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THE MILAN SUPERCONDUCTING CYCLOTRON PROJECT

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Introduction

Design work on a superconducting cyclotron started in Milan in 1975, and a detailed analysis of all major aspects of the project was completed in 1976[1]. Meanwhile a 1:6 scale superconducting model magnet was built and successfully operated toward the end of 1977[2]. Lack of funding prevented the continuation of the project in the following years, till about fall 1980. In recent months the Italian National Institute for Nuclear Physics (I.N.F.N.) has authorized and funded the construction of the machine, which is now underway at the University of Milan.

The machine design has considerably evolved in the past year or so, both in terms of expected performances and engineering aspects. It is the purpose of this paper to rewiew the main characteristics of the accelerator and to update the status of the project.

Main machine characteristics

It may be recalled that the original purpose of the machine, which is a three sectors cyclotron, was to be used as a booster for a Tandem[1]. This capability is still the base of the project, the presently envisaged Tandem being the 16 MV machine to be installed in Catania. However, recent advances in the development of heavy ions sources capable of delivering high charge states[3] led us to the conclusion that the machine should be designed in such a way as to make possible an axial injection. Internal ion sources of the P.I.G. type shall also be usable, both for the purposes of machine testing and for producing beams of deuterons, alphas, etc.

When combined with the Tandem the cyclotron will have T/A vs A operating curves as shown in fig. 1 for both the maximum and minimum energies. The former are between 100 MeV/n and 20 MeV/n for light and very heavy ions respectively, corresponding to an effective K = 800 and K_{FOC} = 200. Also shown in fig. 1 are the operating radiofrequency ranges in 1st, 2nd and 3rd harmonics. The operating diagram in the $(B_o, Z/A)$ plane, namely the center field value and the charge state of the ion, is presented in fig. 2. The bending and focusing limits are shown, together with constant energy/nucleon lines.

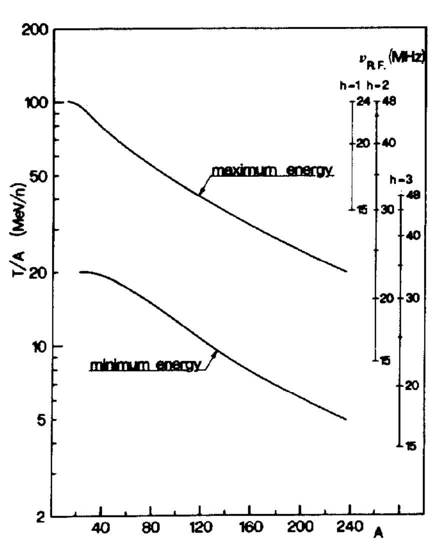

Fig. 1 - Maximum and minimum energies per nucleon for the cyclotron when coupled to the 16 MV Tandem.

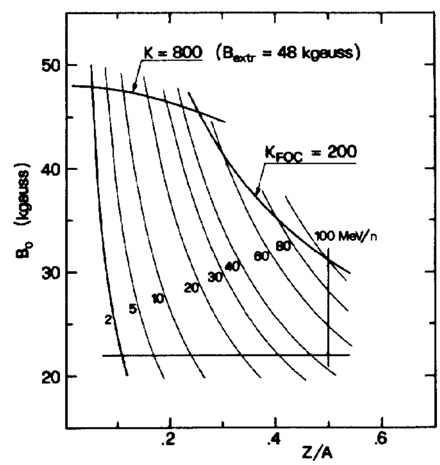

Fig. 2 - Operating diagram of the machine in the $(B_o, Z/A)$ plane. Lines of constant energy per nucleon are also shown.

As apparent from fig. 2, the minimum operating field is 22 kgauss, which is the lowest limit compatible for full saturation of the iron and the $\nu_R + 2\nu_z = 3$ resonance, as discussed later.

Some relevant machine parameters are listed in Table I.

Table I. Main machine parameters

Bending limit	K = 800
Focusing limit	K_{FOC} = 200
Pole diameter	180 cm
Number of sectors	3
Average spiral constant	1/44 rad/cm
Minimum hill gap	8.6 cm
Maximum valley gap	91.6 cm
Main coils At	6.55×10^6 at 3500 A/cm^2 aver. density
Min. and max. center field	22 and 48 kG
Number of trim coils	20
Maximum current in trim coils	400 A
Number of dees	3 (in the valleys)
RF frequency range	15 to 48 MHz
Operating harmonics	1, 2, 3, 4
Peak dee voltage	100 kV

Magnet and coils

A vertical cross section of the accelerator is shown in fig. 3, with all major details, while a median plane sketch is given in fig. 4. As apparent from fig. 4, a cylindrical yoke has been selected, as in the M.S.U. projects[4,5]. The magnet yoke will actually be built in five parts, namely: - upper and lower cap, which include the poles; - upper and lower ring; - central ring. This choice has been dictated by costs considerations in the use of cast iron for the entire magnet. The upper cap can be lifted by about 2 meters, in order to provide access to the machine median plane.

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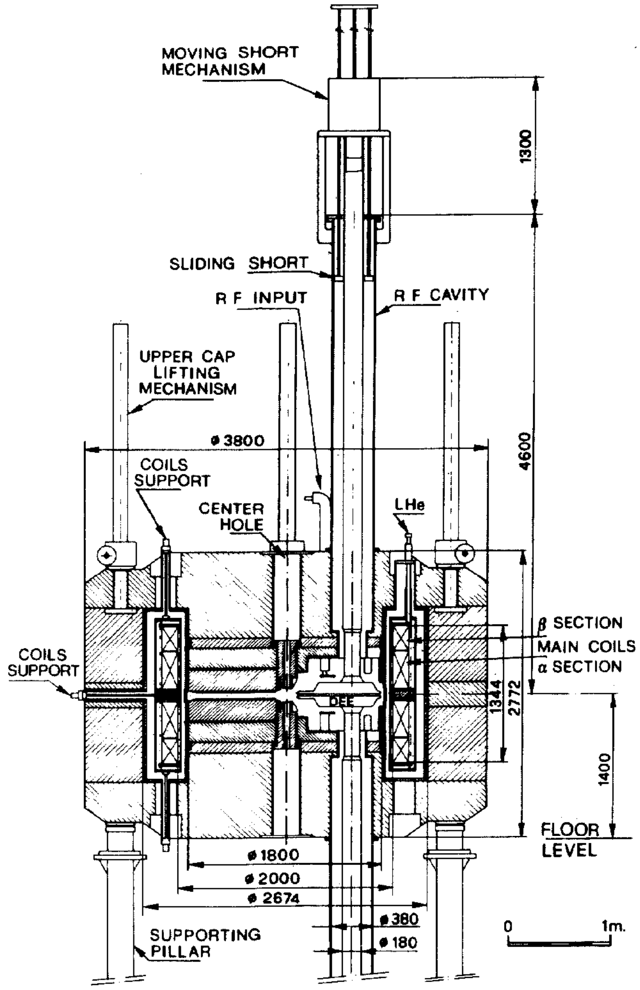

Fig. 3 - Cross section of the cyclotron.

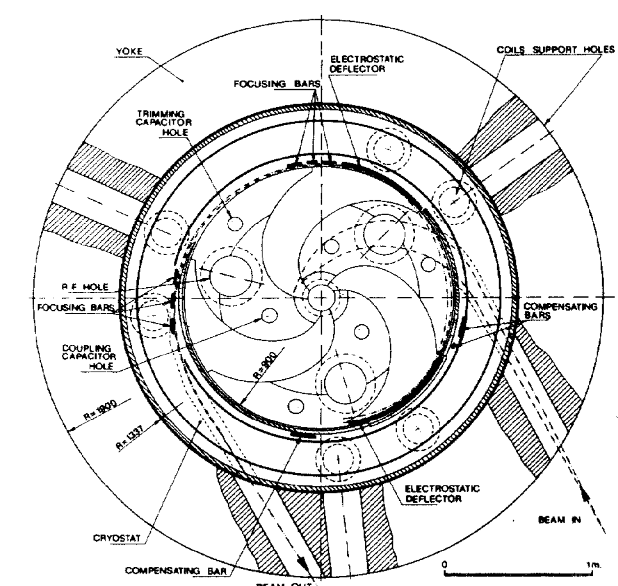

Fig. 4 - Median plane sketch of the cyclotron.

As shown both in fig. 3 and 4, a central hole of diameter 5 cm is provided in the sectors both for the insertion of the internal ion source and for axial injection purposes. In order to accomodate devices needed for axial injection, the hole is increased to a diameter of 25 cm through the poles and the yoke. The sectors are 33° wide at 9 cm radius, where they begin, and increase in width up to 46° at $R = 40$ cm. This width stays constant thereafter up to $R = 70$ cm. From then on it increases linearly with radius, reaching 52° at $R = 86.7$ cm. The sectors are then radial from $R = 86.7$ cm up to $R = 90$ cm, maintaining the constant width of 52°. The rationale for this radial cut is to decrease the axial focusing frequency ν_z in the region where the $\nu_R + 2\nu_z = 3$ resonance plays a major role in determining the machine performance.

As shown in fig. 3, the hills are split into two parts, in order to accomodate the twenty trim coils which will be wound around the upper hill part. The valley is shimmed in order to produce the required field shape. Also a 2.5 cm thick ring, which is actually part of the inner wall of the vacuum tank, extends up to 5.5 cm from the median plane, in order to limit the fringing field decrease.

The twenty trim coils will be of the type already developed at M.S.U.[4]. Each coil shall have two layers, of 5 turns each, of 6 x 6 mm^2 conductor and will carry a maximum current of 400 A.

The main coils, whose cross section is shown also in fig. 3 together with the cryostat, will be in a liquid helium bath. Their main characteristics are listed in Table III.

Table II. Yoke parameters

Pole radius = 90 cm
Yoke inner radius = 134 cm
Yoke outer radius = 190 cm
Yoke height = 277 cm
Yoke weight (incl. sectors) = 180 tons

Table III. Main coils parameters

Maximum At = 6.55×10^6 at 3500 A/cm^2 average density
Internal radius = 100 cm
External radius = 115.6 cm
Height of section α = 36.4 cm
Height of section β = 25.2 cm
Number of turns = 38
Layers in α section = 2 x 13
Layers in β section = 2 x 9

Table IV. Main conductor parameters

Dimensions = 13 x 3.5 mm^2
Cu/NbTi ratio = 20:1
Superconducting insert = flat cable ≃ 1.8 x 3.6 mm^2
Number of filaments ≥ 200
Filaments twist pitch = 25 mm
Maximum nominal current = 1944 A
Critical current (at T = 4.2 K , B = 50 kG) = 2700 A
Residual resistivity ratio ≥ 200
Total conductor length = 22.66 km
Total weight = 9.2 tons

The coils are split into two sections, hereby labelled α and β, α being the one closer to the median plane, for the purpose of isochronizing the total average field.

The coils will be wound with the double pancake technique, and will consist of 38 turns, with 26 layers in section α and 18 layers in section β as listed in Table III.

We have choosen a conductor of 13 x 3.5 mm^2 cross section, with a superconducting insert in a U shaped copper substrate. A 20:1 copper to superconductor ratio has been selected, the superconductor being NbTi. At the average maximum current density of 3500 A/cm^2 the current will be 1944 A. The main conductor characteristics are listed in Table IV.

Beam dynamics, extraction, injection

The previously described pole tips geometry gives a very good behaviour of the iron produced magnetic field. Agreement is excellent, within ± 50 gauss at most, compared with the theoretical "best" field needed to minimize trim coils power over the whole operating range of the machine[6].

With this field, the current densities in the α and β sections of the main coils needed to produce isochronism have been computed. The result is shown in fig. 5, where constant B_o and Z/A lines are also plotted.

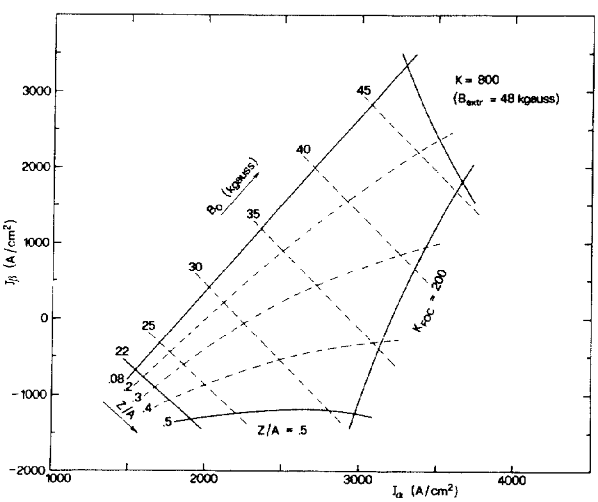

Fig. 5 - Operating diagram of the machine in terms of J_α and J_β. Constant B_o and Z/A lines are shown.

The existence of the $\nu_R + 2\nu_z = 3$ resonance represents indeed a problem, since this resonance[5] tends to move inwards the lower the magnetic field. For our machine the resonance moves inwards about 2.5 cm in going from 100 MeV/n to 44 MeV/n, for an ion with Z/A = 0.5. This is precisely the radial range which the electrostatic deflectors should move.

Extraction, as apparent from fig. 4, is in fact accomplished by two electrostatic deflectors positioned in two consecutive hills, the first being about 52° long and the second 40° long. Both shall be radially movable by the range discussed above. They are followed by a set of 6 magnetic channels, of the passive type, as used in the M.S.U. project[4]. Maximum electric field in the deflectors is 140 kV/cm.

Injection from the Tandem originates from a common point at 2.5 m from the magnet center. A steering magnet there provides the ± 1.5° deflection needed to match the required injection path for all particles and energies. Stripping occurs in a hill, the radial range being between 9 and 21 cm, with both azimuth and radius of the stripping foil being adjustable.

RF system

The main motivation of the 15 to 48 MHz frequency range is the possibility of accelerating, on the single second harmonics, all particles for energies between 100 MeV/n and 8 MeV/n.

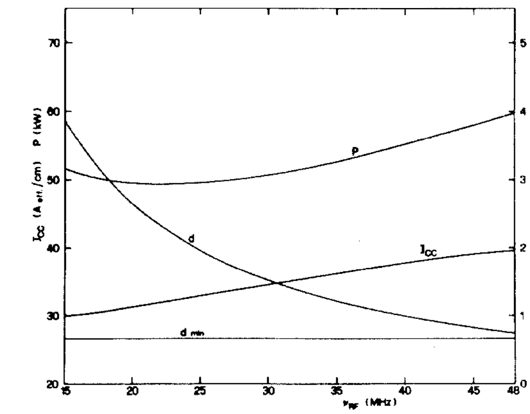

Fig. 6 - Power per cavity, current density at the short circuit and distance of the short from the median plane as a function of the RF frequency.

It is anticipated that, for 100 kV peak dee voltage, a maximum power of 75 kW may be necessary for each of the three cavities. The power, together with short-circuit current density in A/cm and the distance of the short-circuit from the median plane, is plotted as a function of RF frequency in fig. 6. The current density at the short should not exceed 40 A/cm.

For each of the three cavities, the RF power system will consist of a double stage power amplifier, driven by a 200 W broad-band amplifier. The first stage shall have a grounded cathode configuration, with a wide-band input. The second stage will have a grounded grid configuration, the power tube being an EIMAC 4CW 100,000.

As for the resonators, of the $\lambda/2$ coaxial type, it is anticipated that the outer coaxial will have a 380 mm diameter, while the inner one has a 180 mm diameter.

A 1:1 test model of the cavity, including the dee, is now being built for the purpose of checking the RF sliding contacts now envisaged, and the technological solutions adopted for building the cavities.

Project status

Orders are being issued for some of the major machine components, notably the magnet iron, RF power amplifiers, helium liquefier, superconducting cable and other ancillary equipment, like the power supply for the main coils, etc. It is expected that the machine construction will take between four and five years from now.

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