IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 47, NO. 3, JUNE 2000

An Electromagnetic Micrometer to Measure the Wire Centering in High-Resolution Aluminium Drift Tubes

M. Cambiaghi[1], A. Cardini[2], S. Casani[2], R. Ferrari[1], G. Gaudio[1], G. Iuvino[1], A. Lanza[1] and M. Prata[1]
[1]D.F.N.T. Università di Pavia and I.N.F.N., Pavia, Italy
[2]I.N.F.N. Roma, Italy

Abstract

The muon detector of the ATLAS experiment at LHC (CERN) consists of 370000 high-resolution drift tubes assembled in multi-layer chambers. To take full advantage of the single-tube resolution, the high-precision external surface of tube end-plugs is used for positioning a layer before gluing.

The wire position in the tube is defined at construction time by means of a locator inserted in the end-plug. To check that the wire is in the nominal position after the tube assembly an Electro-Magnetic MIcrometer (EMMI) has been developed. EMMI detects the wire position by measuring the electromotive force induced in two sensors symmetrically placed on both sides of the tube when a small sinusoidal current circulates on the wire. An accuracy of two microns on the wire centering has been obtained.

The simplicity of this method and the short measuring time allow every drift tube to be checked, thus guaranteeing the precision requested for the ATLAS muon detector.

I. INTRODUCTION

ATLAS [1] is one of the two general-purpose experiments that are under construction at the CERN Large Hadron Collider. The ATLAS apparatus comprises a high-resolution muon spectrometer to reconstruct narrow 2- and 4-muon final states from decays of Standard-Model and SuperSymmetric Higgs (and new vector bosons).

The muon spectrometer is made of many multi-chamber stations in a 0.5-1 tesla toroidal magnetic field and covers almost the full solid angle around the interaction vertex. Each chamber is made of twice three or four staggered layers of drift tubes glued together. A drift tube is made of a 400 μm thick – 3 cm diameter – extruded aluminium tube closed at both ends by an aluminium/plastic end-plug.

To take full advantage of the single-tube spatial resolution the chamber construction requires special care in the tube positioning before chamber gluing. This is done using the high-precision surface of the tube end-plugs as a reference.

The wire centering inside the drift tube - requested to be within 10 μm rms in both projections - is defined by means of a locator inserted in the end-plug. A quality-control setup for monitoring this parameter is needed.

The device described in this paper - the ElectroMagnetic MIcrometer (EMMI) - provides a very sensitive way for implementing such a control. The wire position is reconstructed by measuring the electromotive force induced in two coils symmetrically placed on both sides of the tube when a small sinusoidal current is circulating on the wire. Within the ATLAS collaboration EMMI has been largely preferred to other methods based on X-ray imaging because it is easy to use, has an equivalent resolution no safety problems and a lower cost.

II. PRINCIPLE OF OPERATION

If an alternating current $i(t) = i_0 \cos\omega t$ is circulating in a wire, the electromotive force $\mathcal{F}$ induced on a rectangular coil of size $a \times b$ placed at an average distance L is given by:

$$\mathcal{F} = \frac{2\omega i_0 \sin\omega t}{c^2} \cdot a \cdot \ln\left(1 + \frac{b}{L - b/2}\right) . \qquad (1)$$

If two such coils are placed on both sides of the wire at a distance $L - \mathrm{d}$ and $L + \mathrm{d}$ respectively (see figure 1a), the difference $\Delta\mathcal{F}$ between their electromotive forces is:

$$\Delta\mathcal{F} = \frac{2\omega i_0 \sin\omega t}{c^2} \cdot a \cdot \ln\left(1 + \frac{2b\mathrm{d}}{L^2 - (\mathrm{d} + b/2)^2}\right) . \qquad (2)$$

For a displacement d much smaller than $(L - b/2)/2$, equation (2) is very well described by a linear relation (see figure 1b):

$$\Delta\mathcal{F} = \Delta\mathcal{E} \cdot \sin\omega t , \qquad \Delta\mathcal{E} \approx \frac{4\omega i_0}{c^2} \cdot \frac{ab}{L^2 - b^2/4} \cdot \mathrm{d} . \qquad (3)$$

The system senses the projected wire position on the plane containing the wire and the coils. It is highly linear and largely insensitive to misalignment of the coils with respect to the wire. The tube is positioned on two supports especially built for the end-plug reference surface and rotated around its axis. Variations of $\Delta\mathcal{E}$ with the angular position of the tube are a quantitative evidence of the wire off-centering.

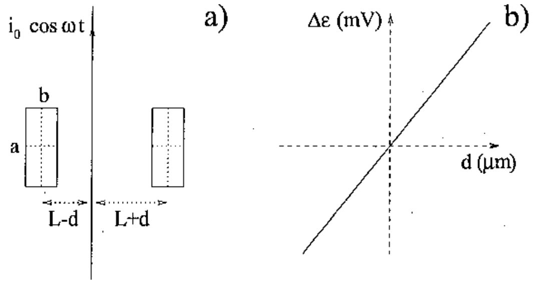

Figure 1: Principle of operation. a) Setup; b) Response for d much smaller than $(L - b/2)/2$.

III. CHOOSING THE WORKING CONDITIONS

In order to maximize the sensitivity of the measurement both the current amplitude and frequency need to be as large as possible. However both parameters are limited for practical reasons.

A. Current

Current induces wire self-heating. By allowing ten degrees as maximum temperature increase a limit of about 70 mA rms was found.

B. Frequency

It was observed that above 1 kHz equation (3) no longer provides a correct description of the system. This behaviour - for which an explanation has not yet been established - is attributed to the effect of the currents induced on the tube and to the differences between the two coils which, above a certain frequency, cannot be considered anymore as simple inductances. An acceptable working frequency was found to be 225 Hz. This value is far away from multiples of european and US mains frequencies, allowing the filtering of external pickups.

C. Coils and Preamplifier

Assuming $i_0 = 80$ mA, $\nu = 225$ Hz and rectangular coils of size 10×2 cm^2 at an average distance of 3.5 cm, the expected amplitude $\Delta\mathcal{E}$ is about 80 pV per winding per micron of wire offset from the tube axis.

In order to increase the value of the induced electromotive force prior to signal amplification, plastic-core multi-winding coils were built. The amplitude of the induced signal is proportional to the number of windings. However the maximum obtainable signal-to-noise ratio also depends on the noise figure of the preamplifier, which is a function of the impedance connected to the input.

Thus the requirements on the coils and the preamplifier are strictly connected. A survey of the lowest-noise amplifiers available on the market suggested the use of the INA103 [2] instrumentation amplifier. Coils made of 1600 windings of 0.25 mm diameter isolated copper wire ($R \simeq 150\ \Omega$, $L \simeq 185$ mH, total wire length of about 400 m) were chosen to optimize the noise performances. With a preamplifier gain of 60 dB the total intrinsic noise at 225 Hz (referred to the input) was measured to be 2.8 nV/$\sqrt{\text{Hz}}$, dominated by the Johnson term, as expected from the INA103 specifications ($e_n \simeq 1$ nV/$\sqrt{\text{Hz}}$, $i_n \simeq 2$ pA/$\sqrt{\text{Hz}}$).

D. Sensitivity. Signal-to-Noise Ratio

With the geometry and the working parameters described above, the expected signal is 130 nV per micron of wire offset from nominal centre. With an electronics gain of 86 dB (see section VB) the expected sensitivity is 2.6 mV per micron.

The signal has to be compared to the input noise density, measured to be about 100 nV/$\sqrt{\text{Hz}}$, due to the coils pick-up from the external environment. Since the readout-board bandpass is about 1 Hz, a signal-to-noise ratio of the order of the wire offset (measured in microns) is expected.

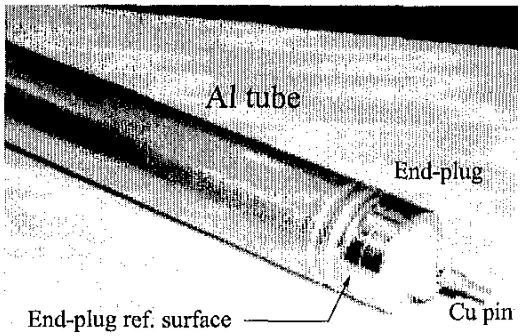

Figure 2: An ATLAS drift tube near the end-plug.

IV. MECHANICS

Before describing the mechanics used for EMMI it is necessary to understand how the drift tubes are made and the way they are assembled together in a chamber.

A. Drift Tube

The drift tube (figure 2) consists of 400 μm thick - 3 cm diameter - extruded aluminium tube crimped at both ends on two especially-designed aluminium/plastic end-plugs.

A 50 μm diameter gold-plated W-Re alloy wire, tensioned at 350 grams, is centred inside the tube and crimped on two copper pins placed outside the end-plugs. The wire position is constrained by a locator housed in the centre of each end-plug.

The wire centering depends on: i) The concentricity of external and internal end-plug surfaces; ii) The fluctuation of the locator position in its housing; iii) The concentricity of external and internal locator surfaces; iv) The fluctuation of the wire position in the locator.

Each term is expected to give an uncorrelated contribution of about 5 μm rms. The two external end-plug reference surfaces, one at each end, are used to position the tubes before gluing a layer.

B. Drift Tube Support

During the wire-centering measurement each end-plug is placed on a support made of two 12 mm diameter high-precision ceramics spheres[1] as shown in figure 3. This permits an accurate tube rotation around its axis, defined as the line joining the geometrical centres of the two end-plug external reference surfaces. Since EMMI monitors the wire position, a wire off-centering is seen as a variation of the output level during a tube rotation. A clamp guarantees that during the measurement each end-plug is bounded to rest on the two spheres.

---

[1] The spheres tolerance on the sphericity is 1.3 μm.

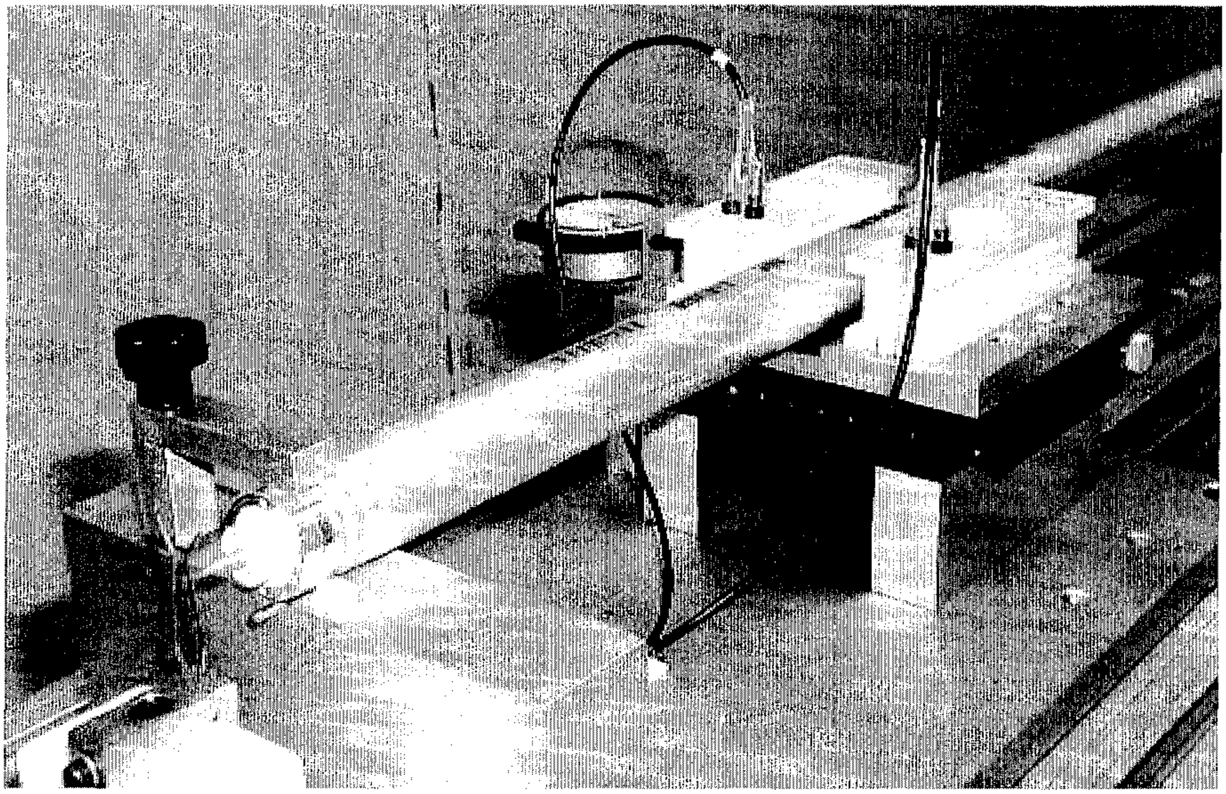

Figure 3: A drift tube on the EMMI support. The tube is held at the end-plug by two symmetrically-positioned high-precision ceramics spheres. The two coils are placed on a micrometrical slide. The piece which guarantees the electrical contact is not mounted. The other side is similar.

The two coils are mounted on a micrometrical slide located 30 cm away from the end-plug. The slide is used for calibration purposes. A sliding electrical contact is used to close the circuit at both ends.

V. ELECTRONICS

The electronics consists of a generator and a readout board. The generator includes all power supplies and the sinusoidal current source needed to feed the wire. The readout board is made essentially of the low-noise preamplifier described in section IIIC and a quadrature lock-in detector.

A. Current Generator Board

It includes a 3.6864 MHz quartz oscillator, a frequency divider down to 225 Hz, an active bandpass ($Q \simeq 10$) to convert the square wave to a sinusoid, a tunable phase shifter ($34° < \Delta\phi < 147°$), an offset and level control and a high-power voltage-to-current converter. This last stage is needed in order to supply a maximum current of about 100 mA rms to tubes with a wire resistance as high as 250 Ω – corresponding to the longest tubes (6 m) in the spectrometer. To guarantee thermal stability of the output stage a high-power internal resistor provides the load when no tube is connected. The board also includes the low-voltage supplies for both the generator and the readout circuits. A block diagram is shown in figure 4.

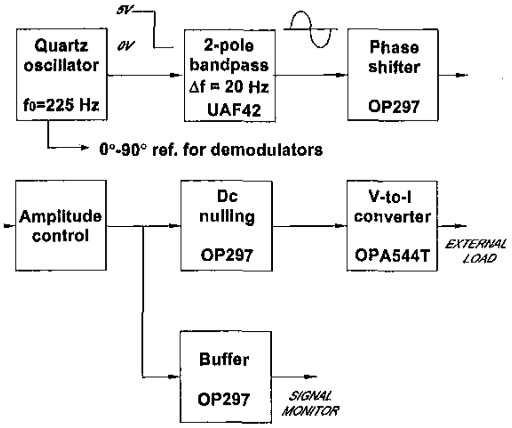

Figure 4: Block diagram of the current generator. The integrated circuits used in each section are indicated.

B. Readout Board

The coils are dc coupled to the differential inputs of the INA103 instrumentation amplifier, configured to provide a gain of 60 dB. It is followed by a 6-pole bandpass filter ($f_0 = 225$ Hz, $\Delta f \simeq 6$ Hz), a tunable phase shifter ($34° < \Delta\phi < 147°$), an additional stage of amplification and a quadrature lock-in detector, made of two identical sections with a demodulator (based on the AD630 [3]), an active 4-pole low-pass filter ($f_{lp} \simeq 1$ Hz) and an offset control. The readout-board overall gain is 86 dB at 225 Hz, providing a sensitivity of a few millivolts per micron of wire displacement. A block diagram of the readout board is shown in figure 5.

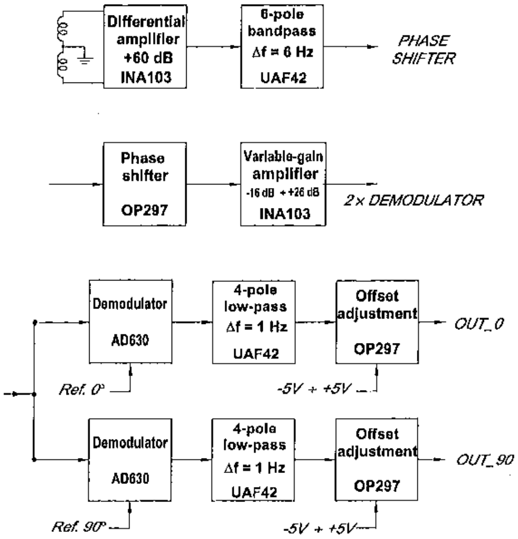

Figure 5: Block diagram of the readout board. The integrated circuits used in each section are indicated.

C. Tuning the Electronics

A small phase difference δ between the signals coming from the two coils adds to equation (3) a term proportional to $\delta \cos \omega t$, independent of the wire position:

$$\Delta\mathcal{F} \propto \frac{2d}{L} \sin \omega t + \lambda \delta \cos \omega t \,, \tag{4}$$

where $\lambda \simeq 0.95$ with our geometry. This undesired term can be completely projected on one of the two outputs of the quadrature lock-in detector with a proper choice of the phase of the signal, allowing for the detection of only the term of equation (3) on the other output.

VI. MEASUREMENTS AND RESULTS

A. Measurement Procedure

The wire-centering measurement is based on a double-differential method. First, the readout signal S is proportional to the difference of the electromotive forces in the two coils. Second, the position of the wire with respect to the nominal centre is reconstructed by means of four consecutive measurements, one every 90°, by rotating the tube around its axis. If $S(\phi)$ is the value obtained when the tube angular position is ϕ, one has

$$r_x = \frac{S(0°) - S(180°)}{2}, \qquad r_y = \frac{S(90°) - S(270°)}{2}. \tag{5}$$

r_x and r_y are the coordinates of the wire in a reference frame centred on the tube axis. The wire offset is $r = \sqrt{r_x^2 + r_y^2}$ - measured in mV.

The advantage of such a method is the rejection of systematics related to the absolute tube position. Moreover the rotation correctly defines the tube centre.

B. Results. Systematic Effects.

The results presented in this section [4] were obtained with a prototype of both the tube-support mechanics and the electronics.

Measurements were taken using 30 cm long drift tubes especially built with the wire displaced from the end-plug centre by fixed quantities, from 5 μm up to 100 μm, and parallel to the tube axis (with a few exceptions - see below). Each tube had eight 3 mm diameter holes at both ends, one every 45°, a few centimeters away from the end-plugs. These holes allowed an independent measurement of the wire position by means of a microscope[2].

The correlation between microscope and EMMI results is shown in figure 6. The linear fit to the data represents the EMMI calibration constant, found to be in agreement with what was expected for the prototype.

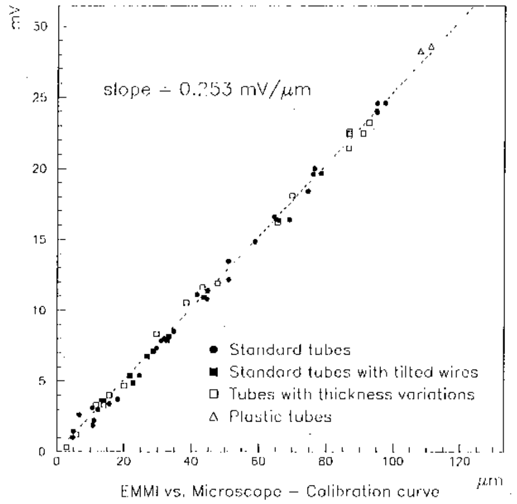

Figure 6: Correlation between microscope and EMMI measurements The line (best fit to data) gives the calibration constant.

---

[2] The microscope has a single-point resolution of the order of one micron.

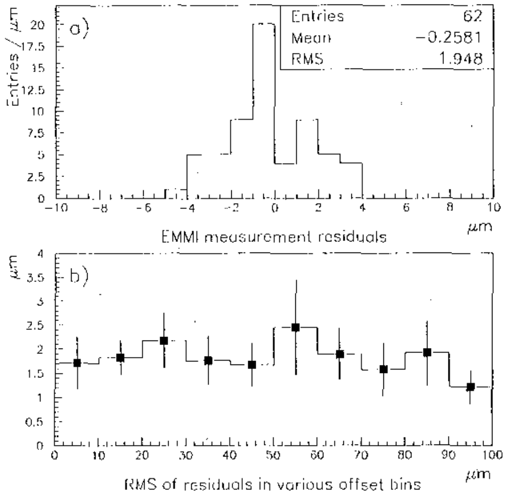

Figure 7: a) Residuals; b) rms of residuals as a function of the wire off-centre.

Different kinds of tubes were measured in order to account for the most common sources of systematic effects: aluminium and plastic tubes, tubes with wires not parallel to tube axis and tubes with azimuthal variations (up to 25% reduction) of the wall thickness. There was no evidence of a different behaviour for the various sets of tubes, suggesting that the results were not affected by important systematic effects.

The distance of the points from the fit, shown in figure 7a, gives a measure of the system resolution, found to be approximately two microns and independent of the wire off-centering (figure 7b).

C. Reproducibility

Repeated measurements on a few tubes were performed in order to evaluate the reproducibility of the results. Each tube was measured many times and the rms of the distribution was found to be about one micron.

VII. ACKNOWLEDGMENTS

The authors would like to thank G. Bressi (INFN Pavia) and P. Podini (University of Parma) for their useful suggestions and advice. This work would not have been possible without the continuous encouragements from the Pavia and Rome ATLAS groups and without the support of the technical staffs of both laboratories.

VIII. REFERENCES

[1] ATLAS Collaboration "ATLAS TDR", *CERN/LHCC/97-22 (CERN, Geneva, Switzerland), June 1997.*

[2] INA103 "Low Noise, Low Distortion Instrumentation Amplifier" data sheet, Burr-Brown Corporation, P.O. Box 11400, Tucson, AZ 85734, USA.

[3] AD630 "Balanced Modulator/Demodulator" data sheet, Analog Devices Inc., One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, USA.

[4] M. Cambiaghi, A. Cardini, R. Ferrari, G. Gaudio "An electromagnetic micrometer to measure wire location inside an ATLAS MDT drift tube", *ATLAS memo ATL-MUON-98-259 (CERN, Geneva, Switzerland), November 1998.*