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DETERMINATION OF THE NORMAL ZONE LENGTH IN THE B0 ATLAS MODEL COIL

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Abstract

The ATLAS Barrel Toroid (BT) is a superconducting toroid made of 8 coils of 25 m length and 5 m width, providing the magnetic field for the muon spectrometer of the ATLAS detector, one of the experiments of the Large Hadron Collider, under construction at CERN. In addition to the BT the ATLAS magnetic structure foresees two End Cap Toroid (ECT) with the same 8 structure geometry of the BT, and a Central Solenoid (CS).

The B0 construction was decided to test the technical construction solutions and reproduce the behavior of the final coils. The most powerful diagnostic sensors for studies of the quench propagation are the pick-up coils.

In this paper a short description of the characteristics of the pick-up coil signal, related to the quench propagation and to the current diffusion from the conductor to the stabilizer is given. Then, from the quench propagation velocity and the pick-up coil signal characteristics, the dimensions of the Normal Zone (NZ), the transited part of the cable, is determined, for different values of the main current in the magnet. The determination of the NZ dimensions is influenced by some experimental parameters, error affected, and by some assumptions. Because of these assumptions the NZ dimensions determined are only indicative, more precise measurements are not so far possible.

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1 INTRODUCTION

The Barrel Toroid Magnet (BT)[1)] is part of the Magnet System of the ATLAS Detector for the Large Hadron Collider (LHC). It provides the magnetic field required by the muon spectrometer. It consists of eight flat superconducting coil of 25 m length and 5 m width, radially assembled around the beam axis.

The field will extend over a length of about 26 meters with an inner bore of 9 meters and an outer diameter of about 20 meters. Because these coils are about 5 times larger than any other superconducting coil ever built, the CEA (Saclay), CERN and INFN (LASA Laboratory, Milan) decided to build a working model, called B0, which will be similar to one BT coil, both for the design concept and the construction procedure with the same width and the same cross section (4.5 m x 0.25 m) but with a reduced length (9 m), in order to qualify the design, verify the manufacturing procedure and validate the technical solutions

In the frame of the ATLAS project INFN-LASA was in charge to provide some diagnostic instrumentation for the B0 model coil[2)]. In addition to other sensors, INFN provided about 20 pick-up coil too[3)].

In Fig. 1 and 2 a schematic view, taken from [2)] of the two faces of the cold mass of B0, together with the sensors installed are shown.

The pick-up coils are the most powerful sensor to study the quench propagation and characteristics. As a matter of fact the signal induced in a pair of pick-up coil, placed at a known distance, allows the determination of the quench propagation velocity, i.e. the velocity of propagation of the transition from the superconducting state to the resistive state.

Beyond this very elementary use of this type of sensors, more informations about the current diffusion process can be derived by an accurate analysis of the shape of the signal induced in the pick-up coils.

It is clear that as higher the sensitivity of the sensors as more detailed information are obtained. The sensitivity for the pick-up coil is the effective cross section linked with the magnetic field variation.

In order to have detailed informations about the quench evolution, the sampling rate of the acquisition system[4)] must be high; scan time of the order of ms are necessary for the characteristics of the B0 model coil.

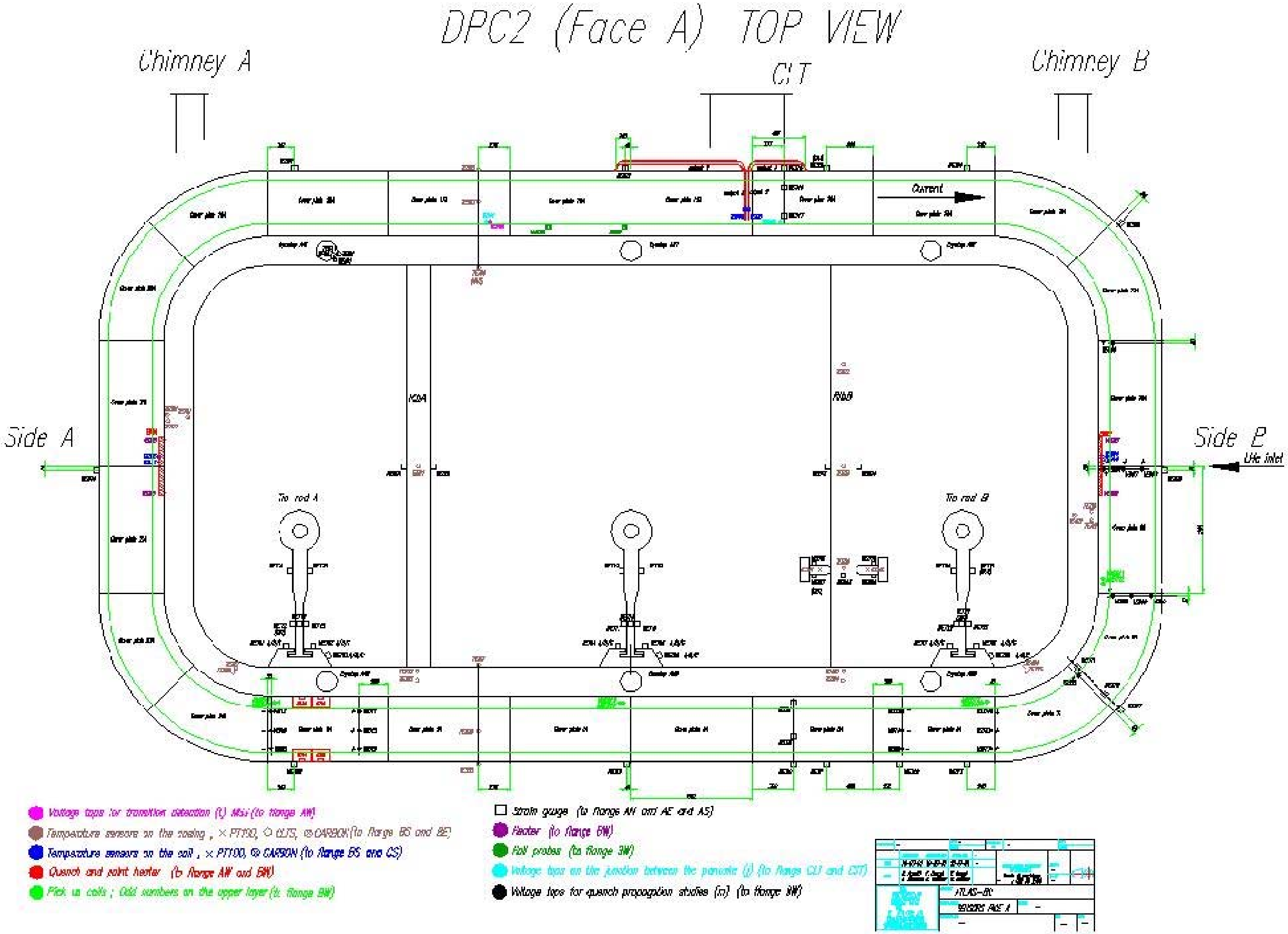

FIG. 1: Scheme of the sensor positions on the face A of the B0 coil casing.

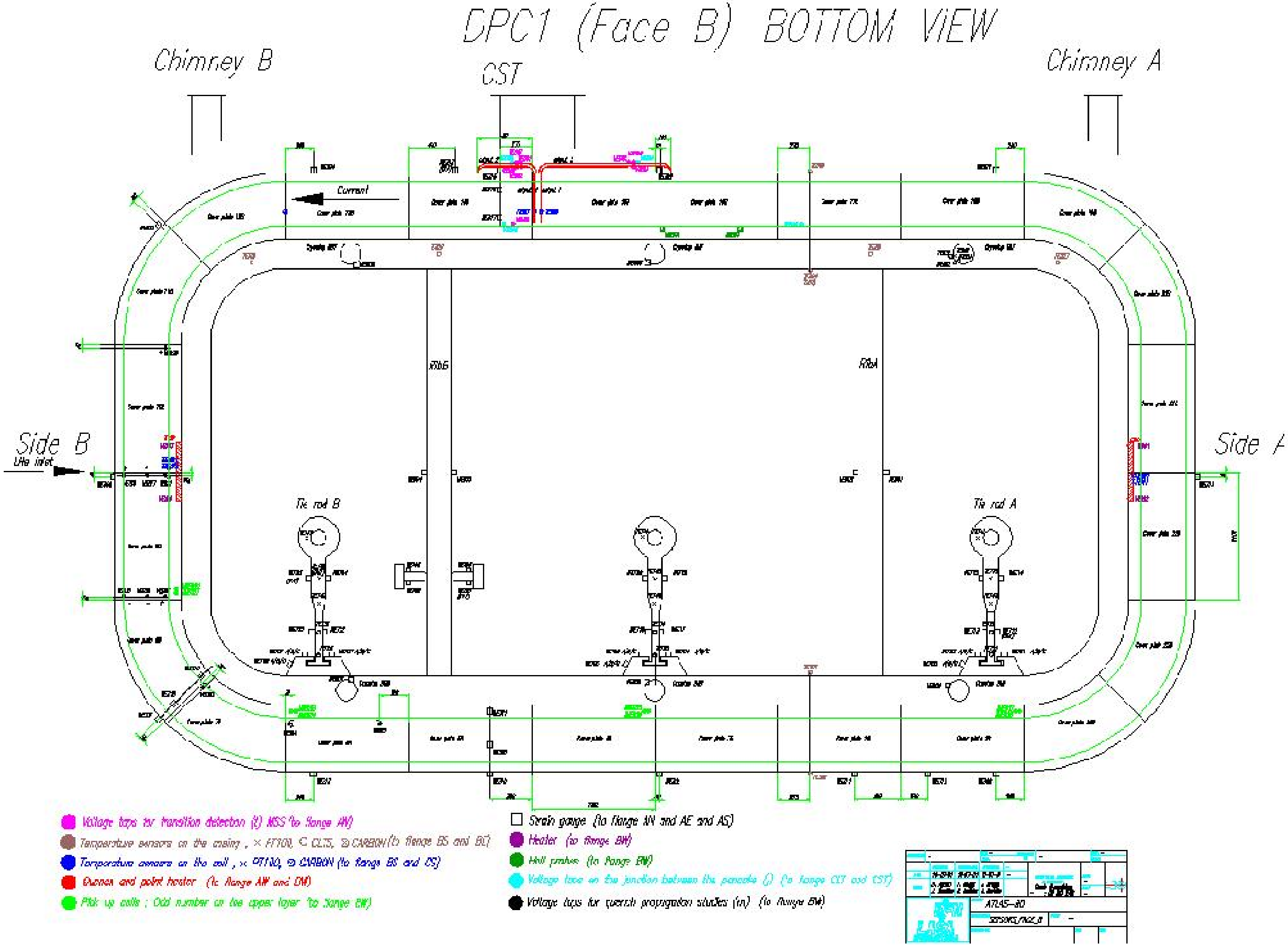

FIG. 1: Scheme of the sensor positions on the face B of the B0 coil casing.

2 THE PICK-UP COIL SIGNAL

2.1 Quench Velocity

The most immediate use of the signal from the pick-up coils is the determination of the quench propagation velocity.

As an example let's consider the signals of Figs. 3 and 4.

In both the figures the signals are from the pick-up coil in the second double pancake (DPC2) that is the upper pancake of the B0 magnet as arranged during the tests.

The signals of Fig. 3 correspond to the pick-up coil signal during a quench at 20 kA, induced by the quench heater E02B, while the signals in Fig. 4 refer again to a quench at 20 kA but induced by the point heater E13A (see Fig.1 and[2]) for the identification of the heaters and of the pick-up coils).

FIG. 3: Pick-up coil signals, quench induced by a quench heater.

It must be reminded that the pick-up coil with odd number (MME011, MME013 etc) faces the external (upper or lower) pancake, while the even ones (MME012, MME014, etc.) faces the internal layer (closer to the median plane).

The quench heater faces the two single pancakes, while the point heater faces only the internal one.

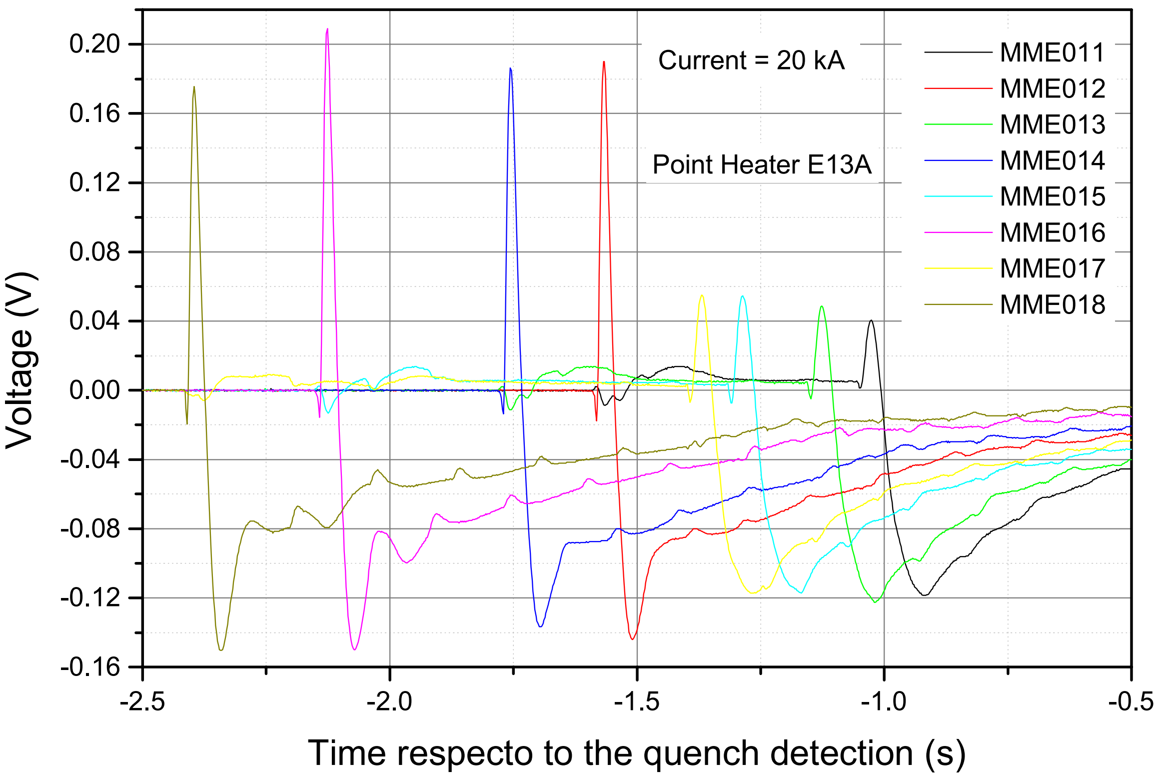

FIG. 4: Pick-up coil signals, quench induced by a point heater.

This fact is shown in Fig. 3 where the signals of the odd and even pick-up are almost contemporaneous, because the quench is induced in the same time in the two single pancakes.

In Fig 4 the signals of the internal pancake (odd numbers) are in advance respect to the external (odd) ones, being triggered by the point heater.

If we consider the signal of MME016 and MME018 in Fig.2, being about 3 m the distance between the two pick-up coils, a quench velocity of 9.1 m/s results.

A more accurate analysis gives for the quench longitudinal propagation velocity the value of $v_q = 9.068 \pm 0.048$ m/s.

In the same way from Fig. 4, considering MME014 and MME016, we get a velocity of about 8.3 m/s. In this second case it is better to measure the velocity between MME014 and MME016 instead of MME016 and MME018 because the point heater E13A is between the sensors MME016 and MME018 (see Fig. 1) and the Normal Zone (NZ) here can still be affected by the heater.

The difference of the quench propagation velocity value is due to type of quench heater used to induce the quench. As a mater of fact, as told before the point heater trigger the quench only in one single pancake, while the quench heater heats both the pancakes.

In this way in the case of point heater quench some heat released is laterally diffused, while in the case of quench heater there is not any laterally heat diffusion, and the quench propagates faster longitudinally.

In addition to this information on the velocity, the shape of the pick-up coil signal reflects the changing of the current distribution in the conductor during the transition from the superconducting state to the resistive state[5)].

In the following analysis of the pick-up coil signal the MME016 sensor (or its corresponding on the other double-pancake MME026) will be considered. This choice because this sensor is in a region of homogeneous magnetic field (in the middle of the long arm of the B0 coil, far from the bends, where the magnetic field is higher) and in a region where the NZ is supposed to be well shaped and formed, i.e. enough far away from the heater (either point or quench).

2.2 Pick-up coil signal shape

The current diffusion process from the superconductor to the stabilizer can be assumed to evolve in three phases[6)], as schematically shown in Fig 5:

- Asymmetric horizontal partial current diffusion (b)
- Horizontal diffusion (c)
- Vertical diffusion (d)

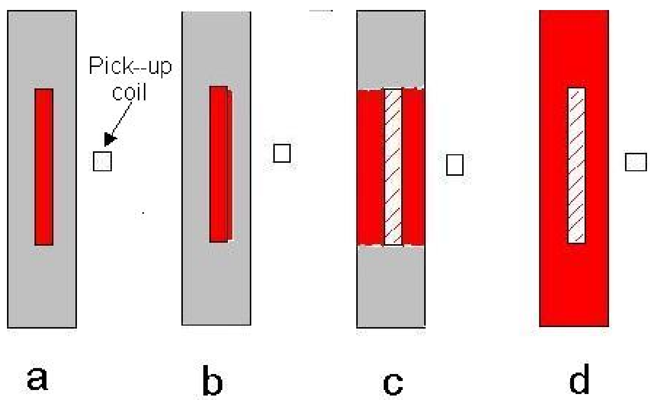

FIG. 5: Schematic representation of the current (red) diffusion from the superconductor to the stabilizer, during the quench.

a) Superconductive state.
b) Partial lateral diffusion.
c) Lateral diffusion
d) Total diffusion in the stabilizer.

These phases of the current expulsion can be identified in the signal of the pick-up coil of Fig. 6; it refers to the pick-up coil MME016 of the quench induced by the quench heater.

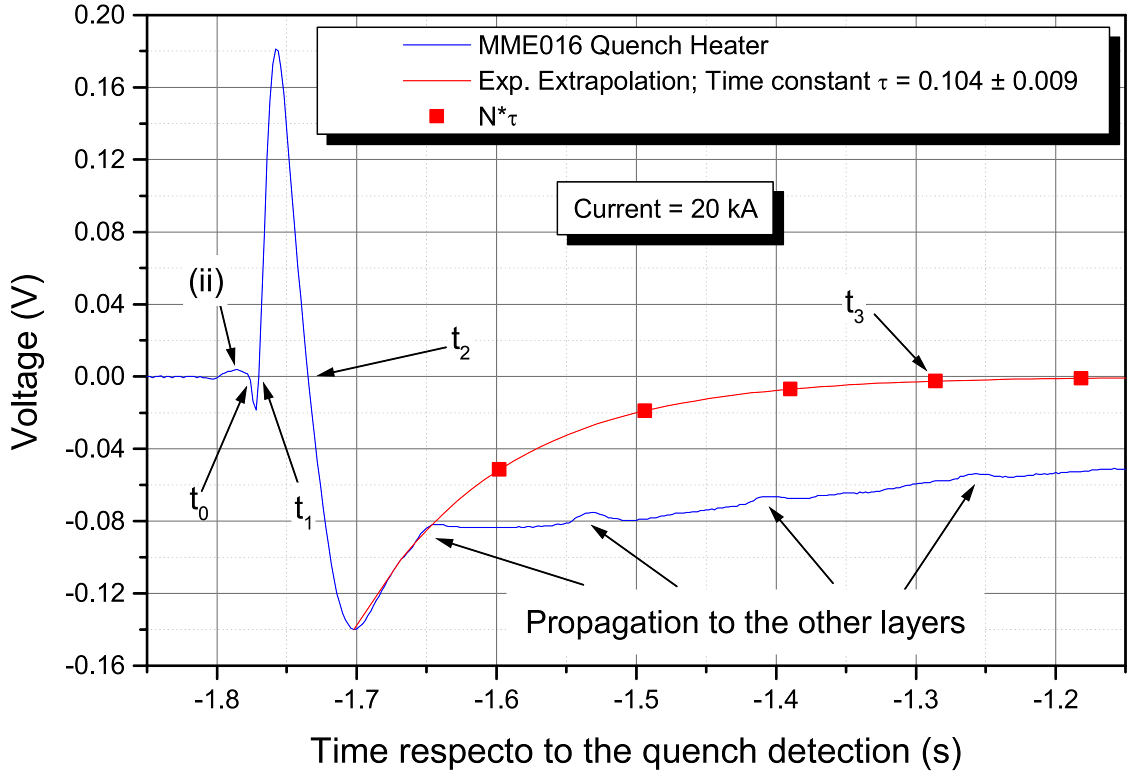

FIG. 6: Pick-up coil signal during a quench induced by a quench heater.
The evolution of the diffusion process from the stabilizer to the current can be seen.
Referring to Fig. 5 there is: phase a) before t_0; phase b) between t_0 and t_1;
phase c) between t_1 and t_2; phase d) after t_2.
The exponential extrapolation of phase d) is shown too.

Here the phases of Fig. 5 occurs in the times:

- t_0 start of the transition (Situation of Fig. 5 (a))
- t_0-t_1 Asymmetric horizontal partial current diffusion (Fig 5.(b))
- t_1-t_2 Horizontal diffusion (Fig 5.(c))
- t_2-t_3 Vertical diffusion (Fig 5.(d))

The small peak indicated with (ii) refers to the transition in the other pancake meanwhile occurring, as shown in Fig. 3 (MME016, MME015).

So the transition in front of the pick-up MME016 has a well defined time structure with the exception of t_3, the end of the full current diffusion into the stabilizer, because during this slow evolution, the quench propagates in the other layers, and the signal is perturbed by this evolution.

For simplicity an exponential decay is assumed, as shown in Fig. 6; the dots indicates the evolution at times multiple of the time constant.

The indetermination on the evaluation of the NZ length is due mainly to the short time interval considered for the phase (a) and the indetermination in choosing the end of the diffusion process; as a matter of fact by taking into account that the quench propagation velocity is about 9.1 m/s it follows that in a time constant the length of the last part of the NZ is more than 0.9 m !!

It can be assumed that the quench evolution is over after a time of 4τ; the signal at this time is inside the noise.

3 NORMAL ZONE LENGTH IN THE REFERENCE CASE

3.1 Method of the quench velocity

This method determines the NZ length by measuring the time interval of the various current diffusion phases and multiplying for the quench propagation velocity.

Let's consider again our reference case, the pick-up coil MME016 for the quench induced by the quench heater at 20 kA of main magnet current.

We have the following time values (the time is the relative time respect to the quench detection trigger, i.e. the opening of the main current breaker) :

- t_0 = -1.776 s
- t_1 = -1.77 s
- t_2 = - 1.734 s
- t_3 (4τ) = -1.289 s (being τ = 0.14 s).

Note once again that the time interval between t_0 - t_1 is 6 ms, corresponding to 3 samples (being the sampling rate of the acquisition system 500 S/s)

By multiplying with the quench velocity (9.068) we obtain the dimension of the NZ :

- NZ1 (Asymmetric horizontal partial current diffusion) = 0.054 ± 0.026 m
- NZ2 (Horizontal diffusion) = 0.327 ± 0.026 m
- NZ3 (Vertical diffusion) = 4.035 ± 0.043 m

Combining the results the NZ total length 4.42 ± 0.06 m.

The value calculated is coherent with the geometry and the dimension of the magnet; As a matter of fact from Fig. 3 it can be seen that the starting of the signal in the pick-up coil MME018 (3.047 m away from MME016) is at t = -1.442 s and the signal of MME016 is not yet arrived at zero at this time, meaning that the dimension of the NZ is larger than the MME016 MME018 distance (3.047 m). It is better to remind that this value is deeply affected by the assumption of an exponential time dependence of the vertical diffusion (the part of the signal between t_2 and t_3) and the assumption of 4 time constant needed to the current to end its diffusion into the stabilizer.

3.2 Method of the calibration comparison

One can think to obtain the NZ dimension by scaling the pick-up coil signal with the calibration one; as a matter of fact being the signal in the pick-up coil:

$$V(t) = -\frac{d\phi(B)}{dt} = -S\frac{dB(t)}{dt} = -Sv\frac{dB(y)}{dy} \tag{1}$$

$$\frac{V_{calib}}{V_{quench}} = \frac{v_{calib}}{v_{quench}}\left(\frac{dB}{dx}\right)_{calib}\left(\frac{dz}{dB}\right)_{quench} \tag{2}$$

Where v is the quench velocity or the extraction velocity during the calibration; “calib” refers to quantities measured during the calibration and “quench” refers to quantities measured during the quench.

The general space variable y used in (1) is, for simplicity assumed as x for the calibration quantities and z for the quench quantities.

From (2) follows:

$$\Delta z = \frac{V_{calib}}{V_{quench}}\frac{v_{quench}}{v_{calib}}\left(\frac{\Delta x}{\Delta B}\right)_{calib}\Delta B_{quench} \tag{3}$$

One can choose to use the peak values for the voltage, the remaining quantities can be derived from the calibration procedure and from the quench signal, so the NZ is determined.

This procedure implies the use of the finite quantities Δx and ΔB (that is correct only if the field variation is linear) and the implicit assumption that the shape of the field variation is the same in both the calibration and the real quench situation; and this is not obviously the case.

As a matter of fact it results :

$$NZ1 = \frac{3.25}{1.86\times10^{-2}}\frac{9.068}{6.6}\frac{0.382}{88.8\times10^{-3}}1.3\times10^{-4} = 0.134\,m \tag{4}$$

Instead of 0.054 m calculated above.

The values relative to the calibration are taken from[3].

For the other dimensions results:

$$NZ2 = \frac{3.25}{1.81\times10^{-1}}\frac{9.068}{6.6}\frac{0.382}{88.8\times10^{-3}}7.14\times10^{-3} = 0.758\,m \tag{5}$$

$$NZ3 = \frac{3.25}{1.4\times10^{-1}}\frac{9.068}{6.6}\frac{0.382}{88.8\times10^{-3}}2.86\times10^{-2} = 3.92\,m \tag{6}$$

Instead of NZ2 = 0.327 and NZ3 = 4.065 previously found.

The errors in the values of NZ1 calculated above are about 7% and 5% for NZ2 and NZ3 respectively.

It can be seen that this method can be applied only to the tail of the signal, to determine NZ3, because in this case the phenomenon is slow and the linear approximation can hold.

4 NORMAL ZONE LENGTH AT VARIOUS CURRENTS

The calculations of the NZ dimensions during quenches determined with the quench heater or the point heater for various currents, with the so-called method of the quench velocity, are summarized in the following figures.

The error bars reported in the figures are calculated by taking into account the error in the time reading and the error in the determination of the quench velocity.

This experimental error is bigger at higher current because of the higher quench velocities, so the evolution time of the current diffusion phenomenon is faster, consequently the time interval measured have a larger relative error.

Conversely at lower current the experimental error is smaller.

It is better to remind that in addition to the experimental error there is an indetermination in the NZ length evaluated because of the difficulties in determining in the signal shape the diffusion phases described above.

In Fig 7 the longitudinal quench velocity at various current is plotted.

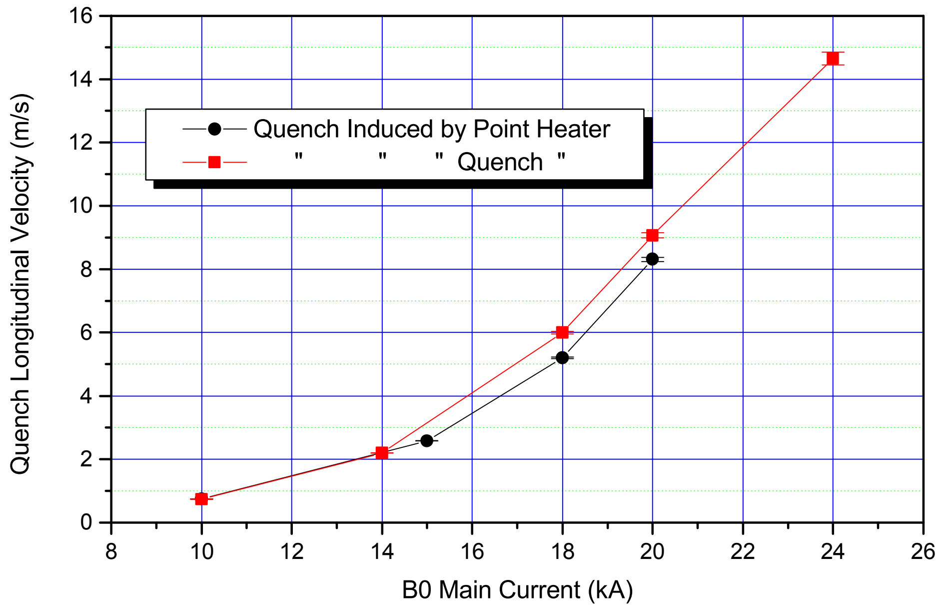

FIG. 7: Quench longitudinal propagation velocity at different current of the magnet, for quench induced by point heater (black) and quench heater (red).

In Fig. 8 the values of NZ1 for different currents in the magnet are shown, both by quench induced by the point heater or by the quench heater.

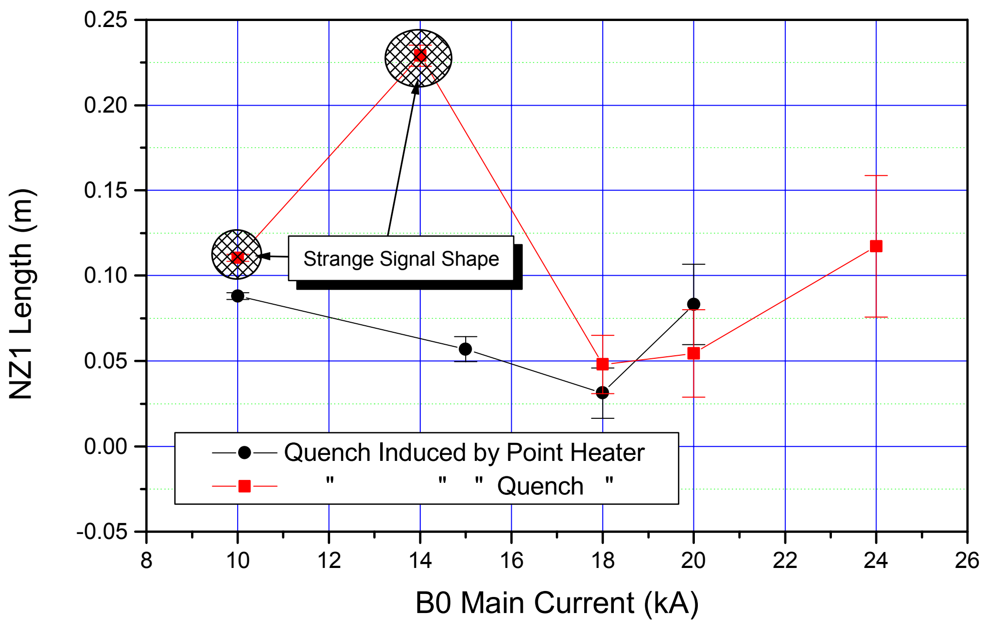

FIG. 8: NZ length of phase b) (partial horizontal diffusion) at various main magnet currents for quenches induced by point heater (black) and quench heater (red). (See text for details about the strange signals).

As it can be seen there is not a defined trend of the NZ1 length as a function of the current.

The points at 10 kA and at 14 kA relative to the quench heater data are indicated in that particular way because the signal is not well shaped like in the reference case shown in Fig.5.

The signal of the pick-up coil at 10 kA and 14 kA, for the quench heater induced quench are shown in Figs. 9 and 10 respectively.

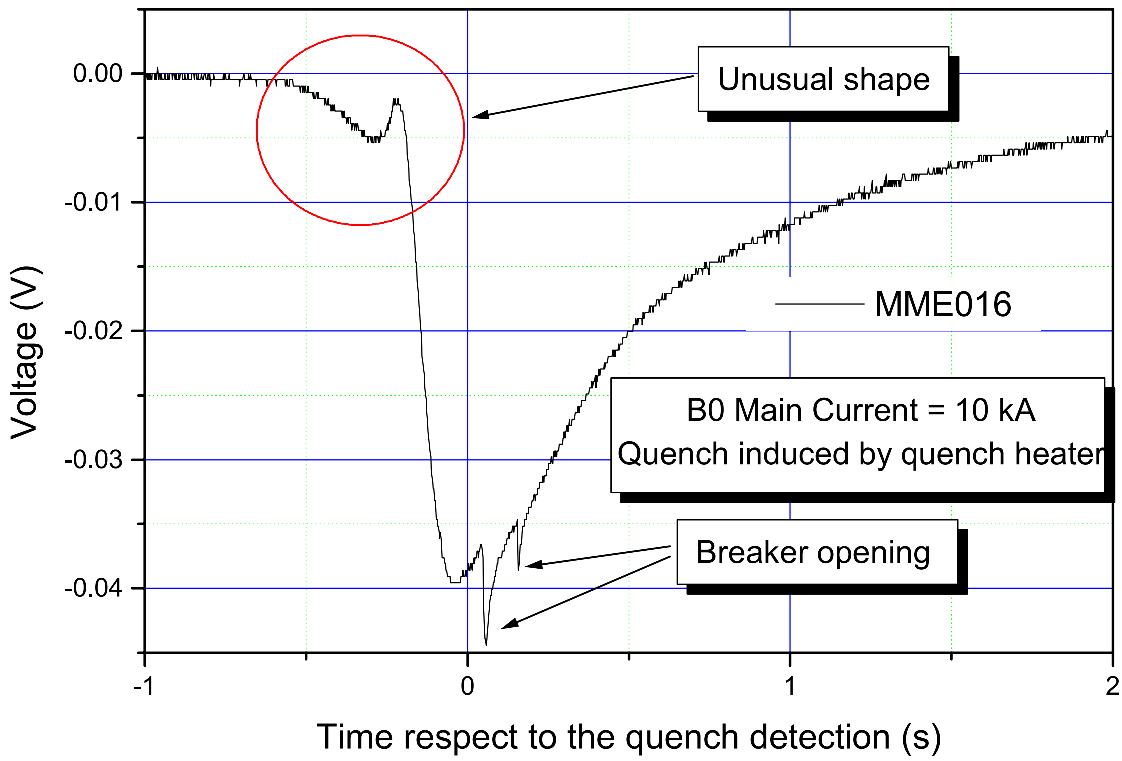

FIG. 9: Pick-up coil signal at 10 kA (strange signal of Fig.8).
The unusual shape does not allow the determination of NZ1 and NZ2.

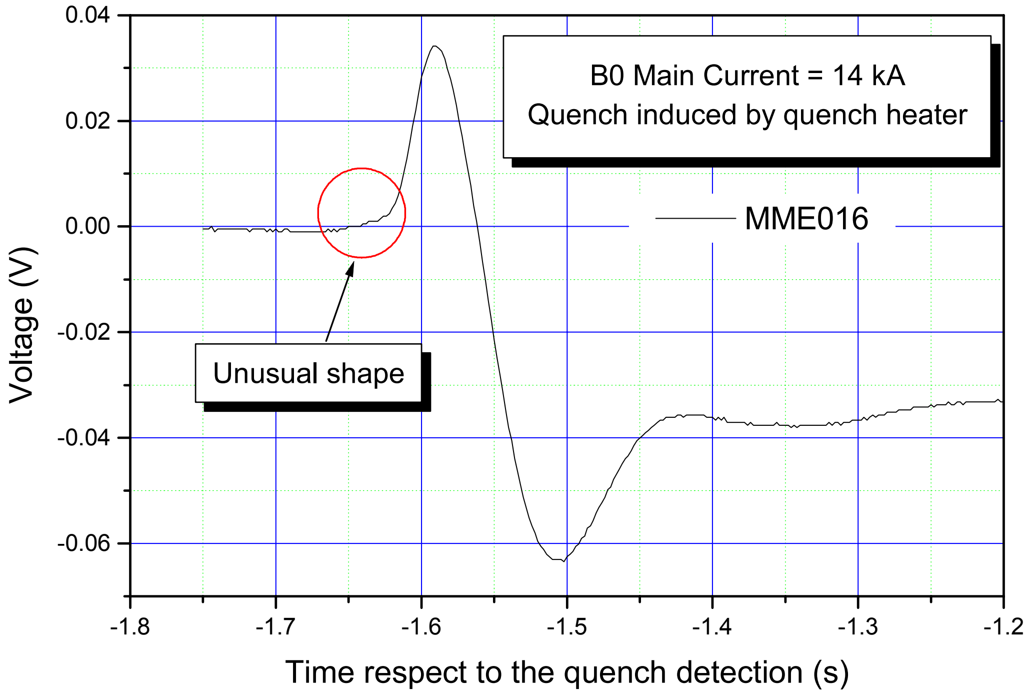

FIG. 10: Pick-up coil signal at 14 kA (strange signal of Fig.8).
The unusual shape does not allow the determination of NZ1 and NZ2.

In Fig. 11 the NZ2 values for the various currents are plotted.

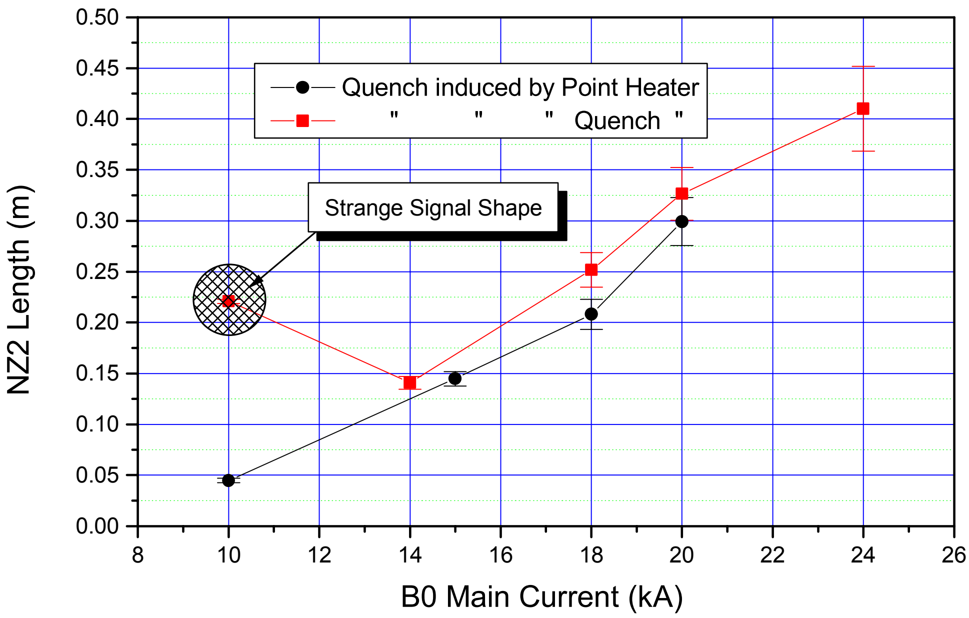

FIG. 11: NZ length of phase c) (horizontal diffusion) at various main magnet currents for quenches induced by point heater (black) and quench heater (red). (See text for details about the strange signals).

In this case there is an increasing of the NZ length with the current, and the data are more accurate because the part of the pick-up coil signal related to this transversal diffusion (t_1 and t_2) are more precisely determined.

Still there is a "dashed point" like in Fig. 8 and it refers again to the quench heater induced quench at 10 kA, shown if Fig 9.

The NZ3 values for the various currents are plotted in Fig 12.

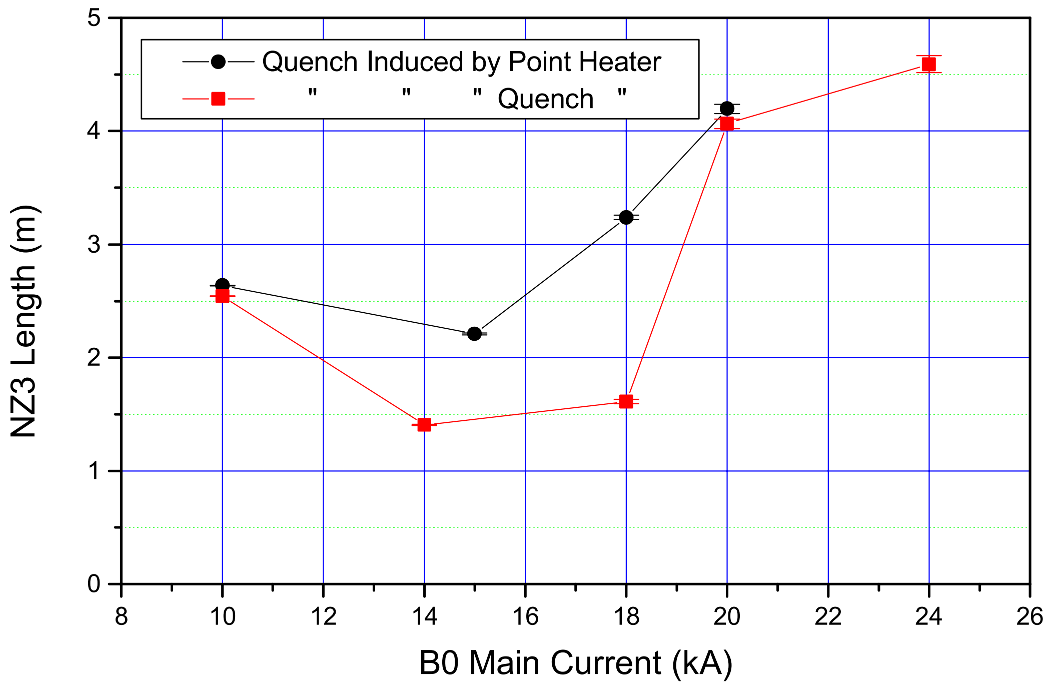

FIG. 12: NZ length of phase d) (vertical diffusion) at various main magnet currents for quenches induced by point heater (black) and quench heater (red).

Here a trend of increasing of the NZ length with the current can be inferred, despite the reverse behavior at low current.

It is better to remind that even in this case big indeterminations can arise by the assumption of the exponential decay of the tail of the signal, as explained before, and the indetermination on the identification of the "zero" point, i.e. the point at which the exponential decay is finished.

In Fig. 13 the time constant of the tail exponential decay, for the various currents are plotted, the time constant decrease at higher current, meaning a faster diffusion process at higher currents.

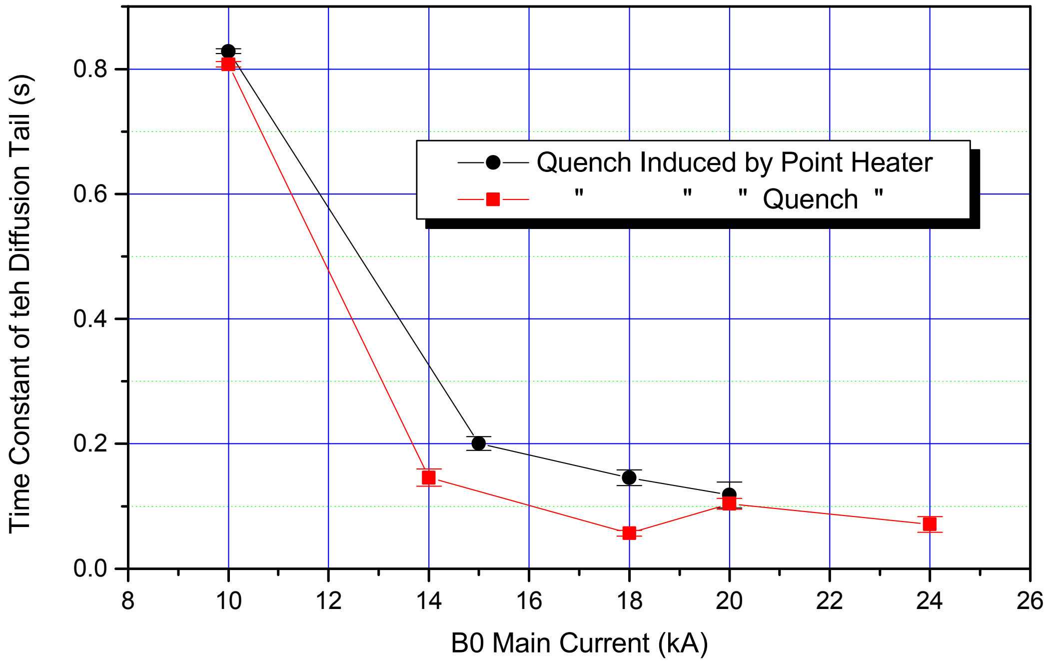

FIG. 13: Time constant of the exponential extrapolation of the tail of the pick-up coil signal (phase d) of the diffusion process).

Let's remind that the NZ propagates in both the directions, so the actual length of the NZ is twice the calculated value.

5 CONCLUSIONS

The NZ length has been determined during the quench at various currents.

It is not possible to have NZ dimensions informations only through a comparison with the calibration signals.

Even with the so called "quench-velocity method" large experimental errors affect the NZ length determination, especially the NZ1, the faster process. Probably a higher sampling rate can overcome this difficulty.

In the determination of the NZ3 length big indetermination comes from the difficulty in determine the end of the exponential diffusion process.

Some difficulties arose in the determination of the NZ length because sometimes the pick-up coil signal is not well shaped, i.e. the current diffusion process does not proceed as expected in a standard reference case.

So, because of the many indeterminations, assumptions and experimental errors, only an order of magnitude of the NZ length has been determined and more precise measurements are not so far possible.

This kind of measurements may be done in a dedicated test coil, where the geometry, localization of the sensors, and winding can be ad hoc designed. Bo is a model coil but not dedicated to this kind of measurements (the general engineering and mechanical analysis were privileged).

Nevertheless, despite all these difficulties, the values determined are in agreement with the geometry of the magnet and of the sensor locations.

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