AN INVESTIGATION OF THE SLOTTED IRIS STRUCTURE WITH DRIFT TUBES

by

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Introduction

The slotted iris structure has been proposed by Giordano[1] for the acceleration of protons. This structure is of interest for a superconducting high energy linac. Because of its relative mechanical simplicity it seems possible to coat the slotted iris with a superconducting layer and to cool away the dissipated power. Earlier measurements[2] have been extended thus giving a rather good survey on the behaviour of the structure under geometrical variations[2,3]. These measurements are interpreted by an approximate analytical treatment from which a systematic optimization of the slotted iris structure will be possible[4].

Experimental Investigations

Since we were not interested in absolute Q-values the following measurements were performed with demountable models consisting of three or six cells, respectively: resonance frequencies for all modes, Q-values for all modes, effective shunt impedance for the π-mode. The slotted iris structure which is shown in fig.1 was intended to operate at 760 MHz in the π-mode. The influence of geometrical parameters was investigated for three different cell lengths:

L_1 = 98.8mm (ß=0.5) i.e. 145 MeV p energy

L_2 =135.0mm (ß=0.7) i.e. 370 MeV p energy

L_3 =178.0mm (ß=0.9) i.e. 1200 MeV p energy

The cavity and drift tube diameters were kept constant for all measurements (D = 288 mm, a = 65 mm and beam hole diam. = 17.5 mm). The length of the drift tubes was varied from a minimum value l = 0 to a maximum l =117.2 mm. Slot width (SW) and slot angle (SB) were changed according to the numbers given in table I (see also fig. 1).

We used a crystal controlled rf-generator (accuracy 10^{-8}) and a microampere meter to indicate the resonance maximum. For all measurements the position of the coupling loop feeding rf-power (20 mW) into the structure was fixed. Very loose coupling was arranged in order to have minimum perturbation by the loops. Thus the ratio 1/SWR was constant at a value of about 1.01 (SWR=Standing Wave Ratio).

SB = 49°	SW(mm)
r_2 = 115 mm	10 30 40 50 82
r_2 = 141 mm	66 108
SB = 57° 65° 73° r_2 = 115 mm	40 '' ''

Table I

The measurements of the Q-value were based on the 3-dB method. The output voltage of the rf-generator (1V at 50Ω) was extremely stabilized and in addition to that controlled by a power meter. Since the coupling of power into the structure was quite weak, the measured loaded Q_L was within 1% identical with the unloaded Q_0 and no correction of the directly measured Q-values was necessary. The accuracy of the Q-measurements was about ± 0.6%. The Q-value of each geometry was measured three times and the average value was taken. The reproducability was ± 1%.

The effective shunt impedance $Z_{eff} = Z\,T^2$ (with T = Transit time factor) was measured according to the well known method introduced by Slater[5]. The brass bead (Ø 8mm) and the Nylon thread (Ø 0.8 mm) were the same for all measurements. The error of the measured resonance frequency shift Δf is about ± 0.5 kHz which corresponds to an error in the calculated Z_{eff}/Q of about 2.0%. This is due to the uncertainty in finding the resonance maximum, because the Q-values are rather low in our demountable models, machined of brass. Measurements of the frequency deviation produced by the bead with a simple lock-in-oscillator were not successful, because no correct rf-phase properties could be achieved. The shunt impedance inferred from these measurements was about 25% too low.

In Fig. 2 the π-mode frequency is plotted versus the ratio of drift tube length over cell length for three different slot widths and cell lengths. As expected the frequency is strongly decreased by inserting drift tubes. The change of frequency for $1/L = 0$ is due to the different coupling.

Fig. 3 shows the π-mode frequencies versus slot width at a constant slot angle of 49° for a certain number of investigated drift tubes (l) and cell lengths (L). The minima of the π-mode frequencies correspond to maxima of the coupling coefficient.

The coupling coefficient is defined by the relative bandwidth of the structure

$$K = (f_o^2 - f_\pi^2)/2\, f_\pi^2$$

where f_o is the zero-mode frequency and f_π the π-mode frequency, respectively. Its dependence on the slot width for a fixed slot angle and various drift tube lengths is shown in Fig.4. The coupling coefficient is increasing rapidly since the magnetic field is large near the outer cavity wall and therefore the magnetic coupling rises steeply when the slot is opened. The decrease of the coupling coefficient beyond slot widths larger than 40 mm is caused by the electric field which produces a coupling of the opposite sign. The influence of the electric field is strongest with no drift tubes whereas long drift tubes keep the electric field away from the coupling slots.

The single point at the slot width SW = 0 was measured in order to check the limiting case. It corresponds to a normal iris structure with a small center hole of 17.5 mm in diameter. The coupling coefficient was K = -0.16%.

Some measured values of shunt impedance are displayed in Fig. 5 as a function of g/L where g is the gap length. The parameter $\beta = v/c$ ranges from β=0.35 to β=0.90. The coupling coefficient is not constant for these measurements since the cell length changes. It decreases with increasing β. A flat maximum of the shunt impedance is found at about g/L=0.5 for small values of β. The calculations reported below indicate that this is approximately true for all values of β. The lines of constant frequency let us conclude that the investigated model which had a diameter of 288 mm ought to be excited with a frequency of about 650 Mc, if one desires to operate at maximum shunt impedance for all values of β.

Besides the slot geometry shown in Fig. 1 we investigated also other shapes of slots, e.g. circular and elliptical holes. In Fig. 6 measurements for a structure are displayed in which the drift tubes are supported by four stems (SB=86°). In one case the disks were rotated from cell to cell by an angle of 45° resulting in a special kind of cross bar structure. The maximum shunt impedance appears again at about g/L = 0.5. In comparison to other slot geometries no remarkable improvement in shunt impedance can be observed.

Finally the complete field pattern was determined experimentally for one cell in order to find the optimum position for the coupling loop and to locate the most dangerous points for sparking. Measurements in which the coupling loop was moved in z-direction at two different azimuthal positions are shown in Fig. 7. At an azimuth corresponding to the center of a slot the magnetic field is much weaker compared to the field between slots. From Fig. 7 it follows that the most efficient coupling of power into the structure is achieved, if the coupling loop is placed in front of the remaining metallic section of the disk.

An Approximate Theoretical Treatment of the Slotted Iris Structure

The fields in a single reentrant cavity are calculated with a simple model. From these the resonance frequency the Q-value and the shunt impedance can be inferred. The influence of the coupling slots is taken into account additionally.

If a cylindrical cavity is excited in the TM 010 mode the electric field has only a z-component. It is assumed that this is still true if drift tubes are inserted. This approximation is good as long as $R/L > 1$. Then the field equation can be solved for the region $r > a$ and $r < a$ separately where a is the drift tube diameter. The fields are matched at the boundary r = a by requiring that the electric potential and the currents are continuous. This procedure yields immediately a somewhat complicated expression for the resonance frequency which, however, for $a/R < 0.3$ can be approximated by

$$\omega_o R/c = 2.4[1+3.95(a/R)^2(L/g-1)]^{-1/2}$$

The resonance frequency ω of a coupled structure is then obtained[6] by $(\omega/\omega_o)^2 = 1/(1+K\cos\varphi)$. The experimental results of Fig. 2 are reproduced by this relation within a few percent.

The coupling coefficient as a function of the slot parameters can be computed by replacing the slot by a layer of electric and magnetic dipoles in such a way that the boundary conditions are satisfied (Bethe[7]). The general expression is too complex to be reproduced here. It is found that K is proportional to α^2 (α = slot angle SB) and this is indeed verified by the experiments (Fig. 8). As a consequence only one or two slots are more efficient than four slots with small α. It is further expected that $K \cdot L$ is independent of L and this is also in excellent agreement with the experiments for different drift tube lengths and slot shapes. The characteristic dependence on the slot width d is also reproduced reasonably well by these approximate calculations as is shown by the curves of Fig. 4.

The attenuation of the cavity which is proportional to $1/Q$ is determined by the ohmic losses in the cavity walls which can be separated in those of a cavity without coupling holes and the extra losses[5] caused by the coupling. For the case $(a/R)^2 \ll 1$ one finds

$$D = \frac{1}{Q} = s\left[\frac{1}{L} + \frac{1}{R}\,\frac{1+K_1 q^2 \frac{L}{g}\left(\frac{L}{g}-1\right)\left[\frac{R}{a}q^2+\frac{R}{L}\right]}{1+K_1 q^2\left(\frac{L}{g}-1\right)} + \frac{2\pi}{d}|K|\right]$$

where $q = (a/R)(2.4/2)$ and K_1 is a numerical constant. From this relation one infers that $D \sim \alpha^2$ since $K \sim \alpha^2$ and $D \sim K \sim L$ because $K \sim L$. Both these expectations are in very good agreement with the measurements as is shown in Fig. 9, 10.

The effective shunt impedance Z can easily be computed using the expression for D and taking into account the transit time factor T. The shunt impedance Z has to be optimized for given $\beta = v/c$, frequency and tank diameter. This implies that the gap length g can be varied adjusting a/R at the same time in such a way that the frequency remains constant. Furthermore it seems advantageous to keep the coupling K constant for all β which can be achieved by opening the slot angle for increasing L such that $\alpha^2 L$ constant. With these conditions one obtains

$$\frac{1}{Z} \approx \left(\frac{x}{\sin(\frac{\pi}{2}x)}\right)^2 \left[C_1 + \frac{C_2}{x} + \frac{C_3}{\sqrt{x(1-x)}}\right]$$

with $x = g/L$. The constants C_i do not depend on g/L but are functions of the frequency, β and K. The most relevant term is the last which implies that the maximum of Z should occur for $g/L \approx 0.5$. The term C_2/x which becomes more important for small β since $C_2 \sim 1/\beta$ will shift maximum to somewhat larger values of g/L whereas the transit time factor favours smaller values of g/L. Since these changes are rather small and the maximum of Z is quite flat values of g/L between 0.4 and 0.6 might be chosen. For a special case numerical calculations are necessary and other considerations like the sparking limit will influence the choice of g/L.

In conclusion it might be pointed out that most of the results obtained here for a weakly coupled π-mode structure can be applied also to a resonantly coupled structure in the $\pi/2$ mode.

A more detailed account of the work reported here will be given elsewhere[3,4].

References

1) Giordano, Minutes of the 1964 Conference of Proton Linear Accelerators, MURA, 60, 1964

2) W. Bauer, H. Eschelbacher, M. Kuntze, KFK No. 346 (July 1965) and KFK No. 403 (Febr. 1966)

3) H. Eschelbacher, Investigations on the Slotted Iris Structure, KFK-Report to be published

4) H. Schopper, An Approximate Treatment of the Slotted Iris Structure, KFK-Report to be published

5) J.C. Slater, Microwave Electronics, D.van Nostrand Comp., New York, 1963

6) D.E. Nagle, E.A. Knapp, Minutes of the 1964 Conference on Proton Linear Accelerators, MURA, July 1964, p. 21

7) H.A. Bethe, Phys.Rev. 1, 163, 1944

DISCUSSION

H. ESCHELBACHER, Karlsruhe

LOEW, SLAC: Have you made any comparisons between this structure and the simple disc-loaded structure without slots for $\beta = 1$?

ESCHELBACHER: No, not at $\beta = 1$. But for lower values of β we got better shunt impedances with the slotted iris structure because of the drift tubes.

LOEW: I am asking this question because we considered this structure when we were looking for structures for the Monster, and consistently found that it had a lower shunt impedance than the disc-loaded structrue at $\beta = 1$. At lower values of β, I don't know what happens. The comparison was only valid for a given group velocity.

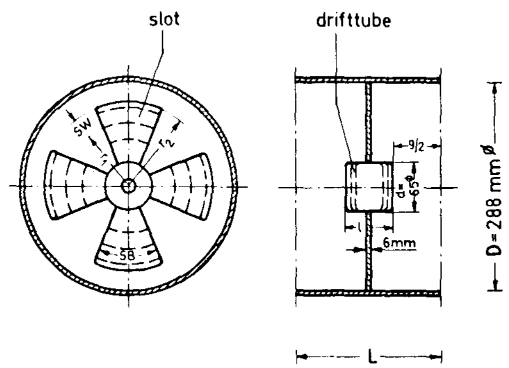
ESCHELBACHER: In the simple disc-loaded structure the shunt impedance and the group velocity are both dependent on the beam hole diameter.

LOEW: I would also like to comment that Dr. Matthew Allen, at Stanford, worked on similar structures for his Ph. D. thesis on traveling-wave tubes.

ESCHELBACHER: I know his paper. I will meet him at Stanford after the conference.

HUBBARD, Berkeley: How low a velocity would you inject into a structure like this?

ESCHELBACHER: While this is not actually clear, I think we will be 150 MeV or so in this region. I don't know the value of β exactly, if that is what you asked, but like 150-MeV proton energy.



dotted lines show the variation of drifttube length and slotwidth

Fig. 1. Slotted iris model.

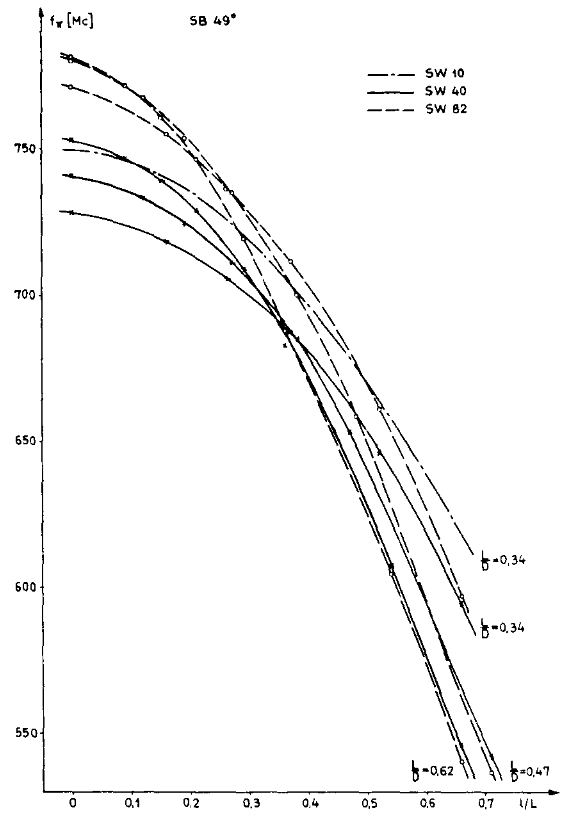


Fig. 2. π-mode frequency vs drift tube length/cell length for different slot widths and cell lengths.

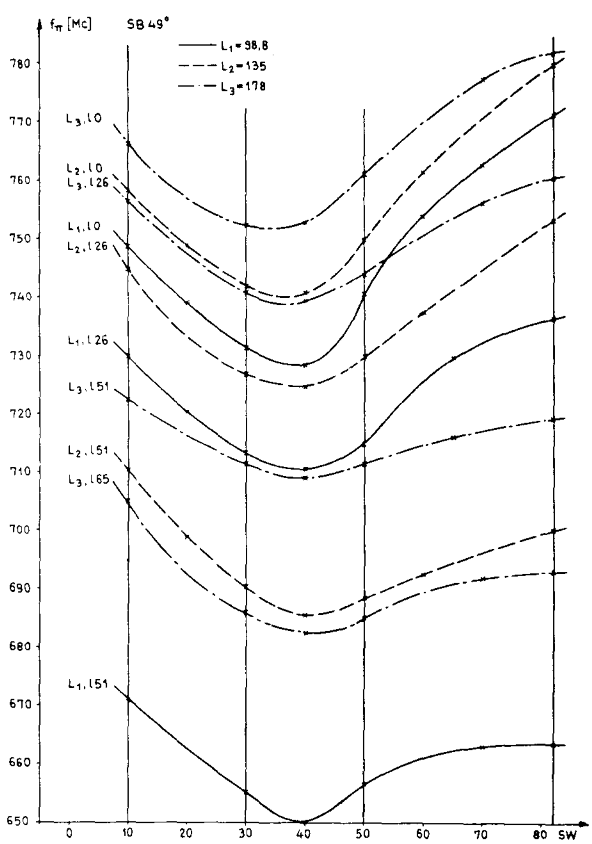


Fig. 3. π-mode frequencies vs slot width for cavities with drift tubes.

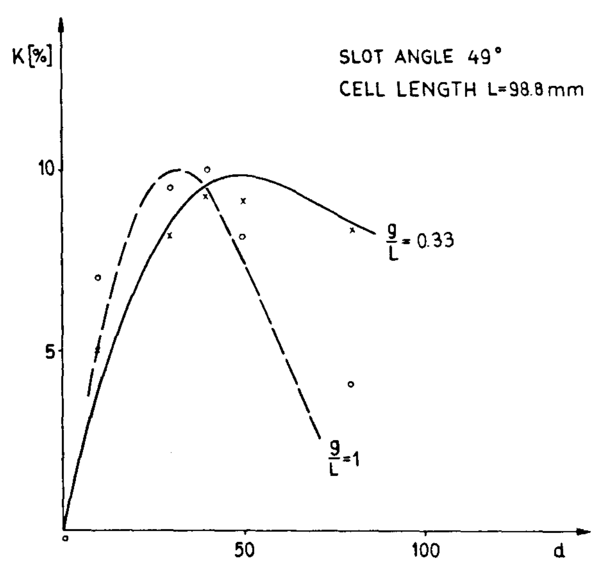


Fig. 4. Theoretical dependence of the coupling coefficient on slot width and drift tube length.

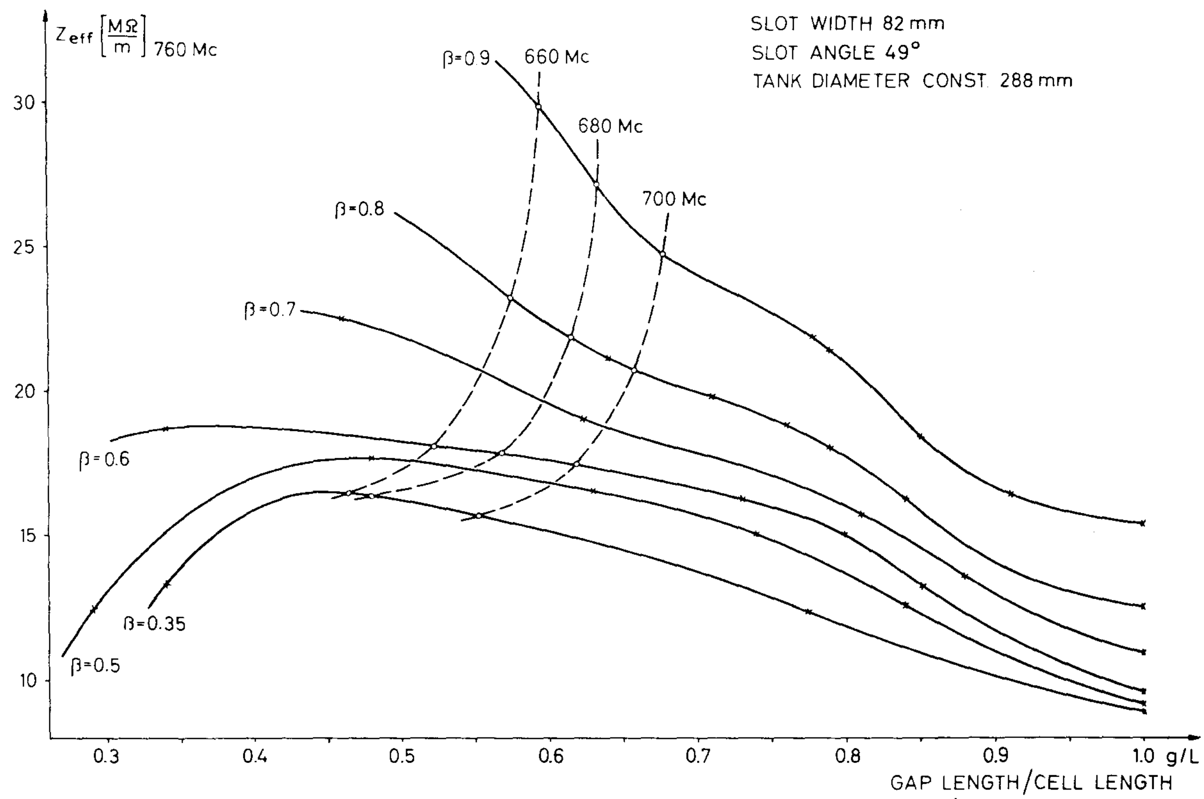


Fig. 5. Effective shunt impedance for different values of $\beta = v/c$ vs gap length / cell length.

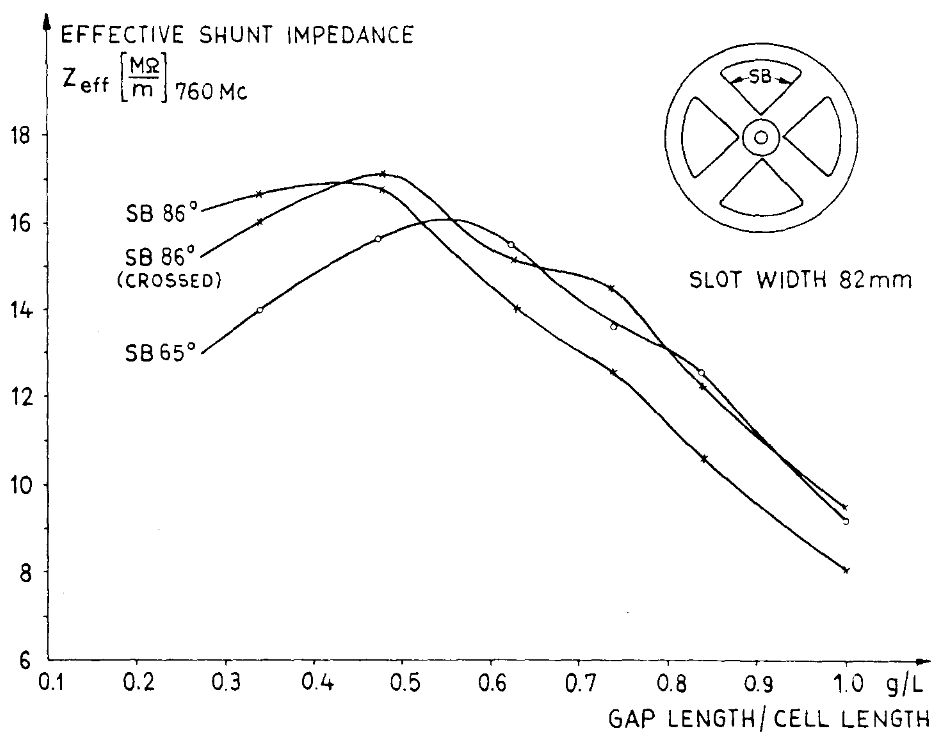


Fig. 6. Effective shunt impedance for drift tube structures with wide slot angles.

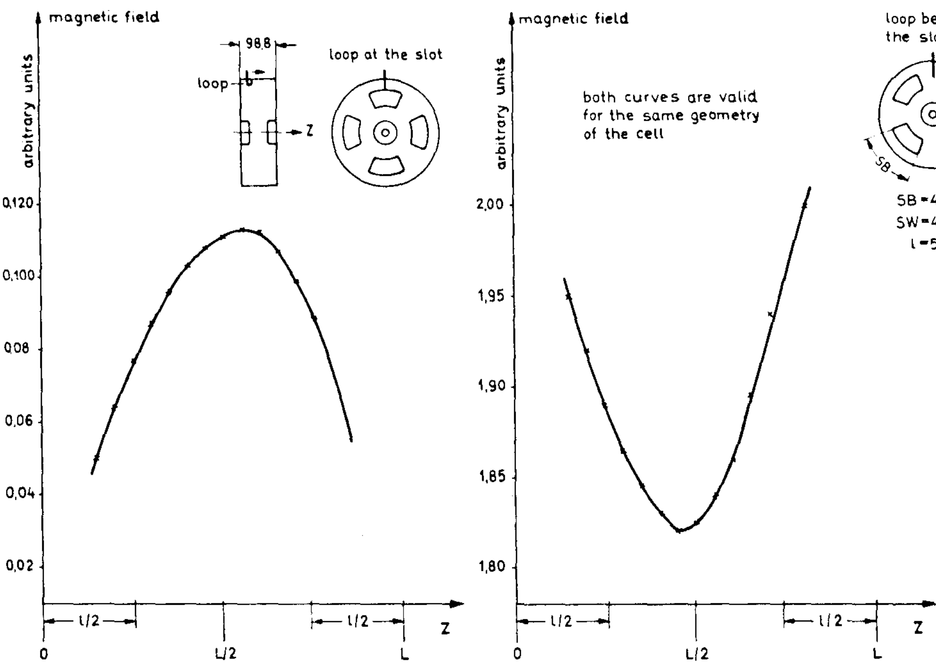


Fig. 7. Magnetic field, seen by a coupling loop which is moved in z-direction near the outer wall of the cavity.

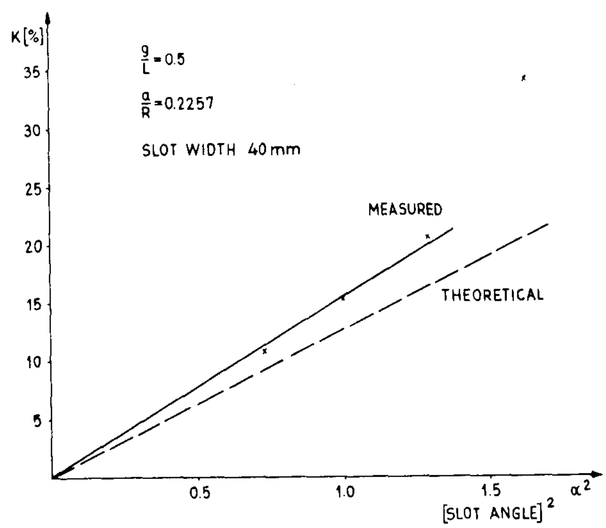


Fig. 8. Coupling coefficient vs the square of the slot angle for a cavity with drift tubes.

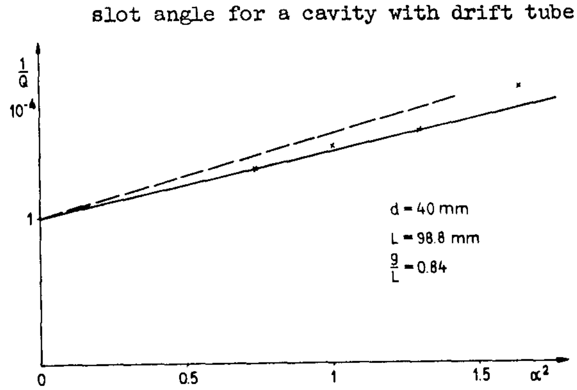


Fig. 9. Damping vs (slot angle)^2

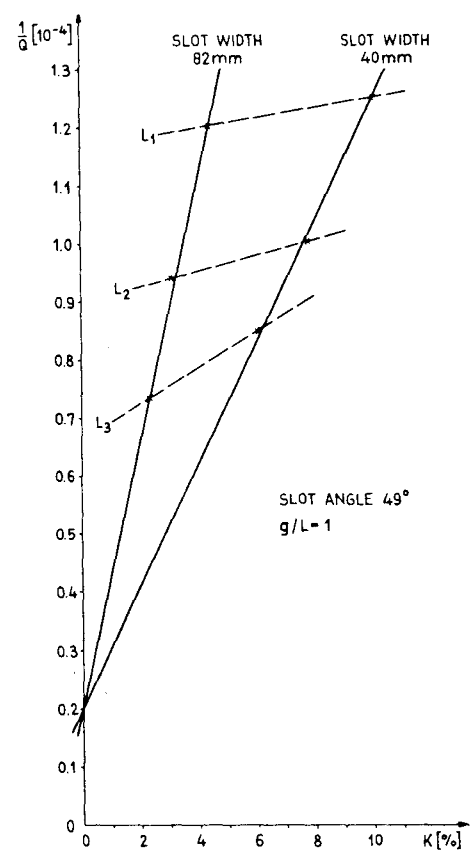


Fig. 10. Damping vs coupling coefficient for a cavity without drift tubes.