C-band Klystron & RF-System Development

Tsumoru SHINTAKE, Nobumasa AKASAKA, Hiroshi MATSUMOTO
Jong-Seok OH*, Kensuke WATANABE**, Hitoshi BABA***
Accelerator Division, High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305 JAPAN
*Linac Division, PAL Pohang Accelerator Laboratory, Pohang, Kyungbuk, 790-600, Republic of KOREA
**Laboratory of Nuclear Science, Tohoku University, Yakiyama, Tashiro, Sendai, 982 JAPAN
***NIHON-KOSHUHA Co. , 1119 Nakayama, Midori-ku, Yokohama, 226 JAPAN

Abstract

Hardware R&D on the C-band (5712 MHz) RF-system for the electron/positron linear collider stated in 1996 at KEK. Up to now (September, 1997), we have developed a 50 MW C-band klystron (TOSHIBA E3746), a "Smart Modulator", a traveling-wave resonator (TWR) and a cold model of the rf-pulse compressor. In this paper, recent progresses in the C-band hardware R&D are reported.

1. Introduction

An e^+e^- linear collider is a large-scale machine. In the main linacs for two beams, we use more than 8000 accelerating structures, 4000 klystrons and their pulse modulators. Therefore, the system must meet the following demands:

(1) High reliability,
(2) Simple,
(3) Lower construction cost,
(4) Reasonable power efficiency,
(5) Easy to operate.

The above list provides a guide-line and boundary conditions to our design work. Among the system parameters, the choice of the drive rf frequency plays the most important role concerning the system performance as well as the hardware details. We proposed the C-band frequency as being the best choice to meet all of the demands listed above [1].

2. System Description

Figure 1 shows a schematic diagram of one unit in the main linac rf-system [1]. We need 2040 units in the actual linear collider at 500 GeV c.m. energy.

Two 50 MW klystrons are driven by two high-voltage pulse modulators independently, followed by a 3-dB hybrid power combiner and pulse compressor to generate 350 MW peak power, which drives four accelerating structures. The pulse-compression action is performed by rotating the phase of the input rf-signal in opposite directions in each klystron. By combining two rf powers at 3-dB hybrid, the phase modulation (PM) is converted to the amplitude modulation (AM) of the ramp-wave form, which compensates the beam-loading effect in the accelerating structure [5]. A cold model of the rf pulse-compressor was fabricated and tested in Spring, 1997. The power gain of 3.25 was observed [6].

The accelerating structure is the choke-mode cavity type [7], which strongly damps all of the HOMs (higher order modes) to avoid a multi-bunch beam instability in the long linac. A 1.8 m long accelerating structure of this type is under fabrication, whose wakefield damping performance will be tested in ASSET beam line at SLAC in May, 1998.

3. Progress in Hardware R&D

3.1 Waveguide Components

A new-type unisex waveguide flange, named MO-flange (Matsumoto-Ohtsuka type), has been developed to increase the reliability and to reduce cost [2]. The waveguide size is EIA-WR187 (3.95-5.85 GHz). The theoretical rf transmission loss is –0.032 dB/m, which is a comparable attenuation in the conventional S-band waveguide (–0.021 dB/m at 2856 MHz). The waveguide was made by OFHC (oxide-free high conductivity) copper with a purity of >99.96%.

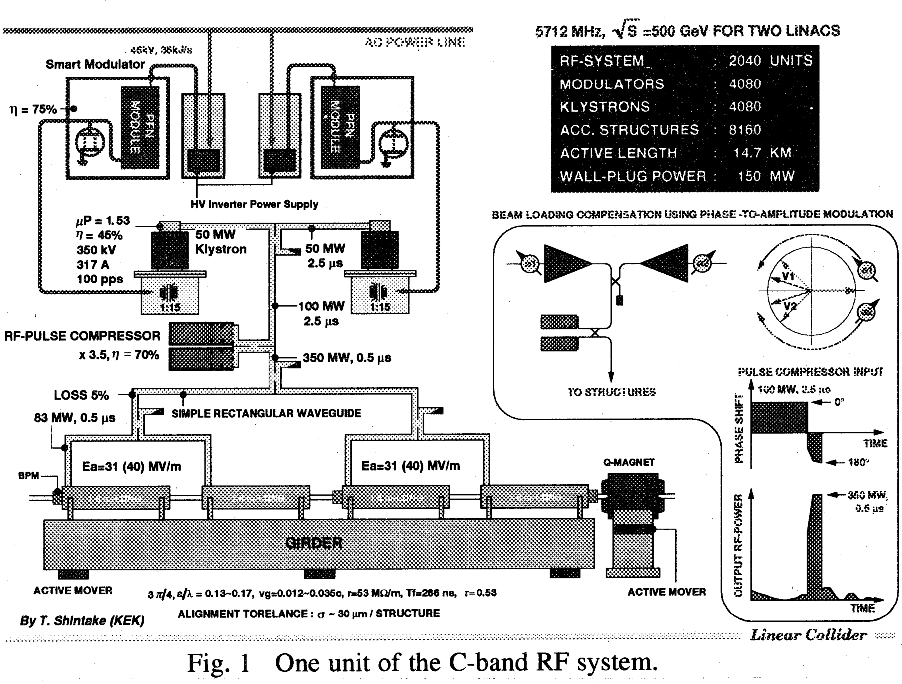

Fig. 1 One unit of the C-band RF system.

3.2 TWR: Traveling-Wave Resonator (Resonant Ring)

To test the rf-window and waveguide components, a traveling-wave resonator (TWR) was developed. The TWR operation was commissioned in July, 1997. To drive the TWR, we use a 5-MW C-band klystron (TH2067, 5 MW, 5710 MHz). After one week processing, the peak power reached to 90 MW with 2.5 µsec; this is enough energy to test the rf-window. The measured power gain was 18.1, which is in good agreement with the design value of 18.8.

3.3 C-band Klystron R&D

Figure 2 shows the newly developed C-band klystron: TOSHIBA E3746 #1. In order to ensure high reliability in the C-band klystron, we designed the main parameters by scaling from existing S-band klystrons. We referred mainly to two klystrons: TOSHIBA E3712-klystron (80 MW, 375 kV) and SLAC 5045-klystron (50 MW, 350 kV). We assumed that the power handling capability will be scaled as

$$VI\tau \propto D^2 \propto \omega^{-2}.$$

This comes from a safety limit of the beam-power density in the drift-tube. At the C-band, we found the safety beam-power being 300~400 Joules/pulse. Considering the requested HV pulse-length of 3.5 μsec, and assuming a power-conversion efficiency of 45%, we decided the target value of the output to be 50 MW. The electron-gun voltage was determined to be 350 kV after optimizing the beam perveance and the surface electric field on the cathode and anode electrodes.

E3746 #1 is a five cavity klystron. The output structure is a single-gap design, connected with two output waveguides, followed by two rf-windows in parallel; then, two arms are combined to one output. The single-gap output-structure has lower power-efficiency than the traveling-wave output, but it has no risk of the self-oscillation. The design details are described in ref. [3].

The klystron was tested at TOSHIBA Nasu Electron-Tube Division in August, 1997. The HV & RF processings were completed in two-weeks. The final test results were summarized in Table-1. This first klystron has already achieved most of the goal performances for the 500 GeV c.m. energy linear collider. Figure 3 shows the output waveform.

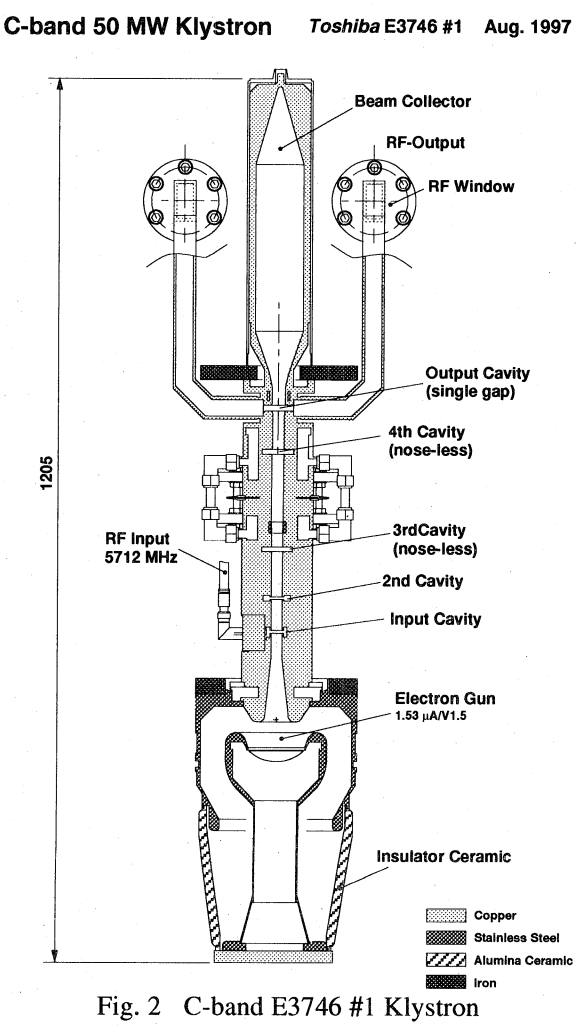

Fig. 2 C-band E3746 #1 Klystron

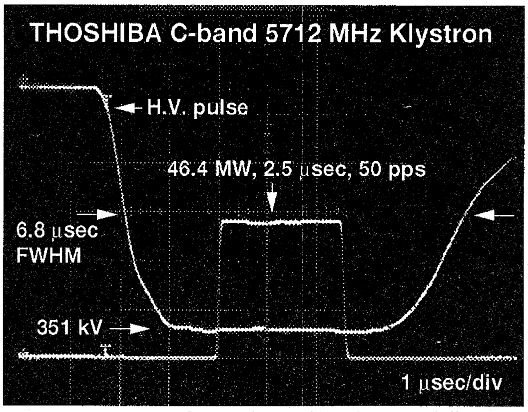

Fig. 3 Output power from the C-band E3746 #1 klystron.

Table-1. E3746 Klystron Performance: achieved vs. goal

	E3746 long pulse	E3746 short pulse	500 GeV Goal
Output Peak Power	46.4 MW	50.1 MW	50 MW
Power Efficiency	41.5 %	42.6%	45%
Pulse Width (μsec)	2.5 μsec	1.0 μsec	2.5 μsec
Repetition Rate	50 pps	20 pps	100 pps
Gun Voltage	351.2 kV	360.4 kV	350 kV
Focusing Magnet	Solenoid	Solenoid	Permanent Magnet
Focusing Power	6.6 kW	6.6 kW	0 .
Life Time	unknown	unknown	>30,000 h

In the electrical design, we use the FCI-code, which predicted only +3% higher output-power than the measured value. This means that the total production system: the CAD-design and simulation, fabrication, processing and the test are well established at TOSHIBA Nasu electron-tube division.

The No.2 tube of E3746 klystron is under design, which uses a traveling-wave output structure to improve the power efficiency and to lower the surface electric-field gradient.

3.4 Smart Modulator (Klystron Power Supply)

The klystron modulator power supply (HV-pulse power-supply) is one of the most expensive part in the rf-system for the electron accelerator. At the same time, it is the most unreliable and troublesome device, and occupies a large volume. Therefore, not only for the linear collider, but also for various scientific and industrial applications, it is quite important task to improve the klystron modulator.

In 1993, Prof. M. H. Cho (PAL Pohang Accelerator Laboratory) and Dr. H. Matsumoto (KEK) proposed a concept: "Smart Modulator". The idea is to use an inverter-type HV power-supply and to develop a new generation sophisticated modulator, which is reliable, compact, modular design, low EMI noise, intelligent control, easy to maintain and low cost.

In the R&D work, we were supported from two laboratories: CERN-PS and PAL-POSTECH. From CERN-PS division, Dr. Peter D. Pearce jointed to our group in 1995 and made a basic parameter design. He also provided many important infromations on details inside the klystron

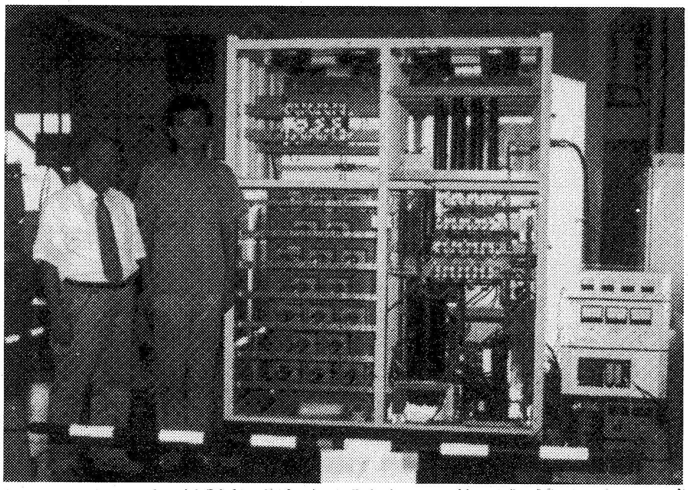

Fig. 4 The first model of the smart-modulator developed by NIHON KOSHUHA Co. (left) Prof. H. Baba and (right) Mr. K. Sato, who designed the details. The small box (right bottom) is the inverter power supply.

modulator based on his various experiences on the klystron modulator.

From PAL (Pohang Accelerator Laboratory in KOREA), Dr. Jong-Seok Oh visited KEK for a half year in 1996. He carefully studied on the efficiency issue in the klystron modulators for linear collider[4].

As the first step toward the smart modulator, we decided to develop a first model to demonstrate high-potentiality of the inverter power supply. Key points in the first model are:

1. Direct HV charging from the inverter power supply.
2. No deQ-ing circuit.
3. Much smaller size than the conventional modulators.
4. Use existing reliable circuit components. We did not use any component based on a new idea. For example, PFN capacitor is a paper-oil type.

The developed smart-modulator is shown in Fig. 4. The main cabinet size is 1600(W) x 2000(H) x 1200(D), this is much smaller than the conventional modulators. We use an 50 kV inverter power supply made by EMI co. USA. It is very compact (483W x 311H), but very powerful: the maximum charging rate is 37.5 kJ/sec. A large traditional charging section was replaced by this.

Figure 5 (a) shows one cycle of charge/discharge process on the PFN capacitors, where the voltage ramps linearly. This is because of the constant charge-pumping operation of the inverter power supply. Since the charging energy in one bucket is very small, it is less than 1 Joule/bucket, damages on the circuit components due to accidental break-down are quite small. Figure 5 (b) is the output waveform into a dummy load of 5 Ω. The pulse height is –23 kV. After tuning the PFN inductance, the flat-top width becomes 2.5 μsec with 0.5 % flatness, which is enough performance to the high-power tests of E3746 klystron.

To eliminate unwanted noise emission associated with thyratron switching, the return-circuit was made by a wide ground-plate using a thin copper. The fast ringing signal in Fig. 5(b) is the leakage noise measure by a loop probe (60 mm dia., 3 turns, with 1 MΩ scope impedance), which is much less than the other our modulators.

This first model of the smart-modulator will be used for the life-test of the C-band klystron.

Acknowledgment

The C-band 5 MW klystron, which is now driving the resonant ring, was loaned from SLAC Stanford University as a part of international collaboration. We would like to thank to Prof. Gregory A. Loew and Dr. Juwen Wang for their kind support of our project. We thank Dr. Norbert Holtkamp for his active discussions on various hardware components, and his suggestion concerning the cooling-water system.

We thank to Mr. Kazuharu Nishitani for his various contributions to build the experimental equipments. We also thank all contributors to this project.

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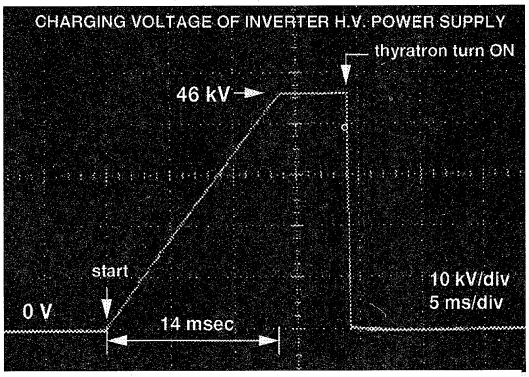
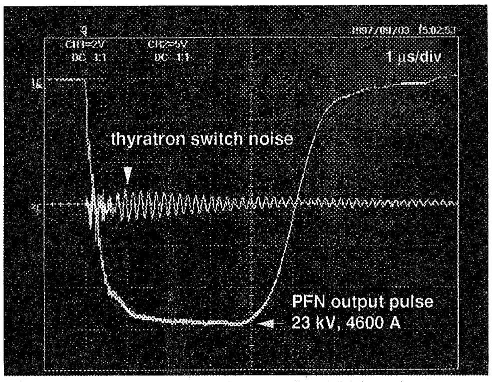


(a) PFN voltage.



(b) Output voltage on 5Ω load.

Fig. 5 Test results of the first smart modulator.