Design of Helical Resonator for the Detection of Signal in Penning Ion Trap

Joydip Nandi1*, Ashif Reza2, Anuraag Misra1, Parnika Das1

1Variable Energy Cyclotron Centre, 1/AF Bidhannagar, Kolkata-700064, INDIA.
2Department of Nuclear and Atomic Physics, Tata Institute of Fundamental Research, Mumbai -400005, INDIA
*Corresponding author E-mail: j.nandi@vecc.gov.in

Abstract. Penning Ion trap is an instrument where charged particles can be stored by means of quadrupolar electric field and high magnetic field. Motion of charged particle within the trap electrodes induces weak image signal which is detected by LC resonant circuit followed by a low noise amplifier. To get a large voltage signal, the quality factor of the resonator should be very high. So, a high Q helical resonator is commonly used in ion trapping devices, as it offers considerably high Q (~ 1000) in a small geometry. Resonating frequency of the resonator is selected based on the trap geometry and mass of trapped particle. For ion trapping system we have designed a 20 MHz helical resonator and studied its parameters through simulations.

Keywords: Helical Resonator; Penning Ion Trap; Quality factor; Resonant detection; Transfer function

1. Introduction

Penning Ion Trap (PIT) is a device to confine charge particles and it is being used for studying fundamental properties of atomic nuclei with high precision [1-3]. It is possible to bunch radioactive ion beam, beam purification [4, 5] using PIT. In a PIT, trapped particles can be observed by detecting the image current induced on trap electrodes. In a resonant technique [6-8] a large voltage signal can be developed using a high Q resonant LC circuit, connected at the trap electrodes. The voltage signal is then amplified using a low noise amplifier having high input impedance. In this technique, the resonator is weakly excited using an RF source at its resonant frequency and the trap potential is swept in a desired voltage range. At a particular trap potential, the axial frequency of trapped charged particles coincides with the resonant frequency of the detection circuit which results in resonant transfer of energy from the RF excitation source to the trapped charged particles. Thus a dip in voltage signal at the output of the amplifier will be observed at that particular trap potential. As a high quality factor resonant circuit is required for signal detection in PIT, it is not suitable to use lumped LC resonant circuit for its Q value (less than 200). Quarter wave co axial resonator could be used as it offers much high Q, but physical dimension of a 20MHz coaxial resonator will be large and...
inconvenient for our PIT setup. So, a quarter wave helical resonator has been proposed for PIT set up as it offers Q ~ 1000 in a compact geometry. So, we have designed a helical resonator of 20 MHz resonance frequency with dimensions calculated using Macalpine’s formula [9]. Simulation studies have been done to see the effect on resonating parameter due to different geometrical conditions of the helix, core material of different dielectric property and different dimension of dielectric core etc.

2. Design Parameter

For a resonant frequency of 20MHz and choosing the inner diameter (D) of the outer shield as 100mm, parameters of the resonator is calculated using following Macalpine’s formula

\[ Q = 50Df_0^{1/2}, \quad d/D = 0.55, \quad b/d = 1.5, \]
\[ N = 1900/f_0D, \quad B = b + D/2, \quad d_0 > 5\delta \]

Where D is the shield diameter, \( f_0 \) is resonating frequency, \( d \) is helix diameter, \( b \) is length of the helix, \( N \) is total number of turns, \( B \) is the length of the cylinder, \( d_0 \) is the coil diameter, \( Q \) is unloaded resonating frequency and \( \delta \) is skin depth. All the dimension of helical resonator as mentioned in Macalpine’s formula set is in inches. With \( D = 100 \) mm, design parameter of the helical resonator is given in Table 1 and obtained unloaded Q-value of 880.34 using Macalpine’s formula set. Fig.1 shows the schematic representation of the helical resonator designed. Helix has been symmetrically placed within the cylinder in such a way, so that top and bottom surface of the cylinder will be at a distance \( D/4 \) from the upper end and lower end of the helix respectively.

| Design Parameter                      | Value    |
|---------------------------------------|----------|
| Diameter of the Cylindrical Shield (D)| 100mm    |
| Helix Diameter (d)                    | 55mm     |
| Length of Helix (b)                   | 82.5mm   |
| Axial Pitch of the Helix (\( \tau \)) | 3.437mm  |
| Total Number of Turns (N)             | 24       |
| Length of the Cylinder (B)           | 132.5mm  |
| Coil Diameter (\( d_0 \))            | 2mm      |

Fig. 1: Geometrical structure of the Helical Resonator

3. Simulation and Modeling

A simulation study has been performed using RF simulation package in COMSOL Multiphysics software with Eigen frequency study. Using Perfect Electric Conductor (PEC) boundary condition in
our simulation we obtained resonating frequency for Quarter wave resonator as 20.17 MHz which is in reasonable agreement as per Macalpine formula. PEC boundary conditions generally deal with the zero tangential electric field. However in a practical situation, finite wall conductivity should be considered and it can be incorporated with the impedance boundary conditions (IBC). Then the Q factor was determined with IBC boundary condition. The quality factor is defined as the ratio of stored energy within the resonator to the dissipated energy in each cycle. Energy stored in the resonator is calculated by multiplying the volume integration of square of electric field with resonant frequency whereas the Surface integration of magnetic field multiplied with surface resistance gives the power loss. The helical resonator is air coupled with two SMA connectors where one port is used for excitation and other acts as an output. Lumped port boundary condition has been used to connect the resonator electrically through coaxial cable and the transfer function has been evaluated through adaptive frequency sweeping.

4. Results and Discussion

Simulating the helical resonator model with IBC condition on the wall gives resonant frequency of 20.696 MHz and Quality factor of 997.94. Electric field of this resonator is shown in Fig.2. Electric field at the lower end of the helix where the outer wall is connected with helix is small and it is increasing continuously and reached maximum at the upper end. This Electric field is similar to the lowest harmonics standing wave in a close end tube. The skin depth is 0.0149 mm in copper at 20 MHz which is much lower compared to the size of the coil. We simulated the geometry using certain wall thickness [2mm] in the outer wall and by meshing within the helical domain and layer domain. Resonating frequency and Quality factor is found as 20.16 MHz and 1075 respectively.

![Simulated electric Field of the Helical Resonator at 20.696 MHz](image)

Fig. 2: Simulated electric Field of the Helical Resonator at 20.696 MHz

Maximum size of the mesh element is kept as winding pitch of the helix (τ). Effect of mesh size was studied and we find the frequency variation ~3 kHz within maximum size of mesh element of ±τ. Q-value variation was less than 0.5%.

As the helix to shield capacitance (~ 9.4pF) of the resonator is higher than Self capacitance of the helix (~ 2.58pF), small changes of axial pitch will not disturb the Resonating frequency significantly. Those two capacitance theoretically calculated from the equations as outlined in [10, 11]. If the axial pitch is increased, it will also increase the surface dissipation and causes the degradation of Quality Factor. The effect of different pitch of winding on resonating frequency and quality factor are also studied and given in Table 2. According to this result it is expected that a slight change in Winding pitch during fabrication of the helix will not affect the resonator parameter significantly.
Table 2: Changes of resonating frequency and Quality factor due to different pitch of winding.

| Axial pitch of the Helix (τ in mm) | Resonance Frequency (MHz) | Quality Factor |
|-----------------------------------|---------------------------|----------------|
| 3.437                             | 20.69                     | 997.9          |
| 3.690                             | 20.594                    | 992.8          |
| 3.945                             | 20.693                    | 985.8          |

To study the transfer function of the helical resonator, two SMA ports are included in the simulation model as shown in Fig.3. The transfer function, plotted in Fig.4, shows that the resonating frequency is 20.68 MHz which is in agreement with the Eigen frequency study.

![Fig. 3: SMA connector is added to Helical resonator.](image)

![Fig. 4: Transfer Function of the resonator.](image)

As the helix has to be wound on a dielectric material for stability, effect of the dielectric material was studied. This dielectric material within the cavity will again increase the capacitance and the losses in dielectric material, which in turn will affect the Quality factor. Dielectric core of 2mm thickness (As shown in Fig.5) has
been introduced within this model. To see the effect of the dielectric core, we also studied the resonating frequency for different thickness of the core material (of dielectric constant 2.1) and it is shown in Fig.6.

![Fig. 6: Resonating frequency changes with the thickness of dielectric material.](image)

We also tried to see the effect of dielectric constant on resonator parameter and result is shown in Table-3.

**Table 3:** Changes of resonating frequency and Quality factor due to variation of dielectric constant

| Dielectric Constant | Resonance Frequency(MHz) | Quality Factor |
|---------------------|--------------------------|----------------|
| 2.1                 | 20.394                   | 991            |
| 3                   | 20.194                   | 986.87         |
| 4                   | 19.988                   | 982.49         |
| 9                   | 19.111                   | 962.75         |

5. Conclusion

In this paper, we report on a helical resonator with resonating frequency around 20MHz and Quality factor around 1000. Effect of resonating parameter for the changes of helical pitch, core material, and dielectric constant of core material and the thickness of core material has been studied. A comparative study of our simulation with Macalpine’s formula for a resonator with and without core is shown in Table 4.
Table 4: Comparison of resonator parameter

| Resonator Parameter | Calculation based on Macalpine formula | Simulation (without Core) | Simulation (With 2mm thick Teflon core) |
|---------------------|----------------------------------------|---------------------------|---------------------------------------|
| Resonant Frequency(MHz) | 20                                    | 20.696                    | 20.394                                |
| Quality factor      | 880.34                                | 997.94                    | 991                                   |

A final design for fabrication had been decided based on this study. Fabrication parameters for 20MHz helical resonator having quality factor 991 are as given in Table 5.

Table 5: Design Parameter of 20MHz Helical Resonator.

| Design Parameter                                      | Value               |
|-------------------------------------------------------|---------------------|
| Inner Diameter of the Cylindrical Shield (D)          | 100 mm              |
| Helix Diameter (d)                                    | 55 mm               |
| Length of Helix (b)                                   | 82.5 mm             |
| Axial Pitch of the Helix (r)                          | 3.437 mm            |
| Total Number of Turns (N)                             | 24                  |
| Length of the Cylinder (B)                            | 132.5 mm            |
| Coil Diameter (d0)                                    | 2 mm                |
| Dielectric Constant of core material                  | 2.1                 |
| Outer diameter of the dielectric material              | 53 mm               |
| Inner diameter of the dielectric material              | 51 mm               |
| Height of the Teflon Cylinder                          | 132.5mm             |
| Thickness of Dielectric material                       | 2 mm                |
| Position of connecting end of the coil to the outer shield from the base of the cylinder | 25 mm               |
| Distance of SMA connectors (on the top surface, diametrically opposite) from the axis of the cylinder | 30 mm               |
| Diameter of the hole required on the top surface to mount SMA connector | 5.3 mm               |

Acknowledgement

This work was supported by the COMSOL community for the modeling of the geometry in COMSOL.

References

[1] K.Blaum, “High-accuracy mass spectrometry with stored ions,” Physics Reports, vol.425, pp.1-78, Jan 2006.

[2] G. Gabrielse, L. Haarsma, S.L Rolston, “Open-endcap Penning traps for high precision experiments,” International Journal of Mass Spectrometry and Ion Process, Vol.88, Pages 319-332, April 1989.

[3] J. Dilling, R. Baartman, P. Bricault et. all, “Mass measurements on highly charged radioactive ions, a new approach to high precision with TITAN ” International journal of mass spectrometry, Vol 251, pages 198-203, April 2006.
[4] V.S. Kolhinen, S. Kopecky, T. Eronen et.al., “A cylindrical Penning Trap for isobaric beam purification at IGIOL” Nuclear Instrument and methods in physics, Vol.528, pages 776-787, August 2004.

[5] H.R. Hartmann, D. Beck, G. Bollen, et. al “A cylindrical penning trap for capture, mass selective cooling and bunching of radioactive ion beams” Nuclear Instrument and Methods in Physics research B126, 378-382, 1997.

[6] A. Reza, K. Banerjee, P. Das, “An in situ trap capacitance measurement and ion-trapping detection scheme for a Penning ion trap facility,” Rev. Sci. Instrum, vol. 88, pp.034705, March 2017.

[7] X. Feng, M. Charlton, M. Holzscheiter, R. A. Lewis, and Y. Yamazaki, “Tank circuit model applied to particles in a Penning trap,” J. Appl. Phys. 79(1), 8–13, 1996.

[8] A Reza, A. Misra, S. Sarkar, A. K. Sikdar, P. Das “Development of a Helical Resonator for ion trap application,” 2015 IEEE Applied Electromagnetics Conference, Dec. 2015.

[9] W. W. Macalpine, and R. O. Schildknecht, “Coaxial resonators with helical inner conductor,” Proc. IRE, vol. 47, pp.2099-2105, Dec 1959.

[10] J. D. Siverns, L. R. Simkins, S. Weidt, and W. K. Hensinger, “On the application of radio frequency voltages to ion traps via helical resonators,” Appl. Phys. B, vol. 107, pp.921-934, Jan 2012.

[11] K. Deng, Y. L. Sun, “A modified model of helical resonator with predictable loaded resonant frequency and Q-factor,” Rev. Sci. Instrum, vol. 85, pp.104706, Oct 2014.