CONSIDERATIONS FOR A CAVITY-BASED POSITION-SENSITIVE HEAVY ION DETECTOR FOR THE CR AT FAIR*

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Abstract

The Facility for Antiproton and Ion Research (FAIR) is a complex yet ongoing project which will allow for a broad range of experimental physics programs as well as a variety of material and medical applications. Being a heavy ion storage ring at FAIR, the Collector Ring (CR) is perfectly suitable for scientific investigations on fundamental properties — such as masses and lifetimes — of short-lived radioactive nuclei when it operates in isochronous mode. To fulfill stringent experimental requirements, a compatible heavy ion detector sensitive to beam intensities and positions is highly demanded. In this paper we present a conceptual design of cavity-based Schottky noise pickup to achieve non-destructive detections of stored particles. Computer-aided simulations follow immediately to justify the feasibility of such a design.

INTRODUCTION

The utilization of a resonant structure in design of beam position monitor (BPM) to enhance its sensitivity has a long history, dating back to 1962 when R. Bergere first introduced the concept into the monitoring device. Over more than a half-century of prosperous developments, cavity-based BPMs, along with capacitive and strip-line monitors, are commonly adopted in many particle accelerators all around the world [1].

Their excellent performance in sensitivity makes them stand out from other types of BPMs, especially in the case of low-current beam monitoring. As an example, a resonant pickup for the detection of heavy ion Schottky noise was mounted into ESR at GSI not so long ago, and has demonstrated its ability of observing dynamic cooling processes of single ions [2]. Based on the previous experiences, we will keep on using cavity scheme for our next generation of heavy ion detector which can discriminate transverse offsets of particles.

CAVITY CHARACTERISTICS

When it comes to a cavity, three figures of merit are of great importance and should be taken into account in the design process [3].

Resonant Frequency

Generally speaking a cavity is a hollow space enclosed by metallic shields, where electromagnetic (EM) field can be trapped to form standing waves. Because of the boundary conditions, only certain patterns of standing waves appear in the cavity, which are normally called (eigen-)modes. Each mode has its unique characteristic field distribution which oscillates at a fixed resonant frequency, denoted as f_0. It is worth mentioning that f_0 is only determined by cavity geometry.

Quality Factor

In the real world EM power loss happens to any cavity, causing the trapped EM waves to eventually vanish. Additionally, due to imperfections an EM wave that is off-resonance can still exist in the cavity but with a smaller amplitude. So a typical resonant curve of a real cavity (Fig. 1) actually resembles a finite distribution rather than a delta function. One can easily understand that the "narrowness"
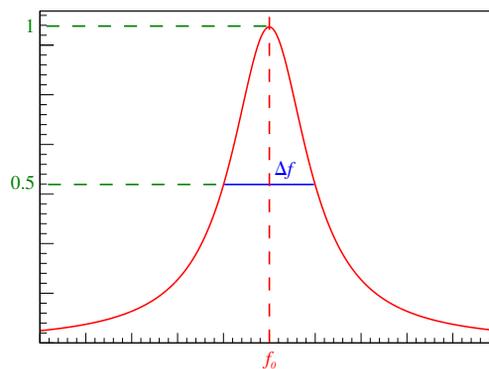

Figure 1: A typical resonant curve.

of the peak shows how good the cavity is in the sense of preserving EM field in a certain mode. Consequently a dimensionless ratio Q called quality factor is defined in this circumstance:

$$Q = \frac{2\pi f_0 W}{P_l}, \qquad (1)$$

where W is stored EM energy and P_l is EM power loss. If Q is high, the relation $Q = f_0/\Delta f$ is also valid.

Shunt Impedance

Apart from quality factor, shunt impedance R is also often used to characterize the power loss of a non-ideal cavity. Like a resistor in a RLC circuit which is responsible

for EM energy conversion to heat, the shunt impedance of a cavity measures the dissipated amount of stored energy. Therefore it is reasonable to quantify the coupling strength between the cavity and the beam with shunt impedance. However in most cases, it is found convenient to use "reduced" shunt impedance R/Q instead, since this quantity is material-independent and only determined by cavity geometry, as shown in the following:

$$\frac{R}{Q} = \frac{\left(\int_0^d E_z \mathrm{d}z\right)^2}{2\pi f_0 W},\qquad(2)$$

where d is cavity's depth.

DETECTION PRINCIPLE

According to Eq. 2, the shunt impedance is directly related to the projection of electric field onto the axis of the cavity, or in other words, beam path. In principle R/Q becomes larger where E_z is stronger, thus the cavity is able to "see" the beam more clearly. So the first requirement of particle detection with a cavity is high shunt impedance. Furthermore in order to differentiate particles' positions, R/Q should not stay constant with respect to transverse offset. This additionally requires a steep variation of shunt impedance for the position detection.
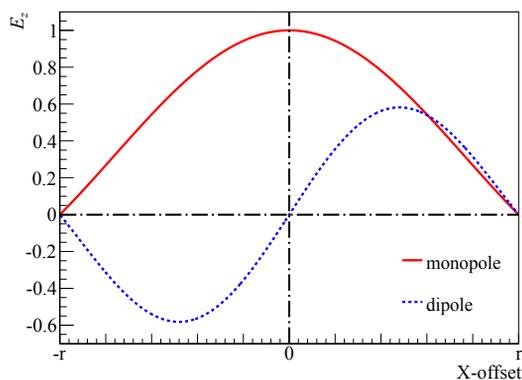

Figure 2: Electric fields in a circular cavity.

Consider a circular cavity which is the most popular configuration nowadays for beam position monitoring. Two basic modes — monopole mode and dipole mode — are of great interest and have wide applications. They have the simplest EM field distributions and the lowest resonant frequencies, therefore can easily be excited in the cavity. Figure 2 outlines the axial electric fields of two modes with regard to the transverse offset. Due to the slope of dipole mode in the central region, it would seem intuitive to place the beam pipe there and tune the cavity in the resonant frequency to detect beam positions.

However this intuition is still naive and needs some cautious thoughts. In fact, two major drawbacks of such a scheme are known.

1. The longitudinal electric field is very weak around the cavity centre, which causes the coupling signal to be buried under noise floor and reduces position resolution in that region.
2. The dipole mode is inevitably affected by interference from the monopole mode which has a much stronger amplitude, necessitating the elimination of parasitic modes.

DESIGN

Specific to our case, a requested position-sensitive cavity is supposed to operate in the CR for mass and lifetime measurements of radioactive beams. The secondary beams of physical interest are in the vicinity of nuclear drip lines, making them difficult to produce, which in turn limits the beam intensities to a great extent. What is more, the pipe opening of CR is so large (40 cm × 18 cm) that interferences between the two lowest modes become more evident. Therefore the aforementioned hindrances become major challenges that need to be addressed.

Fortunately we have proposed a novel design by means of monopole mode in order to overcome those obstacles [4]. From Fig. 2 one can see that the field distribution in monopole mode also has sloping parts which may be used for particle position detection. All we need to do is placing the beam pipe off-centre to one side, as depicted in Fig. 3.
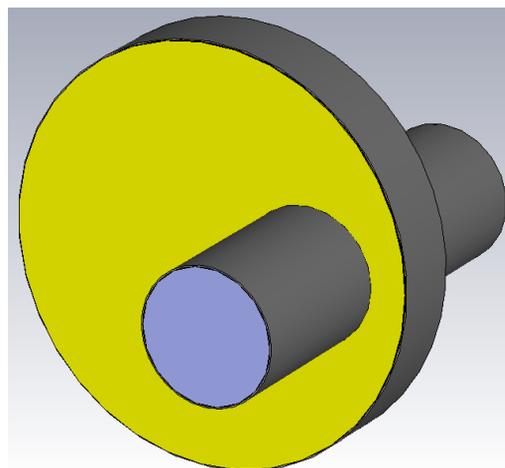

Figure 3: Sketch of the cavity with beam pipes.

Just like most cavity-based BPMs, our design also employs a pillbox cavity, but operating in monopole mode with a certain offset of the beam path. Two magnetic couplers are mounted opposite on the circumference. The downstream amplifying circuits will be tuned in the resonant frequency of monopole mode. Because the shunt impedance of such a mode is relatively high and shows a progressive change within the pipe, our cavity seems to be a promising candidate for detecting particle positions under low intensity conditions. Besides, we are not facing the problem of eliminating parasitic modes any more, since the strength of any

higher order mode is much lower compared with that of fundamental one.

SIMULATION

The radio frequency (RF) properties of our design have been investigated with the help of a simulation software, namely CST MICROWAVE STUDIO® [5]. A complete set of cavity dimensions used for geometric modelling in CST are listed in Table 1 and visualized in Fig. 4.

Table 1: Cavity Dimensions

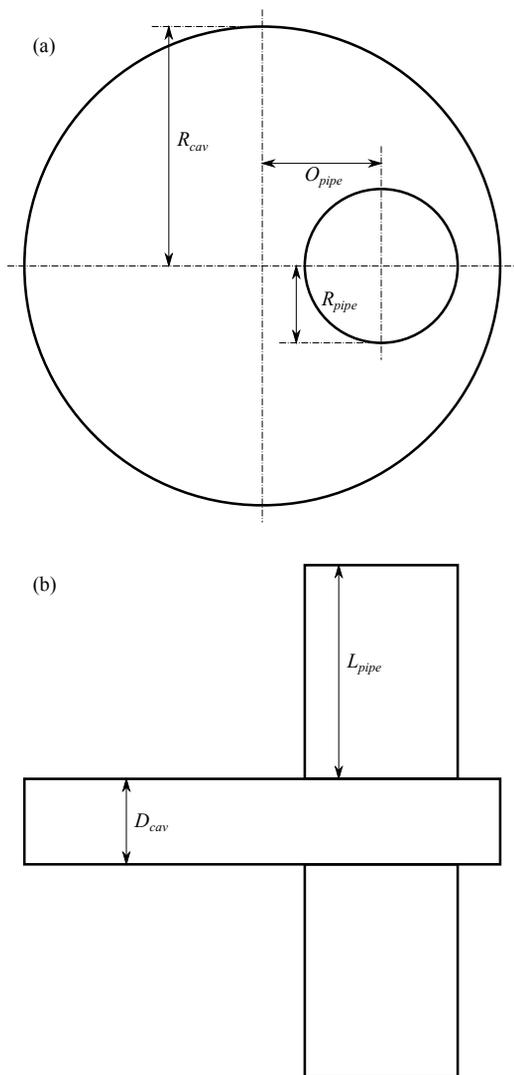| Name	Value	Description
R_{cav}	28 cm	radius of cavity
D_{cav}	10 cm	depth of cavity
R_{pipe}	9 cm	radius of pipe
L_{pipe}	25 cm	length of pipe
O_{pipe}	14 cm	offset of pipe

Figure 4: Multiview of the cavity: (a) front view, (b) top view.

It turns out that with this kind of configuration $f_0 = 409.77$ MHz. The resonant frequency is moderate, being compatible with ready-made electronic components, such as amplifiers, filters and mixers.

We have also considered lossy materials in the simulation to imitate the real world more accurately. This results in a quality factor of 13 673.

What is very promising is the dependence of shunt impedance on the beam offset. In the first step we concentrate only on the central transverse plane. We have calculated the distribution of shunt impedance in the range from -8 cm to 8 cm around the pipe centre. The result, plotted in Fig. 5, shows a considerable change of nearly 90 Ω across the pipe, or 5.6 Ω/cm on the average.
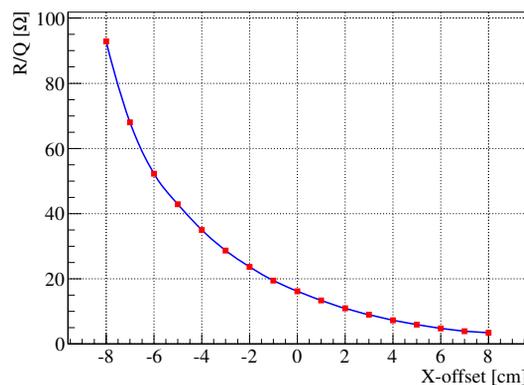

Figure 5: Simulated distribution of shunt impedance around the pipe centre.

We will need a pair of such cavities placed close but reverse such that both of them simultaneously pick up induced coupling signals of different amplitudes from the same passing beam. By subtracting one signal from the other, we can interpret the transverse position of the beam.

However we have to admit that some limitations also exist in this kind of design. It is clear from Fig. 5 that the right side is less sensitive to the beam offset due to its slower drop-off, which causes a worse position resolution. Recalling the fact that R/Q is determined by cavity geometry, as a result, its trend can be tweaked by altering the boundary shape. This is part of our plan to approach the ideal case where the R/Q curve is a straight line.

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