CALCULATIONS OF HALO IN TRACEWIN CODE

N. Pichoff, P.A.P. Nghiem, D. Uriot, M. Valette
CEA, IRFU, F-91191 Gif-sur-vette, France

Abstract

The TraceWIN code is used to simulate the dynamics of the particles and to design linear particle accelerators. The growth of rms emittance along the accelerator is often used to estimate the quality of a design. For high beam powers, the aim is also to limit the production of halo in order to keep particle losses under a requested limit. We present in this article the different ways to quantify this halo in TraceWin.

INTRODUCTION

In high current linear accelerators, beam loss is a big concern as it produces prompt radiation and structure activation which can complicate, increase the cost and reduce the availability of the installation. The sources of these losses are multiple and are mostly accompanied by beam-halo production. The TraceWIN [1] code is used to design linac and simulate the beam dynamics. It should be able to both predict the halo formation and gives user tools to estimate (and reduce) this halo in order to design the safest linac as possible. After having given different definitions of halo, we will show how these "halos" change with different beam distributions. We will then exhibit how these halos develop in simulation**.**

DEFINITIONS OF HALO

It is very difficult to give a simple definition of the "halo". It could be a sole beam characteristic or a beam-accelerator system characteristic linked to the potential losses it can produced. It could be defined by a number of particles (in the halo) or a size (of the halo). It could be described in the geometric space or in the phase-spaces…

In TraceWIN code, we implemented different halo models in order to offer the user a set of diagnostics which can be used to optimize its design according to its own sensibility. They are presented below.

H Parameter [2]

The H parameter is not, strictly speaking, a measure of the halo but it offers a diagnostics complementary to the rms emittance to measure the degradation of the beam quality, which is more sensitive to the beam outer part.

Its definition is the following:

$$H_i = \frac{\sqrt{3 \cdot I_4^i}}{2 \cdot I_2^i} - 2,$$

with:

- $I_2^i = \langle q_i^2 \rangle \langle p_i^2 \rangle - \langle q_i p_i \rangle^2$, the second order momentum of the (q_i, p_i) phase-space distribution,
- $I_4^i = \langle q_i^4 \rangle \langle p_i^4 \rangle + 3 \langle q_i^2 p_i^2 \rangle^2 - 4 \langle q_i p_i^3 \rangle \langle q_i^3 p_i \rangle$, its fourth order momentum.
- $\langle A \rangle$, the average value of A over the beam.

The constants have been adjusted in order to have:

- $H_i = 0$, for uniform elliptical distribution,
- $H_i = 1$, for gaussian elliptical distribution.

Halo Size And Intensity [3][4]

One defines the core-halo frontier of a beam, in x direction, as the location of maximum variation of its profile ***P*(*x*)** slope, that is the location of second derivative maximum. This is a good definition to reveal a possible change of mechanism responsible of the beam profile. This frontier defines the beam core size ***Sc***. ***Sb*** is the beam size.

The number of beam ***nb*** and core ***nc*** particles are then:

$$nb = \int_{-\infty}^{+\infty} P(x) \cdot dx \text{ and } nc = \oint_{<Sc} P(x) \cdot dx.$$

The halo can then be characterised by two quantities ***PHS*** and ***PHP*** which are respectively the percentage of halo size and of halo particles in the beam.

$$PHS = 100 \cdot \frac{Sb - Sc}{Sb},$$

$$PHP = 100 \cdot \frac{nb - nc}{nb}.$$

HALO OF SEVERAL DISTRIBUTIONS

Analytical Distributions

For axis distributions $p_x(x)$, Sb is defined as followed:

$$Sb = x_+ - x_-,$$

such as: $\int_{-\infty}^{x_-} p_x(x) \cdot dx = \int_{x_+}^{+\infty} p_x(x) \cdot dx = \frac{1}{2Np}$.

Np could correspond to the number of particles used to sample the beam.

We selected several axisymmetric distributions $p_r(r)$ with radial repartitions, $\int_0^r r' \cdot p_r(r') \cdot dr'$, plotted on Fig. 1. The evolution of their tails, in log scale, are clearly visible. The associated parameters H, PHP & PHS are shown, by tails in ascending order, in Tab. 1.

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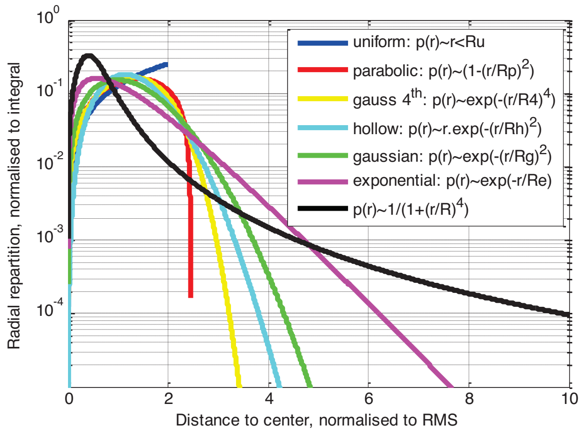

Figure 1: radial repartition of selected distributions with same integrals and x_{rms}*.

Table 1: Parameters For Selected Distributions

Type	H	Cs/x_{rms}	PHP	PHS N_p=10^7	PHS N_p=10^9
Uniform	0	4	0	0	0
Parabolic	0.25	4.89	0	0	0
Gauss 4th	0.356	4.25	1.7	39.1	43.6
Hollow	0.5	3.64	5.6	60.1	65.0
Gaussian	1	3.46	8.3	67.5	71.7
Exponential	3	1.54	36.3	92.3	94.0
4th inverse	∞	1.26	21.6	99.4	>99.9

There is no halo (according to *PHP* and *PHS*) in uniform and parabolic distributions because their derivatives are discontinuous. All parameter gives an halo growing with tails quantity.

Sum Of Two Distributions

We consider a beam made of the sum of a core with elliptic parabolic density in 2D sub-spaces ((x,y) or (x,x')) and a halo with Gaussian density:

$$d(r)=\frac{2}{\pi}\cdot(r<1)\cdot\left(1-r^2\right)+\frac{A}{2\pi\cdot E^2}\cdot\exp\left(-\frac{r^2}{2E^2}\right),$$

with :

$$r^2=\left(x/x_0\right)^2+\left(y/y_0\right)^2$$

$$\text{or}=\left(x/x_0\right)^2+\left(x'/x'_0\right)^2$$

$$\text{or}=\ldots$$

A, varying from 10^{-6} to 10^{-1}, is the ratio of the number of particles in the Gaussian and to that in the parabolic.

E, varying from 1 to 6, is the ratio of the Gaussian sigma to the parabolic size limit.

* the 4th inverse distribution has been truncated to 100 times its rms size.

One can plot the evolution of H, PHS and PHP in 2D (A, E) charts from Fig. 2 to Fig. 4.

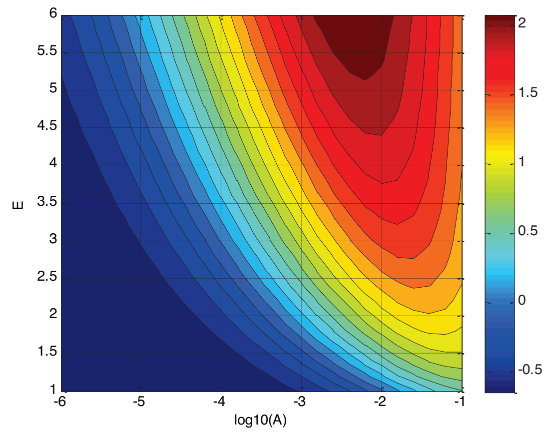

Figure 2: Evolution of log10(H) with A and E.

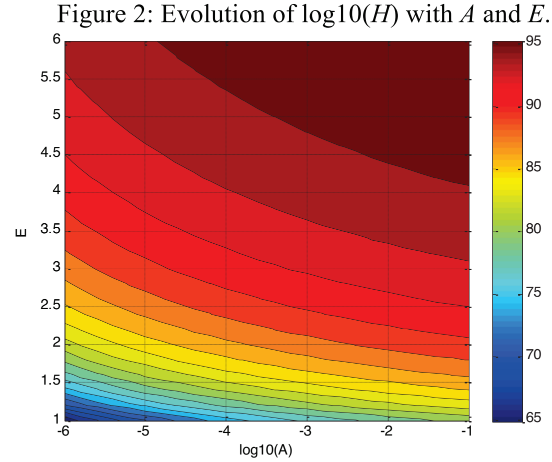

Figure 3: Evolution of PHS with A and E.

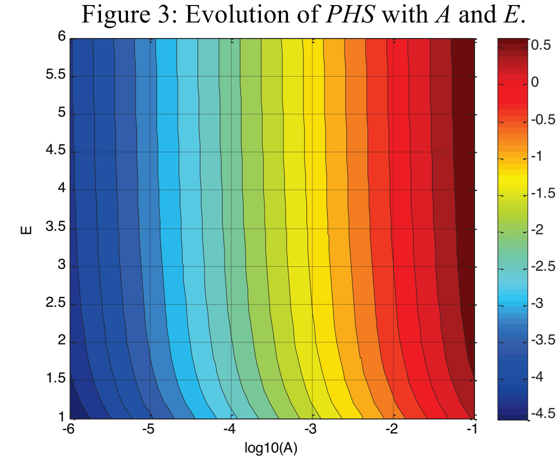

Figure 4: Evolution of log10(PHP) with A and E.

In case only the biggest second derivative maximum is considered, *PHS* and *PHP* always consider that the core is given by the parabolic distribution because its second derivative tends to infinity at its border, and because, in non-noisy analytical conditions, no smoothing of the particle distribution is necessary.

PHS are close to horizontal lines. They are not perfectly horizontal because the lower the number of particles in the halo (over a total of Np=10^9), the smaller it appears (for A=10^{-1}, there are 10^{8} particles in the halo as for A=10^{-6}, there are "only" 10^{3} particles).

PHP are close to vertical lines. They are not perfectly vertical for halo with small extension because, in this case, a non-negligible part of the Gaussian distribution is in the core.

For A<<1%, the H parameter is growing with Gausssian size or intensity. For higher Gaussian proportion (A>1-10%), H decreases because the larger Gaussian distribution dominates. At the limit A>>1, the Gaussian containing much more particles than the parabolic (is it still halo?), H tends to 1.

H parameter proposes a compensation between the halo size and intensity. An intense short halo can give the same H as a diluted large halo.

PRODUCTION OF HALO IN TRACEWIN

In TraceWIN code, the evolution of those parameters can be plotted along the machine (Fig. 5). In order to illustrate, we simulate the transport with space-charge of a mismatched parabolic beam in a FODO-buncher channel. The beam is sampled by 1M macro-particles.

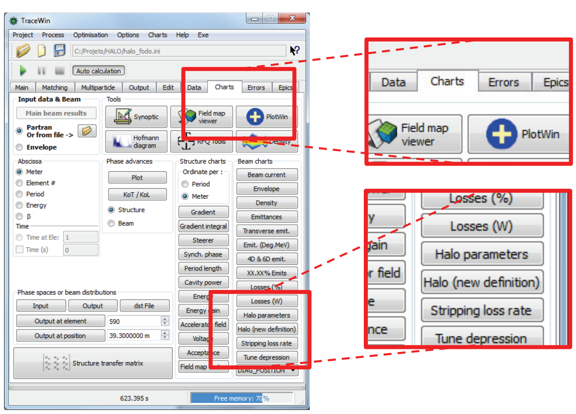

Figure 5: Evolution of log10(*PHP*) with A and E.

The evolution of the rms emittance and the halo parameters in the vertical plane are plotted on Fig. 6. The new equilibrium distribution has led to a halo production.

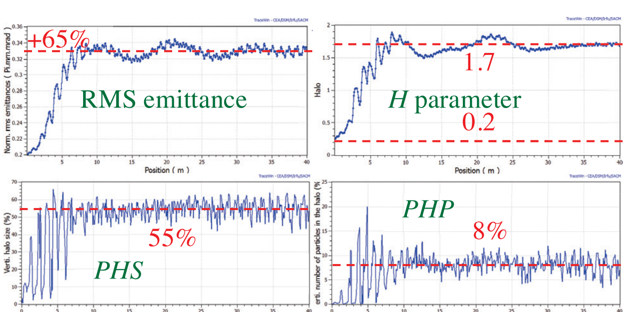

Figure 6: Evolution of RMS emittance, H, *PHS* and *PHP* along the channel.

The final distribution in (y, y') phase space and associated beam profiles are plotted on Fig. 7. At that point, the RMS size is ±1.58 mm, the core size is estimated to 5.7 mm and the beam full size to 12.3. The vertical halo is considered to contain 8% of the beam and to occupy 55% of its size. The H parameter is 1.7, compatible with moderate halo production.

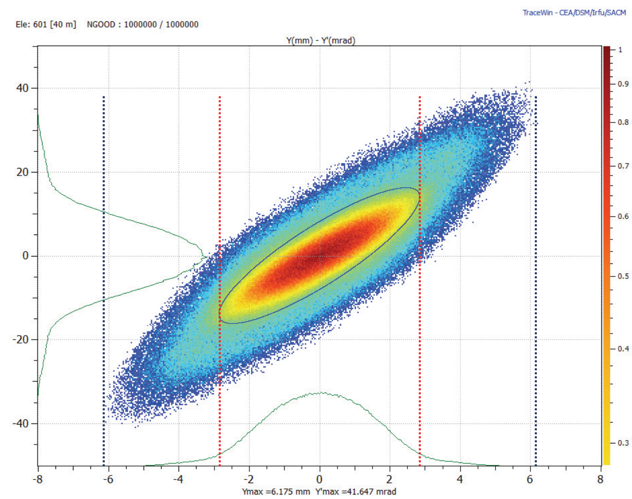

Figure 7: Exit beam vertical phase-space distribution.

CONCLUSION

Halo production can be monitored in TraceWIN using, at least, 3 diagnostics. H has less "physical" meaning but is more robust with a low number of particles. It is then very convenient in a design optimisation process where low particle numbers are used. *PHS* and *PHP* have more physical meanings. Nevertheless, they are a more appropriate with a large number of particles. They are well suited to finalise and benchmark a design.

Other TraceWIN tools can also be used to estimate the "quality" of a design in term of halo production and potential beam losses: emittances at 99.xx%, envelopes containing 99.xx% of the beam… and new technics are in preparation: use of test particles…

However, even powerful diagnostics are useless if significant physical mechanisms are missing or if the beam input distribution is unrealistic.

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