Minutes of the 3rd Meeting of the Quench-Test Analysis Working Group, 23.08.2013

Present: Bernhard Auchmann, Mateusz Bednarek, Chiara Bracco, Francesco Cerutti, Vera Chetvertkova, Bernd Dehning, Pier-Paolo Granieri, Eva Barbara Holzer, Wolfgang Hofle, Anton Lechner, Agnieska Priebe, Stefano Redaelli, Mariusz Sapinski, Nikhil Shetty, Arjan Verweij, Daniel Wollmann

Vera: Summary of MAD-X particle tracking simulations for quench tests with orbital bumps and comparison (by Nikhil) of FLUKA results with measured signals in the BLMs

Fast Losses Quench Test

The MAD-X analysis of the fast ADT quench test attempts to replicate the actual optics conditions in the LHC during the test. The following MAD-X parameters are subject to critical uncertainties: The orbit bump offset, which was set with the help of collimators to 4.3 σ_{nom} from the beam screen wall; the beam size and shape, which was measured roughly a minute before the test and fitted by a Gaussian distribution; the evolution of the tune during the test; and the β-function in MQ.12L6.

β-function: The detailed model used in the analysis contains a thin lens every centimeter of the MQ magnet. It corresponds within 10% to the "official" thick-lens model of the LHC optics. This parameter was therefore not further studied. For the other uncertainties parametric studies were performed to estimate their influence on the longitudinal and temporal loss distribution:

Beam size: The measured horizontal emittance of 5.19E-7 was compared to the nominal horizontal emittance of 3.5E-6. Simulations show that the longitudinal loss profile is virtually independent of the emittance within this range, whereas the loss duration is three times longer for the larger emittance.

Mariusz: The emittance was small because we needed it small to obtain fast losses. It was a low-intensity beam that was scraped to the desired size. The wire-scan measurements were fitted by a Gaussian distribution. This exercise should maybe be repeated offline to obtain a better idea of the actual beam shape during the test.

Tune: Three cases were studied: 1) Starting from the measured tune of 64.28 the tune was left to evolve during the establishment of the 3-corrector bump. The final value was 64.274. 2) An additional matching-step brought the tune at the end of the 3-corrector bump setup to 64.268. 3) The tune was set to the 3rd integer value of 64.333 for purely academic purposes. It is likely that option 1) represents the actual testing conditions best. As for the longitudinal distribution, options 1) and 2) differ by about 30% in amplitude, whereas options 1) and 3) differ by more than 100%. A similar behavior is observed in time. It is worth noting that in option 2) more than 50% of the total number of particles is lost within a single turn. The real loss distribution in time is best approximated by the integer-tune option 3), even though it is clearly the most unrealistic one.

Bernd: Why is there an effect on the longitudinal distribution due to a change of tune?

Vera: The kick-strength changes with the tune. The change in the distribution is probably due to the different kick strength.

Bump amplitude: Three offset (distance from bump to beam screen) values are studied: 4.3, 1.66, and 8.3 σ_{nom}. Smaller offsets lead to spatially shorter distributions. The longitudinal variation between the three values stays within 30%, the amplitude remaining almost constant. The time distribution is significantly different for the 1.66 σ_{nom}, and almost identical for the others.

The model of the ADT excitation has been updated in the following way: The ADT excitation is set to match the tune. Over the duration of the excitation, the ADT settings are now updated three times to follow the tune in the simulation. In this way an even better fit between measured and simulated horizontal beam position at the ADT could be achieved.

Anton: The FLUKA simulations use the longitudinal distribution in the turn with the highest losses. The time distribution is not taken into account.

Daniel: Therefore we need not search much longer to improve the time distribution, since all studies show that the longitudinal distribution is rather stable.

Mariusz: Still, matching the BLM signal's time distribution would increase the confidence in the MAD-X model.

Bernhard: And the losses in the coil scale linearly with the MAD-X results. The insensitivity of the BLM signals to changes in the longitudinal distribution leaves a relevant margin for error in the coil losses.

Independent of the above parametric study, three longitudinal loss profiles were sent to the FLUKA team for comparison: The first model considered a beam-screen inner radius of 2.2 cm, corresponding to the design value minus tolerances for shape and placement. The second model had the beam-screen inner radius at the design value of 2.325 cm. This value is usually used in FLUKA. And the third model used the design beam-screen dimension and the tune-matching during ADT excitation described here above. The three longitudinal distributions differ by about 40% in amplitude and length. Nonetheless, FLUKA simulations by Nikhil show that the simulated BLM signals are not sensitive to this kind of variation. The best MAD-X model, i.e., the one which is probably closest to the real settings in the LHC, is the third model, which does not match the tune after the establishment of the orbital bump, and updates the ADT settings during the excitation.

Mariusz: Is there a way to reproduce the BLM-signal's time structure in MAD-X?

Vera: With a larger or non-Gaussian beam, or with a higher bump amplitude, the matching would be better.

Mariusz: Is there a way to estimate the emittance blow-up during excitation?

Agnieszka does not remember whether this was measured during an MD.

Steady-state loss quench test

Also in this case, Vera attempted to reproduce the LHC optics during the quench test in MAD-X. A 3-corrector orbit bump was set to 4.3 σ_{nom} offset from the beam screen (which translates into 21.54 mm from the center of the aperture). Then the ADT starts to excite 8 bunches with a random kick. As

MAD-X cannot handle 8 bunches, Vera accumulates the data of 8 MAD-X runs with 1 bunch each. The ADT strength in the model is tuned to distribute the losses over a long duration. Nevertheless it is difficult to obtain losses that last over a period of 20 s.

Wolfgang: More particles in the simulation would help.

> *Vera*: Unfortunately MAD-X, even when running in batch mode, crashes due to memory problems.

Mariusz: The simulated time distribution shows large fluctuations. This result should be compared to BLM signals for different running sums. At least the longer sums showed a rather flat loss distribution in time over 20 s. Maybe a larger binning of the simulated data would show a similar flat distribution – to be checked.

Mariusz: Do the losses occur in the same location as for the fast-loss quench test?

> *Vera*: Yes, in both cases they are in the first half of the magnet.

Nikhil: FLUKA Simulation of the ADT Quench Test

As mentioned above, for FLUKA simulations the MAD-X distribution of the turn with maximum losses is used. The time-variation of the spatial loss distribution is small and at least in one case more than 50% of losses occurred in that single turn. In this way the FLUKA simulation becomes independent of the time structure. The three options described above gave similar results within 20% in the BLM signals downstream of the beam losses, and within a factor two upstream of the beam losses. The difference between BLM signals and simulation lies within this uncertainty. The energy deposition in MQ.12L6 was computed for two quench tests with different beam intensities. The results turned out to scale to a high accuracy linearly with beam intensity. The test with 4.E+8 protons, which had not resulted in a quench, was simulated, yielding a peak of the time-integrated energy deposition on the inner radius of the midplane turn of 200 mJ/cm^3. For the test with 8.2E+8 protons, which had resulted in a quench, the simulated peak energy deposition was 420 mJ/cm^3.

Bernhard: An error in the impact distribution from MAD-X might not be visible in the BLM signals, but it would translate directly into an error in the energy deposition in the coil.

Bernhard: Analysis of quench limits for fast ADT quench test

The input for the quench-limit calculation is the radial distribution of energy distribution computed by FLUKA on the midplane turn of the inner layer and integrated over the loss event. To determine the integrated energy deposition up to the moment of quench, a precise synchronization of the BLM PM data and the QPS PM data would be required. Unfortunately, this synchronization is only accurate to about 5 ms, which is an error margin that leaves too much uncertainty. All that can be said for certain is that with 420 mJ/cm^3 a quench occurred, whereas in the preceding test with 200 mJ/cm^3 no quench had occurred.

For losses in the millisecond range, the heat-transfer from strands to the helium inside the cable is essential. The heat-transfer mechanisms go through several stages, from Kapitza cooling to He I conduction cooling, to nucleate boiling, film boiling and, eventually, gas convection. The various models have

numerous parameters with sizable uncertainties. Therefore, a predictive simulation in this regime is more difficult than for fast losses or steady-state losses.
With some tuning of parameters, notably the heat conductance in the film-boiling phase and the helium content in the cable voids, the quench limit estimate was raised from initially 34 mJ/cm^3 to 74 mJ/cm^3. Both values are far away from the FLUKA lower bound of 200 mJ/cm^3. More numerical studies and comparison with literature will be performed to improve the model. For the time being it would look like the error margin due to the cooling parameters is about ±40 mJ/cm^3. At the same time it would be desirable to quantify also the potential error margin in the MAD-X simulation, in particular in the amplitude of the longitudinal loss distribution.

Pier Paolo: Quench limit calculation: based on heat-transfer tests (slow losses) and the THEA code (fast losses) – Comparison to FLUKA values of different quench tests

Steady-state cable quench limits depend on the heat extraction from the cable, through its electrical insulation. They were experimentally determined in the following way: The setup consisted of a stack of six insulated copper-nickel cables, identical to MB inner-layer cable except for the absence of superconductor, equipped with temperature probes. The resistive material allows generating heat inside the cable by Joule effect, thus reproducing the beam loss heat deposit. The pressure across the stack was varied to account for the different mechanical conditions of the cables within the coil cross-section. The measurements show clearly the different mechanisms of heat-transfer to helium for steady-state heating. The results could be scaled to provide a steady state quench-limit map across the MB cross-section. The results are consistent with the result of the 2013 collimation quench test that had not resulted in a quench.
For transient quench limits, the dominant mechanism is related to the local heat transfer from strands to helium inside the cable. Since there are not yet conclusive experiments on the topic, transient quench limits were simulated using two numerical codes: ZeroDee and THEA. ZeroDee averages all properties, loss- and field-distributions over the cable cross-section. THEA is a 1-D model very similar to QP3. The same transversal heat transfer coefficients, depending on the different helium phases, were implemented in both codes. They were deduced from experimental tests found in literature, each of them referring to one or two helium phase(s). However, the whole heat transfer process occurring in the cable would require an experimental validation.
Quench limits for many LHC magnets were calculated with ZeroDee. Several quench tests were equally studied with ZeroDee, and the fast ADT test was analyzed with both tools. Which turn in a magnet cross-section is the most critical eventually always depends on the loss distribution, on the magnetic field and on the loss duration. In the transient cases studied on MB, MQ, MQXA and MQXB the critical turn was found on the horizontal mid plane.
Stefano: For steady-state losses the distribution is usually horizontal, but for UFOs and fast loss mechanisms there is no preferred direction.

> *Anton*: For UFOs in MBs the losses according to simulation are still mostly horizontal.

Daniel: The quench-levels are shown over the coil cross-section. Does the model consider turn-to-turn heat transfer and heat transport to the heat exchanger?

> *Pier Paolo*: For the time being the model is only on the cable level and evaluated per turn of the magnet.

Bernd: Why is Dariusz Bocian's work on the topic not being considered? (Action Ł Pier Paolo will look into that)

For the fast ADT quench test THEA simulated a 10-ms rectangular heat pulse and found a quench level for the peak energy deposition on the inner radius of 125 mJ/cm^3, to be compared to the upper and lower bound from the quench tests of 420 mJ/cm^3 and 200 mJ/cm^3. ZeroDee found a quench limit of 63 mJ/cm^3 average over the cable cross-section, to be compared to the FLUKA bounds for average values of 155 mJ/cm^3 and 74 mJ/cm^3. This does not mean that ZeroDee has the more accurate model. The good agreement is more likely a coincidence, despite the simplified physical model.

For the 2010 wire-scanner quench test ZeroDee overestimated the quench limit slightly, whereas for the 2013 Q6 test the ZeroDee results showed a good agreement with the experiment.

Arjan: For the 2010 wire-scanner quench test in the millisecond range the QP3 model with standard parameters overestimated the quench limit. Now it seems to underestimate the quench limit. Maybe we have to reduce our expectations with regard to the accuracy of calculated quench limits in this regime.

Stefano: What matters for the machine is the scaling of quench levels to nominal energy. How far are these limits from the old Note 44?

> *Arjan*: The scaling is rather well known, a factor 3-6 depending on loss duration.
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> *Stefano*: How confident are we about the accuracy of the extrapolation from 4 to 7 TeV for steady-state losses?
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> *Arjan*: There we are very confident.
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> *Pier Paolo/Anton/Arjan*: It appears that there are different predictions for the step from 6.5 TeV to 7 TeV between the QP3 and ZeroDee models. This needs follow-up (Action Ł Pier Paolo, Arjan, Bernhard)

Francesco: What should be the limit considered for thresholds? T_λ or the quench limit?

> *Bernhard/Arjan*: The magnets do not suffer from operation above T_λ provided that we stay safely away from the quench limit. There are safety factors in the thresholds to ensure this.

Bernd/Stefano: There is money involved when we talk about quench limits! Hundreds of BLMs are being displaced, and the 11 T program is directly linked to the quench limit at 7 TeV.

Next meeting, date and contents to be confirmed

Minutes by Bernhard.