STATUS OF THE FAIR SIS100 KO EXCITER

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Abstract

One of the planned slow extraction options for the SIS100 under construction at FAIR will be the excitation of a 3rd order resonance by means of the radio-frequency knock-out (RF KO) method. The system that is currently in its design phase will consist of two identical RF stations, each capable of providing a voltage amplitude of up to 5 kV between two electrodes (distance: 90 mm, length: 1.5 m) in the frequency range from 100 to 400 kHz. This contribution presents the design of the overall system, highlighting the transformer topology with eight transformers per RF station that are connected in parallel on their primary side and in series on their secondary side. Each primary side will be driven by a semiconductor amplifier via a 230 m long coaxial line. Investigations concerning the magnetic alloy (MA) based ring cores which form the inductance of the transformers and the effects of reflections along the transmission line between the amplifier and the transformer are shown as well as studies on the geometry of the exciter plates. The design presented here fulfills the competing requirements on amplitude, bandwidth, field homogeneity, cooling capacity, and space constraints.

SYSTEM OVERVIEW

The SIS100 KO Exciter will utilize the radio-frequency (RF) knock-out (KO) method, i. e., excitation of a 3rd order resonance to increase the betatron oscillation amplitude. Early studies showed that a stripline design like it is used for the SIS18 KO Exciter at GSI would result in extreme power demands. B. Breitkreutz and colleagues from Forschungszentrum Jülich (FZJ) came up with the current design of a capacitive kicker that is fed by several transformers (winding ratio 1:3) with primary sides connected in parallel and secondary sides connected in series to add the up-transformed voltages [1]. To ease the manufacturing, it was decided to split the available installation space in two parts and build two identical kickers. While this slightly reduces the available length of the electrodes, it also halves the capacitance which the power amplifiers (PA) see, thereby increasing the usable bandwidth (at the cost of a doubled number of PAs, however).

A schematic of the planned layout is shown in Fig. 1. Eight PAs (four for each electrode) will be used for each kicker, and each PA shall deliver up to 1 kW of RF power. Since the Low-Level RF components together with the PAs are located far away from the kickers, approximately 230 m long transmission lines are necessary.

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Further electrical and mechanical properties of the SIS100 KO Exciter are summarized in Table 1.

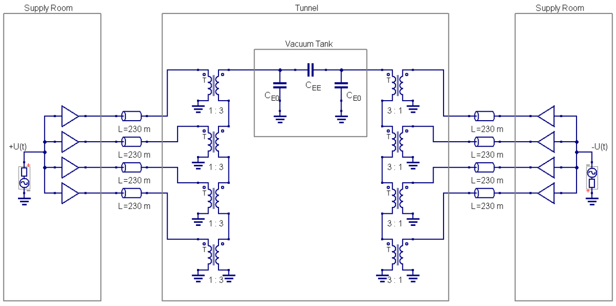

Figure 1: Schematic of the planned SIS100 KO Exciter layout for one of the two identical kickers.

Table 1: Electrical and Mechanical Properties of Each of the Two SIS100 KO Exciters

installation space	1.9175 m
horizontal electrode length (single kicker)	1.5 m
vertical electrode width	60 mm
horizontal electrode spacing	90 mm
vacuum tank diameter	400 mm
frequency range	100 to 400 kHz
voltage amplitude $\hat{U}_B$ (across the electrodes)	5 kV

Excitation Signal

The excitation signal itself and the means of its generation are still being discussed, but one promising option is to use a dedicated spill optimization system similar to the one used at the SIS18 KO Exciter to deliver special excitation signals for increased spill quality [2].

Transformer

To allow for higher harmonics of the 3rd order resonance to be used in the optimized excitation signal, a high bandwidth is desired. This can be achieved by minimizing the capacitance the kicker represents to the PAs. In order to extract as many particles as possible from the synchrotron, the voltage amplitude $\hat{U}_B$ should be as high as possible. This can be achieved by increasing the transformer ratio. However, increasing the transformer ratio also increases the capacitance seen by the PAs and thus limits the bandwidth. While increasing the number of PAs for each electrode would also result in a higher voltage amplitude $\hat{U}_B$, this also increases the capacitance each amplifier sees since the kicker capacitance will effectively be split into a series connection of accordingly scaled higher capacitances, limiting the bandwidth again (e. g., with four amplifiers per electrode the kicker capacity C_{total} seen at the electrode's connection can be split into a series connection of four capacitances with $C_i = 4C_{\mathrm{total}}$ each, so that due to the symmetry every PA sees $C_{\mathrm{single}} = 9C_i$ on the primary side of the 1-to-3 transformer).

Eventually, the combination of four amplifiers for each electrode together with a 1-to-3 transformer ratio was chosen as a suitable compromise that is capable of reaching the desired voltage amplitude $\hat{U}_{\mathrm{B}}$ as well as providing enough bandwidth.

The transformers itself will be based on magnetic alloy (MA) ring cores (Magnetec M-890) that were originally built for the HESR RF cavities [3] but turned out to be suitable for the SIS100 KO Exciter transformers as well. To minimize parasitic capacitances between the windings, only one primary and three secondary windings are used which is sufficient due to the ring core's high permeability of 50 000 at 10 kHz. Their geometrical properties are also suitable for the installation space beneath the beam pipe so that their already developed forced air cooling scheme from the HESR RF cavities [3] can be utilized with minimal adaptations, reducing development risks. This is especially important since the ring cores also serve as the main load for the PAs. The ring cores have been measured in a special test box and a lumped-element model was created based on a vector fitting approach (see [4,5] and references therein for details of this procedure). The results of the measurements and the simulation model are shown in Fig. 2 and agree very well up to 5 MHz, well above the desired frequency range of the SIS100 KO Exciter.

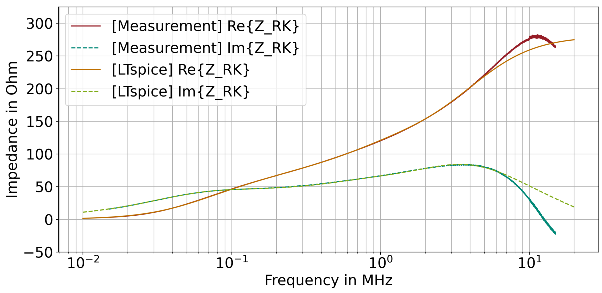

Figure 2: Real and imaginary part of the measured and simulated impedance of one Magnetec M-890 ring core.

Kicker Electrodes and Vacuum Tank

From the kicker's point of view, the aperture should be as small as possible to increase the electrical field while the vertical electrode length should be as small as possible to decrease the kicker's capacitance. The electrode's dimensions are defined based on the calculated beam envelope with a reasonable safety margin and acceptable field homogeneity.

CST field simulations based on the values given in Table 1 were carried out to study the field homogeneity and also to estimate the kicker's capacitances C_{EE} (between the electrodes) and C_{E0} (between one electrode and the vacuum tank) to optimize the vacuum tank diameter.

The support frame of the vacuum tank needs to house the transformers, including cooling, connections for power cables and measurement devices, and it will also house the necessary vacuum equipment. A 3D model of the whole kicker is currently in development.

TEST SETUP

The basic test setup for the SIS100 KO Exciter was created by simplifying the scheme in Fig. 1 using symmetries. First, the push-pull setup allows inserting a virtual ground in the middle of the kicker electrodes, splitting C_{EE} into a series connection of two capacitances of $2C_{\mathrm{EE}}$ each. With this virtual ground, only one kicker electrode has to be investigated. Furthermore, the resulting one-sided setup with four PAs can again be split using symmetries (and assuming all PA branches are equal, which is approximately valid) resulting in the reduced one-sided setup shown in Fig. 3 with the equivalent capacitance $C_{\mathrm{ex}} = 4\left(C_{\mathrm{E0}} + 2C_{\mathrm{EE}}\right)$ of the exciter. While the resulting voltage amplitude across the capacitance will of course be lower, the obtained results can directly be scaled up to the full setup without further distortion of the frequency response.

The ring core is modeled by a T-equivalent circuit with the magnetizing branch based on the model resulting from the measurements of the ring cores (see Fig. 2) and leakage inductance of 0.15 µH on the primary side and 1.35 µH on the secondary side (each with negligible ohmic resistances).

Since for the real-world test setup only 220 m of Cellflex cable (LCF 12-50JFN) were readily available (instead of the assumed 230 m mentioned above), the simulations were carried out using this length as well, accepting a slight error compared to the final setting. The cable itself was modeled by means of an RLC transmission line model with frequency-dependent R'_{tl} and L'_{tl} and a frequency independent $C'_{\mathrm{tl}} =$ 76.6 pF that were fit to measurements of this cable type. For the LTspice model, “G” sources were used with the Laplace functions

$$G_{\mathrm{R,tl}}(s) = \frac{1}{0.021\sqrt{\frac{|s|}{2\pi f_{\mathrm{ref}}} + c_{\mathrm{conv}}}},$$

$$G_{\mathrm{L,tl}}(s) = \frac{1}{s\left(0.192\times10^{-6} + \frac{0.011\times10^{-6}}{\sqrt{\frac{|s|}{2\pi f_{\mathrm{ref}}}+c_{\mathrm{conv}}}}\right) + c_{\mathrm{conv}}},$$

with $f_{\mathrm{ref}} = 0.5$ MHz (and $c_{\mathrm{conv}} = 1\times10^{-12}$ for convergence of the LTspice model), matching the frequency dependence of R'_{tl} and L'_{tl}, respectively. Finally, LTspice's BUS-notation allowed to easily connect the necessary amount of RLC blocks to reach the cable length. One RLC transmission line block is shown in Fig. 4.

Finally, the PA is modeled as voltage-dependent current source with an input voltage amplitude of 100 mV and a constant gain matching the measurements for the PA in use here. For the lowest frequencies of interest there are notable

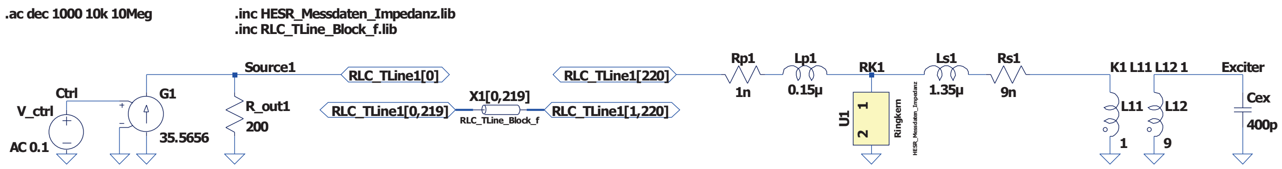

Figure 3: LTspice schematic of the reduced one-sided setup.

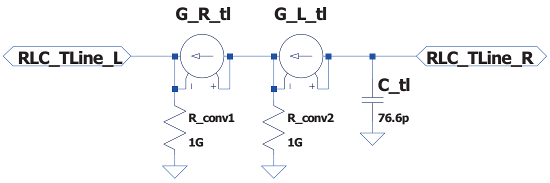

Figure 4: LTspice schematic of one RLC transmission line block.

deviations in the PA's gain from this constant value. For a qualitative and rough quantitative comparison however, this mismatch is acceptable. Additionally, a 200 Ω resistor has been placed in parallel to the source in order to replicate the PA's output impedance. This value was chosen to match the measurement results. While the PA is specified for a load of 50 Ω, the ring core and exciter capacitance do not yield a 50 Ω termination so that reflections between the transformer and the PA's output travel across the long transmission line making it necessary to also model the PA's output impedance seen by the reflected wave.

Figure 5 shows the basic test setup that can also be extended for a slightly less reduced test setup using two PAs and two ring cores for verification of the voltage adding capability (both ring cores are already in place and the capacitance can easily be exchanged as well). The gray box houses three fans for air cooling of the ring cores.

Figure 5: Photo of the reduced one-sided test setup.

Measurement and Simulation Results

Figure 6 shows the comparison of the measurement (blue dots) and the simulation (orange line) for the reduced one-sided setup. Despite its simplifications, the model is capable of predicting the performance of the test setup quite well. Deviations in the low-frequency range are most likely due to the amplifier's output impedance being under-modeled by the pure ohmic resistor. Measurements that will yield proper estimates of this property are currently prepared and a more accurate model will be derived afterwards.

The input voltage amplitude of 100 mV equals −10 dBm and is well below the 0 dBm the PA is specified for. While the reflected power will ultimately limit the maximum output of the PA, this limitation was not a problem for frequencies below 500 kHz and thus the PA's output power can still be increased substantially. Nevertheless, even with this sub-maximum output the single-electrode voltage amplitude reached (almost) 0.6 kV over the whole frequency range of interest. With eight PAs the desired voltage amplitude of 5 kV between the two electrodes thus seems feasible.

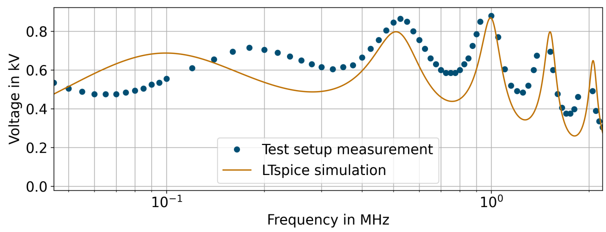

Figure 6: Measured and simulated single-electrode voltage for a constant input voltage amplitude of 100 mV

SUMMARY

This work outlines the current status of the SIS100 KO Exciter. The measurement and simulation results presented herein show that the current design is a suitable compromise achieving the desired voltage amplitude over the whole frequency range of interest.

Further improvements of the modeling and dedicated calculations for the cooling of the ring cores will enhance the exciter's reliability.

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