

ALTERNATIVE WORKING POINT(S) FOR THE LHC *

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Abstract

At present, the LHC operates with a different fractional tunes at injection and at collision energy due to improved dynamic aperture indicated by tracking studies. Therefore, a tune swing crossing the 10th order resonance is needed during the beta-squeeze. A new proposal to alter the working point to collision tunes already at injection and during an energy ramp is foreseen to avoid the tune jump. Simulations and measurements of the optics along with the beam emittances and lifetime are compared to the nominal injection tunes. Feasibility for a working point close to the 1/2 integer is also attempted.

INTRODUCTION

Due to improved dynamic aperture of about 2σ as indicated by tracking studies [1], the LHC operates with a different fractional tunes at injection (0.28,0.31) and at collision energy (0.31,0.32). In addition, the large tune split at injection is to reduce the effects of coupling errors at injection and throughout the energy ramp. However, the optimized sorting scheme [2] of the LHC magnets and the smaller than nominal emittances together with excellent beam diagnostics tools to measure and correct linear optics in the present LHC call for a single tune throughout the energy cycle. This provides operational stability for tune feedback systems and reduces operational complexity. In addition, removing the tune swing reduces the overall cycle time and potentially has an impact on the integrated luminosity.

Therefore, a beam study was conducted to investigate the feasibility of collision tunes throughout the energy cycle [3].

An attempt was made to operate close to the 1/2 integer (0.456,0.466). The primary motivation to move to this working point is substantially large tune space which can accommodate a large head-on and complex long-range beam-beam footprints for the bunches in the LHC. The optics at this working point was measured and is reported in this paper.

COLLISION TUNES EXPERIMENT

Prior to the beam study the local coupling errors in IR1, IR2, IR5 and IR8 were identified and successfully corrected using the inner triplet skew quadrupoles at 3.5 TeV during the test of the optics with $\beta^* = 90$ m [4]. It should be noted that the transverse damper was switched off to avoid any interference with AC dipole excitation measurements.

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The arc tune trim quadrupoles (MQTs) were used to perform the tune change from injection to collision tunes to allow for a scan. The collimators were operated at nominal settings with the exception of the tertiary and the injection protection collimators, which were at relaxed settings. The nominal orbit configuration, separation bumps and crossing angles were used throughout the experiment.

The Tune Scan at Injection

A tune scan between the injection tunes and the collision tunes at injection energy was performed to probe the tune space around this working point. A low intensity pilot bunch was first injected at nominal tunes. The tune scan was performed (see Fig. 1) in 10 steps for both beams simultaneously to reach collision tunes.

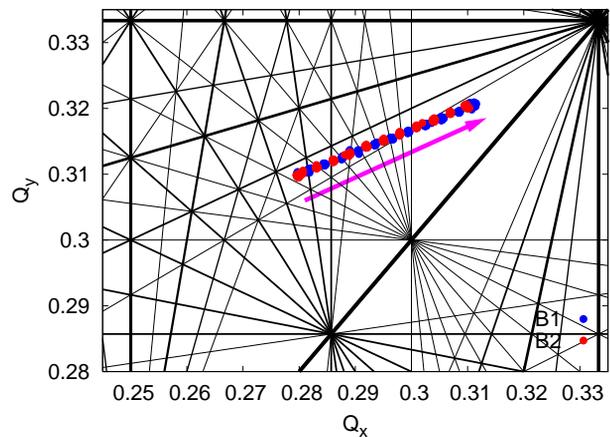


Figure 1: Tune scan at injection energy from nominal to collision tunes in 10 steps for both beams.

Figure 2 shows the corresponding beam intensities and lifetime along the tune scan. The only visible effect appears in the beam lifetimes, which indicates slightly better lifetime for the collision tunes. Transient effects on the beam lifetime close to the 7th order (14:30) and the 10th order (14:36) resonances are visible.

Optics and Coupling Measurements

AC dipole excitations were applied to measure the optics at the nominal injection tunes and at collision tunes. No differences in the optics is measurable due to the tune change as expected from calculations. It should be noted that the final optics at this working point will correspond to the first step of the β -squeeze using IR1 and IR5 insertion magnets to match the tunes to collision working point [5].

Due to proximity of collision working point to the coupling resonance, an initial ramp with nominal settings was

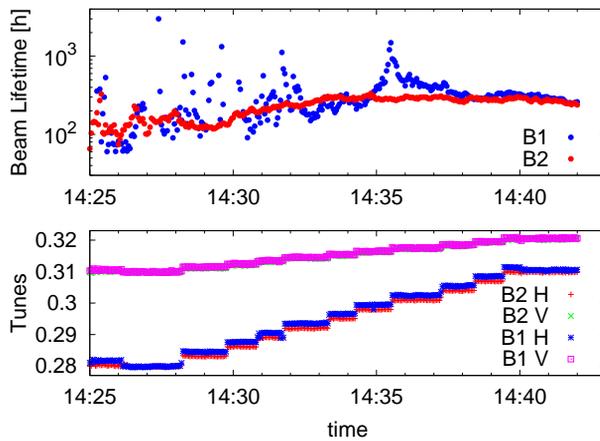


Figure 2: Beam lifetimes, intensities, coupling and beam sizes during the tune scan at injection energy.

necessary to measure coupling and compute corrections along the energy ramp. The coupling for beam 1 did not require further corrections since $|C^-|$ was already in the level of 5×10^{-3} . The corrections for beam 2 were computed for the largest coupling value along the energy ramp (0.9 TeV) using the arc skew quadrupoles. The computed corrections were applied as linear ramp function to reach the maximum value at the measured value and linearly ramped down. It was observed that the phase of the coupling resonance driving term changes between injection and 0.9 TeV but remains constant afterward. Therefore, a single coupling knob with different strength can be used to correct the coupling between 0.9 TeV and 2 TeV.

Energy Ramp with Collision Tunes

A ramp with the new working point was subsequently programmed through the energy cycle along with the computed coupling correction. A tune feedback was used to keep the tunes constant. Figure 3 shows the beam 2 lifetime and coupling parameter along the ramp for three cases: (i) nominal tunes without any correction (from [4]), (ii) nominal tunes with local coupling correction and (iii) collision tunes with local and global coupling correction. Figure 3 shows a slight improvement in beam lifetime after the coupling correction plus a reduction of $|C^-|$ by a factor 2. This coupling correction is also valid for the nominal ramp.

An energy ramp with collision tunes and nominal bunch intensity followed. The transverse damper was switched off to allow for a clear measurement of the tune and coupling along the ramp. The collimators were ran with nominal settings. Figure 4 shows the tunes, beam lifetimes and intensities along the energy ramp. Tunes and coupling remain fairly constant all along the ramp. Approximately 60% of the intensity was lost in the initial part of the ramp as seen in Fig. 4.

An instability in the vertical plane is evident from the fast increase of the vertical amplitude by almost a factor of 200. The turn by turn BBQ signals for both beams and both planes, clearly reveal the coherent bunch oscillations,

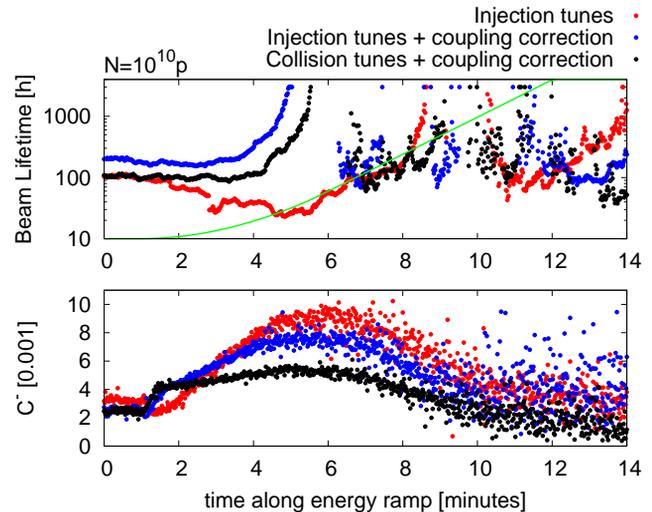


Figure 3: Comparison of 3 energy ramps at low intensity for beam 2.

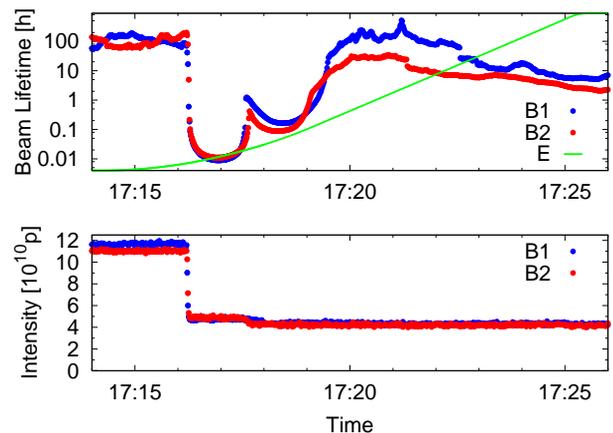


Figure 4: Beam lifetimes, intensities, coupling and beam sizes during the energy ramp.

whose envelope can be fitted by an exponential of the form $Ae^{\frac{t}{\tau}}$ where τ is the rise time of the instability, here around 1.1 s for beam 1 (both planes) and 0.6 s for beam 2 (both planes). For beam 1, rise times of the dipolar mode as a function of negative chromaticity can be computed using the impedance model in the Sacherer formula [6] with the bunch length, intensity and tunes measured during the beam study. The horizontal and vertical rise times are very similar, and around 1.1 second for a $Q' = -1$. This instability is not visible during a nominal ramp as the transverse damper is used to suppress any growth of dipolar modes. The appropriate cure for both nominal and collision tune ramp would be a measurement and correction of chromaticity to slightly positive values. This might not only avoid the instability but also reduce the effect of the damper on the beam to avoid any emittance blowup.

1/2 INTEGER

An attempt was made to operate the LHC beams close to the 1/2-integer at injection energy in a subsequent beam

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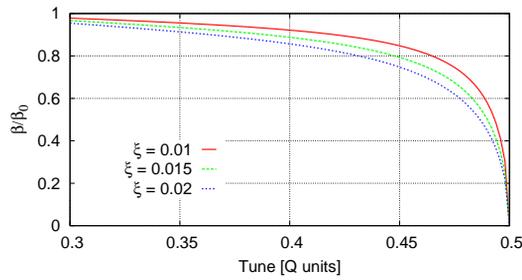


Figure 5: β^* due to dynamic beam-beam effects normalized to the unperturbed β_0 as a function of tune.

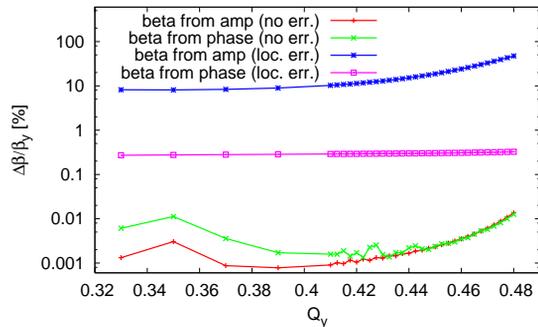


Figure 6: Accuracy of the β -function as obtained from amplitude and phase advance with and without local errors.

study. The motivation for this study was three fold: (i) enhance the optics errors to thereby allow for improved correction, (ii) enhance significantly the tune space to accommodate the large head-on and the complex long-range beam-beam footprints, (iii) reduce the IP β^* from dynamic beam-beam effects enhanced close to the 1/2 integer (see Fig. 5).

Low intensity pilot bunches were injected into the LHC rings and tunes were moved close to the 1/2-integer (0.44,0.46) in a single step with the aid of the trim quadrupoles. Some beam losses were observed only in beam 1 during the tune trim. Optics were only successfully measured for beam 2. When measuring the beta function, a large discrepancy was discovered between the betas as inferred from amplitude and those from phase advance. From simulations it is observed that in the presence of local errors, e.g. triplet errors, the betas from phase are considerably more accurate than the betas from amplitude, see Fig. 6. The measured betas from phase are plotted in Fig. 7 showing an enhancement of up to 100% in the vertical β -beating. A new algorithm is under investigation in order to improve the measurement of the betas from amplitude.

An additional tune step closer to the 1/2 integer (0.47,0.475) was performed without significant beam losses. However, a dedicated optics correction is required to safely operate the LHC at this working point.

CONCLUSION

Beam measurements at injection energy show a total equivalence between the present injection tunes (0.28,

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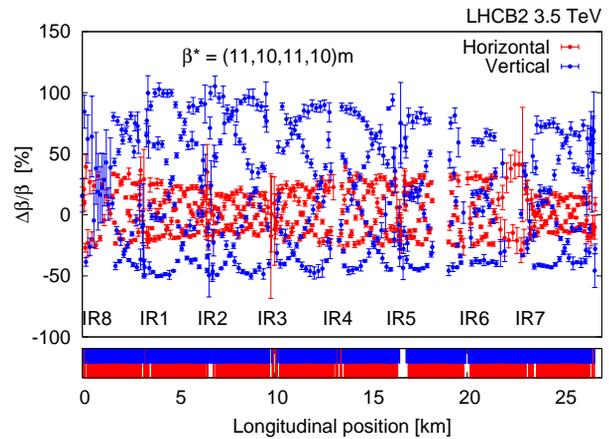


Figure 7: Beam 2 β -beating at injection energy close to the 1/2-integer as inferred from phase advance.

0.31) and the collision tunes (0.31, 0.32) in terms of lifetime, emittance growth and optics. Coupling was identified as a potential obstacle for an energy ramp with collision tunes. A ramp with nominal tunes was used to measure and correct the coupling through the ramp which reduced the coupling and allowed for successful acceleration of pilot bunches with collision tunes to 3.5 TeV. This correction is now used also for the nominal LHC operation. A ramp with nominal bunch intensity (10^{11} protons) and collision tunes was performed where both beams experienced a 60% intensity loss due to transverse instabilities. The origin of these instabilities was identified as negative chromaticity ($Q' \approx -1$) from the observed growth rate compared to that from impedance simulations.

An attempt to operate the LHC beams at injection energy close to the 1/2 integer proved to be successful. This working point, with appropriate optics correction, allows for significantly larger tune space. The peak β -beating was enhanced up to 100% in the beam 2 vertical plane which requires dedicated corrections to operate at this working point safely.

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REFERENCES

- [1] L. Jin and F. Schmidt, LHC Project Note 182 (1998).
- [2] S. Fartoukh, "Installation strategy for the LHC main dipoles", EPAC 2004.
- [3] R. Calaga et al., "Collision tunes at injection and ramp", CERN-ATS-Note-2011-034 MD (LHC).
- [4] Helmut Burkhardt et al., CERN-ATS-Note-2011-032 MD (LHC).
- [5] S. Redaelli et al., MD proposal 2011.
- [6] B. Zotter and F. J. Sacherer, CERN-77-13, p.211 (1976).