



Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Development of an RF resonator for a double junction ion trap

Semester Project

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Abstract

This paper shows complete process of modeling, designing and testing an RF helical resonator suitable for supporting a double-junction ion trap in a cryogenic environment.

Contents

Contents	ii
1 Introduction	1
1.1 Why do we need resonators?	1
1.2 Context of a project	2
1.3 Kinds of resonators	2
1.3.1 Helical	2
1.3.2 RLC	2
1.3.3 Crystal	3
1.3.4 Choosing the right one	3
2 Theory	4
2.1 Helical resonator models	4
2.1.1 Macalpine & Schildknecht	4
2.1.2 Sivers et al.	5
2.2 Comparison	5
3 Design	6
4 Validation	7
5 External circuits & additional features	8
Bibliography	9

Chapter 1

Introduction

Quantum computing is an exciting and rapidly evolving field of a modern science. One of the popular implementations of a quantum computer is based on an ability to control and measure systems of trapped ions. Those ions are typically confined in Paul [6] traps by applying static and high voltage RF signals to trap's electrodes, which on average generates a corresponding stabilizing electric potential.

1.1 Why do we need resonators?

One could potentially couple a radio frequency source directly to an ions' trap. However it imposes the following challenges:

- noise from a source may contribute to heating of trapped ions [9]
- in order to maintain efficient cryostat cooling all internal connections must be manufactured out of materials with low thermal conductivity. Unfortunately following the Wiedemann-Franz law [2] it leads to low electrical conductivity thus resulting in high dissipation of power
- impedance mismatch between source and trap leads to an additional dissipation of RF power

These issues can be avoided by placing an amplifier close to Paul trap, which would filter incoming signal and output it with voltage suitable for operating the trap. Two available options are active and passive amplifiers. Active amplifiers perform better in terms of voltage gain at room temperatures, but cryogenic temperatures do not allow underlying semiconductor technology to function, which leaves us with passive amplifiers (resonators).

1.2 Context of a project

This semester project aims to be a part of an attempt to create a scalable quantum computing architecture by Chiara Decaroli. It provides the following benefits compared to existing solutions:

- using subtractive laser writing to manufacture wafers eliminates misalignment effects
- double junction ion trap was designed for parallel operations, Decoherence Free Subspace (DFS) ion transport across the junctions, and manipulation of long chains of ions
- integrated laser delivery through optical lensed fibers eliminates the need for bulky optics and custom objectives which limit scalability

[TRAP PICTURE HERE]

1.3 Kinds of resonators

Required frequency range limits our selection to the following types of resonators: helical [4] or, for higher frequencies, coaxial, RLC [3], and crystal oscillators. Multiple available solutions require us to do an analysis for a reasoned choice.

1.3.1 Helical

[HELICAL PICTURE HERE]

Helical resonators are commonly selected to be coupled with ion traps due to their high quality factors and ability to operate on high frequencies. It is a perfect option for ion traps operated at room temperatures, since in absence of space constraints they are able to provide Q values of a couple thousands. However in order to achieve those fabrication process needs to be quite precise to avoid reflections of traveling waves which negatively influences overall gain.

1.3.2 RLC

[RLC PICTURE HERE]

RLC amplifiers are a convenient choice for space-bounded environments, such as cryostats. Typical implementation pumps energy between two reactive components — inductor and capacitor. Assembly of RLC circuit is easier than of helical resonator since physical placement of lumped parts does not influence the resulting quality factor. But it also means that quality of these components is a major factor for successful creation. Given that

units' data sheets rarely provide values for cryogenic setup it takes a lot of trial and error to find the right ones.

1.3.3 Crystal

Unlike helical and RLC resonators crystal oscillators do not store energy just in electric field. This type utilizes piezoelectric effect to transform applied harmonic voltage into surface mechanical modes and vice versa.

Narrow excitation spectrum is provided by physical dimensions imposing hard constraints on vibrational oscillations and could have made such device an ideal filtering solution for ions traps. Unfortunately, there are some major downsides that seriously limit its applicability:

- after fabrication resonant frequency can not be widely tuned
- limited stability of the crystal does not allow high voltages

1.3.4 Choosing the right one

In our setup combination of high voltage and frequency values with reasonable constraints on available space makes helical resonator the optimal option. However, difficulties of assembly do not make it a perfect solution in terms of scalability — for a production-grade setup RLC amplifier might be preferred.

Chapter 2

Theory

2.1 Helical resonator models

In order to create a helical resonator satisfying experimental conditions and limitations we inevitably come to a need for a theoretical model that would be able to predict essential characteristics of a resulting unit. The following sections aim to provide an overview and comparison of those.

2.1.1 Macalpine & Schildknecht

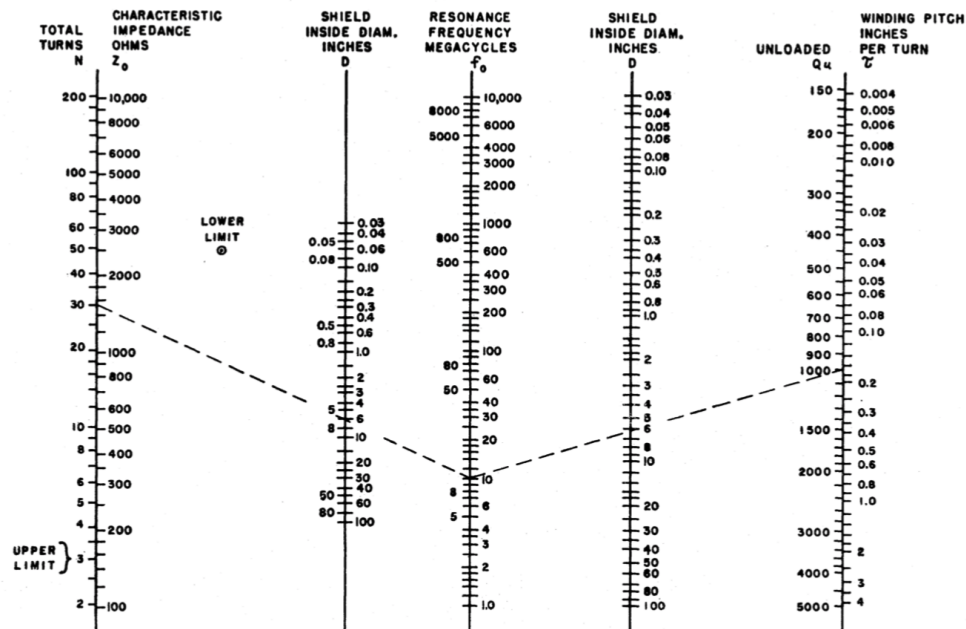


Figure 21: Design chart for quarter-wave helical resonators.

A well-known approach [5] for describing helical resonators was introduced in the same year as Richard Feynman's idea [1] to use quantum systems for computations. It was motivated by the possibility to reduce volume compared to TEM-mode coaxial-line resonators. While skipping a detailed theoretical analysis it nevertheless provides a basis for constructing a resonator: such as regions of usefulness, design considerations and a set of parameters' dependencies maximizing Q .

While describing essential properties of an unloaded helical quarter-wave resonator this paper [5] also predicts shift of resonant frequency if an external load is connected. In order to define new frequency one can make use of telegraph equations [7] by effectively treating the ion trap as a capacitor.

2.1.2 Sivers et al.

Unfortunately modeling ion trap as a pure capacitive load is not always accurate. Introducing resistive losses imposes additional shift of resonant frequency which pushes deviation from self-resonant one even further. It is possible to tune strength of inductive coupling between antenna and main coil to compensate this shift while losing in efficiency.

These limitations of Macalpine's & Schildknecht's [5] model were overcome in a newer paper [8] which takes development of an amplifier specifically for the needs of quantum computing one step further. By taking a look at the joint resonator + ion trap system as a whole it aims to predict effective Q and frequency. This tooling ensures that it's possible to find optimal parameters for given experimental constraints.

2.2 Comparison

Macalpine's and Schildknecht's [5] model gives insides for designing a helical quarter-wave resonator with a given self-resonant frequency. However major shifts from it can be expected when connecting ion trap. Sivers' et al. approach [8] investigates connections between various parameters in the total circuit. As a result one could create a resonator which implements a transfer function closer to a desired one. Considering these benefits a newer model [8] was selected.

Chapter 3

Design

Chapter 4

Validation

Chapter 5

External circuits & additional features

Bibliography

- [1] Richard Phillips Feynman. The Wonders That Await a Micro-Microscope. *The Saturday Review*, pages 45–47, 1960.
- [2] R. Franz and G. Wiedemann. Über die Wärme-Leitungsfähigkeit der Metalle. *Annalen der Physik*, 165(8):497–531, 1853.
- [3] Davide Gandolfi. *Compact RF Amplifier for Scalable Ion-Traps*. PhD thesis, Università degli Studi di Trento and Universität Innsbruck, 2010.
- [4] S. Gulde. *Experimental realization of quantum gates and the Deutsch-Josza algorithm with trapped ^{40}Ca -ions*. PhD thesis, University of Innsbruck, 2017.
- [5] W. W. Macalpine and R. O. Schildknecht. Coaxial Resonators with Helical Inner Conductor. *Proceedings of the IRE*, 1959.
- [6] Wolfgang Paul. Electromagnetic Traps for Charged and Neutral Particles. *Reviews of Modern Physics*, 62(3):531–540, 1990.
- [7] Felix Rohde. *Remote ion traps for quantum networking: Two-photon interference and correlations*. Dissertation, ICFO Barcelona, 2009.
- [8] J. D. Sivers, L. R. Simkins, S. Weidt, and W. K. Hensinger. On the application of radio frequency voltages to ion traps via helical resonators. *Applied Physics B: Lasers and Optics*, 107(4):921–934, 2012.
- [9] Q. A. Turchette, D. Kielpinski, B. E. King, D. Leibfried, D. M. Meekhof, C. J. Myatt, M. A. Rowe, C. A. Sackett, C. S. Wood, W. M. Itano, C. Monroe, and D. J. Wineland. Heating of trapped ions from the quantum ground state. *Physical Review A - Atomic, Molecular, and Optical Physics*, 61(6):8, 2000.



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