Current Status of NewSUBARU

NewSUBARU Storage Ring

Y. Shoji

Storage Ring Parameters

The machine parameters of the 1.5 GeV storage ring are listed in Table I. Although the machine condition remains the same, some of the values are revised according to the new model calculation.

Table I Main parameters of the NewSUBARU storage ring in FY2013.

Circumference	118.73 m	
Bending lattice type	modified DBA	
Number of bending cells	6	
Straight sections	4m X 4,	15m X 2
Bending radius	3.22 m	
Injection energy	1.0 GeV	
Maximum energy	1.5 GeV	
RF frequency	499.955 MHz	
Betatron tune	6.29 (H),	2.23 (V)
Momentum compaction factor	0.0014	
Electron energy	1.0 GeV	1.5 GeV
RF voltage	100 kV	260 kV
Natural energy spread	0.047%	0.072 %
Natural emittance	50 nm	112 nm
Maximum beam current	500 mA	

Operation Status

The ring has two user-time operation modes, 1.0 GeV top-up operation mode and 1.5 GeV operation mode. The basic operation time is 9:00 - 21:00 of weekdays. Monday is used for machine R&D, Tuesday is for 1.5 GeV user time, Wednesday and Thursday are for 1.0 GeV top-up user time, Friday is for 1.0 GeV or 1.5 GeV user time. Night period or weekend is used for machine study and user time with the special mode, single bunch operation and Laser-Compton Gamma ray, if necessary.

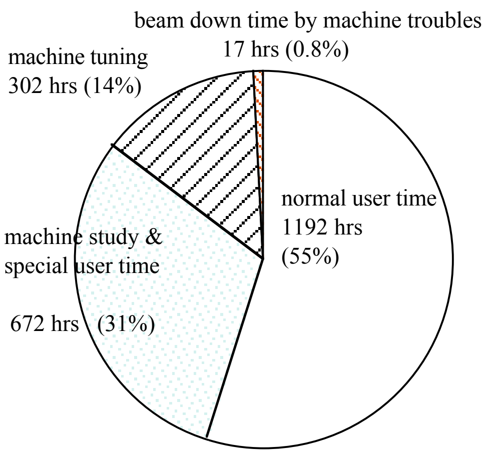

Figure 1: Machine time in FY2013.

The total machine time in FY2013 was 2183 hrs, 82% of that of FY2012, including the beam down time. Fig. 1 shows the breakdown. The beam down time includes not only the down by a failure, but also off-beam periods by a beam abort or others due to the beam instability. The reduced machine time from the previous FY was category 'beam line commissioning' , which had been 659 hrs in FY 2012. The total of the normal user time and the beam line commissioning in this FY, 1192 hrs, was a 100% of that in FY2012. Time for machine study and special users was 123% of that in FY2012. The down time due to the machine trouble was 0.8%, 2/3 of that in FY 2012.

Machine Troubles

The machine troubles in FY2013 are listed in Table II. The rate of hardware troubles were increasing because they get older.

Machine Study and Special User Time

Table III shows the list of machine studies in FY 2013. Most of the study reports are open to the public on the home page of NewSUBARU (http://www. lasti. u-hyogo. ac. jp/ beam_physics/ NewSUBARU).

Accelerator Improvements

The top-up operation current had been raised from 250 mA to 300 mA since October 2012. Fig.2 shows typical operation in these 5 years. That condition was kept during FY2013, even at a worst case when the Compton-gamma line was in operation.

The synchrotron oscillation feed-back system was installed to reduced the coherent synchrotron oscillation. It improved the measurement accuracy of machine parameters at a special operation, such as a non-achromatic mode. The longitudinal oscillation spectrun with the feed-back on and off are shown in Figure 1.

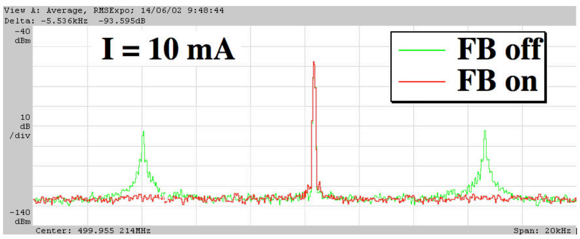

Figure 1: Measured time spectrum of the beam structure with and without feedback of synchrotron oscillation. The center line was the rf frequency and the broad side bands were synchrotron oscillation.

The injection timing system of the linac was improved. It effectively eliminated the dead time for changing the transportation line, to NewSUBARU or to the booster synchrotron. It reduced the time for the beam accumulation of 300 mA from 35 min to 25 min (typical value). It also improved the atability of the top-up current from ±0.5 mA to ±0.3 mA.

Table II Machine troubles in FY2013.

Group	Failure/trouble	beam down time (hr)
Operation	Miss operation (human error)	2.7
	Beam loss by a beam instabilities	2.1
	Short Lifetime	3.9
Control	Program hung-up	1.0
	COD control failure	0.1
RF & Timing	Timing module	0
	Coupler failure	1.0
	Circulator arc	0.1
Magnet	Cooling water leak at Power supply	3.2
	Magnet IL failure	2.8

Table III List of machine studies in FY2013. The unit of study time is counted by shifts (typically 12 hrs).

R＆D theme and special user mode	responsible person	study shift
Laser-Compton backscattering γ-rays	S. Miyamoto	17
Commissioning of visible light profile monitor port SR5	Y. Shoji	3
Optimization of vertical beam size for 1.5 GeV user time	K. Kanda	1
Betatron amplitude dependent orbit shift	Y. Shoji	1
Coherent synchrotron radiation by chromaticity modulation	Y. Shoji	15
Commissioning of the multi-element corrector	Y. Shoji	5

Beamlines

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Total nine beamlines are operating in the NewSUBARU synchrotron facility. Four beamlines of BL01, BL03, BL06 and BL11 were constructed until 1999. Three beamlines of BL07, BL09 and BL10 were started the operation from 2000.

BL03B beamline branched from the BL03 beamline propose for the usage of the EUVL (extreme ultraviolet lithography) microscope for the EUVL finished mask inspection.

BL09B beamline branched from BL09 beamline for the usage of the usage of the EUV interference lithography to evaluate. And BL09C beamline branched from BL09B beamline for the usage of the thickness measurement of the carbon contamination originated to the resist outgassing during the EUV exposure.

BL02 beamline was constructed for the usage of LIGA in 2003.

BL05 beamline was constructed in response to a demand in the industrial world in 2008, which is the enhancement of the analysis ability in the soft X-ray region with the development of nanotechnology.

The arrangement of the beamlines in the NewSUBARU synchrotron radiation facility is shown in Fig.1.

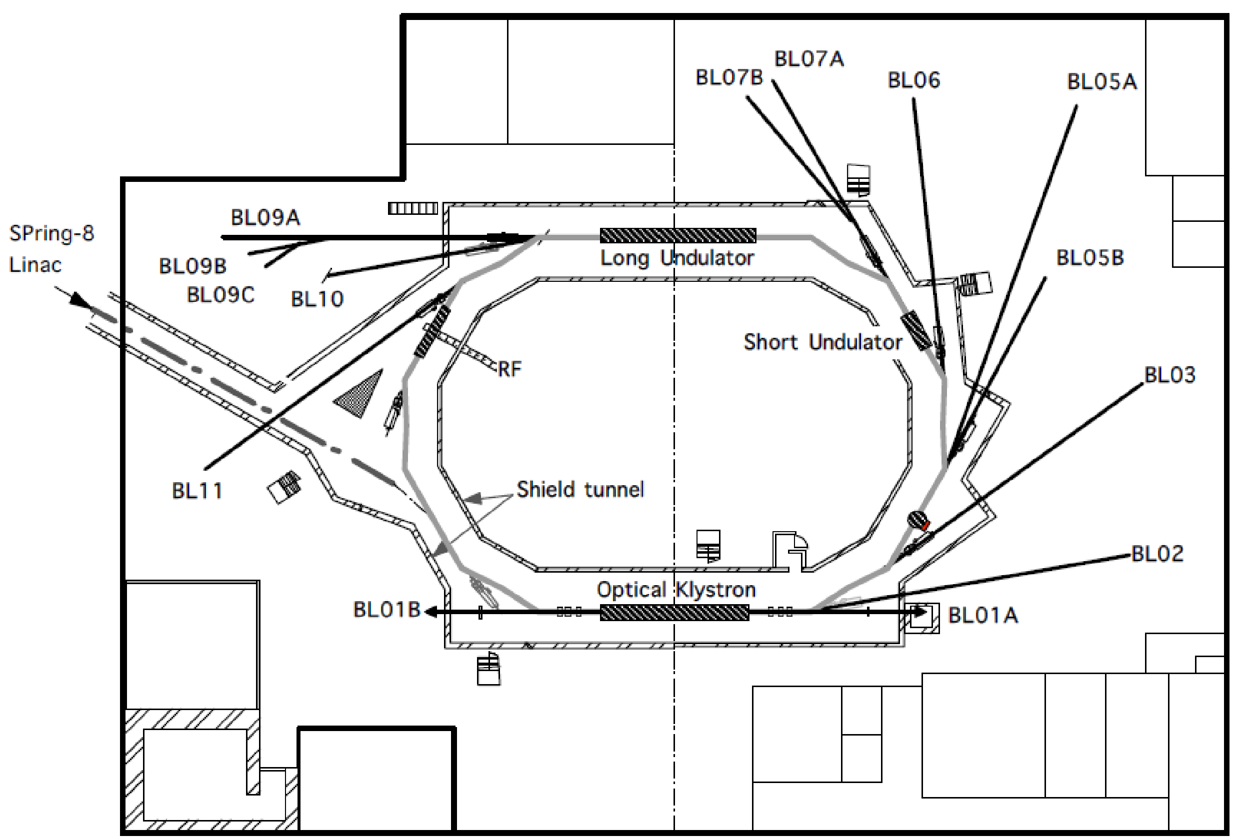

Fig. 1 Beamline arrangement in NewSUBARU.

I. BL01

BL01 is a beamline for research and developing new light sources. This beamline is one of two long straight section on NewSUBARU. Optical klystron was installed at this straight section. Upstream side of this beamline (BL01B) is intended to be used for visible and infrared light generated from free electron laser (FEL) or synchrotron radiation (SR). Downstream side of this beamline (BL01A) is used for laser Compton scattering gamma-rays source. Gamma-ray beamline hutch just outside of the storage ring tunnel was constructed in 2004 for gamma-ray irradiation experiments.

New gamma-ray irradiation hutch "GACKO" was installed at BL01A, collaborating with Konan University.Table 1. shows the specification of “GACKO”.

Table 1. Specification of “GACKO

Maximum gamma-ray power	0.33 mW
Maximum gamma-ray energy	1.7 MeV - 73 MeV
CO_2 laser, wavelength/power	10.59 μm / 10W
1-1.7MeV gamma-ray flux	2×10^7 γ/sec@10W/300mA
Nd:YVO_4 laser, wavelength/power	1.064 μm/ 30W, 0.532 μm/20W
10-17 MeV gamma-ray flux	5×10^7 γ/sec@30W/300mA

II. BL02

The LIGA (abbreviated name of Lithogaphic, Galvanoformung and Abformung) process which consists from deep x-ray lithography, electroforming, and molding process is one of the promising candidates for such 3D micofabrication. More than hundreds aspect ratio for microstructure can be attained by the usage of the higher energy x-rays (4-15 keV) from synchrotron radiation (SR) with deeper penetration depth to the photosensitive resist. In this system we have succeeded to enlarge the exposure area up to A4 size and the fabrication dimension from submicron to millimeter by varying the energy of the x-ray source in accordance with the size of desired microparts. Microstructure with high aspect ratio over several hundred will be achieved using the x-rays over 10 keV since high energy x-ray has deep penetration depth to the photo-sensitive resist materials. Whereas, in the case of lithography for low energy x-rays from 1 keV to 2 keV, submicron structures with high aspect ratio will be achieved using the x-rays mask with precise line-width and thinner absorber, since low energy x-rays has low penetration depth. Based on this principle, the beamilne for x-ray exposure have constructed with continuous selectivity of x-rays from 100 eV to 15 keV by using the x-ray mirrors (plane and cylindrical mirror) and Be film filters. The horizontal angle of the outgoing SR could be obtained up to 12.5 mrad, which corresponds to the horizontal size of 220 mm (A4 horizontal size) at the exposure position. The second characteristic performance of the beamline is the high efficiency differential pumping system. This was necessary for maintain the vacuum difference between the storage ring ($<10^{-9}$ Pa) and the end-station ($<10^{-9}$ Pa) at which gasses for substrate cooling will be introduced in the exposure apparatus.

The flexibility for the shapes and functions of microstructure will be enlarged by achieving 3D microfabrication process using multi step exposure at various configuration between x-ray mask and substrates. The relative positions between x-ray mask and substrates, tilt and rotation angle to the SR incident direction can be moved simultaneously during SR exposure using 5 axis stages. The movement of each axis is controlled by the PC in terms of the scanning speeds, scanning length, and repetition number. In order to decrease the heat load of sample substrate suffered during SR irradiation helium introduction and substrate cooling mechanism were also equipped. Specification of spectrometer is listed in Table 2.

Table 2. Specification of the LIGA exposure system

Optics	Plane and cylindrical mirror, Be filters
Exposure energy	100 - 2 keV, and 4 – 15 keV
Exposure method	Proximity and multi-step exposure
Wafer size	A4 or 8 inch
Exposure area	230 mm(H) ×300 mm(V)
Exposure environment	< 1 atm (He-gas)

III. BL03

BL03 is a beamline for the developing the next generation lithographic technology so called extreme ultraviolet lithography (EUVL). The exposure tool is installed at the end station. Using this exposure tool, the research and development of the next generation lithography such as the less than 70 nm node is going on process. The exposure wavelength is 13.5 nm.

The semiconductor industry plays a very important role in the information technology (IT). In 2006, 256 Gbit DRAM with a gate length of 70 nm will be demanded in the IT industry. The extreme ultraviolet lithography (EUVL) is a promise technology for fabricating a fine pattern less than 70 nm. To meet this schedule, this technology has to be developed in the pilot line until 2004. As for the practical use, it is very important that both to achieve large exposure area and to fabricate fine patterns. Therefore, at Himeji Institute of Technology, large exposure field EUV camera consists of three aspherical mirrors was developed. First in the world, we fabricated 60 nm line and space pattern in the large exposure area of 10 mm×10 mm on a wafer. Furthermore, BL03B beamline branches from the BL03 beamline propose for the usage of the EUVL microscope for the EUVL finished mask inspection. Table 3 shows the specification of ETS-1.

Table 3. Specification of the exposure tool (ETS-1)

Imaging optics	Three aspherical mirrors
Exposure wavelength	13.5 nm
Numerical aperture	0.1
Demagnification	1/5
Resolution	60 nm
Depth of focus	0.9 µm
Exposure area (static)	30 mm×1 mm
Exposure area (scanning)	30 mm×28 mm
Mask size	4 inch, 8 inch, and ULE 6025
Wafer size	8 inch
Exposure environment	In vacuum

IV. BL05

BL05 was constructed in response to a demand in the industrial world, which is enhancement of the analysis ability in the soft x-ray region with the development of nanotechnology. BL05 consists of two branch lines for use in the wide range from 50 eV to 4000 eV. BL05A and BL05B are designed to cover the energy range of 1300-4000 eV and 50-1300 eV, respectively. The incident beam from the bending magnet is provided for two branch lines through different windows of a mask. Therefore, these two branch lines can be employed simultaneously. At the end stations of each branch, the transfer vessel systems were mounted for the measurements of sample without exposure to air. In addition, globe box was placed for the preparation of samples into transfer vessel.

1) The double crystal monochromator was installed at the BL05A. InSb, Ge, Si, SiO_2, Beryl and KTP crystals are prepared for a double-crystal monochromator. Toroidal mirrors are used as a pre-mirror and a focusing mirror of BL05A. XAFS measurement in the total electron yield mode and fluorescence XAFS measurement using SSD (SII Vortex) can be performed. The fluorescence XAFS spectra can be measured for samples at the end station filled with He gas. Table 4 shows the specification of monochromater.

Table 4. Monochromator specification

Monochromator	Double crystal monochromator
Monochromator crystals	SiO_2 (1010) , InSb (111) , Ge (111) , Beryl (1010) , KTP (110) , Si (111)
Energy range	1300-4000 eV
Resolution	E/⊿E=3000

2) The constant-deviation monochromator consisting of a demagnifying spherical mirror and a varied-line-spacing plane grating (VLSPG), which can provide high resolution, simple wavelength scanning with fixed slits, was mounted on BL05B. The optical system consists of a first mirror (M0), a second mirror (M1), an entrance slit (S1), a pre-mirror (M2), and three kinds of plane grating (G), an exit slit (S2) and a focusing mirror (M3). The including angle of the monochromator is 175°. Two measurement chambers are prepared at the end station of BL05B. The XAFS spectra in the total electron yield mode and fluorescence XAFS spectra using SDD (Ourstex) can be measured in a high vacuum chamber. In addition, the photoelectron spectrum can be measured using spherical electron analyzer (VG Sienta, R3000) in an ultrahigh-vacuum chamber. The chambers can be replaced by each other within 1 hour. Table 5 shows the specification of the monochromator.

Table 5. Monochromator specification

Monochromator	Varied-line-spacing plane grating monochromator
Grating	100 l/mm, 300 l/mm, 800 mm/l
Energy range	50-1300 eV
Resolution	E/⊿E=3000

V. BL06

BL06 has been mainly developed for irradiation experiments such as photochemical reaction, SR-CVD, photo-etching, surface modification. The white radiation beam from bending magnet is introduced to the sample stage using a pair of mirror, whose incident angle was 3° . The SR at BL06 sample stage had a continuous spectrum from IR to soft x-ray, which was lower than 1 keV. A differential pumping system can be utilized for experiments in a gas atmosphere, which is difficult in the soft x-ray region. A sample holder can install four pieces of samples at a time. By using heater set in the sample holder, the sample can be heated from room temperature to 220°C. The temperature of sample is monitored using a Cr-Al thermocouple mounted on the sample holder.

VI. BL07A and BL07B

This beamline was designed for the development of new materials by SR technology. This beamline consists of two branch lines, which are provided with an incident beam from a 3-m-long undulator by switching the first mirror. One of them is a high photon-flux beamline with a multilayered-mirror monochromator for the study of SR-process (BL07A) and another is a high-resolution beamline with a varied line spacing grating monochromator for the evaluation of nano-structure characteristics by SR-spectroscopy (BL07B). The useful range of emitted photons from 50 to 800 eV is covered at both beamlines. The light source of BL07 is a 3-m length planar undulator, which consists of 29 sets of permanent magnets, a period length of which is 76 mm. The incident beam from the undulator is provided for two branch lines by translational switching of first mirror.

1) BL07A

The multilayered-mirror (MLM) monochromator, which has high reflectivity in the soft X-ray region, was installed at the BL07A. It consists of a switching mirror chamber, a slit chamber, a MLM monochromator, a filter chamber and a reaction chamber. To obtain a large photon flux, we decided to use only first mirror (switching mirror), M0, for focusing. The MLM monochromator is designed to cover an energy range of up to about 800 eV by combination of three kinds of mirror pairs with 4 kinds of filter. The flux deliver by this design is estimated to be between a maximum of 10^{17} photons/s at 95 eV and a minimum 2×10^{14} photons/s at 300 eV for a 500 mA ring current. Table 6 shows the summary of BL07A. In addition, X-ray fluorescence (XRF) apparatus using spherical varied line spacing grating was mounted at the downstream of irradiation chamber. The poly capillary was used to enhance beam-condensing efficiency. Measurement energy range was from 30 eV to 450 eV. This XRF apparatus was expected to utilize the chemical analysis on the light metals, Li and Be, and light elements, B, C and N.

Table 6. Summary of BL07A.

Energy range (eV)	Multilayer mirror					Filter	
	Material	spacing	Thickness Ratio	number of layers	ΔE/E	material	Thickness
50-60	Mo/Si	20 nm	0.8	20	6.2 %	Al	100 nm
60-95						None	—
90-140	Mo/B_4C	11 nm	0.5	25	3.3 %		
140-194						Ag	100 nm
190-400	Ni/C	5 nm	0.5	60	2.5 %		
400-560						Cr	500 nm
550-800						Ni	500 nm

2) BL07B

The constant-deviation monochromator consisting of a demagnifying spherical mirror and varied line spacing plane grating (VLSPG), which can provide to high resolution, simple wavelength scanning with fixed slits, was mounted on BL07B. The optical system consists of a first mirror (M0), an entrance slit (S1), a premirror (M1), and three kinds of plane grating (G), an exit slit (S2) and a focusing mirror (M2). The monochromator is designed to cover the energy range 50-800 eV with three gratings, of which including angle are 168°. The VLSPG has been well known to obtain high resolution in extreme ultraviolet region by diminishing various kinds of aberration. The total resolving power about 3000 can be realized in the whole energy region. Table 7 shows the specification of the monochromator.

Table 7. Monochromator specification

Mount type	Hettrick-Underwood type
Grating G1, G2, G3	Plane VLS (600 l/mm, 1200 l/mm, 2400 l/mm)
Energy range	50-150 eV, 150 – 300 eV, 300-800 eV
Resolving power (E/ΔE)	～3000

VII. BL9

A purpose of this beamline is studies on a soft x-ray interferometry or a holographic exposure experiment with making use of highly brilliant and coherent photon beams radiated from 11 m long undulator in NewSUBARU.

BL09 consists of M0 mirror, M1 mirror, G grating and M2 and M3 mirror. M0 and M3 mirrors are used for horizontal deflection and beam convergence, M1 is used for vertical beam convergence at the exit slit, and M2 is used for vertical deflection and beam convergence. A monochromator is constructed by M1 and a plane grating. The maximum acceptance of the undulator beam is 0.64 mrad in horizontal and 0.27 mrad in vertical. The acceptance can be restricted by 4-jaw slits equipped at upstream of the M0 mirror.

BL09A beamline is used for material analysis: X-ray absorption spectroscopy (XAS) and X-ray photoelectron spectroscopy (XPS). In 2013, X-ray emission spectrometer (XAS) was introduced at the endstation of the BL09A. The energy range and resolution of the XAS was designed to be about 50-600 eV and 1500, respectively.

BL09B beamline branched from BL09 beamline for the usage of the EUV interference lithography for the evaluation of the exposure characteristics of EUV resist. Coherence length of 1 mm at the resist exposure position was achieved using BL09B beamilne. And BL09C beamline branched from BL09B beamline for the usage of the thickness measurement of the carbon contamination originated to the resist outgassing during the EUV exposure. Table 8 shows the specification of the monochromator.

Table 8. Monochromator specification

Mount type	Monk-Gillieson type
Grating	Plane VLS (300, 900, 1200 l/mm)
Energy range	50 – 750 eV
Resolving power (E/ΔE)	～3000

VIII. BL10

BL10 is for the global use in the Himeji Institute of Technology. M0 mirror is used for horizontal deflection and beam convergence, M1 is used for vertical beam convergence at the exit slit, and M2 is used for vertical deflection and beam convergence. A monochromator is constructed by M1 and a plane grating. At the beginning, the multiplayers reflectivity measurement was carried out at this beamline. The characteristics of this beamline and the result of the Mo/Si multiplayers measurement are carried out for the development of the EUV- mask technology.

BL10 utilizes a monochromator of the varied line spacing plane grating monochromator (VLS-PGM). The line density of the monochromator in central region of the gratings were 600, 1800 and 2,400 lines/mm. The reflectometer is a two axis vacuum goniometer using two Huber goniometers. One axis carries the sample, which may for examplee be a mirror at the center of the reflectometer vacuum tank (θ-motion). The other (φ-motion) carries the detector on a rotating arm. In addition there are through-vacuum linear motions to translate the sample in two orthogonal directions (x,y). All motors are controlled by computer. The sample itself is mounted on a kinematic holder. The control stage monochromator rotation, and data analysis were program using LABVIEW software. The reflectivity result obtained at BL10 has a good agreement with that at LBNL. Table 9 shows the specification the monochromator.

The micro-CSM tool was adapted at the most downstream of the BL10 beamline for the EUV mask defect inspection. This too is very effective for the inspection of the actinic patterned mask.

A large reflectometer was installed in a branch line for large EUV optical component including EUV collector mirrors. The reflectometer has a sample stage with y, z, θ, ϕ, and Tilt axis, which can hold large optical elements with a maximum weight of 50 kg, a diameter of up to 800 mm, and a thickness of 250 mm. The entire sample surface is able to be measured.

Table 9. Monochromator specification

Mount type	Hettrick-Underwood type
Grating	Plane VLS (600, 1800, 2400 l/mm)
Energy range	50 – 1,000 eV
Resolving power (E/ΔE)	～1000

IX. BL11

A beam line BL11 is constructed for exposure Hard X-ray Lithography (DXL) in the LIGA (German acronym for Lithographite Galvanoformung and Abformung) process. LIGA process, that utilizes a useful industrial application of SR, is one of the promising technologies for fabrication of extremely tall three-dimensional (3D) microstructures with a large aspect ratio. This process was invented at the Institut Fur Mikrostrukturtechnik (IMT) of the Karlstuhe Nuclear Center (KfK) in 1980. Microstructures with height of over a few hundreds μm have been widely applied to various fields such as micro-mechanics, micro-optics, sensor and actuator technology, chemical, medical and biological engineering, and so on. This beam line was designed by the criteria ; photon energy range from 2 keV to 8 keV, and a density of total irradiated photons ≥ 10^{11} photons/cm^2. The BL11 can provide the most suitable photon energy for microfabrication in X-ray lithography, while the BL2 is equipped for fabricating fine pattern submicron-scale structure and microstructure with high aspect ratio by selectivity of X-rays using movable mirror system. That is, LIGA process in NewSUBARU can provide the best 3D microfabrication because the BL11 and BL2 are complementary. The beamline BL11 is consisting of an absorber chamber, a first-mirror chamber (M1), a 4-way slit chamber, a Be and polyimide window chamber, and an exposure chamber. The horizontal angle of the outgoing SR could be obtained up to 17.8 mrad, providing a beam spot size on the exposure stage ≥ 80 × 10 mm^2. The micron-scale structure with high aspect ratio will be achieved using the toroidal typed mirror M1 which can produce a parallel collimated beam of X-rays. In addition, the homogeneity of the beam is excellently controlled by a novel adding system.

Using the precision stage in the exposure chamber, the flexibility for the shaped and functions of microstructure will be enlarged by achieving 3D microfabrication process using multi step exposure at various configuration between x-ray mask and substrates. The exposure area of 200 mm × 200 mm is brought to fruition. In order to decrease the heat load of sample substrate suffered during SR irradiation, helium introduction and substrate cooling system were also equipped. The specification of the LIGA exposure system is listed in Table 10.

Table 10. Specification of the LIGA exposure system

Exposure method	Proximity exposure
Wafer size	8 inch
Exposure area	200 mm(H)×200 mm(V)
Exposure environment	< 1atm (He-gas)

Acknowledgement

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Construction of multilayered-mirror monochromator at BL07A

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Abstract

A new multilayered-mirror monochromator was constructed at a 3-m undulator beamline, BL07A. This monochromator was designed to cover an energy range from 80 eV to 800 eV using three kinds of multilayer mirror pairs. Using this monochromator, BL07A can be used as a high-photon flux and energy tunable beamline.

Introduction

A multilayered-mirror (MLM) monochromator designed especially for synchrotron radiation (SR) stimulated process experiments and a light source of X-ray fluorescence spectrometer has been constructed at BL07A. The light source of BL07 is a 3m length planar undulator. Undulator light has higher photon flux compared to light from a bending magnet but it is quasi-monochromatic, because several higher harmonic lights are generated corresponding to an undulator gap. A MLM monochromator can monochromatize incident soft X-rays with a high throughput and its resolving power, E/ΔE, is lower than 10, but, it is sufficient to remove the higher harmonic lights from undulator light except the purpose light. As a result, BL07A can be utilized as a high-photon flux and energy tunable beamline by the combination of undulator with a MLM. By the elimination of unnecessary harmonic lights, BL07A can be used for the SR stimulated process experiments at low temperature, such as crystallization of amorphous silicon, modification of glass as an optical wave guide, and any other surface modification using soft X-rays. In addition, a high-flux photon beam monochromatized with a MLM monochromator can be useful as a light source of X-ray fluorescence spectrometer which is mounted downstream of irradiation chamber of BL07A.

Specification

The MLM monochromator constructed in the present study covers an energy range from 80 eV to 800 eV by combinations of mirror pairs with filter. Soft X-ray is absorbed at the material surface to have high energy, and reflectance is extremely low. The multilayered reflecting mirror stacks a light element and a heavy element in turn and can achieve high reflectance by the borrowed light from the border of the layer interfering it, and strengthening it. The reflectance is decided at the properties of matter of the multilayer film material, a layer thickness and depends on the incidence angle to use interference. Three kinds of mirror pairs are prepared for this MLM monochromator, Mo/Si, Mo/B4C, and Ni/C, whose bilayer spacing , *d*, are 19.5, 11.2, and 5.1, respectively, and whose ratios of thickness of metal layer by d spacing, Γ, are 0.22, 0.53, and 0.51, respectively. Incident angle of this MLM monochromator can be varied from 4° to 65°. The filter is used to eliminate higher energy radiation included in reflected light from multilayered reflecting mirror. Three kinds of metal foil are prepared as a filter, Ag , Cr, and Ni, whose thickness are 100, 500, and 500 nm, respectively and their energy of absorption edge are 368 eV (Ag, M-shell), 574 eV (Cr, L-shell), and 852 eV (Ni, L-shell). As a result, the MLM monochromator constructed in the present study covers an energy range from 80 eV to 800 eV by combinations of three kinds of mirror pairs with three kinds of filter as summarized in Table 1.

Table 1 Summary of MLM monochromator

Energy range(eV)	Multilayer	Filter
80-140	①Mo/Si	None
125-140	②Mo/B_4C	None
140-200	①Mo/Si	Ag
140-360	②Mo/B_4C	Ag
260-400	③Ni/C	Ag
400-560	③Ni/C	Cr
560-800	③Ni/C	Ni

For the estimation of a photon flux, current detected with a photodiode (PD) was measured. During this experiment, the electron energy of the NewSUBARU ring was 1.5 GeV. Measured PD current was normalized by ring current at 300 mA, because the ring current decreased with time. Figures 1-5 depict normalized PD current at each harmonic light with a kind of filter. We can obtained photon flux from these data.

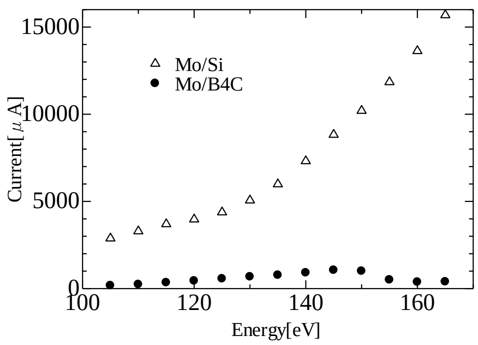

Fig. 1 PD current at 1st harmonic light without filter.

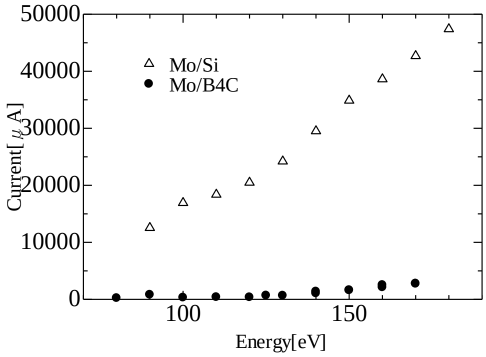

Fig. 2 PD current at 3rd harmonic light without filter.

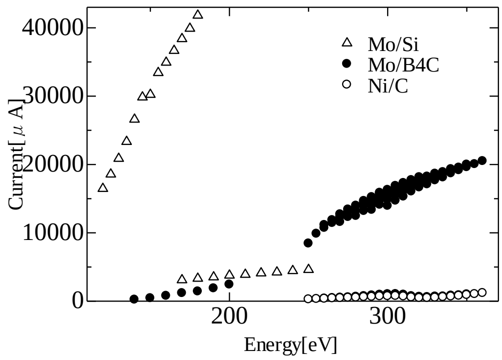

Fig. 3 PD current at 3rd harmonic light with a Ag filter.

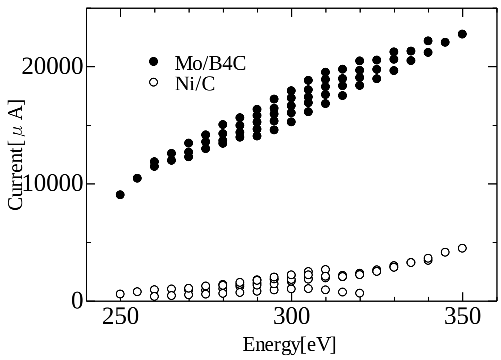

Fig. 4 PD current at 5st harmonic light with a Ag filter.

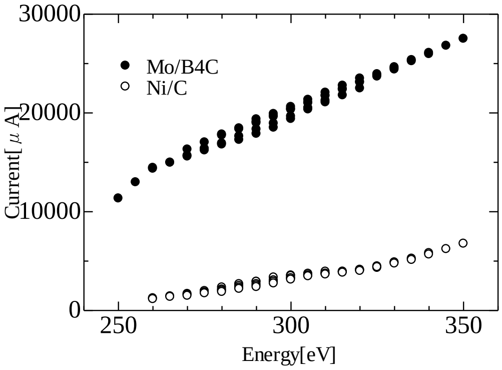

Fig. 5 PD current at 7st harmonic light with a Ag filter.

Construction of X-ray fluorescence spectrometer in the Ultra-soft X-ray region

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Abstract

We constructed a ultra-soft X-ray spectrometer, which can be measured in the range of ultra-soft X-rays of about 33-470 eV at the undulator line BL07A. The high-flux and high-resolution is performed by the use of two kinds of spherical varied-line spacing gratings, a poly-capillary, and a backside illumination type CCD camera. This spectrometer is expected to a high-resolution analysis of light-elements, light-metals, and transition metals.

Introduction

An X-ray fluorescence (XRF) spectrometer is used for routine, relatively non-destructive chemical analyses of industrial materials, biological materials, and environmental materials. The analysis of major and trace elements in samples by X-ray fluorescence is made possible by the behavior of atoms when they interact with radiation. When materials are excited with X-rays, they can become ionized. If the energy of the radiation is sufficient to dislodge a tightly-held inner electron, the atom becomes unstable and an outer electron replaces the missing inner electron. When this happens, energy is released due to the decreased binding energy of the inner electron orbital compared with an outer one. The emitted radiation is of lower energy than the primary incident X-rays and is termed fluorescent radiation. Because the energy of the emitted photon is characteristic of a transition between specific electron orbitals in a particular element, the resulting fluorescent X-rays can be used to detect the abundances of elements that are present in the sample.

For the measurement of XRF spectra, the use of SR presents especially the following advantages: 1) SR has high brilliance. 2) The excitation energy can be selected and adapted to the problem. 3) The radiation is linearly polarized. We constructed the SR-XRF setup at BL07A in the NewSUBARU facility. BL07A has a 3-m undulator as a light source and a high-photon flux and energy tunable light is supplied from a multilayered-mirror monochromator in the energy range from 50 eV to 800 eV. .

Specifications

Undulator light dispersed by a MLM monochromator was introduced to a Cr-coated planer mirror Cr mounted upstream XRF spectrometer to eliminate the high energy light higher than 500 eV, especially for oxygen, from the MLM monochromator. A schematic view of the XRF spectrometer is shown in Fig. 1. Reflected light at the plane mirror was incident to a sample. The fluorescent radiation in the ultra-soft X-ray region was c focused onto a slit using the poly-capillary, whose beam spot was ≈1 mm diameter. Dispersed ultra-soft X-rays by a grating were detected with a CCD camera. This spectrometer can measure the range of ultra-soft X-rays of about 33-470 eV.

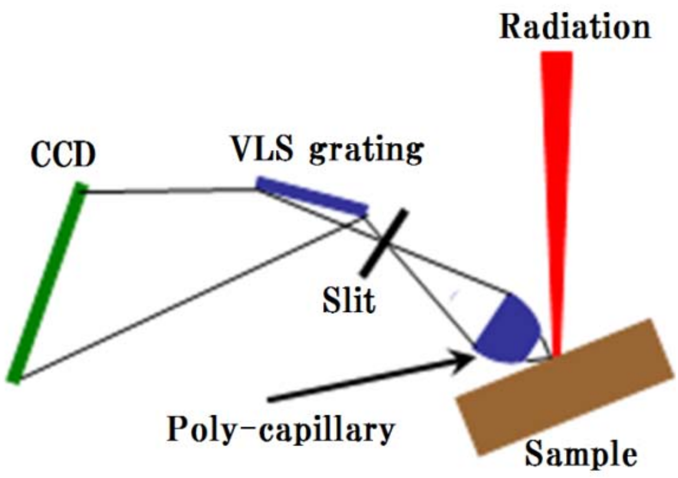

Fig. 1 A schematic view of the ultra-soft X-ray fluorescence spectrometer

This spectrometer has three characteristics. At first, two kinds of spherical VLS (varied line spacing) gratings designed with equal focal curves are used as the dispersion components. By using an appropriate grating properly by the energy range, XRF spectra can be obtained easier than a use of a single grating. The second feature is the use of a poly-capillary as the input component of the spectrometer. Using a poly-capillary, it is possible to increase the effective capturing angle of the ultra-soft X-rays, such that the ultra-soft X-rays can be efficiently converged and the detection efficiency increases. Moreover, the slit can be positioned on the poly-capillay's focus point to get the X-rays dispersed by gratings. The picture of the tip of the poly-capillary is shown in Fig. 2. The final feature is the use of backside illumination type CCD camera. This CCD camera has not a movable part and can detect the X-rays dispersed by the grating. The dispersion direction of the grating is set precisely to match the direction of the pixel lines on the projection plane. This setting made it possible to obtain the spectrum of ultra-soft X-rays because this measures the total signal strength of a pixel line perpendicular to the distributed direction. At the last, the specifications of the main components of the spectrometer are listed in Table 1.

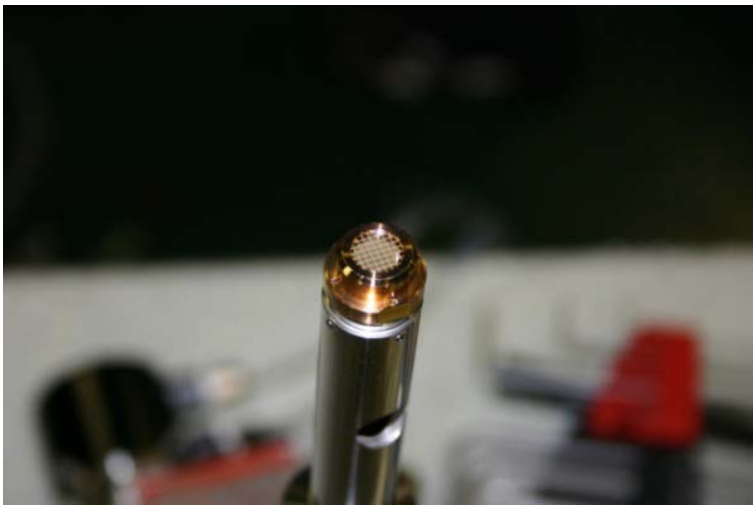

Fig. 2 The photograph of the tip of a poly-capillary

Table 1. The specifications of the main components of the spectrometer

grating	flat field spherical varied line spacing type
	Radius of curvature: 6005 mm
	braze angle: 1.7 ± 0.3°
	the incidence angle: 87.19°
	the incidence focal length: 240 mm
	the injection focal length: 300 mm
	size: 52×32 mm
	grating 1 (33 eV–140 eV)
	the number of the central fissure line: 300 Lmm^{-1}
	grating 2 (106 eV–470 eV)
	the number of the central fissure line: 1090 Lmm^{-1}
poly-capillary	collective solid angle: 0.072 Sr.
	input focal distance: 19.75 mm
	output focal distance: 215 mm
CCD camera	Roper SC-1300B (back side illuminated type)
	number of pixel: 1340×1300
	pixel size: 20 μm×20 μm
	detection area size: 26.8 mm×26 mm
slit	1mmφ, 100 μm×2 mm, 50 μm×2 mm, 2 mmφ (full open)
vacuum system	magnetic-levitating turbo-molecular pump
	spectrometer chamber: ~1×10^{-5} Pa, sample chamber : ~1×10^{-7} Pa

BL05 Operating Status

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Abstract

A material analysis beamline for the industrial enterprises' use was completed at BL05 in March 2008. This beamline is constructed on the basis of strong demand of industrial users for X-ray absorption fine structure (XAFS) spectroscopy. The used time of BL05 increased steadily every year. BL05 was broadly upgraded corresponding to the user's demands. This upgrading was expected to increase used time and to expand the industrial users.

Introduction

BL05 consists of two branch lines, one is a double crystal monochromator beamline (BL05A) for the use in the higher-energy region (1300-4000 eV) and the other is a varied line spacing plane grating (VLSPG) monochromator beamline (BL05B) for the use in the lower-energy region (50-1300 eV) [1]. These branches can be operated simultaneously. BL05 is managed and maintained by the Synchrotron Analysis L.L.C. (SALLC), which is composed of the industrial companies, in cooperation with the staffs of the Laboratory of Advanced Science and Technology for Industry in University of Hyogo.

1. BL05 Operating Status

The operation for public use of BL05 has started since 2008. In Fig.1, used time of BL05 is shown. The used time of BL05 increased every year. This beamline can be used as a trial use from 2010, which is supported from the ministry of education, cultur, sports, science and technology. Total used time, which included paid use and trial use, reached for 185 hours at total time of 2011, and broke through 200 hours in 2012. The used time of 2013 exceeded that of the previous year, although machine time of New SUBARU decreased due to the repair of SPring-8. The upgradings of BL05, installation of the calculation and combination type double crystal monochromator , systems of measurement in an in-situ environment, introduction systems for anaerobic sample, and the operation of beamline optics by remote control, were completed in 2014.

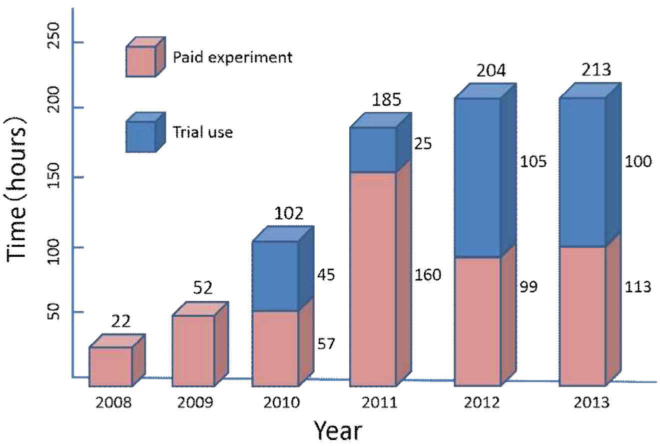

Fig.1. Transition of used time of BL05.

2. The training program for industrial researchers

For the purpose of enhancement the analytical skills using synchrotron radiation of industrial enterprises, we have opened the training program for industrial researchers from 2011 in cooperation with local public body etc (Fig.2). This program is covered not only lesson in the classroom, but hands-on practice of analysis using beamline. Some of the companies that participated in the program, used BL05 as a paid use.

Fig.2. Hands-on practice of analysis using synchrotron radiation.

Reference

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Recent upgrade of 15MeV Electron Linear Accelerator LEENA for THz Radiation Sources

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Abstract

The 15MeV electron linear accelerator LEENA has been upgraded towards tunable and high-power tera-hertz (THz) light sources using relativistic electrons. Recently we installed a solenoid coil for electron beam focusing and an OTR monitor for beam profile measurement. And also we constructed a THz beam-line for user experiments.

Introduction

In the building of NewSUBARU synchrotron light facility, we are developing tunable and high-power THz radiation sources using relativistic electron beams from a 15 MeV compact linear accelerator LEENA [1]. Synchrotron radiation from a bending magnet and Smith-Purcell radiation from a metal grating have been successfully observed in THz regime. A general layout of LEENA is shown in Fig. 1. Main parameters of the accelerator are shown in Table 1. If the electron bunch length is shorter than the wavelength of radiated electromagnetic wave, the electron beam coherently emits high-power radiation. In the last year several components of LEENA have been upgraded; (1) the installation of a solenoid magnet for focusing electron beam radius just after an electron gun, (2) the installation of OTR monitor for measuring electron beam profile and (3) the construction of THz beam-line.

Table 1. Main parameters of LEENA accelerator.

Beam energy	6 – 15MeV
Macro pulse current	100mA
Macro pulse width	5μs
Repetition rate	1-10Hz
RF frequency	2856 MHz
Normalized emittance	< 10πmm-mrad
Energy spread	<±0.5%@15MeV
Electron gun	RF gun
Cathode	LaB6 (thermal)
THz radiation sources	Bend, Smith-Purcell
Radius Curvature (BM3)	0.2m

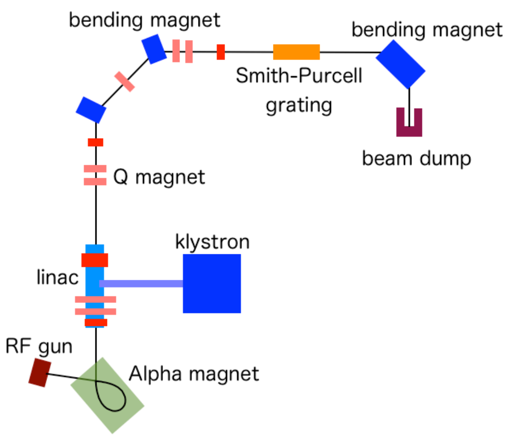

Fig.1 Layout of LEENA.

Solenoid magnet for electron beam focusing

One of problems on beam operation was the beam divergence at low energy region just after an electron gun. In order to correct the divergence of the beam radius, a new water-cooled solenoid coil of 22500 AmpereTurns as shown in Fig.2 is designed and installed at 10cm downstream of the RF electron gun. The maximum current of 300A generates magnetic field of 0.37T. Outside of the coil is covered with an iron plate of 5mm thickness to prevent the magnetic field from leaking. Figure 2 also shows the magnetic field calculated using POISSON code [2] with two-dimensional axial symmetry. It founds that field components on a cathode of the RF gun, which causes beam emittance growth, is very weak. With fine-tuning of the solenoid field, beam current loss became very small.

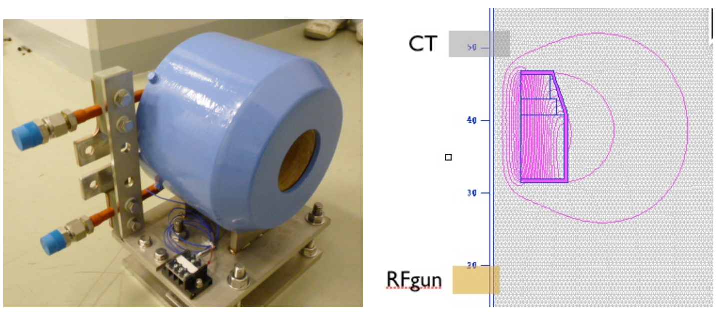

Fig.2 Solenoid coil (left) and 2D axial symmetric magnetic field calculated using POISSON code (right).

OTR monitor for measuring beam profile

When an electron passes through a surface of a thin metal film such as aluminum, the transition radiation is observed due to the difference of the dielectric constants of the vacuum and the metal. The transition radiation in the optical regime is commonly used as an electron beam monitor in linear accelerators (Fig. 3). Changing focal length of CCD camera lens, both the spot size and the divergence angle of an electron beam pulse can be measured.

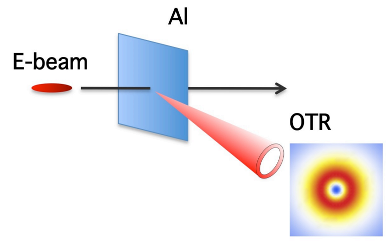

Fig.3 Optical Transition Radiation (OTR).

The installed film is aluminum of thickness 12 um. An IEEE1394 camera observes the OTR of 5 us time duration in synchronization with the electron beam. The acquired CCD image data is transferred to a PC and the application software developed by LabVIEW performs the real-time image processing and beam parameters can be evaluated as shown in Fig. 4.

Beam size measured using the OTR monitor is 0.8 mm in horizontal and 0.24 mm in vertical. And the measured beam divergence is 52 mrad in horizontal and 150 mrad in vertical. Thus the measured normalized emittances of 13.2π mm-mrad in horizontal and 11.5π mm-mrad in vertical are well corresponding to the designed value of 10 πmm-mrad. The OTR monitor is useful tool for the optimization of beam parameters towards the THz light source.

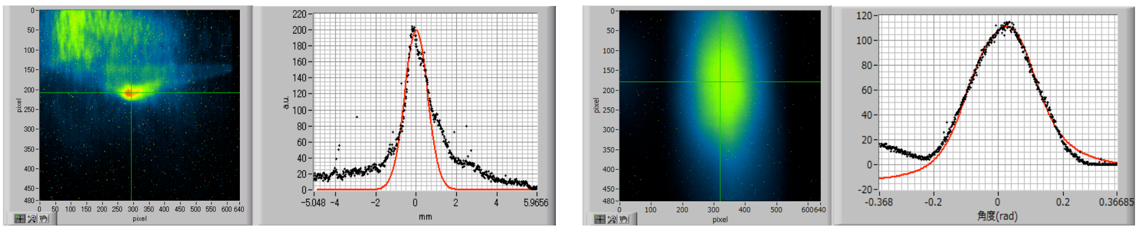

Fig.4 Observation of Optical Transition Radiation (OTR). Beam spot image and data fitting in vertical direction (left). Beam divergence and data fitting in vertical direction (right).

THz beam-line for user experiments

THz radiation was previously measured inside the concrete tunnel for the radiation protection. It was inconvenient to stop the machine every time we enter the tunnel for measurement setup.

In the newly constructed beam-line, THz radiation from the bending magnet is focused and transmitted using two curved-mirrors through a penetration hole in the concrete wall to the next experimental room, where an optical table is equipped for user experiment.

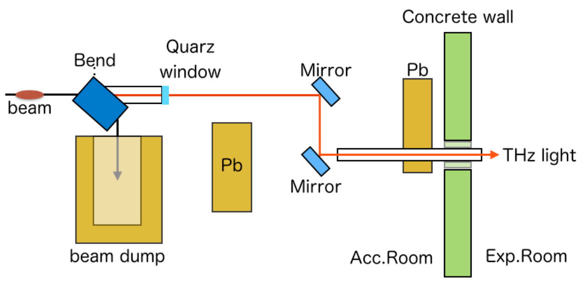

Fig.5 THz beam-line.

Recent operation status and future plans

The beam operation of LEENA has been stopped since January 2014 because of the failure of a high-voltage power supply for the RF klystron. The beam operations towards the generation of the coherent THz radiation by the short-bunched electron beams would be resumed after completion of the repair.

References

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