DEVELOPMENT OF A BROAD-BAND MAGNETIC ALLOY CAVITY AT GSI*

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Abstract

A major success in decade-long efforts towards the development of Magnetic Alloy (MA) cavities has been achieved at GSI, Darmstadt. One Co-based MA cavity was successfully developed and is already in operation as a synchrotron bunch compressor [1]. Two Fe based Broad-Band (BB) MA cavities are under- construction. One is h=2 [2, 3] and the other one is mentioned as a test cavity in this paper. Several other such cavities are foreseen for the upcoming Facility for Antiproton and Ion Research, FAIR at GSI. This paper describes the measurements performed in free-space and in a cavity to test the electrical properties of Fe based MA rings which are to be used for the cavities. Taking Free-Space (FS) measurements as reference, analytical relations have been developed. They define the inductance and resistance of the ring for the whole frequency range of a cavity. The relations, along with the stray-capacitance and resistance, describe the total impedance of the cavity loaded with these rings. This impedance is found in excellent agreement with the measurements. It assures an impedance matching between cavity and power amplifier and hence an efficient power transfer to the cavity.

INTRODUCTION

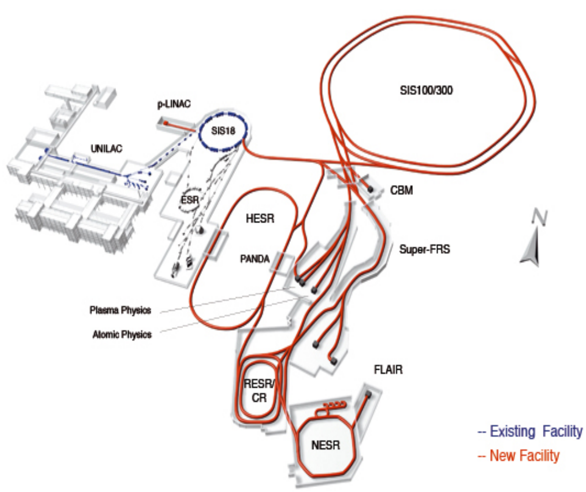

Figure 1: A schematic of GSI and FAIR.

The present facility at GSI is to be upgraded to feed the accelerator and storage rings of FAIR. Upgrade of the radio frequency (RF) system and development of the BB RF cavities is of prime importance for the present as well as for the FAIR rings (Fig. 1). In the recent past, several MA materials from the suppliers across the world have been tested [2]. But, keeping in view the activation property of Co-based MA in presence of heavy ions, a Fe based MA is chosen for the future cavities. Among several Fe based MA materials, FINEMET-3M, a material from Hitachi Ltd., has been finally chosen for the foreseen cavities [2, 4]. After testing the electrical properties of 60 such ring cores in FS, they are, step-by-step, loaded in a test cavity. The cavity measurements mentioned in this paper are performed in the test cavity loaded with two rings (one on each side). This cavity will be installed in the present Experimental Storage Ring (ESR) at GSI.

ELECTRICAL PARAMETERS

The complex impedance of a ring in FS can be described as a series combination of inductance L and resistance R. This definition is applicable in case the capacitance C of the ring core with the surrounding can be neglected. Series impedance of a ring core is $Z = i\omega L + R$ [2]. A ring shows high L and C. From the point of view of an efficient cavity, this capacitance is to be reduced, nearly, without influencing L. By specifications, all the FINEMET rings are expected to possess similar electrical properties along the whole frequency range.

MEASUREMENTS

At first, electrical parameters (R and L) of all the rings are measured in FS. Thereafter, two ring cores out of them are loaded in the test cavity. A change in the properties from FS is expected due to the influence of stray fields in the cavity box.

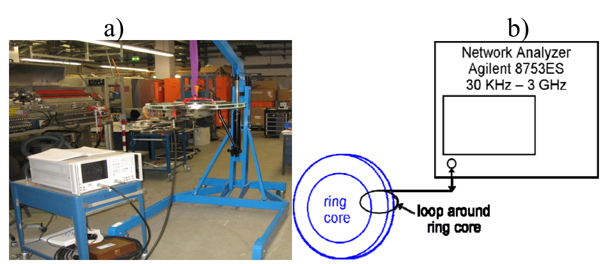

Figure 2: a) Experimental setup and b) a schematic for the ring core measurements in free space.

In Free-space

In this case each ring is hold by a rope at an appropriate height (Fig. 2a), so as to avoid the influence of the capacitance between ground and ring. RF power from a

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Network Analyzer (NA) is coupled to the ring through a single-turn coupling loop (Fig. 2b). The impedance of the ring is measured by observing the reflection factor at the entrance of the coupling loop and by using the smith chart format. In order to get rid of the influence of the cable impedance, the NA is calibrated. A frequency range of 0.1 to 20 MHz is chosen covering the later application range. RF power level was set at 0 dBm.

In measurements, at a particular frequency significant variations in the values of R and L among the rings have been observed (Fig. 3). A statistics for the electrical properties of the rings has been derived for the whole frequency range. This statistics for some specific frequencies is mentioned in Table 1.

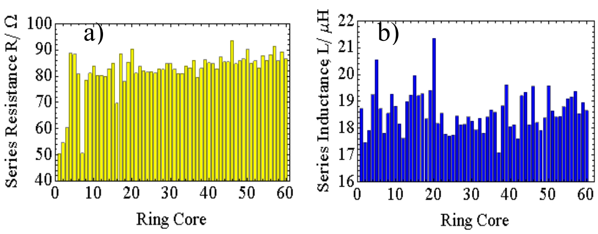

Figure 3: a) R and b) L of all the rings at 0.4 MHz.

Table 1: Statistics Showing R, L and µQf of the Rings at Frequencies 0.4 and 2.5 MHz

	Mean		Std. Deviation		Max. Deviation	
f (MHz)	0.4	2.5	0.4	2.5	0.4	2.5
R (Ω)	82.2	143	8.6	9.6	43.3	54.6
L (µH)	18.6	4	0.8	0.22	4.3	1.28
µQf (GHz)	4.2	6.5	0.22	0.24	1.1	1.24

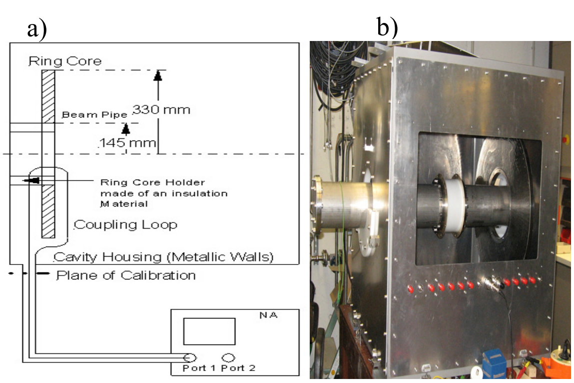

Figure 4: a) Schematic of the setup for measuring the impedance of one ring, mounted in a metallic box. b) BB test cavity under-construction in RF lab at GSI.

Ring Cores Loaded in Cavity, a Metallic Frame

Two rings were mounted in a metallic housing. The metallic housing is commonly used as a cavity with beam-pipe and ceramic gap. For the first measurements as described here, the beam-pipe and the ceramic gap were removed in order to keep the capacitances as low as possible. In further measurements, they will be added. The rings are mounted by using insulating holders (Fig. 4a) and thus remain insulated from the cavity walls. The measurement method and settings here are similar to the FS measurements (mentioned in last section), except that the rings are mounted in the cavity now. As FS measurements show variations in the electrical properties from one ring to another (Tab. 1), each ring in the cavity is measured separately. The measurement results are presented along with the analytical results in the following section.

FREQUENCY DEPENDENCE OF RING IMPEDANCE

Initially, a frequency dependence of the impedance is not taken into account. It cannot be avoided at high frequencies as the capacitances to the environment play a role. In this case series combination of L and R in FS is supplemented in parallel by a capacitance C in series to a resistance r (Fig. 5).

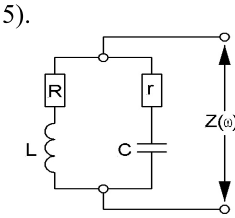

Figure 5: Equivalent circuit to include stray fields.

The impedance of the circuit in fig. 5 is

$$Z(\omega) = r\,\frac{i(LC\omega^2 - \frac{R}{r}) + (\frac{L}{r} + CR)\omega}{i(LC\omega^2 - 1) + C(r+R)\omega} \Rightarrow \begin{cases} R \ldots \ for\ \omega \to 0 \\ r \ldots \ for\ \omega \to \infty \end{cases} \quad (1)$$

Both L and R deviate from their expected frequency dependence from theory [5]. The series inductance L for a ring starts at zero frequency and at the cut-off frequency of about 0.04 MHz it drops down a bit weaker than a simple low-pass filter would predict. Therefore, the formula for the filter is supplemented by additional frequency dependence, namely f^x (in MHz).

$$L(f) = L(0.1)\cdot\frac{\sqrt{1+\left(\frac{0.1}{0.04}\right)^2}}{\sqrt{1+\left(\frac{f}{0.04}\right)^2}}\cdot\left(\frac{f}{0.1}\right)^x \mu\text{H} \quad (2)$$

The 0.1 MHz here is the initial frequency from the point of view of the planned BB cavity. The measurements are compared with this analytical approach and they are found in agreement with each other (Fig. 6a).

The series resistance R of a ring starts at zero frequency and exhibits more or less linearly increasing behaviour with frequency. Following relation with the additional frequency component f^y seems appropriate.

$$R(f) = R(0.1)\cdot\frac{\sqrt{1+\left(\frac{0.1}{0.04}\right)^2}}{\sqrt{1+\left(\frac{f}{0.04}\right)^2}}\cdot\left(\frac{f}{0.1}\right)^y \Omega \quad (3)$$

An excellent agreement between R from the measurement and this analytical approach is observed nearly for the whole frequency region (Fig. 6b).

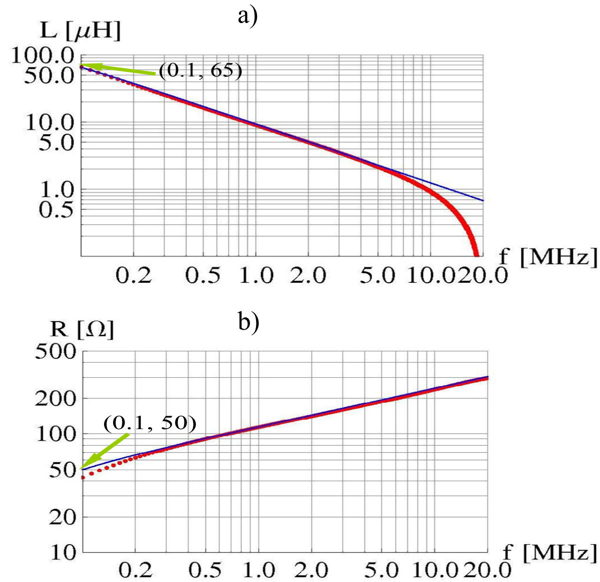

Figure 6: The analytical approach (blue curve) and the measurements in the frequency region from 0.1 to 20 MHz. a) for series inductance L, b) for resistance R

Table 2: Equivalent Circuit Parameters found for the Best Fit to Measurements

Quantity	Left	Right
Capacitance C, pF	8.0	8.0
Series resistance r, Ω	400	300
Series Resistance R (f = 0.1 MHz) Ω	50	55
Exponent x for L	4/32	1/32
Series Inductance L (f = 0.1 MHz) μH	65	80
Exponent y for R	2/3	2/3
Cut-off frequency f_C MHz	0.04	0.04

As shown in Table 2, rings exhibit different properties. Especially the initial inductance (from FS measurements) of right ring at 0.1 MHz is 80 >65 μH for left ring. Also, contrary to the left, the right-sided ring behaves nearly like a low-pass filter. As for the right ring, the additionally required frequency dependence is $f^{1/32} << f^{4/32}$ required for the left ring.

The impedance of a ring is derived by replacing R and L (Eq. 1), by the one from the analytical approaches (Eq. 2, 3), and by taking C and r from the Table 2.

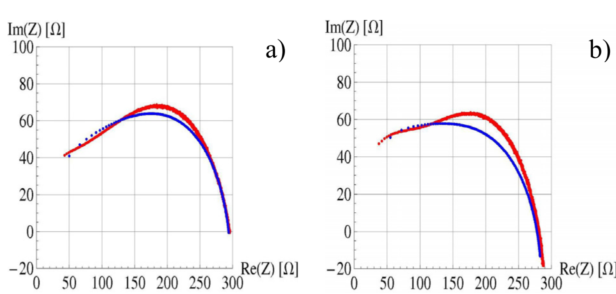

Figure 7: Comparison of the impedance measurement with the analytic approach for left and right rings.

One finds that the both, measured and the analytical, impedances are in agreement with each other (Fig. 7).

CONCLUSIONS AND OUTLOOK

From the Free-space Measurements

- The importance of free-space measurements of the rings is quite evident from the resulting statistics. Also, they provide a reference for further investigations of the rings when loaded in a cavity.
- The rings in a cavity are placed on both sides of the gap(s). The current in a ring near to the gap is the lowest and increases, in steps, in the rings towards the ends. As the electrical properties are known from these measurements, selection of the most suitable rings for each position is possible which significantly contributes to an efficient cavity performance.

From the Cavity Measurements

- It is learnt from the measurements that the frequency behavior of the series inductance L is nearly that of a low-pass filter. Therefore, the analytical estimations of L for the further cavity developments have to be done using equ. 2 with x=0. It means that L drops down proportionally with frequency f^{-1} instead of $f^{-3/2}$ from theory [5].
- The analytical estimations for the series resistance R for the further cavity developments have to be done using equ. 3 with y =2/3. Thus, the resistance increases proportionally with frequency $f^{1/3}$ instead of f from theory [5].
- An important outcome is that an effective capacitance of the ring cores in cavity environment is estimated.
- Knowing R, L, resistance r and the total capacitance of each ring within the cavity finally gives the total impedance of the cavity. This information allows having an efficient coupling of the power amplifier signal to the cavity.

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