Current Status of NewSUBARU

NewSUBARU Storage Ring

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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 FY2011.

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.

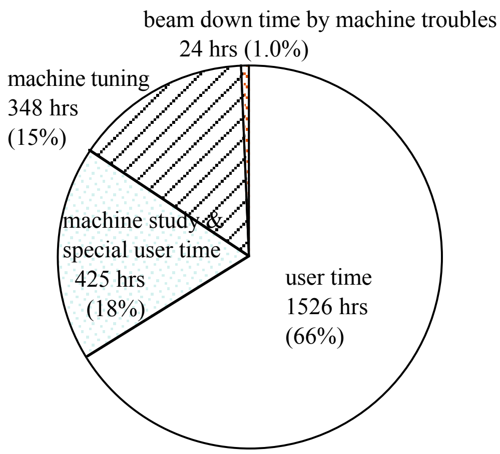

Figure 1: Machine time in FY2011.

The total machine time in FY2011 was 2323 hrs, 90% of that of FY2010, 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 normal user time in this FY, 1526 hrs, was about 102% of that in FY2010. Time for machine study and special users was 58% of that in FY2010. The down time due to the machine trouble was 1.0%, the same level with that in FY 2010.

Machine Troubles

The machine troubles in FY2011 are listed in Table II. Fig. 2 shows the rate of some typical failures in these six years. The rate of the same trouble has been decreasing year by year.

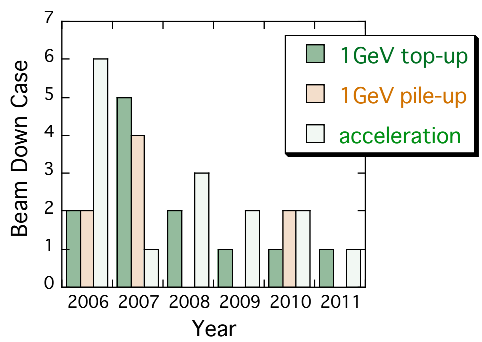

Figure 2: Rate of machine troubles since FY 2000.

The largest loss in this FY, we lost 12 hours, was the hardware trouble in the radiation safety PC. We had to stop beam injection because the PC could not save new radiation data.

Another big trouble was a vacuum leak. In July we identified a slow vacuum leak at BL11 from a reduction of beam lifetime at 1GeV. We needed weeks to understand it because the slow leak stopped at 1.5GeV. The leak point was near the photon absorber. It was fixed immediately after the recognition.

Machine Study and Special User Time

Table III shows the list of machine studies in FY 2011. One special theme, a research related to a production of Laser-Compton backscattering γ-ray and its use, took about 1/3 of the machine study time as had been in the passed FYs.

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 linear lattice model of the ring was improved. Figure 3 shows the ring parameters of 1/4 of the ring using the old and the new model. The new model was based on the measurement of the steering response. The most serious difference was the vertical beta function at the center of the long straight sections (s=0).

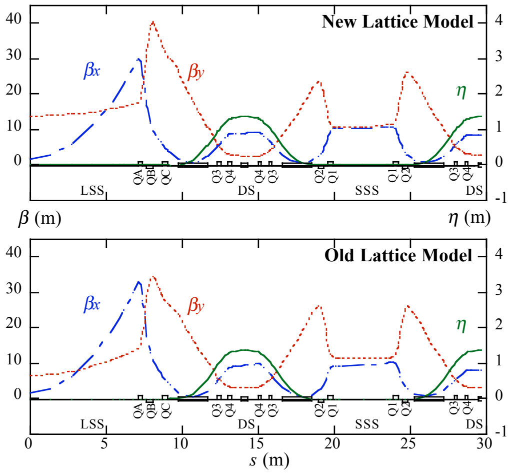

Figure 3: The old and the new linear lattice model for 1/4 of the ring.

The steering response matrix used in the COD correction system was also improved. The old matrix had been the one calculated from the old mode,l which had worse accuracy especially in vertical direction. The new matrices, one for 1GeV and the other for 1.5GeV, was the results of the measurement. The iteration process for the COD correction was improved and became faster.

The topical operational improvement was the raise of the top-up beam current at 1.0 GeV, from 220 mA to 250 mA. Figure 4 shows the history of the top-up beam current in these 5 years. This was achieved by better injection efficiency (Figure 5) and longer beam lifetime (Figure 6). At the best tuned machine condition we succeeded in 300 mA top-up operation.

Many machine studies about the injection process proved the importance of the horizontal quadrupole matching at the injection. The thin (0.1 mm) beam monitor screen was installed to one of the profile monitors in the beam transport line (L4BT). It improved the resolution from 1 mm to 0.2 mm (FWHM) and enabled an accurate Q-scanning, which was necessary for the matching. It realized the stable injection with high injection efficiency.

The commissioning of the multi-element corrector magnets, which were set at both ends of the long undulator, brought in the improvement of the beam lifetime. Not only the excitation of the multipole elements, but also the re-optimization of the existing magnet parameters made a big progress. On the other hand, the machine studies in these some years using the in-gap sextupole windings set at 6 invert bending magnets were not successful. It did improved the beam lifetime, however sacrificing the injection efficiency

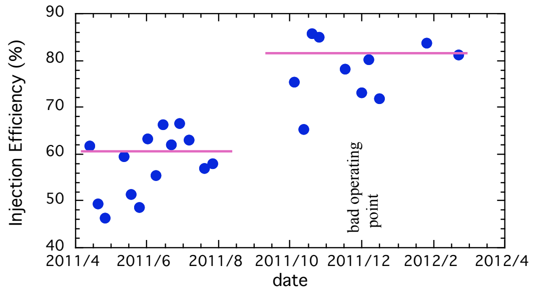

Figure 5: The improvement of the injection efficiency with typical undulator gap in FY2011.

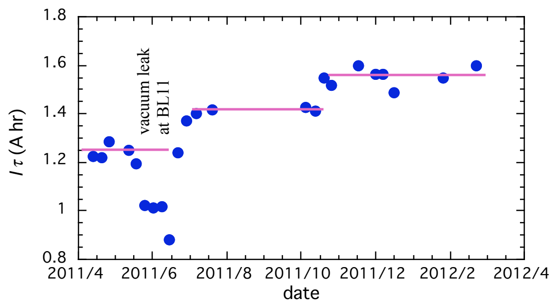

Figure 6: The improvement of the beam lifetime at 1 GeV with typical undulator gap in FY2011.

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Table II　Machine troubles in FY2010.

Group	Failure/trouble	beam down time (hr)
Operation (software)	RF voltage control program trouble	0.5
	Miss operation (human error)	1.2
Operation (others)	High radiation at intentional beam abort	0.4
	beam loss by a beam instabilities	3.7
Trouble of radiation safety interlock system		12.0
Troubles at SPring-8 (delay of starting schedule)		1.8
Vacuum leak at BL11		3.6
Electric power down by a thunder		1.3

Table III　List of machine studies in FY2011. The unit of study time is counted by shifts (typically 12 hrs).

R＆D theme and special user mode	responsible person	study shift
Betatron tune feedback system	S. Hashimoto	4
High Brightness operation	S. Hashimoto	4
Cancellation of LU effect	S. Hashimoto	1
Laser-Compton backscattering γ-rays	S. Miyamoto	19
Commissioning of the new profile monitor port SR5　Corona Graph	Y. Shoji	3
Commissioning of sextupole windings in the invert bends	Y. Shoji	3
Transverse beam matching at the beam injection	Y. Shoji	2
Instability suppression by chromaticity modulation	Y. Shoji	2
Detection of Coherent Synchrotron Radiation	Y. Shoji	4
Measurement of skew-quadrupole field distribution in the ring	Y. Shoji	2
Commissioning of the multi-element corrector	Y. Shoji	9
Measurement of amplitude dependent tune shift	Y. Shoji	1
Trial Shift of 300mA top-up operation	Y. Shoji	1
Coherent Synchrotron Oscillation Feedback	Y. Shoji	1

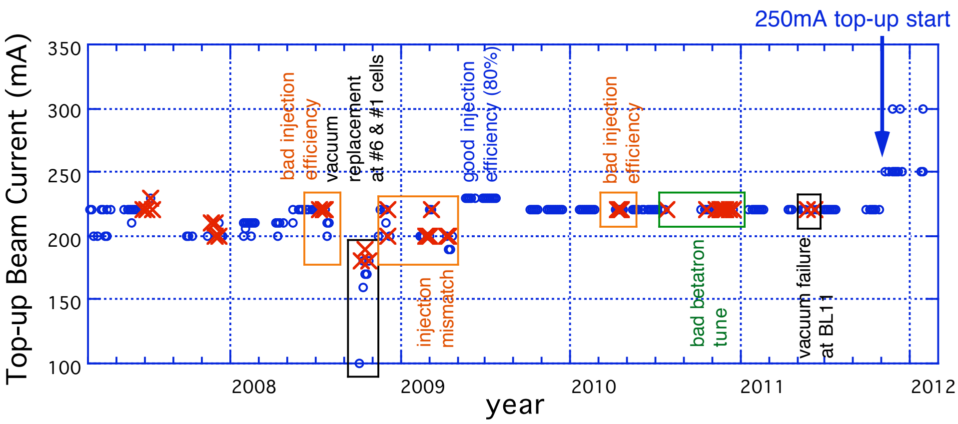

Figure 4　History of the top-up beam current of NewSUBARU since 2007.

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 constracted in response to a demand in the industrial world, that is 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.

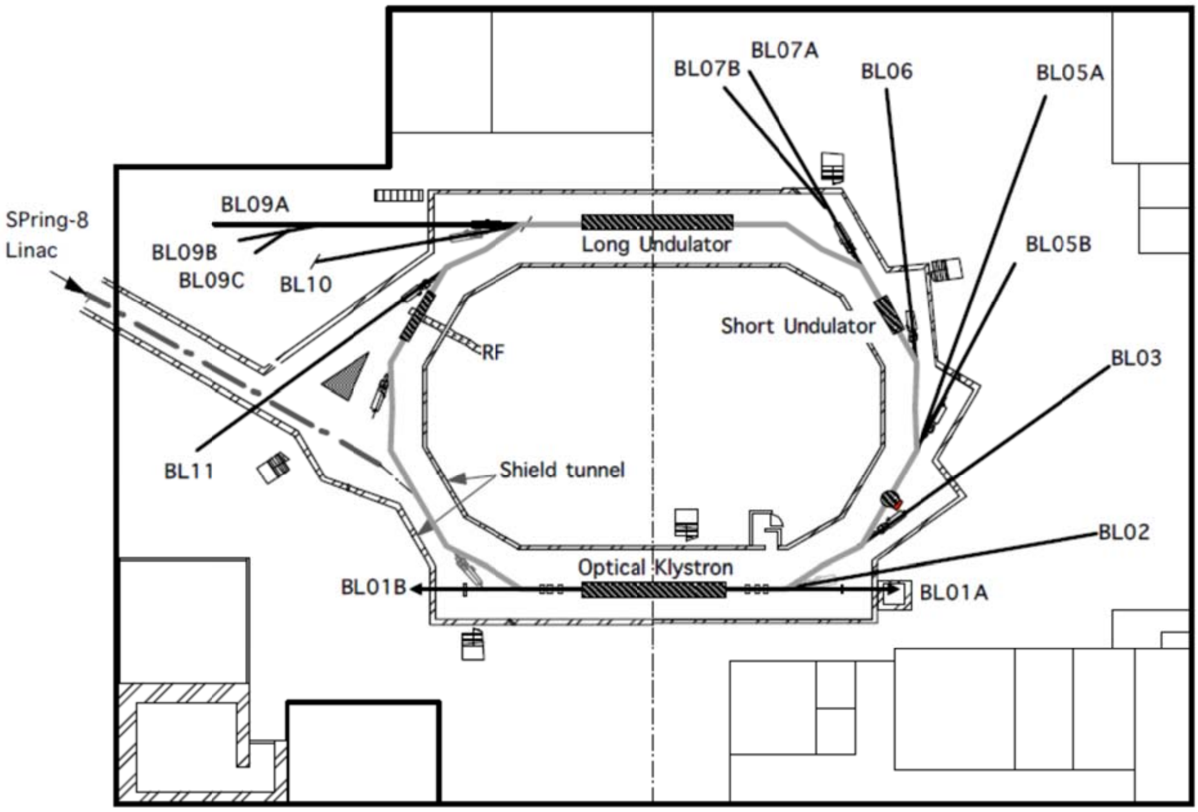

Fig. 1 Beamline arrangement in NewSUBARU.

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 FEL or 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. Specifications of this gamma-ray source are listed in Table 1.

Table 1. Specification of BL01 gamma beam

CO_2 laser 10.52 µm 5W	Gamma energy : 1.7 - 4 MeV Gamma flux* : 9 x106 γ/s : 6 x105 γ/s (1.5-1.7 MeV) (with 3mmφ collimator)
Nd laser 1.064 µm 0.532 µm 5 W	Gamma energy : 17 - 40 MeV Gamma flux* : 7.5 x106 γ/s : 3 x105 γ/s (15-17 MeV) (with 3mmφ collimator)

*Electron beam energy : 1-1.5 GeV
*Electron beam current : 250 mA
gamma-ray beam divergence : 0.5 mrad

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 usa 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 enlarged 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. Micostructure with high aspect ratio over several hundreds will bi 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 frpm 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 alse 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. 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, that 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.

1) The double crystal monochromator was installed at the BL05A. InSb crystals and Si 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. Monochromator specification

Monochromator	Double crystal monochromator
Monochromator crystals	InSb(111), 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 (EDAX) 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 ultra high-vacuum chamber. The chambers can be replaced by each other within 1 hour.

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 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. 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), a 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. Monocromator 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.

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. Monochromator specification

Mount type	Hettrick-Underwood type
Grating	Plane VLS (900 l/mm)
Energy range	50 – 600 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 reflectiveity 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 EUVL mask techmology.

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 grating is 600 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-cacuum 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 controlstage 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. Monochromator specification

Mount type	Hettrick-Underwood type
Grating	Plane VLS (600 l/mm)
Energy range	50 – 600 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 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 4 keV to 6 keV, a beam spot size on the exposure stage ≥ 50×5 mm^2, a density of total irradiated photons ≥ 10^{11} $photons/cm^2$. BL11 of an absorber chamber, a first-mirror chamber (M1), a second-mirror chamber (M2), a 4-way slit chamber, a Be window chamber, and an exposure chamber. The second pre-mirror is bent elliptically using a bending mechanism. Fine bending adjustment of the M2 mirror can be made in the UHV by the pulse motor. The LIGA process needs the photon energies of 3 keV to 6 keV, the optics of a LIGA beam line generally employ a Pt monolayered-mirror and a Be window, which cuts off low-energy photons. The reflectivity of a Pt-coated mirror is about 55 % in the range of photon energy from 2 keV to 4 keV, however, it drops to 30 % at the photon energy of 6 keV. Therefore, new materials with a high reflectivity must to be found for Deep X-ray lithography (DXL) in this energy range. We propose the use of a Ni/W/C multilayered-mirror with a graded d-spacing in the range of photon energy from 3 eV to 6 keV. The calculated reflectivity of the Ni/W/C multilayered-mirror is higher than 56 % at the photon energy of 6 keV with a glazing incident angle of 0.8 degrees, and photons that have higher photon energy than 6 keV can be removed A 200 μm-thick beryllium (Be) window in a Be window chamber is used to separate the ultra-high vacuum part from the low vacuum part and to cut off low-energy photons.

Table 10. Specification of the LIGA exposure system

Exposure method	Proximity exposure
Wafer size	4 inch
Exposure area	50 mm(H)×80 mm(V)
Exposure environment	< 1atm (He-gas)