# THE MILAN SUPERCONDUCTING CYCLOTRON PROJECT

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## INTRODUCTION

A three sector superconducting cyclotron with a K = 800 and a $K_{foc}$ = 200 is under construction since 1981 at the University of Milan. The cyclotron has been designed as a booster for a 15 MV Tandem with maximum energies of 100 MeV/n for fully stripped light ions down to 20 MeV/n for uranium ions. Intensities in the range $10^{11}$ - $10^{12}$ part./s are anticipated. The machine will also be equipped with an internal ion source of the P.I.G. type for test purposes and will have the capability of axial injection from an external advanced ion source.

The machine pole radius is 90 cm; the average spiral constant of the sectors is 1/45.7 rad/cm. The average magnetic field will span between 22 and 48 kgauss with a corresponding R.F. frequency range between 15 and 48 MHz. Peak dee voltage is 100 kV with harmonic operation modes from h = 1 to h = 4. A schematic vertical cross section of the cyclotron is presented in Fig. 1.

Detailed review characteristics and the main design aspects can be found in Ref. 1-6. Since a few paper on detailed aspects of the machine are given at this Conference, the emphasis of this paper will be on a broad overview of the project and on the progress made so far.

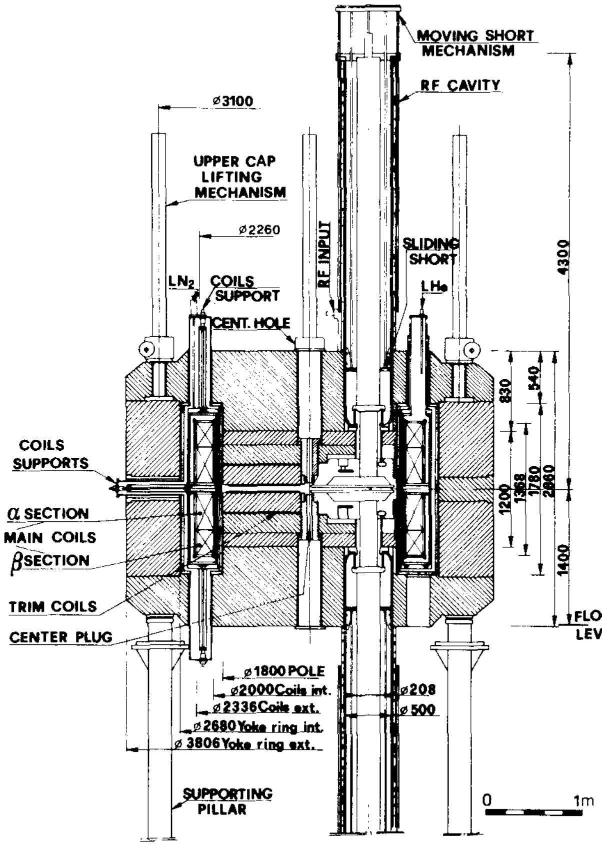

Fig.1 - Vertical cross section of the machine

## GENERAL DESIGN

All the magnetic field and the extraction calculations were concluded in 1983 so that all the necessary median plane penetrations thru the cryostat and thru the yoke have been designed as reported in Ref. 7.

Center region studies for an internal P.I.G. ion source have been completed for the harmonics modes h=1 and h=2. The design is essentially a scaled up version of the MSU K=500 superconducting cyclotron center region. The design of the source and of its insertion mechanism will be initiated at the end of 84 together with the liner design.

Effects of beam off centering during the traversal of the various resonances, in particular the $\nu_r=2\ \nu_z$, have been investigated in detail in order to correct possible off centerings coming from field imperfections or from mismatch in the center region. Two ways of correction have been studied: i) the use of a first harmonic field bump when the Walkinshaw resonance is near or after the $\nu_r=1$ resonance, ii) the unbalance of the dee voltages when the $\nu_r=2\ \nu_z$ resonance is well inside the machine. The correction achievable with the use of a first harmonic field bump is shown in Fig. 2 where is presented the axial envelope for the ion with Z/A=.5 and $B_0$=31.3 kgauss initially off centered by 3 mm at R=16 cm. The correct recentering of the beam in the extraction region has been confirmed also by the radial phase space behaviour which shows no appreciable distorsion. When the resonance crossing is inside the machine, as in the case of the ion with Z/A=.5 and $B_0$=22 kgauss, the calculations indicate that it is possible to correct beams initially off centered by 3 mm with a dee voltages unbalancing of the order of 20%.

A prototype of the electrostatic deflector has been built and high voltages tests are underway. So far voltages up to 120 kV (vs. 112 kV needed for the beam extraction) have been held without magnetic field on this prototype. Test performed inside the Milan Cyclotron indicate that 90 kV can be held also in presence of the magnetic field. More details are given in Ref. 8.

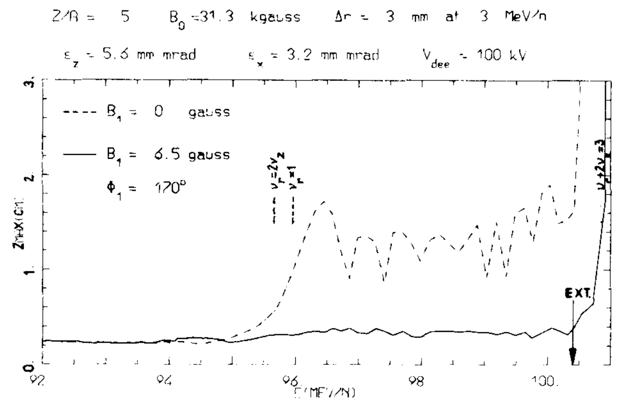

Fig.2 - Axial beam envelope near $\nu_r = 2\ \nu_z$

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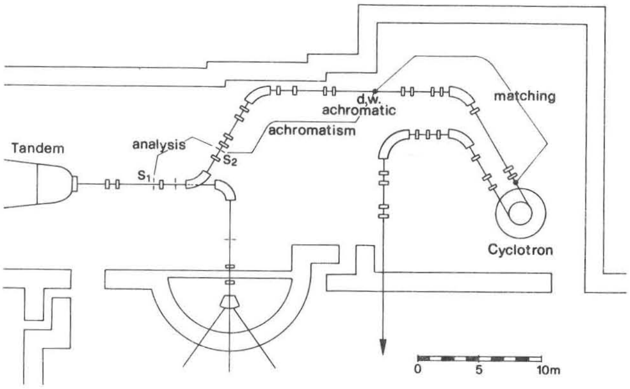

Fig. 3 - Layout of the beam transfer line between the Tandem and the cyclotron

The studies for the beam transport from the Tandem to the cyclotron have been completed and the corresponding beam line is presented in Fig. 2 on a layout of the L.N.S. Laboratory in Catania where the HVEC 15 MV Tandem has been installed.

The beam transport line is divided in three sections: 1) the analysis section which performs the charge state analysis of the Tandem beam and provides the Tandem voltage stabilization, 2) the achromatic section which produces at the end a waist in both planes, thus allowing to decouple the two machines and perform diagnostics, 3) the matching section which matches the Tandem beam to the cyclotron acceptance.

The study of the bunching system, which includes a low energy buncher after the Tandem source and an high energy rebuncher in the achromatic section of the coupling line, is underway and close to be completed.

The beam transfer line will be finalized after the magnetic field measurements of the cyclotron and the emittance measurements at the Tandem exit. The study of the beam line from the cyclotron to the experimental areas has been initiated.

The progress made so far in the development of high charge state heavy ions sources strongly suggest that the machine should be equipped also with an axial injection system. The source presently considered is of the ECR type. Funding has been requested to the National Institute for Nuclear Physics (I.N.F.N.). Since this development has not yet been approved, only the studies relative to the beam transport and injection from the source into the cyclotron are pursued for the moment.

The proposed line from the source to the bottom of the cyclotron is realized with magnetic elements for injection voltages up to 20 kV. The vertical line performs the matching and the confinement of the beam in the traversal of the yoke bore.

An electrostatic mirror inflects the beam into the median plane of cyclotron. Center region studies with the mirror either on the axis or off axis have been investigated. The results so far available indicate that the off axis solution is more effective even though the off axis displacement of 12.5 mm is fairly large. More details on the axial injection system can be found in Ref. 9,10.

## MAGNET

The magnetic yoke, manifactured by Hoesch, Dortmund (Germany), was delivered in Milan in April 83.

The overall radial dimension of the yoke is 380 cm, with an inner diameter of 188 cm. The total height is 277 cm and the weight including the sectors is 175 tons. A window 178 cm height, 44 cm radial width, is provided between the pole and the inner yoke wall to accomodate the cryostat. The yoke is split in seven elements, namely: upper and lower pole caps, upper and lower rings, central ring, upper and lower plates. The pole tips are split into two parts in order to wind the 20 trim coils around the upper part. The hills are bolted to the plate on the side far away from the median plane. The latter is bolted to the pole cap through the valley shims.

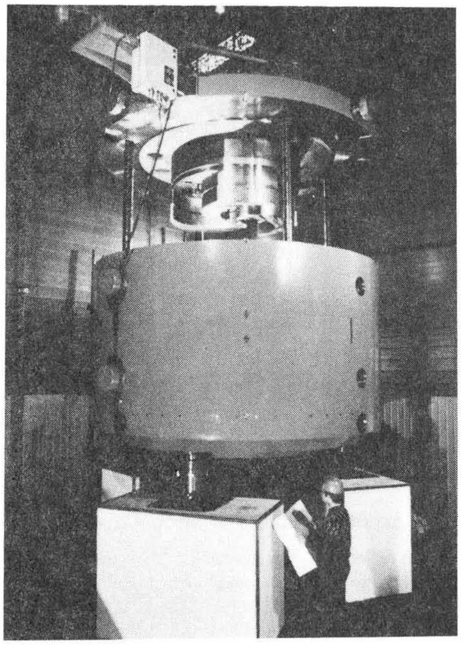

Fig. 4 - Magnet with the upper pole cap raised

Because of the delay in the building complex for the cyclotron, the magnet has been temporarily stored at Ansaldo Breda, Milan, where a suitable crane is available. The yoke has been first completely assembled to measure the mechanical tolerances and to test the upper pole cap lifting system. Fig. 4 shows the assembled yoke with the upper pole cap raised.

The mechanical test of the magnet has been completed. All the tolerances are within the design values. Poles plates parallelism is 0.06 mm and holes alignment near to the median plane, namely in the pole plates, is within 0.1 mm. The lifting system consists of 4 worm gear screw jacks actuated by a 9.2 kW elctric motor. The upper pole cap can be lifted by 1.8 meters in 35 minutes: accuracy in the repositioning of the pole cap is 0.02 mm.

The hills sectors and the valley shims have been completed by Frigostamp, Turin, in September 1983 and thereafter assembled in the magnet. Fig. 5 shows the lower set of polar expansions assembled on the pole.

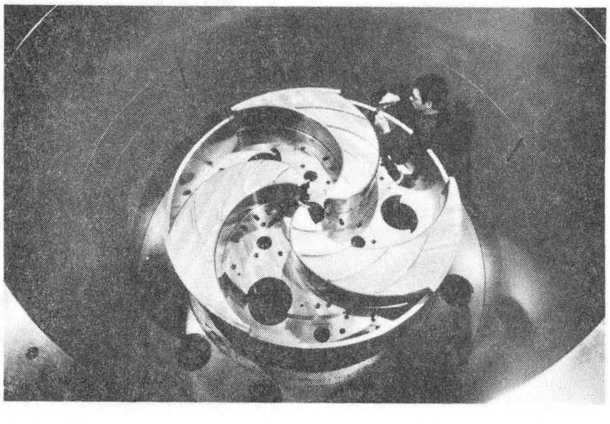

Fig. 5 - View of the lower set of polar expansions assembled on the pole

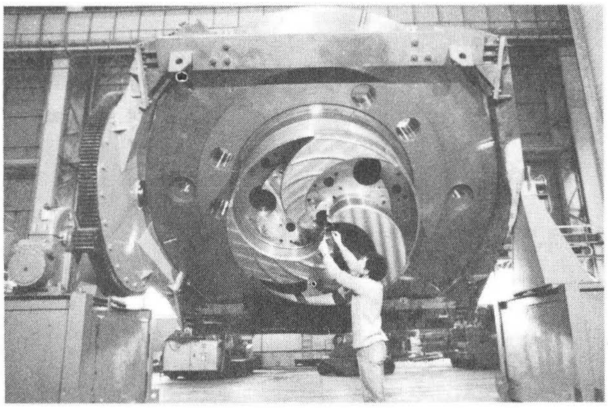

Fig. 6 - View of the upsetting of the upper pole cap

Visible on the picture are also the trim coils spacers mounted on the upper hills, the R.F. holes and the trim coils leads holes. The parallelism between the hills is 0.1 mm, while the axial gap is 0.3 mm less than the nominal value of 86 mm. This discrepancy from the expected tolerance of 0.15 mm is mostly due to the upper pole plate which is 0.1 mm thicker. The parallelism and the height of the three pieces in which the hill is splitted, namely upper and lower hill and hill spacer, is in fact quite excellent being of the order of 0.01 mm. The mirror image simmetry of the hills, once assembled on the poles, is within 0.2 mm.

The system for turning the upper pole cap has been successfully operated. Fig. 6 shows the upper pole tips mounted on the pole during the upsetting.

The construction of the center plug and its insertion mechanism is underway. All these items should be completed for the end of 1984.

The winding of the six sets of 20 trim coils has been completed. The 20 trim coils are packed in five groups of 4 trim coils each, which can slide on the hill in order to allow an easy removal for repairing or substitution. A prototype set of trim coils has been epoxy impregnated under vacuum to check any detail of the operation. The five packs of the prototype are shown in Fig. 7 together with the vacuum feed-throughs for the current leads and the cooling. The vacuum tight is done on the top of the pole caps where the iron structure is covered with 2 mm thick layer of stainless steel. The layout of the electrical and cooling connections on the upper and lower pole caps has been designed and they will be ready at the end of 84. The six sets of trim coils will be impregnated on the hills starting in summer 84.

A prototype of the 30 trim coils power supplies (500 A, 36 V; 400 A, 48 V) has been tested. Current stability and ripple are quite excellent, being of the order of 0.1%. A first unit of six power supplies will be delivered in summer 1984, the other five units will be ready at the end of 1984.

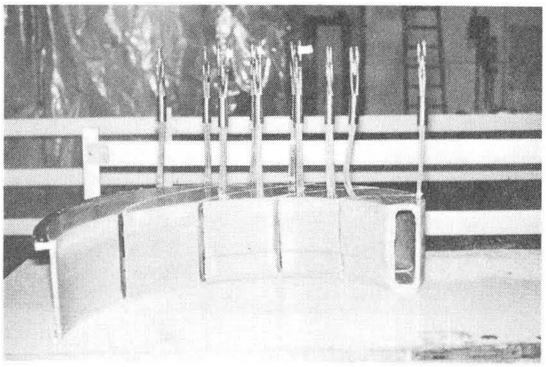

Fig.7 - Prototype set of trim coils epoxy impregnated

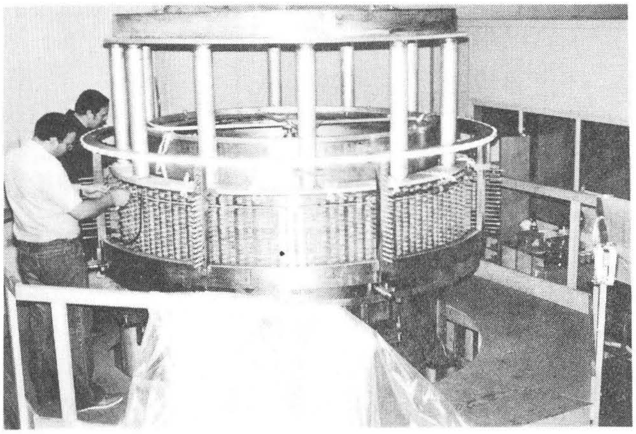

Fig. 8 - Assembling of the double pancakes

## COILS

The main coils consist of two indipendently excited sections running up to 2000 A built with the double pancake technique. The superconducting cable, manufactured by LMI, Florence, is a monolithic NbTi insert, soldered in a U shaped copper matrix with an overall copper to superconductor ratio 20:1. Copper-beryllium tie rods will prestress the coils at room temperature at 700 tons to prevent the axial lifting of the coils section running at negative excitations up to 800 A. A detailed description of the coils structure is given in Ref. 4.

The critical current of the superconducting cable has exceeded, in all samples, the specification of 2700 A at 5 Tesla. The winding of the double pancakes has been completed by Ansaldo, Genua, in october 83. Tests for short circuits and mechanical tolerances have been performed satisfactory for each pancake. However deviations from circularity are of the order of ± 0.7 mm vs a required tolerance of ± 0.3 mm. Since no systematic trend has been detected, errors in the winding have been excluded.

The assembly of the coils started in september 83 and will be completed in June 84. In the Fig. 8 is shown one section of the coils during the addition of a pancake, lifted by a special structure visible on the top of the figure.

Two major inconvenients occurred during the assembly in consequence of the coils prestressing:

- turn to turn short circuits,
- engraved G11 strips (1 mm thick), insulating the pancakes.

These facts forced us to disassembly the coils. The short circuits were given by small metallic chips possibly produced with the soldering of the superconducting insert on the copper matrix or by the prestressing of the cable during the winding. The short were detected measuring the voltage difference between each pair of pancakes simmetrically located respect to the median plane, as illustrated in Fig. 9.

The engraving of the G11 strips was produced by fiberglass pieces, with the height out of tolerance, inserted near the end of the pancake: the 700 tons of prestressing forced the turns to act as a scissor cutting the strips. The height of the fiberglass pieces has been reduced and, as a safety precaution, the prestressing force has been applied adiabatically up to 400 tons.

A view of the completed coils is presented in Fig. 10. Visible in the figure is the central ring of the cryostat with the penetrations and tie rods to prestress the coils.

Owing to the defects of circularity, out of the tolerances,the pancakes have been piled up using magnetic centering in order to reduce first and second harmonic

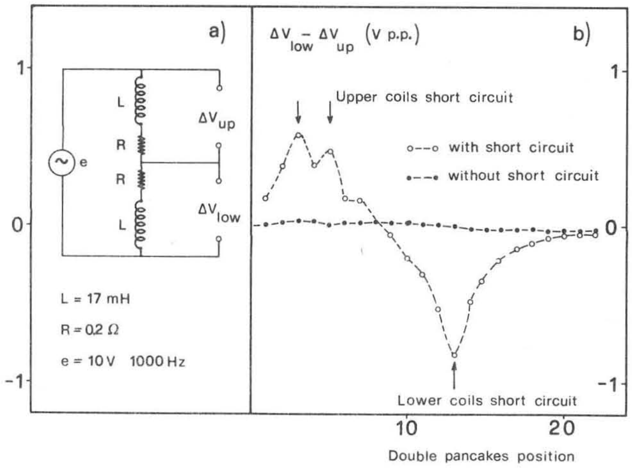

Fig. 9 - Voltages differences between the 22 pairs of pancakes before and after the removal of short circuits

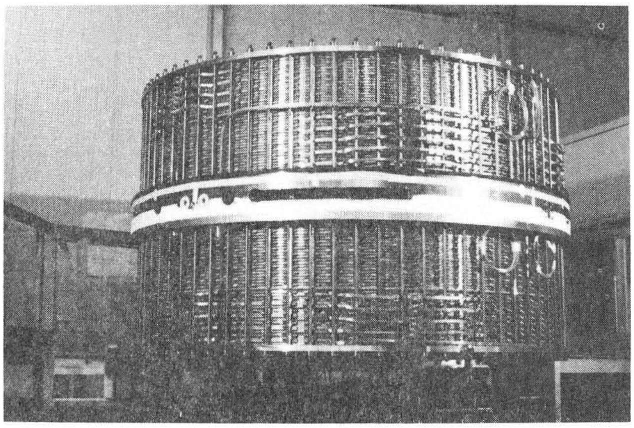

Fig. 10 - View of the completed coils

field imperfections. Eight pushers, simmetrically placed every 45° as visible in Fig. 8, provide the necessary tools to move and/or deform the single pancake. Magnetic field measurements, carried out in the plane of the pancake at 30 A of excitation, allow to determine the movement or the deformation to impose and to check the residual imperfection of the field. The prestressing of the coils will keep on position the pancakes. The values for the first and second harmonic in the extraction region (R=84-86 cm), extrapolated at the maximum coils excitation, are below 2 gauss and 6 gauss respectively. More details are given in Ref. 11 and 12.

Three current leads cooled by self-produced helium gas and optimized for the maximum current anticipated ($I_1=I_2$=2000 A and $I_3$=2750 A) have been built and tested at STIPE, Saclay. The heat flow in each lead is less than 1.5 mW/A and the survival time in case of coolant loss is longer than 1000 seconds (see Ref. 13).

The construction of the main coils power supplies, two identical sections located in one cabinet each one delivering 2000 A at 20 V with a current stability of 20 mA, is completed. A picture of the cabinet is shown in Fig. 11. Connection of the power supplies to the dumping system cabinet which includes the dumping switches, dumping resistors, polarity reversal and DDCT couplers for the two coils sections, is also completed. The capability of the dumping resistors to dissipate the total stored energy (40 MJ) will be checked in Summer 84 with

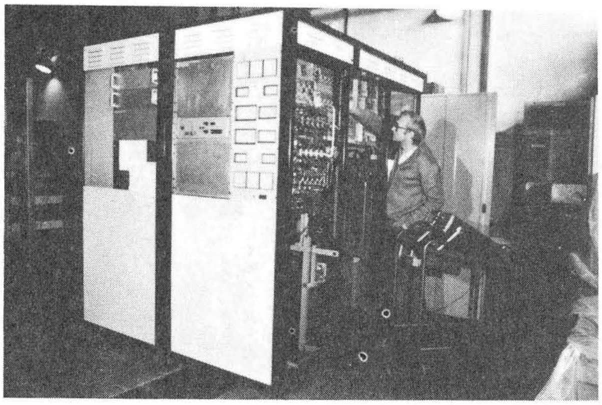

Fig. 11 - Main coils power supplies cabinet

equivalent current pulses.

## CRYOSTAT

The cryostat, i.e. the LHe vessel, the LN shield and the outer vacuum chamber, has been completed by Zanon, Schio (Vicenza). Each component consists of two cylindrical shells and two flat heads from which the necks and the extensions for the supporting and centering rods protude, as reported in Ref. 3.

The helium vessel is divided in two parts by a central anular plate, machined from an hot rolled AISI 316L stainless steel ring, bearing the coils. Connections between the upper and lower halves are given by holes drilled through the plate. The holes for the radial penetrations of the injection and extraction system are also drilled through. In Fig. 12 is shown the central plate with the welded inner shell during the check of shell roundness and ring flatness before the piling up of the coils double pancakes. The plates supporting the coils were found flat within 0.05 mm. Visible in the figure are the midplane penetrations and the holes for the coils tie rods.

The liquid nitrogen shield is made with "roll bond" aluminum plates with integrated canalization. Four plates are needed because of the limited size available for standard plates. Advantages of this solution vs the copper LN shield are:

- the reduced weight for equal strenght against forces due to eddy currents,
- the reduced space required by the integral canalization in comparison with a tube soldered to a plate,
- increased stiffness due to corrugation of the plate.

The half upper part of the inner shell is shown in Fig. 13 together with inlet and outlet tubes. The con-

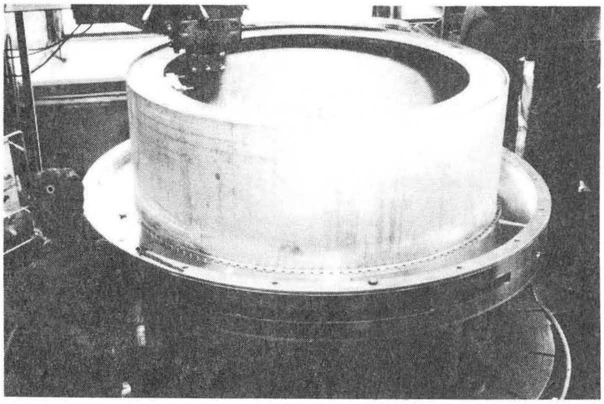

Fig. 12 - LHe vessel central plate and welded inner shell

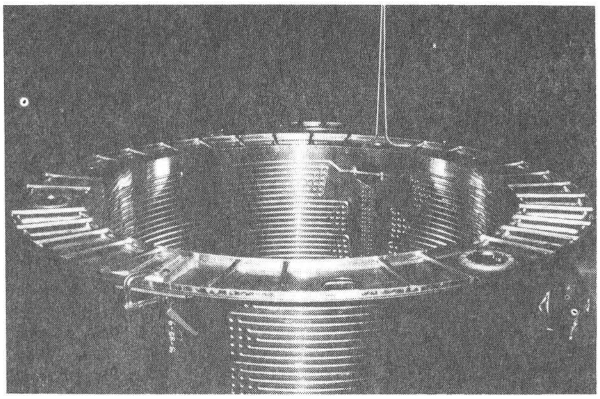

Fig. 13 - Liquid Nitrogen inner shield

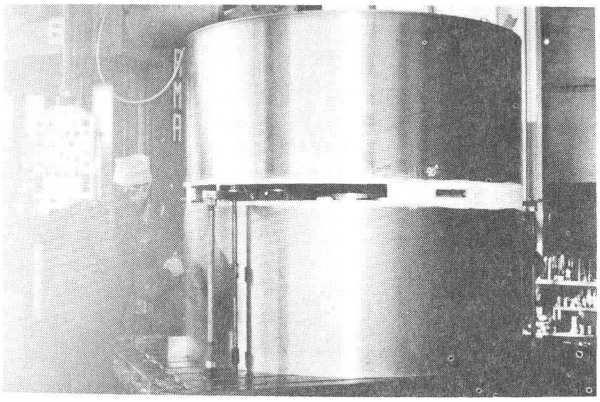

Fig. 14 - Inner shell of the vacuum chamber during the machining

nections to the external lines will be through a transition joint, an axial bellows and a Johnston coupling.

The vacuum chamber make use of stainless steel for covers and extensions and of carbon steel (magnetization M=2.04 T) for the thick cylindrical shell. The inner shell of the vacuum chamber is shown in Fig. 14 during the machining and before the dipping in a bath to deposit chemically a protective layer of nichel, 0.02 mm thick, able to cut down the outgassing of the walls.

The axial and radial titanium suspensions, which hold the LHe vessel in the vacuum chamber, are completed.

## R.F. SYSTEM

A detailed description of the R.F. system is given in a paper at this Conference[14] so that only a short sumary is given here. The three 90 kW R.F. amplifiers manufactured by BBC, Swizerland, have been delivered and one of them has been installed at the Cyclotron Laboratory in Milan. The long term full power tests carried out so far on the dummy load and the preliminary tests on the cavity have been completely satisfactory. On the Fig. 15 is shown the amplifier connected to the dummy load.

The first cavity resonator has been completed in summer 1983. Due to delays in the construction of the new building, the cavity was assembled in the machine shop were it was constructed.

The rationale of this assembling with some dummy components was mainly to verify the overall mechanics, including vacuum tightness, and to carry out a set of low power electrical measurements to check the frequency response, the Q-value etc. These measurements were needed because in the present Cyclotron Laboratory

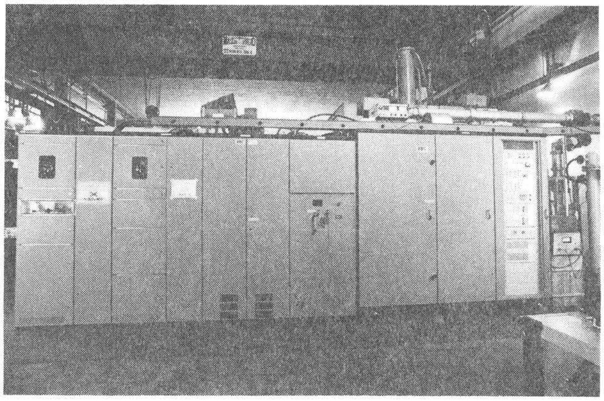

Fig. 15 - R.F. amplifier

just one half cavity can be installed for power tests. The results of the measurements were in agreement with the computed values.

In November 1983 the cavity was disassembled and shipped to Milan for the power tests. The upper half cavity installed at the present laboratory and connected to the power amplifier is presented in Fig. 16. High power tests are now under way, in order to check the short-circuit performance, voltage holding capability, etc.

## VACUUM

A detailed analysis of the surfaces exposed to vacuum shows that the total pumping speed needed to reach the operative pressure of a few $10^{-7}$ mbar in 10-15 hours is about 25000 l/s. High vacuum pumping system needs also good nitrogen and oxigen pumping speed and sorption capacity in order to run the accelerator for a few weeks also with small leaks.

The getter solution previously envisaged[7] turned out not satisfactory because of getter saturation particularly for nitrogen pumping.

We are presently testing a refrigerator-cooled cryopump prototype, made by Leybold-Heraeus, which has the valve assembly separated from the cold head by 5 m of copper tubes. The valve assembly and the cold head are shown in Fig. 17. The valve assembly will be mounted at the bottom of the RF cavity; the cold head, with the moving piston, would be placed in the dee.

The splitting of the pump reduce to one half the refrigerating capacity: 6 W are available at the first stage (80°K) and 1.1 W at the second stage (20°K). Sorption capacity for nitrogen should be at least one order of magnitude better than for getter pump.

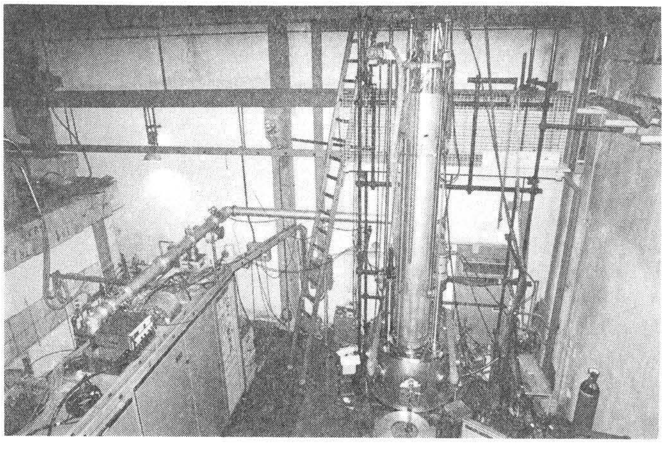

Fig. 16 - View of the R.F. test stand

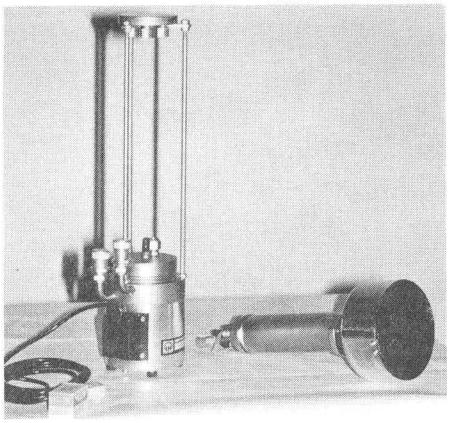

Fig. 17 - Valve assembly and cold head of the cryopump prototype

Measurements are now in progress in a test vessel. Next we shall run the pump in a magnetic field in order to check the reliability of the cold head. If pumping characteristics will be acceptable, we plan to use 3 pumps, one in each cavity, otherwise we may turn to the cryopanel approach.

## COMPUTER CONTROL

The modular architecture of the computer control system is based on a number of Programmable Control Stations (PCS), operating on a functional partition [6] of the Cyclotron equipment. This choice gives the opportunity to design and test independently every control station as soon as the corresponding hardware components of the accelerator get ready.

A complete control station has been developed for the magnet operation [15], i.e. the control of the power supplies and the quench detection system. To meet the field stability requirements, an high accuracy is mandatory for the electronics controlling the power supplies. Satisfactory performances have been achieved with a home made hardware. Further design criteria have been on board diagnostic and on line switching, to back up boards, in case of failure of critical components.

A flow of voltages informations are processed by a microcomputer to detect a quench and to switch the coils to the dump resistors. A fast analog circuit guarantee full operation in case of failure of the computer.

Sensors to measure temperatures and stresses (Pt 100, carbon glass resistors, CLTS, and strain gages) have been selected and are ready to be housed in the cryostat. Driving electronics, signals conditioning and data aquisition have been designed and tested.

The electronic equipment for the magnetic field measurements is ready. Signals from 90 flip coils are stored by 90 integrating devices packed in 15 NIM modules operating in a temperature controlled cabinet (stability 0.1°C). Special care has been devoted to the choice of the main components (capacitors and amplifiers), so to achieve drift rates better than 0.1 mV/s with a time constant RC=25 ms.

## BUILDING

After a two years delay the construction of the building for the new cyclotron started in october 83 with the digging of the cyclotron pit which is 6.5 m deep with a section of 10.5x7 $m^2$. Its construction, which required about 900 $m^3$ of reinforced concrete, ended on January 1984. The jacks for the anchorage of the pillars supporting the cyclotron are shown, before casing, in the bottom of the pit in Fig. 18. The pillars are designed to bear also a lateral stress of 10% of the vertical load, i.e. a lateral stress of about 25 tons.

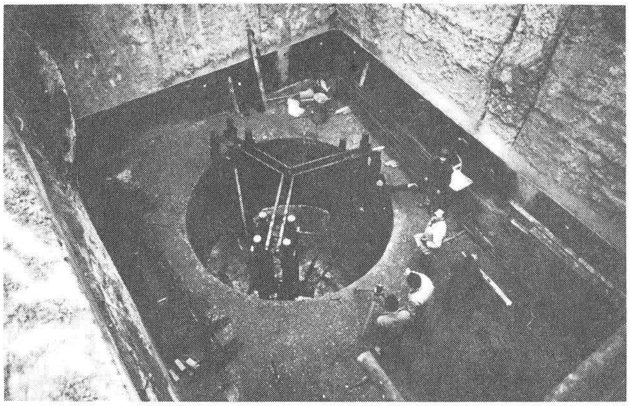

Fig. 18 - Cyclotron pit with the anchorage jacks

The construction of the building started in March 84 and is planned to end in June 85. However it will be possible to assemble the magnet from January 85 so allowing to operate the magnet in spring 85.

Francesco Resmini died on February 29, 1984.
He directed the Milan Superconducting project with a tremendous enthusiasm and energy up to the last day of his life. With his death we all miss a great friend and an ever smiling leader.

(+) Institute Boris Kidric, Belgrad, Yugoslavia

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