PTC-ORBIT STUDIES FOR THE CERN LHC INJECTORS UPGRADE PROJECT

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Abstract

The future improvement of the beam brilliance and intensities required in the frame of the LIU (LHC Injectors Upgrade) project triggered a comprehensive study of the combined effects of the space charge and the machine resonances for the CERN synchrotrons, which are the injector chain for LHC. In frame of this report we describe new features of the PTC-ORBIT code which allow the beam dynamics modeling in the LHC injectors in the realistic way taking into account the time variation of the machine parameters during the injection process. The measurements, obtained during recent ‘Machine Development’ (MD) companies, and simulations for the low-energy high-intensity beams, will be discussed. Finally, basic results obtained in frame of the RCS conceptual design study are summarized.

INTRODUCTION

According to the LHC upgrade scenario the brightness of the LHC25 beam at the flat top should be increased at least 2.4 times. Such high brightness can be achieved by increasing the number of proton per bunch and at the same time by reducing the transverse beam emittance. This significant improvement of the LHC parameters requires an upgrade of whole LHC injector complex. The major mile stones of this upgrade are (1) improvement of the injection process into PS Booster by using new LINAC4 and (2) increasing the injection energy for PS up to 2GeV.

LINAC4 should replace the existing LINAC2, which deliver the 50MeV proton beam to PS Booster. The 160MeV H-minus beam from LINAC4 will improve the efficiency of the multi-turn injection process. The total particle losses in PS Booster should reach 5% instead of (55-60)%, which are typical for the current machine operation. PS Booster should be able to reach the beam intensity of 35e11ppb with small transverse emittances of 1.9μm (normalized rms value). The current beam intensity and the transverse emittances extracted from PS Booster to fill LHC with the 25nsec bunches are 16e11ppb and 2.5μm, respectively. Increasing the injection energy for the CERN PS machine will allow to use this high performance beam from the PS Booster keeping the vertical space charge tune spread as now in PS.

The novel injection scheme, proposed for the CERN PS Booster by using the 160MeV H-minus beam, allows manipulating with the particle distribution in the transverse and longitudinal plans, providing required transverse beam profiles and bunching factor. As the result, the space charge detuning for the PS Booster beam at the injection energy can be kept less than (-0.4).

The transverse emittance blowup and the particle losses after the upgrade of the LHC Injectors should be not more than 5% for PS Booster and PS. To minimize the particle losses during the injection and acceleration process it is necessary first of all to optimize the 'bare' working point for the required beam parameters. This optimization should be done in combination with appropriate correction schemes to compensate effects of machine resonances.

In frame of this report we will summarize new features of the PTC-ORBIT code which allow the comprehensive modeling of the beam dynamics in the LHC Injectors taking into account the time variation of the machine parameters during the injection process. The measurements, obtained during recent MD companies, and simulations for the low-energy high-intensity beams, will be compared. The multi-turn injection study by using new ability of the code will be presented.

COMPUTATIONAL TOOL

To reach the required beam parameters a computational model of the machine should be developed taken into consideration all known field imperfections of the machine magnets and alignment errors. The combined PTC-ORBIT(MPI) code [1], developed in the collaboration between KEK (Tsukuba, Japan) and SNS (Oak Ridge, USA), allows creating the common university for the complete ‘Normal Form’ analysis of the single particle and the multi-particle dynamics, taken into consideration realistic machine imperfections, resonance correction schemes and the collective effects. The code has been used extensively at the early stage of the JPARC Main Ring commissioning process [2]. The combined PTC-ORBIT code is installed and compiled for different multi-processor systems like the KEK supercomputer and the CERN multi-processor cluster.

The bunch length for the CERN Injectors is much more than the transverse beam size, so that the 2.5D model can be used to simulate the space charge effects by the ORBIT part of the combined code. At the space charge nodes, distributed by PTC around the machine, the transverse space charge forces are evaluated as nonlinear kicks using the explicit second-order PIC model and FFT. The particle motion between the ‘space charge’ nodes is simulated by using the high-order symplectic integrators, implemented in to the PTC code.

ISBN 978-3-95450-118-2

For the convergence study we used two different approaches to simulate the space charge kick, implemented in to the ORBIT code: (1)'fixed' and (2) 'adapted' grid. To define the space charge kick for the case of the 'fixed' grid (the maximum grid size is determined by the chamber boundary) by using the 2D Poisson solver the number of transverse mesh points should be much bigger than for the case of the 'adapted' grid (the maximum grid size is determined by the beam size itself). For both methods the number of grid points in the beam area is approximately the same. The optimum parameters for the space charge simulations for the LHC Injectors are collected in Table1.

Table 1: Optimized setting for main parameters of the 2.5D space charge model for the CERN LHC Injector Complex

	Method	**L_{max}[m] / N_{SP}**	**N_{mesh}** (x&y)	**N_{macro}** ×1e3	**L_{bin}**
PSB	Fixed grid	1 / 199	256	1000	128
	Adapted grid	1 / 199	64	500	128
PS	Fixed grid	10 / 70	1024	250	128
SPS	Adapted grid	3.32 / 2688	64	200	128
RCS	Adapted grid	1 / 157	128	500	128

The 'bare' working point (Q_x = 4.27, Q_y = 4.43) has been chosen so that to avoid crossing the systematic low-order resonances. The beam intensity of 24.75^{11} ppb with the bunching factor (B_f) of 0.6 and the normalized RMS emittances of 3μm (H) and 2μm (V) at the 160MeV energy should produce the maximum incoherent space charge detuning about (-0.26) in the vertical plane.

The particle distribution in the longitudinal phase plane was created by using the longitudinal stacking process injecting 20 beam-lets into the longitudinal separatrix. The double harmonic RF system (h=1) with 8kV and 4kV (in anti-phase) without acceleration has been set for the performed convergence study for the CERN PS Booster. The simulated foot-print of the betatron tunes of the individual particles of the beam shows the maximum space charge detuning of (-0.17) and (-0.25) in the horizontal and vertical planes respectively, which is in good agreement with estimation.

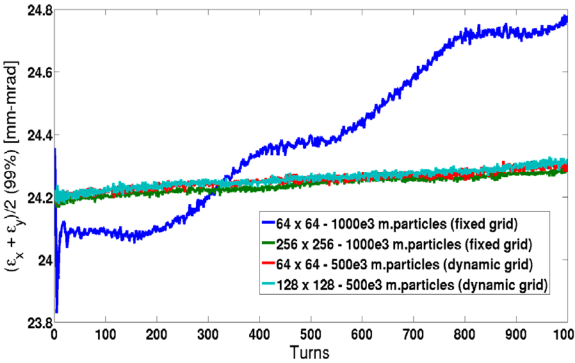

Figure 1: Halo formation (99% emittance) for different sets of the code parameters, used for the CERN PS-Booster convergence study.

Large number of the macro-particles, used to represent the beam for the space-charge simulations, allows to investigate the 'halo' part of the beam by analyzing the fractional part of the distribution, which contains 95% (or 99%) of the total number of the macro-particles. For the case of the 'ideal' machine without any imperfections and nonlinearities for the 'halo' part of the beam remains almost constant for the lattice working point (Q_x = 4.27, Q_y = 4.43), used for the PS Booster convergence study. The halo formation (increasing the 95% emittance) strongly depends on the main parameters, used to simulate the space charge kick. The 'halo' evolution for different sets of the code parameters and for different transverse grids is presented in Fig.1.

The performed optimization of main code parameters to simulate the space charge kick in the case of the 2.5D model allows to study the beam evolution including the 'halo' formation process for all CERN synchrotrons from the LHC Injector chain.

MD AND THE CODE BENCHMARKING

During the period June-July 2012 a few dedicated studies of the beam dynamics for CERN PS Booster have been performed to get useful data for the code benchmarking. Main motivation for this activity was the comparison between the measured and simulated beam evolution near the low-order resonances, first of all near the integer resonances [1,0,4] and [0,1,4], and the Montague resonance [2,2,0]. The current 'bare' working point for the PS Booster operation has the betatron tunes Q_x=4.41, Q_y=4.45. Keeping this working point the resonances, mentioned above, could limit the beam brightness required for the LHC Upgrade for both LHC and CNGS type beams.

In frame of the benchmarking study we intended to check abilities of the PTC-ORBIT code to reproduce the observed beam evolution, including the space-charge effects at the 160MeV energy.

For the dedicated MDs the proton beam with the beam intensity of 17^{11} ppb has been injected at the energy of 50MeV from LIINAC2 using the conventional multi-turn injection process. Before the measurements the beam was accelerated up to 160MeV energy by using the CERN PS Booster RF system with the double harmonics, which allows to control the bunching factor (B_f) in wide range from 0.24 up to 0.5. At the energy of 160MeV the required lattice tunes (Q_x,Q_y) has been set. Evolution of the beam profiles and beam intensity have been measured during 200msec the PTC-ORBIT simulations. For the code benchmarking study the scan of the lattice working point at the 160MeV energy has been performed to have the effects, observable during at least 50msec. This period of time corresponds to about 50’000 turns self-consistent tracking of 500’000 macro-particles, which should represent the realistic 6D distribution of the beam. The emittance evolution has been measured by using the wire-scanners, installed in PS Booster at different locations.

The basic initial beam parameters, measured at the 160MeV energy, were the following: the transverse normalized RMS emittances are 3.4µm and 1.8µm in the horizontal and vertical planes respectively, the RMS longitudinal emittance is 0.16eV.sec with the bunching of 0.4, the beam intensity of 17^{11} ppb.

Fast increasing the horizontal emittance only has been observed for the lattice working point near the [1,0,4] resonance (Q_x/Q_y=4.10/4.21). The vertical emittance remained constant during the observation time. The particle losses have not been registered during these measurements. The simulated space charge detuning, corresponding to this case, is shown in Figure 2.

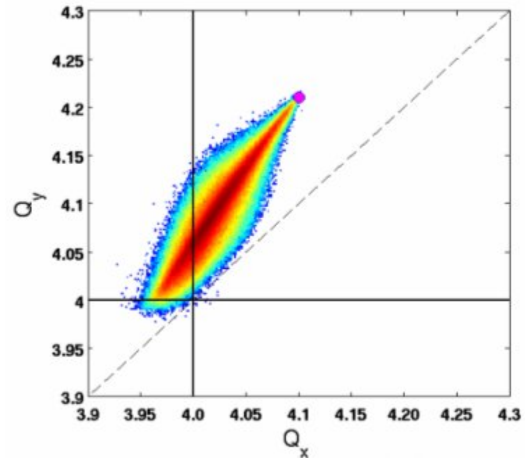

Figure 2: Incoherent space charge dunning of the 160MeV LHC25 type, used for the benchmarking study.

For the working point (Q_x/Q_y=4.18/4.23) the emittance exchange in the transverse planes has been observed during the time period, acceptable for the code benchmarking study. The measured emittance evolution is presented (dashed lines) for both lattice working points near the integer resonance [1,0,4] and the Montague resonance, Figure 3 and Figure 4, respectively.

For the working point near the horizontal integer resonance [1,0,4] the additional effect of the random quadrupole errors of the PS Booster quadrupole magnets has been studied. The obtained results (Fig.3, the solid lines) show the additional contribution of the quadrupole field errors to the horizontal RMS emittance growth. The estimated relative random errors of the PS Booster quadrupole magnets are in the range of $(1\div1.5)^{-3}$, which is in agreement with expected values. Detailed study of the effects of the imperfections of the PS Booster quadrupole magnets will be performed during this year. The simulated emittance evolution in the vertical plane also is in good agreement with the measurements.

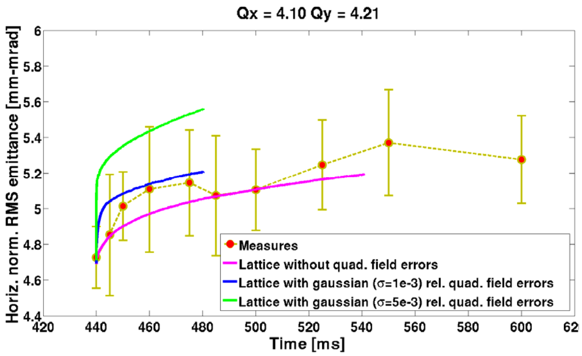

Figure 3: Measured and simulated effect of the integer resonance [1,0,4] for the lattice working point Q_x = 4.10, Q_y = 4.21 and for the LHC25 type beam with the parameters, mentioned above.

The halo formation, which could be observed during the long-term tracking by analyzing the 95% emittance evolution of the beam at the fixed energy of 160MeV, is quite weak (less than 2% during 35’000 turns) in both transverse planes for the working point mentioned above. The particle losses during the measurements have not been observed. The beam intensity remains constant during the 200msec period. The integer resonance [1,0,4] for the lattice working point Q_x = 4.10, Q_y = 4.21 and for the LHC25 type beam with the parameters affects the core part of the beam only.

The measured effects of the high-order coupling, caused mainly by the space charge effect itself for the LHC25 type beam, has been reproduced by the simulations, performed for the corresponding lattice tunes (Q_x = 4.18, Q_y = 4.23). The measured and simulated RMS emittance evolution for this case is presented in Figure 4 for different sets of the random tilt of the PS Booster quadrupole magnets (up to $1\sigma_{TILT} = 4.28^{-5}$ rad). The observed emittance behavior is determined mainly by the Montague resonance. The linear coupling of the PS Booster is small even without the resonance compensation, which has been checked during of the PS Booster recently.

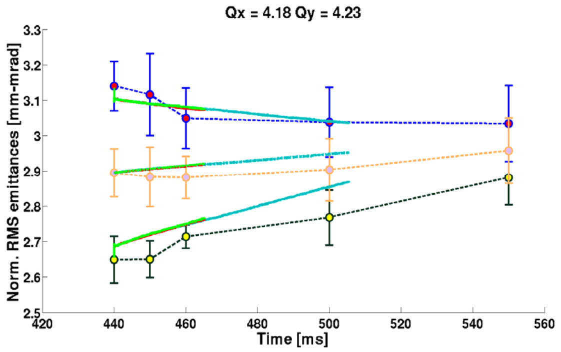

Figure 4: Measured and simulated effect of the 4th order coupling resonance [2,-2,0] for the lattice working point $Q_x = 4.18$, $Q_y = 4.23$.

The observed increasing the vertical RMS emittance is connected to the vertical integer resonance [0,1,4], which will affect the core part of the 'LHC25 type' beam for the case of the lattice betatron tunes Qx = 4.18, Qy = 4.23. For this working point the halo formation of the beam was not observed during the tracking. The measured beam intensity remained constant. The halo part of the beam is not effected by the high-order coupling resonance [2,-2,0] for the case of the LHC25 beam at the energy of 160MeV.

The code benchmarking study demonstrate quite acceptable agreement for the 'LHC25 type' beam between the measured and simulated RMS emittance evolution in the horizontal and vertical phase planes for different lattice working points near the major machine resonances.

For CERN PS and SPS the required data for the benchmarking study have been collected during the machine study sessions, performed last months. The corresponding simulations by using the PTC-ORBIT code will be made soon.

MULTI-TURN INJECTION FOR THE CERN PS BOOSTER

One of the features of the PTC-ORBIT code is the time variation of any machine elements during the tracking simulations. This possibility is extremely important to study the 'multi-turn injection' process for the CERN PS Booster.

The longitudinal stacking process should be used to provide the required bunching factor. This process should be realized for the case of the double harmonic RF system with non-zero reference phase ($d(B\rho)/dt \sim 10$Tm/s). After the longitudinal 'active painting' process the expected bunching factor could be increased up to $B_f \approx 0.6$, which should allow to keep the space charge detuning in the acceptable range for different types of beam, accelerated by the CERN PS Booster. The capture efficiency in the longitudinal separatrix at the injection energy of 160MeV is better than 98%.

The required basic study has been performed by using the PTC-ORBIT code by using the dynamic variation of the fast kicks, slow bump magnets, quadrupole correctors to minimize the 'beta'-beating during the injection chicane variation and the parameters of the PS Booster dual harmonic RF system. The proposed correction scheme allows to suppress the vertical beta-beating from 30% till less than 10%.

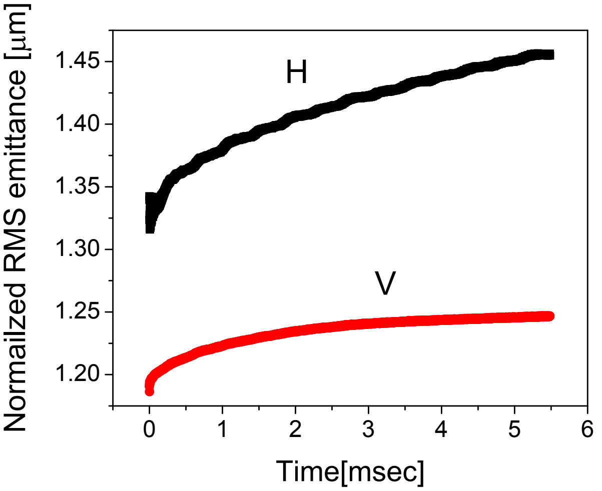

Figure 5: RMS normalized emittance evolution during the variation of the chicane height.

The emittance evolution during the variation of the chicane height has been simulated for the following beam parameters (Fig.5). The 20 turns injection in the horizontal plane has been performed to get the required beam intensity of 35.2e10ppb. The scattering effect at the foil was not taken into consideration up to now. To increase the vertical emittance the vertical off-set has been utilized for 20 bunches, injected into Booster from LINAC4.

The multi-turn injection simulations should be extended further including the scattering process on the foil, the particle losses on the machine aperture and the realistic machine imperfections.

CERN PS AND SPS SPACE CHARGE STUDY

A tune scan by using the low intensity beam has been performed to get information about the machine resonances at different beam energy 1.4GeV and 2GeV. For the space charge dominated beam the effect of the low-order resonances have been investigated experimentally [3].

A tune scan with high brightness single bunch beams was performed using a long LHC cycle with the low gamma transition Q20 optics [4]. The intensity at injection was thereby around 2.5-2.7e11ppb, with a transverse emittance of around 1.2μm in both planes. The tunes were adjusted to be constant during the cycle, i.e. during the 26GeV long flat bottom of around 11s and the ramp to 450GeV. The bunching factor is about 0.5.

Note that the incoherent space charge tune spread for the beam parameters at the injection energy of 26GeV can be estimated around ΔQ_H ~(-0.15) and ΔQ_V~(-0.25). A clear emittance blow-up is observed for working points, where the initial space charge tune spread reaches beyond the integer resonances. Practically no emittance growth is observed for working points sufficiently far above the integers. On the other hand, it is important to note that the particle losses increase significantly when increasing the horizontal tune. It is not clear yet, which resonance is causing these losses. Further tune scans should be performed to study in more detail the area above the coupling resonance with Q_H >0.15 and Q_V >0.25.

RCS CONCEPTUAL DESIGN

Motivated by a study of a rapid cycling synchrotron as alternative to the PS-Booster Upgrade [5], different lattices including space charge effects have been studied.

To investigate the influence of the variation of the beam size a 16 cell triplet, doublet and FODO lattice with a working point of QH/QV=4.28/3.55 have been compared. In the case of the 'broken' symmetry the beta-beating minimization has been performed for each lattice. As shown in Figure 6 the lattices with the symmetry 4 and 16 exhibit the same emittance growth, while the emittance growth increases considerably for symmetry 1 and 2. This can be explained by the crossing of the systematic 4Qy and Qx+4Qy resonances in the case of symmetry 1 and 2, which is nonsystematic for symmetry 4 and 16.

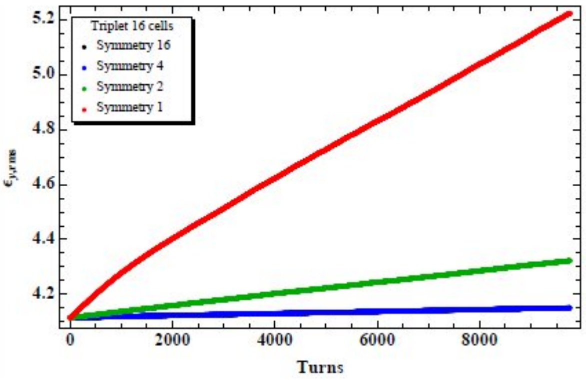

Figure 6: Vertical RMS emittance growth for different machine symmetry with the 'triplet' cells.

The results presented in this paper show that a small variation of the beam size and a high symmetry leading to less systematic resonances is in general favourable for the 'space charge dominated' lattices. Special care should be taken especially in the early stage of the machine design where the free-space requirements and the magnetic field quality are in the focus.

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