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Core-halo issues for a very high intensity beam

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The relevance of classical parameters like beam emittance and envelope used to describe a particle beam is questioned in case of a high intensity accelerator. In the presence of strong space charge effects that affect the beam differently following its density, the much less dense halo part behaves differently from the much denser core part. A method for precisely determining the core-halo limit is proposed, that allows characterizing the halo and the core independently. Results in 1D case are given and discussed. Expected developments extending the method to 2D, 4D, or 6D phase spaces are examined. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4866400]

It is often necessary to employ a statistical description to characterize the millions or billions of particles in an accelerator beam bunch. If each particle i is described by q_i, p_i, the spatial and momentum coordinates in either the horizontal, vertical, or longitudinal directions, it is usual to introduce the statistical second moments

$$\varepsilon = \sqrt{\langle q_i^2\rangle\langle p_i^2\rangle - \langle q_i p_i\rangle^2}, \tag{1a}$$

$$\alpha = -\langle q_i p_i\rangle/\varepsilon, \tag{1b}$$

$$\beta = \langle q_i^2\rangle/\varepsilon, \tag{1c}$$

where $\langle\ \rangle$ stands for the average over the particles. ε is called the emittance and α and β are the Twiss parameters. In case of linear transport along the accelerator, these parameters are relevant to describe the particles, as they can be themselves transported by appropriate matrices. For a high-intensity beam, internal space-charge forces between particles of the same bunch will no longer be negligible and deviations from linearity can be noticed. An example with the IFMIF (International Fusion Materials Irradiation Facility) prototype accelerator is given in Ref. 1, where the 125 mA Deuteron beam is transported 3.5 m downstream, through only 3 quadrupoles. Two different distributions, one Gaussian and one "nominal" (coming from the ion source), although having exactly the same emittance and Twiss parameters at entrance, lead to substantially different parameters at exit. Especially, in the vertical plane, the difference between output α and β reaches 20%, and up to 35% for output ε.

This clearly demonstrates that global statistical second moments are not enough for characterizing high-intensity beams. The reason is that space charge effects that depend directly on the particle density will be very different in the dense core and in the much less dense external part, the halo. Core and halo behaviors will be different and need to be characterized independently, especially when the halo is significant. Furthermore, as the halo is the source of beam losses that are really harmful considering the MegaWatt-class beam power, it is crucial to survey the mechanisms of core-halo interaction and those of core or halo growth. A quantitative description of the halo and the core, as well as its precise measurement, are therefore essential. Yet, no concrete determination of what is the halo and what is the core is available. This article first briefly reviews the existing methods used for characterizing the relative importance of the core and the halo. Then a definition of the core-halo limit is proposed and the resulting consequences discussed. Examples of beam behavior are given for the IFMIF accelerators described in Ref. 2, simulated with the TraceWin code.[3]

Until now, even for high-intensity beams, the core is commonly described by the classical ε, α, β parameters. In contrast, halo characterization has been the subject of considerable additional effort. An international workshop fully dedicated to the definition and measurement of the halo has been organized,[4] where it appears that there is no consensus for a clear and universal definition of halo relevant for any beam distribution type. Since then, different considerations have been adopted in different situations, often based upon comparisons between parts of the beam "far from" and "close to" the beam core.

A definition widely adopted is that proposed in Ref. 5 in 1D and extended to 2D in Ref. 6 and is based on the ratio of the fourth moments to the second moments. This is very close to the kurtosis parameter used for comparing the "peakedness" of a distribution to that of a Gaussian. This defined halo parameter is an invariant in case of linear transport and allows to have an idea of the halo importance. It is, however, an abstract parameter that does not provide concrete knowledge of either the location or the extent of the halo. Its meaning is also difficult to interpret when a distribution can be flatter but with a bigger halo or more peaked but without halo. Typically, a pure triangular or parabolic distribution, which both do not have halo, would be associated with different non-zero halo parameters.

Other studies adopt as definition of halo parameter the ratio of particles contained in the r% external part over s% internal part or r x rms over s x rms, r being well larger than s. This could give a correct image of the halo, at the condition to permanently and suitably adjust r and s to each particular beam evolution. If r and s are let unchanged, it is as if we want to characterize the importance of the halo relatively to the core while we have decided in advance where they should be.

A precise definition of the core-halo limit—suitable for the description of any type of distribution—has not yet been found. Such a definition has been introduced for discussion in Ref. 7. It is consolidated and developed in more details here, and the consequences exposed in the following. A high intensity beam can be described as a combination of[8]

- the central core, very compact and dense, where linear forces are dominant, leaving the emittance unchanged
- the external halo, much less dense, where some particles have been sent after gaining extra energy and where non-linear forces are dominant, leading to emittance increase.

Let us consider the case of a dense, uniform core where self-forces are strictly linear, surrounded by a non-uniform and very few dense halo. In such a configuration, the core-halo limit is clearly given by the location where the density gradient abruptly changes from small variations in the halo to a very steep (infinite) variation when arriving on the "wall" of the core uniform distribution.

For a more realistic distribution presenting a similar topology but where the density gradient continuously varies, the core-halo limit definition can be generalized as the location where there is the steepest density gradient variation, that is where the Laplacian of the density is maximum. In 1D, it corresponds to the second derivative's maximum (not to be confused with the second derivative's zero, which is the inflection point).

Intuitively, when looking at different distribution types, the external halo can be "easily" seen, either by the "foot" of the density profile in 1D, or the change of the color encoding the density in 2D, or by the brim of the "hat" representing the density in 3D representation. This corresponds to the above definition of the core-halo limit, meaning that, although based on the dynamics of the beam, this definition can be used in any other fields in physics where there are different layers of gas or liquids with continuously varying density, as in planetary atmospheres, stars, plasmas, laser beams, etc. These considerations being fully valid in the real space (q_i), we propose furthermore to extend it to the phase space (q_i,p_i), as we can in the same way define the density in the phase space. This makes this definition also applicable to any phenomenon whose parameters can be represented as a cloud of points in an nD space.

Such a distinction between core and halo would help to highlight the different physical mechanisms involved in the two parts, whatever the nature of the objects, beam particles, or others. Only notice that in case of multicomponent population of objects, for example, particles of different nature or energy, the interpretation could be more delicate.

In order to study the relevance of the definition proposed here, we have applied it to various 1D density profiles in Fig. 1 where first and second derivatives of the density profile are also shown. We can see that for a Gaussian profile with σ RMS, the 2nd derivative maximum is as well at $\sigma\sqrt{3}$ as expected, and for other profiles, it is around the visually expected position. Notice, in particular, that the halo size is not related to the distribution flatness. We have also verify that for various distributions with sharp edges, like a K-V (Kapchinsky-Vladimirsky[9]), or triangular, or parabolic one, no halo has been detected.

To achieve those results, a few precautions must be taken, considering that derivative numerical calculations are the worst case for noise amplification. Calculating the derivative a second time can lead to a totally unusable result. To overcome this difficulty, it is usually recommended to smooth or approximate the function to be derived with polynomials that can then be analytically derived as many times as desired. But beam density profiles vary very rapidly over many decades, typically 10^{-6}–10^{0}, which is not the case of polynomials. Furthermore, we must have a very accurate representation of the function for all the decades, at low values as well as at high values, as we want to scrutinize the transition between the two regions. Most importantly, any direct smoothing of the initial function will blur out the specific rapid changes of the function for which we are searching. The method we have found, which overcomes these difficulties, consists of calculating n derivatives around a given point and taking the average of them, without changing the initial function. More precisely, the derivative of the function f(x) at the i_0th point is given by

$$f'(x_{i0}) = \frac{1}{n}\sum_{i=1}^{n}\frac{f(x_{i0+i}) - f(x_{i0-i})}{x_{i0+i} - x_{i0-i}}. \qquad (2)$$

Typically, for 200 bins of the density histogram, n = 10, i.e., 5% of the bins, seems to be a reasonable value.

Let us now apply this precise definition of the core-halo limit to characterize the evolution of the beam along the accelerator. In case of linear transport, it is very common to represent the beam along the accelerator by its so-called "rms envelope" given by

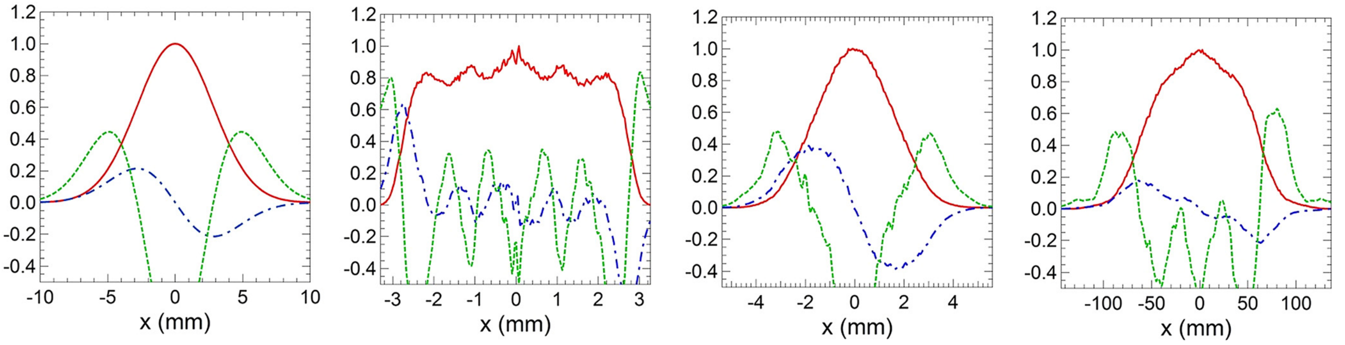

FIG. 1. Normalised beam profile density projected in the horizontal direction (continuous, red), its first and second derivatives (resp. dot-dash, blue then dash, green), for respectively (from left to right) a Gaussian distribution then distributions at IFMIF RFQ entrance, exit and HEBT exit.

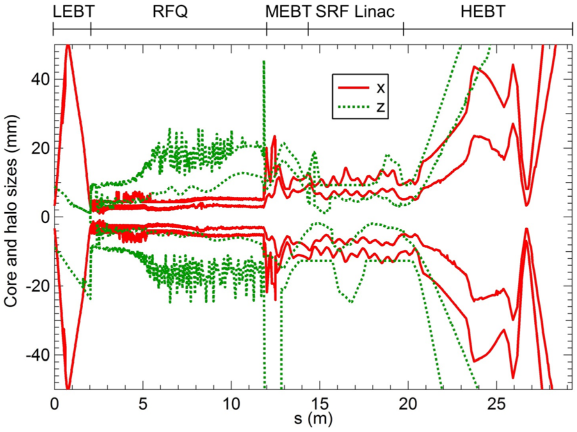

FIG. 2. Core size (internal line) and halo size (external line) for the position coordinates x, z along the Linear IFMIF Prototype Accelerator.

$$\langle q_i \rangle = \sqrt{\beta\varepsilon}. \tag{3}$$

In case of very high intensity beam, the evolution of the core and the halo should be shown instead. We propose to represent the external limits of the core and the halo along the accelerator, as shown in Fig. 2, taking as an example the results from start-to-end simulations of the linear IFMIF prototype accelerator. The continuous beam extracted from the source expands very strongly under strong space charge effects, then is focused and injected into the RFQ (Radio Frequency Quadrupole). There, thanks to the almost continuously focusing, the beam transverse sizes remain small. They increase abruptly when passing to the less focusing parts, the MEBT (Medium Energy Beam Transport) then the HEBT (High Energy Beam Transport), and are strongly expanded on the beam dump. The longitudinal sizes are more perturbed when there is more acceleration and thus are bigger in the RFQ than in the SRF (Superconducting Radio Frequency) Linac. A classical description of emittance and beam envelope will not capture this longitudinal behavior, nor will distinguish the evolution of the core from that of the halo.

Being able to distinguish between core and halo evolution also means that it is possible to quantify the relative importance of the halo to the core, which is really a figure of merit. It is a quality indicator for the design of a high-intensity accelerator. It must be reduced as far as possible to minimize risks of beam losses. Until now, this is done by rather indirect criteria, as reducing emittance growth, or reducing beam envelope beating. As discussed above, these parameters are not enough meaningful in case of space charge dominated beam and furthermore their relation to halo growth is not straightforward. More direct or concrete parameters can be used. For example, the percentage of halo size or the percentage of halo particles can be considered

$$PHS = 100\frac{Y_h}{Y_b}, \tag{4}$$

$$PHP = 100\frac{N_h}{N_b}, \tag{5}$$

where Y_h is the halo size (total bunch size minus core size), Y_b the total bunch size, N_h is the number of particles within the halo, and N_b the total number of particles in the bunch. The Percentage of Halo Size (PHS) and Percentage of Halo Particles (PHP) parameters offer concrete numbers for characterizing the relative importance of the halo at a given position and its evolution along the acceleration structure. The halo density may also be a useful parameter to consider, but its progression is similar to PHP. Ideally, to limit beam loss risks, the total beam size as well as PHS and PHP should be minimized. When that is hard to achieve, some of these constraints can be relaxed, depending on the objective. For a short structure that can be optimized as a whole, minimizing the beam total size is enough to prevent losses. For a longer structure, PHS and then PHP, in this order of priority, must be minimized in order to avoid a too important development of the halo that could induce losses downstream.

The PHS and PHP parameters are also useful for concrete actions on the halo, like halo measurement or scraping. They indicate precisely the part of the beam and the fraction of particles (thus the beam power) with which the instrumentation should interact. After halo cleaning with scrapers, measurement of PHS and PHP downstream will allow to quantitatively appreciate the cleaning efficiency and if there is any halo reformation.

An example of PHS and PHP is given in Fig. 3 for the start-to-end simulation of the IFMIF prototype accelerator. Much information can be extracted from these figures. Let us first comment on the transverse beam sizes in the MEBT section, right after the RFQ exit. At this location, the beam passes from a strong focusing environment to a more weakly

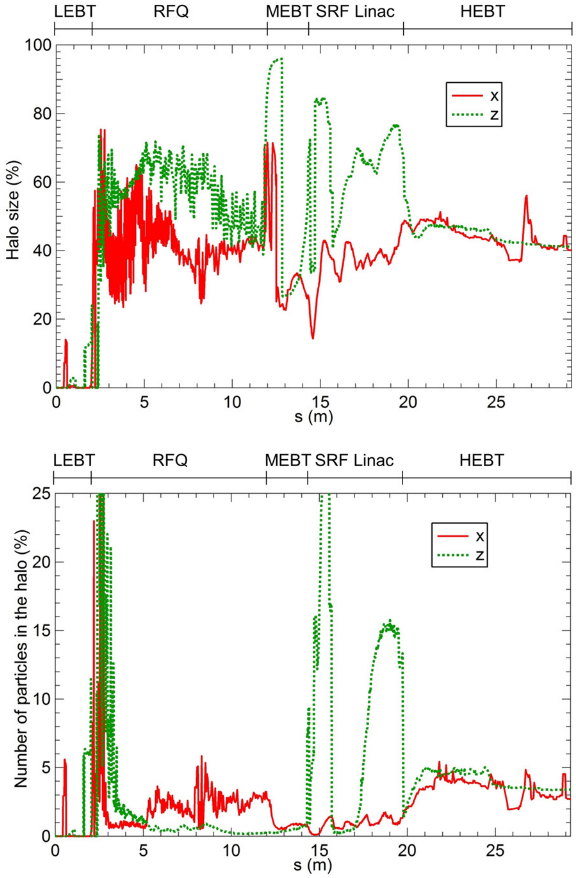

FIG. 3. The Percentage of Halo Size (PHS, top) and Percentage of Halo Particles (PHP, bottom) along the Linear IFMIF Prototype Accelerator.

focusing one, inducing a rapid emittance increase due to a space charge dominant regime, following by an emittance stabilization due to an emittance dominant regime, where the charges are redistributed to shield the beam from external forces, resulting in a more compact profile. This classical mechanism is perfectly described in Ref. 8 and highlighted in the case of IFMIF in Ref. 2. In Fig. 3, it can be seen clearly that the halo grows violently then decreases to almost zero afterwards. That means that an emittance growth is not inevitably associated with halo growth, as in this case core growth is more important than halo growth, well typical of the charge redistribution mechanism. More globally, the halo importance given by PHS and PHP is not much larger towards the end of the structure than in the RFQ, while the emittance is larger by a factor of two. The examination of the longitudinal halo shows that it is very important within the acceleration structures and is well lower in the pure transport section, which is neither seen by the emittance nor envelope examination.

The core-halo limit determination and all the above discussions for the position coordinate (p_i) can also be applied to the momentum coordinate (q_i) and more generally to the 2D, 4D, or 6D phase spaces as well, by using the maximum of the Laplacian instead of the second derivative. Such developments are being implemented. These will be applied to study mechanisms of halo formation[10–12] or of particle exchanges between halo and core.[13,14] In 2D and 4D, the PHS and PHP parameters will no longer exhibit oscillations due to halo transfers between the position and momentum coordinates, but they can be used to study transfers between horizontal, vertical, and longitudinal directions. In 6D, evolution of the "global" halo can be studied, but transfers between different directions, for example, between transverse and longitudinal, can no more be seen.

Once the core-halo limit is determined in a given phase space, the particles of each part are clearly identified, then the emittance and the Twiss parameters can be defined separately for the core and the halo with the formulas (1). These two sets of parameters can replace the only set commonly used for the whole beam. They will provide a more complete description of the beam in the presence of strong space charge effects.

From that, global parameters for the whole beam can be easily obtained. As pointed out by,[15,16] when the fraction of particles constituting the halo

$$f = \frac{N_h}{N_b} \tag{6}$$

is known, any global average parameter can be deduced from the core and halo corresponding parameters. If G_i is such a parameter, its average can be expressed as

$$\langle G \rangle = \sum_{i\ bunch} \frac{G_i(q_i, p_i)}{N_b}, \tag{7}$$

where the sum extends over all the particles of the beam bunch. With N_c, the number of particles in the core, it can be split into

$$\langle G \rangle = \frac{N_c}{N_b} \sum_{i\ core} \frac{G_i(q_i, p_i)}{N_c} + \frac{N_h}{N_b} \sum_{i\ halo} \frac{G_i(q_i, p_i)}{N_h}. \tag{8}$$

As $N_b = N_c + N_h$, we have

$$\langle G \rangle = (1-f)\langle G \rangle_{core} + f \langle G \rangle_{halo}. \tag{9}$$

In summary, we pointed out that for high intensity beams, the classical statistic parameters like emittance, Twiss parameters, or beam envelope are no more enough meaningful. A method for determining the core-halo limit is proposed, based on the dynamics of the beam. The resulting parameters, PHS and PHP, can be used to study the importance of the halo as compared to the core. Characterization or mitigation of the halo can be obtained by direct measurement or minimization of these parameters, while connections with the classical beam emittance are rather questionable. An initial application to the 1D position coordinate has demonstrated the feasibility and the relevance of the proposed method. Extension to 2D, 4D, or 6D phase spaces is straightforward in principle and is currently underway. The core-halo limit can replace the classical beam envelope, then the emittance and Twiss parameters of core and halo particles separately can replace the same only parameter set for the whole beam. This allows independent study of the evolution of the core and the halo, leading to a more comprehensive description of the beam in the presence of significant levels of space charge.

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