HICAT- THE GERMAN HOSPITAL-BASED LIGHT ION CANCER THERAPY PROJECT

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Abstract

Starting in 1997 about 200 patients have been successfully treated with ^{12}C-ions by means of the intensity controlled rasterscan-method within the GSI experimental cancer treatment program. The developments and experiences of this program, accompanied by intensive discussions with the medical community, led to a proposal for a hospital based light ion accelerator facility for the clinic in Heidelberg, capable of treating about 1000 patients per year. [1]
Major aspects of the design are influenced by the experiences of the GSI cancer treatment program; the requirements of this facility, however, exceed in many fields those of this pilot project.
The main characteristics of this facility are the application of the rasterscan method with active intensity-, energy-, and beamsize- variation both at two treatment places after horizontal beam lines and in combination with the usage of an isocentric light ion gantry. The accelerator is designed to accelerate low LET ions (p, He) and high LET ions (C, O) to cover the specific medical requirements.
The project realization has been started and the beginning of the accelerator installations is planned within the first half of 2005.

INTRODUCTION

The realization of a dedicated cancer therapy facility at the University clinics of Heidelberg has been started. The facility is designed to treat about 1000 patients per year with the intensity controlled rasterscan method [2], developed at GSI and successfully applied with carbon ions to about 200 patients treated for more than 6 years within the GSI therapy pilot project [3].

The Intensity Controlled Rasterscan Method

Whereas most of the existing treatment facilities use 'passive' devices, e.g. beam scrapers and boli to achieve a conformed irradiation of the tumor volume, within the rasterscan method exclusively an active variation of the requested beam properties is performed. This method gives the advantage of achieving a much better tumor control, especially for irregularly formed tumor volumes, and gives in a addition a good possibility to react on organ movements.

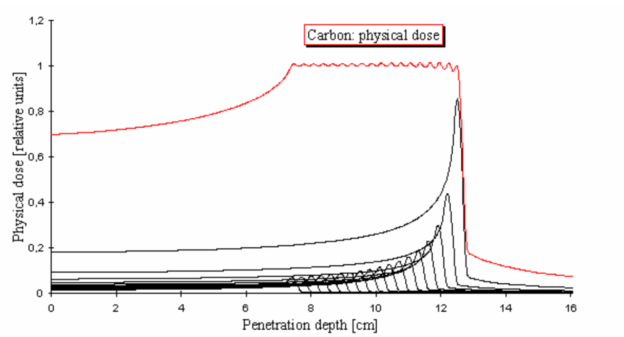

Figure 1: Depth dose profile.

The principle of this treatment method is that the tumor volume can be composed of slices ('isoenergy-slices') of different depths. These slices are irradiated with ions of specific energies, correlated to the requested penetration depth. As the applied dose is enhanced near the maximal range of these ions ('Bragg-peak') a large dose can be applied to the tumor, while the surrounding tissue is affected with much lower dose rates. By a sequential treatment of such slices with adequate intensities the requested dose profile for the tumor volume is achieved. (Fig. 1).

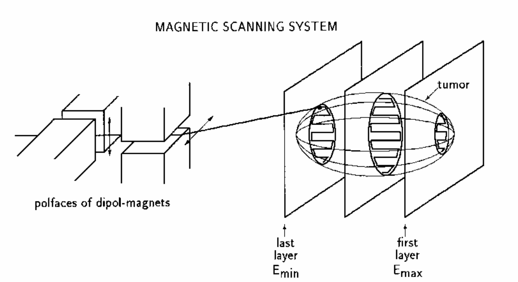

Figure 2: Rasterscan-Method.

To cover the lateral dimensions of the tumor the ion beam passes two fast scanner magnets (Fig. 2) that deflect the ions both in horizontal and vertical direction after being accelerated to the requested energy in a synchrotron and slowly extracted .

The rasterscan control system determines the excitation of the scanning magnets to deposit the requested dose profile, measuring the number of ions at a specific irradiation point by means of ionization chambers and the position and beam width at each scanning point by means of fast multiwire proportional counters in front of the patient. When a required dose limit of an isoenergy-slice has been reached the beam extraction is interrupted very quickly (< 0.5 ms).
This method demands fast, active energy-variation to provide different penetration depths and intensity-variation to minimize the treatment time. Within the Therapy pilot project at the existing GSI accelerator complex a system was developed, that for carbon ions between 90 and 430 MeV/u allows the reliable request of 255 energy-steps for sequential synchrotron cycles. Beside this energy variation also intensity- and beam spot variations at the treatment location on a pulse to pulse basis can be requested.
During the treatment periods of the last years several improvements of the treatment procedure (e.g. a fast position correction system) have been achieved.

DESCRIPTION OF THE HEIDELBERG FACILITY

The main requirements of the proposed facility can be summarized as follows:

- treatment both with low and high LET-ions
- fast change of ion species
- 3 treatment areas to treat a large number of patients
- integration of an isocentric gantry
- ion-species : p, He, C, O
- ion-range (in water) : 20 - 300 mm
- ion-energy $^{(*)}$: 50 - 430 MeV/u
- extraction-time : 1 - 10 s
- beam-diameter : 4 - 10 mm (h/v)
- intensity (ions/spill)$^{(*)}$: $1{*}10^{6}$ to $4{*}10^{10}$

$^{(*)}$ (dependent upon ion species)

These requirements are similar to those already established at the GSI-pilot project, but extended by additional ion species and the gantry application.
In addition to ^{12}C-ion irradiations, proton treatments are requested for special tumor species in order to compare the medical results of C-treatments to those achieved with p-beams, for which an extended medical data base is available. For protons there is a significant blow-up of the beam diameter over the path length, which restricts the localization for deeply seated tumors. As this effect is much smaller for He-ions, this ion species will be favourable for a low-LET-ion treatment.

The Structure of the Facility

The building consists of 3 floors; the accelerator complex is located on the first and a major part of the additional technical installations on the second underground level.

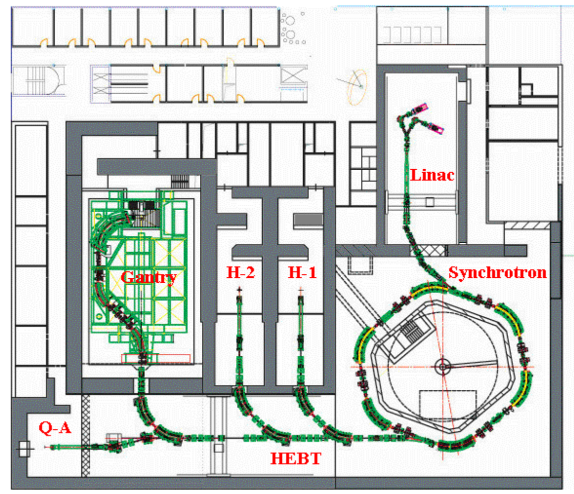

Figure 3: Layout of the first underground floor, housing the accelerator complex.

On ground level offices are located as well as the upper part of the gantry cave, that extends over all 3 floors.
Fig. 3 shows the layout of the first underground floor of this facility with the accelerator sections and treatment places.
The accelerator and beam transport sections consist of the following subsections:

a) Injector And Low Energy Beamline

For the ion generation two parallel ECR-sources will be installed, giving the possibility to switch from proton to carbon treatment within a short time.
The ECR source is chosen, as this type provides a very stable beam intensity over a long time without adjustment of the source parameters.
The required particle currents between 80 μA for $^{16}O^{6+}$ and 1.2 mA for p are rather conservative; beam tests of this commercially available source indicate, that both the current and the requested beam emittance can easily be achieved. The extraction energy of the ECR-source is 8 keV/u.
Within the low energy beam line the requested intensity reduction down to 0.1% of the maximal ion intensity will be performed by means of appropriate beam defocusing.

b) Linac, Medium Energy Beam Transport

A combination of RFQ and IH-linac structure with a total

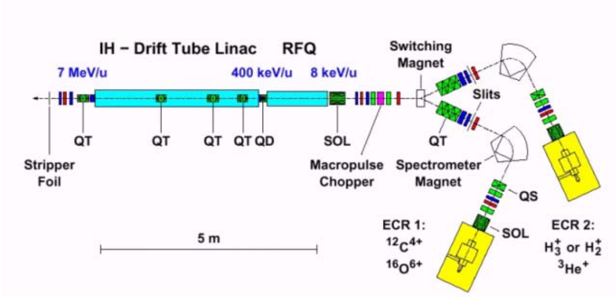

Figure 4: Layout of the injector-linac.

length of about 6 m will be installed to accelerate the ions up to 7 MeV/u [4]. The RF-frequency of these structures is 216 MHz. The pulse length is about 200 µs, the maximal repetition frequency is 5 Hz. The normalized beam emittance is about 0.8 πmm mrad, the momentum spread ± 0.15%.
The medium energy beam transport system to the synchrotron consists of a stripping and a matching section. In addition, for multiturn injection a chopper system is provided to match the pulse length for the synchrotron injection. A rf debuncher cavity is foreseen to reduce the momentum spread for the synchrotron injection in order to maximize the multiturn injection efficiency.

c) Synchrotron

For the synchrotron [5] with a circumference of about 65 meters 6 bending magnets with a maximum flux density of 1.53 T are provided. Four long and two short drift spaces are available for the installation of injection and extraction elements and the RF-cavity. After a 15 to 20 turn injection, corresponding to an injection time of about 30 µs, the acceleration to the maximal extraction energy takes place within 1.0 s.
The synchrotron has a doublet focusing structure with a slightly different ion optical setting for beam injection and extraction.
For slow extraction the 'transverse knock out' method is applied with variable extraction time between 1 and 10 s and multiple beam extraction at the same flat top. The easy realisation of multiple beam extraction in the same cycle with this method gives great advantages both for respiration gated treatments and for the minimization of the treatment duration using the rasterscan method.

d) High Energy Beam Transport (HEBT)

The high energy beam transport system delivers the slowly extracted beam to three treatment places. After the synchrotron extraction section a fast deflecting magnet will prohibit the beam delivery in case of interlocks.
At the end of the high energy transport line a 'Quality-Assurance' (QA)-place is foreseen for beam diagnostic purposes, further developments of the treatment technique and biophysical research activities.

e) Treatment Areas

In order to meet the demand for a patient flow of 1000 patients/year three treatment areas are foreseen. For the first and second area the beam will be delivered from a horizontal beam line similar to that used at the GSI pilot project. The beam for the third treatment place will be delivered by a rotating beam transport system ('isocentric gantry'). All beam lines are equipped with identical horizontal and vertical scanning magnets and beam dignostic devices for the intensity controlled rasterscan. As an option the integration of a PET monitoring system in the gantry beam line is proposed.

f) The Gantry

As up to now no heavy ion gantry system has been built design studies of the mechanical structure were performed by industrial firms during the last 3-4 years. The mechanical Gantry-structure, used for HICAT is shown in Fig 5 [6].

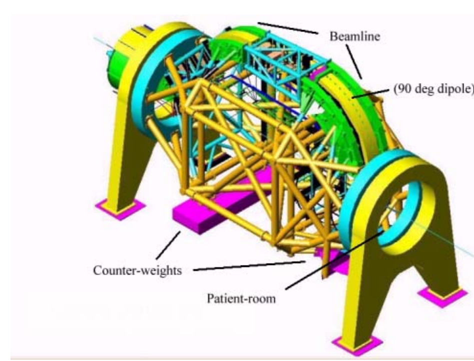

Figure 5: View of a gantry structure mechanical structure (some of the beamline elements are covered by structure elements).

The diameter of the gantry is about 13 m; its total weight including all magnets and supports is estimated to be near 600 tons. FEM calculations for this structure result in a maximum angle dependent deformation of about ± 0.5

mm , which leads to a beam position variation at the isocenter of about 1-2 mm, mainly due to a steering of the last focusing quadrupole. Although reproducable positioning errors can be handled by means of appopriate steerer settings a fast on-line position correction with the scanner magnets, that is successfully in operation at the GSI pilot project, will probably be used in addition.
In addition to construction aspects of the gantry structure beam tests of the last gantry section, including the scanner magnets and the 90 degrees bending magnet in a horizontal setup have been successfully performed within the HGF-strategy funds for investigations on ‚Multifield irradiation techniques‘.

SPECIAL INVESTIGATIONS

Linac-Developments

For the linac several developments and investigations have taken place [7].
For the rf tuning of the IH structure a 1:2 scaled cold model has been fabricated and tuning activities were performed at the IAP of the University Frankfurt [8].
The three long drift tubes inside the IH-structure will be equipped with high gradient quadrupole triplet lenses, that have to operate at yoke flux densities close to 2 T. Due to the high flux densities and the pulsed operation of these lenses their yokes have to be made of stacked laminates of a CoFe-alloy (VX50) with a thickness of 0.3 mm. At GSI prototypes of these very compact magnets were produced in order to investigate optimized fabrication possibilities and to verify the high packing density, requested due to the compact dimensions. Within magnetic measurements the effective lengths and the influence of the field overlap was measured as well as the homogeneity of the gradient and the requested current to achieve the designed field gradients.
The development and fabrication of the final amplifier stage of the 1.4 MW power amplifier has been finished; this amplifier stage will be tested within the next months at GSI and afterwards integrated into the RF power supply system.
The development and construction of the RFQ is completed; alignment- and rf-tests were performed at the IAP; beam tests with a proton beam are in preparation.

Test Gantry-Segment

As a part of the HGF-strategy funds for investigations on ‚Multifield irradiation techniques‘ the components of the last gantry beam line section had been constructed. Beam-tests with this section, including a quadrupole doublet, the scanner magnets and the 90^0 bending magnet in a horizontal setup were performed in 2002 and 2003. [9]

Fig. 6 shows the gantry segment during the installation phase in a GSI experimental cave with the 90^0 dipole magnet in front and the scanner magnets and quadrupoles close to its entrance, seen from the isocenter position.

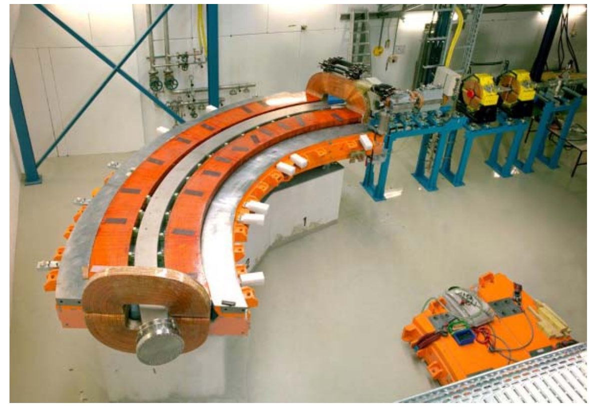

Figure 6: Gantry segment (the upper yoke of the 90^0 dipole and its mirror plates not yet installed).

Before the installation of the segment took place intensive field measurements of the 90^0 dipole were performed, covering both the field homogeneity and its dynamic behaviour, that have also been subject of previous theoretical investigations. [10], [11]
The beam properties of the gantry segment have been tested with p- and C-beams during several short test periods. These measurements included investigations of the beam-position and beam width behaviour over the requested maximum irradiation area of 200 * 200 mm at different ion energies. In addition a therapy-like operation mode was established to check the quality of 2D- and 3D-scanning at the isocenter, located about 1.8 m behind the 90^0 bending magnet.

The measurement results are very close to the predictions and may be summarized as follows:

- the complete irradiation field can be reached,
- no field coupling between the scanner magnets and the dipole occured,
- for constant settings the stability of the beam positions is better than 1 mm,
- the beam position at constant scanner angles varies over the treatment field in a range of about 3 mm (this can be compensated by adequate corrections of the scanner set values),
- due to the edge angle the beam diameter varies linerarly over the treatment field in a range of about ±15 % , which is tolerable.

After having finished the tests of the gantry segment the components were dismounted and are prepared for installation and stored until the assembly at Heidelberg.

ORGANIZATION, STATUS

In May 2001 the scientific council of the federal republic approved the project with total costs of 72 M€, and in April 2003 the final approval of the supervisory board of the clinics took place. Fifty percent of the total costs will be covered by public support and 50% by credit financing of the Heidelberg clinics.

The Therapy facility is being constructed and will be operated under the overall project leadership of the University Clinics of Heidelberg.

During the planning and construction phases the various activities for the facility are coordinated by the Clinics and performed by:

- the Heidelberg building office for the design and construction of the building and the primary technical installations,
- the GSI for the layout and construction of the accelerator and beam transport sections including the gantry and the installations of the rasterscan-treatment; the latter in cooperation with the DKFZ (German cancer reserach centre) and the FZR (research center Rossendorf),
- the Radiological Clinics for the preparation of the medical installations

For the construction and assembly phase GSI will supervise the industrial firms that will deliver the systems for the accelerator facility.

Parallel to the construction phase the employment and training of operating-personnel will start soon at the GSI facility as preparation for the operation phase. In addition GSI will be responsible for the commissioning of the accelerator and treatment systems.

For the final operation a total staff of about 85 persons is estimated, including both the technical and the medical personnel.

A rough schedule for the main steps of the project realization is given in the following table:

Time (Year)	**activities**
2005	assembly of the accelerator systems
2006	overall commissioning
2006/7	patient treatments (horizontal places)
2007	patient treatments (gantry place)

Tabular 1: Major milestones of the Project

At present all components for the accelerator are in the construction or production phase. The tender for the components of the treatment systems was started in May 2004. Concerning the building the excavation has been finished and the construction of the concrete base plate has started.

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