DESIGN OF HIGH INTENSITY, HIGH POWER LINACS

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ABSTRACT

With high intensity linacs, both beam power and space charge should be taken into considerations for any analysis. For such linac, a predictive catalogue of beam losses in all operating configurations is particularly helpful, because due to high power, even tiny losses take away an important amount of energy and in case of high intensity in addition, high power is not only present at the linac end but all along the linac. As a consequence, beam optimization must take care not only the beam core as usual but also the external halo that can induce losses. Beam characterization is an issue too, as a high intensity beam significantly departs from a Gaussian distribution and as the halo, which plays a significant role in the dynamic of the beam and in the particle loss process, must also be quantified. This paper will address the new concepts and methods for beam analysis, beam loss catalogue, beam optimization and beam characterization in the design of a high intensity, high power linac.

KEYWORDS
Linear accelerators, High Intensity, High Power, Space charge

1. INTRODUCTION

Demands for increasingly high intensity beam in linear accelerators have been expressed in many fields of physics like inertial confinement fusion, tritium production, nuclear transmutation or spallation, neutrino physics, material irradiation in particular for magnetic confinement fusion. Depending on specifications, the beam is either in CW or pulsed mode, leading to resp. large average or peak power, which is given by:

$$P = \frac{IE}{n_q} \qquad (1)$$

where P is the beam power in MW, I the beam current in A, E the beam kinetic energy in MeV and n_q is the number of charges per particle.

The larger the beam power is, the more harmful beam losses are, and when beam power is very large, even if a tiny part of the beam is lost, it should not be neglected. But high power is not the only consequence of high intensity. High space charge is the other important induced issue that cannot be forgotten. The latter implies strong nonlinear repulsive forces between charged particles of the same sign. The space charge is characterized by the generalized perveance K [1]:

$$K = \frac{qI}{2\pi\varepsilon_0 m(\beta\gamma c)^3} \tag{2}$$

where q, m are the particle's charge and mass, I is the beam peak intensity, ε_0 the vacuum permittivity, β, γ the relativistic factors and c the speed of light in vacuum. Space charge forces, by their strengths, will require a more compact accelerator lattice to prevent beam blowup and by its nonlinearity will make beam transportation more delicate, in simulation as well as in operation. The combination of high power and high space charge makes the situation particularly critical: the beam should be controlled very precisely even for its most tenuous part to prevent losses while it is at the same time subject to nonlinear blowup forces difficult to simulate or to control. In such a situation, new methods and concepts must be developed to treat the issues induced by high intensity.
This paper presents advanced concepts and methods for beam analysis, beam loss prediction, beam optimization, beam measurement and beam characterization especially dedicated to very high intensity accelerators [2]. Examples of application of these concepts are given in the case of the IFMIF accelerators [3, 4].

2. BEAM ANALYSIS

A beam intensity is not high in absolute but in comparison with another beam. The problem is that in current comparisons, high intensity has often been assimilated to high power. Yet, according to Eq. 1, high power can be due to high energy and not necessarily due to high intensity. Confusing high intensity and high power may hide all the main difficulties specifically coming from high intensity.

Even when studying issues purely due to high power, a high power but not high intensity accelerator will reach high power only at high energy and induced issues will mainly concern its last sections, while a high intensity beam may reach substantial power in the very first sections and may face important challenges all along the accelerator. Besides, high intensity implies in addition high space charge. To be meaningful, a beam analysis should highlight these two properties at once.

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

It is very common until now to symbolize them as a point in a graph like Fig. 1 representing the beam average intensity versus the beam final energy. This graph 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:
- Only the last sections are concerned. This graph does not allow knowing about upstream sections that may face important difficulties or not.
- The other issue, the beam space charge is not considered. It cannot be deduced from this graph as it depends on the peak intensity and not on the average one.

This kind of graph is highly reductive. It may lead to wrong estimates of the difficulties in the first sections and may hide the difficulties due to high space charge.

We propose instead to use the set of two graphs in Fig. 2 and 3 representing the beam power and the generalized 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. Regarding Accel A, it 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 graphs allows highlighting even more the critical aspects. For 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 that when the beam power is so high that even a tiny loss, i.e. 10^{-6} of the beam, is critical, a very precise control of the beam is needed while the beam behavior remains very difficult to predict.

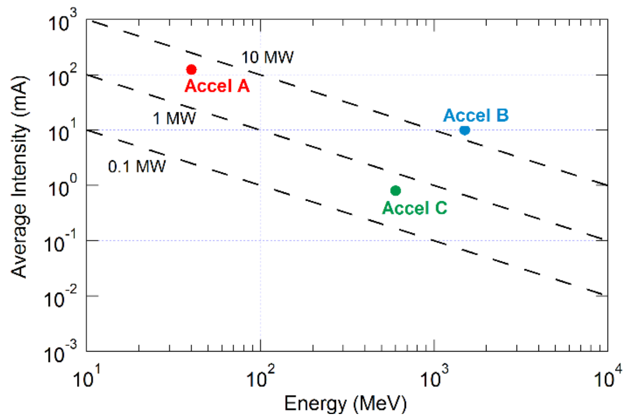
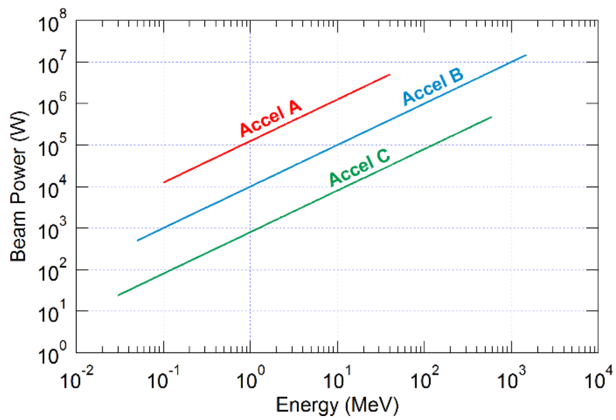


Figure 1: Beam average intensity versus final energy.



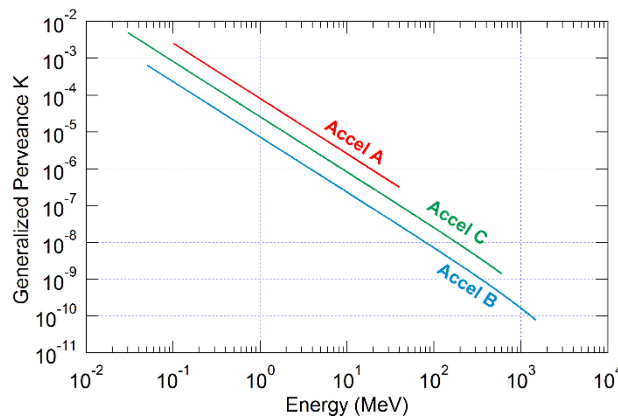


Figure 2 and Figure 3: Beam power and Perveance versus Energy along the accelerator.

Further detailed analysis can be carried out when considering each section of the accelerators[2]. Indeed, accelerators often use typical sections for accelerating and focusing particles: particle Source, LEBT, RFQ, MEBT, Linacs and HEBT. Depending on beam power and space charge, decisions can be taken to pass from a section to another at a chosen energy. The graph in Fig. 1 allows to know only about the beam power at the HEBT and the last Linac end. The two graphs of Fig. 2 and 3 can be used to make meaningful comparisons between different accelerators for every section, so as to estimate their challenging aspect if any. Applications discussed here to some high intensity accelerators, achieved, under construction or planned, are shown in [5, 6].

3. BEAM LOSS PREDICTION

High intensity beam can imply high beam power at the earliest energy stages and this can affect almost the whole accelerator. In such a case, beam losses, even when they represent a small fraction of the beam,

can take away a significant power. Those losses, when they are accidental, can damage equipment surrounding the beam via heat deposition, or when they last a long time, can activate materials and induce harmful radiation for personnel. If superconducting equipment is concerned, cryogenic systems must be able to evacuate the deposited heat. That is why, for designing personnel or machine protection systems, cooling systems or for fixing the limitations to be kept during certain beam manipulations, it is necessary to predict possible beam losses during all the possible situations the accelerator will encounter, accidental or not. The double issue is to define as exhaustively as possible all the typical loss situations in the accelerator lifetime and to define the procedure to simulate and estimate them. After many studies, it appears to us that the situations and the protocols described in the following should be enough:
A. Ideal machine
B. Starting from scratch
C. Beam commissioning, tuning, exploration
D. Routine operation
E. Sudden failure.
A complete 'Catalogue of Losses' has been obtained for each of these situations, for the IFMIF Prototype accelerator. See [7], where the simulation protocols are discussed, the results are detailed, and the impact on every accelerator subsystem is pointed out.

4. BEAM OPTIMIZATION

The very first question for beam dynamics optimization when designing or tuning a linear accelerator is: what are the parameters to be optimized?

As beam optimization is in any case time consuming, it is currently enough to target the RMS parameters of the particle population, namely its emittance and Twiss parameters. As nonlinear space charge forces will induce emittance growth and halo formation, the idea was to minimize this emittance growth as much as possible. For that, many studies have been undertaken, leading to recommendations to avoid energy transfer between transverse/longitudinal movements and to match the input beam to a focusing structure, all of them regarding emittance, Twiss parameters or phase advance.

Yet, the final goal is to minimize halo, not emittance, in order to prevent beam losses, and the relation between emittance and halo is not straightforward. In [8], it is pointed out that there could be emittance growth without halo growth but halo growth always implies emittance growth. So the above recommendations are likely to be efficient only in case of moderate space charge. For very intense beams, they are difficult to apply. The reason is that the classical statistical parameter set is not enough to represent the beam. In [2] and [9], it is proven that two different beam distributions of 125 mA – 9 MeV D^+ particles characterized by the same emittance and Twiss parameters become significantly different after being transported through only three quadrupoles. Beam transport is clearly distribution dependent. Therefore, matching a beam to a structure when considering only its RMS parameters is not sufficient.

Some attempts aim to directly mitigate the halo, as for example using a round input beam [10] or using the transverse-longitudinal coupling resonance to get rid of the longitudinal halo [11]. We propose to use a radical method called 'halo matching' aiming to smooth the extension of the external border of the beam, thus directly minimizing the halo [12]. The method consists in minimizing the radial extension of the most external macroparticles, at locations where it is the largest, i.e. at focusing elements, tuning all of the lattice in this way. This multi-parameter optimization is time consuming. Furthermore, it must be re-done whenever the particle distribution at entrance changes. A specific code has been written for that, using the Particle Swarm Optimization procedure [13], suitable for searching the lowest minimum of an n-Dimension surface having several local minimums. An example of successful result is given in Fig. 4-Top for the Superconducting Radio Frequency (SRF) Linac of the IFMIF accelerators, where a CW-125 mA D^+ particles are accelerated from 5 MeV to 40 MeV, corresponding to beam powers from 0.6 to 5 MW.

This halo matching procedure leads to a significant emittance growth as shown in Fig. 4-Bottom. As an exercise, an alternative tuning has been obtained by applying in the second part of the structure the classical method of minimizing emittance growth consisting in avoiding the transverse-longitudinal coupling resonance [2, 14]. We can call it 'emittance matching'. The emittance growth is indeed reduced, but at the expense of an important halo growth (Fig. 5). This shows the limit of classical methods that consider beam emittance as the critical parameter. Considering the halo as the figure of merit is likely more appropriate for high intensity accelerators.

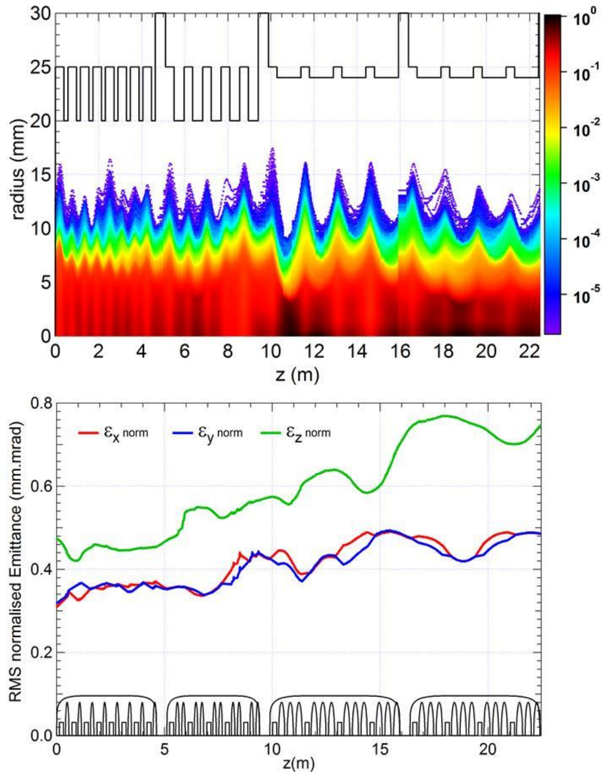


Figure 4. Radial density (top) and RMS normalized emittance (bottom) of the IFMIF beam along the four cryomodules of the SRF Linac. Results obtained by the halo matching procedure using 10^6 macroparticles, consisting in minimizing the extension of the outermost particles.

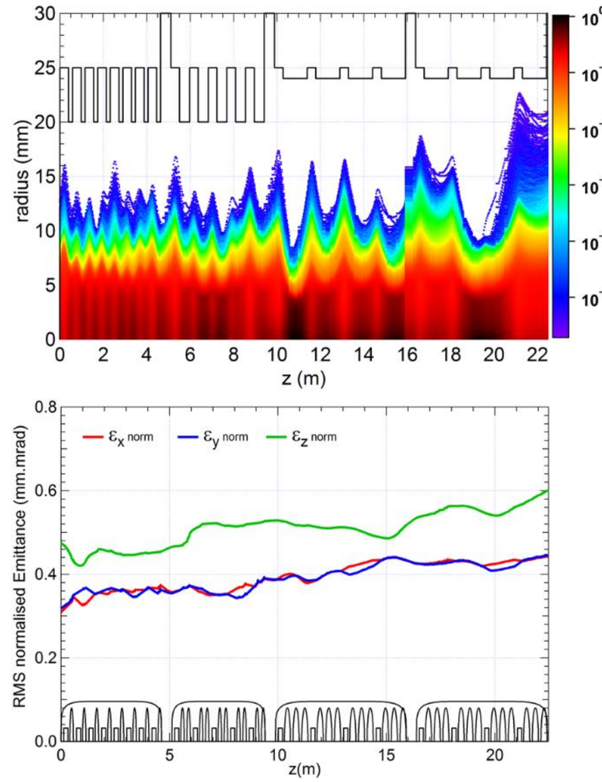


Figure 5. Same as Fig. 4 but obtained by emittance matching, i.e. avoiding the transverse-longitudinal resonance in order to minimize emittance growth.

Another optimization procedure has been developed for the SARAF supeconducting linac [15]. In this accelerator, CW-5mA of D^+ are accelerated from 2.5 to 40 MeV. Those parameters do not make SARAF a very high-intensity machine, but its loss constraints, down to 10^{-7} of the beam, clearly raise the same issues as for high-intensity beam. A first tuning of cavity phases leads to important beam losses, all coming from particles unhooked in the longitudinal space. Furthermore, simulations with errors in envelope mode show that the longitudinal acceptance must be at least 1.5 times the longitudinal rms size in order to have the beam to remain in the acceptance in the presence of standard errors (field amplitude, resp. phase errors of 1°, resp. 1%). Important efforts are then dedicated to enlarge the longitudinal aceptance.

For that, let's first point out that it is useless to enlarge the global longitudinal acceptance as it is currently defined, because the beam phase space is not homothetic to the acceptance but occupies a rather offcentered part of it. It is then decided to tackle the problem in another way: consider the actual input beam with longitudinal emittance homothetically multiplied by $(1.5)^2 = 2.25$ and search to adjust synchronous phases in order to minimize or even to cancel losses with this enlarge input beam. In addition, attention should be put on obtaining a compact output beam, not too strongly distorted by nonlinearities.

Enlarging the acceptance with above conditions is far from easy. That is because a) The RF field sinusoidal behaviour makes the problem totally nonlinear b) The choice of a field amplitude and phase fix the accelerating and the focusing rates at once, and those ones are contradictoring c) The good transmission of the beam at a given cavity depends strongly on the upstream setting, meaning that a big number of phase combinations should be explored.

After trying different methods, we found that the following procedure in 2 steps gives satisfying results:

- With the TraceWin code, adjust cavity phases so as to obtain at exit a maximum beam energy together with a maximum number of particles in a well delimited zone of phase and energy.

- With the above result, starting from the first cavity, search the field phase allowing to obtain the maximum of particles on the above phase-energy zone, use this field phase, then repeat the same investigation for the next cavity, until the last one.

These two steps could be reiterated, always with the enlarged emittance. The numerours multiparticle simulations that should be launched make this procedure tedious. But the main harm is that a better solution may be missed. We will look for another procedure allowing to avoid these inconveniences.

The best result obtained until now is presented in Fig. 6. The longitudinal beam input, compared to the dynamic acceptance, presents now a satisfying margin.

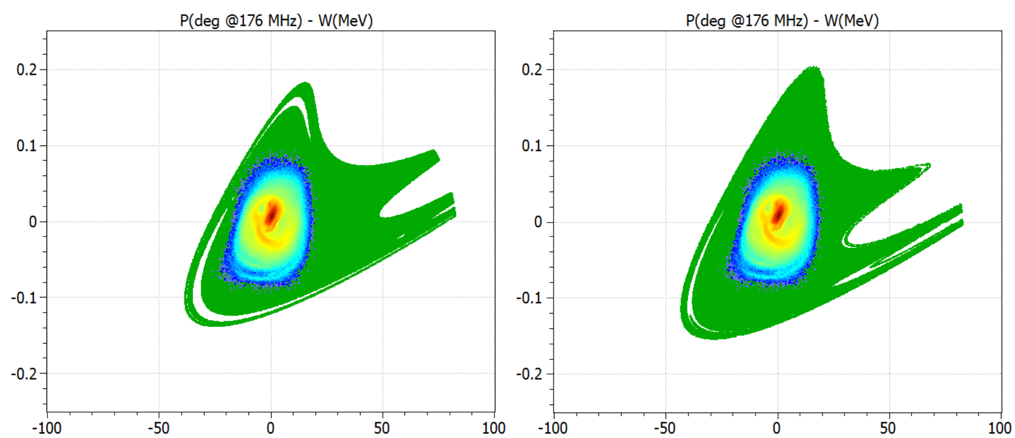


Figure 6: Beam distribution in the phase-energy space at SCL entrance for deuterons, compared to the dynamic acceptance in green. Left and Right: before and after optimization.

5. BEAM CHARACTERIZATION

Particle beams have ever been characterized by either the 6D coordinates of each particle or macroparticle, which is a huge number of data, or else by its RMS emittance and Twiss parameters, of which a combination gives the RMS size, also referred to as beam envelope.

High intensity makes those usual characterization methods questionable: the number of particles is even much higher and, because of the multiple reasons evoked above, RMS parameters are not representative enough. We propose to tackle the problem in three directions: a) Massive simulations with the actual number of particles, b) Characterize the particle distribution by its projections onto axes and c) Characterize it by its core and its halo.

Massive simulations with 4.7 10^9 deuteron particles have been done for the IFMIF prototype accelerator [16], runing on 175 processors for 25 days. Representative statistics of microlosses are then available, confirming that losses remain lower than 10^{-7} of the beam for energy > 5 MeV. Such simulations are necessary when this level of accuracy is needed.

In order to reduce the number of parameters to describe beam distributions, its projections onto a few axes can be considered. Indeed, from the latter, it is known that the MENT (Maximization of ENTropy) method can be used to reconstruct the distribution [17]. In [18], it is shown that for relatively complex 2D distributions, provided that the projection axes are wisely chosen, 2 projections are enough to correctly describe the core of the beam and 6 projections are enough to characterize the very external parts. Those projections, which are 1D profiles, may then be adjusted with functions like a sum of generalized Gaussians, making that, all in all, a 2D distribution can be described by ~10 to 30 parameters.

So as to further reduce the number of parameters, we propose to describe the beam by the global characteristics of its core and its halo separately. Compared to above methods, fine details are lost, but we can gain insight into physical properties of the beam, because growth or decay of the core or the halo are the results of the competition between internal (i.e. space charge) and external (i.e. focusing) forces, which we want to study.

For that, the question is to determine the limit separating core and halo. Despite intensive works launched for decades [19-21], aiming at studying the halo, its formation and evolution, no clear definition of halo has emerged. To such extent that specialists delight in claiming that no definition of halo can be done. Yet halo studies, measurements, mitigations, etc. carry on. See for example [22-24].

Recently, we proposed a precise determination of the core-halo limit for a 1D profile [25, 26]. The idea is to extrapolate from the case of dense uniform core surrounded by a much more tenuous halo. In this extreme case, the space charge field is clearly linear in the core and nonlinear in the halo, and the limit between core and halo is obviously the location where there is the abrupt slope variation in the profile when going from a tenuous density to a much higher one. For a general density profile with continuously varying slope, we propose to determine the core-halo limit as the location of biggest slope variation, that is where the second derivative is maximum (not to be confused with the inflection point that is given by the second derivative zero). Once the core-halo limit is precisely determined (Fig. 7), we can compute PHS and PHP, resp. the Percentage of Halo Size and Percentage of Halo Particles. Instead of the classical RMS parameters, we propose then to represent a high intensity beam along an accelerator structure by its core-halo limit, its overall external limit, and PHS, PHP.

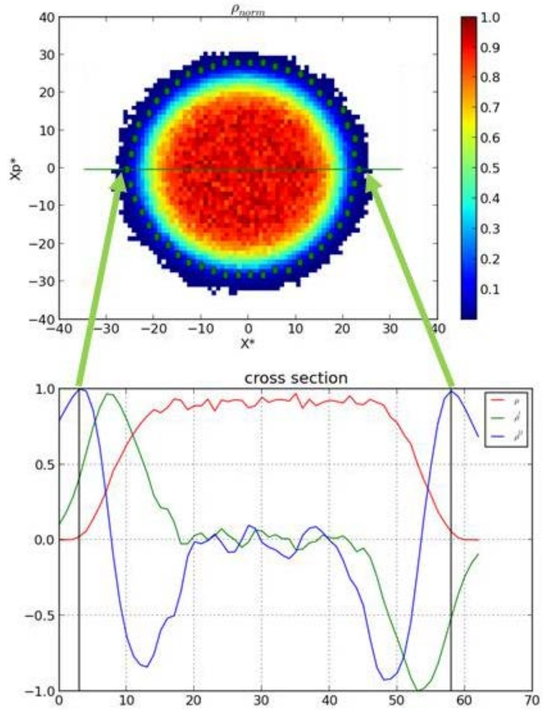


Figure 7. Determination of the core-halo limit in 1D (bottom) and 2D (top).

It is also important to see if this definition based solely on the beam density profile reflects the beam internal dynamics. As the latter is governed by the internal space charge field, which can be easily computed in case of infinite cylindrical beam (1D), substantial studies of various density profiles have shown that the core-halo limit defined here corresponds within 2% to an equivalent limit on the field profile [27, 28].

This core-halo limit determination in 1D has been extended to a 2D distribution [29] by searching the second derivative maximum of the density profile along many sections, all of them allowing to define a limit contour (Fig. 7). Then like above, PHS and PHP can be computed, this time in 2D. Furthermore, when applying to a phase space, emittance and Twiss parameters can be calculated separately for the core and for the halo. All those parameters allow definitely to characterize the beam behavior and its evolution with a good insight.

Like above, it is also important to check if this core-halo contour is consistent with the well-established halo formation dynamics. Studies of mismatched beam in a continuously focusing channel, in particular the variation of individual particle emittances, allow to show that the halo defined here, within 4%, contains exclusively particles that have undergone emittance growth [30].

6. CONCLUSIONS

High intensity implies high power and strong space charge. Both aspects should be taken into account when analyzing the induced effects along accelerators. The combination of the two aspects implies new and serious issues, forcing to study advanced methods and concepts: catalogue of losses, halo matching, microlosses, online avatars of beam tunings, core-halo limit, PHS, PHP. The latter reveal the beam internal dynamics in 1D and are consistent with the halo formation dynamics in 2D.

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