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Overview—Intensity Limitations in Particle Accelerators

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Abstract
A brief and qualitative overview is given of the various intensity limitations that occur in particle accelerators. The aim is to make the participants aware of what is happening in this field in terms of observation, mitigation, and understanding. Such an overview cannot be rigorous nor complete. It serves as an introduction to the lectures on the different topics.

Keywords
Intensity limitations, instabilities, impedance, wakefields, beam-beam effects.

1 Introduction

1.1 Basic considerations

Many applications of accelerators require beams of high intensities [1]. High beam intensities imply large electromagnetic fields generated by the beams, by interactions within the beams, interactions with other beams, and interaction with beam surroundings. The result is a reaction back onto the fields that may lead to unstable beams. High intensities are therefore a strong source of instabilities and limitations and eventually limit the performance of accelerators [2–5]. Dedicated schools on these topics have been published [6–8].

High-intensity effects may affect the stability of single particles subjected to the generated or perturbed fields as well as the entire beam, leading to collective instabilities. Typical effects are direct (free) space charge effects, i.e., self-generated fields acting back on the beam. In a vacuum pipe, image charges are created, which act back on the beam. These space charge effects lead to coherent and incoherent tune shifts. The interactions with the environment are described by the impedance and the generated wakefields.

Another important aspect is that non-relativistic beams lead to collective effects.

1.2 Topics of this school

The limitations discussed in this school can be divided into different categories:

- incoherent single-particle and multiparticle effects;
- collective *coherent* effects and instabilities;
- collective *incoherent* effects;
- more than one beam, e.g., beam–beam effects, electron cloud, beam–gas interactions;
- practical considerations.

Related topics to be discussed are:

- diagnostics: high-intensity and high-brightness diagnostics;
- limitations in low- and high-energy beams;
- passive mitigation (e.g., Landau damping);
- active mitigation (e.g., feedback systems);
- numerical and simulation tools.

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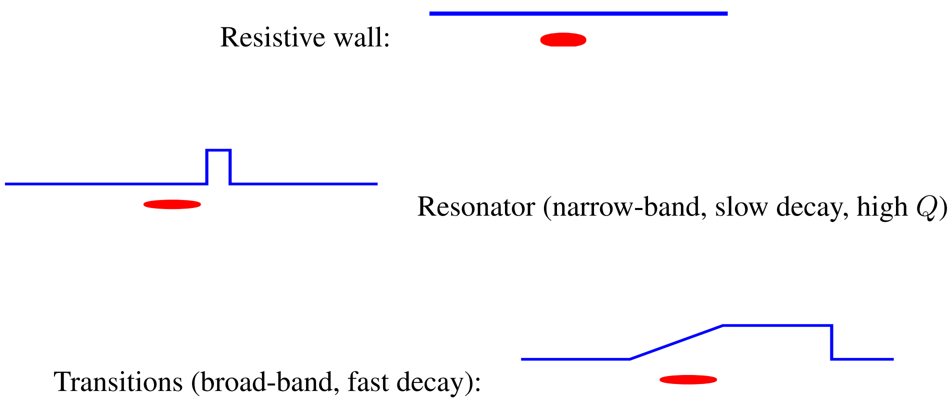

Fig. 1: Different sources of impedance

2 Impedances and wakefields

Wakefields are generated by moving charges and affect other charges in the beam [9–12]. A smooth, perfectly conducting wall will not generate wakefields. Wakefields can have different origins, the most relevant being:

- resistive wall;
- discontinuities.

Depending on the type of discontinuity, the frequency content of the wakefields can be very different: a resonator with a high Q value generates a narrow frequency band and decays over a longer time scale. A vacuum chamber with different structures induces wakefields with a rather broad frequency spectrum, also known as broad-band wakefields. The impedances are the Fourier transforms of the wakefields and are a direct measurement of the frequency content. A sketch is shown in Fig. 1.

The wakefields are stronger as the intensities increase and will eventually lead to instabilities and limit the obtainable intensities. Of large practical importance is the Panofsky–Wenzel theorem, which relates the longitudinal and transverse impedances.

2.1 Resistive wall

In the case of a resistive wall, a charge will leave a wakefield behind it. No field exists in front of the charge. Wakefields due to resistive walls can have a slow decay, affecting trailing particles; in some cases the wakefield decay is sufficiently slow to perturb the motion of the charge after a full turn in the machine (in circular accelerators), i.e., the charge is affected by its own wakefield. Such short- and long-range wakefields, therefore, cover a large frequency spectrum of the corresponding impedance.

2.2 Discontinuities

In general, abrupt changes of the wall boundaries generate rather complex wakefields and impedances. For smooth transitions, a simplified treatment can be applied. Figures 2 and 3 show the real and imaginary parts of the impedance for resonators with different Q values. The exact wakefields (and impedances) for complex structures are rather difficult to compute and numerical methods are required [13]. Beam-based measurements are a rather reliable method [14].

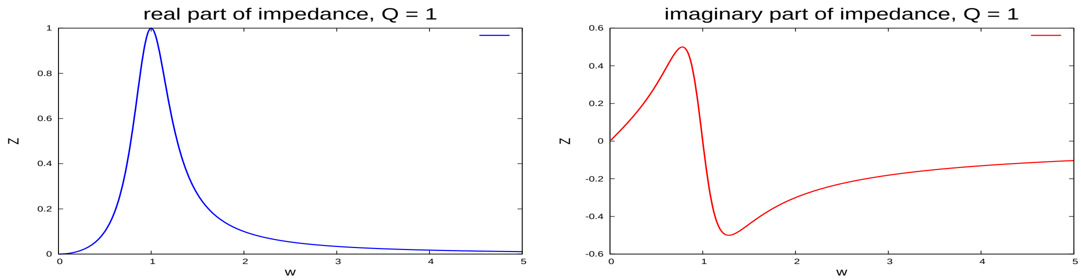

Fig. 2: Impedances: real and imaginary part of a narrow-band resonator with a rather low quality factor Q

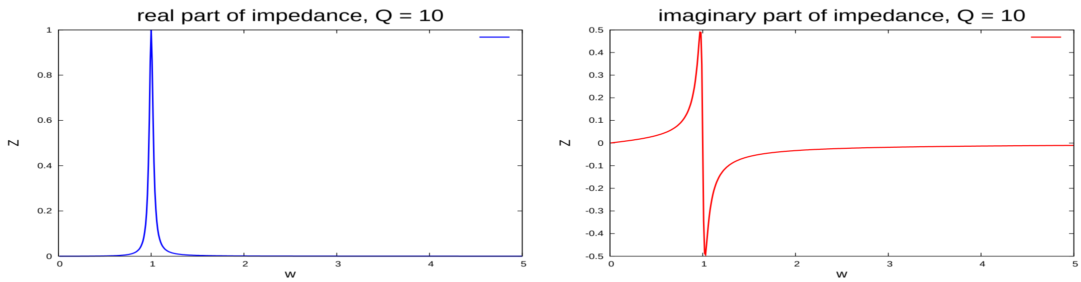

Fig. 3: Impedances: real and imaginary part of a resonator with a high quality factor Q

3 Single-particle effects

The fields generated by high-intensity beams perturb the electromagnetic fields in the surroundings of the beam and can lead to single-particle effects, such as reduced dynamic aperture, emittance growth, and particle loss.

3.1 Non-linear effects and resonances

Space charge effects are a significant source of non-linearities [15, 16]. They lead to strong detuning with amplitudes and particles are subjected to resonance effects. Above a threshold of the space charge effects, the losses may become unacceptable. Beam–beam effects in colliders are another important source of non-linear effects caused by high-intensity beams [17–21].

3.2 Touschek effects and intrabeam scattering

Touschek effects and intrabeam scattering are typical single-particle effects in high-intensity beams and lead to particle loss and emittance growth [22]. The physical origin of these effects is collisions between particles. The collision strengths are directly related to intensity and beam sizes. Collisions where the momentum transfer is large can lead to the instantaneous loss of a particle (Touschek effect). Smaller momentum transfer typically results in emittance growth. An example of the emittance growth as a function of different intensities and different beam sizes is shown in Fig. 4. The observed dependencies can be easily seen.

4 Low-energy effects and transitions

An important concern in hadron accelerators during acceleration is passing through transition [23, 24] at the transition energy. The main effects at low energy are space charge effects and the crossing of transition. The main objective is to maintain the longitudinal emittance during the transition crossing. The main effects at the transition energy are:

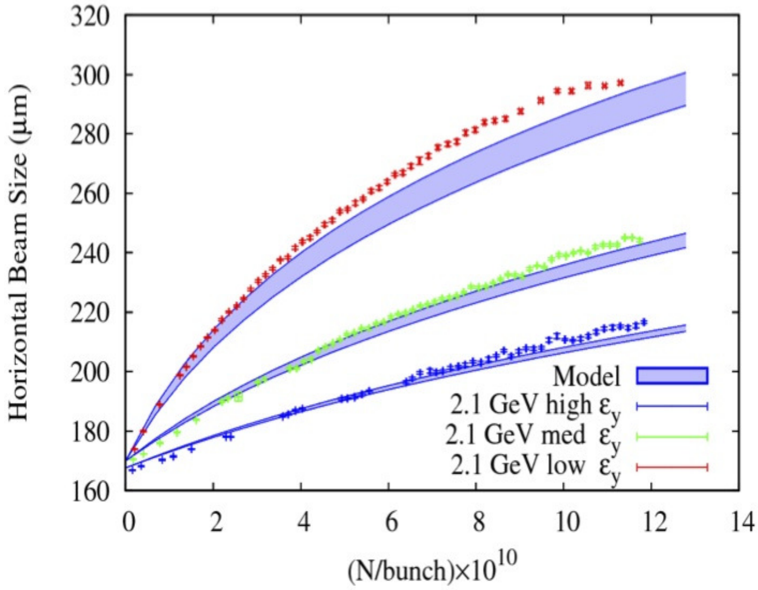

Fig. 4: Horizontal emittance growth due to intrabeam scattering for different beam parameters ([25])

– change of stable phase;
– relative momentum spread $\Delta p/p$ goes to infinity;
– bucket area gets large;
– bunch length gets short;
– Synchrotron frequency goes to zero.

These consequences are not negligible when high-intensity beams pass through transition.

A resistive impedance can cause a microwave instability near transition crossing. If the transition is not crossed fast enough, other slowly growing instabilities may be excited.

5 Linear accelerators

5.1 Space charge in linacs

Particles, in particular hadrons in linacs, are often non-relativistic and high intensities lead to a very significant space charge [15]. An important consequence is emittance growth along the line.

5.2 Energy spread in linacs

Wakefields generated by a charge in a linac produce longitudinal forces on the particles. This leads to an energy change. Not all particles lose the same energy; this uneven energy loss results in an energy spread. In linear colliders, this can become a problem for final focusing.

5.3 Parasitic heating

By interacting with the longitudinal impedance, the charged particles lose energy. This parasitic loss leads to a heating of the vacuum chamber. A large fraction is lost in the presence of sharp discontinuities, e.g., cavities. Trapped wakefields are often the source of instabilities [26].

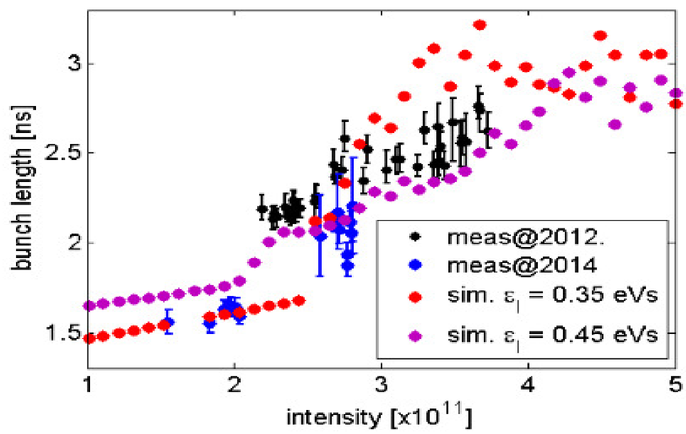

Fig. 5: Bunch lengthening observed in the SPS

5.4 Instabilities in linacs

As a typical example of an instability in linacs, we can mention the beam break-up. A wakefield generated by the head particles of a bunch can cause deflections of the tail; for large wakefields, i.e., high intensities, this can lead to an instability.

6 Longitudinal effects—circular accelerators

6.1 Longitudinal space charge forces

Longitudinal space charge forces can be very large at low energies and introduce longitudinal defocusing below the transition energy. This can limit the acceptance and a careful adjustment of the RF voltage may be necessary.

6.2 Longitudinal effects in coasting beams

6.2.1 Longitudinal microwave instability

In unbunched beams, very short-range wakefields can lead to a longitudinal density modulation. This is often accompanied by high-frequency signals and is therefore termed microwave instability. A criterion linking machine impedance with the maximum intensity is given by the Keil–Schnell criterion [27].

6.3 Longitudinal effects in bunched beams

6.3.1 Longitudinal microwave instability

Increased bunch intensities can lead to longitudinal instabilities of single bunches. A key criterion to characterize this instability is the peak intensity in the bunches [28]. In beams with bunches, we must distinguish between short- and long-range wakefields, or, equivalently, with high- and low-frequency components of the impedance. Typical effects are, e.g., energy loss and bunch lengthening. The bunch lengthening observed in the SPS is shown as an example in Fig. 5. On increasing the intensity, the measured bunch length is increased.

6.3.2 Longitudinal instability

Longitudinal instabilities may be single or coupled bunch effects [2, 29]. Possible different single bunch modes from a simulation are shown in Fig. 6. An observation [30] of the beam profile using a wall

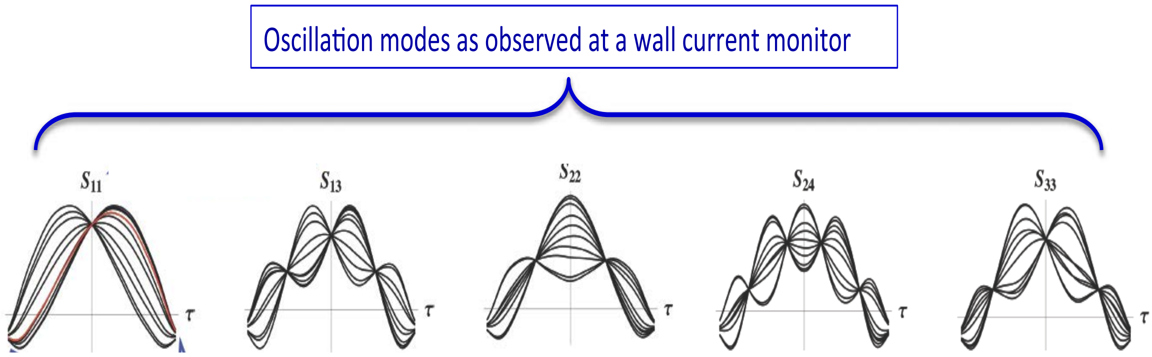

Fig. 6: Longitudinal oscillation modes, simulated. Horizontal axis time τ

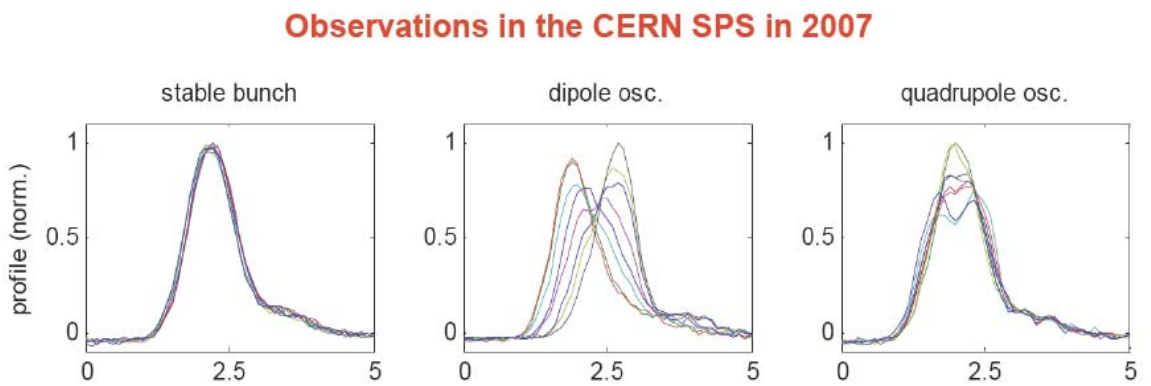

Fig. 7: Profile of longitudinal oscillation modes, observed in the SPS

current monitor in the SPS is shown in Fig. 7, which shows very clearly the different modes of stable beams and the basic modes of oscillation.

A large number of bunches can result in a large number of oscillation modes. For quantitative treatment, the bunches are usually considered as rigid objects [29].

6.3.3 Robinson instability

A longitudinal instability that can occur in circular accelerators is the Robinson instability. The fundamental frequency of cavities is tuned to values of the revolution frequency ω_0 multiplied by the harmonic number. The cavities are a source of impedance; for a value of slightly above or below ω_0 (depending on whether one works above or below the transition), the motion is stable or unstable. Since the quality factor of a cavity is usually very large, fine tuning is required to avoid this instability. The Robinson instability is often considered one of the most fundamental forms of instability.

6.3.4 Potential well distortion

Impedances at high frequencies, i.e., corresponding to short-range wakefields, have an effect on longitudinal focusing. This change in longitudinal focusing is usually called potential-well distortion. It has a strong impact on the charge distribution within a bunch.

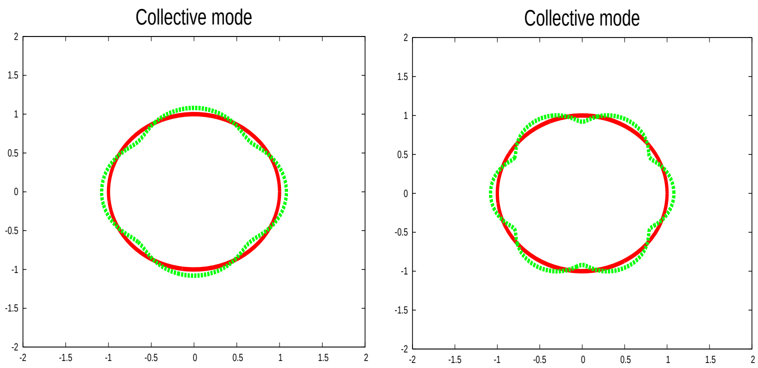

Fig. 8: Transverse collective modes in unbunched beams

7 Transverse effects—circular accelerators

7.1 Transverse space charge forces

Direct space charge effects are the result of the interaction of particles within a beam. Transverse space charge forces are the dominant effect in low-energy hadron machines. Space charge forces are responsible for both coherent and incoherent effects and introduce incoherent and coherent tune shifts. The shifts are always defocusing. By nature, the effects are strongly non-linear and excite resonances or losses driven by different mechanisms. In addition, one must expect an interplay between the space charge effects and machine non-linearities. This makes it difficult to predict the consequences.

7.2 Transverse effects in coasting beams

7.2.1 Transverse microwave instability

Unbunched beams can execute collective modes with different mode indices, depending on the pattern. Examples of two different modes are shown in Fig. 8. One has to distinguish between *fast waves* and *slow waves*, related to orbital harmonics. The beams exhibit a different behaviour concerning possible instabilities; above the intensity threshold they can become unstable. At a fixed observation point, the beams oscillate at high frequencies. This type of instability is usually called 'transverse microwave instability in unbunched (coasting) beams'.

7.3 Transverse effects in bunched beams

7.3.1 Transverse microwave instability

Originally derived and used for unbunched beams, this instability also occurs in bunched beams. The intensity limit is again determined by the peak density of the bunched beam. Typically, the transverse microwave instability is accompanied by a fast increase of the transverse emittance.

7.3.2 Coupled bunch instability

In a beam with a large number of bunches, wakefields can excite coupled bunch oscillations. Here, the wakefields are the sum of those generated by all bunches in the ring. This instability can exhibit a rather large number of different modes with a very different pattern. In general, for a beam with N bunches, one can have N possible modes of oscillation. The growth rate of certain modes depends on the intensity and may become a limitation.

Longitudinal coupled bunch instabilities also exist, but are much weaker, in general.

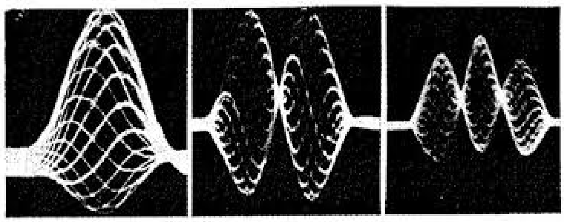

Fig. 9: Head–tail modes, observed in CERN-PS, [31]

Fig. 10: Head–tail mode $m = 1$, observed in the Large Electron–Positron Collider. Screen shot with streak camera

7.3.3 Head–tail instability

This instability is a single bunch instability. Short-range transverse wakefields from particles at the 'head' of a bunch can excite oscillations at its 'tail'. The synchrotron motion exchanges the particles and the new head particles continue to excite the particles behind. The motion becomes unstable if the oscillation grows, depending on the chromaticity and whether the instability is not suppressed by Landau damping.

Head–tail modes as observed with a longitudinal profile monitor in the CERN-PS are shown in Fig. 9. A nice demonstration is shown in Fig. 10, where the head–tail mode $m = 1$ is shown turn by turn, as measured with a streak camera.

7.3.4 Transverse mode coupling instability

This instability, also known as 'fast head–tail instability', appears when two neighbouring modes approach each other as a result of the frequency detuning with increasing bunch intensity. This instability shows a very prominent threshold behaviour. This behaviour was studied with a simulation program; Fig. 11 shows the results. The tune change and the merging of modes as the intensity is increased can be clearly seen. An instability develops at the intensity where the modes have merged.

8 Beam–beam effects

While space charge effects are strongly suppressed for ultrarelativistic beams, the interaction between colliding beams does not vanish. It is by far the strongest source of non-linearities in high-energy particle colliders [7, 8, 17, 18]. This strong non-linearity makes it very difficult to predict the exact beam behaviour; in particular, it is a very complex problem when there are many bunches and collisions. While synchrotron damping helps significantly in avoiding detrimental effects in lepton colliders, such damping does not exist in hadron colliders and the underlying mechanisms and problems are very different.

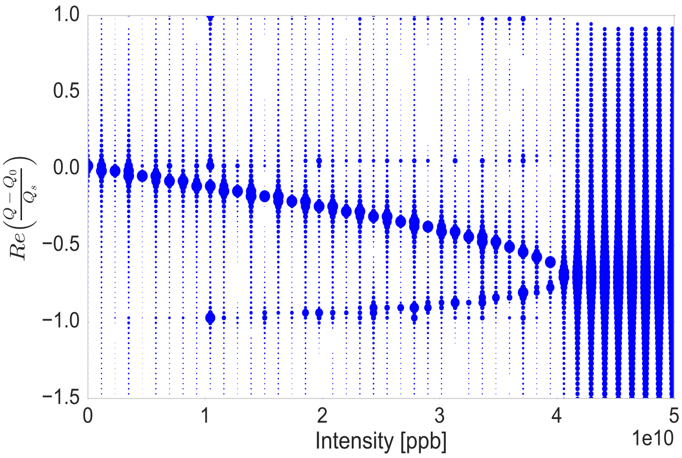

Fig. 11: Transverse mode coupling, simulation

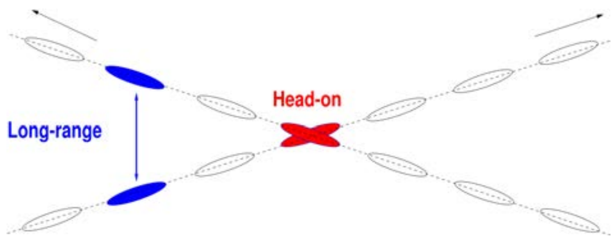

Fig. 12: Beam crossing in the Large Hadron Collider. Head-on (HO) and long range (LR) collisions are indicated

8.1 Hadron beams

In hadron colliders with many bunches, crossing angles (Fig. 12) are required to separate the beams at unwanted collision points and lead to the further complication of long-range interactions [18].

Beam losses due to long-range beam–beam effects as a function of crossing angle are shown in Fig. 13. The crossing angle was reduced in steps from 142 μrad to 72μrad and the lines correspond to bunches with different numbers of long range (LR) interactions. A sufficiently large crossing angle is necessary to guarantee small losses, but leads to further complications [18]. The losses depend strongly on the number of long range interactions.

Other effects are coherent beam–beam motions, which can lead to very fast beam loss within a few turns [20].

8.2 Lepton beams

Colliding lepton beams have a strong interplay with radiation damping and can accept significantly stronger beam–beam effects [19]. However, they show a very distinct threshold behaviour (Fig. 14). Above the threshold (beam–beam limit), the beam–beam tune shift remains constant when the intensities are increased. This is related to an increase in the vertical emittance caused by the beam–beam effects, which are responsible for a strong coupling to the horizontal motion. The interplay between excitation by beam–beam effects and damping leads to an equilibrium and a constant beam–beam tune shift.

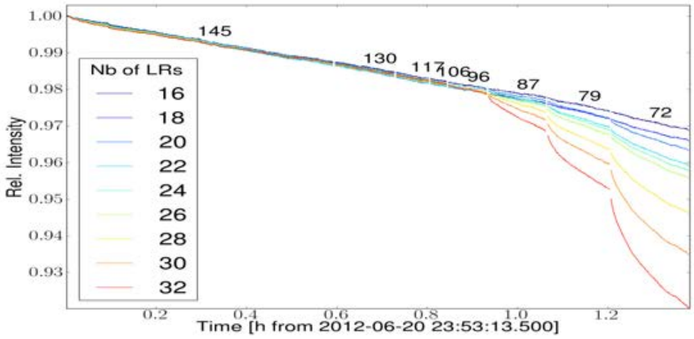

Fig. 13: Beam losses due to long-range (LR) beam–beam effects as a function of crossing angle. The relative intensity is shown as a function of time during the experiment. The corresponding crossing angles decending from 145 μrad to 72 μrad are indicated in the figure. The lines correspond to the bunches with a diffeent number of long range (LR) interactions.

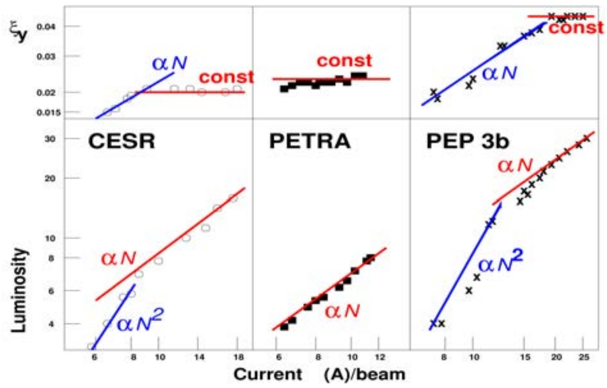

Fig. 14: Beam–beam limit as function of intensity for different lepton collides

8.3 Coherent beam–beam effects

Under the right conditions, coherent beam–beam effects can build up and lead to a very fast beam loss [20]. With a large number of bunches, such as those used at the Large Hadron Collider, many different coherent modes must be expected, some of which are potentially unstable. A detailed analysis of the mechanisms of the excitation of coherent effects and possible mitigation techniques should form part of the design of accelerators with high-intensity beams.

8.4 Linear colliders

Although linear colliders are single-pass, beam–beam effects play an important role in linear colliders [21]. Beam–beam-induced pinching effects are used to enhance the luminosity and control of the disruption is necessary. Furthermore, bremsstrahlung from the collision has a strong impact on machine performance in terms of the useful luminosity, i.e., beam-induced background.

9 Mitigation

To suppress collective instabilities, different mitigation mechanisms are available, passive as well as active.

9.1 Passive mitigation

The most prominent and most efficient mitigation effect is an effect called Landau damping. Strictly speaking, it is not dissipative damping, which would lead to emittance growth and should be distinguished from decoherence (a very common confusion). The computation of the beam stability is rather reliable and is used in most hadron machines [32, 33].

9.2 Active mitigation

Active mitigation can be achieved with different types of feedback systems [34].

10 Electron cloud

10.1 Origin and consequences

Synchrotron radiation from high-energy beams hits the wall of the vacuum chamber and creates photoelectrons [35]. These are affected, i.e., accelerated, by the following bunches and can hit the wall with higher energies, liberating more electrons, as a consequence leading to a build-up of a localized cloud of electrons. The intensity as well as the distance between bunches is an important parameter. Most important is the number of liberated secondary electrons. Consequences of the electron cloud are the coupling of successive bunches, potentially leading to coherent (coupled bunch) instabilities. Another consequence is the deterioration of the vacuum pressure.

10.2 Mitigation

Possible mitigation techniques are a proper design of the vacuum chamber to reduce the effect of the synchrotron radiation. Choice of the proper bunch distance and reduction of the secondary electron yield are very efficient techniques.

11 Ions

Similar considerations hold for ions, degrading the vacuum or ions trapped in the beams [36]. Beam instabilities for high-intensity and low-emittance beams must be assessed.

12 Numerical and simulation tools

Numerical models are essential for the design and operation of an accelerator [37]. Conditions that cannot be studied in existing machines must be simulated. Furthermore, simulation enables one to disentangle the different processes leading to observed effects and provides an excellent analysis tool.

Other typical applications are the computation of impedances and wakefields using, e.g., particle-in-cell codes and particle tracking. The implementation of collective effects via macroparticle and multiparticle simulations is now possible with the available computing resources and relatively easy to implement.

13 Observations and diagnostics

Measurement and diagnosis of beam parameters and the beam quality are essential for the operation and performance of the machine. At high brightness and intensity, it is often not possible to use intercepting devices for the measurements.

13.1 High-intensity beams

Observation and diagnosis of high-intensity beams are vital for the control and protection of the machines [38]. High-intensity beams deliver a stronger signal and better signal-to-noise ratios but signals may be distorted. A typical example is the measurement of the beam profile. In that case, additional effort is needed to obtain a reliable measurement. Care must be taken during the analysis of the measurements; collective effects, such as coherent and incoherent tune shifts, self-fields, and wakes, must be taken into account. Measurement at low intensities is an option, but not applicable in all cases. Some effects are visible only when the intensity is high.

13.2 High-brightness beams

Apart from the intensity, the most important parameter for a high-brightness beam is the emittance [39]. At lower energies, measurement may be done in a regime dominated by space charge. A second challenge is the measurement of the very short bunch length. New ideas are being studied and tested.

14 Sources and injectors

High-brightness beams require a high brightness at the source and its conservation in 6D [40]. The optics of the beam transport and the acceleration must ensure this conservation. An essential part of the chain is the section for beam conditioning, typically before the accelerating section. A limit to the intensity is imposed by the space charge forces leading to emittance growth, even for electrons. For an overview of ion sources see Ref. [41].

15 Practical considerations

The beam intensity may also be limited because of other problems, e.g., engineering or operational difficulties, such as:

- machine protection;
- vacuum;
- cryogenics.

15.1 Machine protection

High-intensity and high-power beams require a sophisticated system to protect the machine against damage. This has become increasingly important for the high-energy machines being studied nowadays. Possible failure scenarios must be considered during machine design at a very early stage [42].

The safety of personnel is of vital importance and is included in the considerations.

15.2 Vacuum

Beyond other problems, beam-induced absorption and multipacting can limit the maximum allowed intensity. A proper design of the vacuum chamber and mitigation techniques, such as conditioning, are required. A particular case mentioned already is the build-up of an electron cloud and the consequences for the vacuum and the beam dynamics [43].

15.3 Beam loss consequences

Beam losses not only affect the performance of the machine, but are significant for such events as [44]:

- failure of electronics, both single events and cumulative effects;
- activation of material and air;
- chemical reactions under the influence of ionizing particles.

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