STATUS OF SCSS PROJECT

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Abstract

In order to establish technology required for the future X-ray FELs at 1 Angstrom wavelength region, RIKEN/SPring-8 started SCSS-project [1] in 2002. It is a soft X-ray SASE-FEL machine aiming at demonstrating FEL operation below 10 nm wavelength with 1 GeV electron beam in 2006~2007. A combination of the short period in-vacuum type undulator and the high gradient C-band main accelerator, makes the machine compact, and enables to fit within a 100 m long tunnel. The name SCSS: SPring-8 Compact SASE Source was made by this reason. To saturate FEL within 22.5 m long undulator line, we need a high quality electron beam: r.m.s normalized emittance should be below 2 π mm-mrad (r.m.s normalized) with 2 kA peak current. To generate this beam, we are developing the HV pulse gun using thermionic cathode (CeB_6 single crystal) and sub-harmonic buncher system. The transverse emittance, experimentally measured using double-slit-method, was 1.1 π mm.mrad (r.m.s normalized) at 1 A beam current and 500 kV beam voltage [2].

INTRODUCTIONS

The X-ray FEL based on the SASE: self amplification of spontaneous emission usually requires a large-scale accelerator and a long undulator, while it can provide a few X-ray beam lines only, therefore the construction cost per one beam line becomes quite higher than that in the conventional SR machines. This is the reason why people propose the X-ray FEL as a parasitic facility attached to an existing electron accelerator, such as LCLS project at SLAC, or TESLA project as an integrated facility into the future electron and positron linear collider. Therefore, opportunity to have X-ray FEL facility becomes quite limited.

If we can lower the machine cost, many X-ray FEL machine will be constructed and contribute to a wide range of new sciences. The reasonable cost will be the today's construction cost of a few X-ray beam lines in the existing SR facilities. One of the most effective factors on the machine cost is the facility size, that is, to lower the cost, the machine has to be compact.

In the SCSS project, the following three key technologies realize the compact machine.

(1) High gradient C-band accelerator. The accelerating gradient can be as high as 40 MV/m, thus 30 m long accelerator is enough to reach 1 GeV.

(2) In-vacuum undulator, which enables the undulator period shorter, thus the beam energy becomes lower, as a result smaller the accelerator size. It also contributes to shorten the FEL gain length.

(3) Low emittance beam injector. The short undulator period reflects back to tight requirement of a low emittance electron beam. We chose HV pulse gun using the thermionic single crystal CeB_6 cathode, which has a high potentiality to generate very small emittance beam for a long lifetime.

MACHINE CONFIGURATION

Figure 1 shows the machine layout of SCSS project, whose parameter is summarized in Table-1. To saturate FEL in the 22.5 m long undulator line, it requests the peak beam current as high as 2 kA with low emittance. The high peak current is generated by compressing the bunch length in the injector and also in magnetic-chicane bunch compressor. We will use four units of the C-band accelerator which generates 40 MV/m accelerating gradient, by which the beam energy will reach 1 GeV within 30 m long accelerator, and the shortest radiation wavelength becomes 3.6 nm.

As seen in Fig 1, the assumed beam current waveform is not flat, nor Gaussian, it has peak of spike-shape at center point, which is naturally generated after bunching with velocity modulation on rf-waveform, because the sin-function is not linear, it has 3rd order non-linearity at zero-crossing point, resulting in peaked spike at center after bunching. Since the FEL gain becomes higher at

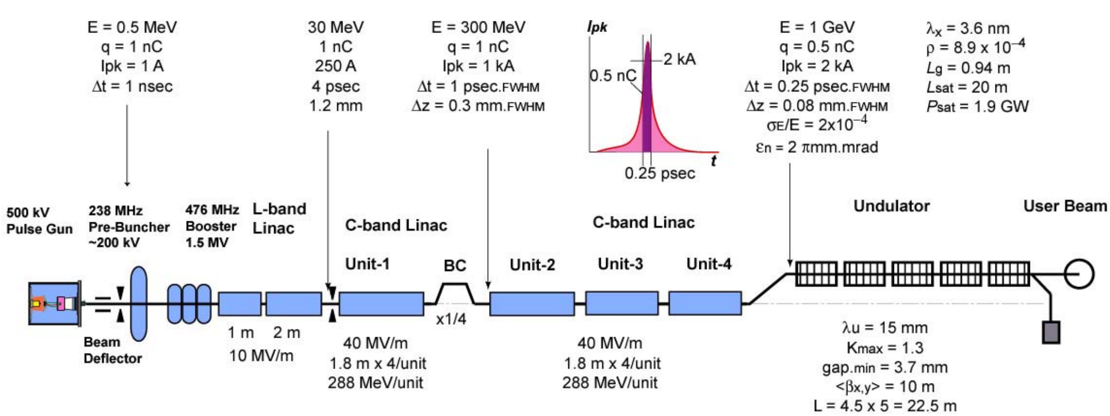

Figure 1: Beam line layout in SCSS of 1 GeV case.

higher electron density, thus X-ray power becomes high enough at center, while it will be low at tail part, as a result, a very short X-ray pulse will be generated. This is quite useful phenomena to generate femto-second X-ray pulse in SASE-FEL machine. The pulse length can be varied with rf-modulation depth in the pre-buncher, and also compression factor in the bunch compressor.

ELECTRON INJECTOR

Electron Gun

In SASE-FELs, the electron bunch generated by the gun directly passes through the long undulator and generates X-ray. This situation is quite different from the storage ring type machine. Any fluctuation of the electron beam, i.e., transverse position, timing, size, will directly affect on X-ray performance. Since SASE-FEL is a kind of high-gain power amplifier, any fluctuation on the incoming electron beam is also amplified. Therefore, to generate stable X-ray production, the electron source has to be very stable.

In the design work of our machine, we took the stability issue as the first priority. As we know the rf-photo-cathode gun has a big advantage to generate a short bunch from the cathode directly. The rf-photocathode gun has been well studied and advanced recently, i.e., using emittance compensation solenoid, emittance below 3 π mm.mrad at 0.3 nC charge becomes possible [3]. However, the beam parameter is quite sensitive to the laser pulse to generate electron beam, and the laser, generally speaking, introduces additional fluctuation source to the system.

From this reason, we decided to use thermionic cathode followed by the buncher system. This is basically old fashion design, and sometimes used in the traditional injector system for many type of electron accelerator, including synchrotron light sources. It is known this configuration is stable and cathode is rather long life. But emittance is usually large, it ranges about 30 π mm.mrad or even higher. To make emittance low we did following upgrade,

Table 1. SCSS design beam parameter at 1 GeV.
Note the bunch length is denoted by FWHM value.

bunch charge (core part)	q	~0.5	nC
normalized emittance	$\varepsilon_{nx,y}$	2	πmm.mrad
final electron energy	E	1	GeV
final r.m.s. energy spread	σ_δ	0.02	%
final FWHM bunch length	Δt	0.25	psec
peak current	I_{pk}	2	kA
undulator period	λ_u	15	mm
radiation wavelength	λ_x	3.6	nm
minimum gap	g	3.5	mm
maximum K-parameter	K	1.3	
undulator segment length	L_1	4.5	m
total undulator length		22.5	m
beta function	β	10	m
FEL parameter	ρ	8.9	x 10^{-4}
gain length	L_g	0.94	m
saturation length	L_{sat}	20	m
saturation power	P_{sat}	2.0	GW

(1) Use small size cathode. The initial emittance from the cathode is dominated by its size. We use a single crystal cathode with 3 mm in diameter. Theoretical thermal emittance becomes 0.4 π mm.mrad at 1400 deg.-C. We chose the CeB_6 material, which is commonly used as the point emitter in electron microscope. It can generate high beam current density at 40 A/cm^2, for a long life time (in electron microscope application, the supplier reported a few thousand hour lifetime) [4]. The Ba-oxide cathode can not generate such a high density beam for a long period.
(2) Eliminate control grid from the cathode. In the traditional triode type cathode, nonlinear field around the grid wire causes emittance growth.
(3) To form a single bunch from a long pulse beam after the gun, we use a fast beam deflector.
(4) Apply 500 kV on the cathode, which minimises the space charge contribution on emittance growth.
(5) Apply pulse voltage in a few micro-sec range, rather than DC voltage. DC field will easily cause high-voltage breakdown in metal-to-metal electrodes or flash over along insulating ceramics. After the long history in the klystron tube development in industry, there is well established criterion for safety design around the electron gun. 500 kV across 5 cm gap for a few micro-second is within the safety criterion. If we apply DC or long pulse, we have to lower the voltage or extend the gap much longer (refer engineering design of the electron microscope operating at 1 MV or higher).

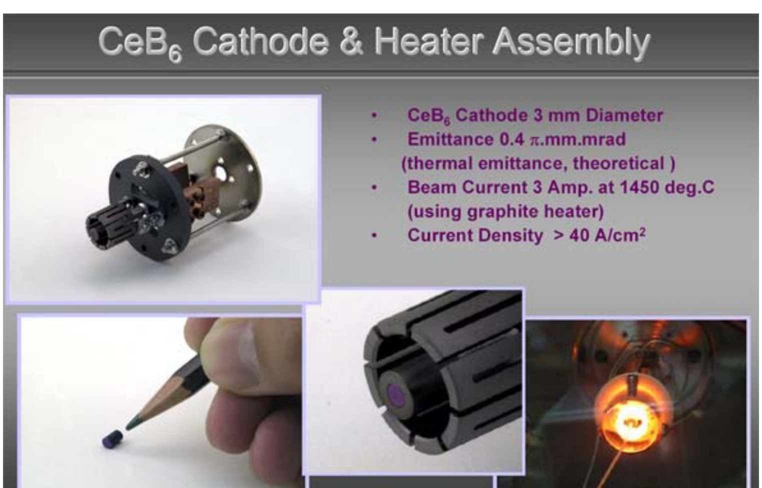

Figure 2: Cathode and heater assembly.

Figure 2 shows the cathode and heater assembly. The CeB_6 material evaporates the boron atoms at high temperature, they sinter into refractory metal and breaks its bonding. To avoid this problem, the CeB_6 crystal is mounted in a carbon rod, which is heated by a graphite heater. Graphite is a stable material in vacuum at high temperature near 2000 deg.-C, that is, temperature coefficient of electrical resistivity is small, and it keeps mechanical rigidity without softening. The Vogel-type heater mount is commonly used as heater assembly, which hold the CeB_6 or LaB_6 crystal cathode by two finger-type current leads sandwiched with graphite chips, heated by direct current flow. This design is rather simple and low cost, suitable for mostly small size cathode, less than 1 mm in diameter. For a larger cathode, thermal radiation from the cathode surface becomes large, to compensate this loading, the temperature at graphite chips has to be higher, resulting in faster the evaporation of cathode material at contact point, and shorten the lifetime. To overcome this problem, in our design, the cathode is heated by thermal radiation from the graphite heater. The cathode and its mount are uniformly heated up to the target temperature, thus there is no hot spot, and no excess evaporation of cathode material, it is important to ensure a long life time.

The 500 kV electron gun is installed in a oil tank. The emittance measurement system is equipped with a set of variable slits, and pulse beam current monitor using triode core, and beam dump. The same pulse modulator power supply, shown in Figure 4, designed to drive the C-band 50 MW klystron, is used to drive the 500 kV pulse voltage through 1:20 step-up.

Figure 3 is the phase diagram of the measured beam profile at 500 kV, 1 A beam current. The r.m.s geometrical emittance estimated from the measured data is 1.1 π mm.mrad. About detail of the measurement, refer the report by K. Togawa [2] at this conference.

Beam Deflector, Buncher and Booster

The beam current from the gun is a long pulse, not a bunched beam. To form a short bunch, we use a beam deflector which sweeps the beam position transversely via travelling wave electrode, and fast high voltage pulser. A part of one nano-sec duration passes through the beam slit, and velocity modulated in the 238 MHz pre-buncher cavity, followed by a two meter long drift section, and booster cavity at 476 MHz to raise the beam energy to 2 MeV. In this year, we will install the pre-buncher cavity and the beam deflector. We will investigate bunching phenomena and emittance break due to space charge effect. At this stage, the beam parameter can be compared with the beam from an rf-photocathode gun, that is, typically 1 nC a few pico-second bunch length.

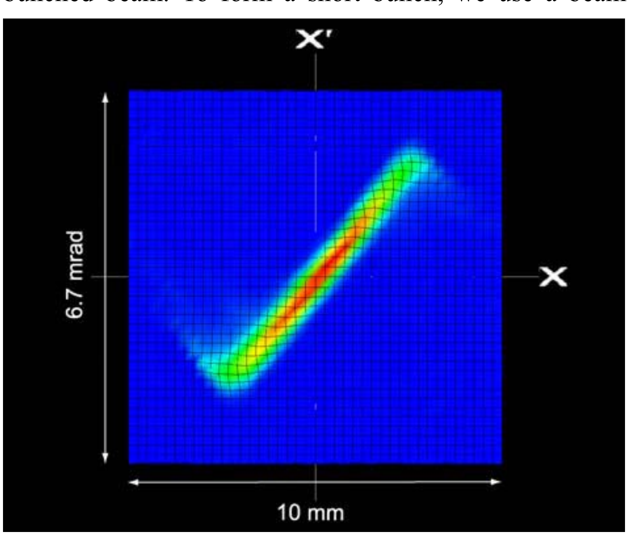

Figure 3: Phase space plot (x, x') of the measured electron beam at 500 kV, 1 A current. The slice time is 5 nsec, and full pulse length is 3 micro-sec.

C-BAND MAIN ACCELERATOR

One of the unique designs in SCSS is the high-gradient main accelerator running at C-band frequency. As well known in theory of the electron accelerators, conversion efficiency of the rf-power to the beam energy becomes higher at higher frequency, it is so called the shunt-impedance become higher. In the course of the e+e- linear collider R&D, we chose the C-band 5712 MHz, which is twice higher frequency than traditional S-band, as the optimum frequency for the main accelerator because of its higher shunt-impedance, and its technology requirement to make accelerating structure and high power klystrons are feasible. After five years R&D effort, KEK group has developed most of all the component required for the C-band accelerator.

SCSS team decided to employ the C-band design in the X-ray FEL machine. Thanks to its higher shunt-impedance, it will generate 40 MV/m accelerating gradient, which is much higher than traditional accelerators. Only 30 m long main accelerator will provide 1 GeV beam.

In SCSS project, before the machine construction, we are performing refinement of detail hardware design, such as, the high-voltage pulse modulator for klystron, the rf-

Figure 4: Pulse power modulator for the 50 MW C-band klystron, and the 500 kV electron gun.

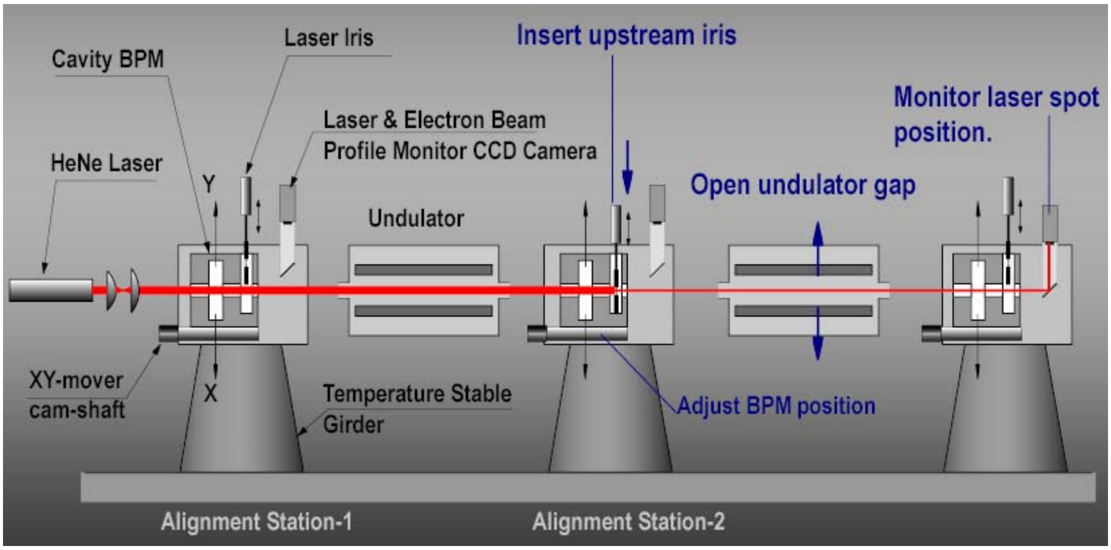

Figure 5: Laser alignment system for the undulator line.

pulse compressor and digital rf-feedback system which maintains the beam energy constant automatically.

Detail of the C-band hardware R&Ds are reported by H. Matsumoto [5] and T. Inagaki [6] at this conference.

UNDULATOR

We use in-vacuum type short period undulator. The benefits of this design to SASE-FEL application are

(1) Since all of the magnetic components sit inside the vacuum vessel, there is no vacuum envelop between the magnetic pole and the beam aperture, thus we can bring magnet close to the beam. Thus higher magnetic field can be obtained at the same gap in the in-vacuum undulator than the traditional undulator.

(2) The undulator gap can be opened to provide a large beam clearance. At the beam commissioning, we can fully open the gap, and provide wide beam aperture, safely transport electron beam to the beam dump.

(3) Before the electron beam operation, we perform precise alignment of beam position monitors using HeNe laser beam. By opening the gap, we can transport laser beam through the undulator for 20 m or longer distance without focusing element, thus we can use HeNe laser as the reference line for the alignment. If the undulator is fixed gap design, we may not introduce the laser in the undulator line, so that we need to prepare a separate vacuum pipe for the laser beam, just like in the two-mile accelerator at SLAC. One difficulty in this scheme is that transferring process of the geometrical reference positions from the laser line to the electron beam line introduces additional error.

ALIGNMENT STATION

To saturate X-ray beam through the long undulator line, the electron beam has to be transported along a straight line. According to the numerical simulation, the alignment tolerance is about ten micron-meters for each undulator segment.

The undulator segment, which is 4.5 m long, is one rigid structure, where magnets are mounted on a solid cooper beam supported in a vacuum vessel through five movable arms. To tune the magnetic field, we adjust the undulator gap along segment, and swap the magnet elements. We have developed a prototype model, and the field integral (expected beam trajectory) after the tuning was within the alignment tolerance. Therefore, the electron beam will flow fairly straight lines in each undulator segment.

We will install the Q-magnets in between undulators, which is necessary to provide focusing field on the electron beam to transport the beam through undulators and keep optimum beam size for FEL interaction. Since Q-magnets have alignment errors, the electron beam will be kicked transversely, resulting in zigzag trajectory. We need to align the Q-magnet position, or beam position using corrector magnets.

In order to perform this alignment, we will install alignment stations in between each undulators, that is, 4.5 m apart, as shown in Fig. 5. The alignment station is a very stable support (low thermal expansion and low mechanical vibration), on which we mount focusing Q-magnet and a high precision electron beam position monitor based on TM110-mode cavity (Cavity BPM), whose position resolution is well below one micron-meter, and absolute electrical center is kept within a few micron-meter referred to the cavity cylinder.

In the alignment process, we open the undulator gap, and bring the HeNe laser beam into the undulator line, which passes through the Q-magnet, and the cavity BPMs. Inserting a round iris into the cavity BPM, and measure the position of iris image on a CCD camera at downstream. By taking the pixel average, we find the center position of iris image from up-stream alignment stations. To overlap those images, we move the cavity BPM in transverse direction using precise mover, and repeat this process on successive BPMs to align them in a straight line. To demonstrate this scheme, we transported a HeNe laser beam in air about 30 m long distance and monitor the laser image by a CCD camera from downstream (without focusing lenses). Inserting an iris in between and moving the iris position in ten micron-meter steps. The measured position from the CCD camera responded fairly linear to the iris position, and the resolution was a few micron-meter. In the actual system, the HeNe laser beam will be transported in vacuum, so that, it will provide enough stability.

When FEL starts operation, we retract the iris from the cavity BPMs, and close the undulator gap, adjust the beam position by using corrector magnet.

The support of the alignment station is made by a special ceramic, cordierite, which has a very small thermal expansion coefficient, as low as, 2 $x10^{-6}$, which is about ten times lower than metal material [7]. If we use a steel structure as traditional support design, when the temperature changes 1 degree-C, the position will move 20 micron-meter at 1 m high, it is larger than the alignment tolerance. In our design, the position movement due to a few degree temperature changes is only a few micron-meters. The interior of the ceramic cylinder is filled with sands to provide vibration damping.

TEMPERATURE REGULATION SYSTEM

Traditionally, in high energy electron accelerator, we uses a large scale water cooling system, based on cooling tower and powerful circulating pumps. This configuration is not suitable to the next generation machine like FELs due to the following reasons.

(1) High power circulation pump generates pressure shocks at a few tens Hz, it sometimes cause unwanted mechanical vibration on accelerator components, such as, the focusing Q-magnet or accelerating structure.

(2) Response time of the temperature regulation is usually long because the water circulating time in the system rages in ten minutes or even longer. Therefore, it can not response to the parameter change of heat load level, quickly.

(3) Start up time of the system is also long.

To solve these problems, we are developing a cooling water system [8], where the main loop temperature is regulated by a recirculating chiller of 100 kW level at +-0.5 deg.-C. For the accelerating structure, the temperature has to be maintained within +-0.1 deg.-C for different heat-load level at operation modes, that is, changing the cycle frequency (10, 20…60 Hz). Since the heat density in high gradient C-band accelerator is about ten times higher than traditional S-band accelerator, an active feedback loop is required. In our new system, by monitoring temperature on the copper body, systems calculates error and applies feedback to the inlet water temperature at the accelerating structure, by using a electrical heater and electrical flow-rate control valve. When the rf-power is off, heater will be ON and the temperature of the accelerating cavity will be kept at 30 deg. C. On the other hand, when the rf-power is ON, the accelerating cavity is heated by rf-power loss, and the heater power is lowered to maintain at 30 deg. C. The feedback cycle period is only 30 second, that is, our accelerator becomes steady state after 30 second by changing operational modes. This is especially important for the X-ray FEL machine, where the user will request to change the X-ray intensity or pulse rate, frequently.

PROJECT SCHEDULE

In this year, we will start operation of one unit of C-band main linac to examine reliability of the system and performance of accelerating structure at operate at 40 MV/m. For the injector, we install pre-buncher system to compress the bunch in 10 psec bunch. The machine construction will be started in 2005, should be completed in 2007.

ACKNOWLEDGEMENT

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