Tuning of the TESLA Superconducting Cavities and the Measurement of Higher Order Mode Damping

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Abstract

The tuning of the TESLA cavity includes the adjustment of the operating frequency, the field flatness and the correction of the cell eccentricity. We used the measurement of the whole passband spectrum of the accelerating mode to tune cavities. A correlation between all frequencies of modes from this passband and field flatness has been analyzed. Two various designs of the higher order mode coupler have been tested up two now and the obtained damping of TE111, TM110, TM011 passbands is presented.

1. Introduction

TESLA Test Facility (TTF) - is an experimental accelerator to explore the feasibility of the superconducting linear collider TESLA. The technical advantage of superconducting collider comes from a low frequency (1.3 GHz) of the fundamental mode (fm). Such a low frequency allows to keep the large iris diameter of the accelerating structure and thus reduces the interaction between Higher Order Modes (HOM) and the accelerated beam. The weak interaction with transversal HOM gives relaxed requirements for the cavity alignment in the linac and small cavity wall losses make efficiency of this accelerator relatively high compared with other proposed type of the collider. Main questions to be answered with the help of the TTF accelerator is the possibility of operation of superconducting cavities at a high gradient up to 25 MV/m and simultaneously lower investment costs [1,2].

2. Cavity

Each TESLA cavity contains 9 cells, the input coupler, two higher order mode couplers and one pick up antenna (Fig. 1). The acceleration mode is TM010-p mode. The end cells are different in geometry from the other cells, what allows to reach an identical field strength in all cells. The cavities are fixed in the helium vessel after the adjustment of cells and a preliminary cold test. One side of the cavity is fixed to the vessel rigidly. The other side is movable in order to tune the cavity during the operation.

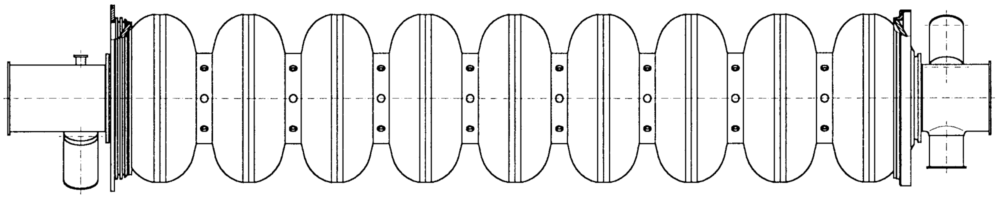


Figure 1. TESLA cavity. 1,2 - welded HOM couplers. 3 - port of the pick up antenna. 4 - port of the input coupler. 5 - bellows.

Table 1. Parameters of the TTF cavity

Fundamental p mode frequency	1300 MHz
Number of cells	9
Cavity length	1376.2
Input coupler	1
HOM couplers	2(both sides)
Rejection filter of HOM coupler	Qext>1.0E+11
Pick up antenna	Qext=1.0E+11
Maximum cell eccentricity	0.4

3. Tuning

Each new manufactured cavity, before cold RF test, requires the following adjustment steps:

final adjustment of cells to the operating frequency field,
field flatness correction,
tuning of the fundamental mode rejection filter of the HOM couplers,
adjustment of the pickup antenna to Qext=1.0E+11,
correction of the straightness of the cavity.

The titanium treatment in the vacuum oven following by the chemical etching of a 80÷150 µm layer improves the thermal conductivity and RRR. This procedure allows to increase an accelerating gradient in the cavity but changes the field flatness and the frequency of the cavity. The rate of the frequency change by the chemical treatment of the inner surface is -10 kHz/µm. The difference in etching speed between cells results in the deterioration of the field flatness up to 70÷80 % for main chemical treatment (80÷100µm) which is done always after the cavity heat treatment. Therefore the process of chemistry is divided into 2 stages. The second final stage of chemistry removes only 20 µm and is done after the set-up of the cavity. After the final chemistry the further installation works are carried out in a clean room (class 10000). An additional chemistry 10 µ is possible, if the cavity was in a crude air environment. This compromise satisfies our requirements to the accuracy of the set-up and to cleanliness of a cavity surface.

3.1 Frequency of a cavity

The cavities are tuned in the air environment at room temperature in the conditions different from the operating conditions at 1.8 K and vacuum. In addition to avoid backlash of the tuner working in the cryostat, the cavity must stay under the compression during the operation. Therefore the initial frequency of a cold cavity has been chosen 600 kHz above operating frequency. The next factor reducing the frequency is the final chemical treatment (20÷30µm).

All factors changing the frequency of the cavity are:

Vacuum	+ 0.39 MHz
Cool down from 300 K to 1.8 K	+ 1.95 MHz
Final chemical treatment	- 0.3 MHz
Backlash pre-tuning	- 0.6 MHz
Sum:	1.44 MHz

3.3 Procedure of set-up

The set-up of a cavity is done in following way:

measurement of the cavity straightness,
measurement of frequencies and the fields profiles of all modes from fm passband,
phase determination of fields in cells for all modes,
simulation of tuning by the mathematical model,
mechanical deformation of cells,
measurement of cavity straightness,.
correction of straightness of a cavity.

3.3.1. Measurement of cavity straightness

The cavity rotates relatively the longitudinal axis and the eccentricities of cells and beam tubes are measured by the mechanical contact sensors. The mechanical sensors slide on the surface of cells in the area of the equator and measure the equator deviation from the circle. The maximum deviation should not exceed ± 0.4 mm for the equators and ± 0.5 mm for the ends of both beam tubes. The azimuth of the maximum deviation of each cell is measured concerning the direction of an input coupler. These data are used for the deformation of cells during the set-up of a cavity for the correction of eccentricity.

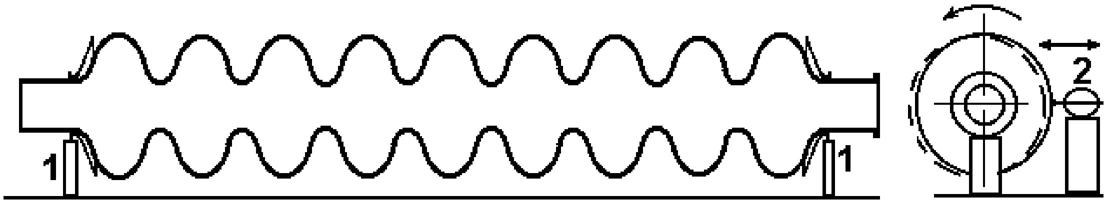


Figure 2. Measurement of cell eccentricity. 1- rotating support. 2- contact sensor.

3.3.2. Measurement of frequencies and fields

The distribution of a field amplitudes is measured by the standard bead-pull technique. As a perturbing object a small metal needle (diameter 1 mm and length 10 mm) is usually used. The needle and pulling string are housed in a plastic tube stretched across the axis of a cavity to prevent cavity from deposition of dust and plastic particles. The frequency of a cavity is changed insignificantly by -80 kHz and the field distribution perturbation is less than 2 %. due to the presence of the plastic tube. Coupling to the cavity is only possible through coupler ports or through beam tubes. This coupling has to be weak (Qext>5.8E+5) to avoid field perturbation of end cells. The 9 resonant frequencies from the fm passband and field amplitudes in cells are measured and the data are used to calculate the fm frequency shift corresponding to correctionof each individual cell frequency.

3.3.3. Phase determination

The phases of the field in cells with small amplitude are difficult to determine. There are two methods to find a phase in an individual cell:

- by means of distribution of amplitude or
- with the help of orthogonalization method.

The electric field component Ez equals zero in the iris region if the phase changes in two neighbouring cells. With beadpull technique one can measure only an absolute value of the field amplitude but not the phase. A sharp minimum between two cells means that phases shifted by 180°. If there is no minimum of the field between the neighbouring cells then these cells have the same phase. The problem appears if the field in the cell is small. For well tuned cavity 6p/9 mode has a very small field in cells 2, 5 and 8 (Fig. 3). The 2p/9, 4p/9, and 8p/9 modes have a low field only in cell No. 5. Even small detuning of the cavity changes phases in the low field cells.

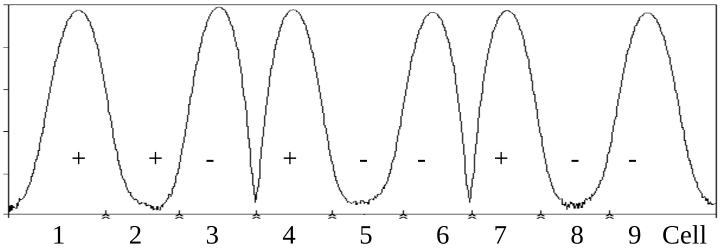


Figure 3. Determination of phase from measured |Ez| profile for 6/9p mode. Signs " + " and " - " are used to illustrate phases. Phase in the cells No 2, 5, 8 are changed for the cavity with wrong frequencies of an individual cells .

If it is impossible to determine a phase from the field distribution then an orthogonalization method can be applied. The fields of modes are eigenvectors of a symmetric matrix and thus they are orthogonal to each other. With Schmidt's orthogonalization method [5,6,7] one can remove errors in a phase. The calculation begins from the good determinate vectors and goes on to the vectors in which a change of a phase is supposed. The calculation of the orthogonal vectors will be carried out in the sequence shown in the Table 2.

Table 2.

Order of ortho-gonazation	mode	nr. cell								
		1	2	3	4	5	6	7	8	9
1	π									
2	7/9π									
3	3/9π									
4	5/9π				&		&			
5	2/9π					X				
6	8/9π					X				
7	4/9π			&		X		&		
8	6/9π		X			X			X	
9	1/9π	&								&

X - the phase changed by small detuning,
& - the phase changed only by large detuning.

3.3.4. Mathematical simulation of tuning

The mathematical model and the simulation of the tuning repeat the method used in the set-up of 4 cells superconducting HERA cavities [3]. The simulation by the mathematical model allows to reduce the number of the deformation cycles up to two. The mathematical model is equivalent to an electrical lumped element circuit. The simulation uses the measurement of the frequencies, amplitudes and phases of all resonant frequencies in the fm passband. There are following approximations in the model:

-Only coupling of neighbouring cells are taken into account,
-The neighbouring cells have only an electrical coupling, a magnetic coupling is neglected,

3.3.5. Mechanical deformation of cells

The cells are adjusted by the plastic deformation (pushing or pulling) of cells under the frequency control of the cavity. The first adjustment of cells, according to the calculated recipe, gives at least 80% of the field flatness. The next correction of 3÷4 cells makes field flatness of 95%. The plastic deformation threshold is different for cells therefore each cell should be deformed in many small steps to ensure finally required plastic deformation. The old HERA tuning machine has been adapted for a TESLA cavity. Fifteen TESLA cavities have been already tuned. The tolerances of the old tuning machine have not been sufficient for keeping the straightness of the cavity. In order to hold straightness of the cavity a lot of deformations and measurements are necessary. A new tuning machine has been constructed and is now under manufacturing. It will be computer controlled with a possibility to make the correction of the straightness.

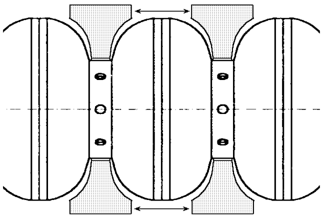


Figure 3. Deformation of cells for tuning.

4. Calibration of a pickup antenna

The length of the pickup antenna is adjusted to get an external quality factor Qpickup = 1.0E+11. To measure Qpickup the second electrical antenna is placed on the other side of the cavity. To avoid the deformation of a cavity field we use the second electrical antenna which is rather weak coupled and has an external quality factor Qext2 ≈ 1.0E+6 (S11≈ -0.1 dB). We measure the reflection of this antenna S11(dB), the transmission through the pickup antenna S21(dB), the quality factor Q of the cavity by the Network Analyzer and calculate Qpickup[8].

$$\text{Qpickup} = 4Q\frac{1-10^{{}^{S11}\!/_{10}}}{10^{{}^{S21}\!/_{10}{}^{2}}}\ .$$

5. HOM couplers

Two HOM couplers are placed on the both sides of a cavity (Fig. 1)[4]. Two versions of the HOM couplers have been developed and tested, one is welded to the cavity and the other one is mountable. The damping efficiency of the HOM couplers has been measured in the cryostat (Table 3). In order to exclude losses of a power of the operating frequency HOM couplers are equipped with a fm rejection filter, which allows to increase the Qext for the fundamental mode up to 1.0E + 13.

Table 3.

	F	R/Q	welded	mountable	Qext		F	R/Q	welded	mountable	Qext
	[MHz]	Ohm/cm2	Qext	Qext	BBU		[MHz]	Ohm/cm2	Qext	Qext	BBU
TE111			x1.0E+3	x1.0E+3	x1.0E+3	TM110			x1.0E+3	x 1.0E+3	x1.0E+3
1	1605.2	0.01	841	328		1	1780.8	0.71	5	1	
2	1605.4		492	1467		2	1781.3		5		
3	1613.7	0.14	149	110		3	1795.9	0.45	4	8	47
4	0.0		0	141		4	1796.4		10		
5	1626.8	0.03	98	26		5	1828.8	0.33	16	16	52
6	1627.0		67	55		6	1829.1		15	13	
7	1639.5	0.75	5	21		7	1847.5	6.47	0	8	76
8	1641.5		9	21		8			8		
9	1645.2	0.04	38	11		9	1861.6	8.75	0	20	120
10	1645.4		24	11		10			11	18	
11	1667.7	10.00	23	8		11	1871.9	1.83	17	27	194
12	1667.8		26	8		12	1872.2		32	30	
13	1694.3	15.40	23	5	8.1	13	1879.2	0.10	72	38	330
14	1694.7		14	5		14	1879.3		41	60	
15	1723.1	2.23	0	1	7.5	15	1884.0	0.18	19	98	670
16			8			16	1884.2		46	87	
17	1752.2	1.40	0	1	7.4	17	1887.0	0.01	78	199	
18			7	1		18	1887.2		178	1252	

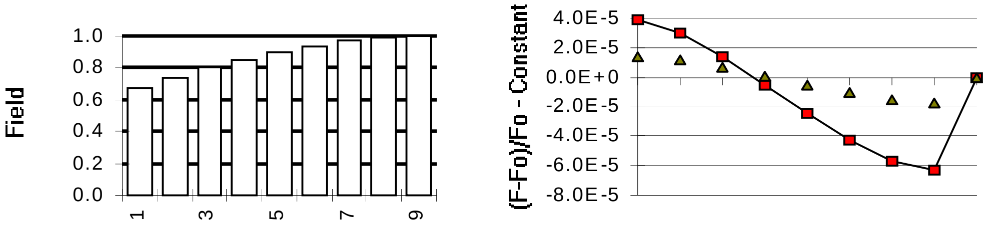
BBU= beam blow up limit

	F	R/Q	welded	mountable
	MHz	Ohm/cm2	Qext	Qext
TM011			x 1.0E+3	x1.0E+3
1	2361	0.00	1239	
2	2367	0.17	116	896.286
3	2375	0.65	47	71.7614
4	2386	0.65	23	59.259
5	2398	2.05	26	60.3199
6	2412	2.93	38	70.427
7	2425	6.93	31	73.7082
8	2434	67.04	44	91.6642
9	2440	79.50	61	225.529

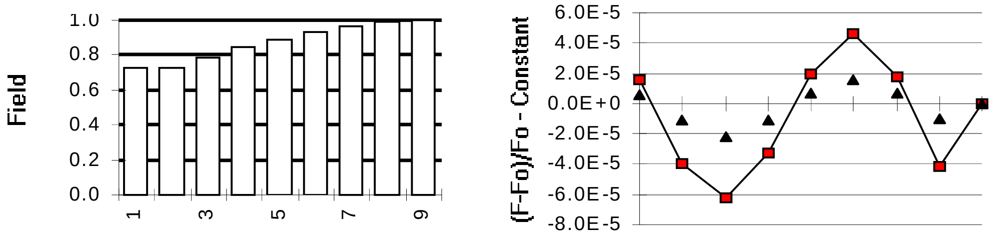
Both designs of HOM couplers need the adjustment of the rejection filter. The Qext of HOM coupler is measured with the same method and with the equipment we use for the pickup antenna adjustment. After the adjustment of the pickup antenna the output antenna of HOM coupler in case of welded coupler or whole mountable HOM coupler are removed from the cavity and installed back after the final chemical treatment.

6. The testing of a field flatness by the measurement of a cavity spectrum

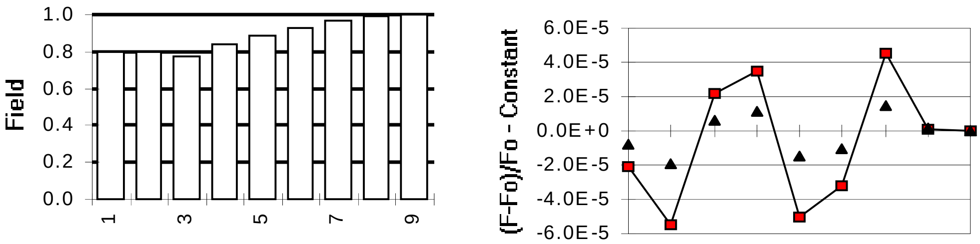
Detuning of 1 cell



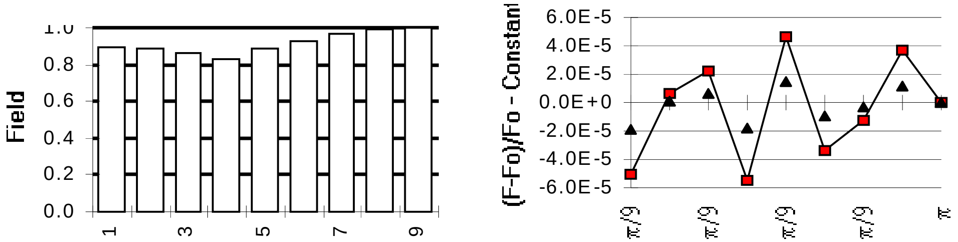
Detuning of 2 cell



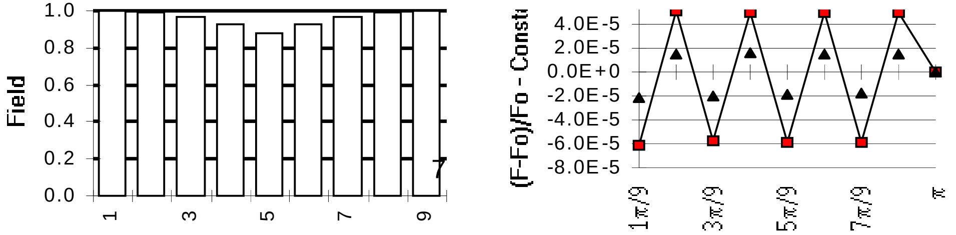
Detuning of 3 cell



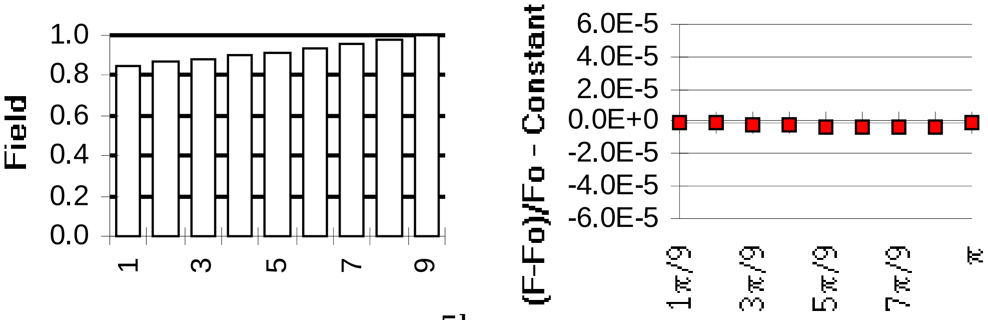
Detuning of 4 cell



Detuning of 5 cell



Detuning of 1 and 9 cell in the contrary directions



5b

Figure 5. a- The change of the field and the spectrum due to detuning of individual cells. Calculation (line), experiment (points). b- Detuning of cells No 1, 9 in the contrary directions.

The mechanical deformation of cells changes the field flatness and the frequencies of fm passband spectrum. The mathematical simulation (based on the electrical lumped element circuit) has been used to calculate the correlation between the field perturbation and the change of frequencies from this passband. The calculation has been compared with an experimental detuning of each cell by a small perturbing object placed in the middle of the cell. Figure 5a shows the amplitudes and the change of modes frequency corresponding to this kind of detuning. These results give only first approximation of a cavity detuning. The spectrum measurement allows to determinate the critical change of the field and gives guess which cell has been deformed. The deformation of the symmetrical cells 1-9, 2-8, 3-7, 4-6 causes an identical change of the spectrum but the opposite influence on the field. The Figure 5b shows that the tuning of cell 9 compensates for the change of the spectrum from the tuning of cell 1 but on the other hand gives the modification of the field flatness. The probability of the random compensation is very low. Therefore the control of the spectrum is used to check the mechanical deformation of cavities without beadpull measurements.

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