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DESIGN AND CALIBRATION OF THE PICK-UP COIL FOR B0 AND B00 ATLAS MODEL COIL

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Abstract

The ATLAS Barrel Toroid (BT) is a superconducting toroid made of 8 superconducting 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 forsees two End Cap Toroid (ECT) with the same 8 structure geometry of the BT, and a Central Solenoid (CS).

B00 is a small coil built to verify the performances of the different cables used in the ATLAS magnets, while B0 is a full scale model, one third length of ATLAS barrel toroid eight coils.

The B0 construction was decided to test the technical construction solutions and reproduce the behaviour of the final coils. To fulfil this aim the coil has been equipped with many sensors, among which the pick-up coil are very important for the study of the quench characteristics. In the frame of this collaboration one of the item of the INFN was to provide some diagnostic sensors, among which about 20 pick-up coil, for the quench propagation studies.

In this paper the design and characteristics of the pick-up coil used in the B00 and B0 model coil are described, together with the calibration procedure.

Some data measured during the magnet test are reported and discussed.

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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], among which about 20 pick-up coil.

In addition an amount of 22 pick-up coil for the B00 model coil were provided.

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.

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 informations are obtained. The sensitivity of 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[3] must be high; scan time of the order of ms are necessary for the characteristics of the B0 model coil.

2 EXPECTED SIGNALS FROM B0 QUENCHES

The signal in the pick-up coil depends on the magnetic field variation due to the current redistribution, from the superconductor to the stabilizer, during the quench process.

The overall variation of the vertical magnetic field is of the order of 100 mT for a pick-up coil whose center is at about 5 mm from the magnet cable.

This value on itself is not enough to determine the induced signal in a pick-up coil, as a matter of fact the field variation multiplied by the pick-up coil section gives the integral of the induced signal, while its shape and peak value depends on the quench propagation velocity and on the dimensions of the normal zone (NZ), i.e. it depends on the diffusion of the current from the superconductor to the stabilizer.

In Fig. 1 the vector representation of the B0 magnetic field around the position of the pick-up coil is shown. Note that the plot gives only the direction of the field, while the length of the vectors is not related to the field magnitude.

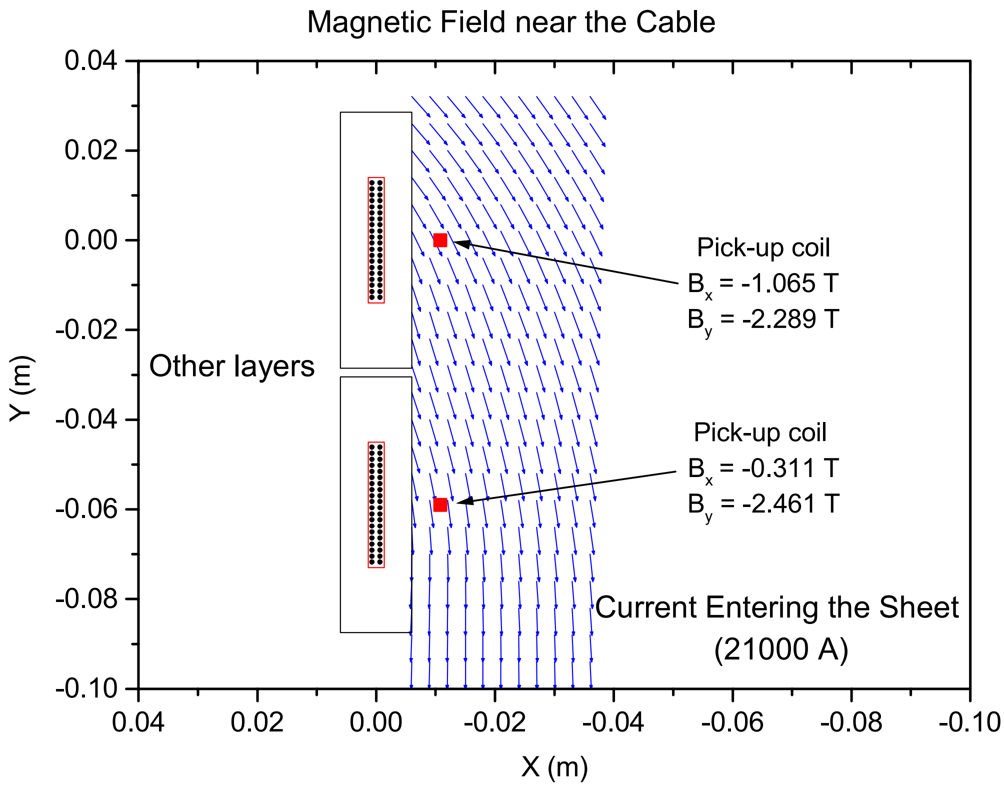

FIG. 1: Vector representation of the magnetic field around the B0 external cables.

The field map of the vertical component is shown in Fig.2.

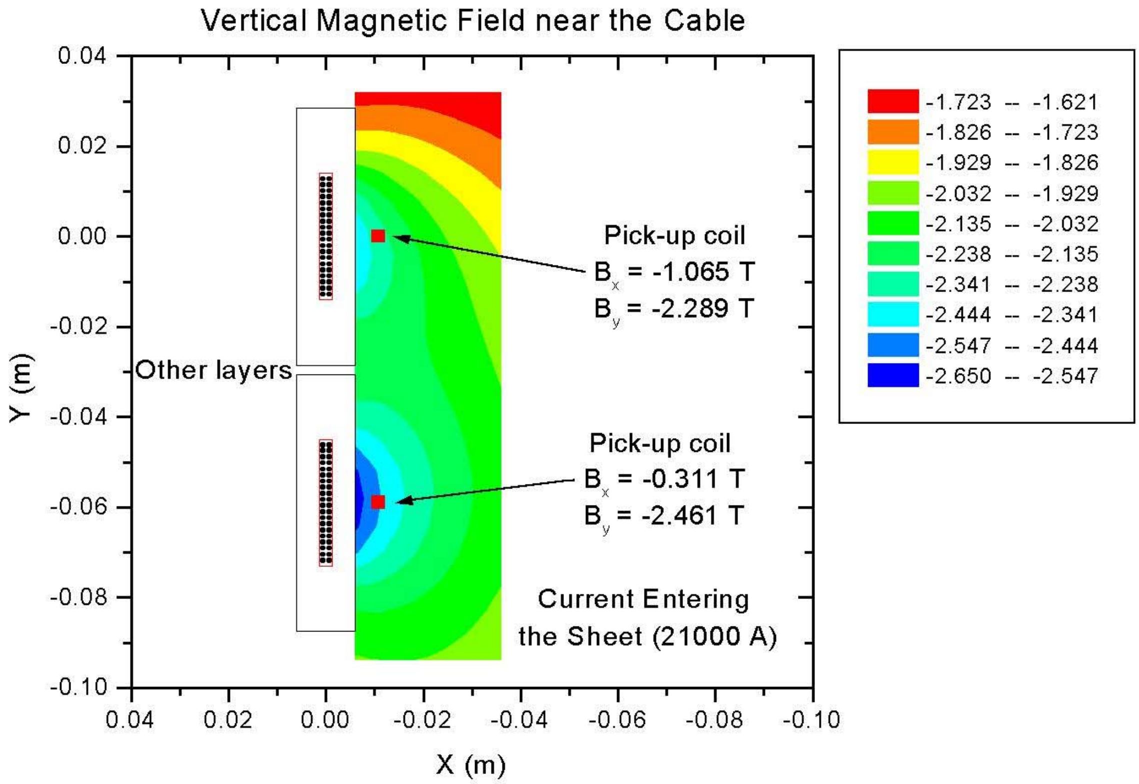

FIG. 2: Vertical component of the magnetic field around the B0 external cables.

During the test on the race-track magnet[4,5], a magnet built to verify some technical solution for the construction, cable impregnation and cooling of the coil, signals with peak value of about 200 mV from a pick-up coil were obtained. The section of the pick-up coil was about 0.5 m^2 and the quench velocity around 20 m/s.

The characteristics of the cable of the B0 model coil are slightly different, so values of 7-14 m/s were foreseen at the time of the pick-up coil design; a section of 0.5 m^2 can provide signal around some hundreds of mV, supposing a NZ dimensions similar to the race-rack ones.

Of course larger sections can provide larger signal, leading to a higher sensitivity of the sensor that can, in this way, provide more accurate data and details on the current diffusion process.

3 PICK-UP COIL CHARACTERISTICS AND DESIGN

In this section the main characteristics of the designed pick-up coil for B00 and B0 are described.

3.1 B00

Three type of different pick-up coil were designed for the B00 model coil.

The first and the second type, called Double Solenoidal Pick-up coil (DSP type (a) and (b)) and Double Rectangular Pick-up coil (DRP), were used facing the coil to get the signal induced by the field variation during a quench, the third one, designed as "Special Pick-up" was intended to measure the transition of the transverse component of the current in the insert, at the starting of the quench process; to this aim these pick-up were inserted around the cable, at the extremities of the winding.

The DSP consist of two separate coils wounded around the same mandrel. This arrangement allows the contemporary measurement on the two type of cable the ECT and the BT cable composing the B00 magnet.

The special pick-ups have different dimensions, to fit the BT (57x12 mm^2) and the ECT (41x12 mm^2) cable dimensions.

The schematic drawings and characteristics of the three type of the B00 pick-up coil are shown in Fig, 3, 4 and 5 respectively.

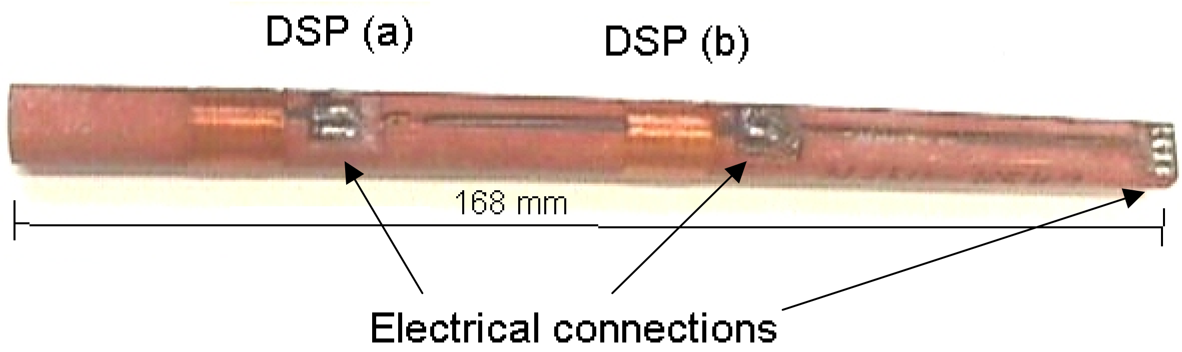

FIG. 3: The B00 DSP pick-up coil
It is composed by two windings, one facing the BT cable, the other the ECT cable.

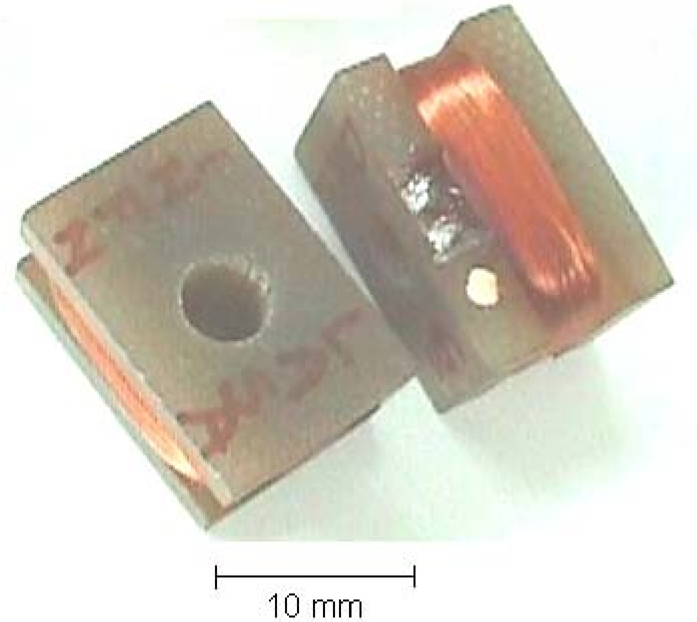

FIG. 4: The B00 DRP pick-up coil.

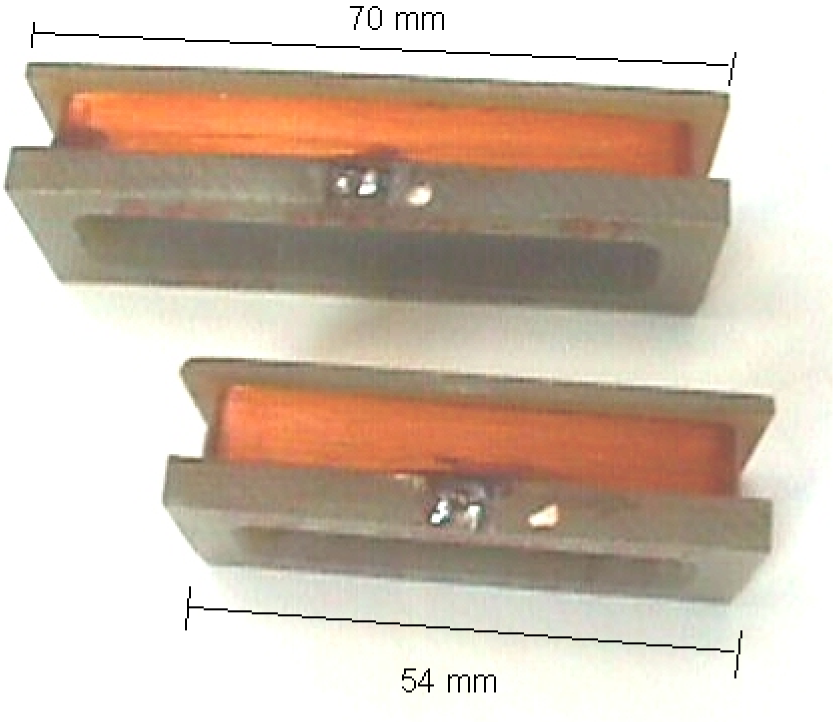

FIG. 5: The B00 Special pick-up coil.
Top the BT Special pick-up
Bottom the ECT Special pick-up

3.2 B0

The pick-up coil foreseen for the B0 model coil were only of the “simple” type.

The positions of the pick-up coil and of all the B0 instrumentation are reported elsewhere[2)].

The pick-up consist of 4600 turn winding of copper wire 0.063 mm diameter around a rectangular smoothed G10 mandrel 21 x 3.5 mm^2 inner section and 14 mm height (see Fig. 5). After the winding an epoxy glass impregnation provide the electrical insulation.

A prototype of the pick-up coil is shown in Fig. 6.

From the geometry of the sensors and the wire dimension, neglecting the wire packing, we can calculate the total section of the pick-up coil, resulting about 0.46 m^2.

The calibration gives a packing factor of 10%, being the section about 0.51 m^2.

FIG. 6: A B0 pick-up coil

4 PICK-UP COIL CALIBRATION

The calibration of the B0 pick-up coil was carried out by measuring the induced voltage signal when the sensor was extracted/inserted from/into a magnet (with known field).

The magnet used was a LASA laboratory magnet, formerly used for the beam transport line of the Milan Azimuthally Varying Field cyclotron.

The map of the fringing field of the magnet is shown in Fig. 7; the residual field (at 0 current) is plotted too (right scale).

The field map was obtained with a Hall probe with sensitivity of 0.1 mT; the error in the position reading of the probe was about 3 mm. At first sight this error can appear large, but it is enough for our purposes. As a matter of fact the field map is necessary just to evaluate the extraction velocity, but this parameter is not very important for the determination of the effective section of the pick-up coil.

As a matter of fact the section of the pick-up coil is determined by the variation of the field, regardless of its shape, as discussed in the following.

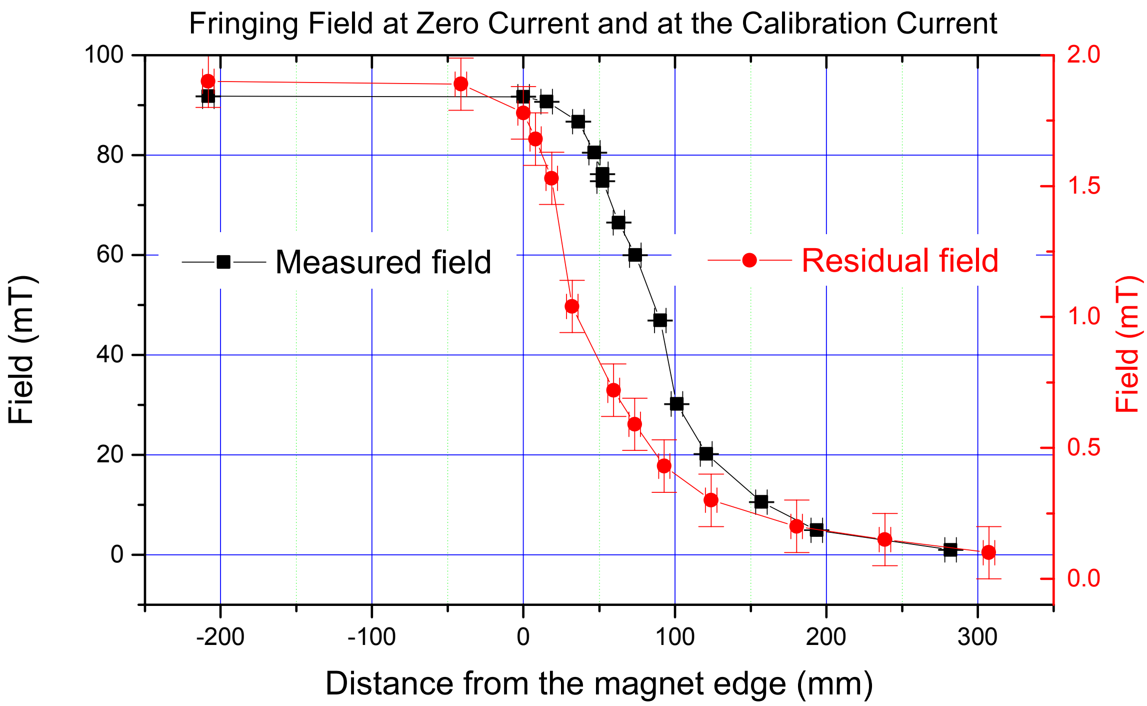

FIG. 7: The fringing field of the calibration magnet.
The residual field (at 0 current) is plotted in red and refers to the right scale.

Typical signals from the pick-up coils, for different velocity and magnetic field are shown in Fig. 8.

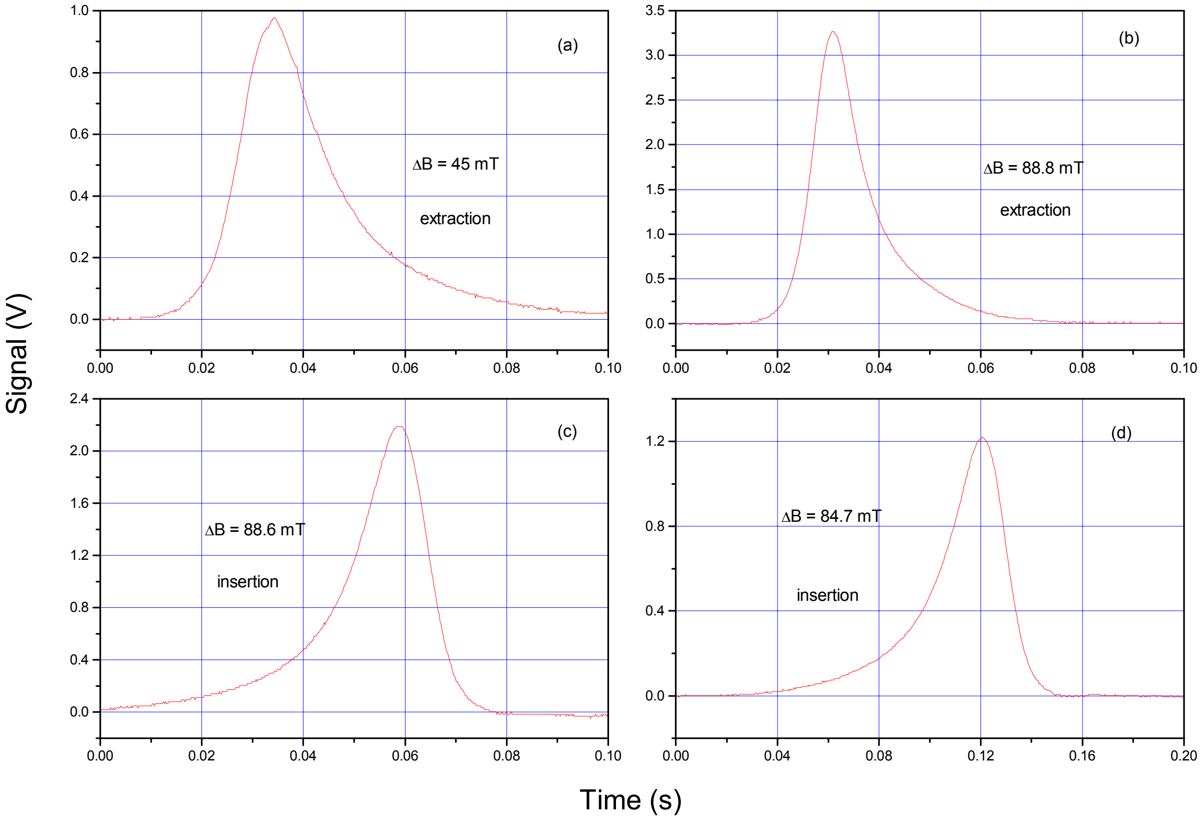

FIG. 8: Calibration of the pick-up coils.
The different amplitude of the signal depends on the insertion/extraction velocity.
(a) extraction of the probe from the calibration magnet with field B = 45 mT;
(b) extraction, B = 88.8 mT;
(c) insertion of the probe into the magnet B = 88.6 mT;
(d) insertion, B = 84.7 mT (the time scale is twice respect to the other plots).

Let's note the asymmetric shape of the signals because of the fringing field of the magnet and, of course, the specular shape of the signal obtained with the extraction of the sensor from the magnet respect to the signal with the insertion of the sensor.

The different signal amplitude is given by the different field and different velocity of the probe insertion/extraction. As a matter of fact the pulse duration is different.

In the following discussion we will consider only the signal of Fig 8(b) because of simplicity and its good shape.

The signal at the probe is given by:

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

where:

$\phi(B)$ magnetic field flux linked with the pick-up coil section

S pick-up coil section

v insertion/extraction velocity.

The most important parameter for a pick-up coil is its effective section, corresponding to the sensitivity of the sensor.

The integration of (1) gives:

$$\int_{-\infty}^{+\infty} V(t)dt = \int_{-\infty}^{+\infty} -\frac{d\phi(B)}{dt}dt = -S\Delta B \tag{2}$$

Considering, as an example, the extraction of the probe from a field of B = 88.8 mT (Fig. 8(b)) we get S ≈ 0.53 m^2. In Fig. 9 the signal of Fig. 8(b) with its integral is shown.

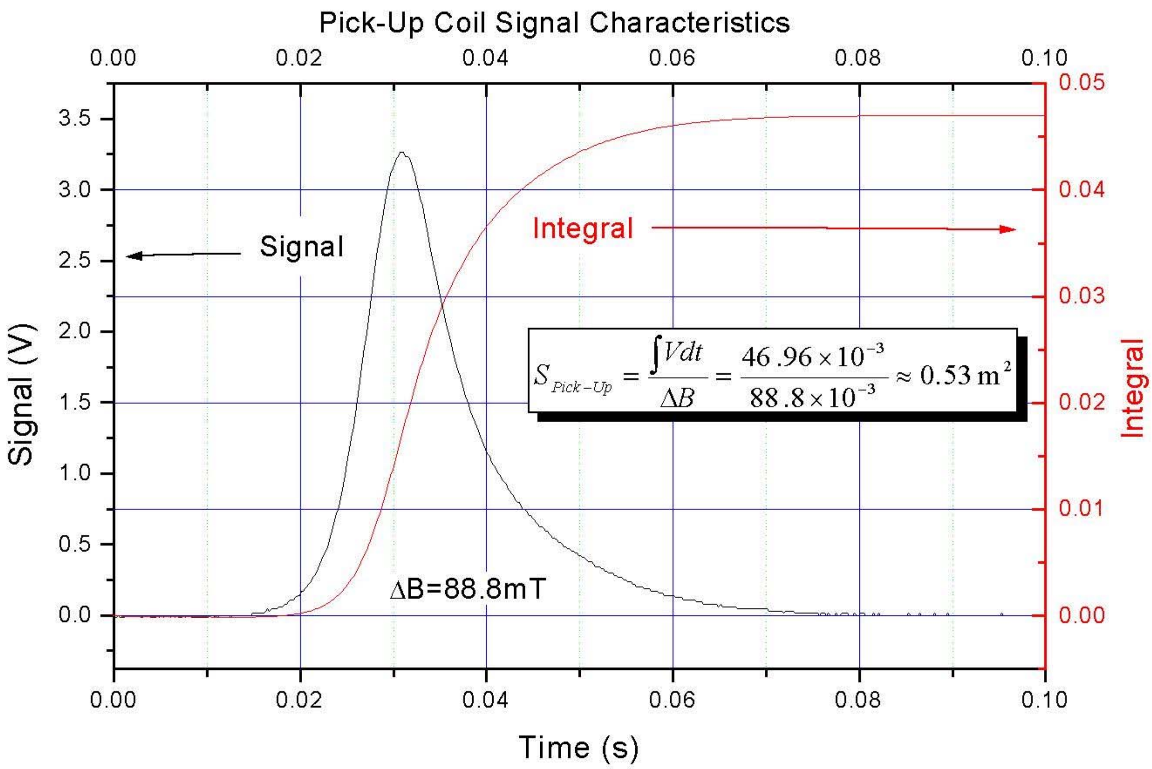

FIG. 9: Signal of the extraction from the calibration magnet with B = 88.8 mT and the signal integral. The section indicated corresponds to this specific signal.

Taking into account all the signals an average value of 0.51 m^2 follows.

If we consider again the integral of the signal of (2) we can write:

$$\int_{-\infty}^{+\infty} V(t)dt = -\int_{-\infty}^{+\infty} S\frac{dB}{dt}dt = -Sv\int_{-\infty}^{+\infty} \frac{dB}{dz}dt \tag{3}$$

by considering finite quantities we have:

$$\int_{-\infty}^{+\infty} V(t)dt = -Sv\frac{\Delta B}{\Delta z}\Delta t \tag{4}$$

Being $\int_{-\infty}^{+\infty} V(t)dt = 46.95\times10^{-3}$, $\Delta t \approx 60$ ms and $\Delta z \approx 0.4$ m, for the velocity of extraction a value of 6.6 m/s follows.

The extraction velocity can also be derived in the following way.
Let's consider the field map of Fig. 7.
The fringing field can be interpolated by:

$$B(x) = a + \frac{b}{1+\left(\frac{x}{c}\right)^{d}} \tag{5}$$

with a = -1.0051978
b = 89.153802
c = 87.2684
d = 3.391594

The measured data and the interpolation formula (5) are plotted in Fig. 10.

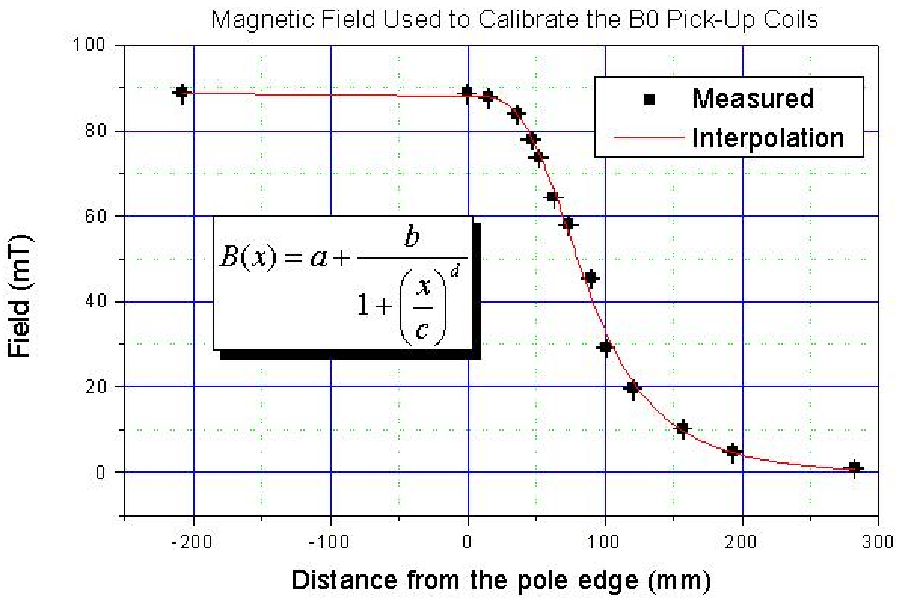

FIG. 10: The calibration magnetic field and the interpolation function

The signal obtained with (5) and the measured section S = 0.5288 m^2 for the case of Fig 8(b) are plotted in Fig. 11 for different extraction velocity, and compared with the actual measured signal.

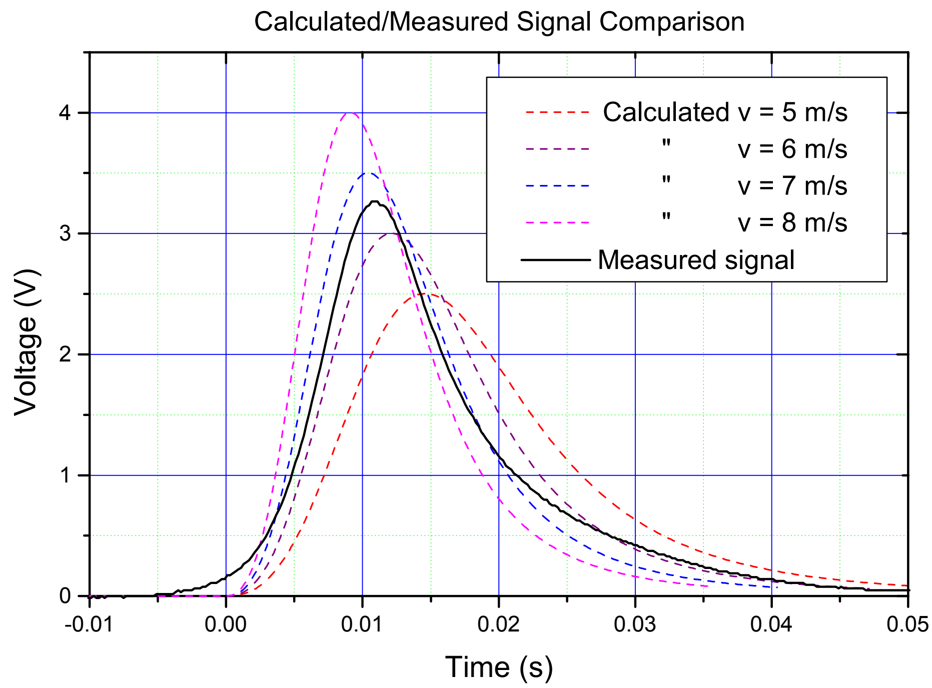

FIG. 11: Calculated pulse shape for different extraction velocities (dotted lines) and measured pulse (solid).

From Fig. 11 we can see that the measured signal is well fitted by a velocity of about 6.6 m/s, according to what stated before.

Considering all the test done in fig 8 (a), (b), (c) and (d) the average section of the pick- up coil results:

$$\overline{S} = 0.51 \pm 0.02 \ \ \mathrm{m}^2 \tag{5}$$

5 RESULTS FROM REAL SIGNAL FROM THE MAGNETS

5.1 B00

One typical signal from the B00 model coil on the DSP a type and b type pick-up coil is shown in Fig. 12. The signals refer to a quench at 20kA main current.

The time scale is the time respect to the quench detection trigger. The main peak (at time –0.35 s) refers to the transit of the NZ in front of the pick-up coil, while the following “waves” correspond to the quench propagation in the inner layers.

The low level signal (DPS 3a) comes from the pick-up that does not face directly he transited cable.

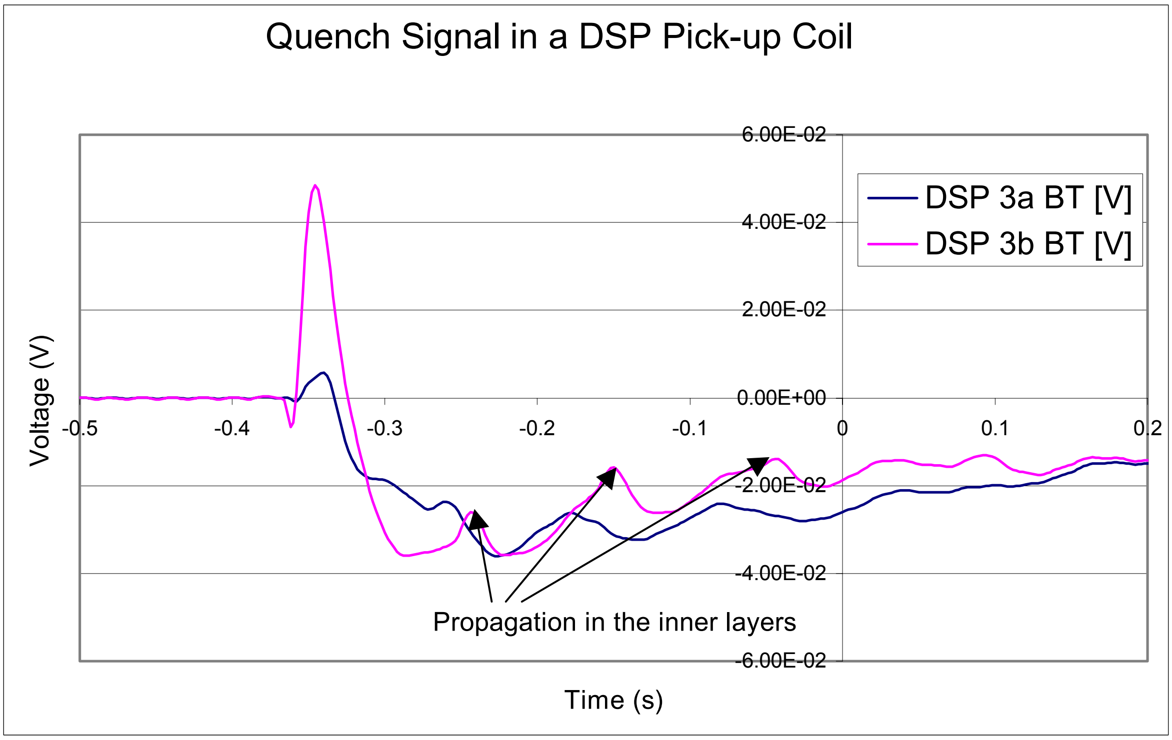

FIG. 12: Quench signal in the B00 DSP pick-up coil.

A signal of the DRP pick-up coil is shown in Fig. 13.

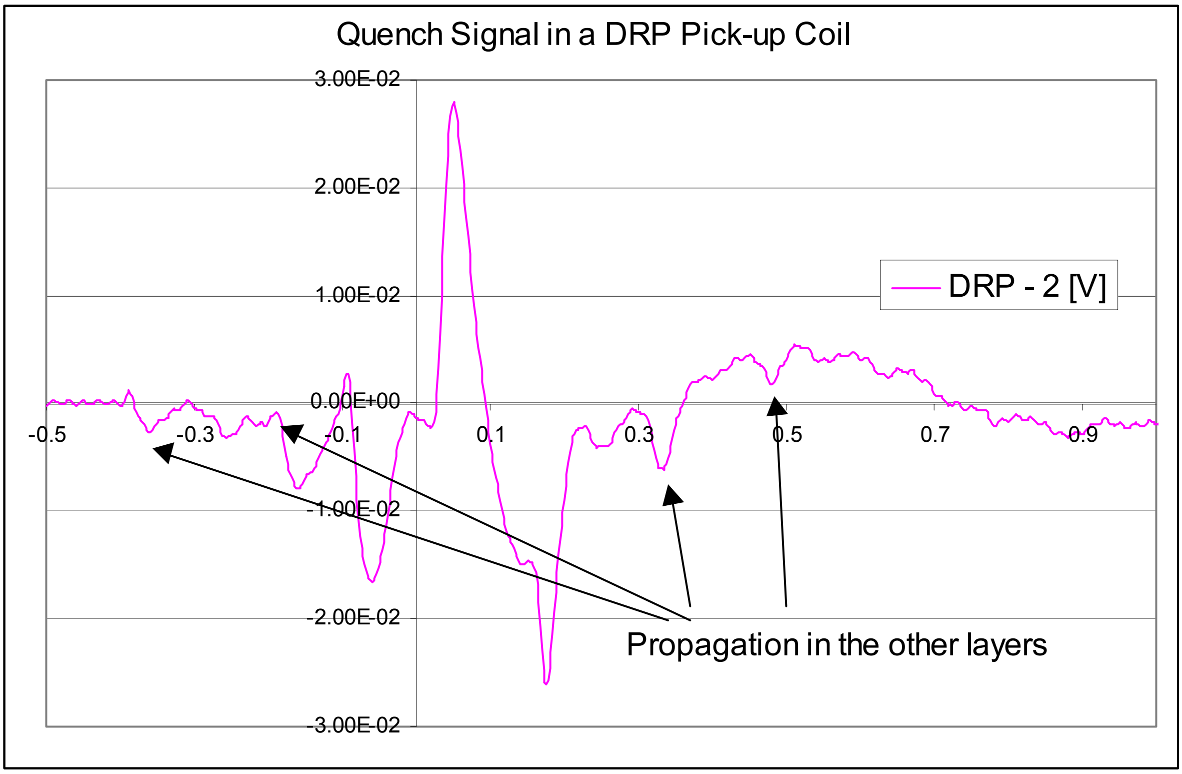

FIG. 13: Quench signal in the B00 DRP pick-up coil.

The signal of the "special" pick-up coil is shown in Fig. 14.

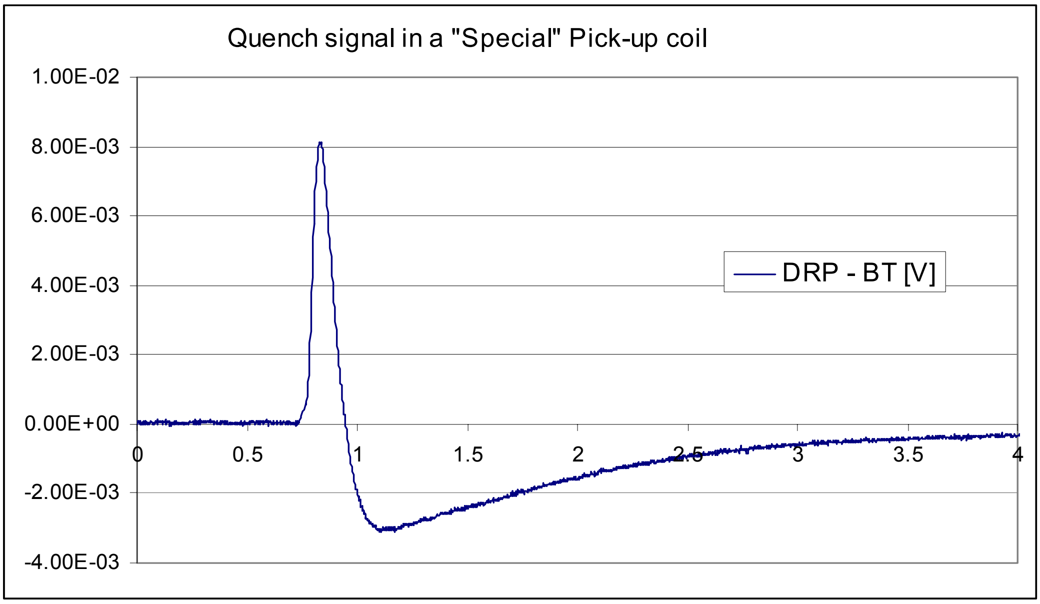

FIG. 14: Quench signal from a "special" pick-up coil

5.2 B0

Extensive tests have been done on B0, in Fig.15 some typical signal are reported. The signals refer to a quench at 20 kA.

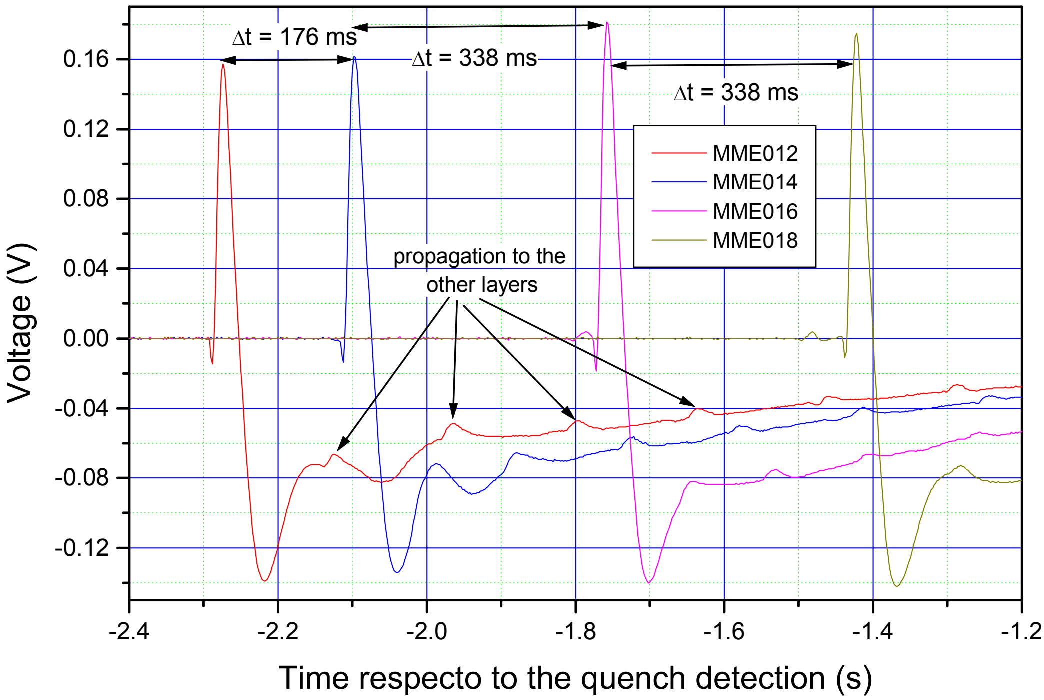

FIG. 15: Quench signal from the B0 pick-up coil

From the data shown in Fig. 15, by taking the time distance between two peaks we can get the quench propagation velocity. As an example let's consider MME012 - MME014, the time corresponding to the peak of the signal is 176 ms, the distance between the two sensors is 1.75 m so a velocity of 10 m/s follows.

If we consider the couples MME014-MME016 and MME016- MME018, in this case the distance is about 3.1 m so a velocity of about 9 m/s results. The velocity is higher in the first case, because the two pick-up coils MME012 and MME014 are in a region where the field magnetic field is higher, so a higher quench propagation velocity results.

More precise measures can be obtained by taking the rising edge of the signal, because it is the time where the transition begins and it is the same for both the sensors.

The peak cannot be considered as homogeneous point because at this point the current has already partially diffused into the stabilizer, and the process can be different in the two points, depending on the temperature and magnetic field, anyway we think that taking the peak of the signal the error in determining the quench velocity is negligible.

As we told before, the shape analysis of the signal can provide informations on the NZ dimensions[6)] and the mechanism of current diffusion[7)].

6 CONCLUSIONS

During the B00 and the B0 tests the pick-up described in this paper, designed and realized at LASA at relatively low cost, showed a good sensitivity, that allows an extensive quench studies and detailed analysis of the current diffusion process during the quench evolution.

In particular the so-called "Special Pick-up" allowed to detect the transition of the transverse component of the current.

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