Ground design of a 3 GeV accelerator-complex for the synchrotron light in Tohoku, Japan (SLiT-J)

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Abstract. A conceptual design of 3 GeV accelerator complex for synchrotron radiation facility in Tohoku area, Japan (SLiT-J) is described. The complex is consisted with a 3 GeV low emittance storage ring and a C-band full-energy injector linac. Circumference of the ring should not be exceeded 300 m because of compactness (saving cost and power consumption). Nevertheless target emittance of the ring is less than 2 nmrad, which will be really competitive with newly constructed 3rd generation light sources. Tentatively designed lattice offers a low emittance of 1.8 nmrad with reasonably wide dynamic aperture. Presuming 4 typical undulators to cover the wide spectral range such as 10 eV to 20keV, the brightness is expected from $10^{17}$ – $10^{21}$ phs/mm²/mrad²/s/0.1%b.w./300mA. For the hard x-ray region, considerable photon flux may be provided by using multipole mini-wiggler with high magnetic field, which is inserted into the middle of cell. Though realistic prospect of the project is not predictable at present, we anticipate that the facility will be open in 2016.

1. Introduction
After the disaster of the Great East Japan Earthquake and Tsunami on March 11, 2011, we are aware that the role of Tohoku area for basic science, technology and industry is very much significant because the Japanese activities of many scientific fields have been paralyzed and atrophied. We are still in recovering stage and have been struggling for the future of the Tohoku area along with a wretched incident of nuclear power plants. A new project of 3 GeV light source is now supported by 7 national universities in Tohoku area (see figure 1).

The accelerator-complex considered contains a 3 GeV low emittance compact storage ring and a 3 GeV injector linac. At the moment the machines are under preliminary design stage. Since huge budget cannot be anticipated, the accelerator-complex has to be compact without any deterioration in performance.

Owing to success of XFEL at SACLA, SPring8/RIKEN, we will employ C-band accelerating structures for an injector. Seeding FEL for high quality laser is now studied worldwide as next light sources following SASE FEL, so Soft-XFEL option of the injector linac should be considered as a next step.

2. Synchrotron radiation facilities in Japan, and the target of SLiT-J
As known there are many synchrotron radiation facilities in Japan (see figure 2), which are mostly located at the southwest area of Japan. We have recognized that small facilities are
supporting domestic activities of science and technology, we have to be aware there is only one 3rd generation facility, SPring-8, which was constructed 15 years ago. Taking look at the world, high brilliant sources employing beam energy around 3 GeV are getting popular. Nevertheless, no project has been discussed in Japan in these ten years. The PF facility at KEK has been operational since 1982, and an accumulator ring of TRISTAN, AR, was converted to SR machine in 2002 (today, namely Advanced Ring for pulse x-rays). As a next generation light source at KEK, they have been developing a 3 GeV ERL project. Meanwhile a lot of advanced accelerator and light source technologies are progressed in Japan such as in-vacuum undulator, superconducting cavity, fine alignment technique, beam dynamics theory and etc. We are definitely sure the time to install a high brilliant 3rd generation light source in Japan is arrived.

![Figure 1](image1.png) SLiT-J project supported by national universities in Tohoku area.

![Figure 2](image2.png) Current activity of Japanese synchrotron radiation facilities.

It is apparent that synchrotron radiation based on a low emittance ring is the key initiative to lead topical science and technology such as nano-science. Consequently our target of maximum brilliance at the photon energy region of 0.1 ~ 20 keV has been settled to be $10^{21}$ phs/s/mm²/mrad²/0.1%bw. However, because the machine has to be compact, circumference of the ring is being limited to be ex mero motu 300 m.

### 3. Lattice design strategy and tentative plan

#### 3.1. Choice of multi-bend cell

Theoretical limit of the horizontal emittance for “non-achromat” lattice can be written as [1]

$$
\varepsilon_x \min = \frac{1}{12\sqrt{15}} \frac{C_q \gamma^2 \theta^3}{J_x},
$$

where $C_q$, $\gamma$, $\theta$ and $J_x$ are a quantum constant ($= 3.83\times10^{-13}$), relativistic factor, bending angle per one dipole and horizontal damping partition number, respectively. According to eq. (1), only 36 bends are required to achieve the emittance of 1 nmrad at 3 GeV by using a standard value of 1.5 is used for $J_x$. However in a practical manner the emittance reached is 2 or 3 time larger than the theoretical one. In this sense we need 54 bends, which is quite large number for the compact ring with its circumference is less than 300 m.

We have estimated the proper number of bends using a formula

$$
C \approx 2\pi \rho + N\varepsilon_{SS} + N(n-1)S,
$$

where $C$, $\rho$, $N$, $\varepsilon_{SS}$, $n$ and $S$ are ring circumference, bending radius of dipoles, number of unit cells, length of straight section for insertions, number of dipoles in a cell and length between
dipoles in the cell, respectively. Assuming the number of bends is 48 to achieve the emittance less than 2 nmrad, and the circumference and the length of straight section 300 m and 5 m, respectively, the lengths between dipoles are estimated for different cell numbers as shown in Table 1.

| \( N \) | \( n \) | \( S \) (m) |
|---|---|---|
| 24 | 2 | 1.4 |
| 16 | 3 | 3.0 |
| 12 | 4 | 3.6 |
| 8  | 6 | 4.0 |

\( \rho = 12 \) m is assumed.

Conventional double-bend lattice with 24 cells seems to not have sufficient room between bends because we have to put at least a quadrupole and two families of sextupoles, and even triple-bend 16-cell lattice seems to be difficult. Compromising with the number of straight sections, we have chosen quad-bend 12-cell lattice. Although 2 straight sections will be occupied by the beam injection and the RF cavity, 10 straight sections can be allocated to insertion devices.

3.2. Choice of field strength of the bend
Because there will be only one RF cavity station, we have to be careful for choice of the dipole field strength. Assuming all 4 m-long undulators inserted into 10 straight sections are fully working with a peak magnetic field of 1 T, the radiation power from the undulators is estimated to be 70 kW at a beam current of 300 mA. A maximum input power to the cavity through one RF coupler is expected to be 3 - 400 kW, so that the radiation loss due to the dipoles is preferred to be less than 200 kW. On the other hand, from the point of view of compact circumference, higher dipole field is better. Consequently we have chosen a bending radius of 10 m that is corresponding to the field strength of 1 T for the present. The radiation loss for this case is approximately 200 kW at 300 mA.

3.3. Lattice functions and characteristics of the SLiT-J ring
Figure 3 shows tentative design of the lattice functions of the ring. Small dispersion of 7 cm is in the long straight section to reduce the emittance down to 1.8 nmrad (\( \sim 2.5 \) nmrad for dispersion-free optics). Short-straight section is inserted into the middle of cell for specific insertions such as multipole wiggler, nevertheless the circumference is still less than 290 m.

**Figure 3.** Lattice function in a unit cell. **Figure 4.** Dynamic aperture.
An original procedure for nonlinear property collection based on genetic algorithm has been developed. Applying this routine for 6 families of sextupoles, wide dynamic aperture even for momentum deviated particles has been obtained as shown in figure 4. Particle tracking has been performed by a code SAD [2]. Although we need further investigation, particularly on errors of field strength and alignment, main parameters listed in Table 2 are mostly within our target.

Table 2. Main parameters of the storage ring.

| Parameter                        | Value   |
|----------------------------------|---------|
| Energy                           | $E = 2.998$ GeV |
| Circumference                    | $C = 288.912$ m   |
| Number of unit cells             | $N = 12$   |
| Betatron tune $(\nu_x, \nu_y)$   | $(22.28, 5.38)$ |
| Natural chromaticity $(\xi_x, \xi_y)$ | $(-58.07, -36.78)$ |
| Natural emittance $\varepsilon_x$ | $1.80$ nmrad |
| Momentum compaction $\alpha$     | $0.00069$ |

4. Summary and prospect

Figure 5 shows expected spectrum brilliance of the radiation from various insertion devices to be operated at SLiT-J. Indeed we will not use radiation from dipoles, but the multipole wigglers located at the short straight section will be powerful source for hard X-ray region because of higher spectrum flux. Since there is no super long straight section, the highest brilliance at ~keV energy region is a bit less than $10^{21}$ psh/mm$^2$/mrad$^2$/s/0.1%bw. However overall performance of the light source may rank with the most advanced 3 GeV light sources.

A floor plan for the facility is shown in figure 6. Because the C-band accelerating structure can provide a very high accelerating gradient such as $\sim 40$ MeV/m, the length of full energy injector linac will be only 100 m, which enable us to extend the use of linac to a soft X-ray FEL driver. In addition, power consumption of the linac at slow repetition rate for top-up operation is much smaller than that of booster synchrotron, which is another advantage of the injector linac.

Figure 5. Spectrum brilliance for the SLiT-J insertions. Period lengths are indicated in the nameplates.

Figure 6. Facility floor plan. The injector linac will be an FEL driver at the 2nd stage.

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References
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[2] SAD URL: http://acc-physics.kek.jp/SAD/