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THE FAIR SIS100 BUNCH COMPRESSING RF STATION

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Abstract

In the frame of the Facility for Antiproton and Ion Research (FAIR) 9 bunch compressor RF stations were ordered for the first stage of realization of the SIS100 synchrotron [1]. For RF gymnastics referred to as bunch rotation, one RF station has to provide a sudden rise in gap voltage of up to 40 kV_p within less than 30 µs. The system is designed for a maximum RF burst of 3 ms per second. The RF frequency will be pre-selectable between 310 kHz and 560 kHz at a harmonic number of h=2 with respect to the beam. Compressed bunches with a peak current > 150 A and a width < 50 ns are the goal.

For this purpose, a 1.218 m long cavity was designed using iron-based magnetic alloy cores. Variable vacuum capacitors are attached for tuning. The cavity is driven by a cross-coupled push-pull tetrode amplifier. This scheme minimizes the influence of the tetrode's DC current at the working point to the cores. The energy for the pulsed system is stored in a relatively small capacitor bank which will be charged semi-continuously and a voltage-stabilizing device is added.

Cavity and power amplifier were realized by AURION Anlagentechnik GmbH – the power supply unit is designed and built by OCEM Power Electronics.

INTRODUCTION

Bunch rotation involves a sudden rise in the RF gap voltage from an initial value (e.g. 0 V) to a final value (large bucket) during some µs (no acceleration). The distribution of particles in the longitudinal phase space is not matched to a constant Hamiltonian contour, which means that the form of the distribution undergoes a rotation. After approximately one quarter of a synchrotron oscillation period the bunch will be extracted and the shortest bunch length is reached at the target.

GENERAL RF REQUIREMENTS

Each RF station must fulfil the following data:

Specified Data

- Frequency range from 310 kHz to 560 kHz
- Nominal voltage of 40 kV_p across the gap
- Amplitude rise time < 30 µs (fall time not specified)
- Burst mode or pulsed wave operation 3 ms/s
- Shunt resistance (cavity || amplifier) < 2 kΩ
- Beam parameters DC 1.2 A, bunch peak 150 A @ 30 ns bunch length

CAVITY DESIGN

The FAIR SIS100 bunch compressing cavity [Fig. 1] is a straightforward adaption of the GSI SIS18 bunch compressor design [2] – but with some new features. The housing is mainly made of aluminium profiles and plates. Three subassemblies form the cavity: Resonator housing, tuning box and anode filter. The amplifier is located below the resonator (see also Fig. 5) - movable on rails in a steel support frame. The height adjustment is made via the feet.

Figure 1: Fully assembled bunch compressor.

Resonator

In principle two series λ/4 resonators oscillate in 180° phase opposition beside a ceramic gap. Both inductive stacks are electrically combined in parallel by means of four crossed coaxial loops – similar to 'figure-of-eight' arrangements - often used for DC biased ferrite cavities. Low permeability ring cores are used. The cavity is electrically shortened by a capacitive tuner – forming a narrow-band resonator. As shown in Fig. 2 a bunch compressing RF station with lower permeability ring cores is more robust against the gap voltage deformation influenced by the peak bunch current. Otherwise the bunch current has to be compensated up to higher orders e. g. by applying feed-forward techniques.

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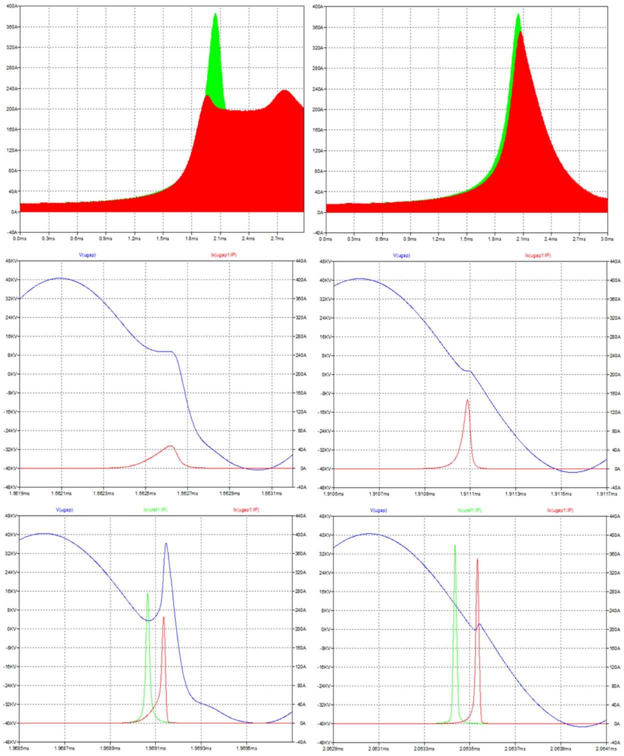

Figure 2: Simulated bunch rotation - currents over time.

Left: Untuned broad-band cavity (e.g. FT3M).

Right: Tuned narrow-band cavity (e.g. 6030F).

Green: Reference RF system with ‘zero’ impedance.

Red: SIS100 type bunch compressor with expected impedance - Blue: Distorted gap voltage.

In the middle row of Fig. 2 the cancellation point was determined by simulation. At this point, the descending slope will be zero and the gradient will undergo a change of sign. Further on, the compression becomes more ballistic and the broad-band solution tends to form a self-consistent ‘saddle’ where the particles smeared out.

Ring Cores

2 × 8 pieces of iron-based magnetic alloy (MA) toroids - T550/290/30 - left and right beside a ceramic gap form the inductive load. The MA tape is a thermo-magnetically processed Nanoperm® material with reduced DC permeability ($\varepsilon_r \approx 2900$). It replaces the Vitrovac® 6030F cores of the old SIS18 design. These toroids were produced by MAGNETEC GmbH, Langenselbold. They got practically the same electrical data as the cobalt-based amorphous alloy. The decision was made after some simulation runs done with LTspice. As shown in Fig. 3, the manufacturing tolerances of the individual toroids allows a good matching of the two half stacks. This might not be seen as critical but regarding the thermal loads it could be beneficial. The overall R_p impedance of the two stacks is around 2.2 kΩ measured by VNA - it will be lowered by dielectric losses in the coupling loops and some other effects. Under nominal conditions at gap voltages of 40 kV_p we determine at least 1.5 kΩ. Since the power amplifier and the power supply were designed for a cavity load of 1.2 kΩ, the reserve is sufficiently large. The total inductance of both stacks is 145.7 µH @ 440 kHz.

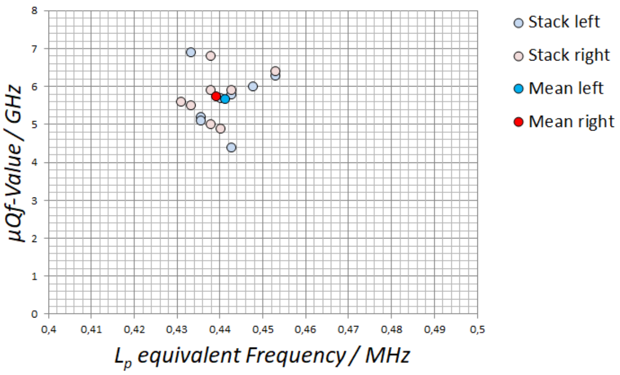

Figure 3: Performance of the individual toroids.

Tuning System

A slow tuning system provides the pre-setting of the resonant frequency. Four variable vacuum capacitors are placed in a 2 × 2 arrangement on top of the cavity. Both sides are altered by two DC servo motors. Position sensing is done by multiturn precision potentiometers. The capacitance-to-position conversion table is stored in a dedicated controller board supplied by AURION Anlagentechnik GmbH. Likewise, the setting can be made via an analogue voltage. It is expected that no closed-loop controlled tuning is necessary.

Coupling Loops

Cross-coupling loops avoid core saturation by the quiescent DC currents of the tetrodes. Feeding both cavity halves in counter-direction provides a good cancellation of the even-number harmonics and – vice versa – the wanted addition of the fundamental RF currents.

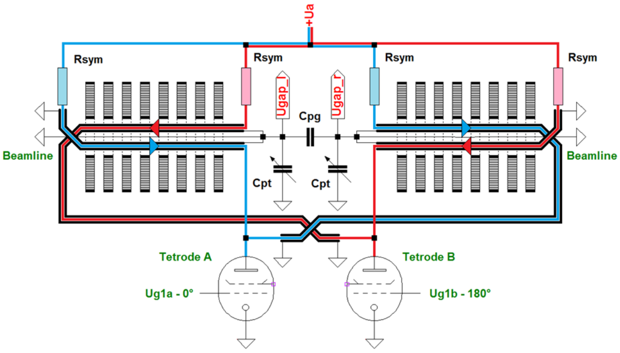

Figure 4: Cross-coupling scheme.

For DC symmetrisation, discrete resistors R_{sym} are added to each path (see Fig. 4). The cross-coupled cavity has only one fundamental mode. This leads to a simpler tuning procedure and no matching between ‘two’ nearly independent resonators is necessary – also there is no need for any additional DC chokes in the anodes’ feed in. The loops are realised using ordinary RG218 cabling –

including the outer conductors between ground and gap-side. Field-steering heat shrink tubing are used as countermeasures against plasma sparking on 'hot' ends – also silicon cones have been beneficially applied.

AMPLIFIER

Two power tetrodes Thales TH555 with grounded cathode scheme are powering the cavity. An AC filament heating has been applied. By means of the cross-coupled cavity described above, the slow periodical gain drift as an effect of the U_{fil} AC swing will be compensated. Due to the high peak voltage of 45 kV at the anodes the amplifier housing is shielded with Pb interlayers to avoid X-ray emission. The amplifier is designed as an easily removable device as shown in Fig. 5. A dedicated hand lift truck has to be used. All connections – electrical, air, water - are taken by a complex contact plate on the rear side. The combined high-power connectors for DC and RF between anode and the cavity are of a Ø100 mm coaxial type – especially designed by AURION Anlagentechnik GmbH. All this minimises the machine-handling time in the synchrotron ring tunnel with regard to the personnel safety during on-call duty.

Figure 5: Undocking the amplifier (left) & contact plates at the rear (right).

POWER SUPPLY UNIT (PSU)

The planned power supply for the RF system as described above is still under construction at OCEM Power Electronics. Therefore, only information based on the latest design report can be given here. Since the anode power supply has to deliver up to 100 A at 25 kV for only 3.2 ms per second, a capacitor bank of > 211 µF will be used. The capacitors are charged quasi-continuously so that no power peaks occur in the mains input. The IGBT-interruptible voltage multiplier chain is uncontrolled and the expected voltage drop will be compensated by means of an additional PWM-controlled power module which acts in series on the negative output. Its output capability is limited to 1.0 kV – a residual voltage drop of 0.5 kV is still allowed. In this manner the two screen grid power supplies are also designed for pulsed operation only. Like the anode power supply, they will be recharged during idle time. The tetrodes' quiescent current is keyed by a joint switchable U_{g1} supply between insulation mode and A/AB in the rhythm of the requested RF bursts. The filament voltage is controlled by an active PWM AC-AC converter – allowing a smooth sine-shaped voltage form after filtering without any distortions compared to common phase angle modulated power supplies.

Table 1: PSU Design Data

Power Supply	Voltage	Max. Current
Anode	20 kV to 27 kV_{dc}	100 A (3.2 ms)
Screen Grids	2000 V_{dc} (× 2)	4.0 A (3.2 ms)
Control Grid	-800 to -100 V_{dc}	1.0 A
Filaments	400 V_{ac} (× 2)	16 A

COMMISIONING RESULTS

For all commissioning tests, the first RF station was temporarily supplied using the existing SIS18BC PSU. So, we were able to confirm almost all of the specified values.

- The gap voltage of 40 kV_p was achieved over 400 µs (burst duration limited by the SIS18BC PSU).
- Tuning and operation was confirmed over the full frequency range.
- The rise time requirement was fulfilled
- Thermal stability of the cavity was shown by CW heating, applying a 2 kW RF driver amplifier.

CONCLUSION AND FUTURE STEPS

The modified SIS18 design was verified with success and most of the desired SIS100 requirements were met already. The new MA core material supplied by MAGNETEC GmbH was qualified for cavity applications. One of the next steps will be the integration of the new PSU - whose completion is imminent - making the proof of full length RF bursts (3 ms) possible. A 12 h endurance test is foreseen to complete the commissioning phase within the next months. One bunch compressing RF station will remain in our testing premises to perform ongoing experiments for optimising our LLRF components and to establish operation readiness.

ACKNOWLEDGEMENT

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