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# EuroCirCol

**European Circular Energy-Frontier Collider Study**

Horizon 2020 Research and Innovation Framework Programme, Research and Innovation Action

# MEETING MINUTES

# VIDEO MEETING

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| **Link to Indico:** | https://indico.cern.ch/event/776591/ |

## Executive summary

The meeting consists of reviews of the work and milestones achieved by the member institutes of WP5 and the institutes of the US Magnet Development Program (MDP).

## Igor Novitski: 15 T Dipole Demonstrator, status and update from FNAL

I. **Novistki** starts by presenting the main design parameters of the 15T dipole demonstrator, which is a $Nb_3Sn$ cosine-theta magnet consisting of 4-layer graded coils with 60 mm aperture diameter. It is designed to produce 15.61 T at 4.2 K and 17.04 T at 1.9K. He also provides details on the conductors of the two inner and two outer coils as well as on the mechanical structure, which features a thin stainless steel coil-yoke spacer, vertically split iron laminations, aluminum I-clamps, a 12-mm thick stainless steel skin, thick end plates and stainless steel rods. He adds that the outer diameter of the cold mass is less than 610 mm. Then, I. **Novistki** states that the fabrication and instrumentation of the two inner and two outer coils is complete, that the shim plane is finalized and that the coil assembly has started. In addition, he indicates that the spare inner coil will soon be impregnated while the spare outer coil is pending the arrival of the cable. Several short mechanical models as well as the magnet structure were assembled and tested. Finally, he concludes that the magnet structure and tooling are ready for the coil installation and pre-loading and that the magnet test will occur in January/February 2019.

## Soren Prestemon: Status update from LBNL

S. **Prestemon** starts by recalling the history of Canted Cosine Theta (CCT) dipole tests at LBNL: the main results are summarized in Table 1. S. **Prestemon** insists on the fact that CCT dipoles require less tooling and parts compared to traditional dipole magnets, and are thus easier to manufacture. He indicates that LBNL is addressing the main technology issues (e.g. field quality, conductor damage, cost and training) along the production of the 2-layer CCT series (from CCT3 to CCT5). As an example, he states that the conductor damage problems were solved with CCT4 while the reduction of magnet training is the focus for CCT5, which, conversely to CCT3 and 4, uses tougher epoxy and shim interface. In addition to these new features, a new method called “Bend-and-Shim” has been developed to enhance the pre-load on coils; this innovation has been successfully applied to CCT5 and tests have shown improvement on the quench training of CCT5. S. **Prestemon** then focuses on C1 magnet, which consists in a 2-layer CCT dipole made with CORC® cable. This magnet has shown high thermal stability during quench, i.e. there was no thermal runaway. He indicates that the next step is C2 magnet, which is a 4-layer CCT dipole with 70 mm aperture diameter designed to reach 3T at 4.2K in a 10 T background field; this magnet aims at testing several key technology features for high-field REBCO accelerator insert magnets. A reasonable decrease (27%) of the critical current of C2 wire has been measured at 77 K after its winding and the application of stycast. Finally, S. **Prestemon** concludes that REBCO wires with thinner tapes would pave the way to higher dipole fields: he thus insists on the need to develop them now because of their strong impact on technology and market.

Table I: History of CCT at LBNL

| CCT dipole name | Superconductor | Aperture diameter | Design field in the aperture at short sample current | Field reached in the aperture during test |
|---|---|---|---|---|
| CCT1 | Nb-Ti | 50 mm | 2.5 T | 2.5 T in 11/2013 |
| CCT2 | Nb-Ti | 90 mm | 5.3 T | 4.7 T in 05/2015 |
| CCT3 | $Nb_3Sn$ | 90 mm | 10.5 T | 7.4 T in 03/2016 (conductor damage) |
| CCT4 | $Nb_3Sn$ | 90 mm | 10.5 T | 9.1 T in 08/2017 (substantial training) |

## Hélène Felice: FCC activities, Status and Update at CEA

H. **Felice** starts by recalling that, within the EuroCirCol program, CEA Saclay focuses on the design of the 16T double aperture block-type dipole for FCC. She states that the 2D magnetic and mechanical model as well as the 3D magnetic model have been built while the 3D mechanical model is under development. H. **Felice** also recalls that a CERN-CEA collaboration has been signed to build a single aperture demonstrator of the 16T FCC block coil magnet (F2D2). She then presents the main features of F2D2, which has 4 layers of conductor with grading, and states that its 3D magnetic model is ongoing while the quench protection studies are about to start. She then focuses on the joints, which represent a key challenge for this magnet, and states that CEA has chosen to use external joints since internal joints require additional technical development (an EPFL/CERN collaboration has started to explore this technique). In addition, H. **Felice** states that the definition of the winding steps and parts design, the winding tooling preliminary design as well as the Nb-Ti/$Nb_3Sn$ splice area are currently being studied. The 2D mechanical model of F2D2 has shown acceptable stress level in the coils and a preliminary CAD model has been built to assess constraints due to the vertical coil size; a 3D ANSYS model will also be built. Finally, H. **Felice** indicates that the schedule and content of the F2D2 project are being discussed within the CERN-CEA collaboration in order to minimize the risk.

## Susana Izquierdo Bermudez: Status and Update at CERN

S. **Izquierdo Bermudez** starts by presenting a general overview of the status and activities related to eRMC, RMM and SMC magnets. She then focuses on eRMC and states that its two $Nb_3Sn$ coils as well as its spare one have been wound, reacted and impregnated without any noticeable issue. She also presents the new features of these coils: mica around pole, polished end spacers, non-coated end parts and extra S2 glass between the cable and the metallic parts. Their aims are to minimize the bonding strength between the cable and the pole, to maximize the one between the cable and the end parts and to enhance the electrical insulation. Unfortunately, in spite of the large amount of insulating material between the cable and the pole, the measurements have exhibited a weak coil-to-pole electrical insulation. S. **Izquierdo Bermudez** continues the review of CERN activities explaining that a dummy structure has been prepared to explore the different assembly parameters of eRMC: it consists of aluminum dummy coils, aluminum shell, stainless steel and aluminum rods (for the longitudinal loading). A first assembly with the dummy coils as well as a thermal cycle to 80 K have already been made; a slight increase of the pre-load and a second thermal cycle are scheduled. As a result of these mechanical assembly tests, she indicates that the increase of stress during cool down is lower than expected for the shell and higher for the coil. She specifies that investigations are currently carried out to understand this unexpected behavior. She also mentions that the longitudinal rods are behaving as foreseen. Finally, she concludes that the assembly of eRMC is planned for January/February 2019. She also adds that the winding of RMM could start as early as beginning of 2019 if the cable is available and that SMC will be used to qualify new resin systems and develop high field internal splices, together with any new feature in the future.

## Alejandro Fernandez Navarro: 16 T common coil dipole, status and update from CIEMAT

A. **Fernandez Navarro** begins by reviewing the status of the FCC activities at CIEMAT. He states that the 2D electromagnetic and mechanical designs of the 16T Common Coil option for the main dipole of FCC are finalized. He adds that the Common Coil section of the long version of the FCC Conceptual Design Report (CDR) is currently being written. In addition, he mentions that two conceptual options of the mechanical support are available: the closed support, which is the classical option in the accelerator magnet community, is the baseline while the open support, which is more innovative, requires technological studies. For this reason, A. **Fernandez Navarro** indicates that a collaboration agreement to develop and study both support structures for $Nb_3Sn$ racetrack coils produced at CERN is being discussed. He then presents more in detail the design parameters of the common coil options as well as the main electromagnetic results: all harmonics are below 13 units and the smallest margin on the load line is 14.1%. He also mentions that quench protection studies have been carried out in collaboration with CERN TE-MPE-PE section: the adiabatic hot spot temperature is below 350 K and the stress in the coils is below 200 MPa during a quench after CLIQ firing. A. **Fernandez Navarro** focuses then on the main features of the mechanical design: the pre-compression in assembly is made with a stainless steel shell, the coil support transfers the stress to the coil copper wedges and a titanium closed support separator (baseline option) minimizes the coil displacement. He presents the main mechanical results and states that the equivalent stress in the coil complies with the design requirements while the one in the other materials of the magnet are all under their yield strength. Finally, as a summary, he concludes that the 2D electromagnetic and mechanical models of the common coil option fulfill the design requirements.

## Riccardo Umberto Valente: Design of 16 T Cosθ bending dipole, status and update from INFN

R. **Umberto Valente** starts the talk by presenting an overview of the tasks accomplished by INFN regarding the 16T double aperture cos-theta type dipole for FCC as well as updates on the design requirements with respect to the first draft of CDR (May 2018). He then shows that the design proposed initially (rectangular window inside the iron yoke) was not meeting the requirements regarding $b_2$ and $b_3$ harmonics (especially $b_2$ variation with coil current). He explains that after modifying the shape of the iron yoke, it was possible to largely reduce the $b_2$ variation; however, the $b_2$ component was still off the specifications. As a consequence, he indicates that breaking the left-right symmetry in each cos-theta aperture was the only possible cure to this problem. He therefore presents the electromagnetic results of this strategy: all 2D harmonics are within the specifications, in particular, $b_2$, $b_3$, $b_5$ are all below 3 units at collision and the variations of $b_2$ and $b_3$ with coil current are below 20 and 10 units respectively. The 3D coil ends are then discussed and R. **Umberto Valente** states that the outcome of their study calls for coil ends as long as possible as it is better for the peak field and the field quality; the 3D mechanics are still to be assessed. After, R. **Umberto Valente** focuses on the mechanical design, and shows the different features of the cold mass: a 20mm-thick pre-compressed outer steel shell, a 50mm-thick aluminum ring, an iron yoke with diameter of 660mm, two steel pads enclosing the cos-theta coils and titanium poles. Finally, he concludes stating that the Von Mises stresses on conductors are always below the limits during assembly, cool down and energization, that there is always contact pressure between coils and pole, apart from very localized region after the energization. He adds that the stress on mechanical structure is always below the threshold, apart from very localized hot spots under the keys, where plastic regime occurs.

## Bernhard Auchmann: Status of the CCT at PSI

B. **Auchmann** begins by recalling that PSI is in charge of the Canted Cosine Theta (CCT) design of the FCC 16T dipole, he presents the main design parameters of this 4-layer magnet and gives some key values (e.g. 9.7 kt are required for all the CCT dipoles in FCC). He also mentions that the use of double-helix in the CCT allows to reduce the unit length and peak voltage to ground during quench. He then indicates that quench and CLIQ discharges simulations are being carried out on CD1 with ANSYS in collaboration with LBNL; simulations on the FCC CCT are to follow. After that, B. **Auchmann** focuses on the presentation of the superconducting magnet lab at PSI and states that the CHART collaboration (Swiss Accelerator Research and Technology Center) supports these activities. He indicates that the reaction furnace is fully operational and that it can accept up to 2m-long coils. Detailed tests have already been performed (e.g. reaction of 5-turn test former) and have shown that the furnace is able to maintain thermal plateaus within +/- 3 K. A vacuum impregnation system was also set-up and, during its commissioning which consisted in impregnating a 5-turn coil, the coil temperature stayed within +/- 3 K during curing plateaus. Then, B. **Auchmann** details the CD1 manufacturing: the winding of its outer layer did not exhibit any issue while the one of its inner layer had a tendency to pop up of the winding channels. To fix this problem, which seems to be related to the insulation, he mentions that 3D printed steel cable keepers were used. Next, he shows detailed pictures of the 5-turn sample after impregnation: some bubbles are visible. Consequently, he indicates that there is a need to improve the control of injection flow rate via peristaltic pump. Finally, he presents a microscopic analysis focused on the sliding planes interface. He concludes his presentation stating that the 16T CCT dipole design is compliant with FCC requirements, including on the field quality for which persistent current simulations have been developed. The commissioning of PSI superconducting magnet lab is complete and the coil manufacturing of CD is ongoing; he states that this step has to be finalized and consolidated before the manufacturing of the 4-layer design for FCC.

## Haris Kokkinos: EuroCirCol Cosθ 16 T dipole, status and update from UPAT

H. **Kokkinos** is with the University of Patras (UPAT) which has recently joined the EuroCirCol collaboration (in March 2018). He thus starts by presenting this university, and more specifically, the Department of Mechanical and Aeronautical Engineering, which is composed of six engineers and which has just entered into the magnet community. He states that they are using Siemens PLM portfolio as simulation tools and ANSYS for crosschecking the results. Their first objective is to build a model of the FCC 16T cosine-theta dipole design developed by INFN using Siemens PLM portfolio, and to compare their simulation results with those of INFN, in order to both enhance their skills in superconducting magnets and consolidate the cosine-theta design since they are using different simulation tools. H. **Kokkinos** then presents the simulation results achieved so far by UPAT on the "initial" design of the FCC 16T cosine-theta dipole developed by INFN, i.e. the design with symmetric coils configurations and on the "CDR" design also developed by INFN, i.e. with asymmetric coils configurations and optimization of the iron yoke shape. The 2D mechanical results (Von Mises stress) obtained by UPAT with Simcenter and ANSYS workbench for both configurations are very similar to those obtained by INFN with ANSYS mechanical APDL at each step (assembly at room temperature, after cool-down to 4.2K and after magnet energization), though some differences can be found. As a conclusion, H. **Kokkinos** states that the differences between UPAT and INFN results are bound to come from differences between the modeling approach of both institutes since the results obtained by UPAT with Simcenter and ANSYS workbench are almost the same. He indicates that the comparison with INFN will go on until they understand the reasons for these differences.

## Antti Stenvall: Status and update from TUT: Quench protection

A. **Stenvall** starts by recalling that, within EuroCirCol, TUT studied the quench protection of FCC main dipoles and quadrupoles. He indicates that they have brought support to the cosine-theta, block coil and common coil magnet designs of the FCC 16T main dipoles by analyzing them from the point of view of magnet quench protection. In addition, A. **Stenvall** states that they have studied the protection schemes of these magnets considering CLIQ as a baseline and quench heaters as a back-up solution; this study was carried out in collaboration with CERN. He then focuses on the ongoing project named Quench Protection Database (QPDB), developed with CERN along 2017/2018. The objectives of this project are to develop a database for the storage of experimental quench results as well as to analyze the heater delays and current decays and to compare them with quench simulations. He states that the database is now built and filled with results from several MQXFS and 11T models; the analysis of heater delays, which features summaries, general trends and assessment of experimental uncertainties, is still ongoing. Finally, A. **Stenvall** concludes his talk mentioning that a quench protection section will be written in January 2019 for each magnet of the FCC CDR and that he is preparing a proposal for a cloud database of materials used in superconductor applications at national and European level. He adds that T. **Salmi** could continue working on quench studies for future high field magnets via a 5-year Finnish fellow funding; this will be clarified in May 2019.

## Ananda Chakraborti: Manufacturing cost modeling approach for 16T dipole arc magnets

A. **Chakraborti** indicates that Research is being conducted at TUT to define performance indicators for $Nb_3Sn$ magnet manufacturing and to select key performance indicators (KPIs) for their manufacturing cost and quality. In order to select such KPIs, machine learning based techniques are currently under investigation. He also mentions that in the following months, it is planned to monitor the production of the 11T $Nb_3Sn$ dipole magnets (for the HiLumi project) at the Large Magnet Facility in CERN with a software named Manufacturing Execution System (MES). He adds that MES will provide a high degree of visibility on the manufacturing in terms of tracing and tracking of magnet parts, production scheduling, tracking major of tooling and quality management. He goes on stating that TUT is working with its industrial partners to develop a MES prototype specially designed for the monitoring of the 11T $Nb_3Sn$ dipole magnet manufacturing; he specifies that additional communication between the involved parties is needed. He then details the concept that will be used for the MES prototype showing pictures of the software and mentioning some of its features such as materials stock balances. Finally, A. **Chakraborti** shows and comments pictures of the software on two examples: work phase execution and traceability report.