# OPERATIONAL EXPERIENCE WITH THE SUPERCONDUCTING COILS OF THE MILAN K800 CYCLOTRON

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## ABSTRACT

The main features of the operational experience with the superconducting magnet of the Milan cyclotron are presented. The characteristics and the problems of the cool-down and warm-up of the coils, LHe vessel and LN thermal shield are described. The procedures adopted during the first excitation of the superconducting coils up to the maximum current and the method to minimize the radial and axial decentering forces are presented and discussed. Lhe vessel and magnet deformations are reported. Finally the measured values of the self and mutual inductances and the stored energy are compared with calculated ones.

## 1. INTRODUCTION.

A three sector superconducting cyclotron is under construction at the University of Milan. The cyclotron has been designed as a booster for the 15 MV Tandem of the South National Laboratory of Catania. The accelerator facility will deliver ion beams from Helium to Uranium with maximum energies of 100 MeV/n for fully stripped light ions down to 20 MeV/n for uranium ions (1-3).

The choice of superconducting coils has reduced drastically the size of the magnet and the final cost of the project but has increased the design problems, mainly connected with machine compactedness and the superconducting and cryogenic constraints. In addition the magnetic field requirements for a cyclotron make the superconducting coil design and construction more complex in respect to similar coils used in other equipments like large bubble chamber detector or test facilities.

For these reasons the initial operation of the superconducting magnet, by allowing the check of the adopted technical solutions, represents an important step for the project and a source of novel experience. This paper will describe the main features of the magnet operation by emphasizing those aspects which represent a peculiarity of the Milan project.

## 2. COOL-DOWN AND WARM-UP OF THE CRYOSTAT.

The operational scheme of the cryogenic plant, consisting of the LHe liquefier (120 W or 45 l/h with LN precooling), He purifier, recovery and storage, and LN storage and distribution, has been presented in a previous paper (5).

The monitoring of the temperatures in the cryostat is assured by 10 platinum resistors (Pt100) distributed on the thermal shield, by 12 platinum resistors sticked on the internal and external walls of the LHe vessel, by 8 carbon glass installed on the median plane ring and compression flanges and by 10 voltage taps located at the ends of double pancake set and normally used for the quench detection. The voltage taps were used to monitor the average pancake temperature by supplying the coils with a small stabilized current (1 A) and using the measured relationship between the copper resistivity and the temperature.

The Fig. 1 shows the temperature of the LN thermal shield, of the Lhe vessel and the coils during the

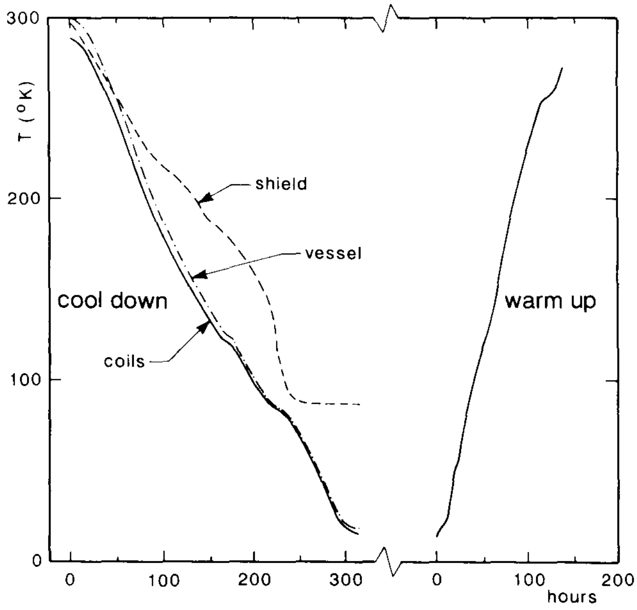

Fig. 1 Cryostat cool-down and warm-up. The cool-down rate has been of about 1 K/h while the warm-up has been carried out with a 2 K/h rate.

cool down. The long time required to reach the operating temperature (4.5 K - 1.2 bar) is due mainly to the limited value of the operating pressure (3 bar) determined by safety devices. The resulting maximum difference of the internal coil temperatures was 10 K while the maximum temperature difference between coils and vessel was 20 K.

The LN thermal shield, built with roll-bond panels in three independent circuits for assembly reasons and cooled by a continuous LN flow, worked properly. One of the three circuits, obstructed by a plugging, was closed but this fact did not produce a significant increase of the temperature in virtue of the good thermal conduction of the connections with the remaining circuits. The total LN consumption was 45 l/h, including the cold-box precooling (15 l/h). The most part of the cryostat LN comsuption was due to the external piping,realized with usual insulating material.

The liquifier/refrigerator worked properly for the whole period (5 months). Some short stops were due to failures of the utilities and one longer stop, after 4 month operation, was caused by the presence of impurities that obturated some valves. This fault required the warm-up of the cold box. During the running of the plant the contents of $O_2$ and $H_2O$ in the feeding gas were continuously monitored with alarms setted respectively at 5 ppm and at a dew point of - 70 C.

The He boil-off rate, measured without LHe feeding from cold box and storage dewar was about 35 l/h at the beginning of the warm-up (region AB in Fig. 2) and reduced to 22.5 l/h when the liquefier was stopped. The initial high LHe consumption is due to the heat inlet from the current leads and also to the shut down operation of the liquefier. The Lhe consumption, about 30-40% higher than the expected one, was probably affected by the fact that the thermal shield temperature was about 90 K and that the multilayer insulation on the concave surfaces has been replaced with an aluminum adhesive strip insulation.

The warm-up (Fig. 1) has been carried out in about 150 hours. The speed of the warm-up was increased by warming the coils with a 2 kW feeder and by circulating warm He gas.

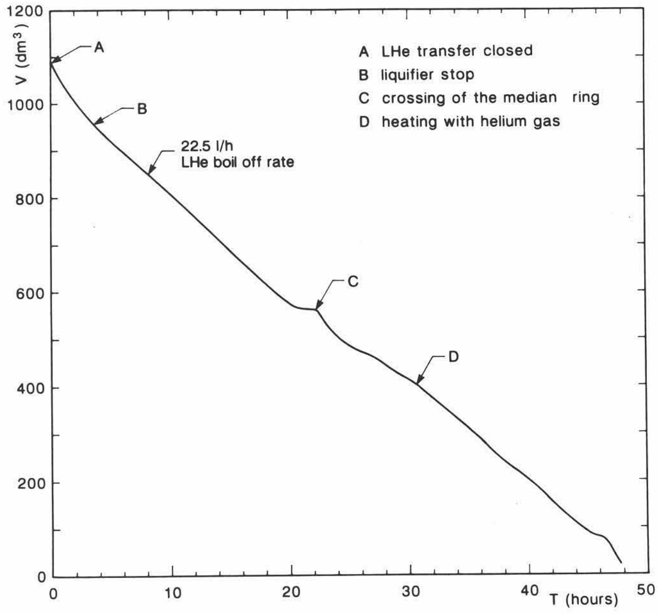

Fig. 2 LHe volume in the cryostat, measured with a superconducting level meter, during the warm-up operation.

## 3. FIRST EXCITATION OF THE COILS.

The first excitation of the superconducting coils has been carried out in two steps. During the first step the coils have been charged up to 300 A (stored energy 1.7 MJ) in order to check at low current the power supplies, the quench detection system (QDS) and the coil protection system. In particular it has become necessary to adjust the power supplies to the pure inductive load and reduce the output voltage ripple from 0.2 mV/A to about 0.02 mV/A in order to avoid disturbances on the QDS. The QDS, based on the analogical comparison of the voltage measured on symmetrical taps of mthe coils, has been tested in local mode both in dynamic and static regime. The algebrical sum of opposite voltages on symmetrical set of pancakes was contained within 10 mV during the maximum current rising rate (about 700 mA/s). Voltage spikes of several tens of mV have been detected by the QDS during the initial charging (0-50 A) when the self and mutual inductances of the two sections of the coils are very high (more than 100 H).

The achievement of the maximum magnetic field ($B_0$

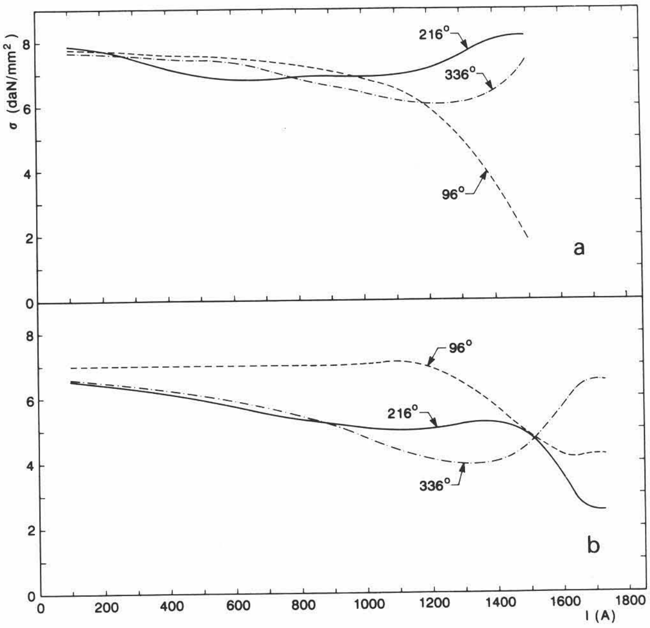

Fig. 3 Stresses measured on the horizontal tie rods (located respectively at the azimuths 96, 216, 336 degrees) as a function of the coil current. The excitation of the coils was stopped in the case a) because the tie rod at 96 degrees approached to compression regime.

= 4.93 T) during the second step has required some radial displacement of the coils in order to reduce the strong decentering forces. The radial position of the superconducting coils is assured by three couples of prestressed Ti tie rods. The prestressing (initially 6-7 daN/mm$^2$ and finally 13 daN/mm$^2$) in each tie rod couple (spring constant: 3400 daN/mm) was read by calibrated strain gauges. The upper limiting value of the stress is 20 daN/mm$^2$ whereas the lower limiting value is 2-3 daN/mm$^2$ in order to avoid that the tie rods go in the compression regime. The Fig. 3 shows a typical behaviour of the stresses on the radial tie rods as a function of the coil current before (Fig. 3a) and after (Fig. 3b) a coil displacement of 0.5 mm. The best centering of the coils has been obtained by minimizing the force over the whole operating diagram of the currents. The decentering forces result opposite in phase at two extremes of the operating diagram ($I_\alpha$ = 1750 A $I_\beta$ = 1750 A and $I_\alpha$ = 1600 A $I_\beta$ = -650 A) so that a residual force of 1600 daN (corresponding to a coil displacement of 0.3 mm) has been obtained with a coil shift of 0.15 mm from the initial position.

At the same time the three vertical Ti tie rods, which support the weight of the coils and LHe vessel, were subjected to unequal additional stresses, corresponding to a resultant force of 2200 daN and a torque of 2000 daN*m. which produced an axial shift of about 0.3 mm and a tilt of the axis of about 0.2 mrad. The torque has been reduced drastically by an axial coil shift of about 0.2 mm and a tilt of 0.4 mrad, while the additional axial force has remained almost unchanged.

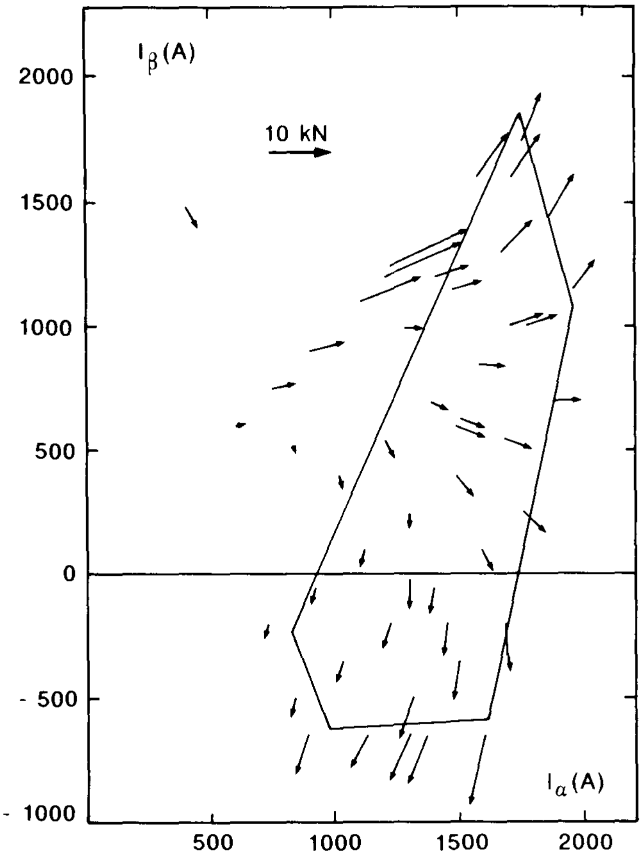

Fig. 4 Decentering radial forces acting on the coils as a function of the current in the two coil sections. The arrows give the intensity and the direction of the forces.

In order to have a record of the residual decentering radial force and to understand, if possible, its causes, systematic measurements were carried out for a set of current in the two sections of the coils. The Fig. 4 shows the decentering force (intensity and direction) as a function of the currents in the two coil sections: the full polygonal line delimits the operating currents of the cyclotron.

The field stability measured by axial NMR probe is ±20ppm, the field reproducibility measured at B=3.2T by reproducing the same currents in the two sections following different pathways is resulted of ±30ppm.

## 4. COIL AND MAGNET DEFORMATIONS.

The average hoop stress supported by the coils at the maximum field is about 7 daN/mm$^2$ and it produces a radial coil extension of about 1.0 mm. The LHe vessel, which is coupled to the coils by means of a compressive axial force (6 MN at I = 0 and 20 MN at I = 1800 A), undergoes a process of stick and slip with the coils. The slip amplitude and the total deformation of the vessel are depending by the friction coefficients (4): in order to reduce them a very thin sheet of teflon has been introduced during the pancake assembly between the G11 fiberglass plate and the median ring of the vessel.

The high sensitivity and reproducibility of the strain gauges sticked on the radial tie rods have allowed to detect the vessel deformation which results of about 0.11 mm in radius at the maximum current. This value is coherent with a low static friction coefficient ($\mu < 0.1$) and this seems to confirm that the slippage occurs at the teflon surface and in a smooth fashion.

At full excitation the attractive force on the pole is 15 MN and the monitored reduction in the mid plane gap (80 mm) has been of 0.6 mm. About 50% of this reduction is obtained at low excitation ($I < 300$ A) and is connected to plays of the yoke rings.

## 5. COIL INDUCTANCE AND STORED ENERGY.

The values of self and mutual inductances of the two coil sections have been derived by current rate and voltage measurements during the magnet excitation. The measuring errors are estimated to 5% at low current ($I < 100$ A) because of the high mutual inductance between the two sections and to about 2% at higher currents. The measured values are reported in Fig. 5: they agree within 10% with the calculated ones. The coupling factor between the sections ($k = M/(L_\alpha{*}L_\beta)^{1/2}$) is near to 1 at low current and decrease to 0.3 at the maximum current.

The energy stored in the magnet has been determined by measuring the voltages $V_\alpha$ and $V_\beta$ at the ends of the two sections and the currents $I_\alpha$ and

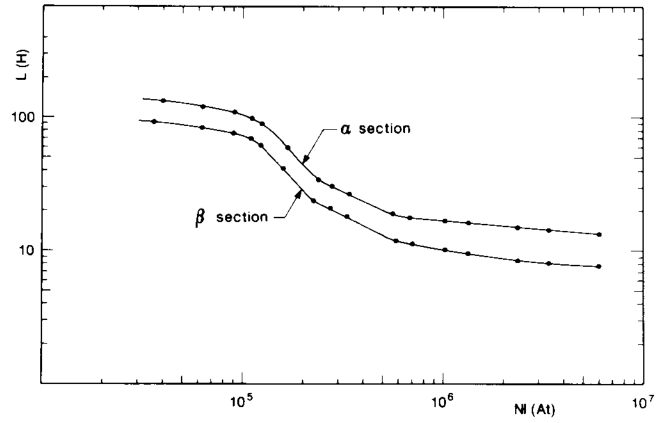

Fig. 5 Measured inductances of the two coil sections. The measured values at NI = $6\ 10^6$ At differ of about 5% from the inductances of the coils in air.

$I_\beta$ delivered by the power supplies as a function of time. The stored energy is given simply by:

$$E = (V_\alpha * I_\alpha + V_\beta * I_\beta)dt - (R_\alpha * I_\alpha^2 + R_\beta * I_\beta^2)dt$$

where $R_\alpha$ and $R_\beta$ are respectively the cable and lead resistance of the two sections.

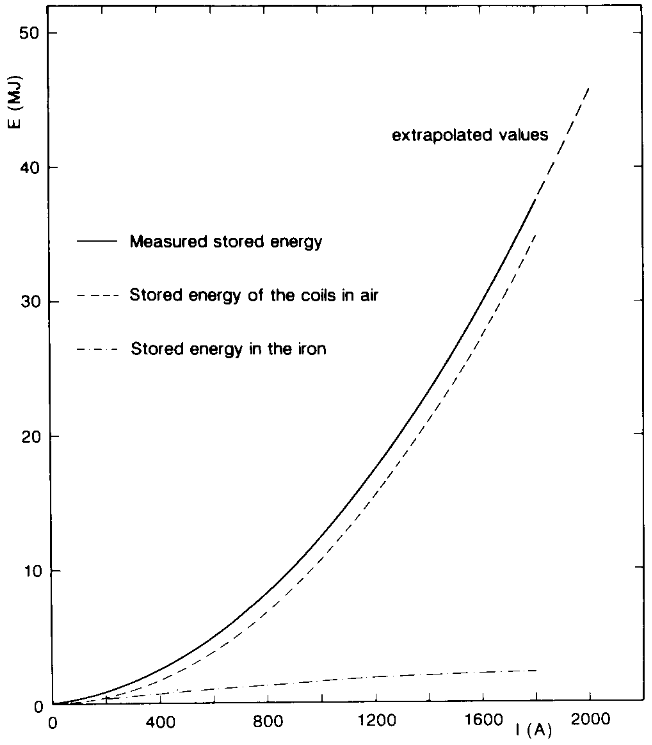

Fig. 6 Measured stored energy (full line) extrapolated up to 2000 A. The dashed curve represents the stored energy of the coils in air and the dotted curve is the stored energy in the iron.

The stored energy as a function of the current is reported in Fig. 6: the estimated error is 2%. The measured values do not agree with calculated ones by using POISSON code and a model (1) which reduces the tridimensional structure of the magnet to a bidimensional one: the calculated value (56 MJ) for I = 2000 A is about 20% higher than the extrapolated one (46 MJ) from the measured values. Probably the model, which works well in calculating the average field in the median plane, is not suitable for energy calculations. A more precise evaluation of the stored energy (within 5-10%) can be obtained by the calculated values of the self and mutual inductances.

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