STATUS REPORT ON JAPANESE XFEL CONSTRUCTION PROJECT AT SPRING-8

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Abstract

New SASE-FEL machine: XFEL/SPring-8 is under construction at SPring-8 site, which has been funded in FY2006 aiming at generating 1 Å coherent intense X-ray laser. The accelerator building construction was completed in March 2009, and the X-ray experimental hall will be ready in June 2010. We are currently installing hardware components in the accelerator tunnel and undulator hall. The high power operation will start in October this year, and beam commissioning is scheduled from March 2011. We expect the first lasing at Angstrom wavelength in summer 2011. XFEL/SPring-8 is based on unique concept of SCSS: SPring-8 Compact SASE Source: by means of the short-period in-vacuum undulator the required electron beam energy becomes lower, and high gradient C-band acceleration system makes facility length shorter. It requires low emittance and high peak current electron beam, i.e., normalized emittance of 1 π.mm.mrad or less and 3 kA peak current. To obtain this beam, we employ the thermionic electron gun using single crystal CeB_6 cathode because of its superior stability and long lifetime.

INTRODUCTION

We started SCSS project in 2001[1,2] in order to develop technology required for X-ray SASE-FEL at SPring-8 site. SCSS stands for SPring-8 Compact SASE Source as schematically shown in Fig. 2. Using 18 mm magnetic period, the required beam energy to obtain 1 Å radiation becomes 8 GeV, which is much lower than the beam energies in the other projects; 14 GeV in LCLS and 17.5 GeV in Euro-FEL. Additionally the C-band rf system accelerates the beam at high gradient as high as 35 MV/m, as a result, the total system length becomes "compact", and whole machine fits within the available site length at SPring-8. The active accelerator length in our design is only 230 m. But we have to note that we need quite long spaces for bunch compressors, and beam diagnostics, as a result the actual accelerator length becomes 400 m.

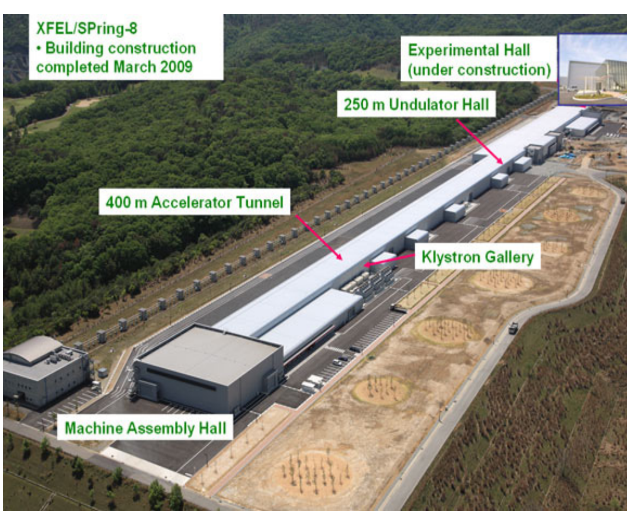

Figure 1: XFEL/SPring-8 is under construction at SPring-8 site.

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CHOICE OF NORMAL CONDUCTING ACCELERATOR

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. Main feature in C-band is its high gradient acceleration capability. It is capable of accelerating the multi-bunch beam in 250 nsec pulse duration (50 bunches x 4 nsec spacing) at 35 MV/m, and single bunch at 40 MV/m. It is "warm" technology, not super conducting "cold" technology. Normal conducting linear accelerator can be constructed with lower cost and shorter production time. The beam repetition frequency is lower in normal conducting linac than the super conducting machines. In XFEL/SPRing-8 machine, the repetition frequency is 60 Hz. Fortunately, most of all scientific cases in X-ray FEL require the high peak power radiation rather than high average power, therefore 60 Hz repetition frequency is acceptable.

In the KEK R&D time (FY1996-2000), the C-band klystron of 50 MW class and related technologies were developed and they were now available from industries as standard products. In SCSS R&D, we upgraded design details on the klystron modulator power-supply[7], the rf pulse compressor and accelerating structure[12]. The high power performance has been well confirmed by sample test on components in test bunker[9].

THERMIONIC CATHODE FOR LOW EMITTANCE ELECTRON SOURCE

Theoretical Emittance

One of the most important technologies in SASE-FEL at X-ray wavelength is the low emittance electron source. There are major two different choices: one is photo-cathode rf-gun and the other is the thermionic electron

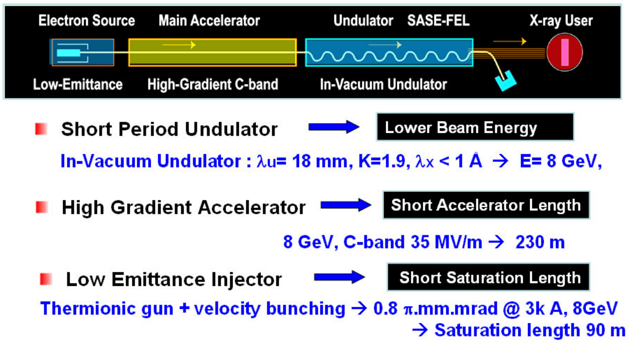

Figure 2: SCSS concept makes FEL machine compact.

gun. Because of XFEL/SPring-8 is X-ray user facility, machine reliability and beam availability have to be very high. There exists the single crystal CeB6 and LaB6 cathode technologies, which have been widely used in various kinds of electron microscopes, and its reliability has been well proven. According to the beam quality available from such a hot cathode (the nominal operating temperature is 1500 degree C), one might think that higher kinetic energy of thermal motion will make the beam divergence larger and emittance worse. In practice, it is not a problem. The theoretical emittance of electron beam right after emitted from the cathode into vacuum is given by the following simple equation.

$$\varepsilon_{xN} = \frac{\gamma r_c}{2}\sqrt{\frac{k_B T}{m_0 c^2}} \qquad (1)$$

where r_c is the cathode radius, k_B is the Boltzman constant, and T is the absolute temperature of the cathode, m_0c^2 is the electron rest mass energy: 511 keV. The temperature dependence is slow because of the function of root. The difference between room temperature to the hot cathode temperature in $\sqrt{T}$ term is only 2.5. If we chose smaller cathode, we can make the emittance fairly low. Using 3 mm diameter, the emittance becomes 0.4 π.mm.mrad, which is good enough for X-ray FEL. The required current density is 14 A/cm^2, which is easily available by LaB6 or CeB6 cathodes. We chose CeB6: cerium hexaboride, because of its superior life time.

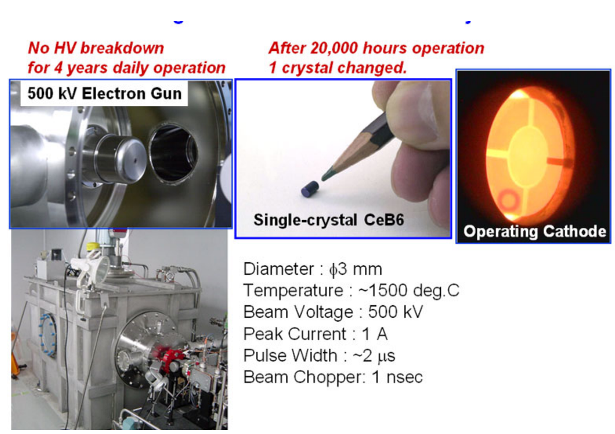

Figure 3: CeB$_6$ single crystal thermionic cathode for low emittance electron source.

Electron Gun R&D

In the course of SCSS R&D, we developed an electron gun using single crystal CeB6 cathode as shown in Fig. 3 which was mounted on the 500 kV pulsed-voltage gun driven by pulse modulator power supply. We do not apply DC voltage, since DC field causes more frequent HV discharges than pulse voltage. We measured beam transverse profile and phase-space distributions right after the gun. We derived the beam emittance as 0.6 π.mm.mrad for 90% electron population at 500 kV [3].

How to Compress Beam from 1 A to 3000 A

The beam current available from the gun is only 1 A, while the peak current required in the undulator to satisfy the requirement for FEL saturation at X-ray wavelength is 3000 A. Assuming two stages of bunch compressors of magnetic chicane type at high energy same as LCLS, we compress the bunch length by 50 times there. Remaining factor is 60, which has to be completed in the injector by means of velocity bunching and additional magnetic chicane. There was a question on how can we maintain low emittance beam along with velocity bunching process.

In the klystron tube, for example in our 50 MW C-band klystron, there is 300 A beam injecting from the cathode, followed by bunching process on periodic energy modulation forced by input rf signal. At the output cavity, the bunch length becomes fairly short. It becomes easily ten times shorter than rf wavelength, which is surprisingly short by taking account the fact that there are strong repulsive forces acting on there electrons due to the space charge. In case of FEL injector, the beam current is only 1 A, thus the higher bunch compression is possible.

SCSS Test Accelerator

In order to demonstrate this velocity bunching process and also check various hardware components, we constructed SCSS test accelerator during FY 2004-2005. It consist of the electron gun and injector rf systems, two C-band accelerator units, and two in-vacuum undulators (period of 15 mm). The radiation wavelength is 50-60 nm at e-beam energy of 250 MeV. Instead of measuring the beam emittance directly, we sent beam into two undulators, and measured FEL gain at VUV wavelength. From the gain curve, we derived the beam emittance as 0.7 π.mm.mrad at the beam current of 300 A [4]. This number clearly satisfied required beam performance for the electron injector for XFEL/SPring-8.

The test accelerator has been delivering FEL beam at VUV wavelength (50-60 nm) for various user experiment since 2007. Operation has been carried out every week from Monday to Friday, from 9 AM to 7 PM, for four years. We keep alive the electron source in hot condition (1500 degree C) during also night and weekend. After 20,000 hours operation, we renewed the CeB6 crystal due to sudden degradation of beam emission (January 2008). Since then, the second crystal has been running till today (May 2010), it has exceeded 2 year and half. We may conclude that the lifetime of our CeB6 cathode is 20,000

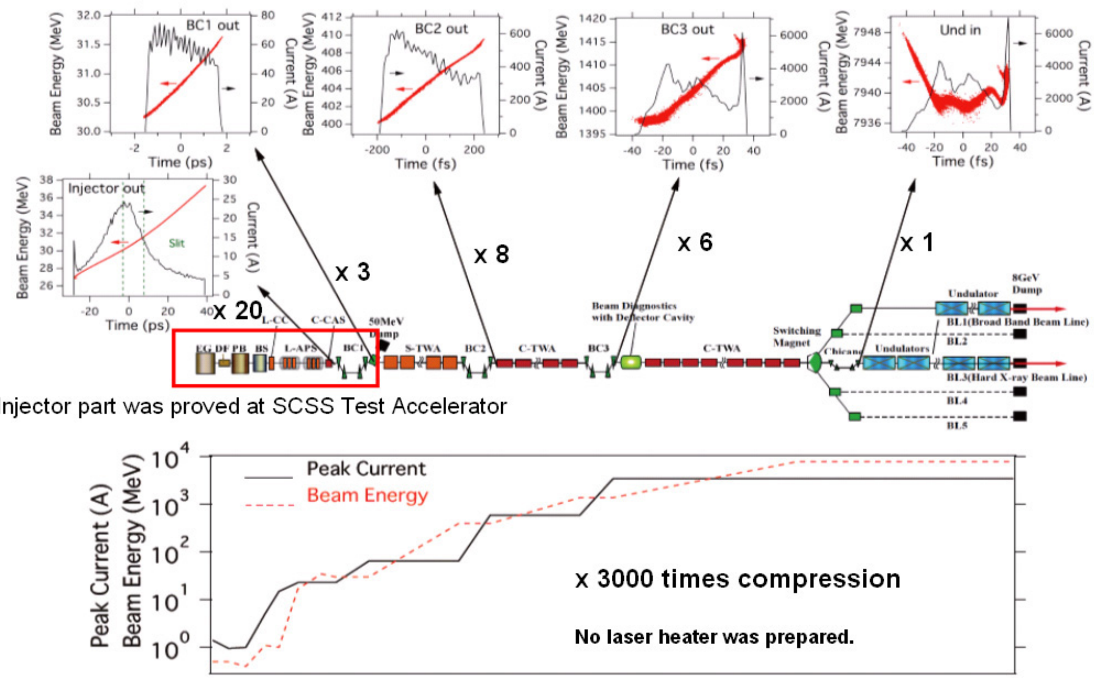

Figure 4: Machine configuration and beam parameters in 8 GeV XFEL/SPring-8.

hours or more in our electron gun condition (high vacuum and temperature, and 500 kV voltage applied).

MACHINE CONFIGURATION AND BEAM OPTICS

Figure 4 shows the machine configuration and simulated beam evolution along with multi-stage bunch-compressions. The optical beam parameter is listed in Table-1. From the gun to the undulator, the beam is processed and accelerated into 8 GeV as follows.

(1) The thermionic electron gun generates 1 A and 3 μsec pulse beam at 500 kV.

(2) Followed by fast-deflector to produce 1 nsec bunch.

(3) Velocity modulation of 200 keV is applied at 238 MHz cavity. This process provide the master time base on the following bunching process, thus this cavity is designed carefully to satisfy very high phase stability and temperature stability (<0.01 deg. C) [13].

(4) Followed by drift section of ~1 m long, peak current becomes higher according to bunching. The 476 MHz booster cavity pushes the beam energy up to 1 MeV to lower the space charge effect.

(5) The L-band (1428MHz) cavity captures the bunch, and quickly accelerates energy to 30 MeV. Since the energy is fully relativistic region, the velocity bunching process is terminated. The bunching factor from the gun to this point is 20.

(6) The magnetic chicane BC-1 compresses bunch length by factor of 3. The peak current reaches 60 A.

(7) Through four S-band accelerator systems (8 accelerator columns, 17 MV/m), the beam energy reaches to 415 MeV. The beam is off-phase by 17 degree to produce required energy chirp in BC-2.

(8) BC-2 compresses the bunch length by factor of 8.

(9) Through twelve C-band accelerator system (24 accelerating columns at 35 MV/m), the beam energy reaches to 1450 MeV. Thy are off-phase by 41 degree to produce required energy chirp in BC-3.

(10) BC-3 compresses the bunch length by factor of 6. The total bunch compression reaches 3000 at this location and peak current 3 kA.

(11) Right after BC-3, the longitudinal beam profile monitor system will be prepared[11]. We are currently developing rf-deflector cavity at C-band frequency. Using transverse beam profile monitor located downstream, we may observe streaked image at resolution 20 fsec, which will provide slice beam parameter.

Table 1: Machine parameter of XFEL/SPring-8. The machine will run single bunch mode at first, the upgrade to multi-bunch in future.

Wavelength	< 0.1 nm
Peak Power	~ 20 GW
X-ray Pulse Length	200 fs ~ 20 fs
X-ray Pulse Energy	Max 0.4 mJ
Photon Flux	2 x 10^{11} p/pulse
Peak Brightness	1 x 10^{33} p/mm^2/mrad^2/0.1% BW
X-ray Pulse Repetition	10 ~ 3000 pps (50 bunch x 60 Hz)
Bunch per Pulse	1 ~ 50 (4.2 nsec spacing)
e Beam	8 GeV x 0.3 nC 0.8 πmm.mrad, 3 kA

(12) Main C-band accelerator consists of 52 C-band units. Through 104 C-band accelerators, the beam energy reaches to 8 GeV. The energy chirp is corrected by the short bunch wakefield driven by series of beam irises in the C-band accelerators.

(13) In order to prevent the dark-current emission in the C-band accelerator from accelerating and irradiating to the undulator magnets, we prepared special magnetic section to cut the dark currents generated up stream. The dark current emissions generated after this section can be eliminated in the small chicane right before the undulator line.

(14) Undulator line consists of eighteen series of 5 m long in-vacuum undulators. In between these undulators, focusing Q-magnets and cavity BPM, they are mounted on precision movers.

To perform stat-to-end simulation, we used numerical tools; PARMELLA in the injector part and followed by ELEGANT in the chicanes and linear accelerators. One special cares were taken to linearize the beam shape in the (z, E) phase space[14]. 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.

C-BAND MAIN LINAC

Figure 5 shows the installed C-band accelerator in the 400 m long tunnel, and compact modulators and control racks in the klystron gallery. Since we use high gradient C-band frequency rf acceleration system, required power density becomes higher, as a result spacing between two adjacent klystrons becomes shorter. This is the reason why the accelerator components are dense in our accelerator and we needed to develop compact klystron modulator[7,8].

Higher accelerating gradient makes temperature change in rf system larger due to heat dissipation during machine operation. We employ precision temperature feedbacks on the accelerating structures and rf-pulse compressors[10]. X-ray FEL requires higher stability on acceleration field, especially phases in upstream sections (before the bunch compressors). Therefore the LLRF (low level rf system) is installed in special racks with fine temperature control[12, 13]. The airflow circulating inside the rack is isolated from the outside, and heat is removed by cooling-fins with temperature regulated water flow.

The C-band accelerating structures use the choke mode design, which damps the higher-order modes associated with running electron bunch, and stabilize multi-bunch beam trajectory. We can run 50 bunches in one pulse, which provide 50 times higher X-ray pulses, which will be great opportunity to the experiments requiring higher average photon numbers.

We took three years to complete mass production of 64 klystrons and rf pulse compressors, and 128 accelerating structures. It was completed February 2010 with a few months ahead of the schedule[5,6].

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. 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 output with nominal beam parameter. It predicted that the FEL will be saturated within 120 m long undulator line. By referring the experimental data on the gain measurement at SCSS test accelerator, the actual slice emittance is expected to be 0.7 π.mm.mrad or lower, thus the FEL will saturate in shorter distance.

STABILITY ISSUE

As discussed in previous sections, our system uses high bunch compression factor, thus the beam parameter, such as peak current, is sensitive to the machine parameter

Figure 5: Left, C-band main accelerator in 400 m long tunnel; Right, klystron gallery. Compact modulators and controls.

Magnetic Circuit		Hybrid
Length		5 m
Period		18mm
Number of Periods		276
Gap	Minimum	2mm
	At 1 Å ope	4mm
	Max	40mm
K-value	Max	2.1
	At 1 Å ope	1.9

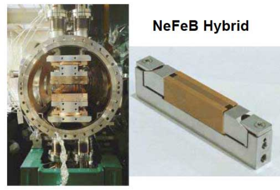

Figure 6: Up, the magnet array is hybrid type consist from permanent magnet and iron yoke; Down, installed undulators in XFEL/SPring-8. Spaces are available to install up to five undulator lines in 17 m wide and 200 m long hall.

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 developed high-power inverter-type power supply with precision of 10^{-4} level of pulse-to-pulse stability, will be used to charge PFN capacitor in klystron modulator in 50 kV, 35 kW power.

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.

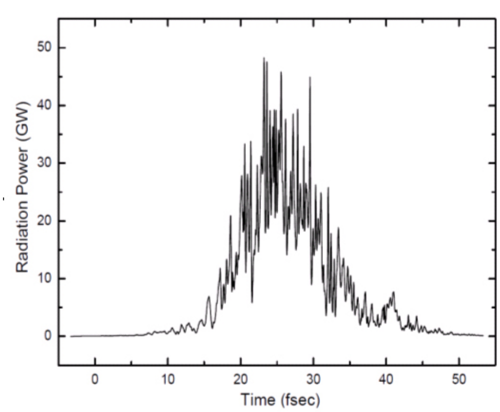

Figure 7: Simulated FEL output power at 1 Å wavelength.

CONCLUSION & SCHEDULE

The accelerator and undulator building constructions were completed in March 2009. The main accelerator components have been installed in the tunnel and klystron galley. We are currently installing 18 undulators, and performing field measurement in the beam line. From October 2010, we will start high power processing of the accelerating structure, and debugging the control system. The beam commissioning is scheduled in March 2011, followed by the first X-ray lasing.

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