HOM COUPLER NOTCH FILTER TUNING FOR THE EUROPEAN XFEL CAVITIES

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Abstract

The notch filter (NF) tuning prevents the extraction of fundamental mode (1.3 GHz) RF power through Higher Order Modes (HOM) couplers. The procedure of NF tuning was optimized at the beginning of serial European XFEL cavities production. It allows keeping the filter more stable against temperature and pressure changes during cavity cool down. Some statistics of NF condition during cavities and modules cold tests is presented.

INTRODUCTION

One of the most important procedures of cavity preparation for cryo tests is tuning of HOM couplers filter [1]. The goal is reaching the minimum RF transmission on the operating mode (π-mode) at 1.3 GHz under cryo-conditions. Notch filter tuning is done by changing the gap between HOM coupler antenna end and cap (capacitance tuning) by applying a force (push or pull) on the HOM coupler cap (see Fig. 1) using a special tool.

The European XFEL cavity has 2 HOM couplers; fundamental mode NF must be tuned for both of them.

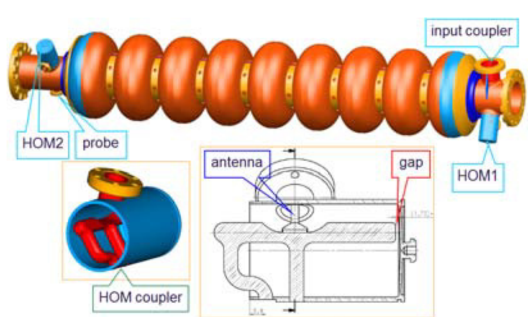

Figure 1: HOM couplers of the European XFEL cavities.

Primarily this operation is done directly before the first vertical cavity test, then constantly checked and in case of necessity adjusted before new tests or integration in the XFEL module.

Procedures of NF tuning and measurements depend on cavity conditions (see below).

CONTROL MEASUREMENTS

The two kinds of measurements will be described here:

- warm (at room temperature), done always before and after cavity tuning or adjustment;
- cold (at 2 K), control the output power of fundamental mode through HOM couplers.

Warm measurements of transmission magnitude S21 values in full TM011 bandwidth (1285 ± 15) MHz (between HOM coupler and antenna on opposite side) allow identification of the resonance frequencies (fundamental mode spectrum) and their amplitudes (9 points in Fig. 2).

Analysing the curve, built by these points, one can see:

1. Curve smoothness shows the direction of detuning:
   - local extremum (minimum) between points #5 and #9 (Fig. 2, green) – $F_{filter} < (F_{(\#8)}+F_{(\#9)})/2$;
   - smooth curve (Fig. 2, red) – $F_{filter} > (F_{(\#8)}+F_{(\#9)})/2$.
2. Amplitudes deviations between definite points (S21(#5) – S21(#8) and S21(#8) – S21(#9)) indicate the quality of the NF tuning (see criteria in "Algorithm of Tuning").

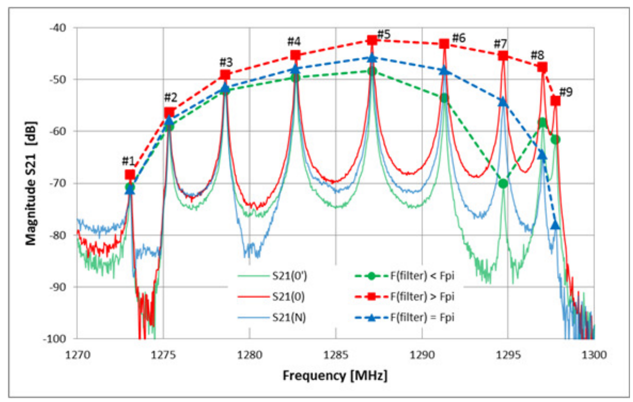

Figure 2: Fundamental mode spectrum with amplitudes ($F_{pi} = F_{(\#9)}$= 1297.75 MHz).

The 9 points (resonance amplitudes) are enough to analyse the NF tuning quality and direction (sometimes quantity) of detuning, therefore they are being saved and collected in the XFEL cavity database (DB) [2].

Additional criterion is used for NF of HOM2 – output power through HOM2 coupler at pi-mode should be at least two times less than through probe antenna. It means that transmission between input coupler and HOM2 should be at least 3 dB lower than between input coupler and probe (Fig. 3, Pickup – HOM2(9)).

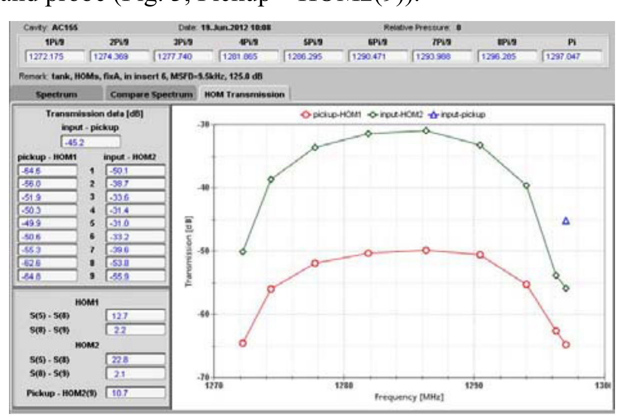

Figure 3: Control measurements at room temperature.

A similar analysis is not trivial under cryo temperatures, because the quality factors of all resonance frequencies strongly increases and amplitude measurements become not precise enough. The calibration values (Fig. 4) are used for output power estimation.

The output power of fundamental mode 1.3 GHz for different antennas depends on the cavity gradient and for TESLA shape geometry can be calculated as:

$$\mathrm{P(Probe, HOM)} = \frac{(E\ acc\ L)^2}{R/_Q\ Q\ (Trans,\ HOM)}$$
$$= 1.04 \cdot 10^{-3} \frac{Eacc^2}{Q\ (Trans, HOM)}\ , \quad (1)$$

where: $Eacc$ – operational gradient [V/m],
Q – quality factor of probe or HOM coupler antenna.

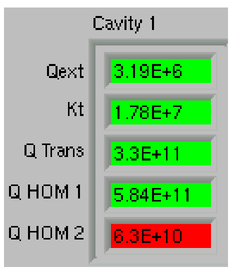

Figure 4: Control measurements at 2 K, red colour indicates a NF detuning (value out of range).

Ratio (2) depends only on calibration parameters and can be used as universal criteria independently on cavity accelerating gradient.

$$\frac{\mathrm{P\ HOM}}{\mathrm{P\ Probe}} = \frac{Q\ Trans}{Q\ HOM}\ . \quad (2)$$

If this ratio is more than 1, the Q HOM value in the calibration table is marked with red background (see Fig. 4).

ALGORITHM OF TUNING

The tuning is always done at room temperature, but in different conditions:

- relative pressure (RP) is 1, almost equal pressures inside and outside the cavity (1 atm);
- RP = 0, cavity has vacuum inside.

Our investigations showed that during pressure changes by cool down between 4 K and 2 K, the filter frequency increases by about 400 kHz. So the NF has to be tuned exactly at pi-mode frequency ($F_{target} = F_{pi}$) for RP = 0, and between 8/9pi and pi-mode ($F_{target} = (F_{(\#8)}+F_{(\#9)})/2$) for RP = 1.

Original filter frequency (Fig. 2 and 5) could be lower (0' – green curve) or higher 0 – red one) than the target one (F_{target}).

In any case the first iteration is filter detuning to opposite direction: (0' – 0) or (0 – 1).

After each iteration, when the tuning tool is relaxed and the HOM coupler cap is free of extra forces, filter frequency should overcome the target, but be closer to it.

To improve the stability of tuning, by reduction of local stresses and hardening the material of HOM coupler, it is necessary to increase the number of iterations and smoothness of frequency deviations $|F_{filter} - F_{target}|$ for iterative sequence: (0')-0-1-2-3-…-N.

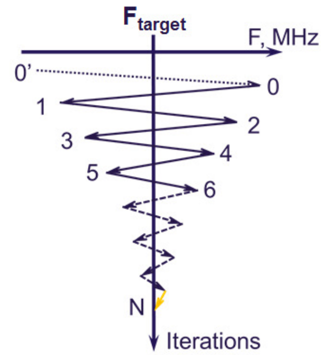

Figure 5: Algorithm of gap tuning.

The NF tuning is ready (N-th iteration, $F_{filter} = F_{target}$), if:

- (RP=1), the amplitude of transmission signal S21 of pi-mode is minimal and usually S21(#8) - S21(#9) > 10 dB;
- (RP=0), the amplitudes of transmission signal for the last two peaks in fundamental spectrum (see Fig. 2) are equal: S21(#8) = S21(#9) .

Amplitudes deviation S21(#5) – S21(#8) in both cases has to be more than 15 dB. Accuracy of amplitude determination is not less than 0.5 dB.

To prevent NF detuning, control measurements are being done after dismounting of the tuning tool.

STATISTICS

The statistics of measurements for the cavities and modules under cryo conditions is based on the measurement results, collected in the XFEL cavity DB.

The analysis of separate cavity results during the vertical and module tests (table 1) shows:

- average output power (and its deviation) through probe antenna reduces for measurements in modules. It can be explained by the accelerating gradient reduction in comparison with vertical tests (VT);
- the discrepancy between maximal and average values for the probe antenna is caused by strong dependency on the operational gradient (1). For some high gradient cavities (Eacc > 30 MV/m), output power of fundamental mode is about (7 ± 2) W;
- at the beginning of serial production, before iterative algorithm of NF tuning was used, some filters were detuned during cool down before VT (with pressure changes). Maximum value during VT had reached almost 8 W. It is about 30 times higher than the average value of P_{HOM}, but still did not exceed the maximum P_{Probe};

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- the HOM1 coupler filter for a cavity of the XFEL module XM4 has been detuned during module assembly and its output power (78 W) is 60 times higher than the average value during module tests, and exceeds the maximum P_{Probe} = 9.4 W in 8 times;
- universal ratio (2) shows that it is possible to keep the average output power through HOM coupler 3 dB less than through probe antenna even during module production;
- the maximum value of P_{HOM} / P_{Probe} during VT was reduced from 2.5 till 0.6 by implementation of iterative algorithm of NF tuning in cavity preparation procedure before cold tests.

Table 1: Output Power of Fundamental Mode from each Antenna in XFEL Cavity

Average and Maximum values for an antenna	in Vertical Tests	in Module Tests
$< P_{Probe} >$, W	3.6 ± 1.2	2.8 ± 0.8
Max(P_{Probe}), W	9.5	9.4
$< P_{HOM} >$, W	0.24 ± 0.21	1.3
Max(P_{HOM}), W	7.8	78
$< P_{HOM} / P_{Probe} >$	0.07	0.5
Max(P_{HOM} / P_{Probe})	2.5 -> 0.6	31

The measurement results for complete XFEL modules (8 cavities) are collected in table 2 and presented in figure 6.

Table 2: Output Power of Fundamental Mode from all Probes' and HOM Couplers' Antennae in XFEL Module

Average and Maximum values for a module	in Module Tests
$< P_{Probe} >$, W	22 ± 4
Max(P_{Probe}), W	35
$< P_{HOM} >$, W	21 ± 20
Max(P_{HOM}), W	189
$< P_{HOM} / P_{Probe} >$	1.0
Max(P_{HOM} / P_{Probe})	9.9

The average ratio P_{HOM} / P_{Probe} for a module is 1. Maximum value for XM23 is almost 10, because of critical NF detuning for 7 HOM couplers. Module XM4 has only two detuned HOM coupler filters, but maximal power for one of them is 78 W – almost two times more than from average complete module.

SUMMARY

Based on our experience, we can come to the following conclusions:

- use of iterative tuning algorithm allows to increase the stability of fundamental mode filtering against relative pressure changes by reduction of local stresses and hardening the material of HOM coupler. It prevents detuning during cool down and warming up between room temperature and 2 K;
- control measurements before and after cavities/ modules transportation show the good notch filter stability against vibrations;
- strong (critical) filter detuning is very seldom and appears only by HOM coupler deformations during module assembly.

ACKNOWLEDGMENT

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[1] A. Sulimov et al., "Description and First Experience with the RF Measurement Procedure for the European XFEL SC Cavity Production", 2nd IPAC'11, San Sebastian, Spain, 2011, pp. 277-279.
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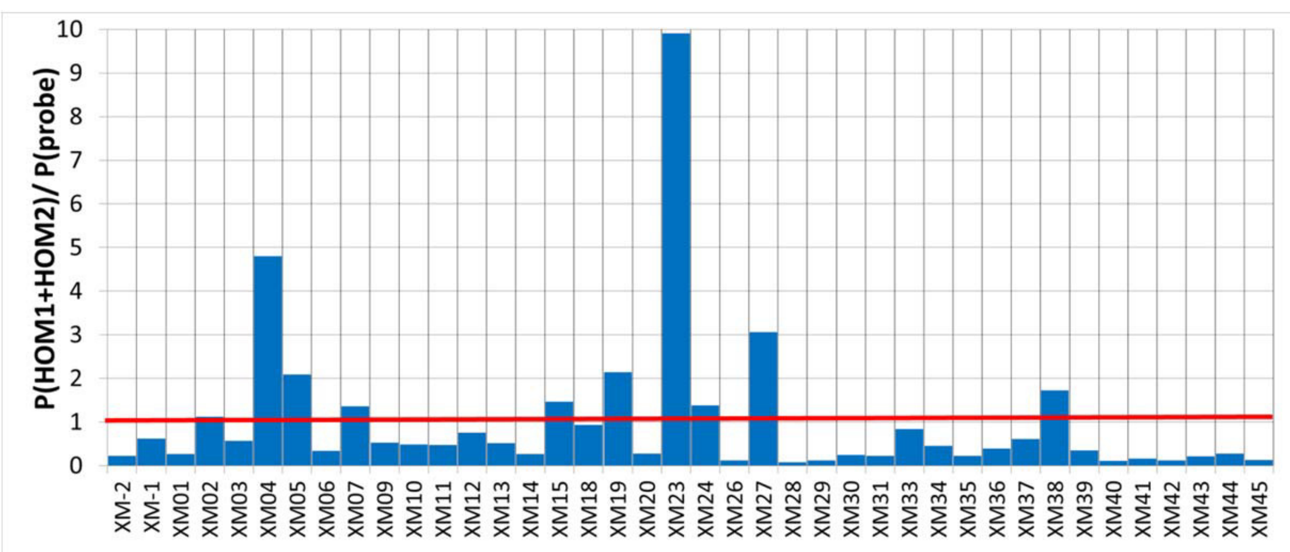

Figure 6: Average ratio P(HOM1 + HOM2) / P(probe) for 8 cavities in module.