STATUS OF THE SCSS TEST ACCELERATOR AND XFEL PROJECT IN JAPAN

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Abstract

On 15 June, the first lasing has been observed at 49 nm in SCSS prototype accelerator for Japanese XFEL. A challenging approach: CeB_6 single crystal thermionic cathode generates low emittance DC beam from 500 kV gun, followed by velocity bunch compression by factor of a few 100 times, and magnetic chicane bunch compression, measured emittance was 3 π.mm.mrad normalized, made lasing. The XFEL project, aiming at generating 1 Å coherent intense X-ray laser, 8 GeV normal-conducting accelerator, has been funded. The construction is scheduled 2006-2010, and beam operation will start in 2011.

INTRODUCTION

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. It was named as SCSS: SPring-8 Compact SASE Source [1]. 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. 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.1. The tunnel length is 60 m long, the maximum electron beam energy is 250 MeV, the shortest lasing wavelength is around 50 nm.

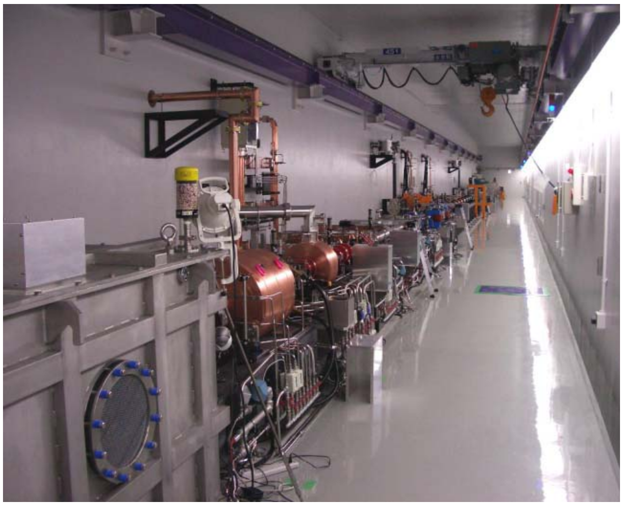
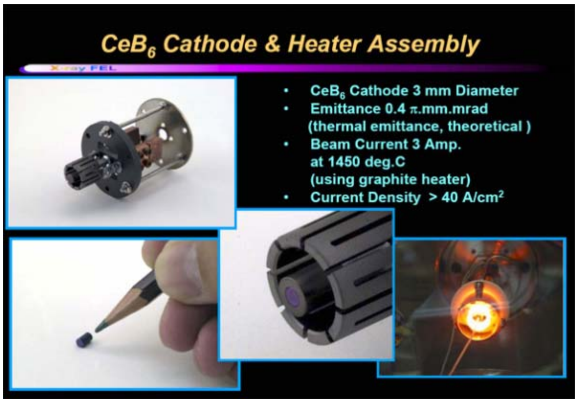


Fig. 1 Tunnel view in SCSS prototype accelerator.

From May 2006, we started dedicated beam tuning to demonstrate first lasing.

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).



CeB_6 Cathode & Heater Assembly

- CeB_6 Cathode 3 mm Diameter
- Emittance 0.4 π.mm.mrad
(thermal emittance, theoretical)
- Beam Current 3 Amp.
at 1450 deg.C
(using graphite heater)
- Current Density > 40 A/cm^2

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

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 contamination [2]. Since they operate at high temperature near 1800 K, no any residual gases can

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condensed on the cathode. Additionally, there is constant flow of material evaporation from the cathode surface, which provides continuous cathode activation, and also self-cleaning process. Using high quality single crystal, after evaporation a very flat surface is formed in a single atomic layer, which provides very uniform emission density and ensures no emittance break associated from 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 is fairly low current beam, typically less than 1 µA. In contrast, the SASE-FEL requires a few Ampere beam from the cathode, thus we need 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. We extract 1 A beam via 10 MV/m acceleration field in the gun (500 kV/5cm), which is in 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 tails from the data, we estimated the emittance as 0.7 π.mm.mrad [3].

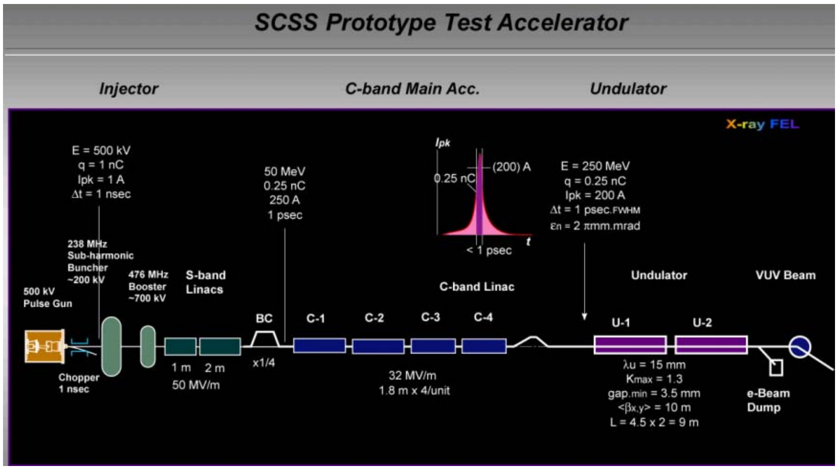


Fig. 3 SCSS prototype accelerator, two undulators of 15 mm pitch, 250 MeV e-beam, generates VUV-radiation.

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 current directly 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 buncher. We designed compression factor 20, 18, 8 in velocity bunching at injector, the first and second bunch compression system, respectively. Big question is how we maintain low emittance 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.

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

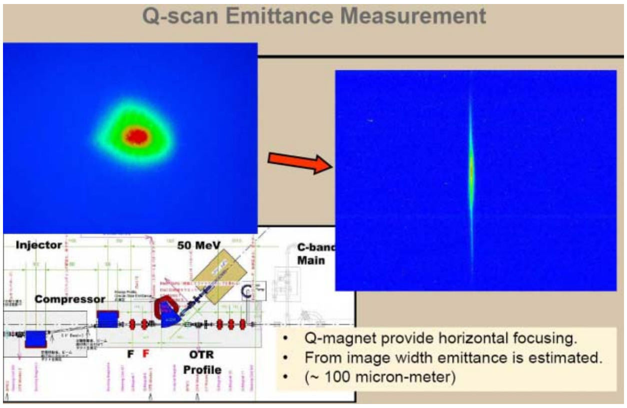
(3) No over-bunching, which mixes and overlaps two or more slice components in longitudinally from different z-position.

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. 1. Beam line layout is shown in Fig. 2. 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 will be obtained.

EMITTANCE MESUERMENT

At the injector end, the velocity bunching and chicane



- Q-magnet provide horizontal focusing.
- From image width emittance is estimated.
- (~ 100 micron-meter)

Fig. 4 Beam profile during Q-san emittance measurement. Transition radiation from Au coating of optical mirror was monitored by CCD camera.

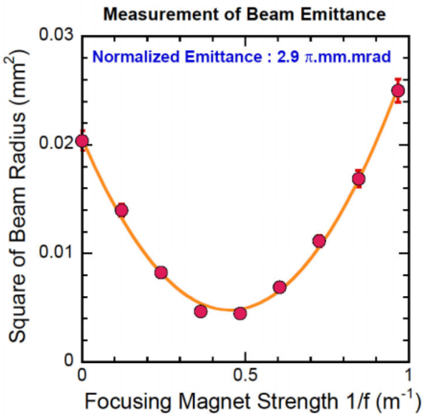


Fig. 5 Beam width as a function of focusing power. At beam energy 50 MeV, charge 0.25 nC, length <1 psec.

bunch compression have been completed, 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. 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.

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.

On 15 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. 6. 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. 7, 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. Further tuning is required. Detail analysis is now undertaken.

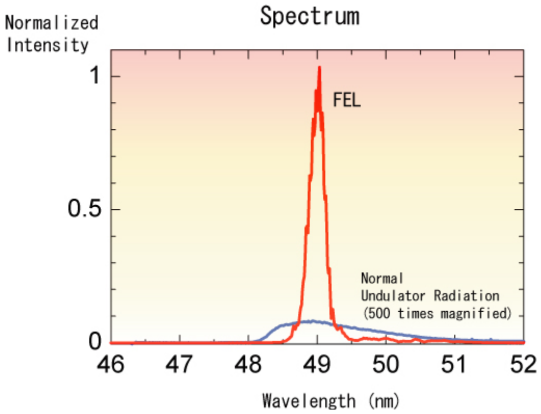


Fig. 6 Radiation spectrum at the lasing condition, 0.25 nC per bunch and 250 MeV. Peak at 49 nm is the coherently amplified signal (6000 times) from the spontaneous undulator radiation (blue line).

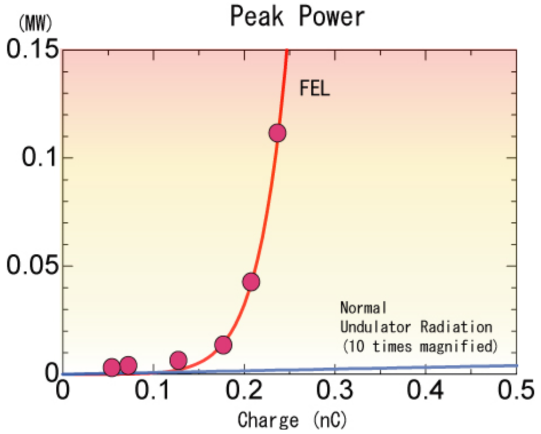


Fig. 7 Peak output power v.s. bunch charge. Using photo diode, peak height was detected from averaged pulses.

CONCLUSION & SCHEDULE

We measured the e-beam emittance and observed first lasing in the SCS 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.feibeamtech.com/
[3] K. Togawa et.al., "Emittance Measurerment on the CeB6 Electron Gun for the SPring-8 Compact SASE Source", FEL2004, Trieste Italy
[4] T. Shintake, Status of SCSS Project, 3rd Asian Particle Accelerator Conference, APAC2004, Gyeongju, Korea, March 2004