

HOM BEAM COUPLING MEASUREMENTS AT THE TESLA TEST FACILITY (TTF)

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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 sidebands at frequency $f_{side} = m.f_b \pm f_{mod}$, 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 δx . 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 insufficiently damped 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 the RF 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 the 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 $f_{SA} = m.f_b \pm f_{mod}$ in order to determine f_{HOM} and the factor $Q_{ext} = 2\pi f/\tau$ from the measured decay time τ .

High Q modes were discovered in the +third dipole band although their frequency is above cutoff. The existence of these 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 5th 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	$1.7 \cdot 10^7$
19.29	3.068209	6,7	$3.4 \cdot 10^7$

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 δx^3 , whereas the dipole kick is proportional to δx , therefore the quadrupole kick was dominant for $\delta x=20$ mm. Instead 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 $(r/Q)=1 \Omega/\text{cm}^2$, 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 were found lower than -30 dBm. Several explanations can account for this situation in D5 band :

- All excited dipole modes have a low (r/Q)
- Modes with $(r/Q) \simeq 1 \Omega/\text{cm}^2$ exist, but their polarization angle ψ 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. This is excluded since the step of the frequency scan of f_{mod} was 2 kHz.

The real situation is likely to be a combination of first and second hypothesis. No definitive conclusion concern-

ing the existence of strong HOMs in the D5 band can be given. Vertical beam deflection would be required to discard the second hypothesis.

3 USING HOM TO MEASURE THE BEAM TO CAVITY OFFSET

Monitoring the beam offset relative to the individual cavity axis would be extremely helpful to reduce the emittance growth in the TESLA linacs. For instance it would 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.

3.1 Principle

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 ψ_i is the polarization angle of the mode. The function f accounts for the resonant response of the mode :

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

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 $N_b t_b \gg 2Q_i/\omega_i$. Measuring P_1 and P_2 respectively on each polarization 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 1-3 GHz frequency range. 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 latter show a very small spread among the batch of cables, excluding one cable of cavity 8. During measurements with beam, the train was 780 μ 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 the 2nd 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)	$\left(\frac{r}{Q} \right)$ (Ω)	Q range
TM011_8	~ 2.450	155.3	$5.7 \cdot 10^4 - 1.3 \cdot 10^5$
TM011_9	~ 2.460	148.7	$9.5 \cdot 10^4 - 2.5 \cdot 10^5$

Measurements of HOM output power were carried out on cavity 2,3,4,6 and 8 in module 3. 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 to as the direct signal. Concurrently to each measurement of the HOM output, the non-resonant 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 show a direct signal weaker than the monopole HOM signal by a least two orders of magnitude.

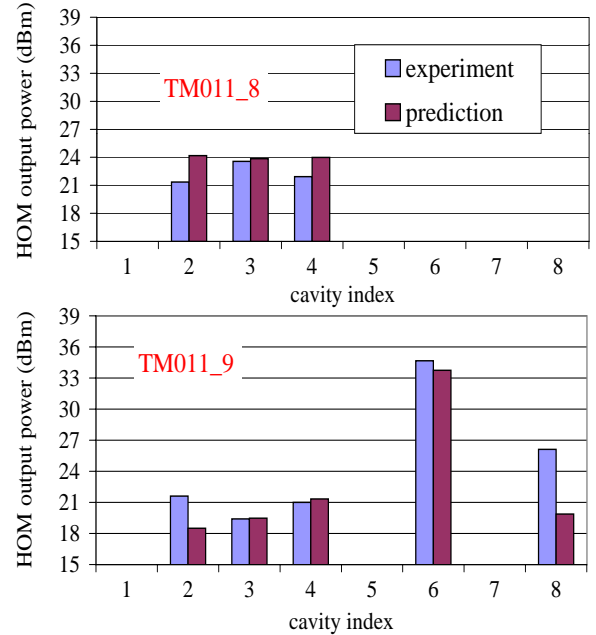


Figure 1: comparison of predicted and measured monopole HOM power

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	~ 1.705	11.1	$5.3 \cdot 10^3 - 4.0 \cdot 10^4$
TE111_7	~ 1.730	15.6	$3.3 \cdot 10^3 - 1.1 \cdot 10^4$
TM110_4	~ 1.865	6.4	$1.4 \cdot 10^4 - 6.9 \cdot 10^4$
TM110_5	~ 1.875	9.0	$1.8 \cdot 10^4 - 1.4 \cdot 10^5$

For cavity number 2, data on 2 modes, 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 consistent 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.

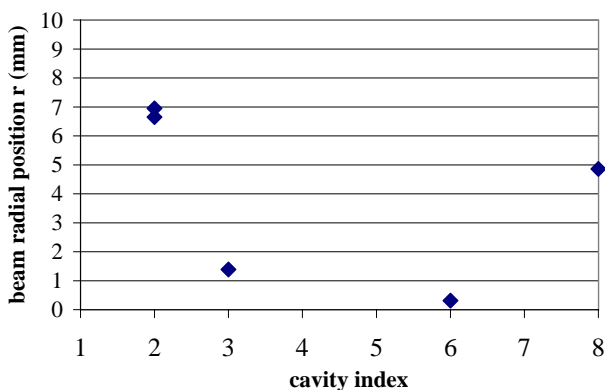


Figure 2: Beam position derived from dipole HOM measurements

3.4 Limitations

For some cavity/mode combinations, the distance from beam frequency to HOM frequency is near its maximum value $1/2t_b$, i.e. ~ 1.1 MHz. In this situation, a resolution bandwidth (RBW) of the order of 1 MHz is required to catch all the 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 with time gating, 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. As a result, no definitive conclusion on the existence of high impedance modes in the D5 band could be given. Measurements of power generated on high order modes appear as a useful source of information on impedance under well know beam conditions. Inversely, they can be used to measure the beam position when the dipole mode characteristics are known precisely.

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6 REFERENCES

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