# STATUS OF THE CONTROL SYSTEM FOR HICAT AT AN ADVANCED STAGE OF COMMISSIONING: FUNCTIONS, RESTRICTIONS AND EXPERIENCES

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*Abstract*

One and a half year after installation of the first components much progress has been made in commissioning of the medical accelerator for the clinic in Heidelberg. In the final state it is designed to produce different kinds of heavy ion beams with energies up to 430 MeV/u to treat about 1300 tumor patients a year at three therapy rooms. Presently the specified parameter space for patient treatment is filled to meet the correct combinations of energies, beam foci and intensities for the therapy. In this contribution we will first shortly describe the concept of the control system which was designed by GSI but developed by an all-industrial partner who furthermore delivered the front-end control units and has another contract with Siemens Medical Solutions to meet the requirements at the interface to the therapy control system (TCS). We will mainly focus on its abilities and experiences with it: different kinds of beam requests, time accuracy, real-time analysis, assurance of consistent device data, offline-diagnostics and the beam diagnostic systems. We also report on known restrictions and the concept to securely provide different operation modes for accelerator adjustment or patient treatment.

## CONCEPTUAL OVERVIEW

### *Framework of the Control System*

The Control System (CS) for Heidelberg is realized on few standard industrial computers using Windows XP operating system and most communication takes place via TCP/IP and broadcast messages. The CS mainly consists of (i) a ORACLE-Database which holds all relevant accelerator settings and amongst others the measured device and beam diagnostic data. (ii) Core of the CS is the so-called maincontrol (C++) which together with a couple of other processes controls all activity of the accelerator. (iii) The data supply module (DSM) calculates all device settings based on an elaborated physical model. (iv) One "Timing-Master" distributes all main accelerator events while similar devices provide necessary triggers for beam diagnostic systems. (v) Gateways for beam diagnostic (BD) and special devices as well as the user-interfaces (Delphi) running under XP as well.

### *Front-End Control Units*

The real-time control of all accelerator equipment like power supplies is realized with special controllers (DCU: "Device Control Unit", see Fig. 1) that, like the CS itself, were developed by the industrial partner[1]. The DCUs consist of a Motorola PowerPC processor (64 MB RAM, 32 MB flash), an Altera Stratix FPGA for real-time-control and communicate with up to five interface cards (bidirectional 32 Bit data-bus). They are interchangeable and initialize automatically with different firmware to one of seven device classes that cover the whole range of requirements. While all device communication takes place over Ethernet the DCUs are synchronized by a real-time bus (RTB). For normal operation mode all necessary device data are stored in the DCUs RAM while nonvolatile memory (flash) is used for therapy settings only.

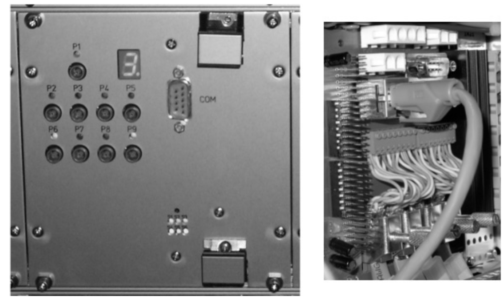

Figure 1: Device Control Unit (front view and rear view with RTB and network cable)

The whole accelerator comprises 170 DCUs of which some have special hardware models: (i) The timing master who generates the accelerator events is connected to several RTBs. (ii) Four DCUs providing TTL trigger pulses for the BD system having each 32 additional programmable output channels. (iii) Besides the timing master 20 DCUs have an additional interface for communication with the TCS e.g. for fast beam cutoff.

### *Interfaces to Further Systems*

**Beam Diagnostic System:** All BD Systems are realized with National Instrument PXI systems and are integrated in the CS software as similar devices compared to DCUs. Overall there are 40 diagnostic chambers with about 70 single BD measurement units. Additionally several stepper motors are controlled as well as pneumatic actuators and HV and gas flow controls.

**Therapy Control System:** Interfaces to the TCS (delivererd by the same industrial partner to Siemens Medical Solutions) are described in subsequent chapters.

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**Further interfaces** allow control of high frequency devices, ion sources, vacuum components and the access control system. Parts of the hardware and independent controls for the latter two have also been delivered by the industrial partner. Monitoring of e.g. temperature of cooling water is intended but not yet implemented. Communication to a simulation program for ion optics is also implemented.

### *Calculation of Device Control Data*

A virtual accelerator (VAcc) describes a group of components and the device data necessary to obtain required beam parameters at one of the four target rooms combined with the possibilities of several ions like carbon and protons extracted from one of the two ion sources. Beside 255 possible experimental VAccs there exist special therapy-VAccs imaging all possible combinations of ion sources and targets. They contain device settings for a parameter range of 255 energies, 15 intensities and 6 foci (EFI)[2].
The necessary set of physical parameters for each VAcc can be customized and optimized with one single GUI while reasonable default values are available. Modification of one or more parameters and recalculation with the DSM takes into account all necessary dependent parameters as well as further dependencies, since a change of one single component may affect other VAccs according to its EFI-dependencies.
Because the whole EFI-parameter-room cannot be individually verified and optimized, splines are used to inter- and extrapolate device settings between selected combinations. Reasonable values for the BD like e.g. integration time or gain can be set for areas of the EFI-parameter space as well. Necessary validation is tested with automated procedures.

## TIMING, DATA ANALYSIS AND BEAM REQUESTS

### *Real-Time Bus and Time Accuracy*

The timing for each component is compensated by signal propagation time, thus achieving a synchronicity better than 50 ns. Instead of a protocol different signal cables for main accelerator events on the RTB are used and a 1 MHz clock signal for time synchronization is continuously monitored. Synchronization with the phase of the power supply system is performed by the timing master.
To meet the desired time-accuracy of devices in the synchrotron, the DCUs contain all information about current- and voltage ramps in form of splines with an accuracy of 32$\mu$s. The FPGA of the DCU interpolates these values and can set and read two values each $\mu$s. For the synchrotron injection some devices are actually supplied with values every 100 ns. Necessary delays in relation to the RTB-events are evaluated with the DCUs internal clock.

[2]The rotatable Gantry-structure utilizes an additional degree of freedom

### *Analysis of DCUs and BD systems*

For real-time analysis set and and real values of most DCU-controlled components can be measured online with an accuracy of up to 5$\mu$s and about $2 \cdot 10^5$ values. In normal operation mode each component sends one pair of values (snapshots) at an essential individual time in the accelerator cycle that can be stored in the database. This holds for DCUs as well as for BD systems while for the latter e.g. averaged values between definable times or FWHM and center of profiles are calculated. Online-Data for all beam diagnostic devices can be measured and evaluated in real-time. The time resolution depends on the individual device but e.g. for AC current measurements up to 10 MSa/s are possible [1].
Most data of devices known to the CS can be stored in the database like snapshot data, parameters of the ion sources or vacuum pressures. Details about beam requests, performed cycles or user entries are saved as well as changes in beam parameters.

### *Beam Requests and Inter-Cycle Delay*

Each cycle is started with broadcasts (beam request) and is executed only if all devices respond and are in the correct state[3]. Upon receipt of a beam request all devices set defined values to prepare for the cycle; in the case of pulsed magnets the dc-values for the cycle are set.
For each device individual conditions can be defined that have to be fulfilled for a successful beam request. In the VAcc groups are also included components like BD devices, vacuum valves, stepper motors and pneumatic actuators. Necessary conditions for each component can vary for different operation modes. While e.g. in adjustment or quality assurance mode pneumatic drives for BD or step motors have to be moved they are checked for defined positions in therapy mode.
The specificated maximum delay between two subsequent cycles is defined to be less than 250 ms but can be further delayed by necessary setup-times (rise and fall times).

## OPERATION MODES

### *Stability cycles and 5 Hz LINAC Mode*

To achieve temperature stability of the rf generators, the Timing-Master continuously generates stability events with an adjustable frequency around 10 Hz where each DCU can be parameterized to respond to this event with set values.
In the case of beam requests one stability event is replaced by start events for both the LINAC and the Synchrotron division. While these events are created simultaneously there exists an additional 5 Hz mode for fast commissioning of the LINAC where only the devices in this section are controlled and can be altered in realtime.

[3]In the case of the 5Hz mode this is only done in the beginning and afterwards the cycles are solely event-triggered.

### *Adjustment Mode*

In this mode either an experimental VAcc or one EFI-combination of a therapy-VAcc is continuously executed. Parameters can be changed to adjust the accelerator settings in order to meet the required beam properties. As soon as all affected devices received their new settings the changes can be analyzed in the following cycles.
As soon as a number of sample parameters have been optimized, parameters for other EFI-combinations may be interpolated, the combinations calculated and downloaded to the devices. The integrity and consistency of all settings is verified with several version IDs that are integrated in checksums to be tested with each beam request. All device master data and parameters that can affect the beam properties are considered as well.
**Procedures for Quality Assurance:** To verify accelerator settings, customized procedures can be defined that automatically run e.g. significant combinations of the EFI parameter space using selectable BD components. Amongst others pneumatic actuators can be controlled via procedural steps as well. Results of each run of a procedure (snapshot data of the BD system or magnets) are stored in the database and can be visualized e.g. as a function of energy.
**Creation of Nonvolatile Device Data for Therapy:** In a special mode the CS transfers all therapy settings from the DCUs RAM into its flash memory. The CS is able to run beam requests with flash data as well to re-check all settings for the therapy mode. In a DCUs flash all device settings for four ion types and ten combinations of ion source and beam target are stored which is only possible because no magnet has the full EFI dependency which in combination with source, target and gantry would yield one and a half million possible set of parameters per ion type.

### *Patient Treatment Mode*

Since the whole accelerator as well as the CS is part of a medical device, a strict functional separation of both systems was necessary: Verification of all relevant beam properties in real-time has to be done by the TCS during patient treatment. The TCS can switch off essential devices to protect the patient in case of wrong beam properties. Additionally the TCS directly controls the scanner magnets that deflect the beam during one (isoenergetic) cycle to scan a designed region of tumor and moreover can interrupt the synchrotron extraction (spill pause). Two events on the RTB are generated by the timing master to signal spill pause start and stop. While all DCUs pause their timing some of them have special control values for spill pause that can be approached with fast linear ramps or one single step.
**Assignment of Authorization and Beam Requests:** Before beam requests from the TCS are possible, the operator has to grant access to beamlines from ion sources to therapy rooms individually. When the TCS takes control, all devices in the approved sections cannot be controlled from the CS any longer and exclusively use their flashed data upon beam requests. Should any error occur the control has to be given back to the CS where problems can be analyzed and fixed.
**Tracing of patient treatment:** All beam requests from the TCS are monitored in the CS: Snapshot data from all non-destructive BD systems and DCUs are generated automatically and it's possible to perform online-measurements of these devices as well.

## RESTRICTIONS AND EXPERIENCES

### *Past and Present Restrictions*

Up to now many minor as well as some major restrictions of the CS have been eliminated by further specifications. Since the whole CS is a pilot project some necessities hadn't been foreseen.
Two examples: (i) A snapshot monitoring function (comparison of set and read values) with large tolerance is implemented to roughly check the proper functionality of each single device at each cycle. Errors like defect interface cards of power supplies without correct status information can thus be easily detected. (ii) The possibility of automated conditioning of magnets with remanent magnetic fields has been included since for a long time it was only possible to operate this devices with current values.
Not yet implemented is the possibility to get all magnets read values per request since the whole concept is based on the execution of accelerator cycles. Especially for dc magnets an automated power saving functionality should be implemented as well.
Albeit properly specified no real parallel operation and optimization without interaction of the two ion source beamlines is possible. Partly this is a result of cost reductions in the BD system at an early stage of the project.

### *Experiences and Problems*

The main problems with the CS so far can be ascribed to an underestimation of complexity from the industrial partner. For example it wasn't possible for about one year to correlate BD data with accelerator cycles. Furthermore the correct implementation of the accelerator model to calculate device parameters regarding all dependencies took far more time than estimated. Still there are many problems regarding the stability and performance of the system. Necessary tools for offline-diagnostics, therapy protocols and visualization are far from being in the final state like the possibility to automatically measure and save high resolution data.
More details about experiences, functionalities and problems of the CS can be found in the papers and poster contributions TPPB39 and RPPB29 in this conference.

## REFERENCES

[1] A.Reiter, A.Peters, M.Schwickert, "INTEGRATED BEAM DIAGNOSTICS SYSTEMS FOR HIT AND CNAO" (TUPCH015), Proceedings of EPAC 2006, Edinburgh, Scotland.