ISBN: 978-3-95450-213-4 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2020-TUVIR14

THE SIS100 RF SYSTEMS – UPDATES AND RECENT PROGRESS

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Abstract

Within the FAIR (Facility for Antiproton and Ion Research) accelerator complex, the SIS100 synchrotron will provide high intensity proton to heavy ion beams to the various beam lines and storage rings. This paper presents the recent progress of the SIS100 overall RF system in its preparation towards installation. The RF system is split into four separate sub-systems with a significant number of RF stations. Each RF station consists of a ferrite or MA loaded cavity, a tetrode-based power amplifier, a switching mode power supply unit and various analogue or digital LLRF components for feedback and feedforward control. Fourteen ferrite cavities will generate the accelerating field, while nine cavities loaded with magnetic alloy ring cores are used for bunch compression. The barrier bucket system, which is used to apply a pre-compression of the beam, as well as the longitudinal feedback system for stabilization of beam oscillations will be realized by in total four cavities of the same type.

INTRODUCTION

The Facility for Antiproton and Ion Research is an accelerator facility, which will provide high intensity beams for experimental programs with a wide range of particles including protons, all kinds of heavy ions as well as antiprotons. The existing accelerators of the GSI Helmholtzcentre for Heavy Ion Research will be used as injectors for the FAIR chain of accelerators, beam lines, storage rings and experimental stations. A major upgrade program is ongoing for the GSI machines as well.

The synchrotron SIS100 is the main accelerator of the FAIR complex. With a circumference of ~1.1 km the machine is designed to accelerate high intensity proton and heavy ion beams. Its name reflects the Bρ value of the ring, which will consist of a mixture of superconducting and normal conducting components [1]. The lattice is optimized for the broad ion spectrum between protons and uranium. Special care has been taken to control particle losses due to residual gas effects. The construction of the SIS100 complex is ongoing and advancing well [2].

Four different RF systems are being prepared for SIS100, namely: the acceleration system, the bunch compression system and the broadband systems: barrier bucket and longitudinal feedback with a total number of 27(+13) RF stations [3, 4]. The "(+13)" stations will be added only in a later stage of a SIS100 upgrade.

- 14 (+6) Acceleration System (AC)
- 9 (+7) Bunch Compression System (BC)
- 2 Barrier Bucket (BB)
- 2 Longitudinal Feedback (LF)

In a simplified view each RF station is a compound of one cavity, with its amplifier, power supply unit and LLRF system. Still, the system with all its details will be much more complex, including the gap periphery, water cooling, controls integration and much more. Figure 1 visualizes the distribution of the RF stations along the SIS100 ring. The RF stations are located in all sectors (except sector 5, where the extraction system is located). For all of those systems the goal is to provide robust components for reliable operation of the RF stations.

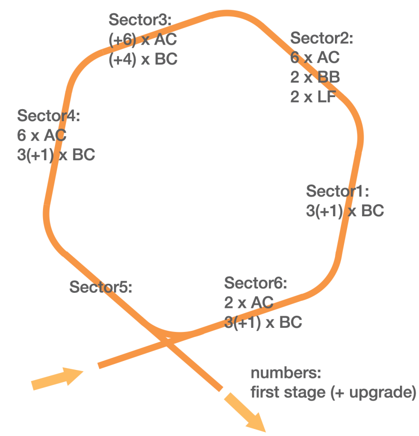

Figure 1: The distribution of the RF stations along the SIS100 ring. The numbers in brackets represent a later stage of a SIS100 upgrade

THE ACCELERATION SYSTEM

The 14(+6) RF stations of the AC system will accelerate ions in fast ramping cycles. The cavities are designed to provide high acceleration gradients of 20 kVp per cavity in cw operation. The design is based on the SIS18 design with two ferrite core stacks operating against one ceramic gap to provide the acceleration voltage. One of the challenges is to control degrading effects like dynamic and quality loss effects (ferrite characteristics) [5]. The tuning rates of ≥10 MHz/s lead to the need of a dedicated frequency tuning system.

The main parameters of the AC RF stations are:

- Continuous wave operation (cw)
- Frequency range from 1.1 MHz to 3.2 MHz
- Nominal voltage of 20 kVp
- Impedance seen by the beam <2 kOhm
- Cavity length of 3 m
- Tuning rate ≥ 10 MHz/s

The acceleration system is being realized by RI Research Instruments GmbH in collaboration with Ampegon Power Electronics AG for the power supply units. The first-of-series RF station has been successfully tested in a test stand

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at GSI [6] and currently, the production of the series is ongoing with a rate of about two cavity and amplifier systems per month. By end of May, 4 cavity and amplifier systems together with two power supply units are expected to be delivered to GSI. Two more systems are undergoing the factory acceptance tests at the moment. The photo in Fig. 2 shows one of the test stands at Research Instruments, where the cavity is tested in the system with a power supply unit and LLRF.

All systems are planned to be completed by autumn this year.

Figure 2: Test stand for factory acceptance tests of the cavity and amplifiers at RI (courtesy of RI Research Instruments GmbH).

THE BUNCH COMPRESSION SYSTEM

The bunch compression system will allow to create bunches of less than 50 ns bunch length due to a bunch rotation in longitudinal phase space by means of intentionally mismatched buckets. Therefore a 3 ms RF burst with a rise time of <30 µs and an overall gap voltage of 360 kV(+280 kV) is planned. The design of the 9(+7) RF stations is (like for the acceleration system) based on the RF stations operating in SIS18 [7, 8]. To be able to generate the peak voltages of 40 kV on a cavity length of just a bit more than 1 m, magnetic alloy ring cores are used instead of ferrites.

The main parameters of the BC RF stations are:

- Burst mode or pulsed wave operation 3 ms/s
- Frequency range from 310 kHz to 560 kHz
- Nominal voltage of 40 kVp
- Impedance seen by the beam <1 kOhm
- Cavity length of 1.2 m
- Amplitude rise time <30 µs (fall time uncritical)

The cavities and amplifiers for the bunch compression system are manufactured by Aurion Anlagentechnik GmbH, while the power supply units are realized by OCEM Power Electronics. All cavity and amplifier systems have been built already, you can see some of them as they are in storage at GSI currently together with a test stand at the manufacturing company Aurion with a power supply unit, cavity and amplifier in Fig. 3. Also all power supply units are in preparation for their factory acceptance tests at OCEM.

The first-of-series of the cavity-and-amplifier-systems as well as the power supply unit have been tested by the GSI

Figure 3: Photo of the test stand at the manufacturing company Aurion (left) and components in storage at GSI (right).

team under high power operating conditions. Those tests have shown that the system reaches the required parameters.

Still some topics were found, which led to adaptions of the series components. During high power tests sparking on the ceramic gap on the bunch compressor beam pipe had been observed. Also the power supply unit showed some issues with overheating on the anode modules, which prevented long term operation.

Both of these topics are currently being addressed. A new gap design has been defined, which is optimized to improve the shielding of ceramic to metal contacts from the high electric fields on the beam axis. New beam pipes with this gap geometry are in manufacturing right now and are planned to be verified before the end of this year. Also the first of series power supply unit has been upgraded and a 16 h duration test (on the cavity) has been carried out successfully (see Fig. 4). The implementation in the series is ongoing and first modules of the „new“ series are expected for testing on site soon.

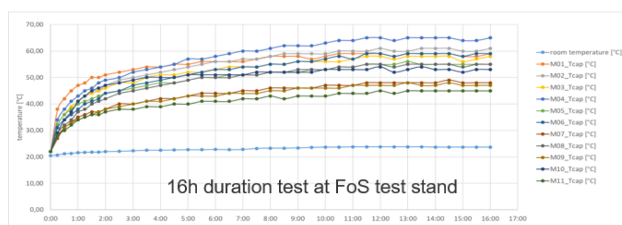

Figure 4: Temperature on the power supply unit anode modules stabilize at ~65°C during a 16 h duration test on the cavity.

LLRF FOR THE ACCELERATION AND BUNCH COMPRESSION SYSTEMS

The LLRF concept [9] for the AC and BC systems is very similar. Each of the cavities will be controlled in amplitude and phase. In addition, the AC system will be equipped with a frequency tuning loop to be able to follow the required tuning rates instantaneously.

One of the challenges for the LLRF systems in SIS100 is the distribution of the supply rooms around the ring. Solutions had to be found to ensure the synchronization of the systems at different locations. Central clock signals on a fixed frequency are distributed with the Bunch Phase Timing System (BuTiS) and processed in the common system to distribute the reference signals to the local cavity systems.

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The generic layout is presented in Fig. 5.

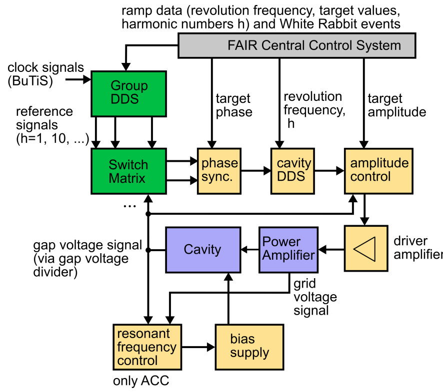

Figure 5: Schematic of the LLRF control loops for the SIS100 AC and BC systems.

Most LLRF modules are dedicated developments (in-house and in cooperation with external partners), e.g.

- rf distribution amplifier
- direct digital synthesis (DDS) module
- analog pre-processing phase detection modules
- DSP system (Sundance Multiprocessor Technology Ltd.)
- FPGA interface board FIB3 (KTS GmbH)

In the past years major developments for those LLRF modules have taken place. The high level of standardization of the LLRF modules for different systems allows to keep a common stock of spare modules for fast exchange in case of failures of modules in operation. Figure 6 shows a test installation of the LLRF racks.

About 50% of the series components have been delivered already and pre-assembly of the racks has started. This will allow us to minimize the installation time for the LLRF racks in the supply tunnel, once the tunnel is ready for installation.

Figure 6: Installation of the LLRF racks in the test stand of the AC first of series RF station at GSI.

THE BROADBAND SYSTEMS

Barrier Bucket System

A barrier bucket system with two RF stations is being designed for SIS100, which will be able to create potential barriers formed by two single sine pulses, whose amplitude and phase difference can be quickly modified within one cycle. This will allow to introduce longitudinal manipulations like for example pre-compression of a coasting beam.

It is planned to build two RF stations with magnetic alloy cavities. This is needed, since 15 kV have to be provided on a short length of 1.2 m.

The main requirements of the BB RF stations are:

- 15 kV pulse amplitude at cavity length ~1.2 m
- broadband pulses of duration 666 ns at repetition periods between 3.7 µs and 9.1 µs

Another major point of the design is the desired signal quality of the single sine pulse. A broad frequency range of 110 kHz up to 15 MHz and a pre-distortion of the input-signal are needed to match this requirement.

To generate the input signal, the transfer function $\underline{H}(\omega)$ is measured for each system and its inverse is calculated. With this information the Fourier-coefficients of the pre-distorted signal $\underline{\tilde{c}}_n = \underline{H}^{-1}\underline{\tilde{c}}_n$ can be defined, which compensates the set up characteristics individually.

Longitudinal Feedback System

The longitudinal feedback system is a preventive system to flexibly cope with different bunch oscillations [10]. For example, it will be used to damp longitudinal oscillations, acting individually on single bunches complementary to the beam-phase control. It consists of two RF stations with Fast Current Transformer (FCT) as beam pick-up and 2 broadband kicker cavities with tetrode amplifiers. The kicker acts on dedicated bunches in addition to the acceleration cavities, which can be used to damp cohered modes. The beam signal for each bunch is extracted to calculate the proper signal for the kicker cavity to correct its phase or shape. The correction signals for all bunches are combined afterwards in the overall kicker signal to generate the correct signal for the full bunch chain.

The main requirements of the LF RF stations are:

- signal processing individually for each bunch
- bunch gap >50 ns results in bandwidth (3 dB) requirement 20 MHz for overall system
- 12 kV required, cw operation

Status of the Broadband Systems

Following a staged approach in the project, the focus had been set on the AC and BC systems first. Meanwhile, machine experiments have been performed in the GSI Experimental Storage Ring and SIS18 to test the concepts of the BB and LF systems with quite good results. To give an example: the plot in Fig. 7 shows the measurement of a single-sine barrier pulse with very high quality that was taken on the BB system in the experimental storage ring. Also the signal processing for the LF system has been demonstrated at the SIS18 acceleration cavities.

Since the requirements in terms of frequency range and gap voltage are very similar, a common design for the cavity and amplifier systems of the LF an BB systems is preferred.

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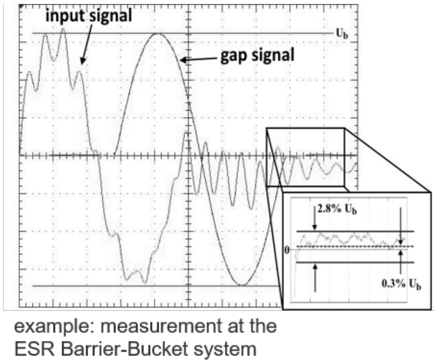

Figure 7: Measurement of a single-sine barrier pulse in comparison to the pre-distorted input signal in the BB system of the experimental storage ring.

A design study for broadband systems has shown that parameters like they are expected for the BB and LF operation in SIS100 are feasible. A visualization from this study is shown in Fig. 8.

Currently, detailed specifications for the SIS100 Barrier-Bucket system are in preparation.

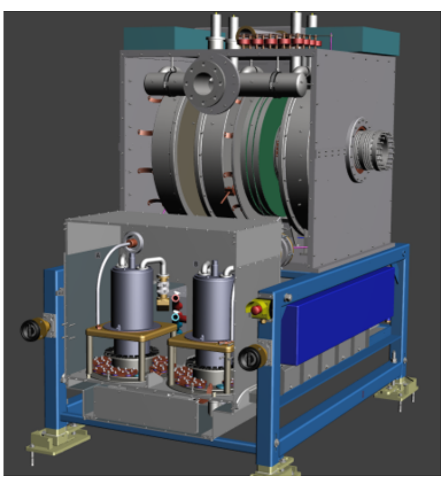

Figure 8: Visualization of a possible broadband cavity and amplifier system from the „Research and Development-study for magnetic alloy broadband cavities“ (Aurion Anlagentechnik GmbH)

LLRF for the Broadband Systems

The general concept of the LLRF systems for the broadband RF stations follows the one as presented for the AC and BC systems. Separate LLRF systems will be prepared for BB and LF in the first stage of operation, a later flexible usage of the LLRF for all four cavities will be studied. While the BB LLRF system is optimized for the generation of the single-sine RF barrier signals, in the LF system, signal processing for the individual bunches is needed as described before [11].

The LLRF systems are realized with many standard modules that are also used for SIS100 AC and BC (e.g. DSP, DDS). Dedicated modules for LF system include:

- Demultiplexer (DEMUX) and Multiplexer (MUX) developed by Novotronik GmbH
- broadband amplitude modulator

Dedicated modules for BB system include:

- waveform generator (Tabor)
- RF disabling unit
- trigger generation unit

Prototype LLRF architecture and machine development experiments have been realized for both systems.

An example of the demultiplexed bunch signals of an emulated chain of 4 bunches is shown in Fig. 9. Experiments like this one have shown the functionality of the systems.

Figure 9: Measurement of demultiplexed bunch signals of an emulated chain of 4 bunches.

CONCLUSION

The current status for the SIS100 RF systems can be summarized like this: The acceleration and bunch compression systems and the LLRF systems are in the phase of FATs and deliveries, while the broadband systems are in the phase of specification and design.

The placement of contract for First-of-Series (FoS) of the broadband cavities is planned for 2020. Other ongoing topics are the development of semi-conductor gap switches, which are needed to cope with the very high expected numbers of switching cycles in the gap periphery, or the integration of the LLRF system into the common control system.

Preparations for the installation and commissioning phase are ongoing. It is planned to start the installation of the SIS100 systems in 2021.

ACKNOWLEDGEMENTS

We would like to thank all our partners in industry and all GSI colleagues for the good collaboration and productive work on these projects.

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