ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-FRYD2

RECENT DEVELOPMENT AND FUTURE DIRECTION OF RING-TYPE SYNCHROTRON LIGHT SOURCES IN JAPAN

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Abstract

Nine storage rings have been used as ring-type synchrotron light sources in Japan until FY2023. Among them, SPring-8 is the only 3rd generation synchrotron light source with high brilliance of 10^{21} photons/sec/mm^2/mrad^2/0.1% b.w. around 10 keV hard X-ray region. To provide a highly brilliant soft to tender X-rays around 1 keV, a new 3-GeV synchrotron light source, NanoTerasu, started user operation in April 2024 as the world's fourth MBA (Multi-Bend Achromat) light source. SPring-8 and NanoTerasu will form a Japanese photon science platform covering a wide spectral range from ultraviolet to hard X-rays from now on. In 2029, SPring-8-II is scheduled to commence user operation with two orders of magnitude higher brilliance than SPring-8 by employing MBA lattice and damping wigglers. Another ring-type synchrotron light source is a compact energy recovery linac (cERL) developed at KEK as a prototype for a 10 kW class high-power ERL free electron laser (FEL) for future EUV lithography. Recently FEL amplification at infrared wavelength was observed at the cERL. This paper will present an overview and future direction of synchrotron radiation light sources in Japan, with a particular focus on recent advances in NanoTerasu.

INTRODUCTION

Nine storage ring synchrotron light sources have been used in Japan until FY2023 [1-8]. The location of each storage ring is shown in Fig. 1. The stored electron beam energy ranges from 0.5 to 8 GeV with beam currents up to 500 mA, as shown in Table 1, covering wide spectral range from ultraviolet to hard X-rays. Among them, SPring-8 with natural horizontal emittance of 2.4 nm.rad and beam current of 100 mA is the only 3rd generation light source capable of delivering highly brilliant light of 10^{21} photons/sec/mm^2/mrad^2/0.1%b.w. in the hard X-ray region around 10 keV, while the emittances of the rest of storage ring light sources are greater than 16 nm.rad. In order to provide a highly brilliant soft to tender X-rays around 1 keV, a new 3 GeV light source named NanoTerasu was constructed as the world's forth MBA (Multi-Bend Achromat) light source in northern part of Japan, Sendai, as a complementary partner of SPring-8 [9]. The specifications of NanoTerasu are natural horizontal emittance of 1.14 nm.rad and beam current of 400 mA with circumference of 348.8 m. NanoTerasu started user operation in April 2024. SPring-8 and NanoTerasu will deliver highly brilliant light from ultraviolet to hard X-rays as a Japanese photon science platform from April 2024. SPring-8 is scheduled to be upgraded to SPring-8-II with two orders of magnitude higher brilliance by employing MBA lattice and damping wigglers [10]. In 2029, SPring-8-II will commence user operation opening the new era of twin MBA light sources in Japan.

Another ring-type synchrotron light source in Japan is a compact energy recovery linac (cERL) at KEK to develop ERL key technologies such as a photoemission 500 kV DC gun, 1.3 GHz superconducting cavity and ERL operation since 2013 [11]. A main objective of the ERL is to develop a 10 kW class high-power ERL free electron laser (FEL) for future EUV lithography [12]. A stable 1 mA ERL operation [13] and FEL amplification at wavelength of 20 µm in a SASE FEL [14] were demonstrated at the cERL with energy of 17.6 MeV.

This paper will present an overview and future direction of synchrotron radiation light sources in Japan, with a particular focus on recent advances in NanoTerasu.

Table 1: The Main Parameters of Japanese Storage Ring Synchrotron Light Sources in 2023.

SR light sources	Energy (GeV)	Current (mA)	Circumference (m)	Emittance (nm.rad)	Ref.
AURORA	0.575	300	3.14	1600	[1]
HiSOR	0.7	300	21.95	400	[2]
UVSOR	0.75	300	53.2	16.9	[3]
AICHI	1.2	300	72	53	[4]
SAGA-LS	1.4	300	75.6	25.1	[5]
NewSUBARU	0.5-1.5	500	118.731	38	[6]
KEK-PF	2.5	450	187	34.6	[7]
KEK-PF-AR	6.5	60	377	290	[7]
SPring-8	8	100	1435.95	2.4	[8]

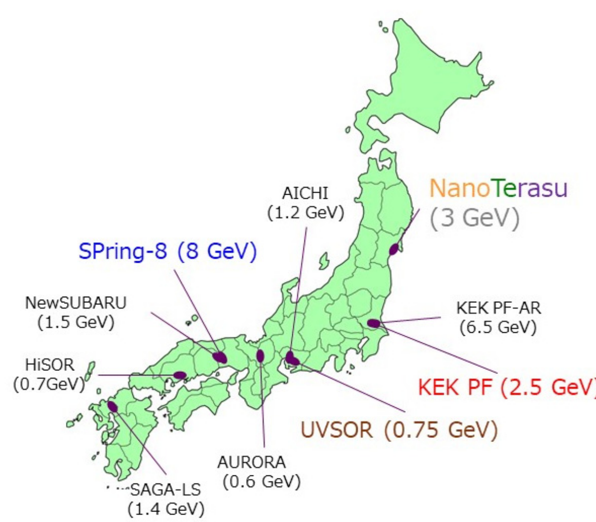

Figure 1: Locations of storage ring synchrotron light sources in Japan.

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ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-FRYD2

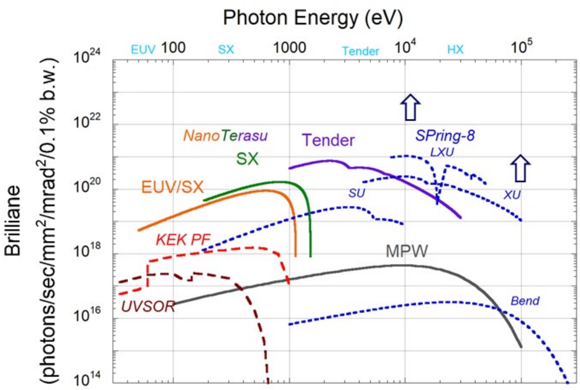

Figure 2: Brilliance as a function of photon energy for SPring-8 depicted by blue dotted lines, NanoTerasu by solid lines, UVSOR by brown dashed line, and KEK PF by red dashed line. Up arrows indicate two orders of magnitude increase in SPring-8-II.

STORAGE RING LIGHT SOURCES IN JAPAN

Figure 2 shows the brilliance as a function of photon energy for SPring-8 by blue dotted line, NanoTerasu by solid lines, UVSOR by brown dashed line and KEK PF by red dashed line. The brilliance for energy lower than 1 keV is shown for KEK PF for simplicity, because the brilliance of SPring-8 had been highest above a few hundreds of eV before NanoTerasu came out in 2024.The brilliances at EUV, SX, and Tender X-ray regions of NanoTerasu are one to two orders of magnitude higher than SPring-8, KEK PF, and UVSOR. Various types of scientific experiments and industrial applications at EUV, SX, and Tender X-ray regions are expected to be performed at NanoTerasu from now on.

The next breakthrough of brilliance is scheduled in 2029 when SPring-8-II commences 6-GeV user operation with two orders of magnitude higher brilliance than SPring-8 by employing 5BA lattice and damping wigglers installed in 30 m long straight sections. The target beam emittance is 0.05 nm.rad and the brilliance at 10 keV approaches 10^{23} photons/sec/mm^2/mrad^2/0.1%b.w. around 10 keV photon energy [10].

The concept of complementary partnership between SPring-8 and NanoTerasu is not only limited to photon energy ranges to be covered but also shared in various aspects to effectively build the Japanese photon science platform. Long-term R&Ds of accelerator system towards SPring-8-II are extensively utilized in NanoTerasu accelerator. Operational experience of SPring-8 for more than 25 years as one of the world biggest synchrotron radiation facilities is fully feedbacked to NanoTerasu. Many accelerator components, technology and network system are common in each other, resulting in fast troubleshooting. Experience of NanoTerasu construction and operation is timely feedbacked to SPring-8-II upgrade planning. NanoTerasu will also serve as a hard X-ray light source during temporary shutdown period of SPring-8 toward upgrade. Table 2 compares main parameters of SPring-8, NanoTerasu, and tentative design of SPring-8-II. The horizontal beam sizes at an insertion device center at NanoTerasu and SPring-8-II are 2.6 and 12 times smaller than SPring-8, respectively, while the vertical beam sizes are almost the same.

Table 2: The main parameters of SPring-8, NanoTerasu and tentative design of SPring-8-II [10].

	SPring-8	NanoTerasu	SPring-8-II
Energy (GeV)	8	3	6
Emittance (nm.rad)	2.4	1.14	0.05
Stored current (mA)	100	400	200
Lattice	DBA	4BA	5BA
Brilliance (ph/s/mm^2/mrad^2/0.1%b.w.)	7x10^{20}	8x10^{20}	9x10^{22}
σ_x at ID (μm)	316	121	20
σ_y at ID (μm)	5	6	5

NANOTERASU: A 3GEV LIGHT SOURCE

Overview

NanoTerasu is a medium-sized highly brilliant SX and Tender X-ray storage ring light source built on a green-field with the layout shown in Fig. 3 [9,15]. A full energy 3 GeV linac is used as an injector. The length of linac is 110 m, which is more than twice shorter than a 3 GeV injector S-band linac [16], by employing C-band accelerator cavities. The injector linac would be used as an SX FEL driver in the future. The circumference of the ring consisting of 16 of 4BA lattices is 348.8 m, which is roughly 2/3 of existing 3 GeV MBA light sources, MAX-IV and SIRIUS [16,17]. The compact accelerator system greatly contributed to significant cost reduction of construction and operation of NanoTerasu facility.

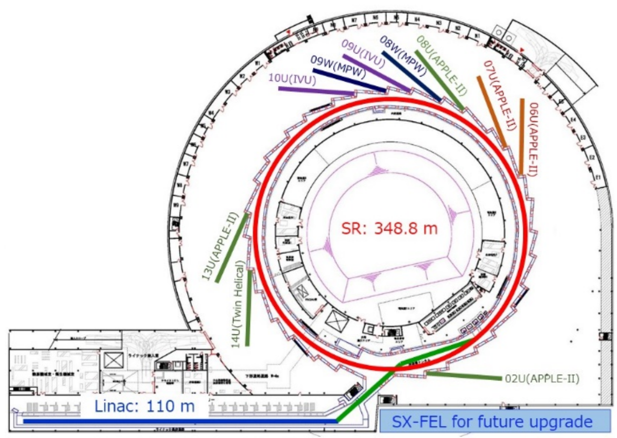

Figure 3: Layout of NanoTerasu facility.

The natural horizontal emittance is 1.14 nm.rad with a maximum stored beam current of 400 mA by employing 4BA lattice with combined function bends in NanoTerasu. The lattice functions and magnet layout of 4BA lattice is shown in Fig. 4. The 21.8 m long lattice has a long straight of 5.44 m and a short straight of 1.64 m at the lattice center. The storage ring consists of 16 cells. The 14 long straights

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-FRYD2

and 14 short straights are used to install undulators and multi pole wigglers (MPW), respectively. In April 2024, two MPWs for hard X-rays, two in-vacuum undulators for tender X-rays, and two APPLE-II and a twin helical undulators for EUV to SX regions were in operation for users and three APPLE-II undulator beamlines are under commissioning.

Although the horizontal emittance of 1.14 nm.rad is roughly 4 times greater than existing 3 GeV MBA light sources, MAX-IV and SIRIUS, the designed vertical emittance of 0.01 nm is almost diffraction limited in SX region and the coherent ratio approaches 10 % at 1 keV photon [9]. The brilliance at NanoTersu will be high enough for soft and tender X-ray users. The details of NanoTerasu design and installation are found in Refs. [9,17].

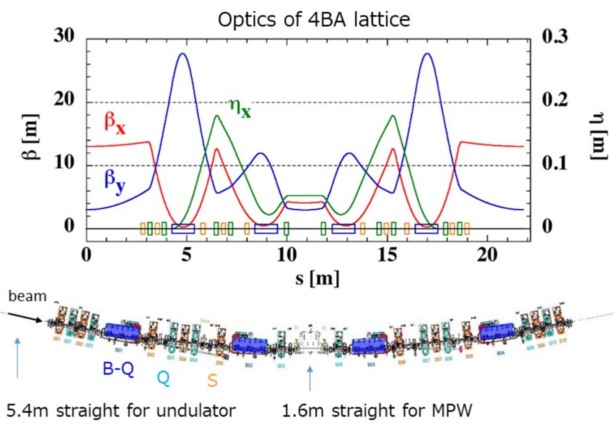

Figure 4: Lattice functions and magnet layout of NanoTerasu 4BA lattice.

NanoTerasu Commissioning

The details of NanoTerasu commissioning are described in Refs. [18,19]. The summary is briefly described here.

The electron beam is generated from a 40 MeV injector consisting of a gridded thermionic cathode 500 kV electron gun with transparent grid scheme [20,21], a 476 MHz subharmonic buncher and a 2 m long S-band accelerator cavity [15]. The first electron beam generation from the electron gun was performed on Apr. 17th in 2023. The electron beam bunch charge is roughly 0.4 nC at repetition rate of 1 Hz.

The 40 MeV injector is followed by 40 of 2 m long C-band accelerating cavities. Since the typical gradient of C-band accelerator is 40 MV/m, 3 GeV electron beam can be generated from 80 m long C-band accelerating structures. First, the electron beam from the injector was transported through a C-band cavity without an input RF power from upstream. The beam-induced wakefield was measured with a directional coupler placed downstream of the C-band cavity. The input RF phase was adjusted to 180 degrees opposite of the wakefield phase to accelerate the beam in the C-band cavity. In this way, the electron beam was transported through 40 cavities from upstream to downstream step by step. Once the electron beam was monitored on a screen downstream of an energy analyzing magnet, fine tuning of the phase and amplitude of each C-band cavity was performed. The 3GeV acceleration was achieved on Apr. 27th in 2023. The linac parameter specifications such as bunch charge, normalized emittance, energy spread and energy stability were finally satisfied.

The features of NanoTerasu storage ring are an in-vacuum transparent off-axis injection system and a higher order mode (HOM) damped TM020 cavity in addition to 4BA lattice. We employ an in-vacuum windowless off-axis beam injection system from the ring inside for stable and transparent beam [22]. An in-vacuum pulse septum and a pair of twin kickers having identical magnet characteristics are used. The system allows an injected beam oscillation amplitude of 7.5 mm thanks to thin septum and small stored beam oscillation amplitude by identical kickers.

The TM020 cavity has nodes of the fundamental magnetic field inside the cavity [23,24]. Slots are prepared along the nodes where ferrite dampers are installed. HOM entering the slots are dissipated on the ferrite dampers resulting in suppression of HOM induced coupled-bunch instability, while the fundamental mode survives. The shunt impedance of the cavity is 6.8 MΩ and RF power of 94 kW is required for 0.8 MV acceleration per cavity, which corresponds to 3.2 MV acceleration and 380 kW RF power for four cavities. The electron beam energy loss due to synchrotron radiation is estimated to be 1.25 MeV/turn where 0.62 MeV and 0.63 MeV are caused by bending magnet radiation and 28 IDs radiation, respectively, under assumption of typical ID power of 9 kW. The klystron RF power of 0.9 MW is thus required for 400 mA beam operation where 0.5 MW is radiaton power loss. The high-power conditioning of four storage ring cavities installed at NanoTerasu was performed from May 29th, 2023. The klystron output power reached 400 kW after two months conditioning.

The beam transport from 3GeV linac exit to the entrance of ring beam injection started on May 29th, 2023. The first ring beam injection was performed on June 8th, 2023 and about 300 turns of an electron beam was observed with one of electron beam position monitors (BPMs) with ring cavity off. The BPM signal starts at the ring injection timing and then decreases as a function of time and dissipates around 300 μs indicating 300 turns since it takes about 1μs per 350 m ring turn. This corresponds to 100 km trip of electron beam. The energy loss per turn of electron beam is 0.02% which corresponds to 6% energy loss for 300 turns. The horizontal electron beam position at 300 turns shifts 11 mm inside at maximum where the dispersion function is 0.18 m, while the horizontal vacuum chamber size is only ±15 mm. The 300 turns with cavity off resulted from good alignment of storage ring magnet system with accuracy of 30 μm rms and good manufacturing of magnets.

When the conditioning of ring cavities reached 230 kW on June 16th, the electron beam was successfully stored after phase adjustment with cavity on. The first synchrotron radiation light from a 3-pole wiggler as an electron beam monitor was observed on June 16th, 2023. A fine tuning of stored beam trajectory was performed since the first light until the end of July for corrections of closed orbit

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-FRYD2

distortion, circumference length, betatron tune, horizontal dispersion, chromaticity, and beta functions by employing seven BPMs per cell and eight steering magnets per cell [18,19]. Beam based alignments of BPMs were also performed with accuracy of 50 μm [18,19].

A 24-hours weekday operation started on Aug. 1st, 2023 for long-term storage ring operation and vacuum conditioning. A stored electron beam current exceeded 100 mA on Aug. 10th, and 200 mA on Sep. 11th. Although a HOM induced coupled bunch instability is observed above 200 mA, the stored beam current reached 300 mA on Nov. 15th. Now the storage ring beam lifetime is more than 10 hours at 160 mA with electron beam dose of 200 Ah.

The electron beam size at a short-straight center where dispersion function is 0.05 m is monitored with a 3-pole wiggler synchrotron radiation measured with an X-ray pinhole camera system, which was used for observation of the 1st light in June 2023. The measured beam size is 84 μm in horizontal and 9 μm in vertical, indicating measured horizontal emittance is close to designed value. The energy spread is estimated to be enlarged to 0.097 % from designed value of 0.084 % under assumption of horizontal emittance of 1.14 nm.rad. We need another electron beam size measurement at non-dispersive section to precisely determine the horizontal emittance and energy spread.

ID commissioning started on Sep. 9th, 2023. First each ID radiation was observed on an alumina fluorescent screen located roughly 10 m from the ID center at beamline frontend with stored beam current of 1 mA. Steering magnets in front and behind of each undulator are used to correct electron beam trajectory in the undulator as functions of gap and phase. A current strip placed on each Apple-II vacuum chamber is used to correct nonlinear dynamics effects of the Apple-II undulator. Beamline commissioning started from Feb. 2024 after preparations of all the correction tables. NanoTerasu commissioning chronological timeline is listed in Table 3.

Table 3: NanoTerasu commissioning chronological timeline [18].

Date	Item
Feb. 13th, 2023	Linac RF conditioning
Apr. 17th, 2023	Electron beam generation from gun
Apr. 27th, 2023	3 GeV electron beam acceleration
May 29th, 2023	Beam transport from linac to SR
Jun. 8th, 2023	SR beam injection 300 turns with SR cavity off
Jun. 16th, 2023	Beam stored with SR cavity on 1st light
Aug. 1st, 2023	24 hours daily operation
Aug. 10th, 2023	100 mA
Sep. 9th ,2023	ID commissioning
Sep. 11th ,2023	200 mA
Nov. 15th ,2023	300 mA with coupled bunch instability (CBI)
Dec. 7th ,2023	Beamline commissioning at exp. hall
Apr. 1st ,2024	User operation at 160 mA without CBI

First User Operation

The first user operation at NanoTerasu was performed from Apr. 9th to Apr. 21st ,2024 for 296 hours. The stored beam current was 160 mA at top-up mode with uniform 400 bunches. A typical lifetime during user operation was 10 hours with initial 10 IDs under operation and typical interval between top-up injections was 5 minutes. The horizontal beam emittance is 1.1 nm.rad monitored with an X-ray pinhole camera system. Seven beamlines were used for various user experiments such as an X-ray coherent imaging and SX spectroscopy. Although the brightness is roughly 40 % of the NanoTerasu specification shown in Fig. 2, it already exceeds more than 10 times compared with that of SPring-8 at soft and tender X-ray regions. The first result of tender X-ray ptychographic coherent imaging at NanoTerasu was already reported [25]. The other three beamlines were under commissioning during the user operation. The total storage ring down time was 1.9 hours due to two failure events of ring RF cavity discharges and the failure rate was 0.6 %. The total user time scheduled in the fiscal 2024 until Mar. 2025 is 3500 hours.

ENERGY RECOVERY LINAC

A 10-kW class EUV source can be an alternative to 250 W laser produced plasma source for EUV lithography. A high-power ERL SASE FEL at EUV wavelength might be a candidate for future high throughput EUV lithography. The EUV FEL is debris-free and more than 10 scanners can be used simultaneously to compensate the initial cost [12]. The design parameters are beam energy of 800 MeV, average beam current of 10 mA at bunch repetition rate of 162.5 MHz with bunch charge of 60 pC [12]. The injector energy is 10.5 MeV with normalized emittance of 0.6 mm.mrad at the injector exit [26]. The SASE FEL system consists of 18 helical (circular polarized) 4.9 m-long undulators with 28 mm period and strength of 1.17 would be used to generate 13.5 nm FEL. Roughly 10 % of injector linac beam power is converted to FEL power for EUV lithography and the rest of beam power of about 90 kW is dumped.

The compact ERL (cERL) developed at KEK since 2013 has achieved various milestones, though the beam energy is 17.6 MeV which is roughly 1/45th of the 800 MeV full scale EUV ERL FEL. Key ERL technologies such as a photoemission 500 kV DC gun and 1.3 GHz superconducting cavity were developed and a high current of 1 mA operation was demonstrated at the cERL. Moreover, two 3 m-long undulators with period of 24 mm and strength of 0.97 were installed at the back straight of the cERL. Measured radiation powers from the two undulators at wavelength of 20 μm increases nonlinearly indicating SASE IR-FEL amplification in a pulsed mode [14]. Preparation of CW ERL SASE FEL operation is ongoing as the next step towards future EUV FEL.

SUMMARY

The present status and future direction of ring-type synchrotron light sources in Japan is presented. NanoTerasu started user operation in Apr. 2024 as the first MBA light

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-FRYD2

source in Japan. Twin MBA light sources, SPring-8-II and NanoTerasu, will lead Japanese photon science platform in 5 years, covering wide spectral range with high brightness. The cERL is anticipated to serve as a prototype of a 10 kW class high power ERL FEL for the future EUV lithography.

ACKNOWLEDGEMENTS

I would like to thank all the members of 3 GeV accelerator working group at QST, NAT, SES, JASRI and RIKEN for their contributions to the NanoTerasu compact light source project. I would like to thank Dr. Hitoshi Tanaka at RIKEN SPring-8 Center and Dr. Takahiro Watanabe at JASRI and RIKEN SPring-8 Center for providing materials on SPring-8-II project. I would like to thank Dr. Takao Asaka, Dr. Kota Ueshima, Dr. Koichi Kan, Dr. Yuji Hosaka, and Dr. Shuhei Obara at QST for carrying out NanoTerasu commissioning and first user operation successfully. I would like to thank Dr. Hiroshi Sakai at KEK for providing materials on cERL.

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