DAΦNE TECHNICAL NOTE

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IMPEDANCE OF DAΦNE SHIELDED BELLOWS

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Introduction

The bellows placed between the DAΦNE [1] arcs and straight sections must allow 35 mm longitudinal expansion and 10 mm horizontal offset. It was decided to avoid any sliding contacts in the bellows which can be burned out due to the high current flowing on the bellows screen. Moreover, if, for any reason, there is no contact between the sliding surfaces the capacitance between the sliding contacts can create a resonant circuit with the rest of the bellows. This can affect the multibunch beam stability and is a source of possible high power loss. Another potential danger is creation of dust particles between the sliding surfaces.

The bellows design originally proposed for DAΦNE is shown in Fig. 1. The bellows screen is made of thin (0.2 mm) strips oriented in the vertical plane and separated by 4 mm gaps. The width of a strip is 5 mm, i. e. wider than the gap between the strips in order to attenuate radiation outside the screen.

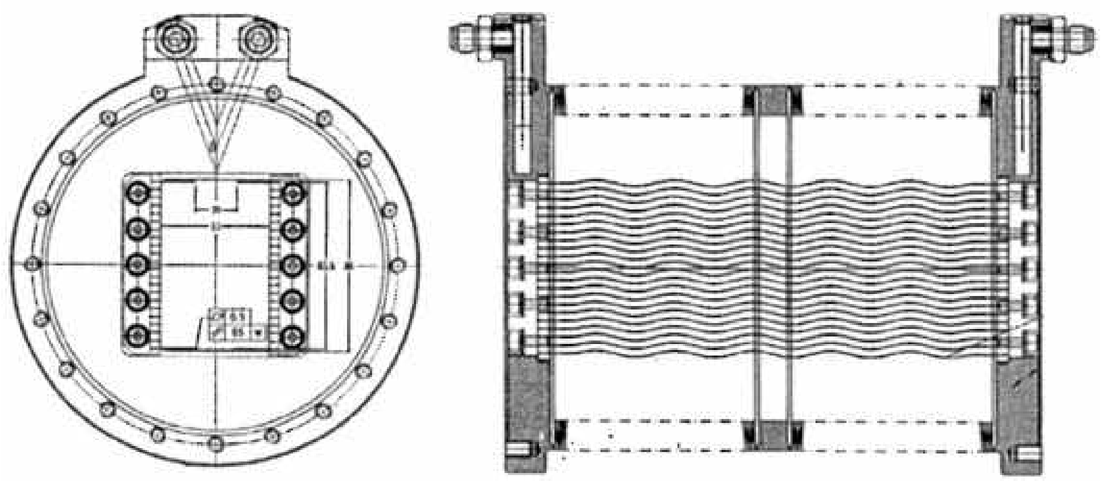


Fig. 1 - Initially proposed DAΦNE bellows design.

The strips are produced by a hot forming method and have a waved shape. This allows longitudinal expansion. In the working regime the strips are supposed to be almost straight.

In this note we discuss the results of bellows impedance measurements and numerical simulations and describe methods to damp residual High Order Modes (HOMs) in such a complicated structure.

First measurements

In order to check the effectiveness of the screen and to measure the bellows impedance a prototype has been built. The strips were produced by DOIG SPRING (UK). The bellows itself was substituted by a pill-box cavity having approximately the same sizes as bellows.

Figure 2 shows the results of the impedance measurements with a standard wire method [2]. Dotted lines correspond to HOMs trapped in the pill-box volume without the screen, while solid ones show the shunt impedance of the HOMs remaining in the structure with the inserted screen.

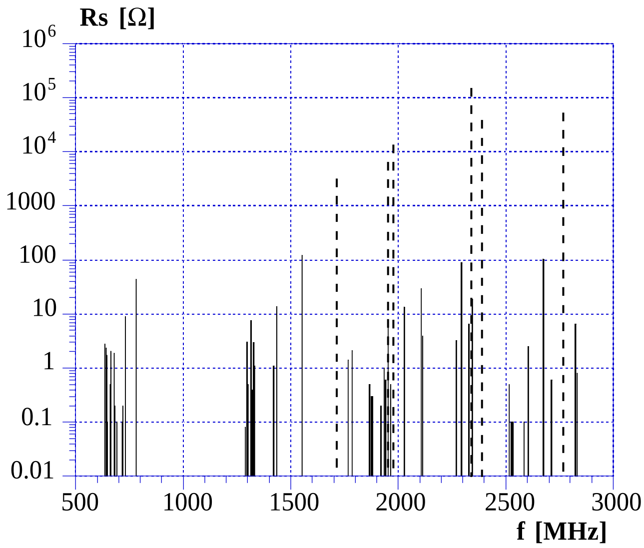


Fig. 2 - Measured bellows prototype longitudinal resonances.

Some observations can be done by analyzing the results presented in Fig. 2. First, the HOMs of the cavity itself having the shunt impedances up to 10^5 Ω are successfully eliminated by the screen. On the other hand, the screen introduces new HOMs. Some of them are at very low frequencies.

The frequencies of the new modes appear to cluster around frequencies f = nc/2l, where n=1,2,3,.. and l is the strip length. Even though the shunt impedances of these mode are very low the rise time of the multibunch instabilities due to the modes is at a manageable limit of the DAΦNE longitudinal feedback system. Moreover, the number of the modes is high and the frequency distribution is rather dense. This means that probability of the coupling of the power spectrum lines to the HOMs is not negligible. The power loss in case of the full coupling can be of the order of some thousand watts.

In order to estimate the possible power loss we can use the expression:

$$P = \sum_{m=0}^{+\infty} \sum_{n=1}^{HOMs} \frac{2(R_n / Q_n) Q_n I_m^2}{1 + Q_n^2 \left(\frac{m\omega_0}{\omega_n} - \frac{\omega_n}{m\omega_0} \right)^2} \qquad (1)$$

Here the summation is performed over all the HOMs with R_n, Q_n and ω_n being the shunt impedance, quality factor and resonant frequency of n^{th} HOM, respectively. ω_0 is the angular revolution frequency. I_m is m^{th} harmonic of the Fourier expansion of the beam current:

$$i_b(t) = \sum_{m=-\infty}^{+\infty} I_m \exp\{jm\omega_0 t\} \tag{2}$$

As an example, let us consider the case of a full coupling with the only HOM at 1.55 GHz having the highest shunt impedance 105 Ω. Then, for 120 gaussian bunches equally spaced in the ring we have the lost power of 2.3 kW.

This gives rise to the problem of how to dissipate such a power. If the HOM fields are mostly trapped between the strips, the problem would get unsolvable: it is practically impossible to dissipate the power under vacuum without strong heating and breaking the strips.

So numerical simulations were undertaken in order to understand why these new modes appear, what is the field configuration of the modes and how to damp them to a harmless level.

First numerical simulations

The numerical simulations for the structure presented in Fig. 3 were performed with MAFIA [3]. Table 1 shows the modes found for the structure. Again we can observe the clusters of modes with wavelengths close to λ = 2l/n.

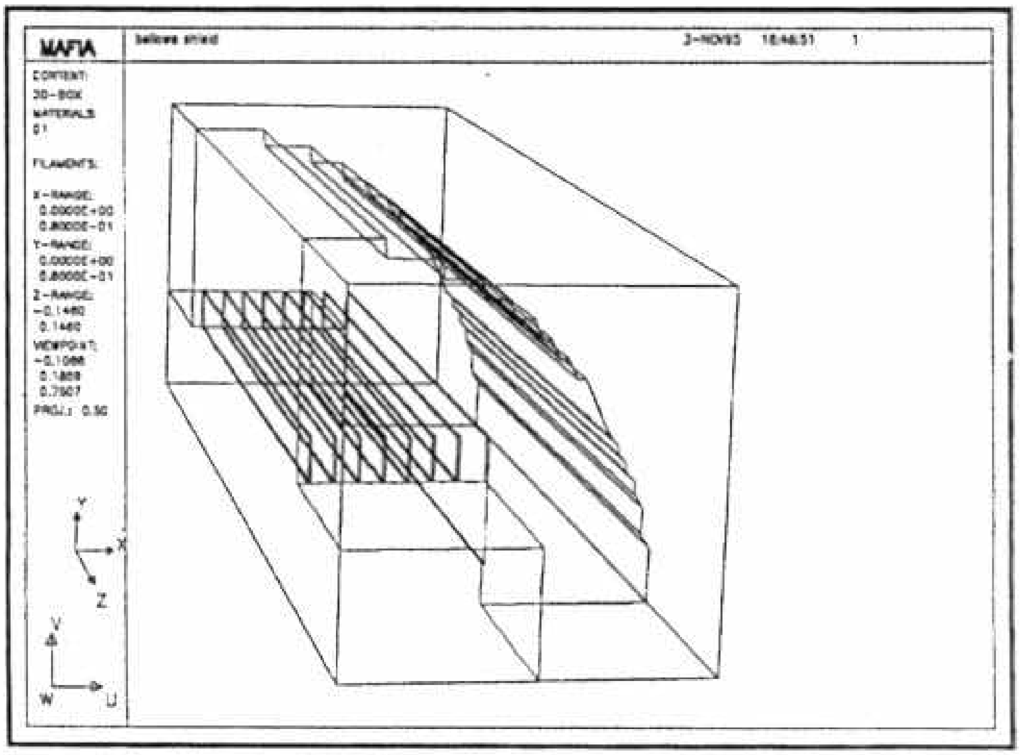


Fig. 3 - MAFIA input geometry (one quarter).

Table 1. Parameters of longitudinal HOMs found by MAFIA for the structure shown in Fig. 3

mode	**f [MHz]**	**Rs [Ω]**	**Q**
1	807.631	0.109	8830
2	823.323	0.387	6651
3	828.950	0.059	5322
4	830.912	0.193	4671
5	831.744	0.018	4319
6	832.165	0.004	4131
7	832.316	0.327	4042
8	833.016	**7.062**	13880
9	1608.646	0.529	12440
10	1644.461	0.247	9400
11	1655.915	2.479	7517
12	1659.926	0.032	6572
13	1661.939	0.231	6027
14	1662.651	1.389	5746
15	1663.741	1.234	19370
16	1969.460	0.043	19820
17	2392.983	1.072	15120
18	2424.712	0.812	22900
19	2466.666	1.341	10280
20	2488.374	1.181	9155

Figure 4 shows different mode field configurations. Among these modes m modes are trapped between the strips, where m is the number of slots created by the strips (See a)-f) in Fig. 4). All these mode have relatively low shunt impedances. The strongest mode in each cluster is the mode of TEM kind (see Fig. 4 g)) concentrated between the pill-box surface and the screen structure playing the role of the inner conductor for such a coaxial.

The shunt impedances in the simulations are lower than in the measurements. This is because the strips were straight in the simulations while in the measurements the strips had the waved shape. Unfortunately, the strips in the first prototype were rather thick (0.5 mm) and we could not expand it . On the other hand, due to memory and CPU time limitations we can not simulate the structure with the waved shape strips of such a small thickness using MAFIA.

Nevertheless, it is possible to simulate the impedance measurements with the wire method with HFSS code [2]. We put a thin wire along the axis of a structure in the numerical simulation with HFSS. Then, the longitudinal impedance is given by [4]:

$$Z(\omega) = 2 Z_0^{'} \left(\frac{1}{S_{21}(\omega)} - 1 \right) \qquad (3)$$

where S_{21} is the transmission coefficient between input and output port directly found by HFSS. $Z_0^{'}$ is the characteristic impedance of the beam pipe tube with the wire inside it.

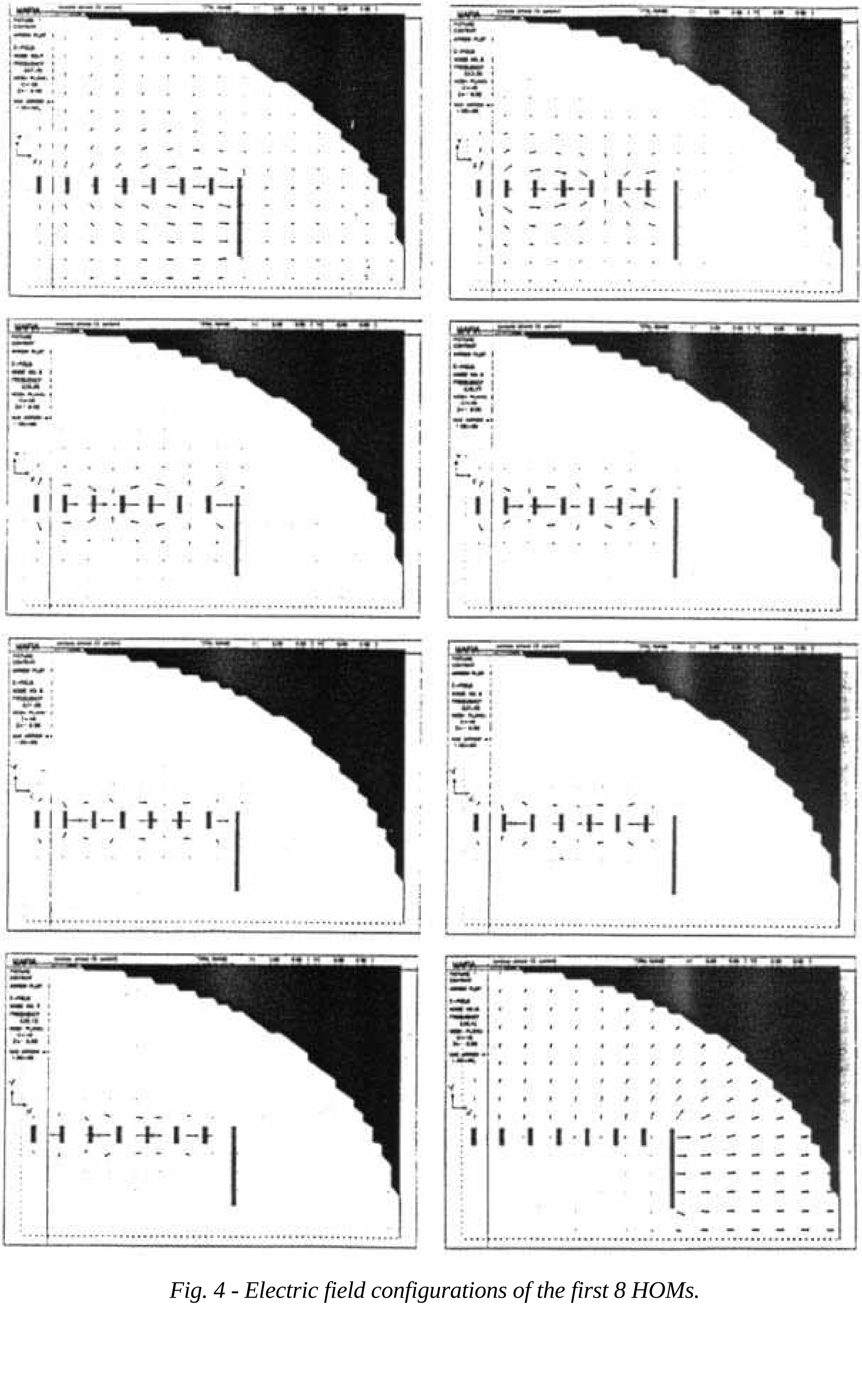


Fig. 4 - Electric field configurations of the first 8 HOMs.

First of all, in order to check the method we simulate the screen with the straight strips and compare the results with those of MAFIA. Figure 5 shows the structure considered in the simulations and the transmission coefficient S_{21} in the frequency range where the first modes appear.

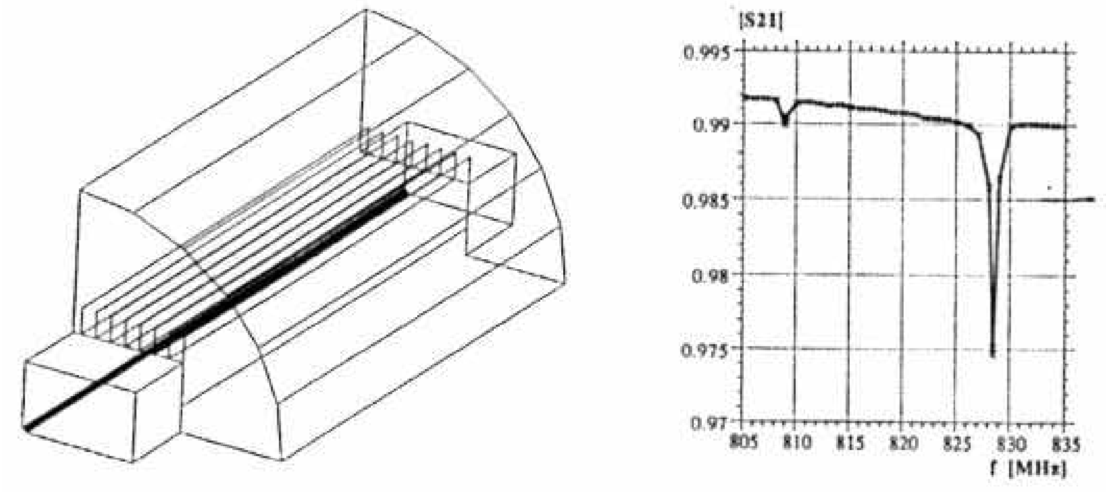


Fig. 5 - HFSS input geometry and frequency dependence of the transmission coefficient.

HFSS has found only 2 trapped modes in the given frequency range while 8 modes have been found by MAFIA. This is understandable remembering that HFSS solves for a single given frequency and to get a much higher resolution one has to perform a high precision scan, i.e. CPU time problem arise or to know the resonant frequency *a priori*. In this sense the HFSS results can be considered as complimentary to those of MAFIA where the HOM frequencies are found by the method of iterations. Nevertheless, some useful information can be extracted from the HFSS results. For example, the two modes have two typical field configurations (see Fig. 6): one is trapped between the strips and the other has the coaxial structure. Their frequencies and shunt impedances coincide reasonably well with MAFIA results (TEM like mode at 828.5 MHz given by HFSS has the shunt impedance of 5.7 Ω, the coaxial mode found by MAFIA at 833 MHz has the shunt impedance of 7 Ω).

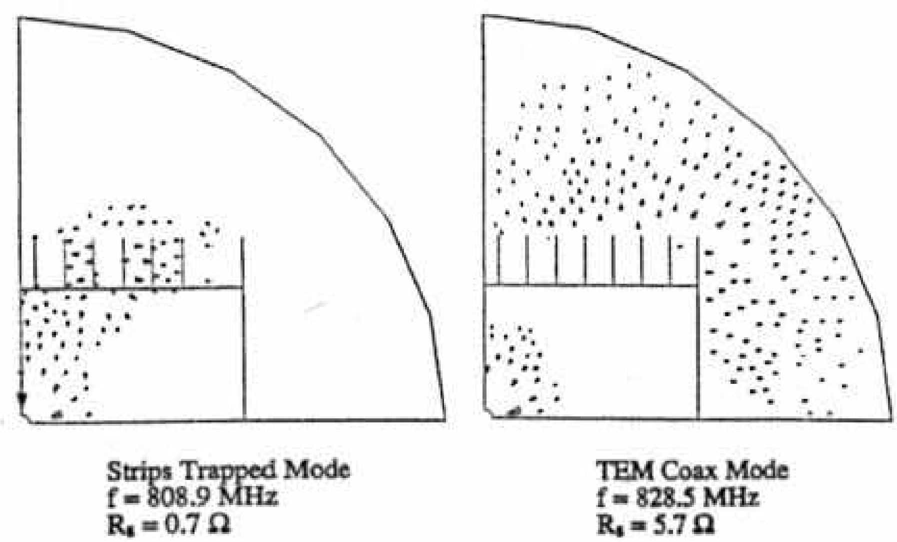


Fig. 6 - Two typical electric field distributions found by HFSS.

The following simulations were performed for the waved strips. One quarter of the structure for the simulations with HFSS is shown in Fig. 7. The mode pattern still has the same clustered structure but the shunt impedances are substantially increased. In particular, the TEM mode in the first cluster reaches the shunt impedance values of 56 Ω, in the second cluster the coaxial mode has the shunt impedance of 206 Ω.

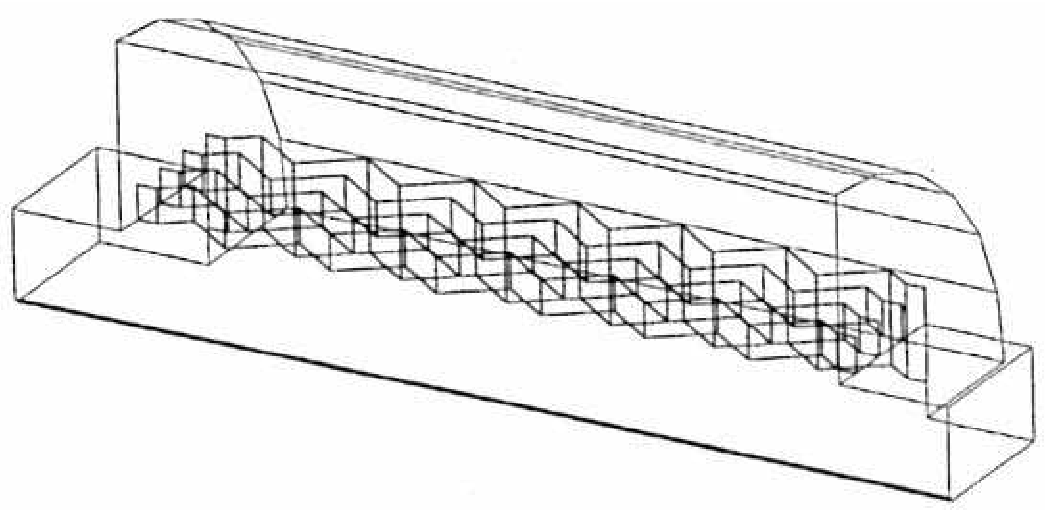


Fig. 7 - HFSS input geometry with undulated strips.

This agrees reasonably well with measurements on the prototype, where these mode have the shunt impedance of 43 Ω and 121 Ω, respectively (see Fig. 2) for the comparison. The same increase is observed also for other modes in the waved strip screen.

Measurements and simulations with "combs"

In order to push frequencies of the HOMs beyond the bunch spectrum roll-off, i. e. to avoid dangerous power losses, it was proposed to put transverse connections between nodes of the waved strips. These connection looks like "hair combs" and we will call them "combs" in the following. In this way we reduce the length of the slots created between each neighboring strips. It means that TM waveguide modes with wavelength $\lambda > 2l$, where l is the reduced slot length, can not penetrate outside the screen and excite resonant HOMs. As far as the connections are placed between the nodes the flexibility of the screen does not change much.

However, due to the fact that the bellows are placed between arcs and straight section there are two lateral slots along the screen which are foreseen for the synchrotron radiation exit. It is clear *a priori* that some modes are left in the structure. At most we can close one lateral slot on the side where the synchrotron radiation does not go.

The measurements were performed for the structure with the waved strips (maximally squeezed) with 5 almost equally spaced combs. Figures 8, 9 present the measured shunt impedances in case of 2 and 1 lateral slots open, respectively. Clearly, that the number of modes is substantially reduced with respect to the structure without any combs, especially in case with the only lateral slot.

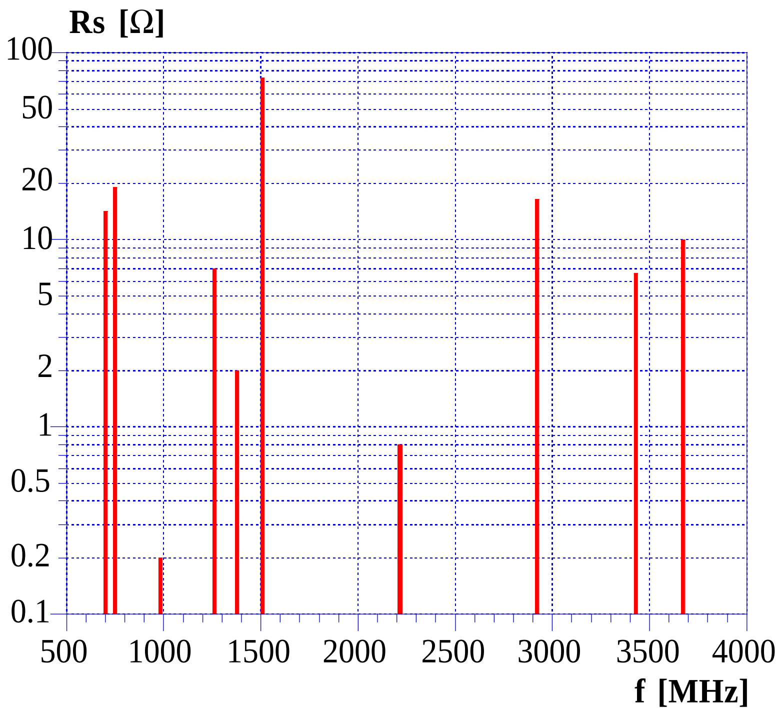


Fig. 8 - Measured longitudinal HOMs in case of two open lateral slots.

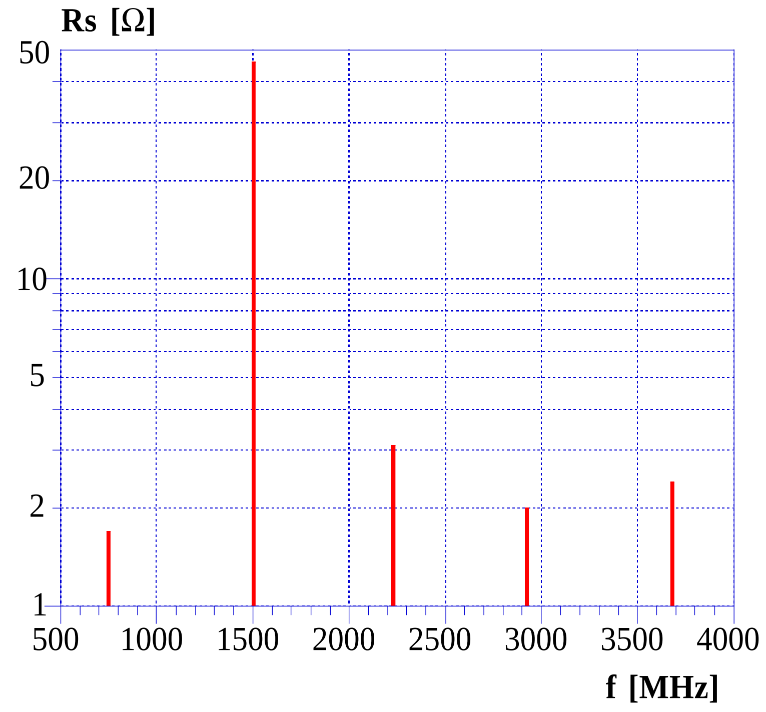


Fig. 9 - Measured longitudinal HOMs in case of one open lateral slot.

The simulations of the structure with 5 combs, one open lateral slot and straight strips were done with MAFIA. Figure 10 demonstrates the input MAFIA geometry. Table 2 gives the parameters of the found HOMs.

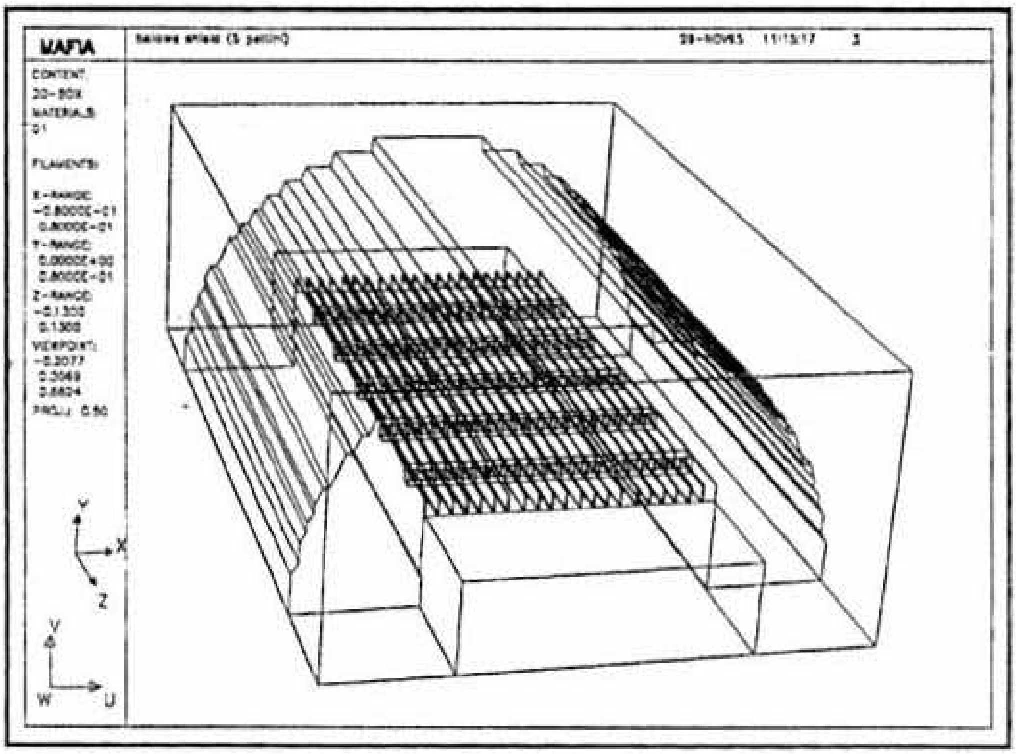


Fig. 10 - MAFIA input geometry with 5 combs and one open lateral slot.

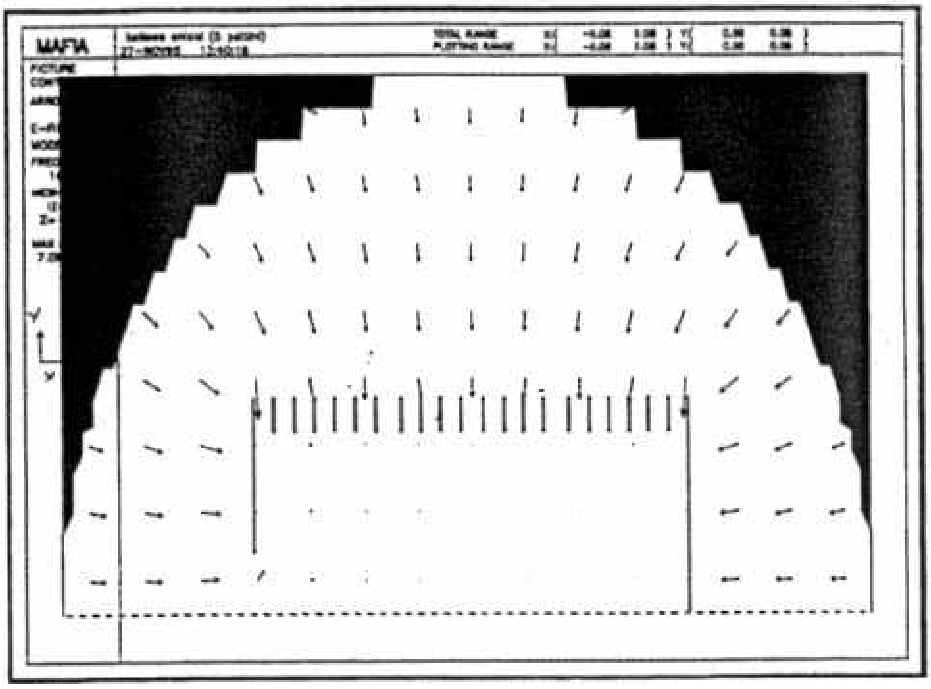
Table 2. HOMS found by MAFIA for the structure shown in Fig. 10.

mode	f [MHz]	Rs [Ω]
1	832.94	2.00
2	1066.24	0.006
3	1663.24	0.18
4	1791.86	1.57
5	1810.22	0.50
6	2312.26	3.24
7	2434.05	0.32
8	2490.26	6.18

Again we should mention here that the difference in the Rs of HOMs in measurements and the simulations is due the fact that in the simulations the strips were straight while in the measurements on the first prototype the strips were in the most squeezed position.

Analysis of the HOM fields shows that modes 1, 3, 8 have the TEM coaxial structure (see Fig. 11) while modes 2,4,7,9 have the structure of the TE11 mode in a coaxial, i.e. first parasitic mode.

We should mention here that appearance of the TE11 type mode depends very much on the symmetry of the structure. It was observed in the measurements that by introducing slight asymmetry the modes of this kind can be damped. Because of that we do not show them in Fig. 9.



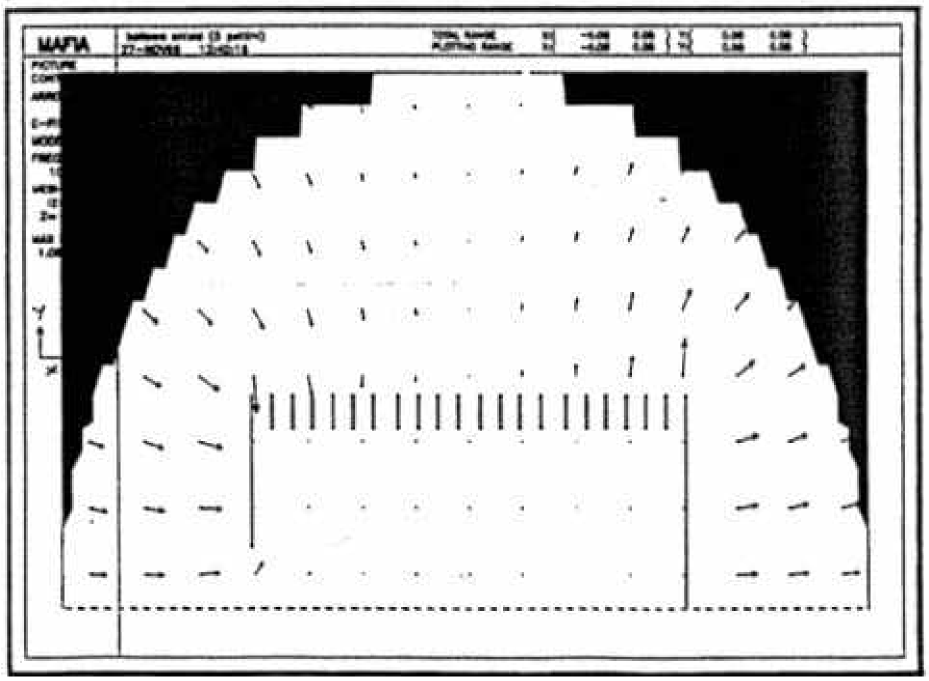


Fig. 11 - Two typical mode configurations found by MAFIA for structure with 5 combs.

Measurements and simulations with "halves of the moon"

Clearly, that in the real situation the strips will not be straight and the shunt impedances of the modes will be somewhere in between measured and simulated values. Moreover, it is not a simple task to produce a wide flexible lateral strip in case when the only lateral slot remains open. So some additional efforts have to be done to eliminate these remaining modes or, at least, to damp them to acceptable values.

We propose in addition to the combs to use transverse plates as shown in Fig. 12. In order to fit the bellows shape the plates have been chosen to have the "half of the moon" shape. In our understanding these plates push the electric fields of the coaxial type modes further from the beam axis thus reducing the coupling of these modes to the beam. The second advantage is that the plates prevent penetration of the TE modes into the outer volume. The third, the plates can be considered as an radiator which helps to dissipated lost power.

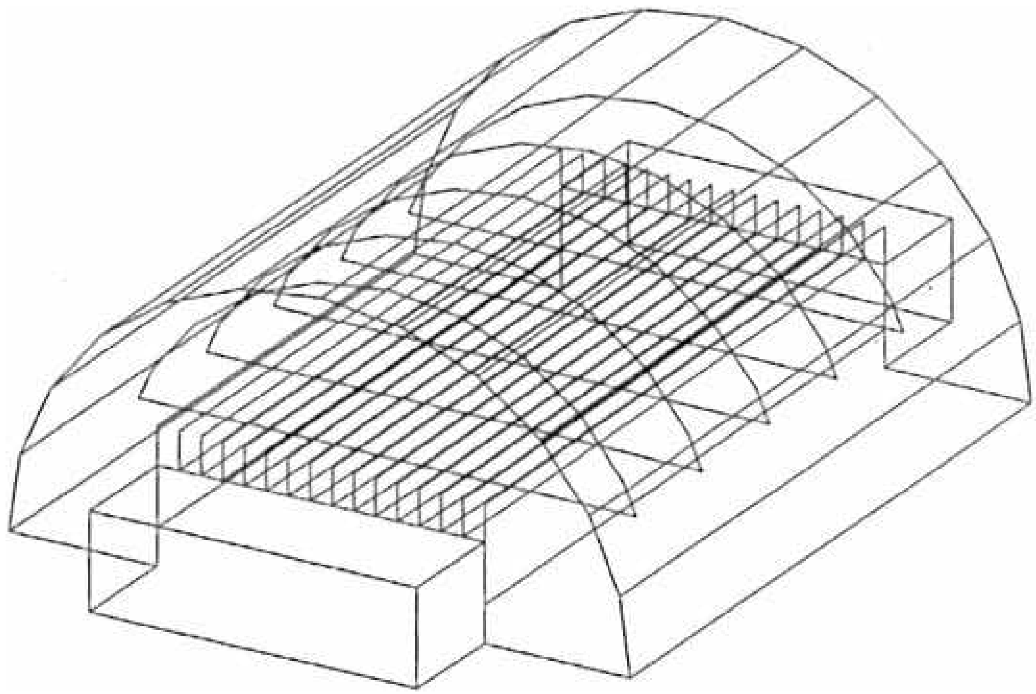


Fig. 12 - Half of a structure with "combs" and "halves of the moon".

The measurements were performed on a new prototype with the thinner strips (0.2 mm) allowing to measure the shunt impedance of the modes as a function of the bellows expansion.

Table 3 and Table 4 show the mode parameters for the 227 mm and 217 mm bellows length, correspondingly.

Table 3. Measured HOMs in the structure 227 mm long
containing combs and halves of the moon

mode	**f [MHz]**	**Rs [Ω]**	**τ [ms]**
1	658.7	------	------
2	947.4	2.2	78.5
3	967.3	2.2	77.9
4	1526.4	0.9	191.7
5	1746.5	1.3	143.5
6	2184.9	0.4	579.7
7	2412.6	1.3	202.9
8	2645.2	2.2	137.3
9	2696.2	4.8	64.9

Table 4. Measured HOMs in the structure 217 mm long
containing combs and halves of the moon

mode	**f [MHz]**	**Rs [Ω]**	**τ [ms]**
1	667.0	0.8	258.9
2	954.1	1.3	132.5
3	974.8	2.2	77.8
4	1511.8	0.9	191.2
5	1528.5	----	
6	1750.2	0.8	233.5
7	2415.9	6.5	40.7
8	2482.4	----	
9	2645.8	1.9	159.0
10	2681.2	5.8	53.2
11	2906.8	0.6	585.3

The rise time of the longitudinal multibunch instability τ in case of a full coupling of a monopolar sideband at $p\omega_0+\omega_s$ with a HOM is given by [5]:

$$\frac{1}{\tau} = \frac{I_b \eta c^2}{\omega_s (E / e) 2\pi\sigma_z^2} \exp\left(-p^2\omega_0^2\sigma_z^2 / c^2\right) I_1\left(p^2\omega_0^2\sigma_z^2 / c^2\right)\frac{R_s}{p} \qquad (4)$$

with I_b the beam current; E/e the nominal energy (eV); η the slippage factor; ω_o the angular revolution frequency; ω_s the angular synchrotron frequency; σ_z the rms bunch length; c the light speed; R_s the mode shunt impedance. I_1 is the modified Bessel function of the first order.

The last columns in Table 3 and Table 4 summarize the estimated rise time for the measured bellows HOMs in case of 120 bunches in the beam. As it can be seen, the rise time is higher than the radiation damping time which is equal to 17.8 ms for DAΦNE. Remembering that there are 8 bellows in the ring one could expect a proportional reduction of the rise time. However, we believe that all the bellows will be differently expanded, i.e. it is hardly possible that all the frequencies of the HOMs having similar field configuration in different bellows coincide exactly. Nevertheless, if this happens the multibunch instability rise time will be still longer than the damping time provided by the feedback system.

In order to estimate the losses in the worst case let us consider the full coupling (hardly possible) of the mode at 2415.9 MHz with a bunch power spectrum line for 120 equally spaced bunches. Expression (1) gives 35 W. This is a quite acceptable value. We should also stress here that not all the power is dissipated under the vacuum. Due to the coaxial nature of the remaining modes a part of the power is dissipated on the bellows surface on air.

The simulations for the structure shown in Fig. 13 were done with MAFIA. It gives even better results in terms of the shunt impedances (see Table 5).

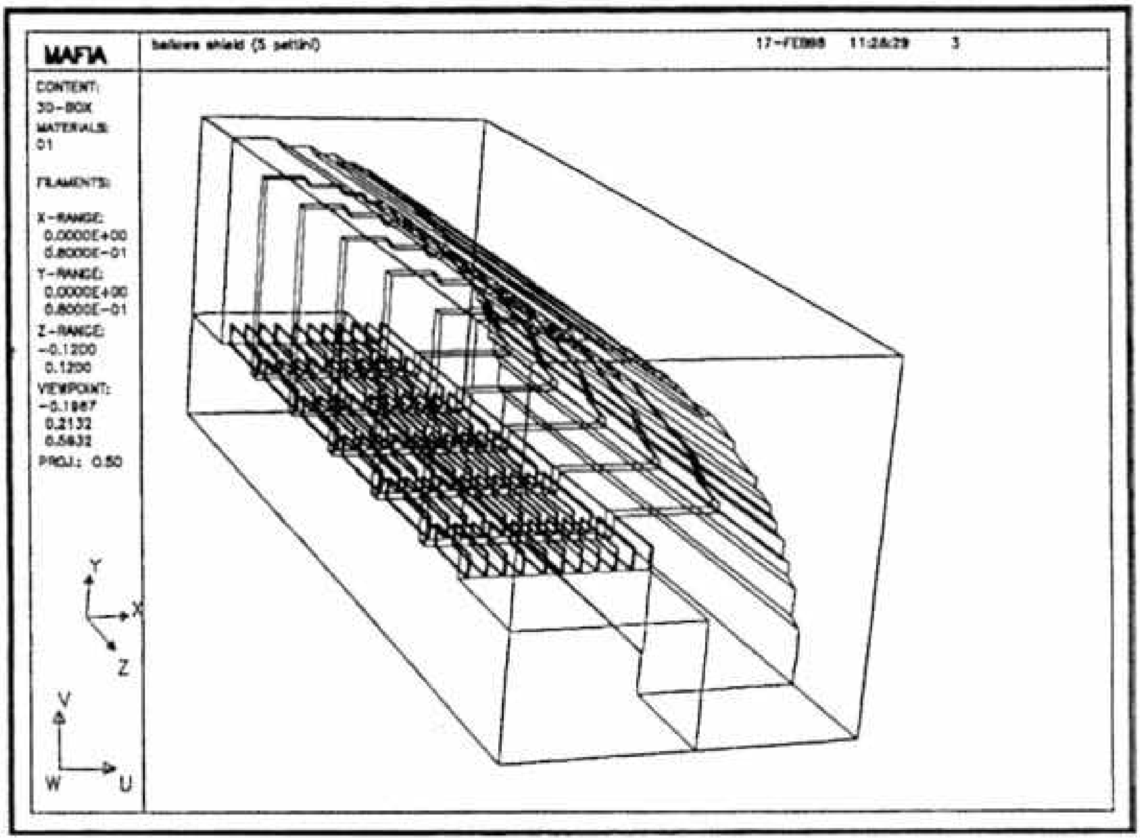


Fig. 13 - MAFIA input geometry (one quarter) with straight strips,
2 open lateral slots, 5 "combs" and 5 "halves of the moon".

Table 5. Longitudinal HOMs found by MAFIA in the structure shown in Fig. 13

mode	f [MHz]	Rs [Ω]	Q	τ [s]
1	310.249	0.38	60	1.026
2	583.464	0.27	8013	0.844
3	800.618	0.003	9282	62.035
4	956.290	0.05	10210	3.446
5	1049.372	0.005	10810	33.521
6	1498.892	0.03	5924	5.708
7	1641.526	0.56	6567	0.320
8	1800.742	1.00	7323	0.192
9	1927.811	0.28	8029	0.723
10	2005.846	0.0002	8542	1054.11
11	2442.676	0.001	12050	268.54
12	2615.953	0.32	13430	0.873

One of our concerns was the transverse instability. We have no a set for the measurements of the transverse modes yet and have to rely on MAFIA simulations in this case. In order to estimate the rise time of the transverse multibunch instability we use [5]:

$$\frac{1}{\tau} = \frac{I_b \omega_r}{4\pi (E / e) \nu_{x,y}} R_{\perp}^{URMEL} \exp\left(-\omega_p^2 \sigma_z^2 / c^2\right) I_o\left(\omega_p^2 \sigma_z^2 / c^2\right) \tag{5}$$

with

$$\omega_p = ((-p + \nu_{x,y})\omega_0 - \omega_\xi)$$

where $\nu_{x,y}$ is horizontal (vertical) tune; R^{URMEL} is the transverse shunt impedance calculated applying the definition of URMEL code [6]; ω_r is the angular frequency of a HOM; $\omega_\xi = \nu_{x,y}\omega_0 \xi/\eta$. I_0 is the modified Bessel function of zero order.

Fortunately, the rise times due to the transverse modes calculated by MAFIA are very much higher that the damping time which is 36 ms for horizontal plane and 37 ms for the vertical one (for the comparison see Tables 6, 7). Certainly, the transverse plates ("half of the moon") help much in damping of the modes.

The last columns in Table 6 and Table 7 give the rise time of the vertical and horizontal transverse multibunch instability due to HOMs in a single bellows.

Table 6. Parameters of the vertical HOMs and estimated rise time.

mode	f [MHz]	$R_\perp$ [Ω/m]	Q	τ [s]
1	356.56	0.003	5590	6807
2	615.77	0.869	7622	28.92
3	814.15	0.549	9052	58.47
4	943.42	0.310	8062	111.73
5	961.13	2.138	10100	16.379
6	1051.14	0.031	10760	1196
7	1351.04	34.828	9696	1.308
8	1668.23	69.558	7197	0.818
9	1740.26	77.288	9152	0.772
10	1750.96	52.251	7672	1.151
11	1831.45	59.561	8351	1.065

Table 7. Parameters of the horizontal HOMs and estimated rise time.

mode	f [MHz]	$R_\perp$ [Ω/m]	Q	τ [s]
1	862.69	2.747	4098	12.01
2	1058.43	7.319	5454	5.09
3	1258.55	3.539	6747	9.20
4	1414.96	0.004	7737	11999.
5	1511.88	0.242	8370	210.92
6	2078.86	0.622	7871	118.95
7	2239.09	0.11024	7950	734.30

Summary

1. The screen consisting of the thin strips eliminates successfully HOMs of the bellows, but introduces new HOMs having much smaller shunt impedances such that the modes are not dangerous from the multibunch instabilities point of view. The new modes cluster around frequencies $f = nc/2l$ with n=1,2,.. The number of the modes in each cluster is equal to the number of slots created by neighboring strips. The strongest modes are the modes of TEM type exited between the bellows surface and the screen itself.

2. Due to the large number of the new modes the probability of the full coupling of the beam power spectrum lines to the HOMs is high. The estimated power loss can be up to 1-3 kW in the most unfavorable case. In order to eliminate the HOMs at low frequencies it was proposed to use the transverse connection between the strips - "combs". It is enough to have 5 "combs" to push the mode frequencies beyond the spectrum of the 3 cm bunch, i. e. completely eliminate possible power loss.

3. However, there are two lateral slot left in the screen, necessary to let the synchrotron radiation go out and to simplify the mechanical design of the screen. Analysis of the modes remaining in the structure with 5 combs and two lateral open slots shows that the total number of the HOMs is substantially reduced and the full coupling probability is much low. All the remaining modes have the field structure of the modes in a coaxial cavity created by the bellows and the screen.

4. In order to push the modes further away from the beam axis to reduce their coupling to the beam application of special plates in addition to the combs have been proposed. Complete set of measurements on the prototype and numerical simulations confirmed that there are no HOMs dangerous for the beam dynamics both in the expanded and squeezed state of the bellows. The some remaining modes can drive neither transverse not longitudinal multibunch instability. Even in the most unfavorable situation the power loss due to these modes is acceptable.

Acknowledgments

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