INTENSE ION BEAM TRANSPORT AND SPACE CHARGE REDISTRIBUTION

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Abstract

The main laws that govern the charge redistribution in space charge dominated (SCD) beam during its transport through a periodical channel with solenoidal focusing are considered. Physical mechanisms of halo production and establishment of uniform distribution inside core for matched and mismatched beams are described. The computer codes KERN+HALO generated for redistribution process of charge density and kinetic and potential energies visual representation are described.

We have a clear knowledge of matched (or ideal) beam only in case when space charge does not change a frequency of transverse oscillations. The matched (or ideal) beam is a one which transverse behavior is repeated (or has a smooth change) from one period to the next.

The question "What a matched beam imply?" is arisen when the above definition is extended on the case when space charges essential for transverse oscillation frequency. We can denote that ideal beam has well-known K-V distribution and this distribution must be used for focusing field calculation and for a choice of bore radius. But real beam distributions differ from K-V one and its redistribution during beam transport leads to beam size and emittance growths. It means that such ideal beam definition results in an serious error of bore radius.

The SCD-beam investigations in channel with different initial beam transverse distributions were made by authors in order to answer on the above question. A simple model must be chosen for better understanding of process of SCD-beam redistribution. It can be a continuous cylindrical beam transporting in longitudinal magnetic field. In this case a Coulomb force calculation is very much simplified. Within the context of this model there are only a few characteristics for understanding the cause and effect of halo formation. Only distributions with beam density growth(or keeping constant) from the origin to outlying area were considered as initial ones [1].

Under above considerations beam motion is described by following equations

$$\begin{cases} x'' = \dfrac{eB(z)}{m_0 c\beta\gamma} y' + \dfrac{2I}{I_0(\beta\gamma)^3}\dfrac{Q(Z)}{r^2}\cdot x \\ y'' = -\dfrac{eB(z)}{m_0 c\beta\gamma} x' + \dfrac{2I}{I_0(\beta\gamma)^3}\dfrac{Q(Z)}{r^2}\cdot y \end{cases}$$

where e, m_0 are charge and rest mass of ion, β is a ratio of ion to light velocities, $\gamma = (1-\beta^2)^{-1/2}$, $B(z)$ is magnetic field induction, I is beam current, $I_o = 3.13\cdot 10^7$ A is Alfven current for proton, $Q(r)$ is charge fraction inside circle with r as radius $(Q(\infty) = 1)$, $r^2 = x^2+y^2$.

The equations of motion have a unitless form after transition to unitless variables $z = L\tau$, $x = A\tilde{x}$, $y = A\tilde{y}$, where L is focusing period length, $A = (\varepsilon L/(\beta\gamma))^{1/2}$, ε is beam emittance

$$\begin{cases} \tilde{x}'' - 2\Lambda\tilde{y}' - \alpha\dfrac{Q(\tilde{r})}{\tilde{r}^2}\tilde{x} = 0 \\ \tilde{y}'' + 2\Lambda\tilde{x}' - \alpha\dfrac{Q(\tilde{r})}{\tilde{r}^2}\tilde{y} = 0 \end{cases}$$

$$\Lambda = \frac{eB(z)L}{2m_0 c\beta\gamma}, \qquad \alpha = \frac{2IL}{I_0\varepsilon(\beta\gamma)^2}$$

This set of equation can be considered as base for further considerations. The magnitude of $B(z)$ is constant inside solenoidal lens and equal zero outside of them.

It is evident from general form of equations that there are only two parameters Λ and α which define the SCD-beam transverse form in the case when a structure of focusing period is preset.

Combinations of uniform and Gauss distributions are used as initial ones.

The main regularities of SCD-beam transporting were carried out [1]:

1. High-density core and low-density halo with particle active interchange are established in every case.
2. Most of core particles are "ex-halo" or "coming-halo" ones which income from halo in previous instant of time or will emerge from core in next instant of time.
4. Uniform charge distribution inside core is established in every case.
5. Final steady states with uniform distribution of core charge are states with Coulomb field minimal potential energy.
   The transition from the SCD-beam initial state into a final steady state is accompanied by particle kinetic energy increasing and emittance growth.
6. A steady state which leaves the core-halo transverse sizes unchanged can be established. Such beam we will be nominated as matched one.
   The value of a beam radius in point where Coulomb force takes its maximum is identified as "core radius". Generally a procedure of matched beam redistribution has been going on the following manner. At the first stage a redistribution from initial to the steady state with an uniform core distribution take place. The potential energy difference between initial and final states (always positive for considered distribution class) transforms into kinetic energy and is accompanied by an emittance growth. In the steady state only small fraction of particles (about 30%) never escapes the core, other particles (about 70%) can

turn up in core or in halo. It means that it's absurd to cut off the halo particles because it leads to large particle losses.

The core radius is kept constant during beam redistribution. It means that the core radius can be determined from initial redistribution. The matched focusing field value can be determined from a core radius and a core emittance. In the point of a crossover (an average radial velocity is equal to zero) the core emittance is equal to an straight ellipse area with r and $k\beta_r$ as semi-axes, where β_r is rms value of radial velocity and $k^2 = 3$ is a square of boundary value to rms one ratio for uniform distribution. As is evident from the foregoing the beam kinetic energy is increasing in the steady state on the difference of potential energies between the initial and final space charge distributions. This difference will be called as "a beam heating up".

The unmatched beam investigations offer a clearer view of how the core-halo is formatted as well as further regularities of the process:

7. During the process of charge redistribution in mismatched SCD beam core oscillations are drastically damping.

8. If potential Coulomb energy of input beam is much larger that the same energy of beam steady state, core is automatically matched with channel (there is a damping of core oscillation in continuos magnetic field and in periodical field only one clearly defined harmonic in close agreement with external force harmonic stays in core oscillation spectrum).

9. A factor of 3 is a sufficient estimate for halo-core radii ratio.

   It is evident that a halo is formatted from particles which increase their kinetic energies during transverse oscillations. A separate particle motion inside the field of oscillated uniform core was considered in order to study of mechanism of particle energy increasing. A comparison of particle potential energy with its kinetic one before and after oscillated core passing gives a possibility to state that:

10. Energy mechanism for halo production is kinetic energy growth in the case when a halo particle have passed through core concurrently with core ultimately decreasing.

At Fig. 1 the changes of kinetic (curve 1), potential (curve 2) and total (curve 3) energies are indicated versus $\kappa = r_{in}/r_{out}$, where r_{in} and r_{out} are the core radius values at the moments of particle entrance into the core and its exit from core correspondingly. It can be seen that potential energy decreasing is much smaller then kinetic energy increasing and total energy is increased with core size decreasing. The duration of particle being outside of the core is increased with increasing of the particle total energy. That is the phase of the core envelope oscillation will be changed in the next core traversal. It means there is a mechanism which desynchronized the oscillations of core envelope and halo particles. It limits a kinetic energy of halo particle and as a result limits a transverse size of the halo.

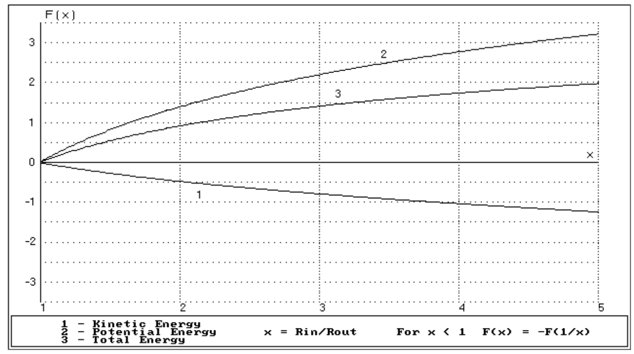

Fig.1.

The important conclusion regarding the choice of focusing channel parameters can be made on the base of performed investigations:

11. The choice of focusing channel parameters must be made from a desired core size and the bore radius choice from a value three times over (a halo size).

References

[1] B.I. Bondarev, A.P. Durkin, B.P. Murin “Halo Production in Charge-Dominated Beams. Single-Particle Interactions”. Contract 9-XG3-5167H-1 between LANL and MRTI, Phase 3, Moscow 1993.