MULTI-ENERGY TRIAL OPERATION OF THE HIT MEDICAL SYNCHROTRON: ACCELERATOR MODEL AND DATA SUPPLY

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Abstract

At the Heidelberg ion beam therapy center (HIT) cancer patients are treated with the raster-scanning dose delivery method of heavy ion pencil beams. The beams are provided by a synchrotron which allows for a variation of the ion penetration depth by changing the ion beam energy for each synchrotron cycle.

In order to change the beam energy within one synchrotron cycle the accelerator and its data supply model within the control system have been extended extensively. In this extended data supply model beam re-acceleration or deceleration between two arbitrary extraction energies is defined.

The model defines an additional transition phase, i.e. current and – more generally – set value patterns between extraction and the re-acceleration yet giving the possibility of setting the beam properties suitable for further acceleration/deceleration. This includes the dipoles, correctors, quadrupoles, sextupoles, KO-Exciter (spill break), and RF.

This allows for the survey and optimisation of the beam properties including possible beam losses of the re-accelerated, transversally blown up beam for arbitrary energy levels.

INTRODUCTION

Cancer therapy with carbon ion and proton beams has been carried out at the Heidelberg Ion-Beam Therapy Center (HIT) since 2009. Approximately 4500 patients have been treated since then. HIT uses the intensity controlled raster scanning method of pencil beams as dose delivery system [1]. The accelerator is based on a linac-synchrotron system accelerating ions to energies up to 430 MeV/u corresponding to ion penetration depths of approx. 30 cm in tissue. The facility is equipped with two fixed horizontal beam lines, a rotating beam line (heavy ion gantry), all for patient treatment, and an experimental area (Fig. 1).

The synchrotron is a cyclic operating device with phases of beam injection, acceleration to the desired particle energy, corresponding to the desired penetration depth (iso energy slice), beam extraction, and preparation for the following cycle. Ions are slowly extracted by the transverse knock-out extraction method with extraction times which last up to 5 s [2].

The number of particles which can be accelerated by the synchrotron usually exceeds the number which is desired for irradiation of one iso energy slice. The basic idea of the multi energy operation at HIT is to fill the synchrotron with a maximum number of particles, to accelerate and to extract the desired number for one energy, and then to re-accelerate and extract remaining particles to the next following energies given by a patient's treatment plan in a consecutive sequence. Within this scenario the time consuming synchrotron phases of injection, acceleration from injection to extraction energy, the ramping down after one extraction phase, and preparation for a subsequent cycle are avoided several times yet reducing treatment time tremendously [3]. A similar approach, but yet different in detail, has been implemented at the HIMAC facility [4].

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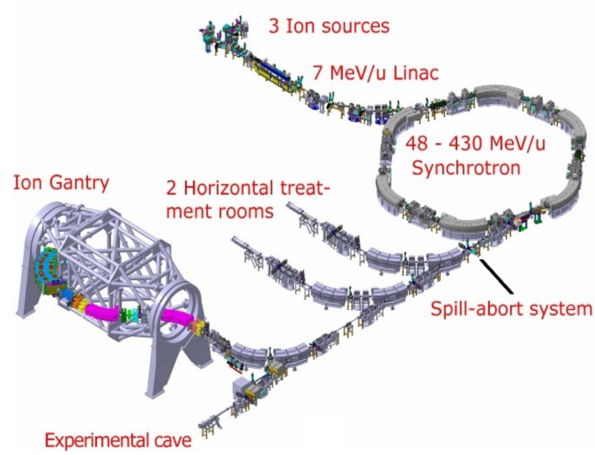

Figure 1: The HIT accelerator: a linac-synchrotron based system delivering 4 ion types to 3 treatment rooms and one experimental room.

This paper briefly reviews the development of an accelerator and test data supply model, i.e. synchrotron patterns with two energy levels which can be chosen arbitrarily to study and optimise the beam properties of the re-accelerated ion beams while first experimental results are given in [5].

DATA SUPPLY MODEL

Status

The ion beams can be accelerated to 255 different energies per ion type. By this the penetration depth of the ion beam in tissue can be varied in steps of approximately 1 and 1.5 mm respectively. For a single energy the control data including power supply ramping for the accelerator components is calculated out of physical input parameters such as deflection angles, field gradients etc. by the data supply module (part of the control system software). It accounts for scaling of the control data with the magnetic and electric rigidity for different energies. Other energy dependent effects have to be compensated by semi-automated adjusting of components [6, 7]. These control values are set, calculated, and stored within the device control units and database individually for the 255 energy levels per ion type, i.e. there is one data set for each energy yielding optimum beam properties desired for treatment.

Test Environment

General The basic idea of the test data supply model is to share the two original data sets of accelerator settings of different beam energies; the settings of which yielded approved beam properties for therapy. These are introduced to an accelerator model containing these two data sets extended by a newly developed transition phase after the first extraction and prior to the second acceleration phase (Fig. 2).

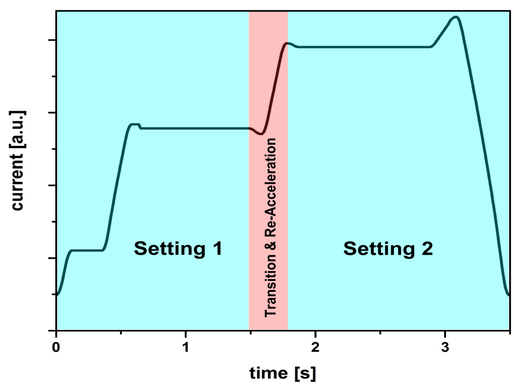

Figure 2: Scheme of a test synchrotron cycle with two energy levels (x-axis: time, y-axis: for instance quadrupole current).

This phase is intended to serve as a matching phase of the transversely blown up beam to the following re-acceleration. In order to investigate this matching (i.e. beam losses, beam quality, and time required for energy change) full flexibility in beam manipulation is foreseen in that sense that all synchrotron devices might be varied in this phase. That is the sextupoles (stop of resonant excitation after extraction), quadrupoles (tune ramp, shift from 3rd order resonance after extraction), KO exciter (interruption of transverse excitation, spill interruption, and – not yet implemented – a possible frequency variation), RF amplitude (RF bucket size), dipoles (radial beam position, orbit), correction coils (orbit bump at septum for instance), vertical steering magnets (beam position), RF frequency (orbit, energy).

Even individual delays are configurable for each device group. Some typical examples of calculated patterns are given in Figs. 3, 4, and 5. The measurements in Fig. 6 show the successful implementation.

Timing and time scales In general the time required to change the beam energy, i.e. the length of the additional phase and second acceleration should be kept at a minimum. The maximum length of the transition phase is determined by that device group which requires the maximum time for its undergoing change of value and additional programmable delay and decay times. In turn this means that the phase length could be reduced to zero if all devices keep their set values and delays and decays are set to zero. This -naturally- is not the case in practice because at least the sextupole

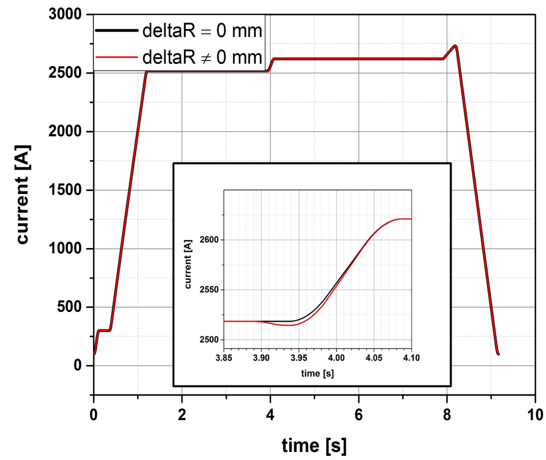

Figure 3: Multi energy current pattern of the main dipole power supply with vanishing radial shift of beam position (black curve: constant current in transition phase), and with radial shift (red curve: current ramp in transition phase).

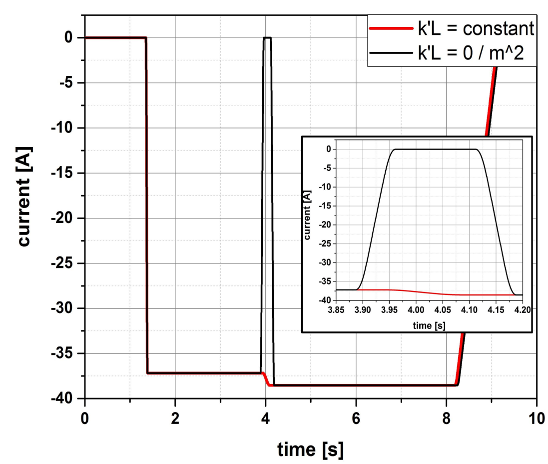

Figure 4: Multi energy current pattern of a sextupole with constant amplitude in transition phase (red curve) and ramping to zero amplitude (black curve) yet turning off the resonance.

strength has to be set to zero after the first extraction phase in order to turn off the resonant excitation (see [5]).

The same idea applies to the second acceleration phase the length of which can be tremendously reduced in the case of small energy changes (it is up to now limited by a fixed minimum value of 150 ms, but will be programmable in the future). Thus the data supply structure is prepared even for timing surveys.

Test data supply module The control values of the transition phase including the matching from the first extraction and to the subsequent second acceleration phase are calculated out of physical input parameters in a similar manner as it is done with the generic data supply module. For this a multi energy accelerator model has been developed according to the physical needs, specified in a requirement document, and converted into programme code, i.e. the data

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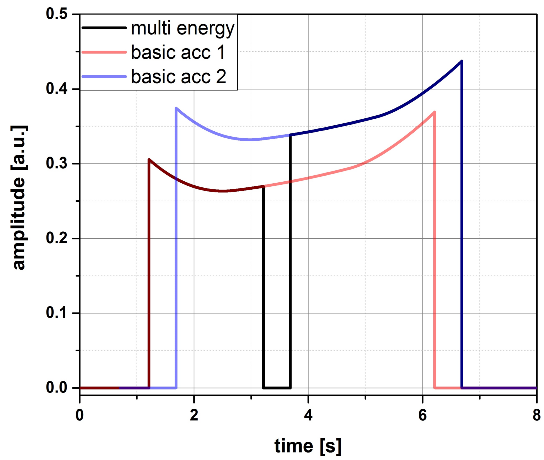

Figure 5: Multi energy amplitude pattern of the KO-Exciter: amplitude is set to zero during transition (spill interruption, black curve). The entire ramp is built out of the two amplitude patterns of the two original data sets (red curve and blue curve).

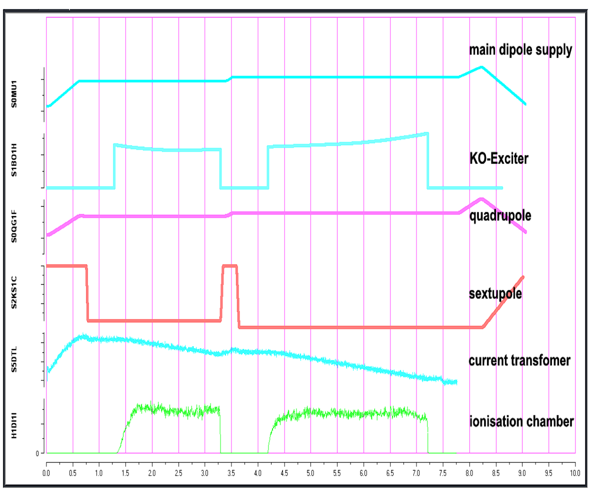

Figure 6: Measurement of different "two energy level" current and amplitude patterns in a.u. vs. time (dipole, KO-Exciter, quadrupole, sextupole) together with the corresponding synchrotron current transformer and HEBT ionisation chamber signals (current, particle number).

supply module (an additional control system software entity) by HIT's industrial control system supplier.

HEBT devices The HEBT devices are operated in pulsed mode and are usually supplied with one set value for a given rigidity. In the multi energy trial scheme those are supplied with two set values according to the different energies, i.e. rigidities. Fortunately this was possible without a change in the data structure in the device controllers and data base by activating existing, but previously unused data fields.

The transition between the two set values is defined as a step function in the test system, while the actual values have to follow according to their individual device capabilities such as current rise times etc. For a typical energy step of a few MeV/u the set up time for most HEBT devices is less than 100 ms, i.e. less than the transition time between the two extraction phases. In other cases the transition time must be sustained by an additional decay time in the test system.

CONCLUSION AND OUTLOOK

An accelerator and data supply model for the re-acceleration (deceleration) of ion beams in a medical synchrotron has been developed and tested. This allows for the survey of the properties of transversely blown-up and re-accelerated ion beams for the multi energy extraction scheme and for accelerator research in general. The beam matching between the first extraction and the second acceleration phase is possible by changing almost every device according to this accelerator model. Thus the model is flexible to a maximum extend. In parallel to this and to the experimental surveys the modification of the HIT control system – allowing for more than two extraction energies – is currently ongoing. This should finally generate synchrotron patterns according to an individual patient's treatment plan.

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