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Thermo-Electromagnetic Design, Operation and Protection Simulations of a 40 T HTS NI Final Cooling Solenoid for a Muon Collider

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***Abstract*—The final stage of the cooling channel of a muon collider contains several cooling cells, each requiring a very high-field solenoid. Such a so-called 'final cooling' solenoid is key in strongly reducing the emittance of the beam during pre-acceleration and subsequent injection of the beam into the collider ring. In the muon collider design, about 12 to 14 final cooling solenoids of different lengths are foreseen. The conceptual design of the final cooling solenoid that is currently pursued has a homogeneous ($\sim$1%) magnetic field of >40 T over a length of approximately 0.5 m and features a stack of 52 No-Insulation (NI) High-Temperature Superconductor (HTS) pancake coils. Its ramp scheme has been investigated and a ramp profile has been derived for a constant dissipation of 200 W during the majority of the ramp, while keeping the overall magnet characteristic time at 2700 s. Protection calculations have been performed and show that these solenoids require active quench protection at nominal field to limit the Lorentz forces and thus tape tensile and magnet radial stress during a quench. This contribution provides an overview of the current state of the thermo-electromagnetic design, operational aspects, and several simulated quench and protection scenarios for our design of a final cooling solenoid for a muon collider.**

***Index Terms*—NI coils, HTS, quench protection, muon collider, final cooling solenoid**

I. Introduction

The Muon Collider (MuC) is a proposed accelerator that aims to provide collisions of circulating beams of high-energy muons. The emittance of the muon beam needs to be strongly reduced before acceleration and subsequent injection into the collider ring. This is achieved in a cooling channel [1], [2]. The final stage of the cooling channel contains several cooling cells each comprising a so-called 'final cooling' solenoid generating a very strong magnetic field [3]. These solenoids are key in further reducing the transverse and longitudinal emittance of the beam before injection into the collider ring. In our current design, the final cooling solenoids produce a homogeneous magnetic field of 40 T over a length of approximately 0.5 m and feature a stack of No-Insulation (NI) High-Temperature Superconductor (HTS) pancake coils. The design of the final cooling solenoid is challenging as the stored energy and energy density at nominal current is significant, and the Lorentz forces are large. An additional challenge of using NI coil technology is that any current ramp causes a part of the current to flow radially between the coil turns. This parallel path for the current increases the time needed to reach the desired field and generates additional Joule heating. Calculations are performed using a modeling tool developed at CERN for NI solenoids to mature the design of the magnet's layout and determine a suitable range for the magnet's characteristic time to ensure the magnet to ramp to the nominal field within 6 hours and to limit the peak ramp loss, and hence cryogenic requirements. An optimization of the ramp scheme is studied to allow a more equal distribution of ramp loss over time. Screening currents pose an issue for HTS magnets, as these currents result in additional loss, a potentially non-neglectable error in the magnetic field profile, and a significant increase in local mechanical stress in the tape. These effects are included in the calculations and used to further optimize the magnet's geometry. Furthermore, 2D quench simulations have been performed to estimate the temperature, voltage and Lorentz force distributions during a quench. These simulations are as well used to evaluate the potential use and effectiveness of several quench protection techniques, with the main focus on the capacitor discharge (CD) quench protection technique [4]. This contribution presents the current state of the thermo-electromagnetic design, operational aspects, and several simulated quench and protection scenarios of our conceptional design of a final cooling solenoid for a muon collider.

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II. Insulated vs Non-Insulated

Quench protection of HTS magnets with a high energy density is not trivial. An estimation of the normal propagation velocity and resulting hot-spot temperatures of a final cooling solenoid were obtained using a 1D quench propagation simulation tool assuming that the magnet uses an insulated conductor and is protected purely by energy extraction. The required peak extraction voltage is presented as a function of the magnet operating current (which affects the conductor dimensions and magnet inductance) in Figure 1. It indicates that if such a magnet would use a practical sized insulated conductor rated for 4.5 kA (6 parallel, 12 mm wide ReBCO tapes), uses 50 mV of detection voltage and a protection delay of 10 ms, an energy extraction system with a peak

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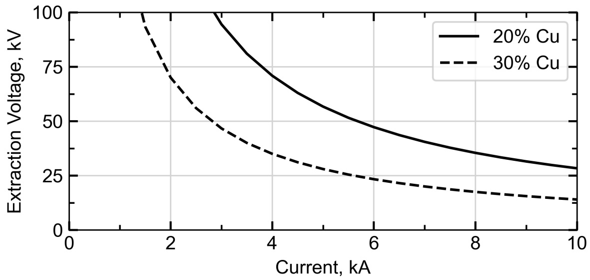

Fig. 1. The required peak extraction voltage as a function of design nominal current. A higher nominal current means a bulkier conductor and a lower magnet inductance. These peak extraction voltages over this current range are far beyond the limit of an acceptable extraction voltage.

extraction voltage of 30-65 kV is required in order to keep the peak temperature below 300 K assuming a reasonable copper content of between 20 and 30%. This voltage is far beyond any currently acceptable standards in magnet design. A conductor comprising many more than 6 parallel tapes, rated for currents of over 5 kA, would not be practical for winding a final cooling solenoid with an inner winding radius of 30 mm. This is because there is no transposition of the tapes, the winding diameter of each tape within the stack is different and thus a separate winding spool for each tape would be required. A homogeneously distributed cable current is less guaranteed with a thicker conductor comprising parallel tapes, which affects the field homogeneity in the coil's center. Moreover, a conductor with many parallel tapes is not practical for low resistance and homogeneous current injection. External quench heaters are also not a viable protection option in this case, given the enormous energy margin of most of the magnet and the volume of the magnet that is required to be transitioned to the normal state within tens of milliseconds after quench detection. Segmenting the magnet and the energy extraction system is in theory feasible, but significantly adds to the complexity of the protection system. Therefore, in our conceptual design, NI coil technology is chosen as the method that offers a chance of survival in case a quench occurs near nominal operating conditions.

III. Coil Properties

The reference layout in our design study of the final cooling solenoids of a muon collider comprises a stack of 52 non-insulated HTS ReBCO pancake coils to generate the required magnetic field of at least 40 T. The design operating temperature of the solenoids is 4.5 K. Each pancake coil has bore radius of 25 mm and the coil pack starts at a radius of 30 mm, see Figure 2. The 46 pancake coils, that are situated in the center of the stack, have an HTS coil outer radius of 90 mm. The three pancake coils on each extremity have more turns to improve field homogeneity in the magnet's end-regions, thus to improve the tape performance due to the field-angle I_c dependency. Further design iterations are expected in the future, especially around the coil's extremities, taking into account the further input and requirements of the beam physicists.

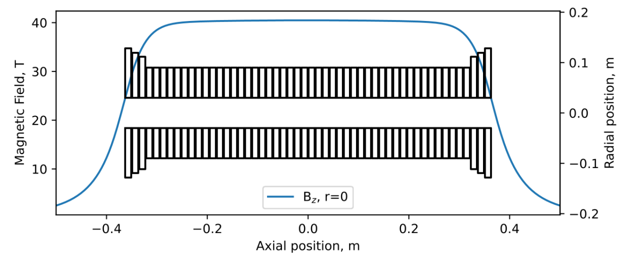

Fig. 2. The 52 coil packs of the stack of pancakes and the magnetic field produced on axis. The magnet produces a field of 40 T over the central 0.5 m of the coil. The support structure around the coils is not shown in this figure.

There are two winding options that are currently considered for the individual pancake coils. One uses a single 12 mm wide ReBCO HTS tape and the second option uses two tapes in parallel. The advantages of the second option are a reduced magnet inductance and a reduced sensibility to local defects in the tapes. However, coil winding and homogeneous current injection into the tapes are more complicated. Tape with a thickness of 75 µm is considered (50 µm of Hastelloy, 20 µm of surround copper plating and 5 µm of silver, buffer layer(s) and the HTS layer) and 5 µm solder between tapes. The aim is that each pancake, whether using a single tape or a conductor comprising two parallel tapes, has a fully soldered coil pack. This assures a good thermal connection between tapes and it is mechanically advantageous. Current winding trials are underway using tapes that are pre-tinned with eutectic SnPb solder metal and hot-winding of the coils. A thick layer of Hastelloy in the tape is essential as it provides mechanical strength to the magnet. The coil properties for both single and double tape winding variants are presented in Table I. The mechanical tensile strain limit of such tape is around 0.4% [5]. During operation the tensile strain remains below its limit and, during a quench of the magnet, the tape's stress limit may be approached or even be reached in some specific cases. Therefore, this coil is considered to be mechanically limited, rather than limited by the critical current of the tapes. A stainless steel mechanical support ring will be fitted around each of the pancake coils for both pre-compression and mechanical support during operation.

TABLE I
The proposed coil parameters of a 40 T final cooling solenoid.

Property	Value		Unit
Number of parallel tapes	1	2	-
Turns central pancakes	750	375	-
Turns outer 3 pancakes	1020/1118/1230	510/560/615	-
Inductance	23.3	5.8	H
Nominal Current	607	1214	A
Current Density	632		A/mm^2
Stored Energy (at 40T)	4.1		MJ
HTS Mass	140		kg
Energy Density	29		kJ/kg
Total tape length	16		km
Tape width	12		mm
Tape thickness	75		µm
Hastelloy thickness	50		µm
Copper thickness	20		µm
Number of pancake coils	52		-

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IV. Ramp to Nominal and Cryogenic Considerations

A 2D axisymmetric simulation tool has been developed at CERN that is able to describe the thermo-electromagnetic behavior of NI HTS solenoids. The model combines the partial element equivalent circuit method (PEEC) for simulating electrical circuits with an explicit ODE solver in Python. It uses smart homogenization of the winding pack allowing fast simulation of magnets with a large number of turns. It is a feature rich tool that includes the ability to model various ramp options, thermal effects, screening currents, quench detection options and various quench protection techniques. This tool is used for both evaluating the ramp behavior and loss of our concept of the 40 T solenoid, as well as the simulation of several quench and protection scenarios.

In the presented case study, the largest contribution to the ramp loss is the heat dissipated in the turn-to-turn resistances of the pancake coils. Depending on the ramp-rate and the characteristic time (τ), defined as L_{total}/R_{total}, of the magnet, this loss can have a significant impact on the requirements of the cryogenic system. In this study, R_{total} is not set, rather the magnet characteristic time is set, and the total resistance of the circuit is calculated accordingly.

The target time for the magnet to be at within 1% nominal magnetic field is 6 hours [3]. In practice, this means that the maximum characteristic time of the magnet can be around 1 hour, as one needs to wait approximately 5 times the magnet characteristic time after a fast linear ramp to nominal current to be within 1% of the target magnetic field. Compared to a linear ramp scheme to nominal current, one can reach the target magnetic field faster by using an over-current ramp scheme and ramping down to nominal current when the magnet approaches the target magnetic field [6]. However, this significantly increases the ramp-loss and it has the potential to quench the magnet near nominal current and is therefore not a favorable ramping method.

The current magnet design embeds 4.5 K forced-flow helium cooling via channels within the inner terminal rings of the pancake coils. Therefore, there will be a thermal gradient in the magnet during ramp and the inner bore of the magnet will have the lowest temperature, while the warmest spot is near the pancakes' outer radius. The largest amount of volumetric loss occurs near the outer radius of the pancake coils. The elevated temperature of the tapes near the coil's outer radius during ramp are acceptable as the magnetic field in this region is much lower and it is even slightly beneficial, as it limits the screening currents that are induced in this region.

The characteristic time of the magnet is a trade-off between thermo-electric stability of the magnet and loss during ramp. In general, a higher τ means better stability, but higher total and peak ramp loss for the same ramp settings. Our aim is to set the pancake τ by either mechanically or chemically removing (part of) the copper on the sides of the HTS tapes after winding. Figure 3 shows the loss for a linear ramp scheme assuming 5 different characteristic times and the single tape pancake coils. Each ramp starts at $t = 0$ s and ends at a time of 5 times the value of τ before the 6 hour mark. The peak loss during ramp is around 880 W for τ = 3600 s and 380 W for τ = 2700 s, which are considered too large for a reasonable cryogenic system and causes significant thermal gradients in the magnet itself. For a τ of 1800 s and below, the ramp loss is within the limits that we deem acceptable, however, this lower characteristic time requires a resistance that impacts the stability of the magnet during operation. In addition, it is important that when the magnet approaches its nominal field of 40 T, the radial loss is low and the temperature of the inner turns does not exceed 6 K. Therefore, a non-linear ramp scheme is derived that limits the ramp loss to 200 W over most of the ramp profile and a much lower loss near the end of the ramp, while keeping τ equal to 2700 s, as shown in Figure 4. This increases the total loss by 3% compared to a linear ramp scheme. The temperature gradients in this scenario do not exceed 10 K between the inner bore of the magnet, which is kept at 4.5 K and the outer radius, which is calculated to be at a temperature of 14 K for the majority of the ramp up to nominal current. In practice, the thermal gradient will likely be less than calculated as no external structures, nor any potential active cooling solutions from the outer radius are taken into account for this simulation. The ramp loss of the winding variant with two parallel tapes is very similar to the single tape variant, as the loss mainly depends on the ratio between τ and the ramp time, which is kept the same for both cases. The minimal acceptable inter-turn resistance for stable operation depends on many factors, such as available cooling power during nominal operation, the thermal connection between the magnet and the cryogenic infrastructure, the quality of the joints and the critical parameters of the ReBCO tapes themselves. A rough estimation suggests that if this magnet is constructed using pancake coils wound from a single tape and has an overall characteristic time below 600 s, corresponding to an inter-turn resistivity of 38 $\mu\Omega cm^2$, the pancake coils near the stack extremities may fail to recover from a sudden 2 K temperature spike near their inner turns under nominal operating current and magnetic field conditions. In that case, part of the current is pushed out of the inner turns, starts to flow radially and dissipates heat in the inter-turn resistance. Subsequently, either an equilibrium is reached between the heat dissipation and cooling power, leading a stable temperature plateau within the pancake coil at T>T_{He} and a local lower azimuthal current density compared to the nominal current density or thermal runaway leading to a quench. This magnet characteristic time and inter-turn resistivity for which the magnet can recover after a small temperature spike is highly dependent on the coil's cooling conditions and thus very subjective to the magnet's final design. The pancake coils in the center of the magnet are slightly more resilient to temperature spikes as the field lines are more parallel to the tape and thus the critical current of their inner turns is slightly higher. It still has to be demonstrated if these ReBCO pancake coils with these parameters can operate under these conditions. A longer magnet characteristic time is advantageous during operation. Therefore, the quench studies presented in this paper are based on a magnet characteristic time of 2700 s. The power loss near the end of the ramp to nominal is significantly lower than the peak power and it reduces the thermal gradient within the

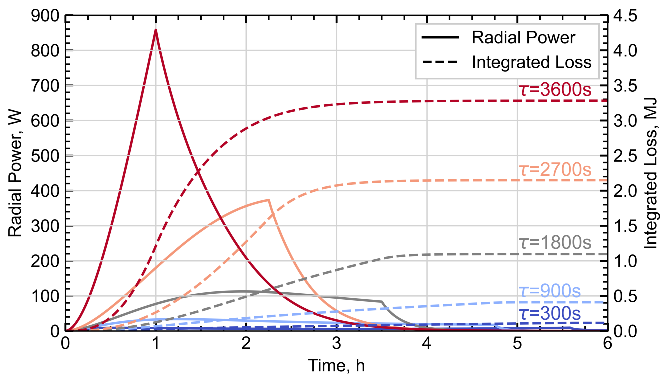

Fig. 3. The radial power and the integrated loss per final cooling solenoid as a function of time for various magnet characteristic time constants assuming a linear ramp to nominal and pancakes coils wound from a single tape. A higher τ significantly increases the ramp power loss as it dictates a much larger ramp-rate in order to be at nominal field within 6 hours. A peak power of over 250 W is considered to be undesirable as it will drive up the requirements of the cryogenic system and can potentially drive the magnet into its current sharing regime during ramp.

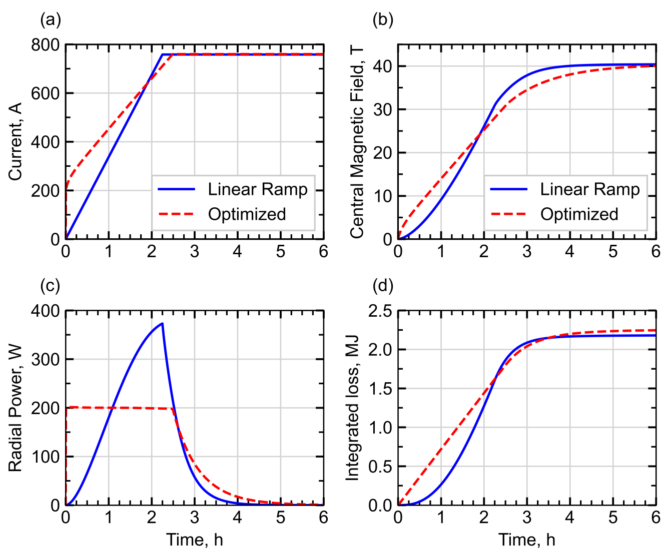

Fig. 4. A non-linear ramp scheme reduces the peak heat load compared to a linear ramp scheme to nominal current. The ramp scheme (a), the central magnetic field (b), the radial power (c) and the integrated loss (d) are shown as a function of time for a final cooling solenoid with a τ of 2700 s.

magnet. This also means that a similar loss curve should be followed on the ramp down to zero current. If the initial ramp down from nominal field is too fast, the losses in the radial turn-to-turn resistance can cause the magnet to heat up and quench. Thus, if any precursors of undesired behavior either in the magnet or its cryogenic system are observed, such a magnet may not be ramped down quickly without potentially quenching it.

V. Quench Protection

Several quench protection solutions are being considered for the final cooling solenoids. The most promising quench protection method that is currently being considered is quench protection by capacitor discharge (CD) [4]. This method relies on heating the magnet by injecting a high-current pulse into the magnet. The majority of this current flows via the low-inductance, radial turn-to-turn path between the terminals of the pancake coils. The energy of this current pulse is dissipated as heat within the pancake coils, i.e. the pancakes' turn-to-turn resistances are used as an internal quench heater. This method seems especially effective for stacks of pancake coils and, in principle, requires no additional internal electrical components. Quench propagation in NI magnets, with a high stored energy and operated relatively close to its load line, does not fully rely on classical thermal normal zone propagation as inductive effects play a large role in expanding the normal zone. Therefore, classical quench heaters between pancake coils, that mainly heat the pancakes' inner turns, also have potential as a viable protection method. However, such a solution has the disadvantage of slower heat deposition in the magnet and it requires many electrical connections.

Many quench protection methods for stacks of round pancake coils can be simulated in 2D due to the axial symmetry of the methods. A parameter sweep has been performed over various quench protection scenarios and protection settings in order to quantify an effective operating range for them. Since these are 2D calculations, it is assumed that a quench starts in one or a few adjacent turns over the full circumference of the magnet, followed by thermal and inductive quench propagation in the radial and axial direction of the magnet. The detection voltage is set to either 50 or 100 mV (full coil voltage), 10 ms of detection time after which the breaker of the power supply is opened and subsequently the energy of a capacitor bank is discharged into the magnet. A high-current capacitor bank of 50 mF is chosen and simulations are performed for charging voltages of 300, 600 and 900 V. The obtained peak force density and peak temperature of several case studies are shown in figure 5. The temperatures of all cases stay below 250 K. The peak force density, however, is increased significantly due high induced currents compared to the nominal operating current.

A simplified mechanical model, considering only the radial component of the force density while neglecting thermo-mechanical effects, was setup to get an indication of the stress and strain involved during operation and quench. In the optimal simulated quench and protection scenario with a detection voltage of 50 mV and a protection delay of 10 ms, a peak force density of 29% higher than nominal is observed due to induced current. In this case, the mechanical model shows that hoop strain increases to a value in the range of 0.2 to 0.4% for the pancake coils that are situated in the center of the magnet, provided that the proper pre-compression is applied [7]. It means that the hoop strain of these central coils remains within the tape's mechanical limits. The pancake coils near the extremities of the coil stack exhibit a higher, but local peak strain of >0.4%, mainly due to screening current effects. Without any action of the quench protection system, the normal zone propagates inductively, and longitudinally through the magnet and locally increases the radial force density by a factor of 2.3. Consequently, an increase the hoop strain is observed to values above 0.4% for almost all of the

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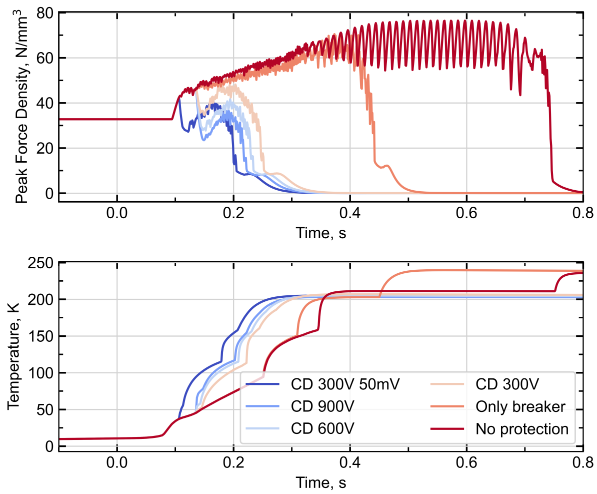

Fig. 5. The peak radial force density within the magnet and the peak temperature as a function of time during a quench for various quench protection scenarios assuming pancake coils wound using a single tape. One scenario uses 50 mV as detection voltage, all other use 100 mV as detection voltage. Screening currents are included in these calculation. Capacitor discharge (CD) quench protection significantly reduces the local peak force density during a quench. Many peaks in force density are observed as the quench inductively spreads from pancake to pancake coil in the case no protection is used. In the 2D simulations, the peak temperatures stay below 250 K.

pancake coils within the stack, pushing the local stress beyond the limit of what the HTS tape intrinsically can handle and potentially damages the magnet. Only opening the breaker of the power supply leads to the magnet current to close its path via the pancakes' internal resistances. However, the heating produced by this, with a magnet τ of 2700 s, is not sufficient to transition most of the pancake coils to the normal state before the initial quench starts to propagate longitudinally through the magnet. High peak forces are still observed in this case. Thus, active quench protection is mandatory at or near nominal field. Further design optimizations are underway to enhance the mechanical robustness of the pancake coils, with particular emphasis on those positioned near the coil extremities, to ensure that the mechanical stress limits of the tape are not exceeded during a quench.

A capacitor bank of 50 mF charged to 300 V is sufficient to quench a significant part of the magnet at nominal current. However, if quench protection needs to be activated below nominal operation, more energy would be required to raise the magnet's temperature well within its current sharing regime. Therefore, charging the capacitor bank to a higher voltage would be beneficial for quench protection during ramp or at operation lower than nominal current. In the case that the pancake coils are wound with two parallel tapes, its inductance is a factor four lower. Since the τ is kept the same for both option at 2700 s, its turn to turn resistance is also a factor four lower. That means that in order to achieve the same loss with a capacitor discharge, the capacitance of the capacitor bank needs to be increased, while its charging voltage can be reduced.

A quench commonly is a 3D phenomena that needs 3D modeling for a more accurate depiction of the involved voltages, currents, temperatures and forces. And it influences how fast a quench is detected and how it propagates through a magnet. A 3D modeling tool is in development to further aid our understanding of all mechanisms involved and to further fine-tune the coil layout and its quench protection requirements. It is expected that the calculated temperature will be higher and the stress in the conductor will be lower compared to the 2D calculations.

VI. Conclusions

The status of the operation and protection studies of our design of a 40 T final cooling solenoid for a muon collider is presented. The magnet design comprises of a stack of 52 ReBCO no-insulation HTS pancake coils. The ramp scheme has been optimized for a constant dissipation of 200 W during the majority of the ramp, while keeping the overall magnet characteristic time constant at 2700 s and be at nominal magnetic field within 6 hours. Protection calculations have been performed and show that these final cooling solenoids require active quench protection to limit the increase of the Lorentz forces and thus the conductor stress during a quench. Quench protection by capacitor discharge is considered to be a promising technology for such a magnet, and it can be achieved with a reasonably sized capacitor bank and charging voltage. Winding the pancake coils with a single tape or two tapes in parallel are considered. In both cases, the loss during ramp is similar and the magnet is protected with active quench protection, though design of the capacitor bank needs to be adjusted depending on the number of parallel tapes of the coil winding. Mechanical modeling is ongoing and a 3D thermo-electromagnetic model is in development to provide further insights in the design and protection considerations of the final cooling solenoids.

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