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Intensity-sensitive and position-resolving cavity for heavy-ion storage rings

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Abstract

A heavy-ion storage ring can be adapted for use as an isochronous mass spectrometer if the ion velocity matches the transition energy of the ring. Due to the variety of stored ion species, the isochronous condition cannot be fulfilled for all the ions. In order to eliminate the measurement uncertainty stemming from the velocity spread, an intensity-sensitive and position-resolving cavity is proposed. In this article we first briefly discuss the correction method for the anisochronism effect in the measurement with the cavity. Then we introduce a novel design, which is operated in the monopole mode and offset from the central beam orbit to one side. The geometrical parameters were optimized by analytic and numerical means in accordance with the beam dynamics of the future Collector Ring at FAIR. Afterwards, the electromagnetic properties of scaled prototypes were measured on a test bench. The results were in good agreement with the predictions.

Keywords: intensity-sensitive, position-resolving, cavity, storage ring

1. Introduction

Schottky spectroscopy on heavy ions in a storage ring is an important and useful technique for beam diagnostics as well as physics experiments, owing to the information embedded in the noise-like incoherent Schottky signal of

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the charged particles [1]. For instance, in the case of a coasting beam, the longitudinal signal provides information on the revolution frequency and velocity spread of the beam, while the transverse signal contains, in addition, the tune and chromaticity. If a cocktail beam is stored in the storage ring, the revolution frequencies of different nuclides will determine the relationship between their mass-to-charge ratios, given that the contribution from the velocity spread is appropriately counteracted. This can be formulated as [2]

$$\frac{\delta f}{f} = -\frac{1}{\gamma_t^2} \frac{\delta(m/q)}{(m/q)} + \left(1 - \frac{\gamma^2}{\gamma_t^2}\right) \frac{\delta v}{v}, \quad (1)$$

where f is revolution frequency, m/q is mass-to-charge ratio, v is velocity, γ is the corresponding Lorenz factor, and γ_t is the so-called transition energy of the storage ring. By selecting as references certain nuclides whose masses are precisely known, the masses of the remaining ones can be determined accordingly. This is the basic principle of isochronous mass measurements at heavy-ion storage rings.

The Schottky noise can be picked up non-interceptively by means of either the image charge of the beam on a pair of capacitive plates, or the excited electromagnetic (EM) fields inside a radio-frequency (RF) cavity [3]. The major advantage of the latter is owing to its resonance nature, so that the intensity sensitivity is enhanced with respect to the former. This can essentially improve the signal-to-noise ratio of the obtained frequency spectra, and necessitate fewer consecutive frames for averaging so as to reveal a weak signal above the background, which in turn helps improve the time resolving power of the whole detection system.

In 2010, an RF cavity as a Schottky noise detector was installed in the experimental storage ring (ESR) at GSI [4]. Its fast response and single-ion sensitivity has been demonstrated in physics experiments under different conditions: either when the electron cooler is on [5], or when the ESR is operated in the isochronous ion-optical mode [6]. We note that with this resonant device, Schottky spectroscopy in the isochronous mode possesses a competitive mass resolving power compared with the isochronous mass spectrometry (IMS) by

46 using a time-of-flight (TOF) detector. Although the time resolution of 32 ms
 47 is orders of magnitude larger than the IMS with a TOF, this technique is most
 48 suitable for short-lived nuclei in the subsecond regime with a beneficial feature of
 49 simultaneous mass and lifetime measurements. In the future FAIR facility, such
 50 measurements of neutron-rich nuclei will, for instance, have a decisive influence
 51 on modeling the pathway of r-process nucleosynthesis and element abundances
 52 in nuclear astrophysics.

53 In practice, the isochronous condition can perfectly be satisfied for only one
 54 nuclide, whose velocity exactly matches the transition energy of the ring such
 55 that the revolution frequency is not subject to any velocity spread. The other
 56 nuclides deviate from this condition to various extents, owing to their differ-
 57 ent mass-to-charge ratios. As an example, the revolution frequency spread of
 58 anisochronous ions in the ESR can be one order of magnitude worse than for
 59 the isochronous ions. This so-called anisochronism effect limits the measurement
 60 precision, and, also likely, spoils the accuracy. It reflects an intrinsic deficiency of
 61 the technique, and hence cannot be overcome solely with the intensity-sensitive
 62 cavity. If one could obtain for every nuclide the relation between its revolution
 63 frequency and orbit, or equivalently the horizontal position, then the measure-
 64 ment uncertainty stemming from the velocity spread would be eliminated by
 65 assigning a fixed orbit and calculating the corresponding frequency. For this
 66 purpose, an intensity-sensitive and position-resolving cavity is proposed to cor-
 67 rect for the anisochronism effect.

68 **2. Correction for anisochronism effect**

69 During the experiment, the beam is coasting in the storage ring. The detect-
 70 ing cavity picks up the Schottky noise of the beam non-interceptively. Under
 71 the assumption of critical coupling, the power spectral density of the coupled
 72 signal at the n th harmonic reads [4]

$$S(nf) = \frac{Nq^2 f_{\text{rev}}^2 \Phi(f)}{n} Q_l \frac{R_{\text{sh}}}{Q_0}. \quad (2)$$

Here, N is the ion number, q is the ion charge, f_{rev} is the mean revolution frequency, and a normalized distribution function $\Phi(f)$ describes the revolution frequency spread. Besides, Q_l is the loaded quality factor of the cavity, and R_{sh}/Q_0 is the characteristic shunt impedance.

It is clear from Eq. (2) to conclude that the intensity sensitivity is crucially determined by Q_l and R_{sh}/Q_0 . Although Q_l can be raised by adopting a better conductive material for the cavity, from the experimental point of view, a very high-Q cavity is not always favored. Such a cavity will limit the bandwidth of the signal, which is not suitable for the cocktail beam with a great variety of nuclides in a typical mass measurement. As an example, the Schottky resonator at the ESR has a moderate loaded quality factor of 500. Consequently, the major task of cavity design is to optimize the geometry so as to obtain a fairly large R_{sh}/Q_0 . The position resolving capability additionally requires that R_{sh}/Q_0 should have a good gradient along the horizontal direction. Afterwards, the revolution orbits of ions can be distinguished by calibrating the signal against a reference level.

In practice, the reference level is provided by an intensity-sensitive cavity, like the ESR resonator, for which R_{sh}/Q_0 barely changes with horizontal position. Briefly speaking, the intensity cavity ($\parallel$) utilizes the resonant monopole mode such that the electric field strength in the central region exhibits a quite flat trend. The design of the position cavity ($\perp$) is the focus of this work, which will be given in Sec. 3. Suppose that both cavities are tuned to the same harmonic of the Schottky noise, based on Eq. (2), the ratio of coupled signals from two cavities is free of the beam attributes:

$$\frac{S_{\perp}}{S_{\parallel}} = \frac{Q_{l,\perp}}{Q_{l,\parallel}} \frac{(R_{\text{sh}}/Q_0)_{\perp}}{(R_{\text{sh}}/Q_0)_{\parallel}} = K \frac{(R_{\text{sh}}/Q_0)_{\perp}}{(R_{\text{sh}}/Q_0)_{\parallel}}, \quad (3)$$

where K is a constant.

The left hand side of Eq. (3) is obtained from frequency spectra, which is naturally a function of revolution frequency f :

$$\frac{S_{\perp}}{S_{\parallel}} = \mathcal{S}(f). \quad (4)$$

100 The right hand side can be obtained from simulations or benchtop measure-
 101 ments, which show the variation as a function of horizontal position x :

$$\frac{(R_{\text{sh}}/Q_0)_\perp}{(R_{\text{sh}}/Q_0)_\parallel} = \mathcal{R}(x). \quad (5)$$

102 As a result, f and x are related by a gauge function $\mathcal{G}$. While this can symbol-
 103 ically be written as

$$f = \mathcal{S}^{-1}[K\mathcal{R}(x)] = \mathcal{G}(x), \quad (6)$$

104 the detailed procedures of estimating $\mathcal{G}$ have been presented elsewhere [7].

105 After the gauge function for every nuclide is obtained, one can assign an
 106 arbitrary representative position x_{rep} , and accordingly calculate the represen-
 107 tative revolution frequencies $\{f_{\text{rep}}\}$ for all the nuclides by using Eq. (6). These
 108 frequencies will be used for subsequent mass evaluations, following the algorithm
 109 described in [8]. Since the revolution orbit is manually set to the same value
 110 for every nuclide, the evaluated masses will be free of the anisochronism effect.
 111 As a matter of fact, it is not necessary to directly measure horizontal position
 112 for each ion. Obtaining the gauge functions $\{\mathcal{G}\}$ for all the nuclides would be
 113 sufficient to correct for the anisochronism effect.

114 3. Cavity design

115 Owing to the resonance nature, an RF cavity is often preferred for beam
 116 position detection when it comes to low intensity (e.g. [9]) or fine resolution
 117 (e.g. [10]). To date, only the dipole mode has intensively been exploited in
 118 those cavities. Although the electric field exhibits a variation in the central re-
 119 gion, the magnitude is quite small around the standing wave node. Because this
 120 work aims at the detection of a few ions, or even single ions based on the inco-
 121 herent Schottky signal, the dipole mode unfortunately becomes inadequate. To
 122 circumvent this limitation, we proposed a novel design by utilizing the monopole
 123 mode [11]. In order to be position resolving as well, the aperture is deliberately
 124 offset to one side. Consequently, the electric field manifests a fairly large mag-
 125 nitude and gradient in the aperture region, and so does the characteristic shunt

Table 1: Machine parameters of the CR in three isochronous modes. The quantities are calculated for the isochronous ions.

Isochronous mode	I	II	III
Transition energy	1.43	1.67	1.84
Velocity [c]	0.715	0.801	0.839
Revolution frequency [MHz]	0.968	1.084	1.136
Kinetic energy [MeV/u]	400	625	790

impedance. Moreover, the cavity is stretched vertically to obtain a nearly uniform variation of R_{sh}/Q_0 , and thus to reduce the crosstalk between the two transverse directions. A bonus of this design is that it greatly simplifies the subsequent signal processing circuit. A 180° hybrid for elimination of possible contaminations (e.g. [12]) will not be needed since any parasitic mode is already higher-order. Phase correlation with another reference cavity (e.g. [13]) will also not be needed since the magnitude of the coupled signal already contains the position information. In fact, the circuit for the ESR resonator with almost no modifications is compatible with the new position cavity.

3.1. Design considerations

The cavity in this work is envisaged to be installed into the Collector Ring (CR) at the future FAIR facility. The CR is the first storage ring after a synchrotron (SIS100) and a fragment separator (Super-FRS). It will mainly be used to collect and stochastically cool radioactive ion beams and antiprotons [14]. It can also be employed as an experimental site, where exotic nuclei are isochronously stored for mass measurements. In order to be able to cover a wider variety of nuclides, the CR will be operated at three different transition energies upon demand. The machine parameters of the CR in these isochronous modes are shown in Table 1.

Suppose we require that the cavity allows for a competitive mass resolving power $m/\delta m$ of the order of 10^6 with a time resolution of 20 ms. The frequency resolution δf is then 50 Hz, according to the reciprocal relation of the Fourier

transformation. To retain the mass resolving power, the cavity has to resonate at a higher harmonic. The resonant frequency f_0 can be estimated from Eq. (1):

$$f_0 = \frac{\gamma_t^2 m \delta f}{\delta m} = 169.28 \text{ MHz.} \quad (7)$$

Here, the third transition energy in Table 1 is taken for the calculation, since it represents the least favorable scenario.

The single-ion sensitivity places a constraint on the characteristic shunt impedance. Suppose that a single ion with a moderate charge state of 60 is circulating in the CR. The Schottky noise power P of the ion can be calculated from Eq. (2):

$$P = q^2 f_{\text{rev}}^2 Q_l (R_{\text{sh}}/Q_0). \quad (8)$$

This weak signal is in competition with, mostly, the thermal noise. If the magnets of the CR remain stable within 20 ms, then the signal bandwidth of the ion is limited to the frequency resolution, i.e. δf . The thermal noise power P' is therefore given as

$$P' = 4k_B T \delta f, \quad (9)$$

where k_B is the Boltzmann constant, and T is the device temperature, which is assigned to be 295 K. If we require that the signal-to-noise ratio must be at least 4, then R_{sh}/Q_0 can be estimated from Eqs. (8) and (9):

$$\frac{R_{\text{sh}}}{Q_0} = \frac{4k_B T \delta f P}{Q_l q^2 f_{\text{rev}}^2 P'} = 37.7 \Omega, \quad (10)$$

where Q_l is assumed to be 10^3 , and the first revolution frequency in Table 1 is taken for the calculation, again because it represents the least favorable scenario.

The vacuum chamber of the CR at dispersive sections has a big size of 41 cm by 20 cm, which also defines the aperture of the cavity. In this rectangular area, the ions virtually feel a two-dimensional R_{sh}/Q_0 map. The contours of the map in an ideal case where crosstalk does not exist would be straight lines perpendicular to the horizontal direction, otherwise the coupled signal strength depends on the horizontal position as well as the vertical position. Although stretching the cavity can well approximate that, bent contours are inevitable,

Table 2: Design specifications of the position cavity. The last row refers to R_{sh}/Q_0 on the central orbit.

Item	Value	Unit
Aperture width	41	cm
Aperture height	20	cm
Resonant frequency	169.28	MHz
Charac. shunt impedance	37.7	Ω

in particular near the cavity center. In general, the cavity design favors least bent contours, however, this requirement is not as rigorous as the previous two, hence no specific numbers can be assigned beforehand. Table 2 summarizes the design specifications of the position cavity.

3.2. Design optimizations

Inspired by the most common pillbox cavity, we have investigated an elongated shape, i.e. elliptical, for the position cavity [11]. Additionally, a rectangular geometry is also addressed in this work. The descriptions of their shapes and the associated Cartesian coordinates are presented in Fig. 1. Besides, the aperture is offset halfway to the left, and indicated with a dotted rectangle.

The EM fields inside the cavity can analytically be obtained by solving Maxwell's equations in free space with a perfectly conducting boundary. For the rectangular cavity, the electric field in the monopole mode is written as [15]

$$E_z = E_0 \cos\left(\frac{\pi x}{b}\right) \cos\left(\frac{\pi y}{a}\right), \quad (11)$$

where E_0 is a scaling factor. The field has only a longitudinal component. The resonant frequency f_0 is written as

$$f_0 = \frac{c}{2} \sqrt{\frac{1}{a^2} + \frac{1}{b^2}}, \quad (12)$$

where c is the speed of light.

Figure 1: Schematics of a rectangular (a) and an elliptic (b) cavity. The associated Cartesian coordinate system locates in the center with its z -axis pointing to the longitudinal direction. The height is a , width is b , and depth is d . The dotted rectangle shows the planned aperture to allow for beam passage.

In the same vein, the electric field expression for the elliptic cavity is written as (Appendix A in Ref. [16])

$$E_z = E_0 \text{Ce}_0(\nu; u) \text{ce}_0(\theta; u), \quad (13)$$

where ce_0 is the even Mathieu function of order zero, Ce_0 is the even modified Mathieu function of order zero, (ν, θ) are the elliptic coordinates of a point inside the cavity with $\nu \in [0, \text{artanh}(b/a))$ and $\theta \in [0, 2\pi)$, and u is a parameter determined by the eccentricity of the ellipse. The resonant frequency is written as

$$f_0 = \frac{2c}{\pi} \sqrt{\frac{u}{a^2 - b^2}}. \quad (14)$$

Afterwards, the characteristic shunt impedance can be calculated according to the definition

$$\frac{R_{\text{sh}}}{Q_0} = \frac{(\int E_z dz)^2}{2\pi f_0 W}, \quad (15)$$

where W is the stored EM energy inside the cavity. For instance, R_{sh}/Q_0 of the rectangular cavity is written as

$$\frac{R_{\text{sh}}}{Q_0} = \frac{8\mu_0 cd}{\pi \sqrt{a^2 + b^2}} \cos^2\left(\frac{\pi x}{b}\right) \cos^2\left(\frac{\pi y}{a}\right), \quad (16)$$

where μ_0 is the vacuum permeability. In order to quantitatively describe to what extent the contours of the map deviate from a straight line, a parameter called skewness is introduced. Suppose the right edge of the aperture is at $x = x_r$. The rightmost contour that connects the upper-right and lower-right vertices crosses the horizontal central line at $(x_i, 0)$. Then, the skewness s is defined as $s = x_r - x_i$. Recalling the aperture size in Table 2, s of the rectangular cavity, for instance, can be calculated as

$$s = \frac{b}{\pi} \arccos \left[\cos \left(\frac{20.5\pi}{b} - \frac{\pi}{4} \right) \cos \left(\frac{10\pi}{a} \right) \right] - \frac{b}{4} + 20.5, \quad (17)$$

where all the variables are in centimeters.

The optimum dimensions of both cavities are visually selected by inspecting the dependence graphs of f_0 and s on (a, b) shown in Fig. 2. The graphs color-code the magnitudes of resonant frequency and skewness at every possible combination of transverse sizes, where the blank areas denote unfeasible

Figure 2: Dependence graphs of the rectangular (a) and elliptic (b) cavities. A higher f_0 is favored for good mass resolving power, whilst a smaller s is favored for less crosstalk. The blank areas denote unfeasible designs. The blue dots represent the optima, after taking all the constraints into account.

Figure 3: The R_{sh}/Q_0 map of the rectangular cavity in the aperture region, after the beam pipes are integrated. The edges of the aperture are not rounded. The coordinates are relative to the center of the aperture with the same orientation as in Fig. 4.

designs. Finally, the sizes of $(a, b) = (180, 100)$ cm are chosen for the rectangular cavity, which leads to $f_0 = 171.48$ MHz and $s = 2.63$ cm. Similarly, $(a, b) = (190, 110)$ cm are chosen for the elliptic cavity, which leads to $f_0 = 169.76$ MHz and $s = 2.75$ cm. The minimum depth of the cavity can be calculated from the constraint on R_{sh}/Q_0 . The final decision is made on 16 cm for both cavities.

Up to now we have not integrated beam pipes into the cavity. When the pipes are attached, it is better to round the edges of the aperture, otherwise the R_{sh}/Q_0 map could manifest some irregularity. This is owing to the abrupt change of boundary from the cavity to the pipe, which in turn distorts the EM fields' distribution, as demonstrated in Fig. 3. To get such a map, the cavity with two opposite beam pipes is first modeled in the CST MICROWAVE STUDIO[®]. Then the electric field in the monopole mode is numerically computed in a meshed space. Afterwards the characteristic shunt impedance is obtained by virtue of Eq. (15). After some trials, it is found that a rounding radius of 1.2 cm gives rise to a satisfactory R_{sh}/Q_0 map for both cavities. The 3D models of both cavities with rounded edges are schematically shown in Fig. 4.

Figure 4: The 3D models of the rectangular (left) and elliptic (right) cavities that are used in the CST MICROWAVE STUDIO[®]. The edges are rounded by a radius of 1.2 cm.

Figure 5: The R_{sh}/Q_0 maps of the rectangular (a) and elliptic (b) cavities in the aperture region, after the beam pipes are integrated. The edges of the aperture are rounded by a radius of 1.2 cm. The coordinates are relative to the center of the aperture with the same orientation as in Fig. 4.

Figure 6: Combined plots of R_{sh}/Q_0 as a function of y at different x for the rectangular (a) and elliptic (b) cavities. They are extracted from and to be compared with the R_{sh}/Q_0 maps in Fig. 5.

Figure 5 shows the simulated R_{sh}/Q_0 maps. It is clear that the two maps share great resemblance. The characteristic shunt impedance rather uniformly increases from left to right, covering a dynamic range of more than 80 Ω . The contours of the maps are straight at the left end, then gradually bent towards the right end. This can more easily be observed in Fig. 6 where R_{sh}/Q_0 as a function of y at different x is plotted. The good gradient along the horizontal direction ensures the position resolving power of the cavity. Although the low magnitude on the left degrades the intensity sensitivity and the bent contour on the right leads to crosstalk, their effects on the cavity performance are quite limited, because most ions will pass through the center, where R_{sh}/Q_0 exhibits sufficient magnitude and uniformity.

4. Benchtop tests

To check the design concept, we have manufactured a prototype cavity for each geometry. The prototype is scaled down by a factor of four, and so is the aperture. Moreover, the rounding radius of the edges is scaled by the same factor. The resonant frequency is accordingly four times higher, while the characteristic shunt impedance is not affected, as already hinted in Eqs. (12) and (16).

The electric field is profiled by the perturbation method [17] with a ceramic bead whose radius is 2.5 mm. The bead detunes the cavity when it is placed inside. The detuning frequency Δf is related to the field strength E at the bead location [18]:

$$\frac{\Delta f}{f_0} = \frac{\alpha_b E^2}{W}, \quad (18)$$

where α_b is the form factor that only depends on the bead, and W is the stored energy inside the cavity.

Since the exact value of the dielectric constant of the bead is unknown, we have to determine it experimentally. Therefore, a calibration cavity is in addition manufactured, which is a pillbox with a radius of 16.8 cm and a depth of 10 cm. The cavity is almost closed, except for three holes machined in

Figure 7: Setup of the test bench for the prototypes. The origin of the Cartesian coordinates is supposed to be in the center of the beam pipe, but intentionally shifted to outside for better visibility. See the text for more details.

the walls: two of them opposite each other on the circumference are for RF couplers, and the other one on the front face is for the bead. The coupler is based on a BNC connector, on top of which a coupling loop is soldered, such that the magnetic field is picked up. In order to minimize the interference of two couplers, the coupling coefficient is carefully tuned to be negligible. The resonant frequency is then obtained from transmission measurement between those couplers by fitting the resonance curve with a Lorentzian function. The left hand side of Eq. (18) is experimentally obtained, while E and W on the right hand side are analytically computed. Eventually, the empirical form factor is obtained as $3.489(17) \times 10^{-19} \text{ Fm}^2$, which yields a dielectric constant of 13.2(8).

To precisely and efficiently profile the electric field in three-dimensional space, a dedicated automated test bench has been assembled [19]. Figure 7 presents the whole setup and the adopted coordinate system. It mainly consists of a Vector Network Analyzer (VNA) for RF measurements of the cavity under test, a motorized displacement unit with its motor controller for movements of the cavity, a digital multimeter with a thermistor for monitoring the ambient temperature, and a PC for coordination of all the instruments. A massive optical table featuring passive vibration damping acts as a stable base. During the

test, the bead is suspended by a tightened cotton thread, which is fixed to a pair of height gauges on the both sides of the cavity. Once the height is properly adjusted, the bead is kept stationary and the cavity is moved to the assigned positions.

The profiling volume is bounded at $x = \pm 4.5$ cm, $y = \pm 2$ cm, and $z = \pm 5.5$ cm with a mesh size of 5 mm in either direction. In order to minimize the thermal effect on the resonant frequency, every perturbation measurement is preceded by a reference measurement where the cavity is moved by 10 cm away from the bead. The detuning frequency at the reference position is within the measurement uncertainty, and hence believed to be negligible. Afterwards, the characteristic shunt impedance is calculated by combining Eqs. (15) and (18), assuming that the electric field has only a z -component. The measured R_{sh}/Q_0 maps for both prototypes are shown in Fig. 8.

The measured R_{sh}/Q_0 map exhibits, in general, an ascending trend as the x coordinate increases, which agrees with the simulated result in Fig. 5. Meanwhile, an anomalous R_{sh}/Q_0 excess is also noticeable near the edges. This is quantitatively shown in Fig. 9, where the difference between the measured and simulated characteristic shunt impedances at the profiling positions is plotted. The results for both prototypes are quite alike. The cause for the positive difference at $y = \pm 2$ cm as well as $x = 4.5$ cm is an artifact of the measurement method with the bead. The isotropic symmetry of the bead makes it insensitive to the orientation of electric field. Therefore, the total field strength is deduced from the detuning frequency. However, the characteristic shunt impedance within the present context depends only on the longitudinal component. If the electric field lies off the z -direction, the resultant R_{sh}/Q_0 will become apparently larger. From the simulated field plot in Fig. 10, it can be seen that the electric field near the aperture indeed deviates from the z -direction. In order to overcome this limitation, one may use a dielectric needle or disk as the perturbing object to be able to distinguish the field orientation [17]. Such a scheme of the benchtop measurements is under consideration and planned for future work. On the other hand, the negative difference around the center $(x, y) = (0, 0)$ cm

Figure 8: The R_{sh}/Q_0 maps of the rectangular (a) and elliptic (b) prototypes in the aperture region. The coordinates are relative to the center of the aperture with the same orientation as in Fig. 7.

Figure 9: The difference between the measured and simulated characteristic shunt impedances for the rectangular (a) and elliptic (b) prototypes at profiling positions, grouped into 9 horizontal planes. The discussions on the difference are given in the text.

is due to the truncation of the integral extent in the calculation of R_{sh}/Q_0 by using Eq. 15. The profiling volume bounded at $z = \pm 5.5$ cm limits the region of interest and discards the electric field outside. Lastly, the reason for the relatively weak R_{sh}/Q_0 excess at $(x, y) = (4.5, \pm 2)$ cm compared to that at $(2, \pm 2)$ cm is that the electric field lies again close to the z -direction while the truncation effect begins to strengthen there.

5. Conclusion

Schottky spectroscopy at a heavy-ion storage ring in the isochronous mode has a unique advantage of simultaneous mass and lifetime measurements. The precision and accuracy of mass measurements can further be improved by correcting for the intrinsic anisochronism effect. A cavity doublet, which consists of an intensity cavity and a position cavity, is thus introduced to distinguish the revolution orbits of stored ions.

In this article, we have presented a novel design of an intensity-sensitive and position-resolving cavity for the CR at FAIR. The design utilizes the monopole mode, offsets the aperture to one side, and stretches the cavity vertically. Based on this concept, a rectangular and an elliptical geometry have been investigated. First, the dependence graph is adopted to assist with the optimization of cavity size. Then, numerical means are used to account for the beam pipes. The simulated R_{sh}/Q_0 maps for both cavities demonstrate their suitability for meeting experimental requirements. Finally, the benchtop test on the scaled prototypes justifies the design concept.

The design process presented here is intended for, but not limited to, the CR. It can easily be adapted to another cavity in a different ring. We note that apart from the CR, there are a few other heavy-ion storage rings that will be operational in the near future, such as the TSR at ISOLDE [20], the R3 at RIKEN [21], and the SRing at HIAF [22]. These facilities will offer more opportunities to test the position cavity and correction algorithm with radioactive ion beams.

Figure 10: Electric field orientation inside the beam pipe of the rectangular prototype. The upper panel shows the field in the horizontal plane at $y = 0$, whilst the lower panel shows the field in the vertical plane at $x = 0$. The cavity gap is between $z = \pm 2$ cm.

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