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COLLIMATORS FOR HIGH-ENERGY PROTON BEAMS

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ABSTRACT

The absorption probability of high-energy protons intercepted near the edge of a collimator jaw is reduced, since the protons may be scattered back into the aperture before being absorbed. The absorption probability in Cu and Al is studied by a Monte Carlo tracking of the protons through the material for different impact distances from its edge and different impact angles in the momentum range of 10-400 GeV/c.

In particular, a collimator system for the 10 GeV/c injection beam towards the SPS is proposed which permits the reduction of the beam width simultaneously in horizontal and vertical direction to 40% if an intensity reduction to 10%, and a halo due to back-scattered protons of up to 1%, in the SPS, can be tolerated. For further beam width reductions, the remaining beam intensity and the background are less favourable.

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CONTENTS

I. INTRODUCTION

For high-energy proton beams one has to allow for the possibility of reducing their lateral emittances, the momentum spread, and the intensity of the beam. This can be achieved by passing the beam between two collimator jaws so that the protons of large betatron amplitudes or undesired momenta fall onto the front of the jaws and are absorbed in the collimator material.

In order to obtain a high absorption probability the collimator must be several interaction mean-free paths long. For example, a copper collimator of 1 m length, used for multi-GeV/c protons, represents about 7 interaction lengths, which reduces the intercepted proton intensity by about 10^{-3}.

In addition, the absorption efficiency of the collimator is further reduced, since protons intercepted by the collimator can drift due to multiple scattering, laterally towards the edge of the collimator and can escape through its aperture before being absorbed. The reduced absorptivity near the collimator edges represents a "grey zone" of certain thickness, which must be kept as thin as possible.

Due to the finite length of the collimator and the divergence of the beam, some protons also hit the collimator faces under small angles and may be scattered back into the aperture or escape at the collimator end, since the path lengths traversed inside the material is not long enough to be absorbed. The described effects are shown schematically in Fig. 1.

II. THE COLLIMATOR EFFICIENCY

To improve the absorptivity of the collimator edges a material must be selected, in which the protons are absorbed before being substantially laterally displaced by scattering.

In order to make a first guess for suitable materials we study the lateral r.m.s. displacement Δ reached after one interaction length X_A:

$$\Delta \propto \frac{X_A^{3/2}}{X_R^{1/2}} \tag{1}$$

X_R: radiation length.

The radiation and absorption lengths depend on the atomic weight A, charge Z and density ρ, roughly in the following way:

$$X_A \propto A^{1/3}/\rho \tag{2}$$

$$X_R \propto A/Z^2\rho \,. \tag{3}$$

Introducing these relations into the above formula yields

$$\Delta \propto Z/\rho \,.$$

To reduce the width of the grey zone of the collimator, which is of the order of Δ, a material should be selected where the ratio Z/ρ is minimal.

According to the above estimation Fe and Cu are suitable materials*) whereas the r.m.s.-width Δ for Al is about 50% larger.

To obtain more quantitative results of the efficiency of a Cu-collimator, a Monte Carlo programme was made which calculates the absorption probability P(X,X',p) of protons of the momentum p entering the collimator at the distance X from its edge under a certain angle X'. The protons are tracked through the material under the consideration of multiple and nuclear scattering (the latter was neglected in the estimation above) and absorption. Also protons entering the collimator at its face under a positive angle (see Fig. 1) are included in the computation.

*) The ratio Z/ρ is smallest for Be and C, which will however be excluded for practical reasons.

The absorption probability $P(X,X',p)$ was studied in a wide range of momenta of 10-400 GeV/c. It was found that one could calculate $P(X,X',p)$ at any momentum p in good approximation from the probability $P(X_0,X_0',p_0)$, known at a certain momentum p_0, where the phase space coordinates X and X' of a proton with the momentum p were scaled in the following way

$$X_0 = X\ p/p_0 \tag{4}$$

$$X_0' = X'\,p/p_0 \tag{5}$$

so that

$$P(X,X',p) = P(X_0,X_0',p_0)\ . \tag{6}$$

This approximation is valid within about ±10%, which is well within the precision of the data characterizing the interaction and scattering in the collimator material. In Fig. 2 the iso-absorption lines $P(X_0,X_0',p_0)$ = const for only one jaw of a Cu-collimator are shown in the phase plane. For simplicity the iso-absorption lines are normalized to the momentum p_0 = 1 GeV/c. The point "A" in Fig. 2 represents, for example, a proton of 10 GeV/c, which hits the Cu collimator at X = 0.35 mm and X' = -2.5 mrad and which is absorbed with a probability of 70%. A 50 GeV/c proton placed in the scaled phase plane at the point "B" corresponds to a proton hitting the collimator at X = 0.02 mm and X' = -0.5 mrad and is absorbed with a probability of only 40%.

To study the efficiency of collimators made from materials which are less favourable, according to the previous estimations, the iso-absorption lines are also computed for Al as collimator material, and this is shown in Fig. 3. The slope of these lines is less steep so that the width of the grey zone is increased in Al compared with that of Cu as was already expected from the first qualitative estimation. The protons "A" and "B", mentioned above, are absorbed in the Al collimator with a probability of only 45% resp. 15%.

It is worthwhile noting that a proton hitting an ideally shaped collimator exactly under zero degrees at its edge, is absorbed with a probability of about 20% and not 50%, as one might expect from the symmetry of the scattering. The additional amount of escaping protons is caused by those which were first scattered from the edge into the material and thereafter towards the face during further scattering.

In the calculations an infinitely long collimator jaw was assumed. In this case protons of negative impact distance X from the edge and positive angles X', populating the upper left quarter of the phase planes in Figs. 2 and 3, hit the collimator at its face. When the length of the collimator is finite, protons of large negative distances X and small positive angles X' can no longer reach the collimator face. In this case a sector in the upper left phase plane quarter between the negative X-axis and a straight boundary, depending on the collimator length, becomes completely transparent. The dashed lines in Figs. 2 and 3 represent these boundaries for different collimator lengths. As shown by the computer calculation for finite collimator lengths, the iso-absorption lines are bent slightly upwards and approach the indicated boundaries smoothly. But the changes are small for realistic distances and angles so that in most cases it will be sufficient to introduce the theoretical upper boundary according to the considered collimator length and to apply the iso-absorption lines computed for an infinitely long collimator.

Finally, to calculate the total amount N of protons absorbed, one has to weigh the phase plane density Q(X,X',p) of the incoming beam with the absorptivity P(X,X',p) and integrate over the phase space coordinates:

$$N = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} P(X,X',p)\; Q(X,X',p)\,dX\,dX' . \qquad (7)$$

III. BEAM OF SMALL DIVERGENCE

In the following, we consider beams of small divergence, i.e. where

$$X_0' \ll 10 \text{ mrad} , \qquad (8)$$

so that the phase plane represented in Figs. 2 and 3 is populated only within a small strip along the X_0-axis. The condition (8) requires, for example, a maximum divergence of $X' \simeq 0.1$ mrad for a beam momentum of 10 GeV/c. For a momentum of 100 GeV/c the divergence should be about $X' \simeq 0.01$ mrad.

Under the condition (8) the dependence of the absorption probability on the impact angle can be neglected and it is sufficient to consider the probability $P_0(X_0)$ only at the impact angle zero:

$$P_0(X_0) \simeq P(X_0, 0, p_0) \tag{9}$$

which is shown in Fig. 4 for Cu and Al. The difference in the absorptivity of these two materials is only of the order of 10% and smaller, as the previous estimations indicated. In general, it is therefore worthwhile considering collimator materials other than Cu or Fe which may be more suitable from the point of view of heating, remanent radioactivity, etc. From Fig. 4 one can see that the grey zone is of the order of $X \approx 0.1$ mm for 10 GeV/c protons, whilst for 100 GeV/c it is only 0.01 mm. The latter value represents the limit of the mechanical surface precision of the collimator face and the alignment precision. Therefore the quality of a collimator used for momenta above 100 GeV/c is mainly defined by the geometrical properties of the collimator, and only to a lesser extent by the choice of the material.

The average angles, under which escaping protons depart from the collimator face, have also been studied. They are below 1 mrad at 10 GeV/c and decrease correspondingly at higher momenta. Since the aperture will normally be of the order of one to several cm, most of the outscattered protons cannot be caught by the opposite collimator jaw, without requiring excessive collimator lengths. Therefore, the collimator length will be defined only by the longitudinal absorptivity necessary to absorb the primary protons and the initiated nuclear cascade.

For a collimator made from copper a length of about 1.2 m is sufficient at 10 GeV/c.

IV. A COLLIMATOR FOR THE INJECTION LINE OF THE SPS

In this chapter a collimator for making a pencil beam of 10 GeV/c protons in the injection line from the CPS towards the SPS, is studied. To obtain a clean reduction of the beam size the horizontal and vertical emittances can each be reduced by a set of two collimators separated by a distance corresponding to a phase advance of 90^o. The optimum position for each collimator is in a region of maximum β-value in order to reduce the proton density intercepted at the edge of the collimators and to have an optimum sensitivity for the collimation.

We propose making the collimator out of copper, which requires a length of 1.2 m and a lateral width for each collimator jaw of about 20-30 cm.

To estimate the number of protons that are intercepted by the collimator and scattered back into the aperture, Gaussian distributions are taken for the lateral beam densities. The half width W_0 of the beam is assumed to represent twice the r.m.s. value of the Gaussian distribution. Therefore, the lateral beam density I(d), is given by

$$I(d) = \sqrt{\frac{2}{\pi}} \; \frac{e^{-2d^2/W_0^2}}{W_0} \; . \tag{10}$$

The fraction F_e of protons escaping from one collimator jaw relative to the incoming protons is given by

$$F_e = \frac{\int_0^{+\infty} I(d + \xi) \; \{1 - P_0(\xi)\} \; d\xi}{\int_{-\infty}^{+\infty} I(X) \; dX} \tag{11}$$

where d is the half aperture of the collimator.

As mentioned previously, a beam of small divergence is assumed. The number of escaping protons depends on the original beam width W_0 and the beam width W resp. the intensity required after the collimation.

In Fig. 5 the number F_e of escaping protons, normalized to the number of incident protons, is shown as a function of the beam width reduction W/W_0 for collimation in only one lateral direction by a set of two collimators of variable aperture separated by a phase advance of 90^{o}. The curves are given for initial beam half widths W_0 of 10, 20, 30 and 40 mm. An assumed mechanical imperfection of the collimator surfaces of 0.1 mm is taken into account. On the abscissa the reduction of the total beam intensity I/I_0, corresponding to a certain reduction of the beam width, is also given.

For very narrow collimator slits, where W/W_0 is small, the number of protons falling onto the edges of the jaws of the first collimator is about independent of the collimator aperture. Therefore, its efficiency is approximately independent of its aperture. Since, however, the inefficiency of the second collimator increases with the aperture of the first collimator, due to the higher beam intensity arriving at the second one, a net increase for the overall inefficiency of the collimator system at small apertures results. With increasing collimator apertures the inefficiency decreases, since the proton density falling onto the collimator edges drops altogether.

From Fig. 5 it can also be seen that the collimator losses depend, fairly strongly, on the width W_0 of the original beam. It is therefore desirable to place the collimators in regions where the β values are large. This implies, for periodical beam transfer lines, that the vertical and horizontal collimators have to be placed in different positions in order to obtain the best possible efficiency.

Fig. 6 shows the inefficiency of a system which reduces the beam width simultaneously in both lateral directions by a set of four collimators. In general, the inefficiency is slightly higher compared to collimation in only one lateral direction. However, the resulting beam intensity I/I_0 after the collimation is considerably reduced. To maintain, after collimation in two planes, a reasonable beam intensity of about 10% of the non-collimated beam, the beam width should not be reduced any more than 30-40% of its original width.

V. BEAM SIZE REDUCTION WITH FOUR COLLIMATORS

To estimate the inefficiency of possible collimator systems in the injection line TT10, we first study an "ideal" system where four collimators are placed downstream from the quadrupoles QIID 1003, QIF 1004, QID 1005 and QIF 1006, respectively. The following horizontal and vertical beam half widths W_H and W_V are expected at these positions with the continuous transfer scheme including phase plane exchange downstream of the collimators, a vertical beam emittance of 3.3π mm mrad, a horizontal of 2.6π mm mrad, and an energy spread of 0.6‰:

1. Vertical collimator W_V = 13.7 mm
1. Horizontal " W_H = 18.7 mm
2. Vertical " W_V = 20.1 mm
2. Horizontal " W_H = 15.0 mm

In Table I the inefficiencies are listed for different beam width reductions resp. collimator apertures for collimation in, respectively, only the vertical plane, only the horizontal plane, and for simultaneous collimation in both lateral directions. The remaining beam intensities after collimation are also given.

Table I

Inefficiencies of an "ideal" collimator system with four collimators for the injection line TT10

	Vertical collimation		Horizontal collimation		Vertical & horizontal collimation	
W/W_0 (%)	F_e (%)	I/I_0 (%)	F_e (%)	I/I_0 (%)	F_e (%)	I/I_0 (%)
10	4.4	2.5	3.6	2.5	4.6	0.07
20	4.8	9.6	3.9	9.6	4.8	1.0
30	4.4	20	4.0	20	5.3	4
40	4.1	34	3.9	34	5.4	12
50	3.6	46	3.5	46	5.2	21
60	3.2	59	3.3	59	5.1	35
70	2.5	68	2.6	68	4.3	50
80	2.0	79	2.0	79	3.0	63
90	1.3	86	1.3	86	2.4	74

These estimates show again that, in case of extreme beam size reductions, the beam intensity drops rapidly, and approaches the number F_e of protons back-scattered from the collimators.

If collimators are used during normal operation of the SPS to remove beam halos, continuous proton losses from the collimators of one to several percent must be expected along the transfer line TT10 downstream of the collimators, due to the scattered protons.

In principle, some of the protons back-scattered from the collimators may still remain within the acceptance of the beam transport and the SPS. It is difficult to estimate that amount precisely, and only a rough estimate is made in the following. As the computer calculations have shown, the back-scattered protons emerge from the collimator face under an angle of up to 1 mrad at the primary momentum of 10 GeV/c, while only those protons which are scattered out under an angle of the order of 0.1 mrad remain within the acceptance of the transfer line and the SPS. The momentum loss of protons escaping from the collimators can be up to 4%, whilst the momentum spread accepted in the SPS is much smaller. From these values, it is clear that the possible halo around the circulating SPS beam produced by the collimators will contain less than 10% of all back-scattered protons. Therefore, the halo will also be below 10% of the intensity of a circulating SPS beam for a beam width reduction of $W/W_0 > 30\%$.

VI. BEAM SIZE REDUCTION WITH TWO COLLIMATORS

In view of the technical effort required for a collimator system with four collimators of variable aperture which must each be placed in a vacuum tank, which must be water cooled and whose positions have to be remotely controlled, we also studied a simpler system which consists of only two collimators, separated by a distance which corresponds to a phase advance of 90° in both lateral directions. They should be placed in a region where both lateral beam widths are of a similar size, to maintain an about equal collimation efficiency and sensitivity in both planes.

Each collimator consists of a solid copper cylinder, with several axial rectangular openings of different cross-sections, placed at a certain distance from the cylinder axis. The size of each hole must be chosen according to a horizontal and vertical beam size required after collimation. Each collimator opening can be placed into the beam through a remotely-controlled lateral movement of the cylinder. This solution only permits a simultaneous collimation in both lateral planes and only a limited number of fixed beam sizes after collimation can be chosen.

In the following, we study a system with two collimators and with four different openings which produces a beam width reduction in both planes of 20%, 40%, 60% and 80% of the above assumed injection beam.

The first collimator can be placed 5.4 m downstream of QIF 1004 and the second one 10.8 m downstream of QIF 1006 in TT10. The horizontal and vertical beam half widths upstream of these collimators are:

	W_H (mm)	W_V (mm)
1. Collimator	18.3	10.4
2. Collimator	12.8	12.2 .

The positions of the two collimators are chosen such that the phase advance μ_H and μ_V in horizontal and vertical direction between the two collimators, is as near as possible to the ideal value of 90^o: $\mu_H = 82.5^o$ and $\mu_V = 94.0^o$.

In Table II the results are summarized for the above-assumed beam width reductions. In the second line, the number of protons F_e escaping from the collimators is given for the different beam width reductions. In the third line, the beam half widths obtained in the SPS after injection, are given at β_H(max), β_V(max) and α_p(max) for the assumed emittances of $\varepsilon_H = 2.6\pi$ mm mrad and $\varepsilon_V = 3.3\pi$ mm mrad expected with a continuous transfer and phase plane exchange. In the last line the intensity, after the collimation, is given for the four different beam width reductions and the above-assumed beam emittances.

Since, however, smaller emittances cannot be excluded, the intensities, which result after the collimation of a beam with the smaller emittances of $\varepsilon_H = \varepsilon_V = \pi$ mm mrad, are also given. The beam widths in the SPS are, of course, the same since the collimator apertures remain unchanged.

Table II

Beam parameters in the SPS after collimation

Beam width reduction W/W_0(%)	20	40	60	80
Collimator inefficiency Fe(%)	3.2	5.7	5.8	4.0
Beam size in the SPS (eq.mm)				
W_H	3.8	7.7	11.5	15.4
W_V	3.7	7.4	11.0	14.7
Beam intensity reduction I/I_0(%) for $\varepsilon_H = 2.6\pi$ mm mrad, $\varepsilon_V = 3.3\pi$ mm mrad	1	12	35	63
for $\varepsilon_H=\varepsilon_V=\pi$ mm mrad	5	42	78	95

VII. CONCLUSIONS

The absorption probability of protons hitting a collimator were studied by a Monte Carlo tracking of the protons through the material. The results are represented as iso-absorption lines in the lateral phase space. Momentum normalized phase space coordinates are used which permit to represent the absorption probability in a way which is approximately independent of the proton momentum in the momentum range of 10-400 GeV/c.

One of the most efficient materials for collimators is copper. However, the application of aluminium was also studied. For small beam divergences ($X_0' << 10$ mrad) the absorption probability is nearly independent of the angle of the incident proton. The width of the partly transparent zone near the edge of the collimator for 10 GeV/c protons is about 0.1 mm if copper is used. The absorption probabilities for an aluminium collimator are only about 10% smaller.

Above 100 GeV/c, where the width of the transparent zone is of the order of 0.01 mm, which is of the same order as the smallest possible mechanical tolerances of the collimator surface, the efficiency of the collimator is mainly defined by the surface quality and only to a lesser extent by the material.

The calculations can be easily extended to the collimation of beams of other types of hadrons. The results are expected to be very similar to those calculated in this report for proton beams.

An "ideal" collimation system consisting of four collimators, and a simpler system of two collimators have been studied in more detail for the collimation of the injection beam of the SPS at 10 GeV/c. It has been shown that with both systems small beam sizes in the SPS at injection of 8 eq.mm lateral half width can be obtained. In this case, the intensity remaining after collimation is about 12% of the original intensity transferred from the CPS. The halo expected in the SPS when protons are back scattered from the collimators and which still enter the SPS, is also below 10% of the circulating beam and should be tolerable.

The beam quality obtained by an "ideal" collimation system, that consists of four separated collimators with continuously adjustable apertures, is about the same as the one achieved by the simpler system which consists of only two collimators with four different fixed apertures, plus one opening for the unobstructed beam passage. Therefore we propose to adopt this latter one, since the technical effort and cost of this system are considerably reduced compared to an "ideal" system with four collimators.

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COLLIMATOR

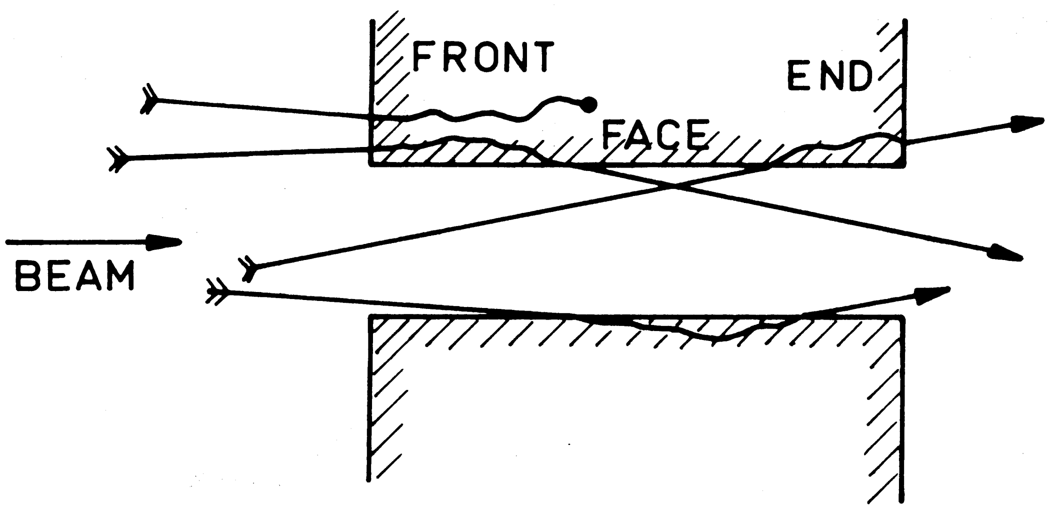

FIG 1 The back scattering of protons from a collimator

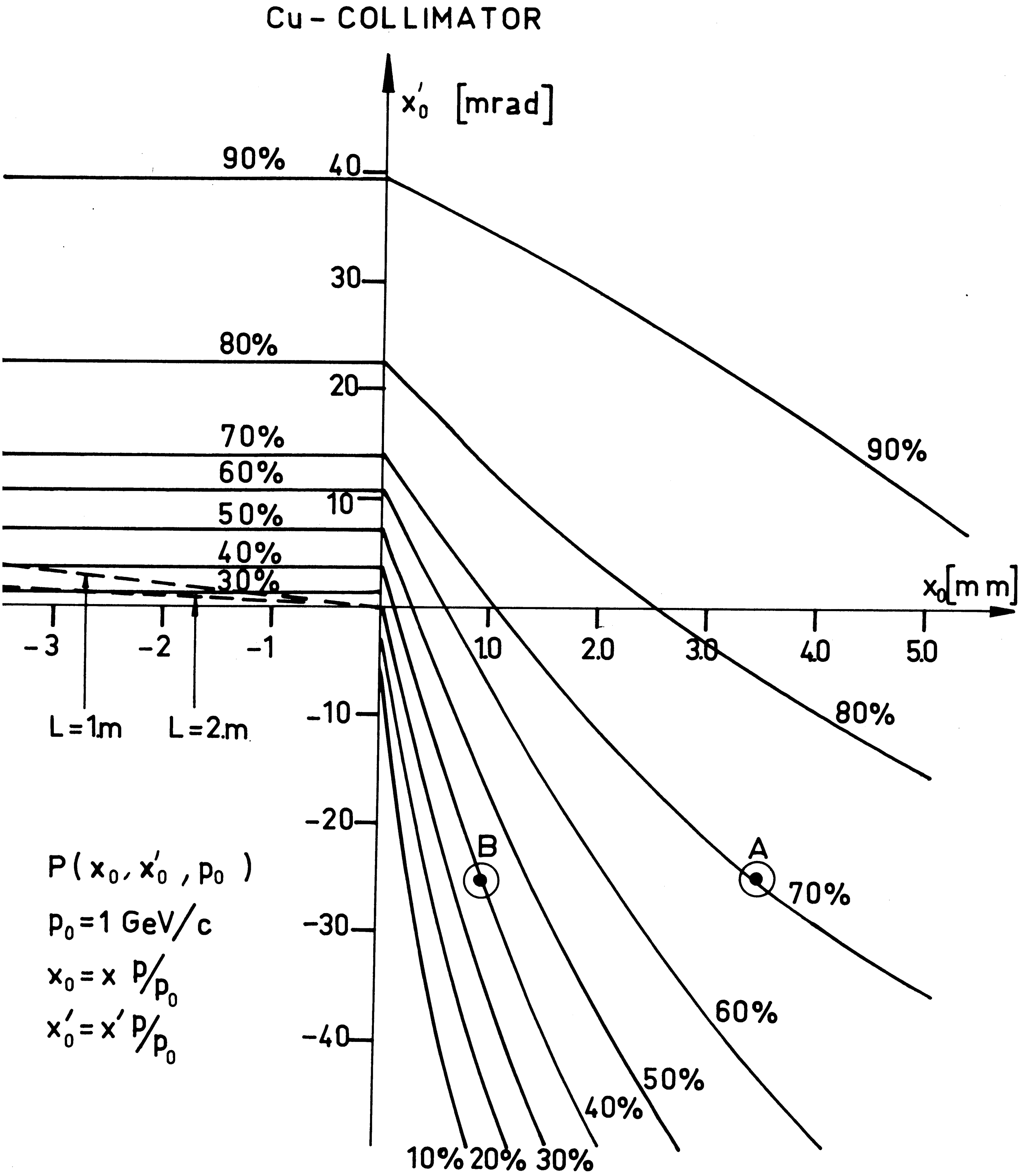

FIG 2 The iso-absorption lines $P(X_0, X_0', p_0)$ = const. in the (X_0, X_0')-phase plane for a copper collimator. For different momenta of the intercepted portons, the impact distance X from the collimator edge and the impact angle X' have to be scaled in the indicated way.

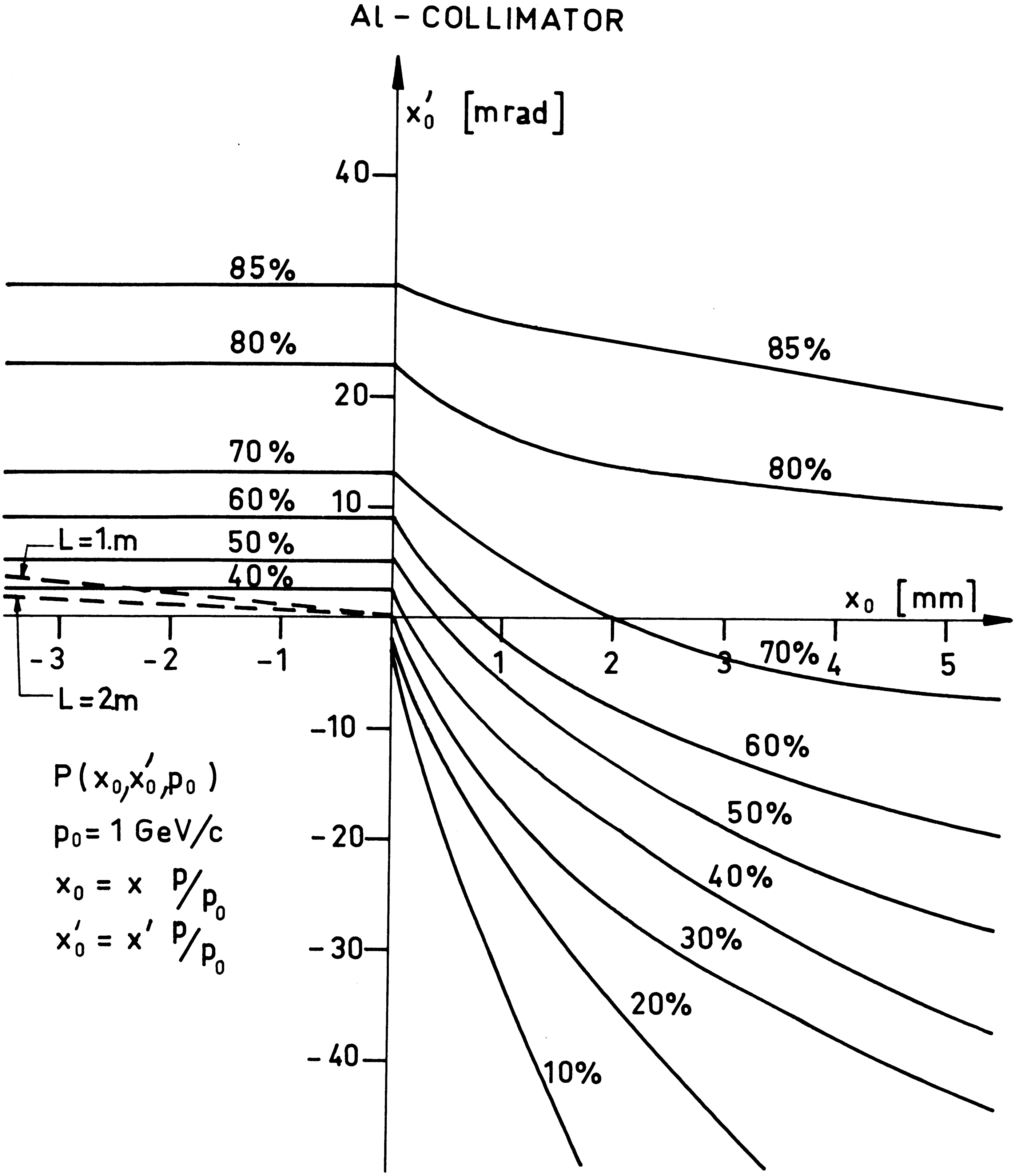

FIG 3 The iso-absorption lines $P(X_0, X_0', p_0)$ = const. in the (X_0, X_0')-phase plane for an aluminium collimator. For different momenta of the intercepted protons the impact distance X from the collimator edge and the impact angle X' have to be scaled in the indicated way.

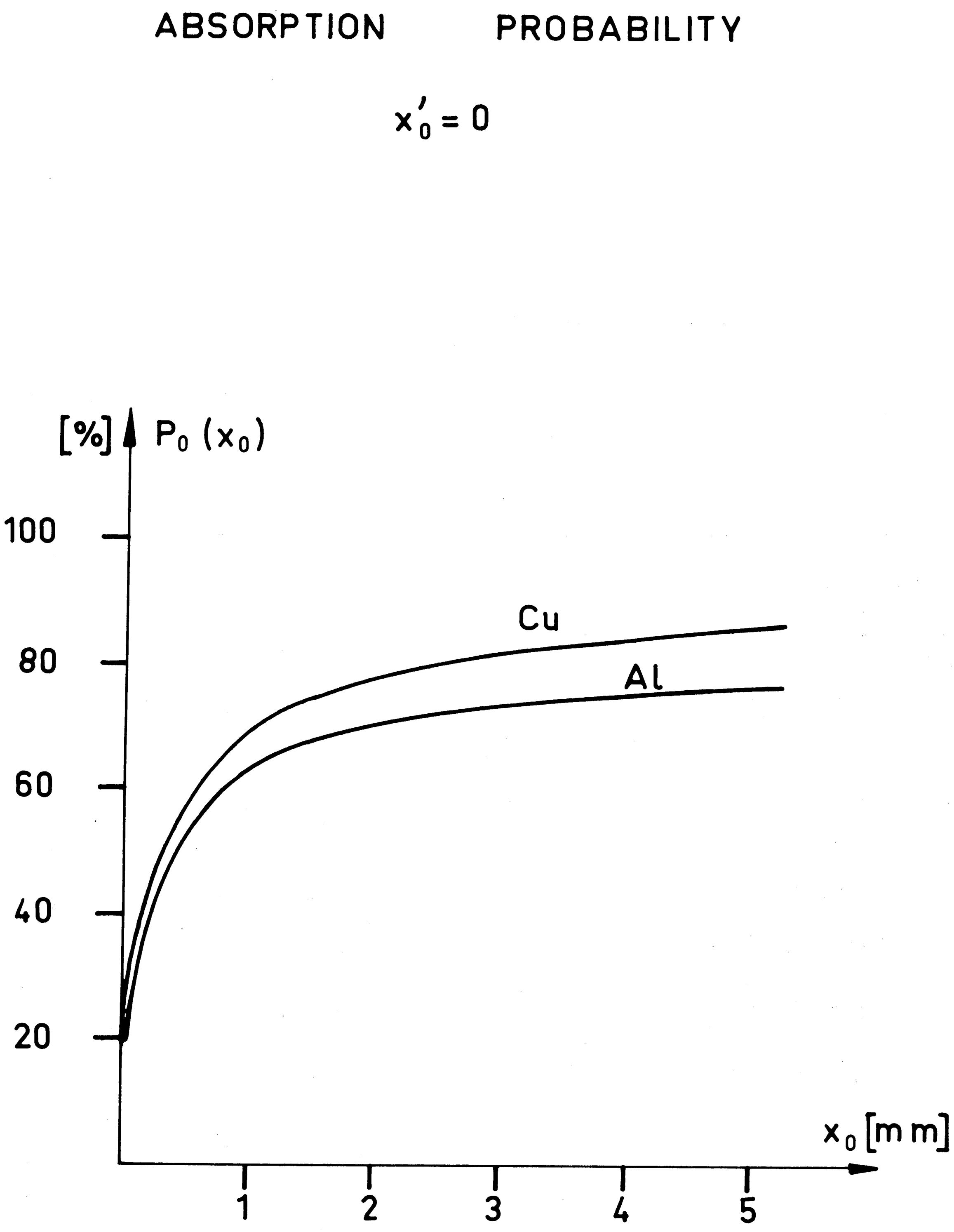

FIG 4 The absorption probability $P_0(X_0)$ for Cu and Al as a function of the impact distance X_0 from the edge of the collimator for zero-impact angle and the momentum p_0 = 1 GeV/c. For different momenta the impact distance X has to be scaled as $X_0 = X\, p/p_0$.

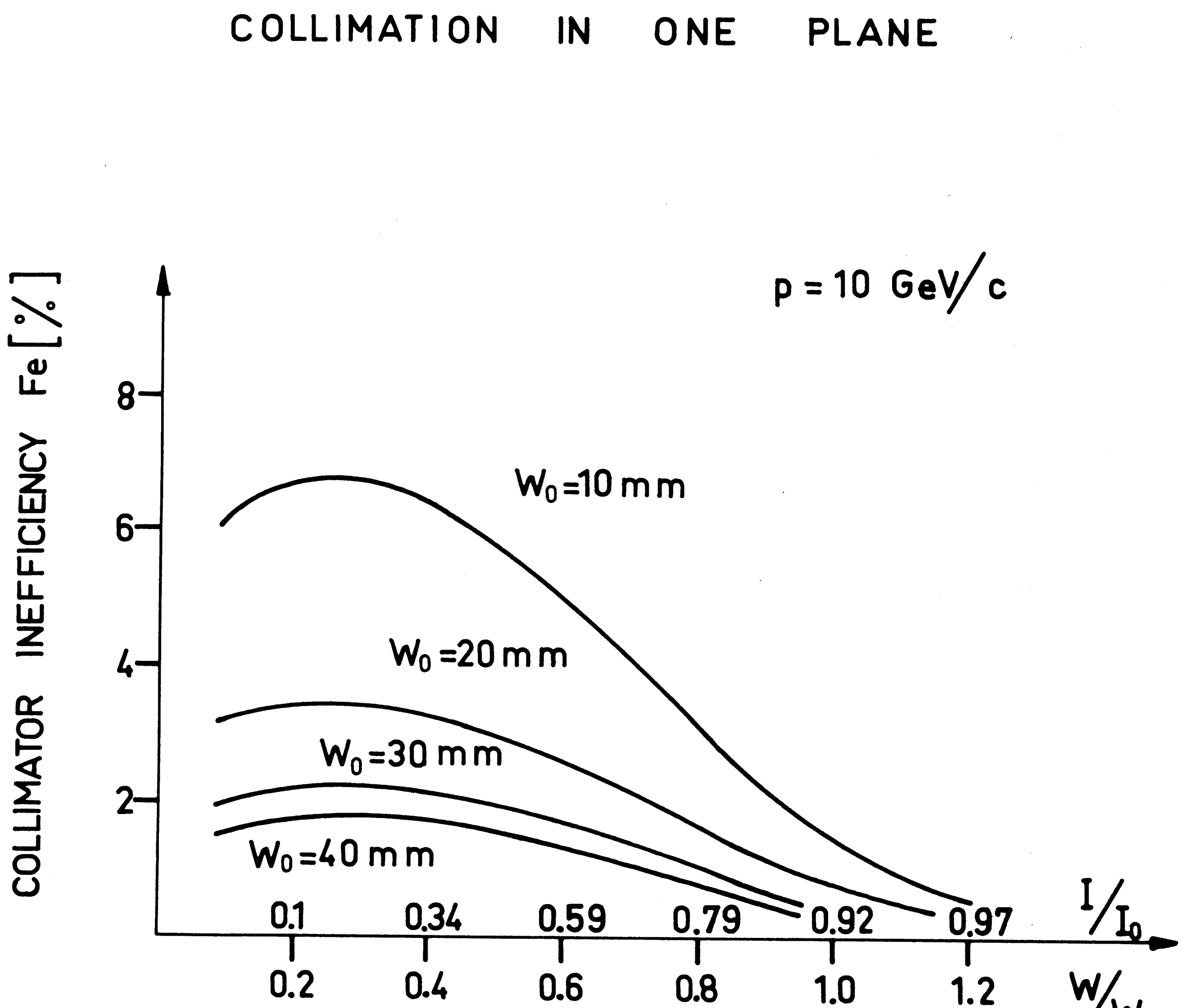

FIG 5 The number of protons F_e back scattered from a system of two collimators for different initial beam half widths W_0 as a function of the desired beam width reduction in one lateral direction. The reduction of the beam intensity I/I_0 is given as well.

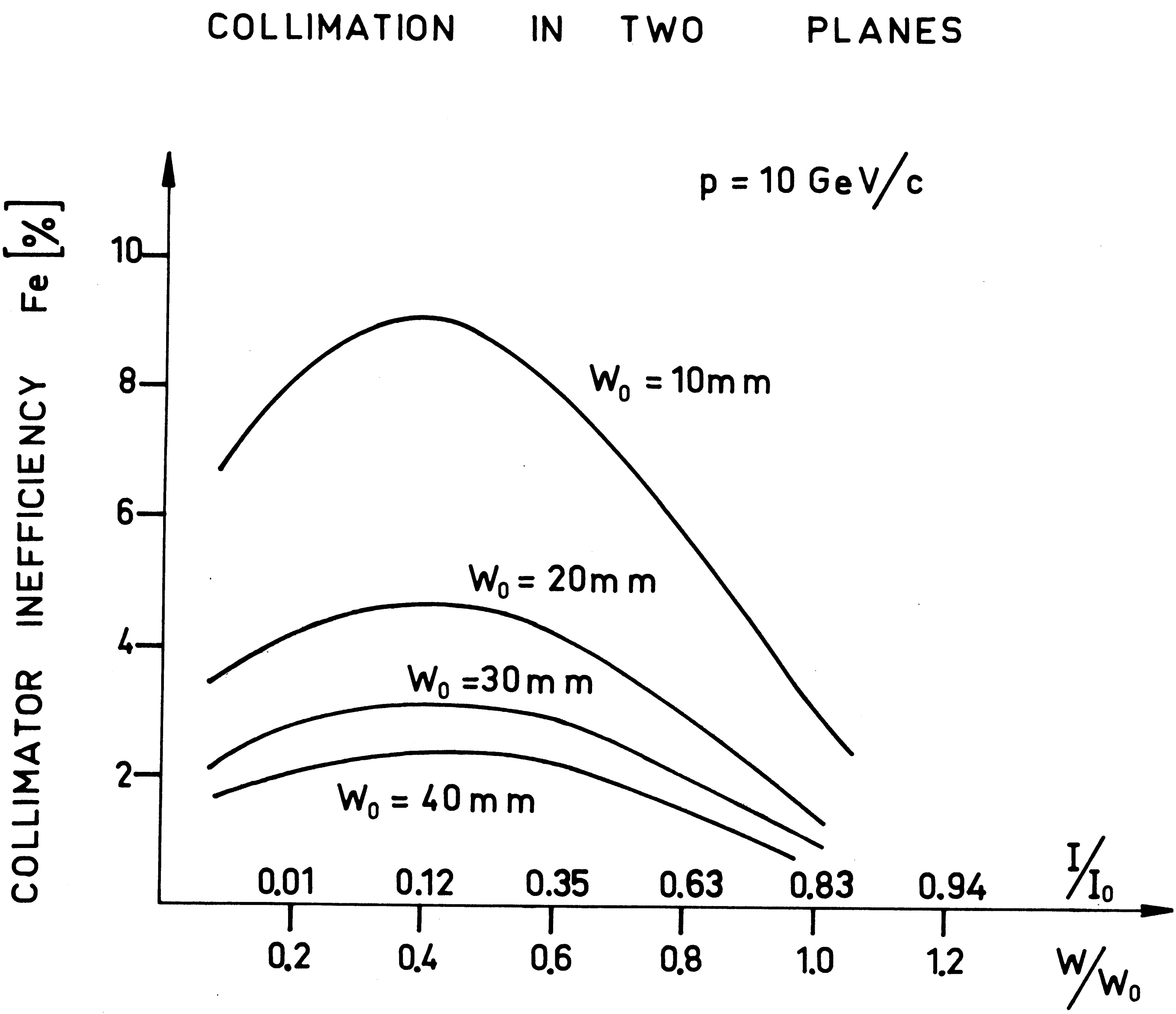

FIG. 6 The number of protons F_e back scattered from a system of four collimators for different initial beam half widths W_0 as a function of the desired beam width reduction in both lateral directions. The reduction of the beam intensity I/I_0 is given as well.