SPRING-8 COMPACT SASE SOURCE AND XFEL PROJECT IN JAPAN

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Abstract

On 20 June, the first lasing has been observed at 49 nm in SCSS test accelerator, which is prototype machine for Japanese XFEL project. A challenging approach is employed in injector system: a low density electron beam is generated from 500 kV gun using thermionic cathode, followed by velocity bunch compression by factor of a few 100 times, and magnetic chicane bunch compression. The injector created high quality and high density electron bunch, whose measured emittance was 3 π.mm.mrad normalized with 800 A peak current and 1 psec pulse width or less. When we firstly closed the gap in one undulator in 15th June, we observed the SASE signal at 49 nm. Using two undulators, the signal amplification gain reached 10^5, which is close to the saturation level. The average radiation energy is 1 micro-J/pulse at moment, we need more beam tuning.

The XFEL project aiming at generating 1 Å coherent intense X-ray laser based on SASE using 8 GeV normal-conducting accelerator has been funded. The construction is scheduled 2006-2010, and beam operation will start in 2011.

INTRODUCTION

SCSS project has started in 2001 [1]. Unique combination of three key technologies: the in-vacuum short period undulator, the C-band high gradient accelerator and low emittance injector using thermionic electron source make possible to realize SASE-FEL at 1 Å within available site length at SPring-8 less than 800 m as shown in Fig. 1. It was named as SCSS: SPring-8 Compact SASE Source because of this reason. From year of 2001, we have been carrying out R&D for key components: the electron gun, injector, C-band klystron modulator with oil-filled compact design, high resolution beam position monitor, digital rf signal processing system, etc [2]. In order to check performance of developed hardware components and verify system performance, especially the low emittance electron injector, we constructed prototype accelerator for XFEL in 2004-2005 as shown in Fig. 2. The tunnel length is 60 m long, the maximum electron beam energy is 250 MeV, the shortest lasing wavelength is around 50 nm. From May 2006, we started dedicated beam tuning to demonstrate first lasing.

In 2006, 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. Figure 2 shows the computer image of the facility, the XFEL will be constructed right next to the 1 km beam line. The construction is scheduled 2006-2010.

One big benefit to have XFEL at SPring-8 site is to share human resources and sample preparation facilities in the existing 8 GeV synchrotron light source.

CHOICE OF ACCELERATOR TECHNOLOGY

We have decided to use normal conducting linear accelerator technology at C-band frequency (5712 MHz). It is “warm” technology, not super conducting “cold” technology. The reason why we chose this technology is

(1) Since C-band accelerator can generate high

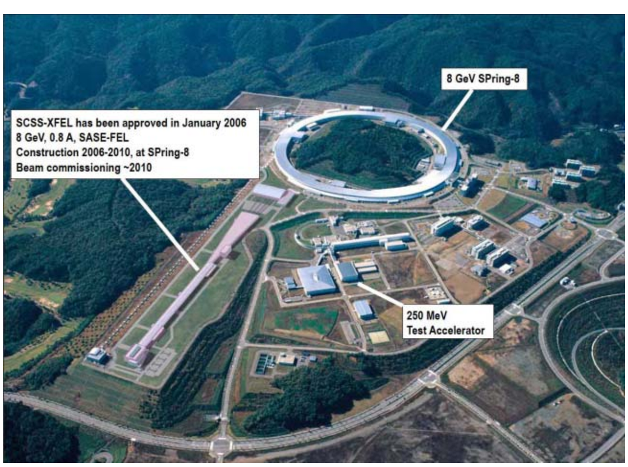

Fig. 1 The XFEL will be build at SPring-8 site.

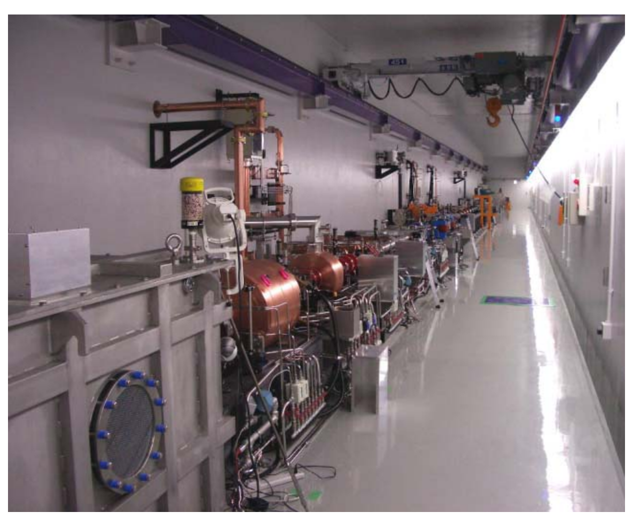

Fig. 2 Tunnel view in SCSS test accelerator.

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gradient, as high as 35 MV/m, with reasonable cost. Technology is available right now.

(2) Pulse repetition frequency of C-band accelerator is limited to 60 pps maximum, and average flux becomes quite lower (about 1/100 times) than the case of super conducting machine. The special feature of XFEL radiation is extremely high peak power (~ 2 GW) and short pulse duration (~30 femot-sec), and most of all scientific case to make use these features does not request high average flux. The existing SPring-8 3rd generation light source provides high average flux, thus XFEL and SPring-8 are complementary facilities in the same site.

CHOICE OF ELECTRON SOURCE

The SASE-FEL at 1 Å wavelength region requires high quality electron beam of extreme parameter: peak current > 2 kA, low slice emittance ~ 1 π.mm.mrad, and low slice energy spread < 10^{-4}. Additionally, it requires fairly long undulator line, near 100 m long, where the beam trajectory has to be guided in a straight line within small error < 10 μm. In this alignment, we use high resolution e-beam position monitors, and relay on beam-based-alignment. To perform this alignment, the electron beam has to be very stable, and also the beam hallow component and dark-current must be negligibly small (clean beam).

The transverse electron beam size at the undulator section is order of 30 μm, from this beam the X-ray is radiated with diffraction limited condition, thus the X-ray beam spot is also quite small, which is order of 100 μm at the sample located 30 m or 100 m downstream from the undulator. Pointing of the radiated X-ray beam follows e-beam trajectory, therefore, e-beam trajectory angle has to be fairly stable, such as, 3 μrad, and otherwise X-ray does not hit small samples.

In order to make such a stable and clean beam, first of all, the initial condition of electron beam trajectory, or the emission condition of the electron from the source has to be very stable. One candidate to meet this requirement is the thermionic cathode.

The LaB_6 or CeB_6 have been widely used in the scanning electron microscope, because of its high brightness and superior performance of quick recovery from contaminations [3]. Since they operate at high temperature near 1800 K, no any residual gases can condensed on the cathode surface. Additionally, there is constant rate of cathode material evaporation from the surface, which provides continuous activation, and also self-cleaning process. If we use a high quality single crystal, a very flat surface is formed in a single atomic layer after evaporation, which provides very uniform emission density and ensures no emittance break associated with rough cathode surface or non-uniform emission density sometimes observed in Ba-oxide cathode materials.

It should be noted that the pin-shaped cathode is commonly used in electron micro scope, since it provides extremely high brightness, i.e., small emission area provides small emittance while high current density, which meets imaging optics in microscope. However, it can emit fairly low current beam, typically less than 1 μA. In contrast, the SASE-FEL requires a few Ampere beam from the cathode, thus we use a flat surface. We chose CeB_6 rather than LaB_6, because of longer life time. At 1700 K operation temperature, expected lifetime is 20,000 hours for 100 μm material loss due to evaporation.

We use rod shape CeB_6 of 3 mm in diameter as shown in Fig. 3. We extract 1 A beam via 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, it was 1.1 π.mm.mrad including tail component for 1 A beam current. Eliminating tail components from the data, we estimated the net emittance of core beam as 0.6 π.mm.mrad [3].

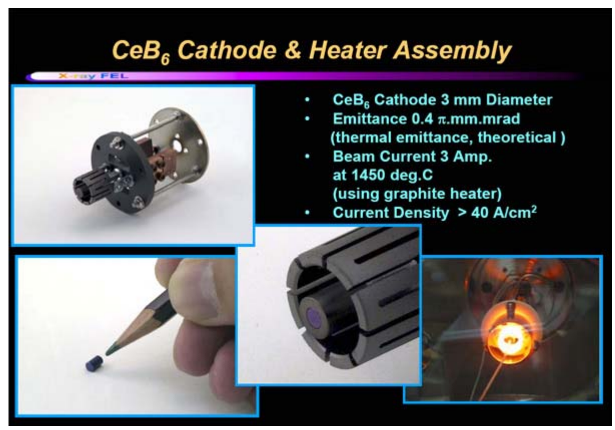

Fig. 3 CeB_6 single crystal thermionic cathode for low emittance electron source.

BUNCH COMPRESSION

In the X-ray FEL for 1 Å wavelength, very high peak current is required for e-beam to obtain high SASE-FEL gain. Nominal beam current value of 3 kA is required in our design. We can not generate such beam from any kind of electron sources, therefore we compress the bunch length in longitudinal direction by means of velocity bunching in injector and magnetic chicane bunch compressor. We designed the compression factor as 20, 18, 8 in velocity bunching at injector, the first and second bunch compression system, respectively. Big question is how we maintain low emittance value from the gun to undulator through these compressions.

In the injector and bunch compressors, if the following conditions are satisfied, the slice emittance can be conserved.

(1) Radiation damping or excitation through synchrotron radiation is small.

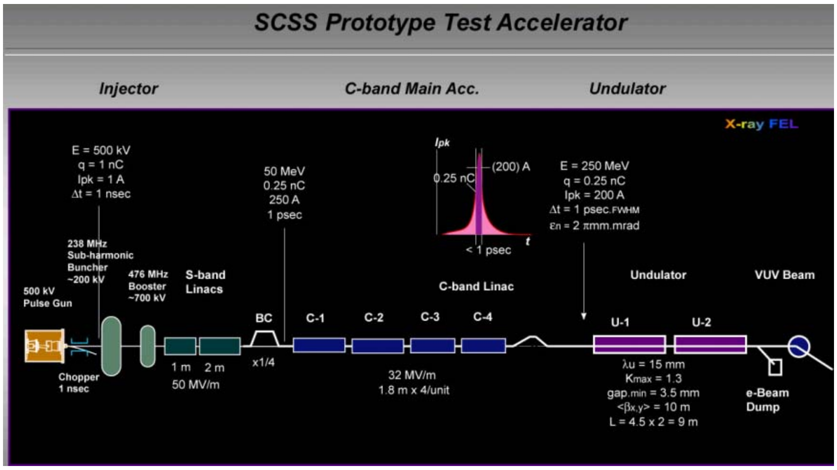

Fig. 4 SCSS prototype accelerator, two undulators of 15 mm pitch, 250 MeV e-beam, generates VUV-radiation.

(2) There is no highly nonlinear optics, which mix particle in radial direction, resulting in non laminar flow.

(3) There is no over-bunching process, which mixes and overlaps two or more slice components from different z-positions.

To satisfy above condition, we designed the injector system based on "adiabatic compression" scheme: the gun with beam chopper generate 1 A x 1 nsec x 500 kV beam, then velocity modulation by 238 MHz sub-harmonic buncher cavity, followed by velocity bunching along a drift section, then the space charge effect becomes severe as raising peak current, then 476 MHz booster cavity accelerates beam energy to 1 MeV, relativistic effect lowers the space charge effect, followed by velocity bunching, and inject into the S-band standing wave accelerator, and capture single bunch.

In order to test this challenging scheme, and check all hardware components developed in our R&D [4], we constructed prototype accelerator in 2004-2005 as shown in Fig. 2. Beam line layout is shown in Fig. 4. We use four C-band accelerating structures, 1.8 m long each, energy gain 32 MV/m maximum. With maximum beam energy of 250 MeV, the shortest wavelength of VUV-radiation at 50 nm can be obtained.

EMITTANCE MESUERMENT

At the injector end, the velocity bunching and chicane bunch compression complete, where the beam energy reaches to 50 MeV, bunch charge is 0.25 nC and the bunch length is 1 psec or less, which depending on operation condition, specifically phase & amplitude tuning of 238 MHz and 476 MHz cavities.

We measured projected emittance right before the C-band accelerators, using Q-scan method. By reversing polarity of one of the Q-magnets to provided strong focusing in X- and Y-direction, and measured the minimum beam width. By varying focusing power, the beam width response was measured as Fig. 5 and 6. We found the normalized projected emittance of around 3 π.mm.mrad for both X- and Y-directions. The slice emittance was also measured at 50 MeV beam dump, it was 2 π.mm.mrad, where the measurement was limited by spatial available resolution of profile monitor.

We repeated many measurements in this kind, always observed emittance around 3~4 π.mm.mrad. This experimental data indicates that the velocity bunching in our system does not largely deteriorate the projected emittance for compression ratio exceeding 100 times. For more detail, refer the report by H. Tanaka [6].

FIRST LASING EVENT

Two in-vacuum undulators were installed, whose undulator period is 15 mm, minimum gap is 3.5 mm, nominal K value is 1.3 and one undulator length is 4.5 m. In the beam tuning, we firstly opened the gap to 20 mm and passed the e-beam through gap and transported into the beam dump. We tuned the beam optics upstream of the undulator. We setup the optics, in coming beta-matching and focusing Q-magnet in between two undulators.

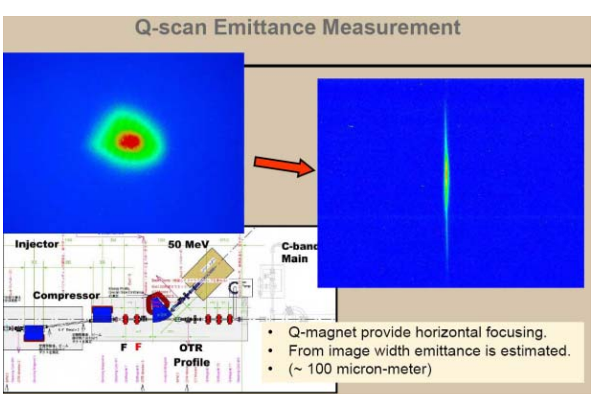

Fig. 5 Beam profile during Q-san emittance measurement. Transition radiation from Au coating of optical mirror was monitored by CCD camera.

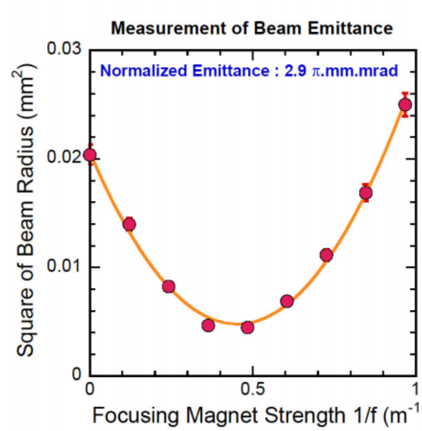

Fig. 6 Beam width as a function of focusing power. At beam energy 50 MeV, charge 0.25 nC, length <1 psec.

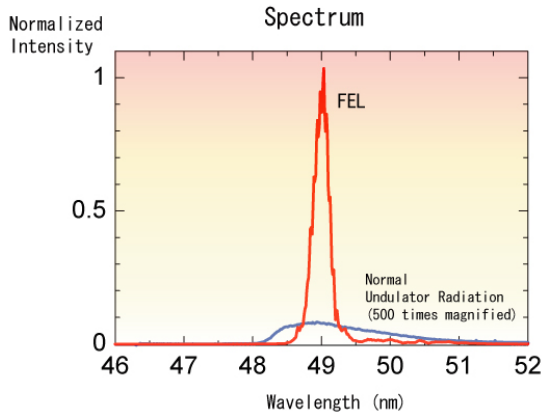

Fig. 7 Radiation spectrum at the lasing condition, 0.25 nC per bunch and 250 MeV. Peak at 49 nm is the coherently amplified signal (6000 times) from the spontaneous undulator radiation (blue line).

On 15th June evening, we firstly closed the gap in the upstream undulator, and measured radiation spectrum, where the spectrum width was already quite narrow, peaked at 49 nm, and totally different from the natural spontaneous radiation, as shown in Fig. 7. The spectrum width is around 1% FWHM, which is much narrower than the spontaneous undulator radiation, while it is dominated by e-beam energy fluctuation, at moment.

As shown in Fig. 8, when we varied the bunch charge, the lasing power drastically changed. This threshold phenomenon indicates high FEL gain. The power has not yet reached the saturation.

By varying K-value of undulator, response of the power gain was measured. Comparing to numerical simulation we determined the electron beam brightness as 270 ~ 310 A/(π.mm.mrad)^2 in the undulator.

FROM TEST ACCELERATOR TO XFEL

To obtain enough FEL-gain at 1 Å, we need ten times higher brightness than the test accelerator case, i.e., 3 kA at 1 π.mm.mrad. This will be easily obtained by the second stage bunch compressor at high energy (designed compression factor is x 8, at 1.8 GeV).

On the other hand, about the X-ray energy, we need improvement. The lasing pulse energy in the test accelerator is 1 micro-J/pulse average, which is about ten times lower than theoretically predicted value for 0.25 nC charge. This is partly due to the fact that the second undulator field is not perfectly matched with requirement, and may be also due to non-uniform charge distribution in electron bunch [6]. While we do not have enough data to determine amount of charge contributed to lasing, it may be 10% or less.

In XFEL machine, to raise fraction of charge for lasing and increase total charge, we improve injector design as follows.

(1) Run the electron gun at 2 A beam current (twice higher than test accelerator case). The cathode and gun handle this beam without loosing cathode lifetime and breaking emittance.

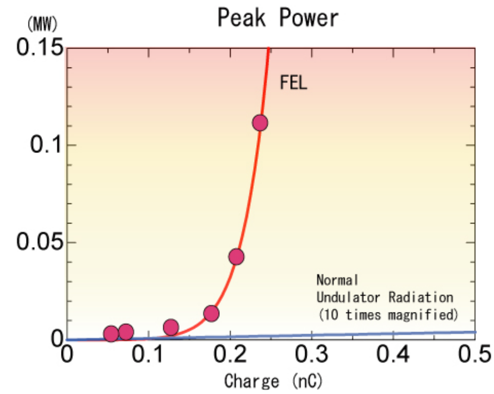

Fig. 8 Peak output power v.s. bunch charge. Using photo diode, peak height was detected from averaged pulses.

(2) Use L-band accelerator instead of S-band at the buncher cavity, which makes beam acceptance 8-times larger. In the test accelerator, acceptance is limited upstream end of the S-band standing-wave buncher. Lowering frequency twice, all structure dimensions will scale twice larger, resulting in larger acceptance in x, y, z-directions.

(3) Flat-topping cavities will be used in the injector. Since we use rf-field to compress bunch, the non-linear curve associated with cosine-function creates non-uniform charge distribution after bunching. Applying higher harmonic cavity, we can obtain a linear response function. This technique is well known as "flat-topping cavity" in traditional cyclotrons.

With this improvement, we will be able to generate bunch to drive FEL with 1 nC charge, with emittance 1 π.mm.mrad and with uniform charge distribution.

CONCLUSION & SCHDULE

We measured the e-beam emittance and observed first lasing in the SCSS prototype accelerator. From this experiment, superior performance of the thermionic gun and injector system has been demonstrated.

Analysing the experimental data carefully, we refine hardware design, and start XFEL construction this year.

REFERENCES

[1] T. Shintake *et al.*, "SPring-8 Compact SASE Source", SPIE2001, San Diego, USA, June 2001

[2] http://www-xfel.spring8.or.jp

[3] http://www.feibeamtech.com/

[4] K. Togawa *et al.*, "Emittance Measurerment on the CeB6 Electron Gun for the SPring-8 Compact SASE Source", FEL2004, Trieste Italy, August 2004

[5] T. Shintake, Status of SCSS Project, 3rd Asian Particle Accelerator Conference, APAC2004, Gyeongju, Korea, March 2004.

[6] H. Tanaka *et al.*, "Low Emittance Injector at SCSS", FEL2006 conference, Berlin, August, 2006.