

# Electro-thermal analysis of the superconducting dipole circuit of SIS100

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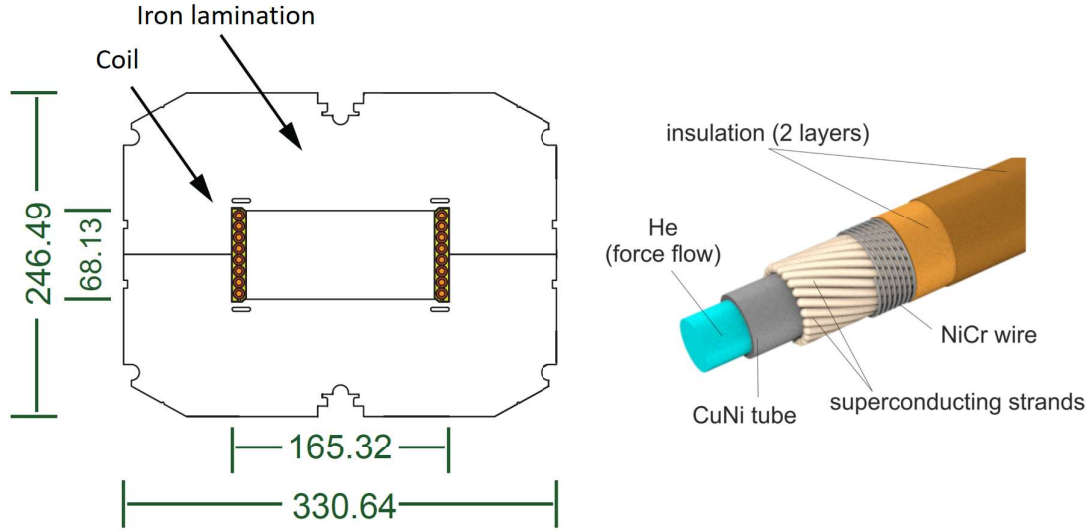
**Abstract.** The heavy ion synchrotron SIS100, the core machine of the new international Facility for Antiproton and Ion Research (FAIR) in Darmstadt, is currently under construction. The 108 superconducting dipole magnets of SIS100 will be powered in series with a cycling rate up to  $30 \text{ kA s}^{-1}$  which corresponds to  $4 \text{ T s}^{-1}$ . The dipole magnet protection system considers 12 energy extraction resistors and two crowbars at the outputs of two power converters. As a part of the Failure Mode and Effects Analysis, the most critical failures of the magnet protection system are simulated. In this contribution, initial studies of the electrical and thermal behaviour of the SIS100 main dipole circuit during a quench are presented. The dipole magnet design and topology of the powering circuit (including the protection system) are described. The electro-thermal model in use is detailed. Finally, simulation of a failure mode of the magnet protection system is presented and results are discussed.

## 1. Introduction

The FAIR facility is currently under construction in Darmstadt [1]. The high intensity primary beam for the experiments will be provided by the SIS100 - a heavy ion synchrotron with magnetic rigidity of  $100 \text{ T m}$  [2]. SIS100 will have more than 400 fast-cycling superconducting magnets, of which 108 are the main dipoles. The peak nominal current in the dipole circuit is  $13.1 \text{ kA}$  and a cycling rate of up to  $30 \text{ kA s}^{-1}$ . In the event of a quench in a dipole magnet, an increasing coil resistance leading to a voltage unbalance between two subsequent dipole magnets will be measured by the FAIR Quench Detection System (F-QDS). When this voltage reaches a so-called quench threshold, the F-QDS will trigger the opening of the energy extraction switches and the by-pass of the power converters.

Although there exist several quench calculation softwares [3, 4, 5, 6], a dedicated software was developed for the FAIR magnets [7]. This software originally written in MATLAB® supports 1D and 3D thermal model and stand-alone magnet electrical circuit. For this work, the software was ported in a Python [8] and further developed to support not only stand-alone magnet but the full SIS100 main dipole magnet circuit. In this article, the thermal and electrical models of the dipole magnet and dipole circuit are described. Two scenarios after a quench occurs are simulated, the nominal case and a failure case with a missing dump resistor. The results of the simulation are presented and discussed.





**Figure 1.** (a) Cross section of the dipole coils and yoke. (b) Scheme of the superconducting cable of the dipole.

## 2. Dipole magnet and circuit

### 2.1. Dipole magnet

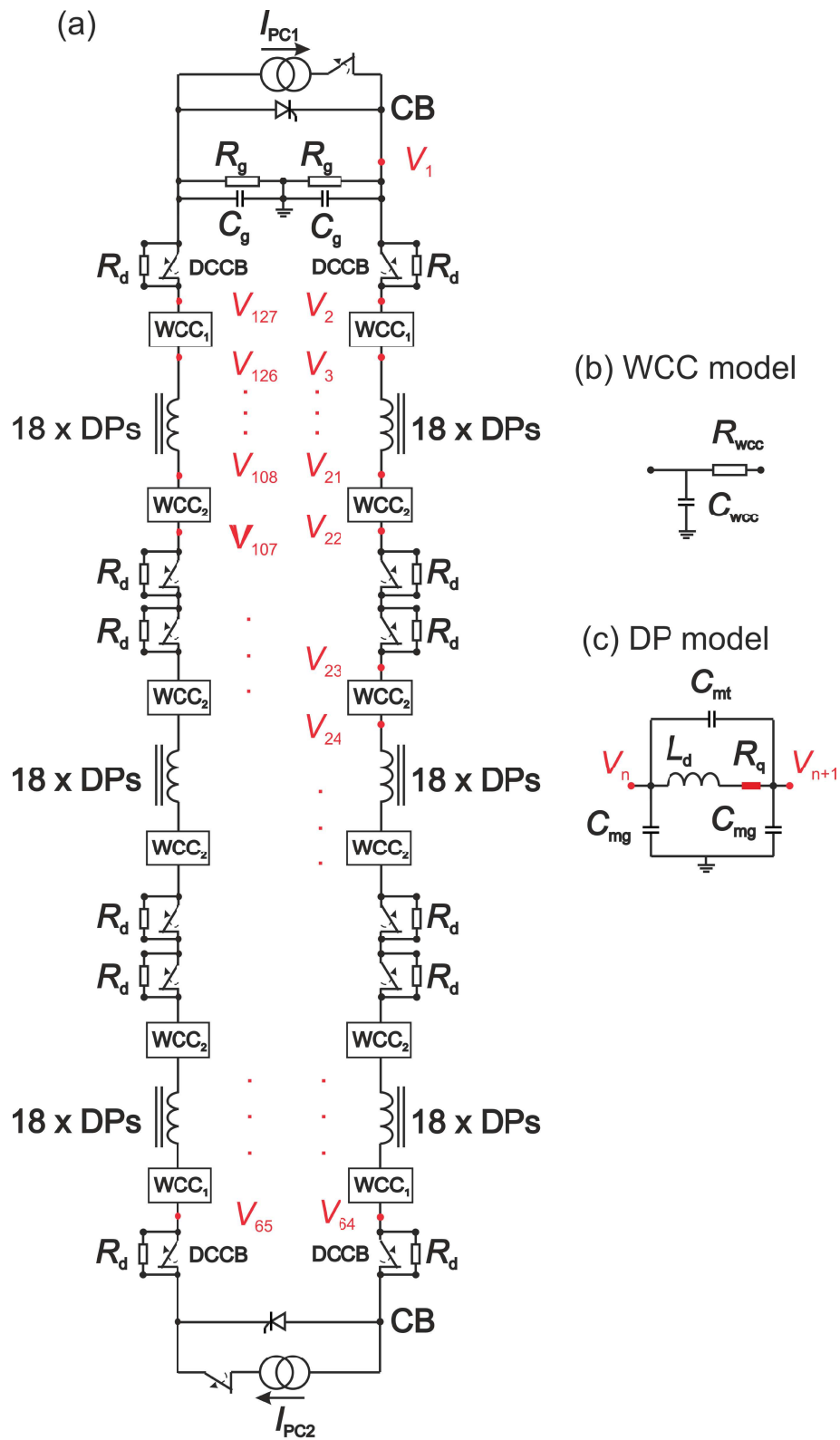
The 108 main dipole magnets of SIS100 based on a super-ferric, window-frame design will provide a maximum field of 1.9 T, ramped with a cycle frequency of 1 Hz [9, 10]. As shown in figure 1(a), each dipole has 8 windings arranged in a single layer. The superconducting cable used is a Nb-Ti, low AC loss Nuclotron-type [11]. It is composed of 23 strands placed around a CuNi cooling tube, the overall insulated with two layers of polyimide tape (see figure 1(b)). The strands consist of Nb-Ti filaments embedded in a resistive CuMn matrix and of stabilizing copper. The main parameters of the dipole magnet and of the superconducting cable, relevant for the electro-thermal model are summarized in table 1.

### 2.2. Dipole circuit

As shown in figure 2 (a), the electrical circuit of main dipole magnets is composed of 108 magnets powered in series. The circuit is divided in six sectors, with 18 magnets in each sector. The magnets are powered by two identical power converters (PCs) symmetrically placed within the circuit. The crow bars (CBs) are used to by-pass the power converters in case of a quench. The extraction energy system consists of twelve electronic Direct Current Circuit Breakers (DCCBs) and twelve dump resistors ( $R_d$ ). Water cooled cables (WCC) are used to connect the magnets to the power converters and the extraction systems.

The model of the first power converter (PC1) includes the two resistors  $R_g$  and capacitors  $C_g$  of the grounding system. The WCCs are modelled with a capacitor to ground  $C_{wcc}$  and a resistor  $R_{wcc}$  (see figure 2 (b)). The models take into account the different cable length (WCC<sub>1</sub> and WCC<sub>2</sub>). The electrical model of the dipole magnets is shown in figure 2 (c), where  $L_d$  is inductance of the magnet, which is current dependant, and  $R_q$  the resistance of the magnet coils, which is zero as long as the coils are superconducting.  $C_{mt}$  and  $C_{mg}$  are respectively the parasitic capacitance of the magnet turn to turn and to ground.  $C_{mg}$  includes the parasitic capacitance due to the instrumentation wires.

The values of the circuit parameters taken for the simulations can be found in the table 2.



**Figure 2.** (a) Electrical circuit schematic of the SIS100 main dipole magnets. (b) Electrical model of the water cooled cable (WCC). (c) Electrical model of a dipole magnet ( $1 \times \text{DP}$ ).

**Table 1.** Main Parameters of SIS100 Main Dipole Magnets.

| Parameter                                   | Value  | Unit          |
|---------------------------------------------|--------|---------------|
| <b>Magnet</b>                               |        |               |
| Effective magnetic length                   | 3.1    | m             |
| Number of turns                             | 8      |               |
| Nominal current $I_0$                       | 13.1   | kA            |
| Inductance $L_d$ at $I=13$ kA               | 0,44   | mH            |
| Inductance $L_d$ at $I=5.5$ kA              | 0,55   | mH            |
| <b>Cable</b>                                |        |               |
| Number of strands                           | 23     |               |
| No-sc/sc ratio                              | 1.4    |               |
| Residual resistivity ratio of Cu $RRR_{Cu}$ | 125.5  |               |
| Strand diameter                             | 0.8    | mm            |
| Filament diameter                           | 2.9    | $\mu\text{m}$ |
| Nb-Ti cross-section                         | 0.2096 | $\text{mm}^2$ |
| Cu cross-section                            | 0.2026 | $\text{mm}^2$ |
| CuMn cross-section                          | 0.0905 | $\text{mm}^2$ |
| CuNi tube cross-section                     | 8,168  | $\text{mm}^2$ |
| Polyimide insulation cross-section          | 6.0696 | $\text{mm}^2$ |

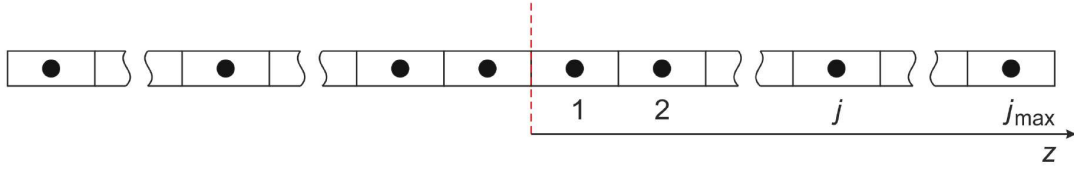
**Table 2.** SIS100 Dipole Magnets Circuit Parameters.

| Parameter                                                 | Value | Unit                       |
|-----------------------------------------------------------|-------|----------------------------|
| Grounding resistors, $R_g$                                | 300   | $\Omega$                   |
| Grounding capacitors, $C_g$                               | 5     | $\mu\text{F}$              |
| Water cooled cable resistance per unit length, $r_{wcc}$  | 5     | $\mu\Omega \text{ m}^{-1}$ |
| Water cooled cable capacitance per unit length, $c_{wcc}$ | 500   | $\text{pF m}^{-1}$         |
| WCC1 length, $l_{wcc1}$                                   | 85    | m                          |
| WCC2 length, $l_{wcc2}$                                   | 60    | m                          |
| Capacitance magnet to ground, $C_{mg}$                    | 10    | nF                         |
| Capacitance magnet turn to turn, $C_{mt}$                 | 2     | nF                         |
| Energy extraction resistor, $R_d$                         | 67    | $\text{m}\Omega$           |
| Voltage quench threshold $V_{th}$                         | 300   | mV                         |
| Quench validation time $t_v$                              | 10    | ms                         |

### 3. Electro-thermal model

The electro-thermal model of the SIS100 main dipole magnet circuit, written in Python, is composed of two main sub-models: a 1D microscopic thermal model and an macroscopic electrical model. Both sub-models are coupled and solved within a common time loop. After each time iteration, thermal and electrical information are exchanged between the sub-models. An adaptive time stepping algorithm [12] allows to control and limit the maximum temperature difference ( $\Delta T$ ) during each time iteration.





**Figure 3.** One-dimensional model of the superconducting dipole coil [7].

### 3.1. Thermal model

The thermal model calculates the temperature profile of the magnet coils after a quench, having as an input the current flowing through the magnet coils.

In case of a quench in a dipole magnet, the heat in the coil propagates mostly longitudinally, i.e. along the cable. Due to the polyimide insulation layers of the superconducting cables, the transverse heat propagation to other turns is negligible. Therefore the thermal behaviour of a dipole magnet can be well approximated by a one-dimensional representation. As shown in figure 3, the dipole coil is represented as a 1D conductor divided in  $j_{\max}$  elements. As the quench propagates symmetrically on both direction, only half of the coil is considered. In the model, the cable is approximate as an uniform conductor. Such a conductor is characterised by its physical properties such as its specific heat  $C_v$ , its thermal conductivity  $k$  and its resistivity  $\rho$  that are weighted by the volumetric proportion of the different materials composing the cables (i.e. Cu, Nb-Ti, CuMn, CuNi and polyimide insulation). These physical properties are non linearly dependant on the magnetic flux density  $B$  and the temperature  $T$ .

The thermal model is governed by the heat-balance equation:

$$\rho(B, T) \cdot J^2(t) + \nabla(k(T) \cdot \nabla T(z, t)) = C_v(B, T) \cdot \frac{\partial T(z, t)}{\partial t} \quad (1)$$

where  $T(z, t)$  is the temperature at the longitudinal position  $z$  within the cable at the time  $t$  and  $J$  is the current density flowing through the cable. The first term of the left side describes the Joule heating within the normal conducting zone and the second term represents the heat propagation in the conductor. The term on the right side represents the heating of the conductor.

A heat-balance equation can be written for each element of the conductor, thus obtaining a system of  $j_{\max}$  equations. In order to solve numerically the system, equation 1 is rearranged to become:

$$a(j, t) \cdot T_{j-1}^{t+dt} + b(j, t) \cdot T_j^{t+dt} + c(j, t) \cdot T_{j+1}^{t+dt} = T_j^t + d(j, t) \quad (2)$$

with

$$a(j, t) = -\frac{dt}{dz^2 \cdot C_v(B, T)} \cdot k(T), \quad b(j, t) = 1 + \frac{dt}{dz^2 \cdot C_v(B, T)} \cdot 2k(T),$$

$$c(j, ti) = -\frac{dt}{dz^2 \cdot C_v(B, T)} \cdot k(T) \quad \text{and} \quad d(j, ti) = \frac{\rho(B, T) \cdot J^2(t) \cdot dt}{C_v(B, T)}.$$

$dt$  being the length of a time step,  $T_j^t$  the temperature of the element  $j$  at the time  $t$  and  $T_{j-1}^{t+dt}$ ,  $T_j^{t+dt}$  and  $T_{j+1}^{t+dt}$  the temperature of the element  $j-1$ ,  $j$  and  $j+1$  at the time  $t+dt$ . A matrix equation is build from the system of equations and is solved using bi-conjugate gradient stabilized method.

### 3.2. Electrical model

The electrical model is used to calculate the voltages and the currents in all the dipole magnet circuit. The resistance of the quenched magnet,  $R_q$ , derived from its temperature profile is used as an input of the electrical model.

The electrical model is solved using the voltage node method. For each of the 127 defined voltage nodes of the circuit (see in figure 2), an equation can be written. For instance, after activation of the energy extraction system (by-pass of the power converters and opening of the DCCBs), the equations of the nodes  $V_3$  and  $V_4$  (voltage terminal of the first magnet) are:

$$V_3 \rightarrow \frac{(V_2 - V_3)}{R_{wcc}} = (C_{wcc} + C_{mg}) \frac{dV_3}{dt} + C_{mt} \frac{d(V_3 - V_4)}{dt} + i_{m1} \quad (3)$$

$$V_4 \rightarrow i_{m1} + C_{mt} \frac{d(V_3 - V_4)}{dt} = 2C_{mg} \frac{dV_4}{dt} + C_{mt} \frac{d(V_4 - V_5)}{dt} + i_{m2} \quad (4)$$

where  $i_{m1}$  and  $i_{m2}$  are the current flowing in the first and second magnet of the circuit. In addition the voltage drop across each of 108 dipole magnet can be expressed as function of the magnet current, as for instance for the first magnet:

$$V_3 - V_4 = L_{dm1} \frac{di_{m1}}{dt} + R_{qm1} \cdot i_{m1} \quad (5)$$

where  $L_{dm1}$  and  $R_{qm1}$  are the inductance and quenched resistance of the first magnet. Therefore a system of 235 equations can be build. In order to solved the model numerically, these equations are rearranged such that the variables at time  $t + dt$  are separated from variables at time  $t$ . For example equations 4 and 5 become:

$$\begin{aligned} -\frac{C_{mt}}{dt} \cdot V_3^{t+dt} + \frac{2(C_{mg} + C_{mt})}{dt} \cdot V_4^{t+dt} - \frac{C_{mt}}{dt} \cdot V_5^{t+dt} - i_{m1}^{t+dt} + i_{m2}^{t+dt} = \\ -\frac{C_{mt}}{dt} \cdot V_3^t + \frac{2(C_{mg} + C_{mt})}{dt} \cdot V_4^t - \frac{C_{mt}}{dt} \cdot V_5^t \end{aligned} \quad (6)$$

$$-V_3^{t+dt} + V_4^{t+dt} + \left( \frac{L_{dm1}}{dt} + R_{qm1} \right) \cdot i_{m1}^{t+dt} = \frac{L_{dm1}}{dt} \cdot i_{m1}^t \quad (7)$$

Then the system of equations can be turned into a matrix equation of the form  $A \cdot X = B$ , with

$$A = \begin{bmatrix} F1_1 & \dots & F1_{235} \\ \vdots & & \vdots \\ F235_1 & \dots & F235_{235} \end{bmatrix}, \quad X = \begin{bmatrix} V_1^{t+dt} \\ \vdots \\ V_{127}^{t+dt} \\ i_{m1}^{t+dt} \\ \vdots \\ i_{m108}^{t+dt} \end{bmatrix} \quad \text{and} \quad B = \begin{bmatrix} G_1 \\ \vdots \\ G_{235} \end{bmatrix}.$$

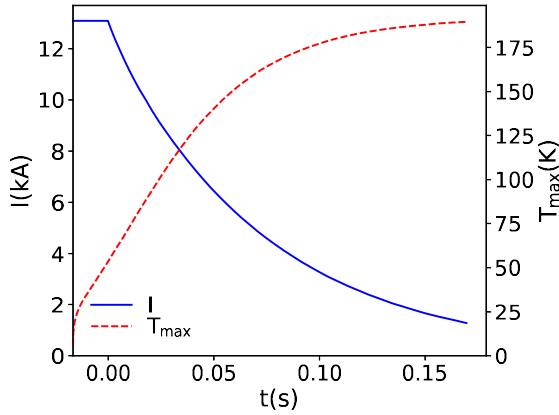
The  $F_{xy}$  elements of the matrix  $A$  correspond to the coefficients of the voltage and current variables at time  $t + dt$ . The  $G_x$  elements of the matrix  $B$  are functions of the voltage and current variables at time  $t$ .

The model can then be solved and one obtains the voltages of the nodes  $V_1$  to  $V_{127}$  and the magnet currents  $i_{m1}$  to  $i_{m108}$  at time  $t + dt$ .

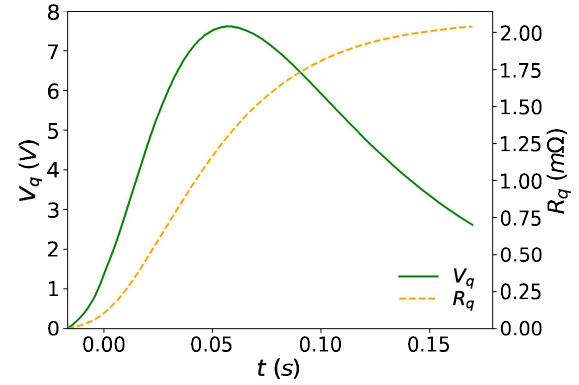
#### 4. Simulation results

The study addresses two scenarios after a quench occurs in a dipole magnet at top energy. In the first scenario, the energy extraction system operates in nominal conditions. In the second scenario, the circuit breaker of the first dump resistor fails to open.

In both scenarios, the quench occurs in the first magnet of the circuit. Once the quench voltage  $V_q$  is above the threshold  $V_{th} = 300 \text{ mV}$  for more than 10 ms, the circuit breakers open



**Figure 4.** Current decay and hot spot temperature  $T_{\max}$  of the quenched magnet in the nominal energy extraction configuration.



**Figure 5.** Quench voltage  $V_q$  and resistance  $R_q$  of the quenched magnet in the nominal energy extraction configuration.

and the power converters are by-passed. This is defined as the time  $t = 0$  s. The current in the magnets before the opening of the circuit breakers is constant with a value of 13.1 kA. The simulations are ran until the current decays below 10 % of its initial value. The thermal model of the quenched coils is 3 m long divided in 1000 elements.

#### 4.1. Nominal case

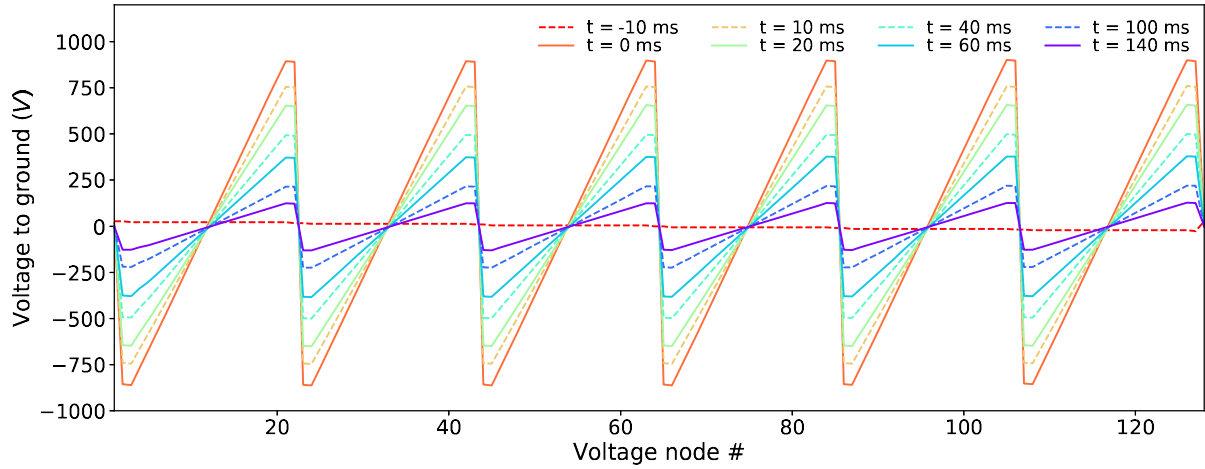
The current decay and hot spot temperature curves in the quench magnets obtained by simulation in the nominal case are shown in figure 4. The current decay time constant is about 70 ms and peak temperature is about 190 K. The maximum quench voltage  $V_q$  happens about 60 ms after the energy extraction system is activated with a value of 7.6 V (see figure 5). The quench resistance  $R_q$  reaches a maximum of about 2 mΩ.

The voltage to ground of the dipole magnet circuit nodes at different time before and after activation of the energy extraction system is shown on figure 6. At  $t = -10$  ms (before the opening of the circuit breakers), the voltage to ground is respectively about +20 V and -20 V at the positive and negative pole of the power converters (node  $V_1$  and  $V_{127}$ ). This voltage drop is induced by the resistance of the water cooled cables. At  $t = 0$  ms, the minimum and maximum voltages to ground are respectively -870 V at the beginning of each magnet sector (nodes  $V_3$ ,  $V_{24}$ ,  $V_{45}$ ,  $V_{66}$ ,  $V_{87}$  and  $V_{108}$ ) and +870 V at the end of each magnet sector (nodes  $V_{21}$ ,  $V_{42}$ ,  $V_{63}$ ,  $V_{84}$ ,  $V_{105}$  and  $V_{126}$ ). After 100 ms, the voltage to ground are down to maximum value of  $\pm 220$  V. The voltage drop across each dipole magnets is about 100 V.

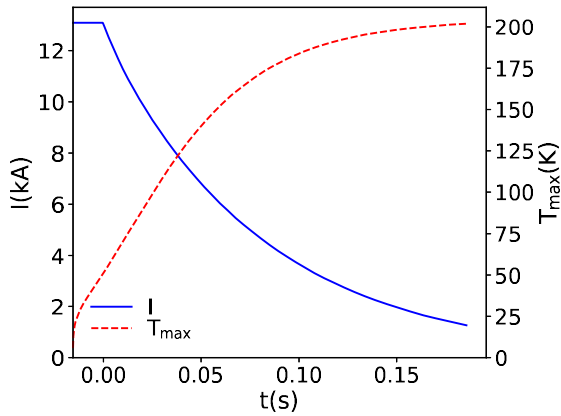
#### 4.2. Failure of dump resistor

In case the circuit breaker of the first dump resistor of the circuit (between nodes  $V_2$  and  $V_3$ ) does not open, the current decay time constant increases to about 95 ms and the peak temperature in the quench magnets reaches 210 K (see figure 7). As shown in figure 8,  $V_q$  has a maximum of  $\sim 9$  V at  $t = 65$  ms and  $R_q$  maximum is  $\sim 2.5$  mΩ.

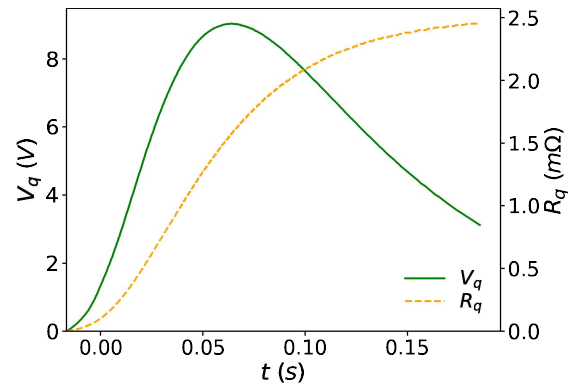
The voltage to ground of the circuit nodes at different time is shown in figure 9. Compared to the nominal case, the voltages are no longer balanced around zero. The minimum voltage is -950 V occurring at the beginning of the last powering sector (node  $V_{108}$ ). The maximum voltage is 1.6 kV and occurring at the end of the first powering sector (node  $V_{21}$ ). The voltage drop across each dipole magnets is similar to the nominal case to about 100 V.



**Figure 6.** Voltage to ground profile along the dipole circuit in the nominal energy extraction configuration.



**Figure 7.** Current decay and hot spot temperature  $T_{\max}$  of the quenched magnet in case one missing dump resistor.



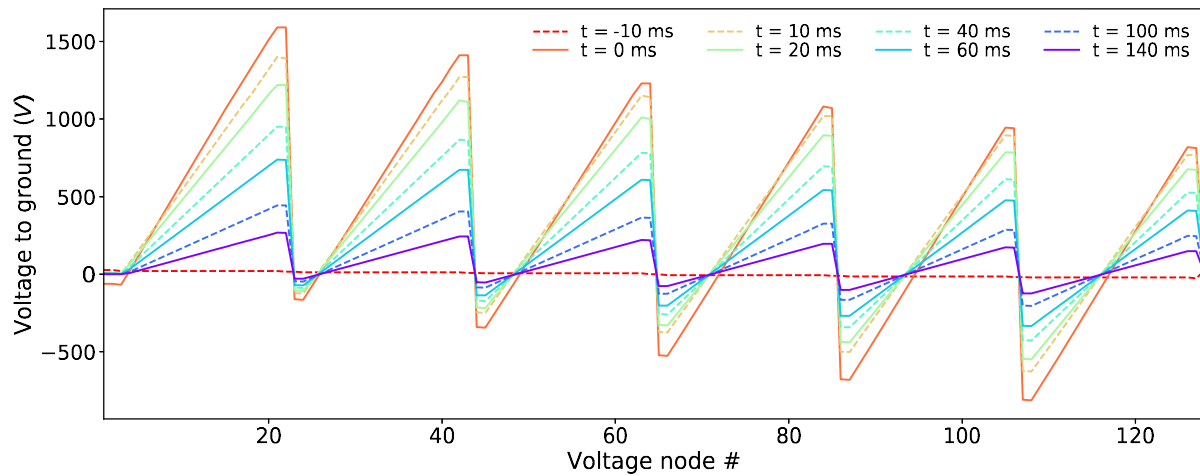
**Figure 8.** Quench voltage  $V_q$  and resistance  $R_q$  of the quenched magnet in case one missing dump resistor.

For the safe operation of SIS100, the maximum allowed hot-spot temperature and voltage to ground allowed are 350 K and 3 kV [13] respectively. Therefore according to these simulation results, in the event of a quench with a failure of one circuit breaker, the energy can still be extracted safely out of the dipole circuit.

## 5. Conclusions and outlooks

Reliable and accurate electro-thermal simulations of FAIR superconducting magnets and circuits are of primary importance to understand the consequences of failures of magnet protection systems.

In this context, an electro-thermal model of the SIS100 dipole magnet circuit has been developed. The thermal behaviour of the dipole magnet can be well represented by a one-dimensional model. The superconducting cable is approximated as an uniform conductor, with its physical properties weighted by the volumetric proportion of the different materials composing it. The electrical model of the dipole circuit includes the power converters, the extraction system



**Figure 9.** Voltage to ground profile along the dipole circuit in case one missing dump resistor.

and the water cooled cables connecting the warm to the cold sections of the circuit. The power converters are modelled with a current source, a crowbar and a grounding system. The extraction energy system is composed of 12 circuit breakers and 12 dump resistors (each one  $67\text{ m}\Omega$ ). The water cooled cables are modelled as a resistor ( $\sim 400\text{ }\mu\Omega$ ) and a capacitor to ground ( $\sim 40\text{ nF}$ ). The electrical model of the magnets includes the capacitance turn-to-turn ( $2\text{ nF}$ ) and to ground ( $2 \times 10\text{ nF}$ ) that includes the capacitance induced by the instrumentation wires.

Two scenarios of quench event occurring at the peak nominal current of  $13.1\text{ kA}$  were simulated. The first one with a nominal operation of the magnet protection system shows a hot spot temperature in the quenched magnet of  $190\text{ K}$  and a maximum voltage to ground in the circuit of  $870\text{ V}$ . The second scenario with a failure of the opening of a circuit breaker (missing of a dump resistor) indicates a hot spot temperature in the quenched magnet of  $210\text{ K}$  and a maximum voltage to ground in the circuit of  $1.6\text{ kV}$ . These results show that the system can be safely operated in case of a quench even with a missing dump resistor.

The electro-thermal software will be further developed to study other failure cases of the SIS100 dipole circuit and possibly be used to study other superconducting magnet electrical circuits of the FAIR complex.

## References

- [1] P. Spiller, O. Boine-Frankenheim, H. Simon, M. Winkler, F. Hagenbuck, R. Tölle, S. Menke, M. Ossendorf, C. Omet, M. Bai *et al.*, “Status of the FAIR project,” in *9th Int. Particle Accelerator Conf.(IPAC’18)*, Vancouver, BC, Canada, April 29-May 4, 2018. JACOW Publishing, Geneva, Switzerland, 2018.
- [2] P. Spiller, I. Pongrac, C. Mühle, N. Pyka, P. Kowina, J. Henschel, D. Ondreka, L. Bozyk, A. Mierau, J. Meier *et al.*, “FAIR SIS100-features and status of realisation,” in *8th Int. Particle Accelerator Conf.(IPAC’17)*, Copenhagen, Denmark, May 14-19, 2017. JACOW Publishing, Geneva, Switzerland, 2017.
- [3] L. Bortot, B. Auchmann, I. C. Garcia, A. F. Navarro, M. Maciejewski, M. Mentink, M. Prioli, E. Ravaioli, S. Schps, and A. Verweij, “STEAM: A hierarchical cosimulation framework for superconducting accelerator magnet circuits,” *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 3, pp. 1–6, 2017.
- [4] W. Hassenzähl, *QUENCHS users manual*, 2005.
- [5] R. Yamada, E. Marcsin, A. Lee, and M. Wake, “3D ANSYS quench simulation of cosine theta  $\text{Nb}_3\text{Sn}$  high field dipole magnets,” *IEEE transactions on applied superconductivity*, vol. 14, no. 2, pp. 291–294, 2004.
- [6] L. Bottura, “A numerical model for the simulation of quench in the ITER magnets,” *Journal of computational Physics*, vol. 125, no. 1, pp. 26–41, 1996.
- [7] P. Szwangruber, “Quench study for FAIR magnets,” Ph.D. dissertation, TU Darmstadt, 2018.
- [8] T. E. Oliphant, “Python for scientific computing,” *Computing in Science & Engineering*, vol. 9, no. 3, pp. 10–20, 2007.

- [9] A. Mierau, C. Roux, P. A. Bartolome, F. Kaether, G. Golluccio, P. Kosek, P. Szwangruber, W. Freisleben, G. J. Ketter, K. Sugita *et al.*, “Testing of series superconducting dipole magnets for the SIS100 synchrotron,” *IEEE Transactions on Applied Superconductivity*, vol. 29, no. 5, pp. 1–7, 2019.
- [10] C. Roux, P. Aguar Bartolome, A. Bleile, E. Fischer, G. Golluccio, F. Kaether, J. Ketter, J. Meier, A. Mierau, C. Omet *et al.*, “Superconducting dipoles for SIS100,” in *9th Int. Particle Accelerator Conf.(IPAC’18), Vancouver, BC, Canada, April 29-May 4, 2018*. JACOW Publishing, Geneva, Switzerland, 2018, pp. 2768–2771.
- [11] H. Khodzhbagiyan, V. Alexeev, S. Averichev, V. Drobin, A. Kovalenko, A. Smirnov, A. Starikov, N. Vladimirova, G. Moritz, E. Fischer *et al.*, “Design of new hollow superconducting Nb-Ti cables for fast cycling synchrotron magnets,” *IEEE transactions on applied superconductivity*, vol. 13, no. 2, pp. 3370–3373, 2003.
- [12] P. Szwangruber, E. Floch, F. Toral, and T. Weiland, “Three-dimensional quench calculations for the FAIR Super-FRS main dipole,” *IEEE Transactions on Applied Superconductivity*, vol. 23, no. 3, pp. 4 701 704–4 701 704, 2013.
- [13] A. Stafiniak, P. Szwangruber, W. Freisleben, and E. Floch, “Electrical integrity and its protection for reliable operation of superconducting machines,” *Physics Procedia*, vol. 67, pp. 1106–1111, 2015.