Lessons learnt from HL-LHC interaction region magnets: two case studies of Nb-Ti

E. Todesco, J. C. Perez, A. Musso CERN, TE Department, MSC Group

F. Toral, J. Garcia Matos, C. Martins, CIEMAT

T. Nakamoto, M. Sugano, S. Enomoto, K. Suzuki, KEK

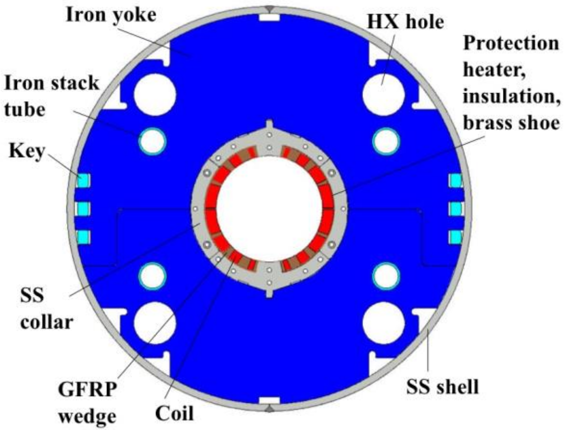
MT-27, 16 November 2021

CONTENTS

- A tentative classification of issues
  - Well known processes that are not done with enough care / fall between interfaces /have been forgotten
  - Continue to optimize beyond targets, and finally introduce issues rather than a not needed improvement (the better is the enemy of the good)
  - Unknown, new technical challenges due to the fact of entering unexplored regions of magnet parameters
- I will deal with two success stories in HL-LHC of the third type
  - Case 1: the field quality in separation dipole D1 in KEK
  - Case 2: the performance of the nested corrector in CIEMAT/CERN

THE CASE OF FIELD QUALITY IN D1: DESIGN

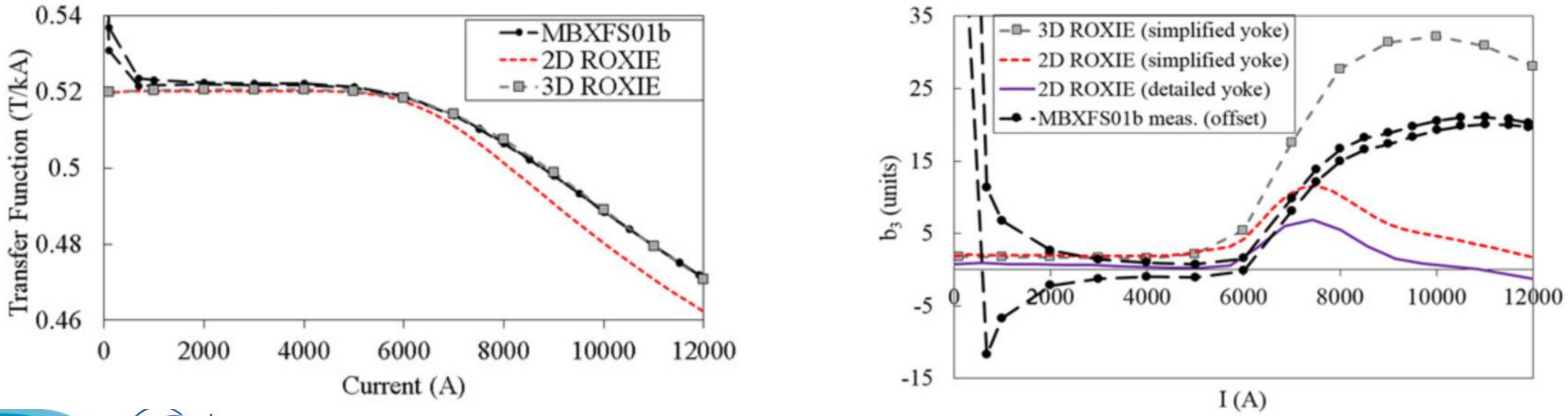
- D1 is a Nb-Ti magnet, 5.6 T bore field, 150 mm aperture
- Field quality is particularly challenging:
  - Small ratio (0.2) between coil width (15 mm) and magnet aperture (75 mm) → the field quality more sensitive to positioning tolerances
  - Thin spacers are used to maximize the field contribution of iron and to have a mechanical support from the iron →iron saturation plays a relevant role
  - As a comparison, iron saturation in the 8.3 T LHC dipoles decreases the magnet transfer function by 0.7%; in HL-LHC D1 saturation decreases the magnet transfer function ten times more (9%)
  - The acceptance range for b3 is (-3,+3) units



D1 cross-section
(T. Nakamoto, et al.)

THE CASE OF FIELD QUALITY IN D1: THE ISSUE

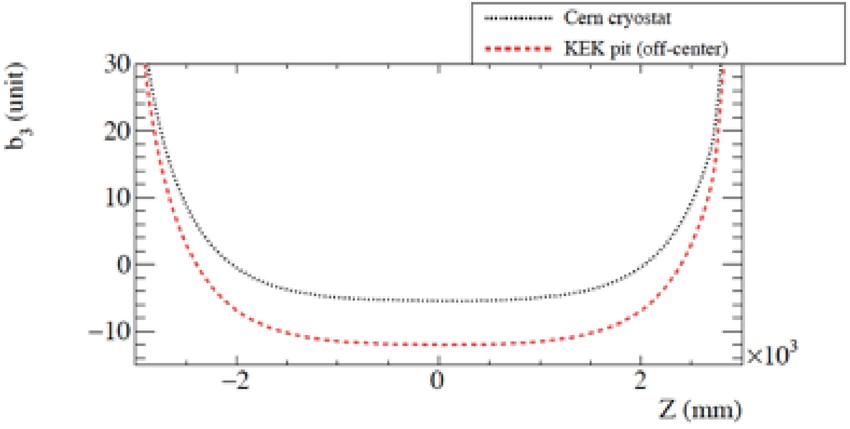
- The issue found in 2017 is related to an unexpected large contribution of the 3D effects to the saturation component of b_3 in the straight part of the magnet
  - This effect is quantified in 30 units, one order of magnitude above the specified acceptance window
  - It is due to the large saturation component, coupled to the large aperture
  - This effects is still visible in the 7-m-long magnet, and has to be taken into account



Impact of 3D modeling on transfer function (left) and b_3 (right) of D1 short model
(S. Enomoto, T. Nakamoto, et al. IEEE Trans. Appl. Supercond. 27 (2017) 0600705)

THE CASE OF FIELD QUALITY IN D1: THE SOLUTION

- Action taken: iteration on the cross-section to remove the effect
  - Second and third short model were built with the new cross-section
  - After a second iteration (due to other issues) done on the prototype magnet, b_3 values are now below 10 units
  - A third iteration will be carried out in the first series magnet to bring b_3 and b_5 well centered around zero



Measured b3 in D1 prototype, KEK, and expected in final cryostat
K. Sukuzi, T. Nakamoto, M. Sugano, et al.

- Action taken: check also other projects to verify that this effect was absent (or not so relevant)
  - Done for D2 magnet and 11 T in E. Nilsson, et al., IEEE Trans. Appl. Supercond. 28 (2018) 4003005

THE CASE OF FIELD QUALITY IN D1: RISKS AND TIMELINE

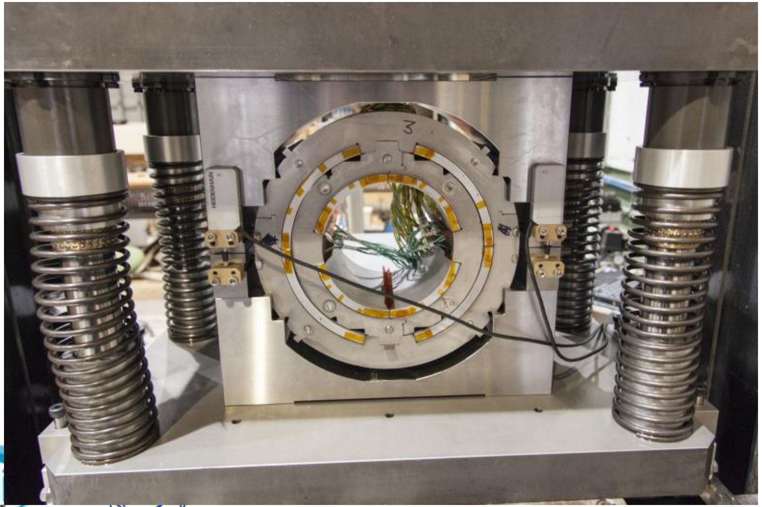
- Risk associated to the change were minimized by
  - Keeping the same design for the cross-section, i.e. the same numnber of blocks, the same number of conductor per blocks to avoid making radical changes to the coil
  - Correct the field quality by minimizing the changes in the position of the conductor blocks of no more than 0.5 mm
  - Avoid changing the end spacers since this is well below the toleracnes of assembly, and one does not want to risk introducing other unknowns
- Timeline: the feedback loop has been 1.5 years
  - This effect can be measured only on the magnet during powering test (being related to saturation, room temperature measurements are not relevant)
  - Therefore, the final validation has a feedback time of order of 18 months (ordering new parts, coil winding, magnet assembly, test)
  - It was not posing special problems to the project since there was time available (D1 activities started as early as 2011)

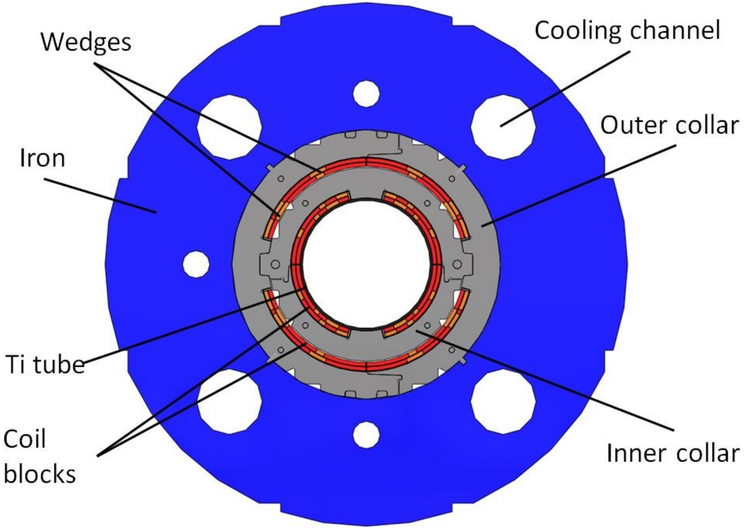
CONTENTS

- Case 1: the field quality in separation dipole D1 in KEK
- Case 2: the performance of the nested corrector in CIEMAT/CERN

THE CASE OF QUENCH PERFORMANCE IN THE NESTED CORRECTOR: DESIGN

- The nested correctors are Nb-Ti nested dipoles providing 2.1 T in H/V plane with any powering combination, in a 150 mm aperture
- In combined powering mode, the torque is particularly challenging
  - For this reason, a double collaring structure was selected
  - The double collaring lock is a prima

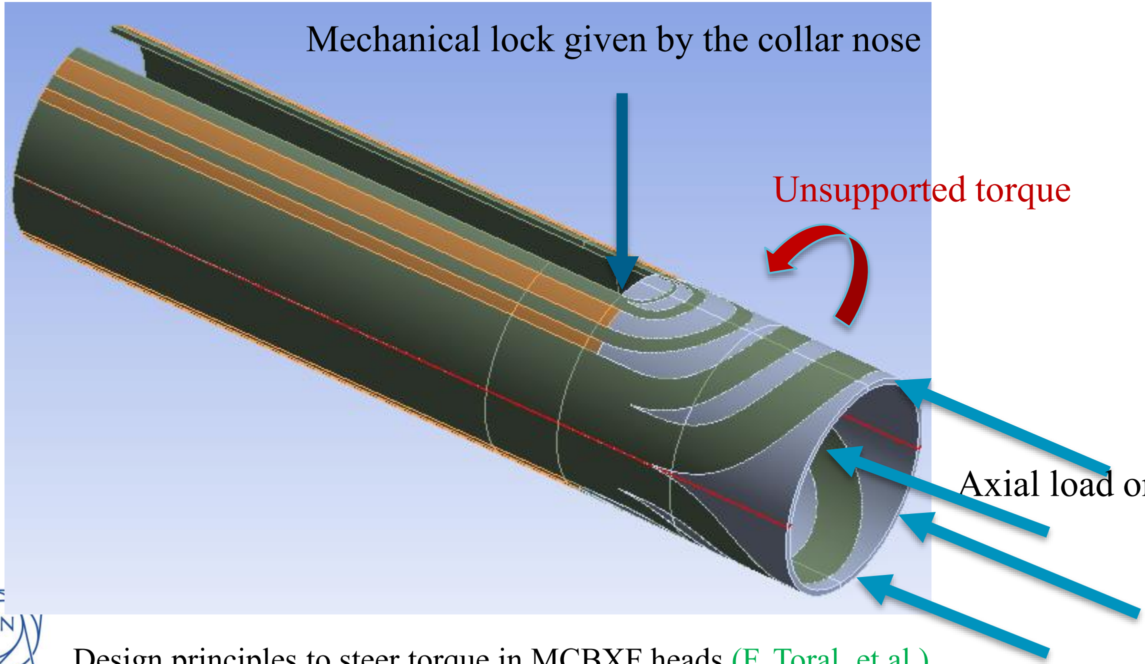




MCBXF cross-section (F. Toral, J. C. Perez, et al.)

THE CASE OF QUENCH PERFORMANCE IN THE NESTED CORRECTOR: DESIGN

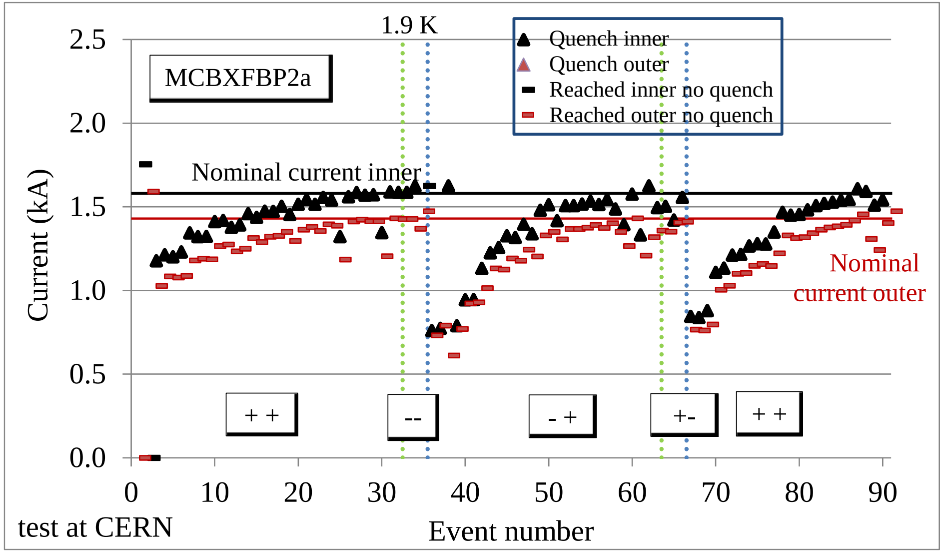
- The torque in the coil ends is not mechanically locked but relies on axial support and mechanical lock in the centre



Design principles to steer torque in MCBXF heads (F. Toral, et al.)

THE CASE OF QUENCH PERFORMANCE IN THE NESTED CORRECTOR: THE ISSUE

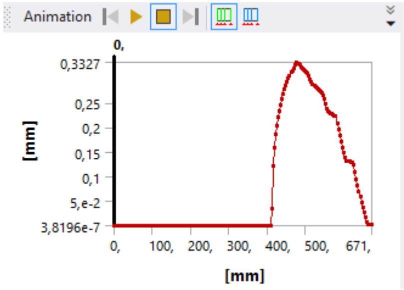
- The torque in the end of the magnets caused training
  - The magnet could reach performance supporting the torque expected for operation in nominal conditions, but with training
  - Therefore, when changing the torque sign, the magnet needed retraining – limitations on accelerator were explored, compatible with operation but if possible better to improve



Quench performance of MCBXFBP2 (F. Toral, J. C. Perez, S. Ferradas Troitino, et al.)

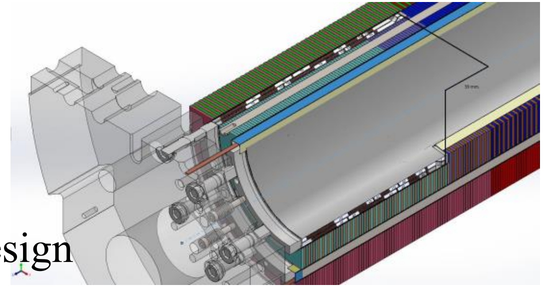
THE CASE OF QUENCH PERFORMANCE IN THE NESTED CORRECTOR: THE SOLUTION

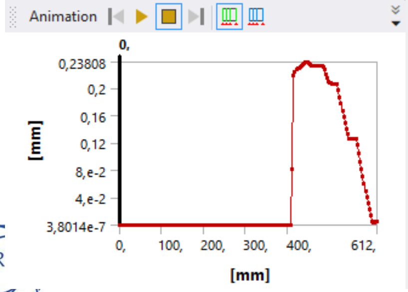
- Idea: (i) reduce the displacement due to the unsupported torque in the coil heads via a realignment of the two dipoles and (ii) increase the head rigidity via longer end spacers whose legs are locked in the straight part



	Length [mm]	Value [mm]
1	0,	3,8251e-007
2	3,3383	3,8197e-007
3	6,6766	3,8196e-007
4	10,015	3,8208e-007
5	13,353	3,8197e-007
6	16,692	3,8197e-007
7	20,03	3,8209e-007
8	23,368	3,8198e-007
9	26,706	3,82e-007
10	30,045	3,8212e-007
11	33,383	3,8201e-007
12	36,721	3,8203e-007
13	40,06	3,8215e-007
14	43,398	3,8205e-007

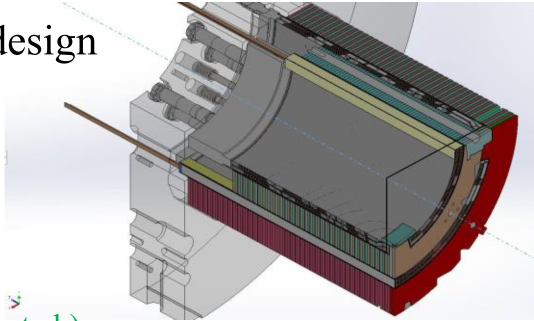
Old design





	Length [mm]	Value [mm]
1	0,	4,2765e-007
2	3,0448	4,2707e-007
3	6,0896	4,2701e-007
4	9,1343	4,2702e-007
5	12,179	4,2709e-007
6	15,224	4,2711e-007
7	18,269	4,2702e-007
8	21,313	4,27e-007
9	24,358	4,2703e-007
10	27,403	4,2712e-007
11	30,448	4,2704e-007
12	33,493	4,2698e-007
13	36,537	4,2697e-007
14	39,582	4,2702e-007

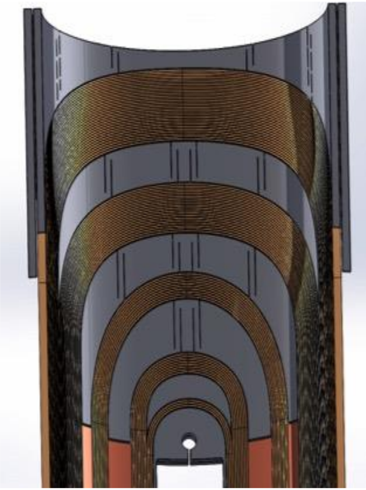
New design



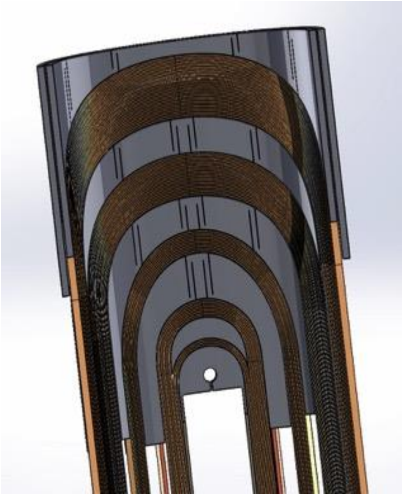
Expected displacement in coil heads (F. Toral, et al.)

THE CASE OF QUENCH PERFORMANCE IN THE NESTED CORRECTOR: THE SOLUTION

- Idea: (i) reduce the displacement due to the unsupported torque in the coil heads via a realignment of the two dipoles and (ii) increase the head rigidity via longer end spacers whose legs are locked in the straight part



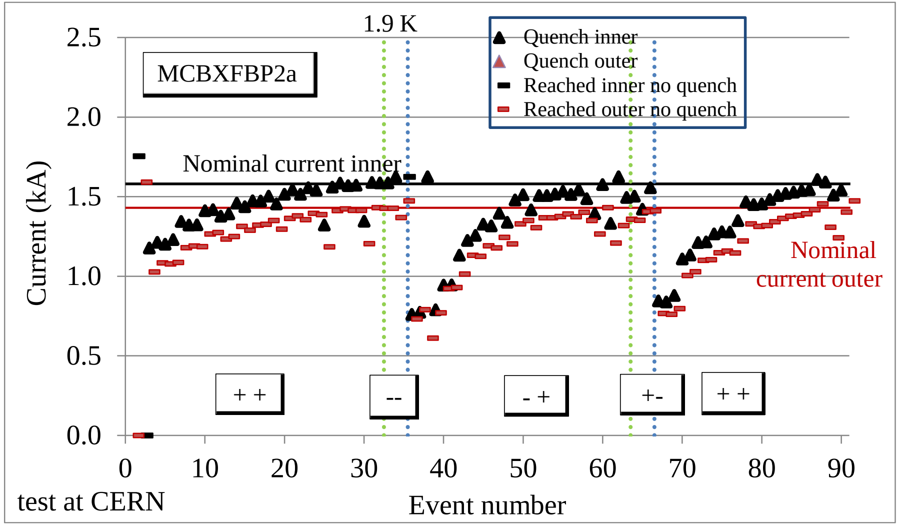
Old design

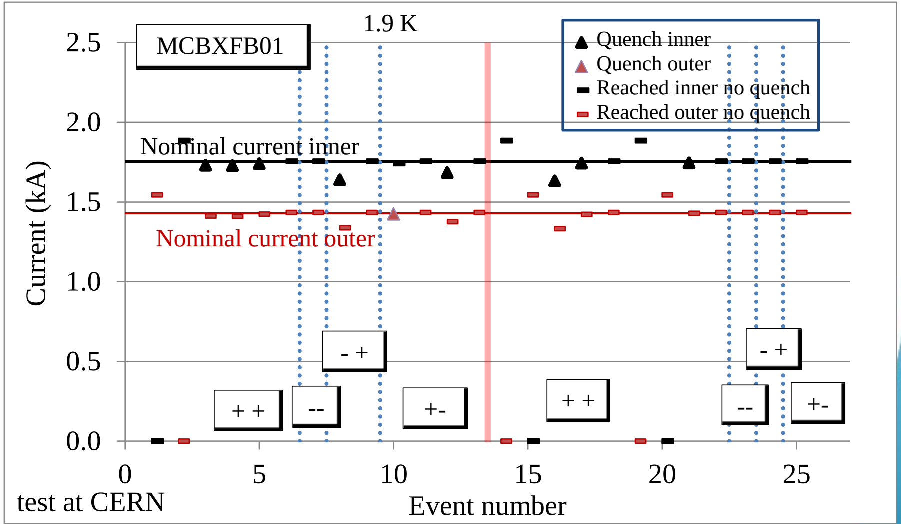


New design

THE CASE OF QUENCH PERFORMANCE IN THE NESTED CORRECTOR: THE SOLUTION

- Test of the design change was carried out in August 2021, and revealed major improvements
  - Few quenches needed for training rather than 30





Quench performance of MCBXFBP2 (left) and MCBXFB01 (right) (F. Toral, J. C. Perez, S. Ferradas Troitino, et al.)

THE CASE OF QUENCH PERFORMANCE IN THE NESTED CORRECTOR: RISKS AND TIMELINE

- This change came at a quite advanced phase of the project
  - Tendering to industry was ongoing
- Risk associated to the change were minimized by
  - Having the possibility of testing on one magnet before implementing in the production
- The performance improvement was so relevant that avoiding having a proof of reproducibility was considered to be a minor risk with respect to the time required for a second magnet (6 months)
- Timeline: the feedback loop has been 1 year
  - First proposition of the design change was in September 2020, magnet was tested in August 2021

CONCLUSION

- We presented two success stories of design iterations in the Nb-Ti magnets of HL-LHC project
  - More complete view about HL-LHC, including issues in E. Todesco et al. SUST 34 (2021) 054501
- In both cases, the issues were related to complex technical issues that were not considered/known at the time of design and enginnering
- Test, analysis, modeling, solution, implementation, and test again: this loops takes 1-1.5 years in the presented cases
  - This is a feature that makes superconducting magnets so difficult: the feedback loop is very long and one always has to afford the risk of a certain degree of parallel activities
- All actions were taken to minimize the risks associated to these design changes
  - Make them reversible
  - Make them minimal