THE KEK C-BAND RF SYSTEM FOR A LINEAR COLLIDER

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Abstract

C-band (5712-MHz) RF-system hardware R&D for an e^+e^- linear collider started in 1996 at KEK. We have already developed three conventional 50-MW class klystrons, a smart modulator, and a novel HOM-free accelerator structure (Choke-mode type, full-scale high power model) [1], [2], [3], [4]. A very stable ceramic high voltage monitor was successfully tested up to 367-kV with 4.5-µsec pulses. Very good agreement in the expected division ratio and signal waveform fidelity was observed in high power tests. A new C-band SiC type high power rf-load, extending the power handling capability up to 50-MW is now being designed. It should have excellent mass production characteristics as it uses circularly symmetric TM_{011} chained cavities [5]. For the first ever, a high power prototype rf compressor (SLED III) cavity made of a low thermal expansion material (Super Invar) was designed to provide stable operation even with a very high Q of 200-k, it was operated up to a 135-MW peak output power in 0.5-µsec rf pulses compressing input 45-MW 2.5-µsec pulses [6]. The C-band linac rf-system will be used for production work in the SASE-FEL (Spring8 Compact SASE Source, SCSS) project at SPring-8 [7]; SCSS will also serve to not only verify the design concepts and components, but will also provide realistic experience and lessons which can eventually be deployed in the main linac rf system for a future large scale linear collider.

INTRODUCTION

The C-band main linac design and development has been motivated by the increasingly urgent need for a lin-

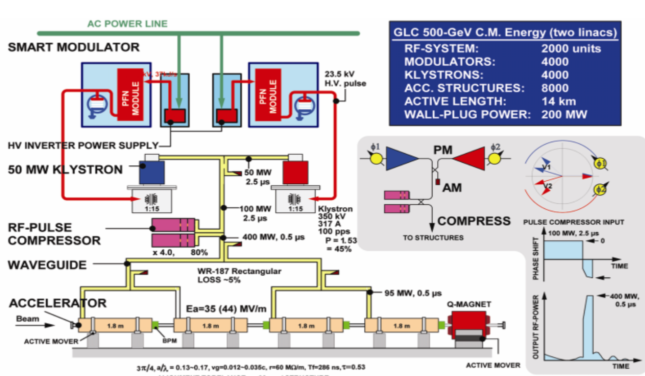

Figure 1: One unit of the C-band main linac.

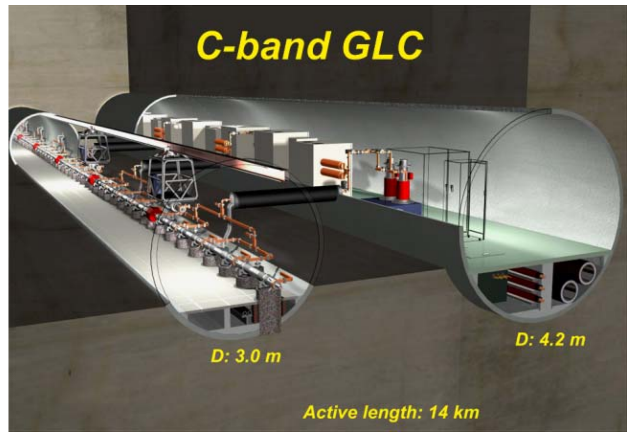

Figure 2: C-band main linac tunnels. The klystron gallery is 4.5-m in diameter and the linac tunnel is 3.0-m in diameter.

ear collider capable of undertaking the next essential physics programs. Choosing a C-band technology entails a minimum of R&D thus facilitating early deployment and reliable operation. The goal is to enable an early start to the physics program, so as to be as concurrent as possible with the LHC operation. Once a new particle threshold is opened with LHC, all angles of the new physics regime can be thoroughly studied in the more straightforward clean experimental environment of e^+e^- collisions.

The main linac system is the heart of the linear collider. It is a huge system, composed of thousands of repetitions of common RF-units. Therefore, in order to realize a successful physics program, these RF-units have to meet strict requirements for: (1) High reliability, (2) Simplicity, (3) Easy operation, (4) Reasonable power efficiency, and (5) Low cost.

These desiderata provide boundary conditions for our design work. Especially the first three items are crucial for such a large scale system to be operated at all; only after clearing them are the detailed discussions about energy efficiency or upgradeability meaningful. As the C-band frequency is only two times higher than the S-band, the size of the accelerator structure is reduced by half. But more importantly, currently available technology for fabricating the components can easily meet the accuracy required for the C-band, thus removing the risk of a non-manufacturable design. This single choice thus directly results in possibilities for high reliability, simplicity, and hence low cost.

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The total C-band main linac rf-system for a 500-GeV C.M. energy includes about 2000 rf-units as shown in Figure 1. In total about 8000 accelerating structures and about 4000 klystrons with modulators are needed for the two main linacs. The numbers of each component are large, but still not enough to bring about the drastic cost reduction allowed by full mass-production. Therefore, from the start of the design of each component, maximum efforts toward cost reduction for mid-scale production are absolutely necessary. Accordingly the C-band group has been inventing novel ideas and carrying out special cost reduction R&D.

We propose that the C-band frequency allows the best set of trade-offs for meeting the demands. And the SCSS project will give an opportunity for a realistic application of the C-band rf technology.

SYSTEM DESCRIPTION

Each unit in the main linac rf-system is composed of two 50-MW klystrons, their pulse modulators, one rf-pulse compressor, four 1.8-m-long choke-mode accelerating structures and an associated wave-guide-system as shown in Fig. 1. The accelerating gradient is 35-MV/m under full beam loading. This was chosen as a practicable accelerating gradient after studying results from the S-band frequency high gradient tests done between 1987 and 1994 at KEK.

The system will be installed in two concentric tunnels with circular cross section diameters of 3-m and 4.5-m for the accelerator and klystron galleries, respectively. For structural stability, the tunnels as shown in Figure 2 have to be constructed in a very stable stratum such as granite.

HARDWARE R&D RESULTS

We started hardware R&D in April 1996, and with the exception of the high-power rf pulse compressor, by June 2003 we had developed most of the hardware components and tested their performances.

Waveguide Components

We chose a conventional rectangular EIA-WR187 (47.55-mm x 22.15-mm) waveguide to make the system simple. The rf transmission loss in the waveguide is –0.032 dB/m, which allows keeping the waveguide rf power loss budget to less than 5%. We have developed various new waveguide components: among which there is a low cost yet highly reliable unisex type rectangular vacuum coupling flange (so-called MO type) [8]. It is now commonly used in various facilities not only for C-band applications.

Klystron R&D

We have successfully developed a 50-MW class solenoid focus type klystron (the TOSHIBA E3746 series), which meets the requirements for a 500-GeV linear collider.

We have a clear design goal of ensuring high reliability

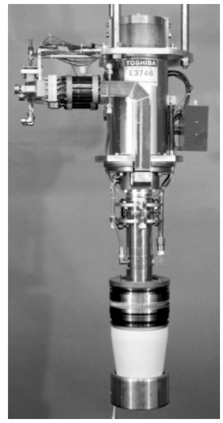

Figure 3: TOSHIBA-E3746.

over long-term operation. Accordingly we decided conservatively on a ceiling value of 300-400 Jules/pulse for the beam power in the klystron, while keeping the maximum cathode emission loading to less than 10 A/cm^2, and with the maximum surface electrical gradient of the electrodes to less than 22-kV/mm [4]. The experimental test results of the three klystrons are summarized in Table 1. The first tube (E3746-#1) employed a conventional design such as having only a single-gap output structure. Its main propose was to fix the mechanical dimensions of

Table 1: The experimental result for C-band klystrons

E3746	No. 1	No. 2	No. 3
Output power [MW]	50 (48)	54	55
Pulse width [µsec]	1 (2.5)	2.5	2.5
Repetition rate [pps]	50 (20)	50	50
Power efficiency [%]	42	44	45
Output gap	1	3[1)]	3[1)]

1) travelling-wave 3-gap output cavity.

the electron gun, beam dump (collector), and the output rf windows; and also to characterize the C-band performance. The 2nd and 3rd klystrons were developed (in 1997 and 1998) to increase rf power efficiency, this was accomplished by the newly introduced 3-cell traveling wave output design. Power efficiency improved to 44% for the 2nd and to 45% for the 3rd klystron. Agreement to within 1% over the operating range was found between simulation (FCI code) and a precision calorimetric power measurement system. Figure 4 shows a typical experimental result for the traveling-wave 3-gap klystron.

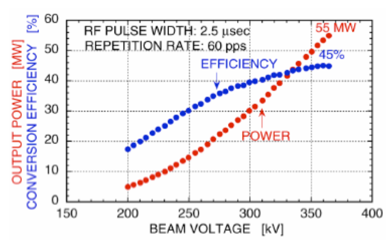

Figure 4: Typical efficiency and RF output power characteristics at saturation output rf power as a function of beam voltage.

Modulator Power Supply

We focused our modulator R&D work on reducing the fabrication cost and improving the reliability. As a first step, we developed a prototype modulator, with features: (1) Direct HV charging from an inverter power supply, (2) No de'Q-ing circuit, (3) Much smaller in size than the usual modulator, (4) Using existing low-risk reliable circuit components, such as the thyratron tube for the PFN switching.

To reduce modulator size and permit removing the de'Q-ing circuit from the PFN, we employed an inverter type DC-HV power supply (the EMI-303L, U.S.A). A first model was built in a compact metal cabinet with dimensions 1.6-m (W) x 2-m (H) x 1.2-m (D). The fluctuation in the measured output voltage was measured to be less than ±0.17% (at 3σ), which meets the energy stability requirement for the linear collider. The timing jitter and drift of the pulse output is around 2-nsec (at 3σ) over a 4-hour run at 50-pps [9]. In 2003, this modulator concept was accepted in China for the Shanghai light source. They fabricated it there themselves, and it was tested in May 2004.

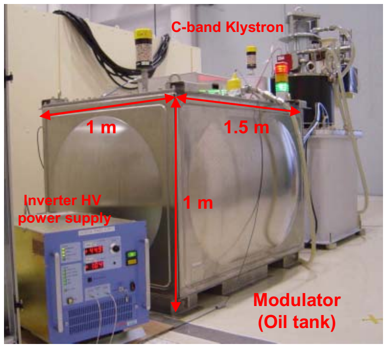

Figure 5: A new developed oil-filed modulator.

The next step in the modulator development was to install everything except for the inverting H.V. power supply in an insulating oil-filled metal tank or cabinet of very compact size as shown in Figure 5 [10]. This is also very compact, being only 1.5-m (W), 1-m (H) and 1-m (D). The prototype was developed by the NICHIKON Co in Japan. Testing was begun in March 2003 at SPring-8. We obtained the expected results as to pulse wave shape, voltage and flatness, and were able to verify the operational repeatability of the unit and also its markedly reduced EMI and noise generation. The main parameters for the modulator and new inverter power supply are listed in Table 2.

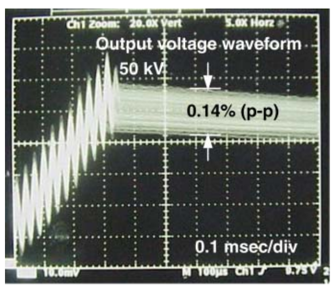

Figure 6: Measured output voltage stability at 50 kV and 60 pps repetition rate.

A new inverter H.V. power supply was developed by the TOSHIBA Co. in Japan and it was tested along with the rest of the modulator beginning in March 2003 at SPring-8. 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 delivering a 350-kV beam voltage. As shown in Figure 6, we obtained an output voltage regulation of within ±0.1% with this first prototype model.

Table 2: Main parameters of oil filed new modulator

Modulator peak output power:	111	MW
Average output power	46.7	kW
PFN charging voltage Nominal:	44	kV
Maximum:	50	kV
Peak switching current:	5.4	kA
HV pulse width:	3.5	μsec
Pulse repetition rate (max):	60	pps
Output voltage reputability:	±<0.5	%
Thyratron timing jitter:	<5	nsec
PFN impedance:	4.3	Ω
PFN cell number:	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
Output current (peak):	30 (37.5)	kJ/sec
Output voltage regulation:	±<0.07	%
Power factor at full load:	>85	%
Power efficiency at full load:	>85	%
Cabinet size (W) x (H) x (D):	48 x 45 x 63	cm

RF Pulse Compressor

At the present, initial testing of a high power rf pulse compressor was begun at KEK at the end of 2003. The prototype rf cavity uses a copper plated Invar metal, this permits simplifying the temperature control system for the rf compressor and thus contributes to reducing the cost of the total system [6]. Figure 7 show a very preliminary experimental result of a 135-MW peak output power, 0.5-μsec pulse width at a 50-pps repetition rate with a total multiplication factor of 3.0. From in this figure, we see the need to improve the flatness of the top of the output waveform, and also need to increase the power gain factor from 3 to 3.3 for a realistic application.

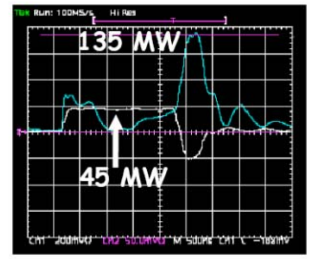

Figure 7: Typical pulse compressor cavity rf power waveforms.

The thermal stability of these rf compressor cavities provides an order of magnitude better performance than that of copper alone. No unusual vacuum out-gassing was found even while in high power operation.

Unfortunately, after a high power test in March 2004, a large water leak developed in one of the compressor cavities, which was flooded. This caused corrosion to start at the junction between the bare Invar and copper metal.

RF Structure

The C-band Choke-Mode type damped rf structure was developed in 1998, and its performance has been confirmed with the ASSET facility at SLAC [3]. A cut-away view of the cavity is shown in Fig. 8. The dark square shapes (top and bottom) in Fig. 8 show where the ring shaped SiC HOM absorbers go in the assembly.

One particular advantage is that since all of the parts are completely axially symmetric, they can be machined on a turning lathe, this easier machined type of cavity is very advantageous in

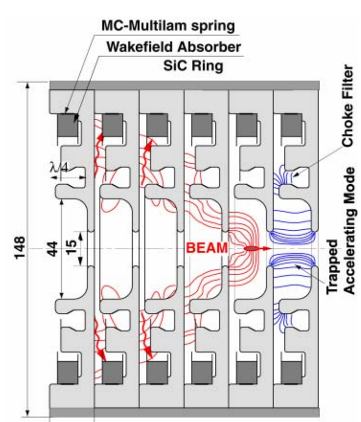

Figure 8: A cut away view of the C-band choke-mode rf structure.

mass production. The first high power prototype model is being fabricated by the MITSUBISHI HEAVY IINDUSTRY Co. in Japan. The main parameters of the rf structure are listed in Table 3.

Table 3: Main parameters of Choke-mode rf structure

Frequency:	5712	MHz
Phase-shift per cell:	$3\pi/4$	
Field distribution on the axis:	Quasi-C.G	
Quality factor (average):	10300	
Attenuation parameter:	0.53	
Filling time:	290	nsec
Shunt impedance (average):	58.5	MΩ/m
Electric filed ratio of Es/Ea:	2.2	(max)
Iris aperture up-stream:	17.330	mm
down-stream:	13.587	mm
Disk thickness:	4	mm
Number of cells:	91	
Number of coupler: (field symmetry & double irises)	2	
Structure active length:	1.8	m

We decided to use a quasi-constant-gradient for the electric field distribution along the axis of the structure; this minimizes the surface electrical gradients, which contribute strongly to breakdown problems in high gradient operation. Doing this, we have successfully kept Es/Ea to a maximum of only 2.2. Higher trapped modes (HOM) of small amplitude appeared at 20-, and 23-GHz in first prototype rf structure. To eliminate them, the absorber disk thickness will be changed from 3- to 4-mm. Fig. 9 shows a MAFIA simulation of the single bunch wake field. As can been seen, the wake field amplitudes are damped enough before the arrival of the 2nd bunch, and also there are no higher trapped modes found in the new rf structure.

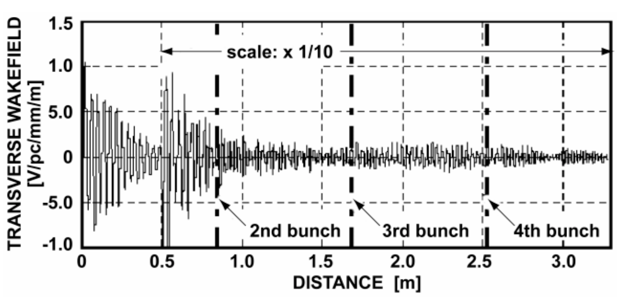

Figure 9: A single wake field simulation of the C-band Choke-mode rf structure.

High Gradient

A series of dark current measurements have been made on two kinds of electrodes made of Molybdenum (Mo) and Titanium (Ti). A new analysis method has been conceived of to separate the primary field emission current from the observed dark current. The analysis shows that the primary field emission current from cathode surface is quite small for a Mo surface, and the enhancement effect is small for a Ti surface. From this analysis, it is strongly suggested that Mo is most suitable material for the cathode and Ti for the anode. This was verified by experiment using Mo cathode and Ti anode electrodes; a field gradient of 130-MV/m was achieved with a total dark current below 1-nA when the separation gap was 0.5-mm as shown in Figure 10.

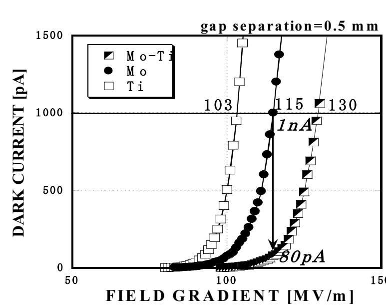

Figure 10: Dark currents for Mo-Ti, Mo-Mo, and Ti-Ti electrodes as a function of field gradient at the cathode surface with a gap separation of 0.5-mm.

Roller Cam Precise Active Mover

The new roller cams mover unit is comprised of two roller cams, their stepping motors drivers, two linear sliders and support frames as shown in Fig. 11. We used 72-mm diameter roller cams to provide ±1.4-mm of positioning area in the horizontal and vertical respectively. We do not use V-blocks and flat plates fixed to the structure (such as is used in the magnet positioning roller cams system in the SLAC FFTB).

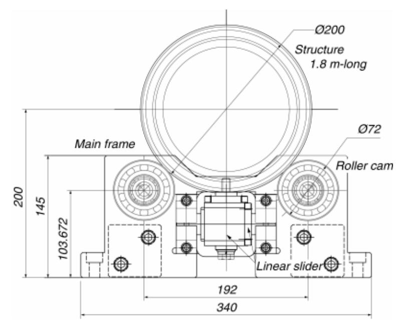

Figure 11: A cutaway drawing of the roller cams mover unit. 72-mm diameter roller cams give an adjustable range ±1.4-mm.

The expected maximum adjustable range of ±1.4-mm was measured, and then the position repeatability was tested and found to be less than ±0.1-μm anywhere within the positioning range while loaded with a 50-kg dummy weight, shown in Figure 12.

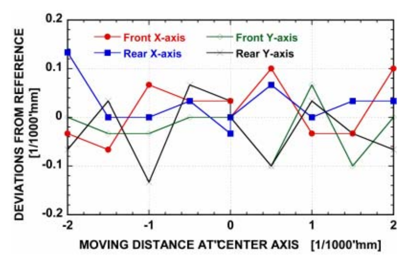

Figure 12: Deviations of roller cams mover from reference.

Pulsed High-Voltage Monitor

We have developed a very stable and accurate high-voltage monitor, to be used for observing the klystron pulse voltage [11]. Since it uses a ceramic material in a capacitive type voltage divider (CVD), the capacitance division ratio can be kept quite stable even under temperature changes, or changes in set-up configuration, or changes in the mechanical stresses applied to the monitor port through the input lead. We successfully operated the monitor up to 367-kV, and 4.5-μsec pulses. The maximum voltage for the CVD test was limited by the available modulator output voltage.

A New C-band 50-MW SiC Type RF Load

There are no commercially available 50-MW class vacuum rf loads for C-band frequencies. Therefore we have constructed a new type rf load using SiC ceramic indirectly cooled by water flowing through the structure; this upgraded the power handling density of the SiC material from 100-W per cc to 300-W per cc, allowing a much more compact overall size. The design uses a chain of circular mode TM_{011} absorbers [5]. One particular advantage is that since the main 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.

REALISTIC APPLICATION

SCSS will provide one realistic application of one or a few rf-units in its linac. SCSS will be a soft X-ray SASE-FEL machine aiming at demonstrating FEL operation below 10-nm wavelength with 1-GeV electron beam in 2006~2007 [7]. The combination of a short period in-vacuum type undulator and the high gradient C-band main accelerator makes the machine compact, enabling it to fit within a 100-m long tunnel.

The first project goal will be to generate 60-nm FEL from a 250-MeV energy beam by November 2005.

Machine Configuration

In the SCSS project, the following three key technologies contribute to the compactness of the machine. (1) High gradient C-band accelerator. The accelerating gradient can be as high as 40-MV/m, thus an accelerator only 30-m long is enough to reach 1-GeV. (2) In-vacuum undulator, which enables creating a shorter period undulator thus the required beam energy is lower, again reducing the accelerator size. It also contributes to shortening the FEL gain length. (3) Low emittance beam injector. The short undulator period does require a low emittance electron beam.

We chose a HV (500-kV) pulse DC gun using a single crystal CeB_6 thermionic cathode, which has the potentia to generate a very small emittance beam while providing for a long lifetime.

To saturate the FEL lasing in the 22.5-m long undulator line, a low emittance beam current with as much as 2-kA peaks is required. The high peak current is generated by first compressing the bunch length in the injector and then further in a magnetic-chicane bunch compressor. We will use four units of the 40-MV/m accelerating gradient C-band accelerator, which should produce a beam energy reaching 1-GeV with only a 30-m long accelerator; and the shortest radiation wavelength should be 3.6-nm as shown in Figure 13.

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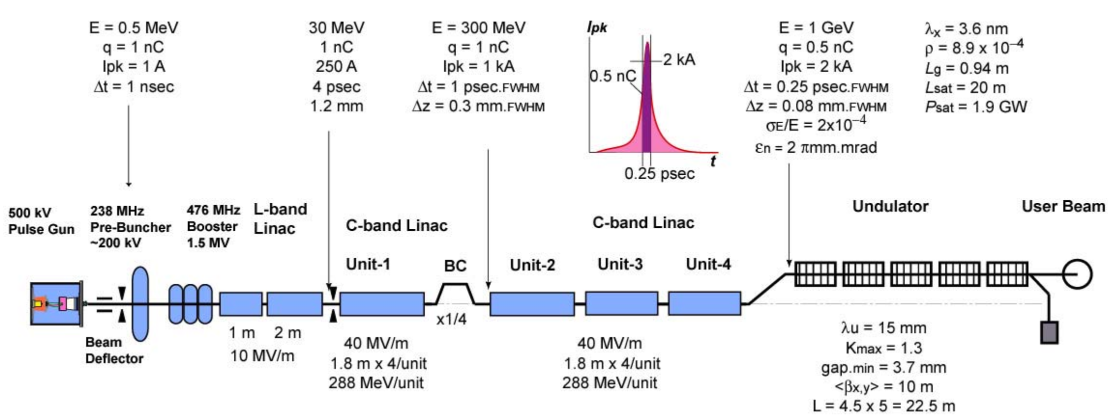

Figure 13: Beam line layout in SCSS of 1-GeV case.