CHART Project Reporting Form

Swiss Accelerator Research and Technology

Scientific Reporting for project: FCC-hh and HE-LHC Stability

In the last reporting period the beam dynamics studies have been focused on three different topics:

1. Continue and extend the instability, Landau damping and emittance evolution studies related to FCC via simulations. In addition a full analysis of data from the LHC available from the RUN2 dedicated experiments have been conducted.
2. Develop a new correction scheme for the LHC experiments evaluation of the absolute luminosity determination with beam-beam effects during Van der Meer (VdM) scans analysis
3. Machine Learning exploration for possible use in future colliders design or for further exploitation of LHC data or operation time. Thanks to the competitive Suisse Data Science Center grant.

1. Beam Stability

The study of beam stability and preservation of beam parameters have been conducted for the FCC hadron colliders and studies have been described in the extended version of the Conceptual Design Report for FCC-hh. The main results have been summarized and used to define the operational scenario for the hadron colliders to reach the luminosity goals. Studies have been carried in static considerations without considering dynamic changes of parameters as emittance and intensities of the beams. The effects analyzed with the proposed scenarios are summarized in [1] and [2] for the baseline choice. In addition results have been published in [3][4][5].

In parallel during the last year we have focused on comparing existing models used for FCC-hh design with LHC data to verify the validity of such models. A full analysis of the available data from dedicated machine experiments on the LHC during RUN2 has been carried out and documented in [6][7][8]. The studies where covering the modification of the stability thresholds when an impedance is presence and in the presence of an external noise source as for example the transverse feedbacks used to suppress dipolar oscillations.

The presence of a diffusive mechanism has shown to be detrimental for Landau damping and therefore in the design one should account for keeping these effects under defined threshold dictated by stability. This means tighter tolerances for element vibrations in general respect to the LHC. The tolerances should be revised and impact to stability should be re-evaluated. This is evident in the experimental and numerical prove of the deviation of the stability thresholds when diffusion is present as described in [9]. In Figure 1 the stable phase scale which represent the stability expectation is shown from models solid line and from LHC measurements. A deviation from models reducing the stability if visible for the Vertical plane (red line) and this can be correlated to a faster diffusion in the vertical plane as shown in Figure 2. The development of the Beam Transfer Function measurements

[10][11][12][13][14] have opened the possibility to explore experimentally the Landau damping properties of the beams and more recently also to possibly use such device for a parasitic measurements of chromaticity. In addition the effect of the transverse impedance and chromaticity on the BTF measurements have highlighted a factor 1.5 stronger impedance in the LHC [7].

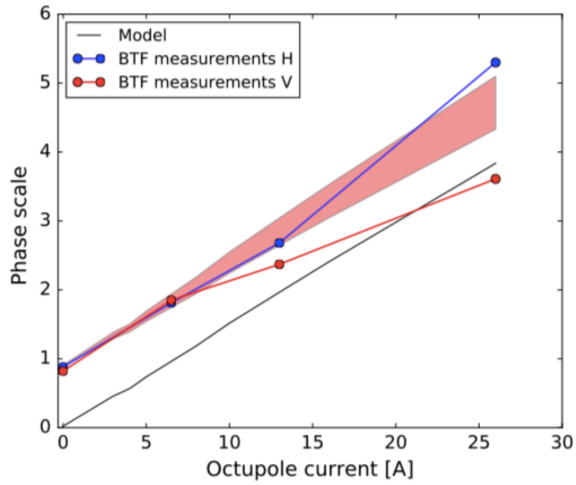

Figure 1 The phase scale parameter evaluated from the fitting function applied to the BTF measurements at injection energy as a function of the octupole current. The blue dots represent the BTF measurements in the horizontal plane, and the red dots are the measurements in the vertical plane. The solid black line represent the expectations from the model with respect to a which no asymmetry in the two transverse planes has been observed and for direct comparison with the operational octupole settings at the time of the measurements. As expected for such a current, the phase scale of the model is equal to one. The red shadow is given by the model expectations including the initial nonzero tune spread corresponding to ≈5.5 A and considering an uncertainty of 10% on the measured emittance.

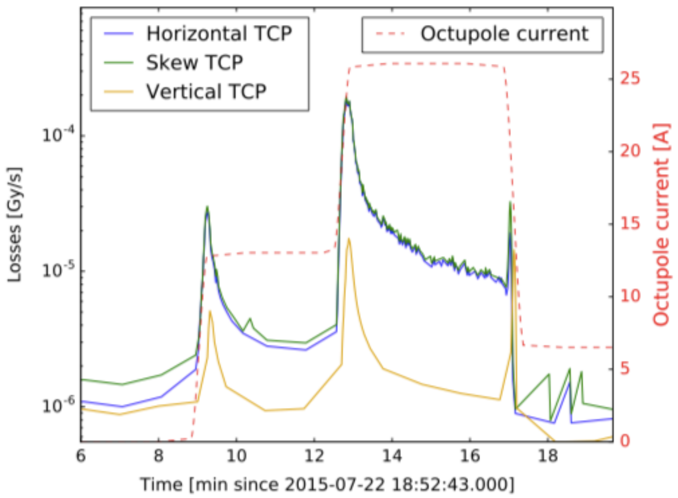

Figure 2 Particle losses detected by the Beam Loss Monitors (BLMs) at the primary collimators location in IR7 as a function of time while changing the octupole current (the dashed red line).

The present understanding of the emittance growth rate of colliding beam due to decoherence in the LHC can be described with a numerical model based on macroparticle tracking simulations. The models well describe the observed emittances qualitatively but can give a realistic numerical comparison when an external source of noise is introduced. Present models can be used for extrapolation to future machine. The experiments revealed a significant contribution of the existing transverse feedback to the emittance growth driven by its BPM noise floor, such that mitigations might be required to achieve the performances goals. The other sources of noise in the LHC remains to be identified and therefore will require further studies during RUN3. All the findings will have to be translated in terms of tolerances for the FCC-hh and HE-LHC design. The full analysis can be found in [15] with estimates for the HL-LHC. With these findings in mind a study on the possible impact on noise due to an electron lens has started and a clear impact is visible [16]. The side effects of such element should be analysed from the stability point of view also in view of a possible use of such devices in the HL-LHC.

2. Absolute Luminosity and beam-beam effect

LHC experiments need the evaluation of the absolute luminosity to be able to calibrate their detectors. This calibration occurs during dedicated experiments in the LHC and uses the well established Van der Meer (VdM) methodology. In 2019 it has been shown that the collective effect known as beam-beam interaction does contribute to the luminosity determination when the VdM method is used. In this frame we have developed the numerical tools to be used to determine the absolute luminosity during a VdM scan and to account for the beam-beam bias to the visible cross section measurements [17]. A full parameter and sensitivity studies campaign has been carried out to provide the four LHC experiments(ATLAS, CMS, LHCb and Alice) with a common correction scheme to be applied in their luminosity analysis. Results and the correction strategy will be published in [18] for the VdM cases. In Figure 3 the luminosity ratio is shown as a function of the beam to beam separation during a typical van der Meer scan. In the figure we compare the ratio using the old linear correction (blue line), when a correct beam-beam beating is accounted for (red line) and if the luminosity is computed by the overlap integral without assuming a Gaussian distribution for the particles. Further studies will follow to address the impact of such beam-beam interactions in the presence of bunch train configurations and crossing angles as in operational mode.

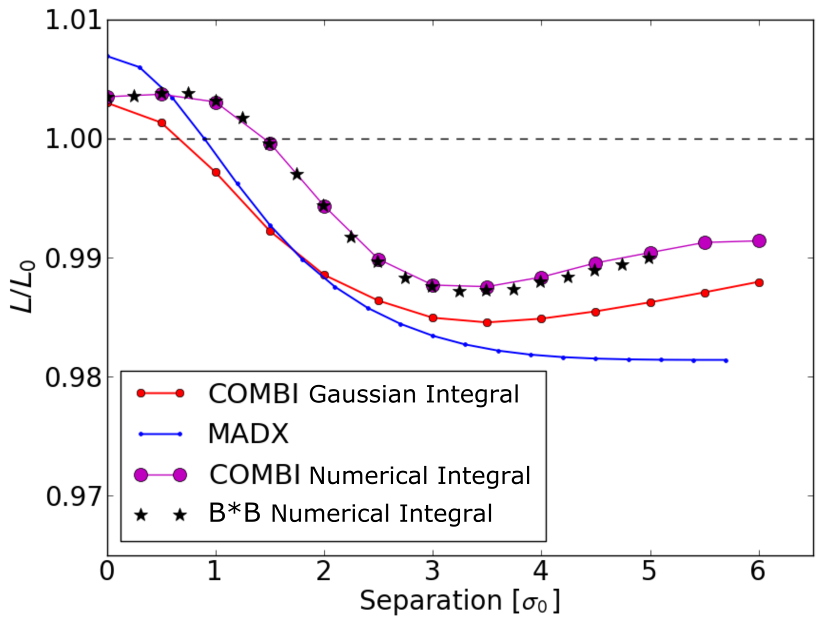

Figure 3 Luminosity ratio between computed luminosity without beam-beam effect L_0 and the results of multi-particle effects L for different relative beam to beam separations during a typical Van der Meer scan expressed in units of the transverse RMS beam size σ_0 for the different models used.

3. Machine Learning

Another important path that is under exploration is the possibility to use Machine Learning (ML) and Artificial Intelligence (AI) technologies to the design and operation of colliders. These studies are done in collaboration with the SDSC and the LHC operation group at CERN. In this frame we have explored three possible applications:

- Beam lifetime optimization for the LHC
- Instability detection using the ADT ObsBox for online fast data analysis and instability classification for RUN3
- Anomaly detection of anomaly beam loss maps from RUN2 LHC data and possible implementation for RUN3

The first two topics have been described in a common paper [19]. In Figure 4 an example of the comparison of a machine learning optimized working point (red dot) versus the machine operational working point (blue dot) and data acquired during a dedicated experiment in the LHC during RUN2 (yellow dots have higher beam lifetime). The new optima seems showing a better operational set-up with much larger lifetimes.

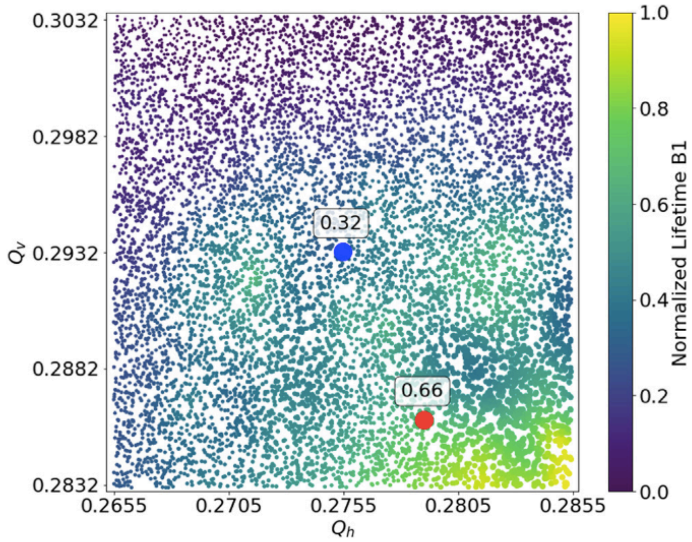

Figure 4 Normalised beam lifetime as a function of the LHC tune working point as measured for Beam 1. Blue dot: Nominal working point. Red dot: Lifetime-optimised working point as determined by the ML model. The model prediction is close,but not exactly equal, to the measured maximum lifetime. The absolute minimum and maximum value of the beam lifetime is 1.05 h and 32.7 h, respectively.

Publications:

- Future Circular Collider Study. Volume 3: The Hadron Collider (FCC-hh) Conceptual Design Report, preprint edited by M. Benedikt et al. CERN accelerator reports, CERN-ACC-2018-0058, Geneva, December 2018. Published in Eur. Phys. J. ST.
- Future Circular Collider Study. Volume 4: The High Energy LHC (HE-LHC) Conceptual Design Report, preprint edited by F. Zimmermann et al. CERN accelerator reports, CERN-ACC-2018-0059, Geneva, December 2018. Published in Eur. Phys. J. ST.
- Jose L. Abelleira et al., FCC-hh Experimental Insertion Region Design, https://arxiv.org/abs/2007.12058
- L. van Riesen-Haupt *et al.*, "Developments in the Experimental Interaction Regions of the High Energy LHC", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 532-535. doi:10.18429/JACoW-IPAC2019-MOPMP039
- F. Zimmermann *et al.*, "Updated High-Energy LHC Design", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 524-527. doi:10.18429/JACoW-IPAC2019-MOPMP037
- C. Tambasco et al., MD 3292: MEASUREMENTS OF LANDAU DAMPING BY MEANS OF BTF MEASUREMENTS, Machine Development Report, CERN-ACC-Note-2019-0045.
- C. Tambasco et al., MD 3290: Instability threshold measurements in the presence of a controlled external excitation, Machine Development Report, CERN-ACC-Note-2019-0044.

- S. V. Furuseth et al., MD3288: Instability latency with controlled noise, CERN-ACC-NOTE-2019-0011.
- C. Tambasco et al., “Beam transfer function measurements used to probe the transverse Landau damping at the LHC”, Phys. Rev. Accel. Beams, vol. 23, no. 071002, 2020, doi: 10.1103/PhysRevAccelBeams.23.071002

- C. Tambasco *et al.*, “Beam Transfer Function Measurements and Transverse Stability in presence of Beam-Beam”, *in ICFA Mini-Workshop on Impedances and Beam Instabilities in particle accelerators*, Benevento, Italy, *pp.105-109*, doi: 10.23732/CYRCP-2018-001.105

- C. Tambasco *et al.*, “Landau Damping Studies for the FCC: Octupole Magnets, Electron Lens and Beam-Beam Effects”, in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, BC, Canada, Apr. 4, pp. 3150-3153, doi:10.18429/ JACoW-IPAC2018-THPAF074

- ICFA mini-workshop on Mitigation of Coherent Beam Instabilities in particle accelerators (MCBI 2019), *BTF and stability diagram*, C. Tambasco, Zermatt, Switzerland, September 2019

- ICFA mini-workshop on Mitigation of Coherent Beam Instabilities in particle accelerators (MCBI 2019), Review of instabilities with beam-beam and possible mitigations, T. Pieloni, Zermatt, Switzerland, September 2019.

- ARIES-APEC workshop on Mitigation Approaches for Hadron Storage Rings and Synchrotrons, Injecting ripples on beam: shall we?, C. Tambasco, June 2020

- X. Buffat, W. Herr, T. Pieloni, and D. Valuch, Modeling of the emittance growth due to decoherence in collision at the Large Hadron Collider, Phys. Rev. Accel. Beams 23, 021002 – Published 18 February 2020
- R. Cai et al., Simulations of particle loss due to hollow e-lens and non-linearities for the HL-LHC, CERN-ACC-NOTE-2020-0046.

- T. Pieloni and C. Tambasco, Beam-beam simulations with COMBI & TRAIN in vdM fills, Lumi days 2019. Lumi talk.

- A. Babaev et al., Impact of Beam-Beam Effects on Absolute Luminosity Calibrations at the CERN Large Hadron Collider, to be published.

- P. Arpaia, G. Azzopardi, F. Blanc, G. Bregliozzi, X. Buffat, L. Coyle, E. Fol, F. Giordano, M. Giovannozzi, T. Pieloni, R. Prevete, S. Redaelli, B. Salvachua, B. Salvant, M. Schenk, M. Solfaroli Camillocci, R. Tomás, G. Valentino, F.F. Van der Veken, J. Wenninger, Machine learning for beam dynamics studies at the CERN Large Hadron Collider, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 985, 2021,164652, ISSN 0168-9002.