FURTHER IMPROVEMENT OF THE PTC-ORBIT CODE TO MODEL REALISTIC OPERATION OF HIGH-BEAM POWER SYNCHROTRONS

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Abstract

The combined PTC-ORBIT code was developed a few years ago to study the dynamics of high intensity proton beams in synchrotrons, including the nonlinear machine resonances and the space charge effects in a self-consistent manner. In order to extend the code's abilities, the time variation of the main elements of the synchrotron has been introduced into the PTC module. This feature opens a direct way to model the multi-turn injection process and the slow extraction process by using a realistic machine description, in particular the dynamic variation of the betatron tunes, the strength of the bump magnets, the dynamic resonance correction or the resonance excitation. To demonstrate the code's abilities the corresponding simulations for CERN PS Booster and for J-PARC Main Ring are discussed.

INTRODUCTION

Space charge effect of the low energy high intensity proton beams in combination with unavoidable machine resonances, caused by the magnetic field imperfections and alignment errors of the synchrotron magnets, are the main source for uncontrolled blow-up of the beam emittance and particle losses at injection and at the beginning of acceleration. This subject becomes extremely important when it is necessary to optimize the performance of proton synchrotrons with beam power of hundreds of kilowatt. Such machines are under operation around the World (SNS, JPARC) and new projects are coming (ESS, FAIR). These effects should be analyzed so as to reach the goal of the LIU Project: the increase of the beam luminosity of LHC. For all these machines one of the most essential issue is minimizing the emittance blow-up, which leads to significant particle losses, radiation damage of the machine and reduction of the beam intensity (reduction of the luminosity for LHC, for example). To optimize the machine performance some realistic representation of the field variation for different elements of the machine, including the RF system, should be taken into consideration.

Another significant feature of all accelerators, which should be studied at the early stage of any project, is delivery of the required beam quality to experiments. Such effects as the high-frequency ripple of the power supply of different magnets can lead to significant distortion of the extracted beam quality. In addition, to reach the required quality of the extracted beam it is necessary to use a high frequency transverse electrical signal as for the case of the transverse RF knock-out.

The combined 'PTC-ORBIT' code [1,2] has been improved to meet all these requirements to provide special features for analyzing the beam dynamics in the case, when the parameters of different machine elements are changed dynamically during the machine operation. This approach allows creating a realistic machine model with different kind of imperfections, including the appropriate resonance correction schemes.

DYNAMIC VARIATION OF THE MACHINE ELEMENTS

The 'PTC' multi-particle tracking procedure, used in the combined code, is based on the 'relative' time. Each particle of the 'herd' will have the "own" field. To perform a dynamic time variation of different field components in different synchrotron elements, the 'table' concept has been chosen. This approach allows the user to use for the study different kind of functions, tabulated independently. The time variation of the magnetic field should meet only one requirement. Changes the particle's energy, caused by this magnetic field variation, should be much smaller than the average momentum spread of the beam. This limitation affects only the high frequency field modulation.

The ripple of the power supply of different magnets can be introduced in the PTC-ORBIT tracking, if the corresponding contribution to the energy is negligibly small in comparison with the longitudinal beam parameters.

The 'dynamic' memory allocation, used in PTC, allows using unlimited time tables for all elements of the synchrotron if the signal has no periodicity. Otherwise, a time table for a single period with the periodicity should be created and is reused by PTC. In addition, the high frequency transverse electrical signal can be added in the machine description. For the 'parallel-pole' element the particle motion in this kind of field can be solved exactly. This solution has been implemented in PTC. By using PTC one can investigate all these effects in the context of a realistic machine representation, including known nonlinearities and imperfections.

To demonstrate the code abilities the corresponding simulations of the multi-turn injection for CERN PS Booster and the slow extraction for J-PARC Main Ring are discussed.

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MULTI-TURN INJECTION

The time variation of different kind of magnets in combination with a variation of the parameters of the RF system is extremely important to simulate the beam dynamics in the case of the multi-turn injection process of an H-minus beam with the striping foil. This process is used to operate Rapid Cycling Synchrotron (JPARC) and the proton Accumulator Ring (SNS). This injection process will be utilized to inject the beam into PS Booster (CERN) from a new H-minus LINAC after the ‘LS-2’ period. Our study of the PS Booster operation shows that to implement this injection scheme for PS Booster it is necessary to use a dynamic variation of different kind of magnets (in particular fast kickers and slow bump magnets) and of the parameters of the dual harmonic RF system.

According to our study, to accommodate a significant space charge detuning the machine working point should be located slightly below (or even slightly above) the half-integer vertical resonance line [0,2,9]. For this working point it is necessary to correct the vertical beta-beating, caused by the edge focusing of the ‘slow’ chicane magnets. This resonance compensation process should be made dynamically.

This case can be used to illustrate new PTC-ORBIT abilities. Figure 1 represents the time variation of the chicane height, created by the combined action of four ‘fast’ kickers and four ‘slow’ bump magnets during the injection process for the CERN PS Booster. The time variation of the quadrupole strength of two independent families of quadrupole magnets is shown in Figure 2. This dynamic half-integer resonance compensation scheme has been investigated for the vertical lattice tune, crossing 2Qy=9 resonance. The vertical tune has been changed dynamically from 4.45 up to 4.55. Figure 3 represents the vertical RMS emittance evolution for two cases (1) without and (2) with the beta-beating dynamic compensation. By applying this compensation the RMS emittance growth can be suppressed significantly.

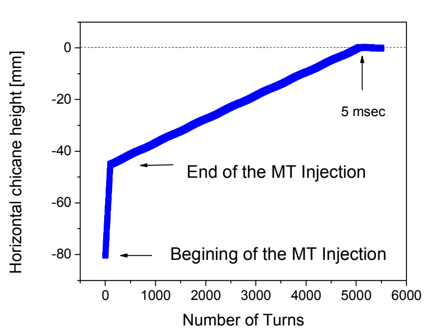

Figure 1: Chicane height variation during the MT injection for CERN PS Booster.

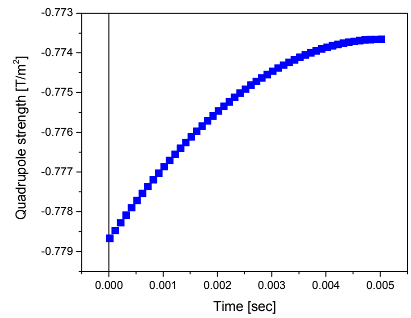

Figure 2: Time variation of the quadrupole strength to compensate the [0,2,9] resonance dynamically.

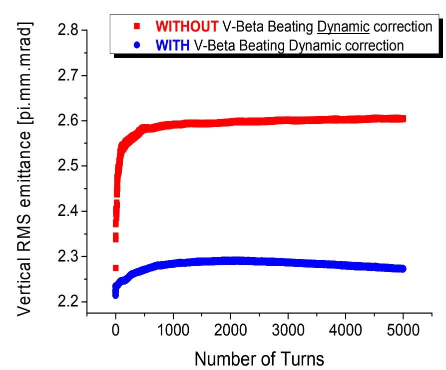

Figure 3: Vertical RMS emittance evolution without and with ‘dynamic’ [0,2,9] resonance compensation.

SLOW EXTRACTION

The ‘slow’ extraction from a synchrotron is another case where the dynamic time variation of many machine elements should be included in the model for the multi-particle tracking. This is the case of the JPARC Main Ring, which should deliver a 30GeV proton beam to different nuclear physics experiments.

The spill structure of the extracted particles should be uniform as much as possible. To realize this extraction technique it is necessary to change during the extraction process the height of the closed orbit distortion at the location of the electro-static septum, change the strength of the quadrupole magnets to move the lattice tune into the [3,0,49] resonance area, minimize the power supply ‘ripple’ effect of these quadrupole magnets and make the transverse high-frequency ‘shaking’ of the beam particles by using the transverse RF-knockout signal. All these dynamic variation of different MR magnets (low and high-frequency) can be represented by PTC for the multi-particle tracking.

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Ripple Effects

The current ripple of the MR quadrupole magnets on the flat-top [5] contains a low-frequency (47Hz) and high-frequency (600Hz) components, which will affect the spill structure of the extracted beam differently. To simulate theses effects the strength of the corresponding quadrupole magnets of JPARC MR has been represented by the time table, which contains the information about the linear changing of the current and the ripple component of the power supply.

The multi particle tracking by using the PTC-ORBIT code has been performed to simulate the slow extraction process from J-PARC Main Ring. The working point has been changed dynamically from 22.300 to 22.335 to extract the beam at the energy of 30GeV during 200msec (35'000 turns).

The effect of the current ripple of the "QFN" quadrupole magnets is presented in Figure 4. The spill structure of the extracted particles indicates a low-frequency and high-frequency modulation of the extracted beam. For the tracking 10'000 macro-particles have been used.

Figure 5 represents the 'ripple' compensation effect, which improves the spill structure of the extracted beam significantly.

Transverse RF Shaking

To modify the time structure of the extracted beam during the slow resonant extraction, the high-frequency transverse electrical signal can be used. This technique is well-known as the transverse "RF-knockout". It is used nowadays especially in the hadron therapy synchrotrons. In J-PARC this technique will be used to minimize the ripple effects on the extracted beam.

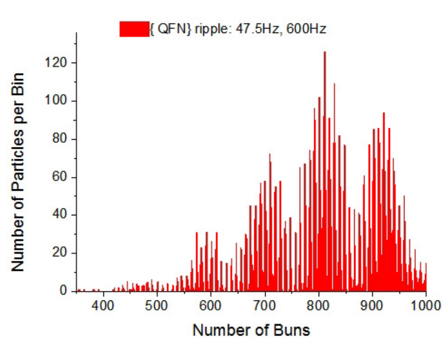

Figure 4: 'Time' structure of the extracted beam, affected by the combined ripple of 48 quadrupoles.

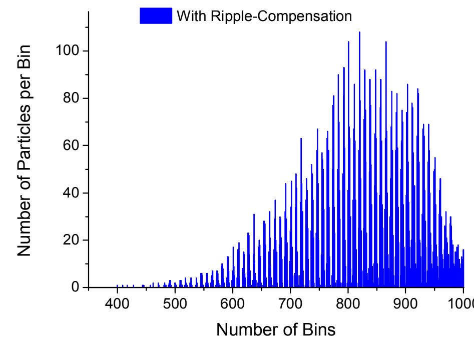

Figure 5: 'Time' structure of the extracted beam after the compensation of the quadrupole's ripple effect.

CONCLUSION

The combined PTC-ORBIT code with the time variation of the properties of the synchrotron magnets and RF system allows modelling the multi-turn injection and slow extraction process in the frame of a realistic model of the synchrotron including magnet imperfections and alignment errors.

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