

## CURRENT STATUS OF SPRING-8 UPGRADE PLAN

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### Abstract

The SPring-8 upgrade plan aims at significant improvement of the light source performance by replacing the existing storage ring with a completely new one. The ultimate goal is to achieve extremely small emittance that is equivalent to the diffraction limit of light in the X-ray regime. For the challenging goal, the new ring features a multi-bend lattice with damping wigglers. Up to now, a six-bend lattice has been mainly studied, and key technologies that support the new lattice are under design. The overall review of the upgrade plan, including discussion on critical issues, are reported.

### INTRODUCTION

Since the SPring-8 was commissioned in 1997, high brightness X-rays have been provided to wide varieties of users ranging from fundamental sciences to industrial fields. The overall performance of the SPring-8 has been continuously updated so that users can take full advantage of the third generation light source. The emittance is now 3.4 nm.rad, which produces the brilliance of in the order of  $10^{20}$  [photons/sec/mm<sup>2</sup>/mrad<sup>2</sup>/0.1%B.W.] from standard undulators of the SPring-8. Longer undulators situated in long straight sections are able to generate even higher brilliance. A stability of the light flux is kept high (~99.7 %) owing to the capability of top-up operation. A bunch purity has been improved so that the impurity is now as small as  $5 \times 10^{-10}$ . The coupling is kept at 0.2 % in user time for generating high brilliance X-rays. The availability of beam time reaches 99 % or even higher by making efforts to improve reliability of every single device. Meanwhile, the demand for using such a light source has constantly grown up. Most of beamlines are already occupied with experimental stations, and very few can be built in future. Leading-edge users have made full use of the current specs, and there is no doubt that even better performances will be strongly demanded as it has already been in part. Thus, users have discussed and defined expected performances of a future light source that are required for exploring future sciences and technology innovations in key fields such as nanoscience and green technology.

Based on the user requirement, we propose to upgrade the SPring-8, aiming at significant improvement in light source performances, especially in brilliance and coherence. Our ultimate goal is to decrease the emittance down to in the order of the diffraction limit of light in X-ray

regime, which is, for instance, 10 pm.rad for 10 keV photons. In addition, the stability and the purity of light, the flexibility of filling patterns, and the availability of beam time should be maintained in the new light source. Although the brilliance and coherence are probably the first figure of merit in designing the new light source, we find it equivalently important to sustain other strengths of the current system that users already take for granted. In addition, not only do we aim to achieve such an ultimate goal, but also we plan to reduce power consumption of the whole system compared with the existing one for saving energy.

One more important aspect is that there are two big light sources on the site. The commissioning of the X-ray Free Electron Laser (XFEL), named SACLA, has been commenced and user time will start soon in 2012 [1, 2]. In order to maximize a synergy between the two ultimate light sources, SACLA and the new storage ring, we have also considered an option of generating short X-ray pulses from the new storage ring for pump-and-probe capability [3].

The upgrade of the storage ring is planned in the year 2019.

### PRIOR TO LATTICE DESIGN

Considering cost-effectiveness and influences on current and future users, the following constraints are set in the upgrade plan: (i) New storage ring will be built in the existing tunnel. (ii) Insertion device beamlines will stay in existing hutches. (iii) Dark time should be about a year.

Correspondingly, the circumference should be almost the same as now, and normal straight sections and four long straight sections will stay at similar positions. Under the conditions, we have started the design of the new ring.

The first thing to define is an electron energy. The current SPring-8 is operated at 8 GeV, covering up to hard X-rays such as 100 keV. Due to the technology improvement of insertion devices (i.e., shorter period with smaller gap), we can reduce the electron energy for covering the same spectral range of X-rays. The natural emittance,  $\epsilon$ , is written as  $\epsilon = C \cdot E^2 / N^3$ , where  $C$  is a constant determined by a lattice structure,  $E$  the electron energy, and  $N$  the number of bending magnets under specific condition, thereby to reduce the electron results in smaller emittance. At low energies, however, the intra-beam scattering (IBS) comes into play. The natural emittance including the IBS as a function of electron energy for a given condition is calculated by the code elegant [4] as shown in Fig. 1.

The lower electron energy also helps mitigate an energy spread, heat loads, etc., while it can drastically deteriorate

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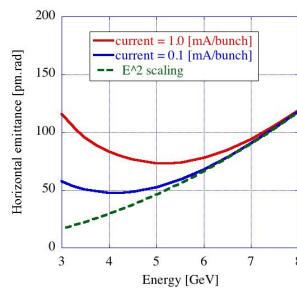


Figure 1: Natural emittance as a function of electron energy. IBS is included. Bunch length of 6 mm, and the emittance coupling of 0.02 are assumed.

brilliance and especially flux in hard X-ray regime. Therefore, in the process of the determination of the electron energy, we carefully compared light qualities for various energies. We then conclude that 6 GeV is a good choice.

Next, the betatron functions at insertion devices need to be defined. The optimum betatron function for generating high brilliance undulator radiation is  $L/2\pi$ , where  $L$  is an undulator length. Since the expected undulator length at normal straight sections in the new storage ring is  $\sim 3$  m, we choose the betatron function of about 1 m.

## LATTICE DESIGN

The current SPring-8 lattice is composed of a double-bend structure. We started the new lattice design with a triple-bend, then increased the number of bends. The code CETRA and other on-house codes are mainly employed in the whole lattice design [5]. The natural emittance is reduced as the number of bending magnets is increased, whereas it will soon result in well-known challenging issues, such as strong multi-pole magnetic fields and small dynamic apertures. So far, we have chosen the 6-bend lattice as the best we can, and optimizations of linear and nonlinear optics have been executed. The 6-bend lattice is supposed to give a natural emittance of 67 pm.rad with its bare lattice, and additional dampings excited by insertion devices and damping wigglers are expected to bring the emittance down to the diffraction limit regime. The lattice work is reported in Ref. [6], and examples of the results are shown in Figs. 2 and 3.

Upon the lattice design, requirements for key components like magnets, injection devices and RF systems are addressed. In order to verify the feasibility of the new lattice, and to see if there are some parameters that need to be modified, design studies of key components have been briefly but extensively explored.

## KEY TECHNOLOGIES

### Injection System

The first requirement for the injection system is to accommodate the small dynamic aperture indicated in Fig. 3.

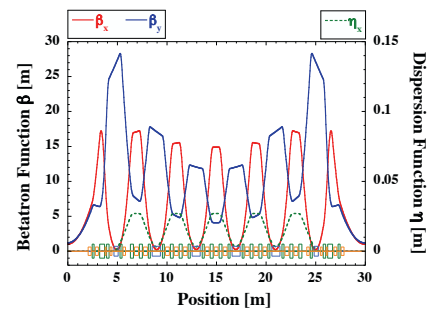


Figure 2: Lattice functions of the 6-bend lattice.

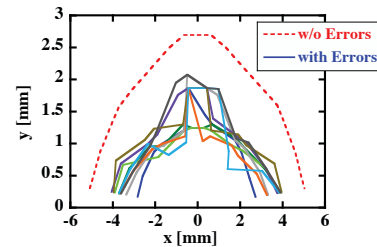


Figure 3: Dynamic apertures (dashed) without and (solid) with sextupole alignment errors of  $10 \mu\text{m}$ .

For the purpose, a new injection apparatus that enables both off- and on-axis injections is proposed. By using a variable field fast kicker, the new scheme can inject beams bucket by bucket separated by 2 ns, so the on-axis injection as well as the off-axis one can be applied to normal operations.

As an injector, we plan to utilize the SACLA linac that produces an emittance of tens of pm.rad. The injection point will be moved from the normal straight section to one of long straight sections where the horizontal betatron function can be adjusted to be 20 m or more. The work on the new injection system is reported in Ref. [7].

### Magnet and Vacuum Systems

According to the lattice design, the maximum magnetic strength of quadrupoles is around  $1.5 [m^{-1}]$  and that of sextupoles is around  $120 [m^{-2}]$ , although the lattice design has continuously been updated at the moment. The strong multi-pole magnetic fields are one of challenging issues in the design. The feasibility will be determined by designing vacuum enclosures with a room for the extraction of synchrotron radiation and multi-pole magnet poles that do not interfere with the vacuum enclosures [8]. So far, a bore radius of 26 mm with a good field region of  $\pm 3$  mm are assumed and the vacuum and magnet systems are under design. At the same time, the lattice has been optimized to make a room for the strong magnets.

### RF Systems

Currently, the SPring-8 is equipped with a 508.58 MHz RF system, of which cavities are distributed in four normal straight sections. It is planned that the same frequency will

be used in the new ring so that RF components, either high power or low level ones, will be reused as far as it is reasonably possible. However, due to the high packing factor of the new lattice, the existing RF cavities are too large to fit in straight sections. Further, we intend to distribute the fundamental RF cavities at three sections to spare one for the harmonic system mentioned below. Thus, a compact RF cavity that is based on TM020 mode has been designed for the effective acceleration. In the new design, the number of cavities at each station is 8 (same as now), the unloaded Q is 60300, R/Q is 113  $\Omega$ , and the shunt impedance is 6.8 M $\Omega$ .

In addition to the fundamental frequency system for the beam acceleration, a higher harmonic RF system plays an important role in lengthening the stored bunch duration. Fig.4 (a) shows the emittance growth due to the IBS, and the lifetime as a function of the bunch length [4]. For obtaining a reasonably long lifetime and suppressing the IBS, the bunch length of 20 ps or more is preferred. We have designed the 3.5th harmonic superconducting cavity, of which frequency is 1780.03 MHz, the RF mode is TM010, the number of cavities is 2, the unloaded Q is 1e9, and R/Q is 80  $\Omega$ . The resulting bunch lengths are show in Fig.4 (b). In case of the passive mode, the bunch can be lengthened to 23 ps, while in the active mode, the bunch can be 50 ps, both of which bunch lengths meet the requirement. Note that the harmonics of the half-integer, 3.5, is not only an optimum for the effective lengthening, but also enables to simultaneously store long and short bunches bucket by bucket.

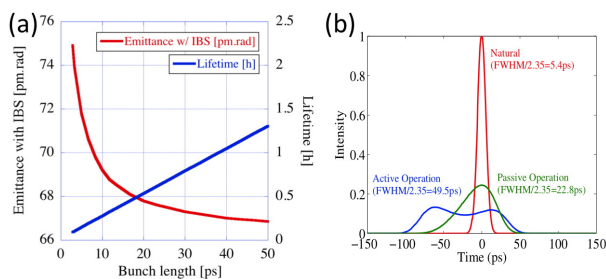


Figure 4: (a) Intra-beam scattering effect and Touschek lifetime. (b) Expected bunch lengths by RF systems.

## LIGHT SOURCE PERFORMANCE

As a result of the above design, the brilliance of the new ring is calculated by SPECTRA [9] and is compared with that of the existing ring. As one can see in Fig.5, the increase of the brilliance in the targeted spectral range (a few to 100 keV) reaches about three orders of magnitude. The brilliance at 10 keV reaches in the order of  $10^{23}$ . Such a high brilliance is expected to work for executing leading-edge experiments that needs small and intense beams, and also for increasing experimental opportunities for users due to the high throughput.

### 02 Synchrotron Light Sources and FELs

#### A05 Synchrotron Radiation Facilities

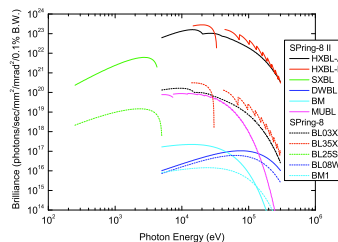


Figure 5: Brilliance comparison between the current (dashed) and upgraded ring (solid).

## ALTERNATIVE DESIGNS

All the parameters described in the report may change as the design study is further proceeded. The electron energy may be increased from 6 GeV for generating even harder X-ray, if required. Or it may be decreased for decreasing the natural emittance, the energy spread and the power consumption. The decrease of the electron energy also helps mitigate strong magnetic fields, which may be the most critical. The 5-bend lattice is also being discussed in order to relax the two critical issues, strong magnetic fields and small dynamic apertures. Note that the combination of the decreases of the electron energy and the number of bends will likely *decrease* the natural emittance with a sacrifice of flux in hard X-rays.

## SUMMARY

The SPring-8 upgrade is planned in 2019. Starting with figuring out the constraints for the upgrade, we have performed the design study to meet our goal. The new lattice features the 6-bend lattice with damping wigglers. The electron energy is set to be 6 GeV in order to improve the emittance and other parameters, while keeping the similar spectral range of X-rays. Through the overall study via design iterations between lattice and hardware developments, the technical challenges that are critical to our goal are addressed in detail. The design study will be continued.

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