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Calculation of transverse coupling impedance
above cutoff for a klystron cavity^{*}

T. HIGO[†], K. BANE AND R. MILLER

*Stanford Linear Accelerator Center
Stanford University, Stanford, California, 94309*

ABSTRACT

Lowest frequencies of transverse modes of the first four cavities in the klystron "SL4" are above the cutoff frequency of the TE_{11} mode in the beam tube. We calculated the Q and R/Q value for such a cavity using TBCI and showed the reduction of a coupling impedance of a transverse mode because of the power flow into the beam tube.

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[†] visiting from KEK, National Laboratory for High Energy Physics, Tsukuba, 305, Japan

As an candidate of an RF power source for a linear collider, a six-cavity klystron "SL4"^[1] at operational frequency of 11.4GHz is being developed by SLAC/LLNL/LBL. To get an output power level of 500MW, it is designed to work at about 1MV 1KA, making 1GW DC peak power. Following an usual design of klystron, the beam tube diameter is designed small enough to prevent the second harmonic from propagating the tube, such as $9.2mm^\phi$ in the region of the fifth to sixth cavity of SL4.

A transverse modulation in this high current can excite transverse modes of a cavity to deflect the following beam which may be lost in the beam tube of small radius. If we assume that the beam is pencil-like and modulated sinusoidally by an amplitude ξ and also couples to a single mode n of a cavity with frequency $\omega_n/2\pi$, the beam is transversely kicked by the magnetic field of the mode by a momentum δp ^[2]

$$\delta p = \frac{eI\omega_n R_n}{c^2} \xi,$$

where I is total current, c velocity of light and R_n a transverse coupling impedance of the mode defined by

$$\left(\frac{R}{Q}\right)_n \equiv \frac{c^2}{\omega_n^2} \frac{\left| \int_{cavity} e^{j\omega_n z/c} \frac{\partial E_x}{\partial x} dx \right|^2}{2\omega_n U_n},$$

where U_n is a stored energy of the mode. The kicked beam does a betatron oscillation of amplitude A

$$A = \frac{2\delta p}{eB}$$

in the following drift space with a solenoidal field B . Therefore, a gain G of transverse oscillation by a single stage is expressed as

$$G = \frac{A}{\xi} = \frac{2I\omega_n R_n}{Bc^2}. \quad (01)$$

If we consider the penultimate and output cavities of SL4, we can estimate

the values ω_n and R_n using the code such as URMEL,^[3] since a resonant frequency $f_n = \omega_n/2\pi \sim 14GHz$ is lower than the cutoff frequency, 19GHz, of the TE_{11} mode in the beam tube. Together with other calculated parameters, $Q_n \sim 7000$ and $(R/Q)_n \sim 25\Omega$, we get a single stage gain of 684 for $I = 1KA$ and $B = 0.5T$ from eq. (1). As this gain is fairly high, we should worry about the beam loss due to the transverse oscillation especially for a multi-cell klystron.

On the other hand, the tube diameter in the region of the first to fourth cavity of SL4 is designed to be $14mm\phi$ to accept the beam with a rather low solenoidal magnetic field of about 0.25T. Then, the transverse mode of cavities in this region may be heavily damped by the power flow into the beam tubes, resulting in a very low transverse gain. Therefore, it is interesting to estimate the transverse coupling impedance also in this region. If we assume the frequency of a transverse mode of a cavity in this region roughly equal to 14GHz, that of the fifth or sixth cavity, the transverse mode can propagate the tube by TE_{11} mode whose cutoff frequency is 12.5GHz. Since such a code as URMEL cannot deal with this situation directly,^[4] we use the code TBCI^[5] in turn to study the property of the beam cavity interaction. Since the frequency is not high enough to make the group velocity in the tube near to the velocity of light, the open boundary condition in TBCI does not mean no reflection of the travelling wave there. However, we can calculate the field around the cavity correctly until the reflected wave comes back from the open boundary in the tube to the cavity region where E_z exists and the beam can exchange energy to and from the field.

In TBCI runs, we excite an input cavity of SL4 with beam tubes in both sides by a gaussian bunch off axis with a bunch length σ of 4mm. This bunch length corresponds to the frequency component of the beam around 13GHz, high enough to excite the lowest transverse mode but not higher ones. Then we trace the transverse wake function till the reflected wave comes back. One of the results is shown in Fig. 1 for the case of beam tube length of 4cm. Assuming that there is only one mode n , we estimate the frequency f_n and Q value Q_n of the mode

by eye directly from this curve to be $f_n = 14 \pm 1 \text{GHz}$ and $Q_n = 12 \pm 2$.

The frequency is also checked by Fourier analysis of the curve within the region of no reflected wave from the boundary, $ct = 0$ to 0.16m in the figure. The result is shown in Fig. 2. A peak in real part of impedance agrees well with that deduced by eye.

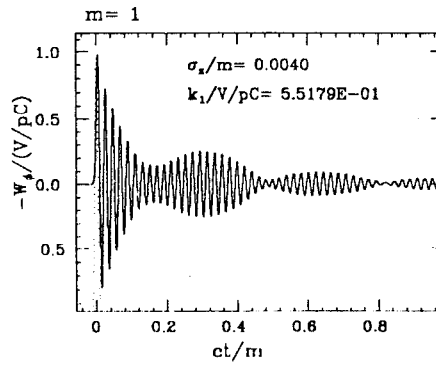


Fig. 1 Wake function calculated by TBCI.

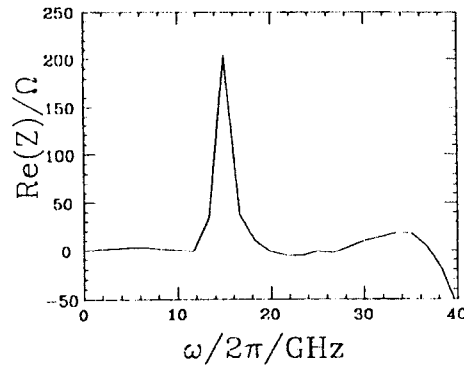


Fig. 2. Real part of impedance calculated by Fourier transform of wake function.

The impedance as a function of frequency gives us also the modal loss parameter k_n of the mode as

$$k_n = \frac{\omega_n a}{\pi c} \int_0^{\infty} \text{Re}(Z_{\perp}) d\omega = 1.6(V/pC),$$

where a is a tube radius. On the other hand, the total dipole kick parameter $k_{\perp}(\sigma)$ for a bunch with bunch length σ is calculated in TBCI to be $k_{\perp}(\sigma) = 0.55V/pC$ and this value is related to k_n as^[6]

$$k_{\perp}(\sigma) = \frac{2}{\sqrt{\pi}} \frac{k_n}{\omega_n a/c} D(\omega_n \sigma/c)$$

where D is the Dawson integral. Then, we get $k_n = 1.9V/pC$, which agrees fairly well with that obtained by Fourier analysis.

Once we know the loss parameter k_n , we get the transverse coupling impedance $(R/Q)_n$ as

$$\left(\frac{R}{Q}\right)_n = \frac{2c^2}{\omega_n^3 a^2} k_n = 10\Omega.$$

The moderately small value of $(R/Q)_n$ and extremely small value of Q_n give us the gain well less than 1 from eq. (1). This is an indication of large reduction of gain because of the damping of the mode through beam pipes. However, we should take into account the effect of the coupling between cells for multi-cell klystron to get an actual gain by many stages, since the existence of this kind of damping itself indicates the coupling between cells.

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