



# General mitigation techniques for coherent beam instabilities in particle accelerators

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**Abstract** An important number of coherent beam instability mechanisms can be observed in a particle accelerator, depending if the latter is linear or circular, operated at low, medium or high energy, with a small or a huge amount of turns (for circular machines), close to transition energy or not (below or above), with only one bunch or many bunches, with counter-rotating beams (such as in colliders) or not, if the beam is positively or negatively charged, if one is interested in the longitudinal plane or in the transverse plane, in the presence of linear coupling between the transverse planes or not, in the presence of nonlinearities or not, in the presence of noise or not, etc. Building a realistic impedance model of a machine is a necessary step to be able to evaluate the machine performance limitations, identify the main contributors in case an impedance reduction is required, and study the interaction with other mechanisms such as optics (linear and nonlinear), RF gymnastics, transverse damper, noise, space charge, electron cloud, and beam–beam (in a collider). Better characterising an instability is the first step before trying to find appropriate mitigation measures and push the performance of a particle accelerator, as some mitigation methods are beneficial for some effects and detrimental for some others. For this, an excellent instrumentation is of paramount importance to be able to diagnose if the instability is longitudinal or transverse, single bunch, or coupled bunch, involving only one mode of oscillation or several, and the evolution of the intrabunch motion with intensity is a fundamental observable with high-intensity high-brightness beams. Finally, among the possible mitigation methods of coherent beam instabilities, the ones perturbing the least the single-particle motion (leading to the largest necessary dynamic aperture and beam lifetime) and easiest to implement for day-to-day operation in the machine control room should be preferred.

## 1 Introduction

In September 2019, an ICFA mini-Workshop on “Mitigation of Coherent Beam Instabilities in Particle Accelerators” (MCBI 2019) took place in Zermatt (Switzerland), focusing on all the mitigation methods for all the coherent beam instabilities [1–4], reviewing in detail the theories (and underlying assumptions), simulations, and measurements on the one hand, but on the other hand trying to compare the different mitigation methods (e.g. with respect to other effects such as beam lifetime) to provide the simplest and more robust solutions for the day-

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to-day operation of the machines [5]. Knowledge transfer and close collaboration between beam dynamics experts and the operations teams in the control room are key to ensure proper diagnosis and understanding of the beam instabilities and to deploy operational mitigations and tools to ensure stable beam operation efficiently.

Beam instabilities, and their mitigation, cover a wide range of effects in particle accelerators, and they have been the subjects of intense research for several decades. As the machines performance was pushed, new mechanisms were revealed and nowadays the challenge consists in studying the interplays between all these intricate phenomena, as it is very often not possible to treat the different effects separately. This led to several new instability mechanisms such as the destabilising effect of resistive transverse dampers [6] and the losses of transverse Landau damping due to linear coupling [7], noise [8], and beam–beam [9]. However, even some more basic mechanisms such as the transverse mode coupling instability (TMCI) for coasting beams were never discussed or predicted in the past [10–13], and therefore, there is still a lot to be done, despite the huge amount of work and results of the last decades.

The beam coupling impedance is the first cause of coherent beam instabilities, but many other mechanisms are important to take into account to quantitatively describe the observed instability mechanisms and thresholds of our particle accelerators. And not only all these mechanisms have to be understood separately, but all the possible interplays between the different phenomena need to be analysed in detail, including the beam coupling impedance (both driving and detuning ones in the transverse planes), the linear and nonlinear chromaticity, the transverse damper (including a detailed description versus frequency of the gain, the bandwidth and the noise), the Landau octupoles (and other intrinsic nonlinearities), space charge, beam–beam (with both long-range and head-on effects for colliders), electron cloud or/and ions, linear coupling strength, tune separation between the transverse planes (bunch by bunch), tune split between the two beams (bunch by bunch, for colliders), transverse beam separation between the two beams (for colliders), noise, etc.

For existing machines, trying to push the machine performance usually requires a detailed impedance model and a systematic analysis to identify the main contributors and reduce their impedance, which requires a lot of time and resources. In case of instabilities due to additional electrons or ions, all the methods to try and reduce/suppress the later should be put in place. (It is worth noting, for instance, that nanostructuring of material surfaces by laser ablation is a well-established science and manufacturing with more than 25 years of experience [14].) In many machines, longitudinal and transverse feedbacks exist and realistic modellings of them need to be included in the beam stability analyses, as they considerably modify both coupled-bunch and single-bunch motions. (It is worth noting that in some machines, many feedbacks are used, such as the 35 feedback loops used for instance in the CERN Proton Synchrotron (PS) to prepare the beams for the Large Hadron Collider (LHC) [15].) Feedbacks are working very well but they cannot, at the moment damp all types of instabilities. (This might change in the future if we succeed to reach the necessary bandwidth with sufficiently low noise.) And in some cases, destabilising effects from feedbacks can also be observed. Therefore, the next step is to optimise the machine linear and nonlinear optics (tunes, linear and nonlinear chromaticity, amplitude detuning, linear coupling, transition energy, etc.) and the RF knobs (such as RF voltage or controlled longitudinal emittance) and rely on Landau damping. However, a trade-off between coherent beam stability and single-particle stability (i.e. dynamic aperture) needs to be found and all the sources of Landau damping should be considered and studied carefully together: some interplays can be beneficial, and some others can be detrimental. Landau octupoles are usually used to provide Landau damping in the transverse plane, but some other proposals have been made, such as using beam–beam (long-range and/or head-on) in colliders, or an electron lens (which is doing something similar

in non-collider rings), or an RFQ (a radio-frequency quadrupole, which has a similar effect as the second-order chromaticity  $Q''$ , providing longitudinal-to-transverse Landau damping). There is still a lot to be done on Landau damping and its possible loss, looking in more detail to theories, simulations, and measurements (e.g. with BTF, Beam Transfer Function, or, as recently proposed, using an anti-damper as a controlled source of impedance [16]). The evolution of the intrabunch motion with intensity is a fundamental observable with high-intensity high-brightness beams to better characterise the observed instabilities [17].

For future machines, it is recommended to try and integrate all the above aspects already in the design stage, i.e. reduce as much as possible the impedance and electron cloud (surface) effects (in close collaboration with all the equipment groups) and optimise the optics design by including already from the beginning all the collective effects, such as Intra-Beam Scattering (IBS).

The plan of this paper is the following: the different stabilising methods are reviewed from Sects. 2 to 9, while the main future challenges for MCBF from different studies around the world are discussed in Sect. 10, before concluding in Sect. 11.

## 2 Time: latency and instability rise time

When a beam of charged particles traverses a device which is not a perfect conductor or which is not smooth, it produces electromagnetic fields that perturb the following particles. Differently from those of magnets and RF cavities, these fields depend on the beam intensity and their amplitude cannot be easily changed. Under some conditions, they can induce instabilities. Using two approximations, the rigid-beam and the impulse approximations, these fields are described in time domain through the concept of wake field or in frequency domain through the concept of impedance [18]. The subject of impedance-induced instability is one of the main topics facing modern high performance accelerators. Even if the roots of this subject are more than 50 years old, it is still a cutting edge in the beam physics. Many researchers have been working over the years on this subject, and very elegant and well-established theories have been proposed explaining many experimental observations. As Migliorati said at the MCBF 2019 workshop [18]: “the best proof about our comprehension of these instabilities is that particle accelerators work and are successful. After 50 years, this couldn’t be only a coincidence. However, there are still dark sides that have to be illuminated by the young generation, which, we hope, will continue the work with the passion that has marked so far the protagonists of this fascinating subject”. We still need to better understand all the mitigation techniques and find the best trade-off with the single-particle beam stability and dynamic aperture considerations. For this, we also need to study in more detail the interplays among all the different mechanisms but also carefully review all the assumptions made in the past behind which some new instability mechanisms are hidden such as the recently identified TMCI for coasting beams (see above), which, in particular, nicely explains the possible exchange of the most critical transverse plane above a certain intensity.

Depending on the conditions, the beam can become unstable and some (or all the) particles can be lost before the end of a linear accelerator or within few turns inside a circular accelerator, such as with the fast vertical instability observed in the CERN Super Proton Synchrotron (SPS) in 1998 where particles started to be lost after only 11 turns [19]. Due to the short muon lifetime, preserving the longitudinal and transverse beam quality is also a major challenge for the new forming International Muon Collider Collaboration (IMCC) [20]. On the other hand, in some other accelerators such as the CERN LHC, some beam instabilities can develop after  $\sim 45$  min (i.e.  $\sim 30$  millions of turns) in similar conditions without beam–

beam or even after few hours (e.g. 4 h, i.e.  $\sim 160$  millions of turns) during physics (with beam–beam collisions) [21].

The basic idea to study the coherent beam instabilities is quite simple [18]: we start with the motion of a single particle, and we include the force (wake field) due to all the others. The (only) problem is that there is quite a lot of other particles per bunch (e.g.  $\sim 100$  billion particles per bunch for the CERN LHC, which is similar to the number of neurons in a human brain or the number of stars in a galaxy) and sometimes many bunches (a bit less than 3000 for the CERN LHC). Instead of considering these  $\sim 100$  billion equations of motion for a single bunch, we generally follow three other possible paths. The first is to go to the extreme by considering a continuous function (distribution function) describing the motion of the beam as a superposition of modes. In this treatment, the force is also described in terms of the distribution function and we use the Vlasov equation in the absence of diffusive terms or the Fokker–Planck equation in the presence of diffusive terms (in particular for electron beams for which synchrotron radiation cannot be neglected). The second approach is to simplify the problem by reducing the number of equations: instead of  $\sim 10^{11}$ , we use macroparticles and simulation codes which track, turn after turn,  $\sim 10^6$ – $10^7$  macroparticles, taking into account their electromagnetic interactions through the wake fields. Finally, the third approach is to develop simple models with few particles (e.g. two-particle model) or few modes (e.g. two-mode model). These simple models allow to understand many physical aspects with quite manageable expressions, but the associated assumptions should always be carefully analysed and the results benchmarked to be sure that important effects have not been overlooked.

In circular machines, the synchrotron oscillation is a stabilising mechanism for both the longitudinal and transverse planes, exchanging the roles of the head and of the tail of the bunch and avoiding thus a propagation along the bunch as observed, for instance, in the beam break-up (BBU) instabilities in linacs. In the latter, we study the beam in a transient regime where the initial conditions are thus important and the Laplace equation is used. In a circular machine, we usually study the beam in a stationary regime with the Fourier transform. However, in some cases the transient behaviour can be important also in circular machines when, for instance, instabilities develop in a time much shorter than the synchrotron period, such as in [19], as discussed previously, or when transition is crossed or when some accelerators are designed close to the isochronous condition to reduce the required RF voltage or profit from the naturally shortest bunch length. In the case of the recently described loss of transverse Landau damping by noise and wake field-driven diffusion [8], the notion of latency was introduced and defined as the time from the start of the noise excitation, on an initially Gaussian distributed bunch, to the bunch instability. Depending on the conditions, this time can be very short or as long as few hours. A new instability mechanism was introduced where the coherent modes, which are excited by the noise in the machine, act back on the individual particles through wake fields (see Sect. 8). The impact is modelled as a narrow diffusion in frequency space, and therefore also in action space due to amplitude-dependent detuning, which leads to a local flattening of the distribution. This distribution evolution corresponds to the drilling of a borehole in the stability diagram, i.e. a local reduction of the imaginary part of the curve. Hence, initially stable regions are changed into unstable ones at the real frequencies of the coherent modes. To mitigate this instability mechanism, one must operate the machine with a stability margin of magnitude that depends on the noise amplitude and the coherent modes.

In summary, there are two important notions of time here: the latency, which characterises the time it takes for the instability to start, and the instability rise time, which is the time it takes for the perturbation to be multiplied by  $e^1 \approx 2.7$ . A first mitigation method here is

thus to optimise the parameters such that these two times are larger than the time spent in the accelerator.

### 3 Chromaticity

Chromaticity, longitudinal and transverse dampers, and Landau (or BNS) damping are the usually mentioned mitigation methods, but there are many more knobs than that, and in particular, it is important to understand what they do and when they should be used. It is, for instance, interesting to observe that the usual damping mechanisms for single-mode instabilities (such as active damping from dampers and tune spread for Landau damping) can be detrimental when several modes are involved [22].

For coasting beams, chromaticity helps to increase the tune spread for Landau damping [23]. For this, the sign of chromaticity should be carefully chosen, to add to the contribution through the slippage factor and not to subtract, and this requires a sign of the chromaticity equal to the sign of the slippage factor, such that the chromatic frequency is positive: this is why the sign of the chromaticity is changed when transition energy is crossed in some machines. The case when modes couple is currently under investigations [10–13].

For bunched beams, two regimes exist: well below the mode coupling threshold where all the modes can be treated independently (sometimes called the low-intensity case) and above the mode coupling threshold (sometimes called the high-intensity case). For the low-intensity case, chromaticity is the key ingredient to explain the head–tail instability mechanism and whatever the chromaticity (different from zero in the case of a single bunch without multi-turn wakes), instabilities exist: chromaticity does not provide Landau damping, and it just changes the mode which will be more critically excited. The most critical mode is the (azimuthal) mode 0, and this is why we usually try and avoid it by choosing, here again, a positive chromatic frequency. Keeping a small chromaticity is usually the best method as it minimises the excitation of the (higher-order) head–tail modes, but this requires a good control of the chromaticity to avoid the chromatic frequency to become negative. In the case of transverse coupled-bunch instabilities, an instability also exists for zero chromaticity, which usually requires the use of a transverse damper. By increasing the chromaticity, higher-order intra-bunch modes are excited, which are usually more difficult to drive, leading to less critical instabilities. This is in particular what is done in the CERN LHC operating with quite a high value of chromaticity  $Q'$  ( $\sim 15$  units). At high intensity, the mode coupling threshold can be increased by increasing the (positive) chromatic frequency, while it can be decreased with negative chromatic frequency (similarly to the coasting-beam case discussed above). Note also that a nonzero chromaticity also excites head–tail modes at a much lower intensity, but the instability is then of a different kind and can be stabilised by other means [24].

Second-order chromaticity provides (longitudinal-to-transverse) Landau damping, which is discussed later in this paper.

### 4 Optics manipulations

In the transverse plane, the effect of the impedance is weighted by the (local) betatron function, which explains, for instance, why it is so important to minimise the impedance in the final triplet of a collider where the betatron function is significantly increased. A first way then to reduce the effect of a transverse impedance is to reduce the (local) betatron function. Collimators are special devices close to the beam with a usually bad electrical

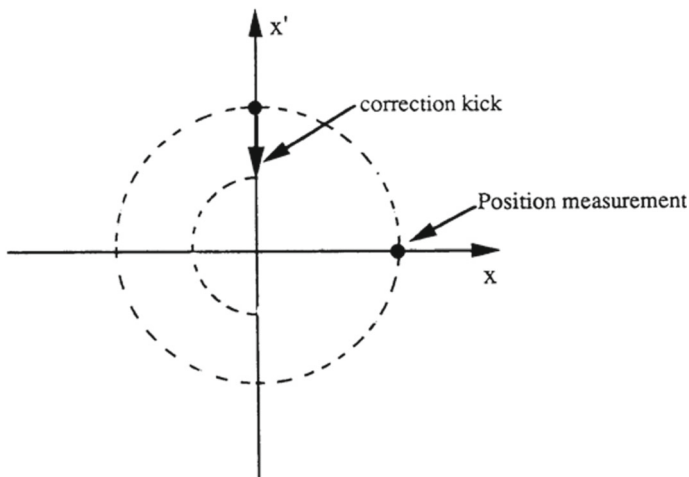
conductivity, leading to a significant impedance. In this case, it might be good to increase the gap (increasing the betatron function to keep the same number of rms betatron beam sizes) as, for instance, the classical resistive-wall impedance goes with  $b^{-3}$ , where  $b$  is the beam pipe radius.

Linear coupling between the transverse planes is also a very efficient mitigation method if only one of the transverse planes is unstable, profiting from the better stability of the other plane (either due to longer instability rise times or more Landau damping) [25]. It has been used to stabilise the LHC beam in the CERN PS for  $\sim 15$  years, and it is sometimes used as well as in the CERN Proton Synchrotron Booster (PSB). Linear coupling has been used also in other machines [26], for both low-intensity and high-intensity regimes, i.e. in both head–tail and mode-coupling regimes. However, linear coupling needs to be optimised as above a certain value it can become detrimental. Furthermore, in the case where the two transverse planes are similar, linear coupling should be minimised as it leads to more stringent requirements than for the uncoupled planes [7, 25, 27].

As previously discussed already, the synchrotron oscillation has a beneficial effect on the coherent instabilities by exchanging the roles of the head and of the tail, perturbing the propagation of a wave along the bunch. This leads to the longitudinal and transverse mode coupling instabilities, for which, in the simplified case of a single bunch interacting with a broadband resonator impedance in the long-bunch regime, the intensity thresholds scale with the absolute value of the slippage factor [28]. Increasing the latter, i.e. the distance to transition to have faster synchrotron oscillations, helps and this can be done by modifying the momentum compaction factor by changing the optics: as a first estimate obtained for a lattice made of FODO cells, the  $\gamma$ -transition is approximately given by the horizontal tune. This method has been used very successfully in the CERN SPS for which the intensity threshold of the fast vertical instability at injection could be increased by a factor  $\sim 2.5$  as predicted by the simple scaling [28]. As transverse mode coupling instabilities can also be observed with beam–beam [29], electron cloud [30], or space charge [31], a similar mitigation method can be anticipated for these different cases (depending on the bunch length regime). For machines where transition crossing cannot be avoided, such as, for instance, in the CERN PS which was the first synchrotron where transition had to be crossed (which happened on November 24, 1959), a  $\gamma$ -transition jump is the only (known) method to overcome all the intensity limitations. Finally, using some nonlinear magnetic elements (such as octupoles), a spread in the incoherent betatron frequency can be introduced, leading to the Landau damping mechanism, which is treated separately in Sect. 8. More details can be found in [32, 33].

## 5 RF manipulations

Depending on the case, it can be beneficial (for the longitudinal or transverse plane) to increase or decrease the bunch length. Considering, for instance, the case of the TMCI from a broadband resonator impedance, in the long-bunch regime it is better to increase the bunch length [28], but in the short-bunch regime it is better to reduce it [34]. In fact, as can be seen in [28] for the TMCI in the long-bunch regime, what needs to be increased is the longitudinal emittance as the intensity threshold is proportional to it, while for the longitudinal plane it is more efficient to increase the momentum spread with respect to the bunch length. The different methods to generate a controlled longitudinal blow-up (with the time constraints) are therefore very important [35]. The RF voltage (and the associated bunch distribution in the RF bucket) has also an important impact on Landau damping (as discussed in Sect. 8).



**Fig. 1** Schematic picture (in the horizontal phase space) of the action of a conventional (resistive) transverse damper, which damps the centre-of-charge motion of the beam. The position of the centre of charge is measured by a pick-up, and a correction kick is applied by a kicker with a betatron phase advance with respect to the pick-up of 90 degrees

## 6 Dampers and feedbacks

Dampers and feedbacks are essential equipment in many accelerators, and they are working very well. For instance, as mentioned already previously, in the CERN PS machine a total of 35 longitudinal feedback loops are needed to produce the LHC-type beams [15]. In the transverse plane, a resistive transverse damper (see Fig. 1) is also often needed in particle accelerators operating with many bunches and it is usually very efficient as it can considerably reduce the necessary amount of nonlinearities needed to reach beam stability through Landau damping. In the CERN LHC, for instance, the required current in the Landau octupoles is predicted to be reduced by an order of magnitude for zero chromaticity. (For the beam and machine parameters used during the last year of Run 2, in 2018, this corresponded to  $\sim 2000$  A without damper and  $\sim 200$  A with damper, knowing that the maximum current available in the Landau octupoles is  $\sim 550$  A.) However, a resistive transverse damper also destabilises the single-bunch motion below the TMCI intensity threshold (for zero chromaticity), introducing a new kind of instability, which has been called ITSR instability (for imaginary tune split and repulsion) [6]. Therefore, realistic dampers and feedbacks should be modelled in our analytical estimates and simulation codes and careful studies should be performed as they can be beneficial or detrimental, depending if they are resistive or reactive, depending on the bandwidth, the noise, etc. [6].

## 7 BNS damping

Many years have passed since the invention of the BNS (for Balakin, Novokhatski and Smirnov) damping, but it still attracts wide attention of accelerator physicists to implement this method in classical accelerators and future high gradient acceleration technique [36]. The method was first published in 1978, and BNS damping was successfully tested at the SLAC linear accelerator and implemented for operation of the first linear collider SLC.



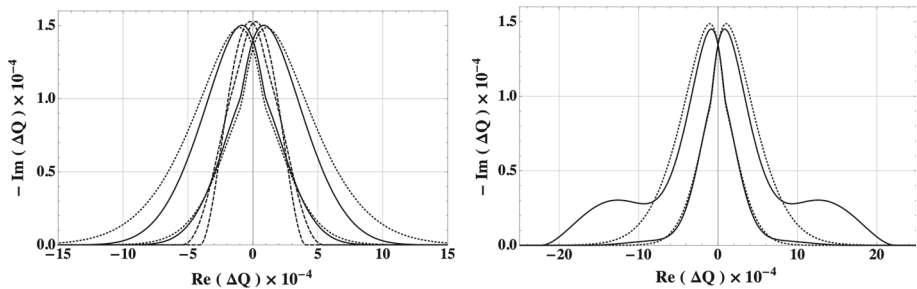
The physics of the BNS damping can be explained as follows. The particles of the head of a bunch do not experience the action of the wake field and freely oscillate in the focusing lattice at the betatron frequencies. However, this oscillation produces a periodical force for the particles of the tail of the bunch because they experience the action of the wake field. As the frequency of the force and the frequency of the free oscillations are the same, then the amplitude of oscillations of the tail particles will grow up in time because of the resonance. Considering that this action goes through the entire bunch, we get an exponential growth of the amplitude of the particle oscillations. An immediate solution for cancelling the oscillation growth is to destroy the resonance that means to give different betatron frequencies to the particle of the bunch head and particles of the bunch tail. It can be done in many different ways, but a simple solution is to utilise the fact that the betatron oscillation frequency depends by virtue of the chromaticity on the energy of the beam particles. So, if we give different energies to the particles, then we will have different betatron frequencies. However, the difference in energy along the bunch must have a definite sign. Since the transverse wake field introduces a defocusing force, we need the additional chromatic focusing to compensate the defocusing. This means that particles of the bunch tail must have a smaller energy. By accelerating the bunch behind the crest of the accelerating field, the tail particles gain less energy than the head. Therefore, the tail particles are focused more by the quadrupoles than the head. The longitudinal wake field actually helps to increase the energy spread. The tail particles lose more energy due to the action of this field. With the increase in the particle energy during the acceleration, the energy difference can be reduced. The BBU effect becomes smaller and the bunch is now moved ahead of the crest to reduce the energy spread in the beam. We can see that that BNS damping does not require any additional accelerator elements like special focusing elements. It can be easily applied to any linear accelerator, one just needs to change the phases of the klystrons along the linac.

The efficiency of the BNS damping strongly depends upon the focusing system. For higher betatron frequencies, less frequency spread is needed, and much higher intensity bunch can be accelerated without emittance growth. This is in general good for any linear accelerator to have more periods of transverse oscillations, made by the bunch particles on the accelerator length. Very important is the sign of the linear energy spread along the bunch to completely damp the instability. For the opposite sign of the energy spread, the instability growth rate decreases, but the instability cannot be fully damped. Such feature is very close to Landau damping, where betatron oscillation frequencies are not correlated with the longitudinal positions of the particles in the bunch. Usually, it is a random distribution of betatron frequencies. This is the main difference between the damping methods. Maybe it is possible to use Landau damping to decrease the instability growth; however, a comparison with BNS damping showed that Landau damping is not so effective as BNS damping. Naturally, BNS works in the multi-bunch regime as well.

## 8 Landau damping

One can determine whether a system is stable due to the presence of incoherent tune spread in a beam, a phenomenon known as Landau damping, by drawing the stability diagrams [37]. A stability diagram is a mapping between two complex planes: the space of eigenvalues of the underlying Vlasov equation, and a space which can most easily be described as the product of beam current and an effective impedance. The stability of the beam depends upon which side of the curve the point lies. The earliest use of stability diagrams was by Pease [38] for the case of longitudinal stability of unbunched beams. Several papers [39–



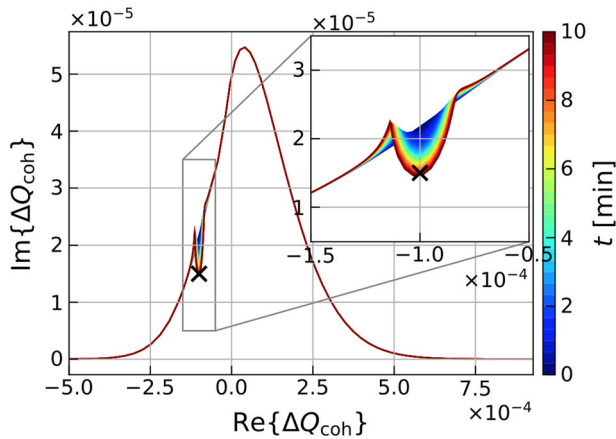


**Fig. 2** Stability diagrams (for both positive and negative detunings) for the CERN LHC at top energy (7 TeV) with maximum available octupole strength: (Left) for the second-order distribution extending up to 3.2 rms beam sizes (dashed curves), the 15th-order distribution extending up to 6 rms beam sizes (full curves), and the Gaussian distribution extending up infinity (dotted curves) distribution; (Right) for the Gaussian distribution (dotted curves) and a distribution with more populated tails than the Gaussian distribution between 3 and 6 rms beam sizes (full curves) [44]

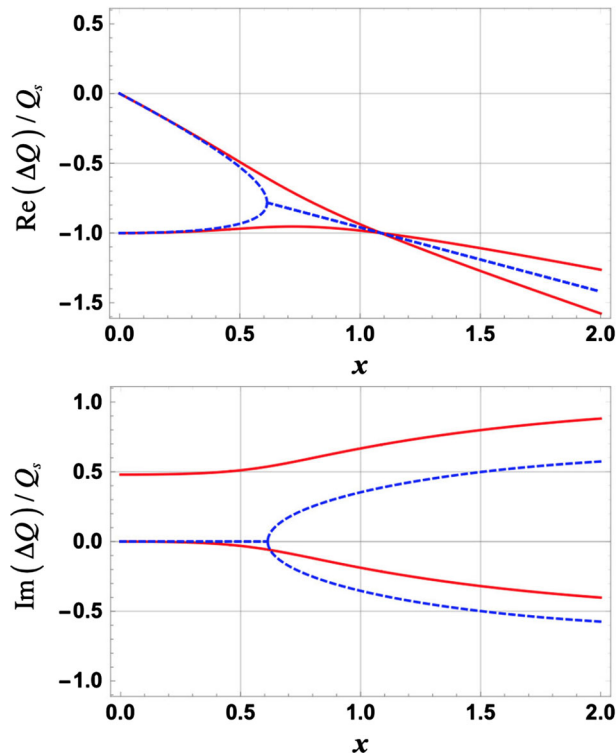
[41] expanded up on this with more examples and including the case of transverse stability of unbunched beams. Zotter [42] was the first to show longitudinal bunched beam stability diagrams, and Chin [43] introduced transverse bunched beam stability diagrams. Examples of transverse stability diagrams (in stationary conditions) are depicted in Fig. 2 to show in particular the importance of the tails of the distributions when (Landau) octupoles are used. The destabilising effect of noise, as already discussed previously, can be observed in Fig. 3, where the mechanism of loss of Landau damping is revealed.

In transverse [45], in the particular case of the beam-coupling impedance with linear (octupolar) detuning as the source of tune spread, using a Hamiltonian formalism and perturbation theory, one can go beyond the traditional stability diagram approach to obtain the general nonlinear determinant equation that leads to the modes determination [43]. The equation can be reduced to the usual stability diagram theory as a limiting case, when all the modes can be treated independently. However, when all the modes cannot be treated independently, the nonlinear determinant needs to be solved, which turns out to be a very challenging task; still, preliminary promising results were obtained in [45]. In the simplified case of the interaction between two modes only, this case can be solved relatively easily as it was done in [6], whose result was very close to the one obtained from PyHEADTAIL macroparticle tracking simulations (see Figs. 4, 5 and 6). This example nicely shows how different Landau damping can be depending on the type of instability (i.e. if only one mode is involved or more).

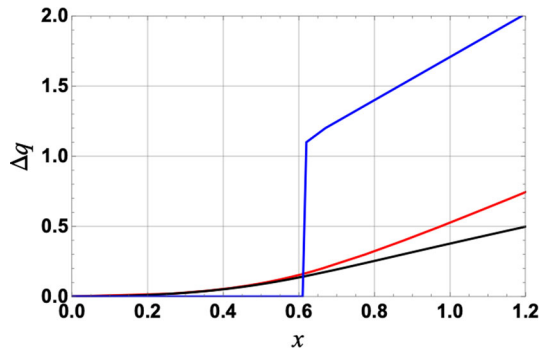
In longitudinal [46], the loss of Landau damping can limit the performance of an accelerator and lead to particle losses via undamped bunch oscillations or to single- and multi-bunch instabilities. The threshold for the loss of Landau damping (LLD) for a single bunch is usually defined by comparing the position of the coherent bunch oscillation frequency with respect to the incoherent synchrotron frequency spread (which can be increased by increasing the bunch length, going in the nonlinear part of the RF bucket). Simplified analytical criteria are often used for the scaling of the loss of Landau damping threshold with beam and machine parameters. The Sacherer stability diagram in the longitudinal plane is justified only for low-frequency impedances and in other cases should be used with caution. More advanced methods (van Kampen modes and Lebedev equation) together with particle simulations are available for accurate threshold estimations, also based on a realistic impedance model, since a constant  $\text{Im}(Z/n)$  may not give converging LLD thresholds [47]. Landau damping can be significantly increased by additional, higher harmonic RF system, but its limitations in bunch-



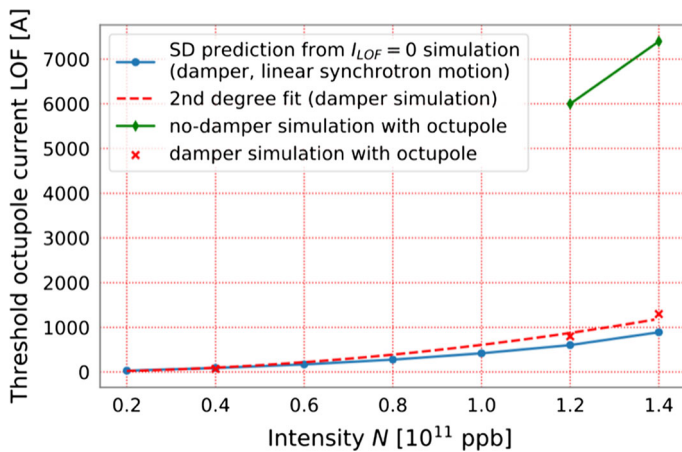
**Fig. 3** Loss of Landau damping due to noise drilling a hole in the stability diagram. This figure is courtesy of Furuseth [8]



**Fig. 4** Comparison between the TMCI instability without a resistive transverse damper (dotted blue line) and the ITSR instability in the presence of a resistive transverse damper (full red line) [6]. The parameter  $x$  is a normalised parameter proportional to the bunch intensity, and  $Q_s$  is the low-intensity small-amplitude synchrotron tune



**Fig. 5** Required tune spread (half width at the bottom of the assumed externally given elliptical tune distribution) normalised by the synchrotron tune  $Q_s$  to reach bunch stability vs. the normalised bunch intensity  $x$  in the presence of a transverse damper for the case of Fig. 4: (black line) using the one-mode approach, leading to the usual stability diagram; (red line) with the two-mode approach. The blue line corresponds to the case without a transverse damper (but considering the mode coupling between modes 0 and  $-1$ )



**Fig. 6** Case of Fig. 5 analysed in detail through PyHEADTAIL tracking simulations (with Gaussian distributions), revealing a good agreement between the two approaches: (blue line) with the usual one-mode approach stability diagram (using the simulation results from PyHEADTAIL without Landau octupoles); (dotted red line) PyHEADTAIL simulations with both Landau octupoles and a transverse damper; and (green line) PyHEADTAIL simulations with Landau octupoles but without a transverse damper. The TMCI intensity threshold without a transverse damper is at  $\sim 0.8 \times 10^{11}$  ppb. This figure is courtesy of Oeftiger [6]

lengthening mode and, for  $n > 2$ , in bunch-shortening mode should be taken into account for the choice of the beam and RF parameters.

## 9 Advanced Landau damping

Landau damping is a powerful mechanism to suppress impedance-driven coherent instabilities in circular accelerators. In the transverse planes, as seen previously, it is usually introduced by means of magnetic octupoles. However, high-brightness, low transverse emittance beams are required in future colliders and the detuning with the transverse amplitudes

from magnetic octupoles becomes significantly less effective at high energy. In this case, generating the required incoherent betatron frequency spread through detuning with the longitudinal rather than the transverse amplitudes might be preferred. Two equivalent methods have been studied [48]: an RFQ cavity and the nonlinear chromaticity.

The purpose of the RFQ for Landau damping is to generate transverse quadrupolar kicks on the beam particles with a strength that depends on their longitudinal coordinates. Every particle feels a different focusing (defocusing) force as it passes through the device and hence experiences a change in its betatron frequency depending on its longitudinal position within the bunch. The result is an incoherent betatron frequency spread which leads to Landau damping in the transverse planes. Contrary to magnetic octupoles, the frequency spread from an RFQ depends on the longitudinal amplitude spread within the bunch. Thanks to the orders of magnitude larger spread in the longitudinal compared to the transverse amplitudes of the beams in future hadron colliders, a longitudinal amplitude-dependent frequency spread can be produced very efficiently compared to magnetic octupoles. In addition, the amount of frequency spread remains unaffected by beam manipulations in the transverse planes, such as beam halo cleaning through collimation, for example. Recently, it has also been demonstrated that transverse linear coupling can strongly reduce the incoherent betatron frequency distributions generated through detuning with the transverse amplitudes [7]. This can lead to a loss of Landau damping, and it requires an accurate correction of the linear coupling in future machines. The shape and amount of frequency spread introduced through detuning with the longitudinal amplitude, on the other hand, are not affected by linear coupling. It is hence expected that there is no loss of Landau damping in that case. The other effect which has been recently investigated in detail is the transverse noise that can locally significantly reduce the stability diagrams generated by magnetic octupoles and hence lead to a loss of Landau damping [8]. It is believed that this effect will not be present with RFQs or nonlinear chromaticity thanks to the separation of the longitudinal amplitude space and the transverse planes where the frequency spread is created.

The existing Vlasov theory on transverse dipole modes has been extended to include the effects of nonlinear chromaticity up to arbitrary orders. This new formalism made it possible to confirm the hypothesis that nonlinear chromaticity and RFQs have two effects on the beam dynamics of transverse coherent modes: they lead first to a change of effective impedance and second they introduce Landau damping thanks to the incoherent betatron frequency spread with longitudinal amplitude. The two mechanisms have been identified and studied separately using analytical formulae. In addition, the theory has been successfully benchmarked up to second-order chromaticity for an airbag model and a Gaussian beam. In the first case, there is no Landau damping due to the missing frequency spread from detuning with longitudinal amplitude. Analytical results have been validated both with a tracking model and a circulant matrix solver which revealed an outstanding agreement. For the Gaussian beam, it has been demonstrated that, given the assumption of a strongly peaked impedance, analytical predictions from stability diagram theory are in excellent agreement with tracking simulations. This proves that detuning with longitudinal amplitude indeed provides Landau damping. The results are also in accordance with experiments and simulations that were carried out on the RFQ and on nonlinear chromaticity in the CERN LHC and provide the foundation for the interpretation of these results. The study also demonstrates, however, that beam stabilisation with RFQs or nonlinear chromaticity is not easily evaluated analytically for arbitrary impedances. Macroparticle tracking simulations are instead the most accurate way to study these effects.

The Lorentz forces of a low energy, magnetically stabilised electron beam, or electron lens can also introduce a transverse nonlinear focusing sufficient for Landau damping of trans-

verse beam instabilities in accelerators [49, 50]. Unlike other nonlinear elements, the electron lens can provide the frequency spread mainly at the desirable range of particle amplitudes, thus permitting to avoid the beam lifetime degradation. Suppression of the collective instabilities can be obtained via the stabilising effect of Landau damping when the spectrum of incoherent frequencies overlaps the frequencies of the unstable collective modes, thus allowing absorption of the collective energy by the resonant particles. But the direct space charge forces in high intensity beam shift the incoherent frequencies away from the frequency of the zero head–tail mode leaving it exposed to instability. A similar effect happens with the  $\sigma$ -mode in colliding beams. To restore Landau damping, the octupole magnets are commonly used. Damping by octupoles has several drawbacks: first of all, the corresponding frequency spread scales with beam energy increase as  $1/E^2$  due to increasing rigidity and smaller beam size; hence, one needs to increase the strength of these magnets accordingly. Secondly, strong octupoles significantly reduce the machine's dynamic aperture. Another method involves beam-based feedback system, which suppresses coherent motion of the beam or bunch centroid. Though generally effective, such feedback systems, which act only on the modes with nonzero dipole moment, leave the multitude of other head–tail modes unsuppressed. Electron lenses were shown to provide effective Landau damping mechanism free of all the above listed drawbacks of other methods.

## 10 Future challenges for MCBI

In this section, we will review the MCBI challenges for some future projects and studies, such as FAIR at GSI, the low emittance rings, LIU and HL-LHC at CERN, FCC-hh and linear colliders, FCC-ee, CEPC and EIC, as discussed at the MCBI 2019 workshop [5], and the muon collider [20].

### 10.1 FAIR

The dominating intensity limitation for heavy-ion beams in synchrotrons is the interaction with the residual gas and thereby generated charge state changes [51]. Due to desorption processes at high beam intensities, the static residual gas pressure becomes the so-called dynamics vacuum. Ionisation in the dynamic vacuum is the dominating beam loss mechanism which appears much below the space charge limit. Ionisation loss drives pressure bumps which itself accelerates the ionisation process, leading to a dynamic vacuum instability. In the SIS100 synchrotron, all charge exchange losses are controlled by a cryocatcher. In the present understanding, the ion intensities are not limited by coherent instabilities in FAIR (the Facility for Antiproton and Ion Research), but the 21st Machine Advisory Committee from May 2019 recommended to include a transverse feedback system into the start version of SIS100.

The SIS18 synchrotron has the world intensity record for low charge state heavy ions (with  $3.2 \times 10^{10}$  U28<sup>+</sup> accelerated and extracted successfully). There is a further upgrade program, and a factor of 6 in intensity is missing, but so far SIS18 has been operated without specific instability mitigation measures.

For SIS100 heavy-ion cycles, the mitigations in place are the following for the transverse stability: the single-bunch and coupled-bunch head–tail instabilities are cured by octupoles (for which the interplay with space charge has been studied in detail) with the help of a transverse damper; double RF bucket as a mitigation at the injection; possibly, stabilising transverse emittance blow-up; TMCI is suppressed by space charge; electron cloud is not an

issue due to the bunch gaps; coasting beam (barrier or weak bunching): chromaticity control with the help of a transverse damper (due to the strong kicker impedance) and possibly octupoles. In the longitudinal plane, the bunches are stable.

For SIS100 proton cycles, the mitigations in place are the following for the transverse stability: the head–tail instability is cured with high chromaticity at accumulation, chromaticity ramp at transition, with the help from the octupoles and additional flexibility with a transverse damper; the BBU instability at transition is cured with chromaticity ramp and octupoles. Most of the issues at transition should be cured using a  $\gamma$ -transition jump.

## 10.2 Low emittance rings

The low emittance lattices, used to increase the brilliance of the synchrotron light sources, have a direct impact on collective effects by the reduction of the aperture of the magnets and vacuum chambers [52]. This leads to an increased beam coupling impedance, which is partially compensated by reduced  $\beta$ -functions, but the impedance minimisation is essential. Modern light sources cover a wide range of parameters on which collective instabilities strongly depend: the energy and dimension (radiation damping, instability growth rate), the time structure (multiple bunches low current, few bunches high current, hybrid), and the optics manipulation (short bunch modes, anti-bends with low or negative momentum compaction factor).

Low emittance rings face single/multi-bunch instabilities in all planes with different sources and sometimes simultaneously (ion instabilities, longitudinal microwave instabilities, cavity high-order modes (HOM)-induced instabilities, TMCI, and head–tail instabilities and transverse coupled-bunch instabilities). With the new lattice designs, the low emittance rings are expected to be more difficult to operate and efficient mitigation measures need to be anticipated. A number of mitigations measures are used such as high chromaticity, bunch-by-bunch feedback, HOM-damped cavities, and harmonic cavity, but the most effective mitigation method is the impedance minimisation [53].

## 10.3 LIU and HL-LHC at CERN

The High Luminosity LHC (HL-LHC) upgrade aims at 3000 (4000) fb<sup>-1</sup> total integrated luminosity over the HL-LHC run (2026–2037), based on operation at levelled luminosity of 5 (7.5) 10<sup>34</sup> cm<sup>-2</sup>s<sup>-1</sup> by lowering  $\beta^*$ , while the LHC Injectors Upgrade (LIU) aimed at matching the beam parameters at LHC injection with HL-LHC target and needed to deploy means to overcome performance limitations in all injectors [54].

The performance limitations in the LHC injectors were the following. In the PSB injection, the performance limitations were the brightness limited by the efficiency of multi-turn injection process and space charge effects. In the PS and SPS injections, the brightness was limited by space charge ( $-\Delta Q < 0.31$  in the PS and 0.21 in the SPS). In the PS cycle, the bunch intensity was limited by the longitudinal coupled-bunch dipolar instability. In the SPS cycle, the bunch intensity was also limited by the longitudinal coupled-bunch instability but by the RF power as well.

For the upgrade of the LHC injector proton chain, LIU included first the replacement of Linac2 (which accelerates protons to 50 MeV) with Linac4 (providing 160 MeV H<sup>+</sup> ions). In the PSB, a new 160 MeV H<sup>-</sup> charge exchange injection was implemented with acceleration to 2 GeV (instead of the previous 1.4 GeV) with a new power supply and RF system. In the PS, a new 2 GeV injection (instead of 1.4 GeV) was implemented as well as a broadband longitudinal feedback. Finally, in the SPS, the 200 MHz RF system was upgraded, a low

$\gamma$ -transition optics was implemented, impedance reduction and electron cloud mitigation were made, and a new beam dump and protection devices were installed.

In the LHC, transverse beam instabilities have been observed with different types of beams and at different stages of the LHC cycle. The sources are mainly the transverse impedance (dominated by collimators, especially when closed at top energy) through loss of Landau damping due to beam–beam, linear coupling, cut tails, noise induced modifications of distribution, and electron cloud (with 25 ns bunch-spacing beams essentially). They were controlled through “extreme” machine settings, e.g. at 6.5 TeV,  $Q' = +15$ –20, octupole strength and damper gain close to maximum. Some margin needs to be gained with stabilisation knobs for operation with HL-LHC beam parameters (double intensity, double brightness), which requires an impedance reduction (with new low-impedance collimators), electron cloud understanding, and partial mitigation.

As concerns the longitudinal aspects, persistent oscillations, and even instabilities, from injection errors have been observed. A controlled longitudinal emittance blow-up is required during the ramp (with target bunch length of 1.1–1.2 ns) to avoid onset of instabilities, and some instabilities have been observed at flat top when the bunch length has decreased below 0.9 ns.

To conclude, mitigation of beam instabilities is key to goal performance in the LHC injectors, mainly relying on active feedback systems in the PSB and PS, while the SPS relies on impedance reduction, electron cloud suppression, longitudinal emittance blow-up, enhanced Landau damping, and optics change.

The preservation of the beam stability in the LHC will be done by avoiding losses of Landau damping, optimising the operational scenarios, impedance reduction, electron cloud build-up and instability scaling, and low electron cloud filling pattern.

#### 10.4 Linear colliders and FCC-hh

Collective effects and instabilities play a decisive role in the overall design. Some cases where collective instabilities are mitigated by design choices are discussed as they are critical for the projects and can have an important impact on the project cost and power consumption [55].

For linear colliders, a high gradient requires a small iris aperture radius but the beam is then less stable. The main limit is the single-bunch and multi-bunch BBU instability, which can be stabilised by BNS damping. For luminosity, one needs to find the limit that is just stable. One should try also to reduce the impedance with novel designs as, for instance, the superconducting technology allows much larger apertures (due to limited loss) but lower gradients. Do dielectric materials allow larger apertures? One could also imagine feedback or feedforward corrections along the train but a very high bandwidth would be needed. Can one imagine any feedback of feedforward within a bunch? RFQs can produce BNS damping but one needs to vary the field a lot over the bunch and the timing jitter will give transverse kicks. Finally, stronger quadrupoles and smaller  $\beta$ -function would help, but one needs solutions for the magnets and the alignment/stability.

The FCC (Future Circular Collider) is a proposal for a project at CERN with several options: FCC-hh (which would be a  $p^+p^+$  collider with 100 TeV centre-of-mass (c.m.) energy, 20  $\text{ab}^{-1}$  integrated luminosity per experiment and an ion option), FCC-ee (which would be an  $e^+e^-$  first stage, which seems like the quite probable first step), FCC-eH (which would be an additional option), and HE-LHC (which would be an LHC with high field magnets).

The impedance at injection is coming mainly from the beam screen, which is the key ingredient of the magnet cost. Therefore, the highest practical injection energy should be



used and the design should be optimised. The resistive impedance should be reduced by copper coating, and one should then choose the minimum aperture with stable beam, reduce the geometric impedance by shielding the pumping holes, and reduce electron cloud by ante-chamber and surface treatment. At top energy, the impedance comes mainly from the collimators, whose aperture and material should therefore be optimised. Curing the multi-bunch rigid bunch mode with octupoles would spoil the dynamic aperture and at top energy, and it would require many octupoles. The idea is to cure it with a damper. The HOMs should then be stabilised with octupoles or using electron lenses, RFQs or an intrabunch damper.

As concerns the situation during collisions, depending on the polarity of the octupoles, they add to or subtract from beam–beam effects, leading to enhanced stability but reduced dynamic aperture, or reduced stability and larger dynamic aperture. The solution is to collide and squeeze.

Electron cloud effects can lead to an important heat source and instabilities. Three countermeasures would be used: beam screen geometry, surface treatment, and beam parameters optimisation. Already the direct photo-production of electrons can render the beam unstable, and the beam screen design should minimise the reflection of photons into the main chamber. The beam stability is ensured by coating or laser treatment for the nominal beam with 25 ns bunch spacing, but there is little or no margin for 5 and 12.5 ns. This has thus a significant impact on the parameters choice, and it would be important to find a better instability mitigation method.

In summary, the collective instabilities are parameter drivers for FCC-hh and linear colliders. They are in part mitigated by technical means (feedback, electron cloud coatings, low impedance design, damping). In part, they are mitigated by parameter choices: bunch charge, length, spacing, and size at the interaction point (IP) for CLIC; bunch spacing and magnet aperture for FCC-hh.

## 10.5 FCC-ee

The FCC-ee is a particle factory with an unprecedented luminosity [56]. The main ingredients are two separate rings allowing to collide many bunches, a crab waist collision concept (with low emittance, low  $\beta$ , high beam–beam parameter), and a longer perimeter allowing to store higher intensity beams with the same synchrotron radiation losses. The FCC-ee transverse emittances are comparable with emittances of modern diffraction limited synchrotron light sources.

The round cross section has been chosen in order to avoid the betatron tune shift with multi-bunch beam current due to the quadrupolar resistive-wall wake fields. Additional antechambers are foreseen for pumping purposes and installation of synchrotron radiation absorbers. Best design solutions of vacuum chamber elements used in modern synchrotron sources and particle factories are considered for implementation in FCC-ee.

A coating is required to suppress the electron cloud (beam-induced multipacting) in the positron ring and/or for pumping purposes in both rings: NEG, TiN, AC. For thin resistive coatings, the real part of the impedance does not depend on both the coating thickness and coating conductivity, and the imaginary part has an additional term depending on the coating thickness, while the dependence on the conductivity is very weak.

Several instability mechanisms have been studied, and it was found in particular that a robust feedback system will be needed to damp the multi-bunch instability whose most critical rise time is predicted to be  $\sim 7$  revolution turns. A distributed feedback system has been proposed, but a feedforward system (producing a damping rate even faster than 1 revolution turn) could also be envisaged.

The electron cloud heat load and instability have been studied in detail, and an extensive measurement campaign was performed at CERN to characterise TiZrV films with thickness below 250 nm.

Ion instabilities have been also studied, and the partial pressure thresholds for residual gas species are probably tighter than vacuum specifications allow. Some mitigation methods are required such as the length of the bunch train (efficient only for heavier species in the straight sections, in the arcs one would have to go to less than 10–20 bunches to observed an effect) and bunch spacing (a larger bunch spacing could increase thresholds in arcs and straight sections. Test for CO<sub>2</sub> in the arcs with 7.5 ns bunch spacing shows significant improvement pressure threshold increased at least by a factor of 20), and feedback (generally efficient at suppressing coupled-bunch instabilities. A damping time of  $\sim 10$  turns would be needed to realistically achievable pressure thresholds. However, emittance growth may still occur).

The coherent beam–beam instability with a crossing angle has also been analysed in detail. Finally, the interplay between different effects/instabilities can be important and should be studied in detail.

## 10.6 CEPC

The circular electron positron collider (CEPC) is a double-ring collider with 2 IPs [57]. The Z mode shows the most critical restriction on the beam instabilities. The collective beam instabilities are potential restrictions in CEPC to achieve high luminosity performance. Different strategies used to mitigate these effects are considered. The single-bunch instability is dominated by the microwave instability, which can induce longitudinal phase space distortions and couple with the beam–beam interaction. The beam parameters and impedance need to be further optimised to get larger stable region in tune. The coupled-bunch instabilities need to be damped by efficient feedback systems. Finally, the two stream instabilities need multi-train filling pattern with certain bunch spacing, along with feedback and vacuum conditioning.

## 10.7 EIC

An electron–ion collider (EIC) is identified as the next exploring machine for probing the quantum chromodynamics (QCD) structure and the dynamics of nuclear matter [58], with a high c.m. energy (30–140 GeV), a high luminosity ( $10^{33} \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ), a wide range of ion species, and a high polarisation ( $\sim 70\%$  for the electron and light ion beams). This machine could have been built either at BNL (eRHIC) or at Jefferson Lab (JLEIC): the US Department of Energy announced on 09/01/2020 that it has chosen BNL as the site for this major new facility called the EIC.

The collective effects have been looked at for the electron ring, the ion ring and the electron cooler. The Fast Beam-Ion Instability (FBII) in the JLEIC e-ring was predicted to be between 10 and 100 times faster (at 3 or 5 GeV) than the PEP-II case (similar to the 10 GeV case). Comprehensive numerical modelling of FBII and its mitigation were proposed to be performed, and the envisaged possible mitigation methods were the use of chromaticity to damp the FBII, the use of multiple bunch trains to reduce the growth amplitude, and the natural Landau damping from beam–beam tune-shift spread.

As concerns the collective instabilities in e-RHIC, in the e-ring the longitudinal and transverse single-bunch instabilities are Landau damped, the longitudinal coupled-bunch instability is mitigated by damper and the transverse coupled-bunch instability sets the threshold current (Landau damping from beam–beam tune spread included). As concerns the ion

effects, a significant fraction of ions survive the abort gap and can allow the tail of the bunch train to drive the head of the bunch train. Landau damping will be provided by beam–beam tune spread. In the ion ring, a coating of the vacuum chamber with copper is planned to reduce the heat load on the cryosystem. Furthermore, the secondary emission yield should be reduced with amorphous carbon and a backup plan involving copper-coated inserts is also being worked out.

In summary, some preliminary assessments of instabilities in JLEIC and e-RHIC have been performed and some vulnerable areas for instability identified. The MCBI in an EIC are a damping wiggler, split dipole, chromaticity, octupole, dampers (requiring state-of-the-art fast bunch-by-bunch feedback systems), Landau cavity, beam–beam, gap in the bunch train, and clearing electrode. More detailed analysis and simulations will be performed, especially when multiple mechanisms are involved.

## 10.8 Muon collider

Muon colliders have a great potential for high-energy physics. They can offer collisions of point-like particles at very high energies, since muons can be accelerated in a ring without limitation from synchrotron radiation. However, the need for high luminosity faces technical challenges which arise from the short muon lifetime at rest and the difficulty of producing large numbers of muons in bunches with small emittance. Addressing these challenges requires the development of innovative concepts and demanding technologies. The Update of the European Strategy for Particle Physics (ESPPU) recommended to integrate an international design study for a muon collider in the European Roadmap for accelerator R&D. In response to this, the Laboratory Directors Group (LDG), which represents the large European Particle Physics Laboratories, has initiated an International Muon Collider Collaboration (IMCC) to study the concept [20].

In the past, a muon collider concept was developed by the MAP (US Muon Accelerator Program) collaboration [59], which conducted a focused program on the technology R&D to evaluate its feasibility. In addition, essential measurements have been performed by the MICE collaboration [60]. This MAP scheme is based on the use of a proton beam to generate the muons and is the baseline for the collider concept being developed by the new international collaboration. An alternative approach called LEMMA, which stands for Low EMittance Muon Accelerator, uses positrons to produce muons, and it has been explored at INFN [61]. However, this option cannot be considered (for the moment) as a possible scheme for a muon collider as not enough muons can be produced and/or the transverse emittance is not low enough and new ideas are needed to overcome these limitations.

A first Muon Community Meeting took place on May 20–21, 2021, with nine working groups coordinated by an international group of conveners, where the key R&D challenges across the project were identified: the ones linked to beam dynamics are discussed below [62]. Even if everything needs to be done quickly with muons (due to the short lifetime), many issues can happen with high bunch charges and high impedances (which is the case here with the many RF stations all along the muon collider chain) and many aspects need to be carefully studied. The beam dynamics working group identified and prioritised 12 R&D items, grouped in 3 levels of criticality.

Five items appear in the group of criticality 1 (i.e. highest criticality). The first item is a *new beam dynamics regime during acceleration*, which is important because the longitudinal and transverse emittances need to be preserved to reach the required collider's luminosity and control the orbit. The issue is that we need to handle 2 high-charge bunches, one of  $\mu^+$  and one of  $\mu^-$ , with a lot of RF (which means a strong longitudinal focusing and a

high impedance) and we need to be fast: this is a unique regime for collective dynamics, and the consequences for beam stability and operation (e.g. phase shifting to compensate potential well distortion) need to be understood. The second item is *Opposite sign bunches—beam crossing and wakes*, which is important because both signs of muons are accelerated simultaneously in the rings. There will be 2 beam–beam collision points with wakes in the cavities, which will vary depending on where the cavities are in the ring (cavities must be distributed in several uniformly spaced stations in the ring). The impact of these collective effects should be understood. The third item is *Design of the full chain (acceleration in particular)*, which is important because right now most of the acceleration designs are conceptual, with few details available. We should start to put together detailed designs and agree on a set of baseline accelerator parameters, which is essential for refined studies (lattices for all stages, from past studies or to be developed/optimised; RF frequencies, etc.). A particular emphasis should be placed on the longitudinal dynamics since preservation of longitudinal emittance is critical, but the transverse plane should not be overlooked. The fourth item is *radiation mitigation by moving the beam/magnets in the collider*, which is important as this might be needed to reach acceptable levels of radiation, which is a fundamental aspect of the study. All the consequences for the beam dynamics need to be carefully analysed. Finally, the last but not least of this list is *collective instabilities during ionisation cooling*, which is important because such mechanism could jeopardise the generation of high brightness muon beams through ionisation cooling. The knowledge of collective instabilities that could arise from the interaction of the beam with electromagnetic wake fields propagating in matter (absorbers, gas-filled RF cavities, etc.) as well as with the pair of charges generated by ionisation is practically non-existing.

Three items appear in the group of criticality 2 (i.e. medium criticality). The first one is *FFAs as an alternative to pulsed synchrotrons*, which is important because particularly at lower energies, driving the magnets requires very rapid ramp rates. The challenges associated with this may drive us towards alternatives, in particular FFAs. For example, the vFFA is a relatively new concept with unique coupled optics and a great importance of fringe fields, no machine was constructed yet and there are no dedicated tools to study collective effects. The second is *longitudinal and transverse beam dynamics studies in the collider*, which is important because we need to operate the collider close to the isochronous condition in order to use a reasonable RF voltage, which means that there will be no help from a high synchrotron tune for beam instabilities (both longitudinal and transverse). The significance of the single-particle effects (resonances, working point,  $\beta$ -beating, etc.) vs. the short muon lifetime needs also to be assessed. Finally, the third one is *development of simulation tools*, which is important because we need to have a detailed understanding of the many challenging mechanisms and new regimes: the collective beam–matter interactions need to be studied; non-standard acceleration schemes need to be developed; tools to study collective effects for vFFA, for instance, need to be developed; and what about the study of the muon losses (we cannot collimate because muons go through everything and the decay products constitute an issue)? Etc.

Four items appear in the group of criticality 3 (i.e. lowest criticality). The first one is *Halo formation and beam losses in the Proton Driver*, which is important because the more protons (and therefore the more muons we create), the easier it is afterwards. The issue is that we need a high (few MW) beam power, with a short (1–2 ns) bunch length and in particular a low (5 Hz) repetition rate. The second is *check of all cooling studies with a second code*, which is important because cooling is the key ingredient for a muon collider, and therefore, it has to be fully understood and optimised. One should not rely on only 1 code (ICOOL, for which the most complete simulation studies were made) and use G4BL and/or G4MICE to check all

the past results (e.g. ICOOL does not do hadronic interactions). The third is *Are sextupoles needed in pulsed synchrotrons?*, which is important because in an ordinary synchrotron, it would be important to correct the chromaticity to mitigate the head–tail instabilities. Is that needed in our operating regime? It would be preferable to avoid sextupoles to maintain a high dipole packing fraction and avoid feed-down since the beam will likely have to move in the sextupoles during the ramp. Finally, the fourth item is *impedance models*, which is important because building a realistic impedance model of a machine is a necessary step to be able to evaluate the machine performance limitations, identify the main contributors in case an impedance reduction is required, and study the interaction with other mechanisms such as optics nonlinearities, transverse damper, noise, space charge, electron cloud, and beam–beam (in a collider). It requires time and resources, with many interactions with the equipment groups and here the impedance of many machines need be built. However, the impedance from RF and the resistive-wall impedance dominate the cooling and the acceleration stages, and therefore, there, it could/should be quickly done.

## 11 Conclusions

Beam instabilities and their mitigation have been studied for several decades, and many intricate phenomena have been revealed. They were very often treated separately in the past but since some time the need to study several mechanisms together appeared, to try and better explain the reality of our accelerators. With the increasing power of our computers, this becomes easier, but the need to continue and develop theories remains, to have a better understanding of the interplays between all these effects, which is the current challenge in the study of beam instabilities. The subject of beam instabilities in particle accelerators is far from being exhausted: many instability and stabilising mechanisms continue to be discovered and/or explained, and some uncharted territories remain such as, for instance, the collective instabilities during the necessary ionisation cooling for a muon collider.

Feedbacks are working very well, but they cannot, at the moment, damp all types of instabilities: BNS or Landau damping still usually needs to be used (after optimisation of all the many machine and beam parameters available), and there is still a lot to be done on Landau damping and its possible loss, both in the transverse and longitudinal plane (see for instance Refs. [7–9,47]).

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