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C. S. Hopper
Old Dominion University

J. R. Delayen
Old Dominion University, jdelayen@odu.edu

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HIGHER ORDER MODE DAMPING IN SUPERCONDUCTING SPOKE CAVITIES*

C. S. Hopper† and J. R. Delayen
Center for Accelerator Science, Department of Physics,
Old Dominion University, Norfolk, VA, 23529, USA and
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

Abstract

Parasitic higher order modes (HOMs) can be severely detrimental to the performance of superconducting cavities. For this reason, the mode spectrum and beam coupling strength must be examined in detail to determine which modes must be damped. One advantage of the spoke cavity geometry is that couplers can be placed on the outer body of the cavity rather than in the beam line space. We present an overview of the HOM properties of spoke cavities and methods for suppressing the most harmful ones.

INTRODUCTION

High-velocity single- and multi-spoke cavities can be relatively compact and have a high velocity acceptance. The former allows for low frequency operation which could benefit small machines intended to operate at 4 K, while the latter would be advantageous for high energy protons and ions. When considering any application, it is important to estimate how much interaction between the beam and the cavity modes is to be expected when determining if higher order mode (HOM) damping is necessary.

When a particle bunch traverses a cavity, it is able to excite all modes of that particular structure. The excitation of these higher order modes give rise to two limiting factors, namely, beam instabilities and additional power losses. All modes contribute to the additional cryogenic load. Deflecting modes can lead to beam breakup while monopole, or accelerating modes, can increase the energy spread of the beam. In this paper we will describe our efforts to characterize the beam-induced power in a 500 MHz (β_0 = 1) double-spoke cavity.

MODE CHARACTERISTICS

We will identify modes based on the orientation of the electric field with respect to the beam axis (z). When the field is longitudinal (E_z), this will be referred to as an accelerating mode while those with strong on-axis transverse components (E_x and/or E_y) will be considered deflecting. There are also hybrid modes and what we will call TE-type modes, but those have not been found to be a concern. A more detailed description of the mode types and $R/Q(\beta)$ calculations are provided in [1, 2]. Figure 1 shows the result of such analysis for the cavity discussed here [3].

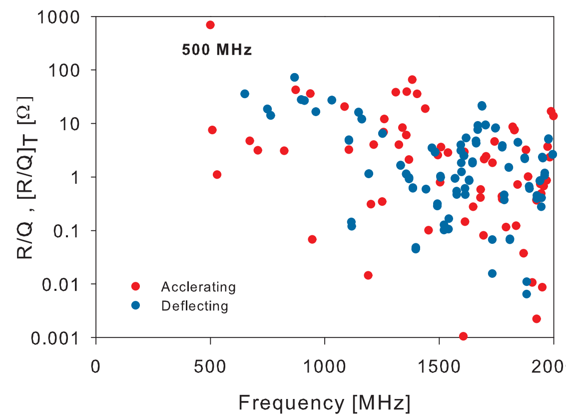

Figure 1: $(R/Q)(\beta_0)$ values for particles at the design velocity for the 500 MHz β_0 = 1 double-spoke cavity.

Electrons being accelerated from 2 MeV to 25 MeV, as in a compact light source, only represent a change in β of 0.97 to 1. Therefore, we will assume the design velocity for particles when analyzing the HOMs in this report.

FUNDAMENTAL POWER COUPLER

Before determining the undamped impedance of each mode, it is important to know how much damping to expect from the fundamental power coupler (FPC). Taking the 500 MHz, β_0 = 1 double-spoke cavity, the beam properties given in [3] lead to an optimal loaded quality factor of

$$Q_L = \frac{V_{acc}}{\frac{R}{Q} \cdot I_b \cos\phi_b} = \frac{(6MV)^2}{670\Omega \cdot 1mA \cdot 1} = 9 \times 10^6\,, \quad (1)$$

where ϕ_b is the phase between the rf field and the particle (zero for on-crest). Because the intrinsic quality factor Q_0 is on the order of 10^8-10^9 for the majority of HOMs, the approximation $Q_L \approx Q_{ext}$ will be made throughout this report.

The multi-spoke cavity allows for a variety of options for where the couplers can be placed. A 50 Ω coaxial coupler is used to couple to the electric field, and the length of the inner conductor is such that an external quality factor of $\sim 10^7$ is achieved for the operating mode. This does not gaurantee a similar Q_{ext} for the other accelerating modes, as can be seen in Fig. 2.

* Work supported by U.S. DOE Award No. DE-SC0004094
† chopp002@odu.edu, chrsthop@jlbab.org

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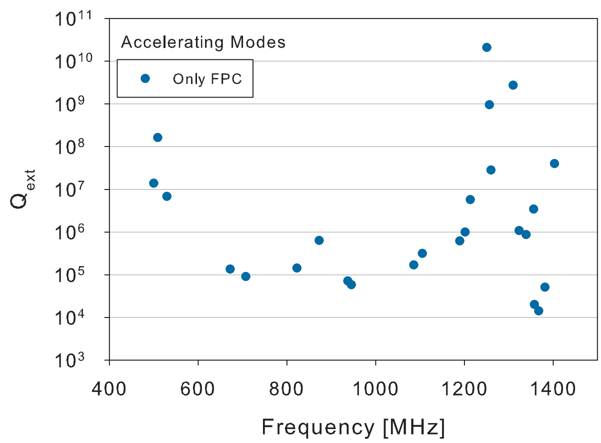


Figure 2: External quality factor of accelerating modes with a FPC placed in one end cell of the cavity.

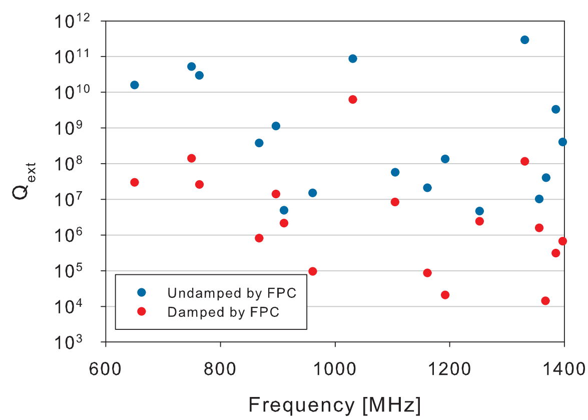


Figure 3: External quality factor of degenerate deflecting modes with a FPC placed in one end cell of the cavity.

The degeneracy of the deflecting modes does not allow for an equal damping of each polarization by the FPC. This is illustrated in Fig. 3 which shows Q_{ext} for both deflecting mode polarizations up to 1.4 GHz. With only a simple 50 Ω coaxial coupler, it is clear that the polarizations which do couple to the FPC do so fairly well (many are below 10^7), while those that do not can be orders of magnitude above that.

If a particular application called for a level of damping not achieved by the FPC, a higher order mode coupler may be necessary.

HOM COUPLERS

In order to damp one polarization of the deflecting modes without adversely affecting the fundamental mode, a HOM coupler similar to [5] and [6] can be used. A simple two-stub coaxial line with a filter for the fundamental mode has been analyzed.

For the purposes of this study, we are interested in a moderate damping of the higher order modes such that the Q_{ext} meets some minimal standard. A detailed analysis of the optimization procedure for such couplers can be found in [7, 8].

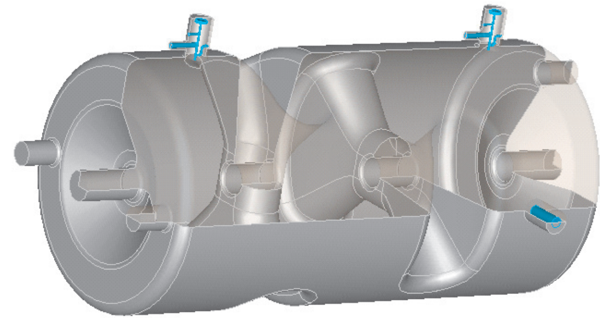


Figure 4: 500 MHz, β_0 = 1 double-spoke cavity with two HOM couplers and the FPC.

Figure 4 shows the 500 MHz, β_0 = 1 double-spoke cavity with 50 Ω coaxial FPC and two of the two-stub coaxial line HOM couplers.

BEAM INDUCED CRYOGENIC LOSSES

The power dissipated by the excitation of mode n is given by

$$P_n = \frac{V_{b,n}^2}{R_{shunt}}, \tag{2}$$

where $V_{b,n}$ is the beam induced voltage of mode n and R_{shunt} is the shunt impedance. When the bunches are resonant and the decay time T_d of mode n is much greater than the time between bunches T_b, the dissipated power can be written as [4]

$$P_n = \frac{R_{shunt} I_0^2}{(1+\beta)^2}, \tag{3}$$

where I_0 is the beam current and β is the coupling factor. By calculating the $R/Q(\beta_0)$ and intrinsic quality factor Q_0 of each HOM, the coupling factor and thus the external quality factor Q_{ext} can be found such that the power dissipated by each HOM is less than one Watt, for example.

From Fig. 2 and 3, we can see that the FPC leaves many modes, both accelerating and deflecting, with very high external quality factors. Even with the introduction of a single HOM coupler, a number of modes have a Q_{ext} above 10^7 (see Fig. 5).

To achieve the level of damping mentioned previously (<1 W P_d for each mode), an additional coupler is placed on the cavity. The Q_{ext} values for this configuration are shown in Fig. 6.

When the actual damped beam-induced HOM power is calculated, the accelerating modes contribute on the order of a few hundred mW (per cavity), while the deflecting modes have the potential to contribute more than 1 kW. The majority of this beam-induced power comes from just a few modes, which will need to be further damped. Table

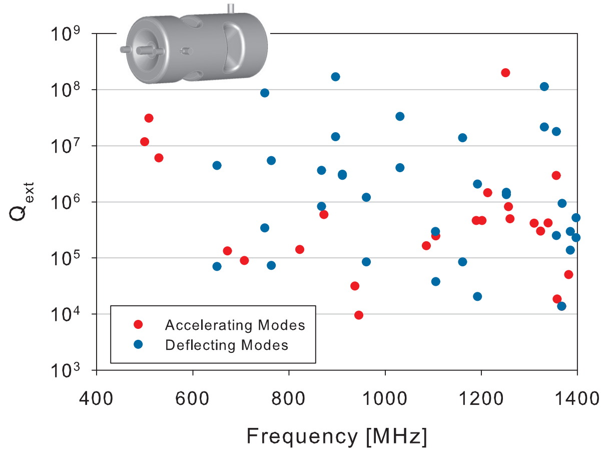
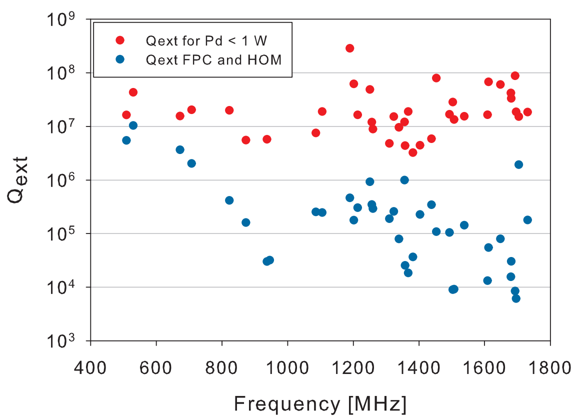
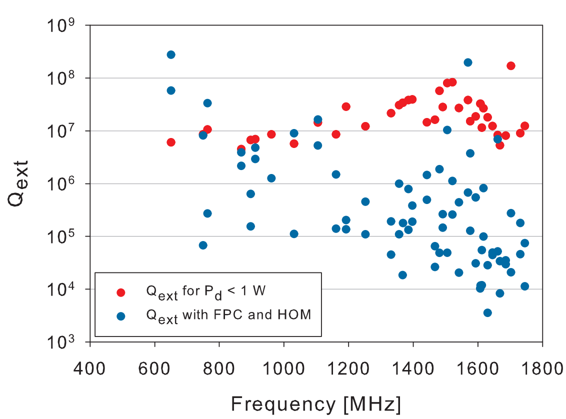


Figure 5: Q_{ext} values for both accelerating and deflecting modes subject to damping by the FPC and a single HOM coupler.



(a)



(b)

Figure 6: External quality factor required for less than 1 W beam induced power (red) and the external quality factor with two HOM couplers and the FPC (blue). (a) shows the accelerating modes while (b) is for deflecting modes.

1 shows the properties of these dangerous modes. These values are for the *resonant* case, and therefore represent a worst-case-scenario.

Table 1: Resonant Beam-Induced Power for Dangerous HOMs

Frequency	Q_{ext}	P_d
650.3 MHz	5.8×10^7	84 W
650.3 MHz	2.8×10^8	1.4 kW
763.8 MHz	3.3×10^7	9.5 W
1569 MHz	2.0×10^8	31 W

FUTURE WORK

The results presented here are meant as a first approximation. A more detailed study using the power requirements dictated by the capability of the cryogenic system is underway. Beam instabilities, such as regenerative beam breakup, are also being explored. The filter frequency of the HOM coupler is still being optimized and multipacting simulations are being performed.

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