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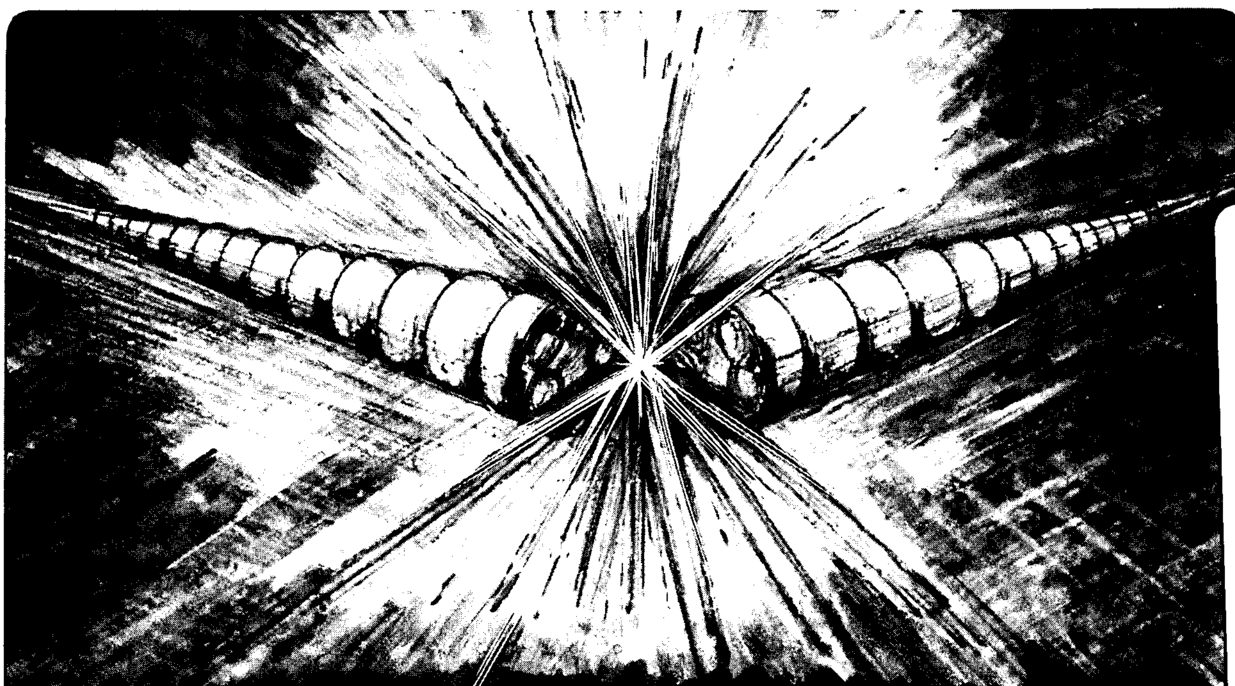

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EXTRACTION AND ABSORPTION OF HIGHER ORDER MODES IN ROOM TEMPERATURE ACCELERATORS

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ABSTRACT

This paper describes methods for extracting and absorbing unwanted higher-order modes (HOMs) from normal-conducting accelerator structures. An introduction to the problems caused by HOMs is followed by a brief history of the development of techniques to suppress them, and some examples taken from existing and planned accelerators. These include damped radio frequency (RF) cavities for storage rings such as the proposed PEP-II *B* factory and accelerating structures for future linear collider projects.

INTRODUCTION

Most accelerators use some form of RF accelerating structures to supply energy to the particle beams. In their simplest form these are single-cell cavities in which RF power is used to generate an electric field through which bunches of particles are passed in order to increase their energy.

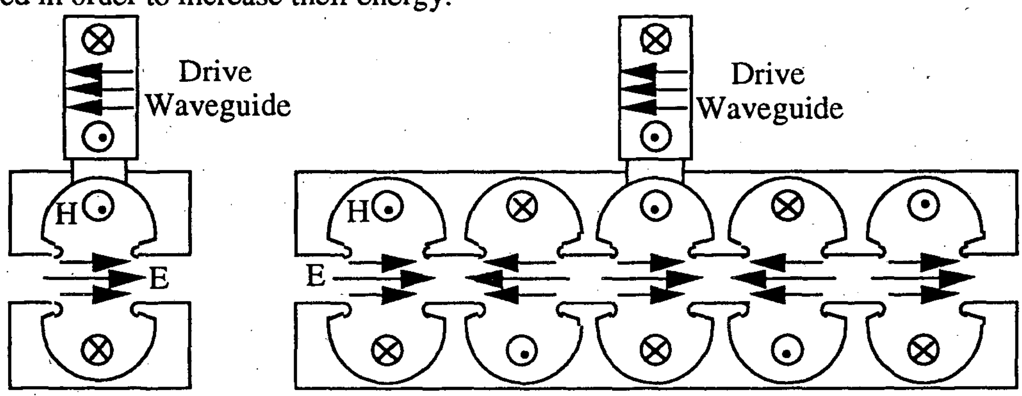

Fig.1. single- and multi-cell normal-conducting cavities

Often groups of cells are joined together and driven from a single RF source. In the case of linear accelerators (linacs), very large numbers of cells may be assembled in a straight line through which the bunches only pass once. In storage rings the bunches follow a closed orbit which brings them back through the same cavities repeatedly, either to continually increase their energy (acceleration), or to make up for losses in other parts of the machine (stored beam). The efficacy of accelerating structures in their normal mode of operation (the accelerating mode) is characterized by the voltage developed for a given amount of RF power. This is known as the longitudinal or shunt impedance $\boldsymbol{R}$, which is variously defined as a true impedance, $\boldsymbol{R = V^2/2P}$, or is often seen in physics circles defined in terms of the peak voltage (squared) for a given

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RF power, $R = V^2/P$. For the accelerating mode of a single-cell cavity this is typically of the order of MΩ. To assess the merit of a cavity shape, independent of the material used, its Q is factored out and the quantity R/Q is quoted, which still has units Ω but is now a function only of the geometry.

To find the effective voltage experienced by the particles it is necessary to include the effect of the time variation of the fields while the particles are crossing the cavity gap [1]. This is expressed in the form of a transit-time factor T ($0 \leq T \leq 1$), where the effective voltage = VT, and the transit-time-corrected shunt impedance, RT^2, sometimes given the symbol R_s. The reader is cautioned that the symbols R, R_s and R/Q are commonly used for either basic or transit-time-corrected quantities. To avoid confusion it is preferable for the transit-time-corrected parameters to be called out explicitly as RT^2 and RT^2/Q.

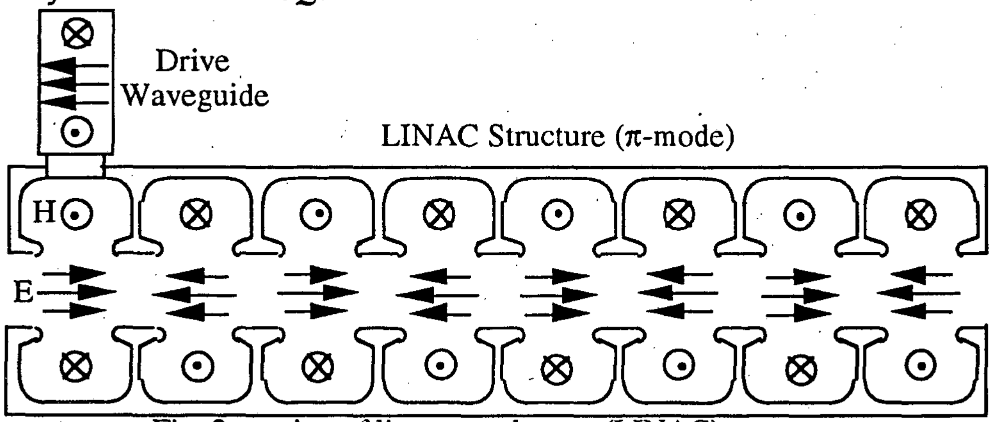

Fig. 2. section of linear accelerator (LINAC) structure

For multi-cell cavities and linacs the performance is often more conveniently expressed in terms of the shunt impedance per unit length of structure in, typically, MΩ/m. (N.B.: this should not be confused with a quantity called the transverse impedance which will be introduced shortly, which also has the units Ω/m).

Room temperature (i.e. non-superconducting) accelerator structures are usually designed to maximize the accelerating-mode shunt impedance to make most efficient use of the RF power source. Unfortunately the cavities can resonate in many other modes besides the one used to accelerate the bunches. Since the accelerating mode is usually the fundamental (lowest frequency) mode of the cavity, these other modes are usually collectively referred to as the higher-order modes (HOMs). Because the beam bunches are usually shorter than the wavelength of the accelerating mode, the beam current has higher frequency Fourier components which may cause it to interact with the cavity through excitation of these HOMs. Many HOMs may have electric field along the beam axis of the cavity and may be characterized, like the accelerating mode, by a longitudinal shunt impedance. Usually the HOMs do not have as high an impedance as the accelerating mode because either their field distribution in the cavity or the effect of the transit time across the gap are not optimal, but the coupling to the beam is often still significant. Interaction between the beam and the cavity HOMs can give rise to instabilities as will be described later.

Most accelerating cavities have at least superficial circular symmetry around the beam axis since these shapes often have the highest Q's, are easier to model on the computer, and are often made by turning or spinning metal. HOMs that have longitudinal electric field on the beam axis, like the accelerating mode, are also usually symmetric around the azimuth of the cavity. These are often called "longitudinal " or "monopole" modes (m=0), to distinguish them from HOMs that have one or more reversals in the direction of the field around the azimuth (m=1 or "dipole", m=2 or "quadrupole" etc.). These other modes usually have no longitudinal electric field on axis and do not interact with particles moving along the center line of the cavity. However if particles pass through the cavity displaced from the symmetry axis then they may well interact with these dipole and higher azimuthal-order modes. The strength of the interaction may vary with the amount of the displacement and with the angle around the cavity azimuth. These off-axis particles may experience a kick at right angles to their original direction of travel which can give rise to transverse instabilities of the beam and leads to these HOMs being known as "transverse" or "deflecting" modes. Of these HOMs usually only the dipole modes are of concern as they have the strongest interaction with off-axis particles and have a linear variation of coupling strength with displacement from the axis.

These dipole HOMs are characterized by a transverse impedance which is similar to the longitudinal impedance but takes into account the variation of coupling strength with radial displacement. Unfortunately there are also multiple definitions of the transverse impedance, the most common being $RT^2(b)/(kb)^2$ which has units Ω, and $RT^2(b)/kb^2$ which has units Ω/m, where $RT^2(b)$ is the transit-time corrected longitudinal impedance at some radius b, and k is the wave number ($k \equiv 2\pi f/c$). Sometimes a transverse R/Q is used, for example in the output of the URMEL code [2], such as $RT^2/Q(kb)^2$ Ω. It is advisable always to state which definition of impedance is being used when reporting results of calculations or measurements.

HOMs in the accelerating structures become problematic when they give rise to instabilities in the particle beams. These usually appear as current-dependent effects which cause the bunches to diffuse, distort or oscillate about their intended trajectories. In machines with high current and/or low natural damping of instabilities they can seriously degrade the operation of the accelerator.

BEAM INSTABILITIES

HOMs in the accelerating structures, or in any other cavities along the beam path, may couple to the beam and drive beam instabilities. These instabilities are of two general classes, those that occur within the dimensions of a single bunch and those in which the motion of successive bunches are coupled together by energy storage in the resonant HOMs.

Single-bunch instabilities tend to be a problem when the charge density in a bunch is very high, because either the number of particles is large or the bunch is very short. The interactions are usually at high frequency and are sometimes known as microwave instabilities. In this kind of instability the interaction of the bunch with HOM fields in the resonator leads to modulation of the charge density within the bunch. The particles at the head of the bunch create an electromagnetic wake which interacts with the cavity or vacuum chamber and which the following particles in the middle and tail of the bunch experience a short time later. Often this can cause the trailing particles to be retarded, causing bunch lengthening, or deflected causing an oscillation about the original trajectory. If the bunch passes through many such cavities or through the same cavity many times the amplitude of the instability may grow. If the growth rate of the instability is larger than the natural damping mechanisms in the machine then the motion will continue to increase. Often this will cause the particles with the largest amplitudes to be lost, but the instability may be self-limiting at some amplitude. For example the bunch length might increase until the charge density drops to the point at which the instability growth rate equals the damping rate, and the beam adopts a new, longer, equilibrium bunch length. This kind of beam blow-up might degrade the operation of a collider or synchrotron light source in which it is desirable to keep the bunches small or short.

The passage of the bunch through the cavities excites the HOMs and if the Q is high enough there will still be energy left in the fields when the next bunch arrives. This transfer of energy from one bunch to the next couples the motion of the bunches and can lead to the build up of coherent patterns of instability along a bunch train or around a filled storage ring. For example the first bunch in a train may go through a cavity and leave energy ringing in the high-Q HOMs which may in turn accelerate, retard or deflect a following bunch. If the phasing is such that the energy in the HOMs is increased with each passing bunch then the interaction will continue and the amplitude of the bunch motion will grow until the process limits or the bunch motion causes particles to be lost.

In storage rings these multi-bunch instabilities are observed as "coupled-bunch modes" (not to be confused with cavity modes!), which are closed patterns of longitudinal or transverse bunch displacement around the orbit. The transverse coupled-bunch instabilities are also driven by the interaction of the beam with the resistance of the vacuum chamber wall, even in a smooth pipe. In some cases the growth rate of this "resistive-wall" instability may be as high as that from deflecting cavity HOMs, particularly if the modes are well damped.

In linear accelerators the coupled-bunch instability is most often seen in the form of beam break-up where successive bunches in the train undergo increasingly large deflections until the particles are lost or the beam profile is degraded.

REMEDIES FOR HOM-DRIVEN INSTABILITIES

In many machines only one or a few HOMs have high enough impedance and Q to drive instabilities. In these cases there are some tricks that can be used to reduce the growth rates of instabilities to acceptable levels. Often an instability will arise because of a sympathetic resonance between one frequency component of the bunch current and a single HOM in the cavity. In this case it may be possible to "detune" the HOM, moving its resonance to harmless frequency. This is sometimes done by changing the temperature of the cavity through adjustment of the water flow [3]. The fundamental mode is maintained at the desired frequency by a feedback loop operating a tuner in the cavity. If a dangerous HOM is calculated in advance to fall at a sensitive frequency the shape of the cavity can be modified slightly at the design stage to avoid the situation.

In machines with more than one cavity there is a danger that the growth rates from the same HOMs in each cavity will add up, that is more than one cavity will drive the same beam instability. To avoid this the shape of each cavity can be made slightly different from all the others to stagger the HOM frequencies while keeping the fundamental-mode frequency the same in all cases [4]. This limits the maximum growth rate to that of the worst HOM in a single cavity, but at the expense of having to design and build all the cavities to different shapes. In accelerators with a very large number of cavities the machining tolerances will yield a statistical distribution in the HOM frequencies which may be sufficient to reduce the cumulative growth rate. Staggering of the HOM frequencies is only really useful if the modes have high Q's, otherwise the detuning required to avoid overlap of the modes becomes large. This method is therefore most useful if the growth rate from a single undamped cavity is tolerable but the total from all the cavities would be unacceptable. If the growth rate from even a single cavity is not tolerable then the Qs of the HOMs must be reduced.

Lowering the effective impedance of the cavity modes by reducing their Q's requires coupling the energy in the modes out to an external load. Many HOMs already couple to the fundamental-mode coupler and the energy extracted this way can be absorbed by HOM filters in the drive network, see fig. 3. Such filters were used successfully in the feed waveguide for the SRS at Daresbury [5,6].

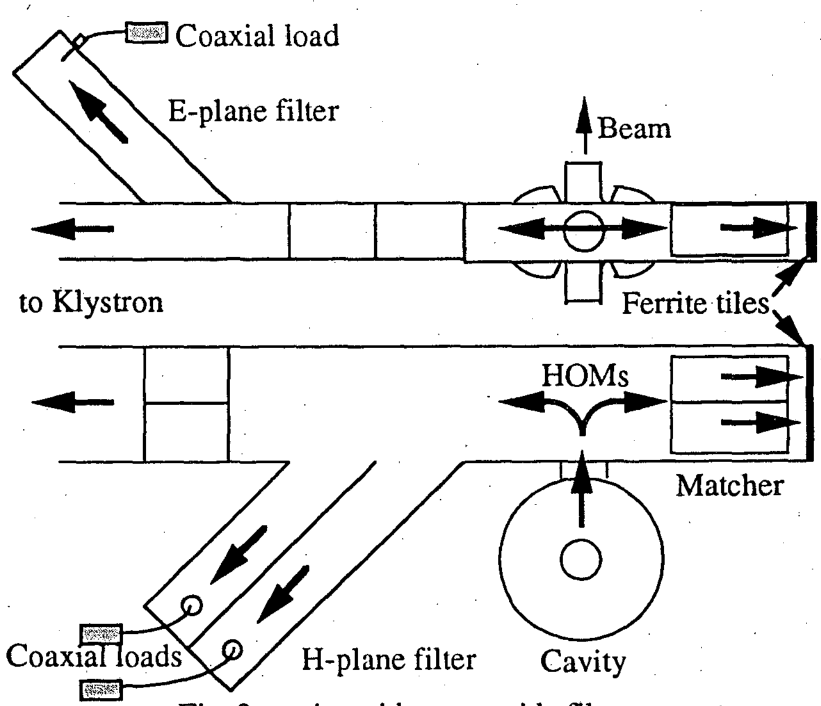

Fig. 3. cavity with waveguide filters

For those HOMs that do not couple to the drive network it is possible to insert additional couplers or antennas in the cavity which are positioned to catch the troublesome mode, see fig. 4. These probes must have some kind of filter to reject the fundamental-mode frequency; otherwise large amounts of power will be coupled into the external loads. In some cases the high circulating currents in these filters have caused thermal problems.

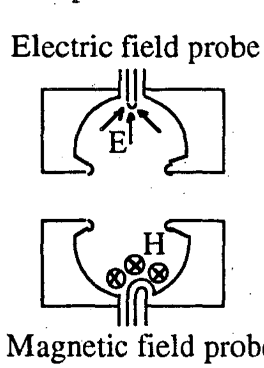

Fig. 4. E and H field probes

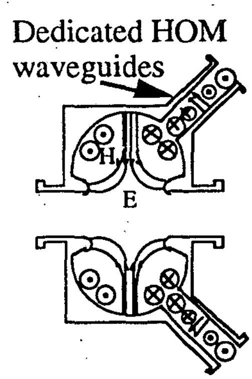

Fig. 5. dedicated damping ports

Internal loop or antenna couplers have been successfully used to de-Q one or a few troublesome HOMs but are not well suited to situations where many modes must be damped or the power in the cavities is very high. Recently much attention has been focussed on aperture couplers dedicated to HOM damping, see fig. 5, which are positioned in the wall of the cavity such as to couple to all troublesome HOMs, and which feed waveguides which are too small to allow the fundamental mode to propagate. Several single-cell and few-cell cavities are under development with HOM waveguides which give good rejection of the fundamental mode while allowing broad-band damping of HOMs [7,8,9,10]. For future linear collider applications, where beam break-up is expected to be a significant obstacle, damped accelerating structures are being developed which employ waveguides, or a radial guide with a choke filter to reject the fundamental mode. Examples of some of these damping schemes are described later.

Another weapon against beam instabilities in storage rings is the use of feedback systems to supplement the natural damping mechanisms of the accelerator [11]. The first systems developed were narrow-band, in which a signal corresponding to a particular coupled-bunch oscillation is detected, processed, and fed through an amplifier to a kicker, which applies a correcting signal to the beam. A separate feedback circuit or channel is required for each unstable coupled-bunch beam mode so this approach is useful only if the number of unstable beam modes is small. If there are many unstable coupled-bunch modes a broad-band system may be used. In a broad-band or bunch-by-bunch system the phase or position error of each bunch is detected and the correcting voltage needed is calculated. This correcting signal is applied to the same bunch further around the ring through a broad-band amplifier and kicker. This system will fight any and all coupled-bunch instabilities or any other effects that cause the bunch to be displaced. For example, the system will act to damp the transient caused by injection of new particles into the storage ring.

WAVEGUIDE-DAMPED SINGLE-CELL CAVITIES

Filters in the drive waveguide are successful at damping those HOMs that couple to the fundamental-mode drive port, but there are many modes that have little or no coupling to this opening. For a single loop or aperture on the equator of the cavity there will be monopole HOMs that have no magnetic field in this region and dipole modes that split into orthogonal pairs so that at least one orientation has no magnetic field at the coupler. Conciauro and Arcioni [12] proposed placing three large apertures around the equator, see fig. 6, to capture all orientations of dipole and quadrupole modes (and many higher modes), and noted that these could be displaced from the equator to couple to modes that have zero magnetic field there.

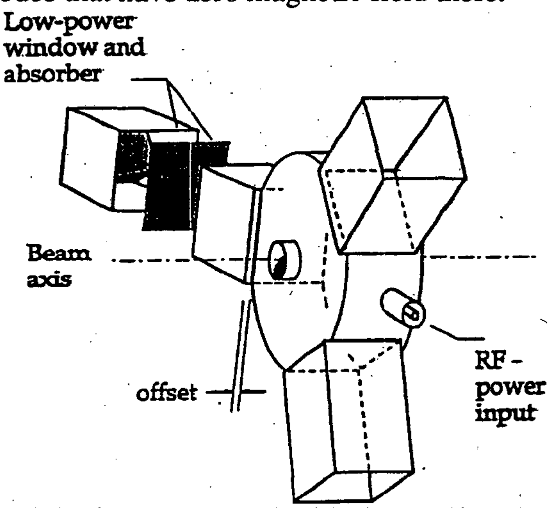

Fig. 6. Conciauro and Arcioni's proposal with three offset damping waveguides

For the single-cell PEP-II cavities it quickly became apparent that the worst HOM by far was the longitudinal TM011 mode, which would only couple weakly to structures close to the equator, and that the size of the waveguides proposed by Conciauro and Arcioni would lose an unacceptable amount of fundamental-mode performance. Once the basic cavity shape had been optimized at 476 MHz the magnetic fields of all the monopole and dipole HOMs up to the beam pipe cutoff were examined and positions on the wall where the modes had zero field were noted. Damping waveguides placed at any one of these points would leave at least one mode trapped in the cavity. Figure 7 shows the positions of all the HOM magnetic field zeros around the cavity wall and the magnetic field of the TM011 mode in the cavity. Clearly there is a position at about 30° up on the curved part of the wall where all the HOMs have some amount of magnetic field and the TM011 mode has reasonably strong field.

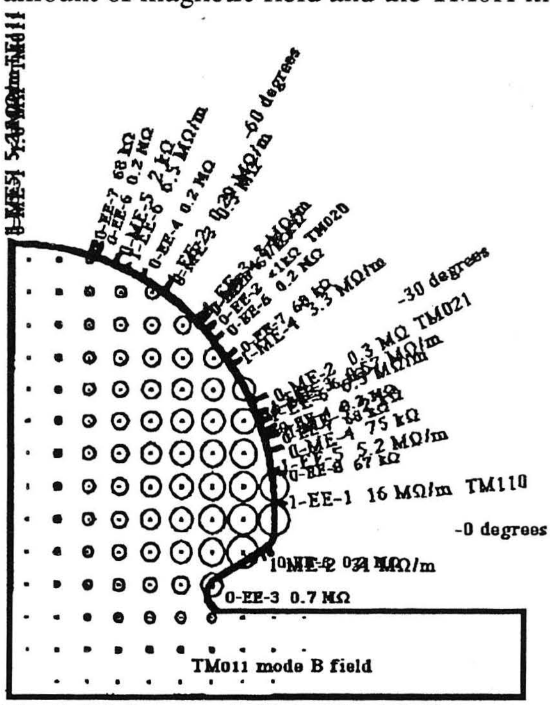

Fig.7. TM011 mode B field + HOM zeros.

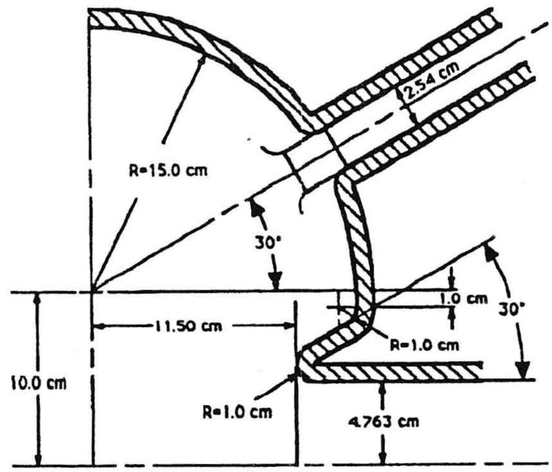

Fig.8. Location of damping waveguide.

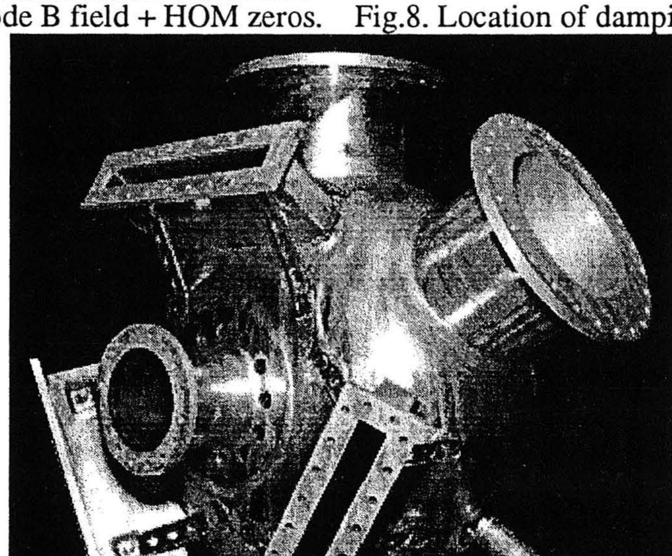

Fig.9. Completed LPTC showing the ports to which the waveguides are attached.

This was the location chosen for the damping waveguides, (see fig. 8), which were made 25 cm wide for a cutoff frequency of about 600 MHz. This allows all of the HOMs to propagate while leaving the fundamental mode trapped in the cavity. The waveguides were made 2.5 cm high to keep as much cavity wall in place as possible and minimize the degradation of the fundamental mode.

3D computer models using the MAFIA [13] and ARGUS [14] codes, and the Kroll-Yu method [15] for estimating the external Q, predicted that good damping should be obtained with this geometry so a low-power test cavity (LPTC) was fabricated to these dimensions (see fig. 9). The LPTC was tested at LBL by inserting two small antennas through the beam pipes and measuring the through response with a Hewlett Packard 8510 C network analyzer. The mode spectrum was recorded with the waveguides plugged with metal plungers and then with them terminated in dummy loads. These loads were made of long tapers of Transtech Ferrite 50 powder set in epoxy, placed against the narrow wall of the waveguides. Figure 10 shows the cavity response without damping and fig. 11 shows the effect of the three damping waveguides

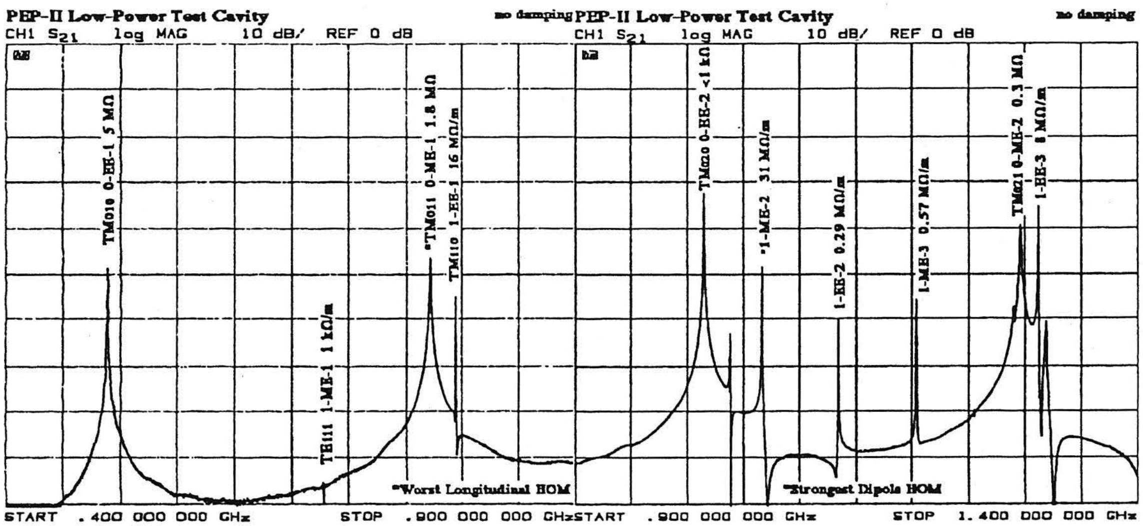

Fig. 10. Fundamental mode and undamped higher order modes in the LPTC

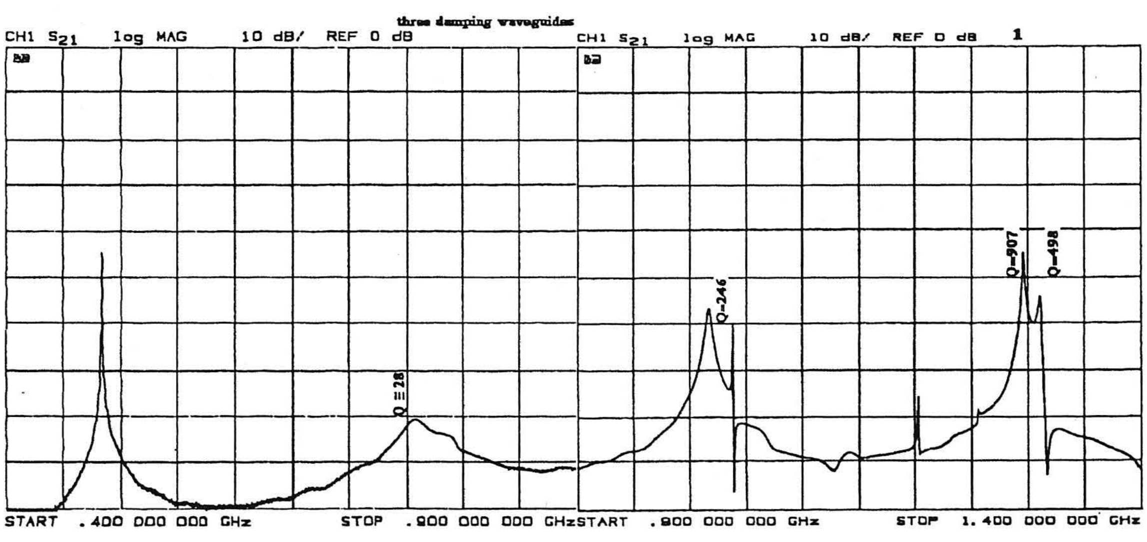

Fig. 11. Fundamental mode and HOMs with three damping waveguides.

The TM011 mode at about 770 MHz is de-Q'd by over three orders of magnitude and most of the other HOMs are also strongly damped. The TM021 mode at 1296 MHz is left with a Q of about 900, which is a little higher than the target value but within the capabilities of the proposed PEP-II feedback system. The estimated loss of fundamental-mode performance is less than 10%, but the HOM ports cause some local current concentration around the irises and increases in losses that must be taken into account in the thermal design. A high-power test cavity is being designed and will be tested to 150 kW, using the 500 kW klystron test stand at SLAC, to demonstrate that such a cavity can be built and conditioned.

DAMPED LINEAR COLLIDER STRUCTURES

Future linear colliders must reduce HOM impedances to prevent beam break-up from limiting the attainable current in these very long structures. In this case the deflecting dipole modes are the most troublesome, but the damping philosophies are very similar. In structures being developed for the next linear collider (NLC) at SLAC, HOM damping waveguides are incorporated in each cell, see figures 12 and 13, or a 10% spread is introduced in the frequencies of the deflecting HOMs [16]. Staggering of the frequencies keeps the cavities simpler but requires variation of the geometry from cell to cell. The damped cavities are more complicated and this may carry an significant cost penalty in a very long accelerator.

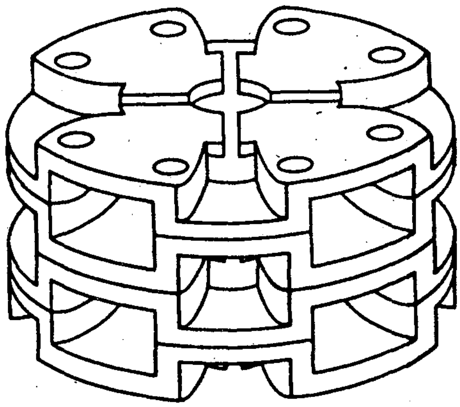

Fig. 12. Early damped NLC structure

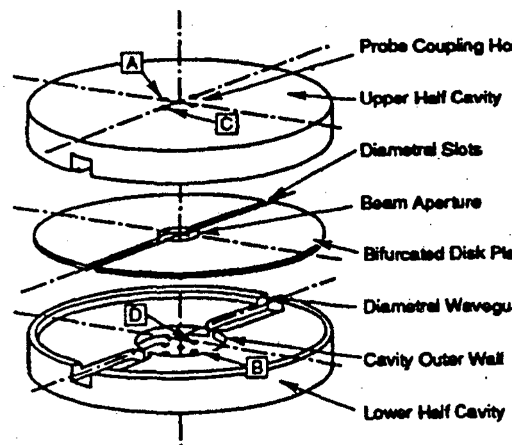

Fig. 13. later cell with four ridged waveguides

Similar damped structures have been proposed for the Japanese linear collider (JLC) [17], using two pairs of waveguides in each cell to catch vertical and horizontal orientations of the dipole modes. T. Shintake [18,19] proposes a scheme using a radial waveguide to couple out the HOMs, see fig. 14. A choke is required to block the fundamental-mode power but the structure preserves circular symmetry so would be cheaper to manufacture. He has made measurements on a test model of this structure and the results are encouraging, see figures 15 and 16. The TM020 mode is still visible because a higher order resonance of the choke blocked it in the same way as the accelerating mode is rejected. This can be overcome by changing the shape of the choke so that its higher resonances do not interfere with any cavity modes. This type of damped cavity can be modelled using 2D simulation codes such as URMEL and the calculated Q's agree well with the measurements.

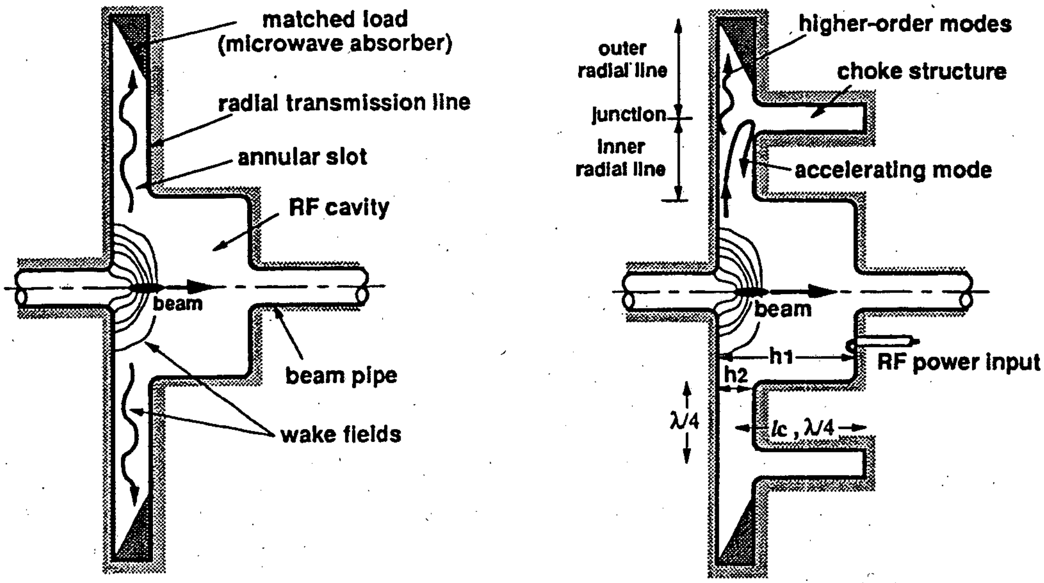

Fig. 14. Pillbox cavity with radial transmission line and choke.

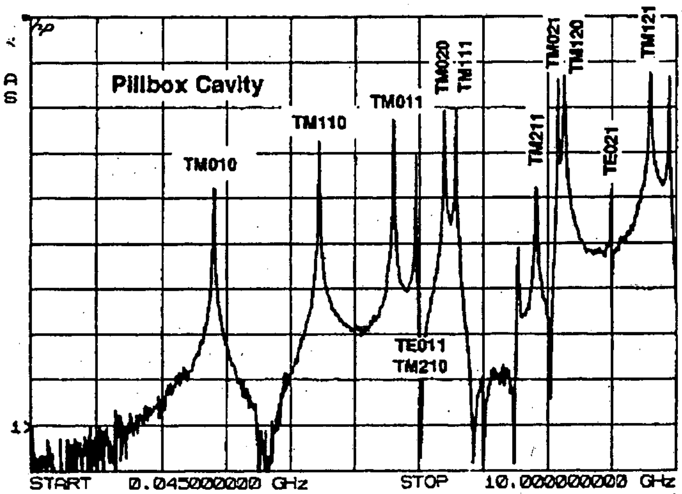

Fig. 15. Response of JLC pillbox cavity without damping

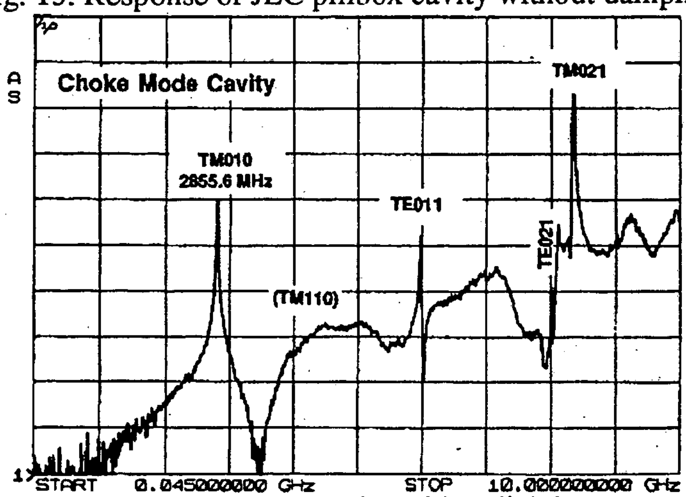

Fig. 16. Response of pillbox cavity with radial damper + choke

CONCLUSIONS

A variety of methods have been developed for damping of HOMs in normally conducting RF accelerating structures. Initially antennas or filters were added to conventional structures as problems became apparent. As machine performance evolves it will become increasingly important to design RF structures to be HOM-resistant and to include damping features at an early stage in the development.. Similarly, feedback systems were originally implemented to tackle one or a few specific coupled-bunch instabilities, usually only identified after the completion of the accelerator. In many present and future machines broad-band feedback systems will be essential to counteract the instability growth rates, *even with* strong HOM damping.

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