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A PRECISE DETERMINATION OF THE CORE-HALO LIMIT

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Abstract

For high-intensity beams, the dynamics of the dense core is different from that of the much less dense halo. Relations between core emittance growth and halo generation are often studied, halo scraping often experienced and halo re-formation observed. For all that, a clear distinction between the core and the halo parts does not exist. This paper proposes a new method for precisely determining the core-halo limit applicable to any particle distribution type. Once this limit is known, the importance of the halo relative to the core can be precisely quantified. It can be more generally used to characterise the beam along an accelerator.

THE CORE-HALO ISSUES

In high intensity linacs, the beam experiences strong self forces coming from the important space charge electric field. Those nonlinear internal forces induce emittance growth and halo formation, two more or less linked mechanisms that lead to particle lost on the pipe wall. As furthermore high intensity often implies high power, the beam power contained in the halo can be significant. That is why a great attention is devoted to the halo behaviour. Not only beam core, beam halo is also a figure of merit in high intensity machines.

It is common to minimise emittance growth and halo expansion in the design or the tuning of an accelerator. Equipment has also been fabricated and installed for measuring or scraping the halo. Despite that, no clear definition of what or where is the halo has been widely agreed [1]. It is not straightforward to quantitatively appreciate if the halo has been minimised or if the beam core has also been minimised. Beam instrumentation teams in charge of measuring the halo often wonder which part of the beam should be measured.

More fundamentally, the very dense core and the much less dense halo are subject to different dynamics, and any distinction between them only makes sense if it reveals this internal dynamics of the beam.

Until now, attempts to quantify the importance of the halo consist in considering the ratio of statistic quantities of the particle coordinates 'far' from the beam centre to that 'close' to the beam centre. The halo parameter widely used is the ratio of the fourth moment to the second moment of particle coordinates [2], [3]. It is also common to use the ratio of 90 or 99 or 99.9% emittance to rms emittance, or n-sigma emittance to 1-sigma emittance, n being larger than 3.

Those ratios allow to have an idea of the importance of the halo, for a given beam distribution. But they are abstract parameters that cannot allow to quantitatively characterise the halo, its location, its extension nor the number of particles involved. Furthermore, it is necessary to carefully choose beforehand where would be the core and the halo for each type of distribution.

A precise determination of the core-halo limit is needed, allowing to quantitatively characterise the halo for various beam distribution types.

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This is possible for any density distribution type when extrapolating from the case of dense uniform core surrounded by a much fewer dense halo [4]. For the latter, the core-halo limit is obviously the location where there is the abrupt change in density, exactly at the border of the uniform part. In case of a more realistic beam distribution where the density continuously varies, the core-halo limit can be equivalently defined as the location where there is the largest slope variation in the density profile, i.e. where the density second derivative is maximum (see Fig. 1). Notice that this is not the inflexion point that is the zero of the second derivative, nor the steepest slope that is the maximum of the first derivative. The criterion here is the biggest slope variation. The interest of this clear distinction between core and halo is that it reveals the internal dynamics of the beam which is governed by two different self-field regimes [5].

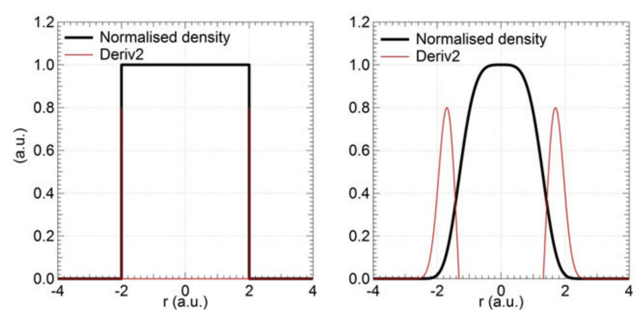

Figure 1: Uniform and continuously varying density profiles with their corresponding second derivatives.

The core-halo limit determined by this way is, as expected, independent of the general shape of the distribution profile. A dissymmetric profile can as well be considered. A flat or peaked profile can have either a big halo or not. A pure Gaussian profile with σ RMS has a halo starting from $\sigma\sqrt{3}$, containing thus 8.3% particles of the beam, which is a rather important halo. A Generalised Gaussian profile has a smaller halo when its shape is flatter [6]. And, as expected, the profiles with sharp external border like K-V, triangular or parabolic ones do not have halo.

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This core-halo limit determination is applied in Fig. 2 to beam distributions at some key positions along the IFMIF-LIPAc accelerator [6]. The distribution types are very different from each other and often very far from a Gaussian one. Those in the longitudinal plane (not shown here) are even much less regular and often strongly dissymmetric. For all these various profiles, the limits correspond well to what can be visually detected, i.e. close to the limit of the 'foot' of the profiles. To achieve those results, the second derivative must be carefully calculated. Indeed, as a derivative numerical calculation strongly amplifies noises, calculating the derivative a second time can lead to a totally unusable result. As specified in [4], classical techniques to smooth the initial profile with polynomials are not suitable in this case. The technic of 'sliding' derivative without modifying the initial function can overcome those difficulties.

Attention must be paid for a multicomponent beam involving several beams of different particles or different energies. Second derivative maxima's would delimit the different beams that are governed by different physical mechanisms. A careful analysis must then be carried out to see which halo, if any, corresponds to which beam.

CHARACTERISING THE HALO

Once the halo limit is clearly determined, the halo can be characterised by two quantities, PHS and PHP which are respectively the percentage of halo size and of halo particles:

$$PHS = 100\frac{Halo\ size}{Total\ beam\ size} \tag{1}$$

$$PHP = 100\frac{Nb\ of\ Particles\ in\ the\ Halo}{Total\ Nb\ of\ particles} \tag{2}$$

PHS and PHP offer concrete numbers for characterising the relative importance of the halo at a given position and its evolution along the acceleration structure. Ideally, to limit beam loss risks, the total beam size as well as PHS and PHP should be minimised. When that is hard to achieve, some of these constraints can be relaxed, depending on the objective. For a short structure that can be optimised as a whole, minimising the beam total size is the most efficient to prevent losses [7], [8]. For a longer structure, PHS and then PHP, in this order of priority, must be minimised 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.

CHARACTERISING THE BEAM

Particle beams are usually characterised by statistical moments of the particle coordinates, giving rise to the well-known Twiss parameters and emittance. The latter are combined in their turn to give the concept of 'beam envelope', otherwise known as 'RMS beam size'. But in the presence of strong space charge forces, that characterisation is no more satisfying. As shown in [9] for the IFMIF prototype linac, a 9 MeV-125 mA Deuteron beam with exactly the same Twiss parameters at entrance but different density distributions, transported 3.5 m downstream through only 3quadrupoles will lead to substantially different Twiss parameters at exit. It is clear that high intensity beam transport is distribution dependent. For such a beam, space charge forces play an important role in its dynamics. As they depend on the particle density, a different distribution of particles in the core versus the halo will lead to a different beam at exit.

It is therefore more meaningful to characterise the high intensity beam in such a way that core and halo are clearly distinguished. A precise determination of the core-halo limit allows doing that. Instead of beam envelope and the associated beam emittance, core size and halo size can give a precise and more exhaustive view of the beam extension. Instead of halo parameter, PHS and PHP can give a more concrete idea of the halo importance. Fig. 3 compares those two characterisations for the case of the IFMIF-LIPAc prototype accelerator, from source extraction to final beam dump. Comparisons between different halo calculation methods are made in [10].

Furthermore, as the method can be applied to any density profile, it can be applied as well to the angle coordinates. Extension to nDimension is also possible by examining the maximum of Laplacian. Studies are currently underway to determine the core-halo limit in the nD phase space. The halo and the core can then be characterised by their own Twiss parameters and emittance, paving the way to clearer studies of core and halo evolutions and interactions.

CONCLUSION

Strong self forces in high intensity beams make beam halo play an important role. A precise determination of the core-halo limit is proposed. It allows to quantitatively characterise the halo and more generally the beam in a more appropriate and exhaustive way.

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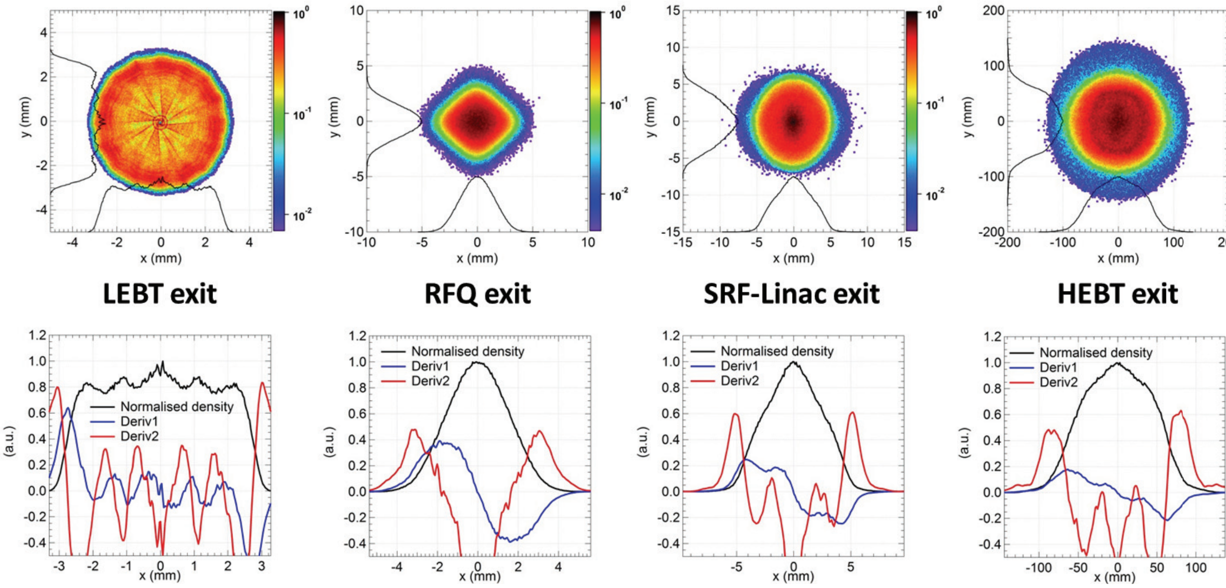

Figure 2: Beam density distribution at some key positions along the IFMIF-LIPAc accelerator.
Top: Density in the transverse plane (x,y) with its projection profiles in x and y directions.
Down: Density profile in x and its 1st and 2nd derivatives.

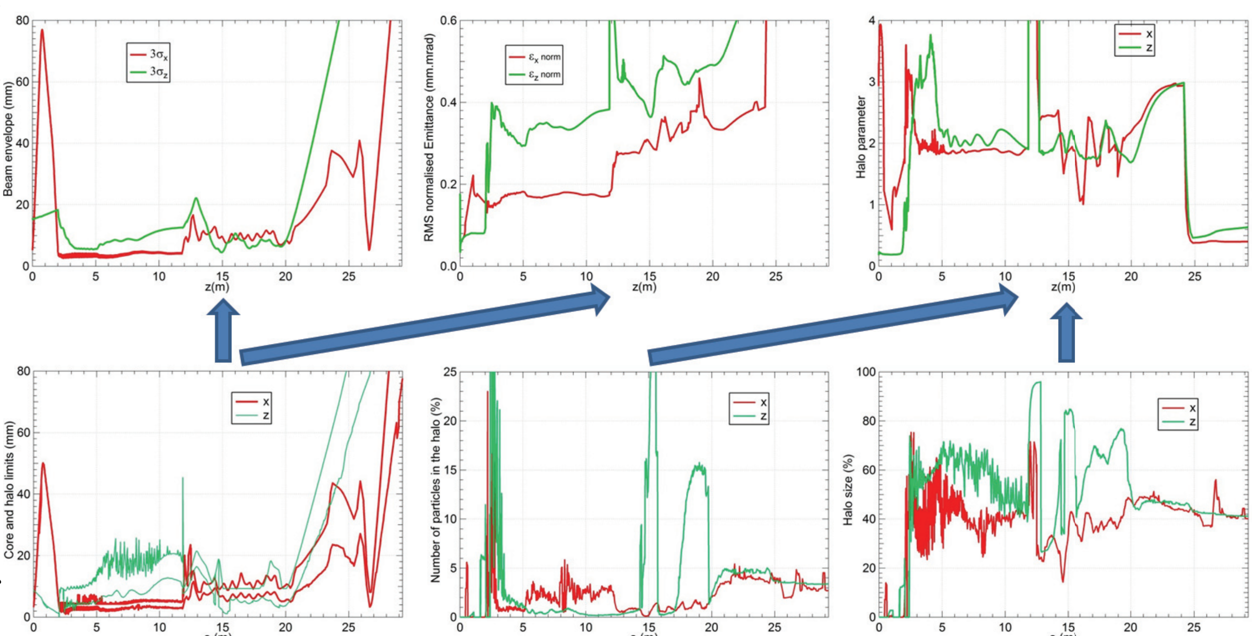

Figure 3: Beam characterisation in horizontal (x, red) and longitudinal (z, green) along the IFMIF-LIPAc accelerator, from source extraction to final beam dump.
Top: Classical characterisation by 1-beam envelope, 2- rms emittance, 3- halo parameter.
Down: Proposed characterisation by 1-core and halo limits (internal and external lines in the graph), 2-PHP, 3-PHS