INVESTIGATIONS ON HIGH SENSITIVE SENSOR CAVITY FOR LONGITUDINAL AND TRANSVERSAL SCHOTTKY FOR THE CR AT FAIR*

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Abstract

For the Collector Ring (CR) at the FAIR (Facility for Antiproton and Ion Research) accelerator complex a sensitive Schottky sensor is required. The CR covers different modes of operation, like pre-cooling of antiprotons at 3 GeV, pre-cooling of rare isotope beams at 740 MeV/u and an isochronous mode for mass measurements. For longitudinal Schottky measurements the concept of a resonant cavity had been introduced [1]. Due to limited space inside the ring, the integration of transversal Schottky analysis into this cavity is desired. In this paper the demands and required changes to implement also transversal Schottky measurements are discussed. An analysis of the expected signal characteristics featuring equivalent circuit is shown, as well as numerical full wave simulations of the cavity.

INTRODUCTION

Within this paper the possible performance of a resonant structure featuring a pillbox-like cavity and two waveguide resonators for transversal Schottky measurements is investigated with respect to geometry, signal and Schottky parameters of the CR (see Fig. 1). For transversal Schottky

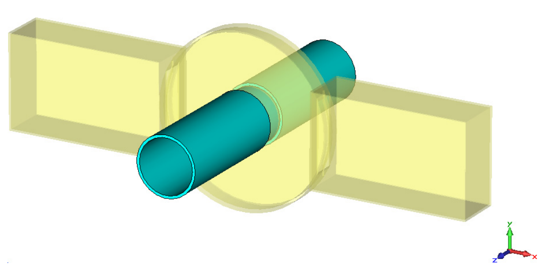

Figure 1: Design of the Schottky sensor, consisting of pillbox-like cavity ($r = 61\,\mathrm{cm}, l = 12\,\mathrm{cm}$) and two identical rectangular waveguide structures ($114\,\mathrm{cm} \times 67\,\mathrm{cm} \times 32.5\,\mathrm{cm}$) to suppress the monopole mode and couple out the dipole mode to the measurement device.

measurements a linear dependency between the offset to the center of a passing particle and the signal is needed. The TM_{110} (**T**ransversal **M**agnetic$_{r\phi z}$) of a pillbox cavity exhibits such a desired behavior for small offsets from the center. The coupling between a certain mode and a moving particle is depending on the z-component of the electric field. The TM_{010} has its maximal E_z at the center, whereas the field of the dipole mode is zero. Therefore, especially for small offsets, the coupling to the monopole mode will be much higher than to the dipole mode. To be able to measure both, longitudinal and transversal Schottky signals with one cavity, one needs to couple out the two mode amplitudes independently. In an ideal case each output signal will just contain the signal from the corresponding mode and the coupling mechanism will not influence the mode separation. Extraction of the monopole mode with a coupling loop at the plane where the magnetic field of the dipole mode is zero will achieve this desired behavior in an ideal case. The monopole signal will be much stronger, so no rejection of the dipole mode is necessary and the loop will not affect the dipole mode to a critical extend. The proposed design utilizes rectangular coupling slots on opposing sides of the cavity to extract the signal for the horizontal or vertical y-plane. Two slots per plane are needed to keep the system symmetric. These slots will couple to both modes, so a rectangular waveguide resonator is used at each slot to reject the monopole signals. Finally, the coupling to the measurement device will be realized by coupling loops inside the waveguide resonators.

SCHOTTKY NOISE SPECTRUM

Schottky noise is the fluctuation of a current caused by the potentially inhomogeneous distribution of the discrete charge carriers. As shown in [2] and in more detail in [3], Schottky noise is distributed to harmonic bands in frequency domain. The width of the n-th harmonic is n times the width of the base band, while the amplitude is decreasing with $1/f$. This broadening in frequency allows a better frequency resolution measured with a spectrum analyzer within a fixed time. Therefore, it is desired to measure at high frequencies. However, above a certain frequency, adjacent bands will start to overlap, making measurements impossible. Transversal Schottky signals differ from the longitudinal ones by a modulation with the betatron oscillation. This creates two sidebands around the harmonic resulting in overlaping bands at a different frequency. Following [3], the overlap frequency of these sidebands is calculated with (1) for the case of overlapping sidebands of one harmonic and with (2) for an overlap between the upper sideband of harmonic n and the lower sideband of harmonic $n+1$. The parameter Q_0^f denotes the fractal part of the tune of the ideal particle.

$$\frac{1}{2}\left(|\Delta\omega_n^+| + |\Delta\omega_n^-|\right) \geq 2Q_0^f\omega_0 \quad (1)$$

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$$\frac{1}{2}\left(|\Delta\omega_n^+| + |\Delta\omega_{n+1}^-|\right) \geq (1 - 2Q_0^f)\omega_0 \qquad (2)$$

The horizontal and vertical tune values are designed to be $Q_x = 3.19$ and $Q_y = 3.71$ resulting in frequencies of 83 MHz and 62 MHz respectively. For the frequency of the dipole mode of around 300 MHz transversal measurements without overlap are possible at beams with a momentum spread below $\Delta p/p = 6.3 \cdot 10^{-3}$. To be able to observe both sidebands a bandwidth of $2 \cdot f_0$ is needed, limiting the quality factor of the sensor to $Q \approx 128$. The effect of Q on the performance of the sensor system is discussed with the help of an equivalent circuit. It was already analyzed for the longitudinal case in [1].

CAVITY CONFIGURATION FOR TRANSVERSAL SCHOTTKY MEASUREMENTS

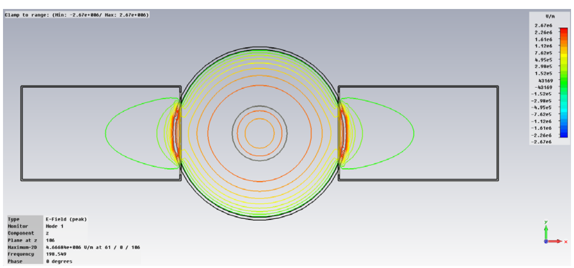

Figure 2: Magnitude of the z-component of the electric field strength of the monopole mode at 198 MHz.

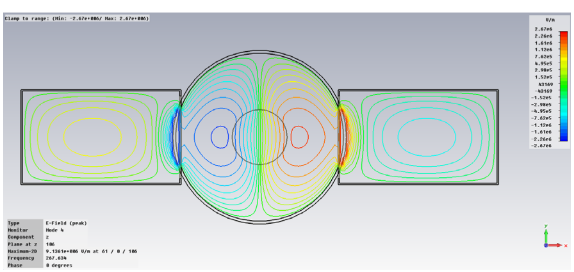

Figure 3: Magnitude of the z-component of the electric field strength of the dipole mode at 263 MHz.

For an ideal pillbox resonator, the z-component of the electric field is zero in the center and changing according to a Bessel function of order 1. From a series expansion one can conclude a linear behavior for small deviations from the center, while for larger deviations an cubic term will affect the signal increasingly. These nonlinear effects will disturb the Schottky spectra. However, this will be neglected for this estimation. Introducing the beam pipe will disturb the field pattern and the resonance frequency of the cavity modes. The large aperture of 40 cm leads to a deformation of the modes as depicted in Fig. 3 and Fig. 2. The field of the dipole mode around the center is stretched horizontally, decreasing the sensitivity of the system for small deviations from the center. Therefore, the coupling to the cavity is too strong at the example shown in the figures.

Resonant Waveguides: The described necessity to suppress the monopole signals will be realized with rectangular hollow waveguide resonators with a cutoff frequency above the monopole mode. In the current work, the waveguides are designed with a cutoff frequency of 220 MHz resulting in a width of 66 cm. To excite the desired fundamental mode of the resonator, the length of the waveguide needs to be half the wavelength inside the waveguide. For a frequency of 263 MHz this leads to 1.11 m. This dimension is altered due to the field disturbance of the coupling between the cavity and the waveguides and will be determined by numerical simulations. The resonance frequency of the waveguide resonator is set to the frequency of the dipole mode. The actual length is affected by the dimensions of the coupling slot between the pillbox-like cavity and the waveguide resonators.

Coupling Slots: The two waveguide structures are coupled to the cavity by dedicated slots. The coupling is mainly depending on the length of the slot, i.e. the dimension parallel to the long side of the waveguide. Because the wall currents of the monopole as well as the dipole mode are oriented along the coupling slot, its width has a strong influence on the modes, and must be designed carefully. The thickness of the wall cut by the slot also influences the coupling behavior. The aim of the optimization is an overall coupling factor of 1 between the low noise amplifier and the cavity system. The complexity of this optimization is increased by the various dependencies of the parameters. The coupling is affecting the energy transport, for the various modes, and the mode patterns itself, which are determining the power loss of a particle passing the sensor, as well as the resonance frequencies of the modes. The possible performance will be estimated based on a non-optimized system. Due to the size limitations, different approaches will be considered to reduce the size. One is rotating the waveguides by 90°, enclosing the beam pipe, and coupling into the long side of the resonator.

Extracted Parameters: The system was simulated with CST Microwave Studio [6] which allows to extract the R/Q values in a post-processing step. The R/Q values are given based on a PEC approximation, because they are defined by the cavity geometry alone. Different materials can be assumed by adjusting the quality factor. The meaning of these values for the performance of the system are discussed in the next section.

EQUIVALENT CIRCUIT MODEL AND SNR ESTIMATIONS

The sensor is modeled by an equivalent circuit according to Fig. 5. The velocity of the particles is set to $\beta = 1$ for simplicity. The calculations are performed for the unloaded configuration. The shunt impedance R_S relates the square of the voltage seen by a passing particle to the losses inside

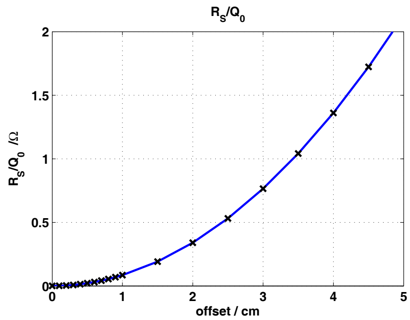

Figure 4: R/Q as a function of the offset.

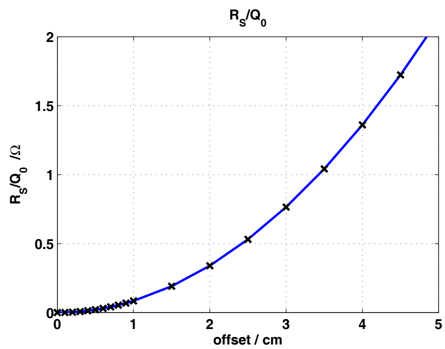

Figure 5: Simplified equivalent circuit model with the beam current I_B, the cavity configuration represented by R, L and C, a transformer representing the coupling between the system and the measurement device, and Z_{LNA} representing the LNA input impedance.

the cavity configuration,

$$R_s = \frac{V^2}{P_{\text{loss}}}. \tag{3}$$

As shown in [4], the energy transferred to the cavity from a particle of charge q is

$$W_{\text{lost,particle}} = \frac{\omega_0 R_S q^2}{4Q} \tag{4}$$

with ω_0 being the resonance frequency and Q the quality factor of the mode under consideration. The indices for the different modes are omitted for simplicity, because superposition can be applied and it is assumed, that the particle is not affected by the energy loss. For the equivalent circuit, the complete energy deposited by the particle will initially be stored inside the capacitor:

$$W_{\text{stored,C}} = \frac{q^2}{2C} = \frac{q^2 \omega_0 R}{2Q_0}. \tag{5}$$

Note that $C = Q/R\omega_0$ is the capacitance for a parallel RLC circuit. Setting $W_{\text{lost,particle}} = W_{\text{stored,C}}$ results in $R = R_S/2$. As shown in [5] this can be further processed to obtain the average power at resonance of one harmonic at the low noise amplifier for certain condition to be

$$P = (q\, f_{\text{rev}})^2 \frac{(R_S/Q_0)Q_l}{2} = (q\, f_{\text{rev}})^2 \frac{R_S}{4}. \tag{6}$$

These conditions include a coupling factor between the resonant structure and the external load of one, which means, that the same power is lost inside the cavity and in the load. This leads to an optimal SNR [5]. The resonator is assumed to behave like the unloaded one and the loaded quality factor Q_l is half the unloaded Q_0. Equation (6) shows that the optimization of the sensor needs to focus on a high R_S. To estimate the SNR of the system the ohmic losses from the resonator walls are the dominant source and further degradation due to the low noise amplifier is not considered at this point. For the matched case, the noise power in the load is assumed to be

$$P_{\Delta f} = k_B T_{\text{resonator}} \Delta f. \tag{7}$$

A temperature of 289 K of the cavity gives a noise power density of around -173.8 dBm/Hz. Assuming $Q = 128$, $f_{\text{rev}} = 1.17$ MHz and an offset of 1 mm the power of one harmonic is -237.45 dBm for a single electron. The number of particles (N) will linearly increase the power. Depending on the $\Delta f/f$ which is determining the height of a sideband with $0.4/\sigma$ and the number of particles the SNR at resonance frequency is approximately

$$\text{SNR} = \frac{0.4 \cdot (q f_{\text{rev}})^2 N R_S}{4 k_B T_{\text{res}}\, \eta \Delta p/p}. \tag{8}$$

OUTLOOK

To estimate the performance of the proposed system, a comparison with other approaches will be carried out. Further optimizations are needed to determine the final performance of our approach. Different geometrical configurations for the waveguide structures will be investigated to reduce the size of the system .

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