THE EUROPEAN LIGHT ION MEDICAL ACCELERATOR

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Abstract: A brief account of the EULIMA light-ion cancer therapy initiative is given. The advances in the design of the EULIMA superconducting cyclotron booster are presented, and some details of the mechanical studies, magnetic field and RF system modeling, and of extraction studies are discussed.

Introduction

With regard to the biological and physical advantages of high-energy charged particle beams in cancer therapy that have been established in the past several years in a series of biomedical experiments and the clinical practice at BEVALAC, the European Organization for Research and Treatment of Cancer has proposed in 1985 the idea of a European Light Ion Medical Accelerator (EULIMA). Following this initiative, a group of potential medical users, radiobiologists, physicists and accelerator engineers from different European countries and CERN, have met to define the goals of the Project and to examine the basic guidelines of the feasibility study. Subsequently, a Scientific Committee and a Project Committee, with representatives from seven European countries, have been constituted to follow the development of the EULIMA project.

Several aspects of the biological and ballistic properties of heavy charged particles have been revisited recently in an attempt to better define the EULIMA reference particle beam and its energy [1]. It is presently thought that the properties of the 400 MeV oxygen-16 beam are sufficiently performant to consider this beam as a therapeutic reference. Furthermore, the choice of a light particle as a therapeutic tool may be complemented by the radioactive percursor and treatment beams (e.g. oxygen-15) for precise dose measurement, imaging and control of the treatment sessions. In either case, a necessary condition for an efficient therapy program is that the particle beam intensity be of the order of 10**9 pps in tissue.

The key technical concept of the EULIMA project consists in adding a booster accelerator to an operational facility with an established heavy particle (neutron or proton) therapy practice. Preliminary studies concentrated on a superconducting separated-sector cyclotron as a most likely choice for the booster, since the desired beam energy is within reach of a two-stage cyclotron facility. The basic parameters of this approach have been presented earlier [2].

In this report we present recent advances of the EULIMA superconducting separated sector cyclotron project. In particular, we discuss some details of the mechanical studies, the work on magnetic field calculations and RF modeling, and certain developments of beam injection and extraction.

General Parameters of the EULIMA

We recall that the EULIMA cyclotron is a separated sector machine of a four-fold symmetry, consisting of four tightly spiraled magnet sectors spanning 35 deg. that are driven into saturation by a common cylindrical superconducting coil. The accelerating system comprises of two spiraled cavities located inside the vacuum chamber. The beam of fully stripped oxygen-16 ions is injected either axially, from an external ion source of the OCTOPUS type [3], or radially, by stripping the beam coming from an injector cyclotron of performance similar to MEDICYC [4]. At the final radius, the beam is radially extracted by a system of electrostatic and magnetic channels. The layout of the machine is shown in Fig.1., and the major parameters of the ensemble are given in Table 1.

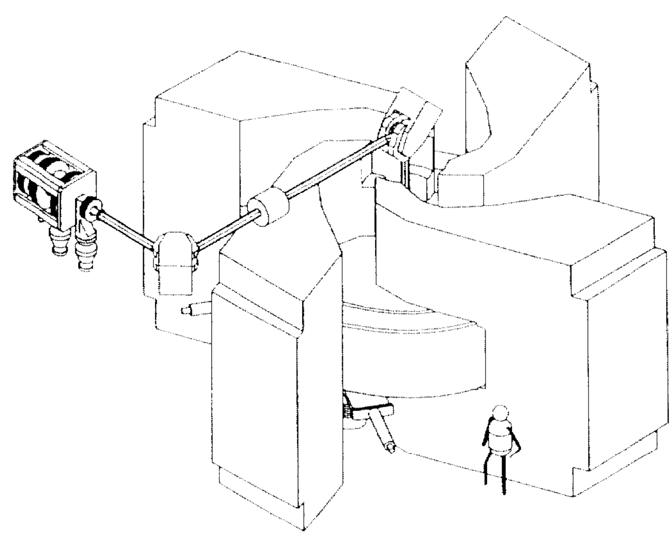

Fig.1

Table 1.

Particle frequency	17 MHz
Max. energy of oxygen beam	400 MeV/n
Number of magnet sectors	4
Sector angular width	35 deg.
Average sector spiral	30 deg/m
Coil internal radius	2.18 m
Coil external radius	2.48 m
Coil current density	1800 A/cm**2
Number of RF cavities	2
RF frequency	119 MHz
RF harmonic number	7
RF peak voltage at extraction	200 kV

The vacuum chamber

One of the main issues of the EULIMA mechanical design was the choice of the type of the vacuum chamber structure, since it plays a major role in the design of the RF cavities and magnet sectors. After considering several possibilities, it was concluded that in a single cryostat superconducting machine the only viable solution is a vacuum chamber of the cylindrical type with axial feedthroughs, which contains the RF cavities. In order to simplify the mechanical structure of the chamber, we opted for the design with completely circular covers, which traverse the magnetic sectors. This has shown to have a small effect on the ampere-turn number and iron geometry.

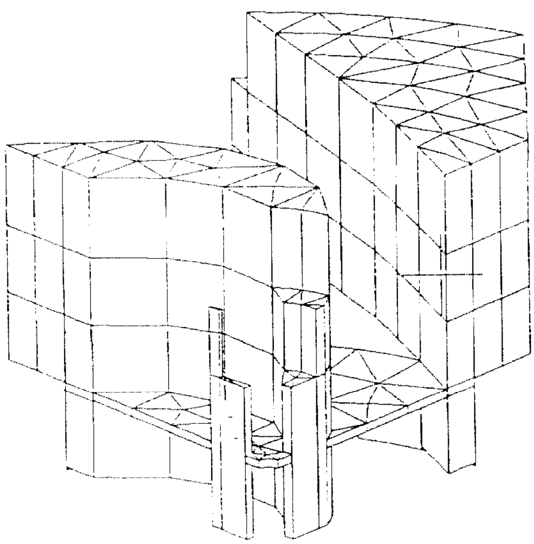

Fig.2

A detailed mechanical study of the vacuum chamber, based on the CASTEM stress-analysis package, followed. In Fig.2, a section of the vacuum chamber under the stress of magnetic and preassure forces is shown. The resulting maximum stress (Von Mises) in the 80 mm thick chamber cover reaches 51 N/mm2 with the corresponding maximum vertical displacement of about .6 mm.

Magnetic field calculations

In order to obtain a realistic approximation of the shape of the magnet sectors, the basics of the oxygen-16 particle dynamics had to be evaluated. This task is somewhat simplified in the EULIMA booster, since it is to be considered as a single beam-fixed energy machine. As a first approximation to the 3-D magnetic field maps we assumed that the magnet sectors are completely saturated. A fast integration technique was employed to solve the magnetostatic problem [5], and a number of coil and sector geometries was analysed. We found that we could accelerate the oxygen-16 beam with the required transverse stabilities up to about 500 MeV/n in a four-sector machine. The isochronism of particle motion is, at this stage of the design, obtained by the adjustment of the main coil current. Thus, employing an optimization scheme for the shape of the main coil, we could achieve a rather compact design. Fig.3 illustrates the azimuthal distribution of the computed magnetic field for the present magnet geometry.

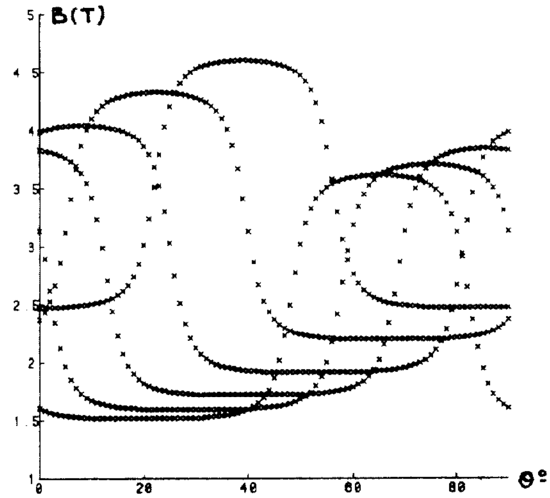

Fig.3

As mentioned, the computed magnetic field distribution served to determine the main properties of the beam dynamics, and, consequently, the sector edges and the location of the RF cavities end extraction elements could be defined. These field maps were also used for extraction studies. Based on these geometrical data, a fully 3-D magnetic field computation using the ANSYS finite element package was launched. This study, presently in progress, will give a detailed picture of the magnetic field distribution both in the median plane of the machine and exterior of the cyclotron.

The RF model studies

Besides the RF frequency of 119 MHz and harmonic 7 operation, the design goals of the accelerating system are an accelerating voltage of 100 kV/gap and 200 kV/gap at injection and extraction, respectively. An appropriate physical shape for the cavities was assumed, neglecting for the moment, the mechanical and thermal implications. We can see from Fig.4 that the cavity can be splitted in two almost equal halves along the S-S line. Each half is considered as a non uniform, variable cross-section TE10 waveguide. The coupling between the two halves has to be such that they resonate in phase opposition, as usual in a cyclotron.

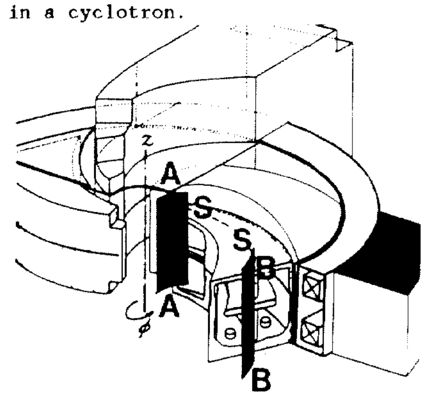

Fig.4

Due to symmetry, at the extremes A-A and B-B of the cavity, the voltages are maximal and minimal, respectively, and the sections see infinite impedance.

The waveguide is in cut-off (index 2) in the vicinity of the A-A region, whereas it is conducting elsewhere (index 1). Varying the cut-off wavelengths λ_{c2} and Z02, and the length l2, with respect to λ_{c1} and Z01, the ratio Vmax/Vmin and the final impedances change. There is a difficulty in interpreting the situation at the B-B section, where a capacitive coupling that generates an unwanted mode, exists. Because of the geometry and lack of space in the injection region, the cross-section of the waveguide is almost rectangular at the A-A section. For larger radii it gradually assumes the characteristic T shape of the loaded guides. The thickness of the delta electrode was taken as 10 cm, and its distance from the wall depends on the angle ϕg which determines the size of the accelerating gap.

For computation purposes, we consider the cavity as split into slices, for which a transfer matrix of a waveguide is written as if it were a transmission line. Unfortunately, for the loaded Zo's we are obliged to make use of approximate expressions [6], which are being corrected following the work with the URMEL program, which is still in progress. Varying $\lambda_{c}1$ and $\lambda_{c}2$, it is possible to get infinite impedance at both ends of the cavity with the appropriate voltage ratio. This procedure has been repeated for various values of ϕg. The minimum power, of the order of 150 kW/cavity is obtained with ϕg=16 deg. The minimum is very broad, as most of the power is lost at injection, where the gaps are of the order of 1 cm. Uncertainties of the calculations are related to the values attributed to Zo's. Measurements on simplified structures have been carried out to check their validity. Discrepancies of the order of 2./.3 db in the voltage ratio have been found. We expect to get better understanding of the electrical properties of the cavities after using the 3-D program MAFIA.

Beam injection

EULIMA could be either a stand alone accelerator using a high energy axial injection system, or a booster of an existing medical cyclotron. The basic features of the axial injection with the spiral inflector that was studied are: maximum ion source voltage of 200 kV, and injection radius of 4 cm. The trochoidal trajectories of partially stripped ions (Z/A=0.25) in a horizontal injection scheme, drift along an iron sector reaching a stripping foil located at point S in the central region. These two injection schemes are shown in Fig. 5.

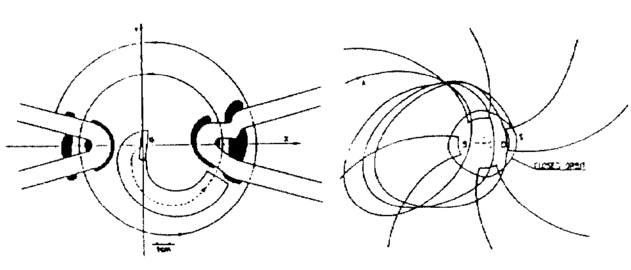

Fig.5

Beam extraction

Initial calculations of the extraction system assumed a single electrostatic deflector 48 deg. long located in the sector valley . An electrode gap varying between 4mm and 8 mm at deflector entrance and exit, respectively, and a maximum electric field of 150 kV/cm at the deflector entrance, were asssumed. The orbit separation of a 400 MeV/n oxygen-16 beam was calculated until the limits of the magnetic field were reached, or a full turn completed. As expected, the maximum orbit separation was obtained 90 deg. downstream from the center of the deflector, and its value slightly lower than 80 mm was not sufficient to obtain clean extraction.

Since a similar deflector cannot be placed in the downstream valley because of the RF cavity, a solution consisting of a shorter deflector placed inside the magnet gap, was proposed. Thus, a second electrostatic deflector 30 deg. long, with similar electrode geometry as the main deflector, was placed inside the magnet sector. The vertical gap between the magnetic poles being only 5 cm, the electric field in the second deflector was limited to 70 kV/cm. This deflector alone produces the orbit separation of 6 mm at the entrance of the second deflector, and a maximum orbit separation of 35 mm. However, this arrangement as a whole radically improves the orbit separation, since the turn separation rises to 130 mm after the beam has passed 30 deg. downstream of the second deflector where the particles exit from the magnetic field map.

Calculations have also been made to check the influence of the radial and vertical displacement and of the vertical divergence. It has been found that the maximum radial beam diameter which can be accepted without having the particles radially dispersed is 4 mm. Also, a particle vertically displaced by 3 mm was extracted without problems. A divergence of 2 mrad was shown to be acceptable in both planes, the maximum displacement from the equilibrium being less than 8 mm.

Conclusions

Several aspects of the EULIMA facility have yet to be studied, notably the design of the superconducting coil. These technical aspects, as well as the strengthening of the bio-medical arguments in favor of a cyclotron, or possibly a synchrotron, as the main machine, will be the subject of the full EULIMA proposal.

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