CURRENT STATUS OF NewSUBARU

NewSUBARU Storage Ring

Y. Shoji

Storage Ring Parameters

The machine parameters of the 1.5 GeV storage ring remain the same as those of the previous year. They are listed in Table I.

Table I Main parameters of the NewSUBARU storage ring in FY2008.

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	6.30 (H),	2.21 (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	38 nm	67 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. Basic operation time is 9:00 - 21:00 of weekdays. Monday is 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.

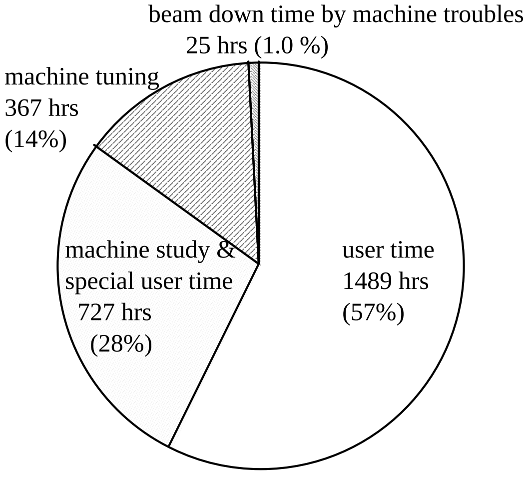

Figure 1: Machine time in FY2010.

The total machine time in FY2010 was 2608 hrs, 98% 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, 1489 hrs, was about 90% of that in FY2009. Time for machine study and special users was 138% of that in FY2009.

Machine Troubles

The machine troubles in FY2010 are listed in Table II. The total down time was only 1.0% of the total machine time. It was about 2/3 of that in FY2009 and 1/3 of that in FY2008. The main troubles in FY2010 were related to the COD control system.

We lost 4.6 hours of operation time related to the newly installed continuous COD correction program. We had some failures by software bugs and also some miss-operations of GUI.

We lost 8.5 hours due to a large COD during the acceleration process from 1.0 GeV to 1.5 GeV, although the current of the steering magnets were changed according to a fixed pattern control table. After the experiences of the beam loss by too large COD at the acceleration, we recognized the shift of the required current for the steering magnets. Figure 2 shows that the required current had changed day by day especially at the beginning of the operation cycle. With this knowledge, the operators reduced the orbit shift by adjusting the rf frequency and the failure almost disappeared. However, the reason of the change is not known.

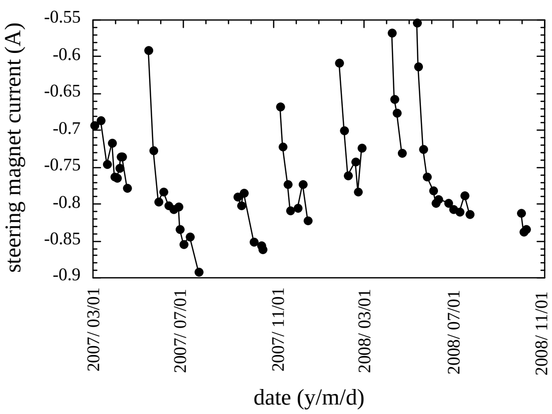

Figure 2: Example of the change of a steering magnet current after the COD correction. The average current of six horizontal steering magnets at dispersion sections is plotted. The values in the same operation cycles were connected with lines. A current shift of 0.1 A corresponds to an rf frequency shift of 2.1 kHz/500 MHz, or a maximum horizontal displacement of 3.4 mm.

Machine Study and Special User Time

Table III shows the list of machine studies in FY 2010. One special theme, a research related to a production of Laser-Compton backscattering γ-ray and its use, took about 1/4 of the machine study time as had been in passed FY.

Most of the study reports are open to the public on the home page of NewSUBARU.

Accelerator Improvements

The ring had some improvements in FY2009.

Bunch current monitor, installed in FY2008 was organized to a new bucket filling control system. It controls the bucket-selector for the injection and realizes a wanted bucket filling.

The COD correction system started continuous working. It operates slow COD correction routine for every one minute. Some soft ware bugs were found and fixed.

Four of the vertical steering magnets were replaced by multi-element corrector magnets (Figure 3). The new magnets worked as vertical steering magnets with exactly the same parameters of the old magnets. They were designed based on 3D field calculation considering the interference with other magnetic yokes nearby. The commissioning as the steering magnets was successful. The change of the deflection angle per current was less than a few %. The new R&D aiming for the improvement of beam lifetime started using their multi-pole field windings.

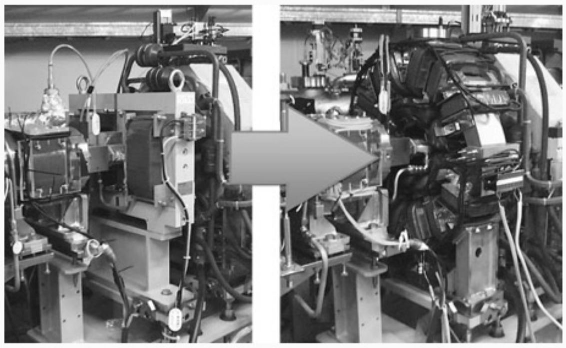

Figure 3: Four vertical steering magnets in the dispersion section were replaced by the multi-element corrector magnets.

Table II Machine troubles in FY2010.

Group		Failure/trouble	beam down time (hr)
Operation	(software)	Failure of COD control program	4.6
		RF voltage control program trouble	2.2
Operation	(others)	RF tuner position error	1.4
		High radiation at intentional beam abort	0.7
		Large COD at 1.5 GeV	8.7
		beam loss by a beam instabilities	2.6
Troubles at SPring-8 (delay of starting user time)			2.2
Electric power down by a thunder			2.3

Table III List of machine studies in FY2010. The unit of study time is typically 12 hrs/shift.

R＆D theme and special user mode	responsible person	study shift
Parameter tuning for 1.5 GeV acceleration	S. Hashimoto	1
Betatron tune feedback system	S. Hashimoto	9
Commissioning of X-ray BPM at BL10	S. Hashimoto	4
Beam profile measurement	S. Hashimoto	2
Measurement of steering response function	Y. Minagawa	2
Laser-Compton backscattering γ-rays	S. Miyamoto	21
Confirmation of cancellation table of undulator effect	T. Shinomoto	2
Radiation shield for L4BT beam profile monitor	Y. Shoji	1
Vertical beam oscillation at the beam injection	Y. Shoji	1
Commissioning of the new profile monitor port SR5	Y. Shoji	5
Commissioning of sextupole windings in the invert bends	Y. Shoji	8
Transverse beam matching at the beam injection	Y. Shoji	7
Effect of the magnetic shield for the DC septum stray field	Y. Shoji	1
Instability suppression by chromaticity modulation	Y. Shoji	2
Detection of Coherent Synchrotron Radiation	Y. Shoji	4
Measurement of beam orbit oscillation in 10 – 300Hz range	Y. Shoji	1
Measurement of coherent betatroon oscillation damping time	Y. Shoji	1
Measurement of skew-quadrupole field distribution in the ring	Y. Shoji	2
Commissioning of octupole component of the multi-element corrector	Y. Shoji	1
Measurement of amplitude dependent tune shift	Y. Shoji	2
Ring parameter measurement for better lattice model	Y. Shoji	1
Test of low emittance lattice	Y. Shoji	2

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.

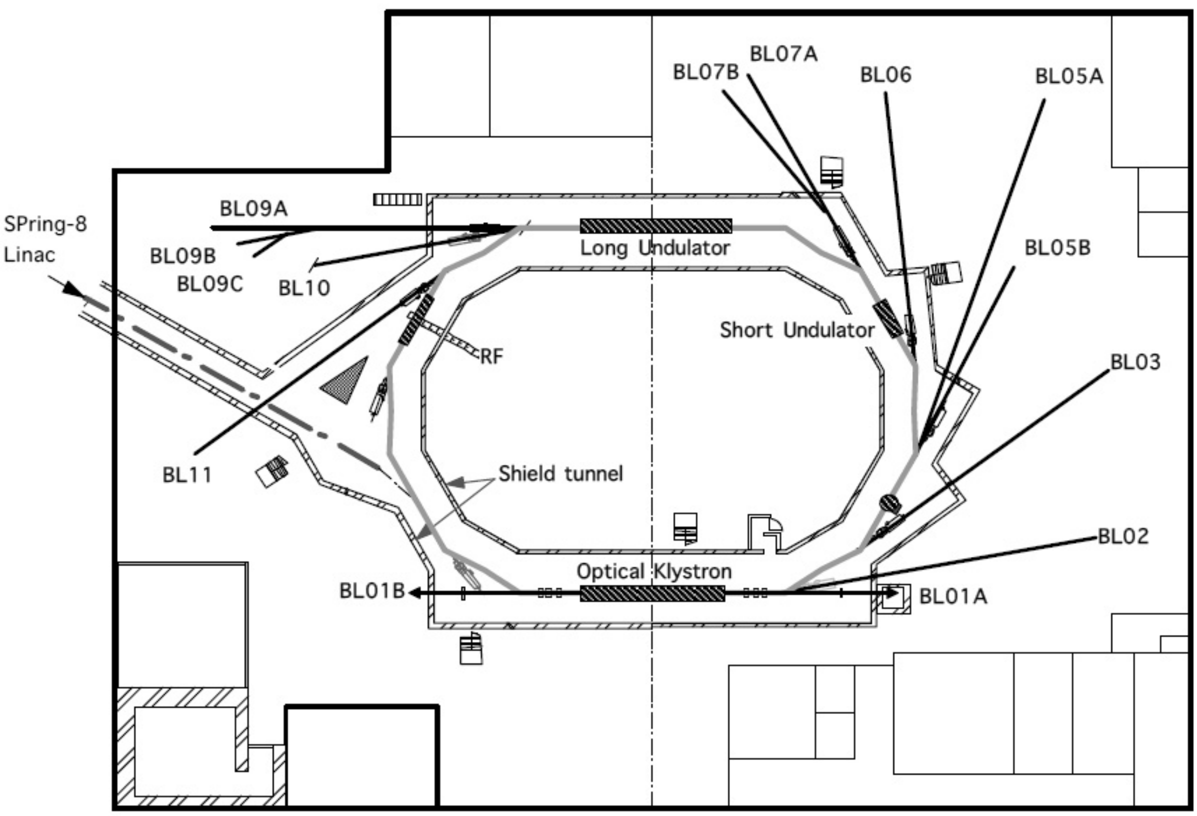

Fig. 1 Beamline arrangement in NewSUBARU.

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 x10^6 γ/s : 6 x10^5 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 x10^6 γ/s : 3 x10^5 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)

Center for EUV Lithography

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1. Overview of CEL

Laboratory of Advanced Science and Technology for Industry, University of Hyogo was established in 1995. EUVL Lithography development has been carried out since 1995 in University of Hyogo. Especially, utilizing the full field exposure tool which we developed, for the first time in the world, hp 40 nm resist fine pattern was replicated with collaborating with ASET in 2000. Following this, in 2001, it was reported that hp 39 nm resist pattern was replicated by EUV-LLC in USA. Related to these results, Dr. Gordon Moore from Intel Corporation decided to employ EUVL technology to apply in the high volume manufacturing (HVM) for the advanced semiconductor devices. Then after, the exposure tools have been developed by the stepper companies, and simultaneously the development of masks and resists have been carried out

Since 2006, Semiconductor Leading Edge Technologies (Selete) which receives a mandate to develop an EUVL technology from New Energy and Industrial Technology Development Organization (NEDO) has been investigated to develop exposure tools such as SFET and EUV1 for the development of the semiconductor devices. As results, it was concluded that “there is no obstacle to develop EUVL technology for 32 nm node”, and investigation program will finish in the end of March in 2010.

In our laboratory, concerning of the mask technology, EUV microscope was developed for the mask defect inspection from 2002 to 2007 by the funding from Core Research for Evolutional Science and Technology (CREST), Japan Science Technology Agency (JST). EUV microscope (EUVM) which is only one tool in the world is placed to use for the mask inspection of the absorber pattern and the mask blanks, and we obtained many results in collaborating with Selete. In addition, since 2008 for the mask inspection for 22 nm node and below, lense-less inspection tool on the basis of EUV coherent scattrometry has been developing in collaborating with RIKEN and Osaka University in the CREST program.

Furthermore, concerning of the resist, outgas evaluation during EUV irradiation has been carried out since 2000, and many scientific knowledge was obtained. Recently, the in-situ carbon contamination in the resist outgas environment by EUV irradiation has been carried out. And for the resist evaluation in 22 nm and 16 nm nodes, it is certain that EUV interference lithographic tool which we developed has a capability to replicate hp16 nm resist pattern.

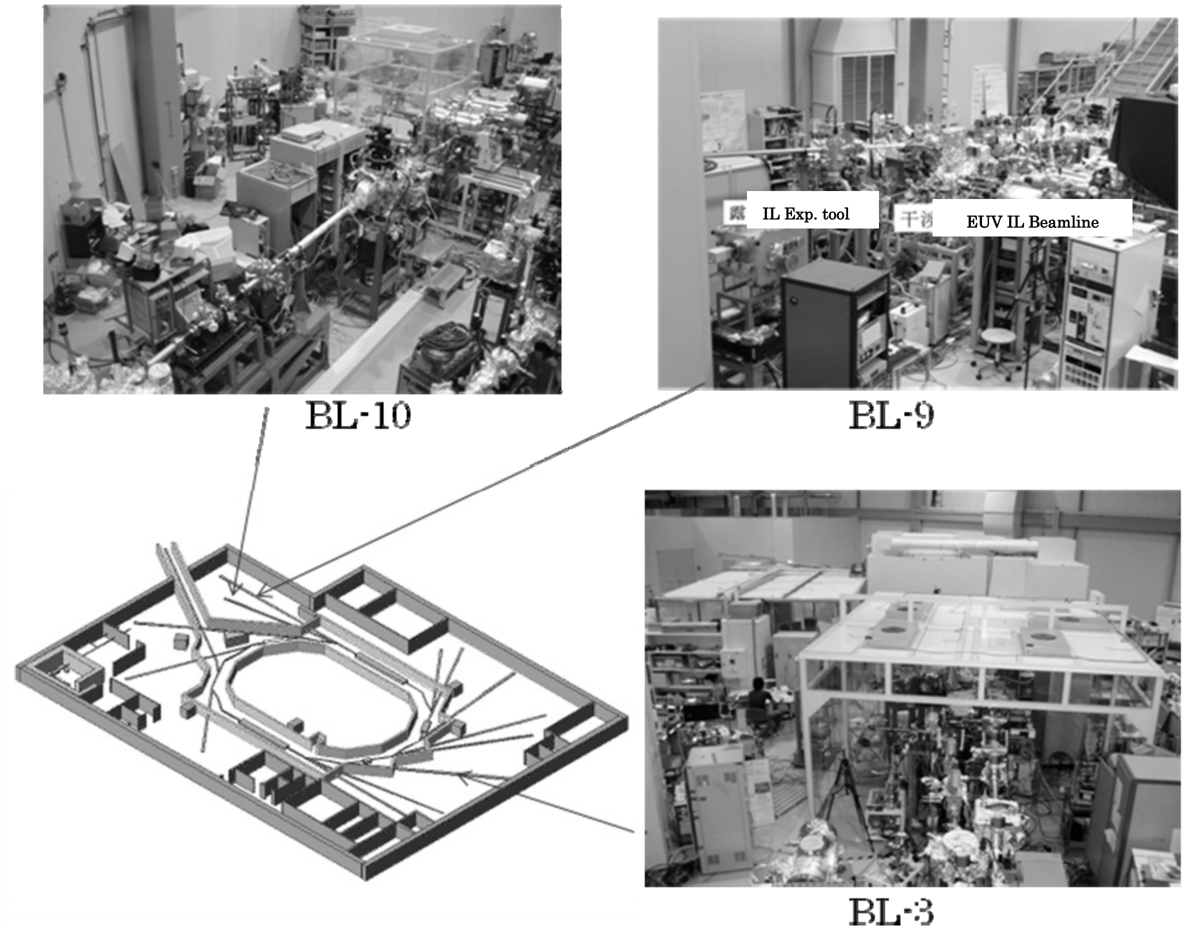
The market shares of the Japanese company supplying masks and resists for EUVL are high, such as 100% for the mask and 70% for the resists, respectively. Taking these shares into consideration, since useful equipments which we have developed in NewSUBARU for the advanced semiconductor devices using an EUVL technology can be opened for common use, we hope strongly that many companies could use the equipments. Consequently, it is consider that University of Hyogo can play a significant part of the development for the advanced semiconductor devices.

As results, “Center for EUV Lithography” is established, and use of NewSUBARU in EUVL technology is promoted. In addition, the experienced researchers from outside will be invited as a guest researcher of this center, and we will make efforts to receive the user’s comments and requirements to support the EUV lithographic technology for the practical use.

2. The Outline of the beamlines for EUVL

The exposure and evaluation experiments related EUVL are carried out at BL-3, BL-9 and BL-10 beamlines of the NewSUBARU synchrotron radiation facility in Center for EUV Lithography.

BL-3 (bending magnet as a light sourc): EUV microscope (EUVM) and EUV coherent scattrometry micropscope (CSM) are installed in this beamiline. EUVM is developed for absorber pattern inpspection for the EUV finishied mask. CSM is developed for the phase defect inspection of the mask blanks and continously developing it to achievce more higher resolution in inspection.



BL-9 (10.8-m-long undulator as a light source): Since monochrometer is installed at the middle of this beam line, high accurate spectroscopic measurement is available using the undulator and the monochrometer. Especially, EUV interfrence lithograpic exposure system is installed in the clean room at the end of this beamline. Furthermore, in the additional bemaline which is seperated from the original one, resist outgas evaluation system and in-situ thickness measuement system for the carbon contamination adhesion under the similar light intensity of the HVM EUV exposure system.

BL-10 (bending magnet as a light source): Since two monochrometers of 600/mm and 1800/mm are installed at the middle of the beamline, a high accurate reflectivity measurement for the optical element such as multilayer mask is available using this beamline. In addition, the optical constants measurement utilizing the vacuum chamber for common use is carrying out. In the future, refelctivity measurement of the illumination optics, multilayer charactreization evaluation, and multilayer evalution using polarized light are planned to use the BL10 beamline.

Study on High Brightness Operation of NewSUBARU without RF Shaker

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Abstract

We studied the possibility of the high brightness operation of the NewSUBARU electron storage ring without lattice modification. By turning-off the RF shaker that is used to enlarge the vertical size and the lifetime of stored electron beams, the brightness can be improved 2.7 times assuming that the stored current is the same. As the lifetime decreases, the top-up current is also reduced due to the limitation for the total charge that can be injected to the ring. Using a top-up simulator, we found that the brightness improvement factor could be 1.6 including the stored current decrease effect.

Introduction

Beam lifetime of the NewSUBARU electron storage ring is dominated mainly by the Touschek effect at 1.0 GeV operation. The industrial users in our radiation facility such as EUVL lithography and LIGA have been performed irradiation experiments and prefer the beam operation with a long beam lifetime and an high top-up current more than that with an high brightness. To improve the lifetime the ring has been operated with intentionally enlarged vertical beam size using RF shaker, where amplified white-noise signal is added to four strip-line electrodes to vertically shake electron beams, and now we achieved the lifetime of 7.4 hrs at the top-up operation of 220mA.

Recently, increasing number of industrial analysis users in our facility want the high resolution of synchrotron radiation and the high brightness operation. Generally speaking, the high brightness operation of storage rings needs re-design of ring lattice and re-arrangement of magnets and vacuum chambers and so on. However, in case of NewSUBARU, there is room for making the brightness higher by an easy way, that is, the operation without RF shaker.

Laws and regulations on radiation safety restrict the total charge that can be injected from a linac to our ring per eight hours (one shift). This fact means that the reduced beam lifetime causes the reduction of the top-up current that should be kept constant for eight hours. It is important to evaluate how much the brightness is improved and how much top-up current is reduced by turning-off RF shaker.

Measurement of Lifetime and Beam Size

The total beam lifetime τ is determined by the Touschek lifetime τ_{Tous} and the gas scattering lifetime τ_{gas}; $1/\tau = 1/\tau_{Tous} + 1/\tau_{gas}$. We measured the dependence of the lifetime on RF shaker power as shown in Fig. 1. The inverse lifetime increases according to the inverse square root of the RF shaker power. Turning-off RF shaker, the lifetime was reduced to 2.1 hrs. The vertical size of electron beams was also measured using a visibility monitor [1]. As shown in Fig. 2, the vertical beam size increases according to the square root of shaker power, that is, kick strength. From these data, we found that $1/\tau = 0.664/\sqrt{W} + 1/\tau_{gas}$, and τ_{gas} is about 470 hrs at 1.0Gev, 220 mA.

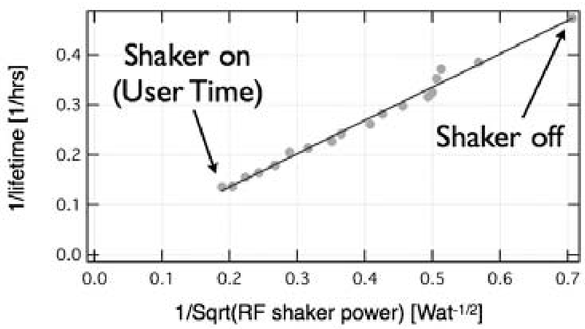

Fig.1. Lifetime vs. RF shaker power

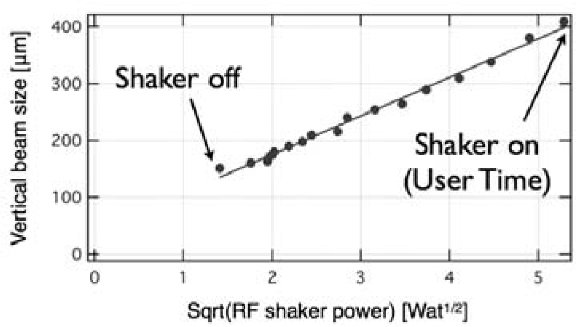

Fig.2. Vertical beam size vs. RF shaker power

Improved Brightness Estimated by Calculation

The brightness of synchrotron radiation is given by

(Brightness) $\propto$ (Photon Flux) / (source dimensions) / (angular spreads of source).

Following the above relation, the reductions of dimension and angular spread of a photon source makes the brightness higher. We evaluated equivalent reduction of vertical emittance by turning-off of RF shaker and calculated the improved brightness using the above equation and SRW [2]. Calculated results show that the brightness could be improved 2.7 times in case of the same stored current by turning-off RF shaker as shown in Fig. 3.

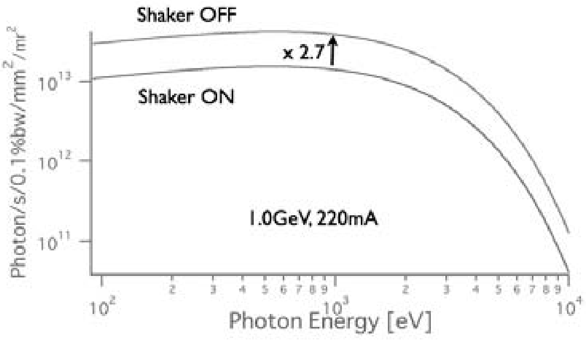

Fig.3. Calculated improvement of brightness.

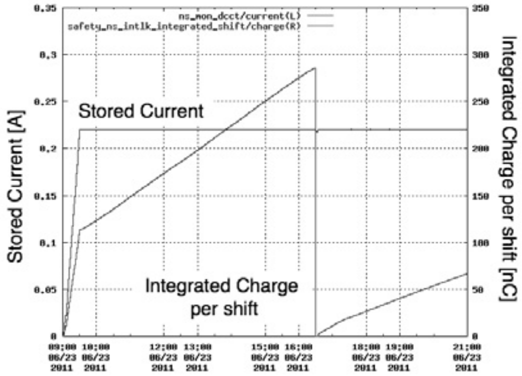

Fig. 4. Beam accumulation and top-up operation in a day

Estimation of the Reduced Top-up Current using Top-up Simulator

The reduced beam size causes the reduction of the Touschek lifetime and the possible top-up current. To evaluate the maximum top-up current, we developed the top-up simulator [3] that can simulate beam accumulation and top-up operation including various effects such as injection beam intensity, injection efficiency and lifetime and so on. Beam accumulation and top-up operation in a typical day is shown in Fig. 4. In our facility a beam accumulation starts at 9 a.m. and if the stored current reaches 220mA the top-up operation for user time starts. The amount of injected charge is measured at a beam transport line. If the integrated charge exceeds the limit in one shift (369nC), the safety interlock system stops beam injections. The integrated value is reset at 8:30, 16:30 and 0:30.

The results of simulation are in good agreement with the realistic operation. Using this simulator, we found that the maximum top-up current is 135mA in the case of turning-off RF shaker. In other words, the operation over 135mA can't keep the top-up current constant until reset time of 14:30.

Considerations

By turning-off RF shaker, the brightness at the same current increases, but the maximum top-up current decreases. The brightness improvement factor including the current reduction effect is shown in Fig. 5. From this figure we found that it is possible to make the brightness 1.6 times higher by simply turning-off RF shaker.

The high brightness operation without RF shaker could be one of operation modes in NewSUBARU, if users require the radiation with higher quality in our facility.

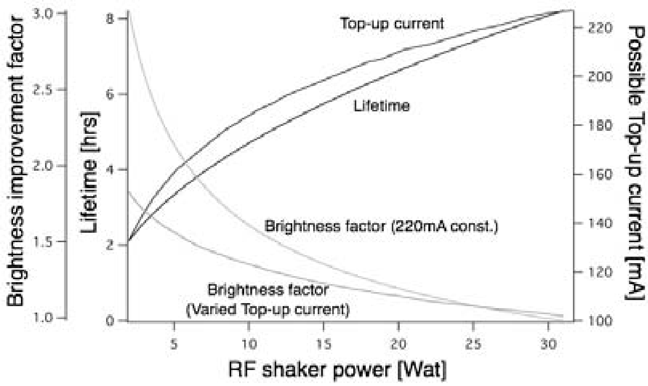

Fig.5. Brightness improvement factor

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[2] http://www.esrf.eu/Accelerators/Groups/InsertionDevices/Software/SRW
[3] S. Chin, Bachelor thesis, University of Hyogo (2010)