QUADRUPOLE HOM DAMPING WITH ECCENTRIC-FLUTED BEAM PIPES

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Abstract

An eccentric-fluted beam pipe was proposed to damp quadrupole modes. The eccentric-flute acts as a mode converter from quadrupole to dipole. Optimized parameters permit to damp both degenerate modes of quadrupole with the eccentric-flute. External Q-values measured with a low power model agreed well with those calculated with MAFIA.

INTRODUCTION

HOM damping is important for superconducting cavities, especially for high current CW machines such as Energy-Recovery Linacs. The lower Q-values of HOMs lead to the smaller capacity of a refrigeration system and the higher threshold current of the beam breakup (BBU). Enlarged beam pipes, which have lower cutoff frequencies, are effective to damp monopole and dipole HOMs, but insufficient for quadrupole HOMs which have high cutoff frequencies. Increasing the diameter of beam pipes to lower the cutoff of quadrupole modes causes the deep penetration of the fundamental mode into the pipes, longer distance to the HOM dampers and a low packing factor.

To solve these difficulties on the quadrupole damping, an asymmetric fluted beam pipe, named eccentric-fluted beam pipe (EFB), is proposed. The EFB is formed by displacing the flute from the beam pipe center and/or by jackknifing around the midpoint of the flute to couple with two degenerate modes.

The present paper describes the results of calculation with MAFIA and measurement of a low power model with the EFB.

ECCENTRIC-FLUTE

Principle

Fluted beam pipes are use to damp dipole modes by lowering the cutoff frequencies of dipole modes in a beam pipe [1]. Since the fluted beam pipes are symmetry for quadrupole modes (shown in Fig.1 left), the fields of them still remain as quadrupole in the fluted beam pipe. By shifting the flute from the beam pipe center, as shown in Fig.1 right, part of quadrupole mode field can be converted to TE11 mode due to its asymmetric shape. Since the cutoff frequency of TE11 mode is lower than that of TE21 mode, the converted dipole mode can propagate through the beam pipe. To confirm this principle of the EFB, the Fourier components were calculated with MAFIA along the beam axis for the TESLA single-cell cavity with the eccentric-flute of 60 mm length, 20 mm height, 31 mm depth and 10 mm shift from the beam pipe center. Fig. 2 shows the Fourier components of dipole and quadrupole modes of two degenerate modes. The cell was located from 0m to 0.113m and the eccentric-flute from -0.014m to -0.074m. These figures reveal that the dipole mode is excited around the eccentric-flute and propagates through the beam pipe. It clearly shows that the EFB acts as a mode converter from quadrupole mode to dipole. The figures also reveal that both degenerate modes of quadrupole, which rotate 45 degrees around the beam axis, can propagate through the beam pipe.

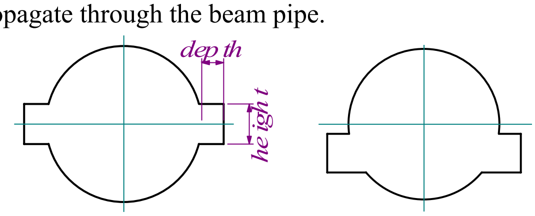

Figure 1: Beam pipe cross-section with normal flute (left) and eccentric-flute (right)

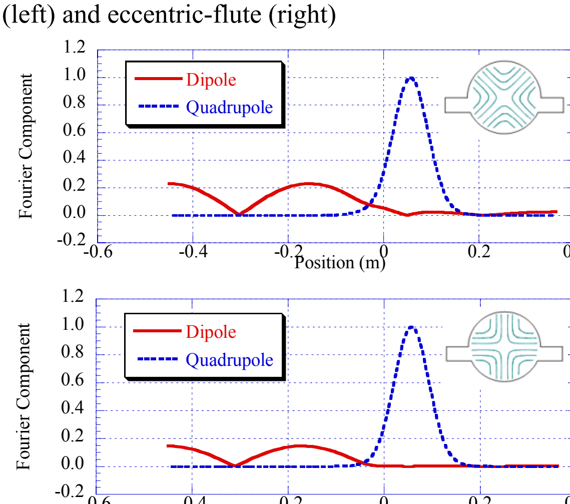

Figure 2: Fourier components of electric field of the cross-section along the axis. The polarities of quadrupole against the eccentric-flute are shown in the

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Method to Calculate External Q-value

The property of the EFB was estimated by calculating external Q-values of the EFB. A method to calculate the external Q-value with non-dissipative codes was proposed elsewhere [2-3]. The external Q-value for a line with TE wave can be calculated by

$$Q_{ext} = \frac{2\pi}{\lambda}\left(\frac{\Lambda}{\lambda}R_E + \frac{\lambda}{\Lambda}R_H\right), \quad (1)$$

$$R_E = \frac{\iiint |E|^2 dv}{\iint |E|^2 ds}, \quad (2)$$

$$R_H = \frac{\iiint |H|^2 dv}{\iint |H|^2 ds}, \quad (3)$$

where λ and Λ are the wavelengths in a free space and in a waveguide respectively. The volume and surface integrations are performed over the cavity volume and the beam pipe cross-section which has electric field antinode for Eq.2 and magnetic for Eq.3. These can be calculated with MAFIA.

Eccentric-Flute Type

Three types of EFB were considered as shown in Fig.3. The first one is a flute shifted from the beam pipe center (type-1), the second one is a flute shifted by the half height from the beam pipe center and bended around the beam pipe center (type-2), and the third one is a flute not-shifted and bended around the beam pipe center (type-3).

Figure 4 shows the calculated external Q-values of the larger one of the degenerate modes for the three types for the TESLA type single-cell case. For the type-2 the bending angle towards the side of the shifted flute is defined as plus. Since the external Q-values are almost comparable for the three types, we selected type-3 of the EFB because of ease of fabrication.

MEASUREMENT OF Q_{EXT} OF ECCENTRIC-FLUTE

A low power model made of aluminum was fabricated to estimate the external Q-value of the EFB. Fig.5 shows the setup of the measurement. The model consists of seven pieces of angularly divided beam pipe as shown in

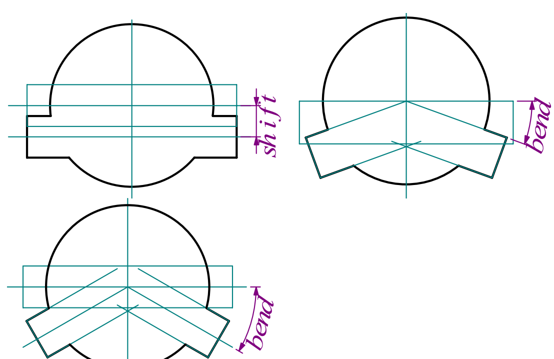

Figure 3: Three types of eccentric-flute. Type-1: shift (top left), type-2: shift and bend (top right) and type-3: no-shift and bend (bottom)

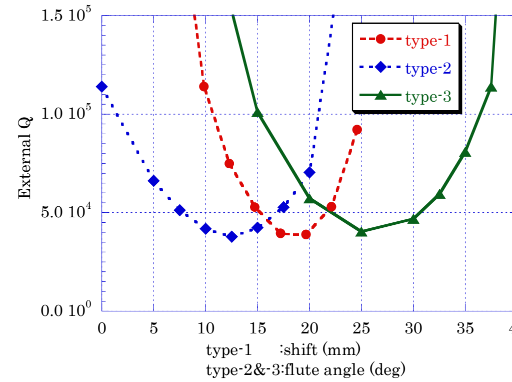

Figure 4: Comparison of external Q-values of three types of eccentric flute as a function of shift distance (type-1) and bending angle (type-2 & -3)

Fig.6. The flute angle can be chosen from zero to 45 degrees by 5-degree step by changing the combination of the pieces. The dimension of eccentric-flute is 60mm long, 20mm high and 31mm deep. The EFB is attached

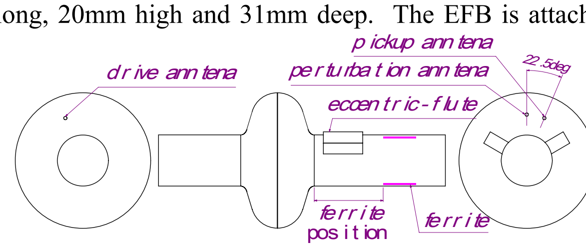

Figure 5: Setup for measurement of the eccentric-flute.

to one side of a single-cell or 3-cell cavity model of TESLA type. A drive antenna is installed at one side of end cell and a pickup antenna at the other side of end cell at the angularly same position. A perturbation antenna is installed at the position rotating 22.5 degrees around the beam axis to separate the degenerate modes into different frequencies. Loaded Q-values were measured with a network analyzer. A rolled-up ferrite sheet is set inside the beam pipe as a HOM damper.

Fig.7 shows the loaded Q-values with and without the EFB for the single-cell cavity. The flute angle was 25 degrees. TE211E in the figures represents a mode for electric boundary on the symmetry plane cut along the axis and TE211M for magnetic boundary. The figure indicates that the loaded Q-values without the EFB remain constant until the ferrite comes close to the cell, where the quadrupole modes penetrate into the beam pipe. Those with the EFB vary according to the ferrite position

Figure 6: Angularly divided eccentric-fluted beam pipe.

even far from the cell. This indicates that the power of the quadrupole modes propagates through the beam pipe.

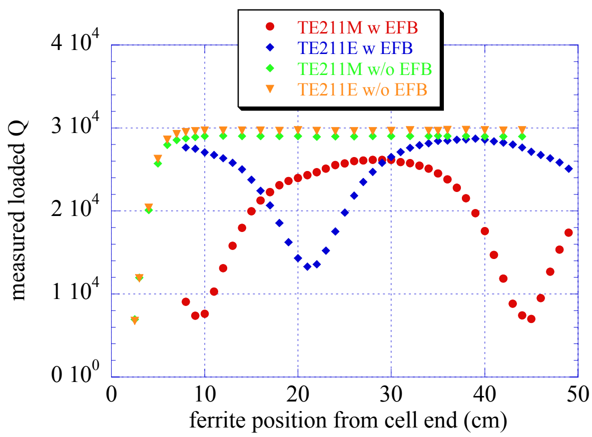

Figure 7: The loaded Q-values as a function of the ferrite position with and without the eccentric-flute.

If the HOM damper has ideal properties of perfect absorption and no reflection, the loaded Q-values are constant despite of the position of HOM damper. Since the HOM dampers have some reflection more or less in practice, the loaded Q-values change at the position of HOM damper. We estimate the external Q-value by the following procedures.

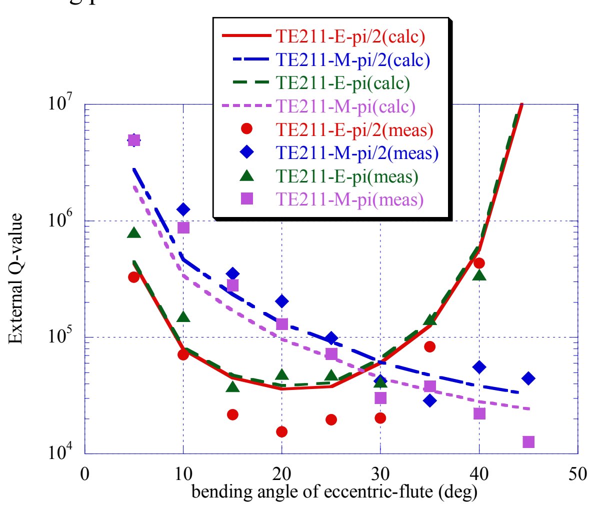

Figure 8: Calculated and measured external Q-values of 3-cell cavity with eccentric-flute as a function of bending angle.

(1) Measure the loaded Q-values by changing the position of HOM damper.

(2) Fit the loaded Q-values with the following equation.

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{g}{Q_{ext}} , \qquad (4)$$

where Q_L, Q_0 and Q_{ext} are loaded, unloaded and external Q-values respectively. In this calculation Q_0 is assumed to include all external Q-values except that of the EFB. The parameter g represents a normalized conductance of a load connected to a transmission line (See Appendix) and is a function of the position of the HOM damper.

The TESLA cavity was designed to enhance some HOMs in one end cell and others in the other end cell by the effect of asymmetry end cell shaping [4]. The 0-mode of the TE211 was enhanced in the cell far side of the EFB. The weak field of the 0-mode near side of the EFB caused weak coupling between 0-mode and the EFB. This resulted in large external Q-value. For this reason the external Q-values of 0-mode could not be measured.

Fig.8 shows the external Q-values of π/2-mode and π-mode of calculation and measurement as a function of the flute angle. The measurements agree well with the calculations. The difference between measurement and calculation is considered due to measurement errors caused by overlap of the degenerate modes in case of low loaded Q-value.

CONCLUSION

The EFB is effective to damp the quadrupole modes. Although various types of the EFB were proposed, optimized parameters can equal the external Q-values of degenerate modes.

One Nb single-cell and one 9-cell cavities of newly designed shapes [5] with the EFB are under fabrication for check of the surface treatment near the EFB and the high power test.

APPENDIX

Assume that a load located at the position of z has normalized admittance $\hat{Y}(z)$. Although $\hat{Y}(z)$ is complex, assume that it becomes real viewed at the position apart dz from the load. This is equivalent to locating a load of a real normalized admittance $\hat{Y}(z-dz)$ at the position of z-dz. The normalized admittance of this load viewed from z=0 can be expressed as

$$\hat{Y}(0) = \frac{\hat{Y}(z-dz) + \tanh\gamma(z-dz)}{1 + \hat{Y}(z-dz)\tanh\gamma(z-dz)} , \qquad (A1)$$

where γ is propagation constant expressed as $\gamma=\alpha+j\beta$, α is attenuation constant and β phase constant. The normalized conductance g is the real part of Eq.A1. When attenuation of the beam pipe can be neglected, the normalized conductance can be expressed as following

$$g = \frac{\hat{Y}(z-dz)\,(1+\tan^2\beta(z-dz))}{1+\hat{Y}(z-dz)^2\tan^2\beta(z-dz)} , \qquad (A2)$$

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