HEM_{11} MODES REVISITED*

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Abstract

Concern with emittance growth in future multi-bunch linear colliders has rekindled interest in HEM_{11} dipole modes (sometimes also called "TM_{11}-like" or "TE_{11}-like") in disk-loaded waveguides. The availability of modern computer codes (URMEL, MAFIA) makes it possible to gain a deeper understanding of these modes and their properties. This paper presents ω-β dispersion diagrams, field configurations and transverse shunt impedances for the HEM_{11} modes as a function of iris aperture. The transition between forward and backward waves of the various branches is explored. This information serves as background material for another paper at this conference which reports recent work on linac structures in which these modes are damped or detuned.[1]

Introduction

In the early 1960's, following the formulation of the Panofsky-Wenzel theorem[2] in 1956, the properties of HEM_{11} dipole modes (sometimes called "TM_{11}-like" and/or "TE_{11}-like") in cylindrical disk-loaded waveguides became a subject of intense research in high energy physics laboratories all over the world. This flurry of interest was triggered by the useful applications of these modes to RF separators, RF deflectors and microwave beam position monitors, as well as by their deleterious beam-induced effects resulting in emittance growth and beam breakup instabilities. Authors such as H. Hahn at BNL, Y. Garault at Orsay, France, I. Aleksandrov, V. Kotov and V. Vagin at Serpukhov, USSR and others attempted to calculate the properties of these HEM_{11} modes by various analytic techniques. A fairly complete bibliography of the early work up to 1963 can be found in Reference 3.

Interest in HEM_{11} modes has recently been rekindled by concern with emittance growth in multi-bunch electron-positron linear colliders. In these machines, two transverse effects take place, one short-range, the other long-range. In the short-range effect, the head of a single bunch of finite length, if slightly offset with respect to the accelerator axis, excites HEM_{11} deflecting wakefields which cause the particles in its tail to experience emittance growth. In the long-range effect, the deflecting wakefields left behind by the first electron bunch produce increasing deflections of later electron bunches which cannot be corrected. Ultimately, these deflections result in losses in the luminosity at the interaction point because the electron bunches and their positron counterparts do not properly overlap. In the short range effect the time constants are very short and only focussing can counteract the RF deflecting forces. In the long-range effect, it is possible to damp or detune the HEM_{11} modes so as to reduce their cumulative transverse force.[4] However, before we attempt to damp or detune these modes, it is important that we first improve our understanding of their properties. This is the purpose of this paper. Modern computer codes such as URMEL and MAFIA are used to calculate the ω-β dispersion diagrams of these modes, their field configurations and transverse shunt impedances in regular unperturbed disk-loaded waveguides. The iris diameter (2a) is varied to explore the gradual transition from forward to backward wave.

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Transversely Deflecting Modes

From the Panofsky-Wenzel formulation[2], it is apparent that transverse deflections can result only from cumulative interactions with RF modes in which the longitudinal E-field has a transverse gradient. Then, over a length l, the transverse momentum $p_\perp$ imparted in the x-direction to a synchronous particle of charge q by a mode of frequency ω is

$$p_\perp = \frac{q}{\omega} \int_0^l \left(\frac{\partial E_z}{\partial x}\right) dz$$

and one can define a transverse shunt impedance r_T as

$$r_T = \frac{\left[\left(\frac{\lambda}{2\pi}\right)\left(\frac{\partial E_z}{\partial x}\right)\right]^2}{-\ dP/dz}$$

where λ is the free space wavelength and the denominator is the RF power lost per unit length.

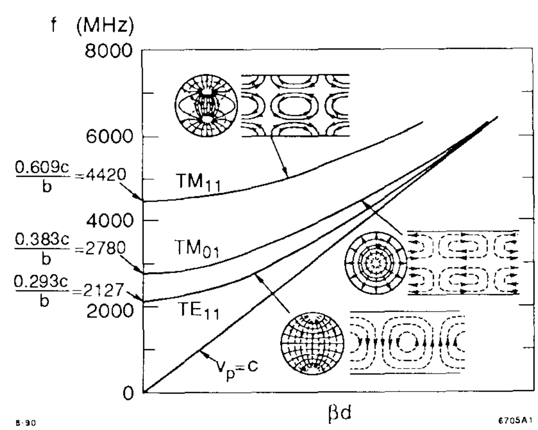

Figure 1. Dispersion diagrams of TE_{11}, TM_{01} and TM_{11} modes in smooth cylindrical waveguide. The length d in this case is arbitrary. For comparison with the example shown in Figure 2, f is given for the case where b = 4.13 cm.

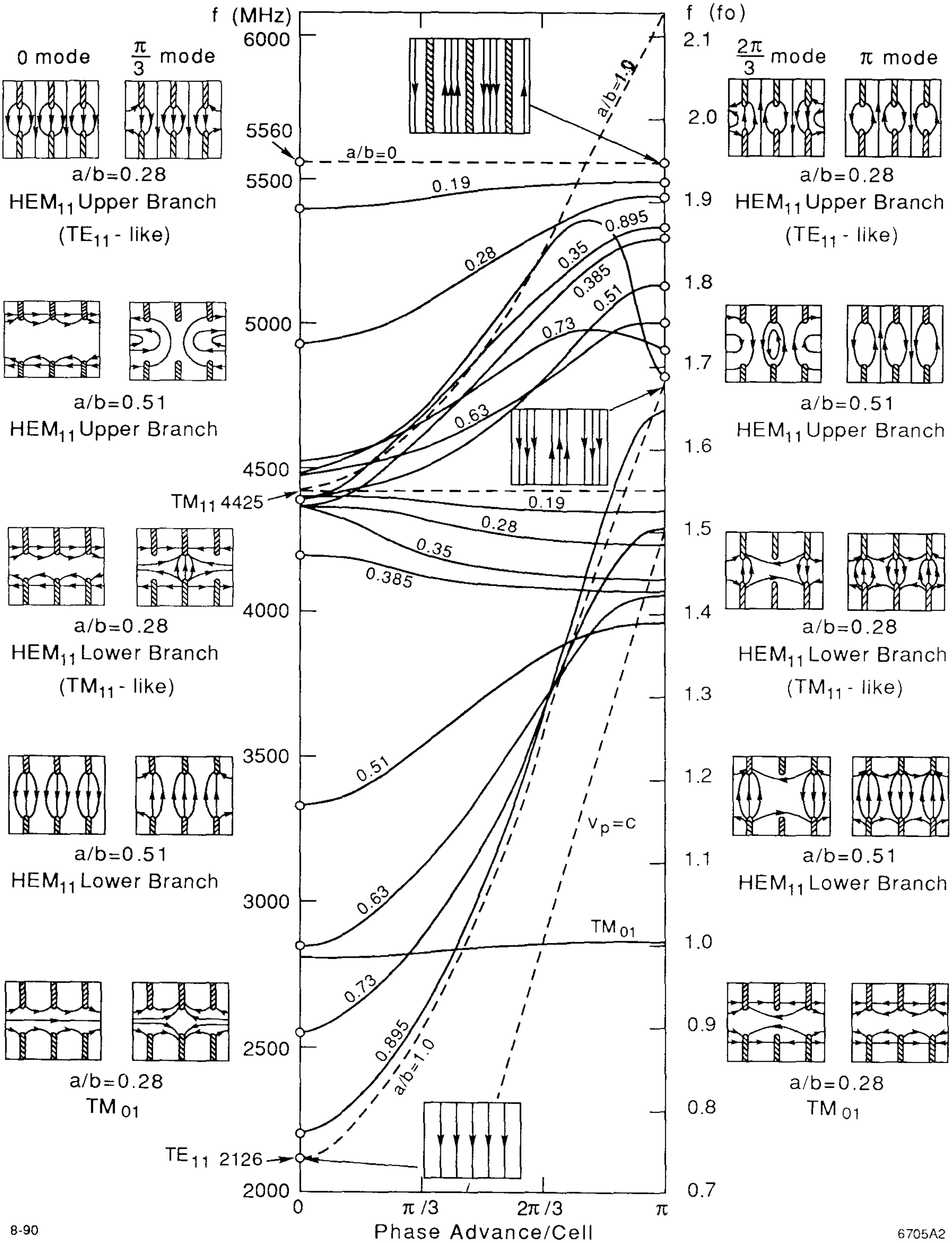

Figure 2. Dispersion diagrams and E-field configurations of TM_{01} and HEM_{11} modes as the b-dimension is kept fixed (4.13 cm) and the ratio a/b varies between 0 and 1.

Now consider first a smooth cylindrical waveguide of radius b in which the lowest modes of interest are the TE_{11} ($f_c = 0.293c/b$), the TM_{01} ($f_c = 0.383c/b$) and the TM_{11} ($f_c = 0.609c/b$). Their dispersion diagrams are shown in Figure 1. It can be shown easily that for all these modes, the quantities in the above equations are zero. However, as the cylindrical guides are made into disk-loaded waveguides of periodic length d and iris radius a, these modes become perturbed. It can be seen intuitively that as the disks are added, some E-lines terminate on the disk edges (a) rather than on the waveguide walls (b), TE_{11} and TM_{11} modes mix and a "hybrid" HEM_{11} mode is born. The patterns are no longer pure and the configurations change as one moves from the 0 to the π–mode frequency.

To facilitate understanding of this process, Figure 2 shows the entire evolution of the ω–β diagrams and E-field configurations as the b-dimension is kept fixed (4.13 cm) and the ratio a/b varies between 0 and 1. We see that the upper HEM_{11} branch keeps its TE_{11}-like identity throughout the band from 0 to π-mode in the range of a/b from 0 up to 0.35, and similarly, the lower HEM_{11} branch keeps its TM_{11}-like identity in this range even though it is a backward-wave mode in which phase and group velocity are of opposite sign. It is particularly interesting to examine the region which is shown in further detail in Figure 3. Note that for a/b between 0.38 and 0.41, the ω–β diagram has a minimum in mid-band and the net power flow through the iris changes direction. The original CERN RF separator structure[5] used dimensions very close to these and resulted in a ω–β diagram with a minimum in the middle which seemed puzzling at the time. The URMEL program is now capable of sorting out all these details. Also, note a similar reversal in the upper HEM_{11} branch when a/b exceeds 0.7.

The reason it is useful to understand this pattern evolution is that most linear accelerator and RF separator structures are designed to operate close to the transition zone of Figure 3. On the other hand, the structure designs for linear colliders tend towards larger a/b values (~0.45) than for example the SLAC constant-gradient design (0.235 to 0.314) because of the need, for single high-intensity bunches, to minimize longitudinal and transverse wakefields which vary approximately as $(a/b)^{-2}$ and $(a/b)^{-3}$ respectively.

Table 1 gives a summary of calculated transverse shunt impedances as a function of a/b using theoretical Q-values. For reference, note that the original SLAC RF separator operating at 2856 MHz (with a/b = 0.386 and $2\pi/3$ mode) had a transverse shunt impedance of 16MΩ/m, and the transverse shunt impedance of the beam-breakup mode at the input of the SLAC 3-m long section (a/b = 0.314, close to π-mode) at 4139.4 MHz was also about 16 MΩ/m, assuming an experimental Q-value of 8000.

The information presented in this paper has been used to work out some of the design details needed in Reference 1. In the future, it will also be useful in the design of new RF separators planned for so-called "crab-crossing" schemes for linear colliders or B-factories.

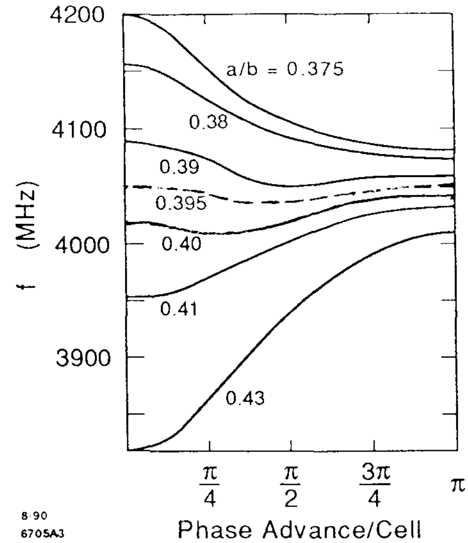

Figure 3. Dispersion diagrams of HEM_{11} modes in transition zone.

a/b	r_T (MΩ/m) LOWER BRANCH	UPPER BRANCH
0.28	29.3(π–mode)	1.58($3\pi/4$-mode)
0.35	21.4(π–mode)	0.54($4\pi/5$-mode)
0.375	18.9(π–mode)	0.29($4\pi/5$-mode)
0.51	8.3(π–mode)	0.28($5\pi/6$-mode)

Table 1. Transverse shunt impedance for HEM_{11} modes with $v_p = c$ as a function of a/b.

References

1. H. Deruyter, et al, "Damped and Detuned Accelerator Structures," This Conference.

2. W. K. H. Panofsky and W. Wenzel, "Some Considerations Concerning the Transverse Deflection of Charged Particles in Radio-Frequency Fields," Rev. Sci. Instr., 27, 967, 1956.

3. O. H. Altenmueller, R. R. Larsen and G. A. Loew, "Investigations of Traveling-Wave Separators for the Stanford Two-Mile Linear Accelerator," SLAC Report No. 17, August 1963.

4. Actually, to control the short-range effect there exists another method called BNS damping, which is similar to structure damping or detuning, whereby the tail particles are given lower energy than the head particles and thereby oscillate at an incoherent betatron frequency. "BNS" stands for the names of the inventors of this technique, V. E. Balakin, A. V. Novokhatskii and V. P. Smirnov, from INP, Novosibirsk, USSR.

5. M. Bell, P. Bramham, R. D. Fortuna, E. Keil and B. M. Montague, "RF Particle Separators," AR/Int. PSep/63-7, June 1963.