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Far-IR/THz Spectroscopy Beamline MIRRORCLE-6FIR at SLLS of Ritsumeikan University

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Abstract

A new beamline, MIRRORCLE-6FIR for far infrared-terahertz (THZ) spectroscopy (FIRS) has been recently constructed at the synchrotron light life science center (SLLS) of Ritsumeikan University. An exactly circular optics with vertical angle has been employed as the first mirror which collects synchrotron radiation (SR) photons emitted into 2π of a circular electron orbit of length 1 m only. An exit opening on its surface can extract SR photons up to 264 mrad in horizontal and 198 mrad in vertical. The optimum optical system has been determined by using ray trace simulation code ZEMAX. The purpose is to develop an FIRS beamline with high power FIR. The design of the beamline optics with the results of its ray-tracing are reported in this article.

Keywords: MIRRORCLE; Synchrotron radiation; Beam line; Ray-trace; Terahertz; Far infrared spectroscopy.

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1. Introduction

The facilities for performing infrared spectroscopy (IRS) have been expanded throughout the world in response to an increasing demand from the scientific community. IRS is now a well-established technique to study local structures of organic materials and biomaterials in THz dynamics [1-4] in the fields of material science and life science, and to investigate molecular vibration in mid infrared region [5]. But, there is a lack of facilities for performing far infrared spectroscopy (FIRS) owing to the limitation of light sources. An advantage of FIRS is to observe the intermolecular interaction through phonon, and that's why it is a suitable technique to investigate network structure like water. To accomplish an

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FIR spectroscopy beamline with better performance, we need high intense FIR light having a bright flux of photons.

Numerous beamlines that are dedicated to infrared spectroscopy have been developed at Synchrotron Radiation (SR) facilities throughout the world, for example, NSLS [6] and CIRCE [7] in USA; SOLEIL [8] in France; BESSY II [9] and ANKA [10] in Germany; SSLS [11] in Singapore; Spring-8 [12] and UVSOR-II [13] in Japan, etc. Infrared spectroscopy beamlines are also found in a number of FEL centers: such as Jefferson Laboratory [14] in USA; IR FEL Research Center of Tokyo University of Science [15] and FELI [16] in Japan: KAERI [17] in Korea, etc. Most of these were designed to exploit the very high brightness of infrared synchrotron radiation for microscopy and other throughput-limited techniques. A few have been instrumented for the far infrared, where the synchrotron source offers both a brightness and power advantage over alternative spectroscopic sources [18].

Synchrotron light Life Science Center (SLLS) of Ritsumeikan University has also SR facilities, in which there are the world smallest storage rings, named “MIRRORCLE”. MIRRORCLE-type synchrotron light sources are unique by the electron energy lower than 20 MeV, the orbit radius of storage ring as small as 8 cm (for 1 and 4 MeV type) [19] and 15 cm (for 6 MeV and 20 MeV type) [20, 21], the storage beam current as large as ampere order, and the compactness of 35 cm (for 1 and 4 MeV type), 60 cm (for 6 MeV type) and 80 cm (for 20 MeV type) magnet yoke diameter. In spite of low electron energy the MIRRORCLE-type generate milliwatt order and sub-millimeter range far infrared (FIR) [4, 22-24], hard X-rays ranging from 10 keV up to its electron energy [20, 22], and 0.1 watt order extreme ultra violet (EUV) and soft X-rays [25, 26].

As MIRRORCLE are low energy storage rings, they cannot compete with large storage ring in the higher photon energies. However, it is possible to surpass them in the FIR/THz regions by collecting SR photons in a wider acceptance angle. MIRRORCLE-20 [20] has been optimized for FIR beam line to analyze water, aqueous solution, protein etc. [4, 5]. We have learned, however, that the smaller machine MIRRORCLE-6X [21] produces more FIR. Therefore, we are now switching MIRRORCLE-6X to MIRRORCLE-6FIR. The specification of MIRRORCLE-6FIR is listed in Table 1.

Table 1. Specification of MIRRORCLE-6FIR.

Electron energy	6 MeV
Orbit radius	156 mm
Magnetic field	0.128 T
Max. Storage current	3 A
Max. Incident beam current	100 mA
Max. Injection rate	400 Hz
Pulse width	100 nsec
Injection method	1/2 resonance
Injection efficiency	nearly 100%

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The 6-MeV version produces critical wavelength of 300 µm. Our aim is to develop an FIRS beamline with high power FIR in THz regime. A designed optical system of FIRS from the storage ring to an FT/IR, and the results of ray-tracing for the first focal point in the optical system are reported in this paper.

2. Optical System

The optical system designed for MIRRORCLE-6FIR beamline can be viewed as two parts: an ultra high vacuum (UHV) section directly connected to the ring chamber, and a high vacuum section containing the optics for focusing, transferring and splitting the beam, to the FT/IR end station. The two parts are separated by a 50 mm clear aperture, 3 mm thick TSURUPICA (Pakkusu, Japan) window. The transmittance of this window is about 85% for the wavelengths $\lambda > 50$ µm [24]. Visible light can pass through the window allowing to arrange other optics.

2.1. *Optical system inside the ring chamber*

The designed optical system in the synchrotron ring chamber is shown in Fig. 1(a). It is composed of only one circular mirror, *M0* concentric with the electron orbit of radius 156 mm. In fact, after installing the circular mirror, there is no enough space to install any other optical system inside the ring chamber. The circular optical system can collect SR

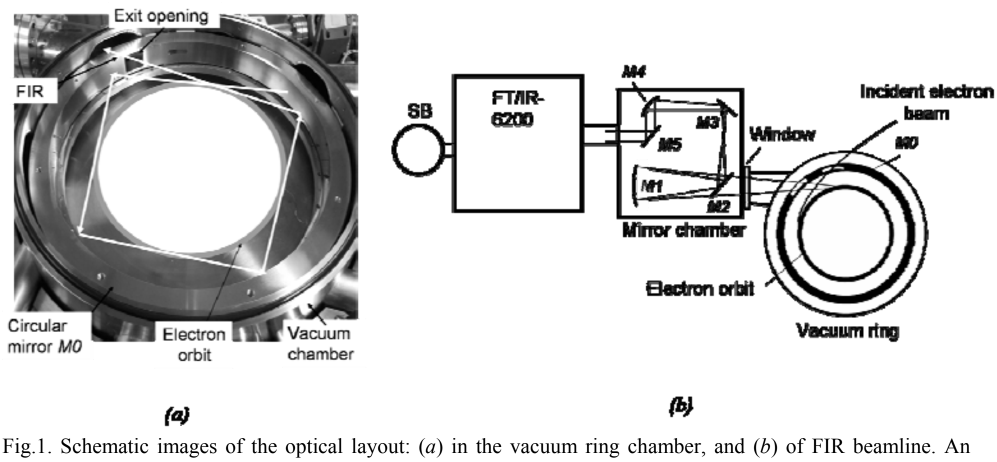

Fig.1. Schematic images of the optical layout: (*a*) in the vacuum ring chamber, and (*b*) of FIR beamline. An exactly circular mirror, *M0* concentric with the electron orbit has been employed as the first mirror. The exit opening on the circular mirror surface can extract a solid angle of 264 mrad×198 mrad. A concave mirror, *M1* (f = 304.8 mm) has been installed at the front end of the beamline to focus the beam at the first focal point. *M2*, *M3* and *M5* are all plane mirrors. *M4* is a parabolic mirror, and SB is a silicon bolometer detector.

photons emitted into 2π of the electron orbit, and so it is also known as Photon Storage Ring (PhSR) [27, 28]. A key characteristic of the PhSR is the reflection of collected synchrotron radiation to intersect the electron orbit again. This configuration, under certain circumstances, induces lasing and significantly boosts FIR output by order of magnitude. In this sense, the PhSR also acts as an optical resonator playing a great role to high intense FIR generation. An aperture on the mirror surface allows the SR photons to be extracted. The importance of this simple opening is that, in the case of a conventional synchrotron facility, the SR photons are extracted through a magic/toroidal mirror having mrad order acceptance angle, thus limiting the efficiency of photon beam extraction. In the case of the PhSR, about 100% of the photons are extracted through this simple opening. The light pulses confined in the mirror cavity propagate along the single photon path finally leading to the exit opening, and form a pulse train with an exact time period. The Fourier Transform of this pulse train corresponds to the frequency of the light wave.

The natural opening cone of synchrotron opens up as a function of wavelength. It increases to several tens of milliradian in the far infrared depending on the radius of the ring as follows [29]:

$$\theta_{nar}(radian) = 1.6\left(\frac{\lambda}{\rho}\right)^{1/3},$$

where λ is the wavelength and ρ is the electron orbit bending radius (in the same units as λ). θ_{nar} is the angle required to transmit 90% of the emitted light at a given wavelength. Thus, efficient extraction of the infrared from a synchrotron is increasingly difficult towards longer wavelengths. The exit opening on the circular mirror surface, designed for the MIRRORCLE-6FIR beamline, can extract a solid angle of 264 mrad×198 mrad. The MIRRORCLE-6FIR ring has a bending radius of 156 mm; therefore the beamline can collect (per horizontal angle) 100% of the infrared down to ~14 cm^{-1}. The fabricated mirror is made of only aluminum. This material is selected because of rigidity and good FIR reflectivity. Mirror curvature is made within 0.1 μm tolerance. For 300 μm wavelength, we have selected the mirror width, D = 38 mm, the curvature in axial direction, R_0 = 125.81 mm, and the mirror radius, R = 217.3 mm.

2.2. *Optical system of FIR beam line*

Fig. 1(b) shows the designed optical system of the FIR beamline. The exit opening of the circular mirror allows SR photons to be ejected out from the storage ring body, and to come directly to the radiation window. A concave mirror, *M1* (f = 304.8 mm) is installed at the front end of the FIR beamline to focus the beam at the first focal point. The beam is then directed by three plane mirrors (*M2*, *M3* and *M5*), and reformed in a parallel beam by a parabolic mirror, *M4* (f = 152 mm, 90 deg. off axis) in order to introduce into a commercial FT/IR-6200 (JASCO Corp., Japan) spectrometer. The concave mirror and the first focal point are located at 600 mm and 1163 mm, respectively from the center of the SR emission point. The concave mirror, plane mirrors and parabolic mirror are enclosed in a vacuum chamber as shown in Fig. 1(b). The FT/IR-6200 (JASCO Corp., Japan) has Michelson type interferometer, step scanning system for its moving mirror, and a function of time resolved measurements. The instrument can be used with both the synchrotron source as well as its internal thermal source. The FT/IR-6200 covers the wavelength range from the far-IR to the near-IR regions of 20-7800 cm^{-1} by choosing suitable beam splitters and optical elements. The detector is a Si-bolometer (Infrared Lab, USA), unit 3118 of composite type, operating at a temperature of 4.2 K. The detector characteristics are: entrance aperture of 12.7 mm at a focal ratio of 3.8, exit aperture of 1.8 mm, area of 2.5 mm diameter diamond, and sensitivity of 2.53E+05 V/W.

3. Ray-tracing Simulation

The beam profile has been simulated using ray-tracing program ZEMAX-EE (Engineering Edition) at the first focal point, and the optimum optical system determined. A special type of light source modeled by DLL (Windows Dynamic Link Library) was used in order to support the desired properties of MIRRORCLE type synchrotron. The sources were placed at different angles around in an orbit of radius 156 mm. The power of each source was set at 30 μW. Beam profile depends on the electron beam profile, whose Gaussian was σ_h = 3 mm in horizontal direction, and σ_v = 1 mm in vertical direction. The emission angle of SR light is ±85 mrad at photon energy of 0.01 eV, which is fairly large compared with that of IRSR in Spring-8 [12]. Toroidal objects consisting of rectangular surface were placed around the source orbit for circular optics. The horizontal and vertical curvatures of this optical system are 217.3 mm and 125.81 mm, respectively as discussed in section 2.1. An exit opening was set on the mirror surface in order to extract SR photons. The opening of size 40 × 30 mm^2 gives the acceptance angle of 264 ×198 $mrad^2$. The concave mirror and the first focal point are located at 600 mm and 1163 mm, respectively from the center of the SR emission point.

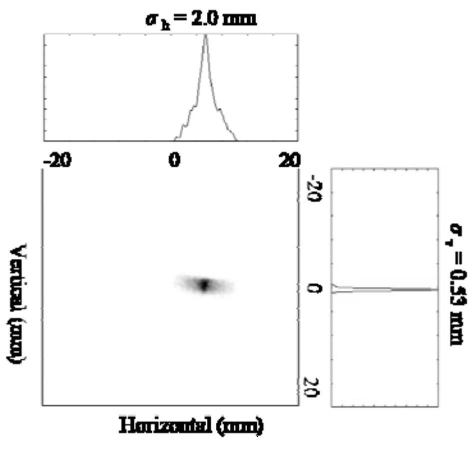

Fig. 2. Simulated beam profile in FIR region (~ 100 cm^{-1}) at first focal point. The beam size is smaller than that of the electron beam. Note that the beam profile is slightly shifted from the origin in horizontal. This might be due to a large horizontal acceptance angle of 264 mrad.

The beam profile at the first focal point was calculated by using an imaginary detector. Fig. 2 shows the beam profile at the photon energy of 0.01 eV (~100 cm^{-1}) which is in the far-IR region. The σ's of the beam are 2.0 mm in horizontal and 0.53 mm in vertical, and the beam pattern is not point like, but linear. We note that, the beam profile is slightly shifted from the origin in horizontal. This might be due to a large horizontal acceptance angle of 264 mrad. The beam size is smaller than that of the electron beam. Different from a low emittance ring, such as Spring-8, it is impossible to obtain such a small spot at the first focal point. The calculated photon flux for $1/\gamma = \pm 85$ mrad is of the order of 10^{14} (photons/s, 0.1% bw), but the stored beam current (ampere order) rather large compared with an ordinary synchrotron. We, therefore, expect high power FIR with such a large beam current.

4. Conclusions

In this article, we have presented the optical layout of MIRRORCLE-6FIR beamline at SLLS, Ritsumeikan University, which is dedicated to FIR spectroscopy. An exactly circular optics has been designed which collects SR photons emitted into 2π of the circular electron orbit, and its exit opening provides 264 mrad horizontal, 198 mrad vertical acceptance. A concave mirror was set at the front end of the beamline to focus the beam at the first focal point. Ray-trace calculations using ZEMAX helped optimizing the optical parameters. MIRRORCLE-6FIR beamline is expected to provide a high intensity and high photon flux in the far infrared-terahertz spectral region.

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