# STATUS AND CONCEPTUAL DESIGN OF THE CONTROL SYSTEM FOR THE HEAVY ION THERAPY ACCELERATOR FACILITY HICAT

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## ABSTRACT

HICAT is a hospital-based heavy ion accelerator facility for cancer treatment presently being built for the university clinics of Heidelberg, Germany. The accelerator was designed by GSI, based on the technique and experience of the experimental cancer treatment project at GSI with over 250 patients successfully treated at present. All major components and systems of the HICAT facility are being supplied by industrial partners. This includes the accelerator control system that is being developed and will be installed, commissioned and maintained by and under the responsibility of an industrial system provider. Civil construction work on the building already started in early 2004, the installation of the first accelerator components is scheduled for the autumn of 2005. This presentation covers the status of the HICAT project, experiences with the industrial partnership and project management as well as the conceptional design of the accelerator control system. Emphasis will be placed on technical challenges such as the pulse-to-pulse operation with different settings as required by the intensity-controlled raster scanning technique, fast timing system and process synchronization.

## THE HICAT FACILITY

The HICAT project is a **H**eavy **I**on accelerator for **Ca**ncer **T**reatment being under construction for the university clinics in Heidelberg, Germany. The accelerator facility was designed to meet the specific medical requirements for the successful GSI cancer treatment program. HICAT consists of two ECR ion sources with independent spectrometer lines to produce both low LET ions (protons, He) and high LET ions ($^{12}C^{6+}$, $^{16}O^{8+}$) to cover the medical requirements and allows for fast switching. The beam will be accelerated by a compact-designed 7 MeV/u linear accelerator (400 keV/u RFQ and 7 MeV/u IH-structure DTL) and a compact 6.5 Tm synchrotron that allows $C^{6+}$ beam energies up to 450 MeV/u. In order to meet the intensity requirements, multi-turn injection will be used for beam accumulation. For extraction, the rf knock-out method in combination with a variable extraction time will be implemented. The facility features four target areas, two of them for horizontal in-plane patient treatment, one treatment place equipped with a 360 degree rotating beam transport system (isocentric gantry) as well as one experimental target area also used for quality assurance measurements.

No passive elements are foreseen to match the dose distribution to the individual tumor geometry. Instead, all treatment areas are equipped with horizontal and vertical scanning magnets and beam diagnostic devices for the intensity-controlled raster-scanning technique that was developed and successfully demonstrated within the GSI experimental cancer treatment program with over 250 patients to date. Fig. 1 shows the cross section of the first underground floor of the HICAT building which houses the accelerator sections, the patient treatment areas, local control rooms and various laboratories and offices. Note that the gantry treatment area vertically spans over all three building floors. For a general description of the accelerator, see [1].

## CONTROL SYSTEM REQUIREMENTS

Major aspects of the HICAT accelerator control system (acs) requirements are based on the experiences of the GSI cancer treatment program; the requirements of HICAT, however, exceed those of the pilot project. Only a brief summary of the most important requirements is given in this section; for a detailed description of the acs requirements, see [2].

The main characteristics of the HICAT facility are the application of the raster-scan method with active intensity, energy and beam size variation to match the dose distribution to the individual tumor geometry. In order to produce the beams with the characteristics required by the treatment system, the accelerator must operate on a pulse-to-pulse base with different settings. The beam characteristics are fixed and pre-defined in a library of beam characteristics, e.g. 255 different discrete energy steps.

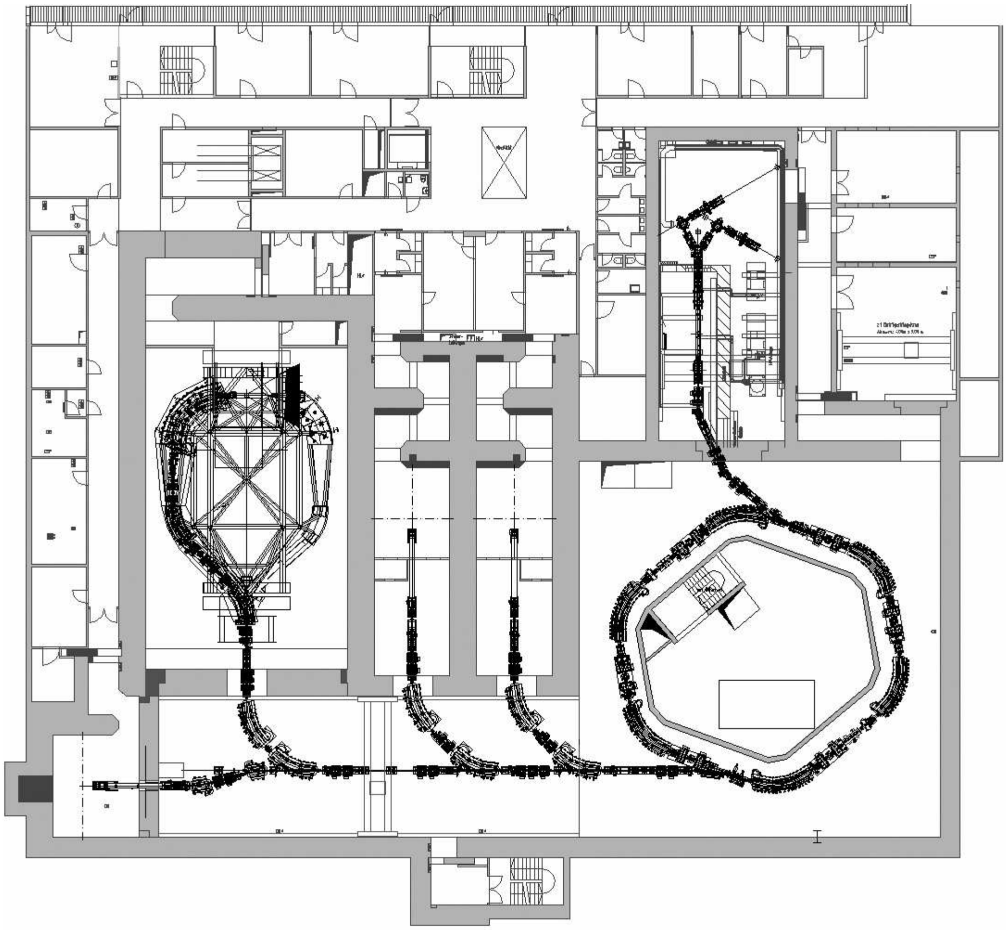

Figure 1: First underground layer of the HICAT facility

In order to achieve high operational reliability the acs must only use proven and validated settings for treatment cycles, protect settings from loss or accidental modification and inhibit operator’s interference in treatment mode. As all settings should be provided in stand-by on a pulse-to-pulse basis, these requirements lead to a high number of settings to be hold in the device controllers. This technical concept imposes strict and challenging demands on the operation of the accelerator and hence the acs of the facility.

For the entire accelerator chain, including linac rf-structures, choppers, bunchers, injection bumpers and all synchrotron power supply and other systems, a strict timing synchronization is required. Time-critical functions (i.e. triggers, acceleration ramps) must by synchronized within about 1   s precision. The acs must implement a timing system for system wide synchronization for locally distributed devices with real-time performance. The timing system must be flexible to react on non-deterministic requests for spill extraction pauses (gated extraction) and early beam cycle aborts. As all devices of the synchrotron must be ramped, functions for setting data must be served in real-time with a data rate of up to 1 MHz. Particular injection devices even need a higher data rate on a short time scale.

Finally, taking into account that such a therapy facility reaches its financial break-even only after a dozen years and is expected to have a life cycle of 25 or more years, the acs must be laid out for long service. At the same time it must be highly reliable and easily and efficiently operated by a small crew.

## INDUSTRIAL PARTNERSHIP

As all other major parts of the HICAT accelerator (magnets, power supplies, vacuum system, beam diagnostics, rf-systems, gantry structure, therapy treatment system, etc.) also the acs was to be developed, installed, commissioned and maintained by and under the complete responsibility of an industrial service provider, using a state-of-the-art system and wide-spread industrial components wherever possible.

In preparation of an open tendering procedure detailed technical requirement specification documents on the acs were compiled by GSI. In these, no particular technical solution for the acs was dictated or favored, allowing for new or even unconventional controls concepts. In the run-up to the tendering procedure a market survey was performed and several industrial companies were contacted in order to invite and motivate them to take part in the coming tendering. Most companies finally backed down when it became obvious that development of a dedicated hardware would be necessary to fulfill the particular timing requirements as the companies standard out-of-the-shelf solutions could not be used.

The public tendering procedure started in May 2002. Soon, a general contractor for HICAT was ruled out due to excessive costs that highly exceeded the approved accelerator budget. As a consequence, offers for all technical sub-systems – one of them the acs – had to be evaluated independently. For the acs three serious offers were handed in and carefully evaluated. All bidders were required to describe a detailed technical concept on critical aspects of the system. The selection of the industrial contractor was finally based on several criteria: quality of the acs concept, price, company's size and economic standing as an outlook for a stable long-term partnership, company's competence on hard- and software engineering, geographical location of the company's site in respect to GSI and Heidelberg, competence and experience in accelerator technology, as well as general reference projects.

In July 2003 the decision for Eckelmann AG, a medium-sized company well established in the control and automation industry was finally been taken. In particular, Eckelmann AG covers the full scale of the project: Being not only specialists in software development they also have a strong emphasis and many years of experience in hardware development of embedded controllers as well as in electrical installation design and control cabinet production. Considering this, there was no need for a hardware development sub-contractor, having a single point of responsibility only. In the ongoing project this has turned out to be very advantageous. Eckelmann AG had no experience in accelerator technology or controls before, but it turned out that the project management as well as the key developers surprisingly quickly took up the challenge to understand the controls aspects of accelerator technology.

The formal procedure in developing the acs is professional as being standard in the industrial sector: The whole project was broken down in several sub-projects or working packages. Based on GSI's basic requirement specifications and many additional discussions, Eckelmann AG generates technical specification documents of high level of detail and quality standard for every working-package. These documents are being reviewed by GSI experts and finally formally approved, being the base of the actual development and for later factory acceptance tests.

After more than two years of close cooperation between GSI and Eckelmann AG on the HICAT acs project a positive interim résumé can be drawn. The cooperation is very efficient and good. The project management and all involved developers are reacting highly flexible to adjust on project needs as well as changes that inevitably occur in a complex development.

## CONTROL SYSTEM

The HICAT acs architecture is based on a two-layer model with a flat hierarchy as shown in Fig. 2: The device control layer primarily comprises a large number of Device Control Units (DCU) as a standard controller for all types of real-time controlled devices, all beam instrumentation controllers and the respective DAQ systems as well as gateway PC systems to slow-control devices.

The upper layer of the acs is based on Intel based PC hardware systems and comprises the control system's Master Control, database and setting generation servers. All operations console PCs and maintenance clients are in this layer, too.

All components are connected by fast Ethernet networking; servers are connected by gigabit Ethernet connections. The network structure is flat: All network nodes have point-to-point connections to a central stack of switches with sufficient performance for the network traffic, even under heavy load. All communication is based on TCP/IP and UDP network protocols.

This system architecture features a reduced complexity and allows fast communication as well as minimal response times.

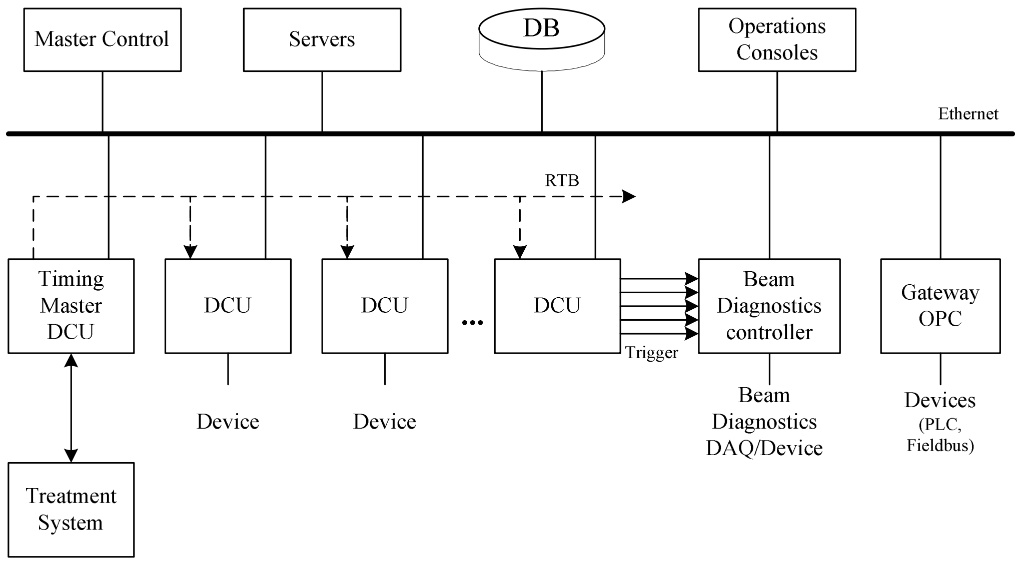


Figure 2: Architectural layout of the HICAT control system

## *Device Control Units (DCU)*

All types of accelerator equipment (power supplies, rf generators, choppers, etc.) that need fast real-time control are being interfaced and controlled by a dedicated custom-developed hardware, the Device Control Unit (DCU). The DCUs are developed to meet the strict timing requirements and are used as a standard project controller.

The DCU is an integrated board with an embedded processor from the Motorola family, based on the Power PC architecture. It is equipped with 32 MB of RAM and 64 MB of flash memory which holds the operating system, program code, settings and the validated therapy settings. The operating system is proprietary; the software is programmed in C++. Fast real-time control is realized by an integrated onboard FPGA from the Altera Stratix family that is directly connected to the data bus of the processor. Triggered by external signals on the real-time bus (see below) the DCU achieves a trigger function precision of 1 µs, features devices with two independent timing functions (ramps) of set-values simultaneously and allows fast data acquisition. The DCU has a freely configurable interface that features a 32 bit bidirectional parallel bus that operates at 10 MHz frequency (register-based access). Both DCU and device controller boards are placed on a common backplane for power supply, digital I/O and bus communication.

A DCU always controls only one single device. This is to keep the number of device classes and thus the complexity of the system low. By extensive unification of the equipment controllers only 7 different classes of DCU soft- and firmware are needed, greatly reducing the soft- and firmware development effort. The DCU hardware only comes in three different types: standard device controller (about 170 units), beam diagnostics trigger generator (with 32 trigger channels) and as a Timing Master Generator.

The DCU is a network node, it communicates to the Master Control and operations applications by Ethernet. Having a resident boot- and downloader mechanism the DCU is automatically loaded with programs, data and configurations needed for its particular device class and function.

## *Timing System (RTB)*

DCUs do not only have a network connection but are also connected to the real-time bus (RTB). On the RTB a 1 MHz clock signal as well as a very limited number of primary timing signals (events) are being distributed in the system. All device activity of the DCUs is triggered by these events, using local programmed delay functions based on the RTB system clock. As only a small number of events needs to be distributed, direct RS 485 transmission without protocol using standard and inexpensive Ethernet cabling can be used. Being a bus system, the RTB can be several hundred meters long.

Individual cable delays in signal transmission can be measured and compensated using an auto-calibration mechanism. All timing events are generated by one particular DCU, the Timing Master (TM). The TM is directly controlled by the Master Control server.

### *Beam diagnostics systems*

The beam diagnostics control and data acquisition are completely based on Labview RT systems. The controller are integrated into the acs. The interface (data telegrams) are similar to those of the DCUs.

### *Master control*

The Master Control is the central server of the control system. It communicates with the database and setting generation servers as well as with all devices of the device control layer and all user processes in the operations console PCs. The Master Control runs the state machine engine, monitors all devices, generates status information of systems and sub-systems and checks if all components for a working mode are in the appropriate states. It processes all user interaction, controls procedures and sequences of accelerator cycles and communicates with the treatment control systems for beam requests.

As the control system must generate beams with different characteristics on a pulse-to-pulse basis to feature the treatment system, the Master Control sends a broadcast telegram via Ethernet with all relevant beam characteristics information as well as security tokens to all systems in the device control layer. By receiving this signal, most DCUs already start to prepare their equipment for the cycle to come. All DCUs that are registered for the announced cycle send an acknowledge telegram back to the Master Control. This telegram contains amongst other data the actual status of the device, as well as a request code token. It is the function of the Master Control to receive, process and evaluate all acknowledge telegrams. If all devices have responded correctly, the Master Control sends a clearance signal to the Timing Master which then actually starts the cycle by sending the appropriate signals on the RTB.

For the Master Control a real-time extension to the Windows OS is being used to allow deterministic performance. As this sever is mission critical, a second server is foreseen to take over its function in case of malfunction in as short as possible time.

### *Slow Controls*

For all accelerator systems without fast real-time controls requirements (e.g. vacuum equipment, radiation & safety protection system, machine cooling system, PLC systems) wide-spread industrial standards were foreseen to be used. These components and systems were ordered turn-key with industrial standards like Profibus or OPC server interfaces and are seamlessly integrated by gateway systems into the acs.

### *Operations Software*

All operations clients as well as service and maintenance stations are PCs and are run with Windows OS. The operations software is being developed using the Borland Delphi software development environment. Delphi allows in particular for the GUI applications a rapid development and easy changing of the user interface.

## PROJECT STATUS

Civil construction work on the HICAT building already started in early 2004. The parts of the building where the accelerator and its infrastructure systems will be installed are nearing completion. For the accelerator a staged installation and commissioning is planned. Installation of the first accelerator components is scheduled for the autumn of 2005. Beginning in the first quarter of 2006 the sources and linac systems will be mounted and commissioned. The synchrotron and high energy beam transport lines will follow in summer 2006. The first patient treatment is scheduled for the end of 2007. The last step is the commissioning of the gantry and experimental treatment areas.

Works on the acs had already started in July 2003. The development and commissioning of the acs will be also conducted in three stages. As the hardware development and device interface definition was identified to be on the critical project path, this sub-project was addressed first. The development of the DCU as well as the common backplane is completed. The soft- and firmware for the device classes needed in the first stage are basically completed. Technical design documents for most other sub-packages (Master Control and database, setting generation server, beam diagnostics integration, personal safety system, vacuum control) are all ready and approved; the development for the first commissioning step is almost completed. A prototype of the acs is currently being intensively tested both at GSI and Eckelmann AG. Formal factory acceptance tests for these systems are scheduled to start in late October 2005. Prototypes of the main operations programs exist. As soon as these prototypes are fully functional and operational, a review will be done that takes into account the experiences with the usability in the test phase, and pre-final GUI versions with a common and consistent look-and-feel will be compiled. The control cabinets of the radiation safety system and the vacuum control are already completed and are ready to be shipped to Heidelberg for installation.

The date for the accelerator installation was changed several times due to delays in the building construction work. Consequently the acs development schedule was matched to allow a steady mean workload at Eckelmann AG. Due to that reason a comparison to the original schedule is a difficult exercise. In total one can find, that the acs development is slightly in delay, only partly caused by Eckelmann AG, but at no risk for the control system and accelerator commissioning schedule, since integration tests are foreseen no earlier then three months from the start of the installation works.

## REFERENCES

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[2] R. Baer, H. Eickhoff, T. Haberer “Status and Controls Requirements of the Planned Heavy Ion Tumor Therapy Accelerator Facility HICAT”, ICALEPCS 2001, San Jose, USA, October 2001.