ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Milano

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1. - INTRODUCTION

The Milan Cyclotron Laboratory is currently building a superconducting cyclotron for heavy ions which requires the winding of 48 double pancakes with 25.500 m of superconducting cable(1-5). The latter consists of a monolithic superconducting insert (3.6 x 1.8 mm^2) with a 2:1 Cu/Sc ratio, which is soldered in a copper matrix (ETP, 13 x 3.5 mm^2), as shown in Fig. 1.

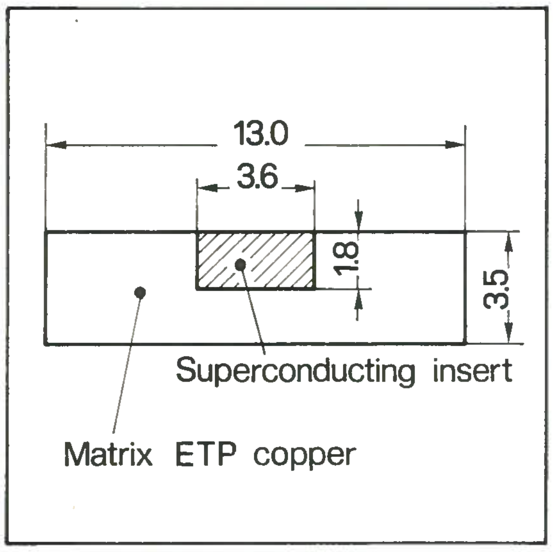

FIG. 1 - Cross section of the Milan superconducting cable.

The coils operating conditions impose some stringent requirements on the soldering quality, namely on the maximum size of possible defects and on their periodicity. Therefore a continuous inspection of the soldering by means of an ultrasonic technique has been requested to the supplying firm. In accordance with the supplier, the inspection of the cable has been carried out at the manufacture during the soldering process: this choice has allowed to determine the best parameters of the process (Sn-Pb alloy temperature and soldering rate) during the apparatus setting up, and to reduce the number of cable handlings.

2. - SOLDERING REQUIREMENTS

As, at our knowledge there is not, in the literature, a criterion to determine the maximum acceptable size of a soldering defect, we have deduced a simple rule to define the soldering specifications.

A superconducting insert soldered to a copper matrix can support a heat perturbation, uniformely distributed along the whole cable, without suffering a transition to the normal state, provided the maximum specific power of the perturbation is limited to:

$$\frac{W_{max}}{L} \leq h(T_{crit} - T_b)\,p_m \tag{1}$$

where L is the considered cable length, p_m its wetted perimeter, T_{crit} the critical temperature at the operating conditions ($I \neq 0$, $B \neq 0$), T_b the helium bath temperature and h the heat exchange parameter.

If a large portion of the superconducting insert is without the solder bonds, it can support a heat perturbation whose maximum specific power is p_i/p_m times lower than the one expressed in the condition (1), being p_i the wetted perimeter of the insert. Tipically the ratio p_i/p_m ranges from 0.1 to 0.2; for the C. S. superconducting cable it is equal to 0.15. This means that the heat perturbations spectrum, which can produce a transition in the superconductor, increases largerly and compromises the normal running of the coils.

To avoid operating troubles in the coils it is necessary that the insert, without soldering bonds, has a short length, so that the perturbation power can be removed by thermal conduction towards the contiguous soldered regions.

Assuming that the heat perturbation is localized to the unsoldered region, as sketched in Fig. 2a, neglecting the power removed by the helium bath and imposing that the maximum specific power removed by the conduction is still given by the expression (1), we obtain:

$$h(T_{crit} - T_b)p_m L \leq \frac{4k}{L}(T_{crit} - T_b)\,S_i \tag{2}$$

where S_i is the copper section in the insert and k the mean value of the thermal conductivity in the temperature range $(T_{crit} - T_b)$. The inequality (2) has been obtained assuming as temperature profile in the insert the one sketched in Fig. 2b.

From the condition (2) we obtain the "critical length":

$$L_c = 2(kS_i/hp_m)^{1/2} \tag{3}$$

which represents the maximum length of a soldering defect for which the superconduct ing cable can support, without a quench, a localized perturbation whose specific power equals the one removed from a soldered cable.

If the heat perturbation is uniformly distributed along the whole cable, it is obvious that the insert without soldering bonds can support only a fraction ε of the specific power given in the expression (1). In this case, referring to the Fig. 2c, the condition to removing the heat from the unsoldered region becomes:

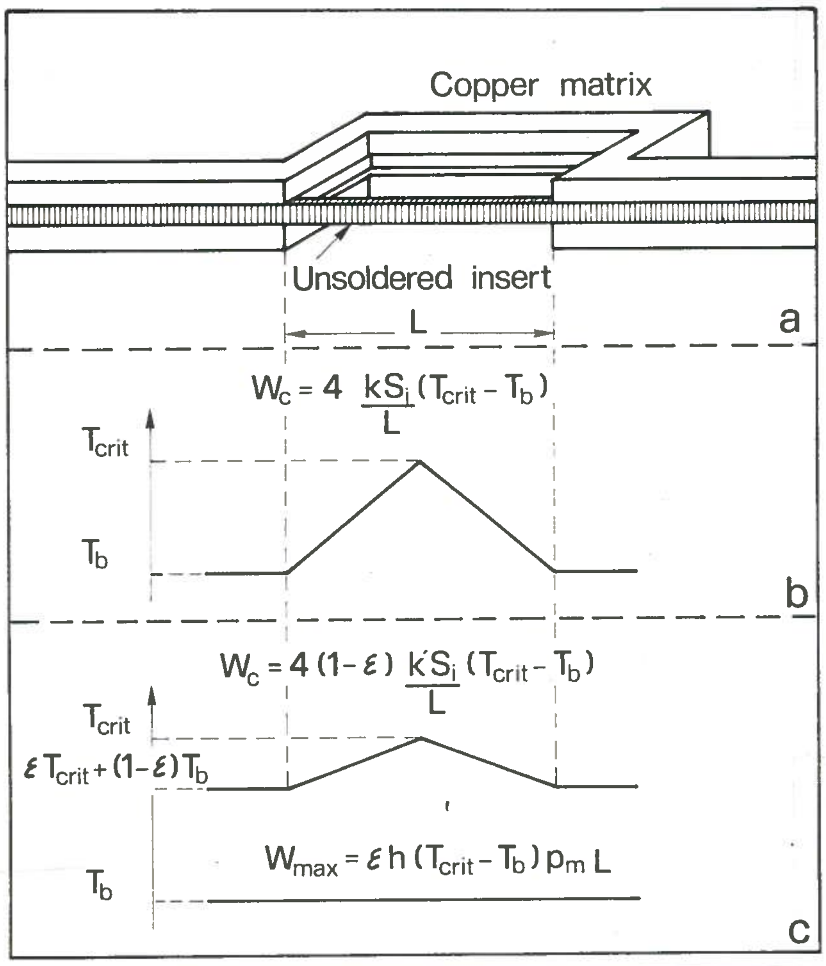

FIG. 2 - a) Sketch of the superconducting insert without soldering; b) Temperature profile in the insert for a localized perturbation; c) Temperature profile in the insert for a uniformly distributed perturbation.

$$\varepsilon h(T_{crit} - T_b)p_m L \leqslant \frac{4k'}{L}(1-\varepsilon)(T_{crit} - T_b) S_i \qquad (4)$$

where k' is the mean thermal conductivity in the temperature range $(1-\varepsilon)(T_{crit} - T_b)$. The critical length is:

$$L'_c = 2\left[(1-\varepsilon)/\varepsilon\right]^{1/2}(k'S_i/hp_m)^{1/2} . \qquad (5)$$

Reasonable values of ε are ranging from 0.6 to 0.8; with these values the portion of the perturbation spectrum supported by the unsoldered insert does not differ too much from the one of the soldered cable.

The critical lengths (L and L') are functions of the material purity and of the magnetic field through the mean thermal conductivities k and k'. In Figg. 3 and 4, the mean values of the copper thermal conductivities k and k' (the latter for $\varepsilon = 0.7$) are drawn as functions of the purity (measured by the residual resistivity ratio: rrr = $= \varrho_{273}/\varrho_{4.2}$) and the magnetic field.

Assuming for the heat exchange parameter the value $h = 0.4\ Wcm^{-2}K^{-1}$ and using

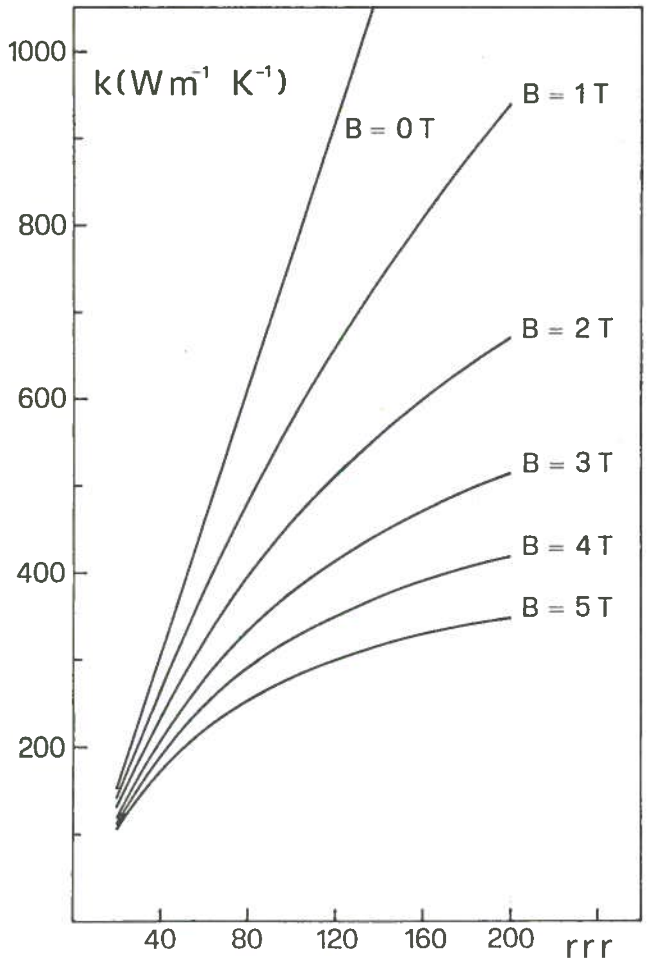

FIG. 3 - Mean values of the copper thermal conductivity in the temperature range (T_{crit} - T_b) as a function of the residual resistivity ratio (rrr) and of the magnetic field.

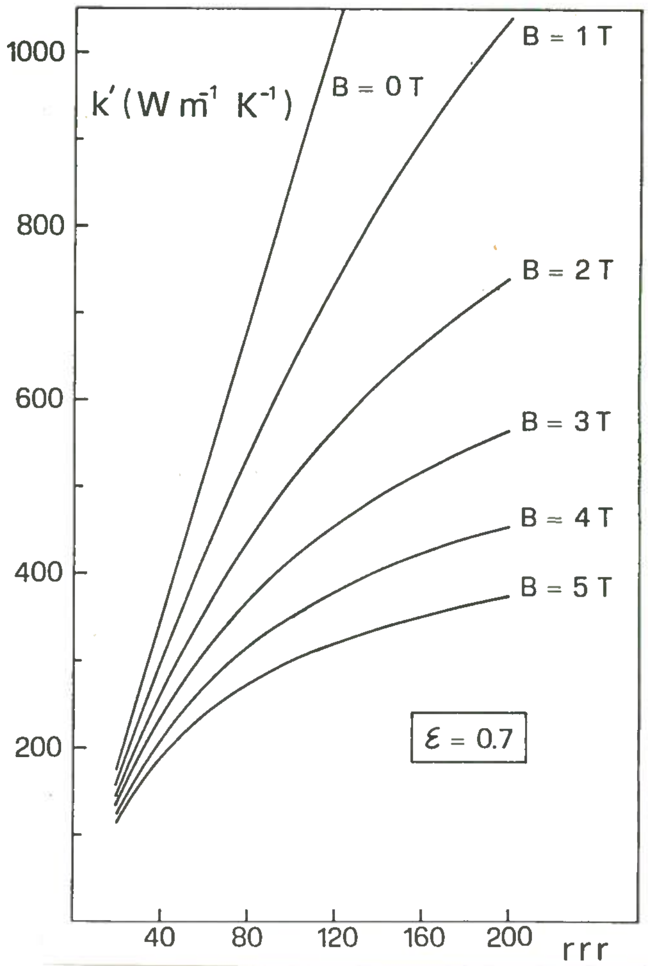

FIG. 4 - Mean values of the copper thermal conductivity in the temperature range $(1 - \varepsilon)(T_{crit} - T_b)$ as a function of the residual resistivity ratio (rrr) and of the magnetic field.

the following data for the C. S. superconducting cable:

$$\text{rrr} = 160, \quad B = 5 \text{ Tesla}, \quad p_m = 1.2 \text{ cm}, \quad S_i = 4.3 \text{ mm}^2, \quad \varepsilon = 0.7$$

we obtain:

$$L = 10.9 \text{ mm}, \qquad L' = 7.3 \text{ mm}.$$

According to these results, we decided to specify a limit to the defect surface, at 25 mm^2 in the bottom channel and 15 mm^2 along the side channels. As a minimum requirement, the apparatus for the ultrasonic inspection must reveal defects in the solder bond which have areas greater than 5 mm^2.

We assumed also that the soldered regions, near the defect, have on the average, at least a length ten times greater than the one of the defect. In other words in any 100 mm length of conductor the total area of the defect in the solder bond shall not exceed 10% of the nominal area either along each side channel or along the bottom channel.

3. - ULTRASONIC EQUIPMENT

The inspection apparatus essentially consists of a commercially available ultrasonic unit(*), four transducers and a water cell purposely designed. The sketch in Fig. 5 shows the arrangement of the transducers. Transducers A and B, each of them operating as a transmitter-receiver system, separately inspect the solder bond along the side channels. Transducer C (transmitter) and transducer D (receiver),

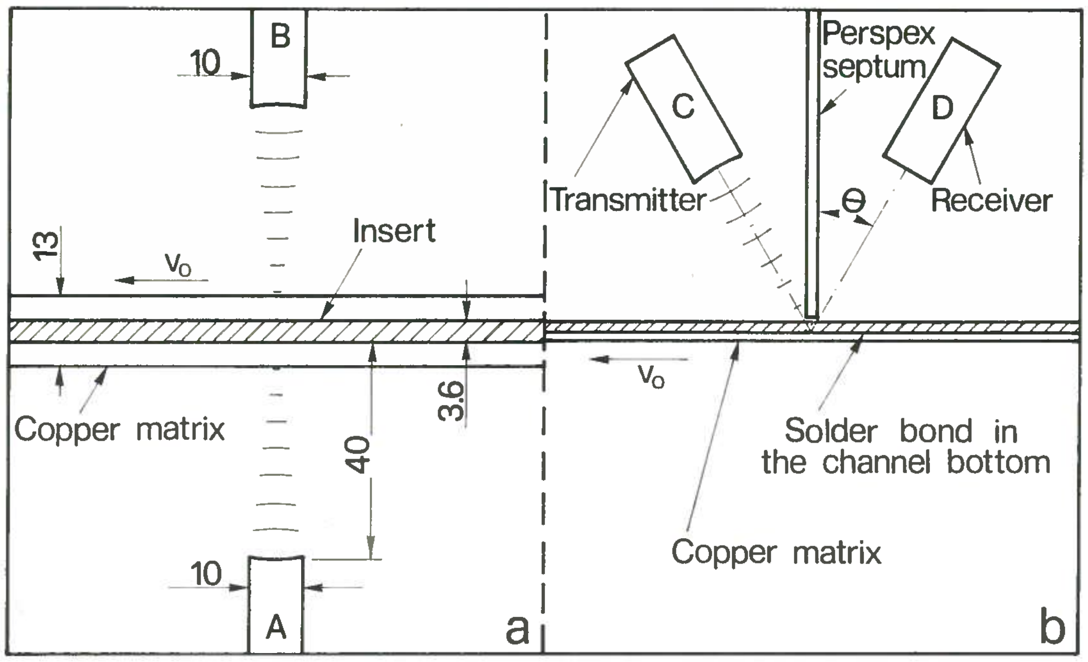

FIG. 5 - Sketch of the transducers and cable arrangement.

approximately placed with an angle $\theta = 30$(o) as to the normal of the cable and separated by a perspex septum absorbing the ultrasonic beam, reflected by the external insert surface, examine the soldering in the bottom channel. The transducers (working frequency = 4 MHz, diameter = 10 mm, focal length in water = 31 mm) are driven by three different channels and work successively in order to avoid interferences of the ultrasonic beams. The signals of each receiver can be independently preamplified and simultaneously displayed by a multiplexer during the apparatus setting up.

The transducers are mounted in a stainless steel water cell (Fig. 6), on movable sypports to allow the focusing of the ultrasonic beam in a rettangular spot ($1.5 \times 4.0\ mm^2$) at the solder bond.

The water cell has also two adjustable guides to avoid the side movements of the superconducting cable and a position optical encoder to record the defect position.

(*) - Gilardoni instrumentation mod. RG20 equipped with a multichannel unit mod. SMT100.

(o) - This angle has been chosen between the first critical angle ($\theta_1 = 22$) and the second critical angle ($\theta_2 = 45$) for the water-copper surface.

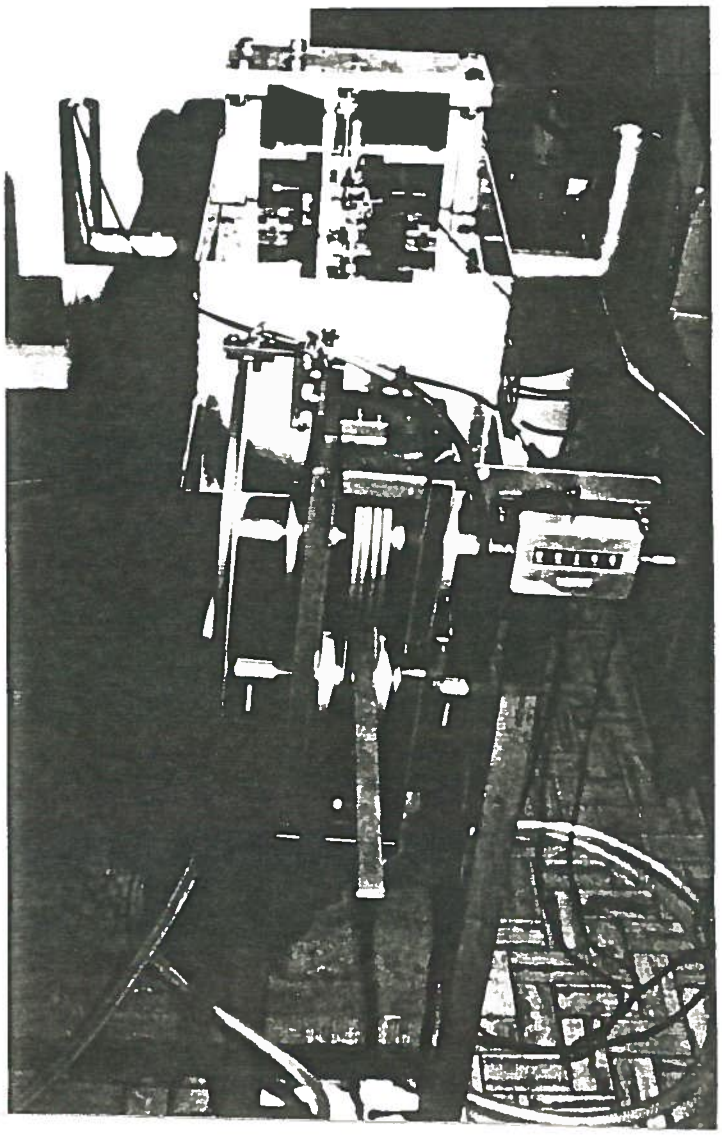

FIG. 6 - Water cell for ultrasonic inspection.

Fig. 7 shows typical displays of the signals produced by soldered and unsoldered sides of the cable; the first and the last signal correspond to the ultrasonic beam reflected respectively by the entry and the exit walls of the cable.

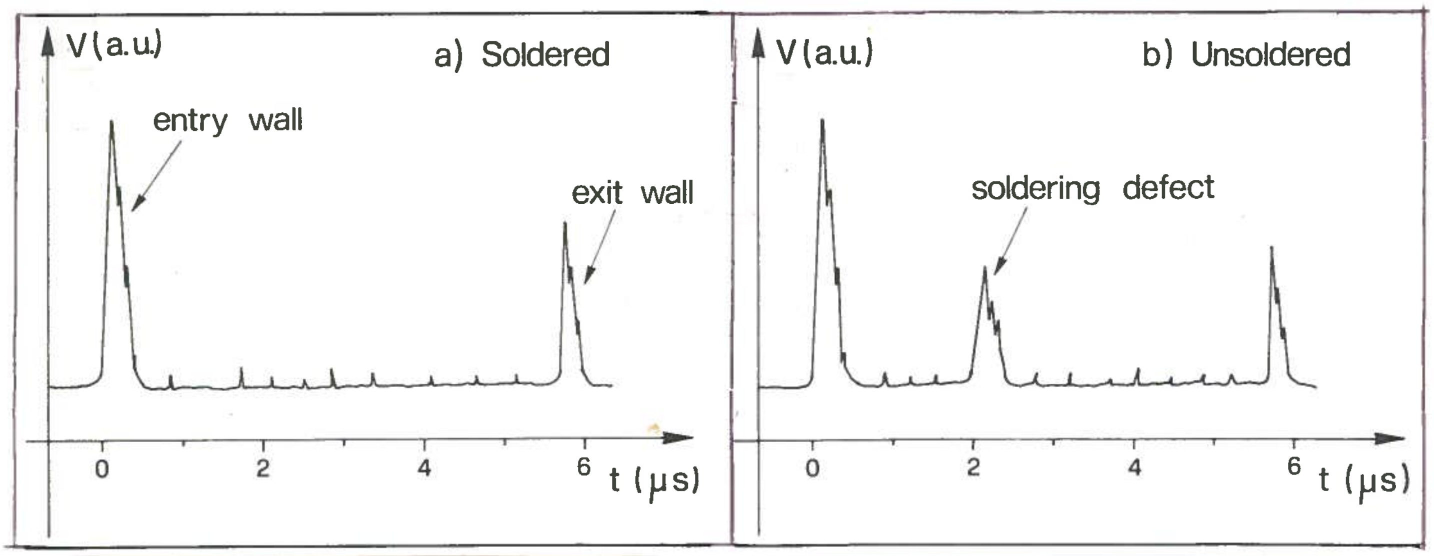

FIG. 7 - Typical displays of the signals produced by the soldered and unsoldered sides of the superconducting cable.

4. - MICROCOMPUTER SYSTEM DESCRIPTION

In order to fulfill the requirements specified for accepting a cable, an objective recording should have been produced. It is easy to understand that a continuous analog signal recording on a printer would have been a quite unacceptable technique for evaluating the quality of the soldering. Thus we decided to design a microprocessor-based system that should be able to perform data acquisition and on-line processing so to produce an intelligible output to be used as a feedback during preliminary tests and on-line production.

The system configuration is sketched in details in Fig. 8. A single board computer based on a Z80 microprocessor with two Kbytes of RAM (Random Access Memory) and two Kbytes of ROM (Read Only Memories) has been used as a controller for the ultrasonic equipment, and for data processing.

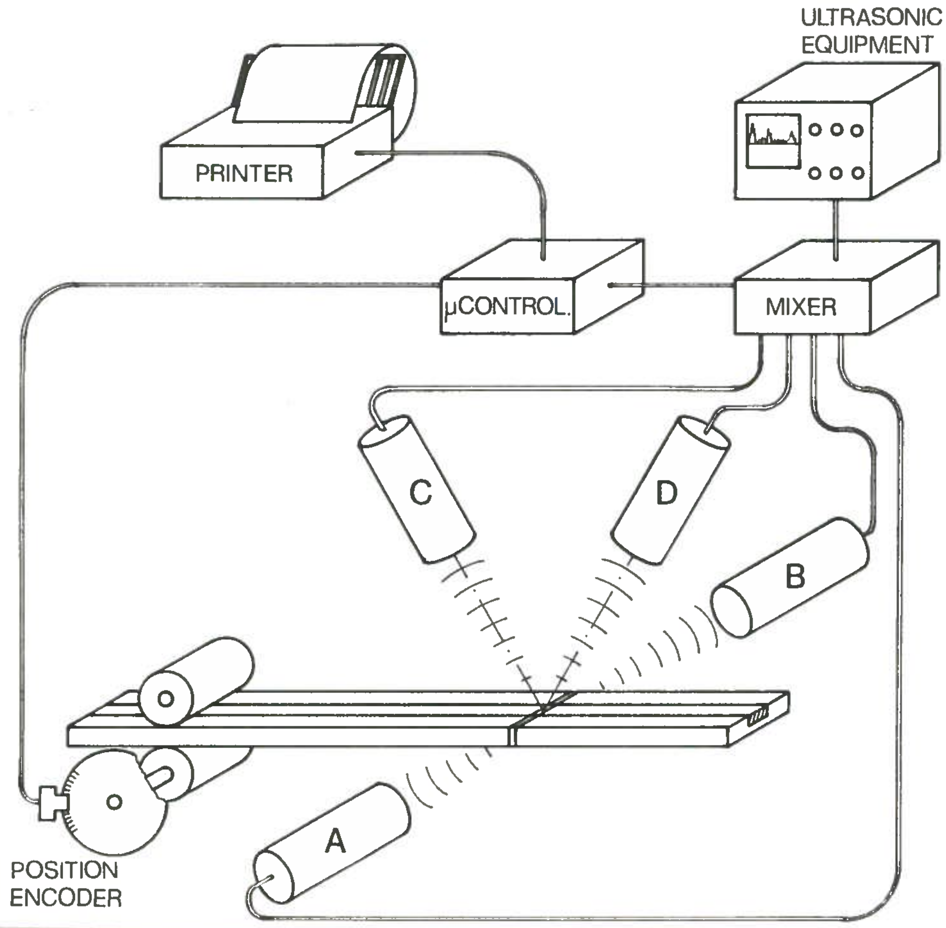

FIG. 8 - Sketch of the ultrasonic equipment and of the microcomputer-based system.

In order to perform both data acquisition and calculations, a home-made board provides fast analog to digital conversion of three continuous voltage levels obtained from the multiplexer SMT 100 (0 to 2 volts) proportional to the amplitude of the echo due to a soldering defect.

The program has been written in Assembler and utilizes simple algorhythms to calculate error percent on soldering bonds according to our specifications criteria.

A third commercial board, controlled by the microprocessor, drives a dot matrix printer on which the results of calculations are printed every 1.5 meters: that means every thousand data acquired for each side of the soldered cable.

Because of the ultrasonic transducers spot size (1.5×4.0 mm^2), and to fulfill the requirements of having a 100% inspection of the superconducting cable we had to synchronize the microcomputer so to have fast data acquisition every 1.5 meters displacement. A position optical encoder supplies, with an interrupt technique, a trigger signal to the microcomputer. In such a way, synchronisation is a function of the position, so being completely independent of the cable speed on the production line.

Such a solution gives a good flexibility to the controller with an upper speed limit of 10 meters per minute due to the time lost by the microcomputer to drive the printer and to process data.

Thanks to this flexibility the initial speed of one meter per minute could be increased till three meters per minute, according to some improvements in the soldering technique, without any change in the control equipment.

5. - SYSTEM OPERATION

We assumed that the equipment should be intended to run independently of any operator, once a start-up calibration has been performed. For that reason a standard procedure has been decided and the interface between the microcomputer system and the operator has been minimized just to a start/stop push button and some test facilities.

Before every new cable production, the ultrasonic detector has to be roughly adjusted by means of a two meters long calibration cable containing some standard defects. Fine adjustement is achieved with the superconducting cable in operating tension.

Powering-up the microcomputer, a self-test program controls the analog components integrity and prints a message of ready to start. When the soldering procedure has started up, every 1.5 m a line is printed, containing the following informations:

a) the absolute distance in meters from the beginning of the cable;
b) the percent of unsoldered area for that length, for each side inspected;
c) the number of unsoldered spots exceeding 15 mm^2 in the right and left side of the cable and exceeding 25 mm^2 in the bottom side, according to the limits specified to the manufacturer.

When all the cable has passed in the inspection cell, a stop button halts the program and a summary report is automatically printed. A sample of a printing is shown in Fig. 9.

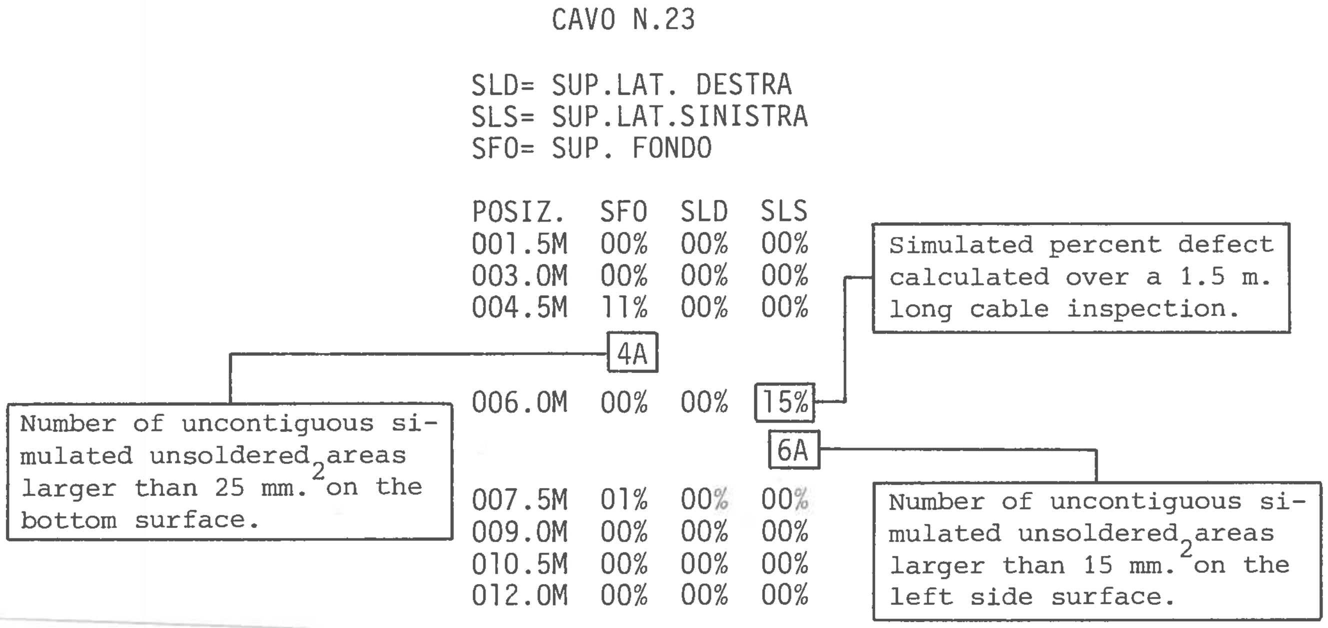

FIG. 9 - Sample of an ultrasonic analysis output recording.

Due to the industrial environment, special attention has been dedicated to the power-supply stability and interferences immunity. Battery back-up has been implemented in such a way that for a power-down period within thirty seconds the system will mantain full operation. Exceeding this time limit, a partial summary will be printed and a acoustic alarm will indicate the power failure.

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