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THE NEW BROADBAND ACCELERATING SYSTEM FOR THE SIS18 UPGRADE AT GSI

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Abstract

This paper describes a new complete RF accelerating system whose cavities are based on novel MA-materials (magnetic alloy materials). It describes cooling issues, the cavity, the power amplifier, the supply units and the low-level system. The RF system works at harmonic number h=2 (f=0.43- to 2.8 MHz) and provides the necessary accelerating voltage for SIS18 injector operation with high intensity heavy ion beams in a fast operation mode with about three cycles per second. The acceleration system consists of three units which are able to operate independently from each other. That is important, since each ion for FAIR [1] has to cross the h=2-RF-system and in the case of a damage a reduced operation has to be ensured. Due to the lossy MA-ring-core-filling the cavities show a broadband behaviour and thus no cavity tuning during the acceleration ramp will be necessary. Due to the high saturation field strength of the magnetic alloy the overall length of all three cavity units can be very short (< 4m).

INTRODUCTION

The GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt is currently realizing a new powerful facility named FAIR (**F**acility for **A**ntiproton and **I**on **R**esearch) [1] which has included an upgrade of the old synchrotron SIS18.

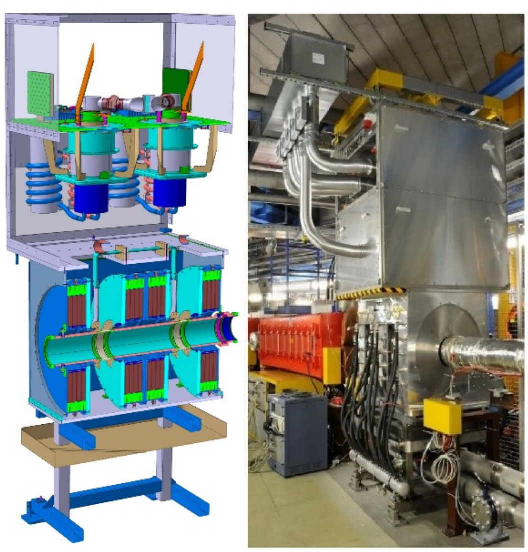

Figure 1**:** The picture to the left shows one unit of the h=2 cavity and power amplifier arrangement already installed in the synchrotron ring. The picture to the right shows a cross-section of the cavity with its MA-cores and ceramic gaps at the bottom and the power amplifier with its two tetrodes on top.

In the past the SIS18 RF systems have usually been operated at the fourth harmonic. Now the new operating mode is at the second harmonic number with the new "h=2-RF-system". Nevertheless, both old ferrite-cavities remained in the ring in order to allow double harmonic RF operation [2] and other multi-harmonic beam manipulations. However, it is important to point out that the old SIS18-ferrite-RF-system alone does not provide enough bucket area in order to accelerate intense bunches in the 3 Hz SIS12 mode. An alternative cavity design which is able to operate at harmonic number h=2 based on ferrite-material would have a length extension of more than 7 m.

REQUIREMENT

The gap voltage requirement with a bucket filling of 2/3 with space charge compensation and under beam loading is 40 kV in the frequency range of 0.43-1.6 MHz (11.4 – 200 MeV/u).

In order to leave a safety margin, we demand a total voltage of not less than 50 kV without beam.

CAVITY DESIGN

Cavity and Ring Cores

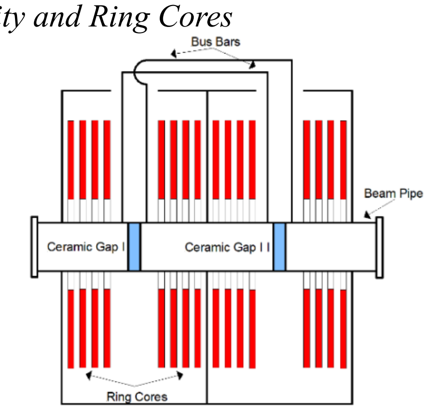

Figure 2: The arrangement for one cavity unit.

Figure 2 shows schematically the arrangement of one cavity unit. Four ring cores per half gap are stringed together and a bus bar system connects the two gaps in parallel. The ring cores are made of FINEMET FT-3M (HITACHI) and they have the following dimensions: outer diameter 660 mm, inner diameter 290mm, thickness 25 mm. The average ribbon thickness is 17 µm and the isolation layer has a thickness of 1-2 µm. The ring cores are stiffened by a very thin resin layer which was superimposed under heat and under vacuum by MAGNETEC.

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Measured Impedance of One Cavity Half

Figure 3 shows the measured impedance of one cavity half which will be seen by the tetrode. Indicated within the plot are the important frequency points. Clockwise one observes the starting point of the operating frequency range, the location of the phase resonance, the maximum of the impedance and the end point of the frequency range. The measurement was taken by a Vector Network Analyzer (NWA) at one bus bar

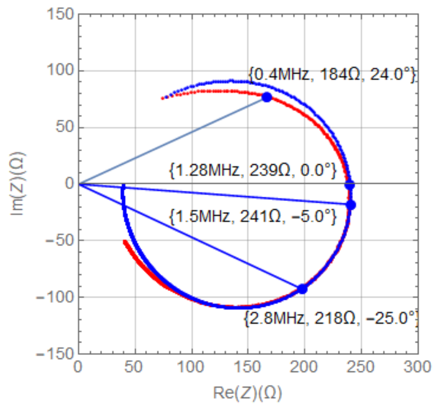

Figure 3: Measured (red)- and calculated (blue) impedance of one cavity half.

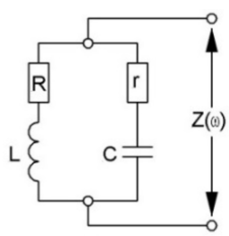

Figure 4: The equivalent circuit for one cavity half.

The impedance behavior can be described by the equivalent circuit shown in Fig. 4 in case the frequency dependence of R and L is known which is mainly determined by the frequency behavior of the ring cores. The following approach for L and R (equation (1) and (2)) has delivered best results in the case the unknowns are estimated by the method of least squares (Table 1, middle row).

$$L(f) = \mathrm{L}_0^{100kHz}[\mu H]\,\frac{\sqrt{1+\left(\frac{0.1[MHz]}{f_C[MHz]}\right)^2}}{\sqrt{1+\left(\frac{f}{f_C[MHz]}\right)^2}}\left(\frac{f}{0.1[MHz]}\right)^{p_L} \quad (1)$$

$$R(f) = \mathrm{R}_0^{100kHz}[\Omega]\,\frac{\sqrt{1+\left(\frac{0.1}{f_C[MHz]}\right)^2}}{\sqrt{1+\left(\frac{f}{f_C[MHz]}\right)^2}}\left(\frac{f}{0.1[MHz]}\right)^{p_R} \quad (2)$$

From the measured impedance values the absolute value of the impedance versus frequency was plotted (see Fig. 5, red curve) to take the 3 dB bandwidth for an estimation of the unloaded Q value. Strictly speaking this approach is only valid for high-Q-cavities but in so doing the unloaded quality factor amounts to $Q_0 = 0.3$.

Impedance with Power Amplifier

Figure 5 shows the measured resonance curve of the complete h=2-RF-system, which means cavity with power amplifier, compared to the measured resonance curve of the cavity. A glance on Fig. 5 shows that the maximum impedance values of both curves remain at the same value, namely 241 Ω, the maximum was shifted from 1.47 MHz to the much lower frequency of 720 kHz and the quality factor is with 0,6 twice as high as the quality factor of the cavity alone.

For modelling the modified behaviour with the same equivalent circuit (Fig. 4 and equ. (1) and (2)) one needs the numbers shown in the last row of table 1. The frequency shift from 1.47 MHz to 720 kHz as well as the doubling of the quality factor Q, is caused by the increase of intrinsic capacitances by a value of 408 pF. This effect is not explainable by the intrinsic capacitances of the tetrodes alone.

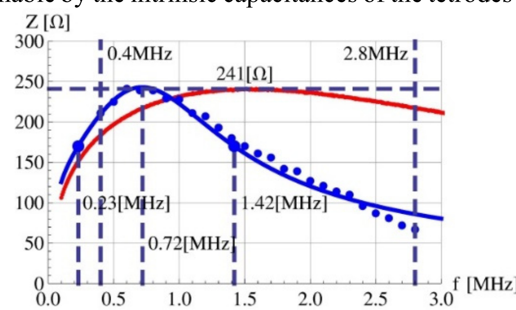

Figure 5: The resonance curve before (red) and after (blue) mounting the tetrode power amplifier to the cavity.

Table 1: Numbers of the Electrical Quantities Required for the Equivalent Circuit Model (Fig. 4)

Electrical quantity	Cavity without power amplifier	Cavity with power amplifier
C	312 pF	720 pF
R	41 Ω	25 Ω
R_0(@100kHz)	75 Ω	75 Ω
L_0(@100kHz)	123 µH	123 µH

Cavity cooling issues

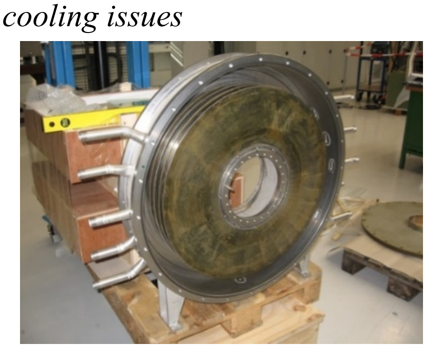

Figure 6: A pressure tank with four ring cores lined up.

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Since no tuning is foreseen the cavity absorbs about 90 kW RF-power at the high frequency end of the frequency ramp at 2,8 MHz. This means a power consumption of 5,6 kW per ring core and therefore a liquid cooling is required. The upper limit for an air cooling is about 3 kW per ring core. Our choice for the liquid cooling was mineral oil namely HT 250 from FRAGOL. There are good reasons for mineral oil since the Finemet FT-3M ring cores are very sensitive for corrosion. This is caused by the fact that the material composition contains 70 % iron. To ensure the stability of the cavities over years a cooling with demineralised water is excluded.

At maximum power a flow rate of 600 l/min per cavity unit is necessary which means 1800l/min for all three units.

Figure 6 shows on the left and on the right side five oil injection- and ejection nozzles installed. Each injection nozzle targets into the empty spaces in between adjacent ring cores. Between the outer radius of the ring core stack and the inner wall of the pressure tank there is some space left. This space is filled by an oil guidance system in order to hinder the oil to take the line of the least resistance. This guidance system is made of glass fiber reinforced epoxide resin.

POWER AMPLIFIER

The RF power is generated by two TH 537 (300 kW) (see Fig. 7) tubes from Thales in grounded cathode scheme operating in push pull mode and working mostly in class A operation [2]. Since the anodes are galvanically coupled to the gap, a large ferrite loaded RF-choke (600 µH@400 kHz) was realized to get rid of the DC-anode-current. The tube stage is driven by a broadband 1 kW solid state amplifier and the power is transmitted via a ferrite loaded toroidal transformer to the control grids.

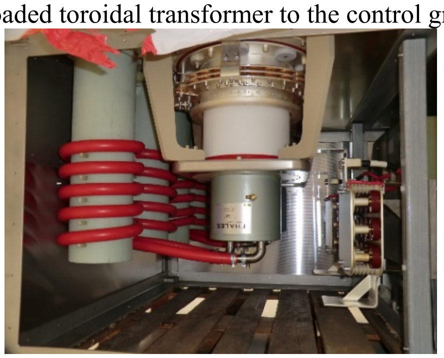

Figure 7: One of both tetrodes TH537 in anode down configuration. At the tube socket one sees the screen grid capacitor (500 nF) to ground unwanted RF currents. To the right there is the coupling capacitor and the contact tab to the cavity bus bar.

POWER SUPPLY

The power supply unit (PSU) was manufactured by OCEM ENERGY TECHNOLOGY SRL and the anode supply as well as the screen grid supply are composed of modules. The anode supply consists of 24 modules and 12 of these are permanently used to generate the anode voltage. After each RF-cycle one used module is replaced by an unused module and so on. The anode supply is designed for 64 A_{DC}@9,5 kV_{DC}. During operation the anode operating point is set to 60 A_{DC}@7,5 kV_{DC} and the screen grid supply to 1,6 kV_{DC}. This is equivalent to an anode dissipation of about 240 kW. At maximum gap voltage, which is 16.7 kV_{AC}@400 kHz, the cavity dissipates 90 kW. Since the power consumption at the mains is 600 kW, the efficiency of the RF-system is with nearly 15% very low as expected. This is understandable since the tetrodes are working in class A-operation on a very low impedance, 241 Ω -at maximum-, which leads intrinsically to a low efficiency.

Table 2: PSU Design Data

Item	Voltage	Max. Current
Anode	5kV_{DC}-9,5kV_{DC}	64A
Screen grid	2kV_{DC}	5A
Control grid C	-800V_{DC}- -500V_{DC}	-2A-2A
Control grid A	-400V_{DC}- -100V_{DC}	-2A-2A
Filament	400V_{AC}	25A_{rms}

LOW LEVEL SYSTEM FOR DUAL HARMONIC ACCELERATION

By means of a so-called group DDS (Direct Digital Synthesis) module, the reference RF signals for the cavity DSP systems ([3], [4], [5]) (Digital Signal Processor) are generated. These DSP systems compare the phases of the RF signals taken from the cavity gaps with the RF reference signals of the group DDS. By modifying the phase of the cavity DDS, the gap signals are synchronised with the group DDS. Additionally, phase ramps are delivered to the cavity DSP systems in order to allow double harmonic operation and other multi-harmonic beam manipulations. Each cavity DDS signal is fed to the amplitude control unit.

CONCLUSION

The first unit of the h=2 broadband RF system is operating successfully with beam in SIS18 since 2014. The second was added in 2016 and both operated on the beam successfully. The system was fully completed (three units) in 2018 and is currently awaiting the upcoming beam time in 2018.

As we have shown in the chapter « Cavity design » it is not easy to conserve the excellent broadband characteristic of the cavity alone. Adding the tetrode amplifier to the cavity has changed the situation.

This type of RF-system will be the basis for developing future broadband RF-systems for SIS100 such as the barrier bucket system and the fast feedback system.

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