A SENSITIVE RESONANT SCHOTTKY PICK-UP FOR THE ESR STORAGE RING AT GSI

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Abstract

A cavity-like Schottky detector for the heavy ion storage ring ESR at GSI is presented. It features both a very good sensitivity even for beams with single circulating ions and the possibility to take valuable spectra in short time. Experiments with the new device are presented which show clearly that it offers new experimental opportunities, both for accelerator diagnostics and nuclear physics experiments. A similar pick-up will be built into the CSRe storage ring at IMP.

OVERVIEW OF THE DETECTOR

The ESR storage ring at GSI has frequently been used for the detection of very low intensity heavy ion beams, down to single circulating ions of a certain nuclear species(see, e.g. [1]). However, the signal to noise ratio of the Schottky lines has turned out to be too poor. Therefore a new resonant pick-up was built, featuring the following properties:

- high shunt impedance in order to reach the desired sensitivity
- variable resonant frequency in order to match different beam energies and orbit lengths
- a possibility to reduce the beam impedance in case of high intensity beams with low momentum width
- cost efficiency and easy installation

Our solution to these requirements [2] is an air filled pillbox-shaped resonator which couples to the beam via a ceramic gap in the vacuum chamber. The working frequency is 245 MHz, the loaded Q is 520 and the shunt impedance is 114 kΩ, using the circuit convention.

RESONATOR DESIGN

The ceramic gap is mounted between the existing vacuum chamber on both sides of the gap. The gap provides the necessary rf coupling between the beam and the air-filled inner volume of the resonant cavity, and assures the vacuum inside the beam chamber. The resonant cavity can be removed from the gap if it should lead to a high beam impedance that could be harmful to intense circulating beams.

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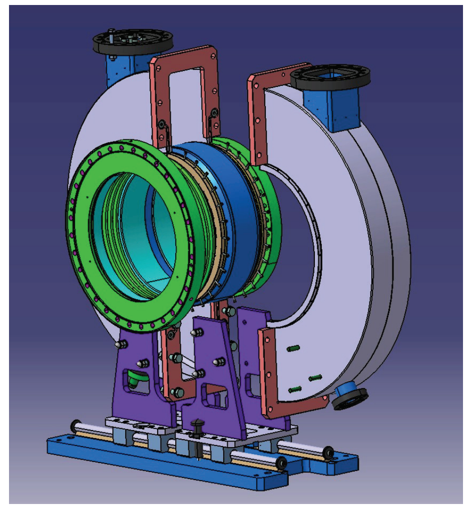

Figure 1: Principle of the pick-up design. The part coloured in green in the centre of the picture is the beam pipe with the ceramic gap (coloured in blue). The two half-shells (coloured in grey) are electrically connected to the beam pipe forming a closed resonant volume around the ceramic gap. In the case the pick-up is not needed, the half-shells can be removed from the ceramic gap in order to avoid parasitic impedances which might be harmful for the beam. Each of the half-shells is equipped with two feedthroughs.

The resonant cavity around the gap is a modified pillbox with an outer diameter of 600 mm, and an inner diameter of 260 mm (see Fig. 1). The length in beam direction is approximately 100 mm. The walls of the pillbox around the centre contact the beam pipe with the ceramic gap by means of rf contact springs. Figure 2 shows details of how the resonator is connected to the vacuum pipe. The pillbox is divided into two halves (dees) to enable the removal of the cavity from the beam pipe and ceramic gap. In the first eigenmode the radial slits between the dees influence neither the quality factor nor the shunt impedance, but they suppress the excitation of unwanted higher eigenmodes with azimuthal current components. In order to simplify the removal of the dees they are mounted to sliding carriages. After the removal of the dees the ceramic gap can be short circuited by copper connections outside the vacuum chamber. Each dee is equipped with two flanges for feedthroughs. The lower one accommodates the output coupler loop in order to tap power from the eigenmode ex-

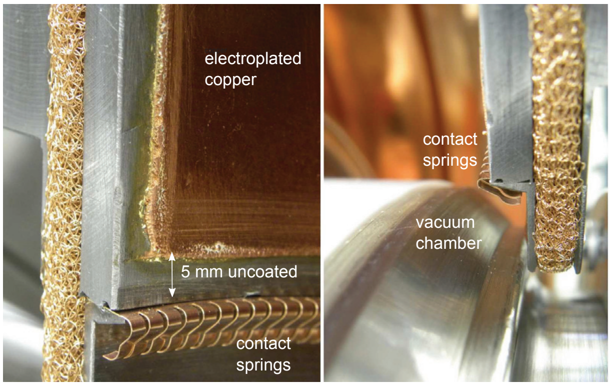

Figure 2: Detailed views of a corner of one half-shell. The left picture shows a view on the electroplated copper surface with the uncoated region and the rf contact springs, the right picture shows how a half-shell can be mounted on the vacuum chamber. In both pictures, rf currents propagate vertically on the half-shell in the fundamental mode.

cited by the beam. The upper port is of rectangular shape and accommodates a moveable plunger piston by which the resonance frequency of the eigenmode can be adjusted. The plunger piston is moved up and down by a step motor mechanism. To assure a frequency shift of somewhat more than 2 MHz without perturbing the field geometry too much, two plunger pistons are mounted, one for each dee. There is an additional lower feedthrough which can be equipped optionally by a slewable second coupling loop, terminated by a resistor, in order to broaden the bandwidth of the pick-up, if needed.

The pillbox is made of construction steel with its inner surfaces copper-coated with a thickness of about 50μm, well above the skin depth at the operating frequency. The plunger pistons are made of copper. Only a 5 mm wide part of the dees right behind the contact springs to the vacuum chamber could not be copper coated because of certain properties of the electroplating process. On this surface a rather high rf current is exposed on a relatively short path to material with a non-negligible magnetic permeability. The beam pipe with the ceramic gap relies on the same well-proven technology which has been used for the two existing ESR rf-cavities. It is made of stainless steel and could not be coated with copper retrospectively.

RF PROPERTIES

The resonator has a tunable resonating frequency around 245 MHz and an unloaded quality factor of 1022. In comparison with a metallic pillbox of 300 mm radius the frequency is lower by a factor of 1.7. This is mainly caused by the dielectric alumina material ($\epsilon_r = 9.7$) of the ceramic gap, where the electric field is concentrated, as can be seen in the SUPERFISH field simulation shown in Fig. 3. The alumina material also leads to dielectric losses, which are mainly responsible for the somewhat low Q value.

Figure 4 shows the calculated transit time factor Λ as a function of β. Due to the large required acceptance of the ESR storage ring the inner radius of the vacuum chamber is 125 mm, leading to an extended longitudinal electric field along the beam axis, and a pronounced drop of the transit time factor towards low beam velocities.

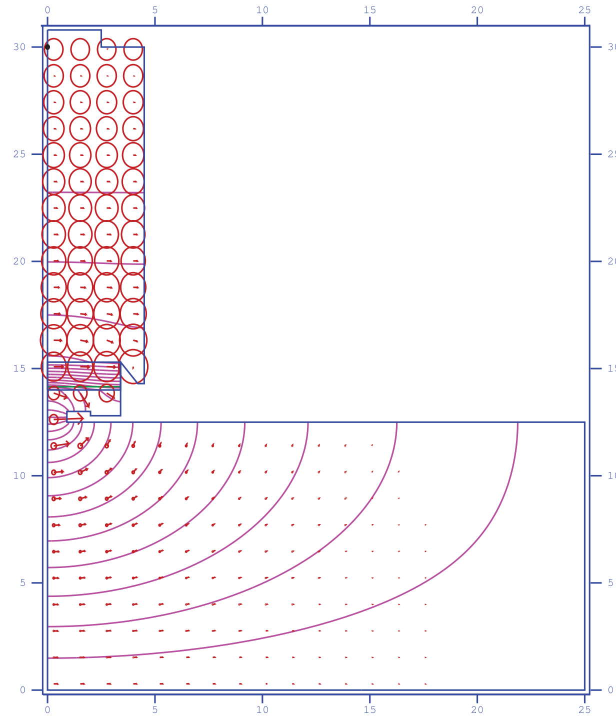

Figure 3: Simulated field pattern in one quarter of the resonator. The lines represent electric field lines, whereas circles illustrate the magnetic field strength.

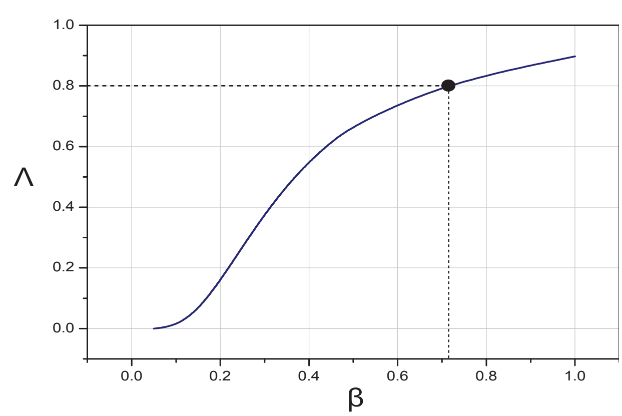

Figure 4: Transit Time Factor Λ as a function of beam velocity β

In order to extract the signal the output coupler loop was dimensioned such as to get a loaded quality factor which has exactly half the value (511) of the unloaded one.

The noise power density on resonance is -173 dBm/Hz. This value is well understood quantitatively using an appropriate model. The main noise sources are the thermal noise from the resonator (effective temperature $T_1 = 290$ K), the output noise of the first preamplifier ($T_2 = 67$ K), and the reflection of the noise from the input of this preamplifier by the resonator (effective temperature ($T_3 = 26$ K). On resonance the noise is mainly given by $T_1 + T_2$, whereas the noise floor off resonance is roughly $T_2 + T_3$.

BEAM RESPONSE

The shunt impedance R_s of the resonator was measured to be 114 kΩ (circuit convention) using a perturbation measurement with a long ceramic rod. This value is confirmed by measurements with beam, assuming the theoretically determined transit time factor from Fig. 4.

The total Schottky power delivered by a single particle with charge q and revolution frequency f is

$$\langle P \rangle = \frac{(qf)^2 R_s \Lambda^2}{8} \tag{1}$$

if the resonator is tuned to exactly one harmonic of the revolution frequency.

An interesting quantity for measurements at the ESR is the charge state $Q = q/e$ at which the signal height is equal to the noise floor. In order to calculate this number we assume a frequency width $\delta f/f = 1 \cdot 10^{-6}$, which is reached routinely by extreme electron cooling of low-intensity ($N < 1000$) beams (see [3] and references therein). We suppose the measurement to be performed at a specific kinetic energy of 400 MeV/u, where $\Lambda \approx 0.8$. Then the signal height equals the noise floor at $Q = 31$ only. This is much lower than the situation was with the Schottky pick-up device used so far at the ESR [4], where the signal to noise was about 20 dB less at this energy. This older device has an optimum working frequency range around 60 MHz.

Another important advantage of the resonating device is due to its higher working frequency. The measurement time T to resolve a relative difference $\delta f/f$ in revolution frequencies must be definitively larger than

$$T > \frac{2}{mf} \left(\frac{\delta f}{f} \right)^{-1} \tag{2}$$

Because the separation of Schottky lines is proportional to the working frequency, the time it takes to resolve lines is inversely proportional to the measurement harmonic m.

OBSERVATION OF ELECTRON COOLING

Figure 5 serves as an example for the diagnostic power of the resonating pick-up. It shows a waterfall diagram of consecutive Schottky spectra taken with a temporal distance of 32 ms. The beam energy was 400 MeV/u. With the momentum compaction $\alpha_p = 0.18$ of the optical ESR mode used during the experiment, the frequency dispersion $\eta = \gamma^2 - \alpha_p$ is $\eta = 0.31$. Therefore the frequency interval 5 kHz at 245 MHz corresponds to a relative momentum deviation $\delta p/p = 6.6 \cdot 10^{-5}$.

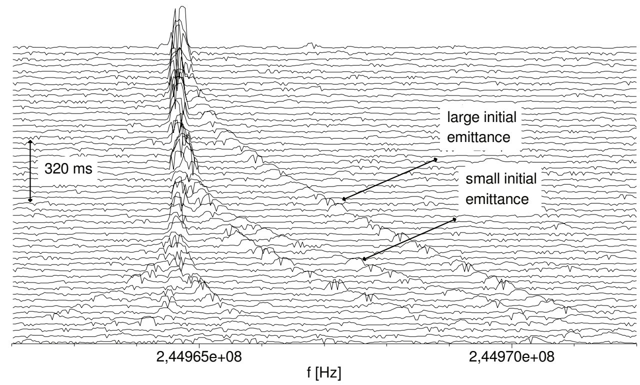

Figure 5: Waterfall diagram showing electron cooling of six $^{142}Pm^{59+}$ ions

After beam preparation by stochastic cooling which is switched off just before the measurement, six single $^{142}Pm^{59+}$ ions are electron cooled and merged into a single line. Each single ion can be clearly identified and its cooling can be observed in detail. For example, one sees that there are two ions at high momentum deviation with quite different cooling times. This can be attributed to their difference in transverse emittance after stochastic cooling, which must have been large enough to lead to this effect.

Another example of valuable measurements with the new device is the observation of neutrino recoils during electron capture decays of highly stripped heavy ions [5].

Such detailed, sensitive, fast and highly resolved spectra are a beneficial feature of our new resonant pick-up. It opens up new ways to both beam diagnostics and to novel nuclear and atomic physics observations.

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