Design of Multi-Beam Klystron in X-Band

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Abstract

Design study of an X-band multi-beam klystron was started to pursuit its feasibility as the power sources of JLC (Japan Linear Collider) main linacs. The gun design together with PPM (Periodic Permanent Magnets) focusing system (which is common for all beamlets) has been done. The RF design and klystron simulation based on annular cavities operating with HOM (Higher Order Mode) has also been done. Discussion on the possibility of 150MW klystron is made.

1 WHY MULTIPLE BEAM?

Japan Linear Collider (JLC) Project [1] is planed to use X-band (11.42GHz) 75MW pulsed klystrons (pulse length 1.5μs) as the power source of its main linacs. The required parameters for a JLC klystron are shown in Table 1 below. Recent R&D work on JLC klystron has been devoted to the design and building a PPM (Periodic Permanent Magnets) focused klystron. Its prototypes have shown very good performance [2].

The combination of high cathode voltage (480kV) and low perveance (0.8μK) has been chosen for the JLC klystron specification, where the klystron is supposed to use a single beam carrying whole beam power (130MW).

One of the issues of JLC klystron is its high cathode voltage. The high voltage may have an impact on the lifetime of the system and may degrade its reliability. Another is the high energy density of the klystron beam (radius 3mm). A rather strong focusing system is necessary to stabilize the beam. The output RF circuit is a multi-cell cavity to handle large RF power from the beam as well as to make the surface field practical.

Table 1: JLC klystron specifications

Frequency	11.424 GHz
Power	75 MW
Pulse width	1. 5 μ s
Repetition	150 Hz
Cathode Voltage	480 kV
Perveance	0. 8 μ K
Efficiency	55%

A multi-beam klystron (MBK) [3] can be another solution to JLC klystron. MBK uses a bundle of small perveance *beamlets*. Although each beamlet carries small amount of current, the total current can be large. As a result, we can choose moderate cathode voltage for MBK. The power density of beamlet can be low due to small current and low voltage.

An MBK has these advantages to a conventional (single beam) klystron. We have looked for a realistic design of MBK operable in X-band to meet with JLC klystron specifications.

2 DESIGN OUTLINE

A pilot design study was started first to see the feasibility of 75MW MBK operable in X-band, which is completely compatible to the prototype klystrons. We found that this kind of device was possible to design. Some detail design of the focusing system and cavity design were done in this study. Right after the study, we began to consider the possibility of double-powered 150MW MBK by an extrapolation.

The design parameters of the 150MW MBK and of the JLC prototype klystrons are compared in Table 2 below. Six (identical) beamlets are used in the MBK. The perveance of each beamlet and the cathode voltage are chosen to be 0.6μK and 340kV. The power of the individual beamlet is 43MW. If the efficiency is 60%, which is reasonable for 0.6μK beam, each beamlet produces the RF power of 25MW and the total output power will be 150MW.

Table 2: klystron parameters

	MBK	**JLC prototype**
Cathode Voltage (kV)	340	480
Beam(let) cuurent (A)	750 (125)	266
Perveance (μK)	3.6 (0.6)	0.8
Number of beam(lets)	6	1
Output Power (MW)	150	75
Efficiency (%)	>50	55

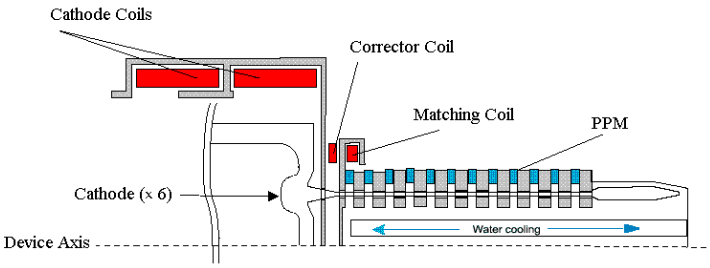

Fig 1: schematic view of the device (diode).

The schematic view of the MBK is given in Fig.1. Each beamlet runs in its own drift tube. The drift tubes are in parallel to each other and distributed in hexagonal way (separated by 75mm with each other) around the device axis.

3 GUN AND FOCUSING SYSTEM DESIGN

The parameter of beamlet gun is given in Table 3. The criterion on the maximum surface field on electrode is that it should be smaller than that of prototype JLC klystron. No trouble has been found in the guns of prototype klystrons during their operation.

Table 3: Gun parameters

Cathode Current	125A @ 340kV
Cathode Diameter	38mm
Cathode Load	< 12 A/cm^2
Surface E max	260 kV/cm
Cathode Voltage	480 kV
Cathode B Field (Beam Radius)	10 – 30 Gs (2 – 2.5 mm)

The focusing system consists of both permanent and electric magnets as shown in Fig.1. Here is a list of their role:

- The main focusing is provided by *PPM* (Periodic Permanent Magnet). The PPM focusing system common for all beamlets.
- The *cathode coils* produce a uniform magnetic field on the whole cathodes. The cathode field controls the beamlet size (cross-sectional) in the drift tube (see Table 3 above).
- The *matching coil* is installed for the good beam transportation from the gun to the PPM focused region.
- The *corrector coil* produces a local transverse B field there to compensate the magnetic interaction between the beamlets occurred in the gun region. The magnetic flux around one beamlet can exert on the others in the gun region.

None of the beamlets is on the device axis. Therefore, there should be the transverse field along the axis (trajectory) of beamlets unless we eliminate it explicitly. Generally speaking, the transverse field affects the beam transmission and/or gives potential danger for a parasitic oscillation.

The magnet screens are necessary at various places to suppress the transverse field near the beamlet trajectory to *restore the local cylindrical symmetry of the field*. This work has been done. This is a trade-off for the use of common focusing system for all multiple beam.

3 RF DESIGN

Let us discuss the cavity structure of the MBK driven by all the beamlets. Note that the wavelength of the operation frequency is 26mm (in free space) while the trajectories of the beamlets are separated by 75mm, which is much larger than the wavelength. Therefore the cavities installed in the MBK cannot be a simple pill-box cavity operated in its fundamental mode, found in most of the klystrons.

We employ an annular cavity structure instead, which is schematically shown in Fig. 2. The E field of TM*mn0* mode in the cavity (without the beam holes) is

$$Ez(r,\phi,t)=e^{j\omega t}\cos(m\phi)\,[\,J_m(k_c r)+N_m(k_c r)\,] \quad (1)$$

where J_m and N_m are the Bessel function of order m. The radial wave number k_c is determined by the boundary condition on the cavity wall. We use m=12, n=1 mode since the neighbors (m=11 and m=13) locate far away (±350MHz). The cavity should be free from mode contamination form them.

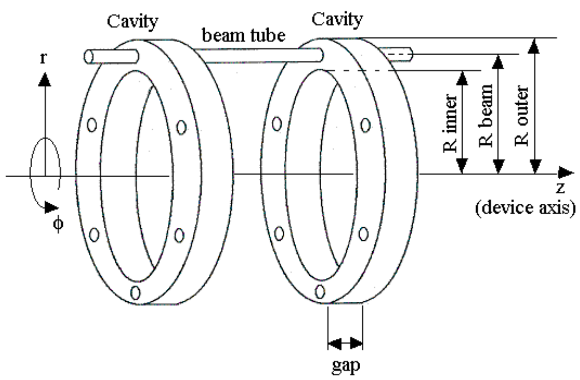

Fig 2: schematic view of the annular cavity.

For $TM_{12,\,1,\,0}$ of 11.42GHz, *R*_outer and *R*_inner in Fig.2 are found to be 84 and 66mm. The width of the cavity is thus 18mm, which is large enough compared to the diameter of the beam hole, 8mm. The local Ez field near the beamlet trajectory has good cylindrical symmetry around the beam axis.

For a 8mm-gap cavity, the shunt impedance is 60kOhms and Q=8500. The R/Q value for a single beamlet is a few Ohms, which is much lower than that in the prototype klystrons (installs pill-box cavities, typically 100 Ohms).

The degenerated mode, which represented by a simple replacement of the cosine function into sine in Eq. (1), is potentially dangerous since it has its B max at the location of the beam holes and it deflects the beam. However, the mode frequency is naturally detuned by the introduction of the beam holes. A 3D calculation shows the detuning is a few hundreds MHz. The detuning should be enough the mode not to be excited.

4 KLYSTRON SIMULATION

We design the MBK with all the cavities being annular. 1D simulation of each beamlet motion is eligible if we are allowed to assume (1) All the beamlet are identical and (2) The local field near the beamlet inside the annular cavity looks like the field in an ordinary klystron cavity. 1D simulation of each beamlet is possible by a proper modelling of Ez field on the beam axis and a redefinition of the cavity parameters in the code.

We found that we needed at least 7 cavities to get enough gain in our 1D simulation study. This is due to low R/Q of the annular cavity, which indicates the interaction between the cavity and the beamlet is weak. By the same reason, we found that a single annular cavity does not work efficiently as the output cavity. However, if we use a double gap output cavity structure as shown in Fig. 3, we found that we could improve the efficiency (as well as to reduce the maximum surface field in the cavity).

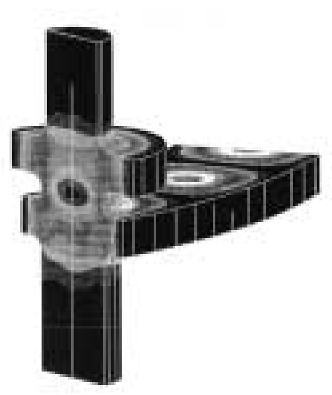

Fig 3: A double-gap output cavity. (1/12 segment.)

In order to simulate the single beamlet motion by 2D code, we introduce an *equivalent cavity* to model the interaction between the beamlet and the annular cavity structure. The equivalent cavity is a pill-box cavity and has the same gap field as the actual field in the annular cavity. The resonant frequency, R/Q and Q values of the equivalent cavity are matched to those of the annular cavity. The actual focusing magnetic field has good axial symmetry with respect to the beamlet axis. The field is recalculated and reproduced by a 2D magnetic code.

In 2D simulation, we found that the aperture of the beam pipe at output region has to be large. The results are summarized in Table 4. The single-gap and double-gap output cavity are compared in the table.

The equivalent cavity works correctly for the operating mode. However, it does not for the other modes in the annular cavity. Their resonant frequencies are known (even analytically known for the cavity without beam holes). In fact, the frequencies are well detuned and we conclude that they will not give rise to a problem immediately.

There remains some important problems: One of them is that the effects induced by an unbalance in the beamlets (their current or phase). This is really a 3D problem. We have no answer yet. The other issue is the way to extract the power from the tube. We did not design the output port connected to the waveguide(s).

Table 4: Simulation results

	Single gap	**Double gap**
Cathode voltage	340 kV	
Beamlet current	125 A	
Input RF power / Gain	134 W/ 60 dB	
Bandwidth	40 MHz	
Efficiency	50 %	55 %
Emax_surface (kV/cm)	910	720
Beamlet tube diameter	8mm	
Tube diameter @ output cavity Upstream / Downstream	10 mm / 12.8mm	
Length from Input to Output cavity	459 mm	

4 CONCLUSION

Our design study thus far shows that the key parameters, such as the maximum field strength, can be moderate and look realistic. The designed performance is fairly good. We have got 55% efficiency, which means we get 150MW at 360kV cathode voltage. We conclude that an MBK of 150MW in X-Band is a realizable device.

If 150MW MBK is realized, we can reduce the number of klystrons by half in JLC main linacs. Even a 75MW MBK has a merit, since this MBK requires *the lowest* cathode voltage (260kV) among the klystrons that we considered here. Although the MBK itself is a rather complicate device (multiple cathodes, multiple beam tubes, multiple collectors, a complicated focusing system, so on), we believe that the low voltage is good for the reliablility and/or the lifetime of the system and can make the system compact.

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REFERENCES

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[1] JLC Group, JLC Design study, KEK Report 97-1.

[2] S. Matsumoto, et al., "Development of PPM-focused X-band Pulse Klystron" in Proc. of the 13^{th} Symposium on Accelerator Science and Technology (SAST 01), Osaka, Japan, 2001.

[3] Some articles on MBK are found in "High Energy Density Microwaves", Editor R.M. Philips, AIP Conf. Proc. **474** (1999).