CONCEPTUAL DESIGN OF A HIGH SENSITIVE VERSATILE SCHOTTKY SENSOR FOR THE COLLECTOR RING AT FAIR*

M. Hansli[†], A. Penirschke, R. Jakoby,
Institut für Mikrowellentechnik und Photonik, TU Darmstadt, Germany
W. Kaufmann, GSI, Darmstadt, Germany
W. Ackermann, T. Weiland, TEMF, TU Darmstadt, Germany

Abstract

The FAIR (Facility for Antiproton and Ion Research) accelerator complex includes the Collector Ring CR, i.e. a dedicated storage ring for secondary particles, rare isotopes and antiprotons. The CR features three different modes of operation: 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 beam optimizations in all three modes a sensitive Schottky setup is required to monitor very low beam intensities down to single particles. In this paper the conceptual design of a longitudinal Schottky sensor based on a pillbox cavity with adjustable coupling and frequency tuning is presented. The basic measurement principles are depicted and a possible realization is discussed with emphasis on the special requirements of the CR operational modes. Full-wave simulations of the proposed sensor cavity allow for further optimizations.

INTRODUCTION

The Collector Ring (CR) is a dedicated storage ring, its architecture is governed by the stochastic precooling of secondary particles, rare isotopes or antiprotons. The CR is a high acceptance ring with an aperture of $40\,\text{cm} \times 20\,\text{cm}$ that has to fulfill three tasks: stochastic precooling of antiprotons from the antiproton target at a fixed kinetic energy of 3 GeV, to be delivered to the RESR storage ring, stochastic precooling of secondary rare isotope beams from the fragment separator (SuperFRS) at a fixed kinetic energy of $740\,\text{MeV/u}$, to be delivered to the RESR storage ring and mass measurements of short-lived secondary rare isotope beams from the SuperFRS in the isochronous mode [1]. Our motivation is to support the optimization of antiproton production and beam injection especially for lowest particle intensities. To achieve the required sensitivity, a resonant sensor structure is chosen. For an optimum performance it is important to adapt to the different modes of operation. The idea is to use a tunable cavity operating at the monopole mode (TM_{010}) with adjustable coupling. In Fig. 1 a detailed overview of important parameters and dependencies for the evaluation of the possible performance of such a sensor system is given. Key points are the ring parameters, defining geometrical restrictions and beam parameters, the beam itself with the Schottky noise, the signal

parameters representing the desired information as well as cavity parameters and the realization of the sensor itself.
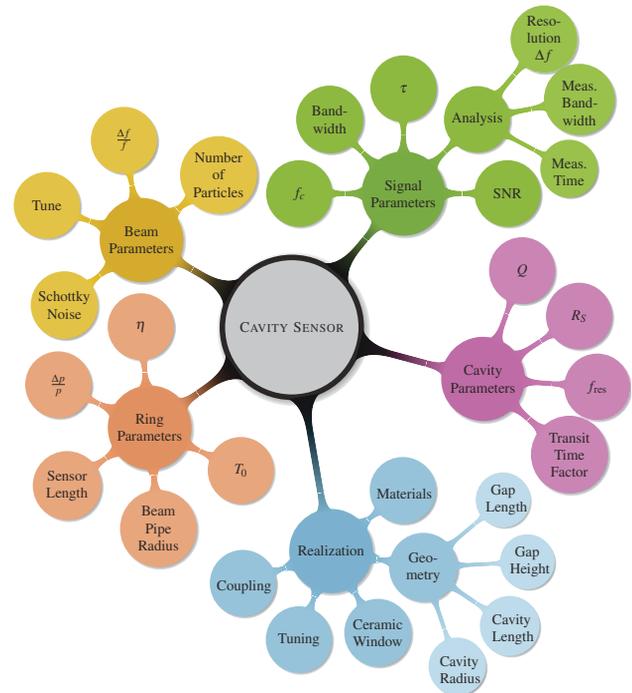

Figure 1: Mindmap showing the important parameters for the design process and their attribution.

SCHOTTKY NOISE SPECTRUM

Schottky noise is caused by the fact that the beam current is given by the sum of discrete charge carriers with potentially inhomogeneous distribution and energies. This leads to fluctuations around a mean value. Beam parameters like momentum spread, revolution frequency, tune and chromaticity can be measured with Schottky sensors. Schottky noise is investigated in the frequency domain and is proportional to the squared charge of a single particle. As shown in [2] and in more detail in [3], Schottky noise is distributed to harmonic bands in frequency domain. Each band contains the same information, so in principle any of the bands at harmonic h times revolution frequency f_0 could be used for Schottky analysis. The width of the h-th harmonic is h times the width of the base band, while the amplitude is decreasing with $1/f$. At a certain frequency, adjacent bands will overlap. This characteristic frequency depends on the

† hansli@imp.tu-darmstadt.de

spread in the revolution frequency $\Delta f_r / f_r$ which is given by the frequency slip factor η times the momentum distribution $\Delta p/p$. The width of the harmonic h is given by

$$\Delta f_h = h f_r \cdot \frac{\Delta f}{f}. \qquad (1)$$

The momentum spread and therefore the frequency spread are Gaussian shaped and different definitions for the width are used. The amplitude relative to the maximum of a Gaussian distribution at $\pm 2\sigma$ is 13.5% and 1.11% at $\pm 3\sigma$, respectively, while in the following the 6σ definition is used for the calculations of the band overlap. The harmonic number h at which the bands start to overlap can then be calculated with

$$h_{6\sigma} = \frac{1}{3 \cdot \frac{\Delta p_{2\sigma}}{p} \cdot \eta}. \qquad (2)$$

As shown in Table 1, for the CR the 2σ values for the momentum acceptance are $\pm 3\%$ for antiprotons, $\pm 1.5\%$ for rare isotopes and $\pm 0.5\%$ for the isochronous mode, while the frequency slip factor $\eta = -0.011$ for antiprotons and $\eta = 0.186$ for rare isotopes.

Table 1: Schottky Noise Parameters

Case	$\Delta p/p$	η	h	$h \cdot f_r$
Antiprotons	$\pm 3\%$	-0.011	1010	1384 MHz
Rare Isotopes	$\pm 1.5\%$	0.186	119.47	139 MHz

SIGNAL PARAMETERS

To determine an operating frequency for the sensor system, the goal of the system is defined as a maximized signal to noise ratio over a sufficient bandwidth. This leads to the parameters center frequency f_c, bandwidth BW, and signal to noise ratio SNR. The Schottky band overlap determines an upper limit for the measurement frequency. Moreover, within a resonant structure oscillating fields will remain after the particle has passed the sensor, possibly leading to interference between successive bunch passings. To support bunch-by-bunch diagnostics this setup is not convenient while it will be useful for detecting single particles over many turns. However, turn-by-turn measurements with a single bunch are possible if the signal is decreasing to an acceptable level within the time span of one turn. This decay time has to be chosen according to the desired application. The revolution time T_0 and the respective relative bandwidth (6σ) are given in Table 2 for the two cases.

CAVITY PARAMETERS

Important influencing factors for the design of the cavity sensor are the coupling between beam and cavity, i.e. the excitation of the cavity modes as well as the coupling to the measurement devices, i.e. the selective extraction of an

Table 2: Signal Parameters

Case	f_c	BW	T_0
Antiprotons	$h \cdot 1.37$ MHz	0.099%	730 ns
Rare Isotopes	$h \cdot 1.17$ MHz	0.837%	855 ns

appropriate mode. In summary this can be described with the parameters quality factor Q, the shunt impedance R, the transit time factor TT, and the resonance frequency ω_0. The quality factor determines the resonator time constant $\tau = 2Q/\omega_0$ and the bandwidth Δf_{3dB} as depicted in (3).

$$Q = \frac{2\pi \cdot \text{avr. energy stored}}{\text{energy dissipated /cycle}} \text{ and } Q = \frac{f_r}{\Delta f_{3dB}}, \qquad (3)$$

The quality factor determines the resonator time constant $\tau = 2Q/\omega_0$ and the bandwidth Δf_{3dB}. With the values according to Table 2 the maximum Q with regard to the bandwidth is given by $Q_{max} = 1010$ for antiprotons and $Q_{max} = 119$ for rare isotopes. One has to differentiate between the unloaded and loaded Q. The loaded Q takes the energy coupled out for the measurements into account and is limited by the demanded bandwidth. The unloaded Q should be as high as possible as long as the desired Q_{loaded} can still be achieved by the coupling to the measurement devices. The field deposited by a single particle inside the cavity will decay proportional to

$$e^{-\frac{t\omega_0}{2Q}} = e^{-\frac{t}{\tau}}. \qquad (4)$$

For turn-by-turn measurements and a requirement of a decay of fields to 1% after T_0 this will limit the Q to

$$Q_{\text{loaded, max}} = \frac{T_0 \, \omega_r}{2 \, \ln(100)}, \qquad (5)$$

resulting in values of $Q = 68$ for antiprotons and $Q = 76$ for rare isotopes. The energy inside the cavity will reach a certain mean value, because the actual energy loss depends on the overall energy inside. For an empty cavity at $t = 0$ and a δ-pulse shaped deposition of energy of a single particle passing the cavity, the energy at time t is given by

$$W_{\text{cavity}}(t) = \sum_{n=1}^{N} W_s \cdot u(t - nT_0) \cdot e^{-\frac{(t-nT_0)\omega_0}{Q}}, \qquad (6)$$

with the Heaviside function $u(t)$ and W_s the energy deposited by a single particle. Using (6) the average energy is around $0.75 \cdot W_s$ at $Q = 1000$ and around $3.5 \cdot W_s$ at $Q = 5000$.

The shunt impedance should be as high as possible, to couple as much energy as possible into the cavity. The shunt impedance can be defined using the instantaneous peak voltage that would act on a particle with infinite velocity. In this case, the shunt impedance is a property of the cavity itself, independent of any beam characteristics. For physical particles with finite velocities the transit time factor has to be taken into account leading to different optimal

solutions for the cavity geometry. For this choice the different level of Schottky noise for varying particle charges is important. For each mode of operation an unique setting of the cavity parameters will lead to an optimum performance. Therefore the idea to have a tunable coupling and frequency tuning is investigated. Varying the coupling, and thereby varying Q_{loaded}, the bandwidth can be adjusted. Frequency tuning is important to adapt to the mode of operation and compensate fabrication tolerances and temperature changes.

REALIZATION

The realization includes the choice of features, materials, geometry, and dimensions. The proposed tunability of frequency and coupling will be done mechanically by a movable perturber and a turnable coupling loop. The realization of movable parts within the vacuum is complex and expensive. For a frequency of $130\,\text{MHz}$ the radius of a pillbox cavity would be around $0.88\,\text{m}$. Introducing a ceramic vacuum shielding with a high permittivity ϵ will reduce the size of the cavity and allow the operation of the movable mechanical parts under non-vacuum conditions. In additional, the ceramic window must be shielded to prevent contact with the beam. Following this restriction and minimizing the effect of the field concentration within the ceramic on the shunt impedance are major goals of the integration of the vacuum window. The range of the coupling out of the cavity, the number of coupling loops required, and their influence on the field pattern are important design parameters. The range of the needed frequency tuning is limited to $f_0/2 = 0.685\,\text{MHz}$, allowing a tuning to a harmonic.
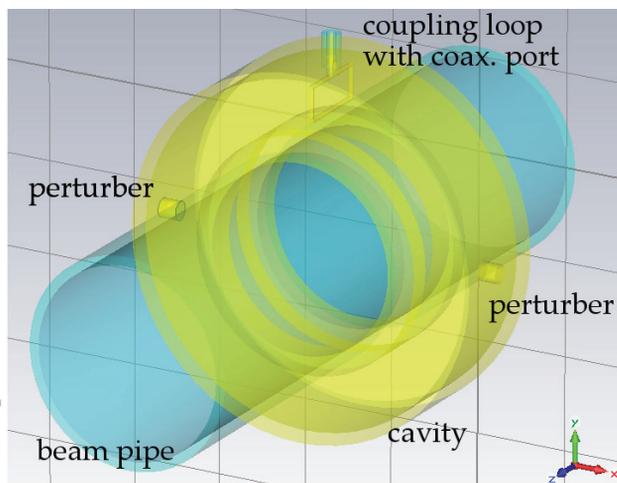
Prototype Design

Figure 2: Prototype design of a tunable sensor cavity modeled in CST Microwave Studio. Two perturbers are included at the left and right, as well as a coupling loop with coaxial feedthrough on top.

A prototype cavity featuring a simple pillbox design with an added angular nose is used for first estimations on the suitability of the concept. The design according to Fig. 2 results in an unloaded $Q_{\text{unloaded}} = 18930$ and a loaded quality factor approximated by $Q_{\text{loaded}} = 150$. For a pillbox cavity (copper, radius $= 60\,\text{cm}$, length $= 12\,\text{cm}$) with a stainless steel beampipe of $20\,\text{cm}$ radius the unloaded quality factor changed from around 23880 to around 22000 by adding an alumina ($\tan\delta = 0.0004$ and $\epsilon_r = 9.4$) window of $1\,\text{cm}$ thickness, values much higher than needed due to the signal parameters. The decrease in quality factor due to the dielectric losses will not be a problem, according to simulations with CST Microwave Studio [4]. A frequency shift of around $1\,\text{MHz}$ can be achieved by moving the two perturbers $5\,\text{cm}$ into the cavity as shown in Fig. 2.

EIGENVALUE CALCULATION

The distribution of the electromagnetic field strength $\vec{E}$ as well as the magnetic flux density $\vec{B}$ inside the proposed resonator can be obtained with high accuracy with the help of appropriate eigenvalue calculation in frequency domain. Because the intended observation is ultimately related to the determination of the field strength of the associated mode pattern the coupling of the loop to the field has to be considered properly during the evaluation. Within the simulation process this can be achieved either on a real-valued eigenvalue calculation and subsequent post-processing steps or using a complex-valued approach where the extraction of the fields is consistently taken into account by suitable absorbing boundary conditions. The solution of the source-free Maxwell's equations in frequency domain naturally results in a complex-valued expression if locally absorbing boundary conditions are applied. The Silver-Müller relation for the port regions

$$\vec{n}\times\text{curl}\vec{E} + j\frac{\omega}{c_0}\,\vec{n}\times(\vec{n}\times\vec{E})\,\Big|_{\vec{r}\,\in\,\partial\Omega_{\text{Port}}} = 0 \qquad (7)$$

is used to model the extraction of the fields in a plane perpendicular to the applied straight coaxial line. This description allows to model an ideal port without reflections if all excited higher order modes are damped sufficiently and only the fundamental TEM mode remains on the line. These kind of eigenvalue calculations are then recursively used to optimize the proposed resonating sensor system.

REFERENCES

[1] Various Authors, "Technical Design Report: Collector Ring", FAIR TDR-CR_2.5_090407.

[2] F. Caspers, "Schottky Noise", CAS 2008 on Beam Diagnostics, 2008.

[3] S. Chattopadhyay, "Some Fundamental Aspects of Fluctuations and Coherence in Charged-Particle Beams in Storage Rings", CERN, 1984, Cern 84-11.

[4] CST AG Computer Simulation Technology, CST Studio Suite 2011, www.cst.com.