BEAM HALO DEFINITIONS AND ITS CONSEQUENCES

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Abstract

In high-intensity accelerators, much attention is paid to the beam halo: formation, growth, interaction with the beam core, etc. Indeed, beam losses, a critical issue for those high-power accelerators, directly depend on the beam halo behaviour. But in the presence of very strong space-charge forces, the beam distribution takes very different shapes along the accelerator, often very far from any regular distributions, with very varied halo extensions. The difficulty is then to find a general definition of the halo capable of describing any distribution type. This paper proposes a definition of the beam halo, studies its consequences and compares it to the most usual ones. It is an introduction to a discussion session on Beam Halo Definition during the HB2012 workshop.

INTRODUCTION

In high-intensity accelerators, great importance is given to emittance growth and halo growth. It can even be said that, in case there is no injection into a circular accelerator, the importance of emittance is only due to its suspected connection with halo formation. The latter should therefore be at the centre of every attention. The reason is that halo directly leads to beam losses, which even tiny, cannot be neglected when considering the high bam power (MW class) induced by the high intensity.

Halo is definitely the figure of merit in nowadays high-intensity accelerators. Paradoxically, a concrete, precise and general definition of halo is still missing. Typically, the four following questions have no clear answers:

- During beam design stage or machine operating, it is well known that halo should be minimised. But how much at which part of the beam exactly should be minimised?
- Scrapers are often employed to cut the halo and it is known that halo can grow up downstream more or less quickly. But where is the halo and where is the core? Is this cut not enough or too much? How to quantify the speed of halo re-formation?
- There is a need to develop dedicated beam diagnostics to measure beam halo. But how much and which part of the beam exactly should be measured?
- When failing to know exactly what halo growth is, it is common to consider instead 1 RMS emittance growth. But is there a clear connection, qualitatively or quantitatively, between emittance growth and halo growth?

The answers to these questions may depend on the definition given to halo. This paper considers the existing approaches aiming at defining beam halo, then suggests a concrete approach to qualify beam halo. Finally, the consequences on the above questions are examined.

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THE EXISTING DEFINITIONS

Many attempts have been made to attribute a quantitative definition to beam halo. A special international workshop, HALO'03 [1] has been organised to assess the ways to define and to measure halo, but no consensus has emerged on how to define what halo is. From this workshop however, it is more and more common to characterise halo by comparing the "far" beam centre to "close" beam centre areas of the particle distribution. How "far" or how "close" may be somewhat arbitrary.

It is for example the ratio of beam sizes including in

$$\frac{m\,RMS}{n\,RMS} \qquad (1)$$

with n being generally 1 and m between 3 or 5. Another way is to consider the ratio

$$\frac{Emittance\,(x)}{Emittance\,(1RMS)} \qquad (2)$$

where x can be between 90% and 100% of the distribution. In the same spirit, a "halo parameter" has been defined as the ratio of nth moments of the distribution

$$\frac{4th\ moment}{2nd\ moment} \qquad (3)$$

The latter was first suggested by [2] for a 1-D geometrical space and then extended to a 2-D phase space [3]. The idea was to characterise the kurtosis, a measurement of the difference in the peakedness with a Gaussian distribution. Contrarily to the definitions (1) and (2) which are model independent, (3) involves a dynamical point of view, as such a halo parameter is an invariant of motion in the presence of only linear forces.

The definitions of these types are useful in the sense that they give an idea of the relative importance of the halo. That is why the term of "halo parameter" is more suitable as they are rather abstract quantities that do not aim to give a concrete measurement of the halo itself. They suffer nevertheless from three defaults:

- They presuppose where the core part is and where the halo part is. The first one is presupposed to be 1 RMS or 2nd moment while the second is presupposed to be 3 or 5 rms, or 95% of the beam, or 4th moment.
- The reference distribution is the Gaussian one, which is not free of halo. In high-intensity machines, beam distributions significantly differ from Gaussian one, with a halo tail more or less important, independently to the

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core that can be more or less peaked than the Gaussian distribution.

There is no direct link, between these definitions and the halo particles that can be intuitively distinguished when visually examining a beam profile.

The consequences are that there is still a need to search for a clear, concrete, quantitative estimation of the halo in the most general case for any distribution type. That is particularly necessary for every operation on the beam like design, cleaning or measurement.

The relationship with emittance growth is neither very clear. Indeed, in [3] it was noticed that "… we find it is possible to have emittance growth without halo growth (however, halo growth always implies emittance growth)." In [4] it is claimed that for the IFMIF very high-intensity linacs, sometimes a perfect "halo matching" can come with a very strong emittance growth while a tuning with less emittance growth can lead to a stronger halo growth.

THE SUGGESTED DEFINITION

The idea is to stick to visual observation of the beam where the core part or the halo part can be clearly identified and only a clear border between the two remains to be determined.

This definition should also be capable to treat every distribution type, whatever the dimensions of space, without going against clear evidences. For example a hard edge square distribution or a uniform distribution within an ellipse in 2D are both free of halo, while their density profiles projected in 1D space are quite different and very different from a Gaussian function. On the other hand, possible halo tails with big size and low density, or small size and high density, must also be pointed out, independently of the core that could be less or more peaked than a Gaussian distribution.

Let us consider the case of a "gas" of particles with a non-zero and variable density gradient. This "gas" can be considered as hosting two different environments if and only if there exists a border between them. We suggest defining this border as the location where the gradient variation is the steepest, that is, in 1D where the second derivative of the density is maximal, in nD where the Laplacian of the density is maximal.

This point of view refers to the diffusion phenomenon that is governed by the equation

$$\frac{dn}{dt} = D\,\Delta n \tag{4}$$

where n is the density, D the diffusion coefficient. The border of two different gases (or liquids) is the location where there is the maximum diffusion, where Δn is maximal. The diffusion phenomenon is an unavoidable phenomenon in any particle distribution because it is due to random motion of every particle. Even it may not be the dominant phenomenon, it is always there in any circumstance. In this sense, this definition is model independent, as no consideration about particle dynamics has been made but a basic and inherent phenomenon common to all gases of particles.

In our case, the maximum of the second derivative conveniently determines a border between the core part and the halo part which is very close to a visual examination, as it corresponds to the biggest change in the density profile slope. It can be applied to a continuously as well as a sharp varying density. For a Gaussian profile, this border is located at $\pm\sqrt{2}$ RMS.

Figures 1 to 4 show examples of simulated beam density profiles at different critical locations of the IFMIF prototype accelerator. The border between core and halo parts is given by the position of the second-derivative maximum. As it is obtained by numerical derivation, special care is needed in correctly smoothing the profile curve in order to limit numerical noises. It can be seen that the importance of the halo tail corresponds well to an intuitive examination and is completely independent to the peakedness of the central part.

Once this limit between core and halo is determined, the halo part can be defined by two different quantities, related to its size, and the number of particles it contains. The percentage of halo size and the percentage of halo particles can be considered:

$$PHS = 100\,\frac{Halo\ size}{Total\ beam\ size} \tag{5}$$

$$PHP = 100\,\frac{Nb\ of\ Particles\ in\ the\ Halo}{Total\ Nb\ of\ particles} \tag{6}$$

These definitions of the halo have the advantage to offer concrete numbers for characterising the halo at a given position and its evolution along the acceleration structure. They also show very clearly the place of the halo within the beam. It can be deduced that during the design of high intensity beams aiming at minimising risks of losses, the ideal is to minimise the total beam size along with PHS, PHP. In case it is not possible, a compromise could be taken by granting the priority to the total beam size first, then to PHS, keeping the lowest priority to PHP. For halo cleaning with scrapers during beam operation, PHS and PHP allow to estimate the part and the fraction of the beam to be removed. Downstream halo reformation can also be quantitatively measured and appreciated. Indeed, what, where and how much to measure when wanting to measure the halo have clear and concrete answers with PHS and PHP.

Preliminary studies with these new halo definitions have been performed on the IFMIF beam for different tunings. Cases with more or less emittance growth and simultaneously less or more halo growth (visually) have been checked. First analyses suggest that the PHS and PHP criteria can help to describe more precisely and in more details the beam behaviour than the precedent halo parameters. The connection with emittance is clearer. Furthermore, PHS and PHP together could be even more pertinent to describe the beam than the emittance itself. But as they result from two successive numerical derivations, some noises can perturb the interpretation.

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CONCLUSION

High-intensity beam implies high beam power and high space charge. High beam power makes that a great importance must be granted to losses, even when they are tiny (microlosses for MW beam power). High space charge makes that classic RMS quantities like beam envelope or emittance are not enough for describing the beam behaviour. All this makes that beam halo become the main figure of merit for high intensity accelerators. Quantitative, clear and concrete definition of halo is then crucial. This paper suggests to determine the limit core/halo as the location of biggest density slope variation, and the percentage of halo size along with the percentage of halo particles, PHS and PHP, to characterise the beam halo. More detailed studies remain to be performed to confirm the apparent pertinence of these halo definitions.

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FIGURES

In the following figures, the density profile is represented by red asterisks, its first derivative by a blue line and ist second derivative by a green line. The imit core/halo is given by the position of the second derivative positive peak.

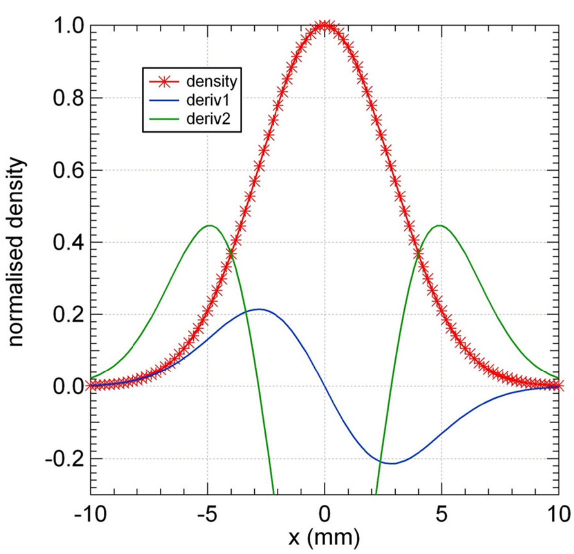

Figure 1: Gaussian density profile. The second derivative peak is located at $\pm\sqrt{2}$ RMS.

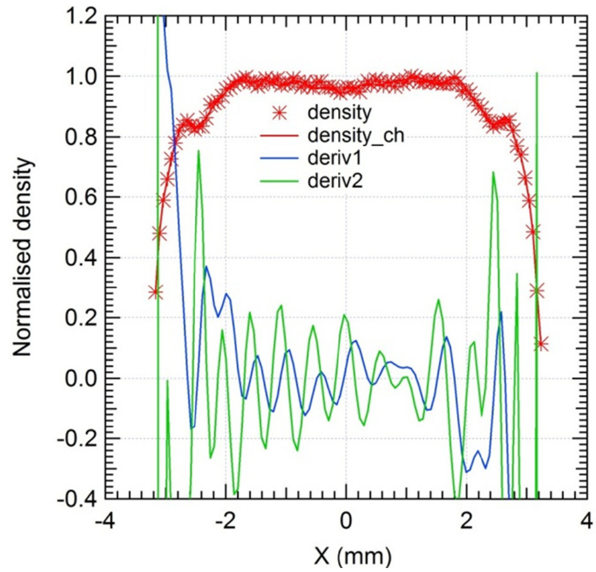

Figure 2: Horizontal beam density at source exit.

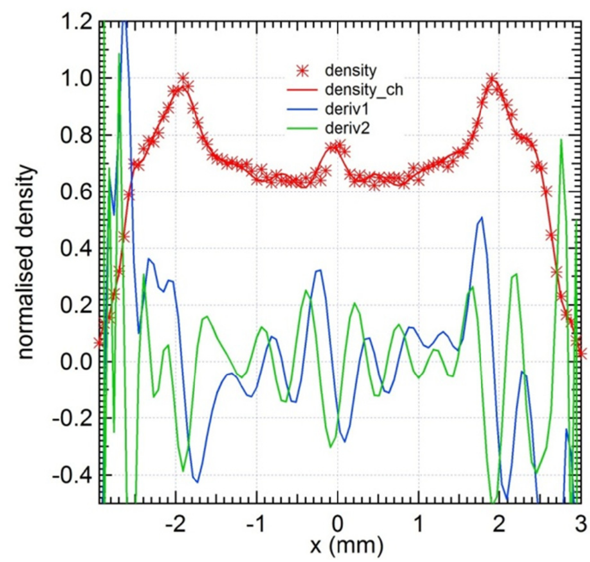

Figure 3: Horizontal beam density at LEBT exit

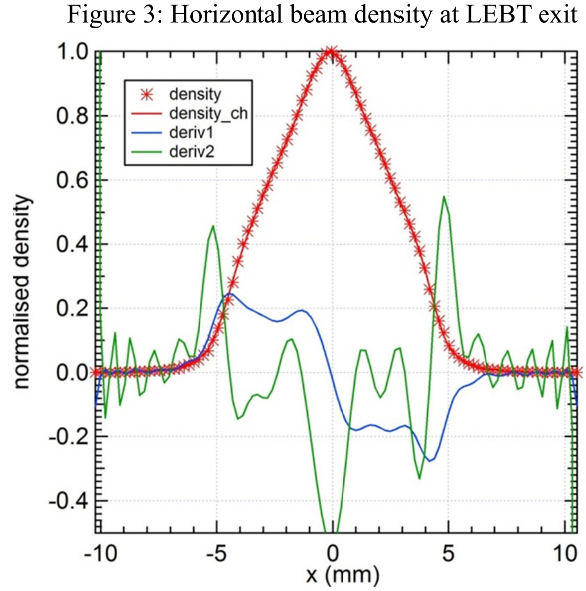

Figure 4: Horizontal beam density at Linac.exit

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