COUPLING METHODS FOR THE HIGHLY SENSITIVE CAVITY SENSOR FOR LONGITUDINAL AND TRANSVERSE SCHOTTKY MEASUREMENTS*

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Abstract

In order to observe rare isotopes and antiprotons in the Collector Ring (CR) at FAIR, a highly sensitive Schottky cavity sensor is proposed, utilizing the monopole mode for longitudinal and a dipole mode for transversal measurements. The charged particle beam excites the dipole mode in the suggested resonator several orders of magnitude smaller than the corresponding monopole mode. Therefore it is crucial to extract both components independently without mutual correlation. Particular focus has to be put on the extraction of the dipole mode to sufficiently suppress the strong monopole contribution by taking advantage of a frequency selective coupling mechanism. An equivalent circuit model is used to determine the signal-to-noise-ratio (SNR) as a function of the element values and the coupling factors. The dependencies between the parameters and the signal-to-noise-and-interference-ratio (SNIR) for longitudinal and transversal measurements are depicted and used to create an optimization algorithm.

INTRODUCTION

To measure Schottky spectra with high sensitivity at the Collector Ring at FAIR, a resonant cavity sensor (see Fig. 1) was proposed in [1] and [2]. The sensor is designed to measure longitudinal Schottky signals at 200 MHz (harmonic number 146 and 170 for antiprotons and heavy ions respectively) with a Bandwidth of $\Delta f/f = 0.56\%$. It consists of a pillbox cavity with an inner length of 30 cm, a radius of 47 cm and a beam pipe radius of the CR of 20 cm. The TM_{010}-mode (monopole mode, $f_r = 200\,\mathrm{MHz}$) of the pillbox will be used for longitudinal Schottky measurements and the TM_{110}-mode (dipole mode, $f_r \approx 300\,\mathrm{MHz}$) will be used for transversal Schottky measurements. The value R/Q is used as a measure for the energy transferred into the cavity from a passing particle. For the monopole mode it is approximately $110\,\Omega$ in the center while it is around $3.2\,\mathrm{m}\Omega$ for the dipole mode at 1 mm transversal offset. This leads to a difference in signal levels for the longitudinal and transversal measurements of about four orders of magnitude. Although the two modes are separated by a factor of about 1.5 in frequency, the bandwidth requirements of the Schottky spectra limit the loaded quality factor Q_L of the overall cavity sensor to around 180, leading to interference between the two modes.

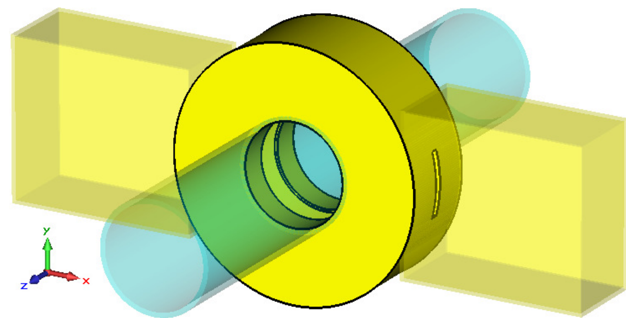

Figure 1: Sensor cavity for the extraction of horizontal Schottky signals with slot-coupled waveguide resonators.

SIGNAL EXTRACTION

The measurements require both extracted signals to be mutually uncorrelated. To extract the monopole mode a coupling loop is positioned at the plane where the dipole mode is zero (the y-z-plane in Fig. 1). Since the monopole mode excitation is much stronger the isolation towards the dipole contribution is sufficient. To obtain a transversal signal independent of the longitudinal signal, two waveguide resonators as high pass filters with a lower cutoff frequency between the two modes under consideration are attached to the cavity in the plane of transversal measurement. Either horizontal or vertical transversal Schottky signals can be measured with this design.

The simulated unloaded quality factor Q_0 of the proposed pillbox cavity is around 30000. In order to achieve the required Q_L one could adjust Q_0 by changing the material or by means of damping structures like additional coupling loops or antennas [3]. Alternatively, a strong coupling to the waveguides and the measurement device can be used. The energy dissipated by additional damping will not contribute to the measurements leaving the second option more promising. However, with the stronger coupling the

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field pattern of the modes are distorted. Especially the gradient of the dipole mode, primarily affecting the sensitivity of the sensor, is reduced. Because of these deformations combining the two methods can give the optimal solution. At the same time, the influence on the monopole mode has to be taken into account.

EQUIVALENT CIRCUIT

Aim of this circuit representation is the determination of the coupling factors between the pillbox and the waveguide filters as well as the coupling to the measurement devices. The equivalent circuit depicted in Fig. 2 models the beam as current source I_B, the dipole mode of the pillbox cavity as a parallel RLC-circuit and the waveguide resonators (WGR) as series RLC-circuits connected by ideal transformers. The coupling loss is taken into account by the RLC-circuits. The monopole mode is not considered at first hand. The two waveguide structures have to be identical to keep the symmetry of the sensor. Their resonance frequency is set to the resonance frequency of the dipole mode. They are connected in parallel and terminated with the load impedance of $R_{\mathrm{load}} = 50\,\Omega$ each.

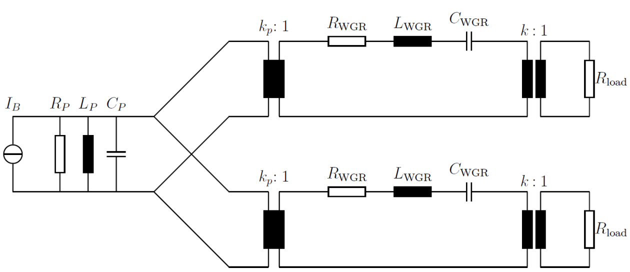

Figure 2: Equivalent circuit model including a parallel RLC-circuit as dipole mode of the pillbox, two series RLC-circuits as waveguide resonators in parallel with respectively attached loads and the ideal transformers modeling the couplings.

The equivalent circuit can be simplified to Fig.3. The values transformed by the ideal transformers and the combination of the two parallel branches are

$$R'_{\mathrm{WGR}} = k_P^2 \frac{R_{\mathrm{WGR}}}{2}, \tag{1}$$

$$L'_{\mathrm{WGR}} = k_P^2 \frac{L_{\mathrm{WGR}}}{2}, \tag{2}$$

$$C'_{\mathrm{WGR}} = \frac{2C_{\mathrm{WGR}}}{k_P^2} \quad \text{and} \tag{3}$$

$$R'_{\mathrm{load}} = k^2 k_P^2 \frac{R_{\mathrm{load}}}{2}. \tag{4}$$

The maximization of the power delivered to the load is analyzed at resonance ($\omega_{r,p} = \omega_{r,\mathrm{WGR}}$) where only the resistors have to be considered. By using a current divider with current I_{load} flowing trough the series RLC-circuit and the

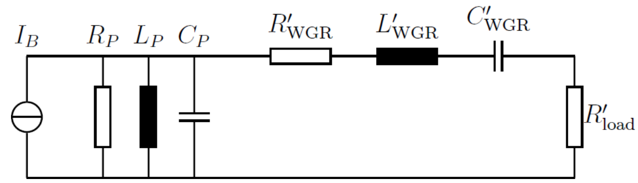

Figure 3: Simplified equivalent circuit model with transformed and combined element values.

load, the calculation leads to a power matching situation. The expression to maximize is given by

$$\frac{I_{load}}{I_B} = \frac{G_{\mathrm{WGR,load}}}{G_{\mathrm{WGR,load}} + G_P}, \tag{5}$$

with

$$G_{\mathrm{WGR,load}} = \frac{1}{R'_{\mathrm{WGR}} + R'_{\mathrm{load}}} \text{ and } G_P = \frac{1}{R_P}. \tag{6}$$

Equation (5) has its maximum at

$$R_P = \frac{k_P^2}{2}(R_{\mathrm{WGR}} + k^2 R_{\mathrm{load}}) \tag{7}$$

To investigate the noise behavior it is assumed that the resistors within the equivalent circuit are the only noise sources and can be combined by superposition as they are considered to be mutually independent. The current source I_B is removed for these calculations. The noise from the pillbox resistor can be modeled as a current source with the value $I_{0,\mathrm{noise}} = \sqrt{4kTB/R'_{\mathrm{WGR}}}$ giving the same circuit as the noiseless case. Therefore changes of the design will alter the noise contribution of this noise source and the signal equally. The resistor noise is modeled as a volt-

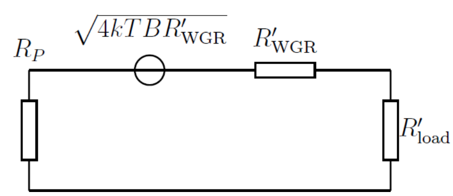

Figure 4: Equivalent circuit model with noise source representing the waveguide resonator resistor.

age source in series to the respective resistor. The power delivered to the load from the waveguide resonator resistor can be calculated, according to Fig. 4, with the current $I_{\mathrm{load}} = \sqrt{4kTBR'_{\mathrm{WGR}}}/(R'_{\mathrm{WGR}} + R'_{\mathrm{load}} + R_P)$ to

$$I_{\mathrm{load}}^2 \cdot R'_{\mathrm{load}} = \frac{2kTB\,k_P^2 R_{\mathrm{WGR}} R'_{\mathrm{load}}}{\left(\frac{k_P^2}{2}(R_{\mathrm{WGR}} + k^2 R_{\mathrm{load}}) + R_P\right)^2}. \tag{8}$$

Inserting equation (7) into (8) gives a maximum at $R_{\mathrm{WGR}} = k^2 R_{\mathrm{load}}$. The transversal SNR is found to be

$$\mathrm{SNR_t} = \frac{P_{\mathrm{signal}}}{P_{\mathrm{n,P}} + P_{\mathrm{n,WGR}}} = \frac{R_P^2 I_B^2}{4kTB(R_P + k_P^2 \frac{R_{\mathrm{WGR}}}{2})}. \tag{9}$$

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Expanding this expression with the Interference terms from the non-dipole modes gives

$$\mathrm{SNIR_t} = \frac{P_{\mathrm{signal}}}{P_{\mathrm{n,P}} + P_{\mathrm{n,WGR}} + P_{\Sigma \mathrm{modes} \neq \mathrm{dipole}}} \quad (10)$$

DESIGN

The coupling is simulated using full-wave simulations with CST Microwave Studio. Kroll and Yu [4] proposed a method to determine Q_{loaded} of a waveguide loaded cavity. Within their method the length of the waveguide is adjusted in a way that resonance frequency of the waveguide mode is shifted as close as possible to the pillbox resonance frequency. The value for the coupling is extracted from the maximum value of the derivative of the phase propagation along the waveguide. Beside the energy transfer, the R/Q-values themselves are depending on the coupling as shown exemplary in Fig. 5 for the dipole mode and two different sizes of coupling slots. A bigger coupling slot leads to an increased distortion of the field, lowering the gradient of the R/Q-value for the dipole mode. The R/Q-value for

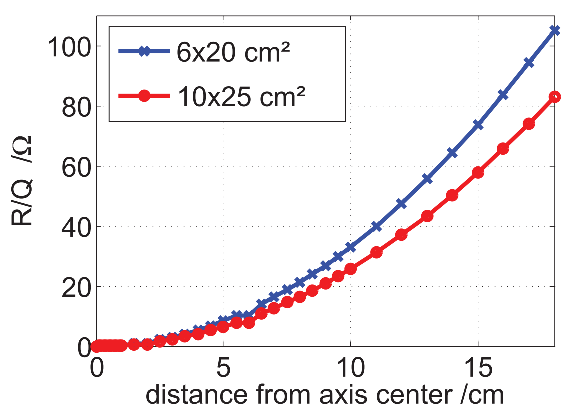

Figure 5: The R/Q-value of the dipole mode as a function of the beam offset for different coupling slot dimensions for a particle velocity of $\beta = 1$.

the monopole mode is depicted in Fig. 6. In contrast to the dipole mode, the R/Q-value is increased for a bigger coupling slot. However, this effect shows that the monopole mode has extended into the waveguide, which is decreasing the isolation between dipole and monopole mode.

CONCLUSION AND OUTLOOK

The strong interaction between the geometrical parameters and the sensor parameters like the R/Q-values and resonance frequencies make it difficult to split the problem into smaller optimization tasks. The overall goal is a combination of the maximized signal-to-noise-and-interference-ratios for the longitudinal and the transversal signals at their respective frequencies. The intended approach starts with the selection of appropriate coupling structures such as the presented rectangular coupling slot. In a second step the radius of the pillbox is adapted to

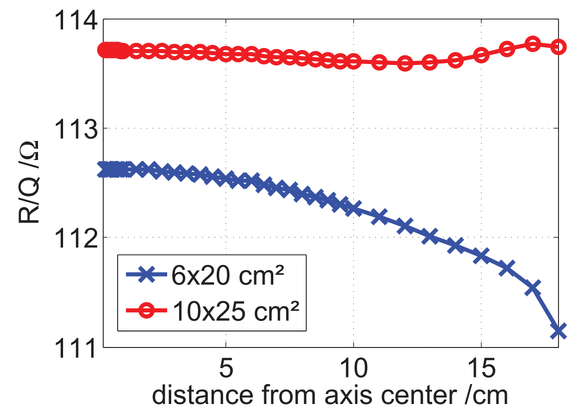

Figure 6: The R/Q-value of the monopole mode for a velocity of $\beta = 1$ as a function of the beam offset for different coupling slot dimensions.

keep the monopole mode at 200 MHz. The geometry of the nose-cones is pre-optimized and kept constant in this context. Afterwards, the length of the waveguide is optimized for maximum coupling between the pillbox and the waveguide resonators. In the last step, the SNIR of both, monopole and dipole mode, are evaluated and compared to preliminary results. The algorithm closes with the adaption of the coupling geometry, until the goal is achieved. The optimization algorithm uses a combination of CST Microwave Studio and MATLAB.

To optimize the extraction of the dipole mode, the gradient of the R/Q-value of the dipole mode is the parameter representing the sensitivity of the device. However, given that the R/Q-value is monotonically increasing with transversal offset, a single value can be used.

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