Report from the Review Panel

Needs for a hollow e-lens for the HL-LHC

CERN

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Review Panel Members

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1. Introduction

Following the experience of the 2016 LHC operation, this review aims to discuss the need and potential benefits of an active halo depletion system for the HL-LHC and give a recommendation for adopting it into the HL-LHC baseline.

The scope of this review is to examine the two initial motivations (loss spikes during operation and machine protection aspects for operation with Crab Cavities), to evaluate the needs in view of the recent project re-scoping and to compare the projected needs with the operational experience from the LHC during Run I and Run II.

Following the close-out by the review chair, the committee is required to compile a short report with findings, comments and recommendations within one month. The report will be delivered to Lucio Rossi, HL-LHC Project leader.

Presentations

1. Introduction, Oliver Brüning
2. Overview and introduction including an outline of the existing installation options, optics conditions, infrastructure requirements (cry, power), Tools for halo measurement and timeline (planning need for the technical design etc.), S.Redaelli
3. Loss and lifetime observations during nominal operation and their extrapolation to HL-LHC parameters, Belen Maria Salvachua Ferrando
4. What did we learn about HALO population during LRBB studies and MDs? Yannis Papaphilippou
5. What did we learn about HALO population during MDs and regular operation? Gianluca Valentino
6. Observations and measurements on the impact of earthquakes and cultural noise on the LHC operation and their extrapolation to HL-LHC parameters. Michaela Schaumann
7. Operational experience from HERA and their extrapolation to the HL-LHC, Mike Seidel
8. Operational experience of RHIC electron lenses and their effect on collimation and halo populations, Wolfram Fischer
9. Operational experience from Tevatron and relevance for HL-LHC, Alexander Valishev et al.
10. Expectations (extrapolated from LHC operation) for the beam lifetime and halo population based on scaling from the LHC observations for radiation damping and IBS excitation, Fanouria Antoniou
11. RF overview of the Crab Cavity system for HL-LHC with presentation on potential failure modes and summary of the KEK operation experience, Rama Calaga
12. Potential failure scenarios in the HL-LHC machine that can lead to very fast orbit changes (e.g. missing beam-beam kicks, damper failure scenarios, Crab cavity failure scenarios etc) and the resulting machine protection requirements for HL-LHC operation (with input from collimation team), Daniel Wollmann
13. Measured effects of depleted halo population with hollow e-lens and relevance for HL-LHC, Giulio Stancari
14. Alternative methods for halo depletion (damper and tune modulation [and wire]), long range beam-beam and comparison of their performance / reliability to that of a hollow electron lens, Roderik Bruce
15. Potential performance reach for the HL-LHC in case of a depleted beam halo, Gianluigi Arduini

2. Some questions

- **Are there sufficient indications that active halo cleaning for HL-LHC is required? Yes.**
    - The committee considers that there are considerable risks for HL-LHC to reach design performance with the proposed baseline related to beam halo population.
    - There are clear observations that the tails are overpopulated. Double Gaussian beams were measured in all phases of operation. Scaled to HL-LHC, the energy stored in the beam halo above 3.5 sigma would amount to 35 MJ.
    - During some phases in the cycle, in particular during squeeze and adjust, beam losses were observed in 2012 and 2016. When scaling the observations to the HL-LHC parameters from 2012, this would lead to an unacceptable performance in operation. Scaling from 2016, the situation would be acceptable. Considering the increase of bunch intensity by a factor of two, the operation with crab cavities, the reduced beta* functions and the required beta* levelling during stable beams, scaling from 2012 or 2016 is not straightforward. Active halo depletion will mitigate the risks.
    - Crab cavities are likely to introduce a new class of very fast failures, due to phase and/or voltage changes, possibly induced by the beams. This would lead to an excitation of betatron oscillations with large amplitudes (depending on the failure mode, more than 1.5 sigma). The reaction time of the machine protection system is not sufficient to fully mitigate these failures in case of overpopulated tails that could damage collimators. A hollow e-lens will mitigate such failures if the oscillation amplitude is below, say, 2 sigma. If failure modes exist that lead to larger amplitudes, other mitigation measures need to be found.
    - With (partially) depleted halo it is expected that the machine is less sensitive to transients due to small variations of orbit, tune and other parameters.
    - With HL-LHC, the LHC will operate in a challenging new regime with very different parameters. Active halo depletion will increase the margins during operation.

- **Is a hollow e-Lens expected to efficiently clean the beam halo? Yes.**

    - There has been substantial experience from Tevatron and RHIC using e-lenses during regular operation. At Tevatron, efficient cleaning was clearly demonstrated as a very elegant method to clean the beam halo. The operation of these devices had acceptable side effects on operation (the RHIC lens as head-on beam-beam compensator introduces some background in the experiments) and worked very reliably.

- **Could there be adverse effects on the beams when operating a (hollow) e-Lens? Yes.**

    - Several failure modes exist that could have an impact on the hadron beam, examples are solenoid quenches and high voltage break down. Such effects need to be mitigated by adequate design and interlocking. Depending on the mode of operation (DC, random and resonant) an e-lens could induce emittance growth of the core. These effects need to be further studied in simulations. The tolerance for such device need to be established (e.g. correct centering, uniformity, cancellation of end fields).
    - In operation with depleted halo (e.g. in situations where the tails are not repopulated) a signal in case of fast beam movement comes with a delay, when the core is already close to the collimator. In case of halo cleaning with an e-lens, this effect can be mitigated by leaving an adequate number of particles in the tails.

- **Are there alternative methods for halo cleaning / addressing the concerns?**

    - Several other methods for halo cleaning were studied, using quadrupole and dipole excitation (with normal conducting quadrupole magnets, with the ADT and with crab cavities). One interesting option is to use the ADT with shaped noise, and the studies should be continued as tool to explore the halo.
    - All these methods rely on detuning with amplitude - not obvious for the HL-LHC beams with complex footprints, different for the different bunches, and changing during the operation cycle.
    - A faster orbit feedback than the present system would not clean the halo, but mitigate beam losses induced by orbit jitter. Such feedback could be limited to the collimation section.

- **Are there other e-Lens applications that could improve HL-LHC performance? Abort gap cleaning, inducing frequency spread, ...**

  - There are some application of an e-lens when using a hollow beam, others would require a different beam profile.
  - With halo cleaning it might be possible to set the collimators closer to the beam, therefore gaining margin in the aperture which would finally allow to further reduce beta*. However, the gain in integrated luminosity would be small.
  - Other bonus features (not drivers): enhanced collimation; scraping functionality; control of impact parameters on collimators for ions; complementary halo measurement;
  - With a Gaussian profile, a tune spread could be generated when the beams are not in collisions, possibly helping the octupoles for fighting instabilities.

- **What are the consequences of having an e-Lens / having no e-Lens on other systems (e.g. BI for halo diagnostics) and are these consequences acceptable?**

  - An e-lens requires space that cannot be used for other systems. Since alternatives for using this space were not presented, the committee cannot comment.Halo diagnostics is obligatory in any case. Biggest impact is presumably to collimator system and the potential for dumping high intensity halo near or above damage limit.

3. Recommendations

Implement active beam halo control using a hollow e-lens

- The extrapolation of the observed losses to HL-LHC are close to the limit of what is acceptable during operation. This does not even consider halo generating effects related to higher bunch intensity and new failure modes due to operation with crab cavities. These risks and the large energy stored in the beam halo of 35 MJ justify an active control of the beam halo.
- The hollow e-lens is by far the best technology to achieve this objective, as clearly demonstrated in the Tevatron.
- An e-lens available in Run 3 would allow exploration of halo cleaning in the HL-LHC beam parameter regime.

Address with high priority failure modes of the crab cavities

- The failure modes of crab cavities are not well understood. Beam induced oscillations in case of a cavity failures observed at KEK should be analysed and a model should be developed to understand failure modes and resulting oscillations. Failure modes of the HL-LHC crab cavities should be investigated experimentally during the SPS tests, including tests with high beam current.

Pursue tests with bunch intensities as planned for HL-LHC during Run 2

- Consider machine development sessions with bunch trains to test beam losses, tail formation and beam stability with beams similar to HL-LHC, despite the limitation of beam that can be delivered by the injectors (e.g. 50 ns bunch spacing in case of high bunch intensity).