C-BAND LINAC SYSTEM FOR SASE-FEL AT SPRING-8

T. Shintake, T. Tanaka, T. Hara, K. Togawa, T. Inagaki, Y. J. Kim,
T. Ishikawa, H. Kitamura, H. Baba: RIKEN/SPring-8, Harima Institute, Hyogo 679-5148, Japan
H. Matsumoto, Shigeru Takeda, M. Yoshida, Y. Takasu: KEK, Tsukuba, Ibaraki 305-0801, Japan

Abstract

Toward the fourth generation light source, RIKEN started research program on X-ray FEL development based on SASE mode in 2002. For the first period of the program, in order to develop key technology specially required for the X-ray FEL, and to study handling technique of high-peak-power radiation, RIKEN is developing SCSS-machine: SPring-8 Compact SASE Source (SCSS), which aims to generate FEL radiation at UVU region using low-emittance electron beam at 0.5 ~ 1 GeV energy. For the main accelerator, SCSS design uses the high-gradient electron accelerator based on C-band technology, which was developed at KEK as a part of the future e+e- Linear Collider project. This is the first trial to use such high acceleration gradient machine in actual electron accelerator, so that, it will provide useful information on machine reliability of high gradient accelerator in the field application.

1 SCSS CONCEPT

The X-ray FEL based on the SASE concept needs a large-scale accelerator and a long undulator, while it can provide X-ray beam in only a few beam lines, therefore construction cost per one beam line becomes quite higher than that in the existing SR machine. This is the reason why people design the X-ray FEL as a parasitic facility attached to an existing electron accelerator, such as LCLS project at SLAC assumes to use the Two-mile Linac, or TESLA project is designed as an integrated facility into a future electron and positron linear collider. Therefore, a chance to have X-ray FEL facility is quite limited and can be regionally localized.

However, to open a wide range of new science using X-ray FEL, many FEL-machines have to be constructed all over the world, at least, like today's SR source facilities. To realize this, the machine cost should be low enough. The reasonable cost will be a few X-ray beam lines cost in SR facility. To do this, the most important point is to make the machine size compact, thus the building cost will be lowered, as well as the machine itself becomes inexpensive. Therefore, we name our machine as SCSS: Spring-8 Compact SASE Source.

In the SCSS project, the following three key technologies realize the compact machine as Fig. 1.

(1) In-vacuum undulator 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.

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

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

This paper describes the basic machine design, and current status of hardware R&D on the electron gun, C-band RF-system and short-period undulator.

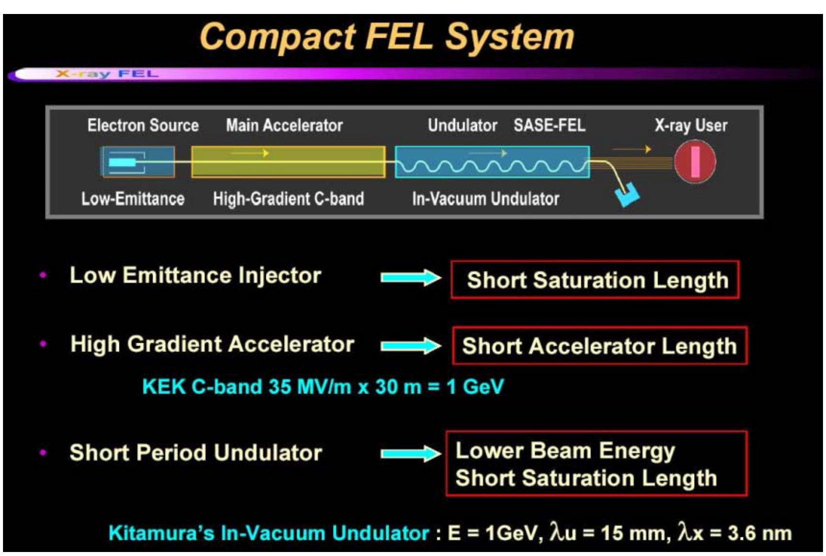


Fig.1. What makes SCSS compact?

2 SCSS MACHINE

2.1 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 main linac, 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 a short bunch of 0.5 psec.$_{FWHM}$, peak current of 2 kA, and 1 nC charge.

Note that, in this paper, we describe the bunch length in FWHM value rather than rms vale (σ_z). This is because in our system the longitudinal current profile has rather flat shape than Gaussian shape.

In Fig. 2 final state, we will have four C-band accelerator units, and the beam energy will reach 1 GeV. However, we

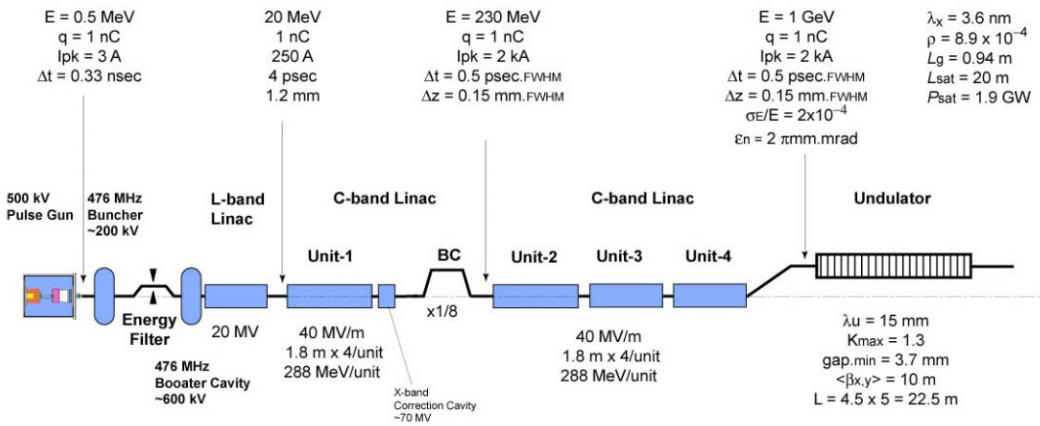


Fig. 2. SCSS beam line layout at final stage (beam energy 1GeV, radiation wavelength 4 nm).

will start FEL experiment at 250 MeV using one unit of C-band system, and observe FEL performance at UV region first, from which we will investigate the electron beam quality.

It should be noted that, the beam parameter in Table-1, and system diagram in Fig. 2 are still tentative design. In the recent study, it has been understood that the emittance dilution due to the CSR effect in the bunch compressor dominates the beam quality. To avoid this, we are designing the system to compress the electron bunch more in the injector, so as to reduce the bending angle in the chicane magnet.

2.2 Electron Injector

In the SCSS project, we chose a high-voltage pulse-gun with thermionic-cathode, instead of RF-Gun. As kwon in SASE-FEL theory, the quality of "internal" structure of bunched beam dominates FEL performance, that is, the slice emittance and slice energy spread directly affect the FEL gain. We believe a single crystal LaB_6 or CeB_6 cathode will provide high performance beam with uniform density, with laminar flow without turbulence.

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 rms 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

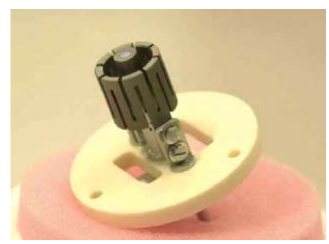


Fig.3. CeB_6 single crystal cathode with graphite heater.

In the HV pulse gun, 3 Amp. beam with 300 nsec flat-top pulse will be generated from a single-crystal CeB_6 cathode of 3 mm in diameter. The R&D issue on this design is (1) development of reliable 500 kV pulsed power supply, (2) reliable heating mechanism for the cathode (nominal operation temperature is 1450 deg-C). We schedule the high-voltage test, and high temperature test in 2002.

As seen in the injector layout of FIg. 4, right after the gun, a beam chopper will be prepared, which cuts out the rising and falling parts of the pulse, and forms a 2 nsec pulse beam. The 476 MHz pre-buncher adopts energy modulation of 400 kV peak-to-peak, followed by energy filter to cut the energy tail (top and bottom). After drifting 800 mm beam pipe, due to the velocity difference, electrons form a short bunch. Before the space charge breaks the beam, we accelerate energy to 1 GeV in the booster cavity.

The L-band accelerator captures the bunch, and accelerates to 20 MeV. Since the bunch length at the entrance is still long, we chose L-band frequency, this is the lowest frequency band where a high-peak power klystron is commercially available and also the fabrication of the accelerating structure is relatively easy. The first section of L-band accelerator compresses the bunch length by off-crest acceleration. In the second half L-band accelerator , the beam energy reaches to 20 MeV.

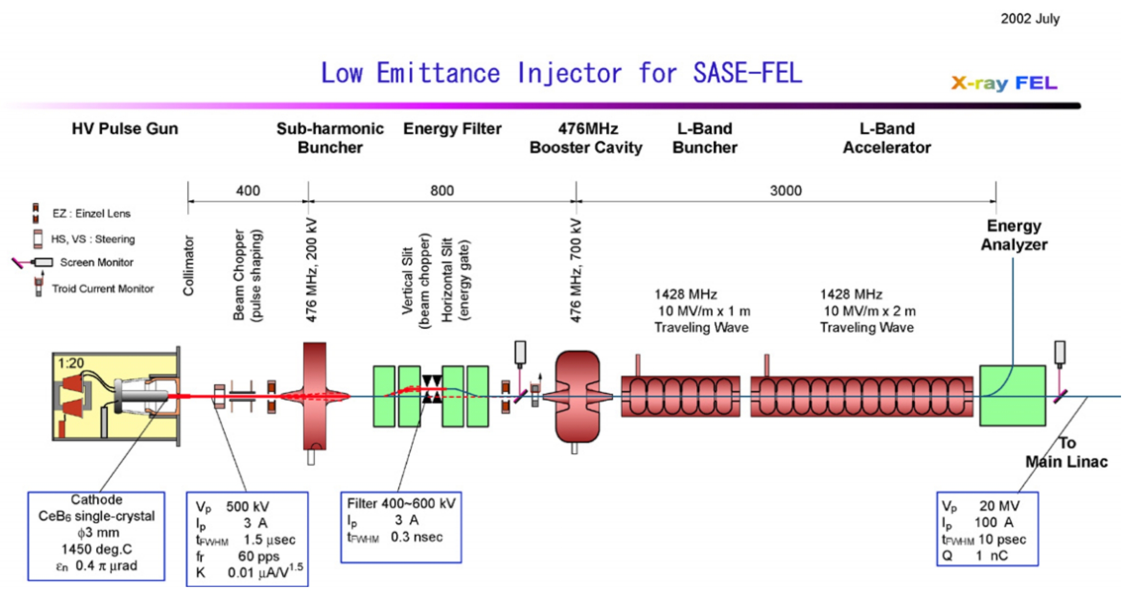


Fig.4. Injector layout.

2.3 C-band Main Linac [3]

Figure 5 shows the C-band RF system of the main accelerator. In one unit, two klystrons of 50 MW peak power drives four accelerating structure of 2 m long each, and generate 35 MV/m acceleration gradient for multi-bunch and 40 MV/m for single bunch. Each unit is capable of acceleration of 288 MV, and total four units provide 1 GeV beam.

The C-band (5712 MHz) accelerator technology has been developed at KEK Japan as the main linac of the future 500 GeV e+e- Linear Collider project. Table-2 summarises results of the phase-I R&D on C-band during 1996~2000. The SCSS will provide a best string test of the main linac system for the Linear Collider project.

Among the recent R&D items, the inverter type HV power supply for charging the PFN capacitor of the klystron power supply (klystron modulator) is very important inorder to realize stable operation of short-wavelength FEL. By means of two-steps charging scheme, the newly developed HV power supply has achieved voltage stability better than 1 x 10^{-3}. This stability had been difficult to obtain in the conventional charging circut regulated by de-Q'ing method.

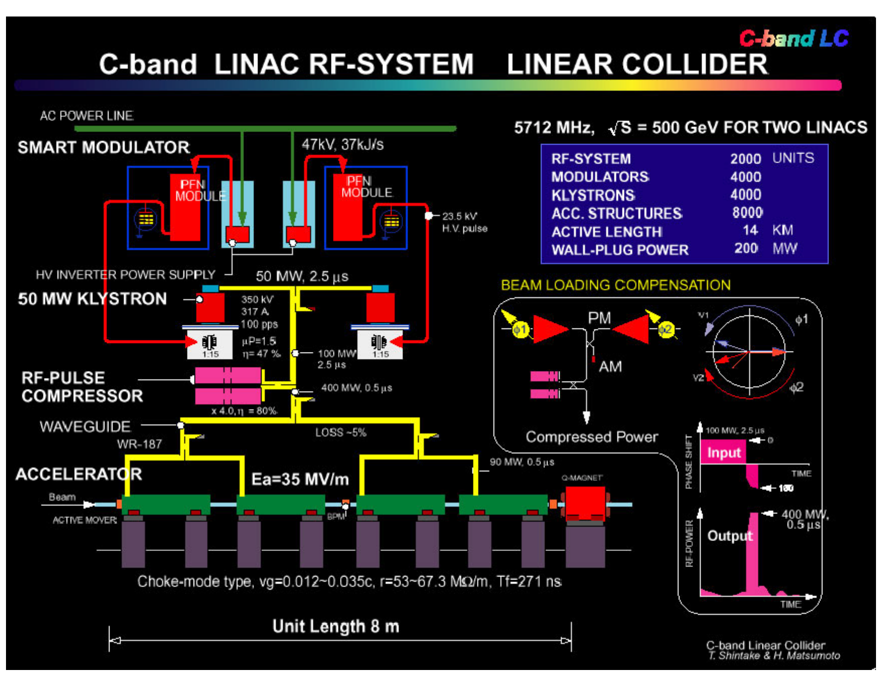
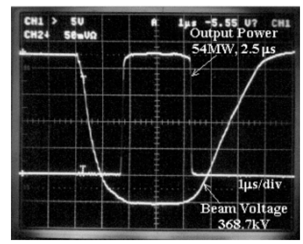
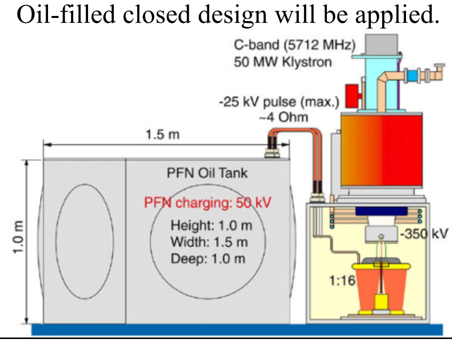
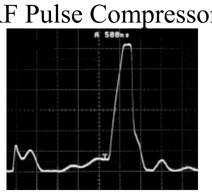
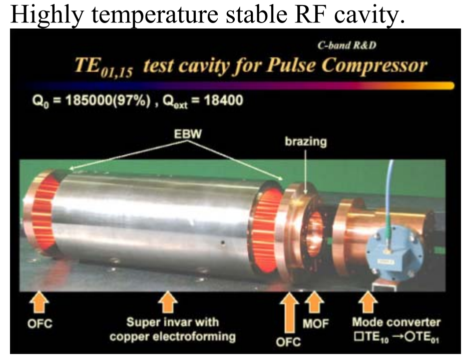
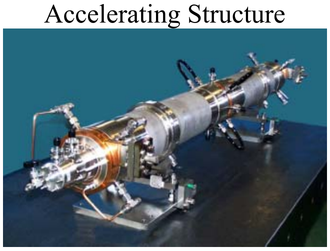


Fig. 5. C-band RF System for high-gradient beam acceleration.

Table-2. Phase-I R&D summary on C-band RF-system and application to SCSS.

<table>
<tr><th rowspan="2">Items</th><th>Phase-I R&D Target</th><th rowspan="2">SCSS Application
(Phase-II)</th></tr>
<tr><th>Achieved Results</th></tr>
<tr><td rowspan="2">Klystron
</td><td>Output 50 MW, Efficiency >45%
Pulse width >2.5 μsec
Pulse repetition 100 pps
Focusing Power < 5 kW</td><td rowspan="2">Refine design details for the mass-production and reducing cost. PPM-klystron is an option.


Example of output power.</td></tr>
<tr><td>All of No.1, 2, 3 tubes achieved 50 MW output, pulse width 2.5 μsec and 50 pps. No. 3 tube showed 47% power efficiency.
Focusing power 4.6kW.
Life test No.2, 3 > 5000 hours.</td></tr>
<tr><td rowspan="2">Pulse Modulator Supply
</td><td>350 kV, 2.5 μsec pulse generation, power efficiency >50%</td><td rowspan="2">Oil-filled closed design will be applied.

</td></tr>
<tr><td>Smart Modulator, No. 1
Inverter HV power supply was firstly used in klystron modulator.
Operation for klystron life-test was very successful.
Power efficiency >52.4%</td></tr>
<tr><td rowspan="2">RF Pulse Compressor
</td><td>Power gain >3.5,
Power efficiency >70%</td><td rowspan="2">Highly temperature stable RF cavity.


.</td></tr>
<tr><td>Cold Model Test (1997)
Power Gain 3.25, Efficiency 65%
Not yet performed the high-power test.</td></tr>
<tr><td rowspan="3">Accelerating Structure
</td><td>Multi-bunch 1.6 nC, 80 bunch
Acceleration gradient> 35 MV/m</td><td rowspan="3">Refine design details.
Optimization for mass-production.
Lowering cost.
The multi-bunch option in SCSS will provide high average brightness.</td></tr>
<tr><td>ASSET test at SLAC demonstrated damping performance of the choke-mode cavity.</td></tr>
<tr><td>Resolution ~ 25 nm (FFTB test)
Position accuracy < 10 μm</td></tr>
</table>

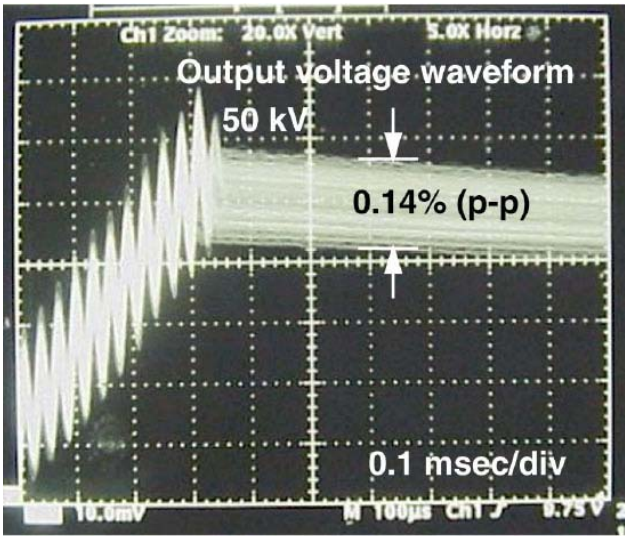


Fig.6. Voltage stability of inverter HV power supply for the klystron modulator.

Other related R&D items are

(1) Compact closed type modulator for klystron.
(2) C-band 50 MW PPM klystron.
(3) Stable HV voltage monitor using ceramic divider.
(4) Pulse-to-pulse energy and phase feedback system using digital vector detector/modulator.
(5) Stable support girder R&D for accelerating structure and other accelerator component, which uses hard concrete and precision mover of cam rotary design.

For detailed information related above items, please refer http://www-xfel.spring8.or.jp.

2.4 Bunch Compressor

In the chicane type magnetic bunch compressor, the bunch is compressed to 0.5 psec.$_{FWHM}$. Since the coherent synchrotron radiation (CSR) effect dominates to break transverse emittance, we need careful design. Recently a new finding was made at DESY SLAC collaboration: the CSR amplifies micron-scale density fluctuation on the incoming bunch, it is now called "CSR instability"[4]. To avoid CSR instability and emittance break-up, we are trying to shorten the bunch length in the injector by proper modulation voltage, and reducing the compression factor at the downstream bunch compressor. For design detail, refer the reference [2].

2.5 Undulator

We use "in-vacuum type" undulator. Merit of this design is

(1) Since there is no vacuum envelop, one can bring the magnet loser to the beam, and generate higher field.
(2) Since there is no vacuum envelop of fixed height, for the machine tuning, one can widely open the aperture, enables to pass a big emittance beam at the beginning of tuning.

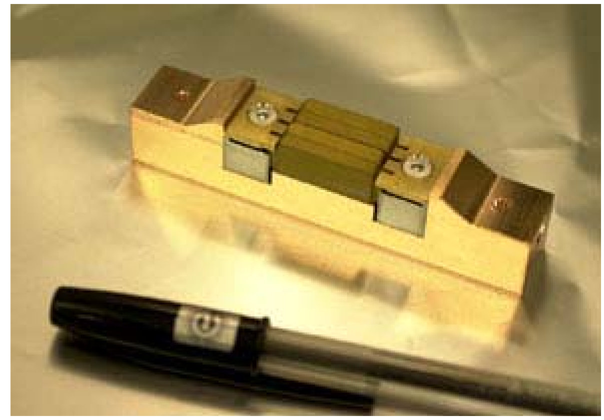


Fig. 7. NdFeB magnet assembly of SCSS undulator. Four poles are assembled in one block and mounted on 1 m long strongback. Each magnet thickness is 3.75 mm, and four magnets (one undulator wavelength) is 15 mm.

(3) Tapering the K-value along the undulator. This is useful to recover a part of the energy loss due to the resistive wakefield can be recovered, or to enhance the power conversion efficiency at the final radiating section.

The SCSS undulator consists of five segment of 4.5 m long in-vacuum undulator, and the total active length is 22.5 m.

One big issue is "phase matching" and "alignment" between undulator segments. With analytical model and 1D simulation, we found that SASE-FEL does not fully require perfect overlapping of optical wave to the electron beam [5]. With 3D simulation, transverse alignment is important to keep matching the wavefront orientation with the radiation wavefront.

3 SCSS SCHEDULE

From 2002 to 2003, we perform technology development of key components required for SCSS machine. From 2004, we will start machine construction, aiming to start FEL experiment in 2006, at 50 nm wavelength region, and ultimately below 10 nm.

4 REFERENCES

[1] T. Shintake, "SPring-8 Compact SASE Source", SPIE2001, San Diego, USA, June 2001.
[2] Y. J. Kim, et al., "Beam Parameter Optimisation for the SPring-8 Compact SASE Source", in this conference.
[3] http://www-xfel.spring8.or.jp
[4] "CSR Workshop 2002", January 14-18, 2002 at DESY-Zeuthen (Berlin, GERMANY). http://www.desy.de/csr/
[5] T. Tanaka, H. Kitamura and T. Shintake, "Misalignment effects of segmented undulator in self-amplified spontaneous emission", Phys. Rev. ST Accel. Beams 5, 040701 (2002)