MITIGATION OF COHERENT INSTABILITIES IN LINEAR COLLIDERS AND FCC-HH

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Abstract

Collective instabilities play an important role in projects as diverse as FCC-hh and CLIC and drive some of the choices. In the paper a few examples are shown where the instabilities were mitigated by design choices and the resulting impact on the collider cost and power consumption is highlighted.

INTRODUCTION

Collective beam instabilities can be mitigated with special technologies which suppres them. Beam-based feedback is a prime example. In some cases they have to be mitigated by design of a facility and can thus be a key design driver. This is the case for CLIC (Compact LInear Collider) [1] and FCC-hh, the hadron collider of FCC (Future Circular Collider) [2] as will be described below.

CLIC

The CLIC study is preparing a staged electron-positron linear collider design that can be implemented in stages with centre-of-mass energies of 380 GeV, 1.5 TeV and finally 3 TeV. The concept uses 12 GHz normal-conducting accelerating structures in the main linac to accelerate 50 beam pulses per second each about 150 ns long and containing more than 300 bunches. It uses a novel drive-beam concept to produce the power for the main linac.

The first energy stage of CLIC has been systematically optimised for cost for the collision energy of 380 GeV and required luminosity of $1.5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ defined by the physics study.

A key ingredient of this optimisation has been the collective effects in the main linac. The particles of the bunches that pass through the accelerating structures extract energy. This beamloading reduces the accelerating field for the subsequent particles in the bunch and can generate an energy spread. The energy spread can in part be compensated by not accelerating the bunch at the moment when the RF field has reached its maximum but rather slightly earlier, typically at an RF phase of 12-15 degress. The RF field at the tail of the bunch is thus larger and can compensate the beamloading. To minimise the spread in acceleration, the bunch length has to be adjusted for the bunch charge; higher bunch charges demand longer bunches. This allows to determine the bunch length as a function of the charge.

Transverse wakefields of the bunch can lead to instabilities if the bunch is not injected perfectly on axis. They have to be suppressed. Whether an instability occurs depends on the focusing strength of the lattice, the RF structure design and the length and charge of the bunch that drives the wakefields. Since stronger focusing helps to mitigate the instability, the strongest practical lattice is chosen, and about 10% of the main linac is filled with quadrupoles. Further increase of this fraction would give minor improvements but start to hurt the effective gradient significantly.

The wakefields produced in each accelerating structure can be calculated based on the structure design. For CLIC a few basic parameters have to be taken into account: The structure length and the iris radius and thicknes for the different cells along the structure. This is achieved by a program developed by K. Sjobaek and A. Grudiev [3]. Since the bunch length is a function of the charge, it is now easy to determine the bunch charge that leads to transverse single-bunch instability. By backing off slightly in order to provide safety margin, this allows to define the maximum bunch charge.

The minimum distance between bunches is given by multi-bunch transverse instabilities. At larger distances the wakefields are weaker with the strong damping in the CLIC structures. The code allows to calculate the long-range wakefield and an analytic estimate can be used to identify the acceptable limit [4].

The number of bunches required to achieve the luminosity goal depends on their charge and the emittances from the damping ring and the beam transport systems as well as the focusing ability at the interaction point. It is a simple function of the charge, since the emittances can also be expressed as a function of the charge.

The number of bunches that is required to reach the luminosity goal is easily estimated. The repetition rate of the collider is fixed at 50 Hz to minimise the impact of magnetic stray fields from the power grid, which operates at 50 Hz[1]. The number of bunches required per beam pulse is thus known. Together with the distance between bunches the length of the RF pulse can be calculated, taking into account the structure design. This allows to determine whether the structure has an acceptable breakdown probability.

This procedure thus defined all relevant beam parameters. Based on the structure and the beam parameters the cost and power consumption of the collider can be estimated. Finally, the cheapest design that reaches the luminosity goal has been used. It has also one of the lowest power consumptions.

FCC-HH

FCC-hh is designed to provide 100 TeV proton-proton collisions with a luminosity of up to $3 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. It uses 16 T superconducting Nb_3Sn magnets in its roughly 100 km long collider tunnel to bend the beam on its orbit.

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[1] Actually, the repetition rate is locked onto the grid frequency to follow the small deviations from the 50 Hz that occur.

A key parameter in the FCC-hh design is the magnet aperture in the arcs. Larger apertures mean that the magnets need to contain more of the expensive superconductor and thus increases the project cost. At injection, the beamscreen is the main source of impedance and too small aperture can render the beam unstable.

At first glance it might be surprising that impedances play an important role in FCC-hh, since the injection and collision energies of 3.3 and 50 TeV, respectively, are much higher than in LHC. But the larger circumference, lower revolution frequency, and larger betafunctions all increase the sensitivity to impedances.

The impedance efffects depend on the lattice, the bunch charge, spacing and energy as well as on the aperture and the resistivity of the surface. Copper coating is applied to reduce the resitivity at the relevant frequencies. The maximum injection energy is defined by considerations of the LHC as an injector to be 3.3 TeV. Higher energies would slow the ramping of the injector, which is a key ingredient in the integrated luminosity.

To maximise the integrated luminosity, the beam current has to be as high as possible since the beam is burning rapidly in the experiments. The time that one can operate without having to replace the beam with a fresh one is thus limited. It increases with the amount of stored beam; in case of FCC-hh it reaches about 3.2 h. The estimated time to refill the collider and resume luminosity operation is 4 h.

The minium beamscreen aperture of 25 mm has been determined by estimating the instability rise times and allowing for some margin with respect to the speed of mitigation techniques, such as fast feedback. The initial studies of N. Monet and G. Rumolo [5] have been later confirmed with full studies including all the relevant detail of the beamscreen geometry by S. Arsenyev et al. [6]. Adding the space required for cooling and vacuum then allows to determine the minimum aperture for the magnets to be 50 mm.

An important collider parameter of FCC-hh is the bunch spacing. The total beam current is largely limited by the emission of synchrotron radiation and the need to remove it from the cold magnets. The distribution of the current over bunches has some flexibility. A smaller bunch spacing would distribute the luminosity over more collisions and thus reduce the number of background events per collision. This can simplifiy the detector design.

One of the key drivers of the bunch distance is the electron cloud, which can also lead to beam instabilities. In FCC-hh the generation and build-up of the cloud is suppressed by a special beamscreen design that removes most synchrotron radiation photons from the beam chamber. The build-up is suppressed by surfact coating on the beamscreen or by laser treatment, both of which reduce the secondary emission yield—the number of secondary electrons produced by each electron that hits the beamscreen. However, the acceptable secondary emission yield depends on the spacing between the proton bunches. The nominal spacing of 25 ns allows for a yield of up to 1.2 in the quadrupoles, the tightest requirement in any component as shown by studies of L. Mether [6]. For the shorter bunch spacings of 12.5 and 5 ns the limit is reduced to about 1.0 and therefore at the current moment does not provide enough margin to be sure to reach the full performance goal if no additional measures are taken.

Further work to reduce the electron cloud is thus required to enable smaller bunch spacings and potentially ease the design of the detectors.

CONCLUSION

Collective instabilities play an important role in future colliderdesigns such as CLIC or FCC-hh. They drive important design choices. In CLIC the beam parameters, the cost and power consumption of the project are a direct consequence of wakefield effects in the main linac. The project has been optimised for minimum cost and power consumptions by going to the limit (with required margin) of these effects and by selecting the optimum accelerating structure.

In FCC-hh, collective instabilities are critical in defining the magnet aperture, which impacts the cost of the project. Also the choice of beam time structure is governed by collective effects. They therefore have a direct impact on the physics performance of the collider.

REFERENCES

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