LONGITUDINAL TRAPPING AND PARTICLE LOSS OF HIGH INTENSITY BUNCHED BEAMS

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Abstract

For a high intensity bunched beam the longitudinal acceptance usually is smaller than the beam emittance at injection energy. This causes longitudinal particle loss and emittance increase. A model is presented which explains the dynamics of the trapping procedure and the related particle loss for a high current bunched beam. The model is in qualitative agreement with numerical results obtained from multiparticle calculations. By varying the injection energy and the phase of the bunch center and the matching parameters of the beam the trapping effiency can be improved.

Introduction

Beam losses can lead to severe problems in proton linear accelerators with a high current and a high duty cycle. It is therefore necessary to do calculations of beam dynamics in order to determine the beam parameters that will minimize these losses. Having no theory for calculating and predicting particle losses extensive multiparticle calculations have been carried through to get some information on losses from a statistical point of view [1].

By considering the particle loss problem some question arise.

- In which part of the phase space at injection are those particles which get lost later on?
- Is there any correlation between the longitudinal and transverse motion of a lost particle?
- What is the energy of the lost particle?
- What can one do to reduce the losses?

This list of questions is not complete but in this paper it is tried to answer these questions. The answers result from multiparticle calculations done for a 200 MHz drift-tube linac [3]. The injection energy is 2 MeV and the output energy 100 MeV. The current was varied up to 400 mA. The beam parameters have been choosen in such a way that the transverse emittance growth is less than 10 %. The longitudinal emittance growth goes up to 2.5 for a current of 400 mA. The emittance growth is a result of a too small longitudinal acceptance at injection. In connection to the emittance growth particles are lost longitudinally. In a previous paper[4] emittance growth of high current linacs was analyzed in detail. This paper deals only with the particles lost longitudinally. The next chapter describes a simple analytical model of the longitudinal phase space including space charge. In the chapter afterwards a discussion of numerical results from multiparticle calculations with special emphasis to lost particles is given.

Simple model of longitudinal motion including space charge

It is common to describe the longitudinal motion of particles with small transverse components by a sum of the nonlinear rf-potential and a quadratic space charge term. For the calculation of the space charge factor μ_1 the bunch is presented by an ellipsoid uniformly filled with charge corresponding to linear space charge forces [2].

A simple model has been developed which allows that a few number of particles can leave the bunch. It has been assumed that outside the bunch the single particle motion will follow from a Coulomb-potential of a sphere. With this model the evolution of the longitudinal phase space distribution could be explained [4].

The assumption of calculating the Coulomb potential outside the bunch by a sphere and inside by an ellipsoid is inconsistent and gives wrong results for large space charge factors, e.g. $\mu_1 > 0.9$. To be consistent the potential outside the bunch is calculated from an ellipsoid of revolution in this paper. The formulas will be presented elsewhere[7]. For zero transverse components the longitudinal potential can be calculated straightforward outside an ellipsoid filled uniformly with charge[6].

With this model the longitudinal phase space has been calculated for a beam current of 400 mA. Fig. 1a and 1b show the longitudinal potential and the phase space at 2 MeV respectively. The space parameter μ_1 is 0.92. Emittances and tunes are chosen in such way that inspite of the large value of μ_1 no collective instabilities are present. The input emittance of 1.8π °MeV is much larger than the acceptance; a quite unstable situation. Fig. 2a and 2b describe the situation at 6 MeV corresponding to half a synchroton oscillation. Due to the acceleration the acceptance has become larger than the emittance; the situation is stable now. It is expected that longitudinal losses will happen between 2 and 6 MeV.

Numerical results on longitudinal particle losses

As an extract of many multiparticle calculations results are presented for a beam current of 400 mA. The simulations were done with 2000 macroparticles. The space charge force is included by summing up the Coulomb forces between the macroparticles. The initial phase space distribution is waterbag like in the transverse and a Gaussian distribution in the longitudinal phase space. By choosing a longitudinal waterbag distribution the results are the same in a qualitative sense. The Gaussian distribution has been choosen to populate the halo with particles.

Concerning the first question Fig. 3a shows the distribution in the longitudinal phase space at injection of those particles which are lost later on. The number of lost particles is 124 which is about 6 % of the total beam current. In comparison Fig. 3b shows the longitudinal input distribution of all particles. The lost particles are localized quite well. They mainly come from the lower halo of the input distribution. These particles can pass the phase $-2\varphi_s$ and therefore get lost. Particles from the upper halo cannot reach the phase $-2\varphi_s$ because of phase damping and the increase of the energy acceptance during acceleration. As a rough rule all those particles are not lost which can complete one synchrotron oscillation.

The longitudinal rms emittance of the non lost particles increases up to 2.5 at 100 MeV. This growth is still consistent with the empirical evaluated law[4]:

$$\text{longitudinal rms emittance growth between 2 and 100 MeV} \simeq \left(\sigma_{L0} / \sigma_L \right)^{0.9}$$

Here σ_L and σ_{L0} are the longitudinal tunes with and without current.

In contrast to the longitudinal situation the lost particles are distributed randomly in the transverse phase space at injection (Fig. 4). No correlation is seen between the longitudinal and transverse direction of motion of the lost particles. It is therefore concluded that for a particle only the input coordinates in the longitudinal phase space are responsible for getting lost longitudinally or not.

In Fig. 5 the spectrum of the energy of the lost particles is plotted. 121 particles are lost between 2 and 6 MeV. Only three particles have an energy between 6 and 10 MeV. This result agrees with the simple model explained above. The three particles with an energy above 6 MeV become close to the unstable fix point. Particles close to the unstable fix point are moving slowly in the phase space and therefore they can be accelerated to higher energies before they are lost.

The energy spectrum looks similar to the one shown in Ref. 5. There the longitudinal input distribution was equal to the output distribution of a bunching system. In the bunching system tails have evolved in the longitudinal phase space, which are lost in the following Alvarez linac. The maximum energy of a lost particles was 13 MeV.

All calculations where done without any consideration of tolerances or misalignments. It turned out that e.g. phase errors can influence the loss of particles strongly. Simulations have been carried through with phase errors from tank to tank < 3° for a beam current of 200 mA. Losses have been observed with a particle energy up to 25 MeV inspite to a no loss situation for a linac without any error.

The main conclusion is now: for any error free high current linac longitudinal losses will happen mainly during the first synchrotron oscillation which corresponds to an energy in the order of 10 MeV. Afterwards no losses are expected. The situation is different in case of field and phase errors. Then particles are lost at higher energies. It is therefore concluded that in existing linacs the losses above 10 MeV are strongly influenced by tolerances in the rf system.

What can one do now to reduce particles losses? It turned out that the number of particles lost can be reduced by injecting the beam with somewhat different parameters (energy, phase, matching-parameters) than the design parameters and by reducing the errors. E.g. if the beam bunch center is injected with an energy of 2.008 MeV compared to 2.000 MeV design input energy the number of lost particles could be reduced to 97 which is about 20 % of the losses.

All numerical results mentioned so far give a more qualitative understanding of longitudinal losses. It is not possible to give analytical formulas for minimizing the losses. Multiparticle calculations so far give a rough estimation of beam loss in the range of 10 %.

Conclusion

Longitudinal beam loss has been studied with multiparticle calculations. Due to the nonlinear longitudinal potential the lost particles can be localized quite well in the phase space at injection (see Fig. 3) There is no correlation between the longitudinal and the transverse motion. It turned out that longitudinal loss can happen within the first synchrotron oscillation only. Without tolerances no loss is expected afterwards. This means the bulk of longitudinal beam loss takes place below 10 MeV. In addition field and phase errors can produce particle losses even at higher energies. By varying the input energy, the input phase and the matching parameters some influence on the amount of losses is possible.

Acknowledgement

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References

1 G.P. Boicourt, "Radial Particle Distributions in PARMILA Simulation Beams", Los Alamos National Laboratory, LA-10063-MS, 1984

2 B. Gluckstern, "Space Charge Effects" in Linear Accelerators, ed. P.M. Lapostolle and A.L. Septier, North-Holland, 1970

3 M. Pabst, "A Design Concept for the SNQ Alvarez Linear Accelerator for low Emittance Growth", Proc. of the 1984 Linear Accelerator Conference, Seeheim, Germany, GSI-84-11

4 M. Pabst, K. Bongardt, U. Funk, "Nonlinear Field Effects and Longitudinal Emittance Growth of High Intensity Bunched Beams", IEEE Trans. on Nucl. Sci, NS-32 (1985) p. 2471

5 K. Mittag, "SNQ Linac Accelerator Beam Dynamics" Proc. Workshop on High Intensity Accelerators and Compressor Rings, Kernforschungszentrum Karlsruhe, KfK-report 3228, 1981, p. 45

6 O.D. Kellog, Foundations of Potential Theory, New York 1953

7 M. Pabst, K. Bongardt, "Longitudinal Potential of an Ellipsoid Uniformly Filled with Charge", KFA-ASI-report, KFA Jülich

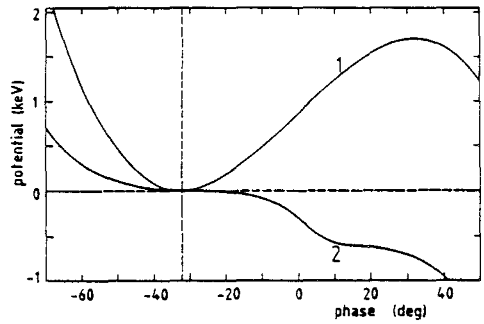

Fig. 1a: Longitudinal potential with (2) and without (1) space charge at 2 MeV

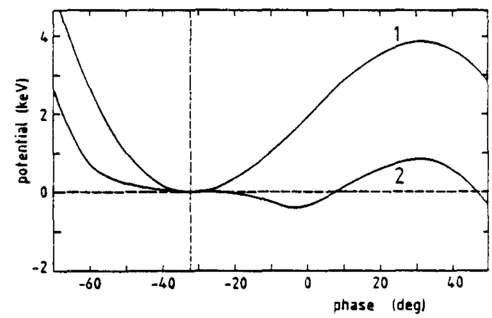

Fig. 2a: Longitudinal potential with (2) and without (1) space charge at 6 MeV

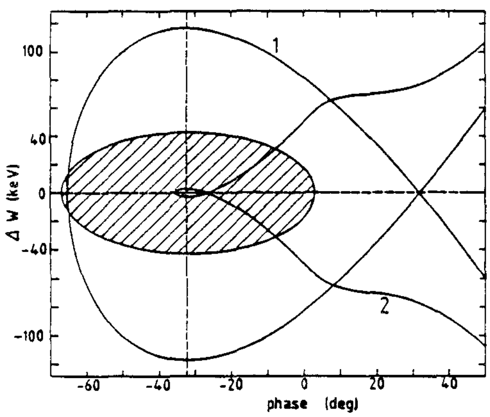

Fig. 1b: Emittance(shaded area)and acceptance with (2) and without (1) space charge at 2 MeV

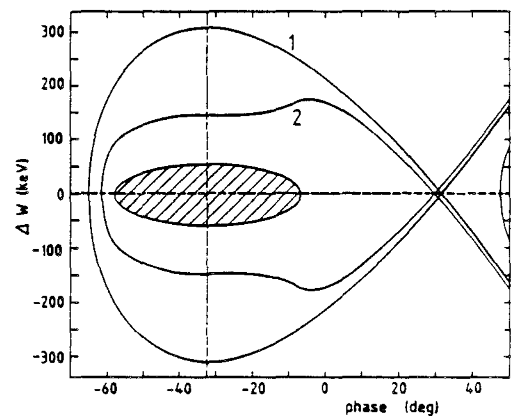

Fig. 2b: Emittance(shaded area)and acceptance with (2) and without (1) space charge at 6 MeV

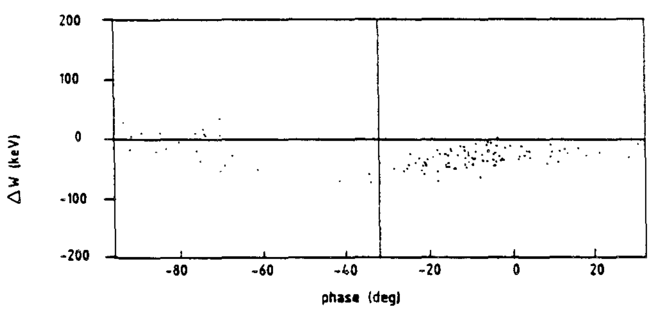

Fig. 3a: The initial distribution of lost particles in the longitudinal phase space

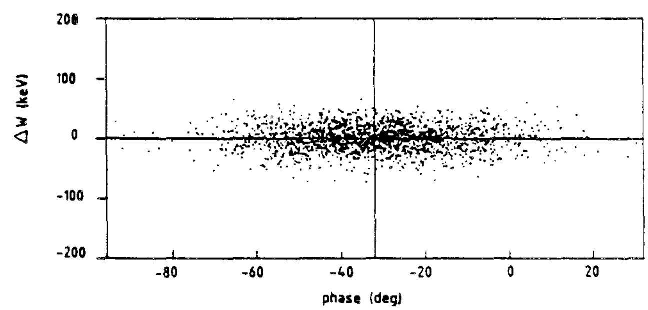

Fig. 3b: Total initial distribution in the longitudinal phase space

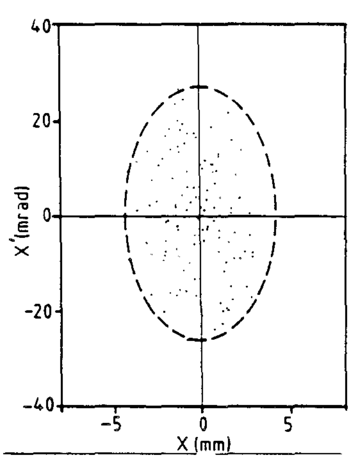

Fig. 4: The initial distribution of lost particles in the transverse phase space and the boundary of the total distribution

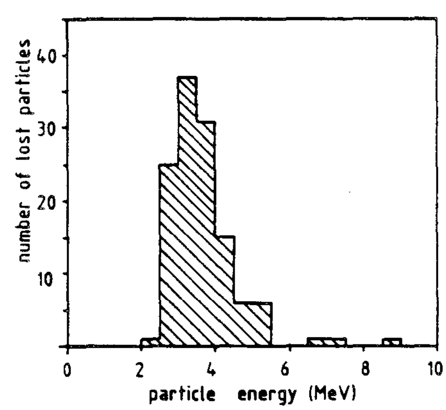

Fig. 5: Energy spectrum of lost particles