CONCEPTUAL DESIGN OF ELLIPTICAL CAVITY BEAM POSITION MONITORS FOR HEAVY ION STORAGE RINGS

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Abstract

Over 50 years in the history of accelerator physics, RF cavities have been used as beam position and intensity monitors. Their structure has been extensively discussed across numerous papers reporting their successful operation (a review can be found in [1]).

The application of RF cavities as pickups has recently been extended to include radioactive ion beam (RIB) facilities and heavy ion storage rings. These pickups allow very sensitive, accurate, and quick characterisation of ion beams and turn out to be indispensable tools in nuclear as well as atomic physics experiments. A notable example is the resonant pickup in the ESR at GSI Darmstadt [2] where single ion detection was achieved for lifetime measurements of radioactive nuclides [3]. A similar cavity pickup was installed in CSRe in IMP Lanzhou [4].

Usually, cavity pick-ups in dipole mode are used to accomplish position sensitive measurements. These achieve high sensitivities for small aperture machines (see e.g. [5] and [6]). In this work, we describe a novel conceptual approach that utilizes RF cavities with an elliptical geometry. While allowing a high precision determination of the position and intensity of particle beams, it has to cope with design restriction at heavy-ion storage rings such as large beam pipe apertures. The latter becomes inevitable at facilities aiming at storing large-emittance beams as e.g. planned in the future Collector Ring (CR) of the FAIR project at GSI Darmstadt.

THEORY OF OPERATION

Schottky Noise Analysis

Schottky noise analysis is meanwhile a well established method in beam diagnostics in storage rings, providing valuable information on beam characteristics. While transversal Schottky noise signals contain information on tune and chromaticity, longitudinal signals can be used for the determination of the revolution frequency and momentum spread of the beam. In an in-ring experimental scenario, longitudinal Schottky signals can be used to identify different nuclear species circulating in the storage ring. Using the fundamental relation of mass to charge ratio and the frequency resolution in storage rings [7], one can measure different nuclear masses by comparing the frequency difference with known reference nuclides. Using time resolved Fourier analysis, it is possible to monitor an unstable isotope in order to determine its lifetime. A more detailed account on mass and lifetime measurement in storage rings using the Schottky signal analysis can be found in [7].

Schottky noise signals are random processes. The power spectral densities show frequency bands around multiples of the beam revolution frequency [8]. These bands contain the same amount of power, and although increasing frequency affects their width and height, they essentially carry the same information about the beam. So provided that the recorded Schottky signal is mixed down into base band, an experimental event which causes a frequency change Δf (a decay event, isomeric states, determination of mass, beam cooling, jitter, etc.) is better resolved at higher harmonics for a given recording time Δt. In other words, for a required frequency resolving power, one needs a shorter recording time.

RF Cavities as Schottky Pick-Ups

Microwave cavities possess a set of eigenmodes, each oscillating at their corresponding eigenfrequency. Each of these modes ν can be thought of as an electrical resonator containing an ideal RLC element [9], each of which can be described by its frequency f_ν, Q value Q_ν and shunt impedance $R_{sh,\nu}$:

$$P_{diss,\nu} = \frac{U_\nu^2}{R_{sh,\nu}} = \frac{1}{2}\frac{U_\nu^2}{R_\nu} \quad (1)$$

where U_ν is the induced voltage after the passage of the particle, and $P_{diss,\nu}$ is the dissipated power to that mode and R_ν is the resistor in the equivalent RLC circuit. For the Q value we have

$$Q_\nu = \frac{\omega_{0\nu} W_\nu}{P_{diss,\nu}} \quad (2)$$

where $\omega_{0,\nu}$ is the angular eigenfrequency and W_ν is the energy stored in the mode. Instead of the shunt impedance, it is often useful to use a material independent version of it which is normalized to the Q value. It is often called *R/Q*, the *characteristic impedance* or *geometric factor* in units of ohms

$$\left(\frac{R_{sh}}{Q}\right)_\nu = \widehat{\left(\frac{R_{sh}}{Q}\right)}_\nu \Lambda_\nu(\beta)^2 \quad (3)$$

where $\Lambda_\nu(\beta)$ is the so called *transit time factor* as a function of the relativistic β of the beam. The hat shows the ideal characteristic impedance for a cavity with zero length and a beam travelling with the speed of light.

The signals from a beam of particles can be used to excite a microwave cavity . The resulting standing waves can

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be coupled out of the cavity by using a loop antenna. At critical coupling the output power of a single particle at the harmonic m is [9]

$$\langle P_{out}\rangle|_{mf_r} = \langle P_{diss}\rangle|_{mf_r} = (Ze)^2 f_r^2\, \widehat{R_{sh,\nu}}\, \Lambda(\beta)^2 \quad (4)$$

Use of RF cavities as pick-ups allows for sensitive detection of particles whenever one of the resonant frequencies of the cavity matches with a harmonic of the beam. For intensity measurements a longitudinally sensitive detector can be designed using a circularly cylindrical shallow pillbox, with connected beam pipes, which oscillates at its fundamental oscillating mode TM010 (see e.g. [2]). By properly choosing the dimensions, and allowing for mechanical detuning of the cavity, the above requirements for sensitive particle detection can easily be met.

TRANSVERSAL SENSITIVITY

The R/Q Map

The characteristic impedance R/Q is an integrated quantity along the axis of the resonator (z axis). Nevertheless, its value depends not only on the transit time factor as seen in equation (3), but also on the transversal position of the beam [10]. The latter is due to the distribution (pattern) of the z component of the electric field in the specified mode. One can plot the R/Q values versus the transversal position in 3D which results in an *R/Q map* clearly showing the sensitivity of the mode for different transversal offsets.

Generalization to Elliptical Cross Section

The shallow circularly cylindrical cavity has, as expected, a nearly flat R/Q map around the beam pipe center. This makes it suitable for intensity measurements. For position sensitive detection, the desired R/Q map should show no variation on one axis, whereas a linear dependency on the perpendicular axis is needed. This would resemble a tilted plane. Two consecutive detectors would be able to cover the transversal plane, if they are placed orthogonally with respect to each other.

One of the best candidates that can show this kind of R/Q map is the TM010 mode of a pillbox cavity with an *elliptical* cross section. The equations governing the elliptical cavities do not depend on the standard Bessel functions any more, but need to be generalized. A detailed account can be found in [11].

Simulations show that the TM010 mode pattern of the electric field shows the same falloff as the circular TM010 mode as the radial distance increases in the direction of circumference. By contrast to the circular case, since the boundaries along the major elliptical axis are further away, a less steep variation is visible in this direction, whereas the electric field approaches zero much faster in the direction of the minor axis.

By putting the beam pipe off center along the direction of the minor axis (see Figure 1), one can make use of the steep *one sided* falloff of the fields while benefiting from the two sided slow variation in the direction of major axis.

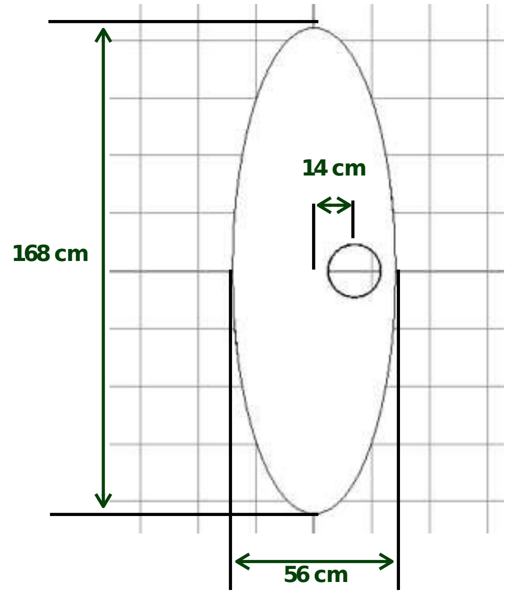
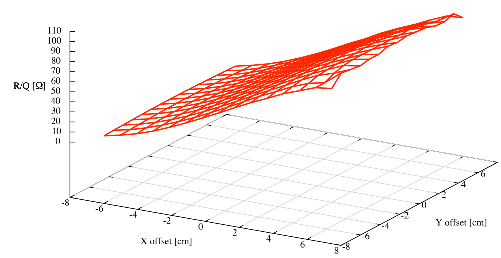
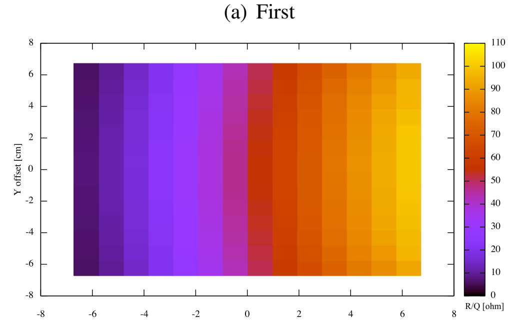


Figure 1: The simulated elliptical cavity.

Simulations using Microwave Studio® show that due to the large aperture, the beam pipe itself has a flattening effect, so that the net effect is a an almost constant field amplitude along the major axis.



(a) First



(b) Second

Figure 2: 3D and top view of the R/Q map of the simulated elliptical cavity in the region around the center of the beam pipe.

The resulting R/Q map of such a cavity is nearly a tilted flat plane (see Figure 2) as was required for transversal detection in the previous section. This approach has many advantages. The fundamental monopole mode is dominant and can be excited easily. While a strong monopole mode

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poses difficulties for designs that utilize dipole mode geometries and needs to be dealt with, in the present design it becomes an advantage. Dealing with higher order modes (HOM) is easier than suppressing the fundamental mode.

Single Particle Position Detection

The elliptical cavity described in this work is by nature a monopole mode cavity since it is operating in its fundamental TM010 mode. The information on the position of the particles is hidden in the amplitude of the coupled signal. For single particle position detection, it is necessary to make a level detection on the mixed down signal from the cavity. This information can be plotted versus time, with the same granularity as the usual time resolved Fourier analysis of the recorded signal. The resulting multi-diagram will show all three values (frequency, x position and y position) versus time.

CONCLUSION AND OUTLOOK

In this work we describe a novel method for position sensitive particle detection of coasting beams in heavy ion storage rings, using a hollow microwave cavity with an elliptical cross section. Simulations show the desired trend in the characteristic impedance. Two such detectors can cover the two dimensional XY plane. The design specifically allows large beam pipe apertures like those found in GSI's ESR and FAIR's future storage rings such as CR.

This is a work in progress, so many optimizations are still needed especially with regard to specific design parameters limited by the target storage ring in order to achieve the flattest possible R/Q map at the location of installation. This in turn should be the place with the highest dispersion. The detection method needs to be optimized to include multi-particle detection.

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