The New Three Cavity RF-Separator of CERN

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Abstract

The principle of operation of a three cavity RF separator using linearly polarised deflection fields is discussed. The advantages of two contaminent rejection over a two cavity system are indicated and separation curves for kaons, pions and antiprotons are given.

The new CERN separator can separate kaons up to 16 GeV/c, antiprotons and pions up to the highest momenta that are possible with the CERN PS.

A short description of the general layout, the main parameters and some technical aspects are given. Furthermore, the tuning procedure and experimental results of a 12 GeV/c antiproton run are described.

The extension of this type of separator to higher energies is discussed.

This paper will be presented by H. Lengeler.

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Introduction

In June 1967 the new three-cavity RF Separator of CERN successfully completed it's first test and produced a beam of antiprotons at 12 GeV/c. 104,000 pictures were taken in the 2 m CERN Hydrogen Bubble Chamber.

The separator was run in conjunction with a fast-ejection system(1) and in a modified version of the RF separated beam of CERN(2).

Already in an early stage of the work on RF separators at CERN ideas on a three-cavity separator using linearly polarized deflection fields were put forward by Schnell(3). The layout of the two-cavity separator realized by B.W. Montague and his group(4,5) was foreseen to be extended at a later stage to a three-cavity separator.

The new layout overcomes a well known drawback of the two-cavity system, namely that the separation of one kind of particles from two other kinds is only possible in some very narrow momentum regions. This limitation is most serious for antiprotons where separation practically is only possible around 7.3 GeV/c. The new separator allows separation of pions, kaons and antiprotons over a nearly continuous momentum region from 7 to 16 GeV/c. It is of course possible to use it also as a two cavity separator allowing e.g. π^+ - separation well above 20 GeV/c.

1. Principle of operation and separation momenta

The general layout of a three-cavity separator is given in Fig. 1. A continuous momentum analysed beam of particles with different rest-mass passes successively through three linear polarised deflecting fields RF1, RF2, RF3. The relative phase of the RF fields is kept constant and can be adjusted to any value. The centre of the deflectors is imaged to the centre of the next one by a lens system having, in the separation plane, a transfer matrix

$$\begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$$

The overall deflecting force on the particles is dependent on their time of flight and thus on their rest-mass. One tries to make the final deflection of unwanted particles zero and stop them with a centrally placed Beam Stopper (B.S.) behind RF3. If the deflection of wanted particles is different from zero, they partly pass the Beam Stopper and thereby spatial separation is achieved.

We introduce the following subscripts and parameters to characterise this system :

- a, b, w : subscripts characterising the two kinds of unwanted particles resp. the wanted particles.
- 1, 2, 3 : subscripts characterising the deflection fields (or deflectors).
- A_i : amplitude of RF deflection field in i^{th} deflector.
- D_i^w, D_i^a, D_i^b: deflection amplitude of wanted (unwanted) particles behind i^{th} deflector.
- L_{12} : distance between RF1 and RF2.
- L_{13} : distance between RF1 and RF3.
- f : frequency of deflection fields.
- φ_{12}, φ_{13}: dephasing of deflection fields.

In the system given in Fig. 1 one has four parameters to play with: the dephasings φ_{12}, φ_{13} and the ratio of amplitudes A_1, A_2, A_3. It can be shown(3) that by a proper choice of these four parameters the final deflection of two kinds of unwanted particles can always be made zero and this independently of their entry phases in the deflecting fields.

The choice of parameters can be most conveniently illustrated by using a (rotating) vector diagram (Fig. 2). Amplitude and phase of the 3 deflecting fields must be adjusted in such a way that their vector sum is zero for particles a and b. There is obviously only one way of realizing this cancellation, i.e.,by symmetrizing their deflection in the way shown in Fig. 2. One can show that the deflection $\vec{D}_3^w$ then is fixed and generally different from zero, but modulated with the frequency f.

The choice of L_{12}, L_{13} is not very critical and has been influenced by two considerations. As a three-cavity separator can easily be turned into a two-cavity separator with three possible intercavity distances L_{12}, L_{23} and L_{13}, we tried to make L_{12} different from L_{23} in order to get more possibilities for separation. Unfortunately due to the strength of the quadrupoles we need at least 22 m for the intercavity optics. So we chose L_{12} = 22m, L_{23} = 28m.

We have computed the choice of parameters giving $D_3^a = D_3^b \equiv 0$ for a large momentum range and for pions, kaons and antiprotons. In Fig. 3 the final deflection amplitudes of wanted particles D_3^w are given for L_{12} = 22m, L_{23} = 28m and the frequency f = 2855.17 MHz. It is convenient to normalize D_3^w by one of the deflection amplitudes A_1, A_2 or A_3, whichever is highest (A_{max})

Taking as a somewhat arbitrary condition for separation that

$$D_3^W \geq A_{max}$$

one concludes from Fig. 3 that separation is possible in the following momentum range

for π^{+}	:	~ 7.3 - 16 GeV/c
for $K^{\pm}$	:	~ 7.3 - 16 GeV/c
for $\bar{p}$	:	~ 7.3 - 19 GeV/c

The lower limit of separation is given by the beam anisochronism due to the finite momentum bite and by the muon contamination. It lies between 7 and 8 GeV/c.

2. Technical layout

No major changes in the technical layout of the CERN two-cavity separator[5] have been necessary except for the addition of a third deflection station and a second phase comparison circuit[6].

It was found experimentally that the phase comparison circuits were remarkably stable without temperature stabilization of the phase cables involved.

During the 120 hours antiproton production run, the phase stability was controlled periodically by counting the number of particles passing the beam stopper (c.f. below) and turned out to be better than ± 2°. Only a very small temperature effect day-night was found.

The RF drive system feeding the 20 MW power amplifiers is the same as for the two-cavity separator[7]. We note the addition of a PIN modulator behind the common RF Generator (200 mW output). It allows a very precise setting of the RF pulse length in the three deflector stations (with rise and fall times of 0.1 μsec instead of ~ 1 μsec as before) and increases the precision of the power measurements.

Although the modulator for the power klystrons deliver HT pulses of 8 μsec duration, we use drive pulses of only 4 μsec duration. This eases the problem of electrical breakdown in the deflectors and is largely enough to accommodate for the maximum duration of the fast ejected CPS beam burst (2 μsec).

During the production run we did not exceed 10 MW for the RF power in the deflectors in order to keep the number of breakdowns down to a tolerable level (~1 breakdown/hour).

The deflectors are temperature-stabilized to about 0.1°C. As for a given temperature their electrical properties are slightly different, they are operated at different temperatures (22°C, 25°C, 26.3°C). Under normal conditions the vacuum inside the deflectors is typically of the order of $7\cdot10^{-8}$ Torr with very small degassings occurring at each RF pulse.

In Table I some important separator parameters are listed.

TABLE I

Some separator and deflector parameters

Operating frequency		2855.17 MHz (λ_G = 10.5 cm)
Cavity length	RF1, RF2	3 m (114 cells)
	RF3	2 m (76 cells)
Group velocity v_g/c		0.0186
Phase shift/cell		π/2
Q-value		~ 9200
Cavity spacing		22 m, 28 m
Duration of RF pulse		4 μsec.

The new RF separated beam (U4-beam) has been derived from the old U3-beam[2] by changing the intercavity optics. Instead of a double doublet imaging over 50 m the centre of the first deflector in the centre of the second one, two systems have been used: a triplet imaging RF1 in RF2 (22 m) and a double doublet imaging RF2 in RF3 (28 m). All other parts of the beam remained unchanged.

Some beam parameters are listed in Table II.

TABLE II

Beam parameters for the U4-beam

Target : copper		2 x 1 x 150 mm³
Production angle		0°
Collection angle: horizontal		± 7.5 mrad
vertical		± 5 mrad
Momentum resolution		± 0.25 %
maximum momentum: separated		15 GeV/c
unseparated		20 GeV/c
Total length		165.5 m
Deflector spacings		22 m, 28 m
Magnifications from target to deflectors :	horizontal	(3.69)
	vertical	(5.68)
Undeflected image size at Beam Stopper (without chromatic aberrations)		15.5 mm

3. Experimental Results

3.1. Tuning procedure

Before starting the first experiment on 12 GeV/c antiprotons we worked out a detailed tuning procedure for the beam[8] and the separator[9]. After the tuning of the beam the vertical acceptance was reduced to 1/5 of the full acceptance (± 5 mrad) and the beam stopper opened completely. The undeflected image was scanned with a vertical finger counter behind the beam stopper (Fig. 4a).

In a first step the phase settings corresponding to equal dephasings of the deflection fields with respect to the pions were determined. They were found by equalizing the deflection amplitudes of two cavities and changing the phasing until the image size behind the beam stopper was a minimum. These settings were taken as reference points for our phase comparison system.

In a second step the power levels in the three deflectors were set to the values giving deflection amplitudes in the ratio $A_1 : A_2 : A_3$ = 0.661 : 1 : 0.53, the power in RF2 being 10 MW.

This was checked by measuring the half width of the deflected images (Fig. 4b, c, d). An agreement within 5% was considered to be good enough and the power levels were held constant throughout the following work. The dephasings φ_{12}, φ_{13} were set by means of calibrated phase shifters to the computed values. By applying all three deflection fields and slightly changing the dephasings φ_{12}, φ_{13} the width of the pion image was made roughly equal to the width of the undeflected particle image.

In a third step we changed the polarity of the beam to positive particles (with same momentum) and checked the deflection of the protons. An agreement within 2% of the computed value was found (Fig. 4e).

In a last step we changed again the polarity of the beam to negative particles and opened the vertical acceptance of the beam to 1/2 of the maximum. The beam stopper thickness was adjusted to be equal to the undeflected particle image width (8.75 mm) and the final adjustment of the phasings φ_{12}, φ_{13} made by looking at minimum particle transmission with a scintillation counter behind the second momentum analyser. In Fig. 5 some phase curves obtained this way are given. By doing - with and without deflection fields - a beam stopper thickness scan, we showed that within counting statistics the deflected and undeflected image widths were equal. No correction for the deflection amplitudes was considered to be necessary.

Finally the beam stopper thickness was increased to 2.5 times the undeflected image width (22 mm) in order to bring the π^- contamination down to some %. With a $\bar{p}$ image width of 35 mm at the beam stopper, the beam stopper losses are estimated to be 70%

All countings were done with scintillation counters[10] by integration of the charge on the last dynode of a photomultiplier because the duration of the beam bursts is only 20 x 10 nsec.

3.2. Results

During the production run of antiprotons at 12 GeV/c, we worked with the full horizontal acceptance but only with 50% of the vertical acceptance in order to reduce the contamination of the beam with muons and pions. The relative momentum bite was chosen to be ± 0.25%. The mean intensity of the CPS was $7\cdot10^{11}$ protons/burst and was fully available for our target. The fast ejection system extracted 20 bunches in 2 μsec with an efficiency of 55%.

Unfortunately the primary energy could not be raised above 20.6 GeV/c because of the ejection system. This gave a very unfavourable production ratio for antiprotons and pions; at the target we had $\pi^-/\bar{p} = 1450$ and the $\bar{p}$ intensity at the bubble chamber was correspondingly low. From preliminary scans of 6-prong, 8-prong events in the chamber, we obtained the following results for beam-like particles:

	measured	estimated
Number of $\bar{p}$ / photo.	2	4.5
π^-, K^- contamination	5% ± 5%	-
$\mu^-/\bar{p}$ ratio	3	1.6

Combining the production ratio of π^- and $\bar{p}$ with the beam stopper losses and the π^- contamination given above, we conclude that about 100 000 π^- had to be rejected for one $\bar{p}$ at the bubble chamber. No explanation has yet been found for the high muon contamination in the beam.

Finally we mention that another production run with K^+ at 8.25 GeV/c has been done using only two cavities but the intermediate optics of the three cavity system. This run can be compared with a similar one done in 1966 with the two cavity separator. No significant differences in intensity and contamination have been found except for the muon contamination which in the last run was 2 times higher. This is due to the additional focus in the intercavity optics.

4. RF Separation at higher energies

We are currently working on the detailed layout of a three cavity RF Separator for the ~~new~~ 70 GeV Accelerator at the Institute for High Energy Physics at Serpukhov USSR. It is foreseen to separate kaons up to 36 GeV/c. Some parameters of the separator and the beam[11] are listed in Table III.

TABLE III

Separator and beam characteristics for 16, 36 and 100 GeV/c separation

	16 GeV/c CERN	36 GeV/c[11] (Serpukhov)	100 GeV/c[12] (300 GeV-project)
Separation range / GeV/c	7-16	17-36	55-100
Wavelength / cm	10.5	10.5	3
Total intercavity distance / m	50	265	610
Deflector length / m	3	5	4
Peak transverse momentum / MeV/c	15	33	30
Target size / mm^2	2 x 1	2 x 1	1 x 1
Collection angles/mrad: horiz.	± 7.5	± 5.8	± 2
vert.	± 5	± 4.4	± 1.5
Momentum bite	± 25 MeV/c	± 30 MeV/c	± 100 MeV/c
Total beam length / m	165.5	480	740

In conjunction with the utilization studies for the future 300 GeV European Accelerator, studies of RF separated beams and separators up to 150 GeV/c have been made[12,13]. The extension of the three cavity separator to those energies seems very promising for combined bubble chamber and counter beams although for low intensity, high purity bubble chamber beams an alternative approach using primary beam modulation could be more interesting. From these studies, the necessity for developing super-conducting cavities and beam transport elements clearly arises. Some parameters for a 100 GeV/c separator are listed in Table III.

One of the most difficult problems seems to be the phasing of cavities over the long inter-cavity distances needed. We are thinking on a system that checks the beam-width in front of the Beam Stopper and uses this information to recalibrate periodically the dephsing between deflectors.

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FIG. 1

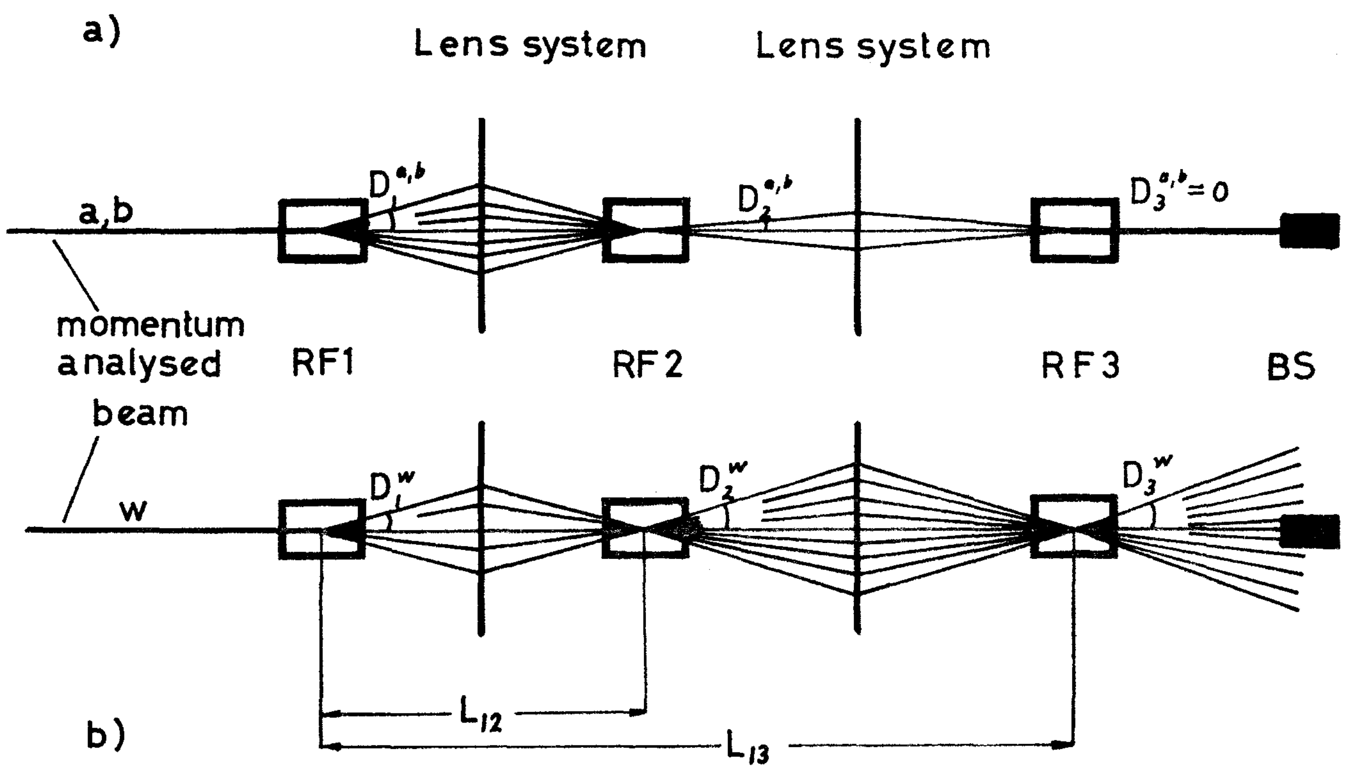

Fig. 1. General layout of a three-cavity RF Separator.
a) unwanted particles (a,b)
b) wanted particles (w).

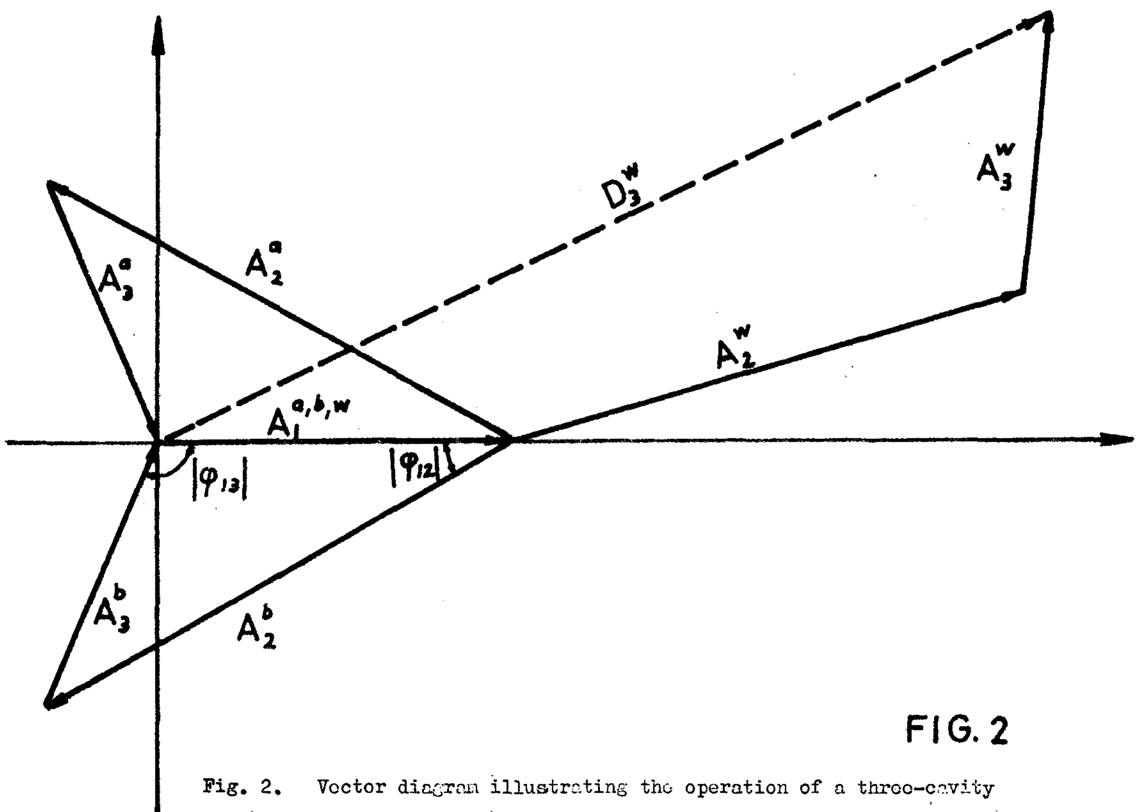

FIG. 2

Fig. 2. Vector diagram illustrating the operation of a three-cavity separator. The deflection vectors correspond to the separation of 12 GeV/c antiprotons ($a : \pi^-$; $b : K^-$; $w : \bar{p}$)
$A_1 = 0.661$, $A_2 = 1$, $A_3 = 0.534$, $D_3^W = 1.85$, $\varphi_{12} = -29.5^\circ$, $\varphi_{13} = -67.0^\circ$.

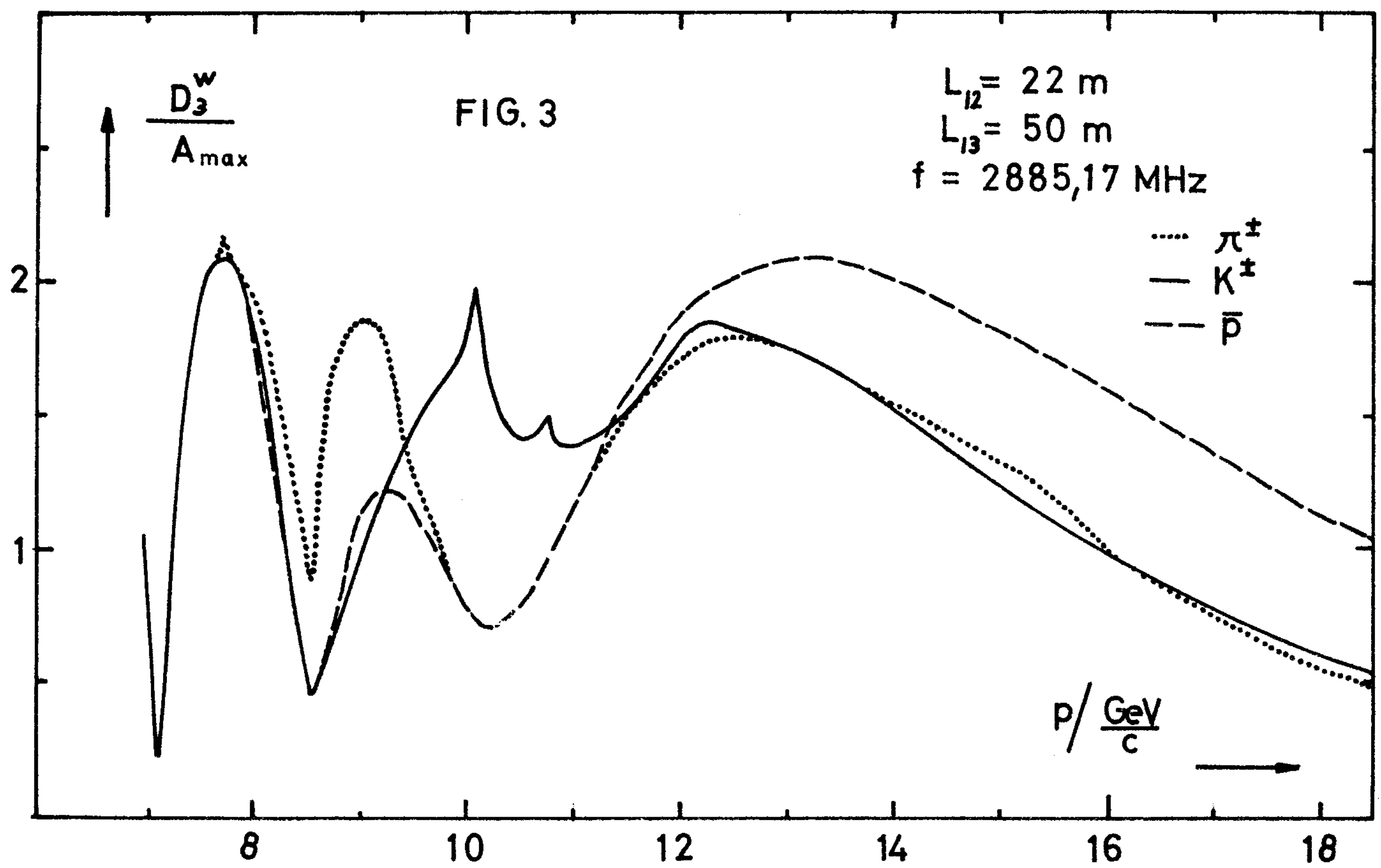

Fig. 3. Normalized final deflection amplitude for wanted particles as a function of particle momentum (separation curves for three-cavity separator) $A_{max} = Max\ (A_1, A_2, A_3)$.

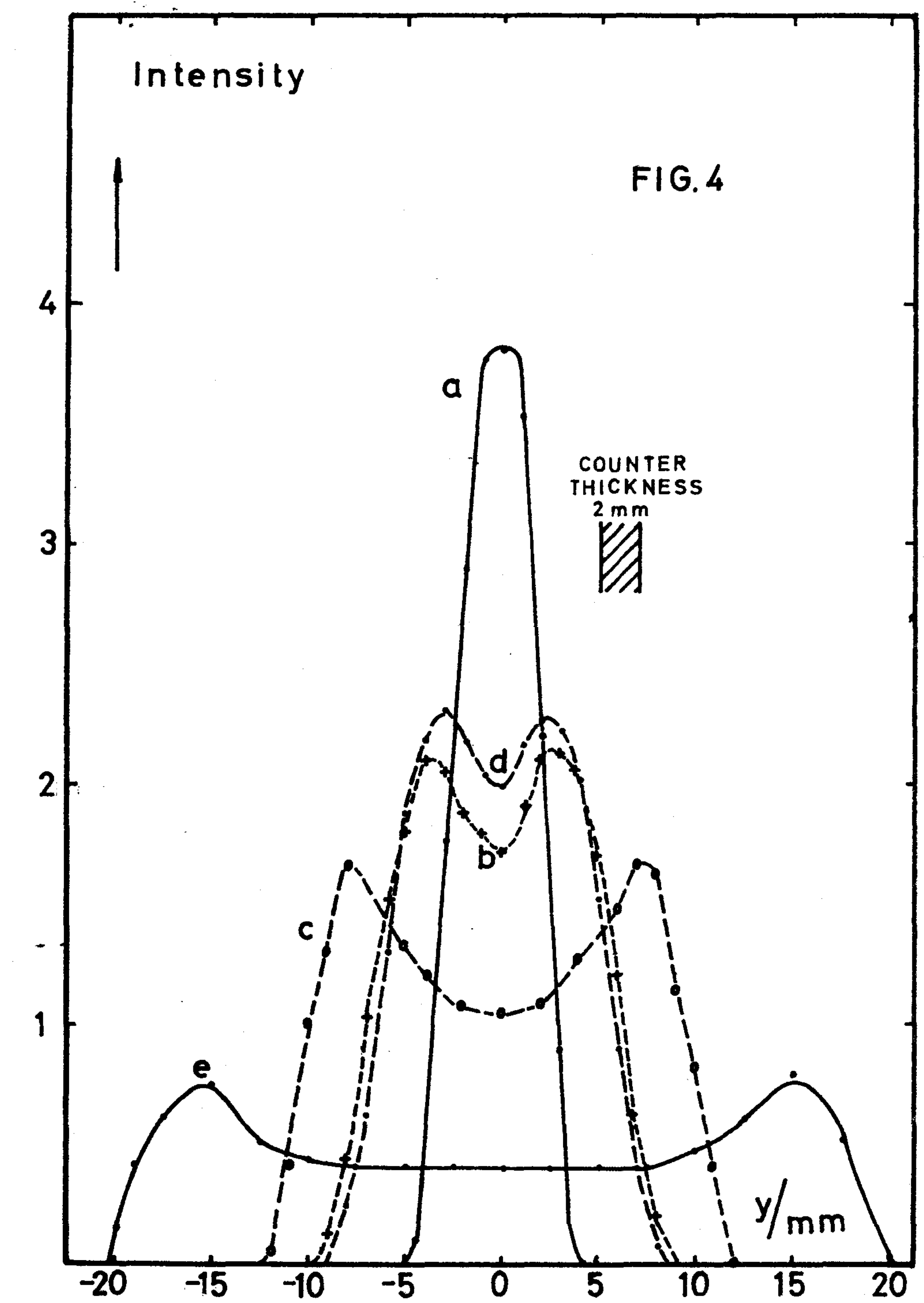

Fig. 4. Experimental beam profiles. The curves are measured with a $2 \times 50\ mm^2$ (time integrating) finger counter at 1.68 m behind the beam stopper (and at 9.38 m from the deflection centre of RF3).

y : vertical counter displacement;

curves are arbitrarily normalized

a) undeflected beam (12 GeV/c negative particles)

b)c)d) deflected with RF1, RF2, RF3 resp. (12 GeV/c negative particles)

e) deflected with all three cavities (12 GeV/c positive particles) (maximum value of deflection during the run = 1.7 mrad)

Vertical angular acceptance reduced to 1/5 of maximum value; beam stopper completely opened.

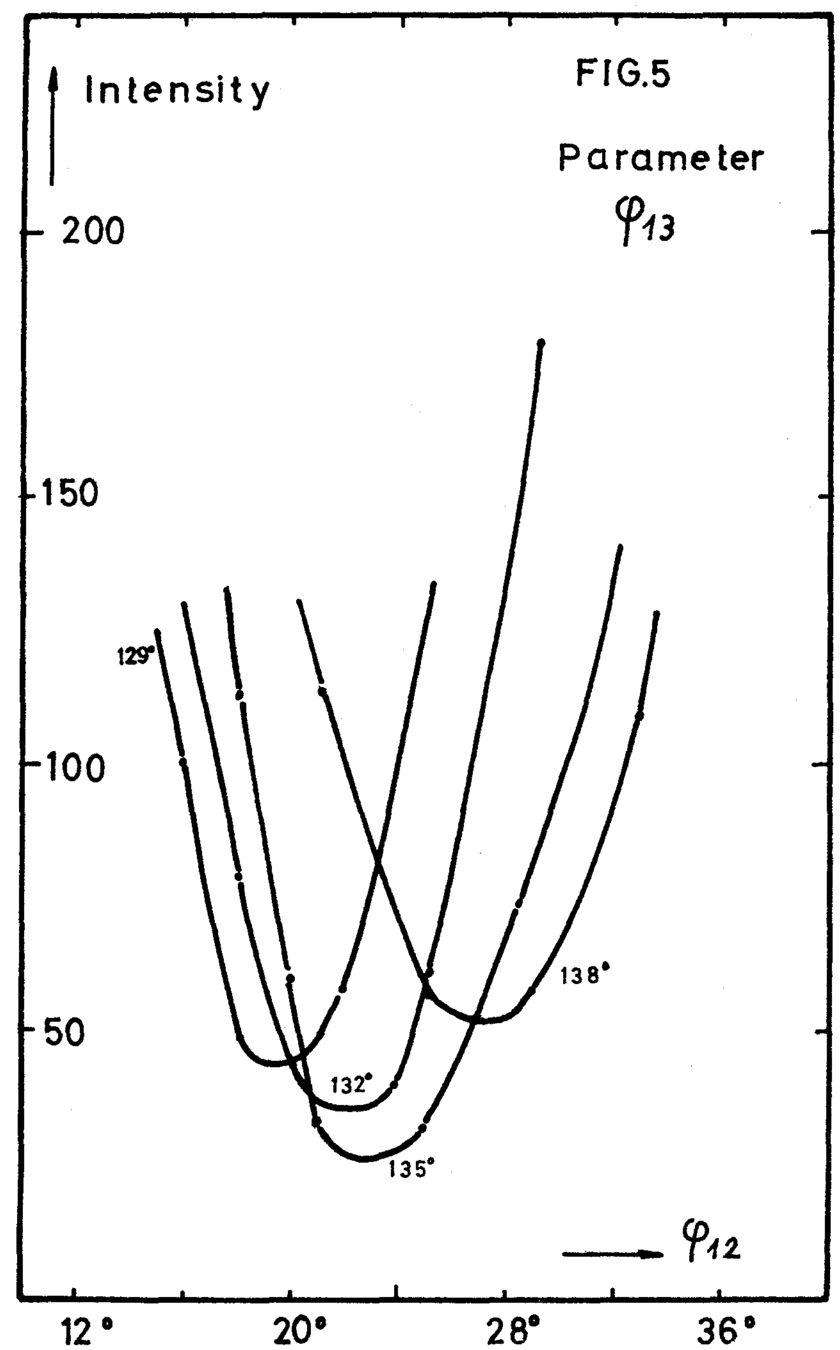

Fig. 5. Phase adjustment curves. Curves are measured with a $20 \times 150\ mm^2$ scintillation counter behind the second momentum analyser; intensity calibration is arbitrary. The curves show a non-symmetrical behaviour with φ_{13} which is confirmed by theory. Vertical angular opening 1/2 of maximum value; beam stopper thickness : 8 mm.