ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB169

# A MECHANISM FOR EMITTANCE GROWTH BASED ON NON-LINEAR ISLANDS IN THE LHC

E. H. Maclean[1], M. Giovannozzi, T. H. B Persson, R. Tomás, CERN, Geneva, Switzerland

*Abstract*

Landau octupoles are used in the LHC to prevent coherent instabilities of the circulating beam. The reduction of their strength occurring during the energy ramp can transport particles in nonlinear islands to larger amplitude. This has the potential to lead to emittance growth and to beam-losses. Beam-based studies and simulations during Landau octupole ramps performed in the LHC are presented to explore this mechanism in more detail.

## OBSERVATION OF PARTICLE TRANSPORT IN LHC ISLANDS

Significant growth of normalised emittance ($\approx 20\,\%$ [1,2]) has consistently been observed during the energy ramp of the CERN Large Hadron Collider (LHC) [1,2]. This causes substantial reduction in delivered luminosity, and is only partly understood. It has also been observed that emittance growth is larger in the vertical plane [1,2]. As such, any mechanism which can generate growth of normalised emittance during the LHC energy ramp, particularly in the vertical plane, is of interest to LHC operation. In this paper, a potential mechanism for vertical emittance growth is considered to arise from transport of particles trapped in islands to larger action upon decreases in strength of Landau octupoles that are used to stabilise the beams.

Figure 1 shows bunch intensity during a ramp-up and ramp-down of the Landau octupole magnet strengths in the LHC. As expected, slow losses from dynamic aperture (DA) are seen upon increasing octupole current. However, an abrupt and unanticipated beam-loss is also observed during octupole ramp-down. This beam-loss can be understood via transport of particles trapped in stable islands to the collimator aperture.

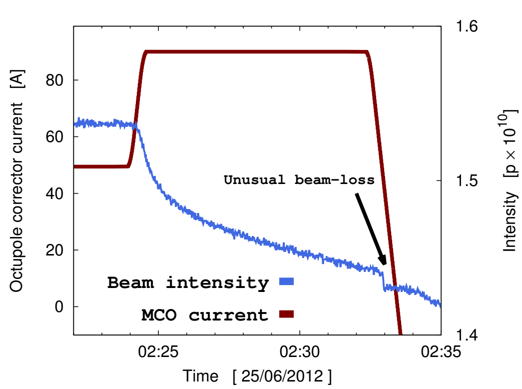


Figure 1: Bunch intensity with increasing and decreasing octupole current.

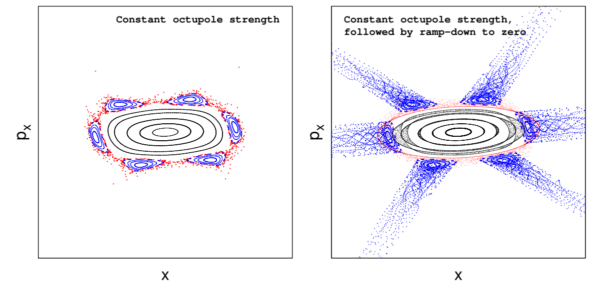


Figure 2: Phase-space portraits for a map of a simple model consisting of drifts, quadrupole and octupole kicks; with constant (left) and decreasing (right) octupole kick strength.

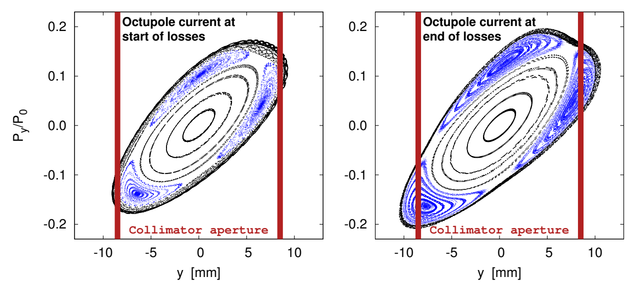


Figure 3: Phase-space section at LHC vertical collimator for octupole current at start (left) and end (right) of abrupt beam-losses observed during octupole ramp-down in Fig. 1.

To illustrate the principle at work, Fig. 2 shows the phase space of a simple model consisting of repeated iterations through a map of drifts, quadrupole and octupole kicks. With constant octupoles (left) a typical phase-space is observed: stable central orbits (black) surrounded by chaotic particles (red) and disconnected stable islands (blue). If octupole strength is slowly decreased between iterations (right) however, particles in islands move to larger amplitude. This is the same mechanism used for multi-turn extraction in the CERN PS [3–6]. Returning to the abrupt beam-loss in Fig. 1, losses were localised to the vertical collimator via BLM signals. Using a LHC nonlinear model (which reproduced well detuning, nonlinear chromaticity, and DA [7–10]) the phase-space at the collimator was simulated in Fig. 3 for octupole currents at the start (left) and end (right) of the losses.

Losses begin as the edge of the $3Q_y$ island touches the collimator aperture (red), and end as the centre of one island reaches the aperture (as particles jump between islands this would correspond to complete loss of beam in the islands). Consequently, the beam-loss observed with decreasing octupole strength is concluded to correspond to particles trapped in the $3Q_y$ island being transported to the collimator.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB169

## EMITTANCE-GROWTH MEASUREMENT WITH CHANGING OCTUPOLES

Observations in the previous section were performed during dedicated studies, not corresponding to the LHC operational configuration. During production fills, however, the LHC does operate with strong Landau octupoles (MO) at injection, raising the possibility that particles may become trapped in stable islands. In the LHC energy ramp, MO strength decreases, as octupole current cannot match increases in beam rigidity, while particles trapped in the islands also undergo adiabatic damping separately from the core. It is conceptually possible therefore for particles trapped in islands to be transported to larger action during the energy ramp, leading to beam-loss or emittance growth. For the positive MO polarity used in LHC operation no islands are expected in the horizontal plane (where the beam detunes to the $(Q_x - Q_y)$ resonance), however such mechanisms may be relevant in the vertical plane, where the beam detunes towards several resonances featuring islands.

To explore this possibility, a beam-based study was performed in the LHC at injection. Low intensity bunches were injected with MO powered to typical operational strength. Remaining at injection energy, MO strength was ramped-down on a timescale representative of the length of the energy ramp (~ 2000 s). This was performed for the operational working point (WP), with small chromaticity ($Q' \approx 2$), and with a high chromaticity representative of nominal operation ($Q' \approx 15$). Emittance was measured via the synchrotron light monitor to look for any change in emittance growth associated with decreasing MO strength.

As expected, no influence of MO ramp-down was observed on horizontal emittance growth for any configuration. In the vertical plane, however, an increase in the rate of vertical emittance growth was observed to be correlated with decreasing octupole strength for the operational configuration (with large $Q'$). This can be seen in Fig. 4.

Figure 5 shows measurements of the change in $\sigma_y$ as a function of time since the start of the octupole ramp-down. Data for the configuration with large $Q'$ (red) can be compared to that for an octupole ramp-down with small $Q'$ (green), and to a measurement of $\Delta\sigma_y$ vs time obtained with high $Q'$ and constant octupoles (black). Consistent with prior operational experience [1, 2] no significant effect of $Q'$ on the emittance growth could be discerned in the absence of an octupole ramp. Similarly no large influence of the octupole ramp on emittance growth was observed with small $Q'$. The combination of octupole ramp-down and high-chromaticity (red data) however, appears to be associated with a non-negligible excess vertical emittance growth.

## ISLANDS WITH HIGH CHROMATICITY AND CHANGING OCTUPOLES

Measurements above suggest an effect of decreasing MO strength on vertical emittance growth occurs, but is dependent on $Q'$. Particle transport via island may be expected to exhibit chromaticity dependence for off-momentum particles, but any role will be complicated since proximity to islands will change dependant on the synchrotron motion. Figure 6 illustrates this, showing 6D LHC tracking data for off-momentum particles with $Q' = 15$ in the vicinity of the $3Q_y$ resonance (with initial coordinates $dp/p = 0, t = 0.07$ m, $x = p_x = p_y = 0$ and $y = 1.7$ mm (red) or $y = 1.6$ mm (blue)). The red particle was initialised on an elliptical trajectory in the core at $dp/p = 0$, but while undergoing synchrotron oscillations (of $|dp/p| \leq 2.5 \times 10^{-4}$) repeatedly crosses into and out of the islands, as changing $dp/p$ moves the tune closer and further from the resonance, and hence the islands between smaller and larger amplitudes. This leads to the highly-chaotic orbit observed. At smaller amplitudes (blue particle) the motion still remains stable.

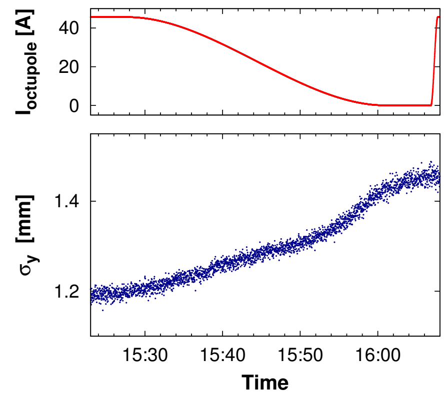


Figure 4: Measured $\sigma_y$ during MO ramp-down with large chromaticity ($Q' \approx 15$).

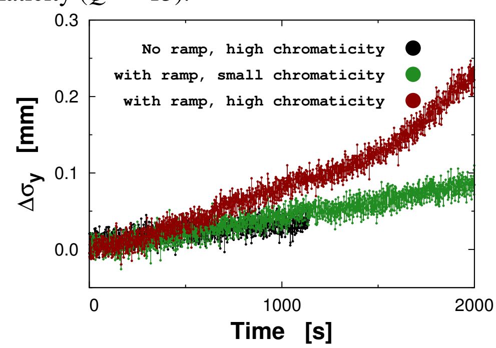


Figure 5: Change in $\sigma_y$ from start of octupole ramp-down with large (red) and small (green) $Q'$, together with change in $\sigma_y$ vs time for large $Q'$ and constant octupoles (black).

To explore the impact of octupole ramp-down, Fig. 7 shows turn-by-turn vertical action from 6D tracking of particles undergoing synchrotron oscillations (with $|dp/p| \leq 2.5 \times 10^{-4}$) in a basic LHC model with linear elements, normal and skew sextupoles, and normal octupoles. In Fig. 7 (top) octupole strength is ramped down from $K_{MO} = 18\,\mathrm{m}^{-4}$ (comparable to the operational configuration) over $100 \times 10^3$ turns (this is faster than the real LHC MO ramp-down, but represented a practical computation time) with $Q' = 2$. In this case, particles initialised in the $3Q_y$ island (black) at approximately $3.7_{\,=3.75\ \mathrm{um}}$ remain trapped and are transported to higher

12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB169



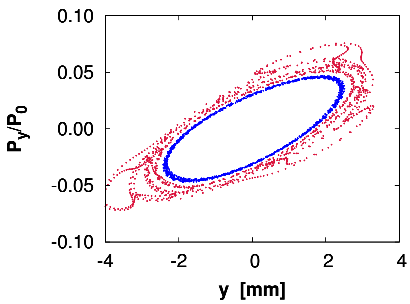


Figure 6: Example of 6D LHC tracking with large $Q'$ for an off-momentum particle near the $3Q_v$ resonance.

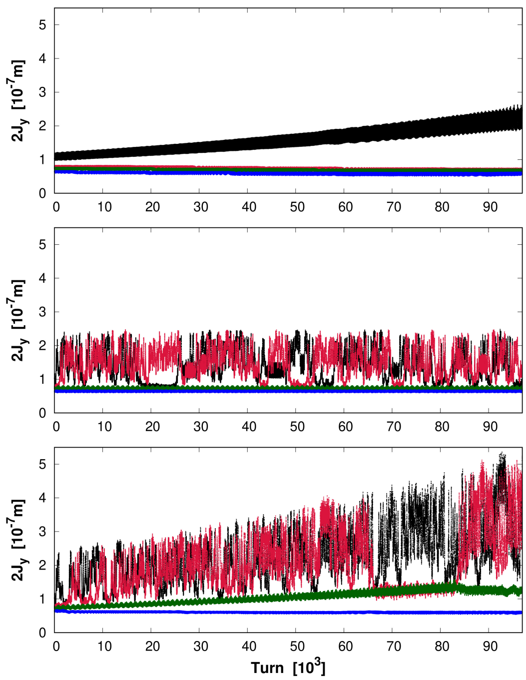


Figure 7: Action evolution of tracked particles of various initial vertical amplitude, undergoing synchrotron oscillations (with $|dp/p| \leq 2.5 \times 10^{-4}$) near the $3Q_y$ resonance, with $Q' = 2$ and MO ramp-down over $10^5$ turns (top), $Q' = 15$ and constant octupoles (center), and $Q' = 15$ and MO ramp-down over $10^5$ turns (bottom).

amplitude, while smaller-amplitude particles (red, green, blue) initialised in the core at $\leq 3_{=3.75\ \text{um}}$ remain stable.

In Fig. 7 (centre) octupole strength remains constant, but particles are tracked with large $Q' = 15$. For these particles synchrotron motion allows the $3Q_y$ island to penetrate further into the previously stable core, and now both black and red particles exhibit a large action smear corresponding to chaotic orbits as shown in Fig. 6. Though varying over a large action range, the motion of these particles still remains bounded on this timescale within an action range defined by the third order islands and synchrotron motion.

Figure 7 (bottom) shows the effect on vertical action from combining decreasing octupole strength with synchrotron motion in the presence of a large $Q' = 15$. The effect on particles which are trapped by the synchrotron motion of the islands is pronounced, with clear increases to smear and maximum amplitude as octupole strength is decreased over time. Compared to the previous case (Fig. 7, centre) of large $Q'$ without any octupole ramp-down (where motion remained bounded) these simulations do exhibit transport to higher amplitudes. In general, Fig. 7 demonstrates that decrease of octupole strength in the presence of a large $Q'$ allows transport of off-momentum particles to higher amplitude, which for small $Q'$ would otherwise remain on stable orbits in the core, indicating that MO ramp-down could give $Q'$ dependent particle transport via the islands.

Any precise relation of specific island chains to observed emittance growth will require further study, as potential impacts will be highly dependent on WP, transverse and longitudinal profiles or longitudinal injection oscillations. For example, extrapolating from various measurements [8, 10–12] to typical MO strength: for $Q_y = 0.31$ trapping at $3Q_y$ could be expected on momentum at $\approx 3 - 3.5_{y,=3.75\ \text{um}}$. Synchrotron motion at nominal RMS $dp/p$ [13] could then allow island penetration to $\approx 2.5 - 3\sigma_y$, but realistic longitudinal injection oscillations [14, 15] could then also allow island penetration to even lower $\sigma_y$. At alternative LHC WP $Q_y = 0.295$ the $3Q_y$ resonance may be less relevant, but the $10Q_y$ islands can penetrate fully into the beam core (further work is required to see if such high-order resonances are relevant to particle transport). Alternative mechanisms based on tune spread-dependent interaction with resonances more generally could also be considered. Nonetheless the potential for particle transport via islands during the energy ramp represents an interesting possibility.

## CONCLUSIONS

Beam-based measurements together with simulations have demonstrated transport of particles trapped in stable islands to larger vertical amplitude upon reduction in octupole strength in LHC. This is of particular interest to LHC operation, since there exists unexplained vertical emittance growth in the LHC energy ramp, during which time octupole strength decreases. Further tests with LHC beams indicated that for a configuration representative of nominal operation, decreasing octupole strength was associated with an increased rate of vertical emittance growth. This was not observed in tests with significantly smaller $Q'$ than employed in regular operation. Simulations have also been presented, which illustrate that transport of off momentum particles via resonance islands during octupole ramp-down can be enhanced by large $Q'$, though any precise relation to the prior beam-based observations will require further study as various mechanisms could be conceived. Nonetheless, transport of particles via resonance islands when decreasing octupole strength represents an interesting mechanism which may be relevant to current or future operation, and motivates further consideration and study of such resonances and islands at injection for the LHC's next operational run.

## ACKNOWLEDGEMENTS

Many thanks to the LHC operators and EICs who assisted the measurements presented in this paper.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB169

## REFERENCES

[1] S. Papadopoulou *et al.*, "What do we understand on the emittance growth?," presented at the 9th Evian Workshop, Evian, France, Jan.-Feb., 2019, unpublished.

[2] S. Papadopoulou, "Transverse Emittance Blow up," presented at the 9th Evian Workshop, Evian, France, Jan.-Feb., 2019, unpublished.

[3] R. Cappi and M. Giovannozzi, "Novel Method for Multiturn Extraction: Trapping Charged Particles in Islands of Phase Space," *Phys. Rev. Lett.*, vol. 88, p. 104801, 2002. doi:10.1103/PhysRevLett.88.104801

[4] M. Giovannozzi and R. Cappi, "Adiabatic Capture of Charged Particles in Islands of Phase Space: A New Method for Multiturn Extraction,"in *Proc. 8th European Particle Accelerator Conf. (EPAC'02)*, Paris, France, Jun. 2002, paper WEPLE047.

[5] R. Cappi and M. Giovannozzi, "Multiturn extraction and injection by means of adiabatic capture in stable islands of phase space," *Phys. Rev. Spec. Top. Accel. Beams*, vol. 7, p. 024001, 2004. doi:10.1103/physrevstab.7.024001

[6] M. Giovannozzi and J. Morel, "Principle and Analysis of Multiturn Injection Using Stable Islands of Transverse Phase Space," *Phys. Rev. Spec. Top. Accel. Beams*, vol. 10, p. 034001, 2007. doi:10.1103/physrevstab.10.034001

[7] E. H. Maclean *et al.*, "Non-linear Chromaticity Studies of the LHC at Injection,"in *Proc. 2nd Int. Particle Accelerator Conf. (IPAC'11)*, San Sebastian, Spain, Sep. 2011, paper WEPC078, pp. 2199–2201.

[8] E. H. Maclean, R. Tomás, F. Schmidt, and T. H. B. Persson, "Measurement of nonlinear observables in the Large Hadron Collider using kicked beams," *Phys. Rev. ST. Accel. Beams*, vol. 17, p. 081002, 2014. doi:10.1103/PhysRevSTAB.17.081002

[9] T. H. B. Persson, Y. Levinsen, R. Tomás, and E. H. Maclean, "Chromatic Coupling Correction in the Large Hadron Collider," *Phys. Rev. ST. Accel. Beams*, vol. 16, p. 081003, 2013. doi:10.1103/physrevstab.16.081003

[10] E. H. Maclean, M. Giovannozzi, and R. B. Appleby, "Innovative method to measure the extent of the stable phase-space region of proton synchrotrons," *Phys. Rev. Accel. Beams*, vol. 22, p. 034002, 2019. doi:10.1103/PhysRevAccelBeams.22.034002

[11] E. H. Maclean, F. S. Carlier, M. Giovannozzi, T. Persson, and R. Tomas, "Effect of Linear Coupling on Nonlinear Observables at the LHC,"in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 3151–3154. doi:10.18429/JACoW-IPAC2017-WEPIK092

[12] F. S. Carlier, E. H. Maclean, T. H. B. Persson, and R. Tomás, "MD1405: Demonstration of forced dynamic aperture-measurements at injection," CERN, Geneva, Switzerland, Rep. CERN-ACC-Note-2017-0051, 2017.

[13] O. S. Bruning *et al.*, "LHC Design Report v.1: the LHC Main Ring," CERN, Geneva, Switzerland, Rep. CERN-2004-003-V-1, Jun. 2004.

[14] H. Timko, T. Argyropoulos, I. Karpov, and E. N. Shaposhnikova, "Beam Instabilities After Injection to the LHC,"in *Proc. 61st ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB'18)*, Daejeon, Korea, Jun. 2018, pp. 163–167. doi:10.18429/JACoW-HB2018-TUP1WA03

[15] S. Albright, P. Baudrenghien, I. Karpov, E. Shaposhnikova, H. Timko and T.Argyropoulos, "LHC MD 2042: Persistent Injection Oscillations," CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2018-0018, 2018.