Controls and Beam Diagnostics for Therapy-Accelerators

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1) Summary

During the last four years GSI has developed a new procedure for cancer treatment by means of the intensity controlled rasterscan-method. This method includes active variations of beam parameters during the treatment session and the integration of 'on-line' PET monitoring.
Starting in 1997 several patients have been successfully treated within this GSI experimental cancer treatment program; within this program about 350 patients shall be treated in the next 5 years. 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. [1] An essential part for patients treatments is the measurement of the beam properties within acceptance and constancy tests and especially for the rasterscan method during the treatment sessions.
The presented description of the accelerator controls and beam diagnostic devices mainly covers the requests for the active scanning method, which are partly more crucial than for the passive scattering methods.

2) Passive scattering and Rasterscan method

a) Passive scattering
At presently existing therapy-dedicated proton- and light-ion accelerators for cancer treatment the particle beam is delivered to the patient after 'passive' manipulations. A broad and uniform beam profile is generated by wobbling magnets with horizontal and vertical deflection in combination with scatter plates. Whereas the tranverse beam profile is matched to the target dimension by means of a collimator, the requested range dose distribution is achieved with range shifters and adequately formed boli.
In general for this treatment mode the beam properties requested from the accelerator are constant over the treatment time.

b) The Intensity controlled Rasterscan
An alternative to the passive method is the rasterscan method, which allows an accurate confirmation also of a very irregular tumor volume and avoids mechanical insertion devices for beam shaping and thus minimizes the production of fragment or stray particles, that also contribute to the dose distribution.
One of the key aspects of a future particle therapy accelerator is the use of the intensity controlled rasterscan technique (Fig. 1), which is a novel treatment concept, developed at GSI and successfully applied within patient treatments of the GSI pilot therapy program.

This treatment method demands fast, active energy-variations on a pulse to pulse base to achieve different penetration depths and intensity-variation to minimize the treatment time.

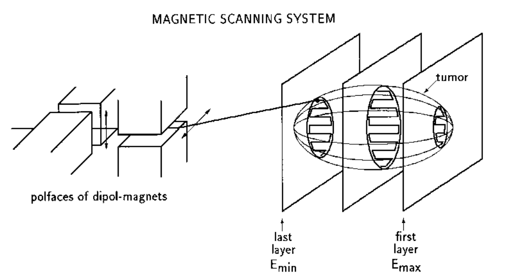

Fig. 1 Rasterscan-Method

The accelerated and slowly extracted beam enters 2 fast scanner magnets, that deflect the beam both in horizontal and vertical direction to cover the lateral dimensions of the tumor. The various ranges in the tumor tissue are realized by different extraction energies of the accelerator.
Fast multiwire proportional counters detect the position and beam width at each scanning point. Ionization chambers in front of the patient measure the number of ions at a specific irradiation point and control the scanner excitation. When a required dose limit has been reached the beam extraction is interrupted very fast (< 0.5 ms).

3) Accelerator requirements

The basis of the accelerator concept has to satisfy the demands of the medical community for the treatment procedures.

Table. 1: Therapy requirements
- 3 treatment areas to treat a large number of patients
- integration of isocentric gantries
- treatment both with low and high LET-ions
- relatively fast change of ion species
- intensity-controlled rasterscan method
- wide range of particle intensities
- 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 (hor., vert.)
- intens. (ions/spill) : $1*10^6$ to $4*10^{10}$ (dependent. upon ion species)

The main requirements of the proposed facility for light ion cancer treatment were intensively discussed with radiotherapists and biophysicists and can be summarized in Table 1.

The essential characteristics of this facility are the application of the rasterscan method with active intensity-, energy-, and beamsize- variation in combination with the usage of isocentric light ion gantries. The proposed accelerator is designed to accelerate both low LET ions (p, He) and high LET ions (C, O) to cover the specific medical requirements.

Major aspects of the design are influenced from the experiences of the GSI cancer treatment program; the requirements of this facility, however, exceed in many fields those of this GSI therapy program.

A dedicated accelerator for cancer treatment with the requested parameters described in the previous section demands a quite different accelerator control than facilities used for experimental physics. Whereas high flexibility is requested for the latter ones a hospital based therapy facility demands an easy to use operation with high reliability and extended safety standards to avoid treatment faults.

At the GSI pilot project these requests have been successfully fulfilled by the following means:

- the settings for all accelerator components and all possible parameter variations are stored on device level in nonvolatile memory.
- the settings are approved in dedicated acceptance test procedures and regularly checked within constancy tests.
- during patients treatments the accelerator is locked which permits parameter modifications.
- all beam-destructive elements are automatically removed at the beginning of a treatment session.
- beam delivery takes place only after verification of the requested energy-, intensity- and focusing steps.
- the control of the appropriate beam parameters is performed with a fast, redundant diagnostic system in front of the treatment room.

As all components settings are approved and stored in general no accelerator tuning is necessary; therefore the accelerator sections can be operated (nearly) without operators. The main operator task is to perform predefined constancy tests and to organize maintenance in case of components failures.

4) Beam diagnostics systems

The requested beam diagnosis components have to assure correct beam energy, -intensity ,-position and -beamwidth within the various accelerator sections and especially at the treatment place.

a) Components in the accelerator sections

For measurements of beam intensity

- current transformers in the linac- and low energy beam transport sections and in the synchrotron.
- Ionization chambers and scintillators in the high energy transport system due to the low average current of the slowly extracted beam from the synchrotron.

For measurements of beam- position and beam width

- profile grids and viewing screens in all transport sections at relevant locations.
- beam halo counters (scintillators) during the treatment time
- pick-up probes to determine the beam position in the synchrotron

Schottky pick-ups are suggested for the measurement of the extraction energy from the synchrotron .

The mentioned components are 'standard', approved devices

b) Components at the treatment area

For the intensity controlled rasterscan method fast and accurate intensity measurements are extremely important as they directly determine the dose that is applied to the patients. At GSI two redundant ionization chambers are integrated in a control loop for the operation of the raster scan magnets. In addition one independent recycling capacitor is in operation.

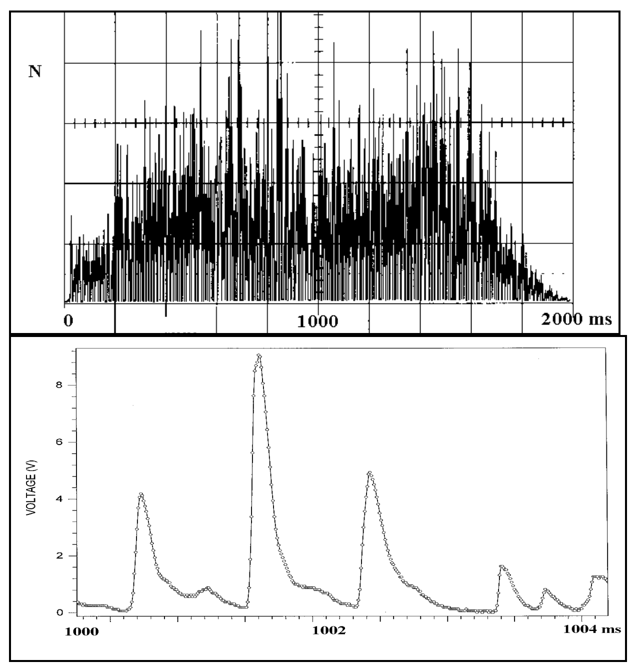

Fig. 2 Measured Spill-structure (total and zoomed) in the lower figure the measurement intervals (12.5 µs) are indicated

In spite of the strongly modulated time structure of the extracted beam (see Fig. 2) the requested dose homogenity of +- 5% can be achieved. due to the fast intensity measurements and the speed of the scanning magnets

Beside the intensity control the beam position control is an important issue. At GSI two redundant multiwire

proportional chambers (MWPC) with an active area of 200 * 200 mm^2 are in operation. The distance of the wires is 1 mm in each plane; the position and beam widths are measured every 150 µs. In addition to monitor the beam parameters a fine adjustment of the beam position was successfully tested by means of a feed forward control of the scanning magnets.
These MWPC-monitors are also essential for the determination of the time dependence of beam position and beam width over the spill duration, which is important for the dose homogenity of the rasterscan technique.
Both the intensity and the beam-position measurements are connected to an interlock unit, which activates redundant spill abort channels when predefined tolerance levels are ecceeded.

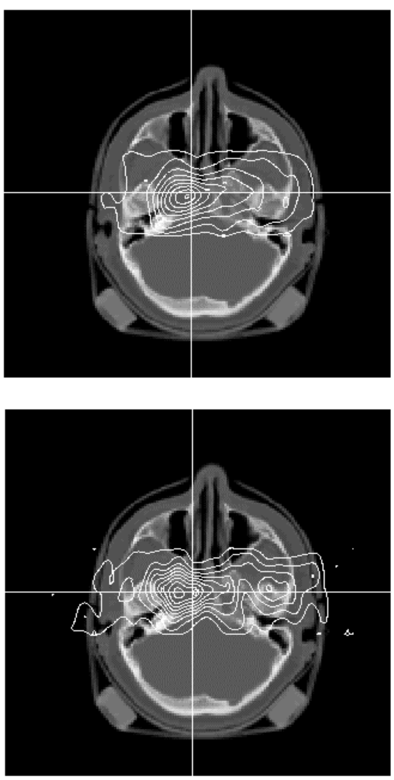

Fig. 3 PET imaging (above: measurement, below: PET-reconstruction)

A third diagnosis system is the 'on-line'-Positron Emission Tomography (PET)-camera. The decay of radioactive isotopes (mainly ^{11}C projectile fragments) is measured during the treatment time. The analysis of these decays gives a three dimensional picture of the dose distribution.
For the acceptance and constancy tests previous to the treatment sessions additional beam diagnostic devices are used.
As the MWPCs and ICs are not located at the isocenter, the beam parameters at the treatment point are measured with separate profile grids or viewing screens and CCD-cameras with digital data processing. The exposure of films is used as well to determine the homogenity of the particle fluence with defined testcycles
For dose verification calibrated thimble ionization chambers are used either in a water tank or located inside predifined phantoms. For fast on line 3D dose verification stack arrays of large area ionization chambers sandwitched between plastic plates are used, which measure the dose simultaniously at different depths of the target volume.[2] Such a device also serves as a verification unit of the particle energy by determination of the bragg peak locations.

5) Controls, Operation

As the environment of a dedicated therapy accelerator is in general a hospital and not a research institute large effort has to be spent on a controls and opertion system, which can be handeled by non accelerator experts.
Within the GSI pilot project predefined procedures have been developed, which both for the accelerator sections and the treatment area allow to confirm the requested beam properties for the large amount of variation possibilities desribed in chapter 3.
For the accelerator predefined test cycles have been prepared to determine the constancy of the requested beam performance. Within these tests a sequence of accelerator cycles for different extraction energies, particle intensities and beamwidths at the treatment place is activated and the beam properties are measured with he appropriate diagnosis components, e.g. ionization chambers, current transformers and profile grids. These data are processed (determination of beam center of gavity and beam-width), stored and displayed to the operator in a graphical representation, which also includes the predefined tolerance levels.

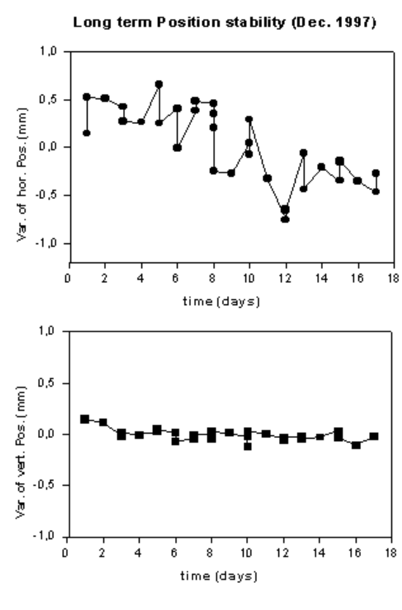

Fig. 4: long term beam position stability

Fig. 4 shows an example of the measured long term position stability of the beam. Each measurement is the meanvalue of position over a complete test cycle with variations of the beam energy and beam widths.
In case of unacceptable deviations from the tolerance levels correction have to be performed. For corrections of the beam position in the high energy transport system to the treatment area an automated beam alignment programm is available, which allows relatively fast position corrections for the whole energy range by means of a correlation of beam position measurements and beam optics calculations [3].

The most crucial demands for the required beam diagnostics occur at the treatment place, as these components have to provide reliable input data for the

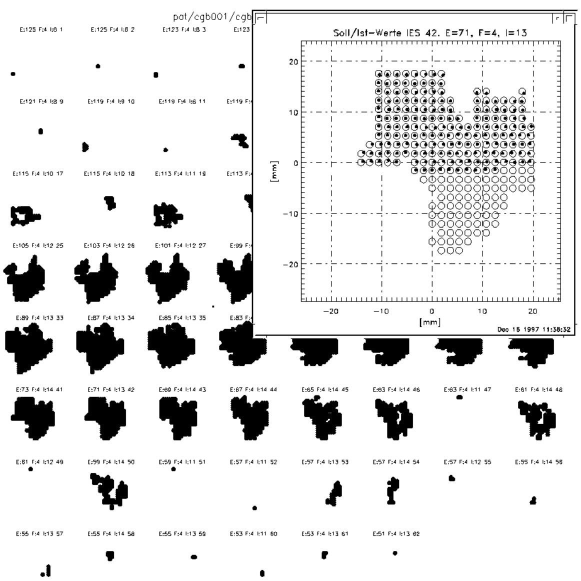

Fig. 5: Observation and control of the irradiation process

control of the scanning magnets and to supervise the requested beam parameters for each treatment point. In addition operating tools have to be available, which despite of the speed and complexity of this treatment modality allow an insight into the actual irradiation progress and a fast, effective response of physicians as non accelerator experts in case of failures.
Figures 5 and 6 give an example of such a measurement and visualization tool. Fig. 5 shows for a specific treatment cycle the individual slices of the tumor volume and the individual treatment locations in each of these slices. The zoomed image indicates, whether the mreasured beam position is inside a predefined tolerance. As all essential data of the treatment are stored a reconstruction and analysis of the beam properties is possible.
Fig. 6 shows the values of the beam position and their deviations from the set value and the intensity variation for a treatment cycle

Appropriate color indications are used in order to give a good overview of the measurements to the physicians. At GSI the commercial IDL graphic package is in use for thze generation of such two- and three-dimensional diagrams.

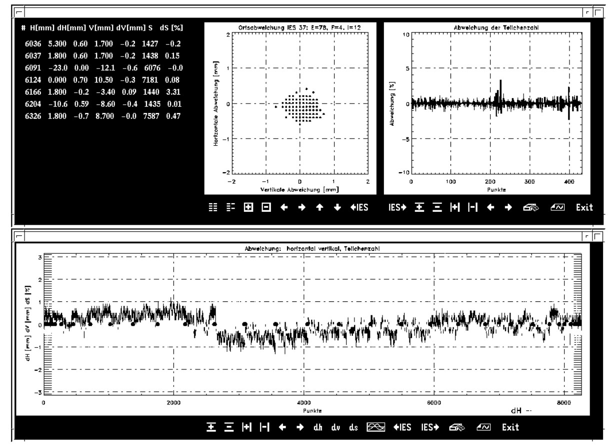

Fig. 6: Observation and Control of beam parameter deviations (position, intensity)

6) Essential future developments

One of the future main goals is to reduce both the treatment time and those periods needed for the acceptance and constancy tests without affecting the patients sefety requests. For the intensity controlled rasterscan technique the amount of patients that can be treated is not primarily defined by the intensity, that can be delivered from the accelerator, but by the required test procedures and the time needed for the measurement and control of the beam properties for each treatment point.
The required test procedures, which even with a horizontal beam line at the GSI facility consume a considerable time, will have to be extended significantly in case of the use of a gantry and additional ion species. These procedures have to be time optimized by means of a larger degree of automatization. In addition automated control and corrections of accelerator settings are essential.
A large effort is necessary to convert the measurement and control tools into an environment that can be handled by non accelerator experts.

[1] J. Debus et al., 'Proposal for a dedicated ion beam facility for cancer therapy', 1998
[2] D. Schardt, 'Beam Delivery Systems and Dose Verification Techniques at Heavy-Ion Therapy Facilities, DIPAC 97, p. 6
[3] B. Franczak. 'Data generation for SIS and the beam lines of the GSI Therapy project', EPAC96