A NEW HOM-FREE ACCELERATING RESONATOR *

G. Conciauro, P. Arcioni

Dipartimento di Elettronica, Università di Pavia,
Via Abbiategrasso 209, 27100 PAVIA, Italy

Abstract - This paper is intended to demonstrate the feasibility of unconventional resonators, where a single resonating mode exists, useful for the acceleration. Unlike conventional cavities, in these structures the interaction region communicates through very large apertures with non-reflecting terminations. The special geometry of the structure permits to trap in the interaction region a single high-Q resonating mode, whereas all HOMs are heavily damped, being strongly coupled to the terminations. These structures can be named "Single Trapped Mode Resonators" (STMR). A model of STMR operating at 3.34 GHz has been developed and tested. Both numerical simulations and experimental tests showed that the shunt impedance and the Q-factor of the accelerating mode are comparable with those of a closed cavity.

Introduction

Coupled bunch instabilities cause serious troubles in the operation of synchrotron radiation machines, where many bunches must circulate for long times. It is well known that these instabilities are strongly dependent on the oscillating fields excited by the bunches in the RF cavity. In a conventional cavity, due to the high Q of the parasitic higher order modes (HOMs), the oscillations excited by the transit of a bunch through the interaction region can survive for a time long enough to interact significantly with the other bunches and, possibly, to start increasingly strong bunch oscillations [1,2]. A sufficient condition to avoid this effect is

$$Q << \frac{\pi\ \omega_r}{M\ \omega_o}$$

where Q and ω_r are the quality factor and the resonating frequency of a parasitic mode, ω_o is the revolution frequency and M is the number of the bunches. This conditions ensures that the oscillations induced by any bunch are damped to a negligible value when the next bunch crosses the interaction region. As the cavity is a nearly lossless structure, usually the Q factors of HOMs do not fulfil the above requirement. Possible cures consist in coupling these modes to external resistive loads by means of suitable coupling devices, in order to introduce a substantial damping and to shorten the "memory" of the interaction structure [3,4,5]. Due to the crowding of the cavity modes in the frequency spectrum of the bunches, it is not surprising that an effective damping of all the "dangerous" parasitic modes is in practice an hopeless enterprise, if conventional cavity resonators are employed for the acceleration.

This paper is intended to demonstrate the feasibility of unconventional resonators, where a single resonating mode exists, useful for the acceleration. Unlike conventional cavities, these structures are nearly open, as the interaction region communicates through very large apertures with absorbing terminations. The special geometry of the structure permits to trap in the interaction region a single high-Q resonating mode which, unlike all other modes, is decoupled from the terminations. As a result the impedance seen by the beam is a smooth function of the frequency, except in a very narrow band around the frequency of the accelerating field. This means that the HOMs oscillations are immediately damped. These structure can be named "Single Trapped Mode Resonators" (STMR).

(*) Work carried out in the framework of a consulting agreement between University of Pavia and SINCROTRONE TRIESTE.

Feasibility of STMRs.

The structures we are considering have a N-fold symmetry axis, coincident with the beam axis (fig. 1). They consist of a central body connected to N lateral waveguides. The RF-power is fed into the central body by a suitable coupling device.

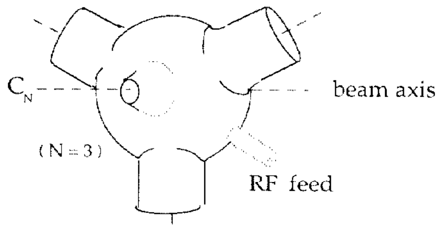

Fig. 1

The lateral waveguides are below cutoff at the operating frequency. In order to simplify the discussion let us refer to the cylindrical structure shown in fig. 2. It has a 3-fold symmetry axis (z-axis) and is laterally surrounded by three uniform rectangular waveguides.

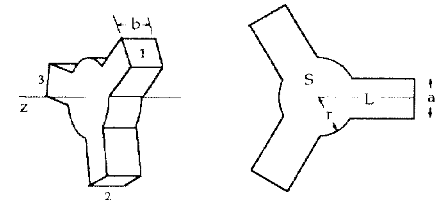

Fig. 2

At first we consider a situation where the waveguides are shorted at the terminal sections 1,2,3. In this situation the structure becomes a cavity resonator, whose modes can be classified as TM_{mnp} and TE_{mnp}, respect to z. If such a cavity would be used for acceleration, the longitudinal and transverse shunt impedance (which drive the instabilities) should be affected only by TM_{onp} (monopole) and TM_{1np} (dipole) resonating modes. In fact, only TM_{onp} have a non-zero E_z component on the axis (accelerating modes), and only TM_{1np} have a non-zero $\nabla_T E_z$ on the axis (deflecting modes) [6]. For this reason the real part of the longitudinal impedance exhibits resonant peaks at the frequencies of TM_{onp} modes, whereas the the analogous peaks in the transverse impedance are placed at the resonant frequencies of TM_{1np} modes. Due to the high Q-factors of these modes, all resonant peaks are very narrow, so that, when the lateral waveguides are shorted, the considered structure should exhibit a very long memory, like any conventional accelerating cavity.

It is well known that TM modes of a cylindrical resonator depend on the eigenfunctions $\psi_{mn} = \psi_{mn}(x,y)$ and on the eigenvalues k_{mn}^2 of the following two-dimensional problem:

$$\nabla_T^2\, \psi_{mn} + k_{mn}^2\, \psi_{mn} = 0 \qquad \text{over the surface S (fig. 2)}$$

$$\psi_{mn} = 0 \qquad \text{along the boundary of S}$$

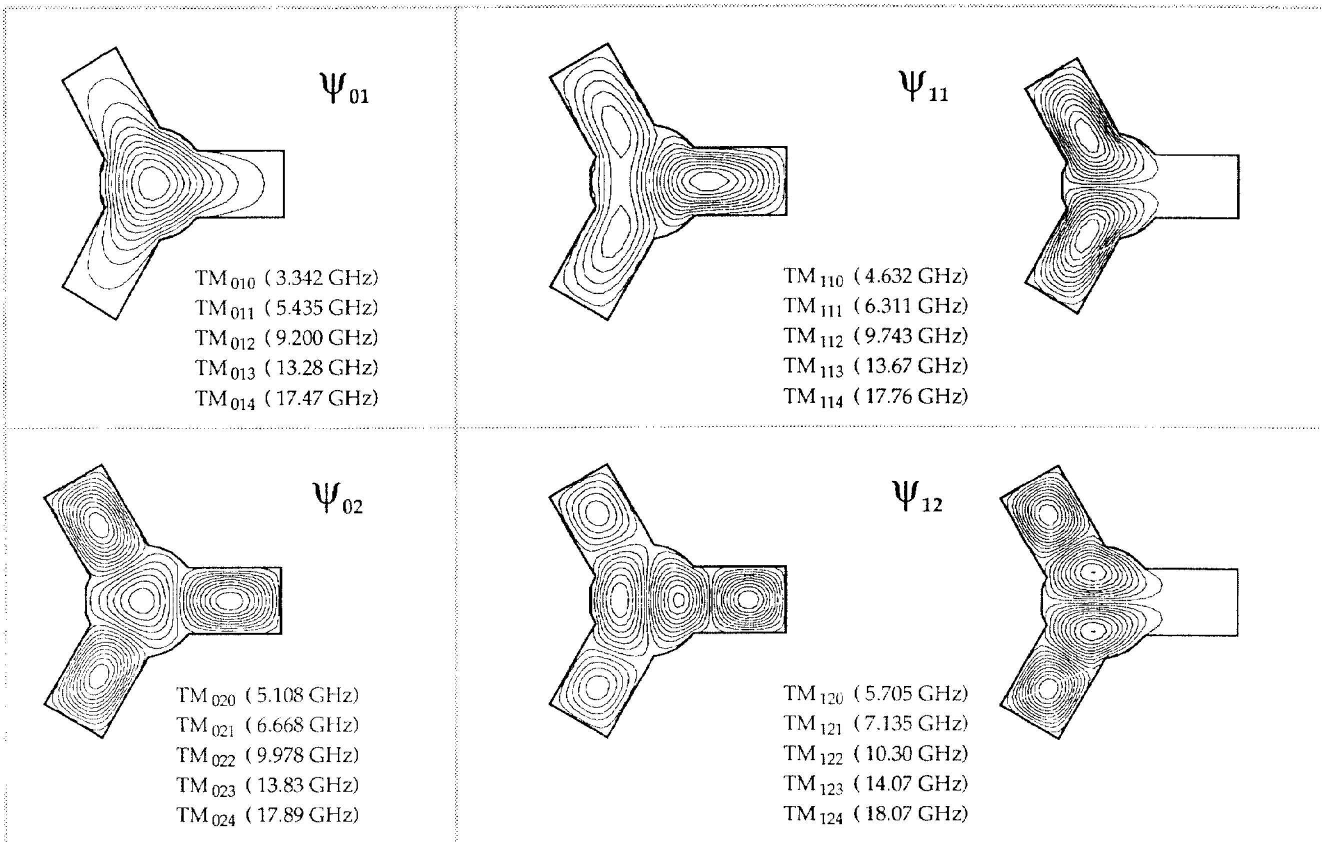

Fig. 3

It is remembered that the resonating frequencies and the axial electric field for a TM_{mnp} mode are given by

$$\omega_{mnp} = c\sqrt{k_{mn}^2 + \left(\frac{p\pi}{b}\right)^2} \qquad E_z = \psi_{mn}\cos\left(\frac{p\pi z}{b}\right)$$

where c is the velocity of light and b is the height of the cavity. Due to the complicate shape of S the eigenfunctions/eigenvalues have to be determined numerically. Suitably choosing the dimensions r, a, L we succeeded in obtaining the mode patterns shown in fig.3, which represent the contour lines of the first six eigenfunctions. Note that the eigenfunction ψ_{01} is evanescent inside the lateral waveguides, whereas all other eigenfunctions exhibit standing wave patterns therein. Furthermore, the amplitude of these last eigenfunctions does not differ so much in the waveguides and in the central region. This means that the coupling between the central body and the waveguides is very strong for all modes, except the TM_{01p} ones.

Now suppose that the waveguides are terminated by matched loads. It is evident that all modes, except the TM_{01p} ones, are heavily damped. TM_{01p} modes are practically unaffected, their fields being negligible at the absorbing terminations. Since all deflecting modes are damped, the transverse impedance becomes broadband, whereas the longitudinal impedance still exhibits the resonant peaks deriving from the TM_{01p} mode trapped in the central body.

Note that the TM_{010} mode can be used for the acceleration because it has a constant longitudinal electric field on the beam axis. This mode has to be confined as much as possible inside the central body in order to maximize its shunt impedance and to reduce the length of the waveguides. The narrower the waveguides are, the better the confinement is. Therefore the width of the waveguides must be optimized by a cut and try procedure, making it as small as possible, compatibly with the need of avoiding the trapping of modes other than TM_{01p} ones. The mode patterns shown in fig. 3 are obtained with the following dimensions: r = 30 mm; a = 35 mm; L = 73 mm; h = 35 mm. With these values the fundamental mode frequency (3.342 GHz) lies in the S-band, which is convenient for the realization of an experimental model.

The following table gives the numerically obtained values of the most relevant parameters of the dominant mode (copper walls as-sumed). For comparison the same values are given for a pill-box cavity having the same height and same TM_{010} resonating frequency. Note that the shunt impedance of the STMR is about 20% below that of the pill-box resonator, a results that appears to be acceptable.

	STMR	Pill-box cavity
Frequency (GHZ)	3.342	3.342
Shunt imp. R (MΩ)	2.3	2.9
Q-factor	13,300	15,100
R/Q	173	192

In the considered structure the complete suppression of HOMs is not achieved yet, due to the modes TM_{011}, TM_{012}, ... which, unavoidably, remain trapped together with the fundamental mode. These modes can be easily suppressed on the basis of the following considerations. Their resonating frequencies are well above the cutoff frequency of the dominant (TE_{10}) mode of the lateral waveguides, and they are decoupled from the waveguides only because their fields vary in the z-direction like $\cos(\pi z/b)$, $\cos(2\pi z/b)$,..., whereas the fundamental mode of the waveguides is z-independent. In other words the decoupling depends on the existence of the symmetry plane perpendicular to the z-axis. On the contrary the accelerating mode TM_{010} resonates at a frequency where the waveguides are below cutoff. Therefore it is evident that it is possible to damp the residual HOMs, without affecting the accelerating mode, by deforming someway the structure in order to eliminate the symmetry plane. This can be obtained in many different ways, for example by introducing a small offset in the z-direction between the central body and the waveguides (fig. 4). The effectiveness of this cure is apparent in the experimental results discussed in the next section.

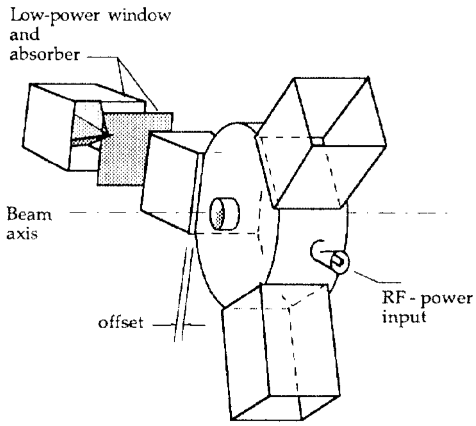

Fig. 4

The use of a structure having a 3-fold symmetry axis seems to be the best choice. In fact, in the case of a 2-fold symmetry axis, some deflecting modes remain trapped (fig. 5). Of course, the trapping could be avoided destroying the axial symmetry, but this would deteriorate the symmetry of the accelerating mode. On the other hand the use of a 4-fold symmetry axis would not give particular advantages from the point of view of the HOMs suppression, and would reduce the clearance for the insertion of the RF feed. Finally it is evident that the order of symmetry cannot be raised at will, because the consequent narrowing of the waveguides would cause an increasing number of HOMs to remain trapped.

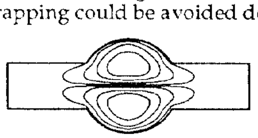

Fig. 5

Experimental results

An experimental model of the previously described STMR was made in order to verify the effectiveness of HOMs suppression. Simple transmission measurements have been performed in order to evidence resonance spectra. A pair of capacitive probes or a pair of small loops placed on the axis were used to evidence TM_{0np} and TM_{1np} resonances. For shortness only the results obtained with the probes are reported.

For comparison fig. 6a shows the TM_{0np} mode spectrum obtained when the waveguides are detached from the central body and substituted with conducting plates. This is a typical spectrum of a cavity, and exhibits a crowd of lines at high frequencies. Fig. 6b shows the spectrum when the matched waveguides are inserted without offset. The suppression of most of the modes is evident. As expected the residual lines occur at frequencies which coincide practically with those listed in fig. 3 for the TM_{01p} modes. Finally fig.6c shows the spectrum obtained after the introduction of a 4 mm offset between the waveguides and the central body. The complete suppression of HOMs is achieved.

The measurements performed with the loops confirmed the complete suppression of TM_{1np} modes.

Further transmission measurements were performed between loops and/or probes placed in different positions. These measurements evidenced that all other HOMs (both TE and TM) were suppressed too. In conclusion the tested structure was really unimodal.

Other non-cylindrical 3-fold symmetric structures were tested. In this case the size of the waveguides were adjusted experimentally by cut and try. Though the length of this procedure could not permit to optimize the structures, the obtained results confirmed that in principle a satisfying level of mode suppression can be achieved using waveguides coupled to the central body trough very large apertures.

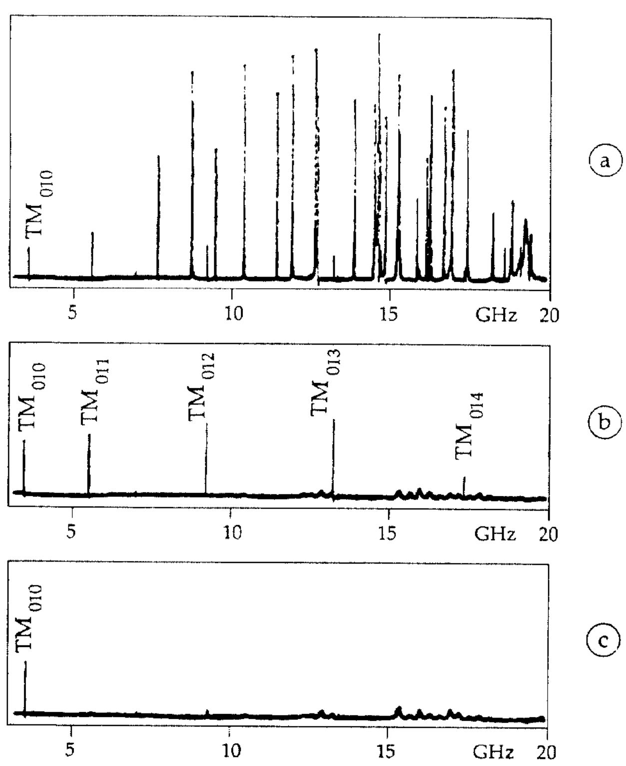

Fig. 6

Conclusions

The feasibility of a STMR was demonstrated. The proposed structures appear to be of practical utility for particle accelerators, because their shunt impedances are comparable with those of conventional cavities and because their realization seems to not give rise to serious problems. In particular the realization of the waveguide vacuum windows and absorbing loads is very simple, because they have to handle small powers, being placed in regions where the accelerating field is negligible. Furthermore, the radial size of the structure can be reduced by bending the waveguides, or by replacing them with more fanciful transmitting structures.

Our experience showed that small modifications of the structure are important if one aims at a really good mode suppression. Though the design of the structure can be carried out experimentally, only a computer simulation can allow the simultaneous optimization of mode damping, shunt impedance and, possibly, of other parameters. In the case of non-cylindrical structures the optimization would rely on the availability of a very powerful 3D computer code, probably better than the ones available up to now.

Acknowledgements

The authors thank Prof. M. Puglisi and his group at SINCROTRONE TRIESTE for the many useful discussions on this subject.

References

[1] M. Q. Barton, E.C. Raka, "High intensity beam instabilities in the Brookhaven AGS", Proc. 1971 Part. Accel. Conf., Chicago, IEEE Trans. Nucl. Sci. Vol. NS-18 n. 3, 1034.

[2] F. Sacherer, Proc. 1973 Part. Accel. Conf., San Francisco, IEEE Trans. Nucl. Sci. Vol. NS-20 n. 3, 825

[3] Y. Yamazaki, K. Takata, S. Tokumoto, "Damping test of the higher order modes of the re-entrant accelerating cavity", IEEE Trans. on Nucl. Sci., vol. NS 28, n. 3, June 1981, pp. 2915-2917.

[4] M. Poole, J. Corlet, "Use of URMEL and MAFIA for predicting HOM in the Daresbury cavity and comparison with measurements", Proc. of the Workshop on Impedance and Current Limitations, Oct. 17-18, 1988, Grenoble.

[5] G. Lambertson, "Beam Impedance Measurements at the ALS", Proc. of the Workshop on Impedance and Current Limitations, Oct. 17-18, 1988, Grenoble.

[6] G. Dôme, "RF Systems: Waveguides and Cavities", CERN SPS/86-24 (ARF), Geneve, Nov. 1986.