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A HIGHLY BRILLIANT COMPACT 3 GeV LIGHT SOURCE PROJECT IN JAPAN

N. Nishimori†, T. Watanabe[1,2], H.Tanaka[2], QST, Hyogo 679-5148, Japan
[1]also at JASRI, Hyogo 679-5148, Japan
[2]also at RIKEN SPring-8 Center, Hyogo 679-5148, Japan

Abstract

A compact 3 GeV light source project capable of delivering the highly brilliant soft X-rays is proposed in Japan. The storage ring is designed based on a 4-bend achromat lattice to achieve the low emittance for a small circumference of about 350 m. The total number of 26 beamlines is available including 12 multi-pole wiggler beamlines. The natural horizontal emittance is expected to be around 1.1 nm.rad, and the maximum brilliance will exceed 10^{21} photons/sec/mm^2/mrad^2/0.1% b.w. for the 1 - 3 keV region with a stored current of 400 mA. The accelerator components are designed based on the studies for the SPring-8 upgrade project. A full energy injector linac equipped with a thermionic gun and C-band accelerating structures developed for XFEL SACLA is employed for the low emittance injection beam to the ring. A future upgrade for the injector linac as an SXFEL driver is also envisioned.

INTRODUCTION

A highly brilliant compact 3 GeV light source project in Japan has progressed toward innovations in science and industry. The light source will be constructed in Sendai, north-east part of Japan. It will provide brilliant soft X-rays and also widely cover the wavelengths ranging from EUV to hard X-rays performing a complementary role to SPring-8, the Japan's flagship photon source for the brilliant hard X-rays. The target light performances are brilliance >10^{21} photons/sec/mm^2/mrad^2/0.1% b.w. and coherent ratio R = 10 % at several keV photon energy. The coherent ratio is defined as

$$R[\%] = 100\left(\frac{\varepsilon_{ph}}{\varepsilon_x+\varepsilon_{ph}}\right)\left(\frac{\varepsilon_{ph}}{\varepsilon_y+\varepsilon_{ph}}\right),$$

with electron beam emittance $\varepsilon_{x,y}$ and the diffraction limited photon emittance $\varepsilon_{ph} = \frac{\lambda}{4\pi}$. Here beta function at an undulator with length L is assumed to be matched to the photon beam: $\beta_{x,y} = L/2\pi$ [1]. The beam current and emittance are designed to be 400 mA and 1 nm.rad, respectively, to achieve the targets. The beam lifetime is designed to be longer than 5 hours as lifetime is crucial for reliable light source operations even though top-up beam injections are routinely used.

Our concept is to deliver the highly brilliant soft X-rays with high stability and reliability to users by utilizing advanced accelerator design and technology accumulated at SPring-8 and SACLA for more than 20 years. Top-up operations at SPring-8 has achieved the stability of stored beam current better than 0.06% and the mean time between failures to be around 200 hours. SACLA is the pioneer of a compact XFEL facility and one of the leading XFEL facilities in the world. The new 3 GeV light facility takes advantage of those experience and knowledge gained at SPring-8 and SACLA to achieve the design goal. In addition, the following issues are taken into account: extensibility to accommodate soft X-ray Free Electron Laser (SXFEL), feasibility of reliable operation by limited number of staffs, and tight schedule and moderate budget for construction.

Table 1: Main Parameters of 3 GeV Storage Ring

Parameter	Value
Beam energy [GeV]	2.998
Circumference [m]	348.8432
Number of cells	16
Long straight section [m]	5.44×16
Short straight section [m]	1.6427×16
Betatron tune (x/y)	28.17/9.23
Natural chromaticity (x/y)	-60.50/ -40.99
Natural horizontal emittance [nm.rad]	1.14
Momentum compaction factor	0.000433
Natural energy spread [%]	0.0843
Lattice functions at LSS ($\beta_x/\beta_y/\eta_x$) [m]	13.0/3.0/0.0
Lattice functions at SSS ($\beta_x/\beta_y/\eta_x$) [m]	4.08/2.962/0.052
Damping partition number (J_x/J_s)	1.389/1.611
Damping time ($\tau_x/\tau_y/\tau_s$) [ms]	8.091/11.238/6.976
Radiation loss in bends [MeV/turn]	0.621
RF frequency [MHz]	508.75905
Harmonic number	592

ACCELERATOR SYSTEM

The accelerator complex of the new 3 GeV facility is composed of a compact storage ring with a circumference of 350 m and a compact 110 m injector linac in length (see

† nishimori.nobuyuki@qst.go.jp

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Fig. 1). A 4-bend achromat lattice with 16 cells is chosen for the ring to achieve the low emittance for the small circumference. Each cell serves a long straight section of 5.4 m for an undulator and a short straight section of 1.6 m for a multi-pole wiggler except for the cells assigned for beam injection, RF cavities, and beam diagnostic instruments. In total, 26 beam lines are available for users. Horizontal emittance is expected to be around 1.1 nm.rad, and the maximum brilliance would exceed 10^{21} photons/sec/mm^2/mrad^2/0.1% b.w. for the 1 - 3 keV region with a stored beam current of 400 mA. The accelerator components such as vacuum chambers, magnets and monitors are employed from those studied for SPring-8 upgrade project [2-6]. A full energy injector linac equipped with a thermionic gun and C-band accelerating structures is employed to produce sufficiently low emittance beams for efficient beam injections. The C-band system is adopted from those developed for XFEL SACLA [7,8] with some modifications. The linac is located outside of the ring. In the future, it would be upgraded as an electron driver for SXFEL. The main parameters of 3 GeV storage ring and injector linac are listed in Table 1 and Table 2, respectively.

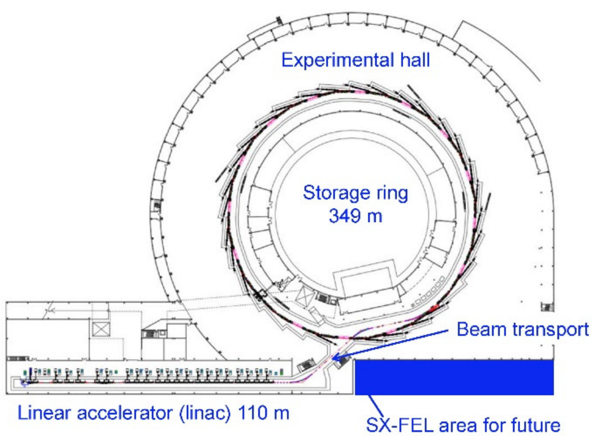

Figure 1: Accelerator complex.

Table 2: Beam Parameters of 3 GeV Injector Linac

Parameter	Value
Beam energy	3 GeV
Normalized emittance	<10 μm.rad
Emittance at 3 GeV	<1.7 nm.rad
Bunch charge	0.3 nC/bunch
Bunch length	5 ps (FWHM)
Energy spread	0.16 % (FWHM)
Repetition rate (Normal)	1Hz
(RF conditioning/ FEL)	25Hz

ON-GOING R&D

A Test Half-cell of 3 GeV Storage Ring

A test half-cell of the 3 GeV storage ring shown in Fig. 2 was constructed to study the performance of magnetic components and to establish precise alignment procedure of the magnets. The test half-cell consists of identical two combined-function bending magnets, different types of five quadrupole and five sextupole magnets, respectively. The magnets are lined up on three girders.

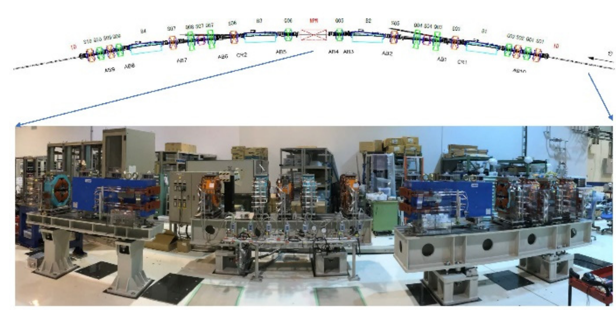

Figure 2: A test half-cell of 3 GeV storage ring.

The combined-function bending magnets are 1.091 [m] long, and provide the defocusing quadrupole fields to reduce the horizontal emittance saving the space for discrete defocusing quadrupoles. The designed dipole and quadrupole magnetic fields are 0.8688 [T] and −7.06 [T/m], respectively. The gap is 28 mm at the center. The magnetic field distributions along the beam trajectory and horizontal axis are measured with a 3D Hall probe in the vendor. The ratio of the measured quadrupole and bending fields agrees with the calculation within 0.1 % accuracy. Although the two bending magnets fabricated for the present test half-cell are electromagnetic, a combined-function bending magnet based on permanent magnets is also fabricated using R&D experience for SPring-8 upgrade project [9]. We will decide which type of magnet to be utilized for 3 GeV storage ring by the end of the fiscal year 2019.

The quadrupole and sextupole electromagnets are made of a laminated iron core. The bore diameters of quadrupole and sextupole magnets are 34 and 40 mm, respectively. The maximum gradient of the quadrupole is 50 [T/m], and that of sextupole is 1200 [T/m^2]. The designed good field region (GFR) where the field deviation from the ideal value is within 10^{-3} is ± 12 mm. The magnetic field distributions measured at the vendor with a Hall probe technique agree well with the design. The integral multipole components of quadrupole and sextupole magnets will be measured with a stretched wire technique.

The mechanical center of each magnet was measured with a 3D position measuring instrument at the vendor. The center position can be relatively obtained from reference positions at reflector holders. All the magnets are aligned with a laser tracker by using the reflector holder on each magnet. Then vibrating wire measuring method [10] is used to align the magnetic center of quadrupole and sextupole magnets. The difference between the magnetic and mechanical centers is within ± 0.05 mm.

Vacuum System

The low emittance storage ring based on multi bend achromat lattice demands fabrication of the precise vacuum chambers with narrow apertures carefully designed taking account of high packing factors for the

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magnets and photon absorbers. The design and R&D of vacuum system addressed for the SPring-8 upgrade project [3] are employed for the 3 GeV project. Thin vacuum chambers fitted to small magnet bores are made of stainless steel. Discrete pumping stations are installed close to the photon absorbers consisting of a principal cartridge NEG pump and a supplemental sputter ion pump for methane and noble gases.

RF System

The radiation loss per turn in 3 GeV ring is estimated to be 1.1 MeV where 0.62 MeV is loss in bends and the rest is loss in insertion devices. An RF power of 440 kW is thus required for compensating the radiation loss of 400 mA beam. To make beam lifetime longer than 10 hours, an RF accelerating voltage of 3.6 MV is required. Installation space of an RF accelerating system is limited to one of the 5.4 m long straight sections, because most of the straight sections need to serve as spaces for insertion devices. A new type of compact TM020 cavity has been developed to accommodate the space limitation [11]. A higher order mode (HOM) excited in the cavity causes coupled-bunch beam instability and needs to be damped. The new cavity has ferrite HOM dampers at the node of the fundamental frequency of 508 MHz inside. Thus, the new cavity does not require external waveguides or pipes along the beam axis to extract HOM power. The total cavity length along the beam line can be short. Four new cavities will be installed in the long straight section and the accelerating voltage per cavity is 0.9 MV for 3.6 MV acceleration. The shunt impedance of the new cavity is estimated to be 6.8 MΩ and RF power of 120 kW per cavity is required for 0.9 MV acceleration. In total, the klystron RF power of 920 kW is required for stored beam current of 400 mA.

We have developed a technique to weld ferrite HOM dampers on the copper cavity surface. The high-power test of the new HOM-damped cavity is underway and will be finished by this autumn.

Injector Linac

The injector system is designed to be compact, cost-efficient, robust and capable of driving SXFEL. The high gradient C-band accelerator technology developed at SACLA/SPring-8 [7,8] is employed to achieve 3 GeV full energy acceleration. Twenty units of C-band accelerator system are installed in the linear accelerator tunnel. The unit consists of two C-band 2 m accelerator structures fed by a 50 MW pulsed klystron. The RF power from the klystron is compressed by an RF pulse compressor (SLED) by a factor of 4 to supply 80 MW peak power to each accelerator structure. Some of the C-band accelerating components such as the accelerating structure itself, SLED, and waveguide vacuum window are modified from their original designs or newly developed in terms of cost efficiency and robustness. The high-power tests for those components will be complete in 2019. The RF phase and amplitude are precisely controlled by a compact digital low-level RF system based on Micro-TCA.4 technology.

A conventional 50 kV dc gun equipped with a commercially available gridded thermionic cathode (CPI Y845) is employed as an electron source instead of a 500-kV pulsed gun with a CeB_6 cathode used to generate low-emittance beam at SACLA [12]. This is because the 3 GeV storage ring does not require such small normalized emittance as 1 mm.mrad as shown in Table 2 and the injector system consisting of the 500-kV pulsed gun is rather complicated [13]. Instead, a 238 MHz cavity is used to accelerate the 50 keV beam to 500 keV. A 476 MHz buncher cavity followed by 2 m S-band accelerating structure provides 0.4 nC bunch charge with 5 ps FWHM to the 80 m long C-band accelerator. An electron gun test stand was built to evaluate the beam quality of our 500 keV electron source consisting of a thermionic 50 kV dc gun and a 238 MHz RF accelerator [14].

The electron beam parameters of 3 GeV injector linac listed in Table 2 are obtained from a particle tracking simulation (PARMELA) in a similar way as those for SACLA [13]. For the future SXFEL, the electron source will be replaced with a new one capable of generating a low emittance beam.

Ring Beam Injection System

The beam injection system of the storage ring needs careful designs for stable operation of the next generation light source having a narrow dynamic aperture. A renewed off-axis beam injection system has been developed for efficient, stable and transparent beam injection together with the capability of top-up operation [15]. The injection system consists of a windowless beam transport, in-vacuum pulse septum magnet, a pair of twin kickers having identical magnet characteristics up to a few tens kHz. The system allows a small injection amplitude of around 4 mm and transparent beam injection during the top-up operation. The vacuum pressure less than 10^{-7} Pa is achieved for the prototyped in-vacuum pulse septum magnet. The detailed studies of the magnetic performance of the pulse septum magnet and the twin kickers are in progress and will be finished by the end of the fiscal year 2019.

SUMMARY

Accelerator system design for the 3 GeV light source project in Japan was completed by taking advantage of expertise acquired in R&Ds for the SPring-8 upgrade project. Some remaining R&D programs on accelerator components should be finished on schedule by the end of the fiscal year 2019.

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