# STATUS OF SCSS & X-RAY FEL PROJECT IN JAPAN

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*Abstract*

The XFEL/SPring-8 project has been funded in FY2006, which is aiming at generating 1 Å coherent intense X-ray laser using 8 GeV normal-conducting accelerator. The construction period is scheduled 2006-2010, and FEL operation will start in 2011. XFEL/SPring-8 is based on unique concept of SCSS: SPring-8 Compact SASE Source. It requires low emittance and high peak current electron beam, i.e., normalized emittance of 1 π.mm.mrad and 3 kA peak current. We decided to employ the thermionic electron gun, which generates 1 A beam from single crystal cathode, followed by the multi-staged bunching system to achieve 3000 times compression. The design is based on the "Adiabatic Bunch Compression" scheme, i.e., compressing bunch length as inversely proportional to the beam energy, thus the bunch length on electron rest frame is kept constant, and as a result the low slice emittance is preserved. To prove this concept, the SCSS prototype accelerator of 250 MeV beam energy was build. On June 2006, the first lasing has been observed at 49 nm. From the FEL gain measurement, the beam brightness was determined as high as 300 A/(π.mm.mrad)$^2$, which is enough value for the beam quality for the 8 GeV XFEL/SPring-8 project.

## INTRODUCTION

We started SCSS project in 2001[1] for developing technology required for X-ray FEL. SCSS stands for SPring-8 Compact SASE Source, in which by means of in-vacuum type short period undulator, the required electron beam energy becomes lower, additionally the C-band accelerator drives the beam at high gradient as high as 35 MV/m, as a result, the total system length becomes "compact", and it fits to available site length at SPring-8.

In the course of SCSS R&D, we developed a low emittance electron gun using single crystal CeB6 cathode shown in Fig. 2 and 500 kV gun driven by pulse modulator power supply: We also developed various hardware components required for SCSS: injector rf system, C-band klystron modulator with oil-filled compact design, high resolution beam position monitor, and digital rf signal processing system[2]. In order to check the developed hardware components and verify system performance, especially the low emittance electron injector, we constructed SCSS prototype accelerator in 2004-2005. The tunnel length is 60 m long, the maximum electron beam energy is 250 MeV, the shortest lasing wavelength is around 50 nm. In July 2006, we observed first lasing. The user beam run will start in October 2007.

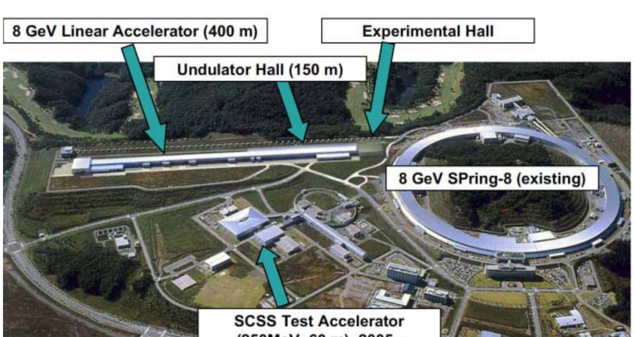


Fig. 1 The XFEL will be build at SPring-8 site.

On FY2006, the Japanese MEXT: Ministry of Education, Culture, Sports, Science and Technology has decided construction of XFEL at SPring-8 site. The project is aiming at generating 1 Å coherent intense X-ray laser, which is based on SASE using 8 GeV normal-conducting accelerator. A big benefit to have XFEL at SPring-8 site is to share human resources and facilities for sample preparation with existing 8 GeV synchrotron light source.

We have decided to use normal conducting linear accelerator technology at C-band frequency (5712 MHz), which was originally developed at KEK for the e+e- linear collider project. It is "warm" technology, not super conducting "cold" technology; therefore it can be constructed with much lower cost. The C-band accelerator is capable of running at high accelerating gradient, as high as 35 MV/m. The 50 MW C-band klystron was developed and it is now available from industries as a standard component. C-band accelerator technology is available right now.

## CHOICE OF ELECTRON SOURCE

SCSS is unique and beneficial, however, it requires extremely low normalized emittance: ~ 1 π.mm.mrad and high peak current: 3 kA. We decided to employ the thermionic electron gun, which generates 1 A beam from single crystal cathode, followed by the multi-staged bunching system to achieve 3000 times compression (3000 = 20 x 5 x 10 x 3). The design is based on "Adiabatic Bunch Compression" scheme as shown in Fig. 3, i.e., compressing bunch length as inversely proportional to the beam energy, thus the bunch length on electron rest frame is kept constant, and as a result the low slice emittance is preserved. We carefully manipulate bunch length and avoid "over bunching", thus we do not mix particle between head and tail within bunch. The bunch length on the electron rest frame is kept almost constant, in practice it is about 30 cm long, while the diameter of the beam is a few mm only, therefore the electric field of space charge is fairly uniform and linear, and has only the radial component, as a result emittance break due to the space charge effect becomes negligibly small.

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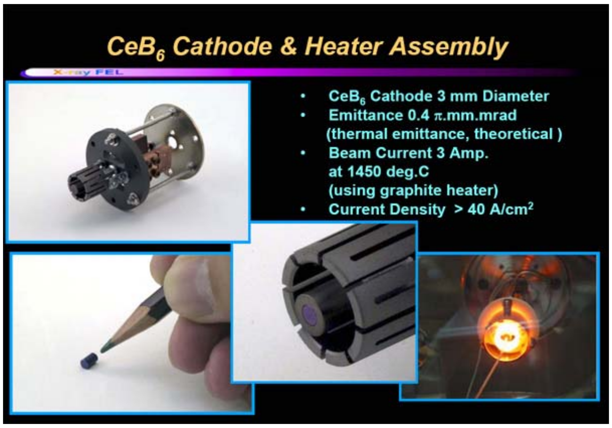


Fig. 2 $CeB_6$ single crystal thermionic cathode for low emittance electron source.

We use rod shape $CeB_6$ of 3 mm in diameter as shown in Fig. 2. We extract 1 A beam by 10 MV/m acceleration field in the gun (500 kV/5cm), which is in the temperature limited condition. The theoretical normalized emittance due to thermal motion at the cathode is 0.4 π.mm.mrad. The emittance was carefully measured at the gun using double slits. The measured emittance of core beam was 0.6 π.mm.mrad [3].

## MACHINE CONFIGURATION AND BEAM OPTICS

Figure 4 shows the machine configuration and its parameter is listed in Table-1. The thermionic electron gun generates only 1 A, and then we compress the bunch length 3000 times in the injector and chicane magnets. We designed the compression factor as 20, 5, 10, 3 in the injector, the first, second and third bunch compression systems, respectively. The highest compression is made in the injector, it is basically velocity bunching using energy chirping on rf field. In the optics design, we introduced new concept "Adiabatic Bunch Compression Scheme"[4], where we maintain the longitudinal bunch length as constant on the electron rest frame (moving frame) during acceleration. In practice, we squeeze the bunch length as inversely proportional to the beam energy, that is, 1 nsec, 500 keV, $\gamma = 2$ at the gun, followed by 0.6 nsec, 1 MeV, $\gamma = 3$ after booster, and 10 psec, 30 MeV, $\gamma = 60$ after bunch compressor 1. In this scheme, we maintain constant bunch length on the electron rest frame, and never over compress, thus we can maintain "laminar flow" of electron beam from the gun down to the undulator.

Table-1. Machine parameter of SCSS prototype accelerator and XFEL/SPring-8

| | | Prototype | X-ray FEL | |
|---|---|---|---|---|
| Beam Energy | $E$ | 0.25 | 8.0 | GeV |
| X-ray Wavelength | $\lambda$ | 60 | 0.1 | nm |
| Beam Emittance | $\varepsilon_n$ | 2 | 1.0 | πmm.mrad |
| Bunch Length | $\Delta_z$ FWHM | 100<br>0.3 | 100<br>0.3 | μm<br>psec |
| Transverse Beam Size | $\sigma_{x,y}$ | 100 | 25 | μm |
| Peak Current | $I_p$ | 1 | 3 | kA |
| Charge per bunch | $q$ | 0.3 | 1 | nC |
| Undulator Parameter<br><br>Length | $\lambda_u$<br>$K$<br>$L$ | 15<br>1.3<br>10 | 18<br>1.3<br>80 | mm<br><br>m |
| FEL Saturation Length | $L_{sat}$ | 20 | 60 | m |

In the SCSS prototype accelerator[5], the projected emittance was measured as 3~4 π.mm.mrad, while it was dominated by the resolution limit of profile monitor and also including the tail component associated from beam deflector right after the gun. To determine the emittance in the beam core, we performed FEL gain measurement by varying K-parameter of the undulator, and peak current, from which we obtained beam brightness 300 A/(π.mm.mrad)$^2$. To determine peak current, we performed bunch length measurement by chirping the beam energy in C-band accelerator, and observed the transverse beam size variation in the downstream chicane. The full width was 1 psec. Therefore we obtained the beam current as 300 A, and the emittance derived as 1 π.mm.mrad. This is enough beam quality for 8 GeV XFEL machine.

From the SCSS prototype accelerator to 8 GeV XFEL/SPring-8, we need further bunch compression by factor of 10. This is straightforward by simply adding another two magnetic chicane bunch compressors as shown in Fig. 4.

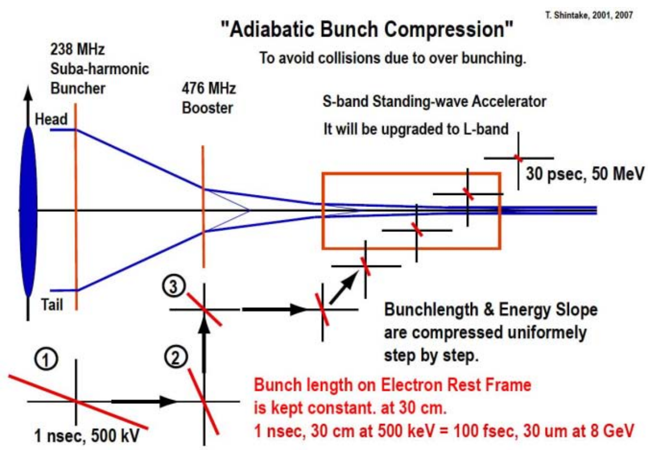


Fig. 3 Adiabatic bunch compression scheme.

One special care is taken in the design of 8 GeV machine to make linear the beam shape in the (z, E) phase space. Overlapping the higher order harmonic field on the dominant rf-field, we may flatten the effective acceleration field. This technique will be applied in the 476 MHz booster cavity with L-band correction cavity and L-band accelerator with C-band correction cavity.

The frequency of the rf acceleration is designed as lower in the injector and gradually raised higher in the following accelerator. This is a part of the "Adiabatic Bunch Compression" scheme, where the wavelength of the rf field is also varied to maintain constant bunch to wavelength ratio. Ideal way is to use static field everywhere until beam energy reaches to 8 GeV, since the static field does not cause emittance dilution associated from time varying transverse kick from radial electric field or azimuthally magnetic field in the rf cavity.

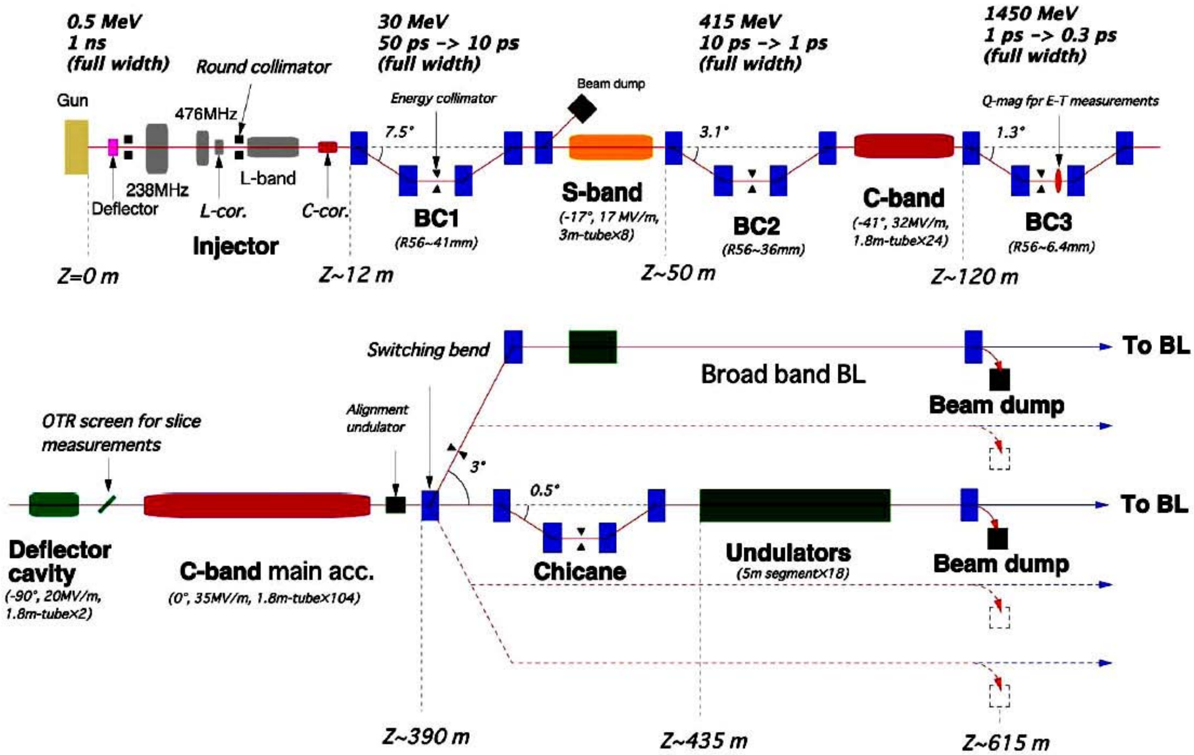


Fig. 4 Machine configuration.

In practice the attainable electric field gradient is lower at lower frequency, especially at DC field. HV break down is caused by avalanche mechanism driven by ion bombardment on metallic electrode followed by gas emission and successive ionisation, which results in more ion bombardment. When the rf frequency becomes higher, the field polarity changes faster than the ion reaches to the electrode, thus the cycle gain of ion population becomes lower, and HV breakdown stops. From this technical point, the higher frequency is desirable for high field acceleration. On the other hand, to minimize the emittance dilution due to the time varying transverse kick, lower frequency is desirable. To make an optimum design for those two constraints under the "Adiabatic Bunch Compression" scheme, we chose the rf frequency lower in the injector and higher in main linac. We start 238 MHz in the sub-harmonic buncher, and 476 MHz in the booster, then 1428 MHz (L-band) in bunch accelerator, 2856 MHz (S-band) in the upstream 30 MeV → 415 MeV in the main accelerator, at the last 5712 MHz (C-band) in the main linac up to 8 GeV. They are schematically drawn in Fig. 5.

A question will be arise, why don't we go even higher frequency. In principle, the answer is "Yes", but "No" in practice. The high frequency accelerator requests smaller size of accelerating cavity structure, whose fabrication becomes harder and harder as frequency becomes higher. The C-band is determined by the technical consideration amount the higher gradient and the practical engineering capability.

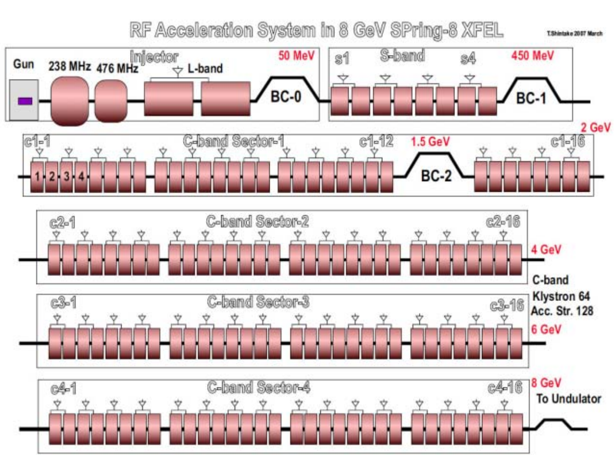


Fig.5 Accelerating structures.

## UNDULATOR

Figure 6 shows the undulator for 8 GeV XFEL/SPring-8. The magnet array is hybrid type consist from permanent magnet and iron yoke. It is in-vacuum design with variable gap (2 mm ~ 40 mm). Nominal operation point is gap = 4 mm and K = 1.9. One advantage to use in vacuum undulator is that we have fairly wide beam aperture by opening the gap to 40 mm, where we can transport guide laser beam for alignment of cavity BPMs. Temperature control of the permanent magnet is one of the most important issue in precise undulator design, in this point the in vacuum undulator design provides ideal heat isolation from the environmental temperature change.

Figure 7 shows one example simulation results on the SASE-FEL amplification with nominal beam parameter.

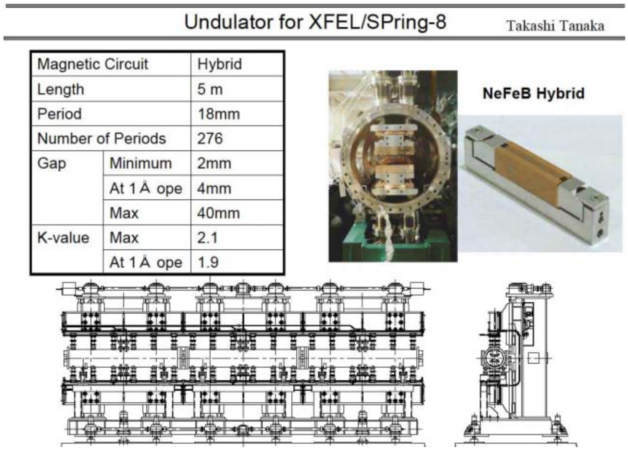


Fig. 6 Undulator for 8 GeV XFEL/SPring-8. The magnet array is hybrid type consist from permanent magnet and iron yoke.

It predicted that the FEL will be saturated within 120 m long undulator line. The estimated saturation power is 2 GW.

## STABILITY ISSUE

As discussed in previous sections, our system uses very high bunch compression factor, thus the beam parameter, such as peak current, is very sensitive to the machine parameter change in the upstream section. By simple analysis, to make the peak current stability better than a few %, it was shown that the voltage and phase stability on the rf acceleration field in the injector has to be $10^{-4}$ level and 0.1 degree, respectively. In order to achieve this requirement, we have been carrying out R&D on stable high-voltage power supply for klystron modulator. By means of parallel operation of high-power fast inverter-type power converter and a small power precise power supply, we successfully demonstrated $10^{-4}$ level of pulse-to-pulse stability in 50 kV, 35 kW power supply. Using this type of power supply in the electron gun, and S-band buncher, the measured beam energy jitter in the SCSS prototype accelerator becomes $6 \times 10^{-4}$. The R&D will be continued during the construction period to achieve $1 \times 10^{-4}$. The beam arriving time jitter was measured at the entrance to the undulator. It was 46 fsec, which is reasonable value if we consider R56 (40 mm) parameter of chicane multiplying with the energy jitter. This is very promising result for pump-probe experiment. And also, this is a surprising result that we have such stable beam timing even through the bunch was made after high compression from a long pulse of thermionic gun.

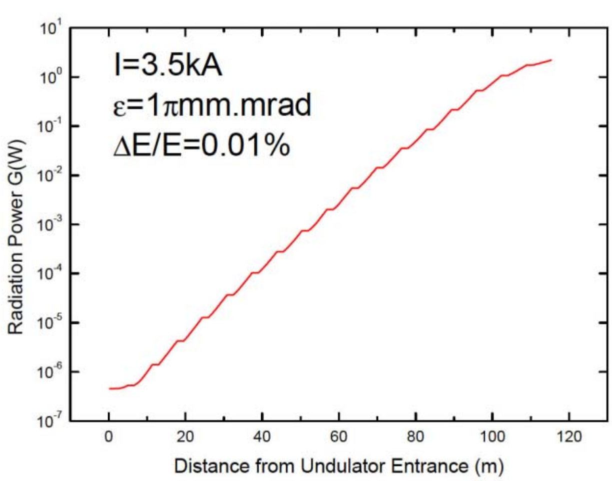


Fig. 7 Simulated FEL power growth along undulator line.

To obtain 0.1 degree phase stability, we are currently developing optical fiber link. For slow drift, phase detection system in optical fiber by reflecting optical signal from one end, and apply feedback on fiber mechanical stretcher. Recently, we stretched 2 km fiber around the SPring-8 ring, where the phase drift was maintained within 10 fsec range.

## CONCLUSION & SCHEDULE

Our design concept on low emittance electron gun and injector, based on thermionic cathode and adiabatic bunch compression, has been proven at SCSS prototype accelerator. XFEL/Spring-8 aiming at generating 1 Å X-ray was designed and its construction has been started in FY2006. The construction will be completed in FY2010 and the first X-ray beam test is scheduled in the end of FY2010.

## REFERENCES

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