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MINUTES

COLLABORATION MEETING ON DS 11 T DIPOLE GROUNDS

21 TO 23 SEPTEMBER 2015

Reported by:

F. Lackner, F. Savary, and A.V. Zlobin on 2016-03-07.

Present:

At CERN (through Vidyo): B. Auchmann, B. Bordini, L. Bottura, L. Fiscarelli, M. Karppinen, J.C. Perez, G. de Rijk, L. Rossi

At FNAL: N. Andreev, E. Barzi, G. Chlachidze, J. DiMarco, S. Feher, S. Izquierdo Bermudez, F. Lackner, C. Löffler, I. Novitski, F. Savary, D. Smekens, S.E. Stoynev, T. Strauss, G. Velev, G. Willering, A.V. Zlobin

Distribution:

Those present, G. Ambrozio, G. Appolinari, V. Baglin, H. Bajas, A. Ballarino, A. Bertarelli, M. Bajko, N. Bourcey, K. Dahlerup-Petersen, M. Daly, R. De Maria, M. Duret, P. Ferracin, J. Fleiter, A. Foussat, R. Gauthier, M. Giovannozzi, M. Guinchard, L. Grand-Clement, J.M. Jimenez, G. Maury, D. Missiaen, E.K. Nilsson, V. Parma, H. Prin, R. Principe, S. Redaelli, J. Rysti, S. Tavares, H. Thiesen, J.Ph. Tock, E. Todesco, R. Van Weelderen, A. Verweij

1. Introduction

The Review Panel of the 2nd International Review of the HL-LHC 11 T Dipole for DS Collimation held at CERN from 8 to 10 December 2014 (https://indico.cern.ch/event/354499/) recommended to organize an internal review in the collaboration, to better integrate the best features of the previous FNAL and CERN developments to the further 11 T dipole development.

The main goal of this collaboration meeting is to address this recommendation. On this occasion, it is proposed to review the original functional requirements of the project and to recall the grounds of the conceptual design.

The meeting is structured in 4 parts as follows: design, technology development and fabrication, tests, and conclusions.

2. Day 1 - September 21st

2.1 Welcome address and original plan at FNAL [A. Zlobin]

Sasha gives a welcome address. He is pleased to see an important delegation from the CERN side present at FNAL.

The beginnings of FNAL activities on the 11 T dipole for the DS regions of LHC date from July 29, 2010. FNAL had held an APT[1] Seminar on this day from which the functional requirements for the 11 T dipole were defined, and later described in a White Paper. A very ambitious three-year plan was initiated with the idea of fabricating a prototype based on a single design with no room for R&D divergence. The production of short models at FNAL started in 2011. Many visits between FNAL and CERN were organized in order to exchange knowledge on the magnet and tooling design and technology. The three phases, from the realization of a short demonstrator dipole to the construction of a dipole prototype, were presented:

- Phase 1 (FY11-12): the design and construction of a single-aperture 2-m long demonstrator dipole;
- Phase 2 (FY13-14): the fabrication and test of two 2-m long, twin-aperture model dipoles to confirm the final magnet design, demonstrate the magnet performance parameters and their reproducibility;
- Phase 3 (FY14-15): the design and technology scale up by fabricating and testing a 5.5 m long twin-aperture dipole prototype.

A 2 m long demonstrator magnet was designed and fabricated in only 18 months. In spring 2013, a DOE review was held and both budget and plan were revised. In addition, the objectives and FNAL deliverables were changed in agreement with CERN. Phase 3 of the program was dropped and the length of the models scope of Phase 2 was reduced to 1-m (NOTE LB for the history: this was a proposal from FNAL, not from CERN).

In 2014, two single aperture models were made and tested at FNAL. The assembling of a 2-in-1 demonstrator was started in summer 2014, with the two collared coils retrieved from the single aperture models. During the cold tests of this 2-in-1 model, carried out in May 2015, a bore field of 11.5 T was reached. This model was limited by the first of the two collared coils. FNAL will carry out the magnetic measurements in the beginning of 2016.

The five-year collaboration program is now close to an end. It is therefore a good time to pass on the relay.

2.2 Some backgrounds on the design choices [M. Karppinen, B. Auchmann]

M. Karppinen gives a comprehensive overview of the project history and development activities.

The project team converged quickly on a cable and strand configuration. The RRP 108/127 strand from OST had been developed for the US high field magnet programs and 0.7 mm diameter was chosen for this project. This also set the copper fraction in the strand from the beginning. There were differences in the way the cable was made at both laboratories. Possible resin systems were discussed in the beginning and it was agreed to use the CTD-101.

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[1] APT stands for Accelerator Physics and Technology

The stainless steel end spacers made by selective laser sintering were to be provided by CERN, also for the models fabricated at FNAL. The original plan in the end of 2010 was to deliver a 5.5-m long magnet by the end of 2013.

The coils were optimised with round yoke inner contour. Both 2-in-1 and 1-in-1 yokes were thereafter optimised to minimise the b_3 and b_5 variation along with the cross talk (b_2) between the apertures in the 2-in-1 configuration. This resulted in systematic b_3 of about 7 units that was to be corrected by re-optimising the coil after the model magnet measurements. Large number of cross-sections were studied and the sweet spot was found at 56 turns. A design with 58 turns would have given marginally more field but at a higher cost. To improve the mechanical stability during winding 25 µm more compaction was applied on the cable. Going further would have required a reduction of the keystone angle to avoid J_c degradation on the thin edge, but it would become challenging to fit the 22 turns on the inner layer. The operation margin of the 11 T dipole is based on FNAL and CERN data for the configuration 108-127 assuming 10 % J_c degradation of the conductor.

The design of the coil ends is based on the more upright end turns @ FNAL, and the minimum strain/torsion @ CERN. On Slide 26, one shows that the cable follows nicely the spacer along the perimeter of the end spacer with the CERN route; however, occasional strands pop-outs occurred. The more upright design appeared to be somewhat better in this respect and the present 5th iteration end design is a combination of more upright end turns with minimised torsion and strain.

The use of passive compensation to mitigate persistent current induced sextupole was studied but not done. On Slide 39, one shows that the magnetization will depend on the conductor batch.

Regarding quench protection, the FNAL team has been more optimistic about protecting the magnets with the outer layer protection heaters alone. CERN view is more conservative in particular to provide sufficient redundancy in the accelerator environment. Inter-layer heaters were proposed by CERN from early on to reduce the peak temperatures in the coils.

The cable insulation scheme for the CERN models was inspired from the experience of F.M. Asner and the MSUT magnet some 20 years ago. Slide 49 summarizes the differences between the CERN coils and those made at FNAL.

The structure based on a vertically split iron yoke is less influenced by friction. Originally, the shell was 10 mm thick for the single aperture structure and 12 mm thick for the two-in-one.

Rather thick end plates were considered to take up the large axial force produced by the magnet, 40 tons per end/aperture, even if we knew that a significant part of it is transferred radially to the shells via the collars and yoke. The central yoke in the 2-in-1 configuration is made in one piece for alignment purpose. Splitting the central yoke in 2 parts would make the alignment more dependent on tolerances. The central yoke works as a spacer between the apertures. The end region design is made in such that the strain in the conductor is limited to 0.2% in the coil ends (250 mm length). The tie rods enhance the rigidity of the end plates, by limiting their deflection under the effect of the electromagnetic forces.

The main difference between the mechanical concepts developed at FNAL and at CERN is the pole that is impregnated in the FNAL concept and removable in the CERN concept.

2.3 FNAL conductor and cable development [E. Barzi]

E. Barzi presents the conductor development and the strand design at FNAL. She compares it to CERN developments.

A number of cable development studies were performed after the release of the specifications for the uncored cable, which was to be fabricated with the baseline strand. The first of these studies was the development of a cored cable technology to suppress eddy currents and obtain better field quality and ramp rate dependence. Such study was first performed at FNAL using the advanced strand 150/169 RRP® and a stainless steel core 11 mm wide and 0.025 mm thick, and it was carried out for cable samples that had undergone an intermediate annealing process between their first forming stage and their keystoning step, and for cable samples that had not undergone such process. To study sensitivity of electrical properties and damage to compaction, the cored cables were made within a range of mid-thicknesses producing Packing Factors, PF, between ~85% and ~90%. The cored technology was then applied to the baseline 108/127 RRP® wire using a stainless steel core 11.7 mm wide and 0.025 mm thick. To demonstrate in an actual coil such cored cable technology with this advanced strand, the 11 T demonstrator dipole MBHSP01 was manufactured at FNAL out of cable without a core made with the baseline 108/127 RRP® strand, and MBHSP02 was fabricated using cored cable made with the advanced 150/169 RRP® wire.

Whereas the development above had been carried out using a two-step fabrication approach, with and without intermediate annealing, after commissioning of a new turk-head designed for one-pass cable fabrication, similar cable geometries were reproduced in one pass (therefore without an intermediate annealing step) using 132/169 RRP® strands. Cables had nominal width of 14.7 mm and packing factors between ~85% and ~90%. All cables had a 0.025 mm thick stainless steel core, varying in width between 9.5 and 11.7 mm.

Coils up to and including MBH11 were made with Ta based RRP wires, whereas coils starting from MBH12 were all made in one step with Ti based RRP wire and were of excellent mechanical quality.

2.4 CERN conductor and cable development [B. Bordini]

B. Bordini presents the wire specification and the available margin. The importance of a high RRR is explained on basis of test results obtained for a 0.7 mm RRP 108-127 wire. A RRR of 150 in round wires is necessary to achieve a local value of at least 100 on the side of the cable thin edge.

Local RRR measurements from extracted strands were presented. For the RRP strand, four different layouts were received with two different sub-element size and hexagonal SE shape. For the PIT cable, two different layouts were received based on a circular SE shape. So far, 135 km of PIT wire were received and additional 40 km will arrive in 2015. Today, the PIT wire has a critical current of about 1-7 % lower than specified. The RRR was measured and found to be of the order of 100. Bruker-EAS is collaborating with CERN to further improve the PIT conductor. The magnetization measurements by D. Richter for PIT and RRP were presented for 1.9, 3.0 and 6 K.

An order was launched with the company OST for 500 km of wire. It would cover a good fraction of the quantity of wire needed for the 11 T magnets required for LS2. The wire will have the 108-127 layout in order to guarantee a sufficient Ic margin during production, relatively large yield and acceptable production cost.

Long lengths of cable have been produced at CERN with both RRP and PIT conductor. The performance reduction in terms of Ic were shown. A reduction of about 3% is observed for the RRP conductor and of 6.1% for the PIT conductor.

2.5 Mechanical structure and analysis FNAL [I. Novitski]

I. Novitski presents the mechanical concepts of the different configurations fabricated and tested at FNAL: dipole mirror, single-aperture and twin-aperture dipole configurations. He also presents the FEA models and the results of the structural analysis performed at FNAL.

In the single-bore magnet structure, the coil mechanical support is provided by stainless collars, a vertically split iron yoke, aluminum clamps and a welded stainless steel skin. The strong collars and the iron yoke create a rigid belt around the Nb_3Sn coils for conductor protection. Coil mid-plane shims generate the initial coil azimuthal pre-stress at the collaring stage. The skin and the clamps deform the iron yoke, reduce the vertical spring-back of the collars, and provide the coil final compression. Collar-yoke-clamp-skin interferences support horizontal Lorentz forces. Coil and inner layer pole in contact at 12T and stress in materials below yield point.

The 2D ANSYS parametric model of the 11 T dipole includes the coil, two layers of collars (front and lock-leg), the collaring keys, the iron yoke, the clamp and the skin. The model has a quarter symmetry. The inner and outer layers and the interlayer insulation are glued together. The titanium poles freely separate from the coil. The coil is surrounded by two layers of stainless steel collars. Short and long leg collars have symmetric boundaries along X-axis (CP and CE equations simulate line motion). Phosphor bronze keys lock the collar laminations, thus fixing the coil azimuthal prestress. The clamped iron yoke supports the collars, and the welded stainless steel skin restrains the iron yoke from outside.

The FEA modelling is based on frictionless contacts. Different properties for RT and 1.9 K were used to compute the coil stresses. The shimming is applied at the coil mid-plane and on the outside radius of the coil. In addition, yoke-collar shims are installed to achieve the azimuthal stress in the pole turns of the inner layer. To achieve sufficient pre-loading, the yoke gap has to be closed. This is similar to the CERN approach. FNAL did not carry out any sensitivity analysis by means of shimming variation. H. Kokkinos carried out such studies for the CERN mechanical structure, which is based on the removable pole and loading plate concept.

A variation of the coil size of ±0.050 mm in the azimuthal direction corresponds to a variation of prestress of ±10 MPa in the inner layer and ±23 MPa in the outer layer. The analysis shows that, at the maximum design field of 12 T, the minimum coil prestress in the pole regions is comprised between 2 and 23 MPa. The maximum prestress in the coil at room temperature does not exceed 160 MPa, which is acceptable for the Nb_3Sn cable and coil insulation.

The maximum stress in the collars and compression in the iron yoke reaches the material yield limit in small regions only near the key grooves and iron yoke corners (model singularities, mesh size). To minimize the stress concentrations, the key grooves and iron corners have been rounded. All the stress values are below the yield limits of the corresponding materials.

The 2-in-1 dipole concept developed at FNAL is based on an Integrated Pole. It requires a different approach w.r.t. the CERN concept. The “Controlled Yoke Gap” concept was introduced (previously tested using TQC design) to deliver additional coil pre-stress.

All the mechanical designs provide the coil prestress required in the operating current range. All the designs restrict turn radial, azimuthal and longitudinal motion under the Lorentz forces up to 12 T. The maximal mechanical stresses in the major elements of coil support structure are below the limits for the materials used.

2.6 FNAL technological choices, cable insulation and coils [N. Andreev]

At FNAL, the cable insulation is made of an E-glass tape, without mica. A tape was used in lieu of braiding, simply because there was a cable wrapping machine available. Ten-stack measurements were carried out, not only for the 11 T dipole but also for other magnets. The tension applied during the coil winding is 156 N; it is controlled by special winding tensioner. Winding tests were used to determine optimal cable tension to prevent cable collapse & popped strands around the ends and to prevent cable collapse in the straight section. E-glass cloth and ceramic binder is used on both layers to glue the coil turns and the layers during curing and to fill the gaps/voids in the coil ends. In the beginning, a 1-mm curing shim was put in place only in the straight part of the curing mould to provide room for coil azimuthal expansion during reaction. Later, the saddles were shaved in the mid plane in order to ensure continuity between the straight part and the ends, keeping the 1-mm shim in place.

After curing, there is always some spring-back. All the gaps are filled with E-glass cloth after reaction and prior to impregnation. Coil heads of the last two coils #11 and 12 have holes in the end spacers to reduce their rigidity. However, these coils have not been tested.

The manufacturing process is well understood at FNAL. S. Feher is wondering whether it is well understood on the CERN side. According to FNAL, the manufacturing process provides good results but they would change some of the features if they had to do it again. Examples were discussed as follows.

The cable insulation would be done differently for a series production (FNAL would not use E-glass tape, rather braiding). The team at FNAL is of the opinion that mica is not necessary. The wedges made of stainless steel deform a lot during the reaction treatment. Wedges bowed as a function of the length in the 2-m long coils. This effect was reduced in the 1-m long coils by adding two transverse cuts along each wedge.

The end spacers, which are made of stainless steel, are very rigid. Ideally, a softer material having an E-modulus close to that of the coil would be better, e.g. bronze. The wedges are 300 mm long and are mounted with a gap of 1.5 mm, which makes about 5 mm for 1 m. This is to make sure that the coil is not stressed during/after the reaction treatment by a larger contraction in the longitudinal direction.

2.7 FNAL assembly and parameters [I. Novitski]

Mechanical models were made and tested at FNAL prior to assembling the demonstrator. The structure of the single aperture magnet is described.

The assembly process is presented in detail for every model. Resistive strain gauges are used to measure the pre-stress induced during the assembly and the cold tests. The collared coil assembly is based on tapered keys which are pressed into the collars. The model MBHSP01 was equipped with welded shells. The models MBHSP02, MBHSP03 and MBHSM01 were equipped with vertically or horizontally bolted shells. The assembly of the 2-in-1 model MBHDP01 was done with welded shells. Strain gauges are glued on the shells on the outside surface only. This does not allow determining the bending and the tensile components of the weld-induced stress.

In the welding press, loading is achieved by means of plates pushing on rods which are welded longitudinally on the outside surface of the shells close to the welding chamfer. When the nominal pressure is reached, the bolts are tightened, or the welding is done. The stresses are measured by means of strain gauges during the manual TIG welding or during the bolting operation. Test results from the three single aperture models, the mirror structure, and the 2-in-1 model were presented. The design parameters are summarized on slide 50.

MBHDP01 reached a bore field of 11.5 T at 1.9 K, which is 97% of its design field and less than 1% lower than the maximum bore field obtained in the single aperture models. The magnet demonstrated quench performance similar to that of the single aperture models, i.e. exhibiting again the limitation by the conductor degradation in the collared coils of MBHSP02. It was mentioned that no additional coil degradation was observed following the re-collaring of one of the collared coils. Magnetic measurements will be performed in the next test run.

2.8 CERN technological choices, cable insulations and coils [D. Smekens]

A. Zlobin asks why CERN is using mica for the cable insulation. D. Smekens replies that mica guarantees to have the required dielectric strength. It is recalled that beyond 35 MPa of compression, the electrical insulation is affected.

Like at FNAL, CERN is using shims for the closure of the mold prior to the curing operation.

The dummy coil #110 was tested with capacitive discharge up to 9 kV before showing signs of degradation.

According to S. Feher, the capacitive discharge requirements should be different for a potted coil (compared to Nb-Ti coils).

The maximum allowable stress in the cable, 150-170 MPa, results from limits on (1) the conductor and (2) the insulation system.

The ten-stack measurements are discussed. At FNAL, they measure more than the 20 GPa measured recently at CERN.

At CERN, different samples produced with different compaction levels have shown identical E-modulus.

Coil 107 was cut and inspected. At one location, the core is folded. According to FNAL, we could reduce the width of the core without affecting its effectiveness. Cracks were observed. These may result from the cutting operation.

According to A. Zlobin, the residues of ceramic binder left over after the reaction treatment reinforce resin, as does glass fibre.

Cracking is an interesting subject that triggers discussions. In particular, the difference between cracks, voids and delamination, were discussed.

The interlayer is made of a glass fibre cloth that is impregnated with ceramic binder, and cured, before it is mounted in the coil.

S. Feher is questioning the vacuum impregnation process (generally speaking, i.e. not necessarily the CERN process, nor the one applied at FNAL). According to him, it is not perfect.

The splices appear to be another point of concern. The quality of an SMC splice, to make an example, was discussed. According to Gerard, the example shown is electrically acceptable, even if it may be weak mechanically.

The current distribution may not be ideal, i.e. current is not evenly distributed.

The current distribution occurs after a certain time constant. For this reason, analysing the holding current quenches in this regard will be useful.

We are following the same procedure for the realization of the splices, and are satisfied with what we have. However, the question whether we have an accelerator quality splice was raised.

Other questions asked were whether the ceramic binder is an ideal product, and whether CTD-101K is the right choice for series production.

A. Zlobin comments on the importance of using the binder agent for Nb_3Sn coil production and suggests trying to produce a coil without using binder (in the ends, when winding). This was done at CERN, with even better results, as the turns do not tend to slip down anymore in the ends (the binder was acting like lubricant facilitating slippage of the turns).

Regarding cracking, open questions are whether there is any reason to be concerned by cracking at all, i.e. whether this is really a problem.

2.9 CERN model assembly and sensitivity to shimming [C. Löffler]

Christian describes the CERN FEA model and the sensitivity analysis that has been carried out to assess the impact of variations of geometrical parameters on the level of stress in the coils. The response of the system to variations of the Young's modulus, and a non-linear behaviour of the coils, were also studied. The analysis that is presented is two-dimensional.

The geometrical parameters considered for the study are the pole lateral shim, the pole–collar nose shim, the azimuthal length of the coils, the mid–plane shim, and the collar–yoke shim.

E-modulus measurements carried out recently at CERN have shown values of the order of 22 GPa after "massage", which is much smaller than what was measured some years ago on other samples and in other laboratories. E-modulus ranging from 33 to 40 GPa were measured at FNAL. However, a direct comparison may not be done straightaway, as the test samples and the measuring procedure applied are likely different. Further researches and measurements shall be carried out in order to clarify the mechanical properties of the coils that shall be used for the structural analysis.

Considerations on elastic-plastic behaviour trigger questions and uncertainty, including on the mechanical measurements.

2.10 Discussion and questions at the end of DAY 1

- Are electrical tests carried out systematically? Yes, both at CERN and at FNAL.
- Should we cut coils after they have been tested at cold? This would allow assessing the effectiveness of the impregnation at the core of the coil.
- FNAL are using stainless steel wedges, and they claim that it should not be used. It deforms a lot and has a very different E-modulus compared to ODS copper.

3. DAY 2 – September 22nd

3.1 Baseline test plan [G. Chlachidze]

It was clear from the start of the collaboration work that a close coordination between the two laboratories would be of utmost importance.

The 11 T Test Program is based on significant experience with Nb_3Sn magnets at FNAL, starting with the first FNAL Nb_3Sn models (HFDA), LARP technological quadrupoles (TQC and TQS), and short and long LQ and HQ models for LARP.

A joint R&D program on 11 T magnets was initiated in parallel at FNAL and at CERN with the objective of coordinating the development activities of the two laboratories, including the test preparation and planning.

Soon after the very first test of the 11 T demonstrator, a CERN-FNAL common Test Protocol was developed. It was the first attempt to standardize the magnet test procedure at CERN and FNAL, including the definition of the major test steps and of their sequence within the test plan, and the description of the basic test parameters and settings. This protocol was meant to facilitate the comparison of the test results between the two laboratories.

After several iterations, a draft of the test protocol was presented on the occasion of a CERN-FNAL meeting on January 23rd, 2013. Lucio Fiscarelli and Hugo Bajas presented the test protocols for the quench performance study and for the field quality measurements.

The 11 T R&D test plan was developed on the basis of standard measurements in order to be applicable to the future production and tests of the 11 T dipole magnets. Parameters of the standard tests are fixed and described in the Test Protocol. A set of extended measurements was also added to the test plan taking into account specificities of the test facilities, magnet specific tests, and the different test equipment available (splice/energy loss measurements). Some minor deviations of the test parameters at CERN & FNAL are still expected.

The main objectives of the cold tests include quench performance study, field quality measurements, magnet protection studies, and the study of mechanical properties. The test plan is reviewed on a case by case basis for each 11 T model.

3.2 Field quality at CERN [L. Fiscarelli]

Lucio describes the magnetic measurements system that is used for the 11 T dipole project at CERN. There is shaft for the measurements at room temperature and there is another one for the measurements at cold.

The measurements at RT are carried out with the magnet model in horizontal position. A relatively long shaft is used in this case and the results are an average of measurements carried out over 1.2 m, which is the length of the measuring coil rotating at a radius of 22 mm. Measurements carried out in two adjacent positions provide an accurate evaluation of the integral field. Measurements carried out with the shaft longitudinally positioned across the homogeneous field section of the magnet provides estimation of the central field.

The measurements at cold are carried out with the magnet model in vertical position.

For the measurements at cold of the first model MBHSP101, an old shaft composed of five 250 mm long segments covering a half of the magnet model was used.

For the subsequent models, a new shaft composed of seven active segments was used. It is made of 432 mm long segments, one at each end, and five 247 mm long segments in the central section.

The magnet models SP101 and SP102 are based on the same electro-magnetic model (ROXIE). The measurements and the electro-magnetic model are compared. The data on the transfer function show that saturation is overestimated by the electro-magnetic model. This can partially be explained by the stacking factor of the yoke laminations (~15 units), and partially by the lack of knowledge of the magnetic properties of the iron actually used at high field (the BH curve is not accurate at high field; using data from the LHC production reduces the discrepancy by ~20 units).

For model SP102, there is an offset and an effect of magnetization on b_3. Globally, the magnetic signature of SP102 is different when compared to SP101.

An inverse analysis was carried out. The effect of cable displacements on the field quality was investigated. The same exercise was done for the transfer function. A displacement of 330 µm, corresponds to about 15 units.

The noise observed at low current on the transfer function and on b_3 may be correlated to flux jumps.

One recalls here that we do not have the same cable in all the models.

In SP102, there is a long decay observed on b_3; this was never seen on the FNAL magnets.

The model SP103 is very similar to SP102 in terms of magnetic signature.

Cold-warm correlation is good on SP102.

The question was raised why different systems are used for the cold and warm measurements. The number of turns is different, and the shaft for the measurements at cold is made to work in vertical position, when the shaft for the measurements at warm is made to work in horizontal position.

3.3 Field quality at FNAL [J. DiMarco]

Joe DiMarco describes the equipment used and the results of the magnetic measurements for the 11 T dipole models fabricated and tested at FNAL. The field quality measurements provide important information on the geometrical harmonics, coil magnetization, iron saturation and dynamic effects in the 11 T dipole models. The data obtained in the single aperture configuration are compared with the simulations. Later, they will be also compared with the results of the magnetic measurements in the two-in-one aperture model to better understand the magnetic coupling between the two apertures and the possible asymmetry of the magnet cross-section following assembling and operation.

The magnetic measurements were performed using two 16-layer probes based on the Printed Circuit Board (PCB) technology. The typical rotational speed of the probe was 1 Hz.

All the higher order geometrical harmonics ($n>3$) are small, ~1 unit or less. The value and difference of the low order harmonics in the tested models are rather large due to the variations of the coil size during fabrication, and to the assembling shims used to adjust the coil pre-stress. In production magnets, these harmonics could be reduced the variations of the coil geometry are smaller.

The persistent current effect in the TF and b_3 is substantial at low currents due to the large diameter of the superconducting sub-elements in the RRP strands. There is a quite good correlation of the measured and calculated data for the persistent current effect at currents above 1.5 kA. The ramp rate effect is small as expected for a cable containing a resistive core. The iron saturation effect in the TF and b_3, seen at currents above 4 kA, is in general consistent with calculations based on the iron magnetic properties and geometry used in these models. At high currents, the difference between the calculated and the measured TF is less than 1.5% and the difference Δb_3 is less than 6 units.

The b_3 decay is reproducible and quite large, ~4-7 units, unlike in previously tested Nb_3Sn dipoles. A possible cause of the unexpectedly large b3 decay could be local damage of the core (e.g. in the coil ends where the cable experiences large and complex bending deformations), which could lead to local reduction of the inter-strand resistance in these areas.

Snap-back in Nb-Ti magnets is usually relating to the current distribution and the transposition pitch. It is due to a change of magnetization at low current, i.e. at injection.

Lucio Rossi is asking why we observe a change of b_3 and b_5 at injection?

We still need to understand the time dependence and, talking about the sextupole standard component, b_3, we need to continue analysing, and understand how to move the shaft or how to measure the sextupole component with Hall probes (e.g. using the CERN-developed instrumentation).

Regarding the 2-in-1, the magnetic measurements will be done soon.

3.4 Quench performance at FNAL [S. E. Stoynev]

S. Stoynev describes the instrumentation used in the FNAL 11 T dipole models and summarizes the results of the magnet quench performance.

Five magnet models, including the demonstrator, were tested. The FNAL models have reached 97% of the designed bore magnetic field. Significant coil degradation was observed in all tests except for the dipole mirror magnet.

Magnet training is reproducible. It was found that during Nb_3Sn magnet training, the magnet quench current does not depend on the temperature. Quench locations are typically outside the straight section of the coils (around the first wedge/pole or second wedge of the inner layer).

Models showing degradation have also holding current quenches. All the holding current quenches develop in the mid-plane section of the outer layer (same for very low ramp rates when the magnet fails during holding current tests). The holding current and the time of holding are related logarithmically.

The presence of a stainless steel core in the cable reduces significantly the quench current sensitivity to the current ramp rate.

The RRR in the coils is stable in the different magnet assemblies.

Regarding holding current tests: a bad splice would imply current redistribution; this may have an influence on the holding current quenches, because of overloaded strands.

L. Bottura recalls that we do not have diagnostic on current redistribution and therefore, we can only make speculations.

The model MBHSP04 (the "collarless" assembly) was tested and had degradation with quenches in only one block. It would be interesting to carry out investigations and micrographic examinations to see whether one can see any damage at the level of the cable.

3.5 Quench performance at CERN [G. Willering]

Gerard recalls the main features of the coils tested so far, and the location of the voltage taps (V-taps) and quench heaters.

The quench localisation results from the analysis of the signals from the V-taps, but it has been also possible to localise the quenches with the pick-up coils of the magnetic measurements shaft.

The quench performance of 3 models is presented: MBHSM101 (single coil assembly), MBHSP101 (single aperture), and MBHSP102 (single aperture).

Holding current tests were carried out. The more demanding on MBHSP102, 10 hours at 11.85 kA without quench, and 2.5 hours at 12.3 kA also without quench.

Thermal cycles were made. A. Zlobin recalls that 15 years ago, we were observing that Nb_3Sn coils would remember training.

Ramp rate dependence tests were carried out, even if less extensively than at FNAL. On MBHSP102, a ramp rate of 200 A/s was applied without quench to 11.85 kA and a quench occurred at 10.8 kA during a ramp rate of 300 A/s.

The gaps between the wedges were discussed, as these are possible weak points depending on how well they are filled with charged resin. It must be possible to correlate with the construction parameters, as we know where are located these gaps.

3.6 Protection at FNAL [G. Chachidze]

A basic requirement for the quench protection system is to provide a reliable protection in all the possible quench scenarios. The quench protection in the FNAL 11 T magnet models is provided by protection heaters glued on the outer surface of the coil. This is a traditional position for the protection heaters in accelerator magnets. It provides good thermal contact with the coils and good ground insulation.

Other heater locations were previously tested at FNAL, including inner layer heaters in LARP LQS and HQ models, interlayer heaters in first Nb_3Sn models at FNAL (HFDA) as well as in short MQXB models (HGQ).

A comprehensive quench protection study was conducted in the single aperture 11 T dipole models, including the effect of the heater insulation thickness, the heater efficiency at different magnet currents, the quench temperature measurements, the heater efficiency in the low-field (LF) and high-field (HF) coil blocks, the radial quench propagation from the outer to the inner layers of the coils, longitudinal quench propagation velocity, the quench integral study with different dump resistors, and fast extraction tests.

The quench protection study was performed at currents up to 92% of SSL and for different external dump resistors in different 11 T single-aperture models. Only a few protection tests were performed in the two-in-one magnet model MBHDP01.

It was found that operation with at least 2 outer layer protection heaters is required for adequate protection of the 11 T dipole magnets. A reduced heater to coil insulation helps to increase the heater efficiency, but sufficient electrical insulation has to be provided. An estimated quench integral budget of 19-21 MIITs provides a reasonable quench detection time budget of ~ 28 ms in the high field coil block. A minimum peak power density of ~55 W/cm^2 is required to quench the magnet at currents $I_{inj.} < I < I_{nom.}$.

Radial quench propagation was measured at different currents and temperatures. Quite small delay at high currents helps to spread energy in the coil.

Longitudinal quench propagation velocity was measured in the mid-plane turn at different currents, and estimated in inner layer pole turns at relatively high currents during training quenches.

Coil temperature increase with time after quench was measured at different currents.

Fast extraction tests did not exhibit noticeable increase of the coil resistance.

3.7 Protection at CERN [S. Izquierdo Bermudez]

S. Izquierdo Bermudez recalls the parameters playing a key role in the protection of Nb_3Sn magnets, including the stored energy, the longitudinal quench propagation, and the quench detection thresholds.

She then describes the quench heater design, and the variants that are considered, e.g. an additional circuit on the outer layer for increased redundancy and an interlayer quench heater. An inter-layer quench heater was put in place in the practice coil 110 with very good electrical insulation performance. The baseline design relies on 4 heater circuits per aperture; this should provide sufficient redundancy. Copper coating is added on the CERN quench heaters (this is not the case at FNAL) to reduce the total electrical resistance of the heater circuits and thus make them applicable to the 5.5 m long magnet.

The quench heater delay has been modelled using COMSOL. The quench heater delays measured during the cold tests are systematically benchmarked with the simulations. The agreement between the two is better for the heaters in the high field region.

The heat propagation within the coil was studied and the thermal conductivity measured. The quench propagation between the 2 layers was also studied, and the measurements results between the two laboratories, CERN and FNAL, are consistent. At nominal current, there is a delay of 15 ms between the two layers. As a matter of fact, it would not help having inner layer quench heaters with a delay of the order of 30 ms.

The quench integrals determined in the two laboratories are consistent, and the measured current decays are within 5% of the computed current decays for different current values.

The computed hot spot temperatures are well in agreement with the values determined experimentally.

For a quench initiating in the high field region at 11.85 kA, a voltage threshold of 100 mV, a validation time of 10 ms, a heater firing delay of 5 ms, assuming an insulation between the heater and the coil composed of 50 μm of polyimide (substrate of the quench heater), 100 μm of G10 outer wrap, and 100 μm of cable insulation, assuming a RRR of 100 and all the quench heaters fired, the hot spot temperature would be 320 ± 20 K with a thermal conductivity between the two layers of 100 W/Km. Any reduction of the copper to superconductor ratio would lead to non-negligible increase of the hot spot temperature, e.g. of the order of 25 K for a reduction of the Cu/SC ratio from 1.1 to 1.0. The impact of RRR variations is less important, on the condition it is uniform along the cable. The time to detect, and to validate, the quench is important. It should not exceed the 15 ms already mentioned above. The thickness of the insulation between the heater and the coil will play an important role. A temperature increase of about 45 K is expected per each additional 0.1 mm layer of G10 insulation. Developments are ongoing to impregnate the heaters with the coils in order to increase the quench heater efficiency and to decrease the hot spot temperature.

Simulations were done assuming that the 2 quench heater circuits of a coil, out of the 16 circuits of a full cryo-assembly (two 5.5 m long MBH connected in series) would fail. In such case, the hot spot temperature would still remain below 400 K.

A. Zlobin suggests placing heater strips in the mid-plane (only if the regular outer layer heaters are not sufficient to provide reliable magnet protection), arguing that these would even work better at high pressure. At this location, the 2 layers can be covered.

A. Zlobin likes the combination of CERN and FNAL data in Susana's presentation.

Similarly, it was suggested analysing the quench data, and put together the data from the two laboratories.

A question discussed is whether Cyanate Ester, if used, would allow going to higher temperature.

It was recalled here that T_{max}, which is now admitted to be 350 K is linked to limitations of the resin system, but also of the cable.

4. DAY 3 – September 23rd – Debriefing

A. Zlobin shares his view on the results of the 11 T dipole development program. He underlines the importance of using at best the test results and stresses that there shouldn't be any restriction in exchanging data between the two laboratories.

There are differences between the development activities and the options considered in the two laboratories. However, we recognize the following:

- There is a common design for the cable, and the cable performance is well reproducible in both laboratories;
- The use of mica in the cable insulation at CERN may explain the low E-modulus measured recently. This needs to be clarified. We suggested sending to FNAL ten-stack samples to carry out E-modulus measurements following their measurements procedure;
- The necessity of using Mica in 11 T magnet needs to be understood and justified based on the FNAL experience with the 11 T models, and the LARP experience with TQ, LQ and HQ models;
- It was recalled that the "free" thickness of the insulation system is 150 μm.
- The CERN technical specification of the LHC main dipoles, in particular the voltages applied throughout the fabrication of the magnets, their installation and the commissioning of the machine, shall be met with sufficient margin, and this is the reason why mica has been considered on the CERN side.
- Regarding the coil size, a consistent approach would require better understanding of the insulation schemes and its change throughout the production process.
- We agree that the layer jump is a weak point in terms of mechanical stability.
- It is suggested to try the instrumentation methods applied at FNAL, i.e. install strain gauges on the wedges and coils.
- Regarding the yoke assembly, there is no major difference between the two laboratories, including for the yoking and welding operations.
- Regarding the bullet gauges, we agree that we do not need large preloading. However, it is important to maintain contact of the coil ends after the magnet cool down. Data shall be re-analysed for optimizing the pre-loading.
- The analysis of the data on protection is common between the two laboratories. It is necessary to continue measurements and analysis to determine the hot spot T and the effect of mica on the coil Tmax and quench propagation in the coils.
- One should continue doing inverse analysis in view of optimizing the field quality, bearing in mind the required trade-off between the pre-stress and the field quality. According to A. Zlobin, to carry out inverse analysis is not very practical. He is also of the opinion that control and optimization of the coil azimuthal size during fabrication can provide an optimal coil preload and geometry.
- Following the test protocol is very important for data analysis and interpretation as well as comparison with other projects, e.g. US-LARP.

- S. Feher believes that we should reduce the number of variables by suppressing the development of the PIT route, which he considers being a distraction that is not needed. L. Bottura replies that CERN needs a parallel development route in order to avoid a single source situation, and we know that PIT conductor can be made at the required level of performance. We see also that there seems to be a better use of Iop/Ic with PIT and that it is more stable (this could be related to the wire itself). Following these explanations, S. Feher feels more comfortable with the idea of working also with PIT conductor;
- E. Barzi is asking why OST was not able to produce wire type 217. L. Bottura replies that today, OST are able to go to 2700 A/mm2 and have tried wire type 217. However, they do not want to go for diameters lower than 45 µm because they want to keep space for the barrier, which is important for the margin;
- E. Barzi is asking why we went back to cable type 127 when 169 was very good. Luca said that it is mainly a matter of conductor cost;
- A. Zlobin argues that cable type 127 is a reasonable compromise for HL-LHC, and type 169 will be needed for high field magnets for FCC;
- A. Zlobin claims that there is still a grey zone as regards to optimization of the pre-stress and possible cable degradation resulting from the stress level;
- There can be variations of b3 along the magnet, in correlation with the twist pitch;
- S. Feher claims that the splice resistance should not exceed 0.1 to 0.2 nΩ when we are measuring 10 times more;
- A. Zlobin argues that there could be a non-uniform field distribution depending on the current sharing and therefore, the measurement of the splice resistance needs to be very precise.