FUNDAMENTAL MODE SPECTRUM MEASUREMENT OF RF CAVITIES WITH RLC EQUIVALENT CIRCUIT

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Abstract

The procedure of the cavity fundamental mode spectrum measurement consists of the following steps: scanning of the accelerating mode passband for any deviation from the standard one, determining all peaks in the accelerating mode passband and evaluating the mean spectrum frequency deviation. The upgrade of that procedure was proposed and successfully implemented. The cavity RLC equivalent circuit is used in order to predict the measured peaks. This method allows more quickly detects the peaks in the accelerating mode passband thereby reduce the time needed for test, which is crucial for serial production cavities testing.

In this paper, an upgrade of the test procedure and its validation with measurements is presented. The method was validated with data taken during testing of the cavities installed in two pre-series XFEL cryomodules. This improvement of the test procedure is implemented into the testing software and it is successfully used for serial production cavities testing.

INTRODUCTION

The European X-ray Free Electron Laser (European XFEL) near Hamburg in Germany will be a scientific facility to generate “ultrashort X-ray flashes with brilliance billion times higher than conventional X-ray radiation sources” [1]. It will give a new nano scale research opportunities for scientists in physics, chemistry, materials science and biology. Its longest part is a linear accelerator consisting of 101 RF cryomodules [1]. For each cryomodule 8 cavities will be installed in a string [2]. Before installation in accelerator cryomodules have to be tested. In the Accelerator Module Test Facility (AMTF), at DESY in Hamburg, a single superconducting RF cavity or cavities installed inside the cryomodule are tested by team from IFJ PAN Cracow, Poland within the framework of Polish in-kind contribution to the European XFEL. At the beginning of test of each cavity or cryomodule the initial testing procedures will be launched at room temperature in order to decide whether cavities will be used for cold tests [3]. Vital test at room temperature is a measurement of frequencies in TM010 mode (one of electromagnetic field distribution in a cavity). The convention follows from cylindrical pill-box cavity model, where TM denotes transverse magnetic and 010 integers refers to the number of sign changes of electromagnetic field in a cylindrical coordinate system [2]. This mode is used for acceleration. The measurement of this mode is called a fundamental mode spectrum (or spectra) measurement and was proposed by DESY experts [3, 4]. This paper describes modification of that test procedure using RLC equivalent circuit that is used for testing of XFEL serial-production cavities and cryomodules. The procedure is discussed in details in the next sections.

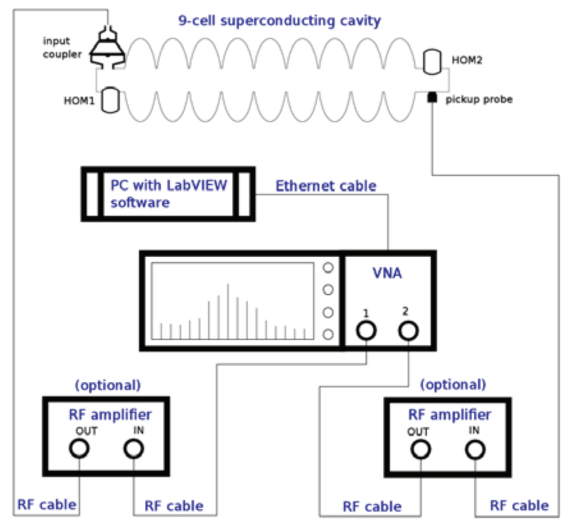

Figure 1: Test setup chart.

FUNDAMENTAL MODE SPECTRUM MEASUREMENT

The fundamental mode spectrum measurement is a basic cavity RF test that provides information about cavity deformation. The measured signal is a coefficient of power emerging from pickup as a result of applying an RF stimulus to input power coupler. In order to simplify the measurement the VNA (Vector Network Analyzer) is used. The measured parameter of VNA is S21 - forward transmission coefficient from port 1 to port 2, where port 1 is connected to input power coupler and port 2 to pickup probe (see Fig.1). The test results with use of dedicated software [5] are shown in Fig. 2.

The nominal passband of measured TM010 mode for that 9 cell cavity is in the range of 1.27-1.3 GHz. In this passband 9 peaks-maximums (called also π, $8/9\pi$, … , $1/9\pi$ modes) are measured. It is known from theoretical consideration that, “n coupled resonators oscillate in n modes for each resonance field pattern being an eigenvector of a single (uncoupled) cell” [6]. These modes have different frequencies. For XFEL operation π mode (set to 1.3 GHz at 2 K) of TM010 passband will be used to accelerate particles. In the frequency domain passband it is observed as 9 maximums, which are measured. These peaks frequencies are different and depend on a temperature and a pressure.

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Procedure and Field Flatness Estimation

One of the objectives of the fundamental mode spectrum measurement is to verify parameter called the Mean Spectrum Frequency Deviation (MSFD), which corresponds to the electrical field flatness and the mechanical deformation of the RF cavity [3]. The field flatness is vital parameter to be fixed during cavity tuning. It is the absolute value of quotient obtained from maximum and minimum values of an electrical field for each cell on longitudinal axis. The flat profile maximizes accelerating voltage in the cavity, so the energy given to the particles is maximized.

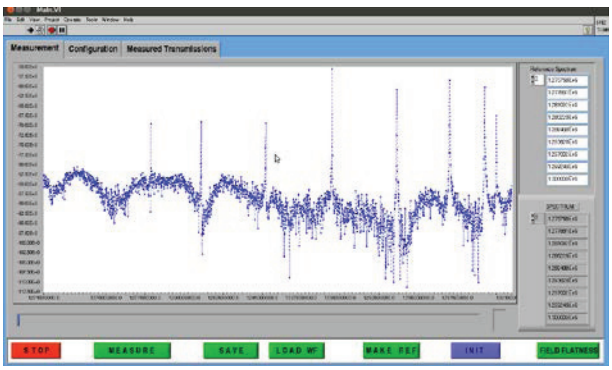

Figure 2: Test software during the measurement at 2 K.

After the cavity tuning the field profile is one of the measured parameter as well. So after fundamental spectrum measurement this data is used to calculate a correlation between measured frequencies of a fundamental spectrum to frequencies measured after final cavity tuning. It shows that the real aim of this test is to check distribution of the field among all 9 cells in accelerating mode

The measurement procedure of the Fundamental Mode Spectrum Measurement was proposed by DESY experts [3] and is as follows:

- Measure all 9 frequency peaks in passband 1.27-1.3 GHz and scan the frequency characteristic for any deviations from standard one
- Measure each frequency peak with high precision (with small span 50 kHz at 2 K and 100 kHz at 300 K)
- Check the Mean Spectrum Frequency Deviation (MSFD)

Frequency Peaks Prediction

A new idea of the second step of the fundamental mode spectrum measurement test procedure is to use an equivalent RLC circuit [2, 6] of cavity and beam tubes in order to predict the peaks during measurement and reduce the amount of time needed for the measurement. Fig. 3 shows a scheme of RLC equivalent circuit of a cavity with beam tubes. The physical explanations of elements in Fig. 3 are:

- C_k – cell to cell coupling
- C – capacitance of each symmetrical cell
- L – inductance of each symmetrical cell
- C_b – capacitance of beam tubes

Using Kirchhoff equations and matrix notation the following eigenvectors (1) and eigenvalues (2) are obtained [2]:

$$v_j^{(m)} = B^{(m)} \sin[m\pi(\frac{2j-1}{2N})] \quad (1)$$

$$f_m = f_0 \sqrt{1 + 2k(1 - \cos(\frac{m\pi}{N}))} \quad (2)$$

Where following parameters are defined as:

- $V_j^{(m)}$ – voltage in the each cell in the cavity
- m – mode number
- j – cell number
- $B^{(m)}$ – is a normalizing coefficient
- N – maximum number of cell
- f_m – frequency of m mode

It was noticed that by applying equation (2) to f_m mode and f_p mode, the parameter k can be calculated. As a result it is possible to predict remaining frequencies, when only 2 frequencies are read from fundamental mode spectrum. That results in automatic measurement of all peaks, except of the first two ones. From the first two measured peaks we are obtaining k coefficient, which among others characterizes cell-to-cell coupling [2]. Other peaks can be predicted using only k parameter.

This method was validated with cavities in two cryomodules PXFEL2_1 and PXFEL3_1. Cavities were measured for each cryomodule minimum 3 times: at 300 K and at 2 K. The results agreed with predictions.

Figure 3: RLC cavity and beam tubes equivalent circuit.

VALIDATION

A parameter k (the same for each cell), calculated from the first two frequencies in order to predict all others frequencies, is one of the solution. Actually not all cells of XFEL 9-cell cavities are identical [6], but for calculations the approximation is used. Cavity is treated as ideal with the same cells to calculate k that the best estimates the cavity behaviour. Several options of k calculation were validated: only one k, average value from all neighbour cells and several k from measured neighbour cells.

As a result, three goal functions were used to compare proposed algorithms: minimum error, quantitative error comparison and mean square error. Their outcomes showed that the last option was the best one. It means that the best of proposed algorithms is to use last two neighbor frequencies to calculate "k" parameter and then use calculated "k" to predict next (following) frequency

RESULTS

The RLC peak prediction algorithm was used for measurement of two previously mentioned modules and some observations were done.

Maximum Error

It was noticed that the measurement error was larger than 50 kHz for 44% of predicted values. The final measurement span was 50 kHz at 2 K and 100 kHz at 300 K. In the modified measurement algorithm (described in conclusions) the predicted peak's frequency was set as a centre frequency in the final sweep. For such errors the searched maximum was out of the measurement range. The solution for that observation was a bigger span. An additional sweep was added to measurement algorithm before final sweep. Its parameters were: 600 kHz span and 800 points. The resolution was selected to be good enough to measure the narrowest peak (about 10 kHz).

Maximum of Peak

It was also noticed that sometimes, for the final sweep, the maximum of peak was found at the beginning or at the end of measured range. This observation was treated as the measurement error and the searched maximum of that peak was out of the span. In such cases an additional sweep was added to the modified procedure. When frequency equivalent to maximum of peak was found less than 5% of measured range (span) ends, the additional sweep was made.

CONCLUSIONS

The peaks prediction procedure was implemented into the software used for testing XFEL RF-cavities. The update of the test procedure using the RLC peaks prediction was proposed and is used for serial-production of cavities as follows:

- Find all 9 frequency peaks in passband 1.27-1.3GHz and scan the frequency characteristic for any deviations from standard one
- The operator chooses which peaks would be predicted and which would be set manually
- The program measures automatically each frequency peak with high precision (with small span 50 kHz at 2K and 100 kHz at 300K), when peak is predicted then the additional sweep (600 kHz) is done before
- The operator checks the mean spectrum frequency deviation

At 2 K operators found peaks prediction to be very useful, because resolution of measurement is limiting peak's visibility. Despite having possibility for predefining markers on maximums (manual operation), the operator cannot see all peaks, because of their width (the smallest are about 10 kHz) and relatively small test system resolution (1600 points for 30 MHz span). The RLC equivalent circuit was proposed to speed-up the measurement, when peaks are not visible in the first step of the procedure. From the measurements one can conclude that in case when the operator cannot distinguish the peak's position in the first step of the procedure, he has to re-measure them again manually. That measurement takes some additional time, which is significant at high-regime measurement at serial-production testing.

The measurement was shortened for well-tuned cavities at cold condition (2 K) by using RLC equivalent circuit. The operator does not have to predefine all markers precisely before the automatic measurement part. The new modified test procedure has been verified with the pre-series cavities and is successfully used for the series cavities measurements.

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