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Contents

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Upgrade of HIMAC Accelerator Complex

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Abstract

The first clinical trial with carbon beams generated from the HIMAC was conducted in June 1994. The total number of patients treated is now in excess of 3,500 as of October 2007. The impressive advance of the carbon-ion therapy using the HIMAC has been supported by high-reliability operation and by the development of the accelerator technology. Furthermore, we have carried out the beam intensity and quality upgrades of the HIMAC accelerator complex in order to increase the irradiation accuracy and the treatment efficiency.

1. Introduction

Heavy-ion beams are very suitable for the treatment of deeply seated cancer because of an excellent physical-dose distribution and high-LET characteristics around the Bragg peak. Therefore, NIRS decided to carry out heavy-ion cancer therapy with HIMAC [1]. Since the first clinical trial on three patients in June 1994 with 290 MeV/n carbon beam, the total number of patients treated at HIMAC exceeded 3,500 as of October 2007. At an early stage of the clinical trials, the number of fractional irradiations was typically 18 and the treatment required 6 weeks, besides the extra time needed for diagnostics and treatment planning. The number of fractions, however, has been decreased for some protocols, especially for the lung and liver, without encountering any serious side effects. At present, for lung- and liver-cancer treatments, only one fractional irradiation is carried out. Such decrease in fraction number can increase the number of treatments. As a result of the accumulating numbers of protocols, at 2003, carbon therapy at NIRS was approved as a highly advanced medical technology by the Japanese government. Such advances of carbon therapy with HIMAC have been supported by highly reliable operation [2] and by the development of beam-delivery and accelerator technologies [3-5]. The HIMAC accelerator complex has been upgraded especially for increasing the irradiation accuracy and the treatment efficiency. Based on the study for the upgrade of the HIMAC accelerator complex, we have designed a compact carbon-ion therapy facility for widespread use in Japan, and the Gunma University has been constructing the compact facility since April 2006. Owing to upgrade of the HIMAC accelerator, further, a design of a new treatment facility as our future plan has been successfully progressed. We review the upgrade of the HIMAC accelerator complex.

2. Study for upgrade of HIMAC accelerator complex

2.1. Gated irradiation with patient' s respiration

Damage to normal tissues around tumor was inevitable in treatment of a tumor moving along with respiration of a patient. A respiration-gated irradiation system, therefore, which can respond quickly to irregular respiration, was developed [3]. In this system, the irradiation-gate signal is generated only when target is at the design position and the synchrotron can extract a beam. This method has been applied to liver, lung and uterus cancers since February 1996. At present, this irradiation method has applied to one-third of the HIMAC treatment. Figure 1 shows the view of irradiation gated with respiration.

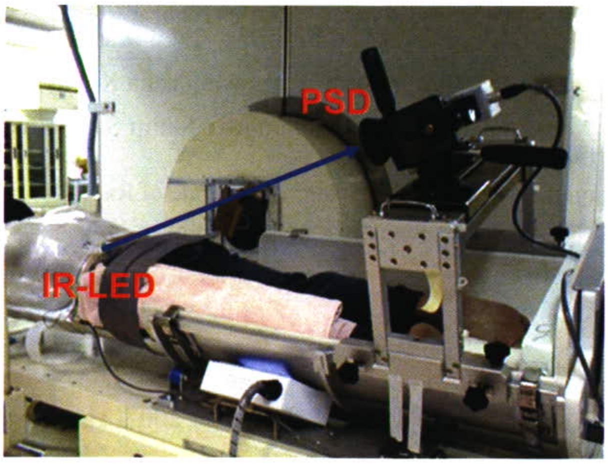

Fig. 1. The view of irradiation gated with respiration using the horizontal irradiation port.

This irradiation method requires the quick response of beam on/off according to the irradiation-gate signal. For the purpose, the RF-KO extraction method with AM and FM was developed. This RF-KO slow extraction method in synchrotron is based on the transverse beam heating while keeping the separatrix constant. One of great advantages in this method has a quick response within 1 ms to a gate-signal of beam on/off, as shown in Fig. 2. As a result, this RF-KO slow extraction method has realized the irradiation gated with respiration.

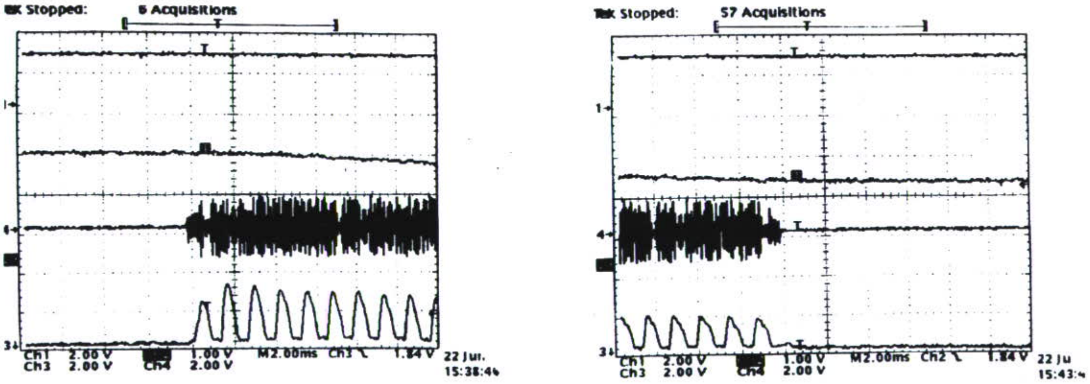

Fig.2. Time response of the RF-KO slow extraction method to the gate signal. (a) From upper trace, sextupole field for the extraction, circulating-beam current, transverse RF wave-form and the time structure of the extracted beam in time scale of 50 ms/div., (b) Beam-on (Left) and -off (Right) response in time scale of 2 ms/div.

2.2. Improvement of time structure of extracted beam through RF-KO slow extraction

The RF-KO method has been a key-technology of the gated irradiation method, although the method brought a huge ripple of the time structure of the extracted beam (spill). The huge spill ripple has never disturbed the dose distribution in the wobbler method, because the ripple frequency of around 1 kHz is much different from the wobbling one of around 60 Hz. On the other hand, sophisticated irradiation-methods such as a spot scanning and a raster one (beam-scanning method) have successfully been developed, because they can provide a high irradiation accuracy even for an irregular target shape and bring a high beam-utilization efficiency [6-9]. In the beam-scanning method, it was anticipated that the huge ripple affects the lateral dose distribution, because the scanning frequency is closed to the ripple one. Further, the intensity modulation of the extracted beam is an important technology for the beam-scanning method. Therefore, both the control method for the microscopic structure (kHz-order) and for the global one (Hz-order) were investigated.

2.2.1 Improvement of microscopic time structure of extracted beam

Since microscopic time structure of extracted beam (spill ripple) should be significantly suppressed in the beam-scanning methods, the source of the spill ripple in the RF-KO method was investigated through both the experiment and simulations [10], as follows; The frequency region of the transverse RF filed, which can extract the beam, was measured. Further, the spill structure during one period of the FM were measured and simulated in various sizes of the horizontal chromaticity. As the results of the investigation, it was found that the RF-KO slow extraction with the FM consists of two processes depending on the RF frequency regions; (1) The particles near the boundary of the separatrix can be extracted mainly due to the amplitude growth of the betatron oscillation when the frequency of the transverse RF field matches with the tune region near a boundary of the separatrix (extraction region). (2) The particles deeply inside the separatrix are diffused toward the boundary of the separatrix when the RF frequency matches with the tune region inside the separatrix (diffusion region). They are overlapped in each other, because of the dependence of the tune on the betatron-amplitude in the third-order resonance. The spill structures during one period of the FM are quite different in each frequency region and they are repeated with the repletion frequency of the FM, which is very source of the spill ripple in the RF-KO method. Therefore we proposed the dual FM method in order to suppress the spill ripple [11]. During the no-beam period, applying an additionally RF field with a frequency that matches that of the extraction region, the particles in the extraction region can be extracted due to the betatron-amplitude growth and/or due to the synchrotron oscillation. Thus, in this scheme, the spill ripple was considerably suppressed compared with that in the original RF-KO method (single FM). Furthermore, applying a transverse RF field with a mono-frequency that matches the tune in the extraction region, the particles in the extraction region can be extracted at a constant rate, because the amplitude-growth rate is almost constant due to satisfying the resonance condition. In this case, the spill ripple is considerably small under the condition that there is no other perturbation. However, the extraction efficiency is considerably degreased in this scheme, because no particle can be delivered to the extraction region from the diffusion one. Thus, the spill ripple will be improved, while keeping the extraction efficiency high, by adding a diffusion function to the mono-frequency RF-field, which we call the separate function method [11]. In this case, the dual FM method can be utilized for the diffusion function. The microscopic time structure, which was improved by the separate function method, is shown in Fig. 3.

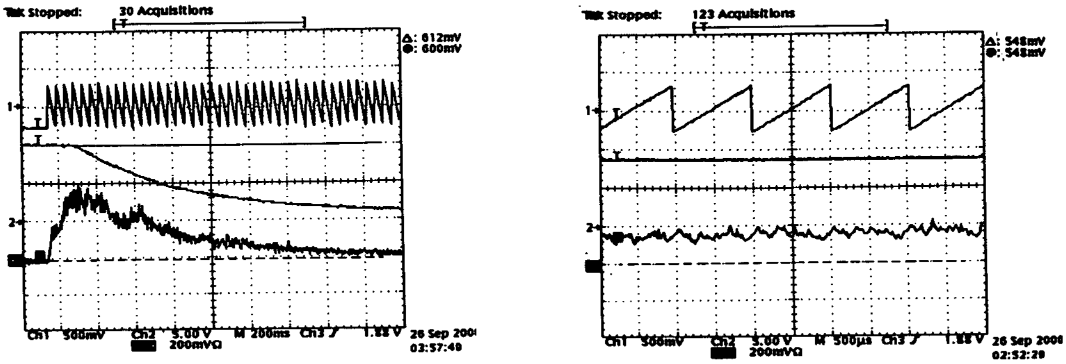

Fig. 3. Improved time structure by the separate function method. (a) Time scale is 200ms/div., (b) enlarged figure (a). Time scale is 0.5 ms/div.

2.2.2 Improvement of global time structure of extracted beam

In the RF-knockout extraction, the global time structure should be control, because it has been strongly required for medical and other applications. Especially for the beam-scanning irradiation method, the uniform spill significantly contributes to obtain easily uniform dose distribution in the lateral direction. For the purpose, we proposed to optimize the AM function for the transverse RF-field. In this optimization process for the AM, the radial distribution function of particles in the normalized phase-space was assumed to be expressed by the Rayleigh distribution function. The width of the Rayleigh distribution is widened by the transverse RF heating and the larger part than a constant width is extracted from the ring. Using this model, we estimated analytically the global spill structure. A diffusion constant by RF kick was obtained experimentally, and we predicted the RF kick angle so as to keep the extracted intensity constant. As a result of the study, it was verified that the function for the AM with the above-mentioned parameters could provide the flat spill within ?23% in both the simulation and the experiment at HIMAC synchrotron. Cooperating with the feedback system, finally, the global spill structure was suppressed less than ?5% [12].

Based on the control of the global time structure mentioned above, further, we have developed a system to control the spill structure and the beam intensity by the AM of the transverse RF-field for extraction [13], because the flat spill and the intensity control allow precise irradiation with a larger dynamic range of dose modulation. The core part of this control system (AM function controller) needs to achieve: 1) calculate and output AM signal based on the requirement comes from the irradiation system, 2) real-time processing more than 1ms time resolution, and 3) feed-forward and feedback control to realize the extracted intensity as same as requested. In order to realize these requirements, we employed a single-chip microcomputer for main processing. By cooperating with the feedback control, the intensity of extract beam was controlled dynamically while keeping its flatness. This system allows us to control the beam current almost as requested, which was experimentally verified at the HIMAC synchrotron. The time structure of extracted beam, which was obtained through the intensity control system, is shown in Fig. 4.

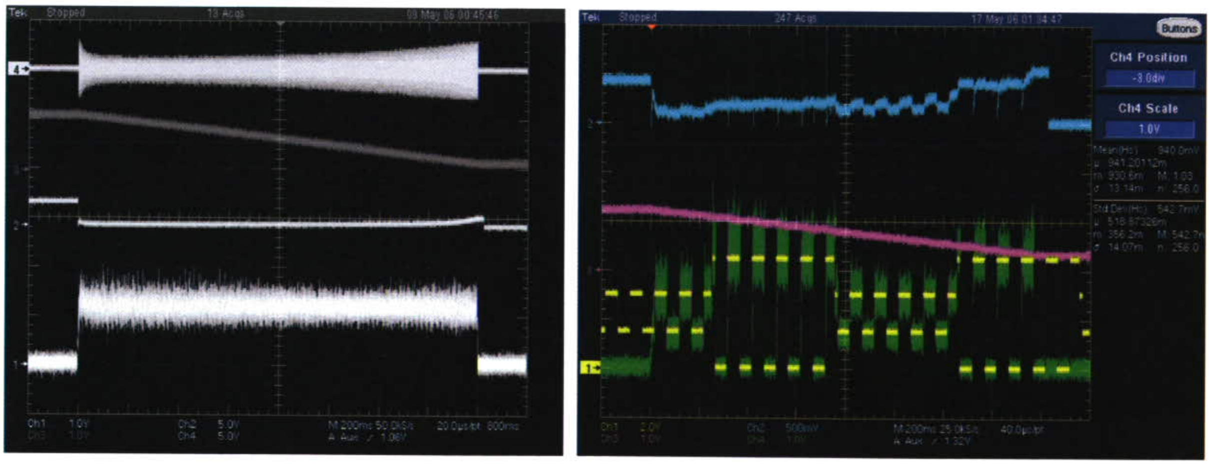

Fig. 4. Time structure of extracted beam obtained by the intensity control system. Left: Constant spill structure (bottom trace) in the time scale of 200 ms/div. Right: Intensity controlled spill structure (green trace) and request signal (yellow trace).

2.3. Control of beam profile and position

2.3.1 Control of beam size

In order to deliver the desired beam size and profiles at a target through a beam-transport line, it has been an essential technology to match the optical parameters, such as the emittance, twiss parameters and dispersion function at an extraction channel of the ring. However, an optical matching at the extraction channel has not been easy, because it has been difficult to directly measure the optical parameters there as an initial condition of the transport line. Thus, an effort has also been made to match the optical parameters by predicting them at the extraction channel based on a simulation. However, the simulation result has a relatively large error compared with a direct measurement due to errors of the magnetic fields and an unexpected non-linear field in the ring. Therefore, we have developed a more accurate prediction method of the optical parameters at the extraction channel. The procedure in the proposed method is as follows: (A) For horizontal plane; (1) An outgoing separatrix was measured at the entrance of the extraction channel by using thin tantalum rods [14]. (2) The lattice parameters in the ring model, such as the horizontal tune and the strength of the separatrix exciters, were modified so as to reconstruct the measured outgoing-separatrix. (3) A simulation with the modified lattice parameters predicts the optical parameters of the extracted beam at the extraction channel. (B) For vertical plane; the optical parameters are estimated by measuring the vertical beam profile of the circulating beam by a non-destructive profile monitor [15] and using the twiss parameters of the ring at the entrance of the extraction channel. In order to verify the proposed method, we compared the predicted beam envelopes and dispersion function along the transport line with the measurement result. As a result, it was verified that the optical parameters reconstructed well the actual beam profile in the beam transport line [16], as shown in Fig. 5.

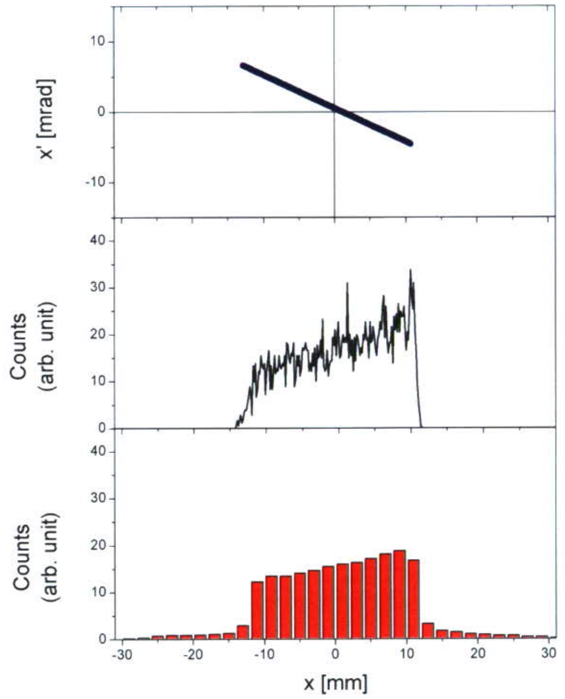

Fig. 5. Comparison of the horizontal beam profile between the simulation and the experiment. From the upper figure, phase-space distribution estimated by the rod-monitor measurement, horizontal profile estimated by the simulation and the measured profile.

As can be seen in Fig. 5, particle distribution in the horizontal plane is not Gaussian distribution, while the vertical one is Gaussian. It is inevitably that the difference between the horizontal and vertical distribution brings the rotating-angle dependence of the beam distribution in a rotating gantry. Therefore, we developed the compensation method for such an asymmetric distribution in the phase space and the difference between the horizontal emittance and the vertical one. This method is based on employing a thin scatterer (thin scatterer method), although the emittance is slightly enlarged by multiple scattering. As a result of particle tracking, the followings were verified [17]: 1) The asymmetric distribution was compensated by the thin scatterer set at the optimum phase-advance from the entrance of the extraction channel. 2) The proposed method could realize the symmetric beam condition at the entrance of the gantry. 3) The horizontal and vertical profiles at the iso-center had no correlation between the rotation angles of the gantry while keeping their Gaussian profile.

2.3.2 Control of beam position

We have investigated the beam-position stability in order to deliver the stable beam for the beam-scanning. It was found from the measurement that beam position of vertical port from the upper synchrotron showed relatively poor reproducibility, especially in horizontal axis, corresponding to the extraction direction. Further, it was confirmed that large change was observed at particular conditions: 1) At the cold start, 2) After high energy operation with 800MeV/n and 3) After low energy operation such as a proton beam with 100MeV/u. it seems that 2) and 3) are caused by the change of residual field of the magnet.

Concerning the cold start, temperature of the cooling water for power supplies and magnets varies according to the excitation level etc. It was found from the measurement that 7 degrees rise in water temperature in the first one hour after the cold start, corresponding to more than 3 mm change of horizontal beam position. We should take an extra time for keeping the water temperature constant in the case of cold start.

It can be conceived that the extreme condition such as maximum energy and lower than minimum-design-value may cause variation of magnetic field via different residual magnetization. Owing to initializing procedure, the magnetic field reproducibility of the DC magnets was measured to be less than 5?10-5 by NMR measurement. Such slight change of the magnetic field in the transport line would not affect the beam quality, such as the position, profile and intensity. On the other hand, the magnetic field reproducibility of the pattern operation magnet was measured to be around 10-4 by search-coil measurement. The slight difference of the magnetic field in the ring brings the tune difference. Since a slight change of the horizontal tune causes the separatrix size difference in the resonant slow extraction, the extraction angle and the emittance change. It was verified by a computer simulation using RF-knockout simulation code. It means the beam quality at the end of HEBT strongly depends on the magnetic field stability of the pattern operation magnet in the synchrotron ring. Since daily fluctuation of the horizontal tune strongly affects beam quality, we have developed the system to compensate the daily fluctuation of the horizontal tune. In this system, we employ online-monitoring system and pulse-to-pulse correction by the correction quadrupole magnet in the ring. The current of the correction quadrupole magnet is changed to center the beam position at the profile monitor, based on measured beam response, which depends on the beam line and its optics. In the preliminary test results, this system makes it possible to keep the beam position and intensity constant at the iso-center.

2.4. Intensity upgrade and extended flattop operation

When the delivered beam intensity can be considerably increased to more than $2 \cdot 10^{10}$ carbon ions, we can complete the one fractional irradiation of almost treatment with one operation cycle of the HIMAC synchrotron, because the scanning method has high beam-utilization efficiency. This one cycle operation can increase the treatment efficiency in the gated irradiation. Therefore, we have pay much effort to increase the beam intensity from the synchrotron.

2.4.1 Intensity upgrade

In order to suppress the beam loss due to space-charge effect, resonance characteristics were investigated at the HIMAC synchrotron by means of a tune survey (Qx = 3.68~3.75, Qy = 3.0~3.5) with a high-intensity beam.

The working point is close to the integer resonance through the incoherent tune-shift under high ion density after bunching. Thus we changed the vertical tune from 3.13 to 3.23. Since the effect of the 3rd-order coupling resonance ($Qx + 2Qy = 10$) is not negligible, however, we tested the resonance correction by using 4 sextupoles. After the correction, the beam lifetime was increased by more than 5 times under $(Qx,Qy) = (3.74,3.23)$. Reducing bunching factor can suppress the space-charge effect. Therefore, an un-tuned RF-cavity, having a Co-based amorphous core, has been developed so as to make multi-harmonics operation possible for reducing the longitudinal space-charge effect [18,19]. By the multi-harmonics operation, the beam intensity was increased by 40%.

2.4.2 Extended flattop operation

Concerning the extended flattop operation of the HIMAC synchrotron, the stability of the beam was tested, firstly. In this test, $2 \cdot 10^{10}$ carbon ions were accelerated up to 400 MeV/n and extracted with the constant rate of $2 \cdot 10^{8}$ particles/s during 100 s of the extended flattop. The extraction beam rate is highly stabilized owing to a dynamic intensity control system with RF-knockout slow-extraction. In the 3D pencil beam scanning irradiation, on the other hand, the stability of the pencil beam is very important issue to assure the scanned field quality. As a result of the simulation study, it was clearly found that the dose uniformity was intolerably deteriorated under the position change of ±2 mm with sinusoidal frequency of 50Hz. Further, it was founded that the long-term difference of the beam position and size during the irradiation bring more critical disturbance on the dose distribution. Therefore, the beam position and profile during 100s extraction was also measured. Figure 6 shows the measured beam profiles during 100s extraction. The measurement was carried out by using the wire grid profile monitor in the beam line where the beta functions are larger than that of the iso-center. By the analysis of this measurement result, it was calculated that both the position and size during the extended flattop are stabilized within ±0.5 mm at the iso-center position.

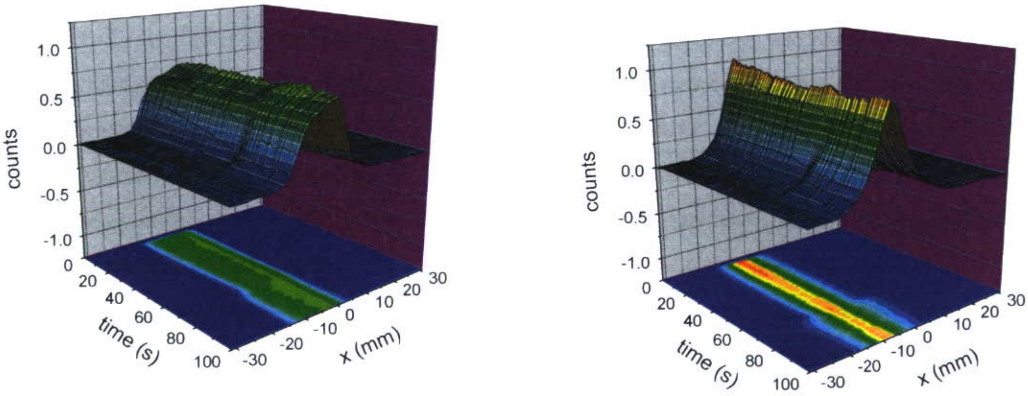

Fig. 6. Measured result of beam profile during 100s extraction.

4. Summary

For the upgrade of the HIMAC accelerator complex, the beam-studies have been carried out. Owing to the studies, not only a compact carbon-therapy facility for widespread use in Japan, but also the new treatment facility at HIMAC with the scanning method has been successfully progressed.

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Status and Developments of the Heavy Ion Therapy Facility HIT at Heidelberg

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Introduction

The Heavy Ion Therapy Facility HIT at the University Clinics of Heidelberg [1] is designed to treat about 1000 cancer patients per year, mainly with p- and carbon-beams; in addition the extension to helium and oxygen beams is foreseen. The 'intensity controlled raster-scan procedure' will be applied, which has been successfully demonstrated at the GSI Experimental Therapy Program [2]. Since 1997 about 400 patients have been treated with this treatment modality.

The accelerator complex of the HIT facility comprises two ECR- low energy branches, a linac with a compact RFQ- and IH- structure, a synchrotron, a high energy beam transport system, leading the ion beam to 2 horizontal treatment places, an isocentric light ion gantry and a 'QA' -place for quality assurance and further developments.

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 favorable 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.

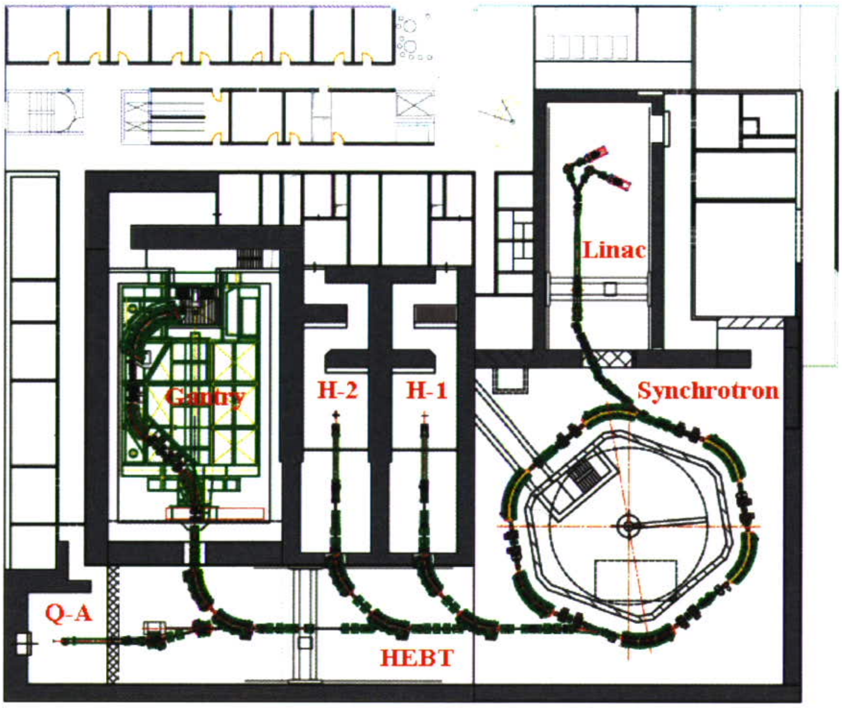

Fig. 1: Layout of the first underground floor, housing the accelerator complex

On ground level offices are located as well as the upper part of the gantry cave, that extends over all 3 floors.

Fig. 1 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 are 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; 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 is be performed by means of appropriate beam defocusing.

b) Linac, Medium energy beam transport

A combination of an RFQ and IH-linac structure with a total length of about 6 m is installed to accelerate the ions up to 7 MeV/u [3-7]. 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 π mm mrad, the momentum spread ±0.15%.

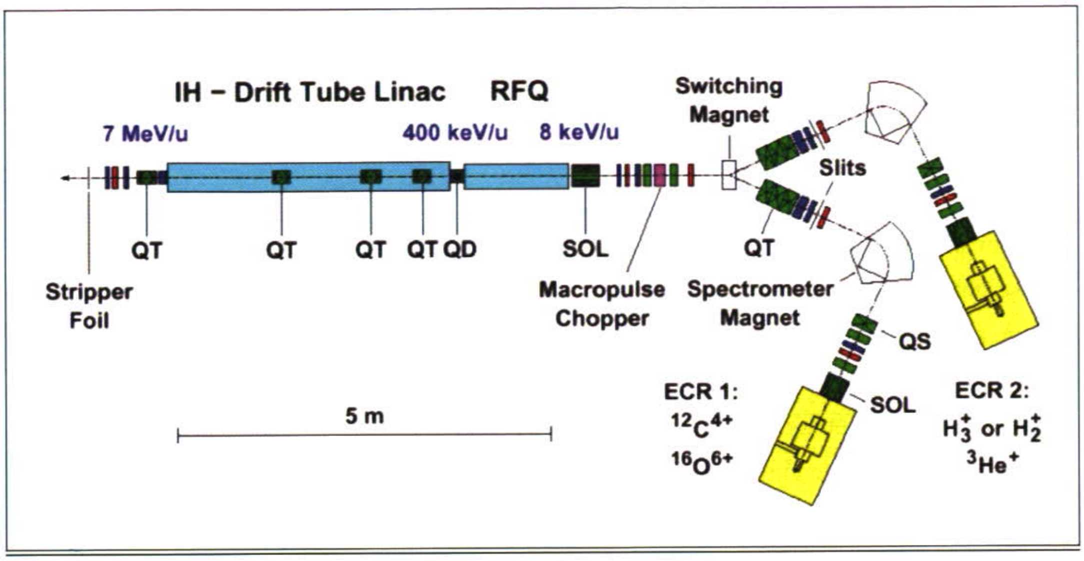

Fig. 2: Layout of the injector-linac

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. An rf debuncher cavity is installed to reduce the momentum spread for the synchrotron injection in order to maximize the multiturn injection efficiency.

c) Synchrotron

For the synchrotron [8] 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 straight sections 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 realization 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 prohibits the beam delivery in case of interlocks.

At the end of the high energy transport line a 'Quality-Assurance' (QA)-place is installed 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 provided. For the first and second area the beam is delivered from horizontal beam lines similar to that used at the GSI pilot project. The beam for the third treatment place is delivered by a rotating beam transport system ('isocentric gantry'). All beam lines are equipped with identical horizontal and vertical scanning magnets and beam diagnostic 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

The mechanical Gantry-structure, used for HIT is shown in Fig 3 [9]. The diameter of the gantry is about 13 m; its total weight including all magnets and supports is near 600 tons. FEM calculations for this structure result in a maximum angle dependent deformation of about ±0.5 mm, which leads to an expected maximum 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 appropriate steerer settings a fast on-line position correction with the scanner magnets, that is successfully in operation at the GSI pilot project, will be used in addition.

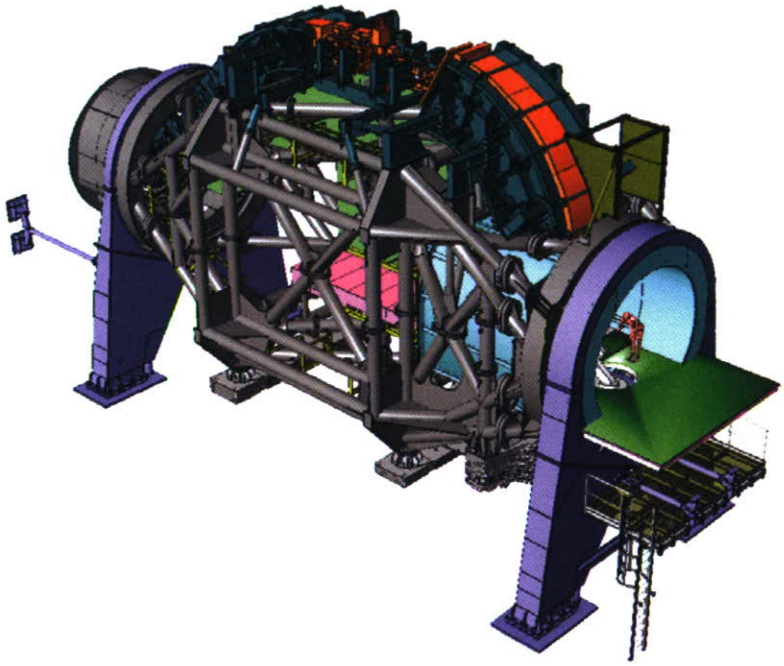

Fig. 3: View of the gantry mechanical structure
(some of the beamline elements are covered by structure elements)

In 2003 beam tests of the last gantry section, including the scanner magnets and the 90 degrees bending magnet [10] in a horizontal setup have been successfully performed within the HGF-strategy funds for investigations on 'Multifield irradiation techniques ' [11].

Status of the facility

After the installation of the accelerator systems, which started in Nov. 2005, the beam commissioning activities with the source and linac-branches began in March 2006. The linac commissioning was finished at the end of 2006; in 2007 the beam commissioning of the synchrotron and HEBT branches started, leading to a first extracted beam to one of the horizontal treatment places in March 2007. Until then the evaluation of the appropriate components settings is going on to achieve the requested beam properties for p- and C-beams at the horizontal treatment places, aiming to have a fixed parameter set in Nov. 2007.

Parallel to the beam commissioning procedures the installation of the isocentric gantry took place, which is the worldwide first light ion gantry, capable to transport a 6.6 Tm beam, equivalent to a C-beam of 430 MeV/u. The first rotation of this gantry took place in April, 2007. The first delivery of a test beam through the gantry is expected for the end of 2007.

Time (Year)	**Activities**
2006	assembly of the accelerator systems
2006-2008	Commissioning activities
2008	patient treatments (horizontal places)
2009	patient treatments (gantry place)

Table 1: Major milestones of the HIT project

Developments of 'treatment technique'

a) Rasterscan treatment method

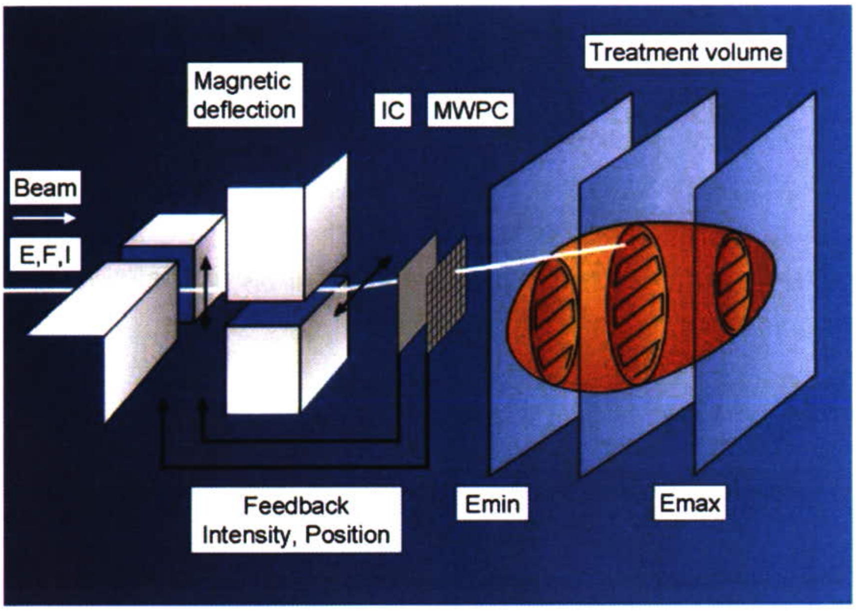

Fig. 4: Rasterscan-Method

The 'intensity controlled rasterscan' treatment modality [12] is foreseen as the only treatment method for all patient places, including the gantry.

The principle of this method, which has been developed at GSI and successfully applied to more than 350 patients within the GSI Experimental Therapy Program, is shown in Fig. 4. 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. By a sequential treatment of such slices with adequate intensities the requested dose profile for the tumor volume within the shown spread-out bragg peak is achieved. (Fig. 5).

To cover the lateral dimensions of the tumor the ion beam passes two fast scanner magnets 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 (< 0.3 ms).

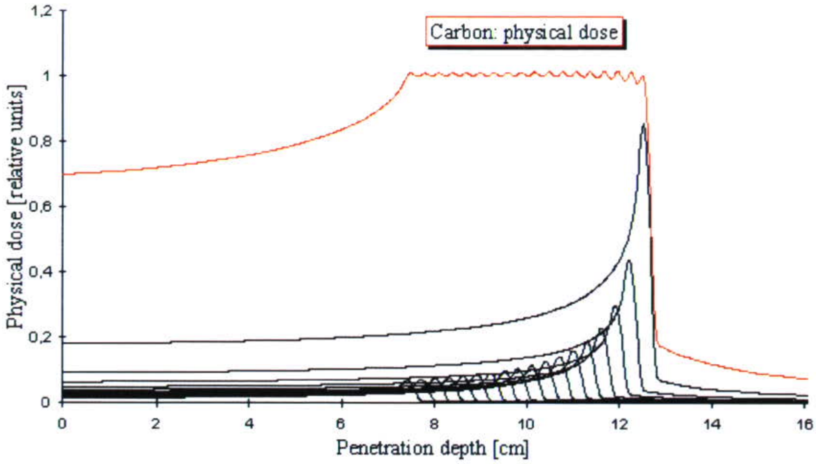

Fig. 5: Depth dose profile for overlapping Bragg peaks

The rasterscan treatment modality demands fast, active energy-variation to provide different penetration depths and intensity-variation to minimize the treatment time. Already within the Therapy Pilot Project at the existing GSI accelerator complex a system had been developed, that for carbon ions between 90 and 430 MeV/u allows the reliable request of 255 energy-steps for sequential synchrotron cycles. Besides this energy variation also intensity-and beam spot variations at the treatment location on a pulse to pulse basis can be requested. The principles of this system are also established at the HIT facility.

b) Advanced positioning -and diagnostic-systems

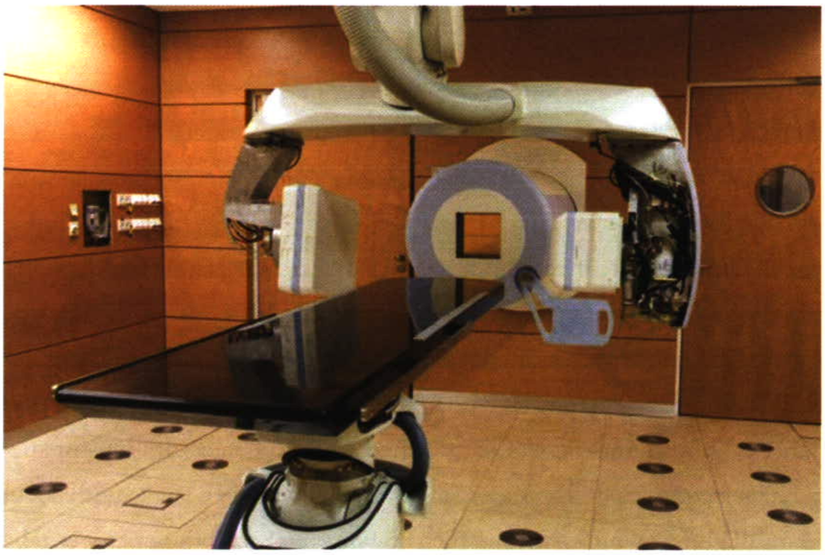

Fig. 6: Combined robotic system at the HIT treatment place

For the HIT-facility a sophisticated combined positioning and diagnostic system has been developed and commissioned by Siemens-MT on the basis of robotic technology (Fig. 6).This system allows an optimized workflow of the patient treatments and an accurate and flexible usage of patient positioning and position verifications.

c) On-line PET-diagnosis

In order to get an indication of the dose distribution during the irradiation-process an 'on-line' PET diagnostic system [13] has been implemented at GSI during the GSI Experimental Therapy program. This 'PET camera' allows to detect the position of gamma-rays of decaying positron emitters, produced either by projectile- or target-fragmentation, during the irradiation and enable the oncologists to verify the correct irradiation after each applied fraction.

d) 'Moving' targets

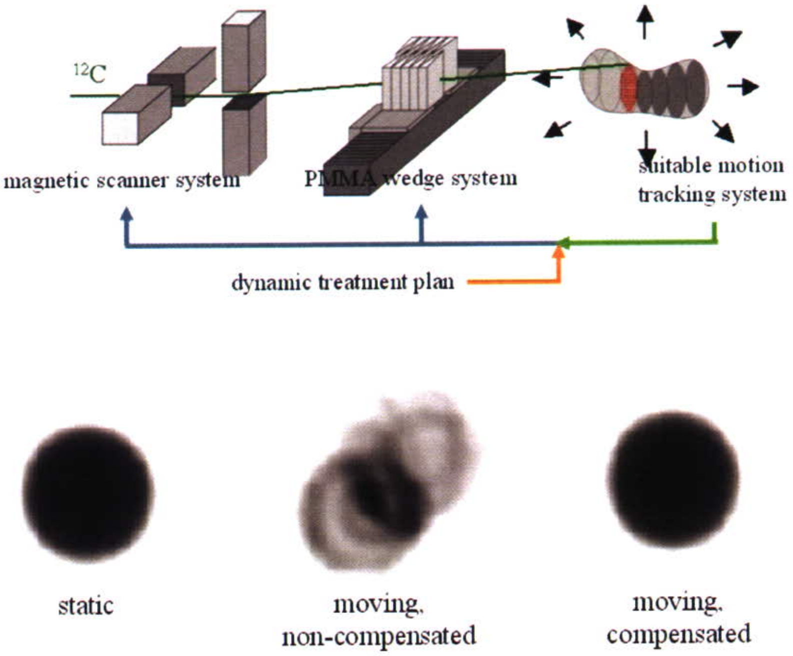

Fig. 7: '3D-online motion compensation method' , schematics (upper part) and test-results for non- compensated and compensated irradiation (lower part)

As a very accurate beam delivery is mandatory for a treatment with high LET beams by means of the raster-scan method the treatment of moving organs is a challenge. At present two methods are under investigation: the (respiration) gated beam extraction and the 3D correction method. Whereas the first method is applied to patient treatments at HIMAC for many years the second method [14] '3D online motion compensation method' (see Fig. 7) has been developed at GSI and is still in a test phase.

To compensate 3D variations of a moving tumor volume the scanning magnets are used for correction in both lateral dimensions; a PMMA wedge system is proposed to realize fast particle energy variations (within certain limits) to cover variations of the penetration depth.

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The Status of CNAO

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1. Introduction

The CNAO (Italian acronym that stands for National Centre for Oncological Hadrontherapy) is a National wide facility conceived to supply hadrontherapy treatments to patients recruited all over Italy. The CNAO is under construction in Pave, about 30 kilometres South-West of Milan. The Italian Ministry of Health, which, in the year 2001, has created the CNAO Foundation to build and run the facility, mainly finances it. The founders of CNAO are five among the largest oncological institutes in Italy: Fondazione Ospedale Maggiore (Milan), Fondazione Ospedale San Matteo (Pave), Fondazione Istituto Neurologico Besta (Milan), Fondazione Istituto Nazionale dei Tumori (Milan), Istituto Europeo di Oncologia (Milan) and the TERA Foundation (Novara, lead by U. Amaldi who was the promoter of the hadrontherapy center since 1992). Since 2003 INFN is Institutional Participant of CNAO, together with the Universities of Milan and Pave, the Polytechnic of Milan and the Town of Pave. The availability of carbon ions at CNAO will be an exclusive treatment modality for Italy and all patients with radioresistant tumours shall be addressed to the centre in Pave. To efficiently recruit patients, it will be created a network to connect the CNAO to the national health system. Pre-selection criteria will be defined on the basis of established clinical protocols and the hospitals and clinics in the network will address to the CNAO those patients that satisfy the criteria. Pathology Committees, with the participation of multidisciplinary experts, have been activated within the Scientific Committee of the CNAO Foundation to define the clinical protocols for each kind of tumour that will be treated at the centre. The contribution of experts from different disciplines (surgeons, oncologists, organ specialists in addition to radiation oncologists) will permit to best tailor the clinical modality and at the same time their participation will grow the consensus and the recruitment capability of CNAO. Three treatment rooms with four beam ports (three horizontal and one vertical) and one experimental room have been realised. At present it is foreseen to start the operation of the machine and to begin the preparation to treatments in summer 2008. The first patient treatment is expected by fall 2008 and regime operation will be fully operational within the next three years. At regime, on a double shift operation, five days per week and at least 220 days per year, the CNAO will deliver about 20 thousands sessions of hadrontherapy per year. The overall number of patients will obviously depend by the fractionation schemes adopted. The actual dimensioning of spaces and fluxes for patients, personnel and people are adequate for about 3000 patients per year. In addition is under construction a room totally devoted to physical and radiobiological researches. The site of the CNAO allows the future expansion of the facility, to add new treatment rooms and also a new research and clinical building close to the centre. The expansion in the direction of the extracted beam is potentially adequate to host two gantry rooms for carbon ions, each with the same dimensions of the present Heidelberg facility. The choice of the CNAO foundation has been to postpone the construction of the expansion in order to validate the clinical necessity of the gantry for ions and also to wait and to contribute to the technological improvements expected in this field.