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Quench Propagation and Detection in the Superconducting Bus-bars of the ATLAS Magnets

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Abstract **-- The ATLAS superconducting magnet system comprising Barrel (BT) and End-Cap Toroids (ECT) and also Central Solenoid (CS) will store more than 1.5 GJ of magnetic energy. The magnet system will have many superconducting busbars, a few meters long each, running from the current leads to Central Solenoid and Toroids as well as between the coils of each Toroid. Quench development in the busbars, i.e., the normal zone propagation process along the busbar superconductors, is slow and exhibits very low voltages. Therefore, its timely and appropriate detection represents a real challenge. The temperature evolution in the busbars under quench is of primary importance. Conservative calculations of the temperature were performed for all the magnets. Also, a simple and effective method to detect a normal zone in a busbar is presented. A thin superconducting wire, which normal resistance can be easily detected, is placed in a good thermal contact to busbar. Thus, the wire can operate as a straightforward and low-noise quench-detector.**

I. INTRODUCTION

In the large superconducting magnet system of the ATLAS detector [1], the stored energy will be dissipated inside the coils in the case of a quench event. Special quench heaters embedded into each coil initiate multiple normal zones to spread the heat and therewith to prevent coil overheating and to minimise thermal shock effects [2,3,4]. In particular, in the case of heater failure, the normal zone behavior in the superconducting busbars, routing inside the cryostats, is important for the quench protection of the whole magnet system. For instance, such superconducting busbars connect all the Toroid coils in series.

At the rated current, the normalization time for one coil is less than ten seconds. The time required to discharge fast the whole magnet system is estimated to be about one minute. The quench-back effect due to eddy currents in the coil casings produces normal zones in initially non-quenched coils within 25-35 s. When a normal zone propagates along the busbar within a few seconds, it will help to dissipate the stored energy more uniformly. In such a case, there is no problem if a quench occurs in the busbar conductor.

However, the busbars will be arranged mainly within a low magnetic field region where the normal zone propagation velocity is correspondingly low. Electrical joints are usually good heat sinks and can also impede or even stop the normal zone propagation. Then, in the case of a quench of the busbar, there is the danger to overheat the conductor, and hence a sensitive quench detection system is needed.

TABLE I
PARAMETERS OF THE ATLAS CONDUCTORS

Conductor	CS	BT	ECT
Width (mm)	30	57	41
Thickness (mm)	4.25	12	12
Operating current (kA)	7.6	20	20
RRR at 1 T & 4.5 K	250	400	400
Stabiliser area (mm^2)	110	630	430

During magnet energizing at low current, a normal zone can be spatially limited or propagate very slowly. In this case, if a normal zone appears, voltage measurements on the busbar will only enable a quench event to be detected with some delay when the conductor is already at a high temperature.

II. BUSBARS AND QUENCH PROPAGATION

The same conductors are proposed to be used both for the windings of the magnet coils and for the busbars. All the coils will be wound from a Cu/NbTi Rutherford type composite superconducting cable co-extruded in a thick aluminium stabilizer. The main parameters of the ATLAS conductors are given in Table I.

The ATLAS magnet coils will be cooled indirectly [1]. A proposed layout of the characteristic superconducting busbars is shown in Fig.1. A conductor is placed into special thick aluminium housing. It is also surrounded with ground insulation, which thickness is about 1-1.5 mm. The layout (a) corresponds to the Central Solenoid and Barrel Toroid busbars. One (for BT) or two conductors (for CS) will be used as conducting path. A liquid helium tube is attached to the housing that provides necessary cooling conditions. The layout (b) is typical for the ECT where the busbar housing is attached to the cold mass of the ECT coil. Its cooling is provided by thermal conductivity.

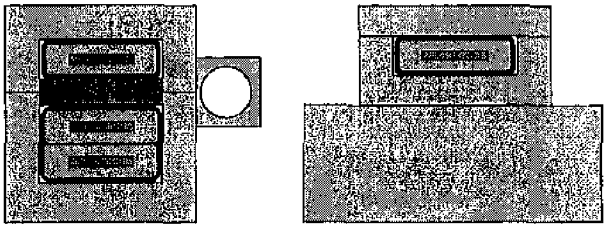
a) b)

Fig.1 Proposed layouts of busbars.

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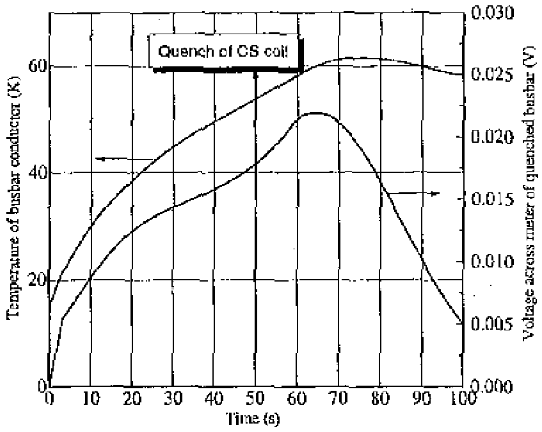

Fig. 2 Maximum temperature and voltage drop across one meter of the quenched busbar of the Central Solenoid (50 s delay in the coil quench).

A. *Central Solenoid*

The Central Solenoid has a 10-m long chimney between the coil and the current lead box. The superconducting busbar made of two parallel conductors is inside [4]. This busbar passes through the Barrel Toroid region where the space-averaged value of the magnetic field is about 1 T at the first four meters of the busbar. The additional parts of the CS busbar are in a region with low magnetic field. The Central Solenoid will be charged by an independent power supply. We assume in our calculations that the conductors are well glued to the aluminum housing.

A computer-simulated behavior of the busbar under quench is shown in Fig.2 demonstrating the busbar temperature and voltage. If the normal zone does not propagate through the low magnetic field region due to the good cooling conditions in the very beginning of the quench event, the power dissipation in the aluminum housing will block the helium flow in the cooling tubes within a few seconds. The cooling conditions in this case become quasi-adiabatic and the normal zone propagates with the velocity of more than 0.5 m/s. Since the joint region is rather short (about 0.5 m), two seconds are enough to normalize the joint. But even in the very pessimistic case, where a quench of the Central Solenoid will start at fifty seconds after the busbar quenches, the maximum calculated temperature of the busbar is less than 70 K.

B. *Barrel Toroid*

The same approach as for the CS busbar can be used for the analysis of processes in the Barrel Toroid busbar. Eight BT coils placed in separated cryostats are connected by a cryogenic ring [2]. In each section of the cryogenic ring, the length of the busbar inclusive joints is about 5 m. The average value of the magnetic field at the BT busbar region is about 1 T. The thickness of the ground insulation is planned to be 1.5 mm. Each joint can be considered as a double conductor. Under adiabatic conditions, starting as a result of helium stopping in a few of seconds after the quench initiation, the normal zone will propagate through the joint within three to four seconds. For the doubled conductor in the busbar housing the normal zone propagation velocity is higher than 0.3 m/s under adiabatic conditions. The temperature and voltage drop versus time is shown in Fig.3. It is estimated that the maximum temperature is less than 160 K when the BT fast discharge starts with 50 s delay after the busbar has quenched.

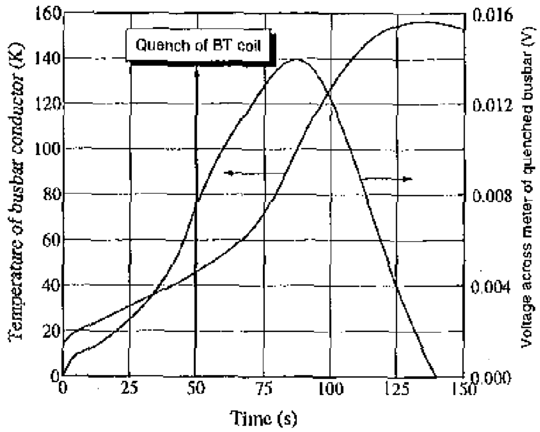

Fig.3 Maximum temperature and voltage drop across one meter of the quenched busbar of the Barrel Toroid (50 s delay in the coil quench).

C. *End-Cap Toroid*

Each of the two End-Cap Toroids will consist of eight coils placed in a cryostat [3]. The coils will be electrically connected in series, using superconducting busbars. The length of busbar between the joints of the coils will be about 1.5 meter. The busbar housing will be anchored to the surface of the cold mass. After initiation, a normal zone propagates within seconds under quasi-adiabatic conditions. If the joint is made in the "praying hands" shape, one can assume that the propagation across the joint is rather fast. Similar results as for the CS and BT busbars are numerically obtained and

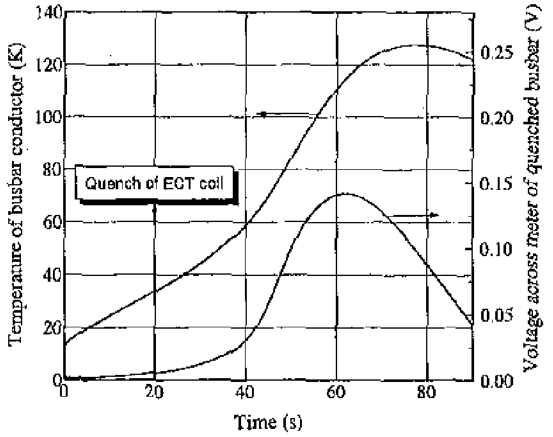

Fig. 4 Maximum temperature and voltage drop across one meter of the quenched busbar of the End-Cap Toroid (20 s delay in the coil quench).

shown in Fig.4. The current density in the ECT busbar is about 1.5 time higher than in the BT and CS and warming up is nearly two times faster. A rough analysis gives that a few seconds would be sufficient to normalize the whole busbar. However, even when this value is twenty seconds, the maximum temperature does not exceed 140 K when the magnet system discharge starts with such delay.

D. Busbar quench and voltage detection

Even when there are no obvious problems with the ATLAS busbars, the protection system has to be activated as early as possible. The fastest way of quench detection is the voltage drop measurements. However, it is of primary importance to prevent false activation of the protection system due to noise. For the whole magnet with well-know bridge detectors, the voltage threshold is chosen to be 1 V. On the worst assumption, a normal zone does not propagate from the busbars to the coils. In the ATLAS coils at operating current, the busbar voltage rise can be reliably detected after the bus conductor temperature reaches 75-100 K. For the quench detection of the BT busbars, a switch/voltmeter would require a voltage threshold of 50 mV which would control each of the fifteen bus lines. A quench event at such voltage level can be detected with approximately 40 s delay. However, the 50 mV detection level causes serious noise problems and it would be better to introduce a new reliable method.

III. SUPERCONDUCTING QUENCH DETECTOR

A. Introduction

A simple method of quench detection in the busbars is suggested. The idea is as follows. On the surface of the aluminum housing of the superconducting busbar an insulated thin superconductor, see Fig. 5, is glued. If a busbar quench takes place, the temperature of superconductor will increase in accordance with the temperature increase of the quenched parts of busbar. When the superconductor temperature becomes equal to the critical temperature, it becomes normally conducting. Through its resistance control, the quench event of the busbar can be detected, of course with some time delay. For the best performance of such a superconducting quench detector (SQD), the following requirements are evident: high electrical resistivity of the superconducting material and a bifilar lay-out in order to avoid noise problems, small thickness of the insulation and small mass of the superconducting element to reach the fast reaction.

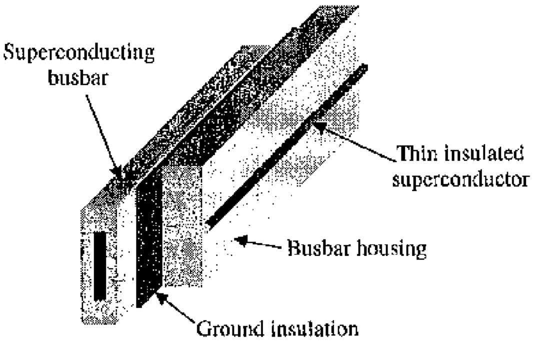

Fig. 5 A simple superconducting quench detector.

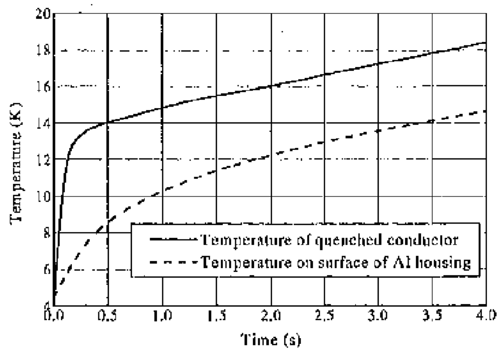

Fig. 6 Temperature rising of the quenched busbar and its aluminum housing.

B. Reaction time

One of the important things regarding any quench detector is the reaction time. For our SQD, the reaction time is determined by the heat transfer conditions between the quenched part and the detector element. Assuming that the dimensions of SQD are much less than the busbar dimensions the characteristic time scale of the SQD warming up is dependent on thickness, heat capacity and heat conductivity of the SQD conductor and its insulation. We have found that the typical reaction time of the detector does not exceed 0.1 s. If the SQD is placed as shown in Fig.5, it is necessary to calculate the temperature evolution of the busbar housing surface. The result of 2-D calculations, taking into account a current diffusion into the aluminum stabilizer and transient heat processes, is given in Fig. 6. The busbar housing is 15 mm thick and made from aluminum alloy. A safe 1.5 mm ground insulation is the main barrier for the heat conduction to SQD. Nevertheless, the temperature of the housing surface turns out to be at 10 K in one second. Therefore, the SQD enables easy and reliable detection of a normal zone within two seconds. Thus, the reaction time of the SQD on quench of the busbar is much shorter than the expected reaction time of the switch voltmeter arrangement.

C. Material and sensitivity

The most suitable material for the superconducting quench detector seems to be NbTi alloy that has high enough resistivity. As obvious, it has also the same critical

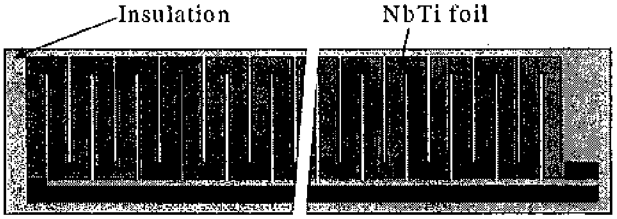

Fig. 7 Sketch of the foil superconducting quench detector (SQD).

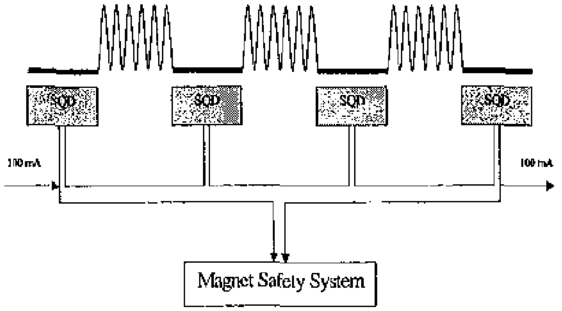

Fig. 8 A one-channel scheme for quench detection in all the busbars.

temperature as the superconductors from which the busbars are made. Thus, if a quench occurs in the region with a high magnetic field the reaction time will be correspondingly shorter than in a low field region. A NbTi foil can be chosen as the sensitive element of SQD. A pattern sketch of the foil SQD is shown in Fig.7. The linear resistance of the detector is expected to be about 100 Ohm/m. With a typical measuring current of 100 mA, the output signal will be high enough to be detected without any problem. In fact, the SQD behaves as a voltage amplifier enabling to detect reliably and noise free quenching busbars. Another simple SQD can be made of a thin NbTi/CuNi-matrix superconducting wire typically used in AC applications. Such a twisted bifilar pair of thin insulated superconductors is free of any noise problems and attractive due to the very low cost.

From the point of view of the reaction time, the distance between the quenched conductor and the SQD should be as short as possible. It can be more easily realised along the connections between the coils and on the joints of the double pancakes in each coil. The exact position of the SQD should be discussed with the coil manufacturer.

D. Electrical Circuit

The simplest way to form the quench detection scheme for the entire Toroid is to connect all the individual SQD on the busbars in series. In this case, one channel is sufficient for quench control which makes the detection system very reliable, see Fig.8. Redundancy in the SQD system can be easily implemented. If connections between the elements are placed inside the cryostat where the resistance of the measurement wires is negligible, the SQD is the simplest logical element with "Yes/No-Quench" reaction. There are no special requirements for the connecting wire. If necessary, each element can be controlled to determine the location of the normal zone origination.

IV. CONCLUSIONS

In the case of a quench event, the ATLAS magnet system superconducting busbars are not expected to warm up higher than 200 K even with very slow normal zone propagation in the busbars.

A normal zone in a quenched superconducting busbar can be detected through direct voltage measurements or with a superconducting quench detector (SQD) as suggested here. We plan to develop and test various types of superconducting quench detectors on model coils to check their reliability for application in the ATLAS magnet system.

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