PROGRESS ON THE C-BAND ACCELERATOR FOR THE SPRING-8 COMPACT SASE SOURCE*

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Abstract

SCSS: SPring-8 Compact SASE Source (Soft X-ray FEL project) was started in 2002 in order to establish the technology required for the X-ray Free Electron Laser at 1 Angstrom region [1]. Three key technologies: the short-period in-vacuum undulator, the high-gradient C-band accelerator and the low emittance electron source using CeB_6 single crystal thermionic-cathode enable to design the SCSS machine size within100 m facility. The C-band RF system R&D was originally started at KEK to establish linear-accelerator technology for the e^+e^- Linear Collider project [2], and transferred to SCSS project at SPring-8/RIKEN. In SCSS, 8 klystrons and modulators, 16 accelerating structures will be used to accelerate the beam up to 1 GeV. Construction and operation of SCSS machine will provide realistic information on reliability, maintainability and cost of the C-band RF system, which will be very useful to judge the reality of Linear Collider project based on C-band technology.

INTRODUCTION

An X-ray FEL based on the SASE concept requires a large-scale accelerator and a long undulator. It can provide X-ray beam into a few beam lines only, therefore the construction cost per one beam line becomes quite higher than that in the conventional SR machines.

Since the X-ray FEL will open a wide range of new science, many FEL-machines will be required all over the world in the future, similar to the today's SR source facilities. To realize this dream, the machine cost should be minimized. Reasonable cost would be the construction cost of a few X-ray beam lines in the existing SR facilities. To do this, first of all, we have to make the machine size compact, because the building as well as the machine itself becomes inexpensive. This is one of the important target in SCSS project, thus we put the word "Compact" in the project name.

In the SCSS project, we achieve this target by the following three key technologies, and they are illustrated in Fig. 1.

(1) Low emittance beam injector based on thermionic single crystal CeB_6 cathode, which makes the FEL gain higher, and saturation length shorter.

(2) High gradient C-band accelerator. The accelerating gradient is as high as 40 MV/m for single bunch, which enables the main linac length being only 30 m long to reach 1 GeV.

(3) In-vacuum undulator provide high field at short undulator period, thus the beam energy becomes lowered, resulting in smaller the accelerator size.

This paper describes the basic machine design, and current status of hardware R&D on SCSS.

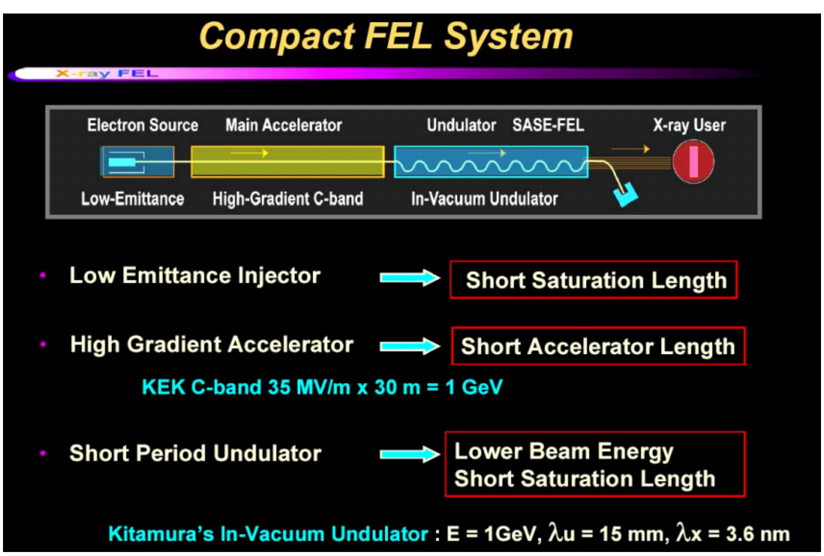

Figure 1: What makes SCSS compact?

SCSS MACHINE

Machine Layout

Figure 2 shows the machine layout at the final stage of SCSS project, whose parameter is summarized in Table-1. SCSS consists of the low emittance electron injector, the C-band high-gradient accelerator, the bunch compressors and the undulator section for FEL interaction.

In order to saturate FEL at shortest wavelength in SCSS: λ_x =3.6 nm within 20 m, we need electron beam with low transverse emittance below 2 π-mm.mrad, and short bunch-length of 0.5 $psec_{FWHM}$, the peak current of 2 kA, and 1 nC charge. The key issue in design is how to generate such a high quality beam. We decided to use high-voltage electron gun using single crystal CeB_6 cathode, followed by sub-harmonic buncher,

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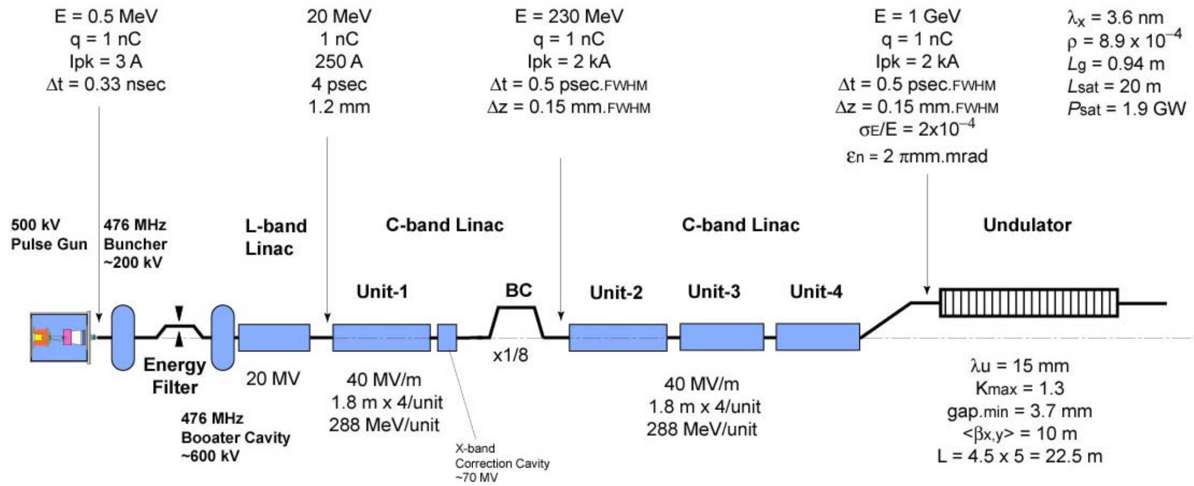

Figure 2: Four unit of the C-band RF-system will be used in the main linear accelerator of SCSS project.

booster and L-band buncher accelerator. This is the commonly used injector configuration in traditional electron accelerator. Using small size cathode, and high voltage gun, the low emittance beam can be generated. The design detail of the electron gun is reported by K. Togawa at this conference [3].

To make short bunch, the beam is chopped by a beam deflector, then velocity modulated in sub-harmonic buncher, and the bunch length is compressed with velocity bunching in drift section. Booster cavity raises the beam voltage to 1 MeV to avoid space-charge break, and the first section of the L-band accelerator compresses the bunch further. The beam energy reaches to 20 MeV after the L-band accelerator. Numerical simulation predicted the r.m.s. emittance around 1 π.mm.mrad, at 5 psec FWHM bunch length, and 0.5 nC charge.

Table-1 SCSS design parameter at final stage: 1 GeV. Note that the bunch length is denoted by FWHM value.

bunch charge	Q	1	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	Δz	0.15	mm
	Δt	0.5	psec
peak current	I_{pk}	2	kA
undulator period	λ_u	15	mm
radiation wavelength	λ_x	3.6	nm
minimum gap	g	3.7	mm
maximum K-parameter	K	1.3	
undulator unit 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

As the undulator section, we use 5 segments of the in-vacuum undulator [4]. The permanent magnet sits inside vacuum, it can come close to the beam, thus it has advantage to generate high field at short period. SPring-8/RIEKN has enough experience on this design of undulator, at present, 19 in-vacuum undulator based on this scheme have been installed at SPring-8. This type has a great flexibility for beam operation of FEL. For example, for initial beam commissioning or machine tuning of upstream, the gap can opened widely. For the FEL operation we can close down to small gap. The first model for SCSS project has been developed in 2002, and its field quality met the requirement.

C-BAND MAIN ACCELERATOR

System Configuration

We use four units of C-band RF-system in 1 GeV machine as shown in Fig. 2. In each unit, two 50 MW klystron will be used in a pair, and those output power will be combined as shown in Fig 3. Through the rf-pulse compressor, the peak power is raised 3.5 times higher and

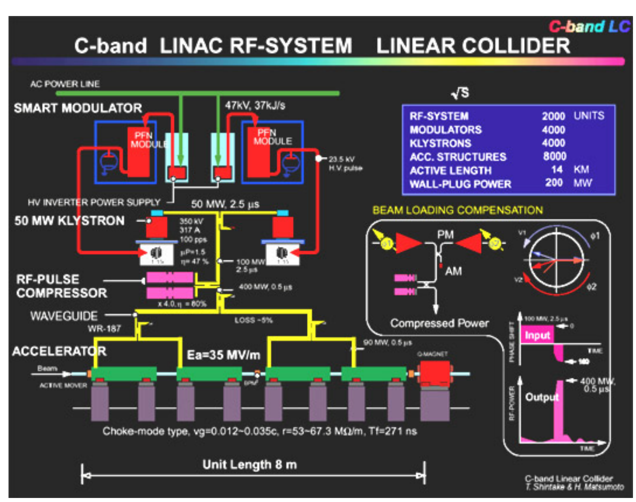

Figure 3: One unit of the C-band electron accelerator system.

Figure 4: Klystron modulator (front) and 50 MW C-band klystron with pulse transformer tank (back).

fed into four accelerating structure. The nominal accelerating gradient is 35 MV/m for multi-bunch mode, and 40 MV/m for single bunch. While the multi-bunch operation is essential in e+e- linear collider to achieve higher luminosity, it is an optional mode in X-FEL project.

Klystron Modulator Power Supply[5]

To make the hardware system simple and maintenance easier, we decided to use the same model of the modulator power supply to feed pulsed HV power to the electron gun, the L-band accelerator and C-band accelerator. Not only the hardware itself, but also the control system, its software and manpower can be shared.

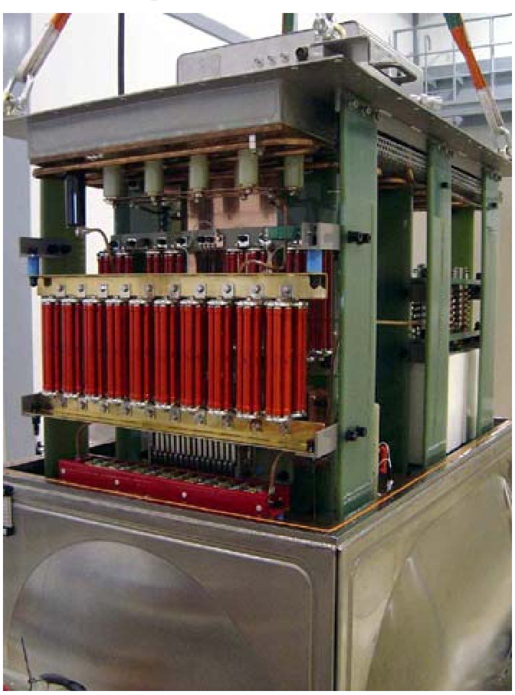

Figure 5: All of the high voltage components are immersed in the insulation oil inside a tank. The oil tank is made by standard panels commonly used in the water supply.

We use the PFN line type modulator. As the HV switching device, we chose the thyratron tube. With careful design on triggering circuitry and assembly method, the thyratron has long enough life-time, and quite reliable. We use twin-pulse trigger, which ensures to form uniform plasma density during hydrogen gas-discharge process. The thyratron tube is housed in a chimney, immersed in forced flow of insulation oil, thus the temperature is kept constant, which is important to preserve optimum gas pressure for the switching.

In SCSS project, we do not have R&D program for solid-state switch to replace the thyratron tube. In the future Linear Collider project, it is certainly necessary to use solid-state switching devices for maintenance reason of large scale machine. SCSS is a still small machine.

Fig. 4 shows the newly developed klystron modulator. All of the HV circuit components are mounted in a shielding tank as Fig. 5, and immersed with insulation oil. Merits of this closed design are

(1) Compact. W 1.7 m x D 1.2 m x H 1m.
(2) Good EMI shield.
(3) Better cooling for HV component.
(4) Eliminating cooling air fan.
(5) No dust accumulation due to high voltage in air.
(6) No environmental effects: moisture and temperature variation.

Inverter Power Supply for HV Capacitor Charging

IGBT switching power supply as Fig. 6 was developed to charge the HV capacitors in PFN circuit. The maximum rating is 50 kV, 30 kJ/sec. One technical issue in inverter switching scheme is the voltage fluctuation due to the finite size of charging step, it is usually 0.5 % level. To make this fluctuation lower, new control technique has been introduced, that is, the charging speed is lowered right before the voltage reaching to the target value. With this method, the voltage regulation level of 0.12% was achieved. Features in this power supply are

(1) Compact. W 480 mm x D 670 mm x H 530 mm.
(2) Maximum rating: 50 kV, 30 kJ/sec.
(3) Voltage regulation: 0.12 %.
(4) Efficiency: 87%

Figure 6: Inverter switching HV power supply. Courtesy of TOSHIBA Logistic Support Co.

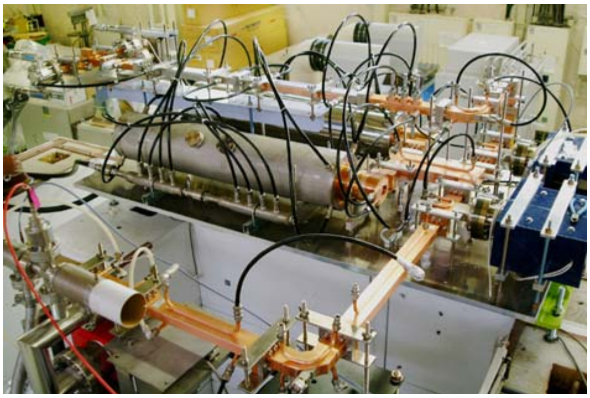

Figure 7: RF pulse compressor high-power model.

This power supply will be commonly used in the electron gun system, the L-band RF and the C-band RF-system.

50 MW C-band Klystron

Two 50 MW klystrons were fabricated in the year of 2002 for SCSS project.

(1) TOSHIBA E3746, C-band pulse klystron.
- Three cell travelling wave output structure.
- Solenoid focus.
- Tested 50 MW, 60 pps, 47%.

(2) TOSHIBA E3758A, C-band PPM klystron.
- Three cell travelling wave output structure.
- Permanent magnet focusing.
- 15 GHz parasitic oscillation was found.
- PPM klystron is 2nd option in SCSS.

RF Pulse Compressor

The high power model of rf pulse compressor has been developed and mounted in test bench as shown in Fig. 7. It is based on the three cell coupled-resonator cavity scheme to generate flat-top pulse [6]. In order to improve temperature sensitivity, the invar metal is used in the cavity cylinder, whose surface is covered by the OFC copper [7]. The temperature sensitivity is 13 kHz/deg.C, which is much lower than 96 kHz/deg.C of the copper, thus the water cooling system becomes simpler. High power test will be performed soon.

Accelerating Structure

In the SCSS project, the nominal operation mode is the single bunch. But we also design the multi-bunch operation mode as an option to obtain higher average X-ray flux. In order to cure the beam break up phenomena due to long-rage wakefield in the accelerating structure, we decide to use the choke-mode cavity [8]. In the C-band R&D at KEK, we developed the C-band accelerator structure using the choke-mode cavity, and tested its electrical performance in the ASSET beam line at SLAC in 1998. From the experiment, we confirmed that the basic wakefield damping performance was acceptable for the multi-bunch beam operation in the Linear Collider. At the same time, we found high-frequency parasitic oscillations in the measured wakefield, whose amplitude was the just on the border level for the beam emittance growth.

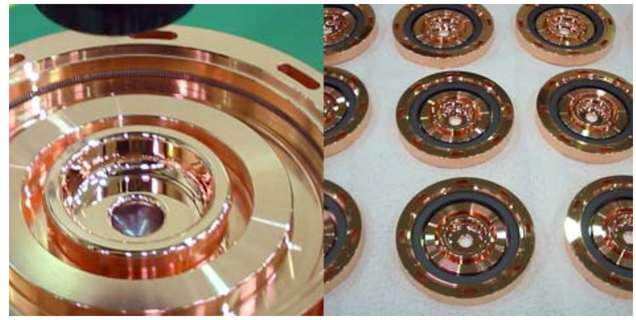

Figure 8 (left): Close-up of the choke-Mode cell. (right): SiC-rings were inserted in each cell for wakefield damping, it acts as a microwave absorber.

In SCSS project, we use the same accelerator structure as the KEK C-band design. Improvements were made on:

(1) By changing cell dimensions, the high frequency trapped mode was eliminated.

(2) For the metal bonding, instead of electro-forming, the brazing was used, because of the fabrication cost.

Fig. 8 shows the machined choke-mode cell, the central par forms the accelerating cavity, the groove is the choke resonator. The SiC ring is inserted in the outer groove, which is captured with wire-spring made of the tungsten wire. The race-track shaped holes are the water cooling channel. Fig. 9 shows, the accelerating structure in the brazing furnace. Total 91 cells are stack up, and active length is 1.8 m long.

Fig. 10 shows the field distribution along the structure measured by the bead-pull method. There are four lobes in phase plot, since the accelerating mode is $3\pi/4$, not the $2\pi/3$, widely used in the traditional travelling-wave

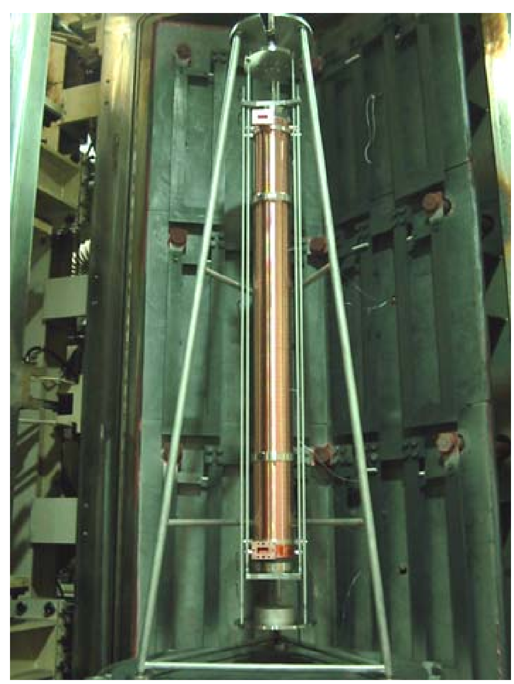

Figure 9: The 1.8 m long C-band accelerator in the brazing furnace.

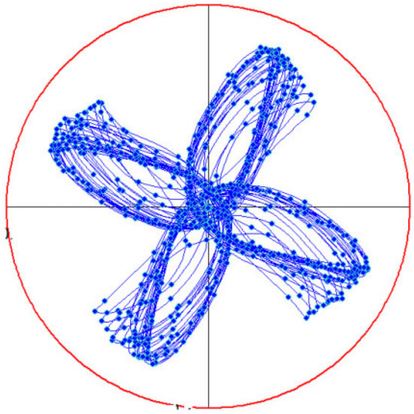

Figure 10: Bead-pull field measurement result. Four lobes correspond to 3π/4 mode.

structure. The 3π/4 mode was chosen to make the cell-length longer to fit the choke-groove in each cell. Each lobes are not overlapping well each other, it corresponds to ± 5 degree phase error, and energy gain loss due to this error is only 0.4 %.

Since the higher-order modes are damped by SiC rings, and those damping oscillation is independent by cell-to-cell, thus the dimension error, and its associated frequency error does not deteriorate the wakefield damping effect in the choke mode cavity. This is a big advantage superior to the other damping schemes, such as the field-cancelling techniques.

RF-BPM

RF-BPM utilises TM110-mode [9], in which the induced voltage has linear dependence to the beam position. The coupling to the signal is relatively large, thus this type of RF-BPM has a very high sensitivity.

In 1996 at FFTB facility of SLAC, using simple pill-box cavities, and comparing BPM signals from three RF-BPM's of series connection, the position resolution around 25 nm was recorded [10].

Using RF-BPM at high resolution and high accuracy, a special care has to be taken on signal filtering. The small BPM signal comes with a large amplitude common-mode signal, mostly TM01-mode, thus we need to eliminate this first, otherwise the head amplifier can be saturated or it causes position offset error.

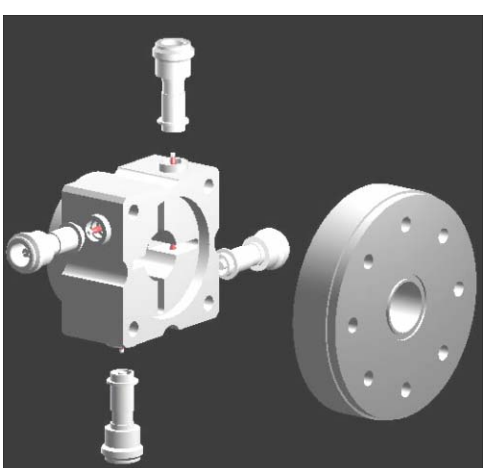

Figure 11: COM-Free RF-BPM for SCSS project.

In order to overcome this difficulty, the COM-Free RF-BPM concept was developed by the author. Using low level RF-signal, and a thin wire simulating beam in a cold model, it was experimentally confirmed that the electrical centre meets with the mechanical centre within 8 μm. The first model was mounted to the C-band accelerator and used for the ASSET beam test in 1998.

Figure 11 shows the newly developed RF-BPM for SCSS project. Four vane shaped grooves form the hybrid circuit, which eliminate the common mode power, and only the BPM signal is send to the detection circuit. The same RF-BPM will be used in the beam alignment station between undulators.

SUMMARY

The high power test and debugging of RF components will be performed in 2003-2004, machine construction in 2005-2006, and the first FEL operation is scheduled in 2007.

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