The Higher-Order Mode Dampers of the 400 MHz Superconducting LHC Cavities

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Abstract

The accelerating system of the LHC consists of two structures per beam, each composed of four superconducting single-cell cavities. Their higher-order modes have to be damped sufficiently in order to prevent coupled-bunch instabilities and to limit parasitic mode losses. The first two higher-order modes do not propagate into the beam tubes between the cells. However, strong damping can be obtained with a special dipole mode coupler resonant at both modes. Because of the restricted space, a compact design is used. The other higher-order modes propagate and form coupled modes with unequal field distributions. They are damped by broadband couplers positioned on either side of each cavity cell. We present the design of the higher-order mode couplers together with measurements on a real cavity.

Introduction

The accelerating system of the LHC [1] consists of two structures per beam, each composed of four superconducting single-cell cavities. The cells are connected by large-aperture beam tubes (ϕ 300 mm). The main purpose of the large diameter is to reduce the characteristic impedance (R/Q) of the fundamental mode (FM) and hence transient beam loading. The end cells are matched to the machine beam tube (ϕ 60 mm) with long tapers. The higher-order modes (HOM) of these structures have to be damped sufficiently in order to prevent coupled-bunch instabilities and to limit parasitic mode losses. In the following we discuss the adopted damping concept.

Damping Concept

A special problem of widening the beam tube is that the first dipole mode (TE_{111}) develops more and more R/Q and moves nearer to the FM [2]. In recent single-cell designs with beam tube ferrite loads, this necessitated special beam tube geometries like the fluted beam tube or the beam tube widening after the iris [3]. In our case, with four cells in one cryostat, ferrite beam tube loads, which have to be at room temperature, are ruled out. Instead, a more conventional HOM coupling approach is used, but with two different types of HOM couplers.

The splitting of the damping task between two coupler types is also suggested by the spectrum of the modes, shown in Fig. 1. The dipole modes (500 MHz and 536 MHz) are clearly separated from the remaining higher-order modes which form a group at frequencies from 760 MHz to 1300 MHz.

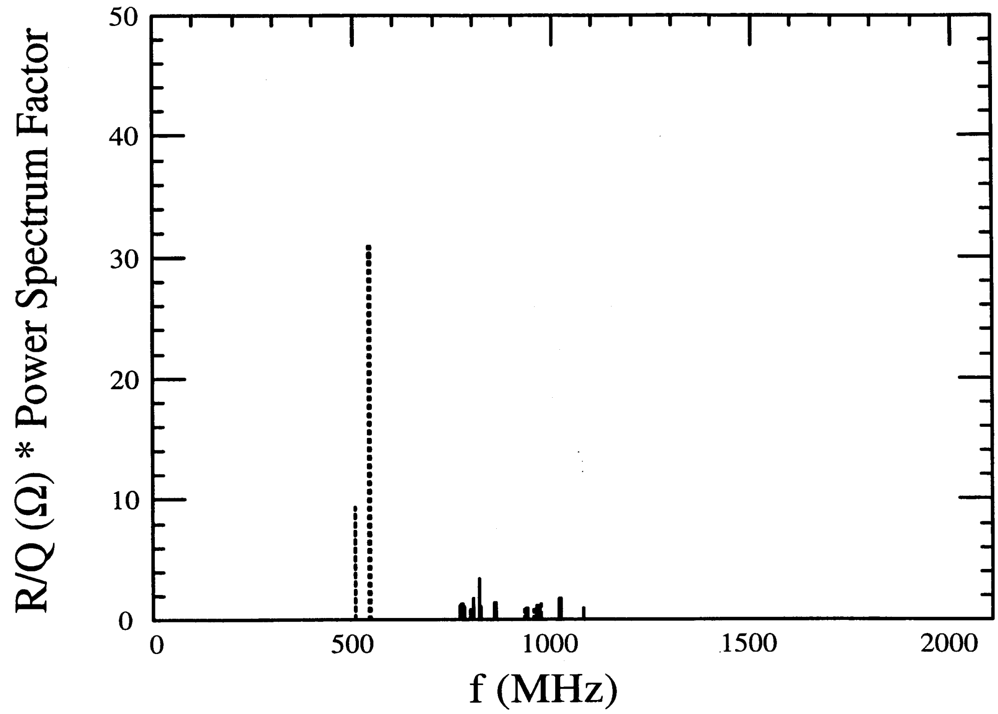

Figure 1: R/Q spectrum of four single cells. The R/Q values are multiplied by the power spectrum factor for the nominal LHC bunch: cos^2 shaped and 30 cm full bunch length.

Another way to classify the modes is to distinguish between propagating (into an infinite beam tube) and non-propagating modes. The non-propagating modes need couplers positioned on the beam tubes as near as possible to the cells. To this class belong, in addition to the FM, the first two dipole modes, and also a mode at about three times the FM frequency which, although nominally propagating, excites a beam tube wave only weakly or not at all. Such a mode is called a trapped mode [4] and is illustrated in Fig. 2.

In our structure, mode propagation leads to coupling between the cells. The resulting coupled modes often have unequal field distributions. An example is given in Fig. 3. To assure damping of all these modes broadband couplers covering the range from 760 MHz to 1300 MHz are mounted on both sides of each cell.

As a result, each cell is equipped with a total of four HOM couplers (two of each type) mounted on the beam tubes adjacent to the cells, and at right angles to each other to cover both possible polarizations of dipole modes.

Dipole Mode Coupler

The dipole mode coupler has a loop as coupling element. Cavity dipole modes excite in the cut-off tubes the TE_{11} waveguide mode (evanescent in the case here) which has

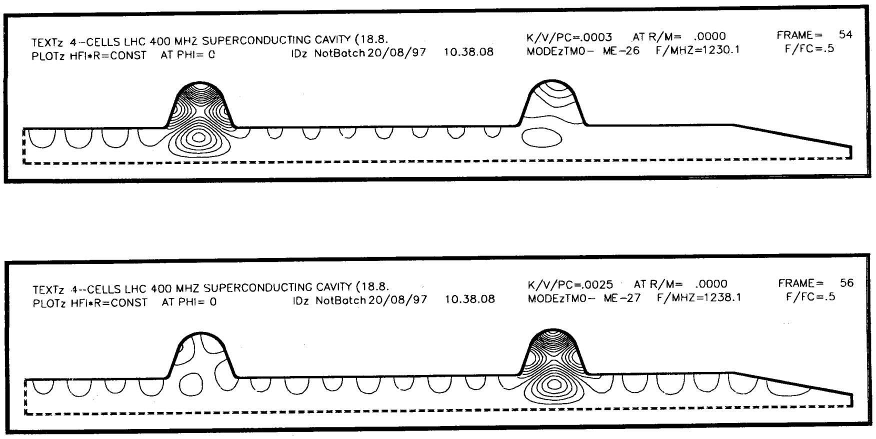

Figure 2: Trapped modes of four single cells (only two cells are shown)

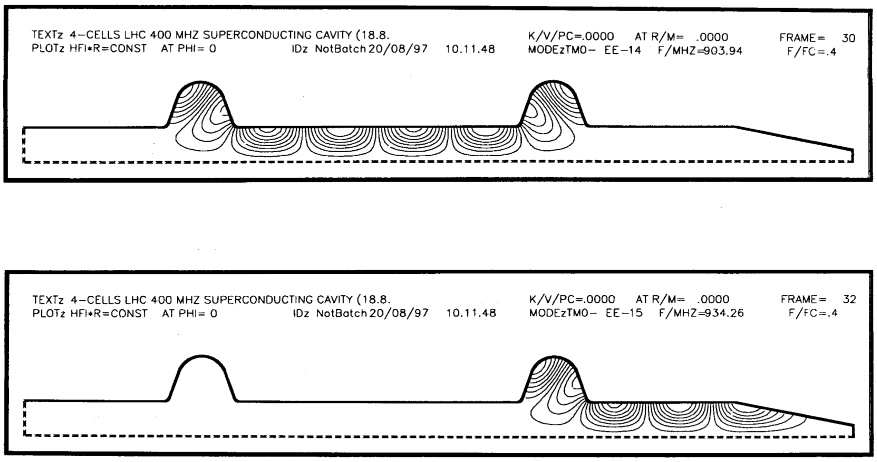

Figure 3: Coupled modes of four single cells (only two cells are shown)

a strong **longitudinal** magnetic field component at the tube wall. In coupling to this component with a loop perpendicular to the cavity axis, magnetic coupling to the FM is eliminated. However, electric coupling to the FM has also to be suppressed. For that purpose the loop is not connected galvanically to the coupler tube (see Fig. 4), leaving a small gap. The gap capacitance C_n forms with the loop's self-inductance L_n a series resonator (see Fig. 5) which is tuned to the FM. It provides a short-circuit to the displacement current I_0 injected by the electric FM field ending on the loop wire. At this point we recall that widening the cut-off tubes of a cavity moves the first dipole modes closer to the FM [2]. Consequently, it becomes increasingly difficult to combine high dipole mode damping with sufficient FM suppression.

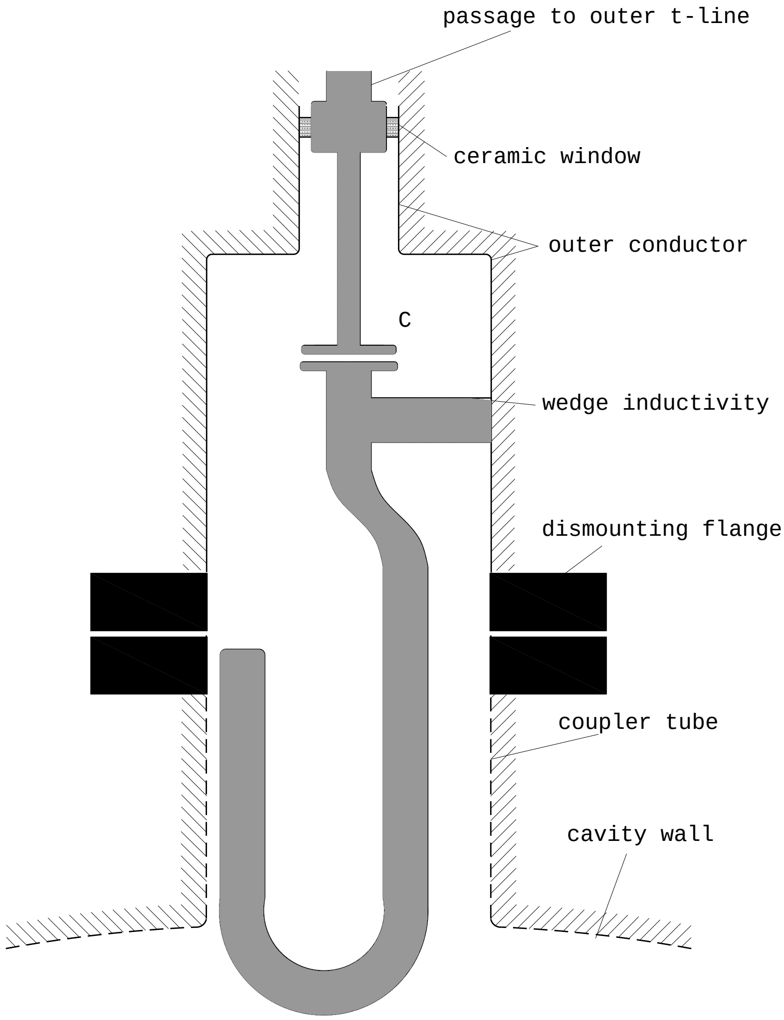

Figure 4: Geometry of the dipole mode coupler

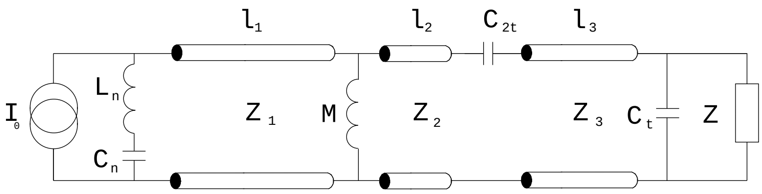

Figure 5: Transmission line circuit for electric coupling

The situation may be eased by resonant coupling. If for a given coupling factor k between loop and a mode the coupler's inner circuit elements complement the loop inductance to form a resonator with quality factor Q at the mode frequency f, then (up to the limit $Q = 1/k$) mode damping is enhanced in proportion to Q [5]. But for modes outside the coupler's bandwidth $\Delta f = f/Q$ damping is reduced. Since we have to deal with two modes, a circuit exhibiting two resonances is employed. For that purpose two resonators have been coupled via a common inductive element M (see Fig. 6). They

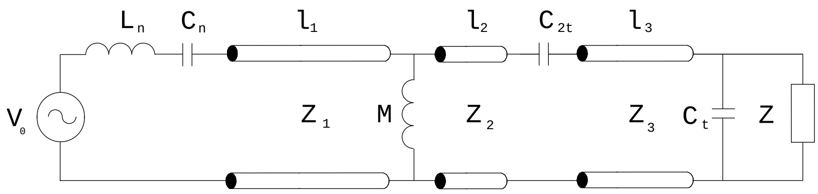

Figure 6: Transmission line circuit for magnetic coupling

transform, at the two dipole mode frequencies, the terminating resistance Z into peaks of the real part of the admittance 'seen' by the induced mode voltage V_0.

Inducing V_0 by a small test loop these coupler resonances may be observed in terminating the coupler into a spectrum analyzer and feeding the loop by a tracking generator. Such a 'transfer curve' is shown in Fig. 7. for the dipole mode (upper curve). Since the higher frequency dipole mode has a higher R/Q value than the lower frequency one the coupler circuit has been tailored to produce resonances of adapted different strength. M is the inductance of the wedge-shaped mechanical support of the inner hook-shaped tubular conductor of the coupler. It provides also a convenient path for liquid helium into the coupler.

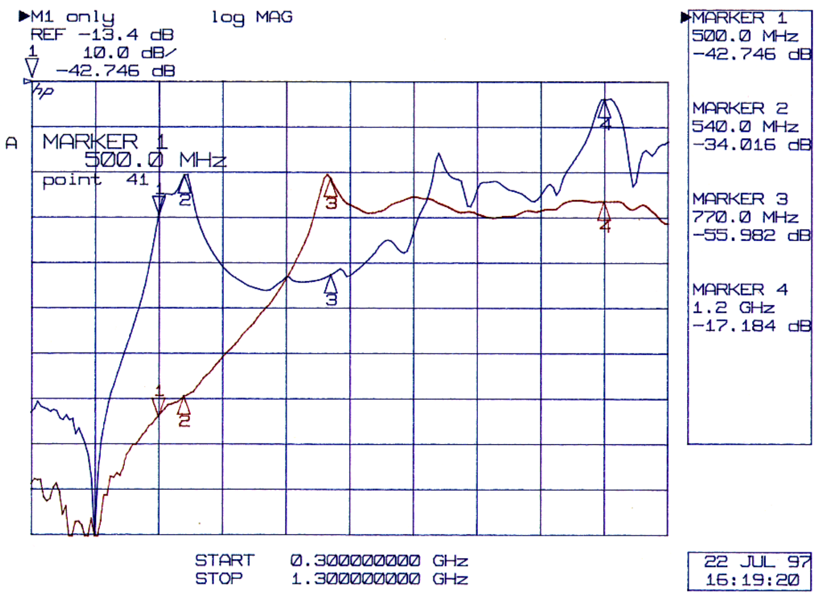

Figure 7: Characteristics of both couplers

Broadband Coupler

The broadband version is an extrapolation of the dipole mode one. Since we want to cover a large frequency range, from 760 MHz to 1300 MHz, three low-Q coupler resonances are put into this range. A third coupled resonator had to be added to the dipole mode circuit. Since most of the modes in the range are of the TM type, electric field coupling had to be employed and an open line stub had to be added to the loop to form an electric field probe (see Fig. 8 and Fig. 9). At a frequency where its length is approximately $\lambda/4$ it transforms a high admittance into a high impedance as required for efficient electric field coupling. A transfer curve obtained with a spectrum analyzer in replacing the test loop by a short test probe is also shown in Fig. 7 (lower curve). The three resonances can be seen where the lowest one has the highest strength and is tuned to the TM_{011} mode.

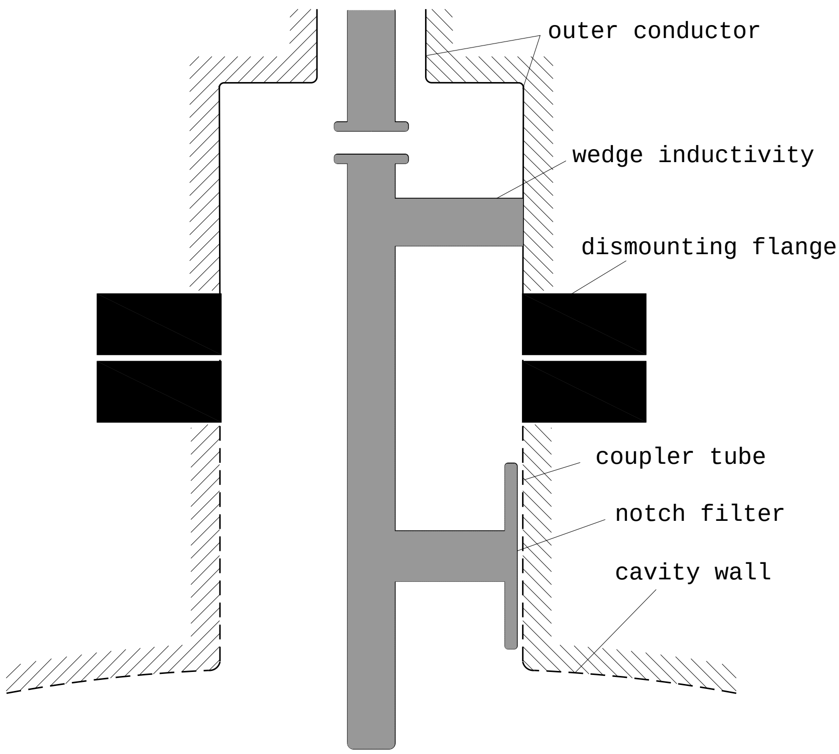

Figure 8: Geometry of broadband coupler

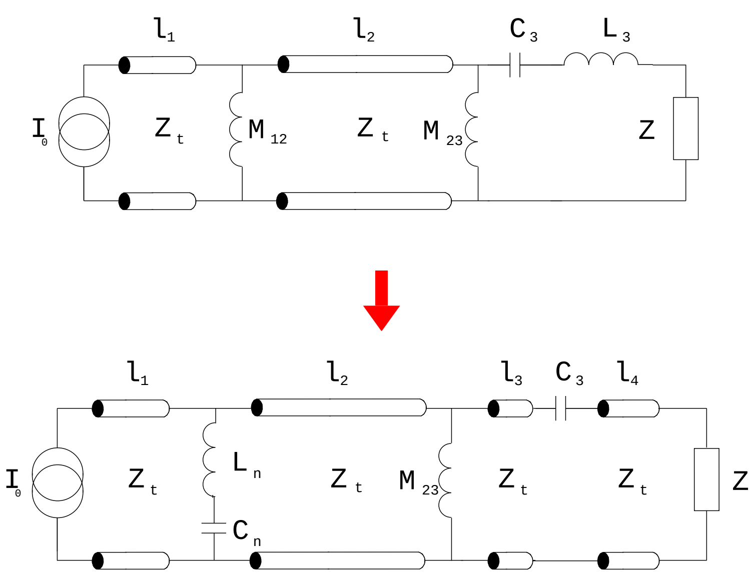

Figure 9: Equivalent circuits of the broadband coupler

Measurements and Conclusion

A single-cell copper cavity has been equipped with two couplers, one of each type. The dipole mode coupler was in one of the planes of polarization of the two dipole modes. Measured loaded and unloaded Q's of the cavity are given in Table 1. In our frequency range of interest (up to 1300 MHz), mode damping figures are comparable to those obtainable with wide beam-tube ferrite loads [3].

Table 1: HOM damping on a single-cell cavity by one dipole mode and one broadband coupler

Frequency (MHz)	**Undamped Q**	**Damped Q**
500 (TE_{111})	38000	137
534 (TM_{110})	40000	93
779 (TM_{011})	50000	270
1184	50000	1000
1238	50000	400

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