NEW DISK-LOADED WAVEGUIDES FOR THE CERN RF SEPARATOR

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ABSTRACT

Three new deflectors for the CERN RF separator have been designed and constructed. The deflection of particles will be nearly doubled compared to the situation with the old deflectors. It will be possible to change the phase velocity of the deflecting fields within some limits, as is necessary in more sophisticated applications of particle separation. This will be especially interesting for lower separation momenta and for deuteron rejection.

The choice of the deflectors takes into account new experimental and theoretical results in the high power behaviour of deflecting modes. New and refined methods for measurements on models, coupler matching and tuning of disk-loaded waveguides have been developed and allowed to achieve very uniform dephasings per cell (within ±2°) and very low standing wave ratios over a frequency range of several MHz.

Problems of machining and brazing in a vacuum furnace are discussed briefly. A high power test on each of the three deflectors showed that they can be operated safely at the design RF power level of 20 MW, confirming fully our calculations and measurements on peak RF fields in disk-loaded waveguides. Results of a deflection test with 16 GeV protons were found to be in agreement within some per cent with computer calculations and measurements on models. The maximum transverse momentum given by one deflector to the particles is 24 MeV/c.

A short description of the machining and brazing technique, the mechanical layout, the alignment system and the vacuum system is given. It is shown that the stability requirements for frequency and temperature can be easily fulfilled.

Finally the formulae for the change of phase velocity of the deflecting fields are given.
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INTRODUCTION

In January 1965 the first RF separator constructed by B. Montague and his group\textsuperscript{1}) started operation at CERN in a bubble chamber particle beam. Ever since, this separator has worked in a very satisfactory way\textsuperscript{2}) and up to the end of 1969 had separated particles for more than four million bubble chamber pictures.

The weak link in this first separator was the deflectors. Despite all our efforts, we were not able to run them at the full RF power level available from our klystron amplifiers (20 MW). This, combined with their rather low shunt impedance, led to low particle deflections which limited seriously the acceptance of the separator as compared to the acceptance of the associated beam line.

Another drawback was the very small frequency passband and the high standing wave ratio (SWR) of the deflectors, mainly due to internal power reflections. Therefore frequency changes, which are necessary in more sophisticated separator applications, were practically impossible here.

We therefore decided to design and construct new deflectors giving about double deflection, holding safely 20 MW RF power and with a passband of several MHz. In all, three deflectors of 3.5 m length were constructed.

The high power behaviour of deflectors turned out to be linked closely to the peak electric field on the inner surface of the disk-loaded waveguides. An extensive experimental and theoretical program\textsuperscript{3-5}) was started in order to study in detail the properties of the peak fields, and the results were applied to the optimization of the new deflectors.

The requirements for the frequency passband and the SWR of deflectors led to the development of new, more versatile and more precise methods of coupler and waveguide tuning. Finally, for the fabrication of the new deflectors, the technology of brazing very high quality copper and stainless steel under vacuum had to be mastered.

* * *

1. OPTIMIZATION OF DISK-LOADED WAVEGUIDE

The procedure of optimization has been explained in detail in an earlier report\textsuperscript{6}) and here we only repeat the main aspects. Essentially, one tries to maximize the number of wanted particles behind the beam stopper.

Let $D_f$ be the final deflection of wanted particles behind the last deflector and $A$ the deflection amplitude in the cavity with the highest deflection, which can be written

$$A = p c / p c$$

(where $p_c$ is the transverse momentum given to the particles, and $p$ is the momentum of the particles).

It is useful to introduce the quantity

$$S = D_f / A$$
which can be calculated\(^1\) (separation curve) for each momentum and for each wanted particle kind.

From experimental results in bubble chamber beams at CERN we found as a condition for \(D_f\)

\[
D_f = 4 \delta_y
\]  

(1)

where \(\delta_y\) is the angular half-opening of the undeflected beam in the centre of the deflectors and in the deflection (vertical) plane.

One tries to choose \(\delta_y\) in such a way that after deflection the particles just graze the deflector iris. The value of \(\delta_y\) then depends on the iris diameter \(2a\), the deflector length \(\ell\) and the size of the particle beam \(2h_y\), in the centre of the last deflector and in the vertical plane (including chromatic aberrations).

\(\delta_y\) is given by the formula

\[
\delta_y = \left( \frac{a}{\sqrt{2}} - h_y \right) \frac{2}{5\ell} 
\]  

(2)

The transverse momentum given to the particles is connected to the deflector parameters by

\[
p_{tc} = \frac{\sqrt{2} P_p}{10} \left[ \frac{1 - e^{-2\ell}}{\alpha} \right] \text{(MeV)}
\]  

(3)

where

\[
Z = E_0^2/P_y \left[ (kV/cm)^2/MW \right]
\]  

is the series impedance of the deflector,

\(E_y\) is the equivalent deflecting field (kV/cm),

\(P_y\) is the input RF power (MW),

\(\alpha\) is the voltage attenuation constant (Np/m).

The power \(P_y\) can be limited either by the RF peak power \(P_k\) available from the klystron amplifiers (in our case \(P_k < 20 \text{ MW}\), or by the peak power \(P_p\) which can be supported by the disk-loaded waveguide if \(P_p < P_k\). According to our assumptions \(P_p\) is determined by the maximum electric field strength \(E_p\) (just not leading to breakdowns) on the disk surface of the structure. Furthermore, we found out experimentally that \(P_p \propto \tau^{-\frac{1}{2}}\), where \(\tau\) is the length of the RF pulse applied to the structure. A convenient parameter for the determination of \(P_p\) (and for measurement) if the ratio of \(E_p\) and \(E_y\) for the case of travelling waves:

\[
\frac{E_p}{E_y} = \frac{E_p(1)}{E_p/E_y} \frac{1}{Z \sqrt{\tau}}
\]  

(4)

Using this parameter one can write

\[
P_p = \frac{E_p(1)}{E_p/E_y} Z \sqrt{\tau}
\]

where \(E_p(1)\) is the experimental peak electric field for copper under high vacuum, and for a pulse duration \(\tau = 1 \mu\text{sec}\).

For the calculation of deflections we assume
\[ P_0 = \begin{cases} 20 \text{ MW} & \text{if } P_p \geq 20 \text{ MW} \\ P_p & \text{if } P_p < 20 \text{ MW} \end{cases} \]

By combining the above equations one can calculate \( \delta_\gamma \) and \( t \) for:

- a given beam layout \( (h_\gamma) \),
- a given separation energy \( (p_c, S) \),
- a given structure \( (a, \alpha, \nu Z, E_p/E_g) \),
- a given pulse length \( (\tau) \) and a given \( P_0 \).

This has been done in Ref. 6 for different structures and under the following conditions:

\[ h_\gamma = 8 \text{ mm}, \]
\[ E_p(1) = 522 \text{ kV/cm}, \quad E_p/E_g = 3.61, \]
\[ P_K = 20 \text{ MW}, \quad P_p \geq 24 \text{ MW for } \tau = 5 \mu\text{sec}, \]

kaon separation at \( p = 10.1 \text{ GeV/c (S = 2.0)} \) and \( p = 14.25 \text{ GeV/c (S = 1.46)} \).

Several modes and disk thicknesses have been considered, and a 2\( \pi/3 \) mode deflector with a (rounded) opening \( 2 \tilde{a} = 45 \text{ mm} \), a disk thickness \( t = 10 \text{ mm} \) and length \( \ell = 3.5 \text{ m} \) was chosen.

The new deflectors have been constructed according to this choice. Meanwhile, however, new and more precise values for \( E_p/E \) have been obtained\(^5\). Furthermore additional information on \( E_p(1) \) has been obtained at SLAC. It thus seemed interesting to recheck the parameters and to find out if the first choice is still reasonable.

In Figs. 1 and 2, \( (E_p/E_g)_{1\gamma} \) values for the \( \pi/2 \) and 2\( \pi/3 \) mode are plotted as a function of disk thickness and disk opening\(^4\). Using these new values we found from the results of \( E \) measurements on the old CERN deflectors \( E_p(1) \geq 470 \text{ kV/cm (instead of the old value 522 kV/cm)} \). New results from SLAC\(^7\) on a deflector seem to indicate that \( E_p(1) \geq 505 \text{ kV/cm} \). We choose however the more conservative figure of 470 kV/cm.

The value of pulse duration should be as short as possible but nevertheless allow a proper operation of our new phase system\(^4\). As a compromise we choose \( \tau = 4 \mu\text{sec} \).

With these new data the calculations have been repeated. In Fig. 3 two typical examples for \( \delta_\gamma, \ell, P_p \), and \( \beta_0 \) as a function of opening and for two modes are given. As before we determine the structure giving a maximum value for \( \delta_\gamma \) by taking into account, however, reasonable limits for the other parameters involved.

i) The group velocity should have a value \( |\beta_0| > 0.02 \) in order to avoid too stringent machining tolerances.

ii) The group velocity should be negative. For positive values and in the region which is of interest to us (i.e. not too big openings), the dispersion curve is double valued. Although this is not a fundamental difficulty we found out that there are several drawbacks. The coupler design gets more difficult because there is a danger of two modes being launched. This can increase \( E_p/E_g \), thus increasing the danger of breakdown. Furthermore the very convenient and powerful RF pulse method for coupler tuning and the plunger method for cell tuning (cf. Section 4) can only be applied with care because they give results which are difficult to interpret.

iii) The corresponding deflector length should not be prohibitive.
iv) In Fig. 3 one remarks the deep "valley" in the $\delta_V$ curves, which corresponds to the region where $\beta_{g} \to 0$ (and where $P_p$ gets small). As we exclude the region where $\beta_{g} \to 0$, the optimization consists in increasing the opening $\tilde{a}$ up to the point where $\delta_V$ falls off. The exact location of this point depends very strongly on the actual value of $E_p(1)$ and $\tau$. Practically, one finds that there is no point in going to regions where $P_p < 20$ MW, because the increase in deflection (or more precisely of $\sqrt{a} (1 - e^{-ax})/a$ in Eq. (3)) is upset by the rapid decrease of $P_p$. Therefore we decided to choose an opening for which $P_p = 24$ MW, so that there remains some reserve with respect to the 20 MW available.
Fig. 2 $(E_p/E_0)^{TW}$ values for $2\pi/3$ mode. The $E_p/E_0$ value for the new deflectors (CERN III) is indicated ($E_p/E_0 = 3.3$).

We note that the limitation to the region $\beta_g < 0$ is not as restricting as one might think. Practically, for $\beta_g > 0$, $\delta_V$ is only slightly bigger (if at all) but the values for $\beta$ are always larger. Nevertheless, there might be applications where this region can be of interest, for example if large horizontal acceptances are wanted. We also note that this optimization is practically independent of the separation conditions ($pc$ and $S$).

In Table 1 some results of optimization are shown for $pc = 10.1$ GeV and $S = 2$. As one can see, the values for $\delta_V$ are practically equal for the $\pi/2$ and $2\pi/3$ mode (with a very slight advantage for the $\pi/2$ mode); the values for the $4\pi/5$ mode were found to be definitely smaller and are no longer considered.
Fig. 3 Optimized values for $\delta_V$, $k$, $P_P$ and $\beta_b$ as a function of the radius $\bar{a}$ of the rounded disk opening for two different modes and disk thicknesses. We assume

$E_p(1) = 470$ kV/cm

$P_P = 24$ MW for 4 $\mu$sec pulse length

$p = 10.1$ GeV/c (K$^+$ separation).
TABLE 1

<table>
<thead>
<tr>
<th>t/mm</th>
<th>ă/mm</th>
<th>(\delta_v)/mrad</th>
<th>(\xi/m)</th>
<th>(\beta_g)</th>
<th>t/mm</th>
<th>ă/mm</th>
<th>(\delta_v)/mrad</th>
<th>(\xi/m)</th>
<th>(\beta_g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>23.7</td>
<td>1.13</td>
<td>3.06</td>
<td>-0.023</td>
<td>7.5</td>
<td>22.35</td>
<td>1.085</td>
<td>2.90</td>
<td>-0.023</td>
</tr>
<tr>
<td>7.5</td>
<td>24.4</td>
<td>1.15</td>
<td>3.25</td>
<td>-0.020</td>
<td>10</td>
<td>23.25</td>
<td>1.11</td>
<td>3.05</td>
<td>-0.020</td>
</tr>
<tr>
<td>10</td>
<td>24.6</td>
<td>1.13</td>
<td>3.34</td>
<td>-0.019</td>
<td>12.5</td>
<td>23.7</td>
<td>1.12</td>
<td>3.12</td>
<td>-0.0185</td>
</tr>
</tbody>
</table>

The best results for \(\delta_v\) are obtained for a \(\pi/2\) mode with \(t = 7.5\) mm and for a \(2\pi/3\) mode with \(t = 12.5\) mm. Our choice (\(2\pi/3\) mode, \(t = 10\) mm, \(\bar{a} = 22.5\) mm) has to be compared to the values of Table 1.

We recall that a \(2\pi/3\) mode was chosen mainly for technological reasons (less cells per wavelength and shorter length). In view of the very small differences between the \(2\pi/3\) and \(\pi/2\) mode this choice remains entirely justified.

From Fig. 3, one concludes that we could have gone up slightly more in \(\bar{a}\) and \(\delta_v\), because the limit \(P_p = 24\) MW has not been reached.

In Table 2 we give a comparison between the optimum for the \(2\pi/3\) mode (\(t = 12.5\) mm, \(\bar{a} = 23.7\) mm) and our choice for three different kaon separation momenta. As one can see the difference never exceeds 6\%.

TABLE 2

<table>
<thead>
<tr>
<th>(p/\text{GeV/c})</th>
<th>(S)</th>
<th>(2\pi/3)-optimum</th>
<th>CERN III</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\delta_v)/mrad</td>
<td>(\xi/m)</td>
<td>(P_p/\text{MW})</td>
</tr>
<tr>
<td>10.1</td>
<td>2</td>
<td>1.12</td>
<td>3.1</td>
</tr>
<tr>
<td>14.3</td>
<td>1.46</td>
<td>0.77</td>
<td>4.4</td>
</tr>
<tr>
<td>16</td>
<td>1</td>
<td>0.575</td>
<td>6.1</td>
</tr>
</tbody>
</table>

The length of the deflectors (\(\xi = 3.50\) m) was chosen as a compromise for different separation momenta. In Fig. 4 we have plotted the corresponding value for \(\delta_v\) as a function of momentum and for kaon separation. As can be seen, it is constant up to 12.2 GeV/c and lies slightly above the beam acceptance (\(\delta_v = 0.85\) mrad). For comparison, we show the values of \(\delta_v\) which would have been obtained if for each momentum the optimum length had been chosen.

2. MODEL MEASUREMENTS

As design frequency for the new deflector we have chosen

\[ f_0 = 2855.167\ \text{MHz} \]
Fig. 4 $\delta_{\nu}$ as a function of momentum for $K^+$ separation and for $\lambda = 3.5$ m. Dotted line: $\delta_{\nu}$ corresponding to the optimum length for each momentum. The lengths are given in brackets.

at 25$^\circ$C and under vacuum. The corresponding wavelength is

$$\lambda = 10.500 \text{ cm}.$$ 

The parameters of the disk-loaded waveguides were calculated with a computer program\(^6\) and a brass model of 27 cells was constructed in order to check the calculations and to design appropriate mode transformers (couplers).

In this model, rounded iris openings were used with a rounding radius $r = 5$ mm and an opening $2a$ which is related by the following equation to the value of the (cylindrical) opening $2a$ used in the computer program\(^1\)

$$2a = 2a - t[1 - \pi/4] = 2a - 2.146 \text{ mm},$$

where $t$ is the disk thickness ($t = 10$ mm).

In Fig. 5 the dispersion curve obtained from this model is shown. For the $2\pi/3$ mode we find

$$f = 2853.538 \text{ MHz}$$

(in air for 25$^\circ$C), a value which was considered sufficiently close to the design value for the model measurements. From the dispersion curve we derive the following value for the
Fig. 5 Dispersion diagram for the 0° mode (27-cell model) and for the 90° mode (six-cell model). The geometry of the mode stabilizing rods is shown (dimensions in mm).

normalized group velocity: $\beta_g = v/c = -0.0233 \pm 0.0006$. The difference with the computed value $\beta_g = -0.0244$ can be explained by the rounding of the irises.

The azimuthal mode stabilization is obtained by using two rods, whose diameter and positions are chosen so that the lowest frequency of the deflection fields at 90° in the passband lies 30 MHz above the frequency of the 0°, $2\pi/3$ mode. This was checked in a six-cell model. The results and the geometry of the rods are shown in Fig. 5. We note that the 0° mode is displaced by less than 100 kHz due to the presence of the mode stabilizing rods.

The R/Q value ($R$ = shunt impedance, $Q$ = quality factor) of the model was checked by a perturbation measurement in the 27-cell model. In Fig. 6 the measured field distributions for $E_z$ and $E_\phi$ are plotted.

The value of R/Q derived from the $E_z$ distributions agrees within the measuring accuracy with the computer calculations:

$$R/Q = 1.376 \text{ k} \Omega/\text{m}.$$
Fig. 6  a) Field distributions for $E_x$ and $E_y$ as a function of axial distance $z$. They have been obtained from a perturbation measurement with a "longitudinal" needle ($L = 4.5 \text{ mm}$, $d = 0.2 \text{ mm}$) and a "transverse" needle ($L = 2.5 \text{ mm}$, $d = 0.2 \text{ mm}$), respectively.
b) Field distribution for $E_z$ derived from the above distributions after correction for $E_y$. The location of disks is indicated.
Fig. 7  a) Distribution of the electric field on the disk surface and in the deflection plane for travelling wave conditions. It is derived from a perturbation measurement and corresponds to an infinitely small dielectric probe.

b) Sketch of iris showing the locations of the peak electric field.
The value for $E_p/E_0$, which hitherto could not be calculated, was measured in a special model and found for the travelling wave case to be

$$\left(\frac{E_p}{E_0}\right)_{TW} = 3.3$$

The field distributions, along the disks, from which this value is derived$^1$ are shown in Fig. 7.

Finally by using the electrical field distributions given above, we have made a sketch of the general field configurations of the $2\pi/3$ mode in our deflector (Fig. 8). In Table 3 some measured and computed parameters of the new (CERN III) deflectors are listed.

3. THE FABRICATION OF DEFLECTORS

The old CERN deflectors were produced by an electroforming technique. Each cavity had a length of three metres and was made up of three sections, of one metre's length. They were bolted together and the RF contact and vacuum tightness were achieved by a layer of

Fig. 8 General electric and magnetic field configurations. They are shown for the standing wave case corresponding to the boundary conditions indicated and correspond to the travelling wave configuration at a given instant. For the magnetic field the plane of projection is turned by $90^\circ$ in order to visualize better the magnetic field lines (A-A: deflection plane).
TABLE 3
Parameters for the CERN III deflectors

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol or formula</th>
<th>Unit</th>
<th>From computation of design</th>
<th>From measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design frequency (35°C, in vacuum and for ( v_A = c ))</td>
<td>( f_0 )</td>
<td>MHz</td>
<td>2855.167</td>
<td>2855.10 (No. 1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2854.90 (No. 2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2855.10 (No. 2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(from deflection test)</td>
</tr>
<tr>
<td>Design wavelength</td>
<td>( \lambda_0 )</td>
<td>cm</td>
<td>10.500</td>
<td>-</td>
</tr>
<tr>
<td>Dephasing per cell</td>
<td>( \phi )</td>
<td>-</td>
<td>( 2\pi/3 )</td>
<td>-</td>
</tr>
<tr>
<td>Opening</td>
<td>( z )</td>
<td>mm</td>
<td>47.146 (cylindrical)</td>
<td>( 45.00 \pm 0.01 ) (rounded)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>117.328</td>
<td>117.64 \pm 0.005</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10 \pm 0.01</td>
<td></td>
</tr>
<tr>
<td>Disk thickness</td>
<td>( t )</td>
<td>m</td>
<td>3.50</td>
<td>-</td>
</tr>
<tr>
<td>Effective length for deflection (99 cells + 2 \times 1 coupler cell)</td>
<td>( \ell )</td>
<td>m</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Normalized group velocity</td>
<td>( v/g )</td>
<td>-</td>
<td>-0.0244</td>
<td>-0.0233 \pm 0.0006 (from model measurement)</td>
</tr>
<tr>
<td>Filling time</td>
<td>( \tau )</td>
<td>usec</td>
<td>-</td>
<td>0.505</td>
</tr>
<tr>
<td>Voltage attenuation coefficients (from measurements on deflectors No. 1 and No. 2)</td>
<td>( a )</td>
<td>Np/m</td>
<td>0.093</td>
<td>0.106 \pm 0.002</td>
</tr>
<tr>
<td>Surface impedance for copper</td>
<td>( r_s )</td>
<td>( \Omega )</td>
<td>( 1.394 \times 10^{-2} )</td>
<td>( 1.66 \times 10^{-2} )</td>
</tr>
<tr>
<td></td>
<td>( R/Q )</td>
<td>kΩ/n</td>
<td>1.376</td>
<td>1.38 \pm 0.07 (from model measurement)</td>
</tr>
<tr>
<td>Limiting power (4 usec; ( E_p = 470 ) kV/cm)</td>
<td>( (E_p/E_q)/\gamma )</td>
<td>( MW )</td>
<td>50</td>
<td>3.3</td>
</tr>
<tr>
<td>Quality factor</td>
<td>( Q = \frac{\omega}{200 \sqrt{E_p}} )</td>
<td>-</td>
<td>12100</td>
<td>-</td>
</tr>
<tr>
<td>Shunt impedance</td>
<td>( R = R/Q \times Q )</td>
<td>( MW )</td>
<td>16.40</td>
<td>-</td>
</tr>
<tr>
<td>Series impedance</td>
<td>( Z_s = \frac{\sqrt{Q}}{Q} \frac{1}{\sqrt{E_p}} )</td>
<td>( \Omega )</td>
<td>1.88</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>( Z_s )</td>
<td>( \Omega )</td>
<td>-</td>
<td>0.371</td>
</tr>
<tr>
<td>Deflector constant</td>
<td>( KL )</td>
<td>( \Omega )</td>
<td>5.49</td>
<td>-</td>
</tr>
<tr>
<td>Transverse momentum for ( P_a = 17 ) MW</td>
<td>( p_T = \sqrt{P_a \times KL} )</td>
<td>MeV/c</td>
<td>22.65</td>
<td>22.1 \pm 0.075 (from deflection test on deflector No. 2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(24.0)</td>
</tr>
<tr>
<td>for ( P_a = 20 ) MW</td>
<td></td>
<td>MeV/c</td>
<td>24.60</td>
<td></td>
</tr>
<tr>
<td>Vertical angular acceptance up to 12.2 GeV/c kaons</td>
<td>( \delta_v )</td>
<td>mrad</td>
<td>( \pm 0.91 )</td>
<td></td>
</tr>
<tr>
<td>Horizontal angular acceptance</td>
<td>( \delta_h )</td>
<td>mrad</td>
<td>( \pm ) 12</td>
<td></td>
</tr>
<tr>
<td>Weight per metre</td>
<td></td>
<td>kg/m</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>Temperature coefficient</td>
<td>( K )</td>
<td>( \text{kHz/F} )</td>
<td>-49</td>
<td></td>
</tr>
</tbody>
</table>

*) Experimental values for \( a \) and \( v/g \).

**) cf. also Fig. 4; we assume \( h_v = \pm 8 \) mm, \( h_\mu = \pm 3.5 \) mm.

***) For a linear expansion coefficient of copper: \( 1.71 \times 10^{-5} /{\text{C}} \).
indium; the couplers were fixed on the structure by the same technique. One of the main drawbacks seemed to us the rather poor surface conditions (partly due to the necessity of removing the aluminium spacers needed for this technique by hot caustic soda etching). Furthermore the electrodeposited copper is heavily loaded with hydrogen and the indium joints made it impossible to outgas the structures under vacuum at some hundred °C. Finally, sufficiently close mechanical tolerances seem to be a problem. These arguments against the electroforming technique are certainly not compelling (at SLAC, for example, very high quality disk-loaded waveguides have been obtained by this technique), but the existence at CERN of a very competent workshop for vacuum brazing led us to this latter technique.

3.1 The copper

From brazing tests at CERN it turned out that only a high quality copper containing very small amounts of gases (especially O₂ and H₂) can withstand brazing under vacuum at 800°C without showing heavy surface damages such as cracks or holes. We decided to use a "certified HOOKOF®" copper, delivered by the firm Outokumpu OY, Finland. Their copper after having passed a very tough quality test at Outokumpu and CERN¹², gave completely satisfactory results.

3.2 Machining of the waveguide

For the machining of the deflectors the machining tolerances had to be estimated. With a computer program we calculated the following frequency dependencies:

for the disk opening 2a: \[ \Delta f/\Delta 2a = -6.4 \text{ kHz/um} \]
for the outer diameter 2b: \[ \Delta f/\Delta 2b = -21.8 \text{ kHz/um} \]
for the slot width d: \[ \Delta f/\Delta d = -0.5 \text{ kHz/um} \]
for the disk thickness t: \[ \Delta f/\Delta t = +1.7 \text{ kHz/um}. \]

We decided to keep the frequency fluctuations from cell to cell due to machining errors below 150 kHz.

In Fig. 9a the general layout of the waveguide assembly with the required machining tolerances is shown.

One can see that our disk-loaded waveguides are assembled from simple disks and rings. After a first machining to 0.5 mm, the copper pieces are annealed under vacuum at 850°C for 30 min. Then follows the final machining which for the first deflector was done with a "tungsten-carbide tool" and for later ones with a diamond tool. The inner diameter of the rings was checked with a three-finger comparator based on the method of a controlled air leak.

3.3 RF test of the rings

The most critical dimensions for a disk-loaded waveguide is the inner ring diameter 2b (cf. Section 3.2). Whereas for all other dimensions a mechanical control was considered sufficient, we decided to recheck the inner diameter of the rings with an RF method.

In Fig. 10 the measuring method is illustrated. The ring is clamped with a constant force of about 10 kg between two silvered steel plates, the lower one bearing two RF loops so that a TM₁₁₀ mode can be excited in the cavity formed by the plates and the ring. We

*) Certified HOOKOF copper (A.S.T.M. grade 1) has a purity of at least 99.99%, the contamination with O₂ being less than 0.0010%; the electrical conductivity at 20°C lies above 1012 Ω⁻¹cm⁻¹.
Fig. 9 Mechanical layout of a disk-loaded waveguide with coupler and end cells.
a) Assembly of disk-loaded waveguide with coupler and end cells.
b) Location of brazing alloy in a normal copper cell.
c) Joining of two stainless-steel cells with an intermediate disk.
d) Intermediate stainless-steel cell with vacuum-tight pick-up for the phase system and tuning stub.
choose the TM_{110} mode because it is, like the deflection mode, a dipole mode and is independent of the height of the ring.

For our value of \( z_b \) a frequency of 3108.255 MHz at 25°C (in vacuum) was calculated with a frequency dependence given by

\[
\frac{\Delta f}{\Delta z_b} = -\frac{26.4}{\mu m} \quad \text{and} \quad \frac{\Delta f}{\Delta T} = -53 \text{ kHz/°C}.
\]

The measurements were done in a temperature-stabilized room and ample time was foreseen to bring all rings and the clamping plates to room temperature. The measurements were reproducible to better than ±25 kHz, which corresponds for \( z_b \) to ±1 \( \mu m \).

With a sweep generator the Q-curve of the cavity was made visible on a scope, and the frequency corresponding to the maximum was determined on the scope with a second generator and a frequency meter. The rings were turned between the steel plates until a good contact was established. Generally it was possible to obtain a Q-value of 5000. If a good contact was not obtained, the ring was rejected and rechecked eventually after a remachining.

Once an azimuthal position with a good contact was established, this was defined as the 0° position and, together with a ring number, engraved on the outer surface. After this the resonance frequency at 90° was measured. Both measured frequencies had to differ by less than ±125 kHz (±5 \( \mu m \)); otherwise the ring was rejected. The ellipticities found decreased during the machining period and were finally as low as 2-3 \( \mu m \).

![Fig. 10 Sketch of experimental layout for the RF check of rings.](image-url)
Fig. 11 Frequency distributions for 100 rings. 1 μm corresponds to -26.4 kHz.

After establishing the mean frequency of the 0° and 90° position, the position corresponding to the frequency nearest to the mean value was chosen for each ring. A frequency distribution of this kind for a sample of 100 rings is given in Fig. 11. After having rejected three rings, the total width of the distribution is ±70 kHz (±2.65 μm), thus well within the tolerances required (±5 μm).

As already pointed out above, two different machining methods were used, the mechanical dimension check being the same in both cases. The RF check, however, showed a systematic deviation in the value of 2b of the order of 70 kHz (2.65 μm). This can be explained by the different surface conditions obtained.

In fact the mechanical check with a controlled air leak tends to measure 2b by the "tips" of the surface roughness, whereas the RF with a skin depth of only 1 μm "sees" the surface roughness. Therefore, the diamond machining giving a smoother surface also gives somewhat higher frequencies. Finally, we mention that a comparison of both measuring methods for the same ring shows discrepancies of up to ±5 μm for the carborundum machining and up to ±3 μm for the diamond machining.

During the final assembly the rings were chosen in order to give the most uniform waveguide structure with respect to 2b. Due to the different machinings, slightly different mean values for the resonance frequency were used in the deflectors Nos. 1, 2, and 3 (Fig. 11).

3.4 The couplers (mode-transformers)

In Fig. 9a the general layout of the input and output couplers is given. Its design is similar to the SLAC design for the LOLA IV coupler\textsuperscript{13}). The tuning is done by changing the iris width W and the inner diameter D. The optimum values of W and D were obtained from
model measurements by using the RF pulse method. The coupler is fitted with a stainless-steel flange at the RF entry waveguide and by another stainless-steel flange for the vacuum connection. An RF choke tube giving 50 db attenuation avoids an exaggerated leaking of RF power in the direction opposite to the disk-loaded waveguide.

3.5 The end cells

As our vacuum furnace did not allow one to braze sections longer than 1.50 m, we had to assemble each deflector (of 3.715 m total length) from three sections. The brazed copper being very soft, there was no hope of clamping the sections together without deformation of the end cells. Therefore, we brazed on each section special stainless-steel end cells (cf. Fig. 9a). For the joining of two sections a copper disk is inserted between the two cells, which are then screwed together until their faces touch.

In order to ensure a good RF contact between the cells and the iris, a copper layer of approximately 7.5 µm thickness is electrodeposited on the inner surface of the end cells. Care is taken to produce a little protruding roll around both edges of the inner surfaces (Fig. 9c). This roll of electrodeposited copper is much harder than the annealed copper of the intermediate disk and plants itself into the disk surface giving a perfect RF contact. The vacuum tightness is obtained by two sealing edges. This method of joining two sections is easy to handle and proved to be very reliable.

The electrodeposition of a copper layer of given thickness is not easy and can give rise to errors in the dimension 2b. Furthermore, a slight deformation of the intermediate copper disks cannot be excluded. Therefore, we had to foresee some means of tuning the end cells after assembly (cf. Section 4.2).

3.6 Brazing

The brazing of the different sections was done in several steps in a vacuum furnace with a vacuum better than 10⁻⁵ Torr. Before the final assembly all pieces were chemically degreased and cleaned by ultrasound. After each brazing a slow cooling down under vacuum of about 48 hours was allowed for. In a first step the coupler, with its two stainless-steel flanges and one deflector cell, is brazed by using brazing alloy containing Ag, Cu and Pa (Wesgo SCP 2), with a brazing temperature between 850°-860°C.

The same alloy is used for brazing the end cells on one copper deflector cell. Afterwards the coupler and end cells are leak tested.

It was necessary to braze a 1.50 m section in two steps because otherwise the weight of the waveguide (about 75 kg) would deform slightly the lowest copper cells during the brazing operation which was done in a vertical position. For these operations another brazing alloy (Wesgo SCP 1), was used with a brazing temperature of 810°C.

In Figs. 9b and 12 a detail of the ring-disk-ring assembly is given. The location and the quantity of brazing alloy (in wire form) was chosen so as to avoid as much as possible an influence on the geometrical tolerances and a penetration of brazing alloy to the internal surfaces of the guide. The polarizing rods were brazed to the disk by placing around the rods and on the upper disk surface a small ring of brazing alloy. No polarizing rods were placed in the coupler and end cells (cf. Fig. 9a). Before brazing, the azimuthal alignment of the polarization rods in each section was checked to better than ±1°.

After brazing the sections were kept as much as possible under rough vacuum.
Fig. 12 Microphotography of a "ring-disk-ring cut" showing the initial location of the brazing alloy and its distribution after brazing (cf. also Fig. 9b).
4. LOW POWER RF MEASUREMENTS

After brazing, the deflector was mounted and aligned on its supporting girder in order to perform the low power RF measurements. As they have to be done in air, the design frequency (2855.17 MHz at 25°C and under vacuum) has to be lowered by about 1 MHz.

4.1 Matching of couplers

This was done by using the RF pulse method described in detail elsewhere\(^{14,15}\). A passband of about 5 MHz was obtained where \(\text{SWR} < 1.1\). Around the design frequency we reached \(\text{SWR} < 1.04\) (Fig. 13).

![Diagram](attachment:image.png)

Fig. 13 Tuning of an input coupler shown on a Smith diagram.
- a) Initial values.
- b) After increase of the iris width \(w\) by 0.1 mm.
The figures stand for the frequencies used (4 corresponds to 2854 MHz, etc.).

4.2 Dephasing per cell

The dephasing per cell was measured by using the movable short method (cf. Fig. 14a). Prior to the measurement, the existence of a "dwell point", i.e. a position where the phase is practically independent of the exact short position, was established (cf. Fig. 14b).

The experimental layout is schematically shown in Fig. 15. The movable short is put near the input coupler of the first section and the sum vector of all internal reflections from the first cell and the coupler is cancelled by adjusting the variable impedance near the input coupler. This is done by comparing the phase of the direct and reverse wave for adjacent dwell points in a few cells and by cancelling the three-cell periodicity which eventually shows up. The phase values then are measured for all successive dwell points.
Fig. 14  a) Location of movable short (plunger) inside the disk-loaded waveguide.
b) Dephasing as a function of short position.

Any internal reflections show up in the plot obtained in this way (Fig. 16) by the occurrence of a new three-cell periodicity. In most of the sections it was not necessary to introduce any corrections because the deviation from the mean phase shift was smaller than ±1°. If this value was exceeded in a copper cell, we tuned it by a slight mechanical deformation in the deflection plane from outside. The errors in the end cells were generally bigger and special tuning stubs were foreseen*).

In Fig. 16 the final result for the deflector No. 2 is given. As can be seen, the deviation from the mean value of dephasing per cell remains everywhere below ±1°. With our measuring accuracy, this result is reproducible to better than 0.2°.

4.3 Over-all standing wave ratio

After the waveguide tuning, its over-all SWR as a function of frequency was checked with a normal CW power method. In Fig. 17 the result is given for two deflectors. As one can see, the passband where SWR is smaller than 1.1 extends over several MHz around the working

*) We also tuned some cells by introducing small metallic or ceramic balls. This method gave no trouble up to the highest RF power levels we achieved (20 MW peak, 2 kW mean power).
Fig. 15 Experimental layout for the measurement of dephasings per cell.
Fig. 16 Dephasings inside deflector No. 2 -- the different corrections of reflections are indicated.
Cell 41 - tuning stub; cell 62 - ceramic ball; cell 71 - steel ball; from cell No. 62 onwards, the dephasing is shown without correction (dotted line) and with correction (full line).
frequency. This result, which is only slightly changed after the mounting of two RF windows and a matched load at the output end of the structure, is of importance if the deflector has to be used at phase velocities $v_p \neq c$ (cf. Section 11).

4.4 Attenuation

We measured the attenuation of the 3.50 m structures including the two couplers (but without windows) in the passband of the structures.

By neglecting the attenuation in the two coupler input guides we find for our working frequency:

$$\alpha = 0.106 \pm 0.002 \text{ Np/m}.$$  

Within the measuring accuracy this value is the same for the three structures.

There is a slight dependence of $\alpha$ on frequency which is given by

$$\frac{\Delta \alpha}{\Delta f} = -0.003 \text{ Np/m/Hz}$$

and which corresponds to the variation of $\alpha$ with $v_p/c$ as one changes the frequency.

4.5 Phase pick-up, coupling and position

Between the first and the second sections an intermediate stainless-steel cell is located, which is fitted with a tuning stub and a vacuum-tight, adjustable RF pick-up for the phase comparison system.
The phase pick-up consists of an antenna whose penetration depth is adjustable from outside (Fig. 9d). It slides inside the copper tube which serves as a tuning stub. The coupling of the phase pick-up has to lie within two limits. The minimum height signal should be such that after a supplementary attenuation of $\sim 10$ dB in the phase comparison cable, there are at least $100$ mW available at the phase comparison bridge. The maximum signal is limited to some kW peak power because otherwise breakdowns would occur in the RF connectors (type N). By assuming a $20$ MW pulse inside the structure, a coupling between $40$ dB and $70$ dB can be accepted. We adjust the coupling to $\sim 50$ dB. Under these conditions the antenna tip is retracted by about $2$ mm inside the tuning stub and does not influence the tuning of the intermediate cell. The change in coupling with the penetration depth is $\sim 10$ dB/mm.

Ideally the position of a phase pick-up should be in the deflection centre of the deflector because the phase errors due to temperature or frequency errors inside the structure are cancelled\(^\text{i}\). The displacement of the deflection centre with respect to the geometrical centre\(^\text{ii}\) can easily be calculated and amounts to $11$ cm towards the power input end.

Because of the limited length of the first section ($1.49$ m), our phase pick-up is located at $24$ cm in front of the deflection centre. This displacement has a negligible effect on the phase errors (cf. Section 10).

5. HIGH POWER TESTS AND CONDITIONING

After the low power tests on the deflector, the RF windows (pill-box type ceramic windows) and the pumping ends were mounted. The structure was evacuated by an oil-diffusion pump followed by a liquid nitrogen trap in order to avoid contamination with organic materials. The whole structure with its pumping ends then was vacuum leak tested to a leak rate $< 10^{-10}$ cm$^3$/sec of helium. After this test the two $80$ l/sec titanium pumps were put into operation and the whole high vacuum system was heated up to $180^\circ$ during $24$ hours. No specially strong gas release was observed during this period showing that the excellent results of an outgassing at $800^\circ$C during the brazing process were preserved despite an exposure to atmospheric pressure for more than $24$ hours. After this, the vacuum measured at the titanium pumps was better than $10^{-7}$ Torr. The forming (conditioning) was done typically at $2$ pps, and with a pulse duration of $4$ $\mu$sec. During the forming we took care never to exceed a pressure of $10^{-6}$ Torr. Breakdowns could be observed through glass windows on both sides of the structure. Below $2$ MW some multipactor effect was observed, but it disappeared after some hours.

For the forming of the deflectors a fast protection system against breakdowns proved to be extremely useful. The principle is illustrated in Fig. 18. Whenever a breakdown at the entry window or inside the structure starts to be produced, a signal from a high power directional coupler, situated in front of the entry window, is obtained and sent to a PIN modulator, which within $0.2$ $\mu$sec cuts the RF input to the klystron amplifiers. The longest response time corresponds to a breakdown occurring near the output end of the deflector. As the filling time for our structures is $0.5$ $\mu$sec, the response time lies in any case below $1.2$ $\mu$sec. However, it was found out that a certain amount of outgassing (either produced by small breakdowns, ion bombardment or local heating up by RF power) is needed in order to
Fig. 18 Schematic layout of the fast protection system against break-
downs. The signal generated by the reflected power from a break-
down cuts the bias current of the PIN modulator within 0.2 µsec
and stops the trigger pulses for the PIN modulator.

improve the forming. Therefore, the breakdown security was manually reset after each "break-
down" as long as the vacuum remained below a pressure of $10^{-8}$ Torr. Small sparkings then
could be seen occurring on the iris roundings all along the deflector, but heavy breakdowns
leading to sparkings inside the pressurized waveguides in front of the entry windows were
completely avoided.

Typically it took 10 hours to form a structure from 0 to 20 MW at 4 µsec pulse duration.
This compares very favourably with the forming conditions in our old deflectors, where it
took about 50 hours to bring the power up to 12 MW.

Towards the end of the forming process the vacuum inside the structure reaches $10^{-8}$ Torr
and remains very near to this value during operation *).

*) During the forming of a 2 m prototype structure we did not yet have a fast security
system and some heavy breakdowns at 20 MW, 8 µsec pulse length, due presumably to a
vacuum deterioration, occurred on the first iris. After this, the structure no longer
accepted RF power. We opened it to air and machined away a layer of about 1/100 mm
from the rounding of the first disk. This rather crude treatment was completely
successful because after a short forming the structure again accepted 20 MW.
6. DEFLECTION TEST AND COMPARISON WITH COMPUTATIONS

A deflection test with the deflector No. 2 was achieved in the CERN RF separated beam¹⁸). The structure was installed at the last deflector station, where no intermediate particle optics was needed between the deflector and the counter recording the deflected particles. The distance between the deflection centre and the counter was 8.48 m ± 0.01 m. For this test the beam was tuned to 16 GeV protons with a relative momentum bite Δp/p = ±0.25%. The mean momentum is defined to better than 1%.

For the detection of particles, a horizontal finger counter of 2 mm × 50 mm cross-section (movable in the vertical plane with a setting precision < 0.25 mm) was used. As this test was done by using one fast ejected beam bunch of only 10 nsec duration from the CERN PS, a counter electronics using integration of the charge on the last dynode of a photomultiplier had to be used¹⁹).

The vertical angular beam acceptance, normally of 0.85 mrad at the deflection centre, was reduced to below 0.1 mrad in order to make the deflection test as independent as possible from the undeflected image shape⁶).

The RF power level in the structure was calibrated by a calorimetric method to better than ±5% and by taking into account the losses in the waveguide system between klystron and deflector. In a first step, the working frequency giving maximum deflection of 16 GeV protons was determined by measuring the height of the deflected image as a function of frequency and for a constant power level at the deflector. This was done over a frequency range of 3 MHz around the working frequency. By correcting for temperature and for the fact that 16 GeV/c protons were used, the frequency giving highest deflection for ν0 = c and T = 25°C is fo = 2854.96 MHz. (For the deflectors No. 1 and No. 3, fo = 2855.10 MHz.)

In Fig. 19 the result of a deflection test at an input power P0 = 17 MW, and for the frequency giving maximum deflection to the protons, is given. As our counting electronics has a non-linear response to particle intensity we were not able to apply the beam profile analysis of Appendix 2 of Ref. 2. In order to determine the deflection angle, we extrapolated the particle intensities of deflected and undeflected images to zero. For a maximum vertical deflection of the particles we get

$$Δ_ν = 11.7 \text{ mm} ± 0.15 \text{ mm}.$$

This corresponds to a transverse momentum

$$p_⊥ = \frac{11.7 \text{ mm}}{8.48 \text{ m}} \times 16 \text{ GeV/c} = 22.03 \text{ MeV/c}. $$

By taking into account the possible errors on the deflection centre position, on the power measurement, on Δν and on the uncertainty in the contribution of the coupler cells to the total deflection, we estimate for p⊥ an error of ±3.4%. This value can be compared with the results obtained from computer calculations and from model measurements (cf. Section 2 and Table 3).

As has already been mentioned, one gets a very reliable calculation for R/Q (R: shunt impedance, Q: quality factor) from the computer. On the contrary, the values for the normalized group velocity are slightly too high and we adopt the value derived from model measurements.
Fig. 19 Deflection test: image of deflected and undeflected particles. Curves are obtained with 16 GeV/c protons at 8.48 m behind the deflection centre. The intensity scale is not linear.

The value of the attenuation constant can be computed from the losses in the structure, but there is some uncertainty in the value of surface impedance of copper. (The theoretical value for pure copper is $1.394 \times 10^{-2} \, \Omega$; for annealed copper one finds in the literature values around $1.428 \times 10^{-2} \, \Omega$; a direct measurement of $\alpha$ in our old structure gave $1.82 \times 10^{-2} \, \Omega$.) Therefore we adopt for $\alpha$ the value measured directly on a 3.5 m structure. For our working frequency we get $\alpha = 0.106 \, \text{Np/m}$. This corresponds to $r_s = 1.66 \times 10^{-2} \, \Omega$.

The slight differences found between the design frequency and the working frequency ($\sim 200 \, \text{kHz}$) can be neglected as well as the uncertainty in deflector length $\ell$ *

From $R/Q$, $v_g/c$, $\alpha$, $\lambda_s$ and $\ell$ other parameters can be derived (cf. Table 3). We obtain for the ratio of the experimental deflection and the calculated value

*) For $\ell$ we adopt a result obtained by Hahn and Halama* stating that the deflection in a coupler cell is about 50% of the deflection obtained in a normal cell. In our case this gives $\ell = 3.5 \, \text{m}$.
a) General layout
A) iris-loaded waveguide
B) End cell (supported by alignment screws)
C) Alignment screws
D) Water jacket
E) Thermal insulation (3 cm expanded polystyrene Frigeric H 25)
F) Intermediate cell with vacuum-tight phase pick-up
G) Hole for temperature measurement
H) Coupler
I) Ceramic RF window
J) RF load (pressurized dry load)
K) RF pick-up
L) Supporting frame with alignment screws
M) Adjustable support for the couplers
N) Double girder
O) Horizontal alignment system
P) Supporting foot
Q) Vertical alignment screws
R) Lifting device
S) Vacuum system; for details cf. Fig. 20b.
T) MD 5/300 titanium pump
U) Particle counter
V) Flange for connection with the beam tube.

b) Details of vacuum system
A) Pumping manifold
B) Roughing valve
C) "Conflat" vacuum flange
D) Copper gasket
E) Mylar window (12 μm thick)
F) Viton O-ring
G) Vacuum valve for protection of mylar window
H) Pneumatic valve
I) Flange
J) Thermocouple of protection system for the mylar window
K) Flange
L) Coupler
M) SLC type vacuum-tight RF flanges
N) iris-loaded waveguide
O) Water jacket
P) Supporting ring
Q) Alignment screw

b) Front view of one deflector (as output coupler)
A) Coupler
B) RF window
C) RF pick-up
D) RF load
E) Adjustable support for the coupler
F) Supporting frame
G) Alignment screws (to align the deflector on a horizontal and vertical plane on the girder)
H) Double girder
I) Horizontal alignment system
J) Vertical alignment system
K) Supporting foot
L) Target for aligning the deflector in the beam line
M) Lifting device

Fig. 20: General layout of one deflector
\[
\frac{\langle p_z \rangle_{\text{ex}}}{\langle p_z \rangle_{\text{ch}}} = 0.980 \pm 0.034 .
\]

From this one concludes that the discrepancy between theory and experiment is 3.4\% for \( p_z C, \sqrt{Z}, k \ell \) and about 4.6\% for \( R/Q \).

Finally we can compare the value of the transverse momentum for the maximum available power, \( P_0 = 20 \text{ MW} \), with the one obtained under normal operation conditions in the old deflectors (12.3 MeV for \( P_0 = 10 \text{ MW} \)). One gets:

\[
\frac{\langle p_z \rangle_{\text{new}}}{\langle p_z \rangle_{\text{old}}} = \frac{24 \text{ MeV}}{12.3 \text{ MeV}} = 1.95 ,
\]

thus nearly a factor of two.

7. MECHANICAL LAYOUT

In Figs. 20 and 21 a general view of the mechanical layout and the alignment system of a deflector is given.

The deflector with its vacuum system is supported by six supporting frames and alignment screws on a double girder. The coupler RF flanges are blocked on a special adjustable frame so that any mechanical effort due to the waveguide system between klystron and coupler is taken over by this frame and the girder.

Fig. 21 Photograph of a deflector with its high vacuum system and its supporting foot. Water jacket not yet mounted.
The vacuum systems are added to both ends and aligned. High vacuum bellows here also avoid any mechanical forces to be taken over by the couplers. Behind the vacuum systems, an electronic counter system is mounted which is used to focus the particle beam at the deflection centre once the deflector is installed in the beam line. Finally, the water jacket and the thermal insulation are mounted.

The structure has a weight of 47 kg/m. By adding to this the weight of the water jacket, the vacuum systems, the counter systems and the double girder, one arrives at a total weight of 650 kg, which is distributed fairly uniformly over the total length of the girder (5.70 m). The rigidity of the double girder and the position of its supporting points on the supporting foot have been chosen to guarantee a deformation of less than \( \pm 0.1 \text{ mm} \) for the structure itself under normal lifting and handling conditions.

The two coupler supporting frames are equipped with precisely machined supports for alignment targets, whose centres are situated horizontally in the middle plane of the structure and vertically at 370 \( \pm 0.1 \text{ mm} \) off axis (Fig. 20c). Together with a horizontal alignment system between girder and supporting foot and with the three vertical alignment screws of the foot, they are used to align the deflector in the beam line. This alignment can be done with a precision in the vertical plane of better than 0.3 mm, in the horizontal plane of 0.1 mm and with an angular error below 0.01 mrads.

The longitudinal alignment is much less critical and can anyway not be defined with higher precision than the position of the deflection centre (some mm).

8. VACUUM PROBLEMS

In order to avoid breakdowns in a deflector at the high RF power levels needed, the structures should be kept under a high and clean vacuum. Enough pumping speed should be available so that degassing products can be pumped away quickly.

The layout of the vacuum system is shown in Fig. 20a, b. Each end of the structure is equipped with a pumping manifold connected to an 80 l/sec cold cathode ion pump. Pumping occurs through the RF choke of the couplers and through the central hole of the disks.

The high vacuum inside the structure (\( \approx 10^{-8} \text{ Torr} \)) is isolated from the entry waveguides and the output RF load which are pressurized to 2 atm of freon by using ceramic RF windows with SLAC type vacuum-tight RF flanges.

The isolation from the rough vacuum inside the electronic counter system and the beam tube (\( \approx 10^{-2} \text{ Torr} \)) is a more delicate problem. Only very small amounts of material can be tolerated in the beam line, because otherwise Coulomb scattering will blow up the beam of unwanted particles and increase the beam contamination behind the beam stopper. We estimated that mylar windows of 12 \( \mu \text{m} \) thickness would be sufficiently thin. As they withstand repeated application of 1 atm pressure differences one does not need a fast protection system for the windows.

When the beam tube end of the vacuum system is opened to air the mylar windows are protected by a valve. Its plate has been put as near as possible to the windows, so that a negligible volume between window and plate remains once the plate is closed. Therefore, we did not foresee a pumping or by-pass system for this intermediate volume.
The protection valve is actioned by a protection system which uses a thermocouple to sense the vacuum in the beam line. Whenever the pressure rises above a preset level (≈ 5 × 10⁻² Torr) the valve is closed.

Despite the fact that the mylar window withstands 1 atm of pressure it cannot be exposed continuously to atmosphere, because under these conditions the leak rate across the window is so high that the titanium pumps cannot be kept in operation.

On each manifold an all-metallic valve can be used to connect the high vacuum system to a roughing system consisting of an 8 l/h roughing pump and a 120 l/sec oil diffusion pump followed by a liquid nitrogen trap. With this system it takes some hours before the titanium pumps can be switched on. All high vacuum flanges are of the Varian ConFlat type; for the roughing system Leybold NW flanges are used.

Except for the unavoidable mylar windows and the Viton O-ring which ensures their vacuum tightness, the whole high vacuum system contains no organic materials and can be heated up to several hundred °C.

From the geometry given in Fig. 20 one obtains for the pumping speed \( U \) inside the coupler and the first iris, where the danger of breakdown is highest, \( U \approx 32 \text{ l/sec} \), and in the middle of the structure \( U = 2 \times 5.5 \text{ l/sec} \).

The final vacuum will depend on the degassing rate of the metal surfaces (about 3.6 m² of copper and stainless steel) and the leak rate through the mylar windows against a rough vacuum of 10⁻² Torr.

It is assumed that the inner surface of the waveguide after a heating up to 800°C and the stainless-steel surfaces after a careful degreasing have an outgassing rate for hydrocarbons and \( \text{H}_2 \) below 10⁻¹¹ Torr l/sec cm² [21].

Furthermore we apply an "in situ" heating of the structure, the manifolds and the pumps up to 180°C, which should bring down the \( \text{H}_2\text{O} \) outgassing also well below 10⁻¹¹ Torr l/sec.

From these figures one can determine that the final pressure in the middle of the structure should lie below 2 × 10⁻⁸ Torr and at the pumps below 5 × 10⁻⁹ Torr. This is confirmed by the vacuum which is obtained after conditioning of the structure, and which lies below 6 × 10⁻³ Torr at the titanium pumps. We note that this value is derived from a measurement of the pump current.

9. COOLING PROBLEMS

During operation a deflector should be kept at constant and uniform temperature to better than 1°C (cf. Section 10). We adopted the solution of two water jackets, made of thin copper sheet, the main characteristics of which are shown in Fig. 20a. The water enters the two jackets at a distance \( l_1 = 1.40 \text{ m} \) from the power input end, leaves at the coupler end and cools the RF windows before its return to the pumping system. Around the water jacket a thermal insulation of 3 cm expanded polystyrene is installed. Water is supplied by a thermostat which gives a water flow of ≈ 5 l/min in each loop and is stabilized to better than ±0.1°C. The water is continuously de-ionized in order to reduce electrolytical corrosion of the copper parts. A cooling loop in the thermostat, using water from the normal water supply, takes away the heat produced in the deflector.
We now estimate the temperature distributions along the deflector under typical working conditions. Let

\[ P(z) = P_s e^{-\alpha z} \]

be the mean RF power per unit length at the coordinates \( z, z + dz \) (in W/cm).

\( P_s \) be the input power (in W/cm).

\( \alpha \) be the voltage attenuation constant of the structure (in Np/m).

\( K \) be the temperature exchange coefficient between the water and the copper surface of the guide (in W/°C cm²).

\( S \) be the cooled surface per unit length (in cm²/cm).

\( T \) be the temperature of the copper between \( z, z + dz \).

\( T_w(z) \) be the temperature of the water between \( z, z + dz \).

\( D \) be the water flow [in (ℓ/min) (cal/g °C) = 70 W/°C].

Two equations connecting these quantities can be established. The power flow gives rise to a temperature gradient between water and copper

\[ P(z) dz = KS \ dx (T - T_w) \]  

(7)

The cooling water heats up gradually, thus

\[ D \ dx = KS \ dz (T - T_w) \]  

(8)

Here we neglect external heat losses of the system. From Eqs. (7) and (8) one gets

\[ T_w = \int_0^z \frac{P(z) dz}{L} \]  

(9)

\[ T = \frac{P(z)}{KS} + T_w \]  

(10)

Equation (9) has to be integrated for the two cooling loops (cf. Fig. 22). In the first half, where water flow and power flow are opposite, one gets

\[ T(z) = P_0 e^{-2\alpha_1} \left[ \frac{e^{-2az}}{KS} + \frac{1}{2\alpha D} \left( e^{2az} - 1 \right) \right] \]  

(11)

In the second half the integration gives,

\[ T(z) = P_0 e^{-2\alpha_1} \left[ \frac{e^{-2az}}{KS} + \frac{1}{2\alpha D} \left( 1 - e^{2az} \right) \right] \]  

(12)

By applying typical working conditions for the RF power in use at CERN (20 MW, 4 usec pulse length, 3 pps) and the cooling loops (5 ℓ/min in each loop), the temperature distributions shown in Fig. 22 are obtained from formulae (11) and (12). Here we use values for \( K \) obtained from a paper by Grauleau et al. (K = 0.2 W/°C cm²). As one can see, the temperature inhomogeneities remain below a few tenths of a degree and so does the mean increase in
Fig. 22 Temperature distribution inside a waveguide with a double cooling loop and a single loop (dotted line).

copper temperature. We also have computed the temperature distribution for a single water loop with the water input near the input coupler. The temperature inhomogeneity is, of course, somewhat higher but would still be tolerable. As one can see, the temperature inhomogeneity is somewhat smaller if the water flow is parallel to the power flow. However, the differences are so small that we decided to use the more simple layout where the water input for both jackets is common.

From the tolerance considerations below it turns out that in all cases the temperature inhomogeneities have a negligible effect on the deflection of particles.

The ohmic losses of the RF fields inside the structure have been calculated and are found to be distributed in the following way: outer wall 25%; disk face 59%; disk rounding 16%; this shows that most of the dissipated heat has to be evacuated through the disks giving rise to radial temperature gradients inside the structures. We measured these gradients in a short brazed disk-loaded waveguide model surrounded by a water jacket. Power at a given rate can be deposited inside the model by electrical d.c. heating of wires stretched along the axis. At power levels corresponding to 20 MW peak power, 8 μsec pulse length and 10 pps, and a flow rate of 5 l/sec, gradients of up to 0.5° were measured over the disk depth. Gradients of this order should again not affect the deflection of particles.

A temperature measurement point at 22 mm depth inside a disk is foreseen near the deflection centre of each deflector (Fig. 20a). It is used in conjunction with a temperature
measuring and security system which switches off the RF power for temperature changes exceeding ±0.2°C around a preset value.

10. TOLERANCES

If one reviews all the factors which can affect the separation of particles in an RF separator, two can be found which are linked to the deflectors.

The first is related to the position of the phase pick-up. If it is not located near the deflection centre, frequency and temperature changes can affect the relative phasing of two deflectors. In our case the phase pick-up is located at 24 cm from the deflection centre and the phase error is negligible for all practical frequency and temperature changes, because a frequency change of 1.85 MHz would produce a phasing error of only 2°.

The second factor affects the amplitude of particle deflection. If the phase velocity $v_\phi$ of the deflection field is different from the particle velocity $v$, a phase slip $\tau_e$ occurs over the deflector length between wave and particle which reduces the deflection approximately by the factor

$$\frac{\sin \frac{\tau_e}{2}}{\tau_e/2}.$$  

(13)

By assuming that this lowering should lie below say 2%, a value of $\tau_e < \pm 40^\circ$ could be tolerated.

A change of $\tau_e$ is related to a frequency change by

$$\Delta \tau_e = - 2\pi \frac{\lambda}{\lambda} \left( \frac{c}{V_G} - 1 \right) \frac{\Delta f}{f}.$$  

(14)

where $v_G$ is the group velocity of the deflecting mode for $v_\phi = c$, $\lambda$ the length of the deflector and $\lambda$ the wavelength of the deflection field.

For our case we have

$$c/v_G = - 42.9, \quad \lambda = 3.5 m, \quad \lambda = 0.105 m, \quad f = 2855 MHz$$

thus

$$\Delta \tau_e = 184.5 \Delta f.$$  

(15)

and from this one obtains that the frequency changes corresponding to $\tau_e = \pm 40^\circ$ are $\Delta f = \pm 220$ kHz. Again, a frequency stability of this order can easily be achieved (here we note that our drive system has a frequency stability of some kHz).

By using the temperature coefficient of the deflector, $K = -49$ kHz/°C, one sees that the corresponding temperature changes could be $\Delta T < \pm 4.5$°C. Again there is no problem to achieve temperature stabilities (or homogeneities) well below this value.

11. CHANGES IN PHASE VELOCITY

There are experimental conditions where one is interested in a systematic change in frequency or temperature in order to change the phase velocity $v_\phi$ of the deflecting waves
Fig. 23 Dephasing between a deflecting field with $v_\phi = c$ and different particles over the deflector length $\ell = 3.5 \text{ m}$ as a function of momentum. The frequency changes necessary for obtaining $v_\phi = v$ are also plotted [cf. Eq. (15)].

and adjust it to the velocity of the wanted particles so that the deflection becomes a maximum.$^{23}$

For ultra-relativistic particles one normally can put $v_\phi = c$ and adjust the frequency so that $v_\phi = c$. But for heavy particles (e.g. deuterons) or momenta towards the lower limit of separation, $v_\phi$ can differ already so much from $c$ that a substantial phase slip $\tau_\phi$ over the deflector length can occur.
From relativistic particle dynamics one obtains for the dephasing of a particle of momentum \( p \) and rest energy \( W_0 \), with respect to a wave with \( v_\phi = c \) and over a length \( l \),

\[
\tau_\ell = \frac{2 \pi \ell}{\lambda} \left( \sqrt{1 + \frac{W_0^2}{(pc)^2}} - 1 \right).
\]

By equating this with Eq. (14) one can calculate the frequency shift \( \Delta f \) which is needed for obtaining \( v_p = v_\phi \).

The result is plotted in Fig. 23 for different particles and momenta. Obviously the changes in \( \tau_\ell \) can be so high that a lowering of \( v_\phi \) is well justified. From the dispersion curve (Fig. 5) one concludes that \( \Delta f / \Delta v_\phi \) must be positive, thus lowering \( v_\phi \) means lowering the frequency.

One of the merits of the new deflectors as compared to the old ones is that their large frequency passband makes such changes possible without a risk of breakdown inside the deflectors.

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