BEAM SHAPING BY MEANS OF A THIN IRIS

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Introduction

In radiation damage and He-implantation experiments, in which ion beams are employed, a good uniformity of the beam density at the target is generally required[1,2]. Due to the Gaussian-like distribution of the particles in a beam, only the central part can be used at the target. As a result of the consequent loss of particles, low target efficiency[+)] is obtained, and long irradiation times are normally needed. Throughout the beam transport from the internal one to the target, the target efficiency results to be the lowest by far, if compared with the extraction and the transmission efficiencies in the beam line, and therefore it is the principal cause in limiting the beam intensity at the target. To improve this efficiency, flattening of the particle distribution by means of a simple device, a thin iris, through which the beam is scattered, is proposed. Preliminary tests give confidence that the suggested device can be employed with benefit, allowing the use of uniform and intense beams.

Theoretical analysis

The particle density distribution in an accelerated beam is usually Gaussian-like, with a maximum corresponding to the beam axis. In the following, the distribution of the charged particles in the beam is assumed to be Gaussian, with a rotational symmetry around the beam axis z with density

$$D_b(x,y) = \frac{I_o}{\pi A^2} e^{-(x^2+y^2)/A^2} \qquad (1)$$

where I_o is the total beam current and A is the rms radius of multiple scattering. In this assumption, low values of the target efficiency are obtained, as shown in Table I, for different maximum disuniformities.

TABLE I - Values of target efficiency vs maximum beam disuniformity in case of Gaussian beams

Disuniformity	Efficiency
2%	2.0%
5%	5.1%
10%	10.3%

The uniformity of the beam impinging on the target is evidently strictly related to the accuracy of the experiments: the uniformity values required and routinely used are 10-15%, but the achievement of lower values is sometimes desirable.

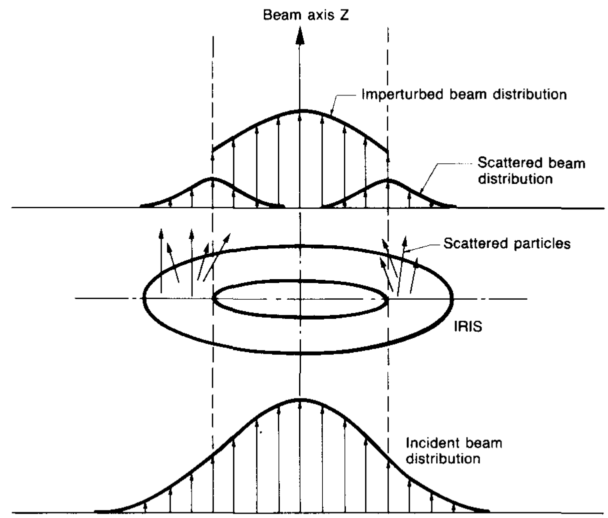

Fig. 1. Effect of the iris on a parallel beam.

The simple device, by means of which a substantial flattening of the central part of the particle distribution is obtainable, is shown in Fig. 1. A fraction of the particles scattered by the bored foil towards the beam axis adds to the particles passing through the central hole of the iris, modifying the shape of the original beam distribution. If an accurate choice of the parameters involved in the experiment is done, it will be shown that the distribution can be greatly modified and a very uniform one can also be obtained.

In the following, computations of the beam distribution as deformed by the iris are shown in detail in the case of a circular iris, for use with circular or square targets. Aim of these calculations is the settlement of the principal parameters involved, as the dimension of the iris, the thickness of the foil and the distance from the iris to the target, for different particles and energies.

Using cylindrical coordinates (r,φ,Z) and assuming for simplicity $I_o = \pi A^2$, we obtain

$$D_b(r)\,r\,dr\,d\varphi = e^{-r^2/A^2} r\,dr\,d\varphi \qquad (2)$$

if the incoming particles are scattered by a circular iris with radius r_o and thickness t (see Fig. 2), the distribution in P' of the particles scattered by the iris will be proportional to

$$\eta_{p''}(P') = \frac{1}{\pi C^2} e^{-R^2/C^2} \qquad (3)$$

[+)] The target efficiency is here defined as the ratio between the beam intensity used on the target and the total beam intensity at the target position.

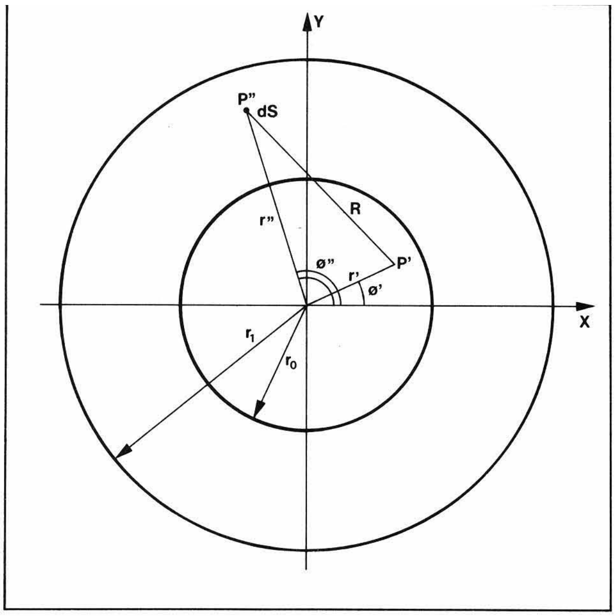

Fig. 2. Definition of the iris parameters and of the coordinates.

where R represents the projection on the iris plane of the distance between the point P" of the scattering foil and the point P' of the target. The parameter C is related to the mean deflection angle $<\theta^2>^{1/2}$ and to the distance Z_o between the iris and the target by

$$C = Z_o tg(<\theta^2>^{1/2}) \cong Z_o<\theta^2>^{1/2} \qquad (4)$$

For instance, for protons of kinetic energy E_c, passing through an iris of aluminium with thickness t, we obtain, in good approximation:

$$<\theta^2>^{1/2} = 1.15 \cdot 10^{-2}\ \frac{t^{1/2}}{E_c}\ (\ln 1.2 \cdot 10^{-3}\ E_c) \qquad (5)$$

where t is measured in microns and E_c in MeV.

The distribution of the scattered particles at the target will be obtained summing up the distribution (3), weighed by means of the incoming beam distribution (2). The distribution of the scattered beam, with the hypothesis of an incident parallel beam, will be given by:

$$D_s(r') = \frac{1}{\pi C^2}\int_0^{2\pi}\int_{r_0}^{r_1} e^{-r''^2/A^2} \cdot e^{-\frac{r''^2+r'^2-2r'r''\cos(\varphi''-\varphi')}{C^2}}\ r''dr''d\varphi'' \qquad (6)$$

where the integration is accomplished on the iris surface. Data obtained by numerical integration of (6), with an iris of radius r_o = 6 mm and r_1 = 12 mm, for different values of the parameter C, and maintaining A values fixed, are shown in Fig. 3. The left part of the curves refers to a parallel beam (zero emittance beam), the right one to an actual beam with an emittance of 60 mm-mrad. In each figure, the original beam distribution and the modified one at a distance Z_o from the iris are given. In Table II theoretical data of the minimum beam disuniformity DIS and maximum efficiency EFF obtainable with the iris, as a function of A values are shown.

TABLE II - Values of minimum disuniformity DIS, and maximum efficiency EFF, as obtainable with the use of a circular iris. Gain in uniformity DIS-GAIN, and gain in efficiency EFF-GAIN, as defined in the text, are also shown.

A	Disuniformity without IRIS	C_{opt}	DIS (with IRIS)	EFF (with IRIS)	DIS-GAIN	EFF-GAIN
7.0	0.52	1.6	0.317	0.585	1.8	1.8
8.0	0.43	2.0	0.185	0.500	2.7	2.7
8.5	0.39	2.3	0.131	0.464	3.5	3.5
9.0	0.36	2.6	0.082	0.432	5.2	5.2
9.5	0.33	2.9	0.043	0.404	9.3	9.1
10.0	0.30	3.25	0.015	0.378	25.0	24.4

In the same table, values of the following quantities are also given:

$$\text{i)}\quad \text{DIS-GAIN} = \frac{\text{DIS}_o(\text{EFF})}{\text{DIS}} \qquad (7)$$

where $DIS_o(EFF)$ is defined as the disuniformity of a Gaussian beam of efficiency EFF,

$$\text{ii)}\quad \text{EFF-GAIN} = \frac{\text{EFF}}{\text{EFF}_o(\text{DIS})} \qquad (8)$$

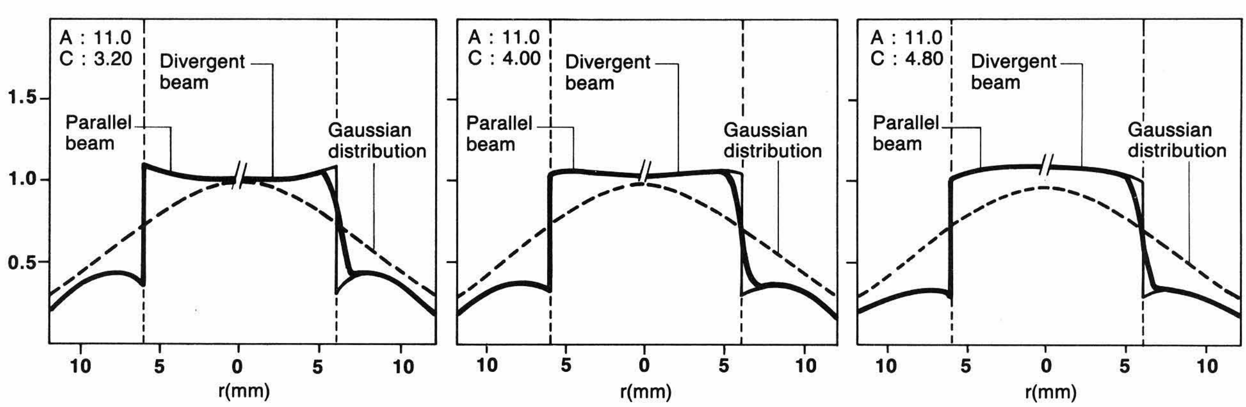

Fig. 3. Calculated beam profiles for A = 11.

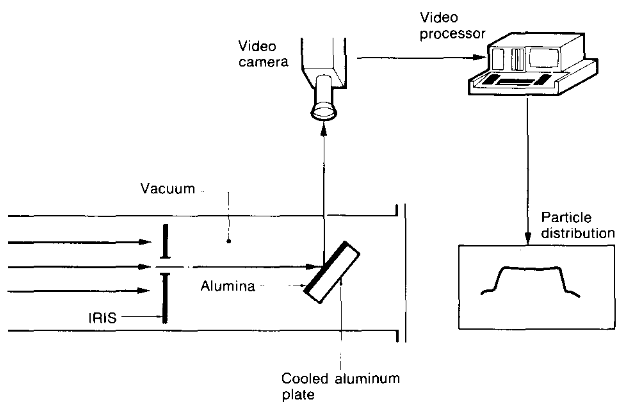

Fig. 4. Scheme of the measuring apparatus.

where EFF_o(DIS) is defined as the efficiency of a Gaussian beam of disuniformity DIS.

The two quantities so defined give, evidently, (i) the gain in uniformity, and (ii) the gain in irradiation time for a given disuniformity DIS, obtainable with an optimized use of the iris. These values correspond to an ideal beam with zero emittance; as will be shown in more detail, in an actual case the efficiency results to be about 30% less. For example, in case of a desired disuniformity of 13%, the effective gain is about 2.5.

Experimental results

Tests to check this beam shaping method, using circular irises of different thickness and with a fixed radius r_o = 4 mm, were accomplished. The simple device is obtained packing few bored aluminium foils with a constant thickness of 25 μ. The irises are cooled at the external radius r_o = 8 mm by compressing them between two water-cooled aluminium rings. The scheme of the experimental rig used to measure the iris effect on a 26.0 MeV proton beam, is shown in Fig. 4. The measurement of the particle distribution is based on the analysis of the light emitted from the alumina target, accomplished by means of an image processor. This method allows a fast response and high spatial resolution, necessary when small targets are used. When used with a low-density beam, less than 1 $\mu A/cm^2$, an alumina plate 0.5 mm thick is employed, mounted in good thermal contact to a cooled aluminium plate. At higher beam intensity, a thin layer of alumina was used, obtained by plasma-spray deposition on an aluminium substrate. This type of target was successfully tested until a current density of ∿ 15 $\mu A/cm^2$.

Preliminary experimental results are presented in Fig. 5, where the particle distribution at y = const (horizontal plane) and x = const (vertical plane) are shown, together with the theoretical curves, corrected for a beam with a horizontal and vertical emittance of 60 mm mrad. Principally due to the poor resolution of the simple image analysing system presently used, the precision of these measurements is not very good: nevertheless, a good agreement with the theoretical previsions was found.

In all the cases analysed up to now, using different iris radius and thickness, the measured efficiency is a little less than theoretically foreseen. This could be explained observing that the beam profile is not perfectly Gaussian, presenting somehow a steeper decreasing, giving, as a consequence, fewer particles scattered towards the beam axis than foreseen from a Gaussian distribution.

Conclusions

Flattening of a Gaussian-like particle distribution with circular symmetry is obtained, drawing advantage from the particles scattered by a thin iris. A gain of about a factor two in the irradiation time is obtainable with circular or square targets, when the requested disuniformity is 10-15%. Higher efficiency is foreseen when a more uniform distribution is requested.

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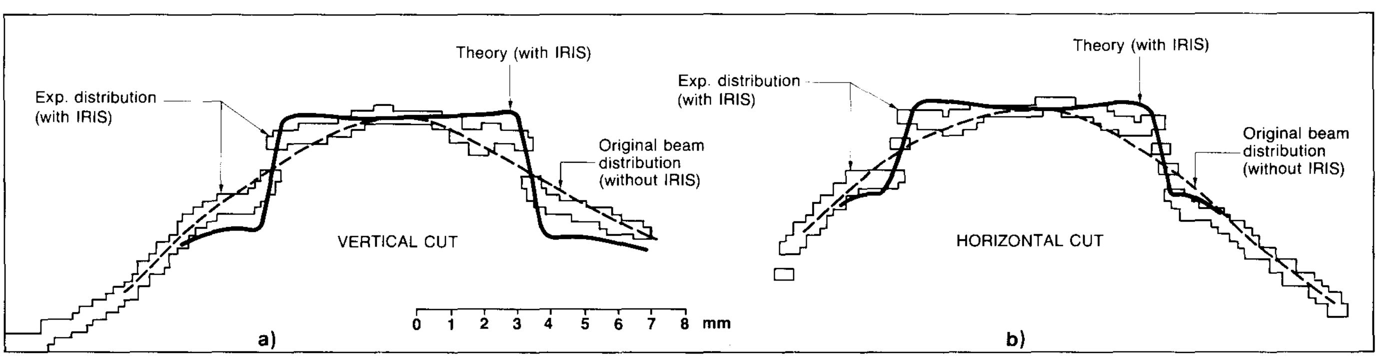

Fig. 5. 26 MeV proton beam profiles as modified by a 225 μ iris.

a) horizontal b) vertical