ADVANCED CONSIDERATIONS FOR DESIGNING VERY HIGH INTENSITY LINACS THROUGH NOVEL METHODS OF BEAM ANALYSIS, OPTIMISATION, MEASUREMENT & CHARACTERISATION

P. A. P. Nghiem*, N. Chauvin, W. Simeoni Jr., D. Uriot
CEA/DSM/IRFU, 91191 Gif-sur-Yvette Cedex, France

Abstract

In high intensity linacs, not only high beam power but also high beam space charge are the major challenges. This double concern often induces conflicting issues, which should be overcome from the accelerator design stage. It appears more and more that the usual methods are no more sufficient. Even new concepts are to be invented. With megawatt beams, losses and also microlosses must be minimised while with very strong space charge, few room can be reserved for beam diagnostics. New strategies for design and tuning are to be carried out. The beam itself can no more be described only by its classical values like emittance and Twiss parameters. Core and halo parts should be instead precisely defined and kept under surveillance.

This paper aims at proposing new considerations for very high intensity linacs while recalling the usual ones, from optimising and measuring procedures to beam analysis and characterisation.

INTRODUCTION

Researches in fundamental physics, nuclear physics or advanced materials, require irradiation sources involving linear accelerators with higher and higher beam intensity. In such accelerators, not only beam power but also beam space charge are the main challenges that will induce many issues, from the design stage to the operation one. Beam optimisation, measurement and tuning will all be affected. Usual strategies and recipes will no more be the most appropriate. New methods and concepts should be considered instead. Even the classical beam characterisation by its emittance and Twiss parameters may become no more enough. The core and halo parts should be in addition precisely described in order to understand and predict the beam behaviour.

In the following, these new aspects will be summarised while recalling the usual ones. First of all, taking the example of three different accelerators, the main challenges due to high intensity are discussed. Then new considerations to deal with the induced difficulties are exposed, especially beam optimisation and measurement. Finally, a beam characterisation according to core and halo parts is proposed.

ANALYSIS

Until recently, only the final beam power or beam power on target is pointed out as the main challenge for high-intensity linacs. It was very common to classify the accelerators according to this characteristic, in the graph representing the beam average intensity versus the final beam energy, like in Figure 1. Indeed, in this graph, lines of same beam power (0.1, 1, 10 MW) can be included, allowing to identify the position of different megawatt-class linacs. But this graph is highly reducing.

Let us take the example of three different proton linacs, called Accel A, B, C characterised by their average, peak intensities and their starting, final energies:

- Accel A: 125 mA, 125 mA; 0.1 MeV, 40 MeV.
- Accel B: 8 mA, 10 mA; 0.05 MeV, 1500 MeV.
- Accel C: 40 mA, 0.8 mA; 0.03 MeV, 600 MeV.

Their final beam powers are shown in Figure 1, and may suggest that Accel B will face the worst issues, followed by Accel A then Accel C. But this is not totally true, because of at least two reasons:

- The other issue, namely the beam space charge is not considered, and it cannot be deduced from this graph as it depends on the peak intensity and not on the average one.
- The accelerator upstream sections may face important difficulties or not, independently of the final section.

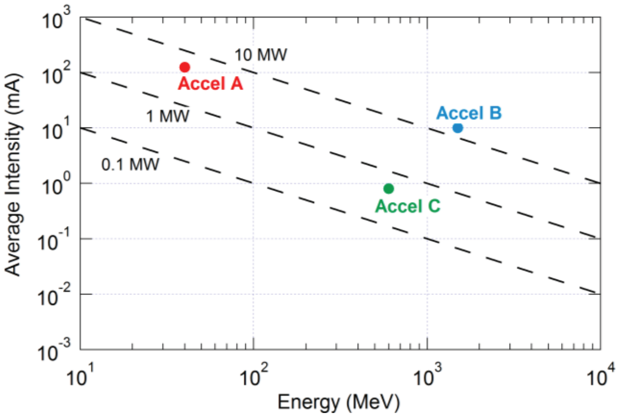

Figure 1: Beam average intensity versus final energy.

We propose to use two different graphs instead [1]: Figure 2 and 3 represent respectively the beam power and the generalised perveance versus the beam energy along the accelerator. It appears that for a given energy, i.e. for a given section of the accelerator, the Accel B beam power is indeed higher than that of Accel C, but from the space charge point of view, Accel C will face much more beam nonlinearities, thus halo, beam loss problems than Accel B. For its part, Accel A will have to face the worst issues. For a given energy, not only its beam power is higher but its space charge effects too. The combination of the two Figures 2 and 3 allows highlighting even more the critical aspect of the encountered difficulties. When considering a given beam power, for example 1 MW, the Accel A general perveance is more than 100 (resp. 1000) times higher than that of Accel C (resp. Accel B). That means

---

* phu-anh-phi.nghiem@cea.fr

that when the beam power is so high that even a tiny loss, i.e. 10^{-6} of the beam is critical, thus a very precise control of the beam is needed, the beam behaviour remains to be very difficult to predict.

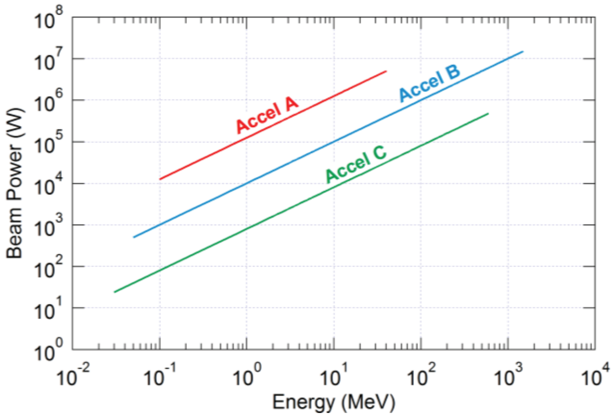

Figure 2: Beam power versus energy along the accelerator.

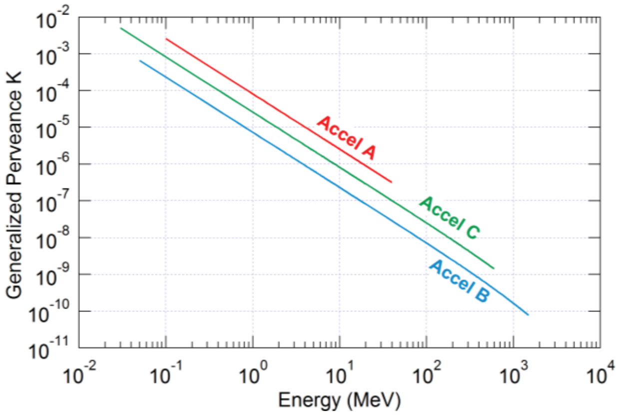

Figure 3: Beam generalised perveance K versus energy along the accelerator.

More precise analysis can be carried out when considering each section of the accelerators, from the Source Extraction to the HEBT, via the LEBT, RFQ, Linacs, etc. Figures 2 and 3 can be used to make meaningful comparisons for a given section between different accelerators. This allows, right at a design stage, either to be aware that the considered section is really challenging because the beam power or/and space charge is/are higher than those of all the other accelerators, or else to adjust the section starting/final beam energy in order to deal with beam power or space charge in the same range as existing accelerators. For example, the Accel C starting energy 0.03 MeV is very low, implying a huge space charge effect, even higher than that of Accel A. A quick look at Figure 3 let us know immediately that for their respective intensities, if the Accel C extraction source can go to 0.05 MeV, its space charge will be the same as of Accel A at extraction. Similarly, if the Accel B RFQ final energy is 3 MeV, the one of Accel A RFQ must be only 0.25 MeV (which is very easy) in order to have the same beam power, or up to 14 MeV (which is very difficult) in order to have the same space charge.

OPTIMISATION & MEASUREMENT

The question of beam dynamics optimisation in linacs is two folds: what are the parameters to be optimised? and how to optimise?

Classically, the parameter that must be taken care is the beam rms emittance. To limit as much as possible emittance growth is considered as the first priority because emittance growth means an irreversible beam size enlargement and possibly a source of beam halo formation. But with very high intensity linacs, the associated beam power can be so high that even very tiny losses of the order of 10^{-6} of the beam, called microlosses, must be avoided. These microlosses come from the very external part of the beam, i.e. the halo. Then the focus is displaced form the beam emittance, or the core, toward the halo. Beam halo is the figure of merit for high-intensity linacs. Optimisations aiming at direct minimisation of the halo has been performed for the IFMIF SRF Linac [2], leading to a satisfying margin between the beam external limit and the pipe wall. Concretely, the optimisation procedure consists in minimising for 10^6 macroparticles the extension of the most external limit of the beam, and making it as regular as possible along the structure. The problem is that during these optimisation studies, it is observed that a stronger reduction of the halo is often associated with a very important emittance growth. The adopted result is a compromise with not too much emittance growth. Another study aiming at minimising emittance growth in priority [3], especially by escaping the transverse-longitudinal coupling, allows on the contrary to obtain a smaller emittance, but with the external beam limit much closer to the beam pipe wall. Unless a better optimisation procedure is found taken better account of the emittance, the result using halo minimisation is adopted as the nominal one. Start-to-end simulations [4] confirm that this solution is suitable for the IFMIF accelerators, where microlosses are more important than emittance.

Notice that in order to avoid microlosses, this halo minimisation procedure should be at the precision of at least 10^{-6}. It is obvious that calculation codes cannot simulate the real beam behaviour at this precision, neither the real accelerator is reproducible at this precision level. Therefore, such an optimisation should be able to be performed on line as often as needed. For that, we ask for permanent measurements of microlosses, the closest to the beam and in sufficient quantity, so that the number of independent measurements is at least equal to the number of tuneable parameters, which are in our case the different solenoid focusing strengths. An on-line tuning procedure can then be implemented, relying on these beam measurements and using the same halo optimisation procedure as described above.

In very high-intensity linacs, the optimisation objective is specific, as well as the optimisation procedure. The latter should have its avatar as an on-line tuning procedure which must be associated with dedicated beam measurements in sufficient quantity.

CHARACTERISATION

According to the above discussion, the relevant parameter to be optimised in high-intensity linacs is the beam halo. In this context, the rms emittance is less important. Yet this emblematic value, together with the other rms values, namely the rms Twiss parameters, are classically used for characterising the beam. In fact, with the beam intensity increase, the rms values are no longer enough to characterise the beam.

Let us take the example of beam transport in the IFMIF prototype accelerator, at a rather 'gentle' area, starting from the HEBT entrance, where the 125 mA D^+ beam is already accelerated to its 9 MeV final energy. When considering two beam inputs with exactly the same rms values, one with the nominal distribution coming from source extraction, the other with a Gaussian distribution, the corresponding beam outputs 3.5 m downstream through simply three quadrupoles are very different. See Figure 4, nominal distribution is above and Gaussian distribution is below. The rms output values are also substantially different, especially in vertical.

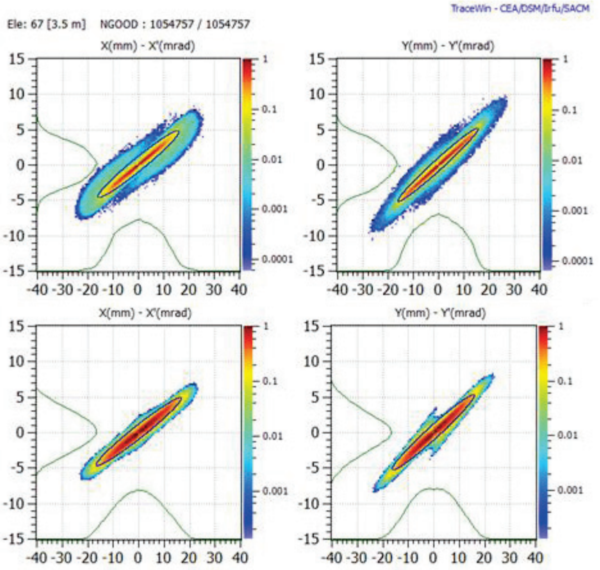

Figure 4: Horizontal and vertical beam phase spaces after transport through 3 quadrupoles of the IFMIF HEBT, coming from two different distributions at entrance, with strictly the same emittance and Twiss parameters.

All this demonstrates that the classical rms values are clearly not enough for characterising the beam. This is due to space charge effects that depend on the particle density, which therefore will be substantially different in the core part, much denser, and the halo part, much less dense. To understand the beam behaviour, the characterisation of the core and the halo separately will be necessary.

But until now, there is no consensus for a clear distinction between core and halo. Only a 'halo parameter' is used, trying to compare 'far-' to 'near-' centre beam areas. It can be either nth moment / 2nd moment [5] or n rms / 1 rms. These approaches presuppose where are located the halo and the core and only give an idea of the importance of the halo.

In order to determine a limit between core and halo according to their density, we suggest [6] to consider the beam as a gas of particles where the density gradient is continuously varying. In such a gas, the mechanism that depends tightly on the density is the diffusion mechanism, and the border between two different environments if any, is where the diffusion is maximum, i.e. where the Laplacian of density is maximum. In 1D, it is the maximum of the second derivative (Figure 5). Applied to a 2D or even 6D beam phase space, it is possible to clearly identify core, halo particles and then to determine their respective emittances and Twiss parameters.

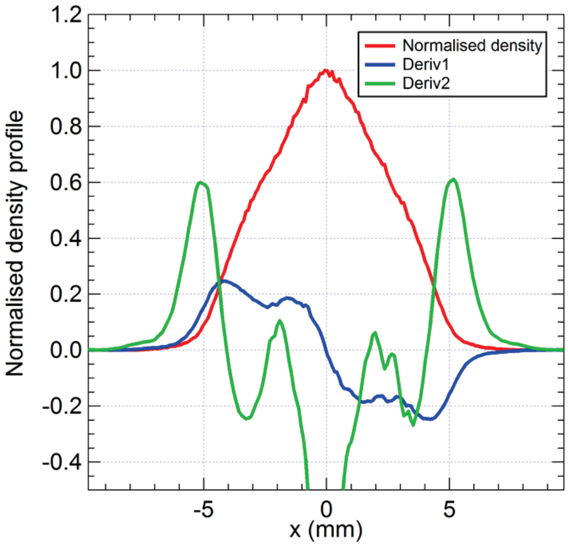

Figure 5: The core-halo limit can be clearly determined by the maximum of the second derivative of the density profile. Example of the beam at the IFMIF prototype HEBT entrance.

CONCLUSION

For the design of very high intensity linacs, we have proposed novel methods for analysing, optimising, measuring and characterising the beam.

REFERENCES

[1] P.AP. Nghiem et al., Nuclear Inst. and Methods, A 654 (2011), pp.63-71.
[2] N. Chauvin et al., Proc. of PAC 2009, TH5PFP005, Vancouver, BC, Canada.
[3] W. Simeoni Jr. et al., Proc. of IPAC 2011, MOPSO27, San Sebastian, Spain.
[4] N. Chauvin et al., Proc. of IPAC 2011, MOPSO26, San Sebastian, Spain.
[5] C.K. Allen and T.P. Wangler, Phys. Rev. ST Accel. Beams, vol. 5, 2002.
[6] P.A.P. Nghiem et al., Proc. of HB2012, THO3A404, Beijing, China.