HOM-FREE CAVITIES

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Abstract

Intense beam current and multibunch operation are the essential features for increasing the luminosity of the modern colliders or improving the performances of the synchrotron light sources. The high order modes (HOM)-free cavities can give the major contribution to these tasks since the beam current limit and the coupled-bunch mode instabilities mostly arise from the parasitic modes of the accelerating cavities. This article deals with the study and the designs which have led to the development of RF cavities with a low content of high order parasitic modes. Different techniques adopted in both superconducting and room-temperature radiofrequency are analysed. Drawbacks in the use of these special devices are also reviewed.

1 INTRODUCTION

The new generation of e^+/e^- colliders and light sources have required the development of several novel and unconventional devices to permit multibunch operation and high current beams. These features are indispensable to achieve the luminosity range of $10^{32} \div 10^{34}$ sec^{-2} cm^{-1} (in the factories and TeV linear colliders) or increase the photon flux in the synchrotron light sources.

Recently, RF experts of numerous accelerator laboratories have concentrated efforts and resources in the design and construction of HOM-free accelerating cavities. The motivation for this demanding job is to eliminate or reduce the interaction of the cavity HOMs with the particle beam spectrum, thus increasing the current threshold limited by the coupled-bunch instabilities and reducing the beam power losses. Even though the totality of the accelerator components contributes to increase the growth rate of both transverse and longitudinal coupled-bunch instabilities, the RF cavities are undoubtedly the major source of problems. This argument has been treated in many articles and technical papers and is still subject of discussions and experimentation.

The mechanism which can produce beam instability or power loss consists in the capability of the charged particles, to induce high order resonant fields in the RF cavities when passing them through. This is possible only for those cavity resonances which overlap beam Fourier harmonics or their sidebands. The HOMs have a decay time τ which can be much longer than the time gap between two neighbouring particle bunches, i.e.: $\tau = 2Q/\omega >> t_b$ where Q and ω are the quality factor and the angular frequency of the induced cavity HOM, t_b is the time interval between two successive bunches. In circular machines $t_b = To/n_b$ with To revolution time and n_b number of accumulated bunches. Particles which travel through the cavity on its longitudinal axis can generate TM0,n,m-like monopoles alone, whereas off-axis particles can generate both monopoles and dipoles. Due to the time persistence of the cavity HOMs, the resonant buildup of the parasitic fields may occur. Thus the beam can get unstable and the storable current severely limited if the instability growth rate is greater than the natural damping. In circular machines, the interaction of the beam spectrum sidebands with the cavity spectrum is responsible for longitudinal and transverse instability [1]. Beside this, power losses are associated to interaction of the main beam Fourier lines with the cavity HOM impedances. These losses can be evaluated by summing [2] the possible contribution for each beam line and cavity mode: $Z \cdot I_b^2/2$, where I_b is the beam line amplitude and Z is the real part of the cavity mode impedance at the beam line frequency. In linear colliders, the beam-cavity interaction can cause the so called beam blow-up (BBU).

The beam/cavity spectra overlapping can be faced by detuning the dangerous HOM frequencies. However, this may not be considered as a real way to render HOM-free the RF cavities. This method consists in the modification of the cavity temperature, for shifting the frequency of the potentially dangerous modes in order to avoid overlapping with the beam spectrum lines. This HOM detuning is an experimental approach for fighting coupled-bunch mode instabilities and in some cases it has been used successfully [3,4,5,6]. An alternative way of HOM detuning, based on the Slater's perturbation theory [7], is analysed and proposed in [8]. Anyway, HOM detuning can help in small rings only, since the particle revolution frequency is high and the beam Fourier components are largely spaced.

2 THE CONCEPT OF HOM-FREE CAVITIES

To counteract more rigorously the effect of the HOMs, the exponential growth of the parasitic fields must be reduced within the range that makes feasible the use of broadband feedback systems [9,10], that is the HOM impedances R and quality factors Q must be reduced the most. To achieve this result, it is necessary to remove the HOM power from the cavities and dissipate it with high RF losses materials or external loads. Several techniques have been proposed to suppress cavity HOMs depending on the accelerator requirements and the cavity frequency. Super-conducting (SC) and normal-conducting (NC) resonators require diverse HOM damping systems as well. In SC radiofrequency it is essential to avoid cavity quenching or strong degradation of the accelerating mode Q since this overloads the refrigeration systems and does not permit to achieve the design accelerating gradients. For these reasons in SC cavities, it is preferred to extract the HOM power from the cavity beam tube instead of from the accelerating cell. Also, low values of the [R/Q] ratios are helpful to minimize the cavity contribution to the broadband impedance of the ring and can be obtained by properly shaping cavity and beam pipe profiles [2]. It is also wise to design the cavity shape so that the worst HOMs lie as far as possible from intense beam Fourier components. Therefore, the beam-cavity overlapping is unlikely in an undamped cavity but can lead to excessive instabilities and power losses. On the other hand, in a heavily damped cavity, the interaction is very probable but more easily controllable.

The concept of "HOM-free cavities" derives from the above considerations.

3 COUPLING OUT THE HOMs FROM THE RF CAVITIES

A detailed and very fine basic description of the HOM damping methods can be found in the ref. [11]. The most used HOM damping systems can be classified in three main categories, i.e. the coaxial couplers, the beam tube damping loads and finally, the waveguide couplers.

3.1 HOM couplers with coaxial structure for application in room temperature resonators

Narrow band and tuned devices belong to this group of couplers. They consist in coaxial structures with LC distributed elements, which penetrate the cavity with antennas (E-probes) or loops (H-probes). The damper position is chosen to couple the most dangerous parasitic fields and the HOM power is carried out and dissipated on external dummy loads. To avoid extraction of the principal mode, such dampers need a filter that can be achieved by means of transmission line techniques. Fundamental mode (FM) decoupling can be also obtained with a correct choice of the damper position.

Loop and antenna couplers were applied to the PETRA NC cavities [12] and used in DORIS e^+/e^- storage ring. The coupling impedance of the most troublesome TM011 has been reduced by several factors. The dampers had FM filtering and water cooling (Fig. 1).

The CERN SPS 100 MHz NC cavity [13] is equipped with three $\lambda/4$ coaxial lines ending with E-probes. Damping of some HOM impedances as much as 30 dB is obtained. Tuning, bandwidth and mode coupling are made by adjusting the length of the coaxial sections. The load resistor is connected at some distance of the line short and determines the coupler Q. Rod-antenna dampers (Fig. 1) have been operating on TRISTAN NC cavities at KEK since 1989 [14], providing significant reduction of the coupling impedance of the TM011 and TM111 modes. This permitted to increase the instability beam current threshold over 20 mA. The antenna is followed by a coaxial line with a short end tuned to reject the cavity FM. The HOM power is extracted at a mid point with a vacuum feedthrough and dissipated on a resistive metal film. E-probes and H-probes dampers have been developed at Argonne for the APS 352 MHz NC cavity [15]. The HOM power dissipation is achieved with vacuum compatible AlN ceramic materials and the damping factors are satisfactory for the machine operation. Installation on APS is foreseen early the summer 1996 [16]. Other similar damping systems have been proposed or developed elsewhere [17,18].

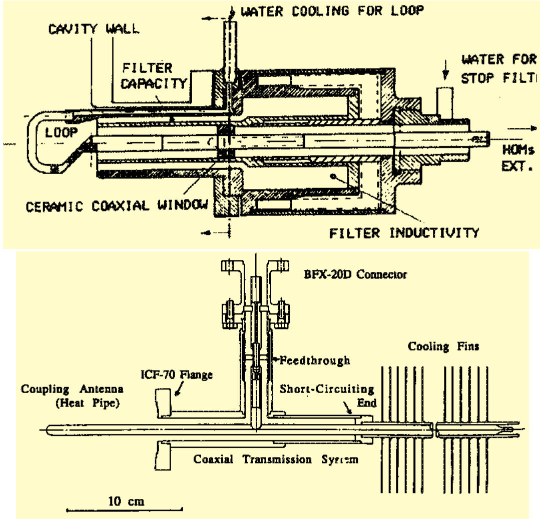

Figure 1 - Coaxial HOM couplers developed for normal conducting cavities technology at DESY (up) and KEK.

3.2 Coaxial HOM couplers for application in SC cavities

Coaxial HOM dampers are essential components of the multicell SC cavities operating at LEP, HERA and TRISTAN colliders and developed for the TESLA project too. Positioning the dampers at the equator of the cavity cells [19,20] has been in general avoided since it can cause multipacting and thermal-magnetic breakdowns. Thus, it has been chosen to put the couplers on the beam tubes [21,22,23] at both the ends of the cavity providing that the HOM wake fields propagate out by opening enough the pipe diameter as proposed in ref. [24]. Usually they are set with azimuthal angle of 90° to damp both polarizations of the dipole modes. The HOM power is extracted with vacuum feedthroughs and dissipated on 50 Ω resistors.

The LEP 352 MHz SC cavities are equipped with HOM couplers evolved through several projects to the final configuration [25] shown in Fig. 2. The original design is due to CEN-Saclay [26] and consists basically in an LC series to ground, intercepting the HOM magnetic fields (the so called "hook type" coupler). The HOM external Qs are in the range of a few thousands [27]. This model presents important features as dismountability, easy FM tuning, simple manufacturing and cooling. HOM coaxial couplers are used in the sixteen 500 MHz SC resonators of the HERA electron ring [28]. The couplers, based on two inductive stubs, have broadband response and tunable FM filtering. Beam energy upgrading has been achieved at TRISTAN main ring by installing 32 SC 508 MHz cavities equipped with beam tube HOM couplers [29]. FM rejection is achieved with a $\lambda/4$ resonator and an output T stub allows the inner conductor cooling. The HOM couplers for the nine-cells 1.3 GHz SC cavities of the TESLA project [30] are also demountable loops and have been developed and tested at Saclay.

Filtering of the cavity accelerating mode is very important in coaxial HOM couplers, especially in SC cavities where FM Q strong degradation is unacceptable.

The HOM Qs are damped down to $10^4 \div 10^5$ without perturbing the SC cavity performances. In NC resonators damping of single HOMs can be excellent. The reduced number of the damped modes is the main limitation of the coaxial HOM couplers and also their cooling in cryogenic environment presents some risks.

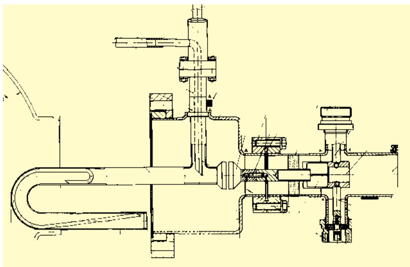

Figure 2 - The "Hook type" HOM Coupler.

3.3 *Beam tube HOM damping loads*

Single cell SC cavities will be used on CESR at Cornell University to upgrade the luminosity [31]. Also SC resonators are being developed for the KEK-B Factory [32]. In the two cases, the HOM power will be dissipated by means of RF lossy ferrites bonded to the inner surface of both cavity beam tubes. The loads are located at room temperature outside the cryostat. The cavity beam tubes are enlarged enough to permit the HOMs, but the FM, to propagate throughout. However, to ensure the propagation of the lowest dipoles (i.e. the TM110-like and TE111-like) the pipe cut-off is further lowered at one cavity side. At Cornell, a grooved pipe is adopted [33], whereas an extra-large tube of 300 mm diam. is used for the KEK-B SC cavity. Figure 3 shows a sketch of CESR-III and KEK-B cavity modules. The 500 MHz CESR-III cavity uses RF lossy ferrite tiles to dissipate the HOM power. The tiles are bonded on water cooled copper plates radially applied to the inner surface of a beam pipe section. Ferrite damping and power handling capabilities have been evaluate and a beam test of a fully equipped cavity has been performed [34]. The results are considered satisfactory for the full beam operation of CESR-III [35].

The KEK-B HOM loads are made by sintering a ferrite powder directly on the inner surface of a copper pipe with a special process developed at KEK [36]. The ferrite damping properties, measured on an cavity model, are excellent as reported in [32] and the bench power tests have proved the loads can withstand average power densities of 14 W/cm^2. A prototype ferrite load has been tested positively with the TRISTAN beam. Ferrites permit to damp the HOM Qs of large pipe single cell cavities down to a few hundreds or less over a 1.5÷2 GHz band without degradation of the FM features. Their outgassing rate seems compatible with the ultra vacuum of the accelerators. A very efficient cooling is necessary to avoid cracks of ferrites due to their low tensile strength and thermal conductivity. The beam line tests have not revealed, till now, other major drawbacks. Other dissipative materials, as the SiC ceramics, have been proposed [37] and their use is foreseen for the beam tube HOM loads of the ATF cavity at the Japan Linear Collider [38].

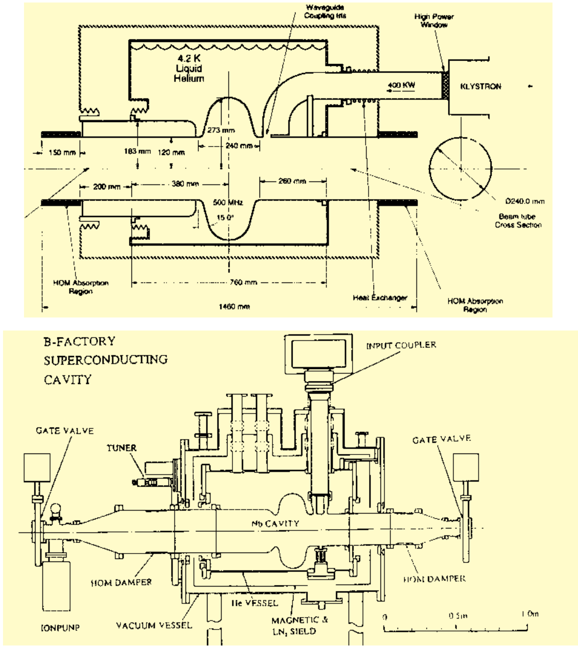

Figure 3 - The CESR-III (up) and KEK-B SC cavity modules.

3.4 *Waveguide HOM Damping*

S-band waveguides (WG) are used in the recirculating linac CEBAF to extract the HOM power from the beam pipes of 338 SC 1.5 GHz cavities. The cavity FM vanishes at the WG position so that its Q is unperturbed. The absorbing loads are made of an AIN based sintered ceramic which has good vacuum properties and thermal conductivity. They are brazed to the WG end flanges and operate in vacuum avoiding the use of a separation window. Because of the low HOM power, the WG dampers are inside the cryostat at 2°K [39]. The HOM Qs are brought down to $10^3 \div 10^5$ and the instability limit is raised over the 200 μA design value. The operation time accumulated till now in beam environment have not shown any drawbacks in the use of these HOM loads [40].

The WGs offer natural rejection to all the under cut-off frequencies and therefore their use in HOM extraction has the great advantage to stop the cavity FM. WGs were proposed in [41] already in 1988 for HOM damping in linear colliders.

The concept of using WGs in accelerating cavities has been stressed in ref. [42] with the proposal of a 3-WG loaded cylindrical resonator which is virtually free of HOMs. In that 3 GHz model, the WGs are considered integral part of the cavity rather than something added afterward. Three equally spaced square apertures are opened around the equator of a pill-box and convey out, by means of WGs, all the parasitic fields in the TE10 mode. The cavity FM, whose frequency is below the WG cut-off, is evanescent and remains trapped in. Terminating loads are placed at each WG short-end but the excellent wideband HOM damping is counterbalanced by a strong FM power loss because of an excessive dissipation in the WGs. A rather similar solution was initially investigated at Trieste for the ELETTRA synchrotron light source [43].

WG dampers have been adopted at SLAC for the PEP-II B-Factory project [44]. A total of 32 NC single cell 476 MHz copper cavities will be used. Since the accelerating voltage is more than 600 kV per cavity, the FM shunt impedance must be preserved as much as possible. Large WG apertures or wide beam tubes for housing lossy materials are therefore avoided. The PEP-II "nose-cone" resonator [45], shown in Fig. 4, is equipped with three WGs attached to rectangular slots opened 120° apart for symmetry reasons. The HOM load terminations [46] are made by brazing tiles of lossy ceramics (the same developed for CEBAF) on the WG broadwall near the short-end side. The RF characteristics and the load shape guarantee a VSWR less than 2:1 in a 700÷2500 MHz range. The calculated HOM power is about 10 kW per load. The WGs have 600 MHz TE10 cut-off and are located to couple strongly the worst parasitic modes. HOM longitudinal and transverse impedances have been significantly reduced over a large frequency band in a cavity prototype as shown in Fig. 5. A full power cavity model is being tested and one HOM load prototype has been powered to 4 kW separately [47].

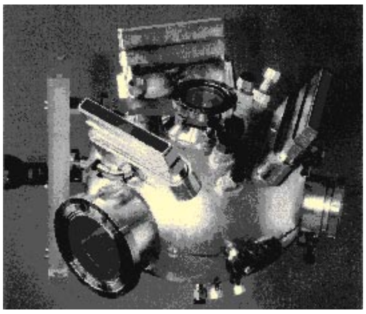

Figure 4 - The PEP-II Waveguide Loaded RF Cavity.

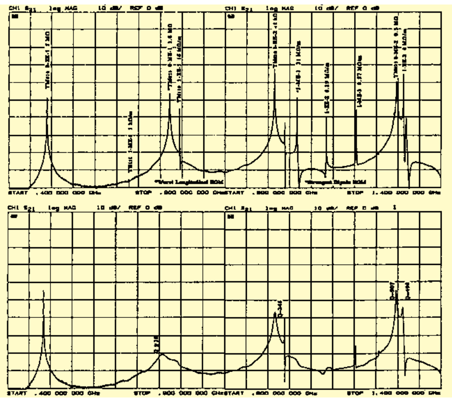

Figure 5 - Undamped (up) and damped spectra up to 1.4 GHz of the PEP-II cavity model [48].

Strong HOM damping is also required at the INFN-LNF e^+/e^- Φ-Factory DAΦNE [49] to reach the design luminosity. The machine is in construction at Frascati and consists of two intersecting rings for multibunch operation. One single cell room temperature 368 MHz copper cavity will be operating in each ring. Because of the low RF voltage required (250 kV peak), the FM impedance optimization was not of primary importance. A "door-bell" resonator with 80 cm long tapered beam pipes has been adopted. This shape, while keeping the FM impedance at an acceptable level, made possible to bring down substantially the r/Q values [2] and consequently, the HOM impedances are lowered by several factors, even without dampers, respect to more conventional solutions. Three rectangular 495 MHz cut-off WGs are applied to the cavity body for HOM coupling and other two with 1.2 GHz cut-off are connected to the tapered tubes to capture the parasitic modes propagating through the pipes. The WGs are then converted to coaxial lines with a gradual double ridge wideband low VSWR transition developed at LNF [50] which allows dissipation with commercial 50 Ω loads, via 7/8" coaxial vacuum feedthroughs. This design avoids the use of under vacuum brazed materials and permits to sample the HOM power. The overall estimated HOM power for a full beam (5 Amps) machine operation is lower than 3 kW and will propagate mostly throughout the larger WGs. The first cavity, equipped with HOM dampers, has been tested successfully to 30 kW that is about twice the nominal power. Figure 6 shows the DAΦNE cavity under test at Frascati.

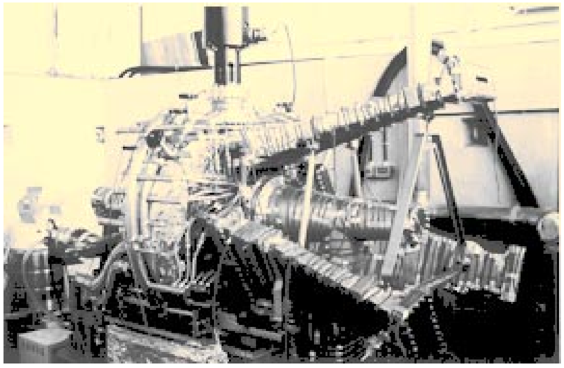

Figure 6 - The DAΦNE Cavity in the Power Test Hall.

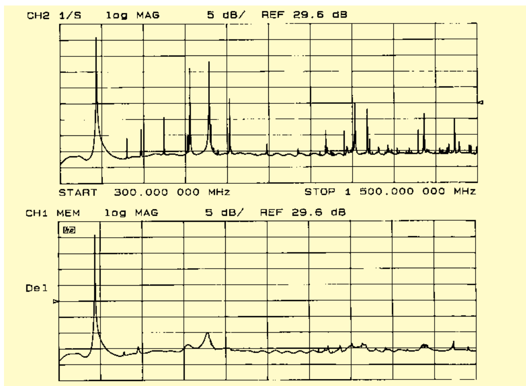

Figure 7 - Undamped (up) and damped longitudinal spectra of the DAΦNE Cavity.

Figure 7 shows the cavity longitudinal spectrum, measured with the "wire technique" [51], before and after connecting 50 Ω loads to the coaxial output of the WG transitions. The HOM impedances are damped to a few hundreds Ωs or less. The worst dipole mode Qs are also reduced to a few hundreds and have been evaluated by probe excitation. The additional power dissipation of the accelerating mode due to its penetration in the WGs is tolerable.

Among the HOM-free resonators, an important role plays the "choke-mode" cavity devised both for a damped linac structure [52] and a crab-cavity [53]. The concept has been applied to the room temperature KEK-B ARES resonator which is under test in Japan in parallel to the SC option [54]. It consists of a single cell copper cavity, sketched in Fig. 8, equipped with a large coaxial guide to extract monopole and dipole HOMs in the TEM and TE11 mode respectively. Since TEM mode has not cut-off, the coaxial guide requires a notch filter to block the cavity FM. However this is an advantage respect to WG loaded cavities where the RF currents are blocked by the WG slots. HOM power dissipation is achieved by 16 bullet shape sintered SiC absorbers inserted from the WG end. Recently [55], power tests have been made up to 150 kW-cw. The HOM damping performances [56] have been studied with simulation codes and found fully satisfactory.

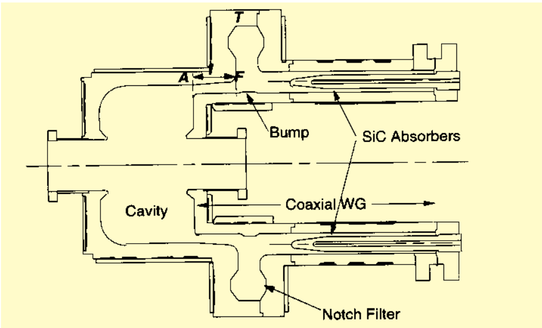

Figure 8 - Sketch of the NC Damped Cavity for KEK-B.

WG damped cavity design would have not been possible without powerful simulation codes (MAFIA, ARGUS) and post-processors [57]. The RF specialists get also great advantage in the use of the HFSS code [58] for designing three-dimensional electromagnetic devices as the Frascati WG-coaxial transitions or distributed structures like the FM notch filter of the KEK-ARES cavity.

Moreover, the HOM external Qs, due to damping WGs, can be predicted by means of methods based on the Slater's theory [59,60,61] and Kirchhoff's approximation [62] which are therefore helpful in the optimization of WG position and size. The author regrets not to have enough room to deepen this important aspect of the HOM-free cavities design. Other projects [63,64] are worthy of mention but they could not find space in this short note.

4 CONCLUSIONS

The HOM-free cavities are becoming real devices in accelerators for fighting beam instabilities and HOM power losses. Each solution offers its advantage depending upon the accelerator requirements. The use of WGs in NC cavities results in a satisfactory broadband HOM damping with a small cost in term of FM loss. Brazing techniques developed for the absorbing materials are getting reliable even though other original solutions, as the coaxial transitions, are worthy of consideration.

All the accelerator community is waiting impatiently full beam operations of the HOM-free cavities.

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