DEVELOPMENT OF C-BAND 50 MW PULSE KLYSTRON FOR e^+e^- LINEAR COLLIDER

T. Shintake, N. Akasaka, H. Matsumoto, KEK High Energy Accelerator Research Organization and
Y. Ohkubo and H. Yonezawa, Toshiba Co., Japan

Abstract

Hardware R&D for the C-band (5712 MHz) RF system was started as a KEK research program for the e^+e^- linear collider project in 1996[1]. In order to achieve 500 GeV C.M. energy at the e^+e^- collision within 25 km site length, the C-band system requests 4080 tubes of 50 MW pulse klystron, which drives the accelerating gradient 32 MV/m at the full beam current. The first 50 MW class klystron at C-band was designed and fabricated (named Toshiba E3746).

1 INTRODUCTION

The e^+e^- linear collider is a large scale machine. In the main linacs for 500 GeV C.M. stage, we use more than 8000 accelerating structures, 4000 klystrons and pulse modulators. Therefore, the system must meet the following demands.

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

Above list provides main guide-line and boundary conditions to our design work. Among the design parameters, the choice of the drive rf frequency plays most important role concerning the total system performance as well as the hardware details. We proposed C-band as the best frequency[1]. Reasons are

(1) Fabrication tolerance of the accelerating structure is not so tight. The straightness tolerance is 30 µm for 1.8 m long structure.

(2) RF pulse length to be generated from a klystron is about 2.5~3.0 µsec. HV pulse power supply for the klystron is easy to generate this pulse length, and we can use a conventional line-type modulator.

(3) Klystron can be made as an extension of existing S-band klystrons.

The item (3) will be discussed in the next section in detail.

2 CHOICE OF MAIN PARAMETER

To do optimum design of a high-power klystron, we scaled operating parameters of the existing S-band klystrons to the C-band frequency. Generally speaking, design of the high-power klystron becomes harder at higher frequency bands, and its power rating becomes lower. C-band frequency is twice higher than S-band, thus we have to limit the design target of the output power lower than the existing S-band tubes. To keep the same level of tube reliability or even better, we laid two boundaries.

(1) Gun Voltage

Use the same level or even lower gun voltage than the most reliable klystrons at S-band. We believe that in the pulsed power klystrons, possibility of HV breakdown in gun region, or idler cavities and the output gap, is a sensitive function of the beam voltage. From the experience on Toshiba E3712-klystron (80 MW, 375 kV), or SLAC 5045-klystron (50 MW, 350 kV), we chose the gun voltage around 350 kV.

Lower voltage design needs higher beam current. The power conversion efficiency tends to be lower in a higher beam current klystron due to the space charge force acting on bunch. We took the reliability issue as the first priority than the power efficiency in our design.

(2) Beam energy per pulse ($VI\tau$)

From a view point of the power handling in a tube, it is reasonable to limit the total beam injection energy lower than a certain amount. If a part of the high power beam collides to the drift-tube wall or an interaction gap, and the power density is high enough, the copper material can be melted or vaporized, it resulting in HV breakdown in the output gap or other high-field regions. Since the drift tube diameter scales as inverse of the rf frequency, the $VI\tau$ energy scaling becomes

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

From the operational experience in S-band klystrons, we found the safety value for C-band klystron as 300~400 J/pulse. The HV pulse length to be applied is 3.5 µsec, and the power efficiency is 45 %, the safety level of the peak power at C-band becomes 50 MW.

Table-1 shows the design parameter and target performance.

Table-1. Main Parameter of E3746 klystron.

Parameter		Unit
Frequency	5712	MHz
Output Power	50	MW
Beam Voltage	350	kV
Beam Current	317	A
Microperveance	1.5	$A/V^{1.5}$
Gain	> 50	dB
RF Pulse Width	Max. 3	µsec
Pulse Repetition	100	pps

3. ELECTRON GUN

To maintain a long lifetime, it is better to keep the maximum loading of the cathode emission lower than 10 A/cm^2. Assuming the power conversion efficiency as 45 %, and gun voltage 350 kV, the required beam current becomes 320 A. Therefore, the minimum required cathode area is 32 cm^2, or a diameter of 64 mm. We use a cathode diameter of 74.5 mm, then the average cathode loading becomes a quite safe value of 6.3 A/cm^2.

Using the computer simulation code EGUN, the gun geometry was optimized to obtain a laminar flow with desired beam envelop.

The designed parameters are listed in Table-2. The maximum electric field is 22.1 kV/mm, which is same level as that in S-band klystrons such as the SLAC 5045 or Toshiba E3712.

In order to eliminate a diode oscillation associated with a high-Q resonance in the small gap around the cathode element[2], we made the volume of the cylindrical pocket as small as possible.

Table-2 Electron Gun Parameter

Parameter		unit
Microperveance	1.5	μA/V$^{1.5}$
Cathode Diameter	74.5	mm
Cathode Loading (average)	6.3	A/cm^2
Type of Cathode	Dispenser Scandate	
Focused Beam Diameter	10	mm
Beam Area Convergence	56:1	
Electric Field on Anode	22.1	kV/mm
on Whenelt	21.7	kV/mm

4. DRIFT-TUBE AND BEAM FOCUSING

Larger size of the drift-tube makes the electron gun design easier and focusing field lower, but it makes danger against spurious oscillation due to positive feedback loop driven by propagating or trapped mode inside the drift-tube. To chose the drift-tube diameter, we basically scaled from S-band tube.

Table-3 summarizes the drift-tube parameter. We use 15 mm diameter at upstream and 16.3 mm at downstream. The Bessel function $J_0(ka)$ value is close to 1.0, which means the interaction gap can keep good coupling to the beam[3].

As listed in the table, the TE11 cutoff frequency at downstream is lower than the operating frequency. In principle, TE11 mode does not interact with a beam in a smooth beam pipe, but it can create a small coupling impedance at a transition of beam pipe or an interaction gap, which sometimes causes a parasitic oscillation in a high current klystron. To avoid this type of oscillation, an rf damper (a small piece of stainless-steel pipe) was inserted at the beam pipe transition taper.

This klystron uses a solenoid focusing. The perfect Brillouin field is 1.13 kG to focus the beam of 10 mm diameter. To maintain beam stability we apply 2.6 kG maximum at upstream, and 2.4 kG at downstream.

Table-3 Drift-tube and Focusing Parameter

Parameter		1st~3rd cavity	4th~5th cavity	
Drift Diameter	2a	15	16.3	mm
Beam Diameter	2Rb	10	10*	mm
Wave Number	ka	0.90	0.97	
Bessel Function	J0(ka)	0.81	0.78	
Cutoff Frequency	TE11	5.86	5.39	GHz
	TM01	7.65	7.04	GHz
	TM11	12.2	11.22	GHz
Brillouin Field	Bz	1.13		kG
Focusing Field	Bz	2.6	2.4	kG

5. INTERACTION CAVITIES AND BEAM SIMULATION

E3746 is a five cavity klystron: the input, 2 gain cavities, the penultimate and the output cavity, whose parameters are listed in Table-4. To optimized those parameters, we used FCI (Field Charge Interaction 2+1/2 PIC code). Example result of the simulation is shown in Fig. 1. FCI said the expected output power is 49.1 MW and the power efficiency is 44.3 %.

Table-4 Interaction Cavities

	Type	Frequency (MHz)	Q	R/Q (Ω)
Input	Reentrant	5712	350	67.3
2nd	Reentrant	5725	2000	62.5
3rd	Nose-less[3]	5738	2000	57
4th	Nose-less	5847	2000	64.2
Output	Nose-less	5712	27.5	79

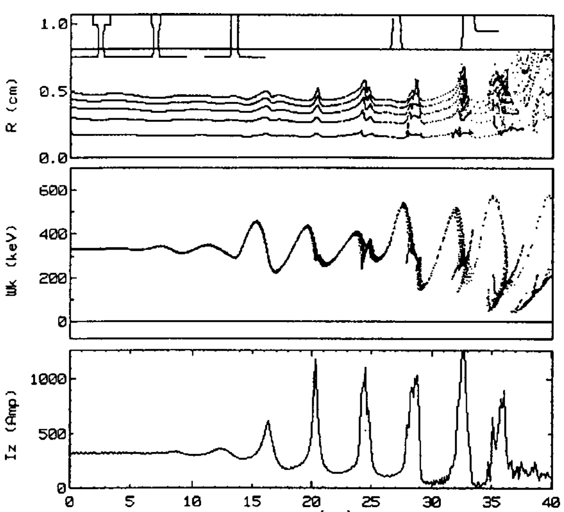

Fig. 2 FCI simulation result (Beam Voltage = 350 kV, Beam Current = 317 A, Drive Power = 250 W, Output Power = 49.1 MW, Power Efficiency = 44.3 %).

6. OUTPUT GAP

6.1 Output Gap Impedance

The output gap extracts the rf power from the beam, as a reaction the beam is decelerated by the rf field. To make the power efficiency maximum, we need to design the output gap at the impedance matching condition. From the equivalent circuit analysis, the optimum impedance is given by

$$Z_{opt} = (R/Q)Q_L = \frac{V_c}{MI_{\omega 1}} = \frac{V_{deceleration}}{M^2 I_{\omega 1}} \qquad (1)$$

$V_{deceleration}$ is the beam deceleration voltage, which is usually close to the beam voltage: $V_{deceleration} = 0.8 \sim 0.9 V_{DC}$. $I_{\omega 1}$ is the rf current on the beam, which takes 1.5 or higher value right before the output gap, and it decays inside the output gap. As an average, we assume $I_{\omega 1} = 1.1 \sim 1.3 \cdot I_{DC}$. M is the coupling constant, in our case $M = 0.62$. From eq. (1), the optimum impedance becomes 1.7 ~ 2.3 kΩ. Togather with the FCI simulation, we decided the impedance at 2.2 kΩ.

6.2 Output Structure Design

Figure 2 shows the output structure, which has two output arms, they are combined again at the external circuit after two ceramic rf-windows. The rf-window is so called the traveling-wave type, newly developed as a part of C-band waveguide R&D[4].

The external-Q was determined by the Slater's method on the MAFIA 3D simulation, and the iris size was decided to meet the desired value. According to the *R/Q* calculation, there is always some ambiguity in estimating the stored energy in the cavity, because some field leaks into the waveguide, and we can not clearly define the cavity volume. We solved this problem by recognizing the total system of the output cavity and waveguide as a coupled cavity system. It has 0- and π-modes according to those phase. We calculate the shunt impedance in each mode. According to the coupled cavity model, the intrinsic shunt impedance of the gap is simply given by

$$(R/Q)_{cav} = (R/Q)_{0-\mathrm{mode}} + (R/Q)_{\pi-\mathrm{mode}}.$$

Using this method, the shunt impedance was determined to be 79 Ω, then the cavity impedance becomes 2.18 kΩ.

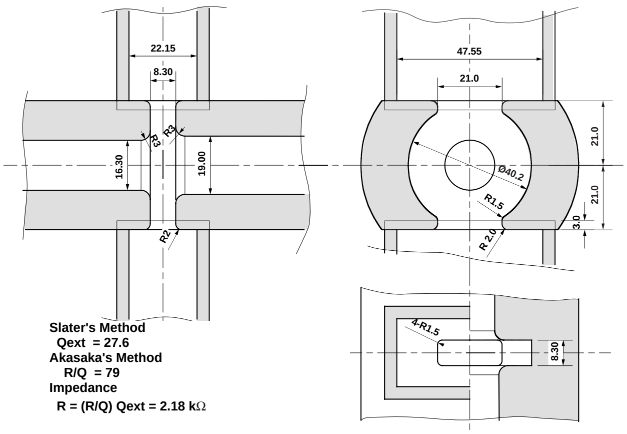

Fig. 2 Output Structure.

7 HIGH POWER TEST AND FUTURE R&D

The high power test is scheduled in June 1997. For the next step, we will try to replace the output cavity by a 3-cell traveling wave output structure[5], in which the field gradient becomes almost half of the single gap design. Additionally, we use the Choke-Mode Cavity[6] in the traveling-wave output structure to damp all of the higher order modes.

7 ACKNOWLEDGMENTS

The authors would like to acknowledge the supports of Prof. Hirotaka Sugawasa, Prof. Yoshitaka Kimura and Prof. Yoshishige Yamazaki to the C-band R&D project.

REFERENCES

[1] T. Shintake et. al., "C-band RF Main Linac System for e^+e^- Linear Collider at 500 GeV to 1 TeV C.M. Energy", Proc. of EPAC96, pp.492-494.
[2] U. Becker et. al., "Simulation of Scillation in High Power Klystrons", Proc. of EPAC96, pp.1274-1276.
[3] T. Shihtake, "Nose-Cone Removed Pillbox Cavity for High-Power Klystron Amplifiers", IEEE Trans. Electron Devices, Vol.38, No.4, April 1991
[4] H. Matsumoto et. al., "Development of C-band (5712MHz) High Power Waveguide Components", contributed to this conference.
[5] T. Shintake, "Recent Status of FCI: PIC Simulation of Coupled-Cavity Structure", Proc. of Linac96, pp.181-183
[6] T. Shintake, "The Choke Mode Cavity", Jpn. J. Appl. Phys. Vol. 31(1992) pp. L1567-L1570