Cryogenics 95 (2018) 102–109

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Research paper

Analytical method for the prediction of quench initiation and development in accelerator magnets

Susana Izquierdo Bermudez, Luca Bottura, Hugues Bajas, Gerard Willering

CERN, Geneva, Switzerland

ABSTRACT

The optimal design of the next generation of accelerator magnets calls for a high current density in the superconducting coil, which makes the magnet protection a challenge. Quenches in the high-field magnets for the High Luminosity LHC Upgrade typically develop within tens of ms, and the reaction time needs to be comparable, requiring active firing of heaters or other heat deposition techniques to increase the quench propagation velocity in the magnet. It is important to have a very good understanding of the behavior of a magnet during a quench. Practical scaling laws, and simplified methods, allow quick scans of design and operation parameters, and swift feedback based on experimental results once the magnet is in test. In this paper we describe simplified methods to predict the quench initiation and development in accelerator magnets using active quench protection. We use data from the recent Nb_3Sn model magnets for the High-Luminosity LHC as a benchmark for the method, discussing expected accuracy and the reasons for deviations.

1. Introduction

Superconducting accelerator magnets, built with long and slender coils tightly packed around the beam tube, operate at high current density, are connected in series of long magnet strings, and store large energy per unit coil volume. These features are necessary for reasons of cost and operation, but make quench detection and protection a challenge. To fix orders of magnitude, the typical value of the engineering (strands) current density at nominal operating conditions in the cables of the large superconducting accelerators built and operated to date varies from 380 A/mm^2 for the HERA dipole cable to 620 A/mm^2 in the LHC outer layer dipole cable, while the energy stored per unit volume of strands ranges from 30 J/cm^3 in the HERA dipole to 70 J/cm^3 in the LHC dipole. Both values will increase further in the next generation of superconducting accelerator magnets, reaching respectively 770 A/mm^2 and 125 J/cm^3 in the 11 T dipoles to be installed in the LHC as a part of the High-Luminosity upgrade project. The values for a 16 T Nb_3Sn dipole under design for the Future Circular Collider [1] would reach nearly 800 A/mm^2 and 200 J/cm^3, respectively. Figs. 1 and 2 show the strand energy and current density for different dipole magnets built in the past, in construction, and being designed for future accelerators. The trend towards increasing stored energy per unit volume of strand vs. bore field is very clear, and is accompanied by a somewhat more modest and scattered increase of the engineering current density vs. bore field.

The above values are the main drivers for the design of the quench detection (voltage threshold and detection time) and protection (dump strategy and circuit topology) of the strings of several tens to hundreds of magnets in series in an accelerator. Indeed, we can show very simply that in case of quench of one magnet operated in the above regime, in a string, it is not possible to dump the magnetic energy on an external circuit. We take for this discussion the example of the LHC dipoles, which is representative of the state-of-the-art. An LHC *arc*, the magnet string in the accelerator, is formed by the series connection of 154 dipoles. Each dipole has a nominal operating current of 11.85 kA, and an inductance of about 0.1H, thus resulting in an arc inductance of about 15.4H. With a ratio of stabilizer (Cu) to superconductor (non-Cu) in the range of Cu:non-Cu of 1.65 (inner layer cable) to 1.95 (outer layer cable) the strand engineering current densities quoted earlier translate in values of Cu current density in the range of 1000 A/mm^2. In case of quench, the temperature increase rate caused by the Joule heating associated with such current density is around 1000 K/s. Wishing to limit the local temperature increase to room-temperature (300 K), which is already a severe condition, this results in a maximum time to dump the magnet of the order of 300 ms. With the above values of operating current and inductance, achieving this dump time would require a terminal voltage of 600 kV on the string of magnets, a value which is clearly not realistic. In fact, voltages in the above range are orders of magnitude higher than desirable for a practical magnet design. This is why the magnet string is subdivided by placing a by-pass diode at every dipole, and every magnet is protected by firing quench heaters, or other fast quench initiation mechanism, as soon as a quench is detected. The magnet itself is used as the *dump*, to dissipate the magnetic energy within the requested few hundreds of milliseconds, while the current of the string, by-passed by the diode in the quenching magnets, is ramped down at a much slower pace, tens to hundred seconds.

E-mail address: susana.izquierdo.bermudez@cern.ch (S. Izquierdo Bermudez).

https://doi.org/10.1016/j.cryogenics.2018.09.004
Received 15 February 2018; Received in revised form 29 June 2018; Accepted 10 September 2018
Available online 14 September 2018

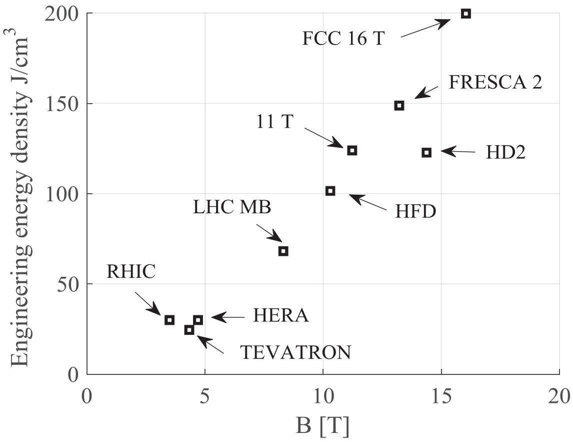

Fig. 1. Engineering (strand) energy density versus the field in the bore for Nb-Ti and Nb_3Sn magnets.

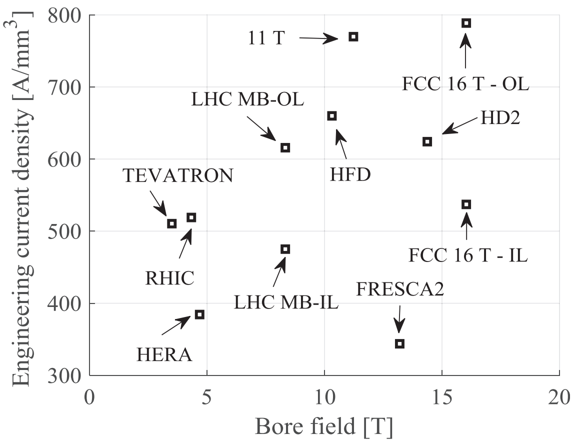

Fig. 2. Engineering (strand) current density versus the field in the bore for Nb-Ti and Nb_3Sn magnets.

An obvious consequence of the above figures is that both the quench detection and quench protection hardware and logics must react relatively fast after the appearance of a normal zone. We distinguish here between the time required to detect and validate that a quench has started, or *quench detection time*, and the time required to actively provoke a quench in the largest possible fraction of the magnet, or *active quench initiation time*. Both detection and active quench initiation times must be kept below few tens of ms, ideally in the range of a few ms, so that most of the time is spent dissipating the magnetic energy homogeneously, rather than concentrated in the *hot spot* located at the initial quench position. In essence, any time between the beginning of the normal zone and the active quench initiation must be considered as wasted to the effective dump of the magnetic energy at minimum temperature gradient in the coil.

The purpose of this paper is to provide a set of simple analytical or semi-analytical scaling expressions that can be used to describe the whole process, and assist in the initial design of the magnet, before going into more complex, time consuming and at times somewhat obscure simulations. The quench parameters of interest here are:

- Quench detection time $\tau_{detection}$, i.e. the time needed to detect that a quench has started based on a voltage signal above a given detection threshold $V_{detection}$;
- Quench validation time $\tau_{validation}$, i.e. the time the voltage signal is above the given detection threshold before triggering the active quench protection system. In the LHC, the validation time is typically 10 ms.
- Active quench initiation time $\tau_{initiation}$, or the time required to spread to the whole coil the quench initiated at a local normal zone in the magnet. Among the possible methods, we consider in our analysis only quench heaters;
- Current dump, i.e. the waveform $I(t)$ of the magnet operating current during the quench, and the equivalent dump time τ_{dump}, i.e. the time that would result in the same integral of the square of the current, if the current had remained constant at its initial value;
- Hot spot temperature T_{hot}, the maximum temperature at the location of the quench start;
- Bulk coil temperature at the end of the dump T_{coil}, the average temperature in the rest of the coil that was forced to quench after detection of a normal zone;
- Coil resistance R_{coil}, the value of resistance through the quench transient, till the end of the quench.

To this aim, we structure our analysis following the sequence of the quench start, propagation, detection and validation, active initiation and dump. In the following sections, we will propose simple analytical or semi-analytical scaling for the above quantities, and we will compare them to data collected in a number of HL-LHC MQXF Nb_3Sn low-β quadrupole [2] and MBH Nb_3Sn 11 T dipole [3] magnets tested recently. The main magnet and conductor parameters relevant for protection are summarized in Table 1. In the case of MQXF, the protection includes a combination of quench heaters attached to the inner and outer coil surfaces and Coupling Loss Induced Quench (CLIQ) units electrically connected to the coils [4]. We limit the analysis to the cases where the magnet is only protected with quench heaters. In the 11 T dipole, the magnet protection relies only on quench heaters attached to the outer coil surfaces [5]. We include in this analysis the test results for five 11 T single aperture dipole models (MBHS), two 11 T double aperture dipole (MBHD) models and two MQXF short quadrupole models. The conductor parameters for the coils assembled in the magnets are summarized in Table 2.

Table 1
Summary of the conductor and magnet parameters relevant for quench protection.

Parameter	Unit	11 T – Single aperture	11 T – Double aperture	MQXFS
Strand diameter	mm	0.700 ± 0.003	0.700 ± 0.003	0.850 ± 0.003
Number of strands	–	40	40	40
Copper to superconductor ratio (cu/SC)	–	1.15 ± 0.10	1.15 ± 0.10	1.2 ± 0.1
Nominal magnet current (I_{nom})	kA	11.85	11.85	16.47
Conductor peak field at I_{nom} including self-field	T	11.7	11.8	11.4
Differential inductance at I_{nom}	mH/m	5.7	11.9	8.2
Engineering (strand) current density at I_{nom} (J_{eng})	A/mm^2	770	770	726
Overall (strand + insulation) current density at I_{nom} (J)	A/mm^2	522	522	469
Engineering (strand) energy density at I_{nom}	MJ/m^3	124	124	123
Overall (strand + insulation) energy density at I_{nom}	MJ/m^3	88	88	83
Magnetic length	m	1.7	1.7	1.2