# HOM Beam Coupling Measurements at the TESLA Test Facility (TTF)

G. Devanz, M. Jablonka, C. Magne, O. Napoly, CEA, Gif-sur-Yvette
M. Huening, M. Wendt, DESY, Hamburg

*Abstract*

The proper damping of the higher order modes (HOM) of the TESLA superconducting accelerating cavities is a crucial requirement for the emittance preservation in the TESLA linacs. Experiments of HOM beam excitation have been performed on the accelerating modules of the TTF linac, with a recent emphasis on the measurement of the beam coupling and HOM polarization, in contrast to the frequency and damping parameters which are easier to measure. We report on the analysis of these experiments and on the measurement results.

## 1 INTRODUCTION

The goal of HOM measurements on the TTF linac is to verify that the requirements on mode damping are fulfilled on installed cryomodules [1]. An original beam charge modulation technique [2] was worked out to investigate HOMs: the beam spectrum is enriched with tunable side-bands at frequency $f_{side} = mf_b \pm f_{mod}$, where $f_b$ is the bunch repetition frequency, $f_{mod}$ is the modulation frequency and $m$ an integer. Resonant excitation of a HOM occurs when $f_{side} = f_{HOM}$. Dipole modes excitation requires the beam to follow an off-axis trajectory. A dog-leg magnet located before the module under test offsets the beam trajectory horizontally by an amount $\delta x$. The beam transverse kick proportional to $(r/Q)\delta x$ is measured by a beam position monitor (BPM) located downstream. This technique allowed the discovery of high impedance modes [3]. In more recent measurements [4], the same experimental method was used to extend the search on possible dangerous modes in higher dipole passbands. An analysis of these experiments focusing on RF signals recorded at HOM coupler output is presented in the present paper. We also propose a method to measure the beam orbit inside an accelerating module by measuring RF the power generated on dipole modes, and we report on the first experiments.

## 2 HIGHER DIPOLE BANDS

Experiments in [4] consisted in covering a large frequency range by scanning the modulation frequency. The beam current was 5 mA and the bunch frequency $f_b$ 54 MHz. When a resonant transverse excitation of the beam is detected on BPM signal, the RF output of the HOM couplers of all 8 cavities in the module is recorded using a spectrum analyzer (SA) in zero-span mode. In this configuration, the SA is equivalent to a tunable bandpass filter, centered on $f_{SA}$, and provides time-domain measurements. A set of $m$ values can be tested by setting $f_{SA} = mf_b \pm f_{mod}$ in order to determine $f_{HOM}$ and the factor $Q_{ext} = 2\pi f/\tau$ from the measured decay time $\tau$.

High Q modes were discovered in third dipole band although their frequency is above cutoff. The existence of this trapped modes is explained in [5] using a complete model of the module based on S-parameters, and a modified coupler design is proposed to cure the problem.

High Q modes were found experimentally in $5^{th}$ dipole band. They are listed in table 1.

Table 1: High Q modes of D5 band

| $f_{mod}$ (MHz) | $f$ (GHz) | cavities | $Q$ |
|---|---|---|---|
| 23.78 | 3.063724 | 1,8 | 1.7 $10^7$ |
| 19.29 | 3.068209 | 6,7 | 3.4 $10^7$ |

For most D5 band measurements, the $(r/Q)$ could not be inferred from the BPM signal, since quadrupole modes were simultaneously excited. The quadrupole kick is proportional to $\delta x^3$, whereas the dipole kick is proportional to $\delta x$, therefore the quadrupole kick was dominant for $\delta x$=20 mm. The $(r/Q)$ has to be estimated using SA time-domain data. For a particular mode, if $f$ and $Q_{ext}$ are known, the HOM output power at steady state can be computed for a given $(r/Q)$. We have chosen to compare RF measurements with calculations for $(r/Q)$=1 Ω/cm$^2$, the highest value for D5 band calculated in [6]. Predicted power levels at SA input are of the order of -10 to 0 dBm, assuming that the polarization angle is horizontal. All measured RF levels of high Q modes are lower than -30 dBm. Several explanations account for this situation in D5 band :

- All excited dipole modes have a low $(r/Q)$
- Modes with $(r/Q) \simeq 1$ Ω/cm$^2$ exist, but their polarization angle $\psi$ is close to vertical: the horizontal beam offset is not efficient to excite them.
- All measurements are triggered by quadrupole modes. The central frequency of the SA filter $f_{SA}$ may be different from the dipole $f_{HOM}$ . The mode is excited off resonance, resulting in lower HOM output power. The 20 to 30 dB difference between the predicted ideal case and measurements implies $|f_{side} - f_{HOM}| \geq 10$ kHz for the mode at 3.068209 GHz. Now, the hypothesis that the modes would not have been excited closer to resonance during automated scan of $f_{mod}$ is in contradiction with the fact that the step of the frequency scan was 2 kHz.

The real situation is likely to be a combination of first and second hypothesis. No definitive conclusion concerning the existence of strong HOMs in the D5 band can be given. Vertical beam deflection is mandatory to discard the second hypothesis.

## 3 USING HOM TO MEASURE THE BEAM TO CAVITY OFFSET

### *3.1 Principle*

Monitoring the beam offset relative to the individual cavity axis would be extremely helpful to reduce the emittance growth in the TESLA linacs. It would, for instance, enable one to optimize the orbit bumps needed to reduce the transverse wake effect, or to localize any badly misaligned module. If local corrections are available, it would also relax the module and cavity pre-alignment tolerances.

Interaction between a train of bunches of constant charge $q$ with bunch spacing $t_b$ traversing the cavity at radial offset $r$ and a dipole mode $i$ characterized by $\omega_i$,$(r/Q)_i$,$Q_i$, and decay time $\tau_i = 2Q_i/\omega_i$ results in RF power generation at the output of the HOM coupler $P_{out,i}$. When the steady state is reached

$$P_{out,i} = \frac{q^2\omega_i^2}{4Q_i}\left(\frac{r}{Q}\right)_i (r\cos\psi_i)^2 f(\omega_i, t_b, \tau_i) \quad (1)$$

where $\psi_i$ is the polarization angle of the mode. The function $f$ accounts for the resonant response of the mode :

$$f(\omega_i, t_b, \tau_i) = \frac{1-e^{-2t_b/\tau}}{2t_b/\tau} \quad (2)$$
$$\times \left(\frac{1-e^{-t_b/\tau}}{1-2e^{-t_b/\tau}\cos(\omega_i t_b)+e^{-2t_b/\tau}}\right)^2$$

Note that the steady state may not be reached depending on the values of $Q$ and the length of the pulse $N_b t_b$. The condition for this reads $Nt_b \gg 2Q_i/\omega_i$. Measuring $P_1$ and $P_2$ respectively on each polarizations of a dipole mode allows to calculate $r$ since

$$r^2 = P_1/C_1 + P_2/C_2 \quad (3)$$

with

$$C_i = \frac{q^2\omega_i^2}{4Q_i}\left(\frac{r}{Q}\right)_i f(\omega_i, t_b, Q_i) \quad (4)$$

using the hypothesis that polarizations are orthogonal. The x and y coordinates of the beam can be determined by combining two measurements which differ by a known beam offset at the structure entrance.

### *3.2 Preliminary measurements*

The attenuation of all RF cables connecting the HOM couplers to the external rack has been measured in the frequency range 1-3 GHz. The cold cables inside the cryostat have been measured using a network analyzer in reflection mode. The attenuation of the room temperature cables was given by difference power measurements. The later show a very small spread among the batch of cables, excluding one cable of cavity 8. During measurements with beam, the train was 780 $\mu$s long, bunch frequency 2.25 MHz, and the current within the pulse 8 mA, unmodulated. Measurements of RF power generated on monopole modes were compared to calculations of $P_{out} = \frac{q^2\omega^2}{4Q}\left(\frac{r}{Q}\right) f(\omega, t_b, \tau)$ The last two modes of $2^{nd}$ monopole band have been chosen for this purpose since they feature a high loss factor. Their characteristics are shown in table 2.

Table 2: Two selected HOM of M2 band

| Mode | $f$ (GHz) | $\left(\frac{r}{Q}\right)$ ($\Omega$) | $Q$ range |
|---|---|---|---|
| TM011_8 | $\sim$ 2.450 | 155.3 | 5.7 $10^4$-1.3 $10^5$ |
| TM011_9 | $\sim$ 2.460 | 148.7 | 9.5 $10^4$-2.5 $10^5$ |

Measurements of HOM output power were carried out on cavity 2,3,4,6 and 8 in module III. Results are shown on figure 1. Discrepancies are all within 3 dB, but for cavity number 8. The fact that all mode frequencies were not known with equal accuracy is the main source of errors in this case. The RF signal at HOM coupler output is the superposition of the cavity HOM extracted by the coupler, and the direct interaction of the beam with the impedance of the coupler itself referred as the direct signal. Concurrently to each measurement of the HOM output, the nonresonant direct signal was recorded, setting $f_{SA}$ several passbands away from $f_{HOM}$. The lack of exponential decay is the signature of direct beam electromagnetic influence on the coupler. All measurements display a direct signal weaker than monopole HOM signal by a least two orders of magnitude.

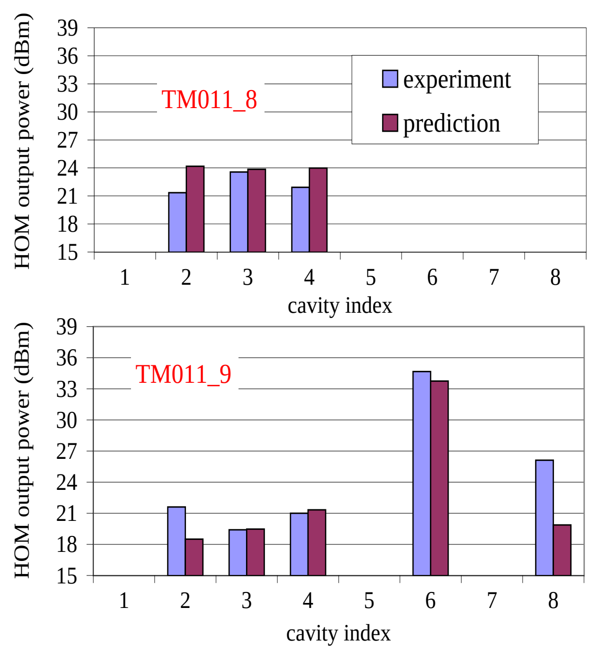


Figure 1: comparison of predicted and measured monopole HOM power

### *3.3 Position measurements*

The best candidates among dipole modes for position measurements are modes below cutoff with high $(r/Q)$, since we want to determine the beam position in each cavity with the highest sensitivity. Selected modes are listed in table 3.

Table 3: HOMs of D1 and D2 band selected for beam position measurements

| Mode | $f$ (GHz) | $\left(\frac{r}{Q}\right)\ \left(\frac{\Omega}{cm^2}\right)$ | $Q$ range |
|---|---|---|---|
| TE111_6 | $\sim$ 1.705 | 11.1 | 5.3 $10^3$-4.0 $10^4$ |
| TE111_7 | $\sim$ 1.730 | 15.6 | 3.3 $10^3$-1.1 $10^4$ |
| TM110_4 | $\sim$ 1.865 | 6.4 | 1.4 $10^4$-6.9 $10^4$ |
| TM110_5 | $\sim$ 1.875 | 9.0 | 1.8 $10^4$-1.4 $10^5$ |

For cavity number 2, data on 2 modes on both polarizations could be acquired which can be considered as two independent position measurements. The two positions derived from the data are consistent within 5 %.

The beam position across the module derived from dipole HOM measurements is shown in figure 2.

Since the beam orbit at the module entrance was kept constant during the experiments, we could access the radial offset $r$ and not the $x$and $y$ coordinates. Since the sign of beam position cannot be measured the data is consistant with the beam crossing the axis of the module around its center. At the operating gradient of $\simeq$ 20 MV/m, this is expected from RF focalisation effect for a beam entering the module with zero angle.

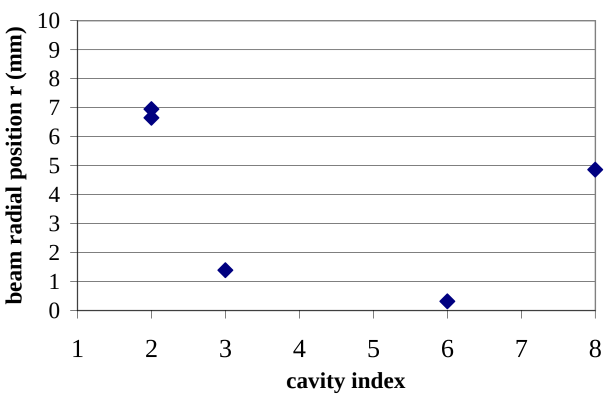


Figure 2: Beam position derived from dipole HOM measurements

## *3.4 Limitations*

For some cavity/mode combinations, the distance from beam frequency to HOM frequency is near to maximum $1/2t_b$,i.e. $\simeq$ 1.1 MHz. In this situation, a resolution bandwidth (RBW) of the order of 1 MHz is required to catch all power generated on the mode. Since the two polarizations of the dipole mode are distant from 100 to 300 kHz in frequency, a proper separation would require an RBW of 100 kHz. In this case, only the total power of the two polarizations can be accessed by time domain measurements. A better method would consist in taking data in frequency domain after time windowing, and post-processing the calibrated spectra to get the integrated power on each of the polarizations. For some dipole modes of some cavities for which the RF level is comparable to the power generated by direct beam/coupler interaction, sensitivity problems arise. These modes should not be used for position measurements.

Bunch to bunch position jitter at module entrance leads to power generation even for a beam which is on axis on average, and sets the maximum sensitivity of the measurement.

# 4 CONCLUSION

HOM beam experiments on TTF linac lead to the discovery of high Q modes in third and fifth dipole passbands. Due to limitations in the experimental setup, polarization information could not be inferred from measurements. A consequence is that no definitive conclusion on the existence of high impedance modes in the D5 band can be given. on high order modes appear as a useful source of information on impedance under well know beam conditions. Inversely, the can be used to measure the beam position when the dipole mode characteristics are known precisely

# 5 ACKNOWLEDGEMENTS


We thank M. Luong for his help on modeling possible artifacts in the measurements and related discussions, G. Kreps and A. Goessel for helping us during RF measurements.


# 6 REFERENCES


[1] R. Brinkman, K. Flöttman, J. Roßbach, P. Schmüsser, N. Walker and H. Weise (eds.), “TESLA Technical Design Report, Part II The Accelerator”, DESY, 2001-11, http://tesla.desy.de/new_pages/TDR_CD/PartII/accel.html

[2] S. Fartoukh, ”A New Method to Detect the High Impedance Dipole Modes of TESLA Cavities”,Saclay Preprint, DAPNIA/SEA-98-18.

[3] S. Fartoukh et al.,”Evidence for a Strongly Coupled Dipole Mode with Insufficient Damping in TTF First Accelerating Module”, Proc. of the 1999 Particle Accelerator Conference, New York, USA, p.922.

[4] Ch. Magne et al., “Measurement with Beam of the Deflecting Higher Order Modes in the TTF Superconducting Cavities”, Proc. of the 2001 Particle Accelerator Conference, Chicago, USA, p.3771.

[5] M. Dolhus et al., “Higher Order Mode Absorption in TTF Modules in the Frequency Range of the 3rd Dipole Band”, DESY-TESLA-2002-05,2002

[6] R. Wanzenberg, “Monopole, Dipole and Quadrupole Passbands of the TESLA 9-cell Cavity”, DESY-TESLA-2001-33,2001