Feasibility Studies of the EULIMA Light Ion Medical Accelerator

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Abstract

This paper outlines the 2 years work of the EULIMA feasibility study group. Several technical issues for a dedicated light ion therapy facility, including the accelerator, the beam delivery system and a gantry are presented.

1. INTRODUCTION

Physical and biological advantages of high-energy charged particle beams in cancer therapy [1] (high precision of the irradiated volume and increased biological effect due to the high Linear Transfer Energy LET) have been established over a number of years in a series of biomedical experiments and clinical trials carried out in institutions whose accelerators were designed for nuclear physics research : Berkeley and Harvard in the United States, Uppsala in Sweden, Dubna and Moscow in the USSR, Tsukuba and Chiba in Japan, PSI in Switzerland. The total number of patients treated in 40 years is about 10,000 throughout the world.

As a result of several initiatives for a dedicated, hospital based high energy light ion therapy facility in Europe [2], a feasibility study was funded by the Commission of the European Communities, by the Conseil Général des Alpes Maritimes (France) and the many participating european institutes.

The main requirements for a dedicated light ion radiotherapy facility have been defined as follows :

1- Installed in a large hospital in order to get an adequate supply of medical and scientific staff for developing high technical level diagnosis and treatment systems.
2- Accelerator highly reliable and easy to operate.
3- Beam delivery system permitting to scan the beam over the tumour volume.
4- Possibility to use different directions of the beam (combined horizontal and vertical beams or an isocentric gantry).
5- Range in tissue : 20 cm for the Oxygen reference beam. This fixes the maximum energy for the Oxygen beam at 400 Mev/n. Ranges of other representative light ions are then :

	Carbon	Nitrogen	Oxygen	Neon
Range (cm)	28	26	20	17

6- Maximum dose rate at the tumour : 5 Gray/minute in a 2 liter volume. This determines the beam intensity of the Oxygen beam at 7 10^8 pps.
7- Maximum irradiated field : 30 x 30 cm^2.
8- Possibility to check the treatment plans by Positron Emission Tomography (PET) of the irradiated volume with radioactive beams. In a later phase, use of these beams for treatment could be considered [3].

2. ACCELERATOR

Two approaches to the machine design have been pursued, namely a cyclotron and a synchrotron. Being partly hosted at CERN, Geneva, the feasibility studies profited from the CERN technical expertise in superconducting magnets and cryogenics for the cyclotron, and conceptual and technical studies for the synchrotron [4].

2.1 Synchrotron

Following similar approaches of other light-ion radiotherapy projects, we have considered a synchrotron solution for EULIMA. This type of accelerator gives pulsed beams with an average intensity of 10^9 pps whose energy can be varied, covering in our case the interval from 100 to 400 MeV/n. This energy range is very similar to the LEAR accelerator at CERN, and several technical concepts that have been developed for this machine could be used. Two possibilities to design a more compact machine have been investigated : a separate function machine (SFM) of 59 m of circumference, with a weaker focusing (Qh=1.66 and Qv=1.75) which is more flexible for developments, and a combined function machine (CFM), if space is crucial. In this case a further reduction in size can be achieved. The focussing is obtained by adding a quadrupole component to the bending magnets where the correcting elements for the tuning and the sextupoles necessary for the excitation of the resonance are also integrated. A very compact CFM machine has been obtained (circumference of 48.6 m). The transition energy of both machines lies above the maximum design energy. For both machines the injection is a standard horizontal multi-turn process. The maximum number of injected turns is 20, with an efficiency close to 50%. The injected intensity is about 2.10^9 ions for both machines.

A classical injection scheme could be applied, with an ion source of Electron Cyclotron Resonance type (ECR) feeding a small Radio Frequency linac (RFQ) followed by a conventional linac (5 Mev/n) with a repetition rate of about 1Hz. This basic design could be refined to include better monitoring of the extracted beam, and a storage and cooling facility. Hence, modulation of the beam intensity and programming of dose across the irradiation volume could become possible.

2.2 Superconducting cyclotron

Having in mind a large number of patients, the accelerator must be capable of supplying beam intensities compatible with a multi-room beam delivery system, it must be cost-effective, of compact size and highly reliable. All these major specifications can in principle be fulfilled by a cyclotron. However, in order to achieve particle rigidity of 6.4 Tm (corresponding to a 400 MeV/n $^{16}O^{8+}$) in a cyclotron of a reasonable size, a superconducting coil has to be assumed from the beginning, since the average magnetic field can then be chosen so as to optimise the machine design both in terms of its functionality, size and cost. Taking into account that the EULIMA cyclotron is envisaged as a fixed-frequency machine, a closed super-conducting cyclotron design was investigated, and a solution comprising a single superconducting coil (exteranal radius, 2.32 m) and moderately spiraled sectors was found to be feasible. The total height of the hieht of the magnet is 3.6 m.

Mechanical studies have been performed to assess the general strength of the magnet structure assuming an integral vacuum chamber. The mechanical studies based on finite element computations have shown that this solution fulfils the requirements concerning the sector stability and the stress level in the structure.

Accelerating peak voltages on the 2 cavities are increasing from 100 kV at injection up to 250 kV at extraction. The total RF power losses are about 150 kW. Following measurements on a half-scale model, a more detailed investigation of the cavity losses has lead to a refined computation of the heat generation in the walls, and to the desing of a cooling system. Finallly, a mechanical design of the caity has been made.

Light ion beams to be injected into the cyclotron are produced in an Electron Cyclotron Resonance Source (ECRIS), which in its latest version delivers intensities of completely stripped Carbon, Nitrogen, Oxygen and Neon ions several orders of magnitude above what is needed for treatment [4]. An axial injection scheme using a spiral inflector was foreseen (elecric field of about 28 kV/cm in a gap of 8 mm). A preliminary layout of the beam extraction system, consisting of two electrostatic deflectors was analysed.

For the coil and cryostat design we adopted a solution in which the coils are wound in the double-layer pancake technique, and are cooled in direct contact at 4.2°K in a liquid helium bath at atmospheric pressure.

2.3 Accelerator choice

The cyclotron gives a continuous output beam, and the intensity can be controlled at the low energy injection side of the accelerator. This is well suited for the beam scanning system. In addition, the high intensity permits simultaneous treatment in different rooms by splitting the beam. Besides, the operation of such a fixed frequency accelerator is very simple and can be controlled by a PLC. On the other hand it is a fixed energy machine, so to change the range in tissue the energy of the ions must be degraded to the value corresponding to the deepest range for a given tumour. This results in increased divergence of the beam and a momentum spread of about 1%. The modulation of the range could be achieved by a simple rotating absorber. Nevertheless such a high energy cyclotron is more of a new design : in order to avoid a large number of RF periods throughout the acceleration process, high dee voltages should be used and the magnetic field should be accurately shaped. The magnet is heavy and if faults develop access to the interior will be time consumming.

On the other hand, the synchrotron requires costrly injectors and sophisticated controls devices to take profit of the inherent flexibility in energy, but has the following advantages :

- well known techniques which should reduce the construction time and the running-in time.
- short repair time, i.e. repairs within 6 hours.
- possibility for further increase of intensity through beam cooling, if necessary.

Based on these arguments, the Eulima project management board has recommended the synchrotron option as the accelerator for EULIMA.

3. BEAM DELIVERY

In conventional radiotherapy the irradiated field is inevitably large and the end point in range badly determined. (Even if the x-rays are well collimated outside the body they spread by scattering to several centimetres at depth). In contrast, ion beams can be exactly localized to a few millimetres laterally and in range. So far the treatment area has been defined by collimators, but in principle the tumour can be treated precisely by scanning in three dimensions over a designated volume of arbitrary shape. The beam delivery system must accomplish this reliably and safely at reasonable cost. This requires:

a) lateral deflection by a fast magnet.
b) variable range.
c) variable exposure time to achieve a uniform biologically effective dose.
d) position sensitive monitors.
e) rapid switch-off in case of misfunction.

A corollary is that the diagnostician must determine where the tumour is with comparable precision.

In a typical treatment plan, by adjusting the range the Bragg curve is placed successively at various depths. Each depth slice is scanned in the transversal plane over the tumour cross-section at that depth. In general each slice requires a carefully computed non-uniform dose. The scanning across the lateral plane may be either continuous (called "raster scan") or intermittent (called "pixel scan"). Detailed scanner studies have been carried out [6]. The characteristics are closely related to the geometry of the treatment rooms and the required optical performances.

The raster scan technique is convenient for a synchrotron. A prototype has been successfully started in 1991 at GSI [7].

4. GANTRY

The possibility of a variable incidence angle system around the patient for a 400 Mev light ions beam was also investigated. Such a device (gantry) will use classical magnets mounted on a large cylindrical support. This design requires detailed optical and mechanical studies in order to fulfil the main optical constraints, namely to focus the beam into a small spot at the target volume, with reasonable apertures of the magnets and size of the entire device.

Various designs have been investigated but setting the patient off-axis, as in the PSI [8] proton gantry design, allows a significant reduction of the gantry diameter. Mechanical studies have been carried out using finite elements methods in order to design a structure for maintaining the alignment of the beam line in such a way as to insure a 1 mm accuracy in dose delivery for every gantry angle. The overall longitudinal dimension of the gantry is about 19 m and its diameter 7.5 m. (See figures below).

5. CONCLUSIONS

The feasibility studies comprise the following 3 parts :

1. Conceptual design studies of all technical components of a 400 Mev/n a light ion facility comprised of an accelerator, beam transport system,beam delivery systems. This phase is now over and recommendations have been made.

2 - An experimental program which was set up in order to establish the radiobiological properties of several light ions at various parts of the Bragg curve.These studies are carried out at GSI and GANIL and additional experiments are needed to determine the optimal ion for therapy.

3- Socio economical impact studies with the following goals:
- establish a list of clinical indications based on epidemiological data from different european countries in order to provide a preliminary estimate of the number of patients suitable for light ion treatment.
- estimate the cost per treatment and compare it with the present price of cancer treatment
- evaluate the number of treatment rooms and optimise the patient turnover.
- Medical logistics to treat several thousand patients per year ; a preliminary estimate indicates that a total number of 3.000 patients could be treated per year.
- Analysis of the cost of the treatment.

All these non-technical aspects should be thoroughly investigated before a decision to build such a facility in Europe could be taken.

6. ACKNOWLEDGEMENTS

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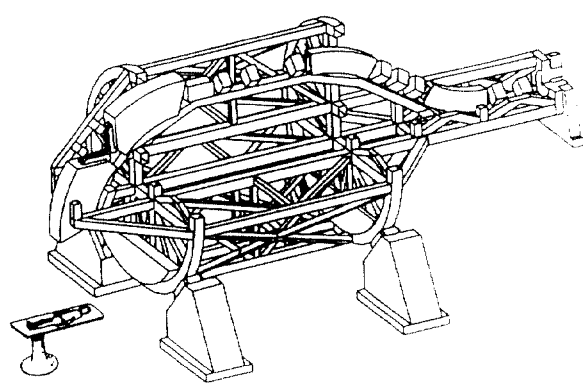
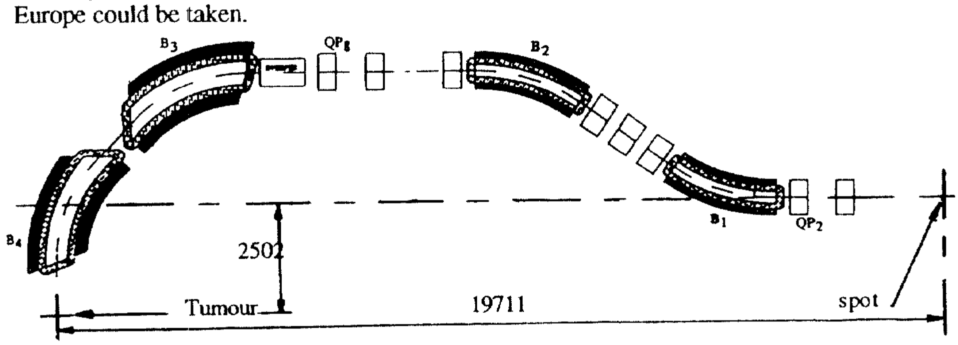


General view of the structure from which one fourth has been removed in order to show clearly the beam line magnets.



Layout of the cylindrical gantry with the patient off-axis (conventional magnets).
The beam is coming in along the axis from the right side.