THE C-BAND (5712-MHZ) RF SYSTEM FOR e^+e^- 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]. 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 [5]. 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 [6]; 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 linear 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^- collsions.

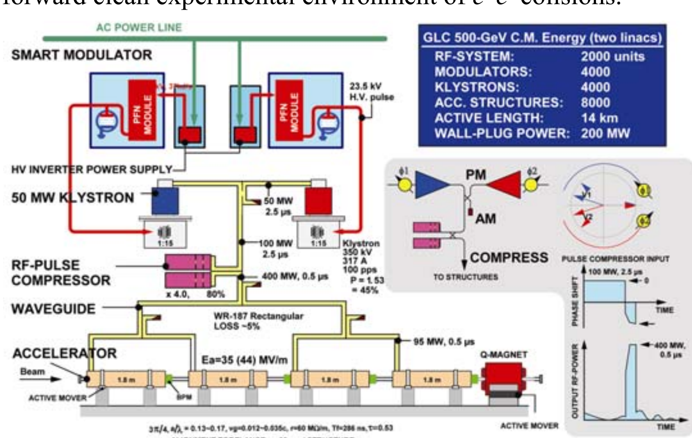

Figure 1: One unit of the C-band main linac.

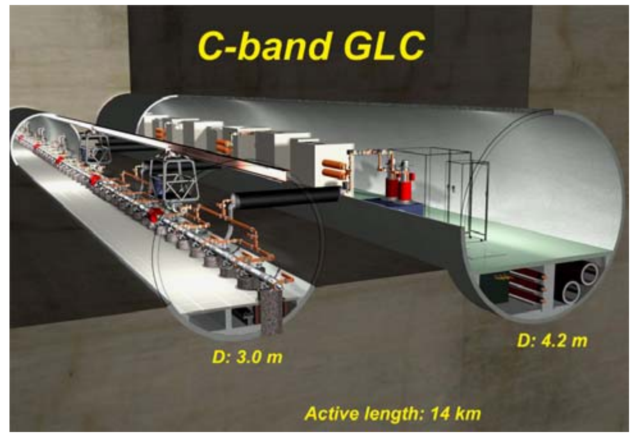

Figure 2: C-band main linac tunnels. The klystron gallery is 4.5-m in diameter and the linac tunnel is 3.0-m in diameter.

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.

The total C-band main linac rf-system for a 500-GeV C.M. energy includes about 2000 rf-units as shown in Fig. 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.

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.

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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 [7]. The experimental test results of the three klystrons are summarized in Table 1.

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 first tube (E3746-#1) employed a conventional design such as having only a single-gap output structure. 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.

Modulator Power Supply

We focused our modulator R&D work on reducing the fabrication cost and improving the reliability. 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) [8]. 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.

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 Fig. 3 [9]. 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. 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. We obtained an output voltage regulation of within ±0.1% with this first prototype model.

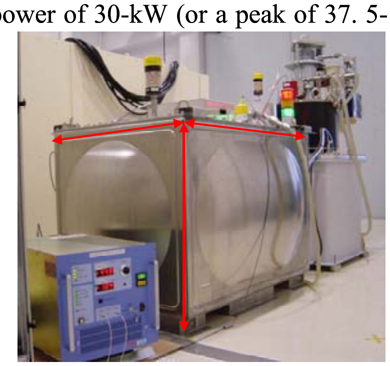

Figure 3: A new developed oil filled modulator.

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 [5]. Fig. 4 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.

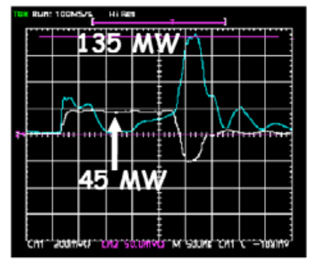

Figure 4: Typical pulse compressor cavity rf power waveforms.

The thermal stability of these rf compressor cavities provides an order of magnitude better performance than that of copper alone. No unusual vacuum outgassing 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].

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 mass production. The first high power prototype model is being fabricated by the MITSUBISHI HEAVY IINDUSTRY Co. in Japan.

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 Fig. 5.

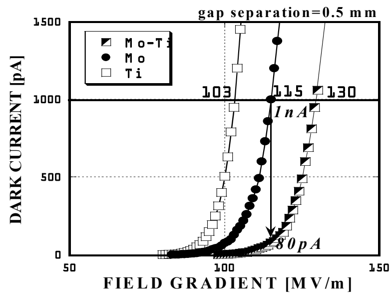

Figure 5: Dark currents for Mo-Ti, Mo-Mo, and Ti-Ti electrodes as a function of field gradient at the cathode surface with a gap separation of 0.5-mm.

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 [6]. 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 potential 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 6.

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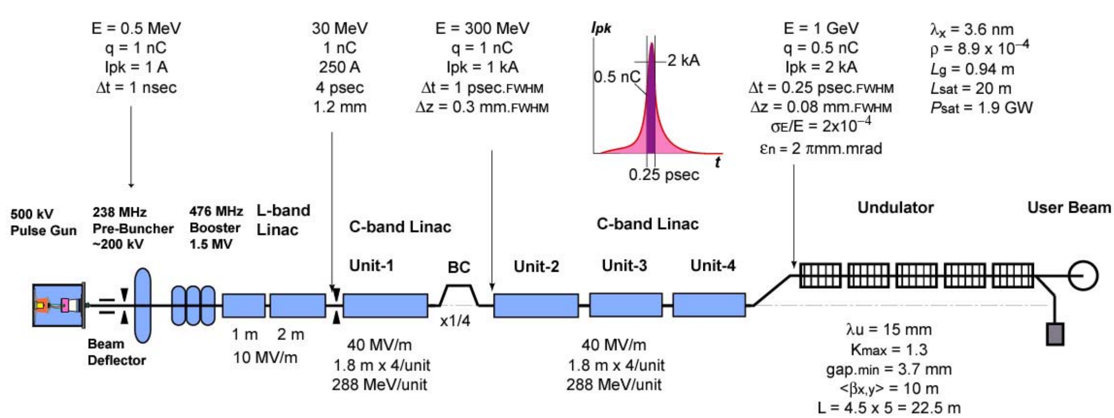

Figure 6: Beam line layout in SCSS of 1-GeV case.