DAΦNE TECHNICAL NOTE

INFN - LNF, Accelerator Division

Frascati, June 28, 1996

Note: **RF-18**

PARASITIC HOM's OF THE DAΦNE ACCUMULATOR RING

B. Spataro

Abstract

The instabilities caused by the interactions between a beam and its surrounding vacuum chamber are one of the main problems in a high current storage ring.

The pipe of the vacuum chamber is interrupted by many devices installed on the machine: rf cavity, diagnostic, bellows, strip lines, cross section jumps, etc. The discontinuities can trap e.m. fields which do not travel with the bunch, but are confined in a finite volume.

The parasitic higher order modes (HOM) resonances excited by the beam may lead to multiturn instability phenomena in small storage rings, which limit the performance of the machine in terms of stored current.

In this paper I calculate the possible parasitic resonances in the DAΦNE accumulator ring and discuss their impact on the beam dynamics. I also suggest a method to fight a dangerous parasitic HOM, if necessary.

Introduction

The injection system of the Φ-Factory project at LNF [1] includes an accumulator ring between the Linac and main rings.

A single bunch with $9*10^{10}$ electrons or positrons is stored and injected from the accumulator to the main ring at a repetition frequency of ≈ 1 Hz. The relevant parameters of the accumulator ring are presented in the Ref. [2].

The beam travelling inside a vacuum chamber induces e. m. fields which can affect the dynamics of the beam itself, producing multiturn instabilities, that could limit the performance of the accumulator, if no cure is provided.

Cross section variations in a vacuum chamber produced by shallow cavities, bellows, transitions tapers etc. and large components as RF cavity, beam diagnostics elements, etc., can create resonant cavities. Part of the fields excited in the cavities is trapped, reflecting back and forth, and generating resonant modes.

The modes with high quality factors produce the so called long range wakefields, which can cause interaction of the bunch with its own fields after one or more turns and excite multiturn instabilities.

The growth rates of instabilities are evaluated by overlapping the beam spectrum with the parasitic resonances of the vacuum chamber.

The inspection of the component geometry enables a better estimate of the contribution of each element to the total ring impedance.

The real part of the HOM impedance is responsible for the parasitic energy losses and the growth rates of instabilities, the reactive part causes coherent synchrotron frequency shifts.

One main characteristic of the instabilities is their growth rate: particularly dangerous are those having a growth time shorter than the synchrotron radiation or Landau damping time.

Generally, for a small circumference storage ring, the instabilities can be avoided by detuning the dangerous parasitic trapped modes.

Here I examine the HOM content of the accumulator ring, analyzing their influence on the beam dynamics and discuss a method to avoid the multiturn instability.

HOM Power Loss

The beam current can be expressed as a Fourier series :

$$\boldsymbol{i_b}(\boldsymbol{t}) = \sum_{\boldsymbol{m}} \boldsymbol{I_m} \exp\left(\boldsymbol{jm}\omega_0 \boldsymbol{t}\right) \tag{1}$$

with ω_0 the revolution angular frequency and m integer.

The energy delivered to the RF cavity HOM's by the single passage of a bunch is given by:

$$\boldsymbol{U} = \sum_{\boldsymbol{n}} \boldsymbol{U_n} = \boldsymbol{k_{pm} q_b^2} \tag{2}$$

where U_n is the energy of the n^{th} HOM mode, k_{pm} is the total loss factor and q_b the bunch charge.

The energy of the n^{th} resonant HOM decays exponentially with a time costant $\tau_n = Q_n/\omega_n$. If τ_n is greater then the revolution time, the amount of power delivered by the beam to the high order modes may be easily described in the frequency domain. The power loss deposited on each of the HOMs depends on the overlap of the beam lines I_m with the RF cavity spectrum. Such a power can be calculated as follows:

$$\boldsymbol{P_t} = \sum_{\boldsymbol{m}=0}^{+\infty} \sum_{\boldsymbol{HOM}} \frac{2(\boldsymbol{R}/\boldsymbol{Q})\boldsymbol{Q}\boldsymbol{I_m^2}}{1 + \boldsymbol{Q}^2 \left(\dfrac{\boldsymbol{m}\omega_0}{\omega_r} - \dfrac{\omega_r}{\boldsymbol{m}\omega_0} \right)^2} \tag{3}$$

The probability that a bunch spectrum line interacts with the RF spectrum is very low for the HOMs having relatively high quality factors, but if this happens the associated power loss can be unacceptable.

RF Cavity Resonator

The shape of the cavity, a so-called "single-ended" structure, has been chosen to have a compact size and to make mechanics and vacuum chamber simpler and less expensive. The geometry of the resonator has been carefully studied to avoid the resonant electron discharges or multipactoring [3].

The cavity is made of copper which has better electrical and thermal conductivity to reduce the RF losses and make cooling easier.

The operating frequency of the RF cavity resonator is 73.65 MHz, exactly one fifth of the main ring one, in order to synchronize injection into any desired bucket of DAΦNE.

At the working energy of 510 MeV and with a single beam current of 135 mA, a peak voltage up to 250 kV is required. To make the bunch short enough for injection into the Main Ring buckets.

The shunt impedance is of the order of 1.7MΩ and the power dissipation is ~ 18 kW @ 250 kV).

Due to the low frequency of the fundamental accelerating mode, I cannot provide broadband damping of high order modes with waveguides that would have too large size. On the other hand, since the accumulator works with a single bunch, the requirements of higher order modes damping are less demanding than those of the main ring cavities of the DAΦNE machine. Nevertheless, I investigated in detail the behaviour of the cavity resonator HOM's.

The analysis in the frequency domain has been carried out by means of Urmel code [4]. I studied the whole cavity up to the cut-off frequency of the beam pipe. This corresponds to 45 monopole modes.

The frequencies and the relevant RF parameters R_{sh}/Q and Q are shown in Table 1; while in Fig. 1 the power losses delivered by the beam to the HOM's as function of the modes frequencies are prsented.

In particular, it has been found that a HOM at f=576.745 MHz can couple to the bunch spectrum line at $f=63*f_0$= 576.746 MHz.

There is therefore a certain probability of full mode coupling to the bunch spectrum line. In such conditions, the power deposited by the beam to the cavity is high, about 18 kW; the longitudinal bunch instability rise time is about $\tau \approx 13$ μsec (full coupling) [5], which is much less than the radiation damping time.

The short rise time and the high power loss will require a method to decouple the dangerous cavity parasitic mode from the bunch spectrum, without affecting the other modes.

Table 1 - Monopole modes of the RF cavity.

Frequency (MHz)	R_S/Q (Ω)	Q
73.238	80.99	21736
244.977	14.30	36300
426.590	9.82	47060
576.745	10.31	48675
609.132	0.62	43527
676.700	1.32	43311
725.149	7.37	53766
784.594	2.70	43776
885.118	6.37	62250
926.733	0.29	45456
1022.834	5.27	60279
1099.407	0.08	51069
1151.558	3.64	60721
1206.817	0.05	62807
1244.356	0.57	58161
1261.217	0.02	58062
1290.009	2.01	61468
1351.574	0.08	67700
1382.677	0.21	53032
1410.529	1.41	60982
1488.155	0.17	70404
1526.116	0.46	52857
1538.010	0.42	62709
1614.260	0.66	65159
1657.292	0.33	60949
1702.813	0.22	58924
1734.753	1.51	63381
1780.306	0.14	62508
1805.182	0.03	79358
1837.802	0.10	68414
1849.468	1.29	69629
1869.187	0.27	69870
1908.010	0.11	69158
1921.606	0.02	68722
1959.467	1.50	66993
1984.133	0.83	72149
2026.533	0.20	74524
2062.783	0.018	65423
2085.697	0.95	65337
2100.238	0.47	75391
2146.303	0.12	78645
2196.167	0.03	64125
2209.439	0.40	63297
2244.715	0.02	80404
2281.207	0.11	83897

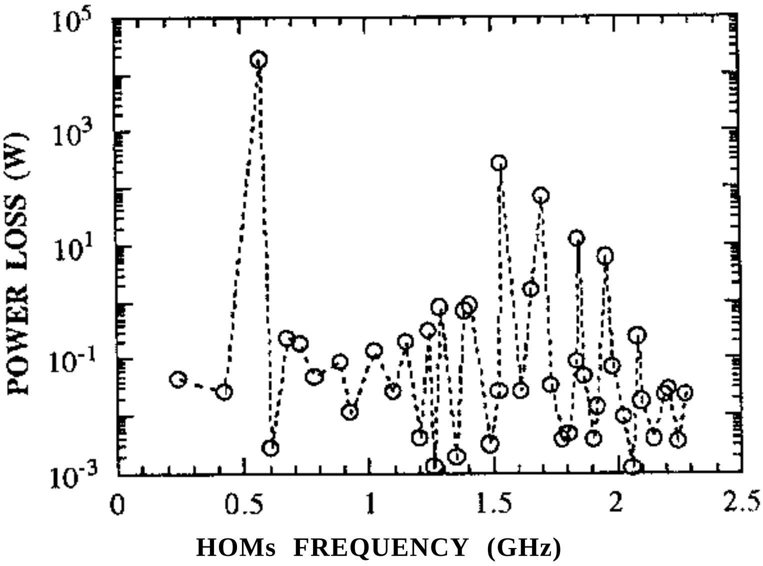


Fig. 1 - Power losses versus mode frequency.

Shallow Cavity

The straight section of the accumulator ring is 2.287 m long. It is shown in Fig. 2. At the beginning of the section two bellows are installed in order to allow the longitudinal expansion of the machine. In that region, the vacuum chamber has different cross sections along the longitudinal coordinate, as presented in Figs 3 and 3a. Its shape is a typical shallow cavity resonator because of the big transitions connecting the central part of the straight section with the bellows.

Since parasitic HOMs are expected to be trapped in the shallow cavity, a careful study in the frequency domain has been performed.

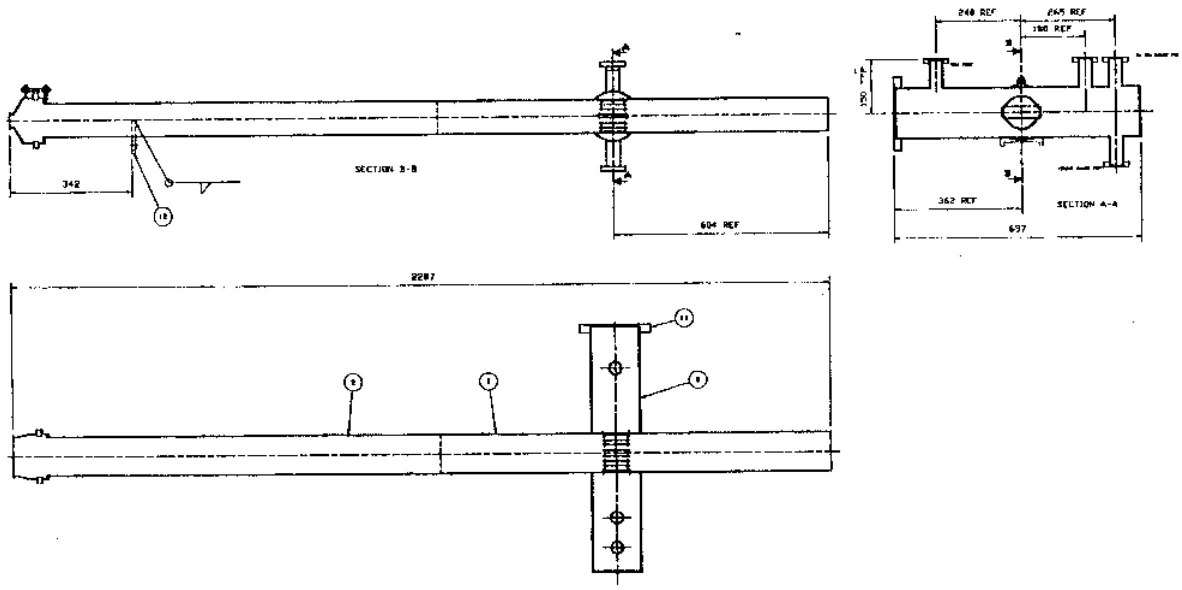


Fig. 2 - Straight section layout.

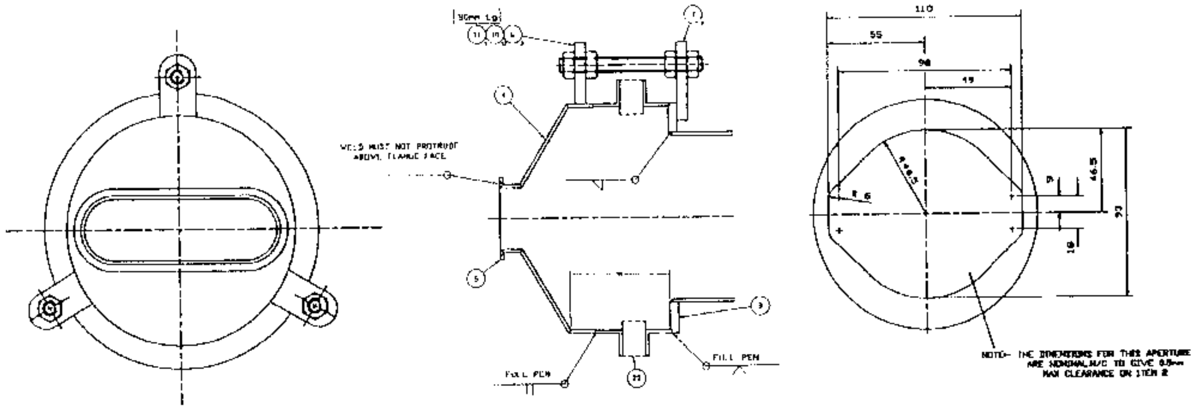


Fig. 3 - Shaped shallow cavity.

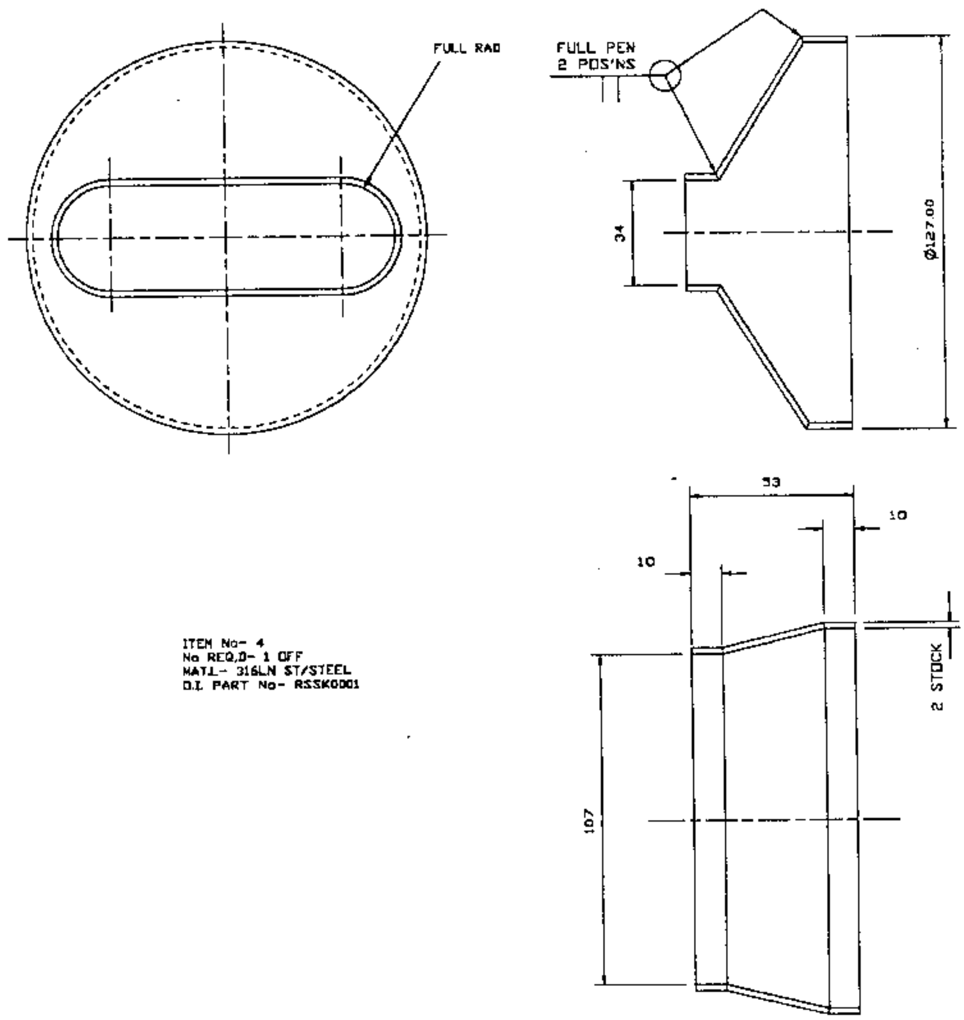


Fig. 3a - Shallow cavity initial part.

The simulations in the frequency domain have been carried out by using the MAFIA-3D code [6] up to the cut off frequency of the larger cross section equal to f_c = 2479 MHz. I assume the smaller cross section beam pipe is 10 cm long, while the beam pipe on the opposite side is 20 cm. The shape is shown in Fig. 4. The frequencies and the relevant RF parameters R_{sh}/Q and Q are shown in Table 2. Only a single dangerous parasitic HOM has been found.

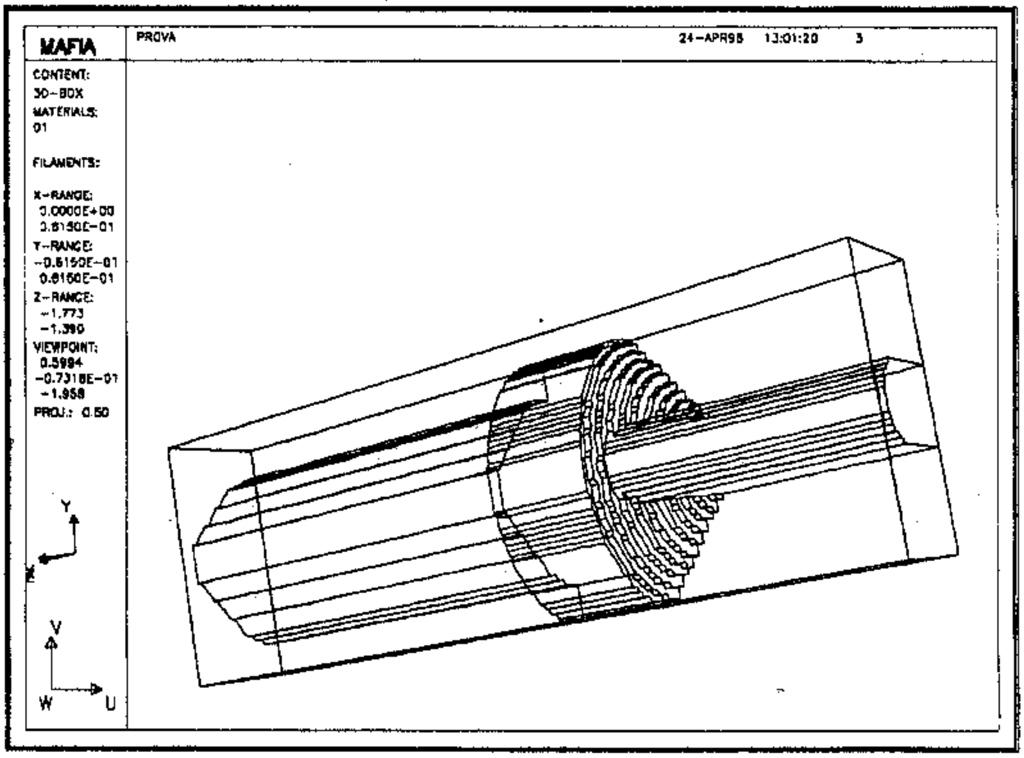


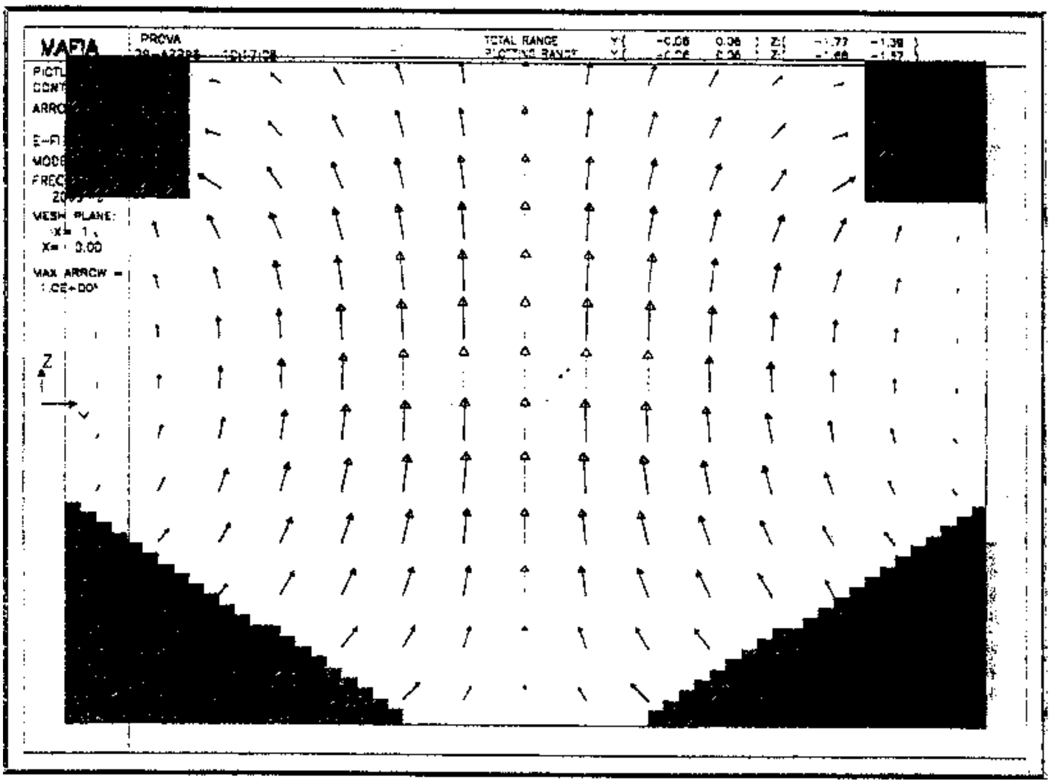
Fig. 4 - MAFIA input for the shallow cavity calculations.

Table 2 - Monopole modes of the shallow cavity.

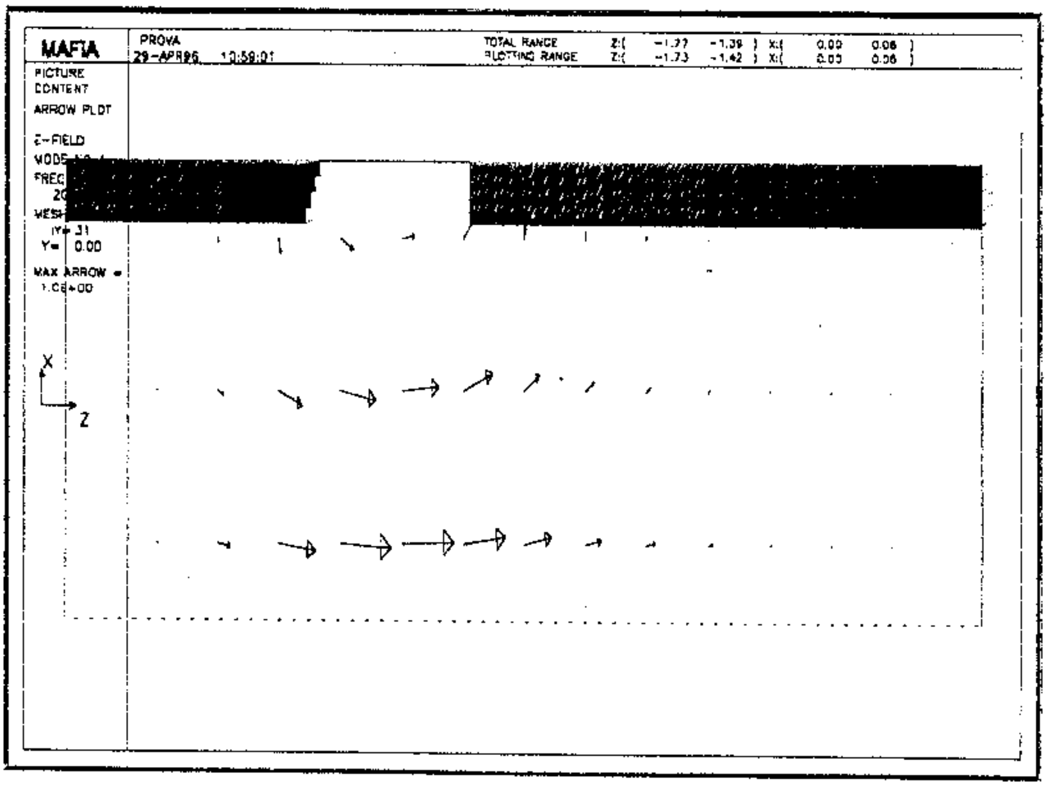
Frequency (MHz)	R_s/Q (Ω)	Q
1650.309	7.34 E-3	15510
1822.100	13.20 E-2	19890
2022.099	55.67 E-2	24500
2099.179	41.62	27630
2289.341	4.50 E-3	24160
2498.385	3.10 E-6	25580

Figure 5 presents the electric field distribution of the parasitic mode. It is clearly confined in the central part of the shallow cavity. The mode has a shunt impedance R_s = 1.15 MΩ, quality factor Q = 27630, frequency f = 2099.179 MHz and a bandwidth of B_w = 77 kHz. This mode would give ~ 2.4 kW of power loss.

The instability rise time is about $\tau \approx 6$ μsec [5] at the full coupling and its frequency is close to the beam spectrum line 228 f_0 = 2099.025 MHz.



Shallow cavity x = 0 plane



Shallow cavity y = 0 plane

Fig. 5 - Parasitic mode field pattern.

Frequency shift techniques

The dangerous modes can be damped with a dedicated loop or detuned by the frequency shift method.

Generally the HOM's frequency shift is obtained simply by changing the operating temperature of the cavity, since the electromagnetic field distributions of the parasitic modes are very sensitive to volume variations.

In the case of the coaxial resonator of the DAΦNE accumulator ring, a temperature variation of 1.4 °C is estimated to yield a frequency shift of the fundamental mode $\Delta f \approx -6$ kHz and for dangerous one $\Delta f \approx -50$ kHz. This seems to be enough to decouple the HOM from the bunch spectrum line, i.e., to avoid excessive power loss and the multiturn instability. The operating frequency can be easily corrected by the plunger [4].

Alternatively, a perturbation method can be applied. A small volume perturbation, located inside the RF cavity, perturbs locally the electromagnetic field. It leads to a frequency shift of all the enginemodes since they are sensitive to the balance between the magnetic and electric energy subtracted by the perturbed volume.

For a better accuracy of the calculation of the frequency shift, the Slater theorem is used [7]:

$$\frac{\omega - \omega_0}{\omega_0} = \frac{\int_V (\mu H^2 - \varepsilon E^2) d\tau}{U} \qquad (4)$$

where the integral is performed over the volume of the perturbation, U is the average stored energy in the cavity, ω_0 is the unperturbed frequency.

Our aim is to find out general features of the HOMs concerning the frequency shift related to the position and size of the perturbation.

I have to fulfill the following conditions:

a) to keep approximately the fundamental mode frequency unchanged;

b) to shift the single HOM by a given amount.

In order to investigate the perturbed region volume inside the cavity resonator, the field flux lines of the accelerating mode and the parasitic one are needed. They are shown, respectively, in Figs. 6 and 7.

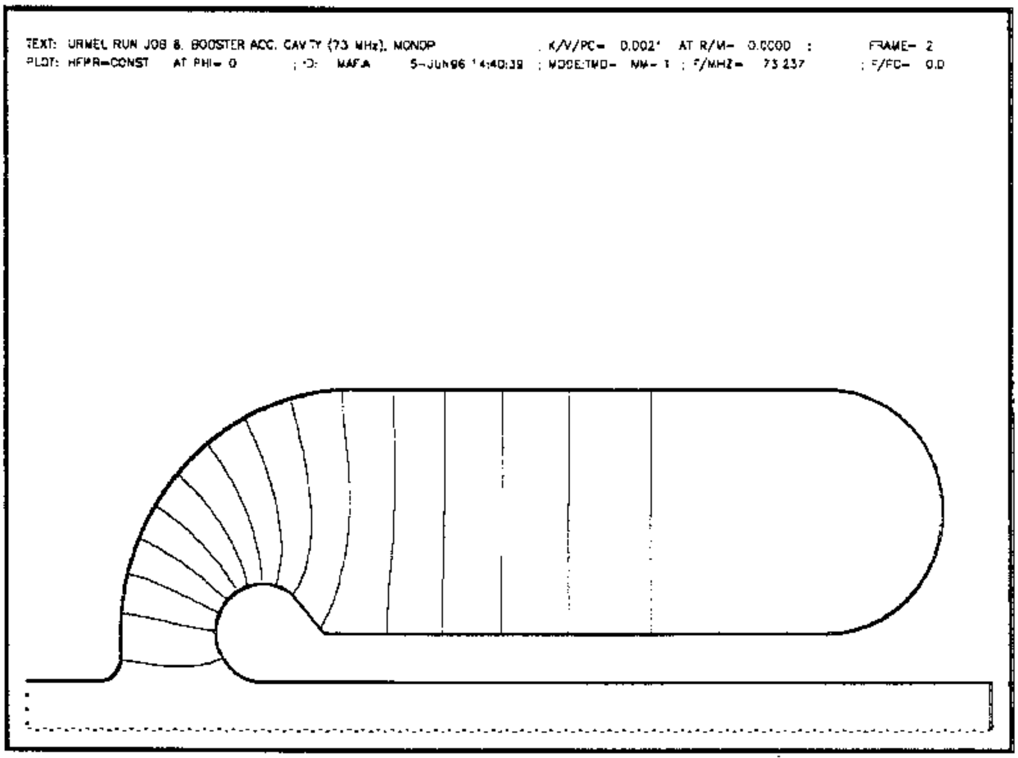


Fig. 6 - Electric field flux lines distribution of the fundamental mode.

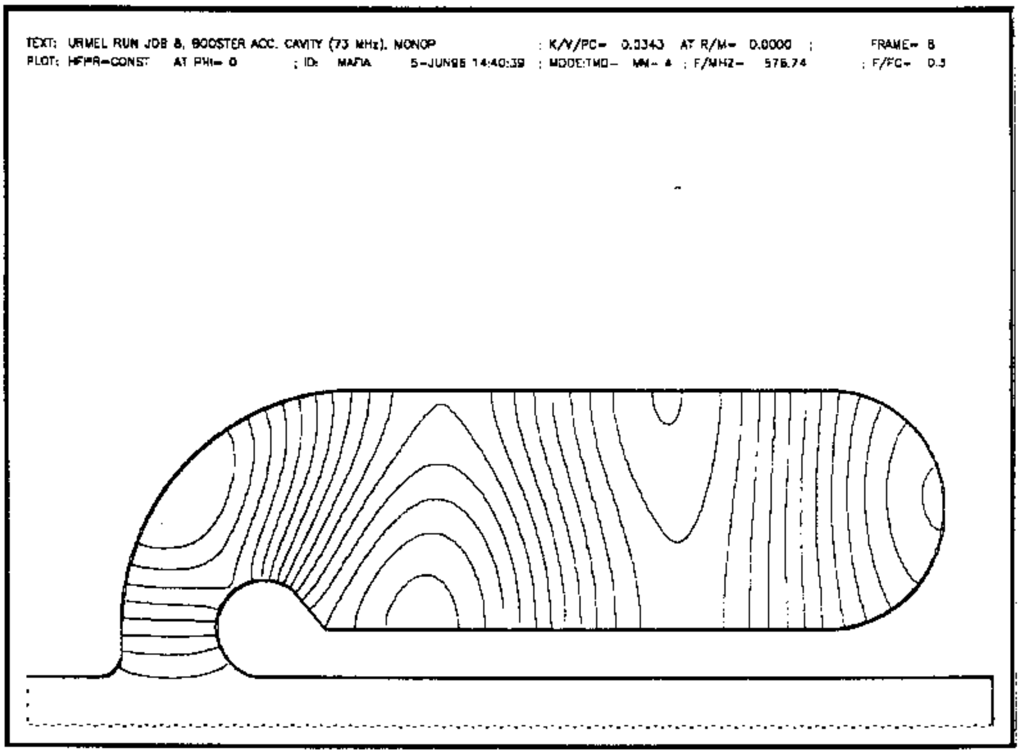


Fig. 7 - Electric field flux lines distribution of the dangerous parasitic HOM mode.

By inspection of the field distribution, the possible perturbed volume position has been chosen on the external surface close to the top corner of the cavity back end, as presented in Fig. 8. In this region, the perturbation subtracts mostly magnetic energy from the fundamental mode and electric energy from the dangerous parasitic mode.

According to Slater's theorem, this leads to the increase of the frequency separation between the operating mode and the dangerous one. Assuming to make a perturbation like a semisphere of 1.6 cm radius, a frequency shift of $\Delta f \approx$ -50 kHz of the parasitic mode is obtained; while the corresponding fundamental mode frequency shift $\Delta f \approx$+3.7kHz is much smaller.

I applied the perturbation method to a pill-box cavity getting encouraging results [8]. I believe that the frequency shift correction with a perturbation method seems to be reasonable.

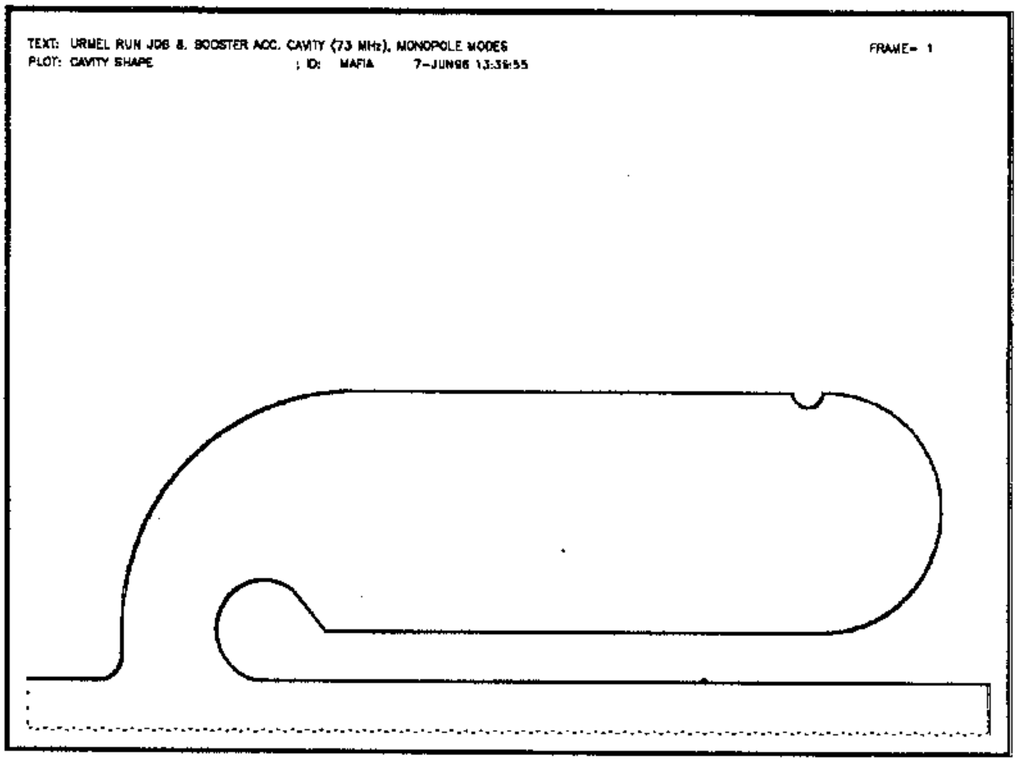


Fig. 8 - Perturbed volume position.

Conclusions

Longitudinal multiturns instabilities can occur in the accumulator ring in the single bunch operation and the RF cavity resonator is certainly the main contributor to the strongest HOMs which could drive instabilities with a growth rate faster than the natural damping.

Very probably, by changing the operating temperature of the resonator, the shift of the HOM's frequencies, can be obtained. If this does not happen, another method could be needed. For this reason extensive calculations of the parasitic modes in the frequency domain were required.

Since I found HOM having a high probability of full coupling with the bunch spectrum line, a perturbation method to shift its resonant frequency could be applied.

A small deformation could shift the HOM without substantially affecting the fundamental mode frequency.

In a next paper the detailed study of each element of the accumulator ring, pumpslots, bellows, strip-lines, etc., will be presented.

However, only the shallow cavity located at the end of the straight section presents a dangerous HOM.

Since in the accumulator ring there are four shallow cavities, the dangerous parasitic modes could give some trouble. In this case, dedicated loops or antennas to damp the mode should be required.

Acknowledgments

I wish to thank M. Migliorati and M. Zobov for very fruitful discussions on the subject of this paper.

References

[1] The DAΦNE Project Team, "DAΦNE, the Frascati Φ - Factory", in Proceeding of the 1993 Particle Accelerator Conference, Washington D.C., May 17 - 20, 1993.

[2] M.R. Masullo, C. Milardi, M.A. Preger, "DAΦNE Accumulator Update-3", DAΦNE Technical Note, I-9, May 1993.

[3] S. Bartalucci, R. Boni, A. Gallo, B. Spataro, "RF Cavity Design of the DAΦNE Accumulator", DAFNE Technical Note, RF-4, September 1991.

[4] T. Weiland, NIM 216 (1983), pp. 329 - 348.

[5] M. Migliorati, Private Communications.

[6] R. Klattt et al., "MAFIA - A Three Dimensional Electromagnetic CAD Systems for Magnets, RF Structures, and Transient Wake-Field Calculations", Proceedings of the 1986 Linear Accelerator Conference, Stanford Linear Accelerator Center report SLAC-303 (June 1986), p.p. 276 - 278.

[7] E.L. Ginzton," Microwave Measurement", McGraw - Hill Book Company, Inc. 1957, pp. 438.

[8] S. Bartalucci, R. Boni, A. Gallo, R. Scalia, B. Spataro, G. Vignola, "A Perturbation Method for HOM Tuning in a RF Cavity", NIM A309 (1991), pp. 355 - 367.