ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MOPO106

NEW DIGITAL LLRF SYSTEM FOR HIT

E. Feldmeier, Th. Haberer, A. Peters, HIT, Heidelberg, Germany

Abstract

The Heidelberg Ion Therapy Center HIT is in clinical operation since 2009. The accelerator complex consists of a linear accelerator and a synchrotron to provide carbon ions and protons for clinical use as well as helium and oxygen ions. The analog LLRF system for the linac should be replaced after more than 10 years of continuous operation. In its life-time the LLRF caused no interruption of the clinical operation with a downtime of more than 15 minutes. In order to keep the reliability in the next 10 years at least as high, a new digital LLRF system is planned. Further difficulties for the installation of a new system are due to the clinical full time usage of the accelerator and the short maintenance slots of only two days in series.

INTRODUCTION

The layout of the accelerator of the Heidelberg Ion Therapy Center HIT [1] includes three ECR ion sources, a 7 MeV/u injector linac, a 6.5 Tm synchrotron and a high energy beam transport line to deliver beam for the four target places: Two treatment rooms with a horizontally fixed beam-line, the worlds first heavy ion gantry and an experimental area.

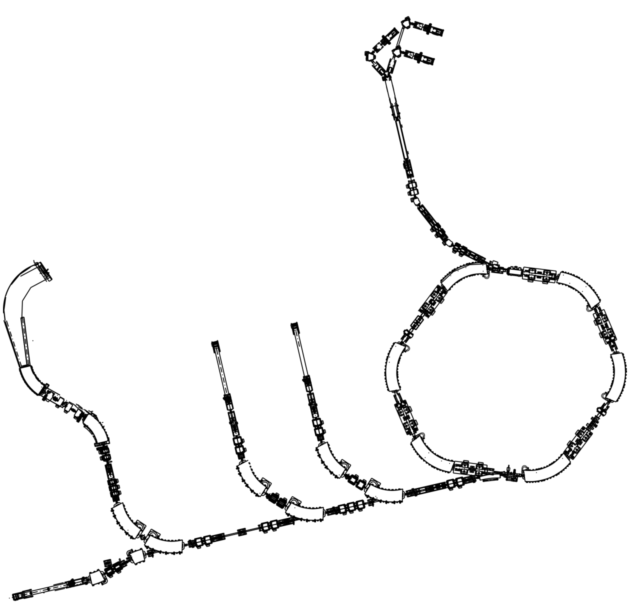

Figure 1: The accelerator of the Heidelberg Ion-Beam Therapy Center (HIT) with three ion sources, the LINAC (7 MeV/u) consisting of a 4-rod-RFQ and a IH-DTL, the synchrotron (48-430 MeV/u), the beam lines to the treatment rooms and the experimental area and the heavy ion gantry [2].

The ECR ion sources produce proton, helium, carbon and oxygen beam, of which the protons and the carbon ions are used for the medical treatment of localized tumors.

In the injector linac, beams with an AoQ of 1-3 can be accelerated to 7 MeV/u. The synchrotron accelerates the beam to an energy of up to 430 MeV/u for carbon ions.

LINAC AND RF SYSTEMS

The LINAC RF system shown in Fig. 2 supplies three RF cavities in front of the Synchrotron to accelerate and form the beam from the ion sources. A 4-rod-RFQ is used to accelerate the beam to 400 keV/u, focus the beam and form bunches. The following IH-DTL accelerates the beam to 7 MeV/u and the Debuncher spreads the bunches longitudinal to match the acceptance of the synchrotron. The cavities are operated at 216.816 MHz. For a beam with an $AoQ = 3$ a power for the RFQ of 200 kW, for the IH-DTL of 900 kW and for the Debuncher of 1.2 kW is needed.

The RF system (Fig. 2) consists of a common master oscillator providing the frequency. A amplifier and splitter is used to distribute the RF signal to the three power amplifiers. The RFQ has a 8 kW transistor preamplifier and a 250 kW tube final stage. The IH-DTL has a 4 kW transistor preamplifier, a 120 kW tube stage and a 1.4 MW tube final stage. The RF system for the Debuncher only uses a 4 kW transistor amplifier.

The analog PI-controller for each system corrects the amplitude and the phase of the decoupled cavity signal.

The RF system was designed by GSI in Darmstadt, Germany and build by Bertronix in Munich, Germany and Ampegon in Turgi, Switzerland.

LLRF SYSTEM

The requirements for the new digital LLRF system are based on the current analog LLRF system. Even there are new advantages with digital systems the great useability of the given system with its various possibilities for fault diagnostics and well-thought-out features must not be reduced. The preferred solution is a ready to use system with a lot of flexibility and free to program. Whether projects like microTCA [3] [4] or Libera [5] [6] can be used has to be proven. Otherwise a complete new system has to be developed.

In the following section the most important features will be discussed.

Master Oscillator

The HIT Linac works at 216.816 MHz and needs a frequency stability of better than 10^{-6}. The master oscillator can be set up separately and needs 4 or more output ports for the 3 rf systems and for the diagnostics. The phase stability of $< 0.1°$ is required.

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MOPO106

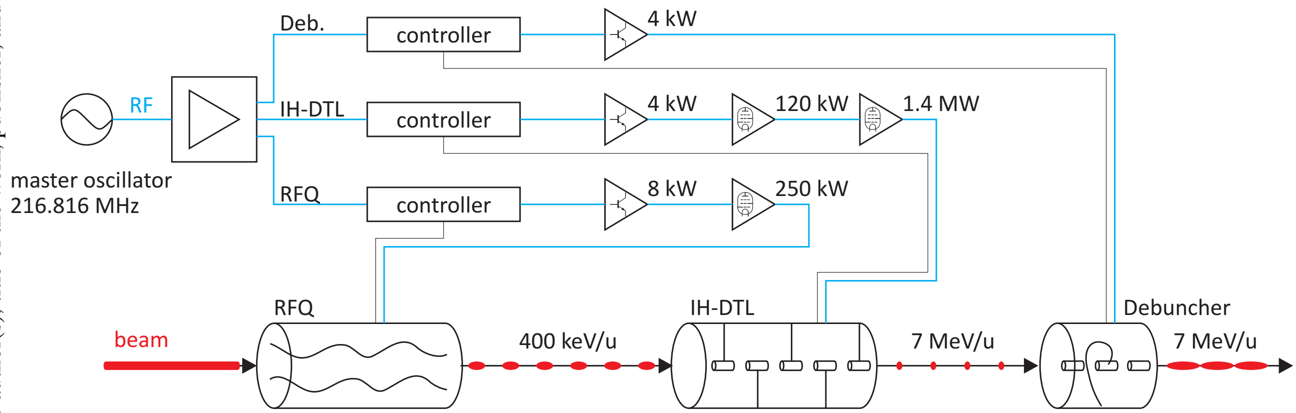

Figure 2: Schema of the LINAC RF System: One Master oscillator at 216.816 MHz, amplifier and divider distributes the RF to the three amplifiers, amplifier for the RFQ (8 kW transistor, 250 kW tube amplifier), amplifier for the IH-DTL (4 kW transistor, 120 kW tube amplifier, 1.4 MW tube amplifier), amplifier for the Debuncher (4 kW transistor). The control loop corrects amplitude and phase of the decoupled signal of the accelerator cavities.

Amplitude and Phase Control Loop

The amplitude and phase control loop has to provide a amplitude stability of better than 0.5% and a phase stability of better then 0.2°. The rf system operates in puled mode with a duty cycle of 0.5% and a pulse length of 500 μs. The repetition frequency is 10 Hz.

Since the beam current with a maximum of 10^{11} proton particles 10^8 carbon particles per pulse are small, beam-loading does not has to be considered.

The regulation parameters of the amplitude and phase control loop are different, since the phase control loop is much slower than the amplitude control loop. In addition to the feedback loop, a feed-forward loop with a non-linear calibration curve is foreseen.

In normal operation, the reference value for the feedback loop is taken from a decoupling loop of the rf cavity (cavity signal). Where the cavity is out our resonance for some reason and only less rf power is accepted, the decoupled cavity signal is very low. Then the feedback controller will operate on the reflected rf power with a fixed small set value (f.e. 10%), since the cavity gets in resonance and the cavity signal reaches the reflected power. The reference value is

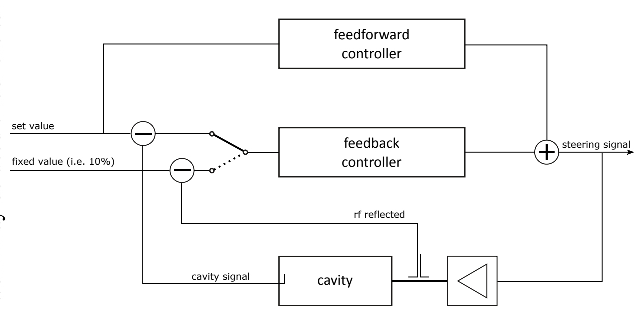

Figure 3: Basic block diagram of the foreseen controller with the feedforward controller and the feedback controller. When the cavity is out of resonance i.e. during startup phases, the reflected rf power is used as the reference value.

now switched back to the cavity signal and the normal set value. This leads to a smooth start up of the cavity and gives the ω_0 controller enough signal to work. A very simple block diagram of the foreseen controller is shown in Fig. 3.

The controller has to handle fast interlocks from the analog measurements in less than a few micro seconds like over ref power, over fwd power, vacuum interlock, et cetera with reducing the rf output and restarting after the interlock has gone within on rf pulse.

ω_0 Control Loop

The ω_0 controller steers the eigenfrequency of the cavity by adjusting the position of one ore more plungers per cavity. Since we are using pulsed rf with a low duty cycle, the feedback controller has to take account of this fact. The reference value can only be measured during a rf pulse but the pulse is to short measure an effect of the steering. When no new pulses are generated by the central control system, the controller has to stop the steering and move the plunger to an inital position. Ideally the controller has a model of the heating and cooling of the cavity and can adjust this position in response to the thermal history of the cavity.

As reference value for the feedback controller the phase difference between forward rf power and reflected rf power is used.

Timing

The timing is delivered by the central accelerator control system (ACS) and is synchronous to the 50 Hz mains supply. In times where no timing is delivered for example during maintenance or in case of a failure in the ACS the LLRF generates its own timing signals. This leads to a more stable operation of the cavities without restarting the rf system after an ACS breakdown. It is also very useful to be independent to other systems which may be down during maintenance.

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MOPO106

Operation Elements and Test Terminals

During operation, maintainance and service of the HIT linac rf system over the past 12 years some operating elements and test terminals were used quite often and improved the workflow. In case of an failure the right test terminals and service friendly systems can be repaired much faster and improves therefor the up-time. Even if they might seem to be obsolete in modern systems, they are foreseen in the new digital LLRF.

The system will have a potentiometer for the local set value of the amplitude and phase and a switch to select feedback mode or feed-forward mode.

Measuring terminals will be preset for pulsed amplitude and phase signal, DC set value for amplitude and phase, steering signal, controller deviation and two free configurable measurement ports for any other signal.

CONCEPT OF THE NEW DIGITAL LLRF

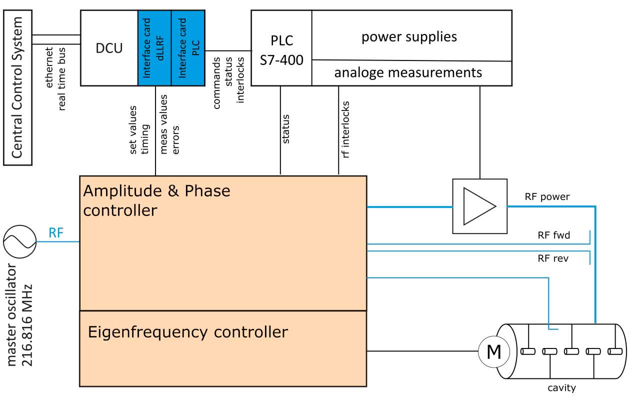

Figure 4: The block diagram of the new digital LLRF system for HIT. Central Control System, DCU, PLC, power supplies, amplifier and cavity are the given parts (white background). The amplitude & phase controller and the ω_0-controller will be renewed. A custom made solution as well as a industrial or scientific system are useful (orange background). While the *Interface card dLLRF* and the *Interface card PLC* has to be custom solutions. A new master oscillator can be taken from the stock.

The basic block diagram of the new dLLRF system is shown in Fig. 4. The central control system with the *Digital Device Unit* (DCU), as well as the power supplies, the amplifier and the cavity is given (white background).

Next to the DCU a new *Interface card dLLRF* and a new *Interface card PLC* has to be developed. They communicate with the DCU by a proprietary back-plane bus and translate signals from the ACS to the connected subsystems, such as set values, timing, interlocks, measurement values, et cetera. These two cards will be custom-made products, since they are only usable for the HIT system.

For the amplitude and phase controller as the centerpiece of the new dLLRF system, an open hardware and open software project with a widespread community is desirable. The advantages of an existing project with an active community leads to a reduced effort in development tasks, the availability of hardware in short term, the possibility to adjust it to the HIT system and program it with the needed features, outweigh a complete new development. Even when a custom made system would fit all the requirements best and could be the slimmest solution with maybe the highest reliability and availability, the effort in building such a system by their own is to much for a small team like HIT.

One boundary condition which cannot be changed is the small amount of space of only 6 rack units for the amplitude and phase controller as well as the ω_0-controller.

The system specifications are listed in Table 1.

Table 1: LLRF System Specifications

Requirements	Value
frequency	216.816 Mhz
frequency stability	$< 10^{-6}$
phase stability of the master oscillator	$< 0.1°$
duty cycle	0.5%
rf pulse length	500 μs
repetition rate	10 Hz
amplitude error	$< 0.5\%$
phase stability	$< 0.2°$
output rf power	+10 dBm

REFERENCES

[1] Th. Haberer, J. Debus, H. Eickhoff, O. Jäkel, D. Schulz-Ertner, and U. Weber, "The Heidelberg Ion Therapy Center", in *Radiotherapy and Oncology*, vol. 73 (Supplement 2), pp. S186-190, 2004.

[2] D. Ondreka and U. Weinrich, "The Heidelberg Ion Therapy (HIT) Accelerator Coming into Operation", in *Proc. EPAC'08*, Genoa, Italy, Jun. 2008, p. 979.

[3] J. Branlard *et al.*, "The European XFEL LLRF system", in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, p. 55.

[4] MicroTCA® is a trademark of PICMG, MTCA.4 specifications: `http://www.picmg.org`

[5] B. Baricevic *et al.*, "Evaluation of the Analog and Digital Receiver Section in the Libera LLRF System", in *Proc. PAC'09*, Vancouver, BC, Canada, May 2009, p. 2210.

[6] G. Jug and A. Kosicek "Libera LLRF – Development and Tests", in *Proc. IPAC'10*, Kyoto, Japan, May 2010, p. 1455.