Update on non-conformities and their evolution. Potential limitations for HL-LHC

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Outline

- Introduction
- Current non-conformities
- Possible time-evolution of non-conformities
- Sensitivity to missing circuits
- Conclusions and outlook

Introduction

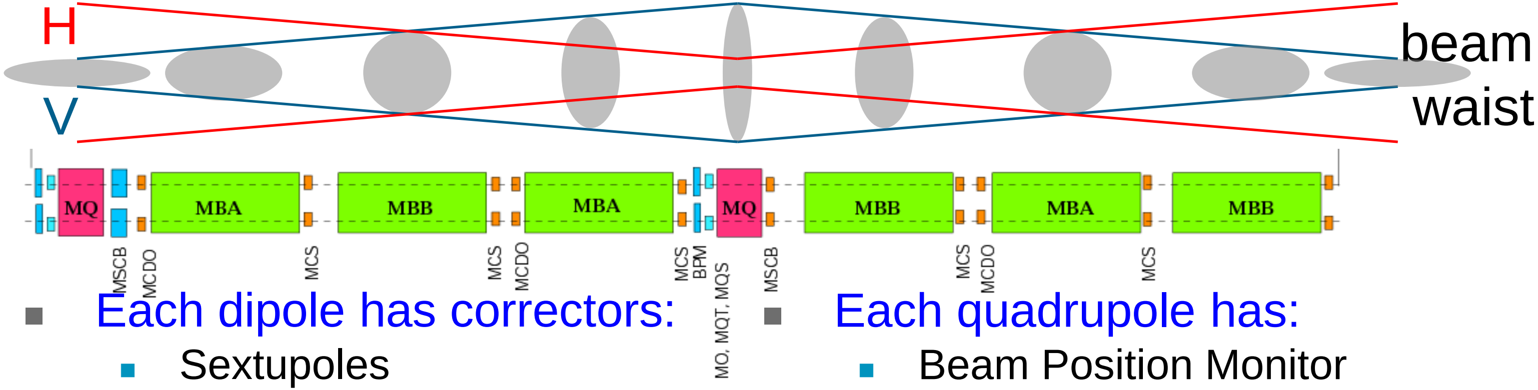
- Different types of non-conformities
  - Limiting beam energy
    - Actively discussed now to devise a strategy to push LHC energy towards nominal
  - Affecting in general beam dynamics
    - Either imposing limits to single magnets or circuits
- When these non-conformities appeared?
  - Sometimes before the production stage
  - During the hardware commissioning periods preceding physics runs

Introduction

- How to cope with non-conformities?
  - Fixing them directly
    - Not always possible due to time (**and other**) constraints
  - Using the **flexibility** of the LHC design
    - For instance compensating the issues using other magnets
    - Changing the strategy to operate the LHC based on the experience gained

Introduction

- Classes of magnets affected
  - Main magnets (dipoles and quadrupoles)
  - Orbit correctors (also for crossing scheme generation)
  - Cell correctors



- Each dipole has correctors:
  - Sextupoles
  - Octupoles and decapoles
- Each quadrupole has:
  - Beam Position Monitor
  - Dipole corrector
  - Sextupoles
- Some have
  - Trim quadrupole, skew quadrupole, skew sextupole, octupoles

Non-conformities limiting beam energy

- **Disregarding main dipoles**
  - D3.L4: slow training, reached only 5784 A instead of **5860 A** (corresponding to **6.9 TeV**).
    - It is believed that no fundamental limitations would prevent this magnet from reaching the nominal performance.
  - Q5.R2: reached 4202 A instead of **4310 A**.
    - It is believed that no fundamental limitations would prevent this magnet from reaching the nominal performance. During operations and MDs in 2016, hence including also ATS optics, the maximum current is never exceeding **3000 A**.
  - MQMs at 4.5 K: Q5.R1 and Q6.L8 that required many more training quenches to reach **4100 A.**
    - Also these two magnets are not expected to limit the overall machine performance.

Only potential limiting magnet is D3.L4, but it does not seem to be a show stopper.

Otherwise, the energy will be limited or the magnet should be replaced.

Non-conformities appeared during production stage - I

- **MQTLI** (long trim quadrupole)
  - Q11: a **single MQTLI** with MQ in **all IRs**
  - Q10: a **single MQTLI** with MQ in **IR3 and 7**
  - Q9: a **double MQTLI** with MQ in **IR3 and 7**
  - Q8, Q7: a **single MQTLI** with MQ in **IR3 and 7**
- The MQ is in series with the arc MQs. Hence, the MQTLI is the degree of freedom for optics matching.
- During the production stage some of the MQTLIs proved to be "weak", i.e., did not reach the nominal performance.

Non-conformities appeared during production stage - II

- **Mitigation measure**: install the weak MQTLIs in IRs in which the optics is rigid and strength margins can be evaluated. Hence weak magnets were installed in
  - IR3 and 7
  - IR6 (**the role of IR6 has changed with the advent of ATS for HL-LHC as the left side of the IR contributes to the squeeze of IR5**)
- **During hardware commissioning campaigns**
  - MQTLI in Q11L6: **further** reduction of operational current (2009)
  - MQTLI in Q11.R5: reduction of operational current (2008-9)
  - MQTLI in Q9L7.B1: reduction of operational current (2009)

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Are these signs of degradation? See later

Current non-conformities

- Some of the NCs date back to 2009, while others have been found in LS1.
- Optics configurations have been adapted (or can be adapted) to these NCs.

A. Verweij, LMC, 13/5/2015

Circuit	Comments
60 A	2 condemned circuits
80-120 A	4 circuits with reduced I_{PNO}
600 A	1 condemned circuit 6 circuits with less magnets 27 RQTL, 2 RU, and 15 RCD circuits with reduced I_{PNO}
IPQ	2 circuits with 4-lead powering
Triplets	4 condemned correctors 1 corrector with reduced IPNO Some constraints for powering of RCBXH/V-RCSX3-RCTX3
RQD/F	-
RB	-

← **This is certainly an improvement for operation!**

60-80-120 A circuits - I

Colour code:

- **Black -> Run I NCs**
- **Orange -> from LS1**

- **RCBH31.R7.B1**, **RCBV26.R5.B1**: correctors condemned. Not too serious, but orbit bump in the region should be monitored as there are strong MOs close by and feed down effects might be relevant (already confirmed to be the case in 2012).

- **RCO.A78.B2, RCO.A81.B2**: in each circuit 2 out of 77 magnets are bypassed. This has a marginal impact on performance as
  - b_4 component in MBs is smaller than anticipated
  - RCO strength can be adjusted to compensate for missing magnets.

60-80-120 A circuits - II

A. Verweij, LMC 13/5/2015

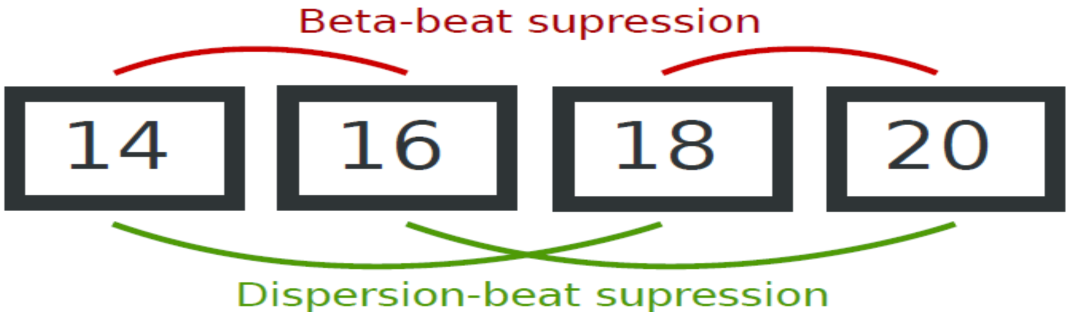
Circuit	Comments
RCBYH4.R8B1	I_{PNO} limited at 50 A if used at 0.67 A/s. I_{DELTA}=0 A.
RCBYHS4.L5B1	I_{PNO} limited at 50 A if used at 0.67 A/s. I_{DELTA}=0 A.
RCBYHS5.R8B1	I_{PNO} limited at 40 A with 0.3 A/s. I_{DELTA}=0 A. (was 20 A with 0.6 A/s during Run-1)
RCBYV5.L4B2	I_{PNO} limited at 50 A if used at 0.67 A/s. I_{DELTA}=0 A.

- **RCBYH4.R8B1, RCBYHS5.R8B1**: impact on crossing angle for LHCb. The strength is limiting the crossing angle at top energy with injection optics -> reduced angle to 230 μrad. Increased to nominal value (250 μrad) during squeeze. No side issues.

- **RCBYHS4.L5B1, RCBYV5.L4B2**: no impact on performance.

600 A circuits - I

- Short to ground of **MQT.18.L1.B1** in circuit RQTF.A81.B1
  - Bypassed 4 MQT magnets in SSSs 14.L1, 16.L1, 18.L1, and 20.L1.
  - 2 % peak beta-beating is generated in Arc 81, only.



Courtesy A. Langner and R. Tomas

- **All RSD/F**: Acceleration reduced (0.25 to 0.15 A/s^2).
- **RU.R4**: ramp rate reduced to 0.08 A/s (acc.=0.0025 A/s^2).

600 A circuits - II

- **ROD.A34B1, ROF.A34B2**: in each circuit 2 out of 13 magnets missing (in Q28R3 and Q32R3). Minimum loss of Landau octupole strength. **The circuit will be recovered in LS2**.
- **RCS.A34B2**: 3 out of 154 magnets bypassed. Not a problem for overall correction of b_3 in sector 3-4.
- **ROD.A56B1**: limited to 450 A (all others brought to 590 A). Overall strength available is more than nominal.
- **RCD.%**: I_PNO reduced to 450 A (except RCD.A78B1/2). More than enough for compensating b_5 (apart from sector 7-8).
- **RSS.A34B1**: Circuit condemned. Not used during Run 1 and considered not essential for Run 2.

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600 A circuits - III

- **RCS.A78B2**: recent NC.
  - For LHC an alternative solution has been proposed (distribute the strength of the circuit to the other RCSs).
  - Studies with ATS optics during MDs showed no particular performance degradation (see later).
  - Impact on HL-LHC optics performance should be assessed (see later).
- **RCBXH/V.%**: The H and V magnets are individually commissioned with I_{PNO}=540 A, except RCBXH1.L5 (490 A). For combined powering they are commissioned to

$$I^2_H+I^2_V < 400^2\,A^2.$$

In Run 2 the crossing and separation bumps are generated using all MCBXs to overcome strength limitations.

ITs

Circuit	Specific magnet	Description	NC	Action	Resolved
RQX.R1	Q1	Faulty electrical insulation of QH vs GND	1017174	Change of the heater voltage and capacitance of the redundant quench heater power supply	Yes
RCBX%	MCBX	Nested H and V magnets. Current lead cooling problem	1027950,1027951	Modification lead cooling during LS1	Yes (after LS1)
RCBXV3.L8	MCBXV	Quenches at flat-top			No
RCOSX3.L1	(MCOSX)	Circuit open	948545	Will not be repaired. Circuit condemned	No
RCOSX3.L2	(MCOSX)	Circuit open after beam impact	1203477	Will not be repaired. Circuit condemned	No
RCOX3.L2	(MCOX)	Circuit open after beam impact	1203478	Will not be repaired. Circuit condemned	No
RCSSX3.L2	(MCSSX)	Circuit open after beam impact	1203479	Will not be repaired. Circuit condemned	No
RCSSX3.L1	(MCSSX)	Circuit trips at 62.9 A	1053719	I_NOM reduced from 100 to 60 A	Yes*

- Correctors circuits not used so far.
- Possibly needed only at small beta* (i.e., for IR2 only in ion operation).
- NCs already considered and **are not believed to be a limitation for LHC**.

Possible time-evolution of non-conformities - I

- **Are there signs of degradation in some of the non-conformities?**
  - With the information available to-date the answer is: **probably not**.
- **Is the situation fully monitored?**
  - Also in this case the answer is: **probably not**.
- Hardware commissioning is usually extremely compressed in time
  - Aims at maximum efficiency -> test the magnets at the level needed for operation plus a small margin
  - Aims at avoiding generating stress in the magnets -> minimise the number of training quenches

Possible time-evolution of non-conformities - II

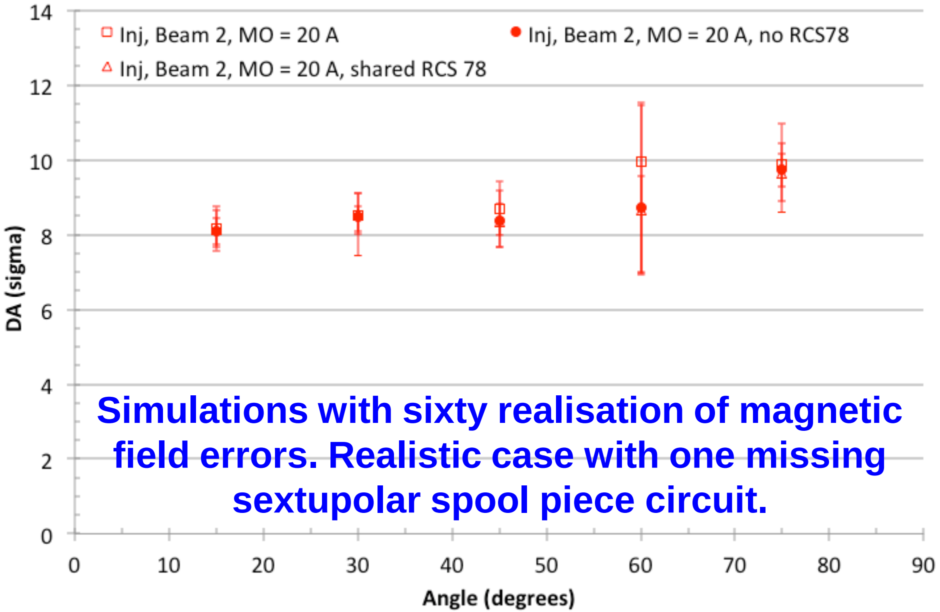
- Given all that, in most of the cases the magnet limit (below nominal) is beyond the level tested in hardware commissioning.
  - Hence, any slow degradation risks to be invisible.
- Probably a different approach should be used
  - A **selected** number of non-conforming magnets should be tested so to assess the actual performance limit at each hardware commissioning campaign.
  - This would provide useful information while keeping the hardware tests short enough.

Sensitivity to missing circuits

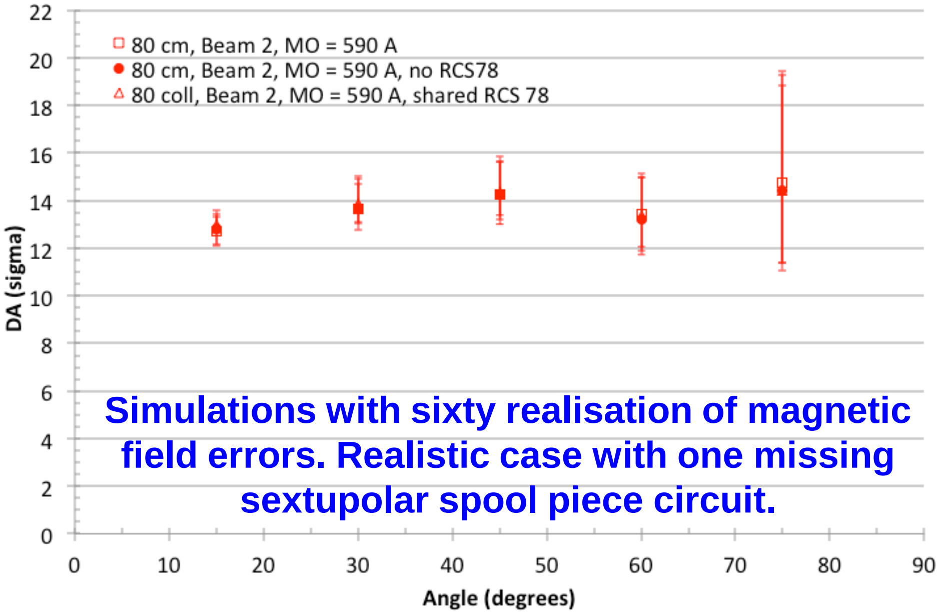
- Margins are present in the LHC design and are (partially) inherited by HL-LHC.
- These margins provide robustness against non-conformities.
- A delicate issue is the impact of non-conformities of the spool pieces on machine performance.
  - This scenario is already affecting the LHC (see previous slides)
  - Is HL-LHC equally robust against non-conformities of spool pieces?
- **Failure scenarios should be devised**
- **Mitigation strategy should be found**
- **Figure of merit: dynamic aperture**

Sensitivity to missing circuits: LHC

- Failure scenarios
  - Missing one or more circuit of spool pieces
- Mitigation strategy:
  - Sharing the missing strength among **all** remaining circuits



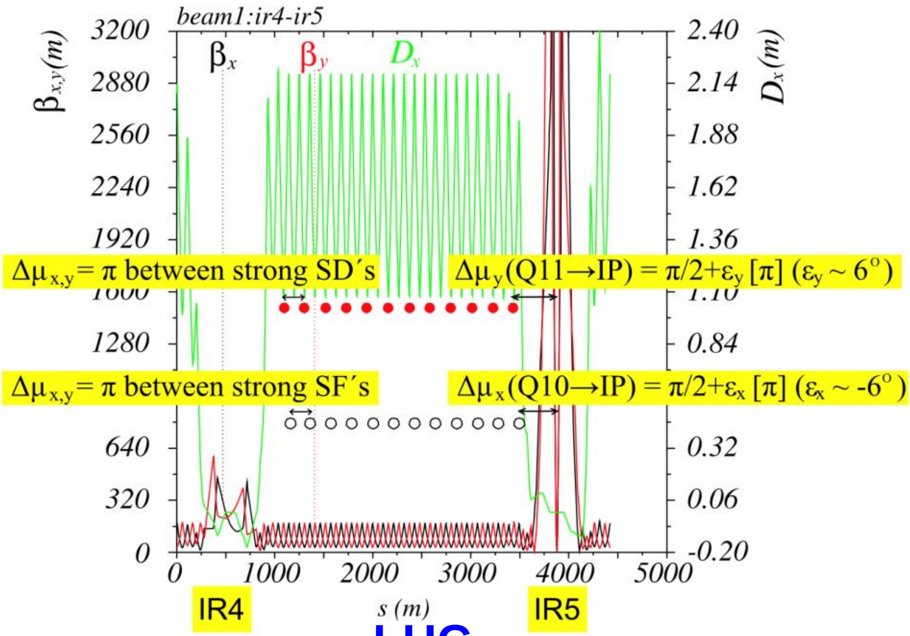
Simulations with sixty realisation of magnetic field errors. Realistic case with one missing sextupolar spool piece circuit.



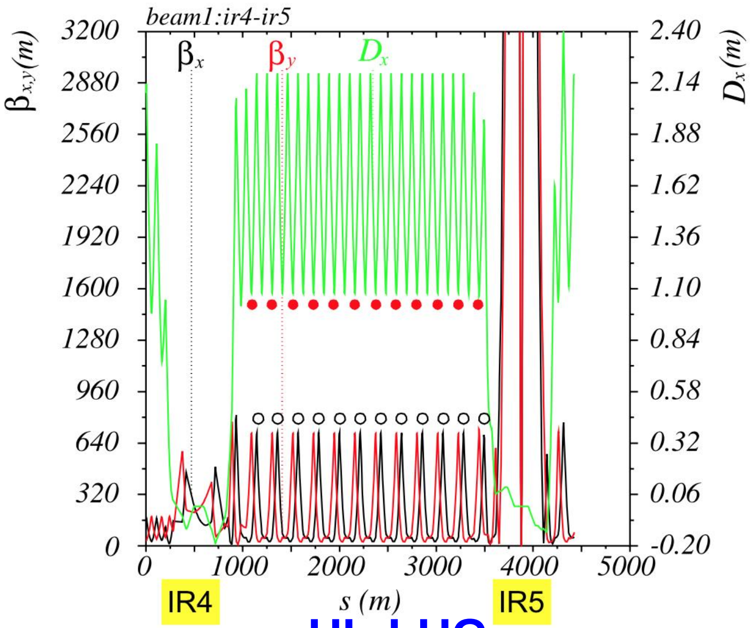
Simulations with sixty realisation of magnetic field errors. Realistic case with one missing sextupolar spool piece circuit.

Sensitivity to missing circuits: HL-LHC - I

- Unlike LHC, HL-LHC features two types of arcs with different values of beta-functions.



LHC

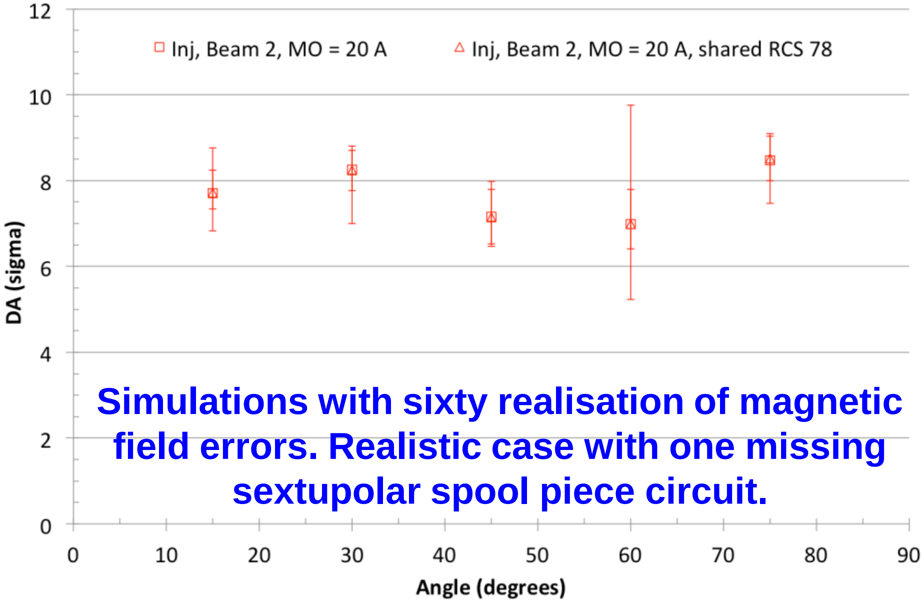


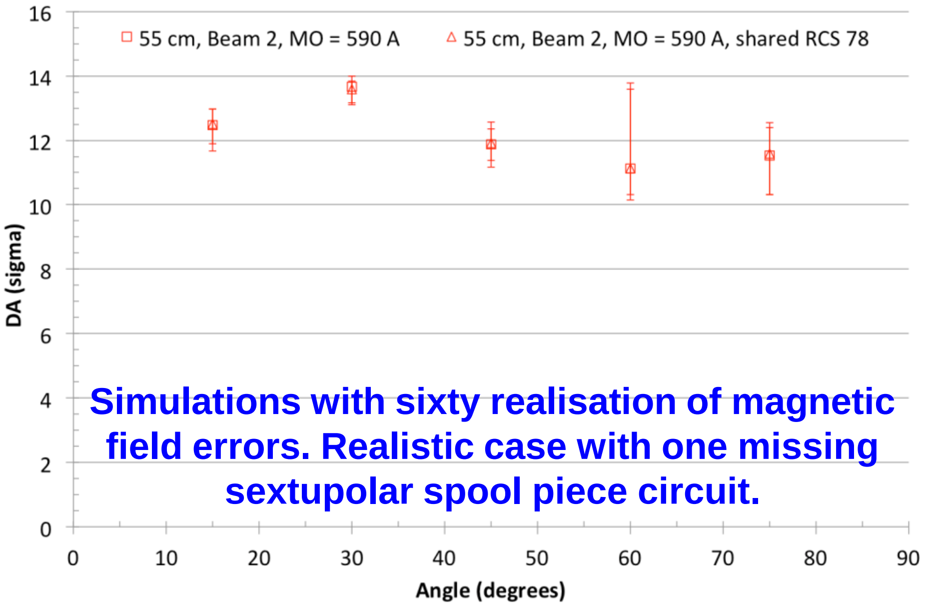
HL-LHC

S. Fartoukh, PRSTAB, 16, 111002 (2013)

Sensitivity to missing circuits: HL-LHC - II

- Mitigation strategy (LHC with ATS, used in MDs)
  - Sharing the missing strength among remaining circuits **of the same type of arcs**





Conclusions (for LHC)

- Current non-conformities should not limit LHC performance.
- Mitigation measures have been found and implemented in the optics configuration (e.g., optimisation of bump shapes/strength requirements).
- Some non-conformities will be fixed in LS2
  - Missing octupole circuit in sector 3-4
  - Restoring beta-beating optimisation from initial MQ slot assignment
- **Time evolution of non-conformities should be monitored with appropriate checks during hardware commissioning**

Conclusions (for HL-LHC)

- **RCBYH4.R8B1, RCBYHS5.R8B1**: limit IR8 crossing scheme.
- **RCBYHS4.L5B1**: this assembly should be moved to a Q5 in IP1/5 and its strength is essential.
- **MQT.18.L1.B1**: short to ground.
- **ROD.A56B1**: limited to 450 A.
- **All RSD/F**: Acceleration reduced (0.25 to 0.15 A/s^2).

These circuits are important enough to carry out further checks to assess their status, and to plan for repairing actions.

- **RCS.A78B2**: circuit condemned.
- **RSS.A34B1**: circuit condemned.

These circuits are important, but additional studies should be carried out to assess the actual impact on machine performance. The outcome of such studies should indicate whether repairing actions are needed.

Thank you for your attention!

Sensitivity to missing circuits: HL-LHC - III

- Mitigation strategy
  - Test other options