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TOWARDS MULTIPLE ENERGY EXTRACTION OPERATION IN ION BEAM THERAPY

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Abstract

In ion beam therapy most cancer patients are treated using the raster-scanning dose delivery method of heavy ion pencil beams, with the penetration depth determined by the ion beam energy. The beams are provided by synchrotrons, which currently have to start a new cycle to change the beam energy. The number of particles available in one cycle typically exceeds the required amount for a single energy. Thus changing the beam energy by reacceleration of the stored beam could significantly reduce the overall treatment duration. Within the HITRIplus project a novel accelerator control system will be designed, which will enable multiple reaccelerations within one synchrotron cycle. As this drastically increases the amount of parameter combinations, it is no longer feasible to use pre-calculated control data for each cycle. Instead the data will be calculated on-the-fly by the device controllers when a new energy is requested. This paper presents the current status of the data generation strategy and the architectural model of the new accelerator control system.

INTRODUCTION

The Heidelberg Ion Beam Therapy Center (HIT, Fig. 1) is a medical facility treating ~700 cancer patients per year. The tumors are irradiated using the pencil beam raster-scanning method [1], while the penetration depth is determined by the ion beam energy. To accelerate the ions, HIT uses a 64 m-circumference synchrotron, from which ions are extracted using RF knock-out extraction.

Patients are treated with protons, helium or carbon ions, while oxygen is available for research purposes. Being operational since 2009, the accelerator control system will be updated within the next years, including a multiple energy extraction mode.

Multiple Energy Operation

In most cases not all ions that are stored in the synchrotron are used in an irradiation at a single energy. In the current operation mode the remaining ions are dumped and the synchrotron is ramped down, filled with new ions and subsequently ramped to the next requested energy. This cycling of the synchrotron leads to more than 50% deadtime between irradiations.

In multiple energy operation the synchrotron will always be filled with the maximum number of ions. After the first extraction, instead of being dumped, the remaining ions are accelerated to the next requested energy. This can be repeated multiple times until the amount of ions stored in the synchrotron is no more sufficient for the next irradiation (see Fig. 2). Only then a new synchrotron cycle will be started. As the reacceleration is much faster, it has the potential to reduce treatment times by about 50% [2]. Shorter treatment times enhance the patience comfort and allow more patients to be treated. Furthermore, the reduced ramping of the magnets leads to energy and cost savings.

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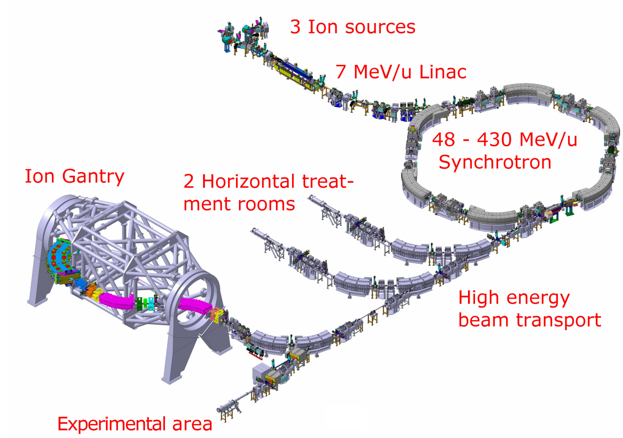

Figure 1: Overview of the HIT facility. Ions are accelerated in the synchrotron and transported to one of three treatment rooms or the experimental area. The beamline mounted on the gantry allows the beam to be rotated around the patient.

The reacceleration of the stored beam has been demonstrated at HIT with two precalculated energy levels [3]. A similar approach, but yet different in detail, has been implemented at the HIMAC facility [4]. To facilitate a routine use of multi energy operation at HIT including an arbitrary number of energy changes, the accelerator control system and especially the data supply module will be upgraded.

ACCELERATOR CONTROL SYSTEM

The purpose of the data supply model is to take the input parameters, which are entered by the operators, and from that calculate the corresponding output values for the accelerator devices. The input parameters are mostly physical quantities (such as deflection angles, field gradients, etc.). The output can be a single value or a complete time-dependent ramp for the devices in the synchrotron.

In the current data supply module, these output values are calculated for all possible ion beam energies (255 energy levels at HIT) and the resulting values are stored in the device control units.

For multi energy extraction, this calculations would need to be done for all possible combinations of energies and

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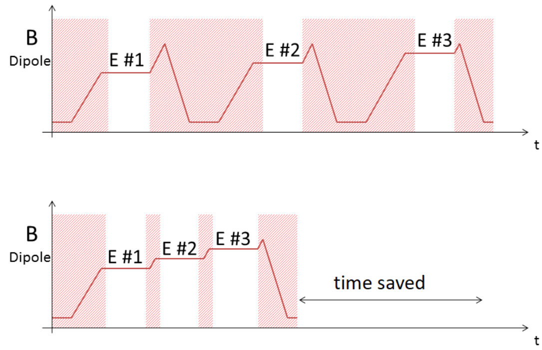

Figure 2: Comparison of the current (top) and planned (bottom) synchrotron operation scheme. Plotted is field generated by the synchrotron dipoles versus time. The red shaded areas mark times at which beam can not be extracted from the synchrotron.

reacceleration steps, which would be very time consuming and requires a very large memory on the device control units.

Instead the control data will be computed just-in-time when a new energy is requested, based on the current energy of the stored ion beam. To avoid delays introduced by sending the resulting data over a network, the control data will be calculated directly on the control device units.

On-Device Calculation

The new device control units will be equipped with an embedded CPU, on which the data supply module will run to calculate the control values. In a first proof-of-concept, the code of the HIT data supply module was translated to C and compiled for an embedded CPU on a Intel Cyclone V chip set. The calculation was successfully executed with a run time of about 400 ms for all control values. As this calculation delays the beginning of each energy step, its duration needs to be reduced, which will be achieved in two ways. First, a more powerful CPU with at least double the speed will be used in the upgraded device control units. Second, the data supply model architecture will be adjusted to the on-device calculation.

The current model calculates all control values, but each device control unit only needs to calculate the control values for the device it is attached to, which would speed up calculation. To allocate the code to the different devices, a dependency tree for all variables of the HIT data supply module was created. It contains more than 1000 variables, a simplified view is shown in Fig. 3. As the timing of the ramping of the synchrotron depends on the slowest element, most devices also depend on variables calculated for other devices. Communication between the devices should be avoided, so those variables have to be calculated on each device separately. In order to keep calculation times short, this should only be done when necessary. Thus restructuring of the code for each device is quite extensive and currently still ongoing.

If the restructuring does not yield the desired speed-up, the calculation rules could also be simplified (especially for the timing) to reduce cross-dependencies.

As shown in Fig. 3, the synchrotron cycle is internally divided into several phases, which are executed subsequently. In case the calculations for one phase can be made reliably faster than the duration of the preceding phase, those calculations could also be performed during that phase, so that effectively no extra time is needed.

Similarly, if the requested energy for the next step would be known to the accelerator control system beforehand, the calculations for this energy could be performed, while the previous cycle is still running. Unfortunately, a communication of future energy requests is not implemented in the current therapy control system at HIT.

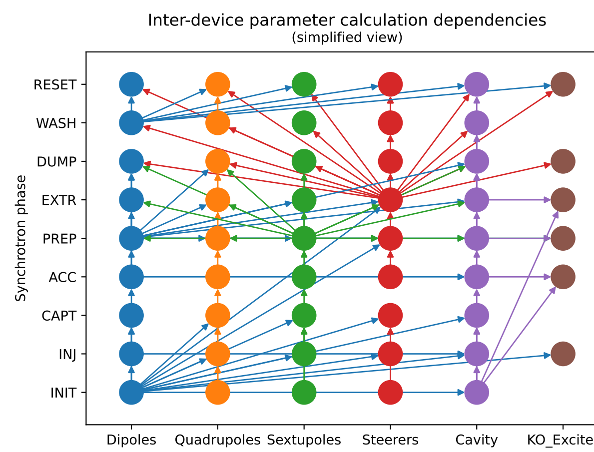

Figure 3: Simplified view of the dependency tree for the HIT data supply module. The internal variables are assigned to the device and synchrotron phase for which they are calculated and only dependencies between these groups are shown. Arrows point towards the group which is depending on the originating group. The synchrotron phases are shown for a single energy extraction (starting from bottom to top), for multi-energy operation, the phases from CAPT to EXTR would be repeated multiple times.

Control Parameter Storage

In contrast to the current system, where the calculated control values are stored on the device for each setting, the input parameters for the data supply module need to be stored.

These parameters can be grouped into three categories:

MEFI data Parameters that can change between each extraction, e.g., energy dependent variables. These parameters have to be stored individually for every possible beam request.

Vacc data Parameters that do not change during a whole multiple energy extraction cycle, e.g., parameters that control the ion species or the beam path. Those only have to be stored once each of the respective combinations.

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Base data Data that is inherent to the synchrotron setup and does not change during normal operation, e.g., synchrotron circumference or magnet excitation curves. Those parameters only need to be stored once on the device.

This classification is also done in the current data supply module, in which the input parameters are stored in a central database.

Similar to the on-device calculations, the amount of memory needed on a single device can also be reduced by only storing the input parameters needed to calculate the values for the attached device. Figure 4 shows that the synchrotron magnets only depend on a small subset of the ~800 MEFI input parameters.

First tests of on-device input parameter storage have been performed using simple embedded key-value store databases [5, 6] and a reduced number of input data sets. They show that the data access times, even for a whole input parameter set, are below 10 µs. If this times holds with the full data set, the aforementioned reduction of stored parameters might not be necessary.

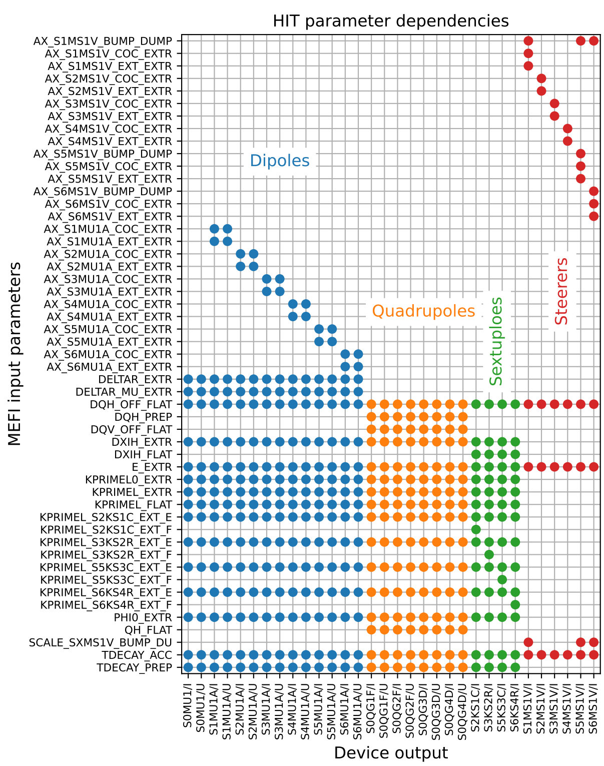

Figure 4: Dependency matrix for the synchrotron magnets. A dot indicates that the device is dependent on the respective input parameter. The labels are the internal names of the parameters in the current data supply module at HIT.

CONCLUSION

Multi-energy extraction has the potential to substantially reduce treatment time and energy consumption. The accelerator control system at HIT will be upgraded to be capable of multi energy extraction operation. This includes the hardware of the device control units as well as the data supply module software.

To accelerate the control value delivery, calculations will be carried out directly on the device control units using an embedded CPU. First tests have shown that the current data supply module, which calculates all values, is too slow for just-in-time operation. Consequently, the structure of the data supply module will be adjusted to calculate each device separately. This work is currently ongoing.

This work is done within the HITRIplus project and the resulting architectural model of the accelerator control system will be shared within this collaboration, to facilitate the introduction of multi energy operation at other hadron therapy centers.

ACKNOWLEDGEMENTS

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