DESIGN AND COMMISSIONING OF THE RF SYSTEM OF THE COLLECTOR RING AT FAIR

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Abstract

The Collector Ring (CR) is under construction at GSI (Darmstadt, Germany) in the scope of the FAIR project. The CR is a dedicated ring to perform efficient cooling of secondary ions and antiprotons coming from the Super-FRS and the antiproton separator. In order to achieve the desired longitudinal cooling, RF manipulations are required. Therefore, the RF system of the CR has to provide a frequency range from 1.1 to 1.5MHz and pulsed gap voltages of up to 200kV$_p$ (0.2 to 1Hz, max. 10^{-3} duty cycle) and up to 10kV$_p$ in CW operation. Five identical RF stations will be built. Each RF station consists of an inductively loaded cavity, a tetrode-based power amplifier, a semiconductor driver amplifier, a switch-mode power supply and two digital feedback loops. The main components of the RF station are designed, built and commissioned in close collaboration between GSI and three companies: RI Research Instruments GmbH, Ampegon PPT GmbH and OCEM Energy Technology SRL. In 2016, the first of five RF stations has been integrated at GSI. In 2017 the system was successfully commissioned to demonstrate that all envisaged parameters have been achieved. This contribution will present the requirements imposed on each RF station, the principal design of the overall system as well as of its key components, and the results of the commissioning of the first RF station.

INTRODUCTION

The FAIR Project is under construction at the GSI site in Darmstadt. This paper presents the RF system of the Collector Ring [1], a storage ring within the FAIR project.

REQUIREMENTS

The Collector Ring is mainly designed to process secondary beams (rare isotopes and antiprotons). In order to do so the RF system has to fulfil three major tasks [2]:

1. Rotation of each injected bunch in phase space to provide a fast reduction of momentum spread.
2. Afterwards the bunch is adiabatically debunched to create a coasting beam.
3. After stochastic cooling, it has to rebunch the beam to allow a full aperture extraction.

To cover these tasks, the RF system has to provide pulsed (0.2-1Hz, max. 1ms length) operation with RF voltages of 500V$_p$-200kV$_p$ and CW operation at voltages between 30V$_p$ and 10kV$_p$. The system will be used at harmonic number 1 over a frequency range from 1.1 to 1.5 MHz.

SYSTEM DESIGN

The RF system of the CR consists of five identical RF stations with a length of 1125mm each providing gap voltages up to 40kV$_p$ (pulsed) and up to 2kV$_p$ (CW). The overall system design [3,4] has been done in close collaboration between GSI and the main contractor RI Research Instruments GmbH (RI). Each station consists of several subcomponents as shown in Figure 1.

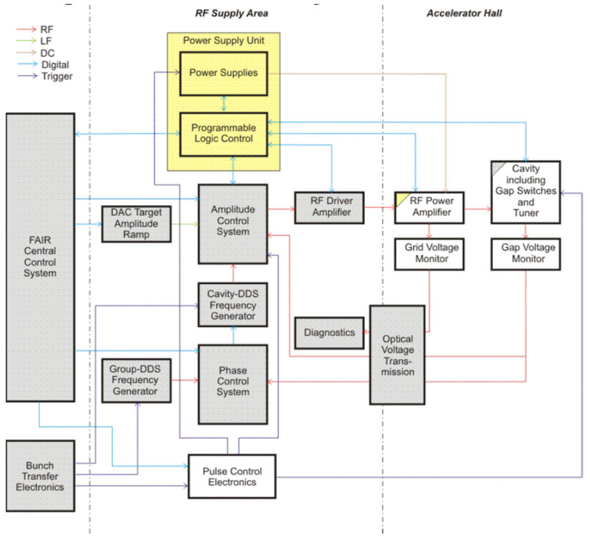

Figure 1: Schematics showing the main components of one CR Debuncher RF station and their interaction.

An inductively loaded cavity (RI) with a ceramic gap is coupled to a tetrode-based amplifier (Ampegon). The DC operation voltages of the tetrodes are supplied by a switch mode power supply (OCEM) which also includes a programmable logic control (PLC) to provide control and machine protection functionality.

Figure 2: First RF station during commissioning.

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Two digital feedback control loops [5] stabilize the amplitude and the phase of the gap voltage. A semiconductor driver amplifier is used for pre-amplification. The main components of the first RF station are shown in Figure 2.

CAVITY

The cavity as shown in Figure 3 is realized as two inductively loaded coaxial quarter wavelength resonators working on a common ceramic gap. It is operated under atmospheric pressure whereas the beam pipe including the ceramic gap is part of the accelerator vacuum.

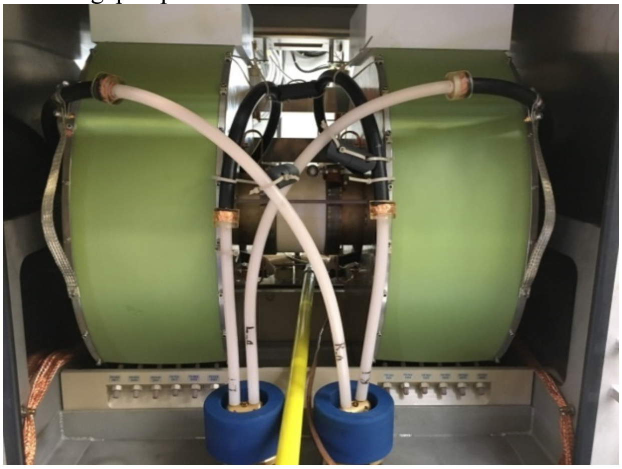

Figure 3: The coupling loops, the ceramic gap and the anode feedthroughs. Both stacks of ring cores are covered by GRP sheets to guide the air cooling.

On each side of the ceramic gap six tape-wound cores made from soft magnetic, amorphous, Cobalt-based alloy type VITROVAC6030F are placed to create the inductive load. These cores with a width of 25mm, an outer diameter of 650mm and an inner diameter of 292mm exhibit in the operating frequency band a measured (LLRF) $\mu_p Qf$ value of 5.0GHz, a shunt resistance of 127Ω and an inductance of 4.4µH per core. The average power dissipation amounts to 170W per core which is cooled using forced air. In order to create a strongly coupled resonator and to suppress higher harmonics, each tetrode is coupled to each half of the cavity using a separate coupling loop (four loops in total) made of a partially shielded coaxial cable (RG218).

The connection between cavity and power amplifier is made by two dismountable coaxial feedthroughs that have been optimised to withstand high fields ($25\mathrm{kV_{DC}}+20\mathrm{kV_{prf}}$) using 3D EM simulations (see Figure 4). The RF station can be motor-tuned using variable capacitors.

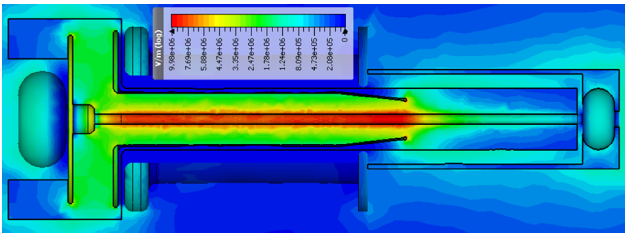

Figure 4: Anode feedthrough FEM calculation including colour coded amplitude of the electric field.

POWER AMPLIFIER

The power amplifier uses two Thales tetrodes TH555A in grounded cathode scheme and push-pull configuration working in or close to class A. The principle schematics of the power amplifier and the coupling between cavity and power amplifier are depicted in Figure 5. Both tetrodes are supplied by a common DC anode voltage via the coupling lines using the inductance of the cavity as main RF choke. Each tetrode has its own screen grid DC power supply to individually balance the gain of both tetrodes. There is a common control grid DC supply which can be switched to change between pulsed and CW operation. The filaments are directly AC-heated. To keep the 50Hz modulation in voltage between cathode and control grid low, a portion of the filament voltage is coupled to the control grid of each tube. The RF driver signal is fed via a transformer with 180° phase difference to both control grids of the tubes. Since the anode dissipation in pulsed operation exceeds the rated values of the tetrodes, a fast modulation of the working point of the tetrodes is necessary. This is done by a modulation of the control grid voltage (typically -210V in pulse, -460V in CW) using two separate voltage sources in the power supply and a semiconductor switch close to the power amplifier. Optionally it is also possible to perform a fast modulation of the output voltage of the anode power supply (typically 25kV in pulse, 8kV in CW) to increase efficiency.

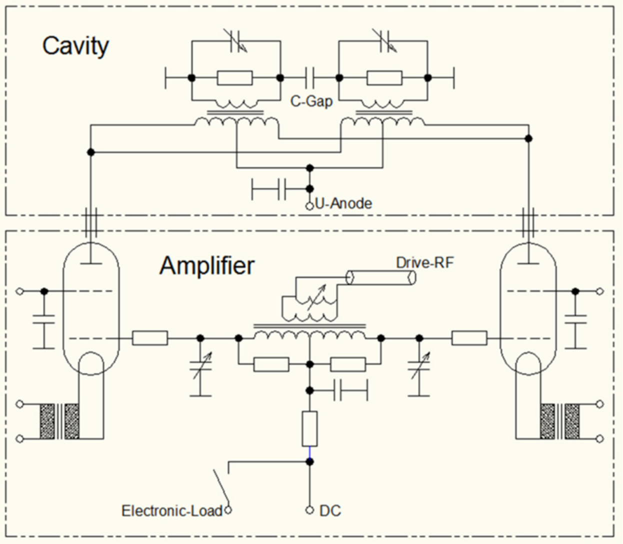

Figure 5: Schematics of the power amplifier.

The amplifier uses forced air and water cooling. It is installed in a trolley directly beneath the cavity to enable easy and fast maintenance.

POWER SUPPLY UNIT

The power supply unit consists of six power supplies:

One modular anode power supply is capable of providing up to 26kV with 10A in CW and 100A in pulsed operation (differential supply). It consists of a transformer with 28 three phase secondary windings in star and delta configuration feeding 28 identical modules in series connection followed by an RLC output filter. The modules (composed of full wave diode rectifier, DC filter, boost converter @10kHz, output IGBTs) will normally work in series connection through output IGBTs. During a fast change of the load (e.g. during a change of tetrode working point) the modules will also use a distributed PWM scheme (280kHz) to drive the output IGBT to control the voltage. All modules are controlled by a fast FPGA-based feedback loop. The output IGBTs will also be used as a fast in series switch, avoiding the use of a crowbar. This topology allows for a fast (<200µs) modulation of the anode voltage in the range from 6kV to 26kV.

Two differential screen grid power supplies provide up to 2kV (4A) each. These off-the-shelf-components feature an input rectifier, DC filter, PWM (full IGBT bridge), transformer, output rectifier and an output filter as well as a fast crowbar for tube protection.

One control grid power supply delivers the CW (up to -1kV, -4A) and pulsed voltages (max. 500V above CW voltage, +3.3A for 3ms, 1Hz). It consists of a power supply similar to the screen grid. In addition a controlled electronic load using three MOSFET lines in parallel is connected via a shunt resistor to the output of the control grid power supply. An analogue feedback loop stabilizes the electronic load output voltage.

Two filament power supplies (AC 400V, 16A) consist of mono phase thyristor regulated units. At the input an autotransformer is used to adapt the working points without thyristor commutation at the end of the filament ramp.

A very high attention has been given to the reliability of the system: all power capacitors of the anode power supply are polypropylene film type with a guaranteed lifetime of more than 100.000 hours, even in case of severe overvoltage events; moreover, the power electronics components (IGBTs, diodes …) are chosen considering margin from thermal and current capability's point of view.

The power supply uses a PLC working as user interface. It provides different operation modes, administers all set values, displays measurement values and handles the switch on and off sequence. In addition it covers the machine protection management of the overall system.

COMMISSIONING

The first CR Debuncher RF station was integrated on GSI premises by all four main partners (GSI, RI, Ampegon and OCEM). The main challenges that were overcome during the commissioning were high frequency self-amplification in the amplifier, X-ray emissions of the tetrodes, spark-overs in the cavity as well as in the anode feedthroughs, RF induced vacuum instabilities in the beam pipe, stability issues of the anode voltage and general problems regarding long term operability. Figure 6 shows a picture from an oscilloscope depicting the behaviour of the RF station in combined pulsed (rectangular 40kV$_p$) and CW (rectangular 2kV$_p$) operation at maximum voltages and a frequency of 1.44MHz. The cycle frequency amounts to 1Hz and the RF pulse length adds up to 2.25ms. CH3 (blue) and CH4 (green) show the RF voltage measured by two capacitive dividers (1:2140) from each side of the ceramic gap to ground potential.

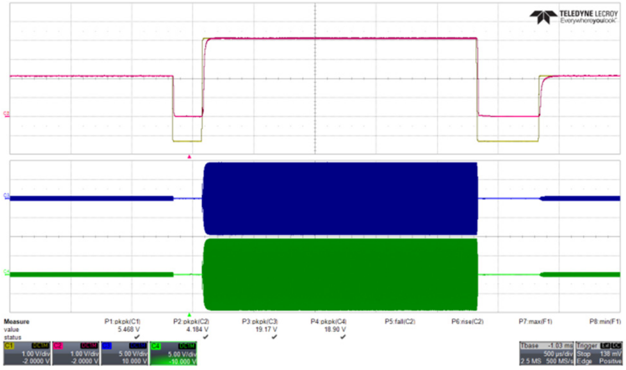

Figure 6: Combined CW and pulsed operation. Scaling: time base 500µs/div, vertical (CH3, CH4) 5V/div.

CH1 (yellow) depicts the target amplitude and CH2 (red) illustrates the actual amplitude of the summed gap voltage. Table 1 shows some of the most important parameters that have been demonstrated by the RF station.

Table 1: Results of Measurements on the CR Debuncher

Resonance frequency	0.85-1.44MHz	
Cavity impedance	1270Ω	
	Pulsed	CW
Harm. purity of gap volt.	<-38dB	<-50dB
Stability (ripple, noise) of gap voltage amplitude	±0.7%	±1.9%
Rise time (10%→90%)	<25µs	<70µs
Fall time (90%→10%)	<10µs	<5µs

CONCLUSION AND OUTLOOK

In 2016 the first CR Debuncher RF station has been installed and commissioned at GSI. After debugging and optimization it was extensively qualified and in 2017 it could be demonstrated that all specified parameters have been achieved. Currently, all components for the four series stations are built by the associated companies. It is planned to proceed with the installation of the second station at GSI in summer 2018. The last station will be commissioned beginning of 2019.

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