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Quench protection of the BabyIAXO magnet

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Abstract. BabyIAXO, a 20 m-long twin-bore helioscope aiming for search of axion like particles, is currently in the engineering design phase and its construction is to be completed within the next 4 years. In addition to X-ray detectors and focusing optics, the system is equipped with a 50 MJ magnet with a common coil layout, containing two 10 m-long NbTi flat racetrack coils cooled by a group of cryocoolers. It has to operate at 10 kA, preferably in persistent mode with disconnected power supply, allowing to simplify the sun-tracking rotation system of BabyIAXO. A direct current mode is possible as well. Hence, quench protection is a high priority. Here, we present the electrical circuit of the BabyIAXO magnet and its protection layout when operated in persistent mode. The quench process is calculated using a 3-D thermo-electrical model of the coil windings, also accounting for the presence of the coil casing and the quench-back effect. Impact of the operating current, conductor properties, voltage detection threshold and location of hot-spot on the peak temperature is discussed. Quench protection aspects of the HTS busbars and persistent mode switch are also addressed.

1. Introduction

Currently, one of the frontier activities in particle physics is the experimental search for theoretically predicted particles called 'axions', which existence would explain violation of symmetry in certain quantum models and may provide better understanding of dark matter. In order to explore the physics case of solar axions, explained in detail in [1], the International Axion Observatory (IAXO), a state-of-the-art experiment in the field, has been conceptually designed [2]. The reliability and readiness of the technology will be demonstrated in a fully functional sub-scale experiment called BabyIAXO.

The three main components of BabyIAXO, superconducting magnet, optics and X-ray detectors, will be installed on a Sun-tracking drive system, providing 360° rotation and ±25° inclination of the experiment, as shown artistically in Figure 1. The BabyIAXO magnet is of quadrupole configuration, with two free bores of 700 mm diameter for detection, sandwiched between 10-m long flat racetracks placed 800 mm apart. The winding pack design of each racetrack, illustrated in Figure 2, is based on two stacked double-pancake windings using an 8-strand Al-stabilized NbTi Rutherford conductor of 20 mm width and 8 mm thickness. This magnet configuration when operated at 10 kA nominal current and 6.2 K current sharing temperature, yields a magnet's figure of merit of 232 $T^2\,m^4$ thereby fulfilling the design criteria of at least 200 $T^2\,m^4$. The ultimate performance is estimated at 12 kA operation, which would further increase the figure of merit by 40 %. The conceptual design of the entire magnet system has been presented separately in [3].

The magnet's cold mass is cooled by a group of two single-stage GM cryocoolers and three double-stage PT cryocoolers, by which two Helium gas cryocirculators are distributing the cooling power. Hence, the cryogenic environment can be established in a rather cost-efficient and independent manner,

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although minimization of the heat loads in the system has become crucial. Further cryogenic details are given in [4].

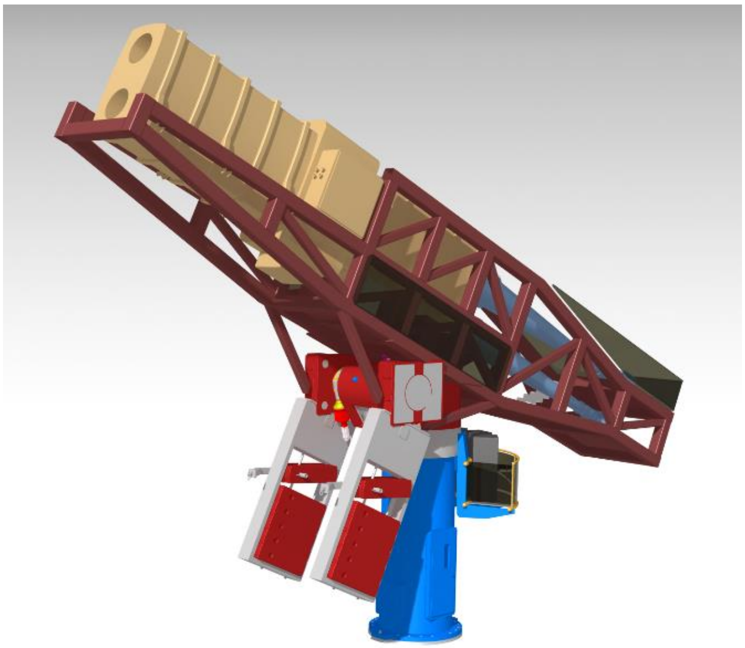
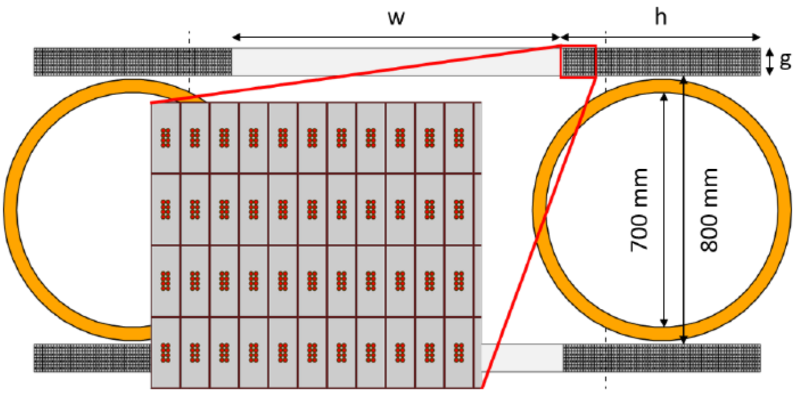


Figure 1. BabyIAXO set-up showing the double bore design based on using baseline IAXO magnet technology. The Sun-tracking drive system provides 360° rotation and ±25° inclination for the experiment. The overall system length is about 19 meter.



winding height, *h*	82 mm
pole gap, *g*	1000 mm
winding width, *w*	595 mm
magnet energy	50 MJ
inductance	1.0 H
peak field	3.2 T
current density	56 A/mm^2
operating current	9.8 kA
conductor length	11.4 km
MFOM 3-D	232 T^2·m^4
MFOM 2-D	326 T^2·m^4

Figure 2. Design of the BabyIAXO winding pack showing a stack of two double pancake coil windings based on using a rectangular Al stabilized 8-strand NbTi/Cu cable.

Using an aluminium stabilized conductor is not only the best for a maximal minimum propagation zone, but also beneficial for transferring efficiently by conduction the cooling power provided by the cryocoolers. From a magnet protection point of view, the cross-section of aluminium in the conductor has a strong impact on the quench propagation velocity, as well as on the peak temperature developed during a thermal runaway. Increasing the aluminium cross-section makes quench protection easier, but at the same time makes the magnet less efficient following a lower current density, larger mass, etc. Hence, the quench process has to be simulated in order to address this effect quantitatively. The main assumptions for numerical modelling are derived from considering the electrical circuit of the BabyIAXO magnet presented next.

2. Electrical circuit of BabyIAXO and its protection scheme

The main power supply is connected to the cold mass through two retractable copper bus-bars operated at room temperature, current leads covering the temperature zone from room temperature down to some 70 K, and finally HTS bus-bars operating between 70 and 4.5 K. For BabyIAXO two operational modes are considered: a straight forward direct current drive with power supply permanently connected and stationary nominal current in the current leads (not further discussed here); or a much more challenging persistent mode operation featuring certain advantages, presented in this paper, by which there is no stationary current in the leads and thus a smaller cryogenic load [4].

The persistent mode based electrical circuit is depicted in Figure 3. For this circuit, the persistent current mode is envisaged allowing to disconnect the power supply after the magnet charging, as it would decrease the heat load on the cryogenic system and simplify the sun-tracking rotation system. For this need, a thermally-controlled persistent mode switch (PMS) made of NbTi/CuNi superconductor shortens the cold mass.

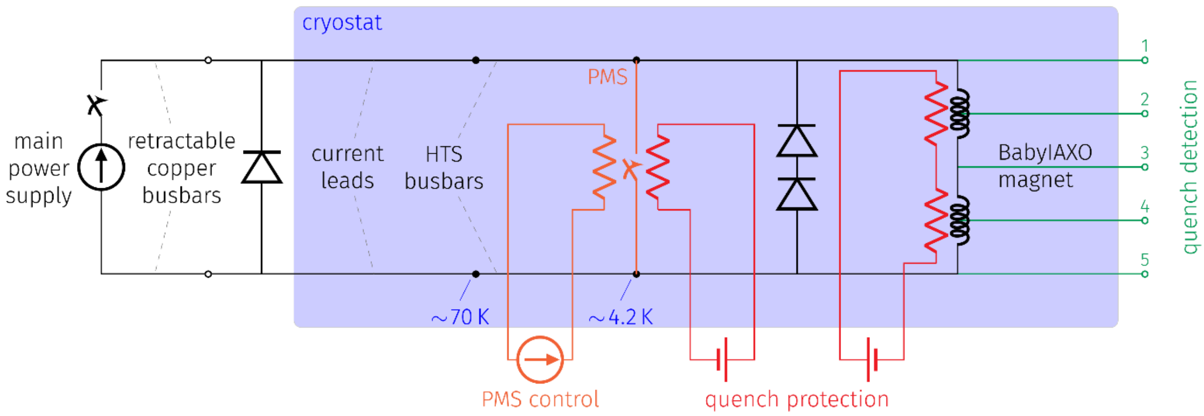


Figure 3. Persistent mode based electrical circuit of the BabyIAXO magnet.

The following failure mode based protection scenarios are considered:

1. **Slow dump:** the stored magnet energy of 50 MJ is released on diodes installed at room temperature; no active heating of the cold mass. The forward voltage drop of the diodes should be similar to the charging voltage of the magnet ramp-up, thus the energy dissipation in the current leads is contained. The electrical circuit is unaffected and readily available for further operation. Hence, this scenario is generally caused by failure of external components requiring a relatively slow magnet shut-down such as the drive system, voltage leak to ground, cryogenic failures and loss of the mains. In the latter case, the temperature rise due to loss of the cooling power is rather slow, around 30 minutes to reach the current sharing temperature, which is considered sufficient to avoid a quench of the magnet during a slow dump discharge.
2. **Fast dump:** the quench protection heaters on the coil windings are fired to speed-up the energy release by quickly turning all coils into the normal state. Depending on the maximum temperature reached, up to some days may be required for cooling down the coil before resuming magnet operation. This is necessary when superconducting parts of the electrical circuit are quenching, namely:
   a. **Quench in main magnet.** A ‘self-dump’ is considered as a worst-case quench scenario for the coil windings, i.e. the magnet stored energy is completely dissipated in the cold mass itself. The peak temperature in the windings should not exceed 150 K for two reasons, to avoid a long delay required for cool down and to limit the thermal stress due to temperature gradients in the coil

windings. The quench can be detected using a set of voltage taps arranged in a bridge layout with adjustable resistors to match inductive contributions. The '1/2' detection scheme requires two resistors connected in series to terminals 1 and 5 (see Figure 3), thus the voltage peak is measured between terminal 3 and a mid-point between the resistors. Similarly, in the '1/4' and '3/4' schemes, the voltage peak is measured using terminals 2 and 4, respectively, and a mid-point of each resistor bridge, which allows detecting a symmetric quench in the system too [5]. In addition, temperature sensors placed at various locations attached to the coil windings as well as SQD detectors [6] installed on interconnections are used for detection. The dedicated simulation model and main simulation results concerning the quench propagation in the case of a self-dump are presented in the next section.

b. **Quench in the HTS busbars.** A rather slow current decay in the circuit, of about tens of seconds, imposes a strict protection requirement for the busbars that must survive a quench inside. Hence, a sufficient amount of stabilizer needs to be present, which requires, however longer and more expensive HTS sections to handle the associated cryogenic heat load. Since the busbar self-inductance is negligible, a quench is simply detected using voltage taps attached directly to the busbars. Conceptual design and HTS tape that can be used for this application are further discussed in section 3.3.

c. **Quench in the Persistent Mode Switch.** In order to minimize the power dissipated in the open PMS during a charge of the magnet, a high open-state resistance of the PMS in the normal state is required, thus the amount of stabilizer is kept minimal and a high resistivity matrix superconductor is used like NbTi/CuNi. If quenched, an instant burn-out of the switch can only be avoided if the operating current can be redirected to a parallel path. For this need, a set of cold diodes shunting several conductor sections of the PMS are used. Fast and reliable quench detection is necessary to activate a set of redundant quench protection heaters embedded in the PMS. The electrical path comprising a set of warm diodes, current leads and HTS busbars also helps to protect the PMS. The principal figures of the process are presented in section 3.4.

The function of the main components in the electrical circuit, including PMS, conduction cooled current leads and HTS busbars, is detailed in [3].

3. Quench analysis

The quench process, a thermal runaway of the coil windings due to local overheating of the conductor, is simulated using a 3-D thermo-electrical model. It allows to investigate the temperature distribution within the coil windings, as well as to study current decay and voltage built-up due to propagation of the normal zone. The effect of various parameters on the process, such as voltage detection threshold, location of the hot-spot, quench-back effect, amount and RRR of the aluminum stabilizer can be evaluated. The obtained current decay profiles are further used to analyze protection of the HTS busbars and PMS.

3.1. Description of the quench propagation model

The heat propagation is calculated along the conductor (60 nodes per turn) and in the cross-section of the winding pack (1 node per turn, 280 nodes in total) and the coil casing (152 nodes). In total 51840 nodes represent the cold mass volume of 2 coil modules. The heat equation can be written for each node as follows:

$$c\frac{dT}{dt} = \frac{d}{dx}\left(k\frac{dT}{dx}\right) + q,$$

where c and k are the effective heat capacity and thermal conductivity of the conductor or the coil casing, q the volumetric heat source that includes the Joule heating in the conductor, heat generated by the external heaters, and the sum of heat transfer terms between the neighboring turns in the winding cross-section. Note that the considered equation has only one spatial dimension x along the conductor, but accounting for the heat transfer terms provides effectively a 3-D representation in the model.

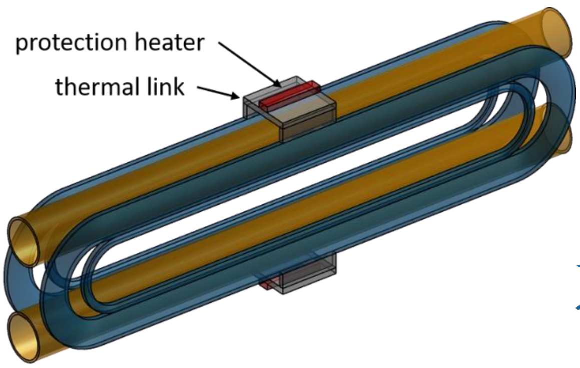
Thermal properties of Al alloy are used for the coil casing, while a mixture rule is applied for the conductor comprising pure Al, Cu and NbTi. In order to evaluate the total Joule heating at each node, the current sharing among the conductor materials is calculated. This is based on equal electric field along the length, while transverse electric field between the domains is neglected. The standard power law is used for the voltage-current transition of NbTi/Cu with 10 μV/m criterion and temperature- and magnetic field-dependent critical current density. Thus, the magnetic field is evaluated at each node and it is varied according to the operating current, decreasing during the simulation due to increasing resistance of the conductor. One extra unknown of the model, the operating current I as a function of time, is obtained according to $L\dot{I} = V$, where the magnet self-inductance L is 1.0 H and the total voltage in the winding V is an integral along x of the electric field distribution.

External cooling is not included in the model such that the entire magnet energy can only be released in the cold mass, which effectively represents conduction cooling conditions of the windings. In addition, as number of support components are also not included in the thermal analysis, thus the modelling approach is considered conservative, potentially somewhat overestimating the hot-spot temperature.

The protection heaters, allowing to distribute generated heat more uniformly, are installed separately on thermal links connected to the coil casing (see Figure 4), which can be installed during magnet assembly. This simplifies the construction and reduces risk of insulation failure compared to installing the heaters directly on the winding pack.

The quench is initiated by applying 50 J deposited during 0.1 s at the selected location of the hot-spot (see Figure 4). After the quench is 'detected' using a 0.5 V detection threshold, 100 W/m (0.5 W/cm^2 per cable face) is applied at the location of the heaters until reaching 20 K.

The quench simulations of the coil windings have been implemented using MATLAB: essentially, the current transfer between the various materials is evaluated by 'fzero' function, following the methodology described in [7] (section 9), and the heat equation is integrated by 'ode23' function, accounting for the field and temperature dependence of the material properties. The boundary conditions at the nodes forming the winding exterior are adiabatic, i.e. zero external heat flux. The initial conditions are set as 4.2 K for the temperature at all nodes and a given value up to 12 kA for the operating current. Each simulation run is rather quick (some tens of minutes), so parametric sweep on various inputs of the model has been performed and further reported below.



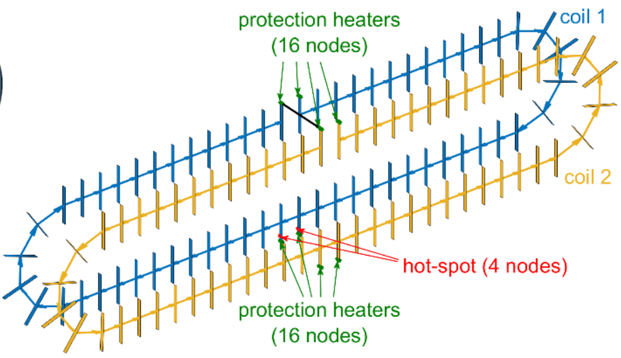


Figure 4. Left: sketch showing the position of the protection heaters installed on the cold mass (coil casing and support structure not shown). Right: geometry of the quench simulation model.

3.2. Simulation results

An illustration of the simulation results for the magnet operated at 10 kA nominal current is presented in the left picture of Figure 5. In this particular example, one single coil without its casing and protection heaters was simulated. As the size of the normal zone increases, the current starts to gradually decrease and the total voltage reaches its maximum V_{max} of 654 V at the moment when the entire coil is in the normal state. On average, the normal zone propagates with about 7 m/s along the conductor and about 20 mm/s across the windings. The peak temperature T_{max}, which stays at the point of the quench initiation, saturates at 200 K. The generated voltage increases with current, thus the time required to discharge the coil decreases characteristically from 120 s at 6 kA down to 30 s at 12 kA, as summarized in the right picture of Figure 5.

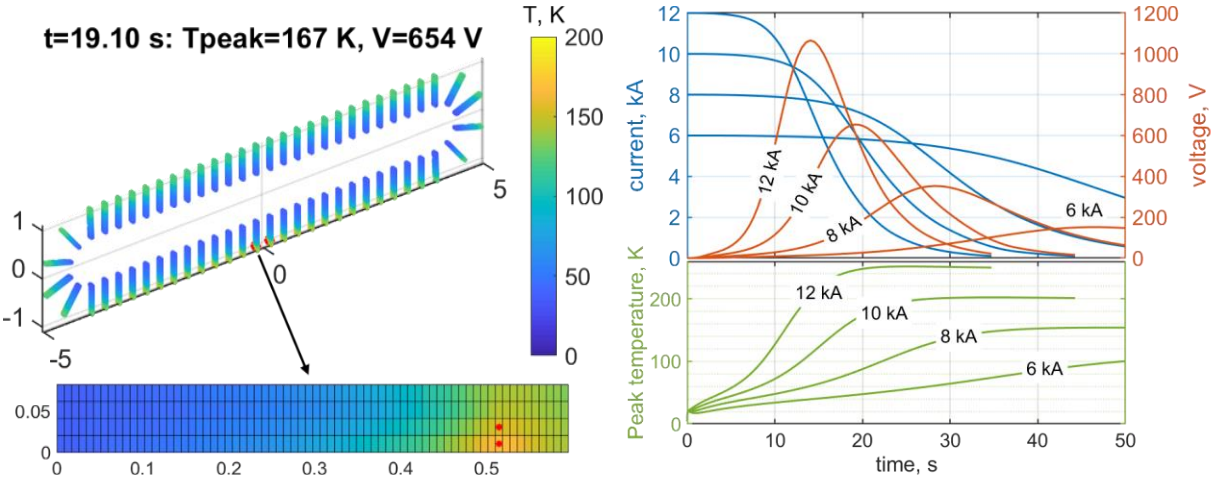


Figure 5. Left: temperature distribution in a single coil operated at 10 kA nominal current at the moment of reaching the peak voltage. Right: evolution of the current, voltage and peak temperature for various initial operating currents.

The impact of the operating current on the peak values of voltage V_{max} and temperature T_{max} for the various model configurations is presented in Figure 6. V_{max} is practically independent of the considered cases, gradually increasing with current up to about 1 kV, thus no insulation failures are expected. T_{max} depends almost linearly on current, decreasing by about 20 % when comparing the case of a not-protected single coil with the case of two coils protected by one heater, and by another 20 % if two coils are further equipped with casing and two protection heaters. In this case, T_{max} stays below 150 K for the entire range of current, which is considered safe, and if protection is not applied it increases by about 15 %.

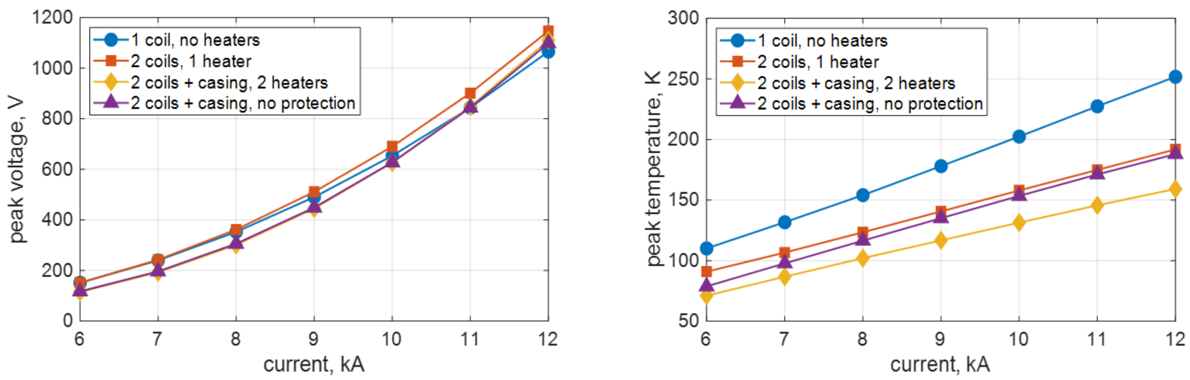


Figure 6. Peak voltage and peak temperature in coil windings as a function of the operating current.

Other effects on the peak temperature, including 'quench-back', an extra heating in the conductor and casing due to currents induced by the magnetic field changing with the operating current, are outlined in Table 1. Due to a strong influence of the cross-section of Al in the conductor, it is suggested to keep its dimensions fixed. Moving the quench initiation spot towards inner turns of the winding brings the peak temperature further up, thus equipping the windings with a quench detection system, suitable for rather low detection threshold near this region, is recommended. While the RRR of the pure aluminum is prone to a strong variation due to conductor handling, practically no influence on the quench process is expected within a wide range of the values. Finally, a weak effect of the quench-back on T_{max} is present because the decrease of current in the windings is in fact rather slow for reshaping the temperature distribution due to extra heating by the induced currents.

Table 1. Impact of various model parameters on the peak temperature.

Parameter	**Range**	**Impact on T_{max}**	
Al content in the cable	Down to 0.8 relative to baseline	Strong:	≈ 20 % increase
Location of the hot-spot	9 selected locations	Moderate:	± 10 % variation
Detection threshold	From 0.1 V to 10 V	Moderate:	up to 10 % increase
RRR of pure Al in field	From 400 to 1600	Minor:	< 5 % reduction
Quench-back	–	Minor:	< 5 % reduction

3.3. HTS busbars

Aiming to minimize the cryogenic heat load, two options are considered for the HTS material: either using 70 parallel Bi2223/AgAu tapes of 4.3 mm width and 0.2 mm thickness, or 120 parallel *Re*BCO etched tapes of 4 mm width and 0.05 mm thickness. Both options provide sufficient current capacity for up to 12 kA keeping the warm end-temperature at 70 K.

Tapes can conventionally be arranged in a set of stacks placed around a steel tube. Alternatively, a rather innovative self-protecting HTS lead as sketched in Figure 7, can be used. This device is presently under development [8]. The principle of operation is as follows. At room temperature the copper shunt is preloaded to the HTS section by tensioning an invar rod (closed gap); then, during normal operation at cold, the gap is open due to thermal shrinkage of the HTS section, resulting in a very low heat load; finally, during a quench in the HTS section, the steel tube expands due to Joule heating and the gap is closed enabling the current transfer to copper shunt thereby preventing further overheating. Furthermore, the presence of the copper shunt also allow a slow-dump of the magnet, instead of a fast-dump, due to a much slower temperature rise.

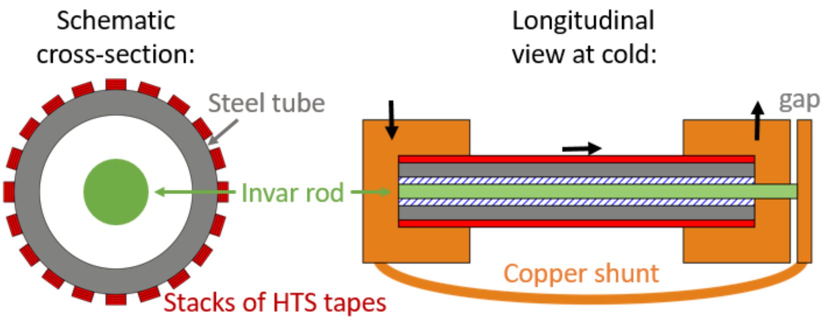


Figure 7. Sketch of the innovative self-protecting HTS busbar shown with gap open at cold.

The current decay profiles, presented in Figure 5, are used to estimate the peak temperature in the HTS busbars under adiabatic condition. As shown in Figure 8, the peak temperature is practically independent of the operating current because the discharge time at high current is noticeably less than that at low current. However, it increases from 200 to 400 K if the steel cross-section is reduced by a factor 2, from about 1340 to 640 mm^2 in the Bi2223 case and from 1900 to 1100 mm^2 in the *Re*BCO case. Assuming 200 K as the limit temperature for the conventional design, around 2.2-m long Bi2223 and 2.1-m long *Re*BCO busbars are needed to reduce the heat load to 0.25 W (i.e. total 0.5 W for pair of leads). In contrast, if 400 K is taken as a reference for the self-protected design, which in fact can only be reached in the case of switching failure, 1.4 m Bi2223 and 1.2 m ReBCO sections can provide the same heat load. Hence, using the self-protecting current leads results in a 40 % cost reduction for the HTS busbars, though the reliability of switching has to be thoroughly demonstrated in a vacuum environment.

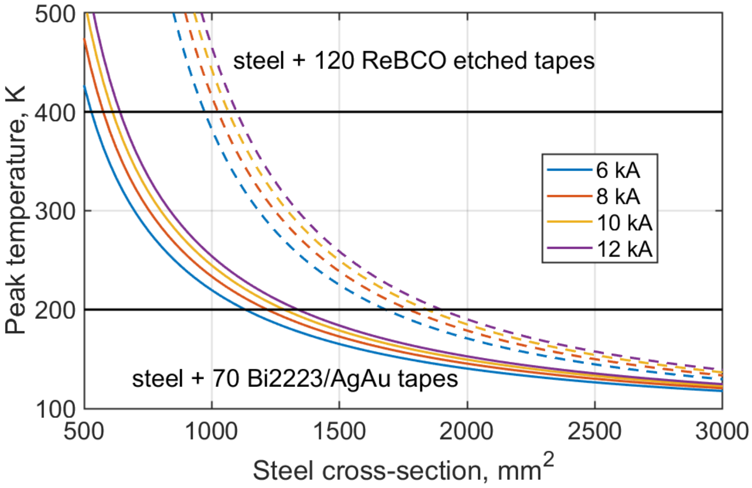


Figure 8. Peak temperature as a function of steel cross-section for the two layouts of the HTS busbars and the selected current decays of the main magnet.

3.4. Persistent mode switch (PMS)

Cryogenic and electrical circuits of the BabyAIXO magnet are designed to charge the magnet to 10 kA in 60 min, corresponding to 3 A/s ramp rate and 3 V charging voltage. In order to reduce the power dissipation in the open state of the PMS during charging, a relatively high open state resistance of the PMS is required, which essentially excludes using stabilizing material in the PMS conductor. As outlined in Figure 9, using 36 parallel strands of NbTi-CuNi matrix wire in a cable of 180 m length results in a 6.6 K current sharing temperature for operation at 10 kA and 4.5 Ω resistance in the open state. The strands can be arranged using 6 sub-cables in a bifilar manner to minimize the PMS self-inductance, which is further discussed in [3].

Total number of wires	36
Single wire length	180 m
Total wire length	6.6 km
Tcs @10 kA, 1.5 T	6.6 K
PMS Resistance	4.5 Ω
Power loss @3 A/s	2 W
Energy required to reach 12 K	≈ 130 J

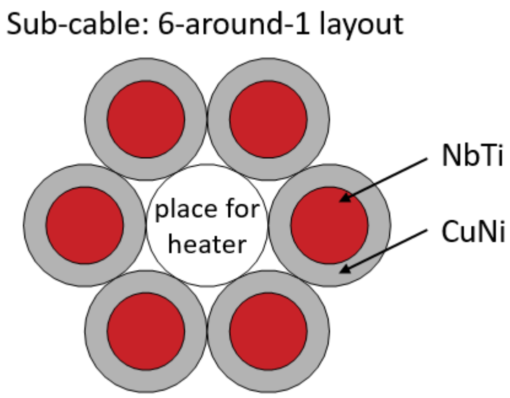


Figure 9. Main parameters of the Persistent Mode Switch for the BabyIAXO magnet (left) and sketch of the 6-strand sub-cable (right), which are arranged in 6 fold bifilar layout.

The temperature increase during a quench at 10 kA in the PMS is extremely fast. Under adiabatic condition, it requires only 5 ms to reach a temperature of 300 K, see Figure 10. Consequently, in addition to a fast quench detection system required to fire protection heaters in a timely manner, use of high current diodes with low forward voltage drop at cold, similar to those used in LHC [9], is foreseen. The switch units has to be split in sections, each shunted by a diode. Considering a forward voltage drop of around 1.5 V at 4 K, a normal zone of 6 mm length is then sufficient to open the diode. Any disturbance leading to a smaller normal zone such as local wire performance drop and local heat source must be avoided. For the set of diodes connected in series, the total forward voltage drop is higher than that of the warm unit of diodes in the electrical circuit, thus the diode protection of the PMS does not affect a slow-dump as it can only be opened by a quench in the PMS.

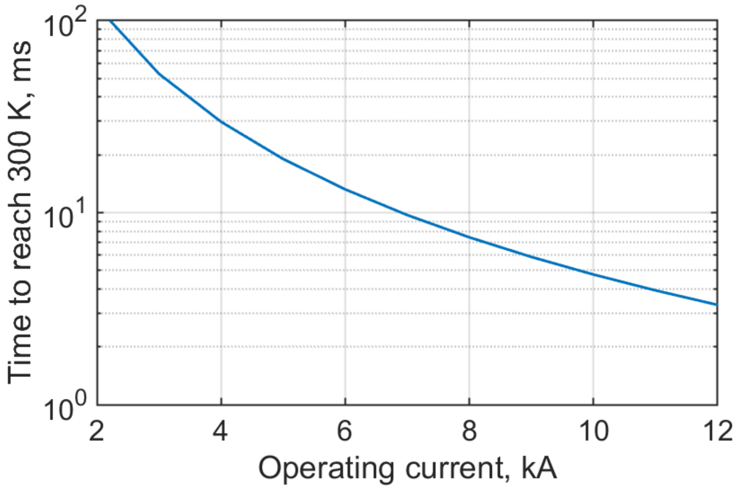


Figure 10. Time to reach 300 K in a quenched Persistent Mode Switch at different operating currents.

4. Conclusion

Quench protection of the BabyIAXO magnet when operating in persistent mode operation has been analyzed. The main mechanisms causing a fast-dump in the magnet like a quench in the coil windings, in the HTS busbars or in the persistent mode switch, have been evaluated. The quench protection of the magnet is based on the self-dump approach, since the magnet will operate on a moving platform in a persistent mode with the power supply disconnected.

The baseline design of the coil windings, analyzed using a 3-D thermo-electrical simulation model, has demonstrated acceptable results for the peak temperature and the generated voltage, which are below 150 K and 1.2 kV, respectively at the ultimate operating current of 12 kA. Following the various effects analyzed during the quench process, the cross-section of aluminum stabilizer in the conductor, location of the hot-spot and the detection threshold are most influential. Hence, when possible, reduction of the Al content should be avoided and the quench detection system should be tuned to identify a quench near the inner winding turns and to fire protection heaters using the detection threshold < 1 V.

In the case of a quench in the HTS busbars, the peak temperature can be adjusted by the steel cross-section. Between 640 and 1900 mm^2 is required to keep the peak temperature below the limit, depending on the busbar layout and the selected type of HTS conductor. The operating current at quench has a rather weak effect on the peak temperature as it changes the magnet discharge time correspondingly.

The principle absence of stabilizer in the persistent mode switch causes a quench at very fast temperature excursion to 300 K within 5 ms at 10 kA, which requires using a fast detection system and a set of diodes with low forward voltage drop connected in parallel.

The engineering design of the Baby-IAXO magnet has essentially been completed and the next step is a start of construction foreseen by early 2020.

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