Present status of MIRRORCLE-type tabletop SR's and unique applications that are difficult with conventional SR and X-ray tubes

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Abstract

MIRRORCLE provides unique X-ray beam due to its unique radiation scheme. White X-ray spectrum is similar to conventional SR's and is different from monochromatic X-rays of tubes. X-rays are generated in wide spectral region so as from EUV up to MeV hard X-ray. The emitter size is currently one micrometer at minimum and will be extended to sub-micron soon, which is smaller than any SR. The radiation field is much wider than that of SR's and is smaller than that of tubes. Because of these natures the imaging is characterized by extremely small spatial resolution and the phase contrast. The 50keV through MeV X-rays are useful for non-destructive testing and medical imaging. The dispersive EXAFS is a good application for MIRRORCLE since the 2 keV spectrum range is covered at once. High X-ray energy resolution by monochrometer is attainable with short beam line because of its one-micron emitter size. A few micron thick fan beam will be suitable for the very small angle scattering experiments combining the few micron resolution computer tomography. Since the total flux/[wavelength, port] is much larger than that of SR and tube, by introducing rotating Johansson type crystal mirror we can realize 10^{17}/mm^2 photon density at maximum, which is useful for sub-micron resolution pinhole X-ray camera.

1. Introduction

Currently 20, 6 and 4 MeV MIRRORCLE's are operated routinely for many different applications including of outside user's request. One MeV MIRRORCLE is under development.

The 20 MeV machine is useful for advanced applications such as a protein crystallography, EXFS and EUV lithography [1]. We could improve the X-ray flux from 20 MeV machine by 10 times when a 1.22GHz new cavity was introduced, which means that the density of monochromatic X-ray is 10 times higher that that of a powerful X-ray tube, and that the integrated flux over $1/\gamma$ radian of monochromatic X-ray reaches to 10^{17} photons/mm^2.

The 6 MeV machine [2] was converted to far-infrared source for the FIR absorption spectroscopy. The 4 MeV machine [3] is useful for an extremely fine space resolution non-destructive testing of heavy constructions such as a bridge, mobile, airplane, and so on. Currently we are developing an X-ray microscope, and a very small angle scattering system on the 4 MeV machine. These applications and medical diagnosis will be shifted to one MeV machine when the machine is ready.

Major subject on the X-ray microscope, which is the pin hole camera type, is the development of the Johansson type crystal mirror. The targeting resolution of this microscope is sub-micron. The targeting intensity of the monochromatic X-ray is at least 10^{16} photons/mm^2/0.1% band width. This value is obtainable when MIRRORCLE is operated at the level of photon density of X-ray tube. When MIRRORCLE is operated at the full power it will be 10^{18}./mm^2 When a Fresnel zone plate is coupled some 10nm resolution X-ray microscope will be realized.

Currently the minimum emitter size is 2.5 μm, which provides big advantages to the small angle scattering experiment. We call the ultra small angle scattering system. The measurable range of macro particle size is nanometer to 1 μm. In combining the CT system the direct measurement of protein shape become a research target.

According to our user's request it is said that the sub-micron resolution and around 20-50 keV X-ray energy microscope is most useful for inline testing of sub-mm size electronic and optical devices. This testing should be carried out at the final stage of the production line. Testing of the devices from outside of package is requested. Our sub-micron resolution magnified imaging will be carried out without an optical element.

In this paper the improvement of machines and unique applications on which we are concentrating are briefly described.

2. Machine status and improvement

2.1 MIRRORCLE-20SX

MIRRORCLE-20SX has been operated with accelerating cavity of 2.45 GHz. When 200W is applied, we observe the radiation damping in the speed as fast as 15ms. Beam size turned to about 5mm diameter (see Fig. 1). When the target was placed, X-ray power increased about 10% only. Three hundreds watts was the maximum power accepted by the beam.

For increasing the acceptance of electron beam, we have changed the RF frequency to 1.22 GHz. New cavity presented the Q-value 4000. Due to this change the radiation damping speed is decreased to 10ms, and the beam size to 1.5mm diameter as seen in Fig. 1.

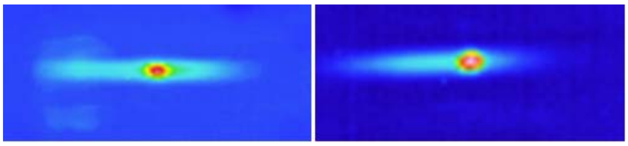

Fig. 1 Typical beam sizes after the damping are shown. Measurement is made by thermograph. The left is the one when 1.22 GHz RF power is applied, and the right is at 2.45 GHz.

The average accumulated beam current is now 4A, and the beam size is 2.2 mm. The X-ray density/0.1% b.w. is 3 times higher than that of 10 KW X-ray tube. We found that the X-ray power is alsmost same for both 1 micron and 50 micron targets. Yamada's theory [4] regarding the X-ray generation mechanism is well established by this observation. In this theory the total X-ray power is independent of target size and the target materials.

The monochromatic X-ray power is compared with one KW X-ray tube as seen in Table 1. In this measurement the same sagittal monochrometer and imaging plate are used for both X-ray tube and MIRRORCLE outputs.

Table 1. Comparison of MIRRORCLE and x-ray tube outputs.

	1KW RF 20 MeV MIRRORCLE	1KW Cu tube
Intensity (mR/pixel/s)	69	30
Distance from the source point (m)	3.1	2.6
X-ray energy (keV)	13.4	8
Width of sagittal bent crystal (± mrad)	3.1	3.1
Intensity (mR/mrad²)	11.1	4.8
Focused beam size	<1mm	3mm
Normalized value by the diffraction efficiency (mR/s/mrad²)	12873	3606

2.2 MIRRORCLE-6X

Since the activity of X-ray imaging is shifted to 4-MeV machine, and the nature of 6MeV machine is useful for far-infrared spectroscopy, we have converted the machine to FIR source. Circular mirror is installed in the storage ring to collect the whole SR emitted from the whole arc of the orbit. Beam line is equipped with FTIR (see Fig. 2).

Observed FIR spectrum is shown in Fig. 3. Compared with an internal black body source, 40 times higher intensity is observed. The 10 um-thick polyethylene beam splitter limits the observable lower frequency.

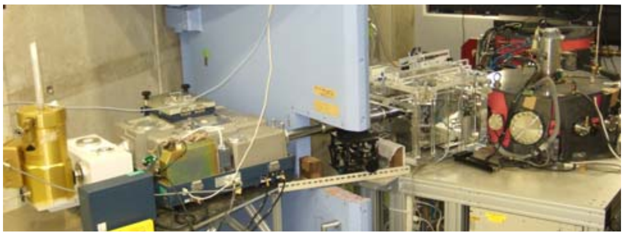

Fig. 2 FIR beam line attached to the 6 MeV MIRRORCLE in the right. FTIR and Si bolometer are seen in the left. Whole system is under the vacuum.

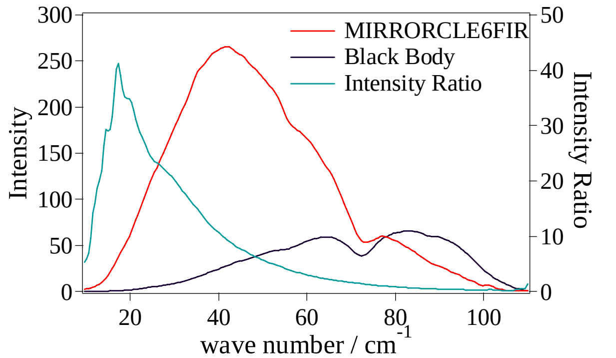

Fig. 3 FIR spectrum taken by FTIR is shown. It is seen that the MIRRORCLE-6X is advanced in the wave number lower than 70 cm^{-1} compared with a ceramics heater internal source.

2.1 MIRRORCLE-CV4

Commissioning of MIRRORCLE-CV4 (see Fig. 4) was carried out. Synchrotron is the world smallest 35cm long rectangular shape and of the exact circular electron orbit of 8cm radius. Injector is a 4-MeV linac made by AET. Pre-bancher is introduced to improve the beam quality. Linac was selected for the non-destructive testing for the use in the field such as bridges according to the radiation safety regulation.

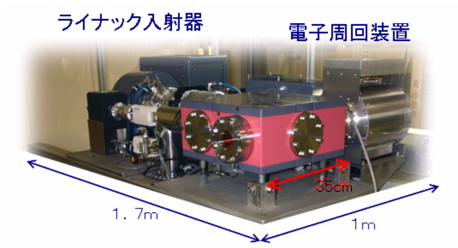

Fig. 4 View of MIRRORCLE-CV4

We learned that the beam quality of LINAC is very poor compared with 6MeV microtron developed by our group. The maximum beam current, emittance and energy distribution of this LINAC are 65 mA, 40 mm·mrad, and 2%, respectively, while our microtron gives 150 mA, horizontally 30 (vertically 5) mm·mrad, and less than 0.5%, respectively. We are planning to build 4MeV microtron for replacing. It is also important to say that the 4-MeV microtron is only 20cm diameter and 10 cm wide.

3. Examples of advanced applications

Advances of MIRRORCLE's X-ray characteristics can be categorized as follows.
a) Micron level focus point defined by the target realizes micron CT system. The space resolution of MIRRORCLE is demonstrated in Fig. 5.

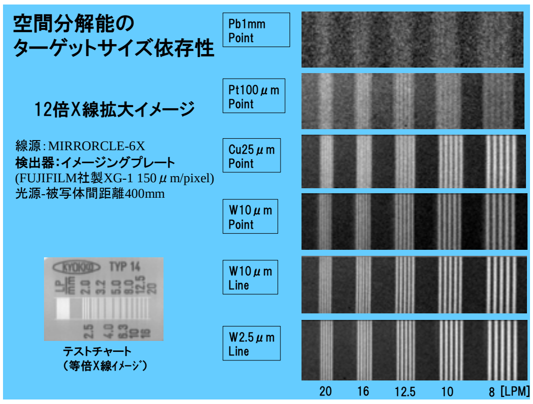

Fig. 5 Demonstrating how space resolution depend on the target size

b) Widely spread radiation angle realize wide view for medical imaging, magnified imaging, zooming function to see the part of interest.
c) Wavelength tunability due to the polychromatic X-ray enables laboratory size material characterization.
d) MeV range X-rays enable the NDT of bridges and heavy constructions.

3.1 Imaging

Diagnosis of concrete and iron bridges, ships, air planes and pipe lines of chemical and nuclear reactor plants are advanced with MIRRORCLE according to the above category d, b, and a. These can not be the target for SR and X-ray tube applications. We could identify 3 mm thick iron wire through more than 45 cm concrete block. The 0.2 mm width cracks and 0.5 mm thick steel wire on 50mm thick steel block are identified.

In the above example a high energy flux is utilized, but MIRRORCLE is also advanced in the medical diagnosis. We are organizing consortium including medical schools and companies for development of CT system.

3.2 Sub-micron resolution CT

Sub-micron CT system will be made without additional optical elements. Sub-micron size target is the key to this technology. When Johansson type crystal mirror or a troidal mirror is introduced we are able to make 10^{16} photon density/mm^2 at the focal point. Combining Fresnel zone plate, a few 10 nm resolution microscope is feasible.

3.3 EXAFS

Dispersive type EXAFS is advanced with MIRRORCLE, since the energy range to be covered is 2keV that is much wider than that of SR. An example in Fig. 6 is 0.5 KeV range spectrum taken in one time in 30 minutes by MIRRORCLE-20SX at 3m distance from source point. If we carry out the experiment at 1m distance, 3 minutes will be enough.

In the case of Fig. 6 the energy resolution, E/ΔE is 2000 with 50 μm width target. We conclude that the energy resolution is satisfactory at 1m distance since we are able to use less than 10 μm width target.

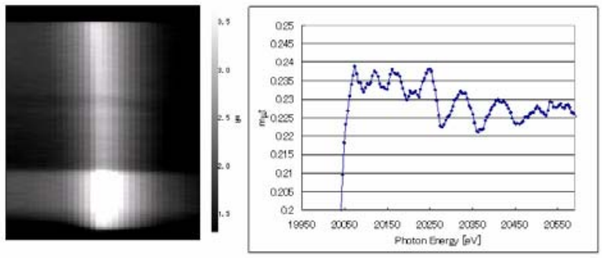

Fig. 6 This EXAFS spectrum is taken in one time. Structures are even seen in the left raw data. The ratio between the data with sample and without sample is shown in the right.

4. Future programs

We are interested in number of projects. These are the development of the X-ray microscope of 10nm level resolution and the ultra small angle scattering system. One micron level focal spot is really the smallest, and should provide the research tool on the particle size in the rage from 10 nano to 100 micron. When we combine the function of small angle scattering and magnified fan beam CT, we should be able to see the structure of micron size particles including proteins and cells.

References

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