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STATUS AND RECENT DEVELOPMENT OF FAIR RING RF SYSTEMS

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Abstract

Five different Ring RF Systems are required for the operation of FAIR (Facility for Antiproton and Ion Research). These systems have to operate at frequencies between 310 kHz and 3.2 MHz, with gap voltages up to 40 kV_p and duty cycles from $5 \cdot 10^{-4}$ up to CW. All systems will be realized using inductively loaded (ferrite or magnetic alloy) cavities driven by tetrode-based amplifiers fed by switch-mode power supplies. To stabilize the amplitude, resonance frequency and phase, versatile digital feedback and feedforward control will be used. This contribution will present the latest development on the power part and the LLRF of the four RF systems of the SIS100 (SIS100 Acceleration, SIS100 Bunch Compression, SIS100 Barrier Bucket and SIS100 Longitudinal Feedback) as well as the CR Debuncher system which is part of the Collector Ring. The progress of these systems varies by a large degree. This note will give an overview regarding the status of the design, procurement, realization, testing, optimization, commissioning and preparation for installation of these RF systems.

SIS100 ACCELERATION SYSTEM

The SIS100 [1] acceleration system consists of 14 RF stations. The design has been presented in [2, 3]. The main parameters of the RF stations are:

- Continuous wave operation (CW).
- Frequency range from 1.1 MHz to 3.2 MHz.
- Nominal voltage of 20 kV_p per cavity.
- Impedance seen by the beam < 2 kΩ.
- Tuning rate ≥ 10 MHz/s.

The company RI Research Instruments GmbH [4] in collaboration with Ampegon Power Electronics AG [5] is responsible for the realisation of the acceleration system with GSI providing the LLRF system. The first-of-series (FoS) RF station has been successfully tested in a test stand at GSI [6] and the latest progress has been presented in [7].

Series Production and Factory Acceptance Tests

The series production of all RF stations has been finished and all components have passed the factory acceptance tests. Those tests have been performed by the manufacturers on their site. The cavities and amplifiers have been tested at RI within the full RF station with a test program comparable to the site acceptance test of the first RF station at GSI. For the testing of the other power supply units a test stand with a dummy load has been used at Ampegon.

The test programs cover checks and measurements of all relevant parameters from the mechanical structure and electrical installation checks, to high power performance runs or the analysis of the beam pipes' conformity with the vacuum requirements for SIS100. Together with the test reports a set of manufacturing documents is reviewed, which represents the status of the components as delivered to GSI. To give an example of those test results, the beam impedance measurements of the series cavity and amplifier systems is presented in Fig. 1.

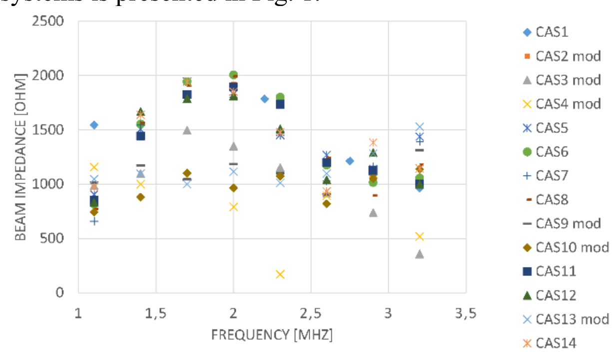

Figure 1: Beam impedance measurements of the SIS100 Acceleration Systems (measurements taken by RI).

Originally, some of the systems have exceeded the specified impedance seen by the beam of < 2 kΩ, but it could be shown that an optimized matching allows to reduce the beam impedance while still being able to operate with an acceptable reflected power on the pre-amplifier (results marked with "mod" in Fig. 1).

In total all cavity and amplifier systems as well as the power supply units have matched their specifications.

Current Status and Outlook

In Dec 2020 all cavity and amplifier systems as well as the power supply units have been delivered and all components have been upgraded to match the latest status. Further tests in the test stand at GSI are still planned before start of installation in order to gain experience and to monitor the systems after a higher number of operation hours.

SIS100 BUNCH COMPRESSION SYSTEM

The 9 RF stations of the bunch compression system [3, 7, 8] will be operated in the SIS100. The main parameters of the RF stations are:

- Burst mode or pulsed wave operation 3 ms/s.
- Frequency range from 310 kHz to 560 kHz.
- Nominal voltage of 40 kV_p per cavity.
- Impedance seen by the beam < 1 kΩ.
- Amplitude rise time < 30 µs (fall time uncritical).

The cavities and amplifiers for the bunch compression system are manufactured by Aurion Anlagentechnik

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GmbH [9], while the power supply units are realized by OCEM Power Electronics [10].

Current Status and Outlook

One cavity and amplifier system has been equipped with a redesigned ceramic gap and coupling loops. After modifications in the amplifier, which were necessary to control sparking around the tetrodes, intensive tests at 40 kV_p and nominal duty cycle were performed on this system together with the pre-series power supply unit at Aurion. The testing has highlighted points to be improved in order to ensure the reliability of the components. Meanwhile all power supply units have passed the factory acceptance tests and will be prepared for delivery soon. The tests on the cavity and amplifier systems are ongoing.

SIS100 BARRIER BUCKET

A total of two Barrier Bucket cavities [3, 5] will be needed in SIS100 to serve several purposes like e.g. precompression of a coasting beam prior to bunch rotation. The main parameters of the system are as follows:

- Creation of single-sine pulses with a period of 666 ns.
- Max. 15 kV_p per cavity.
- Max. repetition rate of 270 kHz.

After completion of a design-study for cavity and power amplifier, development activities focused on ring core evaluation and development of a gap voltage measurement chain with sufficient bandwidth.

Ring Core Evaluation

Measurement results from a prototype core were used for all simulations carried out for system design. Six additional ring cores which have already been manufactured for the FoS outperform this prototype core in the relevant frequency range below 15 MHz, confirming the existing design; manufacturing is planned for 2022; see Fig. 2.

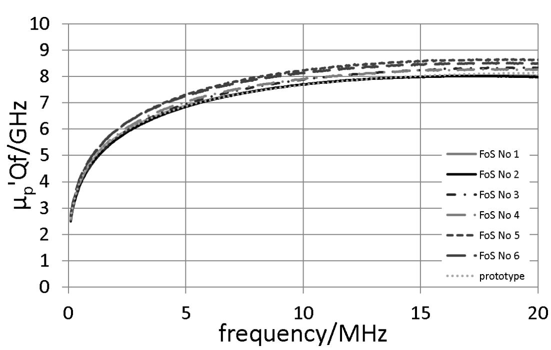

Figure 2: Measurement data of 6 ring cores.

Gap Voltage Measurement Chain

Ideally, a gap voltage divider would be matched to a 50 Ω transmission line to allow signal transfer to the supply room. This can only be achieved for a certain frequency range, while Barrier-Bucket signals have a very high bandwidth. Broadband behaviour can be achieved if the requirement of matching to 50 Ω is changed for high impedance.

Therefore, we decided to use a high-voltage probe connected to the gap. Using a 30 m RG223 cable a radiation-protected area in the accelerator-tunnel can be reached, where an instrumentation amplifier is installed as an impedance converter. From here, the signal will be transferred to the supply room by optical transmission or a long transmission line. All components were connected in a test setup and the transfer function of the full gap voltage measurement chain was measured (see Fig. 3).

Figure 3: Amplitude of the gap voltage measurement chain's transfer function H and phase error compared to a purely linear response (dashed lines: 3° limit).

SIS100 LONGITUDINAL FEEDBACK

A total of two longitudinal feedback RF systems will be used in the SIS100. Their main task is to supplement the beam phase control which is only able to act on coherent dipole modes. The longitudinal feedback system will damp coherent and incoherent modes of higher order. The main parameters are as follows:

- 12 kV_p gap voltage per cavity.
- Overall system bandwidth larger than 20 MHz (bunch gap of 50 ns).
- Separate signal processing for each of the up to eight bunches in the SIS100.

The system is still in an early conceptual phase. The main goal is to reuse the power part of the SIS100 BB system and develop a new LLRF system. For some LLRF components like the demultiplexer and the multiplexer as well as the broadband modulator prototypes are available and have been tested.

COLLECTOR RING DEBUNCHER

In the first stage, five RF stations will be installed in the Collector Ring [11] with the following parameters:

- Frequency range 1.1 MHz to 1.5 MHz.
- Combined CW and pulse operation (max. 1 Hz, max. 3 ms).
- 2 kV_p in CW and 40 kV_p in pulsed operation per cavity.

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For details regarding requirements, system design, integration and testing of the first RF station see [12, 13].

The main activities on the CR Debuncher have covered three topics: manufacturing and delivery of components for the series RF systems, testing of the series RF systems and upgrades to improve the reliability of the RF systems.

Delivery of Components for the Series

Up to now, all five cavities and power amplifiers including water distribution system and interface racks have passed the factory acceptance tests and are available at GSI. These units have been designed and manufactured by RI Research Instruments GmbH. Regarding the power supply units, the design and manufacturing has been done by OCEM Power Electronics. All five units have passed the factory acceptance tests and four have been delivered to GSI. After arrival of this 5th power supply unit which is planned for Q2/21, all power components for the CR Debuncher series will be available at GSI.

Testing of Series RF Systems

Currently, the second system is under investigation. Figure 4 shows the voltages on both sides of the ceramic gap measured with capacitive voltage dividers (green and blue trace) as well as the rectified sum of these gap voltages (red) and the target amplitude (yellow). The system has been operated at 1.43 MHz using the feedback amplitude control loop in pulsed (1 Hz, 2.3 ms, 40 kV$_p$) and CW (2 kV$_p$) operation. A shift of the working point of the tetrodes between CW and pulsed operation has been realized by a nearly simultaneous jump of the control grid and anode voltage. It could be shown that the second RF system is capable of providing the required frequency range, gap voltages, pulse lengths, repetition rates and rise and fall times.

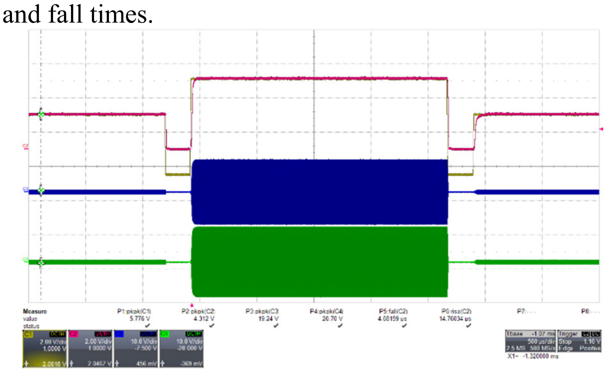

Figure 4: Operation of the second RF system in combined pulsed and CW operation. Horizontal axis 500 µs/div.

Reliability

Extensive testing of the CR Debuncher in a laboratory environment led to several improvements of the reliability of the system. Hard- and software adaptations of the power supply unit as well as enhancement of the EMC led to a reduction of false machine protection interlocks. A rework of the cooling water system in the tetrode-based power amplifier has been implemented to increase the resistance against pressure spikes. The improvement of the reliability is an ongoing process. Currently, the coaxial feedthroughs between the cavity and the power amplifier are reworked, the cooling water guidance inside the tetrodes is adapted by Thales and a study is performed by OCEM to improve the EMI characteristic of the switch mode power supplies.

STATUS OF LLRF SYSTEMS

The low-level radio frequency (LLRF) system architecture of the FAIR Ring RF systems has been described in detail in [14]. For most FAIR Ring RF systems, the realization of the LLRF systems is similar due to the use of standardized digital and analogue LLRF modules. Nevertheless, there are of course differences between the different types of Ring RF systems. For example, SIS100 Acceleration is the only system that needs a resonance frequency tuning loop. In addition, SIS100 Barrier Bucket and SIS100 Longitudinal Feedback need further specialized modules. The development of the majority of LLRF modules has now been completed. During the last year, two important development projects that are realized with external partners made significant progress. The hardware development of the FPGA Interface Board FIB3 has been finished and the first series batch has been produced and delivered by KTS GmbH [15]. Currently, the FIB3 modules are tested with beam in the existing heavy-ion synchrotron SIS18 and in the experimental storage ring ESR as part of Direct Digital Synthesis (DDS) modules. The production of the second series batch of FIB3 is scheduled until the end of 2021. The DSP system that is developed by Sundance Multiprocessor Technology Ltd. [16] has now reached the pre-series production stage and one pre-series system has been successfully tested and approved. One DSP system is now tested with beam in the ESR. Next, the two remaining pre-series systems will undergo a site acceptance test before the approval for series production will be given.

The series production of a large number of LLRF modules has been completed during the last year, including:

- Analog modules for the amplitude detection and control.
- RF distribution amplifiers for the duplication of RF signals.
- Calibration Electronic Modules for the phase and amplitude calibration of the Ring RF systems.
- 19'' RF Backplane crates for the mounting of LLRF modules.

The procurement of the remaining modules is currently under preparation; this includes:

- Data Logging System hardware.
- Fiber Optical modules.
- Optical Transmission System for optical signal distribution of gap signals between accelerator tunnel and supply areas.
- Gap periphery.

As most LLRF modules are available in full quantities, the pre-assembly of the LLRF modules into 19'' racks will take place in 2021. The installation of the racks into the SIS100 supply tunnel is planned for 2022.

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