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 1 and Run 2.

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.

2. Questions to the reviewers

- **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 have been measured in all phases of operation. Scaled with HL-LHC beam parameters, the energy stored in the beam halo above 3.5 σ 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 associated 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 σ). 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 σ. 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 and challenging 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 operational tolerances for such devices need to be established (e.g. correct centring, 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, with the core 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 have been 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 halo reduction.

   - All these methods rely on detuning with amplitude. This is not obvious for the HL-LHC beams, which have complex footprints, with different detuning for the different bunches, and detuning which changes 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) include: 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 in tackling 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. The biggest impact is presumably to the collimator system and the potential for dumping high intensity halo near or above damage limit.

3. Recommendations

1. 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 potentially large energy stored in the beam halo of order 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.

2. 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.

3. 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. The committee recognizes that these tests would have to respect the limitations of beam that can be delivered by the injectors (e.g. 50 ns bunch spacing in case of high bunch intensity).

4. Findings and comments

4.1. Introduction, Oliver Brüning

There are two main motivations for an installation of a hollow e-lens for HL-LHC: suppression of beam loss spikes and protection from very fast losses (within 3 - 5 turns) due to failures of the crab cavities.

Any decision in favour of an e-lens needs a strong motivation. E-lenses are not in the baseline, the budget starts to be frozen as HL-LHC enters into the construction phase. There is space required for such installation that is competing with low/high harmonic RF, ADT and beam profile monitors.

4.2. Overview and introduction including an outline of the existing installation options, optics conditions, infrastructure requirements (cryogenics, power), tools for halo measurement and timeline (planning need for the technical design etc.), S. Redaelli

Findings:

The performance of the LHC during Run 2 with the collimation system has been excellent, with luminosity exceeding nominal, and energy close to nominal. The challenges for the collimation system in the HL-LHC era are operating with 700 MJ beam energy, high bunch intensity, bright beams, impedance, robustness, physics debris, ground motion, cultural noises, operational efficiency plus operation with crab cavities (CC) and luminosity levelling. The upgrade of the collimator system for HL-LHC includes new dispersion suppressor collimators and collimators with novel materials for robustness and impedance reduction.

In order to produce two e-lenses in time, go-ahead is required by end of 2017. Another year of technical design and studies is required before final TDR. Production within the LARP collaboration as in-kind contribution is an option – a statement by January 2017 is required.

Driving motivations for an e-lens are the active control of the beam halo to mitigate loss spikes, e.g. in case of orbit jitters, and to reduce risk of damage with highly populated halos. Losses can be mitigated through the cycle, in particular of interest when going into collisions with high losses from tails due to beam-beam effects (Long Range & Head On). Static control of tails during long stores – continuous depletion for hours – controls the halo population for fast failures of 700 MJ beams.

Key requirements are to select cleaning for particles by transverse amplitude and to adjust depletion rates in time ranges that depend on operational scenario. The effect on the core must be negligible. A “non-material” scraper in the collimation hierarchy adds scraping functionality but particles are disposed of by the present collimation system.

Bonus features (not drivers): enhanced collimation; scraping functionality; control of impact parameters on collimators; new accelerator physics studies; complementary halo measurement. Active halo control could also boost performance, e.g. allow tighter IR7 hierarchy for larger beta* reach and operation at smaller crossing angle.

Drawbacks are an additional complex system: the halo can become too clean for machine protection; risk for loss of Landau damping if tails are removed; perturbations of beam from residual fields and imperfections. Switching off in case of unexpected problems would always be an option.

The cost estimate varies, but is in the order of 5 MCHF for 2 units when built at CERN.

The design of a hollow lens for HL followed a CDR produced together with FNAL could be finalised in less than 1 year. There is an interest by US-LARP and other partners to contribute to construction.

Comments

- How much energy is expected in the HL-LHC beam halo? Today, about 5% or the particles are routinely outside 3.5 σ. Will this be the same with the increased bunch intensities of about 2.2e11 ppb?
- Distribution of halo is double Gaussian from measurements? Again do we expect the same in the HL era? What mechanisms are populating the tails?
- Worry about very fast failures. Survival limits of collimators in fast failure mode - 8 nominal bunches at present (1 -2 MJ).

4.3. Loss and lifetime observations during nominal operation and their extrapolation to HL-LHC parameters, Belen Maria Salvachua Ferrando

Findings

Observations of the beam lifetime during Run 1 (2011 and 2012) and Run 2 are used for scaling to HL-LHC parameters. In 2012 many lifetime drops were observed, in particular during the beta-squeeze and adjust (bringing beams into collision) phase. The reasons for the lifetime drops are not always understood; some appeared repeatedly at the same point in the cycle (e.g. at beta* = 1.3 m). The lifetime in 2015 and 2016 was much better than in 2012, and was at least one hour. Reasons for low lifetime can be incorrect optics parameters (e.g. tune and coupling), orbit movements, instabilities and beam-beam.

Scaling to HL-LHC assumes operation at 7 TeV, twice the nominal LHC beam intensity, and limits of the power that collimators can accept of 200 kW and 500 kW. From Run 1 scaled to HL-LHC, 45/282 fills would be dumped by the 500 kW limit, and 57/282 fills would be dumped for the 200 kW limit. Scaling from Run 2: 1/135 fills would be dumped for the 500 kW limit, and 22/135 fills would be dumped for 200 kW limit.

The validity of such scaling is not obvious, since the HL-LHC parameter are very different from today's parameters, in particular the bunch intensity will increase by a factor of two. An e-lens for tail depletion would give more margins.

Comments

- What scaling is reasonable? Scaling from 2012 to HL-LHC appears to be too pessimistic, scaling from 2016 perhaps too optimistic.
- What power for the collimation system should be assumed for HL-LHC?
- For what type of lifetime drops would an e-lens help?
- The presence of a beam halo helps to detect incorrect accelerator settings and provides an advanced warning in case of fast failures.
- Is it possible to investigate in MD operation with bunches of higher intensity in order to learn more about the lifetime dependence on bunch intensity?

4.4 What did we learn about HALO population during LRBB (Long Range Beam Beam) studies and MDs? Yannis Papaphilippou

Findings

- Experience from 2012 shows that long range beam-beam effects had significant impact on losses in the first hour of the fill and on emittance blow-up. Both losses and blow-up in the first hour were brightness dependent.
- Long range beam-beam experiments in 2015 and 2016 showed a limit of 8.5 σ separation for triggering significant losses correlated to long-ranges.
- Heavy tails and larger emittances may be more sensitive to LRBB effects.
- Dynamic aperture (DA) simulations show margin for crossing angle reduction in HL-LHC (beam stability depends also on chromaticity and octupole settings).
- The beam profiles were fitted to be non-Gaussian, especially for beam 1.
- In order to have a significant impact on lifetime (<10 h) and emittance blow-up, DA has to drop to 3 σ. For DA larger than 5 σ and in the absence of other implications, lifetime should be comfortable (~40h).

Comments

- A significant difference between beam 1 and beam 2 is not understood.
- How reliable are these extrapolations?

4.5 What did we learn about HALO population during MDs and regular operation? Gianluca Valentino

Findings

- The diffusion coefficient and particle escape times are measureable. Beam tails are clearly depopulated during the ramp.
- The experience in operation and with dedicated collimator scans for halo measurements at the LHC demonstrate that scans provide good diagnostics for precise measurements below 5 σ. Several measurements were performed at different energies and beam conditions
- Halo population was observed in a majority of cases, the beam tails above 3.5 σ are more populated than a standard Gaussian by a factor 20.
- Diffusion speed and escape times provide valuable input for HEL operation in HL-LHC.

Comments

- The numbers presented need checking as there was some scaling discrepancies.
- The presence of 5% of beam in tail > 3.5 σ was observed for all energies, this is a very important measurement. This needs further follow-up to understand if this is the case for other operational scenarios.
- Could coupling have an impact on halo measurements and give misleading results?
- Diamond BLMs are now available that allow to measure losses per bunch, this is a very interesting instrument that should be used for tail studies.

4.6 Observations and measurements on the impact of earthquakes and cultural noise on the LHC operation and their extrapolation to HL-LHC parameters, Michaela Schaumann

Findings:

- Measurements of the ground motion around CERN have been reported, including long-distance earthquakes and cultural noise. The response of beam orbits are simulated and compared with the evolution of LHC.

Comments:

- Such effects will be amplified at HL-LHC due to higher values of the beta function at the triplets. The ground motion and the associated vibration of magnets can be the source of the observed emittance growth. Further investigation is encouraged.
- The relative orbit difference between two beams should depend on the wave length of the ground motion and the direction of the wave. Thus the simulation should be done for two beams and compared with luminosity data.
- A non-vibrating ground motion, so-called ATL law, should be discussed together with vibrations to discuss the long-term stability of the machine.

4.7 Operational experience from HERA and their extrapolation to the HL-LHC, Mike Seidel

Findings

- Loss spikes during stable beam were a problem at HERA as these tripped frequently the detectors.
- Collimator jaws in HERA were damaged by the beam, and ~5 mm deep grooves were created. It is not know when or how this happened.
- Tune modulation was tested as a method to compensate for power supply ripples, and also to create controlled amplitude-dependent diffusion. The method was not used in routine operation.
- A tomographic reconstruction of the phase distribution allows for plotting the distribution as a function of action. For a Gaussian distribution in phase space the density falls exponentially with increasing action and a density plot with a logarithmic action axis can reveal deviations from a Gaussian distribution.

Comments

- HERA is significantly different from the LHC due to the synchrotron radiation fan in the interaction region, and not all experience from HERA is relevant for the LHC.
- Loss spikes during stable beam were not observed at LHC and RHIC.

4.8 Operational experience of RHIC electron lenses and their effect on collimation and halo populations, Wolfram Fischer

Findings

- At RHIC, e-lenses are used for compensation of head-on beam-beam effects.
- The e-lenses are operated 1 to 1.5 hours per store. A large number of over 100 stores were performed in 2015.

- The operational experience with the system is good. No equipment failures were observed. No store was aborted due to the lenses.
- Enhanced beam loss rates (1-2%/h) were observed during operation of the electron lens. A few stores were affected by instabilities in the electron beam of one of the two lenses at high currents.

Comments

- RHIC demonstrates successful and reliable operation of an electron beam lens in a large collider on a routine basis.

4.9 Operational experience from Tevatron and relevance for HL-LHC, Alexander Valishev et al.

Findings

- The Tevatron used a 2-stage collimation system with 4 primary W jaws, and 8 secondary L-shaped collimators. In one accident, jaws of the Tevatron collimation system were damaged and showed several mm deep grooves.
- Beam losses, especially uncontrolled beam losses, were a major factor in the Tevatron Run II collider operation. Transition modes like ramping and squeezing had the highest likelihood for losses due to the complex long-range beam-beam interactions.
- The Tevatron electron lenses demonstrated very high reliability and were routinely used to clean the abort gap of uncaptured beam. The lenses were also used in tests to compensate for long-range beam-beam effects, and to improve collimation with a hollow lens.

Comments

- Long-range beam-beam interactions in the Tevatron were global due to the common beam pipe for both the proton and antiproton beams. In the LHC the long-range beam-beam interactions are limited to the interaction regions.
- The high reliability of the Tevatron and RHIC electron lenses gives sufficient confidence that a hollow electron lens can be operated reliably in the LHC.

4.10 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

Findings

- A luminosity model including IBS, synchrotron radiation and luminosity burn off is used for the analysis of the LHC data in 2012 and 2016.
- The observed transverse emittance growth is always higher than the predicted values for colliding and non-colliding bunches in both planes. The evolution of the longitudinal emittance agrees better with the IBS prediction.
- Additional artificial transverse noise can explain the gap.

Comments

- One should continue to investigate the source of the possible noise. Some most probable sources are vibration and noise in the power supplies especially at the IR triplets. This has been already looked at; re-examination is encouraged.

4.11 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

Findings

- The basic behaviour of the crab cavity at several types of failures has been reported. Single cavity failure (including 1-turn) seems manageable, multi-cavity failures are proportionally worse.
- The importance of beam-cavity interaction has been noticed. This brought a large amplitude horizontal oscillation of the beam at trips of crab cavity at KEKB.

Comments

- The beam-cavity interaction should depend on the orbit offset at the cavity and tuning error of the crab mode. Estimation for the allowable range for these parameters must be done.
- Construction of a model for the beam-cavity interaction is necessary. One should start with a regular model for general impedance source considering coupled-bunch instability. Such a model is necessary before the beam test at SPS. One should also try to explain the beam oscillation observed at KEKB.
- One failure mode is a quench of one or more crab cavities, e.g. due to showers from a dust particle traversing the beam. Would it be conceivable to install a wire scanner in front of the crab cavities in the SPS to perform quench tests with beam losses?

4.12 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

Findings

- In case of a failure the beam will be extracted by the Machine Protection System. The time after the detection to fully extracted beams is up to three turns. A number of very fast failure modes have been analysed (D1 magnet, quench heater firing, missing beam–beam kick after the extraction of one beam, crab cavity failure).
- The most critical failure mechanisms are related to crab cavities, e.g. a fast change of voltage and a fast change of phase, for one or for more than one cavity. In case of a phase slip of 60 degrees the core of the beam will be deflected by up to about 1.5 σ, oscillate, and risks to hit collimators.
- The beam energy deposited in the collimators depends critically on the number of particles in the beam halo, and on parameters such as orbit position in the primary collimator, phase advance etc. In case of one crab cavity failure, the impact on the collimators might still be

acceptable. In case of several cavities failing at the same time, the oscillation can lead amplitudes that will damage the collimator system.

- If only one beam is extracted, the missing beam-beam kick will lead to a sudden deflection of the other beam. The amplitude can be up to 1.1 σ. This can be tolerated, in particular if it is considered that both beams are normally dumped at the same time.
- Halo cleaning can mitigate fast failures, in particular for failures of one crab cavity. A complete halo depletion is not desired, since some particle in the tails are useful as witness particles in case of fast failures. The monitoring of tails in the presence of fast failure modes is important to ensure efficient machine protection.

<u>Comments</u>

- It is an important priority to better understand failure mechanisms of crab cavities. The test in the SPS is considered to be very important in this regard.
- The simulations should take into account errors on orbit, beta beating, etc.
- One should reiterate studies on beam-beam deflection, with the most recent HL-LHC parameters. Can the deflection after a crab cavity failure plus the beam-beam kick on the beam that is extracted after the first beam add up?
- For multiple failure with oscillation of 3 σ halo depletion does not help.

4.13 Measured effects of depleted halo population with hollow e-lens and relevance for HL-LHC, Giulio Stancari

<u>Findings</u>

- Successful operation of a hollow e-lens for many periods of tens of minutes was demonstrated.
- Within a certain error margin (measurement was affected by emittance growth for other reasons), no adverse effect on the core emittance was found. No effective closed orbit kick was introduced by the hollow electron beam and this was verified using measurements of difference orbits.
- The halo cleaning can be limited to parts of the bunch train with a rise time of ≈200 ns. Faster switching times should be technically possible, if required.
- The increase of the diffusion rate in the beam halo was measured and confirmed using collimator retraction experiments. The suppression of existing periodic modulation of the loss rate was demonstrated as well. These experiments address directly the potential application in LHC.

<u>Comments</u>

- Experience at Tevatron and RHIC demonstrated reliable operation of an electron lens in a hadron storage ring.
- In particular the experiments at the Tevatron address directly issues for the application in the LHC and are valuable to assess the risks associated with a hollow electron lens in the LHC. Based on this experience the committee is convinced that the concept can be successfully implemented in the LHC.

4.14 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

Findings

- A number of alternative methods to deplete the halo were considered including the application of tune modulation, resonant excitation with the transverse damper (ADT), resonant excitation with crab cavities, the use of long-range beam-beam interactions, and a fast orbit feedback. These often use existing hardware.

Comments

- The alternative methods generally rely on amplitude dependent detuning to select particles in the tail for extraction while leaving the core unaffected. This requires a good knowledge of the amplitude dependent detuning, a quantity that changes dramatically when going into collision and gradually throughout the store.
- The use of long-range beam-beam interactions is likely not possible since several classes of bunches have different long-range interactions, and the crossing angle is not a free parameter.
- The alternative methods also provide study tools for halo detection and depletion while no electron lens is available.

4.15 Potential performance reach for the HL-LHC in case of a depleted beam halo, Gianluigi Arduini

Findings

- The HL mode of operation will rely on luminosity levelling to limit the pile-up, e.g. by beta* changes or separation. Such levelling has also advantages for long-range beam-beam effects. This has not been proven in operation yet and might imply larger loss spikes.
- It might be possible to push performance with depleted halos. Assuming the collimators to be at 4.5 σ, beta* could be reduced, e.g. from 20 to 16 cm or even 13 cm, with reduced margins between MKD and TCT. This leads to a modest increase in integrated luminosity of ~2% and a reduction in pile-up density.
- For other operation scenarios an e-lens might be of interest, e.g. when using wires for LRBB compensation, flat optics, and full compensation of crossing angle with crab cavities or crab kissing.
- The beams are expected to be stable for all configurations, but rely on the impedance reduction measures. It will become more difficult if the collimators are further closed, leaving smaller margins for e-cloud effects etc.
- The stability diagram is used to address the effects of cutting distribution. Tails help - without tails more octupoles strengths is required.
- Instabilities generated from coupling between e and p beam need to be evaluated.

Comments

- A hollow e-lens will help during ramp-up, reduce sensitivity to injected beam parameters, changes in machine configuration, emittance, beam tails. In general, e-lenses would give more margin for operation in the HL-LHC regime.
- There are a number of synergies with other developments.

5. Appendix

Meeting agenda

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