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# DAMPED AND DETUNED ACCELERATOR STRUCTURES\*

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## Abstract and Introduction

This paper reports continuing work on accelerator structures for future TeV linear colliders. These structures, in addition to having to operate at high gradients, must minimize the effects of wakefield modes which are induced by  $e^\pm$  bunch trains. Two types of modified disk-loaded waveguides are under investigation: damped structures<sup>1</sup> in which the wakefield power is coupled out to lossy regions through radial slots in the disks and/or azimuthal rectangular waveguides, whereby the external  $Q$  of the undesirable  $HEM_{11}$  mode is lowered to values below 20, and detuned structures in which the frequencies of these modes are modified from one end to the other of each section by  $\sim 10\%$ , thereby scrambling their effects on the beam. Beam dynamics calculations indicate that these two approaches are roughly equivalent. MAFIA, ARGUS and URMEL codes have been used extensively in conjunction with low-power tests on S- and X- band models to identify mode patterns, dispersion curves and  $Q$  values, and to demonstrate damping or detuning of the HEM modes. Results of calculations and measurements on the various structures are presented and evaluated.

## Damped Structures

### a) Radially slotted disks with rectangular waveguides.

The first structure investigated is best thought of as a conventional disk-loaded cylindrical waveguide in which the disks are divided into four quadrants by four orthogonal radial slots. The slotted disk quadrants continue radially outward past the walls of the cavities, transforming into double-ridged waveguides. These waveguides are dimensioned so their  $TE_{10}$  mode cutoff is below the frequencies of all resonances of the accelerator cavities. The fundamental accelerating mode of the structure is nevertheless undamped because its symmetry is such that it does not couple to the  $TE_{10}$  mode of the waveguide.

An exploded view of a single-cavity version is shown in Figure 1. This simplified structure is able to support only the 0 and  $\pi$  modes, which facilitates understanding its behavior. Figures 2 and 4 show network analyzer  $S_{21}$  plots obtained with coaxial E probes inserted in the designated end-plate holes (Figure 1).

With probes in C and D, the 0 and  $\pi$  resonances for the first two branches of the dispersion diagram ( $TM_{01}$  and  $HEM_{11}$ ) are shown in Figure 2. The fields are oriented so so that they do not couple to the ridged waveguides. When probes are inserted in A and B, the fields for the dipole

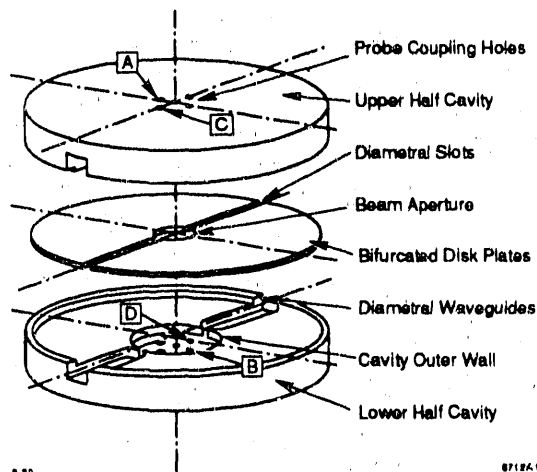


Figure 1. Single-cavity (two halves) model of damped S-band structure with two radial slots and waveguides.

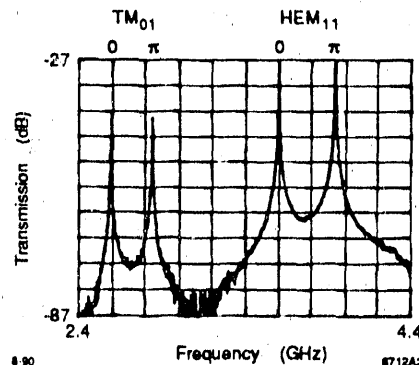


Figure 2. Single-cavity resonances excited through probes C or D so that they cannot couple through the ridged waveguides.

$\pi$ -mode couple to the waveguides which, when shorted at equal radial distances from the structure axis, form a coupled-cavity system with multiple resonances above and below the fixed dipole 0-mode resonance. As the waveguide lengths ( $D$ ) to shorts are decreased or increased, the resonances move up or down in frequency, respectively. The external  $Q$  ( $Q_e$ ) and resonant frequency ( $f_r$ ) of a cavity connected to matched waveguides can be determined from the frequency dependence of the system as a function of  $D$ , as shown in Figure 3. The calculation yields a value of  $Q_e$  of  $8.1 \pm 18\%$  and a value of  $f_r$  of  $3939 \text{ MHz} \pm 0.5\%$  (see Reference 1). When the waveguides are left open at their outer ends, some power radiates outward, lowering the  $Q$  of the resonances. When the waveguides are terminated, the resonances cannot be seen on the display (Figure 4).

A similar experiment was performed at X-band with two full cavities and two half-ones in which 0,  $\pi/3$ ,  $2\pi/3$  and  $\pi$ -modes could be excited. Basically, the same general

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results were obtained. Thus, it can be concluded that this structure can effectively damp the undesirable dipole modes.

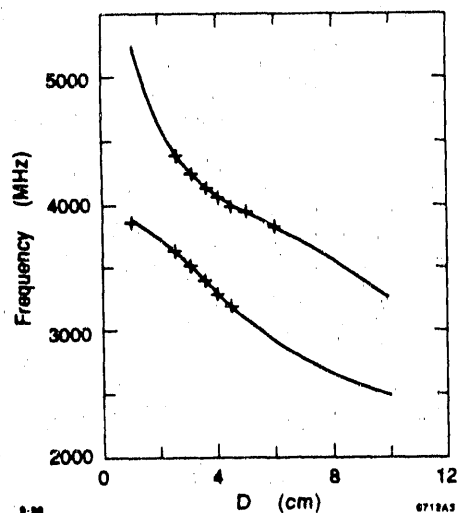


Figure 3. Measured single-cavity waveguide resonance frequencies (designated by +) as a function of waveguide length  $D$ . Solid lines are obtained by calculation.

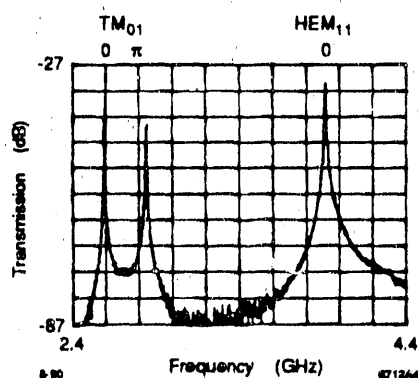


Figure 4. Single-cavity resonances excited through probe A or B so that the dipole  $\pi$  mode can couple to terminated ridged waveguides, but the 0-mode is trapped.

In parallel with these low power tests, a four-cavity S-band model was built with four slots (without radial waveguide outputs) to examine the effect of the disk slots at high power (See Figure 5). After gradual RF processing, the breakdown-limited gradient that was obtained and the corresponding experimental conditions are summarized in Table 1. It was determined from MAFLA that the ratio of the surface field ( $E_s$ ) to the axial accelerating field ( $E_{acc}$ ) was increased 8% by the presence of the slots.

For the corresponding traveling-wave structure,  $E_s/E_{acc}$  would be equal to 2.55, yielding a maximum accelerating gradient limit of 124 MV/m.

b) Azimuthal waveguide structures. The second structure that has been tested is the azimuthal waveguide structure which can trap the fundamental mode while

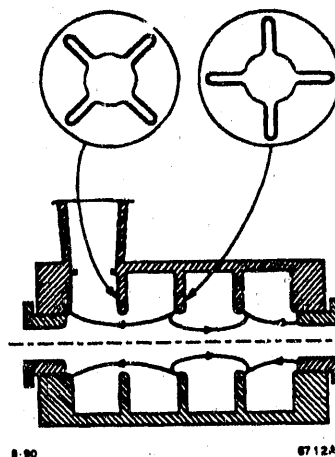


Figure 5. High power slotted-disk structure.

Table 1. Breakdown-limited gradient for  $2\pi/3$  slotted-disk structure

Frequency	MHz	2857
Iris diameter	cm	3.6
Total length	cm	21
Filling time*	$\mu$ s	0.87
Pulse length	$\mu$ s	1.5-2.5
Peak power input	MW	21.5
$E_s$	MV/m	315
$E_s/E_{acc}$ for SW structure		5.10†

\* Assuming critical coupling

† The value obtained from MAFLA was 4.86. However, SUPERFISH being more accurate, we multiplied this value by a factor of 1.047, the ratio of the values calculated for an unslotted-disk structure (4.73 with SUPERFISH and 4.516 with MAFLA).

coupling out dipole and higher-order modes. The structure shown in Figure 6 has four guides forming a cross but another variation of this design with three outputs at 120 degrees is also under consideration. The three-output structure has the advantage that a greater fraction of the cavity wall is available for tuning.

The geometry of this structure possibly has the advantage over the radially slotted structure that it is easier to fabricate. The waveguide width and the diameter of the small remaining segments of the central cylindrical cavity must be chosen carefully so that the waveguide  $TE_{10}$  mode cutoff lies above the frequency of the fundamental accelerating mode and below the frequency of the undesirable  $HEM_{11}$  modes. Figure 7 shows the resonances obtained with a single cavity, with the outer ends of the rectangular waveguides shorted. The resonance patterns are independent of coupling probe positions in the end-plates because the crossed waveguides couple to all mode orientations. Again, a multiplicity of resonances above the fundamental 0 and  $\pi$ -modes are observed because of coupling between the shorted waveguides and the central cavity. With longer guides, the number of resonances increases. When the guides are terminated, first-order dipole resonances above the fundamental pair are heavily damped, as shown in Figure 8.

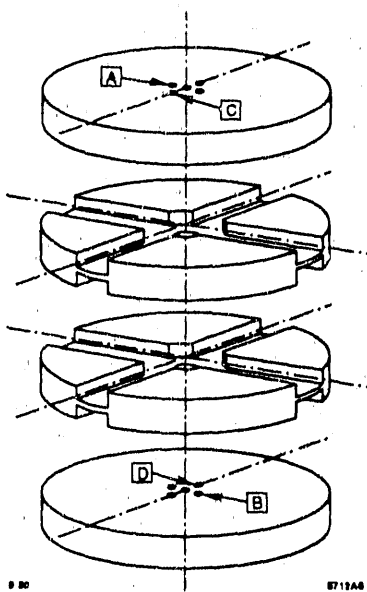


Figure 6. Azimuthal waveguide structure.

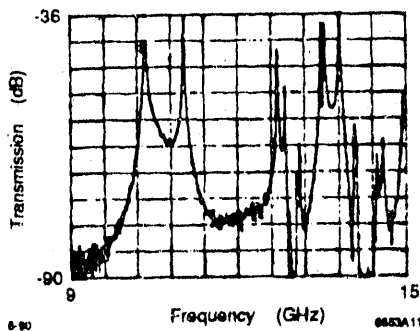


Figure 7. Single X-band cavity resonances with four azimuthal waveguides shorted.

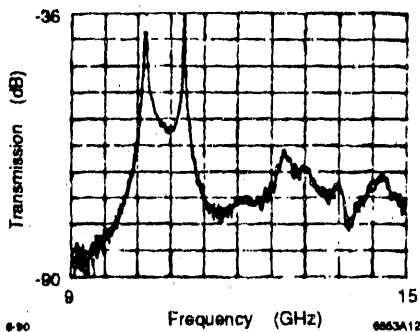


Figure 8. Single X-band cavity resonances with four azimuthal waveguides terminated.

### Detuned Structures

Another approach to minimizing the effect of the  $HEM_{11}$  dipole mode is to design and build a disk-loaded waveguide structure in which the frequencies of these modes

vary over the length of each section by some percentage. Calculations (see Figure 9) show that a frequency spread of about 10% from input to output of each section is sufficient to allow multibunch operation for a bunch spacing of 42 cm with essentially no transverse displacement from bunch-to-bunch at the end of a 3 km machine. A simple example of such a structure with a linear group velocity variation (similar to the constant-gradient design of the SLAC S-band structure) has been calculated with the characteristics shown in Figure 10. The results look very promising and would of course lead to a structure with a much simpler geometry than the damped designs described earlier. It remains to be seen if the longitudinal modes which cause bunch-to-bunch energy differences can also be sufficiently scrambled to make this approach entirely satisfactory.

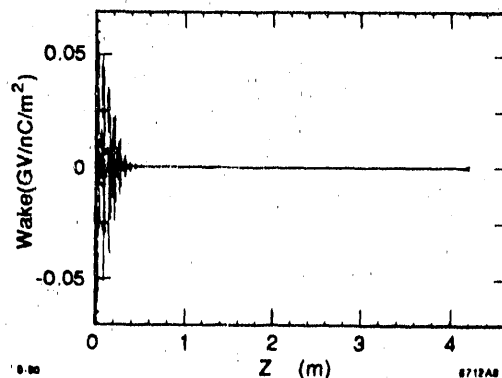


Figure 9. Wakefield behind a bunch, as a function of longitudinal distance  $z$ . The frequency of the fundamental transverse mode is detuned to 25 different values along each section. The weights of the different frequencies are given a truncated Gaussian distribution with total width =  $5\sigma$  and  $\sigma = 2\%$ .

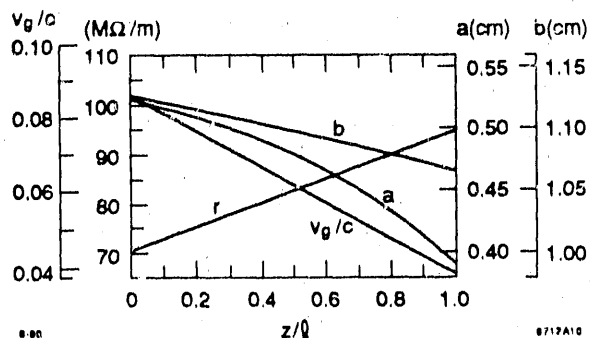


Figure 10. Design example of an X-band 1.5 m accelerator section showing the variations of normalized group velocity  $v_g/c$ ,  $b$ ,  $a$  and shunt impedance  $r$  as a function of normalized length  $z/l$ .

### References:

1. "Damped Accelerator Structures," H. Deruyter et al, Proc. 2nd European Particle Accelerator Conference, SLAC-PUB-5263.

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