RF measurements on the first metre of electroformed loaded waveguide for the microwave particle separator.

by

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Summary

Measurements of phase and group velocities and losses, and the development of a feeding coupler are described. Arrangements are mentioned for identifying longitudinal resonance in a short-circuited length of waveguide when there is ambiguity of phase velocity. The electroformed waveguide is the first section intended for the CERN radio-frequency particle separator.

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1. Introduction

The radio-frequency particle separator under construction at CERN will use two (later three) deflecting structures separated by such a distance that the deflections add for wanted particles and cancel for unwanted ones (see reference 1). Each deflecting structure will consist of a 3 metre length of loaded waveguide operating under travelling-wave conditions. Circular disc-loaded waveguide was chosen because of its relative simplicity of manufacture by methods tried and tested in the construction of electron linear accelerators and because preliminary computations indicated that the RF losses in the structure would be within the capacity of available klystron amplifiers. Later investigations (references 2, 3, 4, 5, 6) allow comparisons to be made between the disc-loaded structure and other structures, and show that the disc-loaded structure is superior from most points of view to the other structures investigated.

The mode chosen for the disc-loaded waveguide is the lowest angular dependent mode, and can be regarded as a combination of $E_{11}$ and $H_{11}$ waves. Neither $E_{11}$ nor $H_{11}$ mode alone will satisfy the boundary conditions, but there are two solutions for the hybrid mode, consisting of different mixing ratios of the $E$ and $H$ waves (references 7,8). This hybrid mode has been shown to be responsible for pulse-shortening in electron linear accelerators (références 9, 10).

The dimensions for waveguide having a phase velocity equal to that of light were determined by computation by H.G. Hereward, B.W. Montague and Mrs. M. Bell and by measurements on brass models. These are plotted in figs. 1 and 2. In the momentum range for which the separator is intended (above 10 GeV/c) negligible error is introduced by operating at $v_p = c$. Dimensions were chosen for a 4 disc-per-wavelength structure which would give a forward wave having group velocity equal to 0.02 c. These are:

- $b/\lambda = 0.551$
- $a/\lambda = 0.263$
- $\lambda/D = 4.00$
- $d/D = 0.20$
where a, b, d and D are defined in the diagram of fig. 1. The free-space wavelength \( \lambda \) was taken as 10.50 cm, corresponding to an operating frequency of 2656 MHz.

Sufficient copper discs (fig. 3) aluminium spacers (fig. 4) and appropriate end cells were machined to make up a one-metre length of waveguide. The edges of the holes in the discs were machined sharp, then given a chamfer of about 0.3 mm without removing metal, by pressing in a steel ball of diameter 80 mm. (Later waveguide sections will have rounded edges in order to have a greater safety margin on voltage breakdown). The parts were sent to Vickers Research Ltd, who mounted them on a mandrel and deposited about 5 mm of copper on the outside, then dissolving out the aluminium spacers with hot caustic soda.

This report is concerned with measurement of the dispersion curve and losses of the waveguide, and the matching of a coupler for feeding it from rectangular waveguide. Shunt impedance and field distribution in the waveguide are more conveniently measured at low-power on short models of the structure and are not considered in this report.

2. **Mechanical Fittings**

While the waveguide was being manufactured fittings were prepared for handling and measuring the finished section. A pair of supports was made to clamp on the outside surface and serve also as carrying handles. For resonance measurements, short-circuit end plates, with arrangements for coupling to the field, were required. Low order axial modes can be identified by passing along the axis a metal or dielectric ball supported by a thread passing over pulleys. For higher-order modes this method of identification breaks down, since a ball large enough to produce a measurable change in resonant frequency will also change the field distribution. Identification can then be assisted by inserting into the waveguide a piston which effectively short-circuits the hole in one of the discs (references 11, 12). A shorter cavity can then be formed, which will have easily-identified resonances.
2.1 End Plates

Two kinds of end plates were made, the first providing a short-circuit in the centre plane of a disc (fig. 5a) and the second in the centre plane of a cell. (fig. 5b). The latter is used with a loose disc of appropriate dimensions. These parts, together with a loose ring forming one cell, allow small changes to be made in the total length of the waveguide. Contact surfaces of the plate of fig. 5a and of the loose disc were indium-plated to ensure good RF contact.

Holes were provided in the end plates for small coupling loops for RF input and detector. These were arranged at the extremes of a diameter, leaving the centre hole free for perturbation measurements and allowing input and detector to be at the same end.

2.2 Pulley System

Brackets were fixed on two of the end plates to hold small pulleys so that a nylon thread could be passed along the axis of the waveguide, returning along the outside to form a loop. A marker on the thread outside the waveguide ran along a metre rule to indicate the position of the ball or rod inside.

In order that the guide could be placed vertical for perturbation measurements, a hinge system was constructed which bolted on to one end plate and on to the bench. The other end could then easily be raised up and the hinge locked when the guide was vertical.

2.3 Piston

This is shown in fig. 6. It consists of a silver-plated brass plate mounted on a nylon block. The nylon block has a groove which rests over a disc edge when the front surface of the metal plate is in the centre plane of the next disc but one further in. There is no metal-to-metal contact. A long bar screwed into the nylon block allows the block to be raised at the back and moved to another disc.
3.1 Phase velocity

The phase velocity is determined by resonant frequency measurements on cavities formed of various lengths of short-circuited waveguide (reference 13). Resonance will occur when the guide is an integral number of half guide wavelengths long. The phase velocity \( v_p \) is then given by

\[
\frac{v_p}{c} = \frac{\lambda_g}{\lambda}
\]

where \( \lambda_g \) is the guide wavelength

\( \lambda \) is the free-space wavelength

There will also be a resonance, independent of cavity length, corresponding to \( \lambda_g = \infty \) in a purely E mode.

The waveguide section was fitted with two end plates as in fig. 5a so as to form a 73-cell cavity having length 99.75 cm. For the \( n \) mode resonance in the cavity \( \lambda_g \) will then be equal to \( \frac{199.5}{n} \) cm. Values of \( \lambda_g \) and \( k_g = 2\pi/\lambda_g \) were tabulated for values of \( n \) from 1 to 38, which corresponds to the \( n \)-mode in each cell.

The frequency of the signal fed into the waveguide was varied, and resonances indicated by crystal detector readings noted. The frequency was measured by means of the Hewlett-Packard 540 A Transfer Oscillator and 542 C Electronic Counter with plug-in frequency convertor. A frequency correction of 50 kHz per \( ^\circ C \) was applied to bring the measurements to a waveguide temperature of 25\( ^\circ C \), the temperature at which model measurements had been made.

In order to identify the axial modes, a short sapphire rod was passed along the axis by means of the nylon thread and pulley system already mentioned. The frequency of the signal was adjusted for maximum detector reading with the rod outside the cavity, then the positions and amplitudes of detector maxima and minima noted as the rod was moved along the axis. These were plotted, as shown in fig. 7.

For the waveguide dimensions chosen, the dispersions curve is not monotonic so that over a certain range of frequencies two phase velocities are possible at the same frequency (see fig. 9). This phenomenon had already
been noticed during the brass model measurements on short cavities and is confirmed by calculation of close-spaced waveguide. At the frequency of each of the low-order resonances (π up to 5π) there was a higher-order mode (corresponding to shorter wavelength) sufficiently close in frequency to be excited. This caused the pattern shown in fig. 7, where the envelope of the curve corresponds to the 2π mode, while the closer-pitch curve represents the deformation of the field in a higher-order mode as the rod passes down the waveguide.

Only the modes up to 5π in the cavity could be definitely identified, since the perturbation technique is no longer valid for high-order modes. The other resonances could be identified by fitting them as closely as possible to the dispersion curve previously measured on the brass models. Since, however the dimensions of the waveguide section did not correspond exactly to any one set of model parts, and since the disc edge contour had been changed, it was considered necessary to use another method of identification. This consisted of using only a small part of the waveguide, ending in the piston described in section 2.3, as resonator. The number of resonances in the cavity is thus reduced, making identification more certain.

The metal plate forming the front face of the piston forms a short-circuit in the centre plane of a disc, but does not make metallic contact with it. The error introduced by not having contact can be judged by comparing resonant frequencies for the same wavelength in different lengths of cavity, since the reactance at the end plane will affect these cases differently. It is seen from the results plotted in fig. 8 that errors introduced are small, except in some cases where the cavity was resonated in the π mode. Fig. 8 also shows the curve obtained from resonances in the full length of waveguide, identified by comparison with brass model measurements. It is seen that this curve fits well with the measurements using the piston. The dotted curves correspond to axial mode numbers being changed by one either way, and show that a wrong identification is unlikely.
The resonance measurements on the full length of waveguide were repeated with an extra half cell at one end, making \(38\frac{1}{2}\) cells. The dispersion curve of fig. 9 is plotted from the measurements on \(38\) and \(38\frac{1}{2}\) cell lengths. The \(v_p = c\) line, corresponding to \(\lambda_g = \lambda\), is also drawn on this diagram. The measurements made with the piston are not plotted, being used for identification purposes only.

It is evident from Maxwell's equations that the composite \(E_{11} - H_{11}\) mode must have a second passband, corresponding to a different ratio of \(E\) and \(H\) waves. This second branch was measured in the same way as the first, over the frequency range 3100 to 4200 MHz (the upper limit of the generator in use), and is plotted in fig. 10. In this case the \(\lambda_g = \infty\) \((2\pi/\lambda_g = 0)\) point corresponded to a pure \(E\) mode, and could be measured. The frequency of this mode was independent of cavity length, and is little different from the \(E_{110}\) frequency in an unloaded circular tube of the same diameter as the waveguide.

Fig. 10 also shows the lower branch of the \(E_{21} - H_{21}\) hybrid mode which has quadrupole symmetry. This was identified by observing the azimuthal variation of the magnetic field at the outer wall in a brass model. In this mode there is no field on the axis, so axial mode identification cannot be carried out by means of a small bead on the axis. A larger bead, or a small bead off the axis, could have been used, but it was found that a series of resonance measurements in different lengths of waveguide terminated by the short-circuiting piston permitted identification of all the axial modes.

### 3.2 Group Velocity

The group velocity \(v_g\) in the waveguide is defined by

\[
\frac{v_g}{c} = \frac{\partial k}{\partial k_g}
\]

where \(k = 2\pi/\lambda\)

and \(k_g = 2\pi/\lambda_g\)

This definition is more convenient here in the form

\[
\frac{v_g}{c} = \frac{2\pi}{c} \frac{\partial f}{\partial k_g}
\]
where \( f \) is the signal frequency, \( \frac{df}{dx} \) at \( v_p = c \)

can be obtained from the slope of the curve of fig. 9 or from the 18π and 20π resonances in the 38-cell cavity. The latter give values \( \delta f = 5.55 \times 10^6 \) Hz
and \( \delta k_e = 0.063 \text{ cm}^{-1} \) corresponding to \( \nu_{e/c} = 0.0185 \).

It will be seen from fig. 2 that the measured value corresponds well with calculations and model measurements.

The group velocity was also calculated for \( v_p = c \) from two points on the \( E_{21} - H_{21} \) curve shown in fig. 10. The value obtained was \( \nu_{e/c} = 0.0903 \).

3.3 Mode-separating flats

A waveguide having perfect circular symmetry can support two independent hybrid \( E_{11} - H_{11} \) modes, of the same form but with polarizations 90 degrees apart in azimuth. It is possible that the second mode might be excited in a deflecting waveguide due to imperfections in the construction, causing a tilting of the net angle of deflection. A deliberate dipole asymmetry was therefore introduced by machining flats on the aluminium spacers, so as to produce a cross section of finished waveguide as shown in fig. 11. The flat was omitted from the end cells of the waveguide, since these cells are machined out of copper and "grown" into the electroform.

Similar flats were tried out on a two-cell brass model before the manufacture of parts for the electroformed waveguide began. In that case segments having maximum thickness 1.5 mm were soft-soldered into the brass rings, with the edges facing the discs chamfered 45° to avoid contact with the discs. Measurements showed an increase of 16.5 MHz in the \( v_p = c \) frequency when the flats were parallel with the magnetic field on the axis, as compared with that with the field turned 90°. In this latter case the frequency was unchanged from that without the soldered segments. Calculation showed that with \( \nu_{e/c} = 0.02 \) a wave pattern 90° round from that intended would slip nearly 6° radians per metre relative to the particles, so that its mean effect would be negligible.
The effect of the flats on the electroformed waveguide was measured by exciting it with loops in an end plate turned $90^\circ$ from the normal position. The piston was inserted so that cavities of two or more cells could be measured. Resonances were plotted on a dispersion diagram, for cavities up to seven cells, as shown in fig. 12. Since the first cell has no flats, the points plotted for a small number of cells would not be expected to be consistent with those for larger numbers. In fact only the 2 and 3 cell points lay off a smooth curve.

Fig. 12 shows also the dispersion curve curve previously measured with correct loop polarization. It is seen that the $90^\circ$ mode is shifted by the flats from $10.5$ to $13.6$ cm in guide wavelength, i.e. from c to about $1.3$ c in phase velocity. This corresponds to $4.6\pi$ radians per metre slip between wave and particles.

4. Power Loss

4.1 Q Measurement

The Q was determined from the frequency difference between half-power points.

The RF signal was passed through a ferrite isolator and a waveguide variable attenuator into a hybrid bridge which divided it equally between the head of a thermistor bridge and a coupling loop in the waveguide. The waveguide formed a 38-cell cavity with a short-circuiting plate at each end. A second coupling loop fed a wideband crystal detector.

The signal frequency was set to that corresponding to $19\pi$ mode in the 38-cell cavity (i.e. $\lambda g = \lambda$), then adjusted for maximum detector reading. This reading was noted, then the variable attenuator adjusted to increase the thermistor bridge reading by 3 dB. The frequency was then changed to bring the detector back to its original reading, the thermistor bridge being maintained at the +3 dB setting.
The signal frequency was measured and the procedure repeated at the other side of resonance. The loaded $Q$ is given by the mean signal frequency divided by the difference between the reading at either side of resonance. A coaxial slotted-line was inserted in the feed to the cavity in order to find the correction to be applied to the loaded $Q$ to give the unloaded $Q$ (reference 14).

Values between 9130 and 9500 were obtained for the unloaded $Q$, depending on the tightness of clamping of the end plates. The frequency of the signal was changed until the next nearest mode was encountered. This was the 5π mode, about 1.2 MHz away. This is not close enough to affect appreciably the measurement of the 19π resonance, since the half-power bandwidth was about a third of a MHz. The unloaded $Q$ in the 5π mode was found to be 7400.

The $Q$ was also measured at a frequency where there was no ambiguity of phase velocity: 2871 MHz which excited the 24π resonance. This gave $Q_u = 8860$.

The theoretical value of $Q$ was obtained from loss/metre figures computed by Mrs. M. Bell. The value, which varied very little with waveguide dimensions was 12200 for $v_p = c$ and the proportions used in the model, but $\lambda = 10$ cm. Scaling to 2856 MHz makes this 12500. The measured value is thus 76% of theoretical. The computations used a figure of 0.01428 ohm per square for the surface resistivity corresponding to a figure of 1.72 microhm-cm. for the copper.

Some of the difference between measured and theoretical $Q$ values may be due to losses in the end plates which had not been taken into account. The rest may be due to the surface finish and possible imperfections in the electrodeposition at the joint between the copper discs and the aluminium spacers.

4.2 Attenuation measurement

The attenuation can be calculated from measured values of $Q$ and group velocity (reference 15), or measured by transmission-line technique (reference 13). This latter method was used, the experimental arrangement being as shown in Fig. 13.
The frequency was adjusted to give a minimum at the loop in the wall of the waveguide. The reflection coefficient was then measured by the twice-minimum technique, changing the frequency and keeping the signal level at the end constant. The attenuation was then calculated from the reflection coefficient and the value of group velocity already determined. Losses in the short-circuit plate were neglected.

The measurement was made first at 2866.5 MHz, corresponding to \(10^2\) wavelengths between the two detector loops. At this frequency only one phase velocity is possible in the waveguide so that difficulties due to the superposition of two waves of different guide wavelengths are avoided. It is not expected that the attenuation at 2866.5 will be greatly different from that at 2856 MHz.

The value of attenuation measured was at first 0.18 neper/m, but fell to about 0.17 when the coupling at the far end was progressively reduced. The value calculated from the measured \(Q\) of 9500 and group velocity of 0.0185 \(c\) is 0.0178 neper/wavelength, i.e. 0.17 neper/metre.

The measurement was repeated in the \(10^2\) mode i.e. 2857.5 MHz. The minimum at the detector was in this case somewhat flatter giving an apparent attenuation of 0.248 neper/m. This high figure could be due to a second wave being propagated at the phase velocity corresponding to this frequency and partly "filling in" the minimum.

5. **Coupler**

5.1 **Development**

A coupler to feed the RF energy from a rectangular waveguide into the disc-loaded waveguide was developed in several stages. In the early waveguide models the signal was fed in from 50 ohm coaxial cable by means of a coupling loop. A sufficient number of rings and discs corresponding to one set of dimensions of brass model was made to form a one-metre length (fig.14). The
far end of the length was short-circuited and a strip of resistive material fitted across a cell at a voltage maximum (ref. 12, p.56). An attempt was made to get a good match, as observed by the standing wave pattern at probe holes in the cells, over a small range of frequencies. The limiting factor seemed to be reflections occurring in the guide due to bad contact.

This waveguide with resistive load was used as matched load for experimental couplers. The first (fig.15) used a rectangular waveguide tapered down so that its narrow dimension was equal to the distance between two discs in the circular waveguide.

The next experimental coupler used a coupling hole covering the full narrow dimension of the rectangular waveguide, coupling into a circular cavity somewhat longer than the hole.

Information gained from these models was used to design a coupler for the first electroformed section (fig. 16). In this case a piece of WG9 rectangular waveguide (3\(\frac{1}{2}\) x 1\(\frac{1}{2}\) inches inside dimension) was brazed into a copper block forming the coupling cavity. The disc-loaded waveguide bolted to one end of the cavity; the other end was formed by an end wall with a hole of the same diameter as the waveguide hole. This hole continues through a tube which permits particles to pass but attenuates the RF field. The coupling window size was determined from the previous experiments. The length of the cavity was decided largely by questions of mechanical convenience and rigidity in the neighbourhood of vacuum seals. The diameter of the coupling cavity was initially made less than the estimated value so that it could be machined out in stages for best impedance match.

5.2 Measurements on coupler

A radio-frequency signal was fed into the electroformed length of waveguide via a rectangular waveguide slotted section and the coupler of fig. 16. The arrangement is shown in fig. 17. An attempt was then made to find a suitable material to absorb the power in the disc-loaded waveguide and form a matched load. A tapered wooden rod was first tried, but tapered
strips of "Morganite" resistive material having 100 ohms per square were found to be more satisfactory. These were mounted on a wooden rod which could be slid into the holes in the discs. Variations of signal on the probe in the rectangular waveguide as the rod was moved were noted as an indication of reflections produced.

When the disc-loaded waveguide was reasonably well terminated, the standing-wave ratio looking into the coupler was measured with this same arrangement of fig. 17. The result of this measurement is shown in fig. 18.

The impedance match obtained so far was considered good enough for preliminary measurements. An attempt at further improvement by increasing the cavity diameter and varying the window opening will be made on the first rounded-edge waveguide. Final matching will be done by fitting a symmetrical inductive iris in the rectangular waveguide part of the coupler.

5.3 Coupling of two wave at the same frequency

When the presence of two waves at 2856 MHz was appreciated (fig. 9), various ways were considered of suppressing the unwanted wave. The model measurements and later calculations showed that if the hole radius was less than about 0.24 λ or greater than 0.27 λ (λ being the wavelength for ν=c/ν₀) the second wave at the working frequency was eliminated. Since a group velocity of not greater (numerically) than 0.32 c was required in order to act on the particles sufficiently in the available length, the hole cannot be made larger. If it is reduced, fig. 2 shows that a hole radius of about 0.235 λ, corresponding to a backward wave, is suitable. This solution is proposed by Hahn and Halama (reference 16), but involves a considerable loss of beam acceptance. An alternative solution proposed by H.G. Hereward is to feed with the input coupler a short section of waveguide having hole radius greater than 0.27 λ, and change (either adiabatically or abruptly) to a hole size corresponding to the forward wave with the desired group velocity. This would involve some model work in impedance matching the two kinds of waveguide.
Experimental work in which a signal was fed by coaxial cable through a fully tunable coaxial-to-waveguide transformer and a coupler into the short-circuited disc-loaded waveguide, indicated that the $v_p \approx c$ mode resonances could be preferred by tuning the transformer. The frequency could then be varied through the values corresponding to resonance at the other phase velocity, without these resonances being excited. This experiment makes it appear hopeful that the coupler itself can be made to excite only the wanted mode and discriminate against the other. As a check on the present couplers, a variable short-circuit was fitted on the rectangular waveguide of a coupler at the far end of the one-metre waveguide, as shown in fig. 19. The input coupler was also fitted with a rectangular short-circuit plate, this time carrying loops for RF input and output to a detector. Piston positions for resonances in the structure were plotted against frequency at half MHz intervals, and parallel straight lines, corresponding to half-guide-wavelength intervals for the piston, drawn in. The slope of these lines gives the group velocity and the sense of the wave. The lines drawn in fig. 20 correspond to a forward wave having $v_g \approx 0.015 c$. The scatter of the points in this graph is probably due to reflections in the couplers, which were not well matched over the range of frequency used.

The study of excitation and identification of the modes in the waveguide will be continued when better matched couplers are available.
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Fig. 1. DIMENSIONS OF DISC-LOADED WAVEGUIDE FOR \nu_p = \infty.

LOWER \mathbf{E}_{11}/\mathbf{H}_{11} MODE.

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\( t/D = 0.2 \) except where otherwise indicated

\[ \lambda/D = \infty \]

\[ \lambda/D = 5.13 \]

\[ \lambda/D = 4.02 \]

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Calculated

\( \Delta \) Model measurements, \( D = 20 \) mm

\( \square \) " " \( \ell/D = 0 \)

\( + \) First electroformed section.
Fig. 2. GROUP VELOCITY OF DISC-LOADED WAVEGUIDE WITH $v_p = c$.
LOWER $E_{II}/H_{II}$ MODE.

See key to Fig. 1.
Fig. 3. COPPER DISC.

Fig. 4. ALUMINIUM SPACER.
Fig. 5. SHORT-CIRCUIT END PLATES.

Fig. 6. SHORT-CIRCUIT PISTON.
Fig. 7. PERTURBATION BY SAPPHIRE ROD.

Fig. 8. ELECTROFORMED WAVEGUIDE WITH SHORT-CIRCUITING PISTON.
Fig. 9. $E_{II}/H_{II}$ HYBRID MODE, LOWER BRANCH.

Fig. 10. $E_{II}/H_{II}$ mode, upper branch. $E_{2I}/H_{2I}$ mode. $\gamma_0 = c$. $\pi$-mode cutoff.
Fig. 11. CROSS-SECTION OF WAVEGUIDE SHOWING FLATS.

Small figures indicate number of cells.

Fig. 12. EFFECT OF POLARISATION MODE SPLITTING.
Fig. 13.

Fig. 16. COUPLER.
Fig. 20. RESONANCES WITH THE ARRANGEMENT OF Fig. 19.