C-BAND (5712-MHz) LINAC FOR THE SPRING-8 COMPACT SASE SOURCE (SCSS)

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Abstract

The SPring-8 Compact SASE Source (SCSS) is a high peak-brilliance, soft X-ray free electron laser project [1]. It will operate as a dedicated linac-based source for Self-Amplified Spontaneous Emission (SASE) Free-Electron Laser (FEL). We will use a high-gradient C-band (5712-MHz) main linac to generate a beam with energy up to 1-GeV followed by an in-vacuum short-period undulator to enables us to contain the entire SCSS within a 100-m over-all length.

1 INTRODUCTION

The SCSS 1-GeV main linac will use high gradient acceleration to achieve a total active machine length of 40-m. There will be an acceleration gradient of more than 35-MV/m for a beam charge of 1-nC per bunch. The normalized beam emittance at the linac exit has to be kept to only 2-πmm·mrad, this is two-orders of magnitude smaller than the emittance of the usual electron linacs such as the injectors for KEKB or SPring-8.

As this paper is mainly concerned with the high power rf system for main linac, we will not discuss the electron gun here. This linac is intended to be used for a production source of soft X-rays, and not to be for accelerator R&D. Accordingly, the design and hardware should be chosen to satisfy the following demands: (1) High reliability, (2) Simplicity, (3) Reduced construction cost, (4) Reasonable power efficiency and (5) Operational ease.

We first chose 5712-MHz in the C-band as the optimum frequency. This is twice the 2856-MHz (S-band) commonly used in more conventional electron linear accelerators. From the energy efficiency point of view, a higher frequency is desirable because the rf power transferred to the beam in the accelerating structure increases with frequency since the shunt impedance increases at higher frequencies ($r \propto f^{1/2}$). However, as frequencies go up, the allowable tolerances in the fabrication of the accelerating structure become ever more stringent, and mass production can become problematical. Additionally, the peak output power from the klystron generally declines as the frequency goes up. We conclude that at this point in time, the advantage in choosing a C-band frequency is that we can obtain a high accelerating gradient as required for this accelerator while still using existing fabrication technology [2].

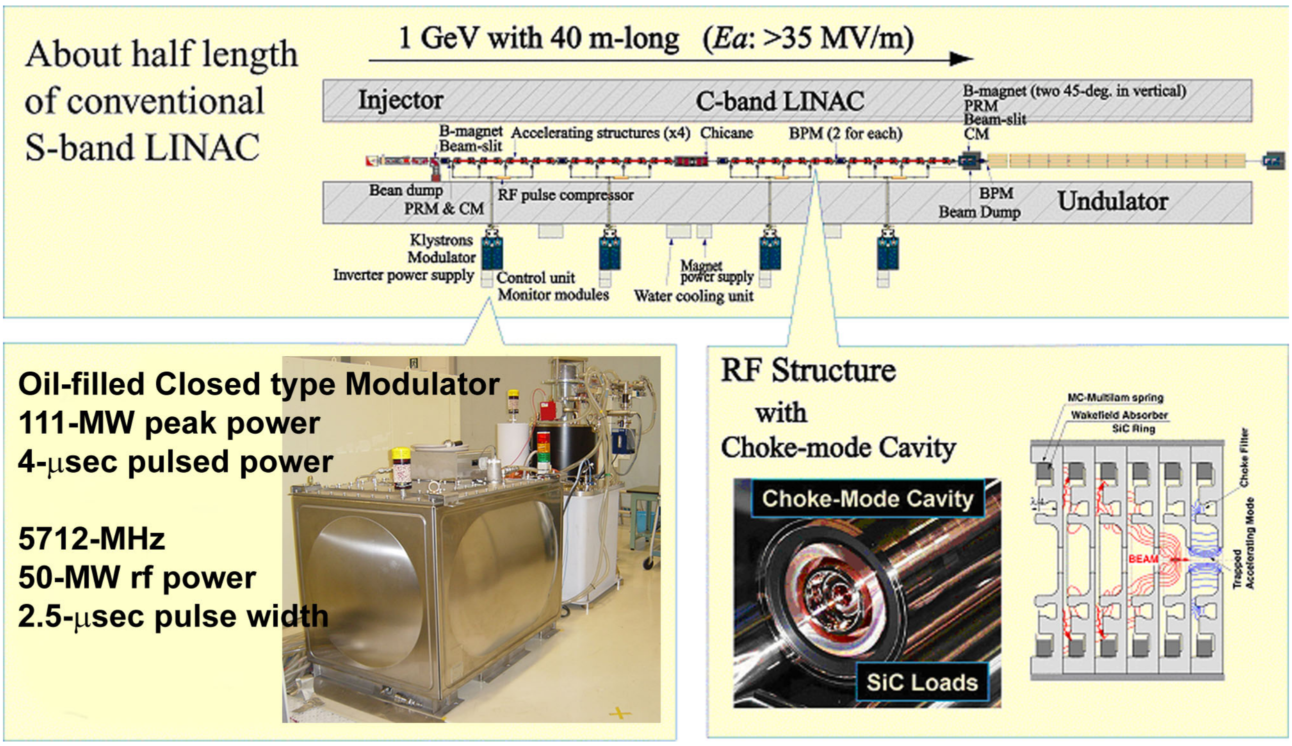

Figure 1: An over-all schematic layout of the C-band linac and 30-m long undulator. The total facility length is less than 100-m. The accelerating gradient of each rf structure is more than 35-MV/m and the beam charge per bunch is 1-nC. The normalized emittance is 2-πmm·mrad at the end of linac.

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Starting in 1996, we began the overall design of the C-band rf system, and developed all the requisite high power devices such as the wave-guide components [2], sexless vacuum flanges [2], 50-MW class pulsed klystrons [2], their 100-MW class modulator power supply incorporating a solid state H. V. inverter [2], a low level rf compression cavity, and a high power Choke-Mode HOM-free rf structure [2]. Recently, we have developed a new ceramic capacitive voltage divider, a roller cam type active mover system, which can provide a position repeatability of ±0.1-µm [3], and a very stable component support stand using a new high compressive concrete [3]. In the following, we will discuss the details of the technologies for the C-band main linac rf system.

2 C-BAND (5712-MHZ) MAIN LINAC

2.1 The C-band RF System Description

The SCSS main linac will use four C-band rf units to generate a 1-GeV beam with a machine only 40 m in length. Figure 1 shows the over all-schematic layout of the linac, and the design specifications of the new C-band main linac are listed in Table 1.

Table 1: Main parameters of the C-band linac.

Klystron:	8	tubes
Modulator power supply:	8	sets
RF compressor cavity:	4	sets
RF structure:	16	structures
Energy (*E*):	1	GeV
Energy spread (rms, σ_δ):	0.02	%
Charge per bunch (*Q*):	1	nC
Peak current (I_{pk}):	2	kA
Bunch length (FWHM, Δz):	0.15 (0.5)	mm (psec)
Normalized emittance ($\varepsilon_{nx,y}$):	2	πmm·mrad
Klystron rf output power:	50	MW
rf pulse width:	2.5	µsec
Modulator output voltage:	25	kV
Repetition rate:	60	pps
rf compressor cavity power multiplication factor:	>3.5	
RF structure length:	1.8	m
Accelerating gradient with beam loading:	>35	MV/m
Wave-guide transmission rf power:	400	MW (max.)

Here we are choosing to use for the main linac the same configurations as arrived at in the previous GLC linear collider design. The reason being that its rf system has been under development since 1996, and is well optimised for high gradient beam acceleration and over-all system reliability. The main components of each unit are two 50-MW klystrons, their modulator power supplies, a pair of the rf compressor cavities, four 1.8-m long Coke-Mode type rf structures, and a vacuum-tight high power wave guide system. The output rf power from the two 50-MW klystrons is combined with a 3-dB wave-guide hybrid and multiplied by rf compressor cavities to supply a 0.5-µsec pulse of more than 350-MW, which is then fed to four rf accelerating structures. They in turn can generate an accelerating gradient of more than 35-MV/m while being loaded with a 1-nC per bunch beam.

2.2 C-band 50-MW Klystron

The newly developed klystron 3-cell travelling-wave output structure provides an output power of 55-MW at 365-kV with a 45% conversion efficiency from beam to rf power, which is a very good performance for a high power klystron. Figure 2 shows the measured characteristics of the klystron, showing the efficiency, and rf output power curves. The 3rd-klystron has already been operating problem free for more than 10,000 hours. From this experimental result, we are confident about its reliability in the actual accelerator application.

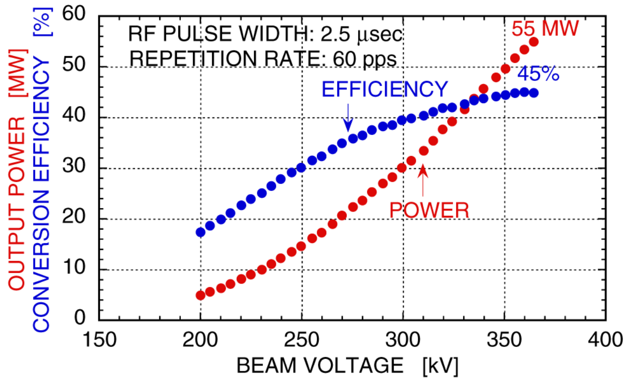

Figure 2: Typical efficiency and rf output power characteristics at saturation as a function of beam voltage.

2.3 Closed Compact Modulator

To improve the insulation and cooling of the high voltage components, we decided to use a sealed cabinet or tank filled with insulation oil [2]. Except for the inverter type PFN charging power supply, all the parts, including the thyratron tube will be enclosed in the oil filled cabinet. The cabinet need only be 1.5-m wide, 1-m high and 1-m deep. A first prototype was delivered by NICHIKON Co. in Japan, and it was tested in March 2003 at SPring-8 [4]. A photograph of the modulator and klystron can be seen in Figure 1; the main specifications of the modulator are listed in Table 2.

We decided to use the usual line-type PFN circuit and thyratron tube (EEV-CX1836) switching device at this time. The reason for the thyratron choice is that from the standpoint of reliability, we find semiconductor switching devices such as IGBTs to be not yet suitable for pulse switching of high currents at high voltages; for example our PFN requires switching 5000-A at 50-kV.

We will use a new inverter type H.V. power supply for charging the PFN. It is very compact, being only 48-cm wide, 45-cm high and 63-cm deep. It generates a maximum output voltage of 50-kV and provides an average power of 30-kW (or a peak of 37.5-kJ/sec); this supply can drive a 50-MW klystron at up to a 60-pps repetition rate giving a 350-kV beam voltage after a 1:16 step-up transformer [2]. We obtained an output voltage regulation of within ±0.1% with a test prototype. The H.V.

power supply was made by TOSHIBA Co. in Japan and it was tested along with the rest of the modulator beginning in March 2003 at SPring-8. The supply is shown in Figure 3.

Table 2. Main parameters of the new modulator.

Peak output power:	111	MW
Average output power:	46.7	kW
PFN charging voltage (max.):	50	kV
Peak switching current:	5414	A
H.V. pulse width:	3.5	μsec
Pulse repetition rate:	60	pps
Voltage flatness (top) and repeat-ability:	±< 0.5	%
Timing jitter:	< 5	nsec
PFN impedance:	4.3	Ω
Energy stored in the PFN:	438	Joule
PFN cells:	18	sections
Transformer step-up ratio:	1:16	
Cabinet size (W x H x D):	1.5 x 1 x 1	m
Inverter output voltage:	0 ~ 50	kV
Inverter Average output Current:	1.5	A
Charge rate average (peak):	30 (37.5)	kJ/sec
Output voltage regulation:	<± 0.1	%
Power factor (50-pps, full load):	> 85	%
Power efficiency (full load):	> 85	%

Figure 3: The first inverter type H. V. power supply prototype.

2.4 C-band RF Structure

We will use a C-band Choke-Mode type damped rf structure for the SCSS main linac. One particular advantage is that since all of the parts are completely axially symmetric, they can be machined on a turning lathe; thus this type of cavity has a big advantage in mass production because of its easier machining. MITSUBISHI HEAVY INDUSTRY Co. in Japan was contracted for the first high power model. The main parameters of the rf structure are listed in Table 3. We decided to use a quasi-constant-gradient for the electric field distribution along the structure axis; this minimizes the surface electrical gradients, which strongly contribute to breakdown problems in high gradient operation. Doing this, we have successfully kept the maximum Es/Ea to only 2.2. Small amplitude trapped higher order modes (HOM) appeared at 20-, and 23-GHz in first prototype rf structure. To eliminate them, the disk thickness will be changed from 3- to 4-mm. Figure 4 shows the wake field from a single bunch as simulated with the MAFIA code. As can been seen in the figure, the wake field amplitude is sufficiently damped before the arrival of the succeeding 2nd bunch, and also there are no higher trapped modes found in the new rf structure.

Table3: Main parameters of the Choke-mode rf structure.

Frequency:	5712	MHz
Phase shift per cell:	$3\pi/4$	
Electric field distribution on the axis:	Quasi-C.G	
Quality factor (Q, average):	10256	
Attenuation parameter (τ):	0.53	
Filling time (t_F):	290	nsec
Shunt impedance (r, average):	58.5	MΩ/m
Ratio of Es/Ea:	2.2	(max.)
Iris aperture ($2a$) up-stream:	17.330	mm
down-stream:	13.587	mm
Disk thickness (t):	4	mm
Number of cells:	91	
Number of Couplers: (field symmetry & double feed)	2	
RF structure active length:	1.8	m

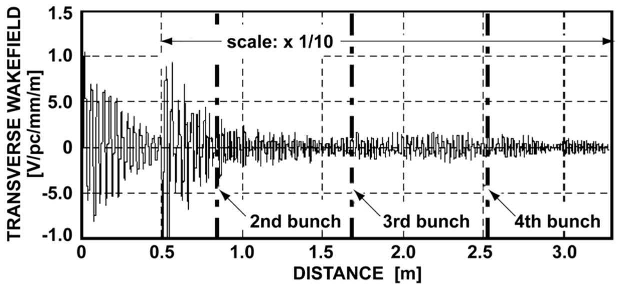

Figure 4: Single bunch wake field simulation of the C-band Choke-mode rf structure.

2.5 C-band RF Compressor Cavity

The first high power prototype uses a copper plated invar metal for the rf cavity [2, 4]. This keeps the thermal expansion coefficient to only $4x10^{-7}$, which is a value 20 times smaller than for copper material alone. This copper plated invar cavity is thus a big breakthrough for the very high Q cavities needed in the rf compression system. It is now under high power testing at KEK.

3 REFERENCES

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