R&D Status of The C-band RF-System Development for e^+e^- Linear Collider in Japan

Hiroshi MATSUMOTO, Tsumoru SHINTAKE, Nobumasa AKASAKA, Mitsuhiro YOSHIDA*, Yuko TAKASU*, Yoshihisa OHKUBO** and Jong Seok OH***
High Energy Accelerator Research Organisation (KEK)
1-1 Oho, Tsukuba, 305-0801, Japan
*University of Tokyo
7-3-1 Hongo, Tokyo, 113-0033, Japan
**TOSHIBA CO.
Ohtawara, Tochigi, 324-8550, Japan
***Pohang Accelerator Laboratory (PAL/POSTECH)
San-31, Pohang, 790-794, South Korea

Abstract

Hardware R&D on the C-band (5712-MHz) RF-system for the e^+e^- linear collider started in 1996 at KEK. We developed three 50-MW class C-band klystrons (TOSHIBA E3746 series), a smart modulator, a traveling-wave resonator (TWR), a cold model of an rf-pulse compressor cavity, and the first HOM-free accelerator structure (Choke-mode type, full-scale high power model) [1][3].

Life test was carried out on the developed klystrons over 6000 hours in total, where thy showed highly reliable performance as high as conventional S-band klystrons. As a upgrading program to 1 TeV c.m. energy scale, we have stated R&D on a new PPM klystron this year. The power consuming solenoid focusing coil will be replace by periodically arranged permanent magnets using today's advanced magnetic material of NdFeB. To achieve efficient beam focusing, the magnetic circuits will be directly integrated into the klystron. Key technologies required to the PPM klystron are under development

The electrical performance on the HOM-free accelerating structure was tested with beam at SLAC-ASSET facility in December 1998. The measured wakefield showed excellent performance on the HOM damping as exactly expected from the theory.

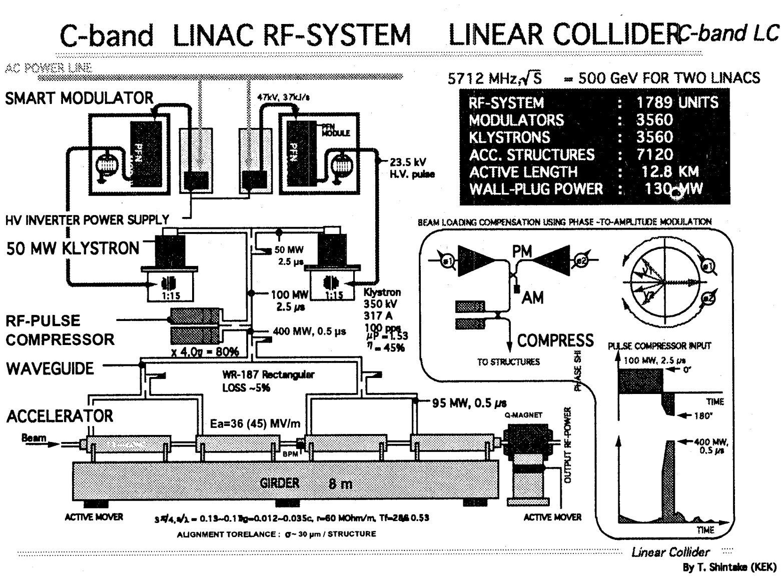

Fig. 1: One unit of the C-band main linac.

1 Introduction

The e^+e^- linear collider (500 GeV C.M.) will use more than 7000 accelerating structures, 3500 klystrons and their pulsed-modulator power supply. No laboratory yet has any experience in fabricating such a large number of devices, or in operating them with beam. Therefore, guidelines for hardware development has to satisfy the following boundary conditions:

(1) Highly reliable,
(2) Simple,
(3) Low construction cost,
(4) Reasonably power efficient and
(5) Operational ease.

The drive rf-frequency is the most important parameter in designing the RF acceleration system, which reflects the hardware details. We chose the C-band (5712-MHz) frequency as a best solution, after the suggestion by T. Shintake of KEK in 1992.

This paper will describe results of the hardware R&D on the C-band RF system and current status.

2 System Description

Each unit in the main linac rf-system is composed of two 50-MW klystrons, their pulsed modulators, one rf-pulse compressor, four 1.8-m-long Choke-mode accelerating structures and associated waveguide-system as shown in Figure 1. The accelerating gradient is 36 MV/m under the beam loading. The total number of the RF-system to achieve 500 GeV C.M. energy is 1800 units; this has been reduced from 2040 units in the earlier version. It was made by two improvements: the shunt impedance of the accelerating structure and the power-gain of the rf pulse compressor. The main linac will be installed in two parallel tunnels with circular cross-section with diameters of 3-m and 4.5-m for the accelerator and klystron gallery, respectively. The tunnels will be constructed in a very stable stratum such as granite.

3 Progress on Hardware R&D

3.1 Waveguide Components

To make the system simple, we chose the conventional rectangular waveguide rather than a special waveguide shapes. We use the EIA-WR187 (47.55-mm x 22.15-mm), whose rf transmission loss is as low as –0.032 dB/m. The rf-power of 5% will be lost along the waveguide between the klystron to the accelerating structure. We have developed various new waveguide components, and a low-cost high-reliable unisex rectangular vacuum flange [5].

3.2 RF Pulse Compressor

A new scheme was proposed as a flat-pulse rf-pulse compressor by T. Shintake in 1996. It is comprised of a cavity chain of two energy storage cavities (TE0.1.15 mode) and a coupling cavity (TE0.1.5 mode) excited in a $\pi/2$ resonance mode. A compression to a flat-pulse was demonstrated using a cold model cavity as shown in Figure 2. The energy gain of 3.25 was obtained [6].

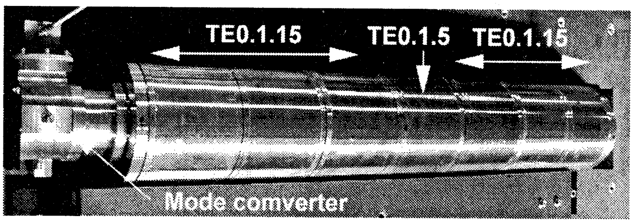

Fig. 2: Cold model of rf pulse compression delay line of 1 m-long.

3.3 C-band Klystron & Modulator

The design goal of the C-band klystron development is very clear: make a 50 MW klystron of reliable performance same level as the conventional S-band klystrons or even better. Accordingly we conservatively decided a ceiling value as 300-400 Jules/pules for the injection beam power into the klystron in each pulse. Also, the maximum cathode emission loading was designed to be less than 10 A/cm^2, and the maximum electrical-gradient of the electrodes surfaces less than 22 kV/mm [7]. We have developed three 50-MW class klystrons during the years 1996-1998. They are conventional solenoid focus klystron as shown in Fig. 3. All of them successfully generated rf output power of 50 MW or more. The developed klystrons are already acceptable for the production tube to develop the linear collider project of 500 GeV C.M. energy scale. The experimental results of three klystrons are summarised in table 1.

Table 1: The experimental results for the C-band klystrons.

E3746	No. 1	No. 2	No. 3
Output power [MW]	50 (48)	54	53
Pulse width [μsec]	1 (2.5)	2.5	2.5
Repetition rate [pps]	50 (20)	50	50
Power efficiency [%]	42	44	47
Output gap	1	3 TRW	3 TRW

3 TRW: three-cell traveling-wave output structure.

The first tube (E3746-#1) employed a conventional design such as having a single-gap output structure. Its main propose was to verify our design and operational performance of the electron gun, beam dump (collector), the output rf windows. The 2nd and 3rd klystrons were developed (in 1997 and 1998) to increase the rf power efficiency. The newly developed 3-cell travelling-wave output structure was employed. The power efficiency of 44% in the single-gap design of 1st klystron was improved to 47% in the 3rd klystron of the traveling-wave output structure. The rf power data, measured with a precision calorimetric power measurement system, was well agreed with the FCI simulation within 1% error.

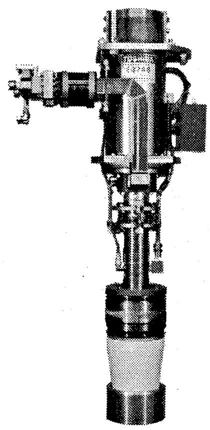

Fig.3:TOSHIBA E3746#3 klystron.

As a part of the RD program toward 1 TeV energy scale linear collider, we started R&D on the PPM klystron this year. We chose the NdFeB magnet (Model N40A, Shin-Etsu Co. in Japan), which has a residual flux density (Br) of 1.22 Tesla and a coercive force of 10.5 k-Oersted.

Voltage and pulse-length required to drive the klystron is –350 kV and 3.5-μsec, which is suitable to the conventional PFN line-type pulse-modulator. Since this type of modulator has been widely used in the linear accelerators, whose technology is well established. Accordingly we focussed our R&D work on reducing the fabrication cost and improving the reliability. In 1993, the concept of the "Smart Modulator" was proposed by Prof. M. H. Cho and the author. As a first step, we developed a prototype modulator, whose features are:
(1) Direct HV charging from an inverter power supply,
(2) No deQ-ing circuit,
(3) Much smaller size than the usual modulator,
(4) Use existing reliable circuit components.

To reduce the modulator size and allow removing the deQ-ing circuit from PFN, we employed an inverter type DC-HV power supply: Model EMI-303L (Electric Measurement Inc., USA), whose size is only 48 (W) x 31 (H) x 56 (D) cm. It generates a maximum voltage of 50-kV and an average power of 30-kW (peak charging rate 37.5-kJoule/sec) with a voltage regulation better than 0.5% up to 200 pps repetition rate.

The smart modulator was installed in a metal cabinet of compact size 160 (w) x 200 (H) x 120 (D) cm as shown in Figure 4. It is now in daily use for driving the 50-MW klystron. The total run time has exceeded 6000 hours. The fluctuation of the measured output voltage was lower than ±0.17% (at 3σ), which meets the energy stability requirement for the linear collider. The timing variation (jitter and drift) of the pulse output is around 2-nsec (at 3σ) for 4 hour run at 50 pps[8][9][10].

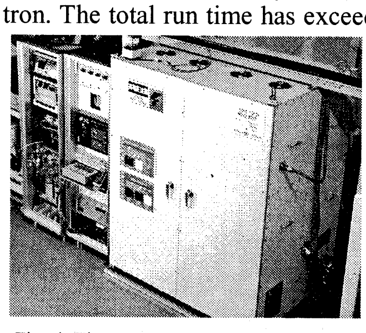

Fig. 4: First prototype Smart Modulator.

3.5 Accelerating Structure

Figure 5 shows the first high-power model of the C-band choke-mode structure, which was originally proposed by T. Shintake in 1992. It is composed of 89 regular cells and input/output couplers attached at both ends. To avoid unwanted transverse kick due to asymmetric rf field, a double-feed coupler using J-shaped waveguide is used in the input/output couplers. Two common-mode-free RF Beam-

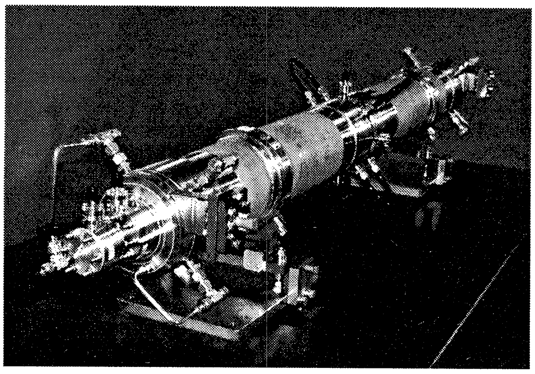

Fig. 5: The C-band accelerating structure of 1.8-m long, 91 cells.

Position-Monitors (RF-BPMs) were mounted on the couplers. Wakefield antennas were prepared in the center cell, which pickup the beam induced HOM spectrum, and determine the beam position.

In the Choke-Mode cavity, all of the parts are axially symmetric, they can be machined on a turning lathe, this type of cavity has a big advantage in mass production because of its easier machining. The SiC-ceramic rings were mounted in each disk with a metal spring insert (Multilum-Contact), which absorb the wakefield power after filtering the accelerating rf power through the choke-filter.

The short-range transverse wakefield is a strong function of the iris aperture ($\propto a^{-3.5}$), thus it becomes very strong at higher frequency bands, resulting in very tight straightness tolerance. At C-band (5712 MHz) frequency, the straightness tolerance becomes ±50-μm (the maximum bow) for a 1.8-m long structure, which can be achieved with today's standard precision machining process.

In 1998, the first high-power model of the choke-mode cavity at C-band was fabricated by MITSUBISHI HEAVY INDUSTRY Ltd. We chose an electroplating method to form the structure from a number of disks. In this method, no any high temperature processes is required, such as high temperature brazing (700-900 °C), thus the high dimensional accuracy was kept throughout the fabrication process. The tensile strength of the copper material drops sharply and elongation becomes pronounced when it is heated over 200 °C. Therefore, this method is one of the best choice for fabricating high precision accelerating structures [12].

3.5 Wakefield Experiment

In December 1998 at ASSET-SLAC, we measured the wakefield in the C-band structure using electron and positron bunches [4]. An intense positron beam was firstly injected as a drive bunch generating a wakefield in the structure with vertical position offset, then a witness bunch of an electron beam was injected into the structure. From the deflection angle of witness bunch, which was measured with the BPMs in the 2-mil-linac, the wakefield was determined as shown in Figure 6. The wakefield is quickly damped from its initial value of 15 to 1 V/pC/m/mm within 1.6 nsec as exactly following the expected waveform (solid line). The high frequency oscillations (20- and 23-GHz) were found after this period. The amplitude of these oscillations is in the range of 0.8-1.0 V/pC/m/mm, which is just at border of the limit for the 25% emittance degradation through the main linac. After careful study with computer simulations, it was found that the high frequency oscillations are trapped modes in the cavity, having no coupling to the opening slot and no power is absorbed by the SiC rings. This was caused by a change in the disk thickness from 4- to 3-mm to improve the shunt impedance by about 10%. It is understand that a small amount of change in cavity shape can shift the field pattern and eliminate these modes. A new model is under design.

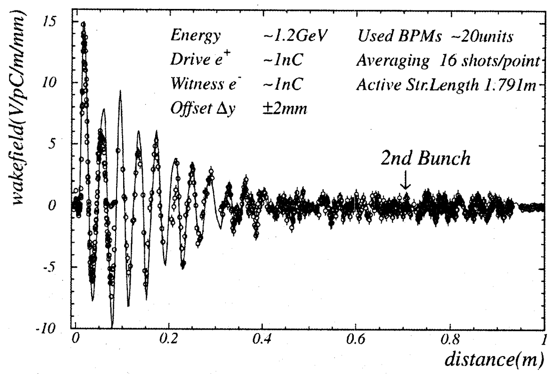

Fig. 6: Measured (circles) and expected (solid line) wakefield.

4 Future R&D

The first stage of the C-band R&D between 1996 and 1998 was successfully completed. For 1999, the first priority is to develop a 50-MW class PPM type klystron with power efficiency of higher than 50%. For the next step, in order to examine the system performance in a realistic situation, one unit of the C-band system has to be installed and tested with beam in an existing machine, such as the KEKB injector. Daily operation will suggest us what we should do next.

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