ADVANCES OF THE FEASIBILITY STUDY 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 superconducting separated sector cyclotron concept are presented, and alternative concepts of the facility design are 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 on the potential value of light beam therapy [1] was organized in Centre A. Lacassagne in Nice by the Commission of the European Communities. The conclusions of this meeting are the following:

1) There are both biological (high Linear Energy Transfer), and physical reasons (Bragg peak) for expecting potential benefits of this kind of cancer treatment.
2) Light ion beam treatment allows a more accurate irradiation of the tumor, thereby preserving the surrounding healthy tissue.
3) The 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.

EULIMA is expected to treat 1000 patients per year. This implies four treatment rooms with beams that are delivered both horizontally and vertically, and that are equipped with dynamic beam spreading systems to provide field sizes up to 20 x 20 cm^2. The beam intensity will be compatible with a scanning beam delivery, and three dimensional scanning of the tumor volume will be also possible. A supplementary radiation area will be available for research and the development of new treatment methods, including diagnostics and treatment with radioactive beams of positron emitters such as ^{10}C, ^{11}C, ^{15}O and ^{20}Ne.

To achieve the planned number of treatments per day, it is essential that patients should spend a minimum of time in the beam line. This means that the preparation of the patients must be carried out in adjoining rooms, equipped with all necessary radiographic and diagnostic aids.

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.

The detailed design study of this facility is 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], and discuss some alternative concepts of the machine design.

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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.

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

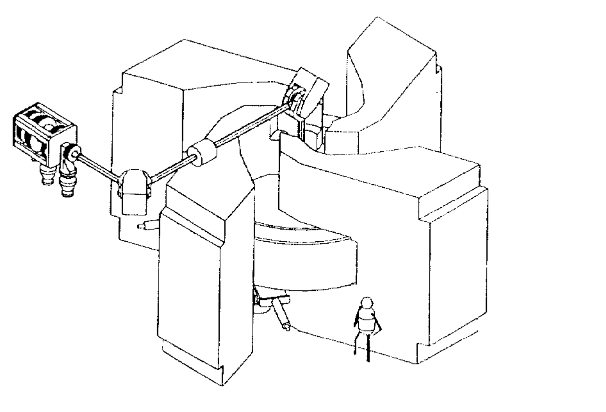

Fig. 1. General layout of the EULIMA accelerator

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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 "comfortable" 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].

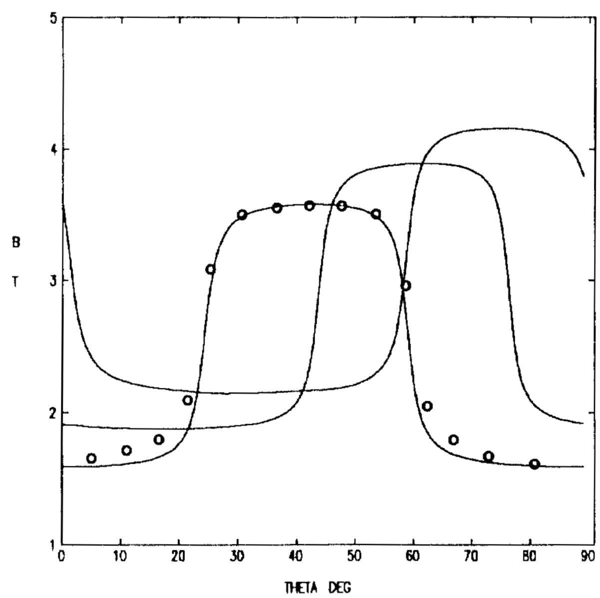

Fig. 2 Comparison of median plane field profiles for integral approach (full lines) and TOSCA calculations (symbols)

Magnet design and beam dynamics

A considerable effort of the feasibility study has been devoted to the design of the magnet, which, besides determining the beam dynamics conditions, enabled a better insight into the cost and implementation issues of EULIMA. Several details of the magnet design are presented in ref [4].

Because of the complexity of the magnet, several approaches to the 3D magnetic field calculations were employed. In Fig. 2, an azimuthal distribution of the median plane field obtained with the integral approach [5] is compared with the results of the TOSCA model of the magnet, confirming the hypothesis of complete saturation of the iron poles. Consequently, the procedures for field isochronization and sector spiral adjustment [4] seem to be adequate for the initial design.

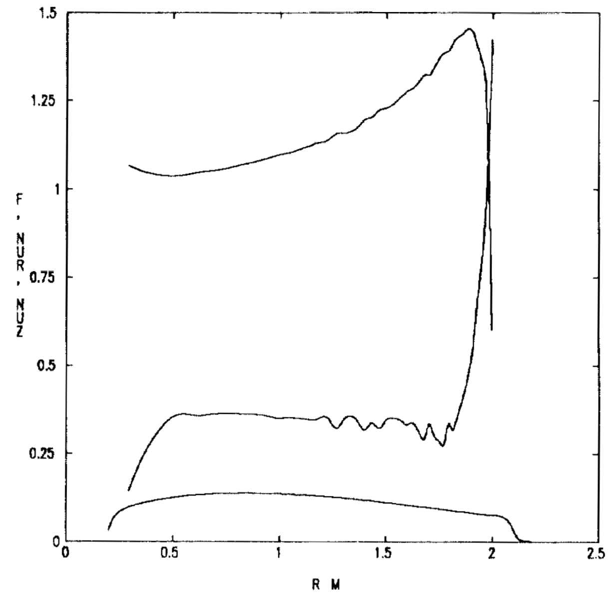

Fig. 3 The focusing frequencies ν_r , ν_z and the field flutter

An illustration of the properties of the beam dynamics in the resulting magnetic field is given in Fig. 3, where the radial and axial focusing frequencies and field flutter are given vs machine radius. As expected for a four – fold geometry, the radial focusing frequency ν_r rises steadily, approaching near the extraction point the $\nu_r = 3/2$ resonance. The axial focusing frequency ν_z is near 0.40 for all radii, which is mainly due to increasing spiral action which compensates for the field flutter drop beyond $r > 0.8$ m.

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, as shown in Fig. 4.

For the purposes of calculation, the cavity can be split in two almost equal halves along the S – S line. Due to symmetry, the voltages are maximal and minimal at cavity extremes A – A and B – B, where the sections see infinite impedance. Varying the cut – off wavelengths, the ratio V_{max}/V_{min} and the final impedances can be changed. Because of the geometry and lack of space in the injection region, the cross – section of the waveguide is almost rectangular at the section A – A. For larger radii it gradually assumes the characteristic T shape of the loaded guides.

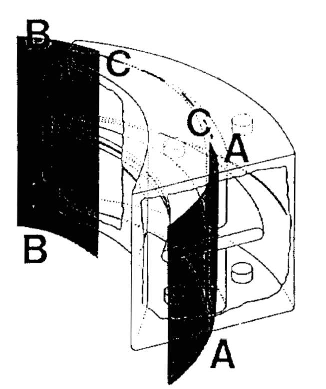

Fig. 4 H_{101} EULIMA cavity cross section

The minimum power in case of a delta electrode 10 cm thick and an acceleration angle of θ_g = 16 deg. was found to be of the order of 150 kW/cavity. The minimum is very broad, as most all power is lost at injection, where the gaps are of the order of 1 cm. Uncertainties in this estimate can be attributed to the values of the impedances at different cavity sections. Consequently, 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.

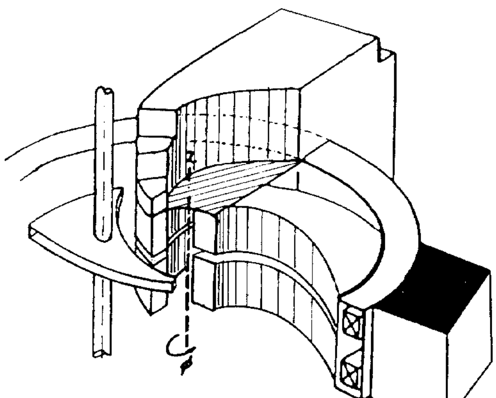

Fig. 5 A schematic drawing of the dee – in – valley accelerating structure

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. A sketch of this layout is given in Fig. 5. Besides the RF studies, several constructive solutions (stem – dee coupling and stability) are yet needed to decide between the two concepts.

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 are observed in the center of the cover (results of finite element calculations give a maximum deflection of about 5 mm). Hence, two possible schemes for increasing the rigidity of the machine are presently being examined:

1) 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.

2) 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. In addition, this plate contributes to the field in the mid – plane, reducing slightly the size of the machine. The height between the plate and the vacuum chamber could be sufficient for access to the internal machine components through large flanges in the valleys. Consequently, no lifting of the magnetic structure is necessary.

Considering that in the first case the mechanical rigidity of the machine must involve an active system coupled to the building structure, it seems that the second solution, with its passive rigidity, is more appropriate for a hospital environment. In any case, both oh these concepts need further elaboration.

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.

Acknowledgments

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