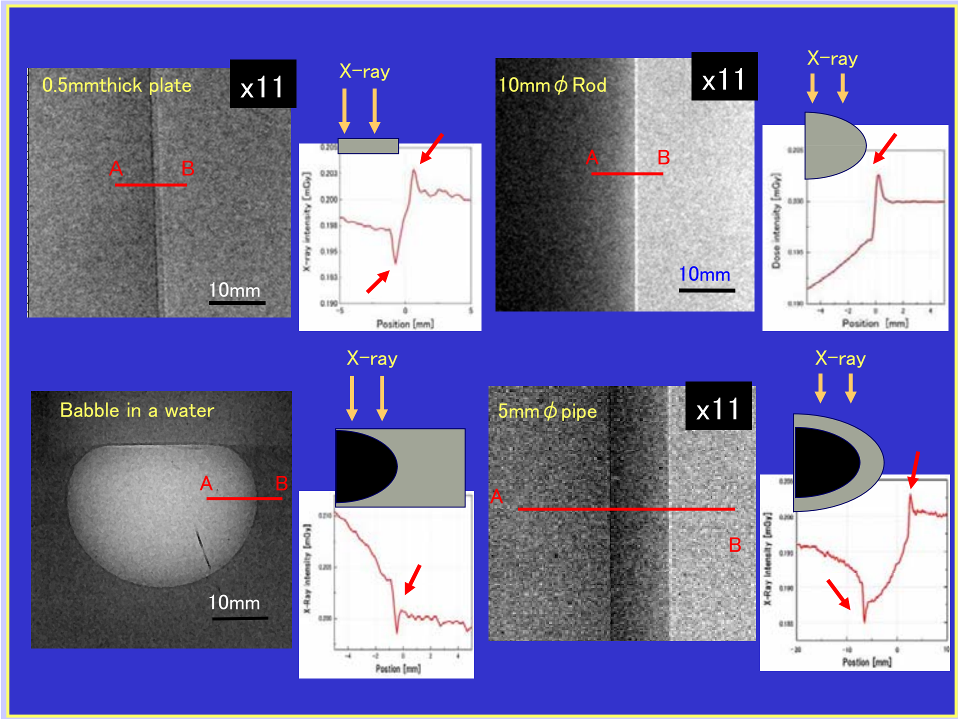



Fig. 5 It is interesting to see how edge effect appears in the different object shape. The left upper represents a plane plate, the left lower is babble in water, the right upper represents solid rod, and the right lower represents hollow rod.

Fig. 5 demonstrates the edge effects to the different object shapes. These examples will be useful for understanding the shape and density of organs in a body from the plane image. In the simple plane images the information of volume and density are presented.

## 4. POLYCHROMATIC X-RAY BEAM IS USEFUL

There is discussion on the usefulness of polychromatic or monochromatic beams for x-ray imaging. If we remember the history of camera, we know that is started with black and white. We know today every body loves color prints, because it includes more information. Probably it is the same for x-ray imaging. If a detector distinguishes the color of x-rays like human eyes, everybody agrees with this statement. Even though let's, however, say that information of color is hided in these plane pictures taken by polychromatic x-ray beam. The deflection of x-ray depends on the energy of x-rays, kind of materials, thicknesses and densities. Absorption contrast image includes the information on materials, volumes and densities. If we use two algorithms for absorption and phase contrast, we should be able to distinguish the materials, densities and volumes. Of course if we use two different targets the obtainable information will be doubled, since x-ray energies are different as seen in Table 1.

The pictures in Fig. 5 demonstrate the feeling of volume. The image of flat plate and air babble in water are so different. Gradation in the black and white density represents the shape of object. There is a significant difference from the picture taken by the monochromatic beam.

### 4.1 Complex materials are recognized

In Fig. 6 we show an x-ray image of valve made of steel. The cap is made of aluminum, and inside there is a sheet of rubber. Apparently the light material rubber is recognized. This happens because of the polychromatic nature of beam.

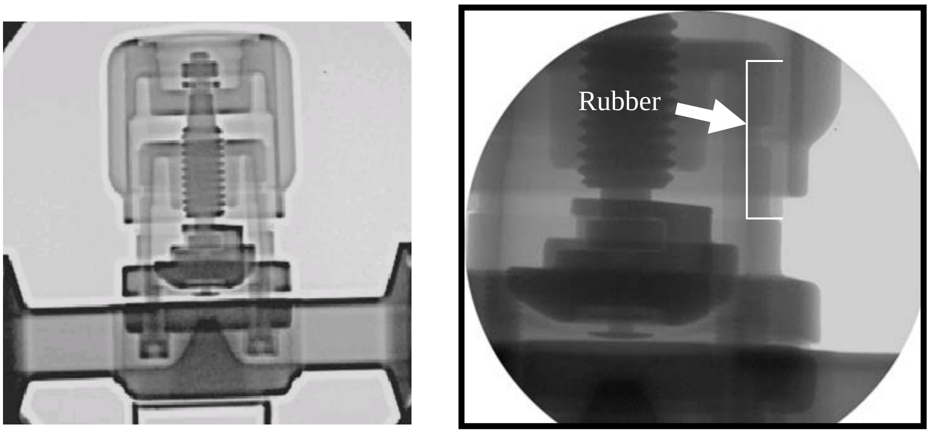



Fig. 6  X-ray image of valve is shown.  The left is 2 times magnified one.  The right is 4 times magnified one.  Every details of valve is seen in the left in which image process is applied.  In the right rubber inside of aluminum cap is identified.

### 4.2  Tomography of solid concrete block

In Fig. 7 we demonstrate the CT image of concrete.  The size of concrete block is about 4cm.  The detector used is Flat panel (Varian Paxscan 2520, pixel size: 250μm).  5 times magnification is applied, thus we are resolving 50μm space.  Total exposure time was 2 minutes for 380 deg.  We applied regular CT algorithm for absorption contrast.  Concrete is supposed to be solid, but we see here complex structures.  Millimeter size holes are seen many.  Patterns were, however, unexpected.  In the process of drying, concentration appears differently at different spot depending on conditions.  Water contents and density must be different.  This must be important information to study how to make a tough concrete.  Anyway in this example we could observe mosaic density in a concrete.  Polychromatic x-ray beam takes an important role.

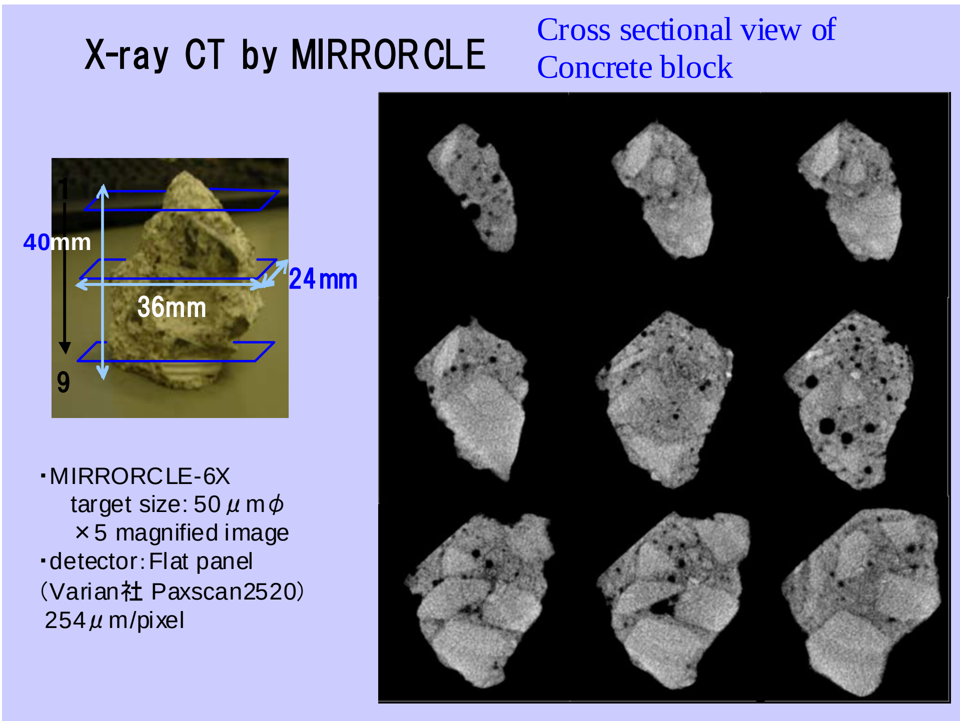



Fig. 7 Cross section of concrete block is seen at the different depth obtained by CT.

### 4.3 NDT by high energy flux

The available x-ray energy from MIRRORCLE is much higher compared to regular synchrotron and x-ray tube. For heavy construction LINAC is usually used, but the resolution is less than 3mm. MIRRORCLE is the machine that achieved the finest space resolution ever observed [13, 14]. In Fig. 8 we demonstrate iron wires through 45cm thick concrete block. This image was taken in 6 minutes by 4MeV MIRRORCLE. In the right we demonstrate how the inside of motorcycle engine is. It should be noted that any image processes are not applied to these images. Particular image process will improve the contrast.

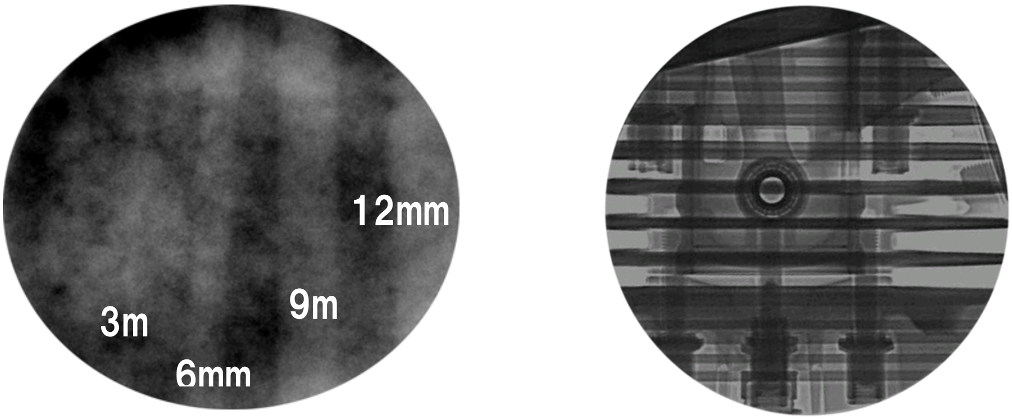



Fig. 8 the left: stainless wires placed at the end of 45cm concrete block are clearly seen. Density of concrete is also demonstrated. The right is the motor cycle engine. Spark plague is identified.

## 5. FURTHER DEVELOPMENT

MIRRORCLE generates high energy, widely spread and large x-ray flux from 1 μm order target. We can select particular wavelength by monochrometer. Extraction of thin fan beam is possible by MIRRORCLE. We are now constructing such a submicron spacing collimator system shown in Fig. 9. We expect less than one micron resolution small angle scattering combining with tomography. We will be able to extract nano-100nm particle information and distribution in volume materials. Proteins space distribution and structure of strings, thin films are the subject to be studied as described in Fig. 9.

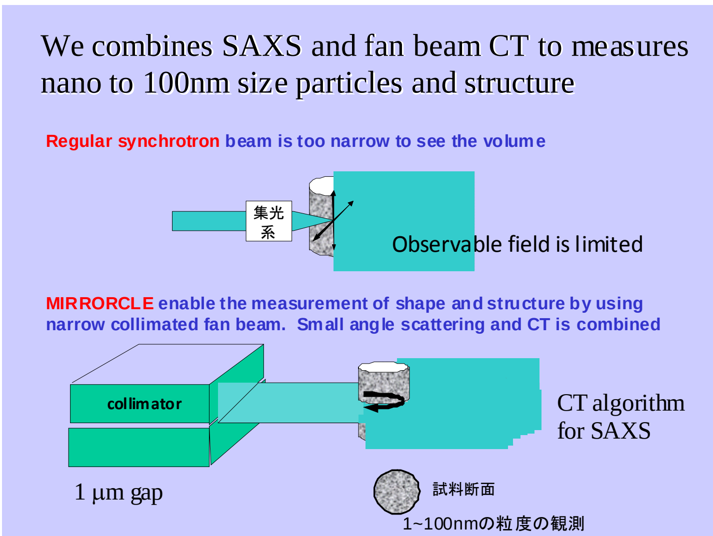



Fig. 9 a schematic view of small angle scattering using 1μm thick fan beam. When tomography is combined we are able to seen 100nm size structure in a volume sample, such as protein.

## 6. SUMMARY

In this paper we have demonstrated variety of unique applications related to imaging by MIRRORCLE-type x-ray source. Uniqueness comes from its unique x-ray characteristic; very small emission size, polychromatic spectrum, and widely spread cone beam. Advantages of MIRRORCLE are summarized below.

1, MIRRORCLE is different from synchrotron light source or X-ray tube, thus the obtained image shows different quality.

2. Magnified imaging presents significant phase contrast and reduced scattering background.

3. Polychromatic beam is useful to see complex material in both phase and absorption contrast.

4. Image by the polychromatic beam is quite different from one by monochromatic x-rays. More information is behind.

5. Density distribution is seen by CT. We think two algorithms for reconstruction will be useful. One for phase contrast and the other for absorption contrast

6. MIRRORCLE is the machine which can provide a very thin fan beam. By combining small angle scattering and micro-CT, we will be able to see nano to 100 nano level particle phenomena. Image of protein will be the next target to see by MIRRORCLE.

7. Ten micron resolution medical imaging is now realized by MIRRORCLE

8. Non destructive testing steps into new stage with less than 1 mm resolution. Such resolution has never been reached with other methods.

9. Of course most important fact is its machine size. MIRRORCLE realized the small machine size as well as high quality beam which is adaptable at small laboratory, hospital and factory.

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