HALO FORMATION FROM BEAM COULOMB SCATTERING ON RESIDUAL GAS

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Abstract

Coulomb elastic scattering of beam particles on residual gas in a transport channel is experimentally and theoretically studied. Using the basic differential cross section formula, which gives the probability for a particle to scatter at a given angle, the amount of those few particles which scatter at rather large angles is estimated. We present a transport code dedicated to the scattering of a beam on the residual gas which we validate with an experiment in which the beam is transported in a drift space. We then use our code to simulate the transport of a beam matched to a uniform focusing channel and show how the collisional halo develops.

1 INTRODUCTION

Experimental observations and theoretical predictions have shown the existence of a low-density halo surrounding the central core of a high-intensity beam. This halo not only leads to particle loss along the accelerator, but also induces activity in the structures of the machine. There are many contributions to the formation of the halo. Several theoretical studies have been recently undertaken to understand the formation of the halo through the dynamics of particle-beam transport [1]. However, up to now, very few attempts have been made to study halo formation via interactions of beam particles with the residual gas of the accelerator.

We have undertaken an experimental study of halo formation and development surrounding an intense, low-energy, low-emittance proton beam during its transport through a periodically focusing FODO channel [2]. In order to provide a coherent interpretation of this halo-producing process, it appears necessary to estimate the amount of halo produced by the scattering of beam particles on the residual gas, and to subtract it from the measured data.

Analyzing the basic scattering process, we show that its effect is not negligible in the case of our experiment. Then, we validate a simple theoretical and numerical model by an experiment which consists of measuring, over a large dynamic range, the transverse profile of a proton beam at the end of a drift space, for various gas pressures. Using this model, we simulate the transport of the proton beam under our FODO experimental conditions and estimate the magnitude of the scattering-induced halo.

2 THE SCATTERING PROCESS OF A PROTON BEAM

2.1 Scattering probability for a proton

We consider, here, the Coulomb elastic scattering of beam particles on the atoms of the residual gas in an accelerator. The probability of collisions is governed by the well known Rutherford differential cross section formula [3], whose simplified expression is :

$$\frac{d\sigma(\theta)}{d\theta} = \frac{13\, z^2 Z^2}{E^2} \cdot \frac{1}{\sin^3\theta} 10^{-26} \qquad \textbf{(1)}$$

where : σ is the scattering cross section (in cm^2),
θ is the scattering angle from the incident direction (in rad),
z is the incident particle charge number,
Z is the target nucleus charge number,
E is the incident particle energy (in MeV).

Let n be the number of particles per unit volume in the residual gas. We have from the perfect-gas formula : $n = \frac{\mathrm{N_A}\, P}{\mathrm{R}T}$, where $\mathrm{N_A}$ is Avogadro's number, R is the perfect gas constant, T is the absolute temperature and P is the gas pressure.

The probability per meter for a particle to scatter, in a single shot, at an angle between θ and $\theta+d\theta$ is :

$$d\mathbb{P}(\theta) = d\sigma(\theta) \cdot n \qquad \textbf{(2)}$$

This gives for protons (z=1) in a gas at temperature T=300 °K:

$$d\mathbb{P}(\theta) = \frac{0.31\, Z^2 P}{E^2} \cdot \frac{d\theta}{\theta^3} \qquad \textbf{(3)}$$

with P in hPa, E in MeV, θ and $d\theta$ in mrad.

This formula applies only for angles between a minimum angle θ_{min}, corresponding to a large impact parameter of the order of the atom radius, and a maximum angle θ_{max}, corresponding to a small impact parameter of the order of the nucleus radius [3].

From equation **(3),** we calculate the probability, per meter, for a particle to be scattered, in a single shot, at an angle larger than θ_0 ($\theta_{min} < \theta_0 < \theta_{max}$) :

$$\mathbb{P}(\theta \geq \theta_0) = \frac{0.155\, Z^2 P}{E^2} \cdot \left[\frac{1}{\theta_0^2} - \frac{1}{\theta_{\max}^2}\right] \qquad \textbf{(4)}$$

2.3 Projection in the transverse phase space

We examine now the effect of collisions on the transverse profile of a proton beam. The beam profile is further observed through its projection on a given axis, say the horizontal axis Ox (**Fig.1**).

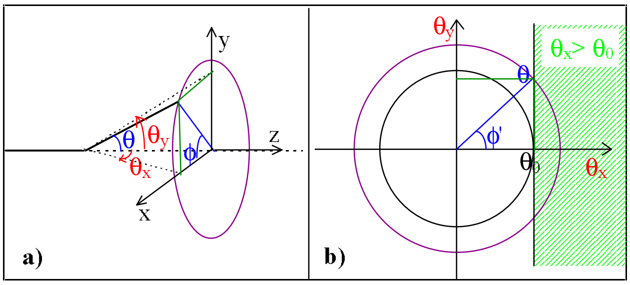

***Fig. 1** : Projection of the scattered particle trajectory onto the horizontal plane.*

We consider a particular proton which is scattered at the azimuthal angle $\theta \in [0,\pi]$ and at the radial angle $\phi \in [-\pi,\pi]$). The angle of the proton trajectory, projected onto the horizontal plane xOz is $\theta_x = \theta.\cos(\phi)$ (**Fig. 1a**). The particles scattered at an angle $\theta_x \geq \theta_0$ (hatched part of **Fig.1b**) are those scattered at an angle $\theta \geq \theta_0$ with a radial angle ϕ such that $-\phi' \leq \phi \leq \phi'$ with $\cos(\phi')=\theta_0/\theta$.

We obtain :

$$\mathbb{P}(\theta_x > \theta_0) = \int_{\max(\theta_0,\theta_{min})}^{\theta_{max}} \frac{1}{\pi} \arccos\left(\frac{\theta_0}{\theta}\right) \cdot \frac{d\mathbb{P}(\theta)}{d\theta} d\theta \qquad \textbf{(5)}$$

Putting $a=\theta_0/\theta$ and defining G(u) as :

$$\begin{aligned} G(u) &= 8\int_0^u \frac{x}{\pi} \cdot \arccos(x)dx \\ &= \frac{2}{\pi}[-u\sqrt{1-u^2} + 2u^2 \arccos(u) + \arcsin(u)], \end{aligned} \qquad \textbf{(6)}$$

we finally obtain for the probability law :

$$\mathbb{P}(\theta_x > \theta_0) = \frac{3.9\ 10^{-2} Z^2 P}{E^2 \theta_0^2} \cdot k(\theta_0) \qquad \textbf{(7)}$$

with

$$k(\theta_0) = \begin{cases} G\left(\frac{\theta_0}{\theta_{min}}\right) - G\left(\frac{\theta_0}{\theta_{max}}\right) & \text{if } \theta_0 < \theta_{min}, \\ 1 - G\left(\frac{\theta_0}{\theta_{max}}\right) & \text{if } \theta_{min} \leq \theta_0 \leq \theta_{max}, \\ 0 & \text{if } \theta_{max} < \theta_0. \end{cases} \qquad \textbf{(8)}$$

3 EXPERIMENTAL OBSERVATION

3.1 Experimental results

A 500 keV pulsed proton beam, with 500 µs pulse duration and 50 mA peak current, is delivered by a duoplasmatron source. The beam is collimated by two diaphragms to obtain a flat transverse profile with sharp edges, which ensures accurate observation of the collisional halo. The beam propagates through a drift space toward a scintillating screen located downstream 2.8 m from the first diaphragm placed at the exit of the source. It is observed with an intensified CCD camera. This imaging technique is very powerful since it allows density-distribution measurements over a very large dynamic range [4]. The residual gas pressure can be changed by injecting nitrogen gas.

The beam profile is observed by progressively moving the screen toward the beam centre and adjusting the light intensification. Beam profiles are presented in **Fig. 2** for two different nitrogen-gas pressure values. We notice that an increase of the residual gas pressure, by approximately a factor 3, induces an increase of the beam halo intensity by the same factor.

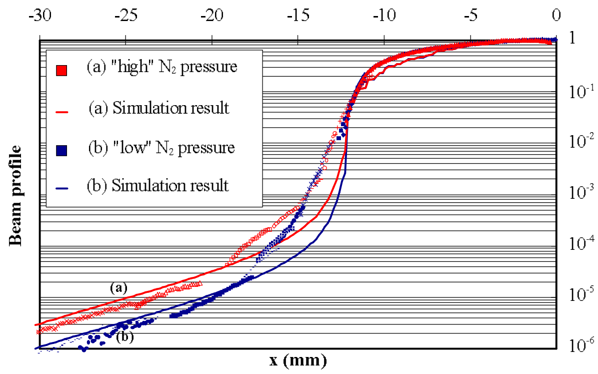

***Fig. 2** : Experimental and simulated beam profiles for two different nitrogen-gas pressures.*

3.2 Simulation of the experiment

We have simulated the experiment using the analytical results presented in section 2.2. The simulation method is schematically presented in **Fig. 3** and described below.

A 2D array (called T, with a size of N×M) contains the beam density distribution digitised in the (x,x') phase space. It is sampled with a step dx in the x direction and a step dx' in the x' direction. This array is initially filled with a homogeneous parallelepiped, corresponding approximately to the measurement of the beam distribution in this (x,x') phase space, presented in ref. [2] (See **Fig. 3-*(1)***). A 1D array (called P, with a 2M size) contains the probability for a particle to scatter at an angle θ_x between i.dx' and (i+1).dx', i being the index in the 1D array. We note that dx' is the numerical sampling step in both arrays T and P. We then simulate the evolution of the beam distribution function. For each processing step length dz, we determine :

- The beam scattering, by folding each column of array T (at x=C^{te}) with the array P (See **Fig. 3-*(2)***),
- The beam transport, by translating each point of the phase space pattern T along the x axis of a quantity proportional to the coordinate x' (that is $x_f = x_i + x'.dz$, $x'_f = x'_i$). This corresponds to the beam transport in a drift

space without space charge effect (See **Fig. 3-*(3)***).

In order to take into account the space-charge effect, we have multiplied the coordinate x of each point of the simulated profile by a factor k determined to obtain the same beam-core diameter for experiment and simulation. The simulation results are compared to the experimental ones in **Fig. 2**, they have been established for the pressure conditions of the experiment.

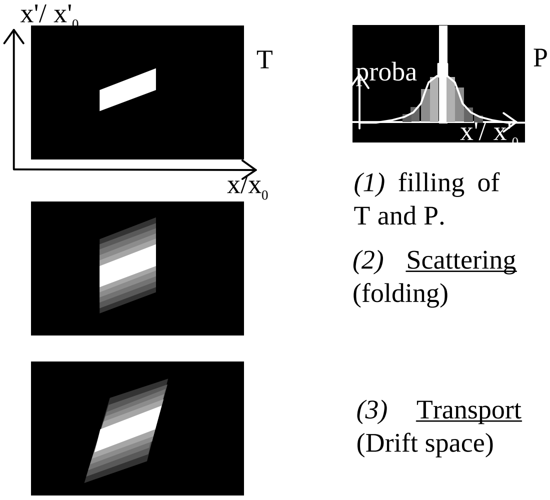

***Fig. 3** : Schematics relevant to the simulations. See text for explanations.*

The calculated results are in quite good agreement with the experimental data, especially far from the beam centre, beyond 1.5 times the beam-core radius. We observe, however, a discrepancy between the measured and simulated transverse distributions in the halo region close to the beam-core (between 1 to 1.5 times the beam-core radius). This can be explained by the crude description of the initial beam emittance in the simulation, which leads to sharper beam edges than in the experiment. Nevertheless, we can conclude that our simple model of beam scattering on the residual gas is good enough to allow predictions on the scattering halo formation in the FODO experiment, or in a high-intensity linear accelerator.

4 SIMULATION OF THE FODO EXPERIMENT

We now consider the simulation of the proton beam transport in our FODO experiment. The beam is assumed to be transported in a uniform focusing channel of 20 meters in length. Moreover, we assume that the proton beam is matched to the channel and has a Kapchinsky-Vladimirsky (KV) distribution in the transverse phase space. This means that each particle of the beam core moves in an harmonic-oscillator potential well. The other beam properties are: a proton beam energy of 500 keV, a maximum angular spread $x'_0=\pm 2$ mrad and a residual gas of monoatomic oxygen (Z=8). The simulation method is nearly the same as that used for the drift space and described above. The only differences are the following :

- The array T is initially filled with a homogeneous disc (K-V distribution in the transverse phase space).

- The beam transport consists of rotating the phase space pattern T. This corresponds to the transport of the beam in an harmonic-oscillator potential well.

The beam profile obtained at the exit of the channel is represented in **Fig. 4**, for different pressure values.

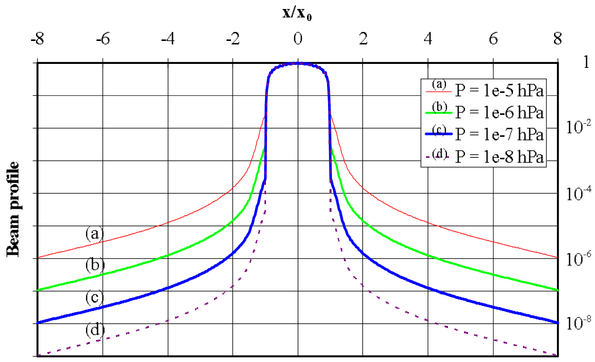

***Fig. 4** : Influence of the scattering process on the beam profile.*

5 CONCLUSIONS

In the conditions of our planned FODO experiment, the scattering process of the beam particles on the residual gas in the evacuated transport line will strongly compete with other halo-producing phenomena such as the particle-core coupling through transport dynamics.

In a linear accelerator, the scattering process can be very significant, particularly in the low-energy end and near the source, where the vacuum pressure is generally high. The transport of this "collisional halo" through the high-energy accelerating structures, where its effects may be serious has to be studied, as well as a means of eliminating it before it reaches these structures.

We notice that the larger the angular spread of the beam is, the less important the scattering effects are. This means that, for a given emittance, it is better to transport a small-size beam, with a large angular spread. Unfortunately, a small-size beam also means strong space charge effects and halo production from beam transport dynamics.

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