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Guidelines for the quench analysis of Nb3Sn accelerator magnets using QLASA

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Abstract

QLASA[1] is an analytical program for simulating the rapid transition from the superconductig to the normal state ("quench") in solenoids. With some adjustments it can be used also for quench analysis of accelerator magnets, like dipoles or quadrupoles. Actually, QLASA has been used since a long time for NbTi accelerator magnets, but it needs procedures for the simulation of the new generation of accelerator magnets using Nb_3Sn. This document presents some guidelines suggested for the simulation of the quench in Nb_3Sn accelerator magnets. These guidelines are the result of the first validation with experimental data based on test performed on LARP LQ and HQ magnets[2].

1. Introduction

The aim of this document is to describe how to set up a QLASA input file for the simulation of a quench in a Nb_3Sn two-layers long quadrupole. All the guidelines described in the next sections have been validated by means of comparisons with experimental data. These guidelines can be easily adjusted for simulating other accelerator magnets.

2. Geometrical transformation in 8 coils

QLASA was developed for solenoids. Anyway, it's possible to describe a quadrupole by means of a geometrical transformation that preserves the coil volume. The simplest way is to describe each layer of each coil with a solenoid. So, we need 8 solenoids to describe a two-layers quadrupole. Considering a quadrupole of length L, it can be shown that the transformation (1) preserves the coil volume

$$R_{in} = \frac{L}{\pi} - \frac{w}{2}$$

$$R_{out} = R_{in} + w \qquad (1)$$

$$H = Nh$$

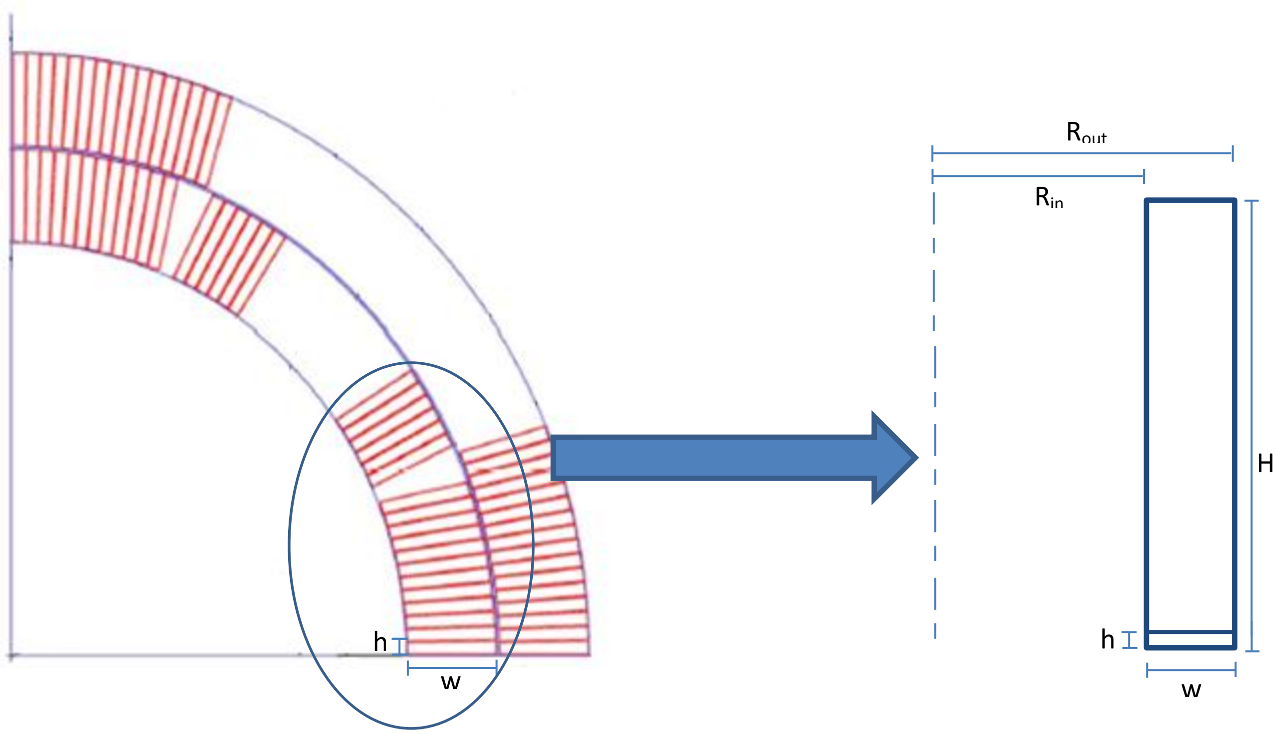

Fig.1: Geometrical transformation of a quadrupole coil in a solenoid

N is the turns number per octant. The solenoid's unit cell has the same size of the quadrupole turn, and the number of unit cells in the equivalent solenoid is equal to the number of turns in the corresponding layer.

3. Geometrical transformation in 9 or more coils

The transformation described in section 2 does not take into account spacers between turns. If you want to take into account spacers, you can easily divide in two parts the equivalent solenoid: in this way, the two resultants solenoids are not in thermal contact (just as if a spacer is between them). **<u>This model is the best to describe the coil where the quench starts</u>**. Next sections explain the reason.

4. Magnetic field

In QLASA the magnetic field is set by input parameters: you have to define the field in four points (see fig.2), then the field map across the whole coil is computed by linear interpolation assuming top-bottom symmetry.

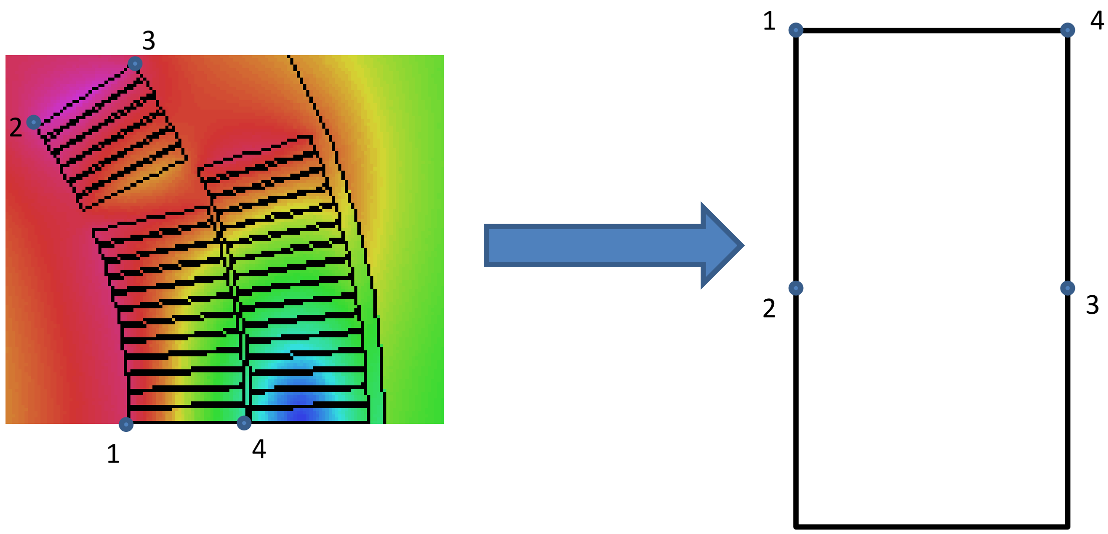

Fig.2: Magnetic field has to be defined in the blue points

If we put the peak field on the top of the solenoid we obtain peak field also on the bottom because of the top-bottom symmetry. Therefore, the best way to describe the magnetic field is to put the peak field in the middle of the solenoid (points 2 and 3) and the midplane field on the top of the solenoid. In this way, a quench starting in the peak field region is going to propagate from high to low field regions, as in the real coil. On the contrary, if the peak field is set on the top of the solenoid, then the quench is going to propagate from high to low and back to high field regions.

5. Quench start location

The best way to describe a real quench starting in the peak-field turn of the quadrupole (point 2 on the left in Fig.2) is by starting a point-like quench in the peak field zone. Then the quench propagates in the three directions with the appropriate quench velocities. If you want to take into account the spacers, you have to simulate the coil where the quench starts using two coils, as we have described in section 3.

6. Transversal propagation velocity

If you start a quench in the peak field zone of the solenoid, it propagates up and down. Instead in the quadrupole the quench starts on the top of the coil, and then it propagates only in one direction. In order to preserve the normal zone size during quench propagation, the correction factor of the transversal quench propagation velocity must be set to 0.5, but **only** in the coil where the quench starts.

7. Quench heaters

Quench heaters can be simulated by fictitious quenches starting at the right time with the appropriate size. The radial thickness should be 0, the azimuthal length should be the conductor height times the number of turns covered by the heater. If there are not heating stations, the normal zone length should be equal to the quench heater length. If the heater has heating stations the best simulation is achieved by starting a quench with initial length set to 0, but with a longitudinal quench propagation velocity increased (using the correction factor) by a factor equal to the number of heating stations. This procedure preserves size of the normal zone under the heaters during the whole propagation.

In order to find the right time for quench induced by quench heaters, this procedure has to be followed:

1) Run one simulation without quench heaters, and see in the output file what time the voltage threshold is reached (IMPORTANT: in the output file the "voltage" column means resistive plus inductive voltage! We are interested only in the resistive voltage, so the best thing to do is to multiply the current column times the resistance column)
2) Set the time for starting quenches induced by heaters at the time obtained in the previous point (voltage threshold time) plus possible delays (validation, electronic delay, heat diffusion time etc…)
3) Run another simulation and see the results

IMPORTANT NOTE: in every coil only one quench can start! So, the coil in which the spontaneous quench starts cannot be covered by quench heaters! If you want to simulate quench heaters, the best model is that described in section 3: you can separate the coil in which quench starts in two coils, then the quench will propagate in one of them, and the other can be covered by quench heaters. In this way the resistivity is not too underestimated after quench heaters induce quench.

8. Heaters delay time

When heaters delay time experimental data are available, it's possible to estimate the best time to set as input value for quenches induced by heaters start. If the heaters cover almost all turns of a layer, quench induced by them has to start about 2 – 2.5 times the experimental delay time from heaters firing to detection (this procedure works well when the threshold is of some hundreds millivolts). This is due to the fact that in QLASA heaters are perfectly efficient (all the turns quench in the same instant), instead in the actual case quench induced by heaters is a complicated phenomenon that takes several milliseconds.

9. Inductance

Inductance is an input value for each coil. You can assign at each coil the nominal inductance divided by the number of coils.

Inductance can be modified in order to simulate dynamic effects (for instance eddy currents) contributing to energy dissipation: at high dI/dt eddy currents dissipation in coils and iron can be considerable, so you can simulate this effect by means of an "effective" inductance lower than the steady-state one. You can measure the effective inductance on experimental data by means of an exponential fit of the first ms after dump (when coil resistance is negligible) $L = \tau R_d$.

10. HF and LF quench heaters

Sometimes, quench heaters design is different for the HF (High Field) zone and for the LF (Low Field) zone of a layer coil. In order to simulate this heater design, you can divide the solenoid representing the coil in two solenoids, taking care of the input magnetic field. In this way, you can simulate independently the protection of the two solenoids (for examples, different time delays or heating station numbers), so you can describe the HF and LF zone quench protection independently.

11. Maximum number of solenoids

Currently, QLASA cannot simulate more than ten solenoids in series. If you want to take into account different heaters design for LF and HF zone for both inner and outer layer, it's easy to get over this maximum number. A solution could be to assemble all the solenoids with the same cross section magnetic and geometrical features and the same quench protection parameters in one big solenoid: for example, if you have four solenoids of length L, with the same cross section and magnetic field, in which equal quench heaters with N_{HS} induce a quench at time t, you can model them by using one big solenoid. This big solenoid should have length $4L$, the same cross section and magnetic field of the small solenoid, and $4N_{HS}$ heating stations. In this way, the normal zone size is preserved, and your simulation has fewer solenoids

Bibliography

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