# OPERATIONAL EXPERIENCE OF BEAM STABILITY CONTROL

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## *Abstract*

The CERN accelerator complex, as well as other accelerator facilities world-wide, produce a large variety of particle beams for use in experiments. The beam quality is of prime importance and can be characterised by many parameters, such as beam or bunch intensity, longitudinal and transverse beam size, time structure, etc. Certain combinations of these beam parameters, along with the machine characteristics such as impedance, can lead to challenging configurations that can drive the particle beams unstable, potentially leading to degradation of the beam quality and particle losses around the circumference of the accelerator. These losses result in activation of the accelerator components and therefore prolong the cooldown time to allow for hands-on preventive and corrective maintenance, hence reducing the beam time available for physics.

Beam stability control is therefore of major importance for the operation of accelerators and can be obtained through distinct means for different accelerators and beam characteristics. This paper outlines the principal operational instability observations and mitigations applied for the CERN accelerator complex, complemented with approaches used in some other accelerator laboratories around the world. An attempt is made to illustrate the interplay between the beam dynamics experts and the operations teams.

## CERN ACCELERATOR COMPLEX AND PARTICLE BEAMS

The CERN accelerator complex (Fig. 1), as it is in used today, has evolved over more than 60 year. The CERN Proton Synchrotron (PS), initially foreseen for internal target experiment, was designed for beam intensities of a few $10^{10}$, while upgrades and addition of the PS Booster (PSB) allowed to increase the beam intensity up to more than $3\times10^{13}$ protons per pulse. Similarly, the Super Proton Synchrotron (SPS) has gone through many transformations and performance increase steps. Initially it was used as high energy protons synchrotron, then transformed into a proton – antiproton collider, before being used as injector to the Large Electron Positron (LEP) collider. Today besides producing the beams for the Large Hadron Collider (LHC), the PSB, PS and SPS provide various types and configurations of particle beams to a rich variety of fixed target experiments. The performance increase and the large spectrum of beam characteristics gave rise to rich panel of beam instability observations and mitigation techniques, most of which are used operationally.

Another interesting period is upcoming, with the commissioning of the LHC injector upgrade project that has as principal aim to more than double the LHC beam brightness. Although potential beam instabilities have been studied and mitigation measures have been foreseen, new challenges will arise and will have to be dealt with efficiently, by beam dynamics experts and the operations teams.

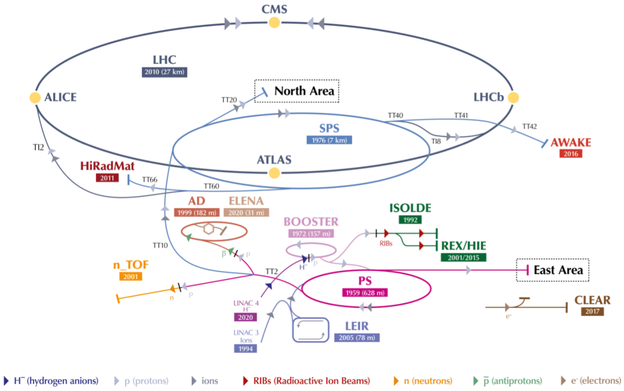
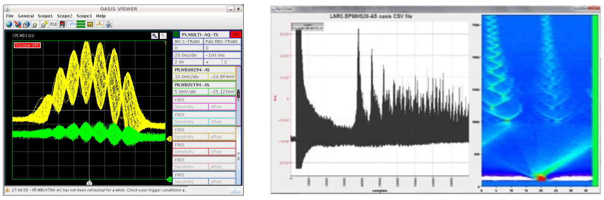


Figure 1: Schematic overview of the CERN accelerator complex today.

## *Operational Instability Observation*

Beam instabilities that developed over the years as a result of the performance increases have been studied in detail analytically, through simulations, but also during numerous machine development sessions. The latter led to the implementation and/or extension of a large spectrum of observation and diagnostics tools. Many of these were initiated as proof of principle or prototypes to cover the need of the study, but many were later converted into operational tools.

Wideband longitudinal and transverse pick-ups, power converter signals and feedback loop signals are connected to a distributed analogue/digital signal observation system, called OASIS [1]. This allows remotely connecting signals or data streams around the accelerator complex to the local OASIS sub-systems and to visualise them, using a common trigger, on displays in the control room. A few examples of the signals and their observation modes are given in Fig. 2.



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5.0mV/div -25.123mV

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Figure 2: Examples of visualisation of signals on the OASIS system, normal analogue mode (left) and analogue mode with waterfall image (right).

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More dedicated systems, such as Bunch Shape Monitors (BSM) combined with tomographic algorithms, allow for tools such as Tomoscope [2] and Beam Quality Monitors (BQM). The BQM makes a real-time analysis of the beam quality and can be parametrised to dump the beam prior to transferring it to the LHC if the quality does not meet the pre-defined requirements [3].

More recently, the LHC transverse damper system was equipped with enhanced diagnostic tools, called ADT-Obsbox [4]. This system forms a rich source of digitised beam signals for instability studies. It triggers on instabilities and stores the signals for many thousands of turns bunch-by-bunch for off-line analysis (see fig. 3). In some places spectrum analysers are still available and used for on-line observations, but the abovementioned systems allow more sophisticated analysis, hence the decrease in number of spectrum analysers over the years.

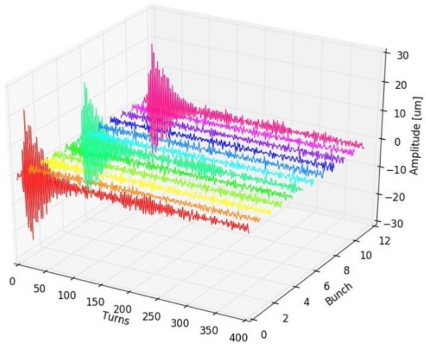

Figure 3: Example of ADT-ObsBox signals for four bunches over 400 turns.

The extensive logging of machine parameters, as is done for the LHC, but also more and more, for the LHC injector chain, froms a rich source of data for the analysis of beam instabilities and allows correlating them with machine parameters.

## Operational Instability Mitigation

Once beam instabilities are observed and analysed mitigation measures will have to be applied. The most common operational knobs in the control rooms for the transverse plane are tune, chromaticity, linear coupling and Landau octupoles, complemented by the various parameters of the transverse feedback system. For the longitudinal plane these are RF cavity voltage, higher order cavity voltage and the various parameters of the longitudinal feedback system. If the beam specifications allow, controlled transverse and/or longitudinal blow up are also powerful tools to palliate operationally beam instabilities.

Synchrotron radiation damping is an effective means to moderate beam instabilities, but apart from the CLEAR facility, only protons, antiprotons and different ion species are accelerated and decelerated at CERN, which do not provide useable synchrotron radiation damping in any of the accelerators.

Stochastics and electron beam cooling are used in the low energy machines at CERN, such as the Antiproton Decelerator (AD), the Extra Low ENergy Antiprotons machine (ELENA) and the Low Energy Ion Ring (LEIR), but not for any of the high energy, high intensity and/or high brightness proton beams.

# OPERATIONAL EXPERIENCE WITH BEAM INSTABILITY AT CERN

## PS Booster (PSB)

The PSB is the first link in the LHC injector chain and is at the source of all beams for the downstream experimental areas and machines. It has its own experimental facility, the Isotope mass Separator On-Line DEvice (ISOLDE) for which it produces a 4-bunch high intensity beam of $\sim 3.4\times10^{13}$ protons per pulse at 1.4 GeV kinetic energy and 2 GeV in 2021.

The PSB beams can potentially be impaired by a horizontal beam instability in the presence of high space charge, resulting in a tune spread of up to $dq \sim 0.5$. This instability is efficiently suppressed owing the good working transverse damper. The cause for this instability, which was recently identified, are the cables of the extraction kicker system [5]. The PSB relies on the transverse feedback in coming years for the mitigation of this instability. However, studies for a definitive solution at the source has been launched.

Apart from the transverse damper and the capability of applying a controlled longitudinal blow-up, the PSB is not equipped with chromaticity sextupoles nor Landau octupoles.

## CERN Proton Synchrotron (PS)

All operational beams, apart from the ISOLDE beam, are accelerated and manipulated in the PS. The main instability related phenomena observed on some of these beams are:

- Head-tail instability in the presence of space charge, resulting in a tune spread of up to $dq \sim 0.5$;
- Beam break-up at transition crossing in the presence of space charge [6], or Transverse Microwave Convective Instability [7];
- Longitudinal coupled bunch instabilities;
- Transverse coupled bunch instabilities.

The principal means in the PS to correct for beam instabilities are:

- Transverse damper, not much used until recently;
- Tune and coupling, for coherent instabilities;
- Chromaticity, sign flip at $\gamma$-jump;
- Landau octupoles, rarely used and only available below transition crossing (~6 GeV/c);
- RF cavity voltage, reduced after $\gamma$-jump to maximise Landau damping;
- Controlled longitudinal blow-up though dedicated 200 MHz cavities;
- Longitudinal damper, recently installed.

The following paragraphs illustrate examples of operational beams on which the abovementioned phenomena have been observed and to which corrections are applied, together with some operational experience where relevant.

The n-TOF beam, which is a single bunch high intensity beam (~$8\times10^{13}$ protons), suffered from the beam break up instability at transition crossing. Initially the controlled longitudinal blow up was increased with a positive effect on the instability, but a detrimental effect on the beam quality occurred, as ghost bunches were created by particles leaking out of the bucket into the neighbouring empty buckets. Careful studies on the controlled blow-up parameters have identified a set of parameters that blow up most efficiently the core of the bunch and less the particle trajectories on the outskirts of the bunch. These blow-up parameters are now routinely used and if necessary adapted by the operations teams.

The LHC beam uses a double batch injection, hence a waiting time of 1.2 s for the first injected batch on the injection plateau. The beam is intrinsically unstable in the horizontal plane with nominal chromaticity, $\xi_{h,v} = -1$ below transition. Until recently, approaching the horizontal and vertical tunes close to the coupling resonance and adding linear coupling through skew quadrupoles were used to damp the instability, hence improved the beam quality and reduced the beam losses [8]. More recently, the low energy working point was modified. Small but negative values for the chromaticity in both planes were, combined with the use of the transverse damper to damp the head-tail modes. The working point adjustments together with the transverse damper settings are performed by the operations teams.

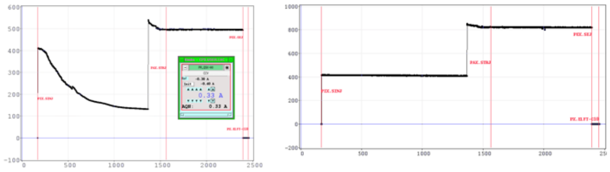

Figure 4: (left) the instability causing losses on the flat bottom, (right) Stable beam without losses.

The LHC beam, during the energy ramp, exhibits dipolar and quadrupolar coupled bunch instabilities, limiting the bunch intensity [9]. The RF system was modified such that two out of the ten 10 MHz cavities could be used to damp the instability. In addition, partial mitigation was found applying controlled longitudinal blow up in the PSB prior to extraction, and in the PS at low energy. However, for beam specification reasons the maximum longitudinal emittance at extraction cannot exceed 0.35 eVs. For the future a dedicated longitudinal damper has been installed and the 10 MHz cavity impedance will be reduced through an upgrade of the amplifiers. The operational experience with this is that the two 10 MHz cavities used to damp the instabilities in addition to their main role, accelerating the beam, tripped more regularly, causing beam downtime. The bunch splitting processes, used to produce the 25 ns bunch spacing, required regular manual adjustments by the operations team for the optimisation of the beam quality. Good measurement and correction tools are available in the control room to diagnose and mitigate the instability.

### *Super Proton Synchrotron (SPS)*

The SPS receives its beam from the PS and produces various types of beams for the LHC, the Fixed target experiments in the North Area of the Prevessin site, the AWAKE experiment and the HiRadMat facility. The main instability related phenomena observed on some of these beams are:

- Fast vertical single bunch instability;
- Horizontal coupled bunch instability during the injection plateau for $1.8\times10^{11}$ protons per bunch on the LHC beam;
- Electron cloud induced instability
- Longitudinal coupled bunch instability, due to RF cavity beam loading.

The principal means in the SPS to correct for beam instabilities are:

- Chromaticity;
- Landau octupoles;
- Transverse damper;
- Lowering of the γ-transition, through a well-studied optics modification;
- Prototype intra-bunch damper in the vertical plane only. Presently only used for studies and limited in power;
- 800 MHz RF cavity used as Landau cavity, in the past also for controlled longitudinal blow-up;
- RF cavity voltage, but no or little margins available.

The following paragraphs illustrate examples of operational beams on which the abovementioned phenomena have been observed and to which corrections are applied, together with some operational experience, where relevant.

The TMCI-like fast vertical single bunch instability or Transverse Microwave Convective Instability forms a performance limiting factor in the SPS. Running the machine at higher chromaticity values contributes to stabilising the instability but is not satisfactory. Studies and tests with beam have confirmed that lowering the γ-transition by switching from the so-called Q26 optics to the Q20 low gamma transition optics, provides an efficient cure for this TMCI-like instability [10]. For the Q20 optics, the frequency slip factor increases by a factor 2.8 at injection and 1.6 at high energy compared to the Q26 case. The drawback of the Q20 solution is that it imposes a higher RF voltage, which is already limited with the present RF system. As a result, the SPS RF system is being upgraded and more voltage will become available. In addition, an alternative scheme with Q22, a compromise between stabilisation and available RF voltage, is being studied. The Q20 optics has been deployed operationally on the LHC beams and is used for routine operation and filling of the LHC. The SPS is now awaiting the upgrade of the RF system to take full benefit of the scheme. This is a clear example of an expert driven change with a good and close collaboration with the

Operations group for operational deployment of the new scheme.

A horizontal coupled bunch instability is present at flat bottom in the SPS on the LHC beam for bunch intensities approaching $1.8\times10^{11}$ protons. The transverse damper in combination with the Landau octupoles are used rather efficiently to mitigate this instability. With the Q20 optics the Landau octupoles generated a large second order chromaticity as a result of the high dispersion at their location and enhanced the beam losses due to the large incoherent tune spread. As a result, in 2018, following careful machine studies the Landau octupoles were partially re-configured with the aim to reduce the second order chromaticity *Q”* for which the before and after situation is given in Fig. 5 [11].

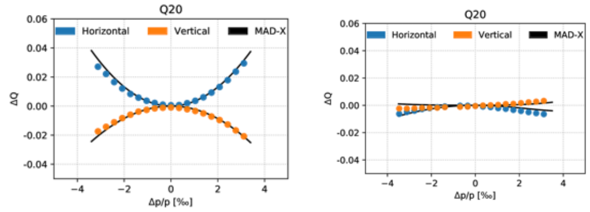

Figure 5: The non-linear chromaticity before (left) and after (right) deploying the Landau octupole reconfiguration.

The LHC beam in the SPS is also undergoing electron cloud induced instabilities, which can severely impact the beam quality. Two main operational mitigation measures are used to combat the build-up of electron cloud:
1) running the machine with higher values for the chromaticity and 2) perform scrubbing runs following vacuum interventions or prolonged stops. The latter is very effective but can be rather time consuming depending on the extend and duration of the vacuum interventions. The operations team, in close collaboration with the electron cloud experts, perform the yearly scrubbing runs. Until recently the scrubbing run required frequent interruptions to avoid overheating of the kickers due to impedance. The serigraphy on the ceramic chambers will be adapted to reduce the kicker heating in the future. A solution at the source, amorphous Carbon coating of the vacuum chambers, is also being deployed gradually, reducing or even eliminating the need for the scrubbing runs in the future.

### *Large Hadron Collider (LHC)*

The LHC receives the beam from the SPS in multiple batches of bunch trains, ranging in length from 12 to 288 bunches. In order to increase the physics production, the luminosity in the LHC is continuously optimised by reducing as much as possible the physical beam size in the interaction points, but also by injecting beams of increased brightness from the injectors. The main instability related phenomena observed on the beam in the LHC are:

- Electron cloud driven instability at injection;
- Beam instability driven by the impedance from the closing collimators;
- Very fast instability as a result of a vacuum related non-conformity (16L2);
- Longitudinal beam instability after injection.

The principal means in the LHC to correct for beam instabilities are:

- Transverse feedback (ADT) in both planes;
- Tune and linear coupling control;
- Chromaticity, a large chromaticity is imposed during the whole cycle due to instabilities;
- Landau octupoles;
- RF Cavity voltage;
- Controlled longitudinal blow up, to maintain constant longitudinal emittance and bunch length that decreases over log fills, as a result of synchrotron radiation damping.

The following paragraphs illustrate examples of operational beams for which the abovementioned phenomena have been observed and to which corrections are applied, together with some operational experience, where relevant.

The electron cloud driven instability at injection is cured in a similar manner as for the SPS. Prior to a physics run and during the gradual intensity ramp-up, a scrubbing run is performed to reduce the secondary electron emission yield. This drastically reduces the electron cloud formation but does unfortunately not suppress it. Therefore, the LHC runs with a chromaticity of ~ 15 units in both planes, which, combined with an increased strength of the Landau octupoles and the correction of the linear coupling at low energy, allows for sufficient mitigation for operation with the required bunch intensities and bunch patterns. The operations teams regularly measure and correct the chromaticity. Following the findings on the linear coupling by beam dynamics experts, the operations team has developed a tool to measure and correct the linear coupling which is also used by the operations teams on a regular basis.

The closure of the collimators at high energy gives rise to an impedance induced beam instability that is cured by applying a high value for the chromaticity in both planes of ~ 15 units, in combination with the Landau octupoles that run close the maximum available current of 550 A. The latter have been used both in negative and positive polarity. This topic is generally seen as very complex by the majority of the operations team members, but they closely collaborate with the beam dynamics experts for the measurement campaigns. The accelerator physicists in the operations team are highly involved in the setting-up of the cures and development of the monitoring tools.

Following a beam vacuum non-conformity, fast beam instabilities, caused by a local high gas density, have led to beam dumps in 2017 and 2018 [12][13]. Since this phenomenon arose unexpectedly during the intensity ramp-up in 2017, no predefined cure was readily available, and the logging of the beam and machine signals prior to and during each instability-induced beam dump contributed significantly to the understanding of the instability mechanism.

Through trial and error several mitigation measures have been attempted. An extra solenoid to evacuate electrons and/or ions in the suspected area of the machine was installed and contributed to the reduction of instability induced beam dumps. Also conditioning with a lower beam intensity, following a beam dump, turned out to be a working recovery strategy. Taking a step back on the beam performance contributed significantly to the reduction of the number of instability-induced beam dumps and increased again the beam availability for the experiments. Combing in the operational experience with the enhanced understanding of the instability mechanism by the beam dynamics experts resulted in exploiting the enormous flexibility of the injector chain. The so-called 8b4e LHC beam, where the short 8-bunch trains were separated by four empty buckets, was setup in a short period of time and suppressed the electron cloud production in the LHC at the expense of a slightly reduced, but still respectable peak luminosity of close to the $2\times10^{34}$ cm$^{-2}$s$^{-1}$, twice the LHC design value. This beam configuration therefore contributed greatly to the reduction of the beam-induced heat load, hence the number of instability-induced beam dumps. The definitive cure of the problem is the removal of the non-conformity, foreseen for LHC Run 3.

Persistent injection phase oscillations caused a longitudinal beam instability after injection prior to 2018 (Fig. 6) [14]. This was identified to be due to the mismatch between the LHC bucket height and the momentum spread of the arriving bunch. The theoretically optimum voltage with respect to the momentum spread of the injected SPS bunch is 2 MV. However, this voltage resulted in too high injection losses in the past. As result, the RF beam dynamic expert performed studies and found that 4 MV would be the optimum voltage for the beam coming from the SPS as opposed to the 6 MV that was applied operationally. During the 2018 physics run, under a close collaboration between the RF beam dynamics expert and the operations team, the voltage was reduced in steps over many LHC fills. This was done by carefully observing the effects and evaluating if a next step could be made safely without compromising beam quality or perturbing the collisions for the experiments. Since then the 4 MV has been successfully used beam injection without observing the longitudinal instability after injection.

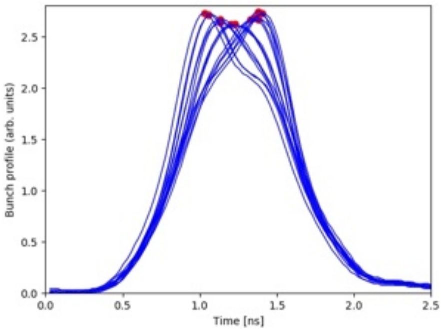

Figure 6: Dipole oscillations observed on the bunch profile approximately one minute after injection.

## BEAM INSTABILITY OBSERVATION AND MITIGATION IN OTHER ACCELERATOR LABORATORIES

### *J-PARC*

The J-PARC complex is a multipurpose high-power proton accelerator facility comprising a 400 MeV H$^-$ Linac, a 3 GeV Rapid Cycling Synchrotron (RSC) and a 30 GeV Main Ring (MR). The design power of the MR is 750 MW, but a performance improvement scheme aims at increasing the beam power to 1.3 MW with a beam intensity of $3.3\times10^{13}$ protons per pulse [15].

A transverse instability causing beam losses in the RCS is suppressed effectively by programming a negative chromaticity of seven units. Reducing to smaller absolute values of the chromaticity the beam is unstable and larger negative values provoke beam losses, likely due to the large chromatic tune spread.

In the longitudinal plane of the MR, dipolar coupled bunch instabilities have been observed for beam powers approaching 500 kW, as a result of RF cavity beam loading. A feedback system has been developed and is being tested on low power beams before being deployed operationally on the high-power beams.

A resistive wall impedance and kicker impedance cause transverse beam instabilities in the MR. Also here, a large value for the chromaticity, together with Landau octupoles provides a cure [16].

The performance increase and optimisation are iterative processes that are mainly driven by the beam dynamics experts. The operations team is not really involved in this process, until new settings and procedures have become fully operational.

### *FermiLab*

The FNAL Booster experiences a transverse instability under high space charge regime [17]. These instabilities are until now suppressed by applying a large value for the horizontal and vertical chromaticity of ~12 units. The plans to build and install a transverse damper will allow lowering the values for the horizontal and vertical chromaticity again.

Longitudinal coupled bunch modes are also observed, probably as a result of RF cavity beam loading. The longitudinal emittance is blown-up after transition by voluntary mismatch of the bucket. Longitudinal dampers are available, but the longitudinal coupled bunch mode 2 is not yet well-controlled.

The booster is tuned on a daily basis by experts with all the knobs available.

### *Brookhaven National Laboratory*

The BNL Booster accelerates protons and ions and is running near its natural chromaticity without losses. The octupole winding were retired, as they had little or no use anymore. Space charge issues are prominent at injection and a dual harmonic RF system is used to control the bunching factor.

The AGS accelerates polarised protons and ions, but at low or moderate intensities. In the past the AGS accelerated proton beam intensities of more than $8\times10^{13}$ protons per pulse for slow extraction to fixed target experiments. At that epoch many beam instabilities have been observed and cures have been put in place. The main systems used were transverse damper, higher frequency dilution cavities at injection and transition, skew quadrupoles for empirical linear coupling correction by the operations teams and higher order multipoles used by the operations teams to empirically improve beam transmission.

Today the AGS no longer accelerates these high intensities and activity on the beam instability front has decreased drastically.

At RHIC [18] that collides polarised protons and ions the injection is dominated by intra-beam scattering and capture losses. The transition crossing with high intensities was often accompanied with beam instabilities, most likely due to electron clouds. NEG coating has been applied and scrubbing runs to reduce the secondary electron emission yield are performed. The transverse damper combats the injection oscillations and is, if necessary, adjusted by experts and monitored by the operations teams. A transverse bunch-by-bunch system was deployed in 2014 but is not yet fully operational for technical reasons. The chromaticity, which is slightly increased with respect to the design value (5 units instead of 2 units) for higher intensities, to avoid beam losses, is measured and controlled by the operations teams with support from the beam dynamics experts. Linear coupling and tune are controlled by feedback systems. The setting up of these systems is done by experts and the monitoring by the operations teams.

Landau damping cavities are necessary for beam stability at high ion intensities during injection and acceleration past transition. A longitudinal bunch-by-bunch damper is in use since 2013 for protons, which allows for relaxing the voltage on the Landau cavities. For low energy physics the Low Energy RHIC electron Cooling (LEReC) has been commissioned and the operations teams start now participating in the electron beam tuning too.

## CONCLUSION

Beam instabilities and their mitigation are sometimes seen as black magic from an operations point of view, but this perception changes when basic understanding of the phenomena and their mitigation have been achieved. The good communication and collaboration between the beam dynamics experts and the operations teams are of key importance to achieve this basic understanding,

In different accelerator laboratories various approaches towards the operational mitigation of beam instabilities are applied, ranging from full expert control to a large involvement and autonomy by the operations teams. At CERN the much appreciated inter-group collaborative approach is favoured, leaving a large autonomy to the operations teams and freeing up time for the experts to study and/or simulate in more depth the theoretical background for the phenomena and to provide reliable models that help to predict and correct beam instabilities. At a later stage, these models are often integrated by the operations teams in operational software applications, increasing the ability to act upon arising instability issues more autonomously by the operations teams that is present 24/7.

There is also a general tendency to push the performance wherever it is possible. However, making a small step back, to the benefit of the stable and routine operation, often results in an overall gain of the performance for the experiments.

The presently available diagnostics systems and tools for the mitigation of beam instabilities in the control room seems adequate, and wherever shortcomings were identified upgrades are foreseen in the near future.

With the commissioning and subsequent performance ramp-up following the deployment of the LHC Injector upgrade programme, there will be challenges and interesting times ahead.

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.

## ACKNOWLEDGEMENTS

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