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

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ABSTRACT

An account of the biomedical background of the initiative for the European Light Ion cancer therapy facility is given. Recent advances of the feasibility study of the various subsystems of the superconducting separated sector cyclotron concept are presented. Certain alternative concepts of the facility design are also discussed.

INTRODUCTION

Since the idea of a European effort in light-ion radiotherapy has been proposed in 1985, the main objectives of the EULIMA project have been subsequently refined both in terms of biomedical and technical issues. In November 1988, a workshop supported by the Commission of the European Communities was organized by the Antoine Lacassagne Centre in Nice in order to review the potential values of light ion beam therapy [1]. It was concluded that there are both biological (high linear energy transfer), and physical reasons (Bragg peak) for expecting potential benefits of this kind of cancer treatment, even more since light ion beams allow a more accurate irradiation of the tumor, thereby preserving the surrounding healthy tissue. Clinical trials performed so far indicate that there is a clear advantage of this type of treatment for certain tumors types.

In order to meet the need for such a treatment, the European Commission is in favour of the implantation in Europe of a prototype accelerator, EULIMA, for carbon, oxygen and neon beams of energy up to 400 Mev/nucleon. This facility is expected to treat 1000 patients per year which implies that four treatment rooms with beams that are delivered both horizontally and vertically should be provided. The beam intensity should be compatible with a scanning beam delivery, and three dimensional scanning of the tumor volume should be possible as well. A supplementary radiation area should be available for research and development of new treatment methods, including diagnostics and treatment with radioactive beams of positron emiters such as ^{10}C, ^{11}C, ^{15}O and ^{19}Ne.

The proposed EULIMA accelerator should therefore produce light-ion beams of sufficient energy and intensity to be of clinical and biological relevance. Furthermore, this accelerator should be cost-effective, of compact size and highly reliable, as its pilot role should enable an assessment of the clinical value of light-ion therapy and the need for similar installations elsewhere.

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The detailed design study of this facility is presently being carried out by the EULIMA feasibility study group hosted by CERN. In this report, we present the advances of the feasibility studies of the current EULIMA concept based on a superconducting cyclotron [2]. In particular, attention is given to the mechanical concept of the cyclotron. Some alternative concepts of the machine design are also discussed.

THE SEPARATED SECTOR SUPERCONDUCTING CYCLOTRON CONCEPT

If a compact accelerator of the cyclotron type is to be built with an energy constant of about 2000 MeV, the only viable solution seems to be a separated sector machine with a single cylindrical superconducting excitation coil, contributing as much as 50% of the necessary average magnetic field of about 3 T.

Aside from mechanical simplicity of having a single cryostat, this concept brings several novelties in the machine design since the magnetic field in the valleys plays an important role in determining the machine parameters. The layout of the machine is shown in Fig. 1, where the four-sector magnet structure with a single cryostat is visible. An external source of the ECR type with an axial injection system for the stand-alone operation of the machine, as an alternative to a radial injection system from an injector cyclotron, is also shown. The main parameters of this machine are given in Table 1.

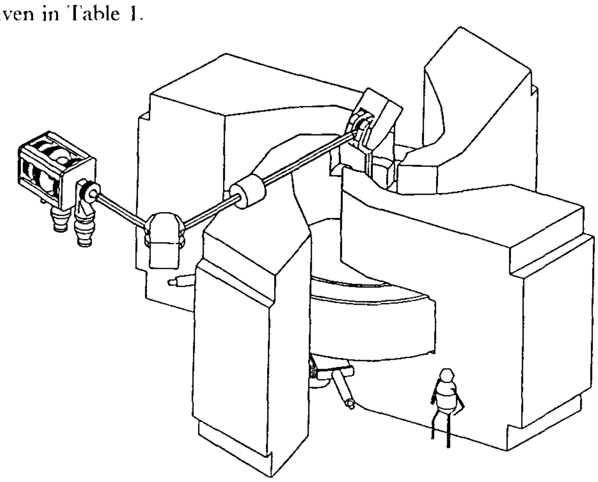

Fig.1. General layout of the EULIMA accelerator

Table 1
EULIMA Main Parameters

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	2.20 m
Coil external radius	2.60 m
Coil current density	2650 A/cm^2
Number of RF cavities	2
RF frequency	119 MHz
RF harmonic number	7
RF peak voltage at extraction	200 kV

The Ion Source and the Axial Injection

It was considered appropriate at the beginning of the feasibility study to explore the possibilities of operating EULIMA in either of the two regimes, i.e. as a stand alone dedicated facility, or as a booster cyclotron for an already existing machine with an active therapy programme, such as are those in Nice, Louvain−la−Neuve and Liverpool. In the former case, due to its excellent reliability and high intensity, an Electron Cyclotron Resonance ion source may be used to produce high charge state ions that are matched to the first accelerating orbits in EULIMA by a suitable axial injection system.

The feasibility of injecting a beam from an ECR source into EULIMA along its axis depends on various technical constraints, such as the injection energy (given either by a high voltage or an RFQ), the distance from the dee nose to the center of the machine, the maximum energy gain and the inflector type. An initial study has indicated that there should be no major technical problems in designing an axial injection system for EULIMA, provided that 125 kV can be achieved on the dee tips. There is enough room in the machine center to locate a "comfortably" sized inflector, with an interelectrode distance of the order of 1 cm and width of 2 cm. In this case, the inflector acceptance will be much larger than the emittance expected from an ECR source (150 to 200 mm mrad at 20 kV).

An important issue in assessing the feasibility of the axial injection is the particle beam that can be expected at the exit of EULIMA. In estimating this quantity, a value of 0.7 for the transmission of the beam to the outside the machine area may be considered as reasonable. In that case, the total efficiency is estimated to be at the level of 5−10% of the number of particles produced by the ECR ion−source. In terms of the number of ions delivered outside the machine area, the axial injection scheme could give about 10^{12} eμA of carbon, and 5 10^{11} eμA of oxygen beam, where the initial ion−source currents are those of the OCTOPUS source[3]

The RF cavities

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. A solution in the form of two RF cavities that are located in two opposite valleys has been investigated. Due to mechanical reasons the cavities should have a delta shaped electrode that is supported by the stem which is, to reduce the power losses, as broad as the electrode itself. Thus a cavity of the H_{101} reentrant waveguide type is obtained.

Although the H_{101} cavities have several advantages, notably a very high Q value (=40000) and hence a large energy gain for a given dissipation, a high harmonic number acceleration (h=7) has to be used if the cavity is to be reasonably high. Hence, an alternative solution based on a classical dee and operating on second harmonic is being examined. We would like to point out however that there might be a certain interest in raising the resonant frequency (e.g. to 136 MHz for h=8), since in that case the H_{101} cavity becomes smaller, reducing the mechanical problems connected to its introduction and removal from the vacuum chamber.

The Magnet Design

In our study of the magnet we considered a four sector design with a single superconducting coil. A sector gap of 50 mm and a coil contribution of the order of 1 T in the valleys were assumed. Thus, the poles of the magnet may be considered as completely saturated. With these assumptions, the coil shape was optimized (current density of 2650 A/cm^2), and sector angular width and spiral angle which give satisfactory transversal focusing and isochronism (35 deg and 30 deg/m on the average) were derived. Due to the complexity and great size of the magnet, several approaches to the 3D calculations of the magnetic field were employed. These studies are presented in detail in ref (4). A result that should be pointed out is that 3D TOSCA calculations, obtained with a magnet model shown in Fig.2, are in a quite good agreement with the calculations based on the saturated iron hypothesis.

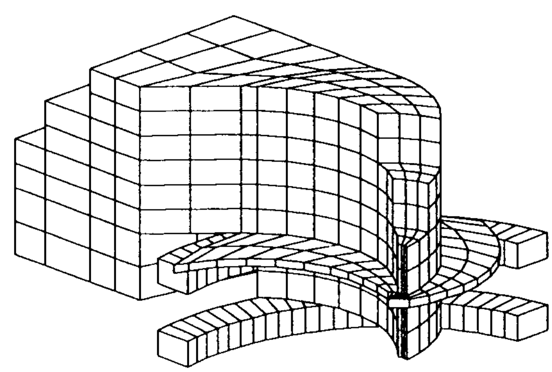

Fig.2. TOSCA model of the EULIMA sector magnet

With the extraction diameter of 1.9 m, a EULIMA sector magnet is 4.3 m high with an external radius of 4.60 m and weighs approximately 155 tons. These yoke dimensions, as discussed below, may be considered as a starting point for various concepts of increasing the mechanical rigidity of the structure. One should note that the top circular plate, in one of the proposed solutions, contributes about 0.1 T to the valley field, so that the exact sector dimensions are susceptible to further discussion.

The Mechanical Design

One of the important issues of the EULIMA feasibility study is the choice of the mechanical design of the vacuum chamber structure. Due to the size and design of the cryostat, an access to the removable parts of the machine (RF cavities, extraction channels, diagnostics probes,etc.) is possible only vertically. Hence, a concept of the vacuum chamber consisting of a large cylindrical body covered by a disk (traversing the poles of the magnetic sectors) has been proposed.

The total load on this structure includes the weight, the atmospheric pressure and the magnetic force, which is about an order of magnitude greater than the pressure. Due to the large radial size of the machine, considerable axial displacements may be expected in the center of the cover. Hence, two possible schemes for increasing the rigidity of the machine are presently being examined:

1) a thick iron plate is to be placed on the top of the magnet, forming a secondary yoke which supports the axial and tangential forces acting on the sector magnets. The height between the plate and the vacuum chamber should be sufficient for access to the internal machine components through large flanges in the valleys. Consequently, the magnetic structure need not be lifted for machine servicing.

2) all forces and moments are to be transmitted to an external structure, e.g. the concrete shielding. In this case, the upper part of the machine must be removed for access to the machine interior.

In order to quantitatively compare the two concepts a series of calculations using 3D finite−element structural package ANSYS were performed. The basic model of 1/8 of the machine (covering 90 deg in a helical shape) is constituted by the pole piece, the vacuum chamber cover and the horizontal and vertical yoke. All parts of the model are meshed with 8−node brick elements with 3 degrees of freedom per node. Adequate boundary conditions (all d.o.f equal to zero in the median plane, coupled d.o.f. at θ and $\theta + 90$, and axial deformations only on machine z−axis) were respected throughout the calculations. In the idealistic case that the iron yoke is a single piece, the maximum deflection under the weight, preassure and magnetic forces is 0.68 mm at the pole face edge, and may be considered as a limiting value for a stand−alone structure. Modeling the yoke as being assembled from different parts (e.g. 50 cm thick plates) that are separated by a thin layer of material of zero shear modulus, and representing the fixations by coupling the corresponding nodes, a value of 1.3 mm for the maximum deflection is obtained. It appears, therefore, that the means of fixing different magnet parts is very important for the rigidity of the structure, which certainly has to be reinforced.

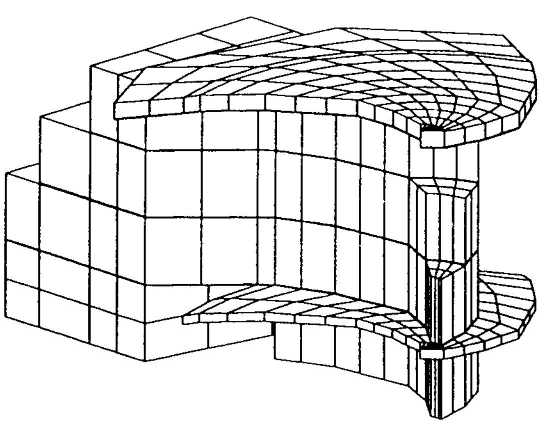

Fig.3. ANSYS model of the structure with a top plate

For these purposes, the model of Fig.3. was introduced, a solution in which it is possible to manipulate with the RF cavities and other equipment inside the vacuum chamber without lifting the horizontal yoke. For these reasons, the yoke is slightly higher than is otherwise needed for magnetic field design. The axial displacements along the pole axis and the axis of the top plate are shown in Fig.4 and 5., and reach maximum values of 0.84 and 0.62 mm respectively. The equivalent Von Mises stresses are 7.6 and 5.4 kg/mm^2. These figures should be compared to 0.45 and 0.31 mm in idealized case when the whole structure above the chamber cover is considered as a single piece.

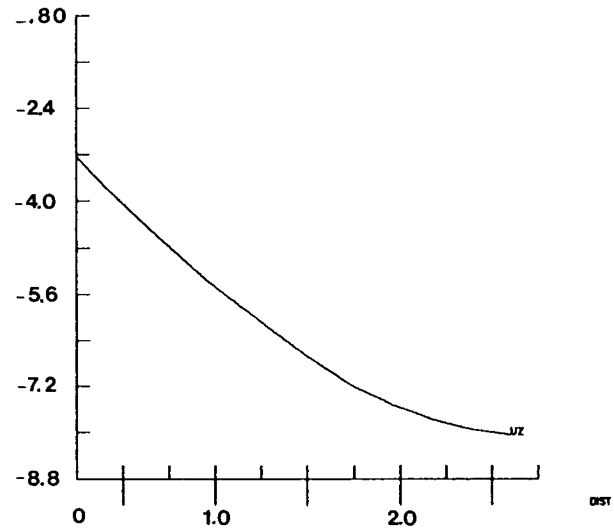

Fig.4. Axial displacement (U_Z x10^{-4} m) of the structure along the axis that passes through the azimuthal median of the pole face

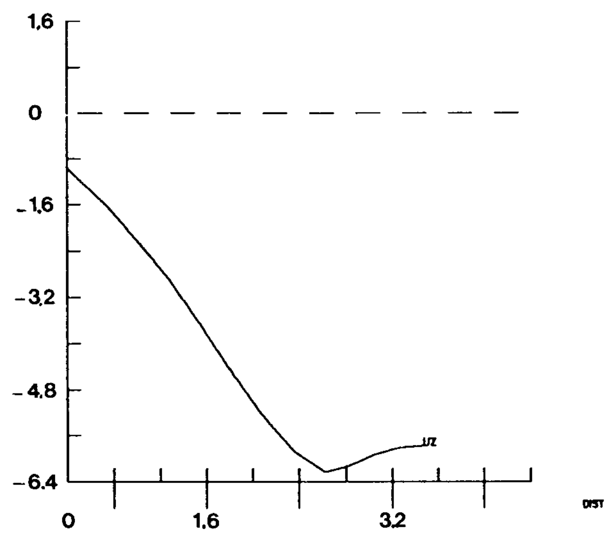

Fig.5. Displacement (U_Z x10^{-4} m) along the median axis at the level of the top plate

It may be thus concluded that the top cover plate, while adding about 20 tons to the 1/8 of the machine, does not suffice in providing adequate rigidity of the structure. This solution, however, has the virtue that it naturally compensates the large torsional forces due to the spiral magnet shape, which could thus be increased, if necessary.

In the second concept, the sectors are linked to the shielding beams with rods, so that the displacements are compensated by a system of hydraulic jacks. In order to get an idea of the necessary number of rods and of their size, the vertical displacements at the anchor points in the model were forced to be zero. A total reaction force of 3.5 MN was found, with a maximum of 0.6 MN close to the pole radius of 2.1 m, giving a rod diameter of around 10 cm (tensile stress of 10 kg/mm^2). The corresponding deflection of the pole face is very suitably 0.05 mm, as shown in Fig.6. However, besides the axial reaction, azimuthal forces as large as 0.02 MN are acting at the anchor points, so that torsional compensation must be foreseen.

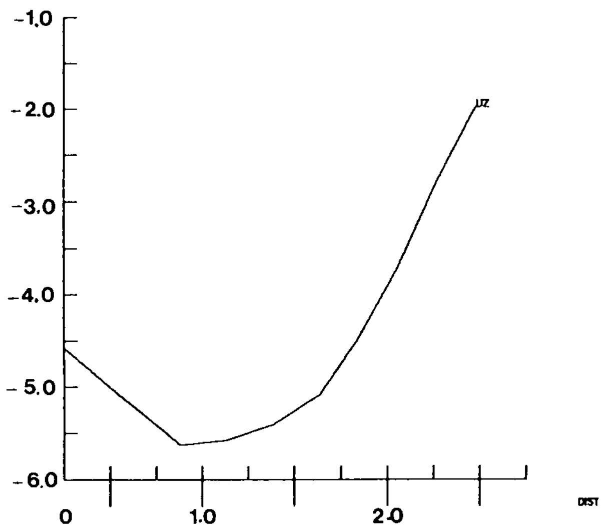

Fig.6. Displacement (U_z x10^{-5} m) along pole face axes for the rod suspended structure

A spacer between the pole faces can, of course, also be considered. A reaction force of 0.9 MN is obtained when no vertical displacement of the pole face near the z-axis is imposed. The corresponding maximum displacement is 0.25 mm at 1.0 m radius. In order to have the stress in the spacer only solution below 10 kg/ mm^2, it should be at least 10 cm long, which is quite unacceptable.

In finally evaluating the proposed solutions, it must be kept in mind that the passive rigidity of the first concept is more appropriate for a hospital environment than an active system coupled to the building structure. In any case, either of these concepts need further elaboration, since none is by itself completely satisfactory.

Beam extraction studies

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 assumed. The orbit separation of a 400 MeV/n ^{16}O 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 scheme as a whole radically improves the orbit separation, since the turn separation increases to 130 mm after the beam has passed 30 deg. downstream of the second deflector where the particles exit from the magnetic field map.

In considering the feasibility of this design, we recall that similar deflectors have been developed and successfully used in the extraction of high intensity beams in the 600 MeV cyclotron at PSI. The septum consists of tungsten or molybdenum strips about 50 microns thick and 3 mm wide which are stretched by springs. Due to the large vertical space available (1.20 meters), ESD2 could be realized in a technology similar to that employed for the CERN long electrostatic deflectors which use septum made of wires.

ALTERNATIVE CONCEPTS

Synchrotron

Several high energy light ion medical projects based on classical synchrotrons, have been proposed recently (HIMAC, LIBRA). Hence a first approach to such a solution has been initiated in collaboration with the LEAR group at CERN. Preliminary considerations show that a reduced LEAR type (square) synchrotron could be a realistic solution provided that some more focusing is added to its present structure. Nevertheless, due to the required space for the extraction the size of the machine cannot be kept smaller than a square of about 15 meters side. Furthermore, a costly injector system is needed, usually composed of an RFQ section followed by an Alvarez type linac giving an output energy of several Mev/nucleon. Thus a large and expensive building is required (for example, the building costs in the LIBRA project are as high as is the cost of the accelerator). Despite this disadvantage, classical synchrotrons permit an easy energy variation, which may be desirable for better treatment planning.

Compact superconducting Cyclotron

At the Michigan state University, H. Blosser is presently exploring the possibility of using a compact superconducting cyclotron with a closed yoke, similar to the K500 and K800 machines, as a basis for a medical accelerator of similar performance as EULIMA. A magnet with an external diameter of 5.4 m and weighting approximately 550 tons has been proposed. Although in this kind of machine beam extraction can be expected to be quite tedious and, due to lower energy gain and higher magnetic field, certainly more difficult than in a separated sector design, this alternative seems to be worth considering, as it may be considered as an extrapolation of existing technology.

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 fulfiling 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 need to be considered and their relative merits evaluated.

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