A Compact Facility for High Energy Proton Therapy Based on a Superconducting Cyclotron

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Abstract

The global features of a facility that could be installed in an hospital for high energy proton therapy, are presented in this paper. The main elements are a compact superconducting cyclotron using a neutral beam injection scheme and an innovative "supertwist" gantry that takes advantage of the specific beam properties of the cyclotron.

1. Main Features

The main key-element of this facility is a three-sector superconducting cyclotron that presents the following advantages. Its compactness, inherent stability and ease of operation make it a very reliable and suitable component of a hospital-based proton therapy facility. The proposed neutral beam injection line makes it simple to switch the beam on and off within microseconds. Combined with its high inherent beam intensity, this feature makes the cyclotron particularly adequate for use with a raster or spot scanning device and possibly, in a treatment sequence coupled to organ movement [1]. In order to make the controls electronics simpler, the three dees are connected together in the central region so that only one amplifier is used for the set of three cavities and no RF phase control between the cavities is needed. No dedicated cylindrical vacuum chamber is planned. Vacuum seals are located near the coil cryostat and the various holes in the yoke. Pumping is to be performed through the six stems and corresponding vertical holes in the yoke.

Two options corresponding respectively to beam energies of 238 and 185 MeV [2][3] have been investigated and their characteristics are presented below. In order to avoid the well-known stop-band limit, a central groove machined along each sector center line is necessary in the higher energy case.

In addition, the main features of a new concept of a low-weight "supertwist" gantry, enabling to rotate the bean around the patient while providing variable beam incidence on the tumour volume, is also described.

The control system proposed for this facility is a modular, distributed one based on microcomputers with standard operating systems that control separately all the processes of the treatment rooms, accelerator and beam lines.

Table 1
Cyclotron main characteristics

Final energy	238 MeV	185 MeV
Number of sectors	3	3
Harmonic number	3	3
Sector groove	yes	no
Number of RF cavities	3	3
Particle frequency	36.666 MHz	36.666 MHz
Cyclotron outer radius	1.6 m	1.45 m
Cyclotron height	2.0 m	1.9 m
Total weight	90 tons	75 tons

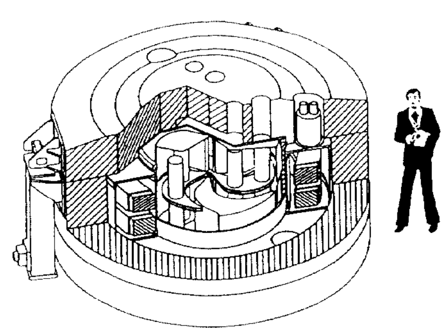


Fig.1 View of the 238 MeV Superconducting Cyclotron

2. Superconducting Cyclotron

2.1 Injection Line

An H^- beam is produced outside the cyclotron with a conventional source operating with a 100 kV voltage. Before entering the cyclotron, the H^- atoms are converted into neutral atoms by stripping off one electron when passing through an hydrogen gas cell (1 mTorr pressure). When the neutral atoms arrive in the machine center, a thin (25nm) carbon foil strips off the remaining electron. A test bench has been built and operated in order to check the validity of the concept and its expected performances. It can be seen on Fig. 2. An lifetime of more than 20 μAh was routinely obtained, which corresponds to about 20 days of normal hospital radiation therapy. A fast foil-changing mechanism enabling to store a set of stripper foils (for about a year of operation) and replace damaged ones, has been designed.

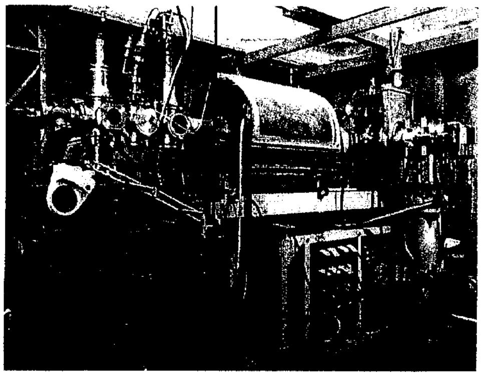


Fig. 2: Neutral beam test bench

2.2 Central region

The central region of the cyclotron has been designed with dedicated codes using the methodology described in ref. [4]. It can be seen in Fig. 3. Optimization of the dee-liner geometry has been performed, leading to a RF phase acceptance of +/- 30°, which can be easily reached with the buncher installed in the injection line. Simulations have shown that the injected beam must be focussed within +/- 1 mm at the stripper location.

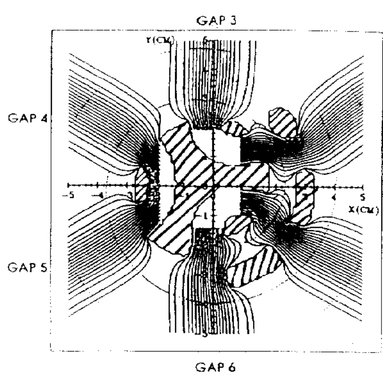


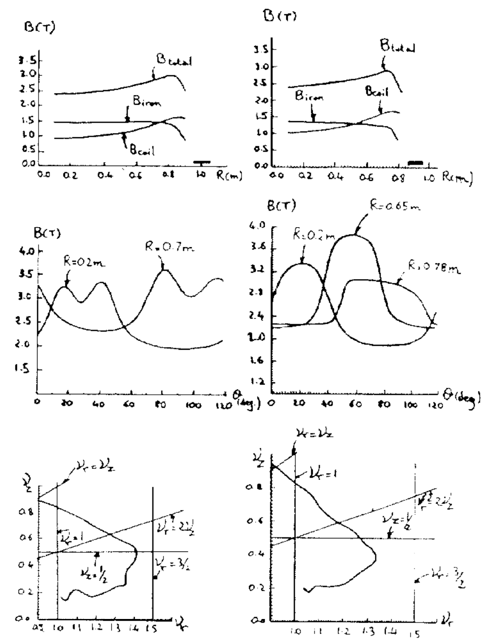
Fig. 3: Central Region

2.3 Magnet system

The magnet poles and coil configuration have been determined with the well-known method used for designing superconducting cyclotron [5], combining computations with POISSON for the yoke contribution and dedicated codes for the coil and sector contributions. Isochronism imposes a radially increasing value of the azimuthally-averaged field, which is mainly obtained by properly positioning the coil and optimizing its dimensions and current density. Adequate focusssing properties characterized by the radial and axial frequencies ν_r and ν_z are obtained by optimizing the sector and pole geometry. In particular care must be taken not to cross the 3/2 stop-band resonance near the extraction region. Sufficient vertical focusssing (ν_z>0.15) is obtained by adjusting the sector spiral. Fig. 4 shows the main characteristics of the magnetic field and focussing properties.

The superconducting coils would be operated in the persistent current mode in order to reduce the cost of operation . In routine operation, a standard power supply will be needed only to recharge the coils every few weeks to compensate for the very low but unavoidable losses in the coils. The total number of ampere-turns in each coil is about 800000 for an average density of 6800 A/cm^2 and a coil cross-section of 117.5 cm^2. The stored energy is 6.0 MJ.

No trim coils are required for the fine tuning of the isochronous field, which would be achieved by additional iron shims once magnetic field measurements are carried out.



a) 238 MeV b) 185 MeV

Fig. 4: Magnetic Field Profiles and ν_r - ν_z diagram

2.4 RF system

The three cavities are strongly coupled in the center by a dee connection. Power coupling is achieved by a single coupling loop located in one of the cavities. A classical coax transmision line is used to transfer RF power from the final amplifier. A full-scale model of the RF system for the 238 MeV version has been built and measurements carried out in order to check the theoretical predictions (power, voltage distribution and current density). It can be seen on Fig. 5. Two designs of the power amplifier have been made; The first one is based on a very classical scheme with a single cathode-driven tetrode in the final stage. An alternative has also been studied and would be to use four tetrodes in parallel with power combiners. Motor-driven pannels are used for frequency-tuning. With respective peak voltages of 80 and 130 kV at injection and extraction, a total RF power of about 150 kW is needed.

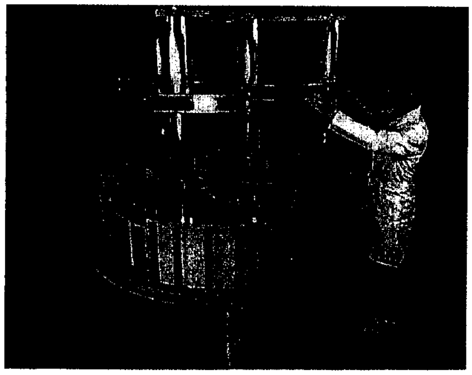


Fig. 5: RF Cavity model

2.5 Extraction system

Harmonic coils are installed on the sectors in the extraction region to generate the precession of the orbit center in order to increase the turn separartion. Beam dynamics simulations have been carried out in order to optimize the design of the extraction channel. Conditions close to 100% extraction efficiency have been obtained with the given values of the acceleration voltage. A classical extraction channel using simple focussing bars (without current) has been designed and is composed of two electrostatic deflectors followed by passive magnetic elements. Additional compensating bars will be added to compensate first harmonic effects at lower radii. The mechanical layout of the extraction system is shown in Fig. 6 for the 238 MeV version.

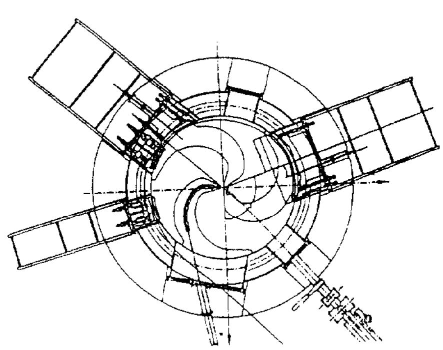


Fig. 6: Layout of the extraction channel

3. Beam Layout and Beam Delivery System

An overriding concern in designing the beam layout has been to save as much space as possible.and so use the small footprint of the cyclotron to reduce the cost of the building. Two alternative layouts have been proposed.

The first one is based on a modified version of the corkscrew gantry that has been designed and built at the Loma Linda Hospital [6].

The second layout referred to as the "supertwist" gantry corresponds to a significantly different and new design approach, which enables to decrease the gantry overall dimensions. As opposed to the corkscrew gantry, two twist angles in the main 270° achromat have been incorporated, with the effects that the beam spirals away from the point of entry and the isocenter is moved along the axis away from the accelerator. This gives more room for the patient and enables to decrease the gantry outside diameter.

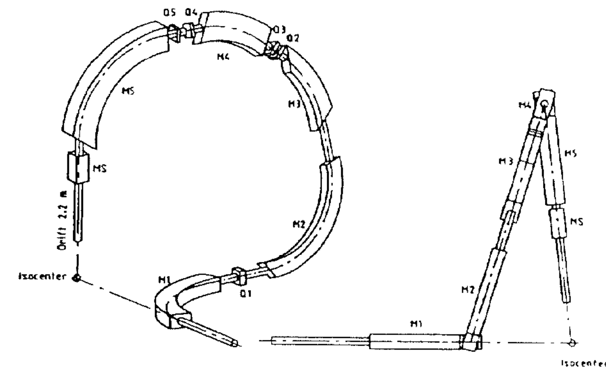


Fig. 7: Supertwist Gantry Without Support

4. Conclusion

Clearly, it is only possible to give here a very summarized overview of the project that has been developed. We tried to focus on the parts directly related to the accelerator and mainly to possibly innovative and simplifying concepts compared to cyclotrons used in Physics research.

5. Acknowledgements

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6. References

[1] E. Pedroni, "Accelerators for Charged Particle Therapy: Performance Criteria from the User Point of View", 10th International Conference on Cyclotrons and Their Applications, Vancouver, 1992, pp. 226-233.

[2] P. Mandrillon et al., "Status Report on the Design of a 238 MeV Superconducting Cyclotron", C.A.L. Internal Report, September 1993.

[3] N.Fiétier, "Preliminary Design of a 185 MeV Superconducting Cyclotron Dedicated to Proton Therapy", C.A.L. Internal Note, October 1993.

[4] J.P. Schapira, P. Mandrillon, "Axial Injection in the Orsay Project of a Superconducting Cyclotron and in the Medical Cyclotron MEDICYC", 10th International Conference on Cyclotrons and Their Applications, East Lansing, 1984. pp. 332-336

[5] G. Bellomo, L. Serafini, "Design of the Magnetic Field for the Milan Superconducting Cyclotron", INFN/TC-84/5, March 1984.

[6] J.M. Slater et al., Proceedings of the NIRS International Workshop on Heavy Charged Particle Therapy and Related Subjects, 1991, Chiba, Japan, pp. 82-91.