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STATUS OF X-BAND POWER SOURCE DEVELOPMENT FOR JLC

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Abstract

The main X-band linac consists of klystrons, modulators, DLDS pulse compression/delivery systems, and RF accelerating structures. The periodic permanent magnet (PPM) klystrons are under development in the two-year/two-stage project with Toshiba. The goal is to produce 50MW output power at 1.5 μs pulse length at the first klystron and then to advance to 75MW at the second one. The first PPM klystron has been tested, and it achieved 56MW power with 50% efficiency at 1.5 μs pulse length. The second PPM klystron is currently under testing. Up to date (June 6,2001), the klystron already produced 73.2MW at 500 kV at the 1.4 μs pulse length. The maximum efficiency reached 56% at the specified cathode voltage. As for the modulator, KEK is now developing a new IGBT (Insulated Gate Bipolar Transistor) modulator as a two-year project. Two prototypes, with three and ten stages of modules for 6kV and for 20kV output pulse each, were built and tested successfully. KEK is developing the multi-mode 2x2 DLDS (Delay Line Distribution System) power distribution system. For the study the stability of propagation modes on a delay line and for the measurement of their transmission losses, joint experiments with SLAC and BINP were performed at KEK on a 55 m long waveguide assembled in the ATF linac. The experiments showed the best combination of two modes to be TE_{01} and TE_{02} modes. The design of all RF components for the TE_{01}/TE_{02} 2x2 DLDS was completed and their cold models will be tested soon. Details of these developments and measurement results are presented.

1 PPM KLYSTRON

The 1-TeV JLC (Japan e^+e^- Linear Collider) project [1] requires about 3200 (/linac) klystrons operating at 75 MW output power with 1.5 μs pulse length. Periodic Permanent Magnet (PPM) klystrons are being developed to eliminate the expense and power requirements of the focusing solenoids. KEK has begun a two-year project with Toshiba to produce two PPM klystrons in two stages [2]. The design parameters of those klystrons are shown in Table 1. The main emphasis of the KEK PPM-1 klystron is to test a new gun design and to study the design and manufacturing of the PPM circuit. The damping structure of parasitic modes was adapted by using the stainless steel beam pipes and the Monel cavities, and by tilting the output couplers slightly to break the symmetry in the output cavity to damp TE_{01} modes. The beam size is tuneable between 2.3 mm and 3.3 mm by changing a combination of the bucking coil and matching coil currents. A critical issue for klystron performance is the actual dimension of the gun at operating temperature (so-called hot dimension). The PPM-1 hot dimension was estimated by the thermal code ANSYS (see Fig. 1). An actual measurement was conducted using a anode-like test fixture and a laser beam, showing a good agreement with the ANSYS calculation within 100μm. Prototyping of the 4.5 period (13.5cm long) PPM circuit and the fabrication of this PPM circuit established the quality control method on the magnet pieces of 0.5%.

Table1: Main parameters of the KEK PPM-1 and PPM-2 klystrons.

	PPM-1	PPM-2
Peak power (MW)	>50	75
Beam voltage (kV)	480 - 500	480 - 500
Micro-perveance	0.8	0.8
Efficiency (%)	>50	55
Pulse length (μs)	1.5	1.5
Repetition rate (pps)	50	150
Bandwidth (MHz)	80 at -1 dB	80 at -1 dB
Cooling of PPM	Air	Water

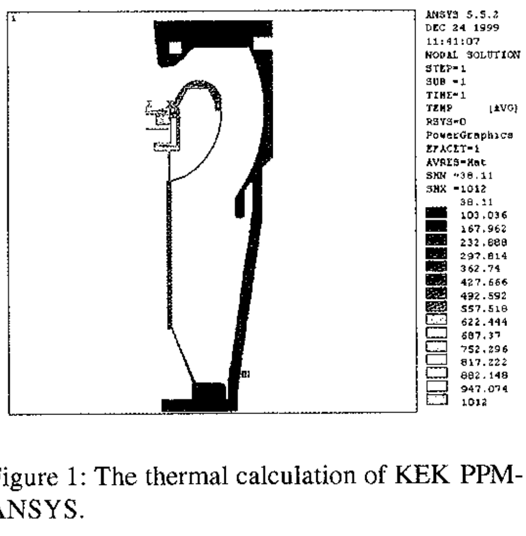

Figure 1: The thermal calculation of KEK PPM-1 gun by ANSYS.

Figure 2 shows the KEK PPM-1 klystron before mounted on the test bench. The high power testing of the PPM-1 klystron was started in July 2000. Figure 3 shows the output power and the efficiency as a function of the cathode voltage. It achieved the output power of 68MW at 514kV cathode voltage with the corresponding efficiency of 47%. It also produced 56MW power with standard 1.5

μs pulse length. Neither oscillation of parasitic mode nor gun oscillation was observed. The particle transmission was found to be 100% when no RF signal is applied. The perveance agrees well with the design within 1.5 %.

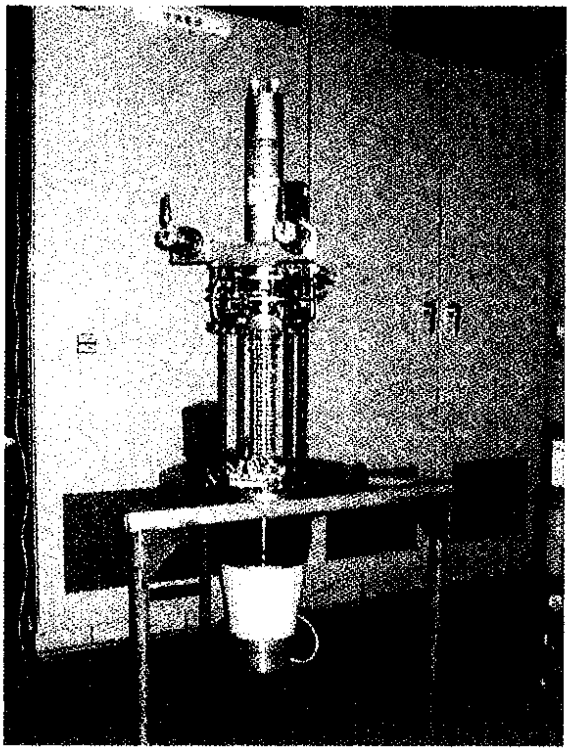

Figure 2: Photo of KEK PPM-1 klystron.

The gain cavities were mistakenly fabricated at wrong frequencies by the manufacture. It was expected to cost 2-3% on the efficiency. PPM-1 klystron was sent back to the manufacture to apply the following corrections; (1) replacement of the gain cavities by the ones with correct frequencies (2) fine tuning of the output cavity fundamental frequency to a value closer to the design (3) replacement of the RF windows by the more robust Kazakov windows for a better high-power capability. PPM-1 was returned to KEK as PPM-1.5 and testing was resumed from February 2001 and is still under way. Now, the efficiency was increased to near 50% at 470-500kV region as shown in Fig.3. The performances of PPM-1 and PPM-1.5 are tabulated in Table 2.

Table 2: Performances of the PPM-1 and PPM-1.5 klystrons.

	PPM-1	PPM-1.5
Peak power tested (MW)	68	67.5
Efficiency (%)	47%	49.6
Pulse length (μs)	1.5 (at 56MW)	
Micro-perveance	0.79	

The second PPM klystron has been delivered and is now under high-power testing. This klystron incorporates

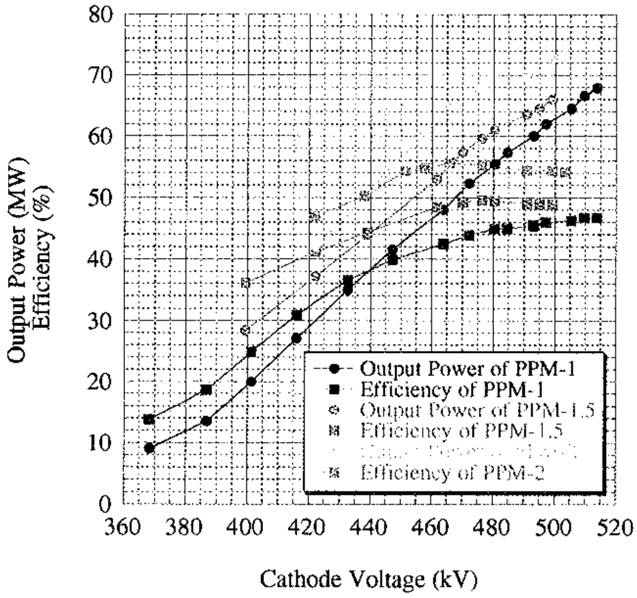

Figure 3: Output power and efficiency vs. cathode voltage at PPM-1, PPM-1.5 and PPM-2 klystrons

experience and knowledge gained from the design and testing of PPM-1. The main emphases of the PPM-2 klystron are full satisfaction of JLC specifications and refinement of the design and manufacturing process for future mass production. To meet these goals, the PPM-2 introduced the water-cooling system of the PPM klystron body and the PPM circuit. At the same time, the water-cooling system of the output cavity was improved for a higher repetition rate. Some revisions of resonant frequency of the penultimate cavity and design of the output coupler were also applied for a higher efficiency. Up to date (June 6,2001), the klystron already produced 73.2MW at 500 kV at the 1.4 μs pulse length. Oscilloscope traces are shown in Fig. 4. The maximum efficiency reached 56% at the specified cathode voltage. The performance of PPM-2 klystron up to date is tabulated in Table 3. The high-power testing will be continued to attain 75MW output power with the standard 1.5 μs pulse.

Table 3: Latest measurement results of performance of the PPM-2 klystron (June 6, 2001)

	Design	Achieved
Peak power (MW)	75	75.1
Efficiency (%)	55	56
Pulse length (μs)	1.5	1.5 (@70MW) 1.4 (@73.2MW)
Micro-perveance	0.8	0.79
Repetition rate (pps)	150	25

Following the success of those two klystrons, the development plan is now expanded to the coming two years. In FY 2001, we will build the PPM-3 klystron; this klystron has an even higher efficiency of 60% by installing two 2nd-harmonic cavities to increase the beam bunching. A small revision of the output cavity shape realises a lower (70MV/m) surface electric field there for an improved reliability. The PPM-4 klystron to be built in FY 2002 is a mass production version. For this end, the design of a clamp-on magnet system is under way.

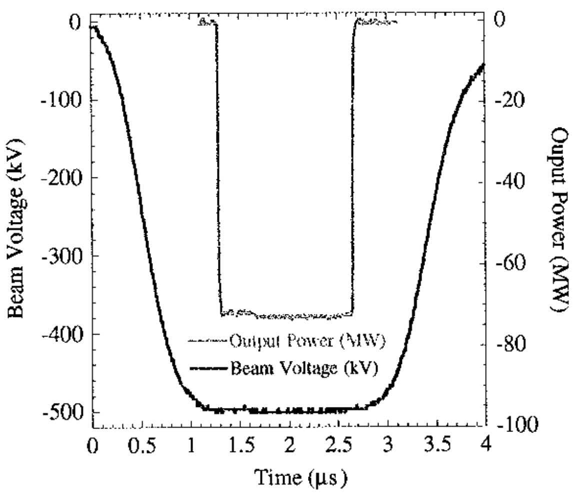

Figure 4: Oscilloscope traces of the output power and beam voltage of PPM-2 klystron for 73.2MW output power at the 1.4 μs pulse length with 54% efficiency.

2 DLDS PULSE COMPRESSION AND DISTRIBUTION SYSTEM

In the simplest DLDS (Delay Line Distribution System), illustrated in Fig.5, the RF power from two klystrons with independent phasing is combined through a 3-dB coupler. One output port of the 3-dB hybrid is connected, through low-loss waveguide, to a linac feed about one half of the compressed pulse width times the speed of light upstream of the klystrons; the other port is connected to a local feed. The first half of the input RF pulse, of duration equal to the sum of the structure fills time and the bunch train time, is sent to the upstream feed through the delay. The second half of the RF pulse is fed into the linac close to the klystrons, without delay [3].

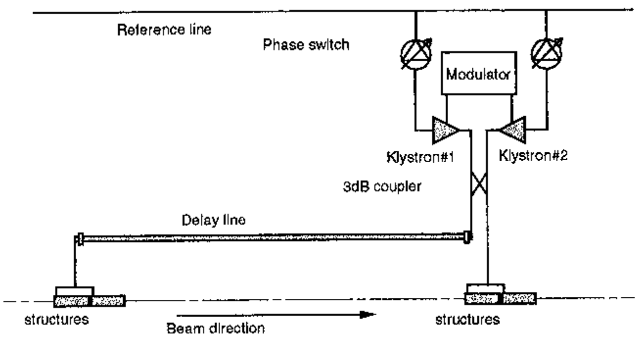

Figure 5: A schematic diagram of the simplest factor-2 DLDS.

The largest drawback of the original (single mode) DLDS is that it requires long waveguides: the maximum of 17 waveguides runs together inside the linac tunnel. A conceptual improvement was proposed by SLAC to further reduce the length of waveguide system by multiplexing several low-loss RF modes in a same

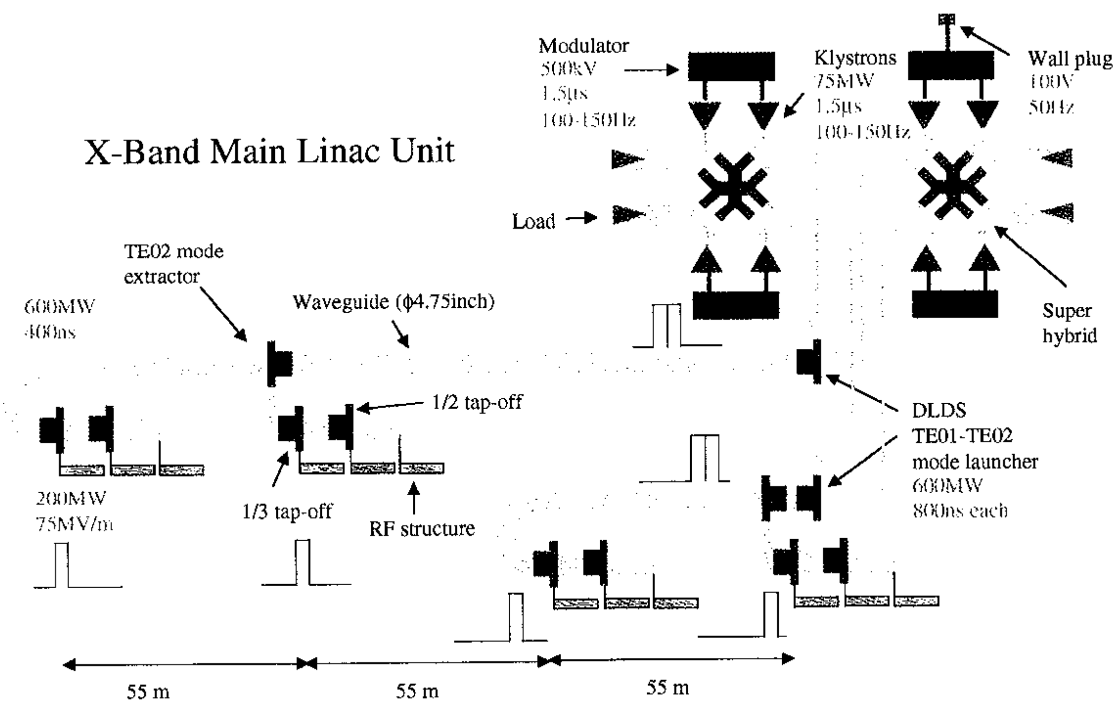

Figure 6: Schematic view of TE_{01}/TE_{02} 2x2 DLDS

waveguide. Thus, the sub-pulses in the distribution waveguide are carried by different waveguide modes so that they can be extracted at designated locations according to their mode patterns. Taking advantage of both the single mode and the multi-mode DLDS, a 2x2 DLDS was proposed at KEK to deliver RF power to four RF clusters [4]. Its scheme is illustrated in Fig.6. It consists of almost identical dual mode DLDS systems with long and short waveguide. Only two modes (TE_{01} and TE_{02} /or TE_{12}) are used in each waveguide to minimise the complication caused by handling of multi-modes in one waveguide, while still providing some of the benefit of multi-mode operation by considerably reducing the total length of waveguide. The advantages of 2x2 DLDS can be summarised as (1) Cost saving: It reduces the total length of waveguide to 2/3 of single mode DLDS. (2) High efficiency: The power loss is about 30% smaller than the SLAC 3+1 DLDS. (3) High expandability: It can be easily expanded to feed up to 5-7 RF clusters. The last advantage is truly beneficial for cutting the construction cost of LC if a long RF pulse (2-3 ms) is available from klystrons in the future.

To demonstrate the fundamental principle of the 2x2 DLDS, a cold model of the dual mode DLDS basic unit (almost identical to the system with the shorter waveguide manufactured and tested at KEK. The testing results proved that it was plausible to deliver power at different places using different modes with good efficiency (better than 95%) [5].

In the initial design of the 2x2 DLDS, the TE_{01} and TE_{12} modes were chosen to be the propagation modes due to their theoretically small surface losses (smallest among all modes) on a round pipe. The critical issues in this scheme were the stability of linearly polarised TE_{12} mode and the actual loss in a long waveguide against the imperfection of the pipe shape and the surface condition due to the fabrication error, pumping slots, flanges, etc. Meantime, the TE_{02} mode was conceived as an alternative choice against TE_{12} mode due to its small loss (3rd smallest) and less sensitivity to the pipe imperfection (no electric field at the surface of the pipe). This allows a looser tolerance for the pipe fabrication and the insertion of expansion joints (to absorb the thermal expansion of the pipe) without increasing the transmission loss too much. Joint experiments with SLAC and BINP were performed at KEK on a delay line assembled in the ATF linac tunnel [6]. The typical set-up is illustrated in Fig. 7.

The transport line in these experiments was composed of eleven sections of a circular waveguide with a diameter of 12.065 cm. Each section was five meters long, for a total length of 55 meters. The sections were connected using either a choked flange or conflat flange. The mode analyser was installed at the end of the line to measure mode conversion due to this highly over-moded waveguide (102 modes can propagate in this guide.). The main findings of the experiments are;

1. The rotation of the TE_{12} mode is smaller than 1 degree. Furthermore, the level of the circularly polarised component in both cases is very small. Hence one can conclude that there is no significant mode cross polarisation mixing.
2. The mode contamination in all modes is well below -20 dB before and after the transport line.
3. The power transmission losses over the 55m long pipe are approximately

TE_{01}	2% (theory: 1.7%)
TE_{02}	4% (theory: 3.2%)
TE_{12}	6% (theory: 2.5%)

As for the discrepancies between the theoretical losses and the measured ones, one can only conjecture that there are additional losses due to conversion to some TM modes, which were not measured by our mode analyser.

From these experiments, one can conclude that all the modes are well stable and their transmission losses are within tolerances. But, TE_{01} and TE_{02} modes are the best choices in terms of low loss, less sensitivity to the pipe imperfection and the simplicity of the system. KEK is now pursuing the TE_{01}/TE_{02} 2x2 DLDS scheme and we completed the design of all RF components. Their cold models will be tested soon.

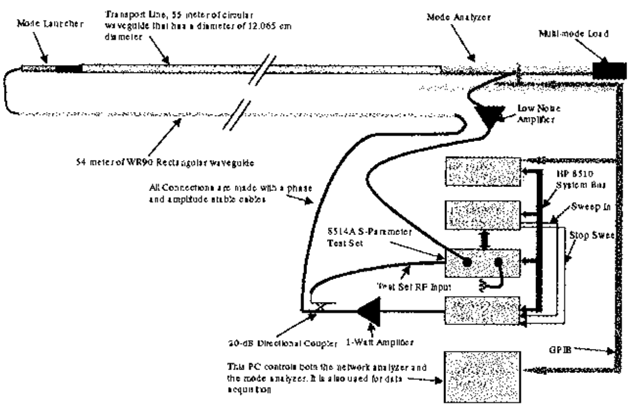

Figure 7: Experimental setup for the mode transmission experiments.

3 MODULATOR

To improve the reliability of the modulator, KEK is now developing a new IGBT (Insulated Gate Bipolar Transistor) modulator as a two-year project. The main specifications of this modulator are tabulated in Table 4. The IGBT is another solid-state switch and is mainly used in trains. The IGBT typically operates at 2.5kV and switches up to 3000A. Thus, it cannot replace a thyratron as a single device and needs to be stacked. The IGBT modulator diagram is illustrated in Fig. 8. It consists of a DC power supply, four modules of switching unit at 25kV, a pulse transformer with a ratio of 1:5, and a waveform compensation circuit. Each module contains 10 stacks of energy storage capacitors, IGBT switches and IGBT gate drivers, and it produces 25kV voltage in total. The four modules are connected in a series-parallel arrangement and turns on into the primary of a pulse transformer to produce 500kV-output pulse at 530A with a flattop width of 1.5μs. The individual IGBT has its own gate driver, which can control the output waveform to an arbitrary form. The diode network allows the isolation of faulted klystron load and protects the IGBT circuits from an over-current. Two prototypes of the modules, with three and ten stages for 6kV and 20kV output pulse each, were built and tested. The three-stage prototype of switching module is shown in Fig. 9. Figure 10 shows the measured voltage waveform. The waveform can be made flatter by using a waveform compensation circuit. The entire system at full specifications with the waveform compensation circuit and the over-current protection circuit will be built and tested in spring 2001.

Table 4: The main specifications of this modulator.

Number of klystrons per modulator	2
Peak klystron voltage	500 kV
Total peak current	530 A
Pulse width	1.5 μs
Pulse top flatness	2 %
Energy efficiency	70 %
Repetition rate	100 Hz

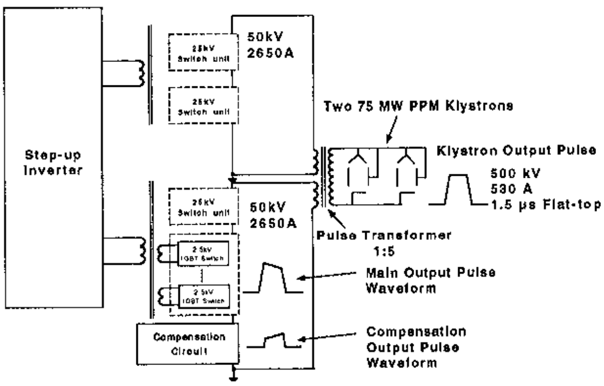

Figure 8: Diagram of the IGBT modulator.

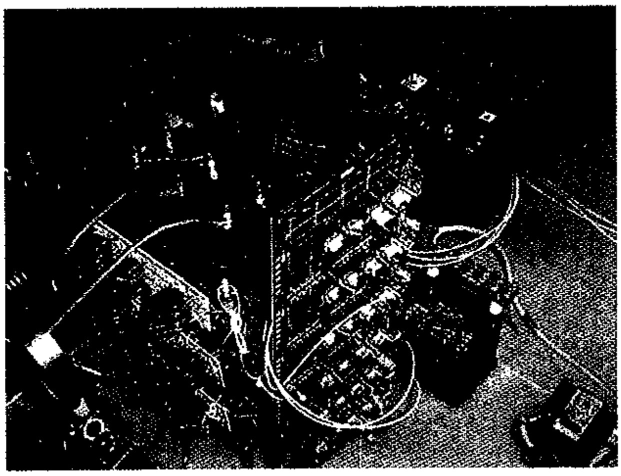

Figure 9: The three-stage prototype of switching module.

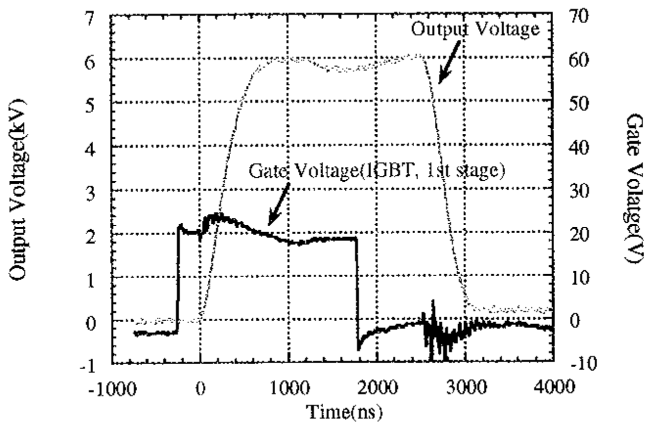

Figure 10: Output voltage waveform of the three-stage prototype module.

REFERENCES

[1] "JLC Design Report Study", KEK Report 97-1, 1997.
[2] Y. H. Chin et. al., "Development of the X-Band RF Power Source for JLC", in Proc. of PAC99, 1999, p.3414.
[3] "International Study Group Progress Report on Linear Collider Development", KEK Report 2000-7, SLAC R-559, 2000.
[4] Y. H. Chin et. al., "Status of the X-Band RF Power Source Development for JLC", in Proc. of EPAC2000, 2000, p.456.
[5] J.Q. Wang, Y.H. Chin , et. al., " Study of RF Components for JLC 2x2 DLDS" in Proc. of PAC99, 1999, P.1058.
[6] S. Tantawi, et. al., "Evaluation of the TE(12) Mode in Circular Waveguide for Low-Loss, High-Power RF Transmission", Phys. Rev. ST Accel. Beams 3: 082001, 2000.