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LONGITUDINAL SPACE-CHARGE-EFFECTS IN THE SIN INJECTOR II AND IN THE SIN RING CYCLOTRON

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Abstract.- With the operation of the SIN Injector II it is planned to accelerate proton beams of an average current of more than 1 milliampere to an energy of 590 MeV. At this current level the increase of energy spread due to longitudinal space charge forces will become an important effect, which can produce high beam-losses at extraction.
This paper presents the results having been obtained so far in studying these effects for the SIN Injector II as well as for the SIN 590 MeV Ringcyclotron. The DISKS model for the numerical simulation of the longitudinal space charge effect is explained. This model has been incorporated in a computer program simulating the acceleration process in the cyclotron.

Introduction

In spring 1978 it was decided to upgrade the SIN accelerator facility by adding the Injector II [1]. This new machine should produce a 72 MeV proton beam of an average current of more than 1 milliampere which has to be accelerated further to 590 MeV by the existing SIN Ringcyclotron [2]. In order to achieve this new goal it is necessary to study the effects limiting the beam current which the machine can accelerate.

The increase of energy spread in the beam due to longitudinal space charge forces is an important effect. In an isochronous cyclotron the repelling forces between neighbouring particles are not counteracted by any focusing if they point in the longitudinal direction.
They add up during the acceleration and increase the energy of the leading particles inside the bunch while the energy of the lagging particles is decreased. A compensation is possible by adjusting the RF parameters: one can arrange that the leading particles gain correspondingly less energy in the acceleration.

A simple estimation of the longitudinal space charge effect for the planned situation at SIN showed that such a compensation will be necessary [3]. With usual RF-systems, even including 3rd harmonic flat-topping [4], only the part of the energy spread varying linearly with phase can be cancelled. The high beam currents foreseen at SIN require extremely low extraction losses. In order to predict the remaining energy spread after compensation, a detailed knowledge on the energy variation as a function of phase is essential.

Special computer programs for the numerical simulation of the longitudinal space charge effect have been developed. This paper reports the ideas behind those programs as well as some of the results that have been obtained.

The DISKS Model

The simplest simulation of a beam, considering it as a cloud of particles, is not favourable for a cyclotron. Calculating the coordinates of many thousands of points over 100 or more turns would need too much computational effort. Another idea would be to simulate the beam bunch by a series of charged points arranged along a line. However, the rapid increase of the Coulomb forces at low distances forbids such a simple approach. The next step, breaking up the beam in a series of charged line segments still produces singularities of the field at the points where the charge density is discontinuous (see fig. 1).

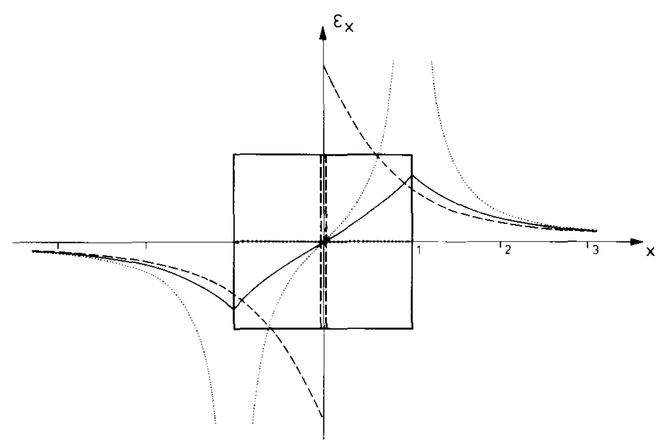

Fig. 1: The electric field along the axis of a charged line segment (dotted), of a thin disk (dashed) and of a cylinder (line). The three items all carry the same total charge uniformly distributed over the length, surface or volume respectively.

For a proper simulation of the longitudinal forces, the finite thickness of the beam has to be taken into account. The first successful model was the approximation of the beam with a series of thin disks having the same diameter as the real beam. Later, the disks were replaced by uniformly charged cylindrical pieces, but the name 'DISKS model' remained. Such a little cylinder is represented by its center point. An individual charge value is assigned to each cylinder.

Various functions of the longitudinal charge density have been studied (fig. 2). The charge density 'Q' (~'Ipeak') as a function of the phase 'Ph' is described with the binomial distribution depending on 'Phlim' and 'm'. The maximum phase extension 'Phlim' is expressed in terms of the exponent 'm' and the effective phase width 'Phwid' (=4* standard deviation). A uniformly charged insert can be added in the center of the distribution.

$$Q(Ph) \sim Ipeak(Ph) \sim \left(1 - (Ph/Phlim)^2\right)^{m-0.5}$$

$$Phlim = SQRT\left((m+1)/2 \right) * Phwid/2$$

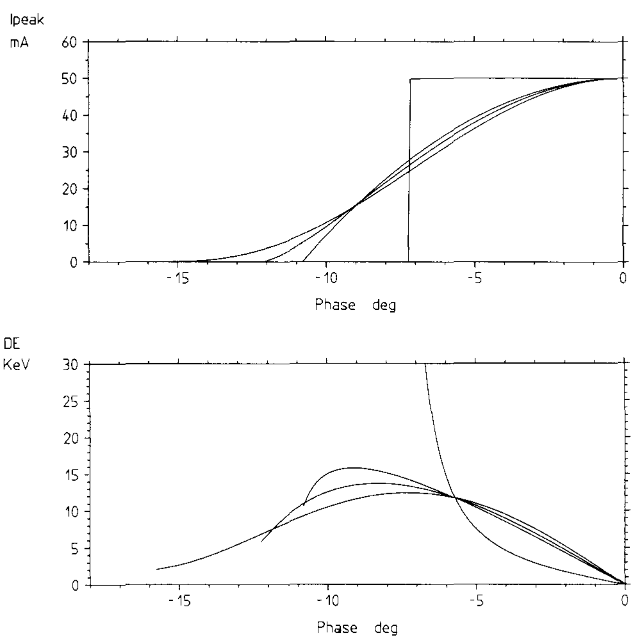

Fig. 2: Different charge density distributions (top) and the corresponding energy increase of leading particles due to longitudinal space charge forces (bottom). The values are calculated for one turn of Injector II at R=2000 mm with a beam diameter of 5 mm and an average current of 2 mA. The exponent m of the binomial distribution varies from 0.5 (uniform), to 1.5 (parabolic), to 2.0 (short tail) to 5.5 (long tail).

The beam bunch is bent only very mildly. The force can be approximated therefore by the value it has along the axis of the cylindrical piece. For the same reason no slant is assumed for the closing planes of the little cylinders.

The DISKS model was tested comparing its results to analytical expressions for special charge density distributions. Generally the forces are proportional to the inverse square of the phase width and to the inverse of the beam diameter.

The space charge forces in the cyclotron

The longitudinal space charge effect which can be calculated for one turn with the "DISKS model" has to be accumulated during the whole acceleration process. For this purpose the model was patched into the existing program MATADOR. This program uses transfer matrices to simulate the behavior of an accelerated beam. Now, after each turn the energy of the particles is updated, accounting for the longitudinal space charge forces. The vortex motion predicted by Gordon [5] is clearly shown by the program (see figs. 3,4).

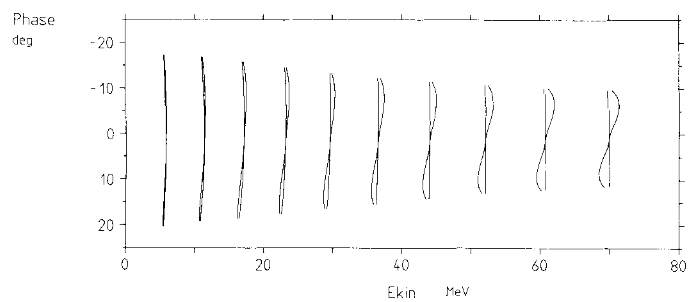

Fig. 3: The energy spread growing from turn 10 to turn 100 for a beam current of 2 mA in Injector II. The curves of energy vs. phase for zero current are included for comparison. The sign of the phase axis is reversed in order to achieve a similarity with a top view of the beam in the cyclotron.

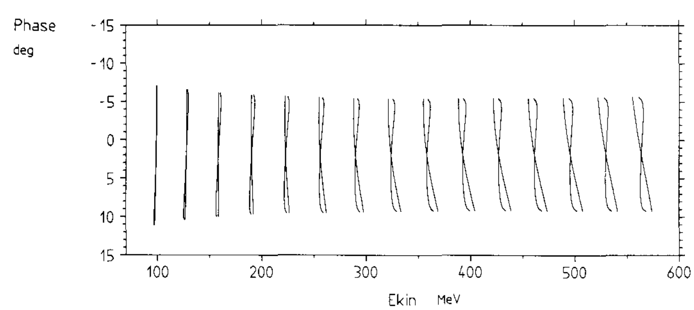

Fig. 4: Energy vs phase for the turns 20 through 300 in the Ringcyclotron. The energy differences relative to the central particle are extended by a factor of 5. A 2 mA beam, where the longitudinal space charge is compensated, and a zero current beam simulated for the same RF parameters are compared.

For the moment, the radial components of the longitudinal space charge forces are neglected in the program. (These forces could also be called the coherent part of the radial space charge forces). These radial forces will produce phase displacements of parts of the beam bunch. From first estimates one expects that these displacements will be detectable but not severe. The radial forces are anyhow kept low by the fact that the compensation tends to align the bunches azimuthally. It is planned to include the calculation of the radial forces when the model will be extended to cover the effect of neighbouring orbits.

In a first version of the space charge simulation in the cyclotron, the precise radial position and phase of each little cylinder were taken into account. In that model a curious resonance occured: a few of the cylinders were kicked out radially from the bunch. Further investigations led to the conclusion that this resonance had been brought in artificially by the tight coupling of the charge within one cylinder. This effect was then cured by smoothing the coordinates of the disks before evalutating the space charge forces.

The effects of the conducting surfaces above and below the circulating beam were taken into account in a simple way. The forces due to parts of the beam being at a distance larger than the gap of the vacuum chamber were progressively screened (see fig. 5).

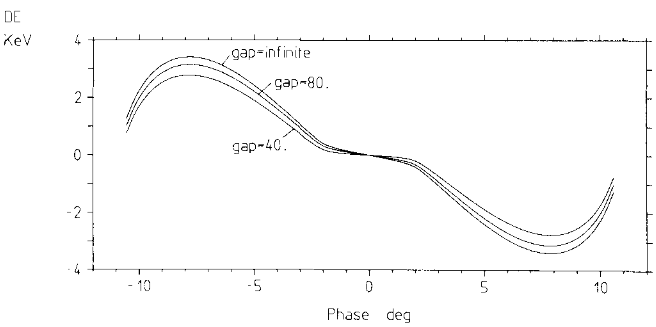

Fig. 5: The variation of the longitudinal space charge forces due to the conducting surfaces above and below the beam. The effect of the simple screening model is shown for one turn in the Ringcyclotron at R=3800 mm.

The final energy spread

The result of the simulation is the final energy as a function of phase (see fig. 6). The major part of the compensation is already included by the simulation of the acceleration, but a fine adjustment of the RF parameters can be added as a small linear correction. This fine correction is determined with the help of an interactive plotting program.

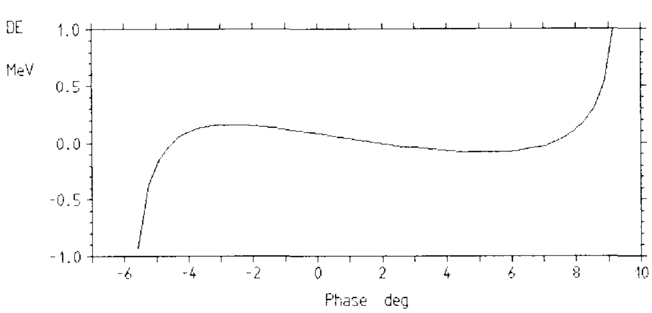

Fig. 6: The final energy of a beam bunch as a function of phase at turn 315 in the Ringcyclotron. A beam of 2 mA with a longitudinal distribution of m = 1.5 and Phwid = 18 deg with no insert was assumed at injection.

The theoretical background of the adjustment of the RF parameters for the compensation of the space charge effect is discussed by W. Joho in [3]. For the accelerators at SIN the theory gives only approximate values because the flattop voltage follows a different function of the radius than the main accelerating voltage does.

At first the situation from fig. 6 looks much worse than it is in reality. After ideal compensation the tails of the energy spread extend to 1 MeV in both directions. It has to be taken into account that these tails carry only a minor amount of charge. This fact is visualized in fig. 7, which gives a more realistic picture of the resulting energy spread than the one from fig. 6.

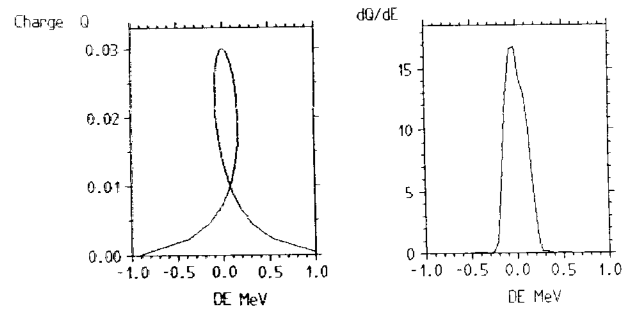

Fig. 7: The charge Q in the beam bunch is plotted vs. the energy for the same beam as in fig. 6. In the right picture this function of charge vs. energy is transformed into a charge density distribution dQ/dE as a function of energy. The resulting effective energy spread is only 0.5 MeV.

Conclusions

The DISKS model together with the simulation of the acceleration seems to be a useful first tool for the investigation of the longitudinal space charge effects. It will be extended to cover the effect from neighbouring orbits and of the radial forces. It has shown that compensation of the energy spread with the RF will be necessary. It has also become clear that details of the charge density distribution as a function of phase are essential to the size of the final energy spread. Further study will have to be devoted to the problem of how the longitudinal charge distribution can be shaped with the help of collimators and high frequency bunchers.

Acknowledgement

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