PROGRESS OF THE FEASIBILITY STUDIES OF THE EUROPEAN LIGHT ION MEDICAL ACCELERATOR

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Abstract: A status report on the feasibility studies for the EULIMA medical accelerator project is given. Recent advances in the assessment of the various basic accelerator types for the facility are presented in terms of their advantages for heavy ion beam acceleration. Details of the technical studies of various critical subsystems for the superconducting separated sector cyclotron concept are also presented.

Introduction

The main objectives of the EUropean Light Ion Medical Accelerator (EULIMA) have been defined recently in terms of biomedical and technical issues in a series of expert meetings [1]. In order to take advantage of the biological and ballistic properties of high energy light ion beams for radiotherapy, the European Commission is in favour of implantation in Europe of a prototype accelerator, EULIMA, for carbon, oxygen and neon beams of energy up to 400 Mev/nucleon. The facility is expected to treat 1000 patients per year with beams that are to be delivered both horizontally and vertically. The beam intensity should be compatible with a three dimensional scanning beam delivery system. A supplementary radiation area should be available for research and development of new treatment methods, including diagnostics and treatment with radioactive beams of positron emitters such as ^{10}C, ^{11}C, ^{15}O and ^{19}Ne. The accelerator should be cost-effective, of compact size and highly reliable, as its pilot role should enable an assessment of the clinical value of the light-ion therapy and the need for similar installations elsewhere.

The feasibility study of the facility is being carried out by the EULIMA feasibility study group hosted by CERN. The study has concentrated on several important issues concerning the basic conceptual design of the accelerator and its specific facilities. A detailed analysis of the beam delivery system, including a design of the beam energy degrader (with implications on accelerator operation) has been done, and is reported elsewhere at this Conference [2]. Following the initial concept of a superconducting separated sector cyclotron as the accelerator for EULIMA, several issues pertaining to the RF design have been clarified [3].

In this report, we present the advances of the conceptual studies of the accelerator system, and discuss several features of the separated sector and box-type superconducting cyclotrons and of a conventional synchrotron, as the basic accelerator options. Several technical details of the separated sector superconducting cyclotron mechanical design and extraction system are also reported.

Accelerator Conceptual Studies

Superconducting Cyclotrons

Previously, we have reported the basic features of the EULIMA accelerator based on the separated sector superconducting cyclotron [4]. The basic approach was that a machine with a bending constant of about 2000 MeV, needed to obtain the required 400-450 MeV/n $^{12}C^{6+}$ or $^{16}O^{8+}$ beam, could be built on the basis of a four-fold symmetric magnet excited by a single cylindrical superconducting coil, contributing as much as 50% of the necessary average magnetic field of about 3 T. This approach implies certain simplicity of the mechanical design, since the machine is of the open type, freely accessible in the valleys, and with a single cryostat. The beam is injected axially from an ECR ion source and accelerated in two RF cavities located in the valleys. The layout of the machine is shown in Fig. 1 and its operating parameters are summarized in Table 1 (SSC1).

As an alternative to the basic separated sector design aiming at the extracted beam energy of 430 MeV/n, a scaled down version, with the final energy of 340 MeV/n was also considered. Since the range of light ions scales as z^2/A, this design has the carbon beam in mind as the workhorse of the therapy programme as opposed to the oxygen beam in the basic design. The resulting design, with the basic parameters given also in Table 1 (SSC2), has hence been termed "carbon" machine, and obviously has smaller overall dimensions.

Further development of these solutions was primarily concentrated on the analysis of single particle dynamics in a highly spiraled magnetic field generated by the sectors, and in particular on the influence of magnet tolerances on the working diagram of the machine. Details of these studies are presented in ref [5]. Here, we note that the sector entrance angle and angular width as function of radius were precisely determined, as well as the dimensions of the main superconducting coil. The conductor cross-section was chosen, and the principles of the cryostat design laid out. The concept of trimming coils winding on the sector surface was considered, and their operation as harmonic coils conceived. As a consequence, the configuration of the extraction system could be studied and the mechanical properties of the structure analyzed. The results of these studies are presented below.

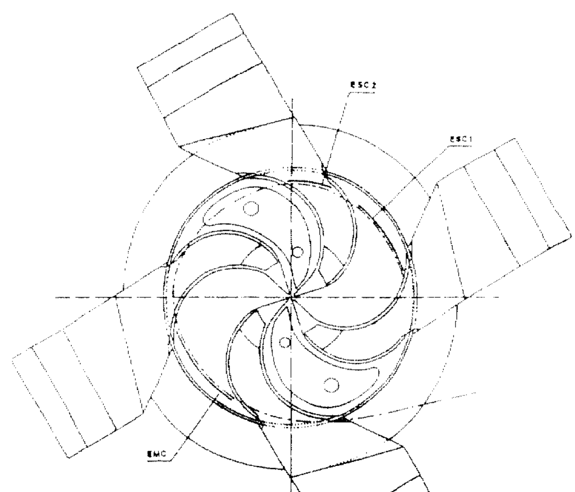

Fig. 1 Lay-out of the separated sector superconducting cyclotron for EULIMA

In the realm of superconducting cyclotrons, it was natural to compare the separated sector machine to a more classical design with a completely closed yoke. Several of these machines (MSU, Calk River, Milan, AGOR) have been completed, and their construction and operational experience is of great value for all similar projects. A four sector, four dee-in-valley design was analyzed, and its basic parameters (BSC) given in Table 1. The advantage of this approach is basically a slightly more compact design producing lower fringing fields in the vicinity of the machine. However, due to the closed valleys, a very high spiral has to be applied, limiting the RF frequency. Consequently, the apparent machine compactness has to be paid for by a four dee system, substantially reducing the space in the machine interior. Furthermore, a split coil (or a two coil) excitation (also originating from the box-type yoke), complicates the design of the cryostat. These properties of the box-type solution persist in the case of the carbon machine.

Table 1 Main Parameters of the SC Solutions for EULIMA

	SSC1	SSC2	BSC
Particle frequency (MHz)	17.4	18.0	20.5
Energy of z/A=0.5 beam (MeV/n)	430	340	440
Number of magnet sectors	4	4	4
Sector angular width (deg)	35	35	40
Average sector spiral (deg/m)	35	35	50
Coil internal radius (m)	2.31	2.12	1.90
Coil external radius (m)	2.61	2.42	2.05
Coil current density (A/cm^2)	2850	2500	3440
Number of RF cavities	2	2	4
RF frequency (MHz)	69.6	72.0	82.0
RF harmonic number	4	4	4
RF peak voltage	200	200	100

Synchrotron

Following similar ideas of other light-ion radiotherapy facilities, we have also considered a synchrotron solution for EULIMA. The natural advantage of a synchrotron is its easy energy variations covering, in our case, the interval from as low as 100 MeV/n, for superficial treatments, to 450 MeV/n, corresponding to the magnetic rigidity of 6.8 Tm. This interval is very similar to LEAR at CERN, and several technical concepts that have been installed in this machine could be exploited. The circumference of the EULIMA synchrotron is estimated at about 60 m (cf Fig. 2), and the machine could de designed in a form of a ring or a racetrack, depending on the site conditions and the design of insertion devices. Eight bending magnets of B_{max}=1.2 T and $\dot{B}_{max}$=2.5 T/s with 16 quadrupoles with G=10 T/m seem to be quite adequate for the lattice arrangement. The accelerating section will consist of one (or, eventually two) 10 kV ferrite loaded RF cavities. The vacuum is conceived to be reasonably low, 10^{-9} Torr, requiring UHV techniques but no in situ baking out seems necessary.

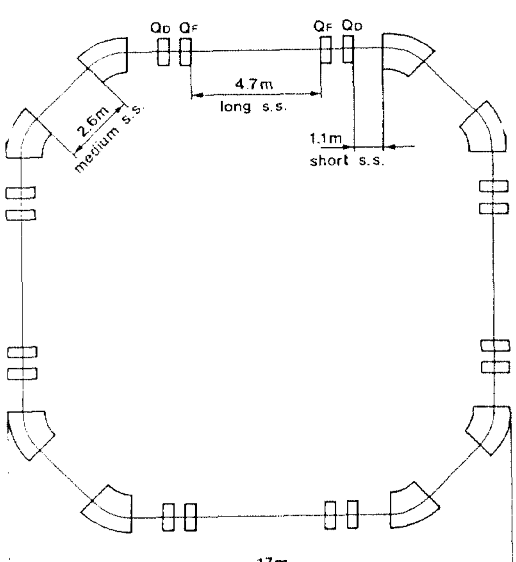

Fig. 2 An arrangement of EULIMA synchrotron lattice

A classical injection scheme has been considered, with a ECR ion source feeding the RFQ (or alternatively, a linac) with a repetition rate of 1 Hz, giving a total 10^{14} pps in a useful pulse of 100 µs at the exit. The extraction time in the range of 10 ms to few minutes (average spill length of 400 ms), gives, for example, ten slices of ten pulses each (and a mean dose per pulse of 10^9), with possible adjustment of individual slice energy, supplying a total dose of 10^{11}.

This basic design could be refined to include better monitoring of the extracted beam, and beam storage and cooling facility with a higher repetition rate injector. Hence, modulation of the beam intensity and programming of dose across the irradiation volume, as well as storage of radioactive beams could become possible.

The Mechanical Studies

One of the important issues of the EULIMA superconducting cyclotron feasibility study is the achievement of the mechanical stability of the magnet structure, as it should serve as a mechanical support for the vacuum chamber, the RF cavities and the extraction devices. To achieve the necessary stability, and having in mind that the machine should be installed in a hospital-based facility, we have chosen the solution of a passive structure as it is more appropriate for this kind of environment.

Taking into account the magnet symmetries, a model which covers only one eighth of the machine has been defined as shown in Fig. 3. Since the magnetic force, which is estimated on the basis of the TOSCA model of the magnet to be 7.8 MN, is much greater than the atmospheric pressure, for the purpose of an easier description of the ANSYS model, the cover of the vacuum chamber, which is conceived as a large cylinder covered by a disk that traverses the poles, has been suppressed in the valleys. The finite element model uses 3-D 20-node isoparametric solid with 3 degrees of freedom per node (u_x, u_y, u_z), and contains 1266 elements and around 7000 nodes. The model supposes that the magnet sectors are built as single massive pieces, which is certainly not a realistic assumption. However, since the horizontal yoke contributes most to the rigidity of the magnetic circuit, the model should be fairly correct in determining the behavior of the structure. Several calculations have been made on the basis of various boundary conditions. The main results of the calculations for the ^{16}O (SSC1) and ^{12}C (SSC2) machines are summarized in Table 2.

The deflections which occur in these stand-alone structures during energizing of the magnet lead to a reduction of the total accelerating gap of about 10 % (5 mm) in the central region of both machines. These displacements are large and may influence the stability of the cyclotron operating parameters. However, due to large magnetic forces and inevitable manufacturing errors of parallelism and adjustment, it will be very difficult to reduce the deflection of the poles below 1-1.5 mm. Hence, if this proves necessary, the pole face displacement during magnet energizing will be compensated by magnet shims, to be fabricated after initial magnetic field measurements.

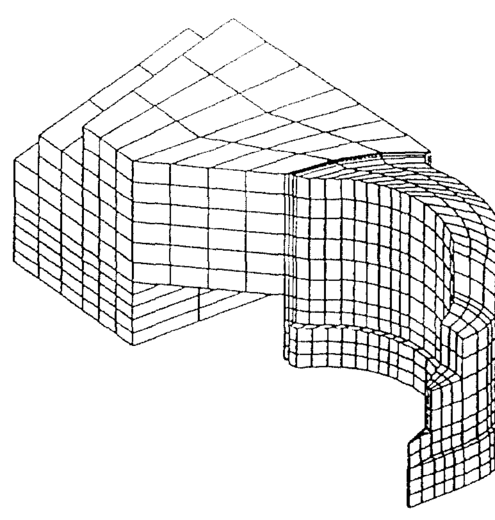

Fig.3 Finite element model of the EULIMA magnet

Table 2 Comparison of the mechanical structures of the superconducting separated cyclotron designs

	SSC1	SSC2
Outer dimension (m)	9.2	8.5
Pole radius (m)	2.1	1.9
Soft iron total mass (tons)	680	570
Magnetic force per pole (MN)	7.90	7.00
Vacuum chamber reaction (MN)	7.10	6.70
Max. deflection (mm)	-2.9	-2.3
Ave. Von Mises stress (kg/mm^2)	1.2	1.2
Max. Von Mises stress (kg/mm^2)	18	21

A very important point concerning the mechanical design is that the behavior of the magnet must be reproducible in order to recover properly the operating conditions of the machine. However, as seen from Table 2, a stress concentration occurring near the contact between the horizontal yoke and the vacuum chamber cylinder reaches the Von Mises equivalent stress value greater than 18 kg/mm^2, which is unacceptably high for soft iron and stainless steel. This stress concentration should be eliminated from the structure. As a consequence, a thick iron disk has been added on top of the magnet in order to reduce the torsion effect due to the spiral shape of the pole. This solution reduces the displacements to 1.7 mm, but since the torsion due to pole spiral is compensated only in the region close to the machine axis, the stress concentration around the contact between the horizontal yoke and the vacuum chamber cylinder still persists. Further reduction of the stress concentration from the structure will be attempted by designing a horizontal yoke with a spiral shape slightly different from that of the pole.

Beam extraction studies

The beam extraction system has been studied for both separated sector cyclotron designs. A preliminary layout, consisting of two electrostatic deflectors and one electromagnetic channel , as shown in Fig. 1, was studied and its main parameters listed in Table 3.

The design constraints for the hill and valley deflectors are quite different, and two types of deflectors are envisaged. As the clearance under the hill is narrow (50 mm), several technical details of this deflector need to be optimized. In particular, the shape of the cathode, design of the septum and of a reliable HV connection and supporting system have been considered. The gap between the septum and the cathode (5 mm) is dictated by optical requirements, while the length of the housing (70 mm) is given by the distance between the deflector and the vacuum chamber.

Tests with similar deflectors [6] have shown that a reduction of the deflector performances may be expected due to the modifications induced in the discharge mechanism by the presence of the magnetic field. Since a maximum electric field of 150 kV/cm for the valley deflector and 100 kV/cm for the hill deflector is required, maximum voltages of 75 kV and 50 kV, respectively, are implied for a 5 mm wide gap between the two electrodes. These figures are not too large in comparison with the known high voltage capabilities of the electrodes, but they are likely to be difficult to achieve in a machine with small clearances and a very high axial magnetic field. In order to minimize the electric field on the HV electrode, the effects of different geometries are under investigation.

In order to minimize extraction losses, the electrostatic septum must be as thin as possible. For this reason it has been proposed to construct the first septum of the valley deflector as a curtain of wires or strips. Each wire (or strip) is stretched by a spring, which retracts should the wire break. The technology for the wire septum is well known and it could be made very thin. In its construction the usually materials will be employed. However, in order to avoid outgassing, we propose to use ceramic cables for HV connections instead of the usual polyethylene.

Table 3 Main Extraction Parameters for the SSC1 and SSC2 Machines

	SSC1	SSC2
Extraction energy (MeV/n)	427.5	339.0
Extraction radius (m)	2.006	1.811
Emittance (π mm mrad)	0.14	0.16
Electrostatic deflector 1		
Position: valley (deg)	0.	0.
Length (deg)	45	40
Electric field (kV/cm)	150	150
Gap (mm)	5	5
Orbit separation		
entrance (mm)	-	-
exit (mm)	11	10
Electrostatic deflector 2		
Position: Hill (deg)	54.	50.
Length (deg)	35	35
Electric field (kV/cm)	100	100
Gap (mm)	5	5
Orbit separation		
entrance (mm)	16	14
exit (mm)	56	42
Electromagnetic deflector		
Position: Valley (deg)	-	180
Length (deg)	-	45
Orbit separation		
entrance (mm)	-	30
exit (mm)	-	52
Magnetic field (T)	-	0.35

Conclusions

The feasibility study of the EULIMA accelerator performed in the past two years concentrated on several important issues of biomedical and physical basis of the project. It has been shown that a superconducting separated sector cyclotron, while fulfilling the basic requirements for the reference oxygen beam energy of 400 MeV/n and extracted beam intensity of 10^{12} pps, can lead to a compact, cost-effective and overall technically feasible design. Nevertheless, other technical solutions have been considered and their relative merits evaluated.

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