

## HIGHER ORDER MODE ABSORPTION IN TTF MODULES IN THE FREQUENCY RANGE OF THE THIRD DIPOLE BAND

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### Abstract

Measurements in the TESLA Test Facility (TTF) have shown that modes with unexpectedly high Q-factors and R/Q values occur in the third dipole band. The present work quantitatively analyses the fields and their damping in the frequency range of the third dipole band (~2.5 GHz). In our investigation we use a scattering (S)-parameter concept. For the calculations the TTF accelerating module is split into several components, for which the S-parameters are independently calculated. Using the S-matrices of all these components, we have the ability to calculate the S-matrix of complex systems or of complete modules. The frequency dependence of the S-parameters permits us to find resonant frequencies and Q-factors of complex devices. An understanding of the damping mechanisms in the third dipole band was obtained and an improved design of the higher order mode (HOM) couplers was proposed in order to suppress those third dipole band modes with high values of R/Q.

### 1 INTRODUCTION

**Cavity Design:** HOMs must be damped to avoid multi-bunch instabilities and beam break-up. The lower the quality factors (Q) of the HOMs the lower the amplitude of the fields will be which are excited by the bunch train. The quality factors of the HOMs are reduced by HOM couplers, which are mounted on the beam pipes at both ends of a TESLA 9-cell cavity [1]. Two types (SACLAY and DESY) of HOM couplers have been developed and tested. Especial care was taken to achieve the desired HOM absorption of  $Q \sim 10^4$  for modes with high shunt impedance in the lowest two dipole passbands. For dipole modes in the third and higher passbands the beam pipes are above the cut-off frequency so that such modes can couple not only to the next absorbers but also to the absorbers of the adjacent cavity-coupler units. To damp not only monopole and dipole but also quadrupole modes and modes of even higher azimuthal order, the angle between two HOM couplers of one unit is chosen as  $115^\circ$ . An asymmetric shaping of the end cells is used to avoid 'trapped modes' that have negligible field in the end cells.

**HOM-Experiment:** To excite higher order dipole modes in the TTF, an intensity modulated beam is sent off-axis through a module with eight nine-cell cavities. Modes are detected either directly by HOM coupler output signals or by beam deflections at downstream beam position monitors. Dipole modes at the end of the third passband (~2.58 GHz) with Q-value of the order of  $10^6$  were observed during measurements in 1998 and 2001 [2,3]. The weak damping of these modes was unexpected because the modes are not 'trapped' and the

coupling from the end cells to the beam pipe (above cut-off) is good. As the shunt impedance ( $>10 \Omega/\text{cm}^2$ ) of this mode is comparable and even higher than that of the modes in the first two dipole bands, special attention was paid to this problem.

**S-Parameter Approach:** In order to quantitatively analyse the fields and their damping in the frequency range of the third dipole band we use the S-parameter concept. The accelerating module is split into several components (e.g. TTF cavity, HOM coupler, HOM coupler together with input coupler, bellows, cold and warm windows and doorknob of the input coupler) for which the S-parameters are calculated independently. These components are either connected by waveguides or terminated by loads with known impedance. We have the ability to study the frequency dependence of transmission and reflection coefficients. This permits us to find resonant frequencies and Q-factors.

### 2 S-PARAMETER CALCULATION OF COUPLERS

**Upstream HOM Coupler:** The orientation of the upstream HOM coupler can be seen in Fig 1. The cavity is equipped either with DESY or SACLAY type HOM couplers. For both types, the coupling to the RF fields is made through a loop. The loop couples capacitively to a 50 Ohm transmission line, which is terminated outside the cryostat by a load, the angle between the horizontal axis and the axis of the coupler cylinder is  $-150^\circ$ . The two coupler types differ by the orientation of the loop and the realisation of the notch filter that prevents the damping of the accelerating mode.

**Downstream HOM and Main Coupler:** The downstream HOM coupler and the main coupler (power coupler) have the same longitudinal position and are computed together. The shape of the HOM coupler is the same as on the upstream side of the cavity, but the orientation is different (see Fig. 1 and 2). The geometrical transformation from downstream to upstream coupler is a rotation of  $5^\circ$  around the z-axis and a  $180^\circ$  rotation around the y-axis. (This is not the same as a rotation of  $115^\circ$  around the z-axis although the angle between the two HOM coupler axes is  $115^\circ$  as mentioned in the introduction.)

**DESY HOM Couplers:** The transmission from the beam pipe ports to the coaxial HOM coupler port can be seen in Fig. 3 for the up- and downstream HOM coupler. It is remarkable that both HOM couplers provide a very good coupling to the horizontal polarisation (0.35 ... 0.4) while the coupling to the vertical polarisation is one order

of magnitude weaker although the orientation of the couplers is very different (see Fig 2).

**SACLAY HOM Couplers:** In contrast to the DESY type, both SACLAY couplers provide very good coupling to the vertical polarisation (0.35 ... 0.5) but a much weaker coupling to the horizontal polarisation (<.05). The damping of modes with horizontal polarisation depends additionally on the power absorption through the main coupler.

**Main Coupler:** The reflection coefficient,  $r_{\text{main}}$  (see Fig 2) was calculated for three different types of main couplers (FNAL, DESY-I, DESY-II). As the reflection coefficients of both DESY main couplers are large at the upper end of the third dipole band, almost no HOM power is transmitted into the waveguide system and S-parameter calculations are insensitive to boundary conditions behind the windows. The reflection from the FNAL window exhibits a more complicated frequency dependency and is considerably smaller in the frequency range between 2.57 and 2.6 GHz. Additional details can be obtained in [4].

### 3 SINGLE CAVITY WITH COUPLERS

**Measurement:** Fig. 4 shows the transmission between the two HOM ports of a cavity in a test cryostat. The beam pipes and the main coupler are shorted. In this picture one can identify resonances of the second monopole band, the third dipole band and the second quadrupole band. In the frequency range where the dipole band does not overlap with the quadrupole band, the characteristic double resonances of polarised dipole modes can be observed. One of the peaks of a double resonance is always much sharper than the other. This is a clear indication that the two polarisations of a dipole mode have very different quality factors.

**Calculation for a Perfect Cavity:** The transmission between the HOM coupler ports of a cavity, which is equipped with DESY HOM couplers, is plotted in Fig. 5 for the full bandwidth of the third dipole band. A series of eight double resonances can be observed. As DESY HOM couplers are much more effective for the horizontal than for the vertical polarisation (see Fig. 3), the broader resonance is associated with a mode with essentially horizontal polarisation and the sharp peak with one essentially vertically polarised. For similar reasons this is otherwise for SACLAY HOM couplers. The resonance frequencies and quality factors are:

DESY		SACLAY	
$f$ / GHz	$Q$ / 1000	$f$ / GHz	$Q$ / 1000
2.576971	3576	2.577020	21.5
2.577146	18.2	2.577122	2101

Resonances with quality factors of the order  $10^6$  are possible in cavities with ideal geometry. The mode polarisation by the couplers causes a frequency split of 175 kHz for the DESY HOMCs and of 102 kHz for the SACLAY HOM couplers.

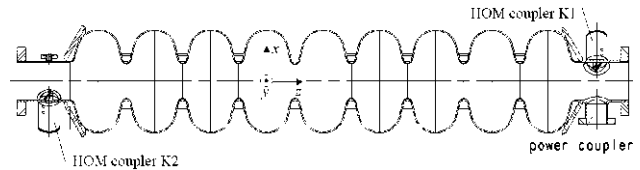


Figure 1: Design of the TESLA cavity. When viewed from the right end, the angles between HOM couplers and power coupler are  $145^\circ$  (K1) and  $30^\circ$  (K2). The  $x$ - $z$  plane is the horizontal plane,  $z$  is the direction of the beam axis.

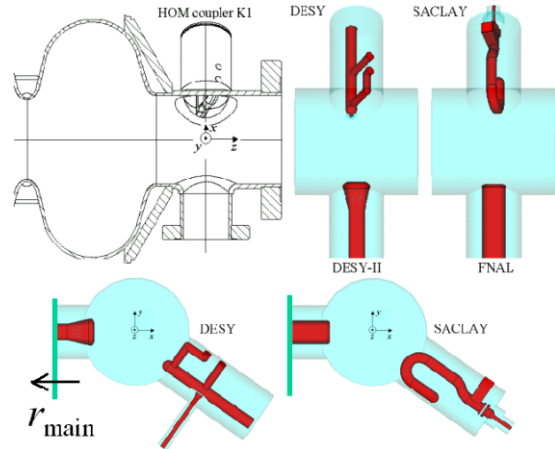


Figure 2: Orientation of downstream HOM and main couplers. The angle between horizontal axis and axis of the HOM cylinder is  $-35^\circ$ .

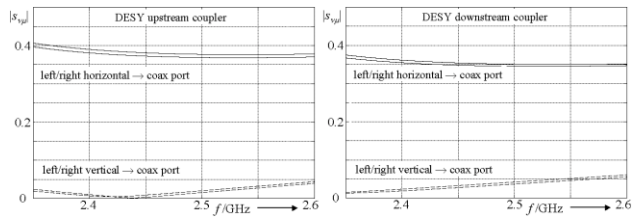


Figure 3: Amplitude of the transmission coefficients from the waveguide ports to the load port.

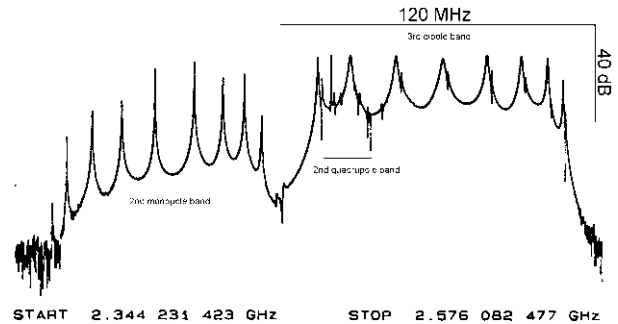


Figure 4: Measured amplitude (in dB) of the transmission between the HOM couplers.

**Cavity Polarisation:** The frequency split of a double resonance has three sources: the polarisation by the input coupler, the polarisation by HOM couplers and the 'eigen'-polarisation of the cavity due to perturbations of the axial symmetry. The polarising effect of the input coupler depends on the standing wave pattern along the coaxial line. Large 'eigen'-polarisation can cause the

coupler damping to be more equally divided between both polarisations.

#### 4 MODIFIED HOM COUPLER

To achieve a better balance of the suppression of modes with different polarisations, we propose a symmetry transformation of the geometry of the upstream HOM coupler as shown in Fig. 6 for the DESY HOM coupler but also proposed for the SACLAY type. This modification has several advantages: the modification is small, the location of the coupler flange is unchanged, the frequency characteristic is unchanged, the coupling to monopole modes is unchanged, the 1.3 GHz notch-filter still works, but the polarisation of maximal coupling is rotated as it can be seen in the figure. Therefore the polarisation of maximal coupling is now different for the upstream and downstream couplers. The same modification is proposed for the upstream SACLAY type coupler.

#### 5 MODULES OF EIGHT CAVITY-COUPLER UNITS

Results from simulations of 8-cavity modules with DESY type couplers were analysed. The numerical simulations allow an interpretation of the observation of localized as well as non-localized high Q modes (which couple through several cavities). Seven cases of modules with randomly detuned cavities were calculated. For the original configuration, modes with  $Q \sim 10^6$  and  $Q \sim 10^4$  were found. For the set-up with modified couplers the Q-factors of the high Q-modes are reduced by more than one order of magnitude while the Qs of the low Q modes remain similar (see Fig 7). In all cases modification of all upstream HOM couplers creates strong suppression of high Q-factor modes and very little change in those with low Q-factors.

#### 6 CONCLUSION

The damping mechanisms of modes in the frequency range of the third dipole band were quantitatively analysed with the method of coupled S-parameters. Two main reasons for the very weak damping of some modes in this frequency range were identified: 1) Due to their design DESY type couplers are insensitive to vertically polarised modes and SACLAY type to horizontal ones. 2) Interference effects of forward and backward waves in the beam pipe can reduce the coupling. It was shown that the measured high Q modes are in agreement with the numerical model. For several arrangements of systematically and randomly detuned cavities with modified upstream HOM couplers, the highest Q-factors of modes in the third dipole band are always  $< 10^5$ . The Q-factors in the first and second band are not markedly changed. Interference effects depend on random differences between cavities. Therefore the number of HOM couplers has to be large enough so that the damping is sufficient even if some couplers are ineffective.

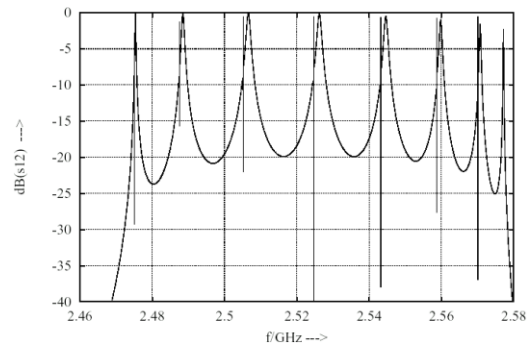


Figure 5: Calculated amplitude of transmission between the DESY HOM couplers for the third dipole band.

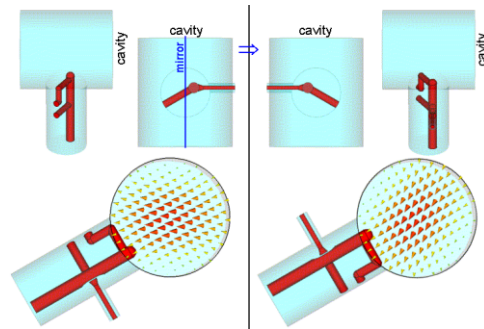


Figure 6: Proposed modification of the upstream coupler. Due to a 'mirror' transformation the polarisation of maximal coupling is rotated.

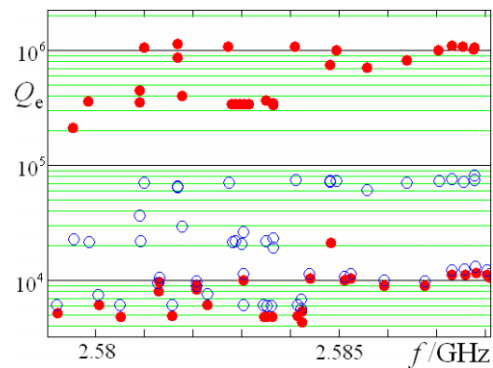


Figure 7: Q-values of different modules with randomly detuned cavities at the upper end of the third dipole band, the original couplers have filled circles (red) and the modified upstream couplers, open circles (blue).

#### 7 REFERENCES

- [1] TESLA Technical Design Report, Part II [http://tesla.desy.de/new\\_pages/TDR\\_CD/PartII/accel.html](http://tesla.desy.de/new_pages/TDR_CD/PartII/accel.html)
- [2] C.Magne et al: "Measurement with Beam of the Deflecting Higher Order Modes in the TTF Superconducting Cavities", PAC2001, Chicago, June 2001
- [3] N.Baboi et al.: "Investigation of High-Q Dipole Mode at the TESLA Cavities", Proc. 7th European Particle Accelerator Conference, EPAC2000, pp. 1107, June 2000
- [4] [http://tesla.desy.de/new\\_pages/TESLA/TTFnot02.html](http://tesla.desy.de/new_pages/TESLA/TTFnot02.html) (2002-05)