WP2 Meeting #167

Tue 18 Feb 2020, 9:00 – 12:00

Chair:	Rogelio Tomás
Speakers:	Davide Gamba, Lucio Fiscarelli, Michele Martino, Joschua Dilly
Participants:	Gianluigi Arduini, Riccardo De Maria, Joschua Dilly, Ilias Efthymiopoulos, Lucio Fiscarelli, Davide Gamba, Ewen Maclean, Michele Martino, Elias Métral, Nicolas Mounet, Fabien Plassard, Galina Skripka, Guido Sterbini, Carlo Zannini

AGENDA

MEETING ACTIONS

Davide	Summarize the effects on the orbit only for the 11T dipoles, highlighting which assumptions are conservative or optimistic
Michele	For the triplets investigate the details of crosstalk between magnets due to the nested powering
Lucio	Discuss possibility of getting the diagnostics to measure the dipolar field jump in a quadupole
Lucio	Attempt measurement of reproducibility on 11 T magnets with NMR

GENERAL INFORMATION (ROGELIO TOMÁS)

Rogelio briefly went through the minutes of the last meeting. From Frederik's talk D2 magnet errors were identified as the main contributors to the DA, followed by the large effect of MCBRD and MCBXF orbit correctors. This was known and discussed before, **Ezio** should add this in the field imperfections and report on the meeting.

For the magnetic measurements, there was a request for HiLumi to have a possibility to sample fringe fields every 2 cm instead of 10cm. This should be discussed with magnet experts.

1 REVISITING FLUX JUMPS IMPACT ON ORBIT (DAVIDE GAMBA)

This was already presented last year. Here updates were given. Summary of flux jumps was presented and together with estimated effect on the orbit, with the main message if this could trigger a beam dump during the ramp.

On the typical dependence of the differential voltage on the current, measured on the short version of an 11T dipole, spikes can be observed in the beginning of the ramp (2-4kA) caused by flux jumps and later narrow fast spikes appear at around 10-12kA. The latter is believed to be a result of mechanical stress on the coils and the magnet. The effect on the beam is proportional to the integral of the signal, so the fast spikes have negligible effect, while the ones caused by the flux jumps are wider and can be seen by the beam as a kick. The region of concern for the flux jumps (2-4kA) corresponds to a timescale of 200s.

Analysis of the flux jumps measured on 11T dipole gives an occurrence of 4.4 events/s with 50ms rise time. The FWHM of the signal is around 120ms, thus, if the coil is experiencing a jump it will be in this state half of the time. For the quadrupoles in the triplet the frequency of jumps is not known. More measurements are required.

The intensity for the jumps in 11T dipoles was measured to be 0.2 units r.ms. of the main field. For the quadrupole the quadrupolar field jump is expected as a main contribution. There is no information on the dipolar field jump in a quadupole when the jump occurs. The only gradient-like measurement that has been registered was a 0.15 units up-down gradient into the 11T dipole, which is neglected in the presented study. The power converter will see the jump and react on it as an additional contribution to this jump. This is estimated to be 0.06 units both for RQX and 11T dipoles. This value is non negligible only at injection. In these studies the quadrupoles of the triplet were considered individually. There is no information on the crosstalk between magnets due to the nested configuration of the powering of the quadrupoles in the triplet, and what would be the overall effect on the triplet when there are jumps. Dedicated studies need to be done.

The impact on the orbit at the TCPs was estimated assuming a 0.2units jump of a single half-magnet with ß*=1m at 7TeV. The worst half-magnet is Q2 with an effect in the order of 2% σ_{beam} orbit jump at the TCPs. Other magnets contribute less. For the 11T dipoles we get about 1% σ_{beam} orbit jump.

To sum up, the total number of magnets in this study is two 11T half-magnets on each side of IP7 acting in horizontal plane and two Q1/Q2/Q3 half-magnets on each side of IP1/5 at each IP contributing to only one plane because the crossing angle is either horizontal or vertical. The estimated number of jumps for each magnet during a ramp is 880 events, which gives $2.64*10^6$ total events per magnet assuming 3000 fills in a 10-year lifetime of the HLLHC.

A probability of a magnet being in a jump was calculated. A single magnet is in the jump (positive or negative) half of the time, hence, in a jump of a given sign it spends ¼ of the time. Thus, for n magnets the probability of being in a jump of a given sign is $(1/4)^n$. If taking a more realistic scenario, assuming:

- 1m optics in the middle of the ramp at around 3TeV
- no cross-talk between the magnets (jumps are completely uncorrelated), this is expected to be the case for the 11 T magnets but needs to be studied for the triplet quadrupoles,
- no contribution from power converters
- only horizontal plane (this is the worst case scenario as the 11 T dipoles act only on this plane)
- all the jumps of 0.2 units
- 120ms long events
- 4.4events/s

the effect on the orbit in σ_{beam} at TCP can be estimated. The expected value is at least one 6% σ_{beam} orbit jump at every ramp and at least one case of 8% σ_{beam} during the HLLHC lifetime. Similar value is valid for the vertical and diagonal direction. For the more conservative case with the total is 0.6 unit gives up to 20% σ_{beam} orbit jump.

At present there is a limited knowledge on power converter behavior for complex circuits like triplet and the dipole field jump in the quadrupole magnet. These two topics need to be studied further. Run 3 will be fundamental to collect data for the 11T dipoles for which the effect is expected to be negligible on the orbit: ADT spectra, BPM 25Hz rms data, turn-by-turn data during the ramp to see if the jumps occur and the data is consistent. Possibly would like to have a string test to measure dipolar and quadrupolar field jumps on the triplet quadrupoles in a realistic powering configuration.

- **Ilias** pointed out that the jump can be both positive and negative. **Lucio** added that in a dipole you always lose flux, so it is always negative followed by a slow recovery in the positive direction. All coils have same voltage, so whatever is different is signaled as flux jump. The coils are oriented in the same direction, so you can only lose. The physics is so that you always lose magnetization. **Michele** mentioned that for the power converters the sign of the jump can be both positive and negative. **Davide** said that in this study both signs for a jump are assumed but this should not make a significant effect. He will look at it in more detail.
- **Riccardo** asked if the dipolar field in the quadrupole could be measured and added in the study. **Lucio** replied that with the standard equipment the field components cannot be separated. **Gianluigi** wondered if there is a way to instrument for such a measurement. **Lucio** and **Michele** replied that another instrument would be needed and this measurement is not in the baseline.

- **Gianluigi** asked to summarize the effect from only the 11T dipoles for the next meeting, highlighting which assumptions are conservative or optimistic (Action: **Davide**) and considering the case of negative flux jumps for the 11 T dipoles. Another thing to work on is the behavior of the triplet. The details of the crosstalk between circuits for the triplets and the effect of the power converters have to be investigated in more detail (Action: **Michele**). The results should be summarized for the 11 T and triplet quadrupoles separately at the Technical Committee: while it appears that for the 11 T dipoles the effect should still be negligible more studies and measurements are required for the triplet quadrupoles. The possibility to add diagnostics for the dipolar fields in the quadrupole has to be investigated (Action: **Lucio**).

2 FIELD REPEATABILITY OF MQXF (LUCIO FISCARELLI)

The talk reports on the cycle-to-cycle repeatability in the measurements on the main field in the triplet quadrupoles. The data is measured on the short magnet models. The first full-length magnet will be tested next month.

The standard instrument for the measurements of the field is a rotating coil. There are pick-up coils mounted on a shaft that is inserted to the magnet aperture and rotating at the speed of 1Hz. The short model magnets are tested in a special cryostat in vertical position: the sensor is put in the magnet aperture in the helium bath.

The measurement of the gradient in a quadrupole is done by taking the difference of signals from two coils located at well-known distance from each other. Apart from the precision of the flux measurement, the factor limiting the repeatability of this measurement is the stability of this distance. The repeatability measurements are done at nominal field at which level the magnetic field should be stable from one cycle to another. The rotating shaft on which the coils are mounted is 2.1-m long and made of fiberglass, the coils are at about 50 mm. To get the repeatability better than 10^{-5} at that distance of 50 mm, its stability should be better than 0.5 µm, which is challenging because it is a rotating object subjected to mechanical stresses. This is one of the main limitations to the repeatability of the measurement system.

For the multipoles there are other factors, but in general it is less challenging. A bucking (compensation) scheme can be used to compensate effects of mechanical deformations. However, depending on the haft cross section, when increasing the multipole order the sensitivity could get smaller and the precision get worse. In the specific case of the rotating coil used on MQXFS magnets the sensitivity is decreasing to almost zero for n=13. Therefore, the repeatability of multipoles is reported up to the order n=8.

For the MQXFS6b the repeatability was measured on the plateaus at nominal current of three cycles preceded by a pre-cycle. On the current measurements there is a drift in the beginning of the plateaus on the level of 10^{-4} relative to the nominal level. The relative noise on the current is at the level of 10^{-5}. Comparing the average current during the plateaus the stability is in the order of 10^{-6} while the field stability is slightly larger but still better than 10^{-5}.

On the MQXFS4a the jitter in the beginning is gone and the noise on the current measurements is significantly better. The average current during the plateaus here is better than 10^{-7} what is typically expected. For the cycle-to-cycle field measurement in the order of 10^{-6} was obtained. This can mean that this precision is given either by the magnet or by the limit of the measurement system. More likely this is the limit of the measurement system and therefore the repeatability of magnet cannot be measured with this system.

For the multipoles the bucking (compensation) is applied and the cycle-to-cycle repeatability is better than 10^{-6}. Since the main field is removed the small quantity is simpler to measure directly. This value is an indication that the field is stable. If there is a movement on one magnet coil/part of the coil (change of symmetry), this should be clearly seen on the multipoles, nevertheless an overall movement of the coils will not be seen because of the normalization that is applied. The good repeatability of the multipoles is an indication that there are no changes to the field distribution.

In conclusion, the cycle-to-cycle repeatability in the MQXF magnets is better than 10^{-5} for the main field and better than 10^{-6} for the normalized multipoles. The measurement precision is the limiting factor.

- **Gianluigi** asked what the bucking is. **Lucio** explained that for the multipoles the measurement is taken by combining the signal of many coils. This signal is called “compensated signal”. Ideally, if the coils are at the nominal position with nominal surface properties it is possible to completely compensate the main field and get a signal that is only proportional to the multipoles with reduced sensitivity to mechanical deformations.
- Related to the current jitter measured in the beginning of the cycle **Gianluigi** asked if these power converters are going to be used. **Lucio** replied that this setup is very specific to this exact test since in SM18 power converters are used for many magnetic tests, and the software and power converter are not always adapt for the magnet under the test. **Michele** added that there is no check to optimize the performance of power converters during the tests in SM18.
- **Rogelio** pointed out that the precision required for optics is higher than the one that is measured. The fill-to-fill tolerance given in specification for power supplies is less than 10^{-6}.
- **Gianluigi** asked if it is possible to go off-center in a quadrupole and measure the field stability with an NMR probe. **Lucio** replied that the NMR sensor can only work in a very homogeneous field. If there is a gradient, it is not possible to measure anymore. This is the challenge for the quadrupoles compared to dipoles.
- **Gianluigi** asked what happens if the rotating speed is changed. **Lucio** replied that in a narrow range there is no difference in the measurements. The speed can be changed to 2-3 Hz, but not much more (10Hz). At lower frequency there could be larger errors coming from the integration drift.
- **Gianluigi** asked if the coordinated movement of the magnet coils will not be detected. **Lucio** said that if all the coils move in the same direction keeping the symmetry, this will not be seen on the not-allowed multipoles but on the quadrupoles and allowed multipoles, however, this this is quite unlikely. One region of a coil is expected to move, and this will most likely provoke a quench. Even very small displacements would provoke a quench.
- **Gianluigi** asked if it possible to perform an NMR measurement on 11T dipole. **Lucio** replied that they could try but the mechanics of the magnets is very different. The

results could probably even get worse because of the different pre-stress method used. Anyway, if the field is enough homogeneous for the NMR there could be a test. There is experience with the measurements on the standard dipoles, but there were troubles because the field can be locally nonhomogeneous and prevent the NMR equipment from working. (Action: **Lucio**)
- **Rogelio** asked if there would be a test on the long magnet and **Lucio** said yes but this can be done with the standard rotating coil. No better results are expected since the same method will be used.

3 FLUX JUMPS DURING K-MODULATION (MICHELE MARTINO)

This is a report on the test confirming that no flux-jumps occur at nominal current in MQXF magnets during k-modulation.

Flux jumps occur in magnets at low to medium current and their occurrence decays with increasing current. They need to be excited and during the ramp-up and ramp-down it is the ramp rate that excites them. The test aimed to check if the ramp rate involved in k-modulation can trigger flux jumps at nominal current. The maximum ramp rate in k-modulation is 23% of the RQX circuit maximum ramp rate of 14.6 A/s.

During the test performed in December 2019, 20 periods of k-modulation signal were acquired. The measurement is done in the following way: there are four main coils and the voltage is taken in the two halves of the magnet. The power converter is affected by the sum of these voltages, whereas for the detection of the flux jumps the difference of these voltages is measured. Ideally, the difference is zero, meaning no flux jumps, and only noise can be detected. This is what was observed in the test. Using the 35A modulation current the differential voltage was measured. It is very stable but noisy. When removing the 50Hz harmonics the signal drops to 3mV peak value and the signal is very stable independently of the ramp rate. This allows concluding that the k-modulation will not induce a flux jump at nominal current in the magnet.

When magnets are tested they are often ramped up with a ramp rate greater than the nominal one. When the current is very close to nominal and the full ramp rate is still applied, usually there are no flux jumps. So, this also confirms that during k-modulation there are no flux jumps.

- **Gianluigi** asked if the noise level is the same at the steady state with no modulation. **Michele** replied that this was not checked, but should not be much less, still in the order of mV. There is no difference with full or zero ramp rates so this is the noise level. In case of a jump the differential voltage should go to hundreds of mV.
- **Gianluigi** asked what is the threshold used to protect the magnet. **Michele** and **Lucio** both say that it is a variable threshold. At low current it's bigger, then it decreases and at nominal it's the usual one used for a quench.

4 AMPLITUDE DETUNING FROM MISALIGNED TRIPLETS AND IR MULTIPOLAR CORRECTORS (JOSCHUA DILLY)

The results of simulations and measurements of amplitude detuning caused by misalignments of corrector package and triplets are reported for LHC and HL-LHC. They are compared to other sources of amplitude detuning.

The procedure for this study with corrector package misalignments is the following: firstly the lattices for the triplets of LHC and HL-LHC were set up, including the corrector packages; then the WISE errors or the HL-LHC error tables respectively are applied for the higher multipoles; after that a dedicated script calculates the corrections for powering the MCX and 50 misalignments for the MCX (uniformly distributed, for each corrector independently) are simulated to check the amplitude detuning. The procedure for the triplet misalignments is the same, with an exception of setting Q1-Q3 to be misaligned (not uniformly but truncated-Gaussian distributed with σ = 0.4 mm for Q1 and Q2, σ = 0.8 mm for Q3 truncated at 2.5σ) instead of MCX. (Remark from Rogelio: The misalignment uncertainty is different for different quadrupoles as a worst-case scenario as studied by Davide and Joel. This will be followed up according to their more recent findings. It is important to note that the relevant quantity in this study is the final quad-to-beam offset after alignment and orbit correction.)

The assumptions for the optics are given on slide 5. A flat orbit is used to exclude any feed-down from the crossing angles and really see the effect of the misalignments alone. The first order amplitude detuning was calculated manually via python scripts.

The simulated effect of the corrector misalignments in the LHC is compared to the measured one (horizontal direct term for beam 1). Starting with the uniformly distributed misalignments gives a Gaussian distribution in amplitude detuning. Simulation results have an offset due to amplitude detuning from sextupoles in the arc. The amplitude detuning spread is small and of the same order as the already corrected machine. For the HL-LHC there is a slightly larger spread but also in the same order as the measured amplitude detuning. For the studied misalignments of corrector package in both LHC and HL-LHC the effects on the amplitude detuning are very small.

There is a larger spread in the amplitude detuning from misaligning the triplets than from corrector misalignments in the LHC, however it is still in the same order as amplitude detuning in the corrected machine. From the simulations the spread in HL-LHC is much lower, possibly because of the cancellations due to shorter magnets/independent misalignments or differences in error-tables. One way to test that is to align the halves of the HL-LHC quadrupoles to exclude the cancellations.

The study of misalignments was done with MOs off. Powering them to 300A (max up to 570A) causes the direct term of amplitude detuning to increasing from $5*10^3 m^{-1}$ to $100*10^3 m^{-1}$.

In conclusion some amplitude detuning from misalignment of the corrector package and the triplets is present, however it is much smaller compared to the one caused by the MO powering and is not expected to be problematic.

- **Gianluigi** asked if the correctors are nested. **Rogelio** replies that not in HL-LHC but in LHC yes. But only the b6 corrector misalignment was in the LHC anyway.
- **Davide** asked how the measurements were done. **Joschua** said that kicks of different strengths were applied with an ac- dipole and the natural tune of the

machine was measured. He also mentioned that the measurements are very sensitive to noise.

5 AGENDA OF NEXT MEETING (GIANLUIGI ARDUINI)

The next WP2 meeting will be on February 25th, starting at 16:00. The agenda will be

- Update on the No MS10 status for HL-LHC (F. Plassard)
- Update on DA at injection for HL-LHC (F. Plassard)
- Update on the effects on the orbit from 11T dipole flux jumps (D.Gamba)

Reported by G. Skripka