TRANSVERSE EMITTANCE BLOW-UP IN COMPACT PROTON SYNCHROTRONS CAUSED BY THE SPACE-CHARGE EFFECTS

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Abstract

Space charge effects play significant role in low-injection-energy synchrotrons with the repetition frequency less than 1 Hz. Accurate consideration of these phenomena is required in the case of 'medical' proton machines to avoid limitation of the beam intensity. Common features of these accelerators are small ring circumference (~20÷25m), small injection energy (<10 MeV) and the 'flat' beam cross-section, produced by the multi-turn injection to accumulate the required beam intensity (~10^{11} particles per pulse). In the compact proton synchrotron the high-order resonances can be exited by the beam itself without any magnetic field imperfection. To minimise the transverse emittance blow-up during the capture process that leads to the particle losses, the parameters of the machine should be optimised. We studied influence of the space charge effects on the beam parameters during the 'quasi-adiabatic' capture process. The report presents results of simulations of these effects for the 'medical' machines, based on the multi-particle tracking in the 6 dimensional phase space including the transverse and longitudinal motion.

1 INTRODUCTION

Hadron therapy by charged particles is one of the most promising applications of the high energy physics and technology that is supported by extremely good clinical results obtained in many centres around the world. Main requirements for the medical machines are compact design, reliability and beam stability with reasonable small particle losses. The needed beam intensity is defined by the given dose/fraction and is a complicated function of many other parameters like an irradiation time, tumour shape, time structure of the extracted beam etc. The dose of 2 Gy delivered to a target volume of 1liter per 1 minute requires the primary average beam current up to 10 nA. To accumulate the required beam intensity in the synchrotron with the repetition rate of 0.5 Hz, the pulse beam intensity should be about 10^{11} particles-per-pulse. Then, if the injector for such kind of machine is a linear accelerator (RFQ/DTL structure) the multi-turn injection process should be utilized. In the case of the horizontal injection the vertical emittance of the beam will be much smaller than the horizontal one. So the incoherent tune shift of the vertical betatron tune caused by the space-charge of the beam will be the most important problem for this compact high-intensity proton machine. Estimation of the Laslett tune shift predicts the incoherent tune shift more than 0.2 for the compact 'medical' synchrotron with the low repetition rate then it could lead to crossing resonance lines.

After construction of first proton synchrotrons, the space charge effects were recognized as one of the most important problems, which limit the beam intensity. According to obtained computational and experimental results for 'big' proton rings the space charge force itself can excite high-order resonances without magnetic field imperfection of machines, that could lead to blow-up of the transverse beam emittance and significant particle losses [1]. A beam with a non-uniform particle distribution always gives rise to coupling motion, even where there is complete rotational symmetry [2]. As the result there is an observable effect of beating in amplitude between the transverse directions and very rapidly increasing of the smaller beam emittance. It means that the coupling effect could change the particle distribution during the multi-turn injection and lead to significant particle losses even in the case of 'ideal' magnetic elements of the synchrotron.

Optimization of the 'bare' working point position during the injection and capture processes should be performed to eliminate these effects. An accurate prediction of the optimum working point position could be make by a modelling of the particle dynamic in the machine using the self-consistent multi-particles tracking technique in the 6-dimensional phase plane.

We presented simulation results of the space-charge effects for the 'medical' proton synchrotrons obtained by using the Accsys code [3].

2 STUDY OF THE SPACE-CHARGE EFFECTS DURING THE CAPTURE

The required value of the betatron tune-split in the Montague's estimation [2] to avoid the transverse emittance dilution caused by the fourth-order coupling resonance was obtained for the stationary case, when the bunching factor does not change. In real situation the longitudinal and transverse beam parameters are function of time during the capture process when the beam space-charge potential changes the external RF voltage. This changing depends on the transverse particle distribution. In the case of the compact proton synchrotrons (operating on the main harmonic of the RF voltage) this correlation between the transverse and longitudinal particle distributions is not significant. The space charge force on a given macro-particle can be scaled according to the longitudinal charge density at its position in the bunch thus introduce coupling the longitudinal motion into the transverse tune space.

The space-charge effects have been studied for two different proton synchrotrons which will be used for cancer treatment [4,5]. Main difference of these machines

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is connected first of all with definition of the 'bare' working point position and influence of the high-order resonances on the beam parameters.

2.1 Fourth integer resonance

In the first case [4] the 'bare' working point position on the betatron tune diagram is chosen so that ν_{H0}/ν_{V0}=1.68/0.81. The RF voltage during the 'quasi-adiabatic' capture process is changed till 180V linearly during 10msec [4, 6]. The designed beam intensity after the injection process is 2.4×10^{11} ppp. The momentum spread of the particles at the beginning of the capture process is equal to ±0.0005. The energy of the reference particle is 10MeV. Changing of the vertical emittance at the beginning of the capture process is shown in Fig.1 without limitation of the chamber for different beam intensity (A) and including the vertical chamber size in the dipole magnets for the design beam intensity (B). The initial vertical emittance is equal to 10π·mm·mrad assuming the uniform particle distribution in the transverse and longitudinal phase planes. The initial horizontal emittance is equal to 200π·mm·mrad.

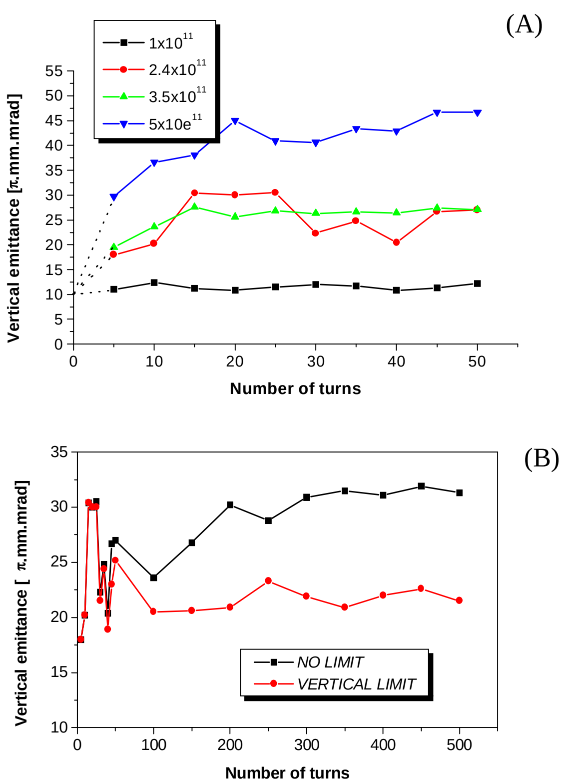

Figure 1: Changing of the vertical emittance caused by the fourth integer resonance exited by the beam.

From this result one can see that the vertical emittance is changed rapidly at the beginning of the capture process if the beam intensity is high. In the case of the high beam intensity the betatron tune of the particles is changed by the defocusing effect of the space charge. The betatron tunes of the particles in the vertical plane are located in the range $\nu_V\cong0.65\div0.80$. As the result the particle distribution in the vertical plane has the 'tail' part. This part of the beam will be lost if the vertical limitation of the chamber is included.

Changing of the working point position can eliminate this effect. Fig.2 presents changing of the vertical emittance of the beam for the corrected 'bare' working point ν_{H0}/ν_{V0}=1.68/1.24 in the case of different beam intensities. The limitation of the vertical chamber size in the dipole magnet is included.

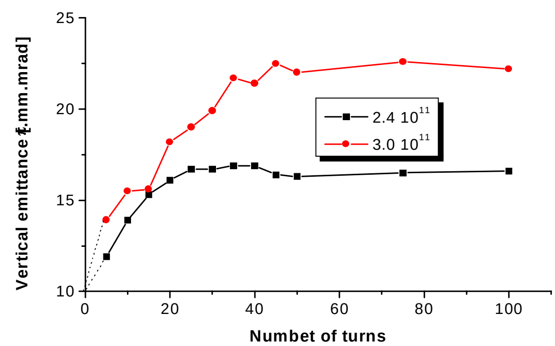

Figure 2: Changing of the vertical beam emittance for different beam intensities in the case of the corrected 'bare' working point position.

In this case the betatron tunes of the particles in the vertical phase plane are in the range $\nu_V\cong1.1\div1.22$. For the design beam intensity the capture process without particle losses was obtained theoretically. Simulation of the capture process predicts that the maximum RF voltage at the end of the capture process should be increased till 270V to prevent particle losses during acceleration. This requirement is connected with increasing of the beam intensity at the end of the capture process.

2.2 Fourth-order coupling resonance

The lowest order of the difference resonance we have excluded from the consideration by assuming that the axis of the beam cross-section coincide with the coordinate axis thus eliminating any (xz)-term in the Hamiltonian. Since, in general, we are dealing with a fourth order non-linear coupling resonance caused by the space-charge of the beam. According to the single particle stationary model [2], the amplitude growth is incoherent. If the synchrotron operates near a space-charge limit, the emittance growth in the plane with smaller emittance occurs in the range of less than 10 revolutions of the particles in the accelerator.

Influence of the coupling resonance on the beam intensity was studied for the compact proton synchrotron for hadron therapy [5]. The momentum spread of the 7MeV proton beam from the injector is ± 0.002. First of all, the capture process was simulated. The full emittances of the beam are assumed to be equal to *90π·mm·mrad* and *15π·mm·mrad* in the horizontal and vertical phase-planes with the uniform particle distribution inside of the corresponding phase-ellipses. The 'bare' working point position has the betatron tunes $\nu_{H0}/\nu_{V0}=1.70/1.762$. The designed beam intensity after the injection process is equal to 4×10^{11} ppp. The vertical emittance blow-up caused by the fourth-order coupling resonance and excited by the space-charge of the beam is presented in Fig.4 for different beam intensities. The horizontal emittance of the beam remains almost constant at the beginning of the capture process when the RF voltage is zero.

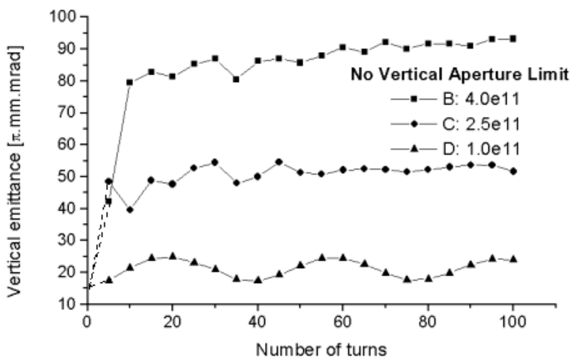

Figure 3: Changing of the vertical beam emittance of the beam at the beginning of the capture process in the case of the 'bare' working point near the coupling resonance without vertical limitation of the camber.

The betatron tunes of the particles in the case of the designed beam intensity are located around the vertical half-integer resonance. Study of the influence of this resonance on the transverse emittances shows that this effect is not so strong in comparison with the fourth-order coupling resonance.

The particle distribution after the multi-turn injection will be non-uniform that could change the particle behavior inside of the high intensity beam dramatically. The simulation of the multi-turn injection process including the space-charge effects in the case of the low injection energy allows optimizing the injection process (strength and timing of the injection bump-magnets, required duration of the injection and other parameters) to get required beam intensity with minimum particle losses in the compact synchrotron.

Improving of the MT-injection efficiency should be obtained by a proper choice of the 'bare' working point position on the betatron tune diagram to minimize influence of the high-order coupling resonance. The simulation result of the betatron tune optimization is presented in Fig.4. The horizontal 'bare' betatron tune is fixed (ν_{H0}=1.70). The vertical tune is changed from 1.76 to 1.40. The particle losses caused by the increasing of the vertical beam size (that is connected with the influence of the high-order coupling resonance) are reduced till zero. The particle losses in the horizontal plane is connected with the chamber size inside of the focusing quadrupole magnets of the synchrotron. This particle losses could be reduced by the proper choice of timing of the injection process and by reduction of the current from the injector.

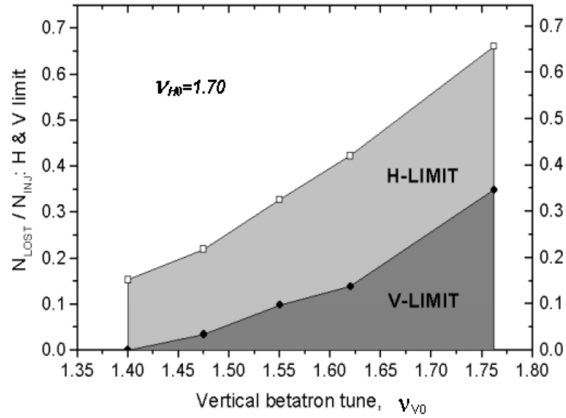

Figure 4: Changing of the particle losses in the horizontal and vertical planes during the injection process for different 'bare' working point positions.

3 DISCUSSION

The obtained simulation results of the study of the space-charge effects in the case of compact proton synchrotrons for hadron therapy are in good agreement with experimental results obtained during tuning of the machines. In the case of the multi-turn injection it is necessary to avoid coupling between the horizontal and vertical particle motion to prevent increasing of the smaller transverse emittance of the beam. The fourth integer resonance excited by the space-charge of the beam also leads to the emittance blow-up and limitation of the beam intensity. The crucial point for the compact synchrotrons could be influence of the fringe effects of the magnetic elements. Even if the space-charge is dominant concern, it is the interaction of the space-charge and the magnet non-linearities that could severely reduce the dynamic aperture of the accelerator and could lead to the particle losses in the compact machine.

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