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LHC Collimation Review 2019, report of the review committee

Review committee:

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Introduction and charge to the committee

The main objective is to review the collimation system of HL-LHC in view of the LHC Run1 and Run2 experience and the suitability for installation in the LHC. The review will examine the upgrades in the experimental and cleaning insertion regions as well as the new cleaning systems in the dispersion suppressor regions of P7 and P2.

Presented material can be found under: https://indico.cern.ch/event/780182/overview

General comments and recommendations

The excellent performance of the collimation system contributed to the success of LHC, particularly the increase of luminosity via reduction of beta* over time. Efficiency and reliability of operation was strongly improved by automated methods and the use of integrated BPM's. Particle tracking, impedance calculation and radiation transport simulations were improved over time, showing good agreement with measurements. With the development of MoGr collimators and low impedance coatings, important improvements were achieved.

Overpopulated beam tails (5% of beam intensity beyond 3.5 rms beam widths) were measured using collimator scraping scans. Profile measurements using collimators are destructive and time consuming. In order to understand better the origin of these tails, improved diagnostics should be made available for monitoring the tail distributions during the run. Furthermore the committee recommends to perform a comprehensive beam dynamics study, aimed at developing a diffusion model for the LHC that reproduces the observed amount of beam in the tails.

Using the hollow electron lens will allow removing tails continuously in a controlled way, providing safety margin for accidental beam movements. In addition the enhanced halo diffusion would result in a wider impact parameter distribution on primaries, thereby improving cleaning efficiency. The committee supports the realization of the electron lens concept.

The team is encouraged to establish an overview table on power loss to elements, such as collimators, magnets, walls, masks around the ring during the different operating phases.

The reach of beta* and intensity are key parameters for HiLumi LHC. The committee recommends exploring all capabilities of the upgraded collimation system to approach the ultimate performance.

If single limitations are identified, such as the gap dependent energy deposition in TCDQ, mitigation strategies should be developed.

Simulations of cleaning efficiency and energy deposition should be performed by taking into account multiple imperfections, for example jaw flatness, gravitational sagitta, angles, aperture imperfections.

Charge Questions I and Answers

Is the collimation system in the present baseline addressing the design criteria required for the HL-LHC operation?

Yes.

Charge Questions I: Findings

The HL-LHC will double the bunch intensity and stored beam energy to almost 700 MJ. In normal operation the HL-LHC collimation system must be able to sustain a continuous beam lifetime of 1 h, and a beam lifetime of 0.2 h for 10 s (corresponding to 1MW power).
In off-normal operation, the collimation system must be able to sustain the impact of

1) injection errors that lead to 288 bunches of 450 GeV energy with 5 σ (σ = 0.7 mm) orbit excursions
2) asynchronous beam dumps in which 8 bunches of 7 TeV energy hit the TCSPM and TCPPM with 5 σ orbit excursion
3) an asynchronous beam dump in which 1 bunch of 7 TeV beam energy hits the TCTPM with 500 μm distance from edge.

The present LHC collimation system comprises 118 collimators (108 movable, 10 fixed). Primary and secondary collimators are made of carbon-fiber composite (CFC), and tertiary of tungsten alloy. More than 18 collimators in the LHC already have integrated BPMs. The LHC and HL-LHC impedance budget is dominated by collimators. Octupole strength settings that ensure beam stability were found to be about a factor 2 larger than calculated.

The LHC collimation system improved the cleaning efficiencies over the years with tighter collimator settings and has reached an excellent cleaning efficiency. Peak losses in operation are observed when beams are put into collision. The LHC had only one instance of an asynchronous beam dump, and with only 4 bunches stored the beam was extracted cleanly to the dump.

The HL-LHC collimation upgrade consists of 4 pillars:

1) impedance reduction through metallic secondary collimators
2) dispersion suppressor cleaning improvement (with or without 11 T dipoles)
3) new interaction region collimation
4) consolidation of all collimators not upgraded, faster alignment and a new control system.

Replacement of all secondary CFC collimators with bulk MoGr or bulk MoGr coated with 5 μm Mo would reduce the impedance by 40% and 60% respectively. The inner triplet is the IR aperture bottleneck, and the critical limiting loss location will still be in the dispersion suppressors (DS).

Charge Questions I: Comments

It is not known how the tail population (presently up to 5% of intensity in the amplitude range >3.5 σ) scales with the bunch intensity. In the HL-LHC 5% of the intensity corresponds to 35 MJ of stored energy, which has a substantial damage potential.

The operational experience in the LHC shows a low probability of a beam lifetime below 1 h. Nevertheless, in view of planned higher intensities and the operation with crab cavities, the collimation design criteria should maintain the requirement of sustaining a possible beam lifetime of 0.2 h for 10 s to account for rare but potentially damaging conditions.

Considered the complexity of simulations, a factor 2-3 agreement of the calculated beam loss monitor signal with measurements is a remarkable achievement.

No operational experience with LIU beams can be gained before the LHC Run III.

Charge Questions II and Answers

Are the original design criteria of the collimation system validated by the LHC Run1 and Run2 experience and by the various tests carried out on each component? Is there room for modifications or simplification after the LHC Run1 and Run2 evaluation and what would be the resulting risk implications?

Yes, all concepts have been validated by tests.

A primary collimator (TCP.C6L7.B1) and a secondary collimator (TCSPM) were successfully tested with beam. Beam position monitors integrated in collimator jaws were used already in 18 collimators installed in the LHC. The impedances of MoGr jaws (without coating and with coatings of Mo and TiN) were evaluated through the observation of the LHC beam tune shift as a function of gap opening. The outgassing specification of all collimators of a flux not exceeding approximately 10^{-7} mbar·l/s was demonstrated in TCA, TCD, TCL, TCP, TCS and TCT. The TCSPM require the integration of NEG cartridges to meet the outgassing specification. Quench limits were experimentally determined to be 20-30 mW/cm^3 (with Pb beam only, the LHC did not quench with p beam so far).

Charge Questions II: Findings

The MoGr bulk material is close to the vacuum acceptance limit, in some case a factor 2 above acceptance. This can be mitigated by NEG cartridges.

The impedance reduction of the collimators is addressed through the use of MoGr as a less resistive material, the additional Mo (or TiN) surface coating for the secondary collimators and tapering to reduce the geometric impedance.

The surface coatings comply with the vacuum standards of adherence. Mo-coated MoGr was tested for vacuum with one surface coated. The vacuum performance was a factor 2-3 worse than without coating. An additional heat treatment of coated MoGr at 400°C is necessary to recover uncoated MoGr outgassing levels.

Beam impact tests were done with 55% of the HL-HLC bunch intensity (but equivalent density).

There are still some discrepancies in calculated vs observed quantities (a factor 2 in tune shift of Mo jaws, a factor 2 in octupole strength to ensure stability, a factor 3 on observed BLM signals).

A 5^{th} axis with +/- 10 mm range in case of "soft damage" of the jaw allows longer operation time without impacting too much the impedance budget for secondary collimators. However, it may be difficult to detect damage.

Charge Questions II: Comments

The committee is impressed by the presented results on the R&D, design, prototyping and production of advanced jaw materials, optimized collimators and critical hardware components for the system.

We congratulate the teams on the careful follow-up on the prototyping and production, carefully addressing non-conformities and developing mitigation measures. In particular we acknowledge the outstanding performance of the collimator controls including the sensors and actuators. The availability of the system is remarkable.

Quench tests are necessary to validate the simulations and should be given adequate priorities, in particular for the new 11 T dipoles.

Beam tests in the HiRadMat facility provide important insight for problems that are difficult to assess, such as the adherence of surface coating.

Charge Questions III and Answers

Review the observed hardware performance during the present prototype production: are there non-conformities and how relevant are they for the HL-LHC operation and could they limit the HL-LHC performance reach (or the LHC performance for the collimator installed in Run3)?

The project presented the status of collimator production. Several non-conformities or potential issues were identified, e.g. in the roller screw quality, measured resistivity of material, vacuum outgassing. All of them were carefully analyzed and solutions were implemented. A few studies are still ongoing, in particular on radiation hardness of the final material. For the presented results we conclude that the ongoing collimation upgrade has no evident shortcomings. We expect that the upgraded collimators in production will fully deliver the specified improvements and will therefore contribute to maximizing collimation performance reach for the next decades of LHC operation.

Are the observed hardware characteristics compatible with the HL-LHC operation requirements?

The presented collimation upgrade plan includes novel hardware components that address several critical issues for HL-LHC operation. We list the most important hardware improvements of the overall system that were presented to us:

- Improved collimator hardware for reduction of both resistive and geometric impedance.
- Jaw materials for improvement of cleaning efficiency.

- A new local collimator in the dispersion suppressors that protects super-conducting magnets against localized peaks of beam loss from specific physics processes in the primary collimator jaws (single diffractive scattering of protons, ion fragmentation).
- Improved collimator control with smoothened movement of jaws, resulting in reduced stress for the mechanical movement systems and thus longer component lifetime.
- NEG cartridges for vacuum optimization.
- A crystal assistance system for ion operation that has the potential of allowing for higher ion beam intensities. (not baseline)
- A hollow electron lens for limiting power in the beam tails and providing more resilience to beam perturbations. (not baseline)

We conclude that the hardware specifications and test results presented to us represent highly significant and important improvements to the system. We could not identify any incompatibility with the HL-LHC requirements. As only residual major worry we point out the missing conclusion from radiation damage tests for the new MoGr material with coating.

Review in particular the motivation for using coated MoGr as collimator material [robustness, likelihood of damage and impact of damage on the rest of the machine] also based on the LHC Run2 operation: Is the use of MoGr as collimator material well justified or could other materials with better conductivity or other combination of jaw bulk material with coating be used instead?

The Mo coating of the jaws with MoGr bulk material reduces the collimator-induced impedance and therefore directly maximizes performance reach of the LHC. The speakers presented careful investigations of the coating in terms of resistivity, adherence, robustness against damage and vacuum performance. The committee is impressed with the quality and completeness of the studies. The choice of MoGr material with Mo coating is supported, subject to successful radiation damage tests.

Charge Questions III: Findings

The MoGr bulk material is close to or slightly outside of the acceptance limit for vacuum outgassing rates, in some cases even a factor 2 above the acceptance criterion. NEG cartridges mitigate the vacuum risk.

Impedance minimization is addressed on two fronts.

1) Low impedance material, namely MoGr plus a Mo coating, for secondary collimators reduces resistive impedance.
2) Tapering of the collimator jaws reduces geometric impedance.

The effect of Mo-coating on the vacuum performance of MoGr was tested with one surface coated. Vacuum performance was a factor 2-3 worse than without this coating. An additional heat treatment of coated MoGr at 400°C allowed to recover the outgassing level of uncoated MoGr.

The 5th axis of movement for the collimator tank has a range of +/- 10 mm. In case of “soft damage” of a jaw coating this movement will allow continuing operation with an undamaged part of the coating such that the impedance budget for secondary collimators stays acceptable.

Charge Questions III: Comments

The committee is impressed by the presented results on R&D, design, prototyping and production of advanced jaw materials, optimized collimators and critical hardware components for the system. We acknowledge the careful follow-up on the prototyping and production, adequately addressing non-conformities and developing mitigation measures. In particular we congratulate the team for the outstanding performance of the collimator controls including the sensors and actuators. The availability of the system is remarkable.

Charge Questions IV and Answers

Is the cleaning upgrade envisaged for the DS still justified and good enough for both proton and ion beams at their maximum intensities or are there alternative solutions?
Yes, the IR7 DS collimator upgrade and proposed position is required for ions, is a reasonable compromise and should be executed.

Is the IR cleaning envisaged for the HL-LHC well justified or are there alternative solutions?
The proposed IR1/5 cleaning with TCLX collimator and masks provides a good solution with sufficient margin for power deposition.

Is the choice of installing collimators in the dispersion suppressors of point 7 still adequate taking into account the results of proton and ion operation in Run 1 and 2 including crystal tests.
The DS upgrade in point 7 is still adequate, taking into account the results from runs I, II.

Charge Questions IV: Findings

The presented scheme of DS collimators in-between a pair of 11T magnets in IR7, and in a connection cryostat in IR2 leads to just acceptable heat deposition in s.c. magnets, both for proton and ion operation.

The development of the 11T magnet prototype is sufficiently advanced and performance requirements are inline to be met.

The upgraded IR cleaning schemes with additional tertiary collimators for IP1/5 provide sufficient suppression of losses. The situation is well understood.

Charge Questions IV: Comments

For the case of the minimal 0.2 h lifetime, the calculated power deposition of 50 mW / cm^3 in the 11 T magnet coil is just below the estimated quench limit of 70 mW / cm^3. The assumed power deposition is already multiplied with an empirical factor of three in order to account for a discrepancy between measured and predicted loss rates. This correction factor illustrates the uncertainty of the prediction. There are reasons to believe in the correctness of the calculated quench limit, but the tolerance is small. For such critical parameters margins should be specified and potential mitigation measures be established. In case of operational problems, going back to the original baseline with two pairs of 11T magnets and two collimators per side could be considered as a long-term solution.

The schedule of the 11 T magnet production is rather tight and presents a risk that installation in LS2 cannot be achieved. The possibility of installation in EYETS is a backup.

The IR1/5 cleaning scheme will be less constrained after Run-3 in the HL era, due to absent Roman pots.

TCTs in cells 4 and 6, made either from W or CuCD, are fully safe over a realistic range of setting. Thus Tungsten can be chosen as cost effective solution. In the unlikely case of a single bunch impact the collimator had to be exchanged. If the team decides to pursue the CuCD variant, the case for this solution should be strengthened.

Crystal collimation shows excellent performance for ions. This option should be further developed especially for ions, but not be considered as a replacement for DS collimators.