Multibunch Instability Investigation on a Cavity equipped with a broad HOM suppressor

E. Karantzoulis
Sincrotrone Trieste, Padriciano 99
34012 Trieste, Italy

Abstract

An investigation of the longitudinal and transverse multibunch instabilities based on an assumed frequency shift behaviour during tuning of the remaining parasitic modes of an ELETTRA cavity prototype equipped with higher order mode (HOM) suppressor(s) is presented and compared with similar results from the undamped cavity. The goal of the analysis is to provide information about the importance of these HOMs and to define (if necessary) shunt impedance thresholds below which no multibunch instabilities occur.

I. INTRODUCTION

ELETTRA is the Synchrotron light source under construction in Trieste optimized for photon energies from ultraviolet to soft x-rays.The required performance is achieved by using an electron (positron) storage ring in the energy range from 1.5 to 2.0 GeV and a full energy linac as injector.

To satisfy the user requirements the storage ring will operate in two different filling modes; namely in a single(or few) bunch mode with high current per pulse (~ 9 mA) and in a multibunch operation with a large number of bunches (~ 400) each containing a relatively low current (≤ 1 mA). However this high number of bunches may in general lead to multibunch instabilities due to HOMs of the cavities.

The main task of the RF-system is to replace the energy losses due to the radiation and to provide a large momentum acceptance to confine Touscheck scattered particles. The main parameters of the RF-system are listed in table 1.

Table 1
Main parameters for the synchrotron RF-system

Energy	2.0		1.5	GeV
Number of cavities	6		4	
Total rad. losses (+)	380		127.6	keV/turn
Peak effective voltage	1.8		1.7	MV
Synchronous phase	169.76		175.69	degree
Revolution freq.		1.1566		MHz
Harmonic number		432		
RF- frequency		499.654		MHz
Max. RF power (cw)		60		kW/cavity
Cavity radius		263		mm
Cavity axial length		302.6		mm

(+) includes radiation losses due to insertion devices.

The RF-system as well as the cavity design and construction was accomplished by the ELETTRA RF-group [1]. The cavity has a smooth shape to prevent multipactoring and a few prototypes have been built. The measured resonance frequency is 500.1 MHz and the quality factor Q = 42000 which together with a R/Q of 166 Ω gives a shunt impedance of about 6.9 MΩ. The effective shunt impedance is 3.38 MΩ since the transit time factor of the accelerating mode is 0.7 and consequently the $R_{eff}/Q = 80.5\ \Omega$. In the following we shall use only R_{eff}/Q since this is the quantity relevant for the instability calculations.

The bandwidth of the accelerating mode $\Delta f = f/Q = 12$ kHz whereas when loading effects are considered it is estimated to be approximately 60 kHz so that the impedance curve will have an effective frequency width of some 200 kHz. To compensate for the beam loading the cavity has to be detuned below the RF-frequency by a maximum shift (for the maximum stored current) of 58 kHz and 82 kHz at 1.5 GeV and 2.0 GeV respectively (see table 1.).

The tuning is achieved by means of an external mechanical tuner acting on the length of the unit [1]. The tuning range is approximately 200 kHz with some 800 Hz /µm with a speed of 200 Hz/sec and a relative frequency stability of $\pm 4\ 10^{-7}$ within this range. A fast phase control will be also used (and has been tested) with response time of 5ms for 1° of phase variation. It is also worth mentioning that the frequency variation due to temperature changes is about 9 kHz/1°C.

II. MULTIBUNCH INSTABILITIES IN THE UNDAMPED ELETTRA CAVITY

That analysis was made using the well known theory for the calculation of the growth rates and then performing statistics [4]. The results of the investigation are summarized in tables 2 and 3.

Higher frequencies are not quoted here since they are above cut-off. The instability estimations were made for the first bunch shape modes and for the statistics 10,000 data sets were used. In the longitudinal case the instability growth is counteracted mainly by radiation damping (~4.5 ms at 2.0 GeV) whereas for the transverse case the Landau damping time resulting from the betatron frequency spread is dominant with a value comparable to that of the radiation damping.

From the measured HOM values may be observed that the bandwidths of the HOMs are of the order of ~20 kHz i.e. comparable with that of the fundamental. This means that by detuning the cavity to compensate for the beam loading also

0-7803-0135-8/91$01.00 ©IEEE

the HOMs will be detuned by a certain frequency shift, their induced growth rates being thus affected since the value of the impedance will drastically change due to the HOM narrow bandwidths.

Table 2
Longitudinal HOM and their instability probability

Longitudinal (measured) HOMs				Instability probability	
mode	frequency (MHz)	Q-factor	$R_{sh(eff)}$ (kΩ)	4 cavities (1.5 GeV)	6 cavities (2.0 GeV)
2	944	43500	1600	49%	99%
3	1060	57000	30	rad.damped	rad.damped
4	1421	49500	400	52%	74%
5	1509	53500	400	100%	100%
6	1614	53000	1600	80%	91%
7	1875	42000	400	100%	100%
8	1947	64000	200	88%	99%
9	2087	24000	40	rad.damped	rad.damped
10	2120	30000	2200	99%	100%

Table 3
Transverse (dipole) HOM and their instability probability

Transverse (measured) HOMs				Instability probability	
mode	frequency (MHz)	Q-factor	$R_{sh(eff)}$ (kΩ/m)	4 cavities (1.5 GeV)	6 cavities (2.0 GeV)
1	743	44000	320	Land.damped	Land.damped
2	749	40000	1240	>>	>>
3	1120	39500	1880	14%	17%
4	1221	89500	8	Land.damped	Land.damped
5	1248	37000	920	21%	26%
6	1307	58000	170	Land.damped	Land.damped
7	1561	38000	6	>>	>>
8	1638	32000	1440	8%	12%
9	1713	62000	144	Land.damped	Land.damped
10	1720	38000	340	>>	>>

However the cavities to be used are not (and can not be) identical due to manufacturing errors, temperature variations etc. (e.g. 800 Hz/µm, 9 kHz/1°C). Therefore although in one cavity might happen that a HOM is damped in another cavity the same mode can be unstable because its frequency has been shifted. This brings in the idea of performing statistics whereby it is assumed that the HOM frequencies are only known within a certain interval. This interval varies for every HOM and it has been measured [4] by shifting the frequency of the accelerating mode within its tuning range (i.e. ± 100 kHz).

By choosing randomly a number (equal to the number of the cavities e.g. 4 or 6) of frequency shifts within the tuning range of the fundamental, the corresponding shifts of the chosen HOM are extracted from the measured data and the growth rates are superimposed. This calculation is performed many times (arbitrary many frequency shifts in combinations of 4 or 6) and the probability of an instability that exceeds the damping rates is evaluated as % of probable instability shown in columns 5 and 6 of tables 2 and 3.

One may interpret this % of instability by imagining that in e.g. 100 days of machine operation t% of the time the mode will be unstable. According to this explanation the longitudinal mode number 4 for instance (see table 2) will be during 100 days of machine operation at 1.5 GeV 52 days unstable whereas mode number 5 or 7 will be always unstable!

It is clear that in the evidence of the above analysis most of the modes are unstable and therefore an adequate damping of the HOM spectrum of the RF cavity is necessary.

III. MULTIBUNCH INSTABILITIES IN A DAMPED CAVITY PROTOTYPE

The concept of broadband damping whereby one couples waveguides directly to the cavity in order to suppress, if possible totally, the HOM spectrum has been chosen and developed for the ELETTRA cavities [2,3].

Two different configurations were tested and measured in especially built prototypes. Until now measurements have been performed for the frequency identification of the remaining modes and their Q values. The first configuration involves only one waveguide coupled to the cavity which is enough to damp almost all longitudinal modes. However the dipole (first transverse) modes due to their polarization may partly be trapped into the cavity at an angle of 90°. Then the second configuration is to use two wave guides at an angle of 90° degrees. The results of these measurements [5] are summarized in tables 4 and 5.

Table 4
Longitudinal modes for 1 and 2 waveguides

	1-waveguide		2-waveguides	
mode	frequency (MHz)	Q-factor	frequency (MHz)	Q-factor
1	482	30900	468	26000
2	935	690	935	90
9	2070	640	2070	320

Mode number 1 is the accelerating mode whereas modes 2 and 9 correspond to the ones shown at table 2

Table 5
Transverse(dipole) modes for 1 and 2 waveguides

	1-waveguide			2-waveguides	
mode	frequency (MHz)	Q-factor		frequency (MHz)	Q-factor
		φ=0°	φ=90°		
1				732	300
2	747	10600	900	737	250
3	1110	2250	-----		
5	1248	1500	-----		
6	1305	700	-----		
7	1556	500	500		
8				1627	240

(compare also with table 3)

From the above tables it is obvious that the 2 waveguide solution is more effective in eliminating the HOMs, however it is interesting to see what kind of growth rates are introduced for the two schemes.

In doing this we must first assume a reasonable value for the HOMs effective shunt impedance. First of all we do not expect that the ratio R_{eff}/Q will exceed that of its undamped value and if one knows no better it seems reasonable to assume that this ratio will remain constant. Some preliminary measurements on the accelerating mode (where measurements are more precise since the resonance can be easier identified) show that R_{eff}/Q decreases about 20% but still we do not know the amount of the reduction for the higher modes.

Accordingly the investigation consists of firstly checking whether with the nominal R_{eff}/Q (taken from the undamped cavity data) the remaining modes are still unstable and if this is the case then by using the instability limits the maximum R_{eff}/Q that ensure the modes stability are found.

Table 6

Longitudinal HOMs and their growth rates

1-waveguide				stability	
mode	Q-value	R_{eff}/Q Ω	growth rate (Hz)	4 cavities (1.5 GeV)	6 cavities (2.0 GeV)
2	690	37_c	700	Unstable	Unstable
2	690	4	70	Rad.damped	Unstable
2	690	2.5	35	Rad.damped	Rad.damped
9	640	1.7_c	40	Rad.damped	Rad.damped
2-waveguides				stability	
mode	Q-value	R_{eff}/Q Ω	growth rate (Hz)	4 cavities (1.5 GeV)	6 cavities (2.0 GeV)
2	90	37_c	90	Unstable	Unstable
2	90	25	70	Rad.damped	Unstable
		15	35	Rad.damped	Rad.damped
9	320	1.7_c	20	Rad.damped	Rad.damped

Table 7

Transverse HOMs and their growth rates

1-waveguide $\phi=0°$				stability	
mode	Q-value	R_{eff}/Q Ω/m	growth rate (Hz)	4 cavities (1.5 GeV)	6 cavities (2.0 GeV)
2	10600	31_c	190	Land.damped	Land.damped
3	2250	48_c	60	Land.damped	Land.damped
5	1500	25_c	32	Land.damped	Land.damped
6	700	3_c	1.5	Land.damped	Land.damped
7	500	0.16_c	0.06	Land.damped	Land.damped
1-waveguide $\phi=90°$				stability	
mode	Q-value	R_{eff}/Q Ω/m	growth rate (Hz)	4 cavities (1.5 GeV)	6 cavities (2.0 GeV)
2	900	31_c	19	Land.damped	Land.damped
7	500	0.16_c	0.06	Land.damped	Land.damped
2-waveguides				stability	
mode	Q-value	R_{eff}/Q Ω/m	growth rate (Hz)	4 cavities (1.5 GeV)	6 cavities (2.0 GeV)
1	300	7_c	1.6	Land.damped	Land.damped
2	250	31_c	5.0	Land.damped	Land.damped
8	240	45_c	7	Land.damped	Land.damped

Next observation from the data in tables 4 and 5 is that the bandwidth of the most HOM is very large due to their low quality factor. For example the longitudinal mode number 2 in the 1-waveguide case has a bandwidth of 1.4 MHz whereas in the 2-waveguide configuration it becomes 10 MHz. This means that no substantial variations of their impedance is expected during the tuning of the cavity and therefore the statistical analysis applied previously becomes marginal. However for modes with Q greater than 2000 statistical analysis was applied. For Q less than 2000 the norm of the instability frequency shifts (~growth rates) of the HOM is multiplied by the number of the cavities and the product is compared with the damping rates. In this case stability is ensured if the mode growth rate value is approximately N (≡number of cavities) times smaller than that of the corresponding radiation or Landau damping rate.

Concerning the behaviour of the HOM frequencies during tuning we assume that it is similar to that of the undamped case. However since the exact frequencies are not known, the frequency range between the undamped and damped modes were swept observing the variation of the growth rates. This variation was at the maximum 10% and therefore the calculations are not strongly dependent on the exact frequencies of the HOMs. The same order of variation was found between growth rates of 1.5 and 2.0 GeV and therefore the above quoted values are accordingly averaged. All this is shown in the tables 6 and 7 where also the safe maximum R_{eff}/Q is indicated. The subscript "c" in the values of R_{eff}/Q indicates that the ratio was taken to be the same as in the undamped case and therefore the shunt impedance will be scaled.

IV. CONCLUSIONS

The above analysis shows that in both 1- and 2- waveguide configurations, transverse instabilities induced by the remaining modes are damped. However the 2-waveguide solution appears better since it is more effective in reducing induced longitudinal instabilities. The very low Q of the second longitudinal HOM also suggests that probably this mode is or can be fully damped. It is then clear that the choice of the 2-waveguide HOM suppressor is justified leading towards an instability free cavity.

ACKNOWLEDGEMENTS

I would like to thank M. Svandrlik and the ELETTRA RF-group for many discussions and A. Wrulich for carefully reading the manuscript.

REFERENCES

[1] A. Massarotti et al., "500 MHz Cavities for the Trieste Synchrotron Light Source ELETTRA", in *Proceedings of the 2nd EUROPEAN PART. ACC. CONF.*, Nice, France, June 1990, pp. 919-921.

[2] A. Massarotti and M. Svandrlik, "Proposal for a broadband higher order modes suppressor for the RF cavity", Sincrotrone Trieste, Trieste, Italy, ST/M-90/5, 1990

[3] A. Massarotti et al., "Status report on the ELETTRA R.F. system", This conference

[4] E. Karantzoulis and A. Wrulich, "Multibunch Instabilities Investigation for the ELETTRA Cavities", in *Proceedings of the 2nd EUROPEAN PART. ACC. CONF.*, Nice, France, June 1990, pp. 1618-1620.

[5] M. Svandrlik, Private communication.