THE PROTONTHERAPY SUPERCONDUCTING CYCLOTRON

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In the Italian program for the cancer treatment with hadrons a superconducting cyclotron has been considered as a possible solution for a compact and cheap proton accelerator to be installed in few hospitals. The paper presents the main characteristics of a 200 MeV proton superconducting cyclotron and in particular it describes the technical solutions adopted in the design in order to reduce the construction and operation cost.

1 Introduction

In the last few years several Italian researchers have been involved in a large program for the cancer therapy with hadrons (protons and light ions).
This program consists in the design of:

- a hadron therapy center (installed in the North of Italy) equipped with a synchrotron (250-300 MeV for protons and 400 MeV/n for light ions) and several treatment rooms with gantries[1]. The estimate cost of this facility (including the building) is about 80 millions of dollars;
- a compact and accelerator to be installed in some hospitals suitably distributed in the national territory[2]. This accelerator is limited to protons with a maximum energy of 200 MeV. This energy allows the treatments of about 80% of the tumours for which the hadrontherapy is unreplaceable or in any way advantageous. The accelerators considered by different research groups are: a synchrotron, a linac and a superconducting cyclotron.
- an informatic network with links the hadrontherapy center with the hospitals equipped whith the compact accelerator in order to allow information exchanges on the patient, on the case-hystory, on the treatment planning and to optimize the use of the center and the satellites[2].

This paper presents the design of a superconducting cyclotron, we describe the main technical solutions adopted in order to keep within the budget constraints (10 millions of dollars) and to simplify the operation of the accelerator in the hospital environment.

2 Beam requirements and cyclotron parameters

The physical specifications of the beam delivered to the patient, as deduced by the clinical requirements[1], are summarized in the Table 1.

Table 1 : Requirements for the proton beam

Energy range	70 - 200 MeV
Energy spread	± 0.4 MeV
Beam intensity, max	10 nA
Beam emittance	≤ 15 π mm·mrad
Duty cycle	as large as possible

The superconducting cyclotron can completly satisfy these specifications. In particular because the change of the beam energy from 70 MeV to 200 MeV can be obtained with suitable absorbers (thanks to the high intensity of the beam delivered by the cyclotron) a fixed energy machine has been chosen.

In order to reduce the construction and the operation cost of the cyclotron, the design of the accelerator has been developed with the following assumptions:

- the isochronous magnetic field is obtained by a suitable size and positioning of the superconducting coils and a suitable shaping of the sector profiles. The final correct field is obtained by shimming the iron poles, without aid of trim coils or rods;
- the superconducting coils are operating in the persistent mode. The cryostat is equipped with two thermal shields (at 20 K and 80 K) cooled by a small cryorefrigerator. These choices allow to obtain a very low LHe

consumption (about 10 l/d) and avoid the use of a LHe liquifier, reducing the operation costs and the maintenance problems of a cryogenic plant;

- the RF cavities are operating at high harmonics and are installed inside the valleys. An unusual configuration of the cavities , realized with two stems, has been studied and shaped in order to have an optimized electric field distribution in the accelerating gap along the dees.

The main parameters of the superconducting cyclotron are summarized in the Table 2.

Table 2 : Main parameters of the cyclotron

General parameters	
Sector number	3
Extraction radius	0.70 m
Magnetic field at R=0	2.531 T
RF frequency	115.8 MHz
RF harmonic	3rd
Proton source	hot filament, internal
Magnet parameters	
Pole diameter	1.54 m
Hill gap (min - max)	0.0374 - 0.084 m
Valley gap (min - max)	0.14 - 0.90 m
Spiral costant (min - max)	3.05-3.30 rad/m
Valley aperture	68 - 75 deg
Coil diameter (internal - external)	1.68 - 1.90 m
Coil height	0.165 m
Gap between the coil sections	0.10 m
Magnetomotive force	$1.527 \cdot 10^6$ At
Overall current density	4208 A/cm^2
Yoke external diameter	2.8 m
Yoke height	1.8 m
Magnet mass	$70 \cdot 10^3$ kg
RF parameters	
Accelerating voltage (inject. - extr.)	42 - 85 kV
Total RF power	40 kW
Quality factor Q	3700
Cavities height, total	0.58 m

In the cyclotron project a particular care has been dedicated to the magnetic field shaping, the beam dynamics, the extraction process, the superconducting coils and the RF cavities.

In the following main results and some technical solutions will be briefly reported. Studies and results obtained with a 1:1 scale model of the cavities are reported in a separate paper presented at this conference[3].

3 Magnetic field design

The magnetic field design has been carried out by using the method already tested in the design of the heavy ion superconducting cyclotron designed and tested by the Milan group[4].

The Figs. 1 and 2 show respectively the upper view of the polar tips and a lateral view of the hill with the groove profile for the fine correction of the magnetic field. An isochronous field has been obtained up to extraction radius: the residual field defects always produce a small shift, lower than 10°.

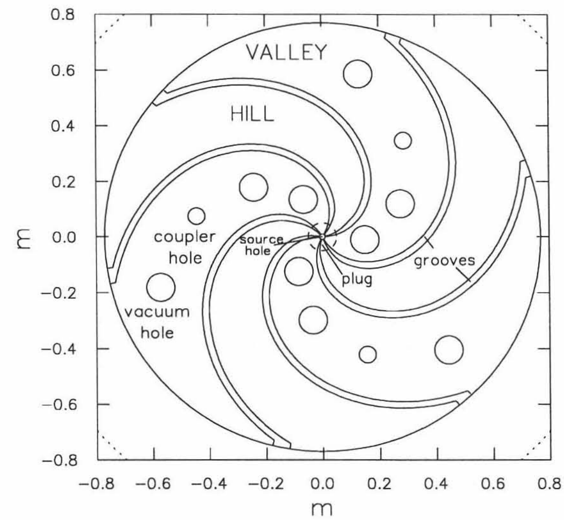

Fig. 1 : Upper view of the polar tips

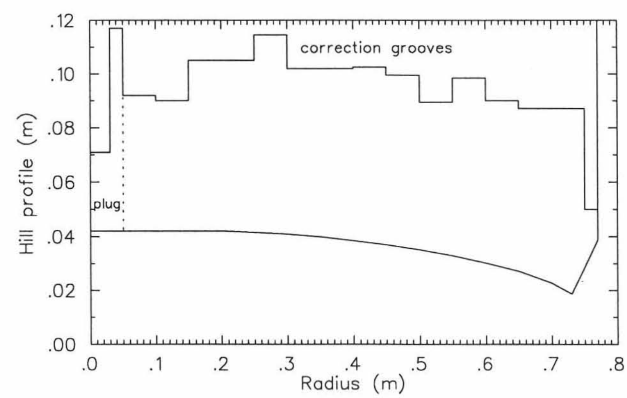

Fig. 2 : Hill profile

In Fig. 3 the axial and radial focusing frequencies of the accelerated particles and the main resonances are represented. The beam in the resonance map is far from the stop band ($\nu_r = 1.5$) and is extracted before the the resonance $\nu_r + 2\nu_z = 3$. The resonances $\nu_r - 2\nu_z = 0$ (Walkinshaw resonance) and $\nu_r = 1$ are crossed in the extraction region. This crossing is rather fast and the beam would not suffer losses if the first and second harmonics of the magnetic field are sufficiently low. Two sets of harmonic coils will be installed in the extraction region, in order to correct an eventual too high first harmonic and to superimpose to the magnetic field a first harmonic of suitable intensity and phase in order to obtain a more efficient resonant extraction of the proton beam.

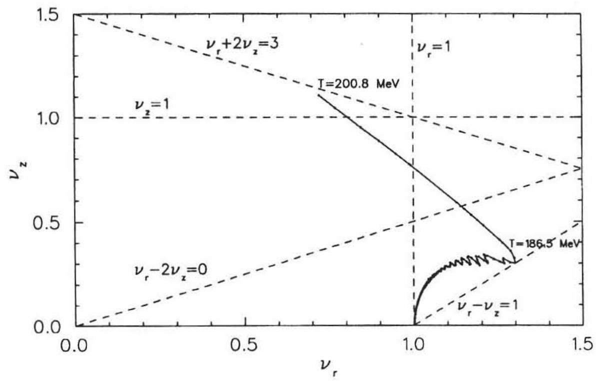

Fig. 3 : Axial vs. radial frequencies and map of the resonances

4 Extraction process

In a very compact cyclotron the extraction process is perhaps one of the most critical process. It was verified that the best configuration is that which uses the electrostatic deflector installed in the valley (inside the dee) rather than in the hill. The reason of this is that the fringing field is quite lower in correspondance of the hills (because they have very closed gaps), consequently the particles, deviated by a deflector installed in the valley, have to cross a region with a lower field and therefore can get out more easily.

The extraction system consists of an electrostatic deflector (30° azimuthal lenght, 6 mm gap and 100 kV/cm electric field) and four passive magnetic channels whose gradient is ranging from 13 T/m to 23 T/m and whose field bias is ranging from -700 gauss to about -2500 gauss. The Fig. 4 shows an overall view of the beam trajectories during the extraction process with the azimuth positions of the electrostatic deflector and three magnetic channels (M.C. in the picture).

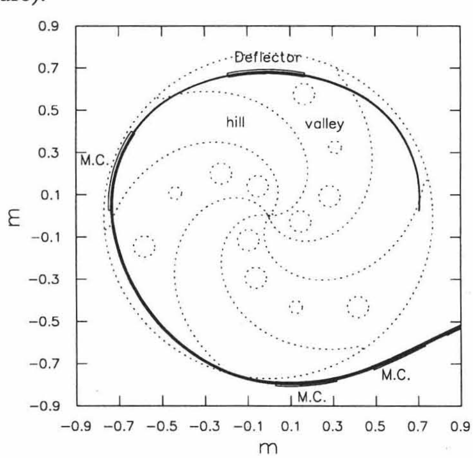

Fig. 4 : Beam trajectories during the extraction process

The Fig. 5 shows a vertical cross section of the electrostatic deflector with the high voltage feedthrough inside the dee. The calculated efficiency of the extraction is evaluated to be about 40% without resonant excitation of the first harmonic and 80% with resonant excitation.

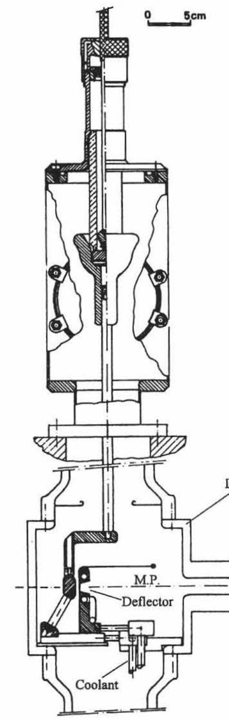

Fig. 5 : Vertical cross section of the electrostatic deflector with the high voltage feedthrough

5 Superconducting coil and cryostat design

The size and the position of the superconducting coils have been imposed by the magnetic field requirements. The coils will be realized with a NbTi cable soldered in a Cu matrix. In order to avoid the cable movements inside the coils under the magnetic forces, the coils will be impregnated with epoxidic resin in vacuum. The main characteristics of the coils and cable are summarized in Table 3.

Table 3 : Characteristics of coils and cable

Nominal current	500 A
Stored energy	~ 5 MJ
Maximum attractive force	$3.3 \cdot 10^6$ N
Maximum repusive force	$6 \cdot 10^4$ N
Total weight	$1.6 \cdot 10^4$ N
Maximum hoop stress	5 daN/mm^2
Cable dimensions	2.0×4.0 mm^2
Cu/NbTi ratio	12:1
Filament diameter	50 µm
Critical current (B=3 T and T=4.6 K)	1200 A
Twist pitch	50 mm
Copper RRR	100
Total cable lenght	21.5 km

To obtain a very low consumption of LHe, the superconducting coils are operated in the persistent mode. This is obtained by shortening the coils with a superconducting cable which may be driven normal by an heater in order to vary the current driving the cyclotron operating. When the desidered current has been reached, the heater is switched off, allowing the persistent-current switch to become superconducting. The external power supply is turned off and the current continues to circulate through the switch. It is then possible disconnect the current leads at their lower ends, thereby reducing the heat leak. A further advantage of persistent-current operation is that, provided resistances of the joint are sufficiently low, the stability of current is extremely good, much better than the one delivered by the best power supply.

The total resistance of the coils (mainly due to the cable joints) must be lower than 10^{-9} Ω in order to assure the isochronism of the magnetic field for about a month. The magnetic field of the cyclotron will be so operating 24 hours over 24 hours for about a month.

The switch cable is realized with NbTi superconductor in a cupronickel matrix in order to obtain, with a short length, an high resistance (few Ω when the cable is in the normal state). The switch protection in constitued by a diode set (2 or 3 diodes) connected in parallel with the switch. Switches for the persistent-current operation are frequently used in the medical MRI, for this reason this technique should be easily transferred to the cyclotron superconducting coils.

The low consumption of the LHe is assured by the persistent-current operation, the adoption of a double thermal shield, the few penetrations in the cryostat, and the use of fiberglass suspensions. A cross section of the cryostat at the azimuth of the vertical and radial tie rods is shown in Fig. 6. The power input in the LHe vessel has been estimated to be about 0.3 W, corresponding to a LHe consumption of about 0.42 l/h. This very low consumption will be obtained by eliminating the heat input of the current leads (about 1.5 - 2 W) and reducing of about a factor 100 the radiation input (the radiation input in the LHe vessel is about 1W if the thermal shield is operating at 80 K and about 0.01 W if the thermal shield is at 20 K). We will adopt a solution with two thermal shields (respectively at 20 K an 80 K) cooled by a commercial cryorefrigerator.

6 Conclusions

The present studyof a 200 MeV proton superconducting cyclotron have shown that the problems connected with the high compactness of this machine can be overcome.

The advantages, given by the reduced cost of the machine (both in construction and operation) largely counterbalance a design complexity and use of cryogenic systems. In particular the operation of the accelerator without a LHe liquifier can be easily employed in the hospitals since superconducting MRI are already operating.

Preliminary design of the most important components (magnet, superconducting coils with cryostat and the RF cavities) has been carried out and budgetary offers for them have been obtained by several firms.

The cost of the facility, including an absorber system, a transfer line and an analyzing magnets necessary to obtain the energy variation, has been estimated in 5 million of dollars.

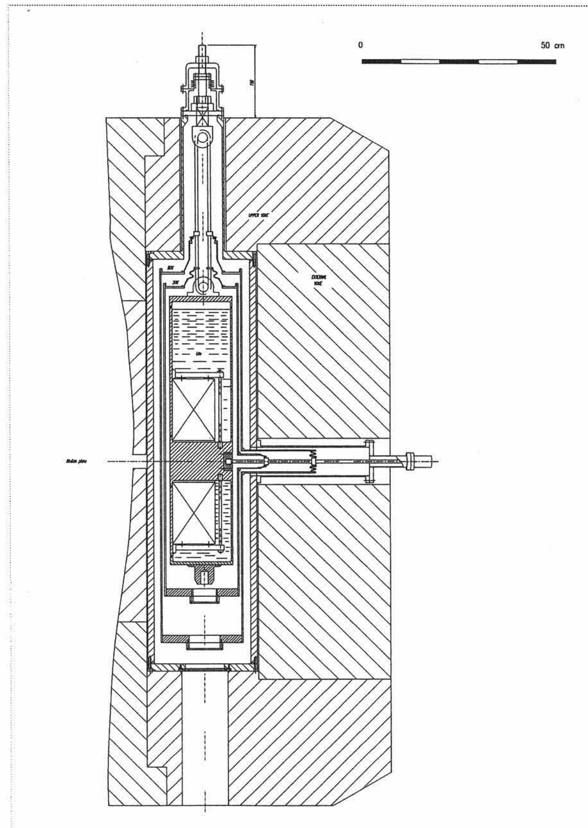

Fig. 6 : Vertical cross section of the superconducting coils and the cryostat at the azimuth of the vertical and radial fiberglass suspensions

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