THE MAIN REGULARITIES OF CORE-HALO FORMATION IN SPACE CHARGE-DOMINATED ION BEAM*

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Abstract

The laws that govern the charge redistribution in space charge dominated (SCD) beam during its transport is considered. Physical mechanisms of halo production and establishment of steady distribution inside core for matched beams are described. The image-based computer codes were generated and charge density redistribution process in the beam with concurrent phenomena was described. The main regularities of SCD-beam transporting were carried out. High-density core and low-density halo with particle active interchange are established in every case. 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. Final steady states are ones 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. A steady state with constant transverse sizes of core can be established. Such beam state would be nominated as matched one.

1.INTRODUCTION

Growing needs in high-current CW ion linac aggravate both problems of beam losses and radiation purity. It turned out that acceptable beam loss standard is very tight. Linac designers were obliged to study beam physics mechanisms that lead to emittance growth and core-halo formation. Computational methods were widely used because analytical approaches are effective only in limited idealized cases (for example, K-V distribution). SCD beam study in linear transport and accelerator channels as well as computer code generation were performed and published by authors starting from 1986 [1-5]. The general results were obtained such as: (a) formation of quasi-uniform core and rarefied halo; (b) core oscillation damping with concurrent emittance growth; (c) beam matching using information of input beam distribution in phase space; (d) minimization of the space charge potential energy and concurrent emittance growth; (e) impossibility of halo stripping by diaphragm and so on. These results are agreed very closely with ones published by different researchers later.

In recent years works on convenient in operation computer codes for space SCD beam physics study were developed using modern image-based computer technology. The new code tools make calculations with higher then formerly accuracy. They are adopted for education and training. In

recent report a lot of numerical experiments are discussed in order to clear out the main regularities of core-halo formation in SCD ion beam. The results were obtained in the frame of longitudinal and transverse uniform focusing. Solenoids were used directly as focusing elements. This relatively simple focusing gives a possibility to clear demonstration of all essential SCD-beam effects.

2. MATCHING INJECTION

The solution of the above task is well studied only for K-V distribution [6]. For more real (but not too exotic) distributions authors proposed the matching injection procedure based on rms parameters of the distribution. The procedure despite the fact that it gives only approximate matching offers practically steady state for beam with not very high beam current (tune depression $\eta \approx 0.8$) during further beam transport. A fast formation of beam halo takes place for beam distributions limited in space (such as uniform or waterbag) In all cases beam simulations extend to some tens of core oscillations. For large currents ($\eta \approx 0.2$) beam injection with distributions limited in transverse directions does not lead to emittance growth and beam is practically stabilized at once. For Gaussian transverse distribution there are both fast emittance growth up to 50% and core oscillation damping with further stabilization.

If a beam evolves to equilibrium state the charge distribution with the quasi-uniform central region in transverse coordinate plane is established. This distribution is very similar to stationary self-consistent analytical solution of Maxwell-Boltzmann type. But exact radial dependence in the region of the distribution ″tail″ remains in reality unknown.

Let us note that in spite of frequent using of term ″beam core″ nowhere the size of the beam core was defined. Following the work [1] we define core size as a distance between beam axis and the point where the maximum value of the space charge field is achieved. Physical sense of the definition is evident for the beam with elliptical cross section and uniform charge density - the core size coincides with the beam size. For Gaussian charge distribution in transverse plane the core radius is 1.12 of rms radius.

3. MISMATCHED BEAM INJECTION

Beam calculations with initial mismatch factor 1.5 were performed in order to study of effects of unequilibrium beam relaxation after its injection in focusing channel. For

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low currents ($\eta \approx 0.8$) there is a damping of the core radius oscillations on the length of 15÷20 oscillation periods with simultaneous emittance growth up to 30÷40%. The results fall into a pattern of filamentation phenomena due to nonlinear betatron frequency spread. The halo formation in the cases of distributions limited in transverse directions is followed by phase contours of nonlinear parametric resonance-2 (look below).

For the large beam currents ($\eta \approx 0.2$) a role of initial mismatch factor considerably increases. For various initial distributions the core oscillations caused by initial mismatching do not damp practically and emittance growth by factor of 2 or 3 on the length of 30 ÷ 40 oscillations takes place. The core oscillations lead to fast halo formation particularly for limited distributions. The phase trajectories of particles follow by phase contours of resonance-2 (look below). Indeed the time of halo formation may be evaluated taking into account the period of phase oscillations in near resonance region.

The absence of the core oscillation damping for large currents does not have satisfactory explanations so far. Maybe space charge strong nonlinearity would enhance a process of beam filamentation. It is possible that quasi-uniform beam core formation converges the distribution to KV type. It is necessary the further study of the problem.

4. HALO FORMATION

The simple (but effective) model of the halo particle dynamics reduces the problem to analysis of the sole particle behavior under linear focusing force and nonlinear force of space charge field. The own field of halo particles is supposed as negligible small. The analytical calculations [2] show that energy of external particle increases when it crosses the compressing uniform beam core and vice versa: particle energy decreases when core extends. R.L.Gluckstern [7] studied the halo particle dynamics in periodically alternating field of mismatched beam core. He has found the conditions of nonlinear parametric resonance. The particle amplitude can enhance considerably in the frequency band of the resonance. The resonance is often named as ″resonance-2″ because the particle oscillation frequency is 2 times less than core frequency. The convenient visual image of the resonance was used in work [8] by means of so called Poincare mapping. The pictures of phase contours in near resonance region allow to evaluate the maximum amplitudes of halo particles. For low currents the individual phase contours are clearly separated. The typical duration of resonance phenomena is characterized by the oscillation periods along the phase contours. For large currents the resonance separatrix is destroyed and near the core region arose island regions of high order resonances. Overlapping of the resonances and destroyed separatrix are formed the stochastic layer. As the beam current more as the layer broader. The halo formation is now caused by the particle diffusion along the layer.

Curves of the maximum radial size versus mismatching factor for resonance separatrix are shown on Fig.1 for various tune depression values.

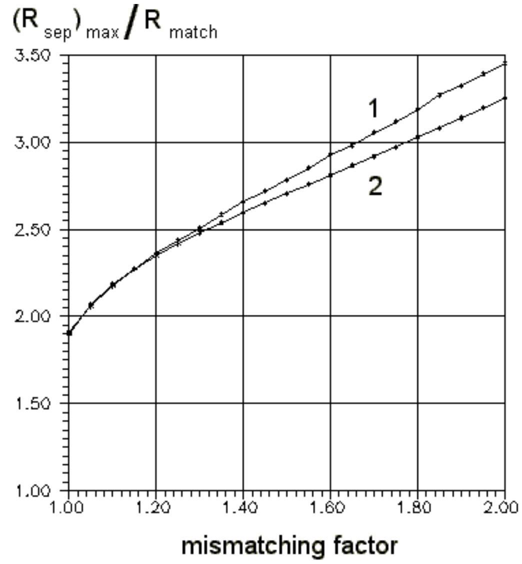

Fig.1: Resonance-2. Maximum radial size of separatrix: 1 - η = 0.82; 2 - η = 0.24.

In many of our PIC simulations the particle ejection along phase contours of the resonance-2 are observed (Fig.2). They are seen particularly clear if the initial distribution do not possessed the extended halo. Possible sources of halo particles in the initially bounded distributions are discussed in work [9] and more completely in review [10].

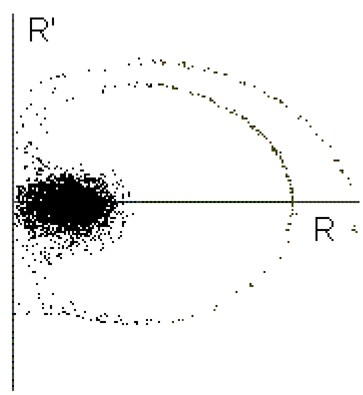

Fig.2: Phase trajectories of resonance-2 as result of PIC simulation.

Hence for many of the beam transport simulations the resonance-2 model gives satisfactory qualitative explanation of halo formation and possibility of its scale evaluation. But all approaches described above concerning resonance-2 do not give a reliable quantitative algorithm to calculate the transverse distribution of halo particles that must be the main goal of halo researches. Only the knowledge of distribution function opens the opportunity to receive the based data about the probable particle losses.

5. ADIABATIC TRANSFORMATIONS

The heating of halo particles due to compressing core (look [2]) may cause the halo extension in the time of adiabatic growth of the focusing field. We have made corresponding calculations. The effect of halo heating tells on the relatively less halo compression comparatively with the core. The behavior of halo particle having the initial radius double the radius of uniform core is shown on Fig.3.

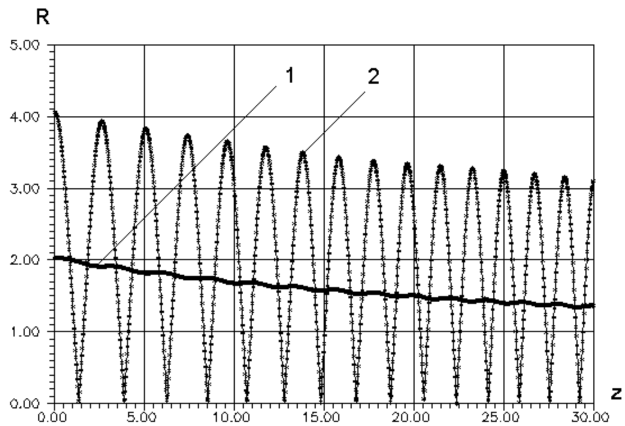

Fig.3. Adiabatic compression of beam: (1) – core radius; (2) – halo particle. Focusing grows ~(1 + 0.044z).

Analogously in the time of adiabatic beam extension the halo extends in the less degree than the beam core.

6. CODE PACKAGE DEVELOPMENT

The package is creating for visual study of the physical processes accompanying high current beam transport and bunching. The first part of the package is used for transverse beam dynamics describing. This part contains two tools that are used for beam simulations by analytical model and by PIC model respectively. The analytical model describes the motion of halo particles in collective field of the external focusing and oscillating uniform core. The PIC-model calculates the beam transport in solenoid or quadruple channels. The space charge forces are resulted as digital solution of Poisson equation at the circular or square boundaries. Parameters of beam and channel are input either in generalized dimensionless form or in form of physical units. Initial distributions of the three types are used: Waterbag, Gauss or Uniform. By means of the last two ones it is possible to get distri describing.butions on coordinates and velocities independently. The visual information about beam cross-section and phase portraits (for various pairs of the dynamical variables) may be received as well as an evolution of distribution moments and of space charge field energies. Both intermediate and final visual images may be kept for consequent comparison of variants. Two previously saved variants may be displayed simultaneously

The second part allows to calculate the high current beam bunching under the constant transverse characteristics (″frozen beam″). The periodical charge distribution in longitudinal dimension is supposed. The visual information showing charge redistribution phenomena and the evolution of harmonic spectrum of the longitudinal distribution are presented.

The last part of the code package combines two above ones describing together the longitudinal and transverse dynamics of high current ion beam.

7. CONCLUSION

One of the main problems in our opinion remains a reliable quantitative evaluation of the halo size or more exactly the distribution function for the halo particles. It is only way for correct calculations of the particle losses in the beam transport. The existing halo models do not solve the problem. We proceed a work to construct the algorithms for those calculations based on the beam PIC simulation data.

The most interesting are the time scales of the relaxation processes.. According to our PIC simulations for the tune depression $\eta \le 0.5$ the core oscillation do not damp on the channel lengths measured by many tens oscillation periods. Accuracy of the calculation results is confirmed by the clear view of Poincare mappings for that lengths.

We shall proceed the HALO-KERN code package design and the ion beam studies for more complicate configurations.

7. REFERENCES

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