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DETAILED MAGNETIC MODEL SIMULATIONS OF THE H- INJECTION CHICANE MAGNETS FOR THE CERN PS BOOSTER UPGRADE, INCLUDING EDDY CURRENTS, AND INFLUENCE ON BEAM DYNAMICS

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Abstract

The CERN PS Booster will be upgraded with an H- injection system. The chicane magnets for the injection bump ramp-down in 5 ms and generate eddy currents in the inconel vacuum chamber which perturb the homogeneity of the magnetic field. The multipolar field components are extracted from 3D OPERA [1] simulations and are included in the lattice model. The β-beating correction is computed all along the ramp and complete tracking simulations including space-charge are performed to evaluate the impact of these perturbations and their correction.

INTRODUCTION

A major upgrade of the CERN PS Booster (PSB) within the LHC Injector Upgrade Project [2] foresees the increase of the injection energy from 50 MeV to 160 MeV, to mitigate space-charge effects and to allow doubling the beam brightness and fulfill the needs of the High Luminosity LHC [3]. At the same time, the conventional multi-turn injection of protons from Linac2 will be replaced with a H- charge-exchange injection of ions from Linac4, which is presently under construction on the CERN site.

The main challenge for implementing the new H- injection scheme in the PSB is the tight space available in the injection region [4, 5] with a straight section of only 2.6 m. The four chicane magnets (BSWs), which need to provide a horizontal bump of 46 mm during the injection process, have a magnetic length of only 316 mm. Their deflection angle is 66 mrad, which is provided by an integrated field of $\int Bdz = 0.126$ Tm.

The edge focusing at the rectangular chicane magnets induces strong β-beating in the vertical plane, where the tune is close to the half integer. For this reason, trim power supplies on two defocusing quadrupoles of the ring at a proper phase advance (QDE3 and QDE14) are foreseen for the compensation [4].

PERTURBATIONS INDUCED BY EDDY CURRENTS

The vacuum chamber inside the BSWs was initially foreseen to be made of ceramic, to avoid disturbances to the magnetic field. However, advantages in terms of mechanical robustness and cost moved the design toward a corrugated inconel vacuum chamber, which is now the baseline [6]. In order to bring the injection bump to zero, the chicane magnets are ramped-down in 5 ms and generate eddy currents in the metallic chamber. This induces a delay in the magnetic field of the order of 50 μs [7, 8], which can be compensated by individual power supplies for the BSWs, and inhomogeneities, whose impact on the beam should be carefully evaluated.

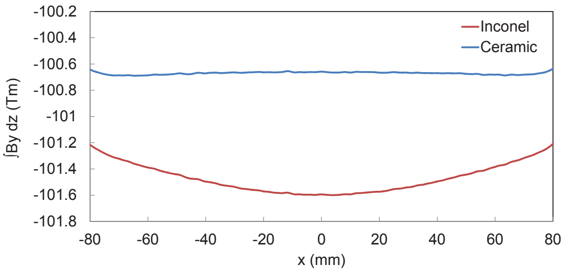

Figure 1: Integrated field in the horizontal plane at 1 ms after injection, for the proposed metallic vacuum chamber (red line), for BSW2. In blue, the field in a ceramic pipe. From 3D Opera simulations.

In particular, eddy currents induce a sextupolar field component proportional to the ramp-down rate of the BSWs. Figure 1 shows the field integrated along the magnetic length as a function of the horizontal position in the mid-plane, at 1 ms after injection, computed from 3D Opera simulations assuming a linear bump decay. Both the delay, i.e. an higher value of magnetic field with respect to the ceramic case, and the sextupolar component, proportional to the second derivative, are visible for the inconel pipe. The excitation of the third order resonances should not be a problem, since the four BSWs have opposite polarities. However, due to the large orbit excursions inside the chicane magnets causing feed-down effects, the sextupolar components lead to quadrupolar perturbations comparable in size to the ones induced by the edge effects. Indeed, the maximum focusing strength at the entrance or exit of the rectangular magnets, for a beam trajectory which is not perpendicular to the magnet edge is $k_1L \sim \phi^2/2L \approx 6 \times 10^{-3}$ m^{-1}, where $\phi = 66$ mrad is the magnet deflection and L is the magnetic length. The eddy-current induced sextupolar perturbation extracted from Opera simulations during the ramp (see Fig. 1) is $k_2L = d^2 \left(\int B_y dz \right) / dx^2 / B\rho \approx 0.094$ m^{-2}, where $B\rho \sim 1.9$ Tm is the beam rigidity at 160 MeV. Assuming a maximum beam offset $x_{off} = 50$ mm, this leads to a quadrupolar feed-down effect of $k_1L = k_2Lx_{off} \approx 4.7 \times 10^{-3}$ m^{-1}.

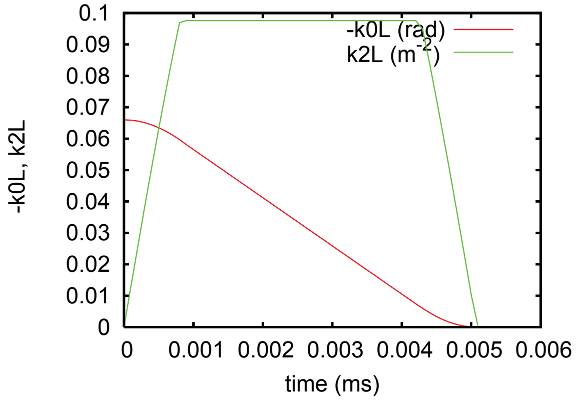

Figure 2: Dipole and sextupolar component at BSW2.

Compensation Settings

Both perturbations vary during the fall of the chicane: the edge effects decrease to zero as the bump collapses, while the feed-down focusing due to the sextupolar components from eddy-currents depends on the ramp rate and on the offset with respect to the magnet center. They both induce vertical β-beating, due to the working point close to the vertical half-integer, therefore they can be cured by the same set of trim power-supply, which should also vary with time. Figure 2 shows the functions of the dipolar and sextupolar component at one magnet (the other three are similar), assumed for the beam dynamics studies. We considered an almost linear ramp-down of the power supplies, with roundings at the beginning and at the end to avoid transients [9]. The sextupolar component was extracted by scaling the values from Opera simulations by the new values of the derivative of the power supplies function, after cross-checking that it is indeed strictly proportional. The normalized strengths required in the standard lattice quadrupoles and in the two defocusing elements QDE3 and QDE14, equipped with extra trims, are shown in Fig. 3.

The vertical β-beating due to the perturbation and the resulting value after correction is plotted in Fig. 4 at 1 ms after injection, when the edge effects are still important and the sextupolar component has reached its maximum.

SPACE-CHARGE SIMULATIONS

Simulations including space charge effects and the chicane decay have been done for two representative beams whose parameters are summarized in Table 1. The aim was to compare the case where only the rectangular dipole edge-effects are considered (corresponding to the situation of a ceramic beam pipe) and the effect of the eddy-current induced multipoles (i.e. with an inconel vacuum chamber). The PSB model is "ideal": it does not include any non-linearities, errors, misalignments or other perturbations than the ones described above, therefore the results are valid only as a relative comparison, to determine if the metallic chamber was not generating any showstopper.

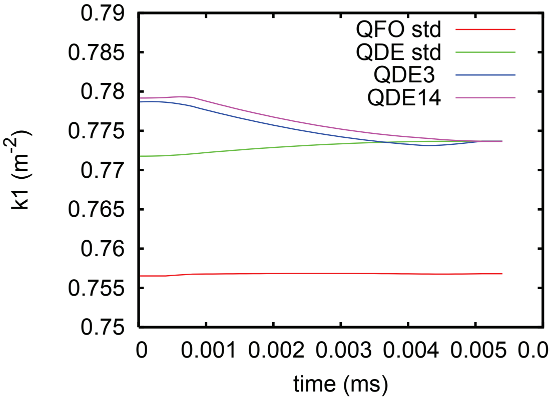

Figure 3: Computed normalized strength (in absolute value), of the standard lattice quadrupoles and of two equipped with trims, QDE3, QDE14.

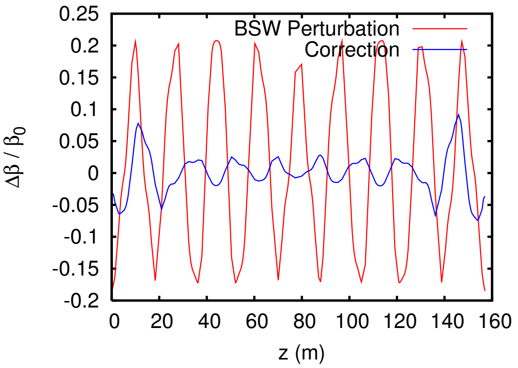

Figure 4: Vertical β-beating at 1 ms after the injection, before and after correction.

PTC-Orbit [10] with time varying elements [11] was used as simulation code. About 200 space-charge nodes are set, where the 2D (with longitudinal weighting factor) space-charge Particle-In-Cell computation is done, and 250k or 600k macro-particles are tracked for the high-brightness (HB) and high-intensity, large emittance (HI) beam.

Figure 5, top and bottom, shows the evolution of the rms horizontal and vertical normalized emittance for the HB beam, whose parameters are even more challenging in terms of brightness than what required for the High Luminosity LHC [3] and for which emittance control is important. In Fig. 6 the beam intensity evolution is shown

Table 1: Parameters for the two simulated beams: High Brightness (HB) and High intensity (HI) beam.

	HB beam	HI beam
Intensity (ppb)	320 e10	1000 e10
Rms norm. emittance H/V (μm)	1.2 / 1.2	8.8 / 5.7
Bunching Factor	0.60	0.60
Programmed tune	(4.28, 4.55)	
Injection energy (MeV)	160	
Acceleration ramp (Tm/s)	10	

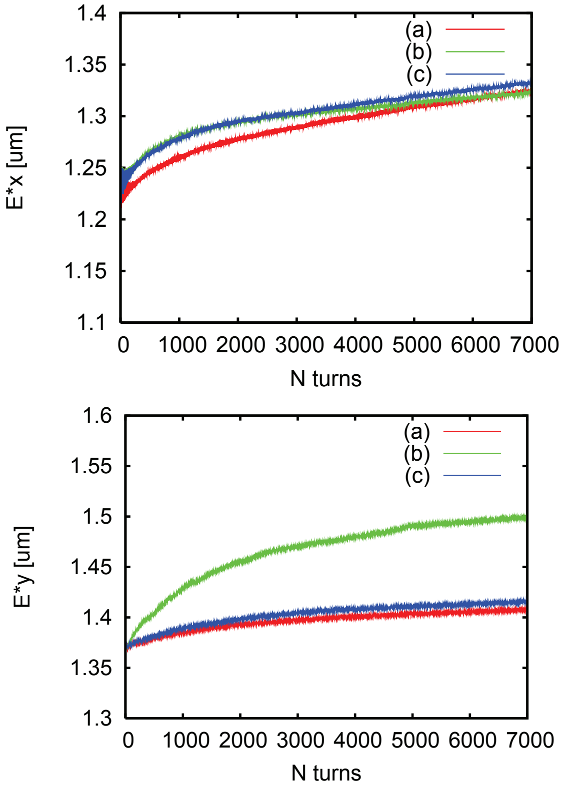

Figure 5: Horizontal (Top) and vertical (Bottom) normalized emittance evolution during the fall of the chicane bump (~ 5000 turns) for the HB beam, for the case of: (a) ceramic: only edge effects taken into account and corrected, (b) inconel: edge and multipoles effects, only edge effects corrected, (c) inconel: edge and multipole effects, all corrected.

for the HI beam, similar to the one provided to the CERN Isolde nuclear experiments, for which emittance blow-up translates directly into losses. For both beams, the eddy currents generate additional emittance blow-up in the vertical plane or losses. However, when the trim power supplies on the QDE3 and QDE14 are properly set to correct also for these multipole components, the situation becomes similar again to the one with a ceramic chamber.

CONCLUSIONS

3D modeling of the future PSB chicane dipoles for the H-injection has been performed, taking into account the ramp-down of the magnets and the effects of the metallic (corrugated inconel) vacuum chamber. The high order field components, generated by eddy currents, have been extracted by a polynomial interpolation of the integrated field at different times during the decay of the bump and the effects on the beam have been evaluated. A time-dependent correction has been computed for the quadrupolar feed-down effect induced by the sextupolar term which, due to the large excursion of the beam in the magnet aperture, is comparable with the perturbation induced by the edge effects at the short rectangular magnets. Via space-charge tracking simulations, we have demonstrated that the trim power supplies on the lattice quadrupoles QDE3 and QDE14, already foreseen to cure the vertical β-beating induced by rectangular magnets, can successfully compensate also this effect. Our conclusion for the design of the injection region was therefore that the inconel vacuum chamber is acceptable, provided that a proper compensation for the eddy-current effects is implemented.

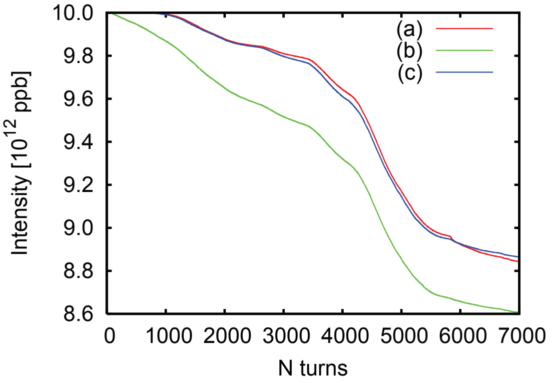

Figure 6: Beam intensity evolution during the fall of the chicane bump for the HI beam, for the case of: (a) ceramic, (b) inconel, only edge effects corrected, (c) inconel, all corrected. The losses starting after 3000 turns are uncaptured particles due to an initial distribution exceeding the bucket.

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