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Beam halo formation in high-intensity beams

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Abstract

Studies of beam halo became unavoidable feature of high-intensity machines where uncontrolled beam loss should be kept to extremely small level. For a well controlled stable beam such a loss is typically associated with the low density halo surrounding beam core. In order to minimize uncontrolled beam loss or improve performance of an accelerator, it is very important to understand what are the sources of halo formation in a specific machine of interest. The dominant mechanisms are, in fact, different in linear accelerators, circular machines or Energy Recovering Linacs (ERL). In this paper, we summarize basic mechanisms of halo formation in high-intensity beams and discuss their application to various types of accelerators of interest, such as linacs, rings and ERL.

Key words: beam halo, space charge, emittance growth

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1 Beam loss and beam halo

Recently, significant efforts were made to understand various mechanisms which can contribute to beam loss in high-intensity beams. Both experimental observation and multi-particle simulations showed that high-intensity beams can produce halos which can lead to particle losses. The structure of beam halo and its characteristics are different depending on the mechanism of halo production. Not surprisingly, there are many mechanisms which may contribute to halo formation. A detailed discussion of dominant halo mechanisms in high-intensity circular and linear accelerators can be found, for example, in [1].

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Many mechanisms of halo formation can be understood in the framework of single-particle beam dynamics. Such type of halos can be compensated with a proper design and non-linear correction schemes. However, emerging application of high-intensity beams showed importance of another class of halos driven by the space-charge forces itself. A useful parameter which describes strength of the space-charge effects in the focusing channel is the tune depression η which is defined as $\eta = k/k_0$ where k is the wavenumber of particle oscillation depressed by the space charge, and k_0 is the wavenumber of particles oscillations without the space charge (in a periodic focusing channel one typically uses the notation of a phase advance per period rather than the wavenumber). For a typical storage ring operating in emittance-dominated regime, the tune depression η is very close to unity (which, in fact, allows us to treat space charge as a small perturbation). While for high-intensity linacs η could be as strong as $0.2 - 0.5$ which corresponds to the space-charge dominated regime.

1.1 Resonant space-charge driven halos

The most pronounced high-intensity beam halos are of a resonant type. In this type of halo the particles are pushed out of the core by a resonantly acting force. In linear transport channels the force arises mainly from the coherent motion of the beam itself. The individual particles can then get in resonance with the modes of collective beam oscillations which produces a halo around the beam. For modest tune depressions (η in the range $0.5 - 1.0$) the dominant is the parametric $1 : 2$ resonance driven by an envelope mismatch. High-order non-linear resonances become important for more severe tune depressions ($\eta < 0.5$). Such intrinsic mechanism does not require any resonances with the lattice since the collective oscillations are induced by a mismatch. In rings, however, such collective beam modes may have a fast excitation as a result of both the space charge and machine resonances [2]. The resonances of the individual particles with such driven collective beam modes are called “driven incoherent resonances”, since the collective modes are first resonantly driven and then incoherent particles are trapped into the resonance with the corresponding collective mode. In such a case, the incoherent resonances may play an important role in halo formation even in the limit of a weak tune depression ($\eta \rightarrow 1$) [2].

Another type of a mechanism common for both high-intensity linacs and rings are the space-charge coupling resonances, which are driven by the coupling terms in the space-charge potential itself rather than the field potential of magnets. For anisotropic beams such resonances are important both for coupling and energy transfer between two transverse degrees of freedom as well as between the transverse and longitudinal motion. Also, collective modes of beam oscillation resonating with the lattice structure (space-charge structure

resonances) generate substantial emittance growth (see Ref.[3] and references therein).

The rate of halo development due to the space-charge induced resonances is a function of tune depression (see for example, [4]), which allows us to estimate its importance for different high-intensity accelerators:

Linear hadron accelerators: Space-charge tune depression is typically strong. As a result, the rate of such space-charge driven halos is very fast. In such machines, the space-charge induced resonant halos are important - both the transverse and longitudinal mismatches should be minimized. Since bunches are typically rather short, it is also necessary to consider the effect of the longitudinal-transverse coupling [4].

Circular accelerators: Tune depressions are relatively weak (apart from "cooler rings" or specific small scale rings for dedicated space-charge studies). In addition, there are such effects as multi-turn injection (phase-mixing), redistribution, etc. - in most practical situations space-charge induced beam halos of resonant type have little chance to develop. However, the "driven incoherent halo" is possible [2].

ERL: There are two very distinct regimes. The first one which describes beam dynamics in photoinjector corresponds to an extreme space-charge limit ($\eta \rightarrow 0$) where dynamics is completely dominated by plasma oscillations. The beam is then very rapidly transformed into emittance dominated regime (due to fast acceleration). In the emittance dominated regime very weak tune depression and the lack of periodic oscillation makes it not susceptible to the space-charge resonantly driven halos.

Also, when these type of mechanisms are studied with application to accumulator rings or ERL, one should take into account many other realistic effects which may lead to the phase-mixing and detuning from the resonance condition.

1.2 Intrabeam Scattering

Linear hadron accelerators: From the kinematics of Coulomb collisions one can find the extent of a shell (halo) around the beam core taking into account the space-charge effect. However, the probability of particle to occupy such a shell in proton linacs is very small. To confirm this rigorously, some simple scaling formulas were derived [5]. For the class of 6D stationary self-consistent

distribution, given by:

$$f(\mathbf{r}, \mathbf{v}) = \begin{cases} N(H_0 - H)^n, & H < H_0 \\ 0, & H > H_0 \end{cases}, \quad (1)$$

where the Hamiltonian includes the space-charge potential (Φ_{sc}), and is given by

$$H(\mathbf{r}, \mathbf{v}) = mv^2/2 + kr^2/2 + e\Phi_{sc}(r), \quad (2)$$

one finds that the fraction of ions which leave the beam due to the single scattering events per unit length is

$$\frac{dP}{cdt} \sim \begin{cases} \frac{r_p^2}{\epsilon_N^3}, & n > 0 \\ \frac{r_p^2}{\epsilon_N^3} \ell n(\epsilon_N^2/r_p a), & n = 0 \\ \frac{r_p^2}{\epsilon_N^3} (\epsilon_N^2/r_p a)^n, & -1 < n < 0 \end{cases} \quad (3)$$

where, for singular distributions with $0 \geq n > -1$, we assume that the Coulomb force between ions is screened at the Debye length λ_D . Taking typical example of proton accelerators with $r_p = 1.5 \times 10^{-18}$ [m], $\epsilon_N \cong 10^{-6}$ [m rad] and $a \cong 10^{-2}$ [m], for the uniform distribution ($n = 0$) one gets $\frac{dP}{cdt} = 10^{-14}/\text{km}$, which is clearly negligible. The multiple scattering leads to a generalization of formulas in Eq. (3) with logarithmic behavior:

$$\frac{dP}{cdt} \sim \frac{r_p^2}{\epsilon_N^3} \ell n\left(\frac{1}{\theta_D}\right), \quad (4)$$

where θ_D in the minimum angle corresponding to the screening length impact parameter. For the same parameters, as used above, the rate is also negligible.

Circular accelerators: - In storage rings, the intrabeam scattering (both single large-angle and multiple small-angle) is typically one of the dominant mechanisms of emittance growth and is always considered.

ERL: In proposed high-brightness ERL the phase space-density is strongly increased. When one uses formulas in Eq. (3) for typical 6-D volume of high-brightness electron beam the rate of halo formation due to this process becomes important. In addition, when the rate in Eq. (3) is transformed into

the lab frame particles can be simply lost longitudinally, which is well known Toeschek effect in circular accelerators.

1.3 Misalignments, magnet errors and noise

Such effects should be considered in both linacs and rings to estimate realistic emittance growth. By itself, very small misalignments, magnet fields errors or magnet noise may not lead to a significant growth of halo but they can enhance other halo mechanisms. For example - the enhancement of parametric halo due to a mismatch by misalignments or halo generation due to RF noise. Understanding of emittance growth, as a result of many effects combined together, requires realistic computer simulations.

2 Beam halo in ERL

In typical high-intensity rings tune-depression is weak: $\eta = 0.9 - 0.96$, which corresponds to the emittance dominated regime. In proton linacs: $\eta = 0.5 - 0.8$. While in heavy-ion linacs one encounters strong space-charge dominated beams: $\eta < 0.5$. In ERL, there are two very different regimes: 1) in the RF photoinjectors: η is close to zero - this limit corresponds to a full depression of betatron tunes by the space-charge, which allows one to use cold-fluid (laminar) approximation neglecting thermal emittance. Space-charge dominated behavior in photoinjector is described by emittance oscillations at plasma frequency during initial acceleration and transport. 2) due to a very rapid acceleration to high γ beam dynamics in the remaining part of the ERL corresponds to the emittance dominated regime.

2.1 Halo in photoinjectors

The dominant mechanisms of emittance growth, due to Carlsten [6], are: 1. linear space charge; 2. non-linear space charge; 3. non-linear time-independent rf fields; 4. linear time-dependent rf. The first process is associated with different behavior of longitudinal beam slices - the theory describing this process is called "emittance compensation" [6], [7]. Space charge force is different for different slices which results in their different expansion or different angles in the phase space rotation. Emittance compensation lines slices back up with external focusing. Non-perfect emittance compensation will result in halo formation.

Any non-stationary distribution results in substantial emittance growth due to a redistribution process in a quarter of plasma period. Presently, an effort is being made to minimize contribution from this effect by producing distributions with the linear space-charge forces (3-D ellipsoidal beams). Recently, it was shown how such distributions can be produced with a proper radial shaping of the photoemission laser pulse [8]. Alternatively, one may consider non-linear external focusing to compensate the non-linear self-fields on the beam [9].

The effect of non-linear time independent rf can be taken into account by a proper consideration of electromagnetic fields and appropriate cavity design. The effect of time-dependent linear rf can be minimized by reducing radius and length of the beam until the non-linear space charge force becomes significant. Like in other regimes/applications there is a possibility of various "design-related" halos, like non-perfect transport of the laser beam, etc.

2.2 Halo in high-energy part of the ERL

Proposed very high phase-space densities require to take into account beam loss due to both single and multiple Coulomb scattering (see section above). Very short bunch length results in significant energy spread and transverse emittance growth due to the Coherent Synchrotron Radiation (CSR), which is the subject of extensive present studies. Recent studies showed that CSR can amplify any microbunching in the longitudinal phase-space. Also, space-charge oscillation and microbunching instabilities can be driven by the longitudinal space charge which results in significant distortion of the longitudinal phase-space of electron bunch (see for example [10] and references therein). Various types of non-linear single-particle effects should be also considered.

3 Summary

In applications of high-intensity beams for hardon linear and circular accelerators it was realized that understanding of beam halo formation is essential in order to achieve required low beam losses. In the ERLs under operation, beam halos are already a subject of present discussion. In proposed high-brightness ERLs with extreme phase-space densities subject of beam halo certainly becomes an issue. With a good progress in the design and study of primary beam dynamics topics in proposed ERLs, a detailed consideration of beam halos is now also important.

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