REVIEW OF INSTABILITIES WITH BEAM-BEAM EFFECTS AND POSSIBLE MITIGATIONS

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Abstract

In circular colliders the two counter rotating beams interact electromagnetically at various locations along the ring, where sharing a common beam pipe, and at the interaction regions via the so called beam-beam force. These interactions are of different nature, long-range or head-on and they represent a very important non-linear force acting on the particle beams. When mitigating impedance driven instabilities the impact of beam-beam effects has to be accounted for, since these effects change many of the optical properties and particle dynamics with very important impacts to the stability conditions. Since the beam-beam force can change single particle properties as well as coherent beam oscillations they need to be added in all their aspects to the study of mitigation methods for coherent impedance driven instabilities. The beam-beam effects can help mitigating but can be detrimental in enhancing the coherent motion. Several observations from past colliders have shown the impact of beam-beam effects on beam stability but more recently the Large Hadron Collider (LHC) has given the possibility to experimentally probe the impact of these interactions on the beam stability due to the constant appearance of instabilities. A very dense experimental and theoretical campaign has been motivated to better understand their role in the instability picture. In this paper the main contributions to beam stability and mitigations coming from beam-beam effects are explained with direct observations and experimental evidences from the LHC. The challenges arising from the higher energy reach of future colliders has also boosted at a study level the development of alternative mitigating methods and a new strategy for the design of future accelerators with conventional mitigation techniques.

INTRODUCTION

The accelerator impedance [1, 2] can be a source of coherent instabilities. The general strategy for mitigating such effects is that the coupled-bunch instability modes will be cured by a transverse feed-back [3], while single-bunch instabilities will be suppressed by Landau damping [4]. As for the LHC, Landau octupoles provide the necessary Landau damping [5–7] while a transverse feedback is constantly used to suppress any coupled bunch mode [8,9]. Over many years of operation several instabilities have appeared requiring a much larger octupole strength providing Landau damping. Therefore several studies have been conducted to understand the effectiveness of Landau damping and the role of beam-beam interactions in the stability of the beams. In Fig. 1 a factor 2 difference between expected and required octupole strength to mitigate coherent instabilities via Landau damping is shown together with an historical sketch of the different types of instabilities observed over RUN I and II [10]. In colliders anything relevant in conventional single beam instabilities [3] (i.e. chromaticity, tune spread, tune shifts, linear coupling) will be modified by the beam-beam interactions. Depending on the operational configuration the beam-beam effects can enhance stability or might deteriorate it [11]. For these reasons these effects need to be understood, evaluated and kept under control to ensure long term stability. An extensive campaign devoted to understand the impact of beam-beam effects as a possible source of this discrepancy between expected and measured instability thresholds has been conducted and a summary is given in this paper.

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BEAM-BEAM INTERACTIONS AND BEAM STABILITY

In synchrotrons, the beam is kept stable partially by Landau damping due to the tune spread within each bunch. The stability diagram in plane j = (x, y) is calculated from [12]:

$$SD^{-1} = -\int_0^\infty dJ_x \int_0^\infty \frac{J_{x,y}\frac{d\Phi(J_x,J_y)}{dJ_{x,y}}}{Q_0 - Q_{x,y}(J_x,J_y)} dJ_y \qquad (1)$$

where $J_{x,y}$ and $Q_{x,y}$ are the action variable and particle detuning, respectively The horizontal and vertical planes are indicated as x or y. Q_0 is the unperturbed betatron tune, and Φ is the particle distribution. Due to the dependency on the particle distribution derivative, it is clear that the stability can be changed significantly by a small change in the distribution and or by a change in the detuning with amplitude. In addition a transverse feedback is constantly used to damp the coupled bunch instabilities. The fastest growing instability modes can be damped with very low damper bandwidth, while the damping of the high frequency modes is very sensitive to the exact frequency response of the feedback system above the cutoff frequency [8, 9]. Impedance driven instabilities have still be present during the LHC operations. The beam-beam interactions are strongly non-linear electromagnetic interactions that modify in a substantial way the beam properties and optical characteristics in addition to the accelerator lattice [13]. For the case of Gaussian particle distributions the angular deflection a particle will fill going through the opposite beam has only a radial component and can be expressed by the known relation:

$$\Delta r' = \frac{2Nr_0}{\gamma} \cdot \frac{1}{r} \cdot (1 - e^{-\frac{r^2}{2\sigma^2}}) \qquad (2)$$

where N is the number of charges, r_0 is the classical proton radius, γ is the relativistic factor and σ is the transverse RMS beam size.

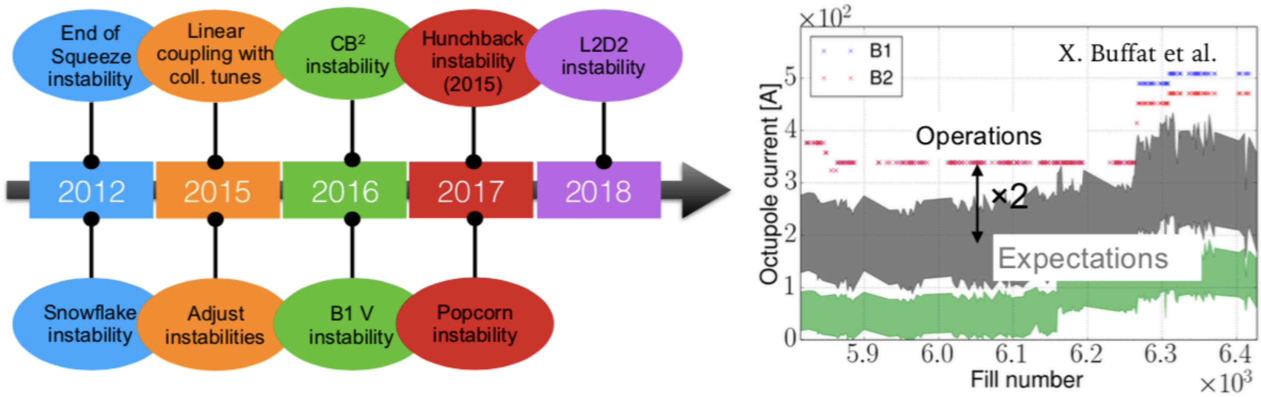

Figure 1: Chronological summary of the different instabilities detected in the LHC (left plot). Plot of the expected (green and grey lines) versus operationally used (red and blue crosses) octupole strengths to mitigate coherent instabilities (right plot) for different physics fills. A factor two is evident between the models and the reality. Courtesy of X. Buffat.

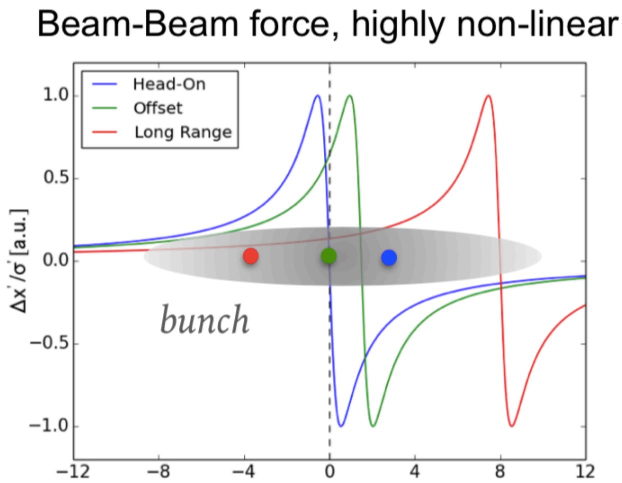

Figure 2: Beam-beam force as a function of the test particle position in units of σ for different beam to beam separations: the blue line for zero offset, the green line for offset of 1 σ and the red line for 8 σ separation.

In Fig. 2 the beam-beam force, as expressed in Eq. (2), is shown for different separations r in units of σ between the force produced by a bunch and the probing one (the grey area). The blue line shows the force when a head-on collision occurs $r \approx 0$, the green line shows the case of a small offset $r \approx 1\sigma$ (as for example when levelling luminosity with a transverse offset or when collapsing the separation bumps) and the red line shows the case of a 8 σ long-range interaction. The interactions can occur at different beam to beam distances and the effects on the counter rotating beam can be very different because different particles are involved in the interactions. In head-on collisions the core of the beams are the most affected while for long-range interactions tail particles are the one most affected. In a collider with many bunches and multiple Interaction Points (IPs) all these effects occur at different stages of the operational cycle and at different locations along the ring. While head-on or small offsets collisions can occur only at the IPs the long range interactions can occur either around the interaction regions where the beams are bought into collision (i.e. a la LHC [5]) or regularly spaced around the machine when they share a common beam pipe (i.e. at the Tevatron [14]).

In the LHC the interactions are of all types: head-on, long-range or with small offsets. The beams interact at more than 124 locations along the circumference at each turn.

These effects can enhance stability or reduce it depending on the effects involved, for this reason they must be taken into account when understanding the coherent stability of beams in hadron colliders. Several lessons come from past experience (i.e. Tevatron, RHIC) but more have been experimentally explored in the LHC during the past years of operation due to the continuous presence of instabilities during the operation of the collider.

INCOHERENT EFFECTS

Since 2012 the LHC has experienced strong impedance driven instabilities during the whole physics runs. To mitigate such effects the Landau octupoles have been powered at maximum strength and high chromaticity operation has been put in place (from 2 to 15-17 units increase) as summarised in [10, 15]. These strong non-linearities have negative effects on the beams dynamics of colliding beams but were necessary to mitigate the instabilities. In addition they interplay with beam-beam incoherent effects change the beam stability thresholds. This occurs via several effects: the detuning with amplitude [16], via a change of chromaticity from long-range as well as head-on collisions, the impact of noise and diffusive mechanisms at reduced dynamical aperture.

The beam-beam LR separation at the first encounter can, for the high luminosity experiments, be defined as:

$$r = \alpha \cdot \sqrt{\frac{\beta^* \cdot \gamma}{\epsilon_{norm}}} \quad (3)$$

where α is the crossing angle, β^* the beta function at the IP and ϵ_{norm} is the normalized emittance at the IP. This approximation is valid only for the case where the β^* is much smaller than the s location of the first long-range encounter (for a 25 ns beam spacing, this corresponds to 3.75 m from the IP). Reducing the long-range separation will make the force stronger and reduce as a consequence the dynamical aperture.

Detuning with amplitude and Stability

In the presence of the beam-beam interactions, the transverse beam stability provided by the Landau octupoles is modified [15, 17, 18]. In fact, the detuning with amplitude (tune spread) given by the octupole magnets is modified by the beam-beam detuning with amplitude coming from the different types of interactions. When the beams collide head-on, the transverse beam stability is maximised due to the large tune spread provided by the beam-beam head-on interaction [7]. For this reason, a detailed analysis of the transverse beam stability is required taking into account the presence of the opposite beam.

The transverse stability of the beams can be evaluated by solving the dispersion integral [12] in the presence of all non-linearities in the machine. The detuning with amplitude is obtained from multi particle tracking simulations through a realistic model of the machine lattice and through the different beam-beam interactions [18] while the particle distribution is assumed Gaussian.

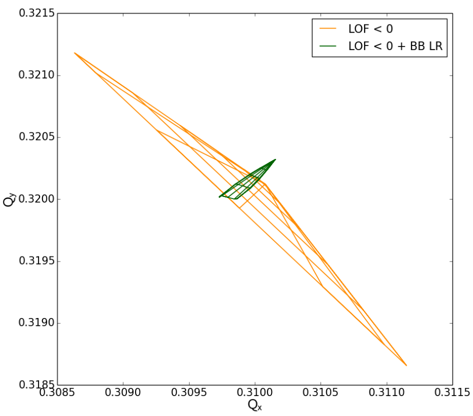

Figure 3: Two dimensional detuning with amplitude from Landau octupoles (yellow lines) and Landau octupoles plus long-range beam-beam interactions (green lines). Courtesy of C. Tambasco.

Figure 3 shows the detuning with amplitude from the Landau octupoles alone (yellow lines) and when beam-beam long-range interactions are added (green lines). A reduction of the detuning is visible for the configuration studied in these cases: the beam-beam long-range interactions compensate, due to their octupolar component [16], the effect of the octupole magnets. One can have also the case where the beam-beam detuning enhances the octupoles effects increasing the tune spread. As a consequence the Stability Diagrams (SD) are strongly modified as shown in Fig. 4. Coherent modes otherwise damped when beam-beam effects reduces the detuning with amplitude can become unstable because the stability area is reduced. This is clearly visible in Fig. 4 where in yellow line the SD due to only octupoles is compared to the one obtained when also beam-beam long-range interactions are included. The black dot is illustrative of an impedance induced coherent mode that can become unstable when the SD is reduced. In addition to the beam-beam effects any other non-linearity can give similar results. When the beams collide, the head-on interaction affects mostly core particles creating a much larger stable area [7]. In Fig. 5 the SDs for the Landau octupoles (green-line), in the presence of long-range beam-beam (blue line) and for a head-on collision (red line) are shown. In collision, thanks to the very effective and large stability area, beams have shown a very stable behaviour in physics. This has also inspired the possibility to use collisions to stabilize the beams and has pushed for the implementation of the collide and squeeze [19].

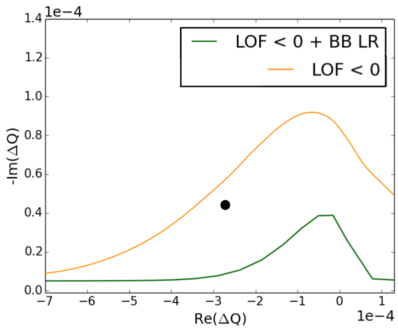

Figure 4: Stability diagram for the case with Landau octupoles and long-range beam-beam interactions (green lines). Courtesy of C. Tambasco.

The idea beyond the collide and squeeze mitigation is to reduce the effects of long-range beam-beam interactions by keeping the beam to beam distance r of Eq. (3) as large as possible. This is obtained by keeping a large β^*. Instead of reducing the beta function to its minimum value (squeezing the beams) with a consequent increase of the beam-beam effects and then collide. One should collide before the detuning from long-range beam-beam becomes relevant and after reduce the β^*. By colliding the stability is then ensured by the head-on interaction as illustrated in Fig. 5 where a comparison of the SDs from the different effects is shown. More details can be found in [15, 18].

Dynamic Aperture and resonance excitation

Increasing the particle spread to have a larger stability diagram is not the whole story. By increasing the tune spread, either pushing non linear elements (i.e. Landau Octupoles) or enhancing the beam-beam interactions, the particles long

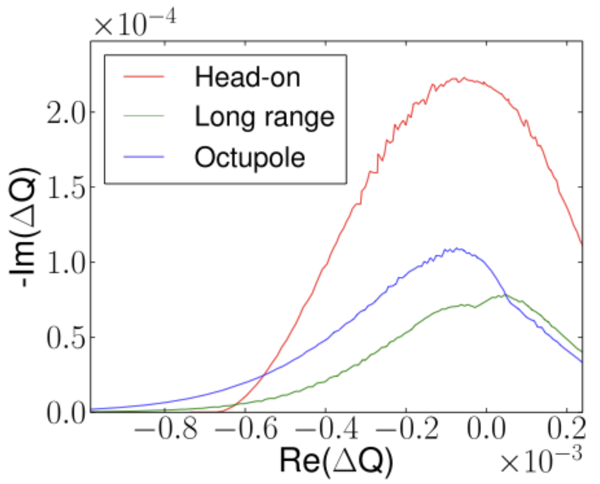

Figure 5: Stability diagram for the case with Landau octupoles (blue line), octupole magnets and long-range beam-beam interactions (green lines) and for a head-on collision (red line).

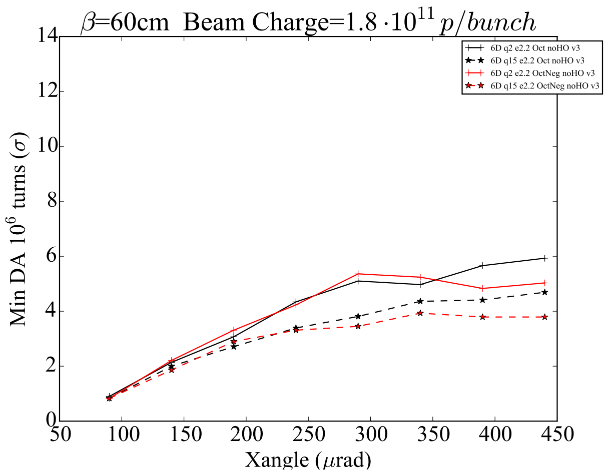

Figure 6: Dynamic aperture as a function of crossing angle for different configurations of the LHC 2012 beams with high octupole strength, high chromaticity operation and long-range beam-beam effects.

term stability will be affected and particles might be pushed to larger amplitudes and they could eventually be lost if they reach the dynamic aperture amplitude [20, 21]. If too many particles are lost then the damping efficiency of the Landau octupoles is reduced because of the modifying particle distribution. Another mechanism that can reduce the Landau damping stability areas is due to the very strong non-linear elements resonant behaviour that can change the particles distributions in frequency space via the excitation of resonances in tune space [22–24]. The indicator of the non-linear and chaotic behaviour of particles is the so called dynamical aperture defined as the amplitude in units of the transverse beam RMS size beyond which particles are eventually lost over long tracking, typically 10^6 turns. If particles drift at larger apertures due to the non-linearities and or are trapped into resonant behaviours they will create a change in particle density and finally they might eventually be lost. These two effects have a clear impact to the Landau damping with octupole magnets since this depends on the derivative of the particle distribution, that in case of particle losses due to a reduced dynamical aperture or by the mutation of the particle distributions due to strong resonances can change the Landau damping properties in a fundamental manner. The fact that particles re-distribute has a clear impact to the distributions in action space and consequently to the stability diagram via the dependency on the derivative of the distributions ($\frac{d\Phi(J_x,J_y)}{dJ_{x,y}}$ in Eq. (1)). Reducing the long-range separation of Eq. (3) will make the force stronger (Eq. (2)) and reduce as a consequence the dynamical aperture. This is visible in Fig. 6 where the dynamic aperture as a function of the crossing angle is shown for four different configurations of the LHC 2012 operation [11, 25, 26].

The impact of a reduced dynamic aperture can be evaluated by cutting particles at the DA aperture in units of the beam RMS size. This is done in Fig. 7 where the SDs are computed for different values of dynamic aperture. A collider with operational settings too close to the dynamical aperture can result in a drastic cut of large amplitude particles that provide Landau damping. As a result a relevant reduction of SD is expected [27]. Such a scenario is not far from the LHC 2012 physics configurations [28].

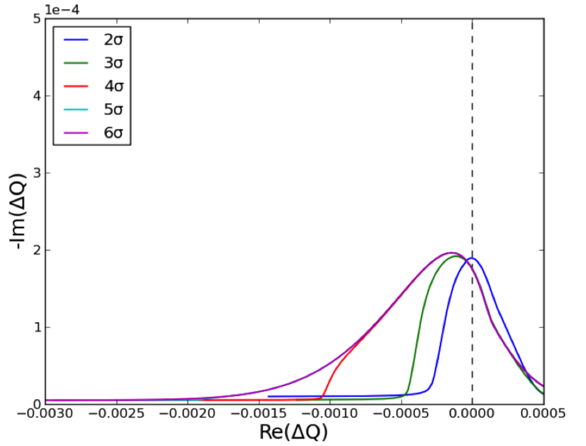

Figure 7: SD diagram for different dynamic aperture values from 6 to 2 σ for the LHC case.

In addition to the dynamical aperture the presence of strong resonances excited by the non-linearities in the machine and among them beam-beam effects can also have detrimental effects to the Landau damping. Among many the linear coupling as studied in [29] can be a very important source of distortion in the detuning with amplitude. This is shown in Fig. 8 where the two dimensional tune spread (left plot) is shown when linear coupling is applied (blue lines) and when it is (red lines). On the right the particle distributions in action space are also plotted with the particle density as color code. This plot shows the change in particle distribution as a consequence of the resonance excited. In Fig. 9 the stability diagrams are plotted for two different unperturbed tunes using the tracked particle distributions from Sixtrack of Fig. 8. The horizontal plane SD (cyan and dark blue lines) are large and not changed by the resonance. On the contrary the vertical plane shows a very strong reduction of the SD (the pink line) and a sensitivity to a tune change that enhances the resonance effect (the green line). This effect has been described in [30] and experimentally measured via Beam Transfer function measurements in [31].

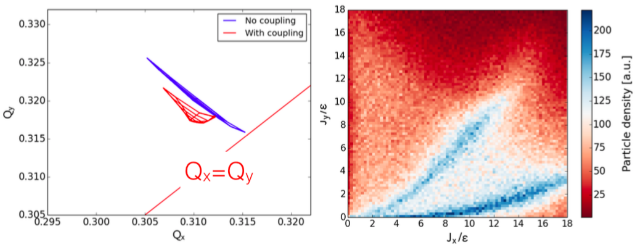

Figure 8: Two dimensional footprint (left plot) for different tune values and particle distribution in action space for the case with shifted tune closer to the linear resonance (right plot).

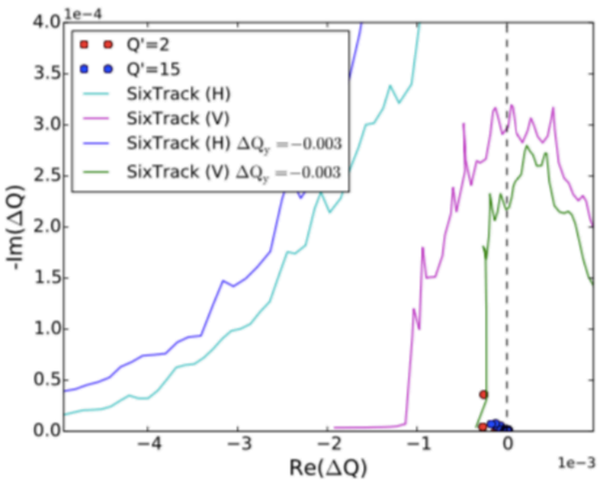

Figure 9: SD diagram in the presence of linear coupling resonance and for different tunes moving the footprints far away from the resonance.

The dynamic aperture and resonances effects on the beam stability has been proved to play a very important role. For these reasons it is fundamental to include in the overall stability strategy a global optimisation of the non-linearities to avoid a deterioration of the Landau damping properties.

Noise

As initially explored in [15] the long lasting delay of instabilities in the LHC already back in 2012 raised the question if this very slow process could have been linked to a modification of the particle distributions due to resonance excitation, diffusion and/or noise.

Two approaches have been followed to try to bring light to these effects: an experimental effort to characterise the Landau damping properties of the beams via beam transverse transfer function measurements [31] and the theoretical and numerical studies of the impact of noise and diffusive mechanisms to the beam stability [15].

The experimental evolution of Landau damping with and without beam-beam effects has been probed in the LHC via beam-transfer function measurements. The goal was to try to experimentally observe the evolution of the Landau damping during an operational cycle in the presence of all non linearities, beam-beam interactions included. This was achieved with the development of the beam transfer function measurements because of the relation $BTF \propto SD^{-1}$. These measurements are meant to understand the effective Landau damping for different machine configurations and to possibly collect evidences of possible particle distribution deformations due to diffusive processes and or resonances effects as in [22].

The second path was to theoretically and numerically explore the impact of noise sources to the beam stability [15]. The aim was to understand the mechanisms that can lead to a loss of Landau damping linked to diffusive mechanisms as a possible explanation of the observed beam behaviours. Instabilities of high latencies have been observed in LHC before collision. The impact of coloured noise to the beam stability has been observed with direct measurements during BTF experiments [32] while indirect measurements have reproduced fully the instability characteristics in [33]. The instabilities observed are driven by noise and not caused by machine variations. Instabilities of high latencies can develop in high-energy hadron machines with noise and impedance, by changing the distribution of particles. Several studies have shown such behaviours theoretically and experimentally [34–37]. A possible mitigation technique considered is to reduce the modification speed of particles but studies are still on-going. More recently also [38] proves the possibility of such mechanism for instabilities in hadron synchrotrons. Studies of the impact of noise to the beam dynamics will have to change to take into account the possible loss of Landau damping associated to. This is a new feature never evaluated before for any collider.

COHERENT EFFECTS

Due to the beam-beam interaction particles of the beams organise their motion and coherent oscillations take place during collision [39–43]. This coherent behaviour of the bunches in a beam can lead to limitations to the machine performances since the system of bunches colliding is a coupled system and actions of one bunch are transmitted to all the rest. These coherent modes have been routinely observed in various colliders and are generally not self-excited. The coherent motion moreover is not always damped by Landau damping mechanisms mainly when the frequencies of the collective oscillations are outside the continuum incoherent spectrum. Under external excitation, such as machine impedance, these modes could therefore become unstable. Therefore, one should always try to avoid or suppress collective motion by breaking the organised dynamics of particles.

In addition a transverse feedback is constantly used to damp the coupled bunch instabilities.The fastest growing instability modes can be damped with very low damper bandwidth, while the damping of the high frequency modes is very sensitive to the exact frequency response of the feedback system above the cutoff frequency.

Mode Coupling

The existence of a strong mode coupling instability when one of the beam-beam coherent modes crossed a higher order head-tail mode has been studied theoretically and experimentally in [44]. The instability has very similar characteristics as the classical impedance driven TMCI [8] and could occur even at low bunch intensities providing the beam-beam parameter is sufficiently large to overlap the $\pi - mode$ frequency with the higher order head-tail modes. In [44] it has been shown that the chromaticity appears to be rather inefficient by itself to cure this instability while a bunch-by-bunch transverse damper would easily suppress it. From these studies it is clear that an optimum combination of damper gain and chromaticity should be found to minimise unwanted side effects as for example reduction of beam lifetime or emittance degradation. In Fig. 10 the amplitude of the spectral line (color code) is shown as a function of the coherent beam-beam and synchro-betatron modes frequencies Q per different beam-beam strengths (ξ). It is evident that when the coherent beam-beam pi-mode approaches the head-tail mode -1 ($\xi \approx 0.003$) the modes couple leading to a strong instability.

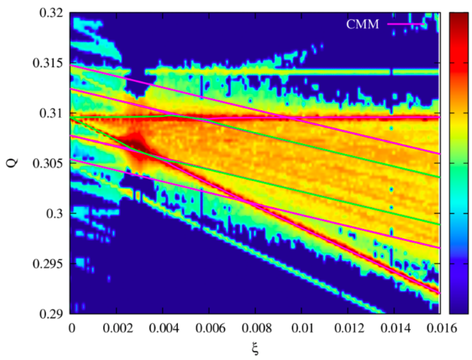

Figure 10: Synchro-betatron modes as a function of the beam-beam parameter ξ. The color code represents the amplitude of the spectral line.

While in Fig. 11 the amplitude of oscillation and rise time of a single and two-beam instability is shown. The magnitude of the instability and rise time is increased by an order of magnitude with respect to the single beam one when it occurs at the overlap of a beam-beam coherent mode. In addition the beneficial effect of a transverse damper in suppressing such instability is also marked with a black line.

Details of such study can be found in [44]. The coupled-bunch beam stability in the presence of the transverse

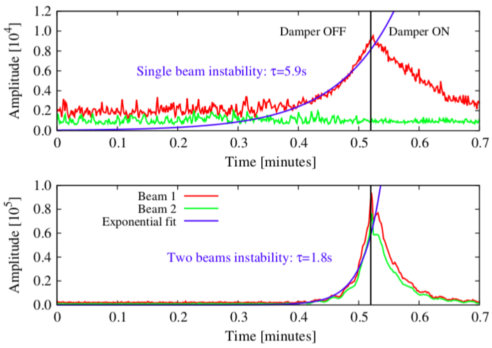

Figure 11: Measured oscillation amplitude in the vertical plane of both beams and exponential fit. An example of the single beam instabilities and two beams instabilities are shown on the top and bottom plots, respectively. The time at which the damper was turned ON is marked by the vertical black line.

feedback, chromaticity, and Landau octupoles using the NHT [45], DELPHI [46] and BIM-BIM [47] has been described in [10].

Suppressing coherent beam-beam modes

Due to the beam-beam interaction, particles of the beams organise their motion and coherent oscillations take place during collision [40–43]. This coherent behaviour of the bunches in a beam can lead to limitations to the machine performances since the system of bunches colliding is a coupled system and actions of one bunch are transmitted to all the rest. Since coherent beam-beam modes are not always damped by Landau damping mechanisms one should always try to avoid or suppress collective motion by breaking the organised dynamics of particles. Since coherent behaviours develop mainly when a high degree of symmetry is present between the two beams (same betatron frequencies, same intensities, same sizes) one can reduce these effects by breaking this symmetry. There are different ways to suppress coherent beam-beam modes. Here a list of the mitigation methods:

Different bunch intensities: if the two bunches will have intensities that differ of around 60% then the coherent motion between the colliding bunches will be suppressed [40,48]. This technique is not used operationally because of its very bad impact to the colliders luminosity that will be reduced by the reduction factor on the bunch intensity.

Different tunes in the two beams: in the case the two beams will have different tunes the system will be decoupled if the difference in tune will be larger than the beam-beam parameter ξ [22, 49, 50]. This technique has been also proved experimentally at the Relativistic Heavy Ion Collider RHIC for example.

Unequal distribution of interaction points: multiple interactions will create a mixing of coherent modes as for example for the case of the LHC with multiple long-range interactions. The coherent modes will be so many to create a continuum of frequency [41,51,52].

Phase differences between interaction points: similarly to the impact of the tunes, if the phase advances between interaction points are not symmetric the phase difference will make coherent motion more difficult to organize [43, 53].
Synchrotron motion: if transverse coherent modes overlap with the incoherent spread coming from the longitudinal motion then transverse modes can be damped thanks to the synchrotron betatron coupling one has in the beam-beam interactions when a crossing angle is applied at the interaction points [54, 55].

FUTURE STUDIES AND CHALLENGES

Future colliders aim at beams of much higher energies to explore new physics process beyond the known playground. In particular presently CERN has undertaken a preliminary conceptual design for a 100 TeV center of mass energy hadron collider and a conceptual design report has been recently issued [56]. For such machines stability of beams is an issue since the classical approach of using octupole magnets to provide the needed Landau damping can be quite inefficient. Octupole magnets provide the frequency spread needed for Landau damping, the effectiveness of such devices decreases with energy because the detuning is affected by both adiabatic damping and increased beam rigidity. The tune spread follows the scaling law $\Delta Q_{octupoles} \propto 1/\gamma^2$. For this reason new devices and or techniques should be studied and explored to mitigate coherent instabilities. The main mitigation methods explored for the design of future colliders are:

- **Optics and beam-beam global design**: at the design stage fully integrate beam-beam effects into the Landau damping evaluations and in the lattice design to maximise the Landau damping and the dynamical aperture. This is obtained by fully integrating the beam-beam effects at the lattice and interaction region design level (i.e. phase advance studies, larger beta functions at the location of the Landau octupoles, global compensations schemes) [57–59]. Maximise the tune spread ΔQ.
- **Collide and squeeze**: as soon as the beam stability approaches its limits ,i.e. at top energy, go into collision to have maximum Landau damping from the head-on beam-beam interaction. Then squeeze the beams to introduce gradually the long-range effects and allow a luminosity levelling knob on demand. With very little impact to the collider performances it allows to have the largest stability diagram and the best use of the lattice and of the two beams for mitigating coherent impedance driven instabilities [59, 60]. Use the $\Delta Q_{bb\ head-on}$ which is independent of the beam energy.
- **Electron lenses**: since the beam-beam head-on collision is independent of the beam energy the tune spread (Landau damping) produced can be much larger and if margins are needed then the use of a well controlled electron beam can be a powerful source of Landau damping. Detailed studies of electron lenses and their proved impact on the beam tune spread can be found in [61–63]. The impact on the beam stability and Landau damping is studied in [64].
- **Radio frequency quadrupoles**: these devices are studied because the detuning with amplitude comes from the longitudinal action variable and not from the transverse plane. The tune spread for Landau damping is given by $\Delta Q_{x,y} = \Delta Q_{x,y}(J_z)$ and therefore it is not affected by the adiabatic damping due to the higher energy. The RF quadrupole is only affected by the increased beam rigidity, so the tune spread is $\Delta Q_{RFQ} \propto 1/\gamma$.

These devices have been studied and a first experimental test to prove the Landau damping has been attempted in the LHC with very promising results. Detailed studies are reported in [65–69].

From the experience of the LHC it is clear that the effort at the design stage to fully integrate Landau damping devices and the impact of all beam-beam interactions to Landau damping, mode coupling and the modification of the optical properties of the lattice has to be studied and optimised in order to maximize the stabilising effects of such strong non-linearity.

Designing a future collider will then require a challenging set of studies to foresee:

- Full study of the impact of beam-beam effects to the Landau damping and use them to enhance it where possible with operational choices as learned from [15]
- Analysis of the dynamic aperture and resonance excitation in terms of impact to the Landau damping to foresee possible losses of stability as done in [20].
- Study the effect of particles diffusion and or emittance growth from noise sources as a possible source it self of loss of Landau damping as learned from [34].
- Explore the interplay of a transverse feedback and mode coupling instabilities from beam-beam coherent modes as described and proved experimentally in [71, 72]
- Explore alternative methods to provide efficient Landau damping at very high energies.

Any future design study has to take all these lessons into account at the design stage in order to fully implement all the effects in the design of the optics to optimise the stability and have a better control of the different aspects. This has been the strategy for the FCC-hh design as presented in [**?**] and summarised in the conceptual design report [56]. Stability studies cover fully the impact of two beams and the lattice design is also conceived to optimise at the maximum the beam-beam effects interplaying with octupoles and sextupole magnets. Operational scenarios have been defined to profit of head-on collisions using collide and squeeze [59] to further increase the Landau damping when at top energy. And in parallel effort has been made to advance the concepts and studies of new devices to possibly support and increase the Landau damping [64, 65].

SUMMARY

Beam-beam effects typical of colliders have shown over the last 10 years at the LHC to be a fundamental ingredient for beam stability. This has manifested in many ways as explained and highlighted in this paper. Several experimental tests and evidences have been carried out to demonstrate the mechanism beyond the effects linked to beam-beam interactions and their role in loss of Landau damping and the mode coupling instability. The understanding of the impedance driven instabilities at the LHC over this last decade has paved the path for an improved design of a future hadron collider. Pushing the single particle studies to merge into collective beam stability as shown to be fundamental because the resulting stability of the beams is the result of the interplay of all these effects. The treatment of the effects independently is not anymore sufficient to describe the behaviour of operational beams and to reproduce the observations. Pushed by the need to mitigate the still present LHC instabilities, new devices to experimentally verify the Landau damping and or to possibly explain the discrepancies with respect to the known models have been developed. The use of this techniques have brought a much better understanding of the underlying physics and they have highlighted the need for new tools to model and explain the beam stability issues observed. Interesting developments on active devices to provide Landau damping as electron lenses and RFQs have been studied in the recent years showing very powerful tools for future machines. At the present the study of noise and its impact to stability is very demanding but can represent the missing ingredient to the understanding of the coherent instabilities observed.

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