SPring-8 UPGRADE PROJECT

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Abstract

Plans are underway for the upgrade of the SPring-8 facility, targeting completion in the early 2020's. Sustainability is a key guiding principle for the fourth-generation X-ray source - a beam emittance of around 100 pm.rad is pursued simultaneously with substantial energy-saving. The five key concepts enabling the above scenario are (i) to set the proper beam performance taking account of a role of the fourth generation source in the X-ray source evolution, (ii) to adopt advanced undulator technologies for the total system optimization, (iii) to reduce the power consumption as much as possible by reasonably integrating innovative designs and technologies, (iv) to utilize the SACLA linac as an injector to the upgraded ring for the high performance operation, and (v) to minimize the blackout period for quick restart of the user operation.

INTORODUCTION

The third-generation X-ray SR (Synchrotron Radiation) sources emerged all over the world in 1990's providing brilliant undulator radiation. Investigations of the next generation light sources surpassing the existing ones were initiated in early 2000's. However, they all followed the old design concepts and could not solve a problem to drastically improve the light source performance maintaining the same facility scale as the third generation sources [1].

The design concept for MAX IV made a breakthrough in this deadlocked situation and achieved an emittance value of 0.3 nmrad or less by using a seven-bend achromat as a unit structure with beam energy of 3 GeV and a circumference of approximately 500 m [2]. The innovative design concept [3] for ESRF upgrade presented in 2012 generalized the MAX IV concept and have successfully formed a global trend to improve the third-generation SR sources to the next (fourth) generations. The ESRF design concept have shown potentiality to achieve an extremely low emittance of ~100 pmrad with sufficient stability for operations by using a multi-bend achromat based on an individual magnet system.

Construction of the SPring-8 facility was started in 1991 and it has been open for user experiments since October 1997. In 2007 the SPring-8 upgrade project was started aiming at converting the current SR source to a diffraction-limited X-ray source. Even after extensive investigations, we faced several difficulties to reach the goal. The project target has thus been reinvestigated in consideration of the time schedule, predicted difficulties, ESRF design concept, etc. In 2013 we have decided to aim for an ultra-low emittance ring with an emittance value of ~100 pmrad. The conceptual design report on upgraded SPring-8, which we call SPring-8-II, was published in September 2014 [4] and R&D on the accelerator components was started in FY2015.

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FACILITY UPGRADE CONCEPT

Here, we summarize the five major concepts of the SPring-8 upgrade.

X-ray Source Evolution

SR sources have provided brilliant and pulsed X-rays for more than half a century. This situation may be maintained by difficulties in developing X-ray lasers. However, LCLS opened the door to new era by success of SASE (Self-Amplified Spontaneous Emission) XFEL (X-ray Free-Electron Laser) generation in 2009 [5]. We thus predict that this impact will accelerate the evolution of X-ray sources in two separate directions, a pulse and CW-like lasers as seen in a wavelength range of visible light. Our final goal for light source upgrades at the SPring-8 site is to build both the pulse and CW-like laser facilities to provide two kinds of X-ray lasers for synergistic experimental use.

It is quite important for setting the target performance to understand where upgraded SPring-8 locates in the X-ray source evolution. Simple extension of a chaotic ring-based X-ray source never reaches a CW-like X-ray laser. The role of the upgraded SPring-8 facility is to accelerate the movement towards a CW-like laser by shortening the gap between the chaotic SR sources and the target laser facility as shown in Fig. 1. We have carefully defined the target emittance of 100 pmrad by the following three reasons: (a) significant gain in the practical brilliance, (b) equivalent emittance required for SASE XFEL enabling tests towards a CW-like laser, and (c) feasible R&D of accelerator components in the planned time schedule.

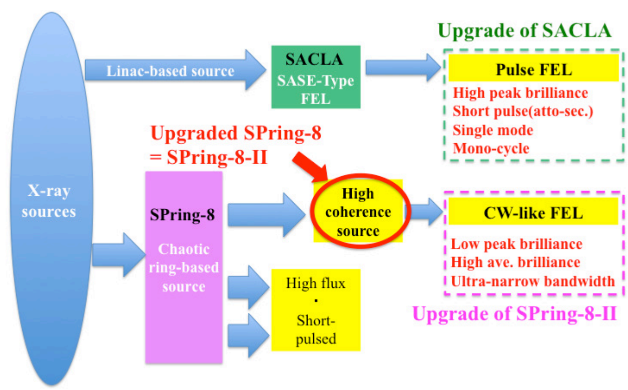

Figure 1: Schematic chart of X-ray source evolution and the SPring-8's strategy for the light source upgrade.

Advance in Undulator Technology

At the time of the SPring-8 construction, a shortest undulator period practically achievable was around 30 mm.

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We therefore adopted a period of 32 mm for the standard in-vacuum undulators of SPring-8. Advances in undulator technologies in the last two decades have shortened the feasible period length down to 15 mm or less. And also, a minimum achievable gap of an undulator has been lowered to ~5 mm due to lots of operation experiences, improvements of beam tuning, and developments of BBF (Bunch-by-Bunch Feedback) systems for instability control. We can currently adopt a period of ~20 mm for the standard in-vacuum undulator keeping reliable and stable user operations.

Shortening the undulator period length offers two major merits. First, it enables us to allocate the space to magnets and vacuum components by reducing the space for undulators. In our upgrade of SPring-8, the ID (Insertion Devise) straight sections are shorter than present by about 2 m even keeping the number of undulator periods. Second, it is also possible to lower the stored beam energy keeping the same undulator spectra as obtained with the current beam energy. Lowering the beam energy much contributes to energy-saving and a compact magnet design.

All the insertion devices of current SPring-8 will be converted to shorter devices or replaced by new ones fitted to the shorter straight sections. We are therefore developing: (a) a reasonable remodeling procedure of the existing insertion devices, and (b) a cost-effective and compact new undulator system by cancelling out an attractive magnetic force [6].

Energy-Saving

After the Great East Japan Earthquake, energy-saving is one of critical issues even for research infrastructures such as SPring-8. We integrate five policies in order to dramatically decrease the power consumption.

The first is to lower the beam energy, which reduces the radiation loss depending on the fourth power of beam energy. The most part of the radiation dissipates as heat, which is so far not utilized. And also, huge energy is consumed to recover this useless thermal energy. Lowering the beam energy has a double gain for energy-saving.

The second is to replace an electromagnet by a permanent magnet. In the magnet system, BMs (Bending Magnets) occupy a large portion of the total power consumption and also, these magnets are basically operated at the same excitation current. We adopt a permanent magnet based BM and its R&D is in progress [7].

The third is to utilize the SACLA linac as an injector of upgraded SPring-8. By time-sharing the same linac, we can shutdown the dedicated injector system composed of the 1-GeV linac and 8-GeV booster synchrotron, which enables huge energy-saving as well.

The fourth is to replace the old utility systems, e.g., the cooling water system and air conditioning system by new ones with higher efficiencies.

The fifth is not to use the current SC (SuperConducting) RF technology based on liquid He. This is because the total RF system including a cryogenic plant requires the relatively larger energy consumption. Furthermore, since He is rare and strategic material, there is a concern for rise in the price that could potentially increase the running cost.

Integration with SACLA

Utilization of the SACLA linac as an injector of upgraded SPring-8 is important to assure stable and reliable beam operations. The new optics for upgraded SPring-8 adopts a five-bend achromat as a unit cell in order to reduce the natural emittance below 150 pmrad without any extra radiation damping [8]. Resultantly, the dynamic aperture markedly narrows compared with the current one. We therefore cannot use the existing injector system without a large-scaled modification improving the injection beam quality such as emittance. Utilization of the SACLA injector contributes not only to energy-saving, but also to cost saving and stable operation. Figure 2 shows a schematic drawing of the SPring-8 accelerator complex after upgrading of SPring-8.

Short Blackout Period and Minimum Beamline Modification

Since SPring-8 is a running facility, it is required to minimize a blackout period in which users cannot make their experiments. For this purpose we take the following three policies.

The first is to keep optical axes of all the ID beamlines. This imposes rigorous constraints on the unit cell length, same as the current one, and also on locations of BMs. With respect to the BM beamlines, small deviations from the current beamline axes are allowed for the lattice design flexibility.

The second is to reuse the existing machine tunnel. The ring lattice configuration must keep the four straight sections of 30 m long with a four-fold symmetry to fit the existing tunnel.

The third is to keep the current beam injection point to reuse the existing beam injection line. It may be better for optimizing the beam injection scheme to use one of the long straight sections as the injection point. However, this change brings a large scaled civil works and extends the blackout period because the civil works cannot be done during the user operation.

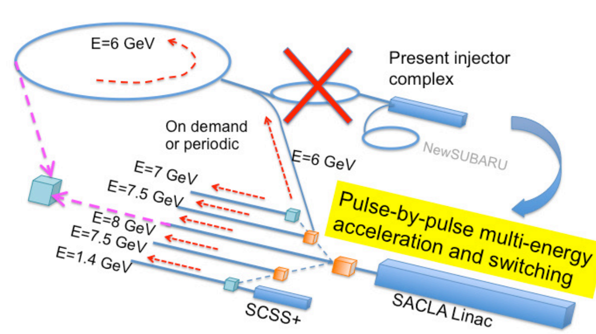

Figure 2: Schematic drawing of the SPring-8 accelerator complex after upgrading of SPring-8.

PROJECT STATUS

Although the SPring-8 upgrade project is currently not officially approved yet, the master schedule was built supposing that the upgrade project will start in FY2018. Three years' R&D activities on accelerator components will be completed in FY2017. User operations of current SPring-8 are continued by the end of FY2020. Component manufacturing, conditioning, integration, alignment, and so on will be carried out for three years from FY2018 to 2020. Via the one-year blackout period, beam commissioning of upgraded SPring-8 will be started at the beginning of FY2022 and user experiments by upgraded SPring-8 will be restarted by the end of 2022.

The basic design of the accelerator components was completed in FY2015 and through this process critical boundary conditions, i.e., physical spacing, functional separation, and so on, among all the sub-systems were reasonably determined. The following detailed component design for each sub-system has been underway independently in parallel with R&D activities.

Table 1: Comparison of Main Ring Parameters

Item	Upgraded	Current
Energy (GeV)	6	8
Circumference (m)	1435.5	1436
Unit Cell Structure	5BMs	2BMs
Ring Structure	2Inj[*1]+42Unit[*2] +4Str[*3]	44Unit +4Str
ID Straight (m)	4.734	6.65
Emittance (nmrad)	0.14(0.1[*4])	2.8
HV Coupling (%)	10	0.2
Tune (νx, νy)	(109.14,42.34)	(41.14,19.35)
Chromaticity (ξ_x,ξ_y)	(-155, -146)	(-117, -47)
Mom. Compaction	3.32×10^{-5}	1.59×10^{-4}
Beam Lifetime	~10	10~100
@ID Straight		
(β_x, β_y) (m)	(5.5, 3.0)	(31.2, 5.0)
η_x (m)	0.0	0.146
(σ_x, σ_y) (μm)	(23, 5.4)	(316, 4.9)
($\sigma_{x'}$, $\sigma_{y'}$) (μrad)	(4.2, 1.8)	(8.8, 1.0)
@BM1		
CPE [*5] (keV)	13.0	28.9
(β_x, β_y) (m)	(1.8, 15)	(2.9, 28)
η_x (m)	0.000015	0.039
@BM2		
CPE (keV)	22.8	28.9
(β_x, β_y) (m)	(0.8, 2.6)	(2.4, 31)
η_x (m)	0.0027	0.059

*1 Injection cell with a horizontal high beta
*2 Unit cell
*3 Straight cell without BMs
*4 Emittance with ID gaps closed
*5 Critical photon energy

In the upgraded ring, the space between the components is much tighter than in the current one. This is one of the biggest R&D themes. To solve the problem, various efforts have been made in component designs, e.g., long flange-free stainless vacuum chamber [9] and compact and stable BPM head [10] are under development.

Another big issue is how to manage two operational functions simultaneously, a XFEL electron driver and a ring injector, using a single linear accelerator. A sophisticated system changing both beam energy and bunch length in a pulse-by-pulse manner has been developed [11] and a proof-of-principle experiment was already carried out.

Table 1 shows the main parameters of the upgraded ring together with those of the current ring. To reduce the horizontal beam size at the ID source point, a doubly achromatic condition is adopted for the upgrade and hence, a smaller beam size of 23 μm in rms is obtained. This achromatic condition is effective for reducing the emittance by additional radiation damping from operating IDs. The practical emittance in the user operation is predicted to be around 100 pmrad.

Figure 3 shows the undulator radiation spectra of upgraded SPring-8 compared with those of the current one. The brilliance is enhanced by a factor of 20 up to photon energy of 60 keV.

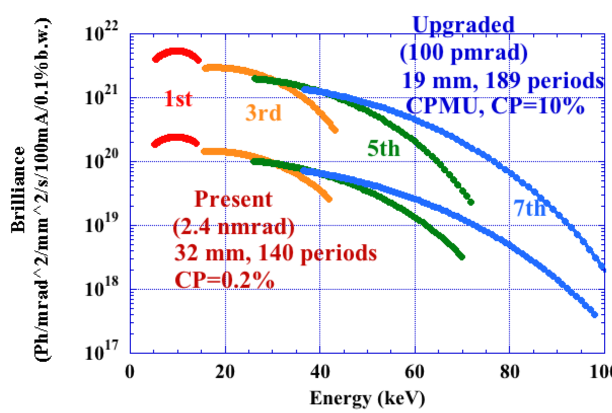

Figure 3: Comparison of undulator radiation spectra between upgraded and present SPring-8.

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