# Design of Compact Vacuum Setup for $Al^+$ and $Ca^+$ Ion Trapping with Homogeneous Magnetic Field

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***Summary*—We present our arrangement of new apparatus for trapping $Ca^+$ and $Al^+$ ions. The apparatus consists of a compact vacuum chamber, linear quadrupole trap, one pair of Helmholtz coils, two pairs of saddle coils, and a magnetic shield. The new design respects the requirement of the large optical access for laser beam integration, a homogeneous magnetic field in the position of the ion in the trapping area, and an ultra-high vacuum regime to avoid interactions between residual gas and ions. The new apparatus is designed in a way so that all important subparts can be changed easily and allow us to minimize the time when the inner parts are exposed to the air during a component exchange. All parts of the arrangement, including the quadrupole trap, have been designed and developed by the Institute of Scientific Instruments in Brno, Czech Republic.**

**Keywords—Ion trap, vacuum chamber, homogeneous magnetic field, calcium ions, aluminium ions**

## I. INTRODUCTION

Ion trapping, a fundamental technique of ultraprecise frequency metrology, requires a highly sophisticated experimental vacuum setup. Numerous newly developed advanced techniques for high-resolution spectroscopy with trapped and cooled ions exist. A new trapping apparatus with improved properties must also be developed to apply these techniques. After many years of working with trapped and laser-cooled $Ca^+$ ions and developing improved methods for ultra-precise spectroscopy and frequency metrology, we went on to design and develop new apparatus that would exploit newly developed techniques that are nowadays limited by our current setup [1].

The view of the new arrangement and current setup is in Fig. 1. When comparing both apparatuses is evident that significant improvements have been made in terms of the dimensions of the vacuum chamber and the magnetic shielding. It increases efficiency in shielding the external magnetic field, allowing for more precise measurements and higher performance in frequency metrology.

As a source of atoms for the ion trap, a combination of a resistively heated oven is available to allow high-current evaporation of calcium, and the assembly is also ready to use a laser ablation method to generate both calcium and aluminium atoms. The combination provides a wide range of possibilities for experiments with Coulomb crystals. Atoms are subsequently ionised in the trapping region by appropriate lasers.

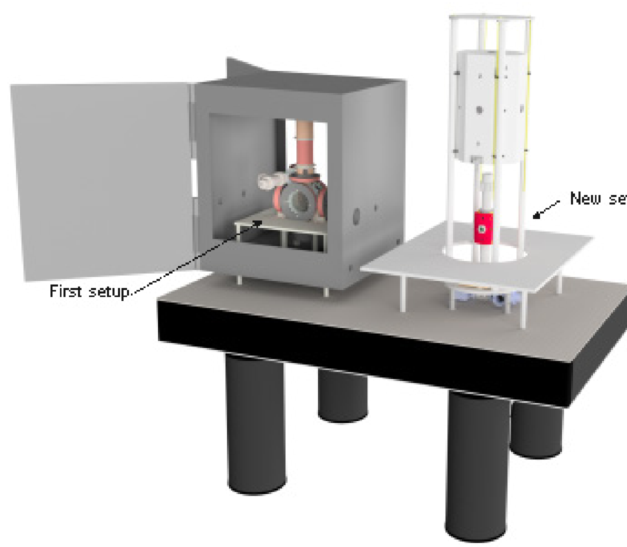


Fig. 1. Comparison of our current setup (on the left) and the new design (on the right).

## II. DESIGN DESCRIPTION

### A. Ion trap

The ion trap (Fig. 2), a key component of our setup, is made from high-quality materials emphasising structural quality and functional properties. A solid titanium body is bonded to sapphire blocks to create a strong and precise structure. Its linear shape presents a quadrupole structure, which includes four blades and two hollow endcaps. This design has been carefully engineered to maximize the efficiency and accuracy of the ion trap.

All electrodes are coated with a layer of gold to increase conductance for RF drive and thus reduce electrical noise that could negatively affect the accuracy of our measurements.

Using a titanium body in conjunction with sapphire blocks ensures the stability of the ion trap. The combination of materials was chosen with low thermal expansion in mind. Sapphire provides an excellent combination of electrical insulation and thermal conductivity to transfer excess heat from the trap. This combination of materials ensures the longevity and stability of the ion trap, which is key to achieving accurate and repeatable results in our ultra-precise frequency metrology.

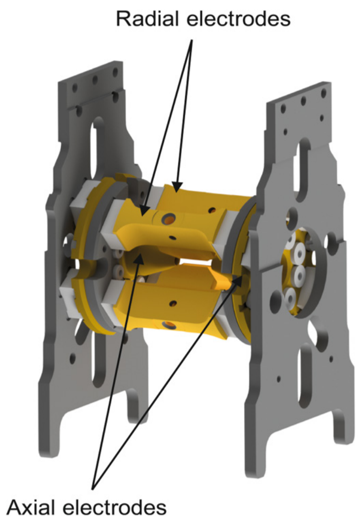


Fig. 2. Model of the ion trap.

### B. Vacuum chamber

The main part of the ion trap is in the middle of the magnetic shielding to ensure optimal conditions for ion trapping and measurement with ions. The chamber part of the trap is designed and fabricated from high-quality titanium [4] to maintain a homogeneous magnetic field and suppress residual fields from the chamber body.

The titanium part of the chamber (Fig. 3) is equipped with windows for photons from the ions and optical accesses for positioning the laser beams in all available directions. This configuration allows efficient collection and detection of photons generated by the ions, essential for accurate measurements of their properties and interactions. The optical approaches also provide flexibility in the placement of the laser beams, allowing various ion manipulations to be performed with high precision and control.

The small size of the ion trap chamber is also an important factor, allowing ultra-high vacuum pressures to be achieved. During initial tests, we achieved pressure values below $10^{-11}$ mbar, which is the measurement limit of the ion pump that is an integral part of our setup. This extreme vacuum level is key to minimizing collisions between ions and residual gas, which contributes significantly to our measurement setup's high accuracy and reliability.

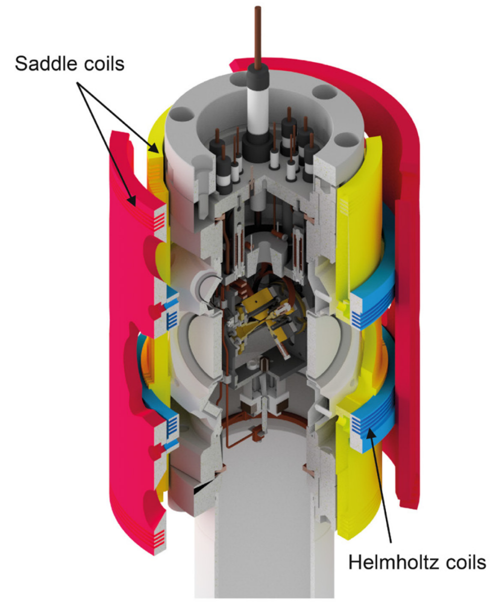


Fig. 3. Details on the inside of the vacuum chamber and on the coils.

### C. Magnetic shielding

The vacuum chamber was designed with an emphasis on compactness leading to a significant reduction in the size of the magnetic shielding. The shielding, which consists of three layers of mu-metal sheet, was optimized to have a minimal dimension, not affecting the magnetic field of designed coils while maximizing the shielding effect (Fig 4). Due to the designed dimensions of the shielding, we performed all-optical mountings outside the shielding. This solution gives us the advantage of not opening the shield when handling optical components.

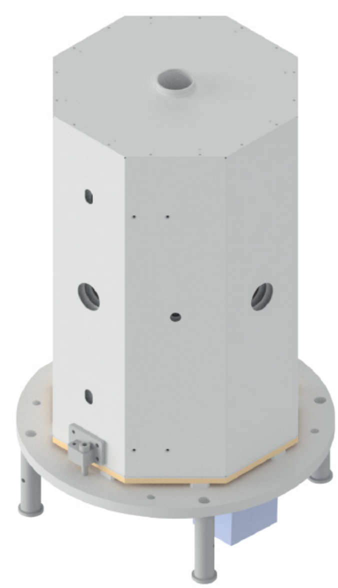

Fig. 4. Assembly covered by 3-layer magnetic shielding.

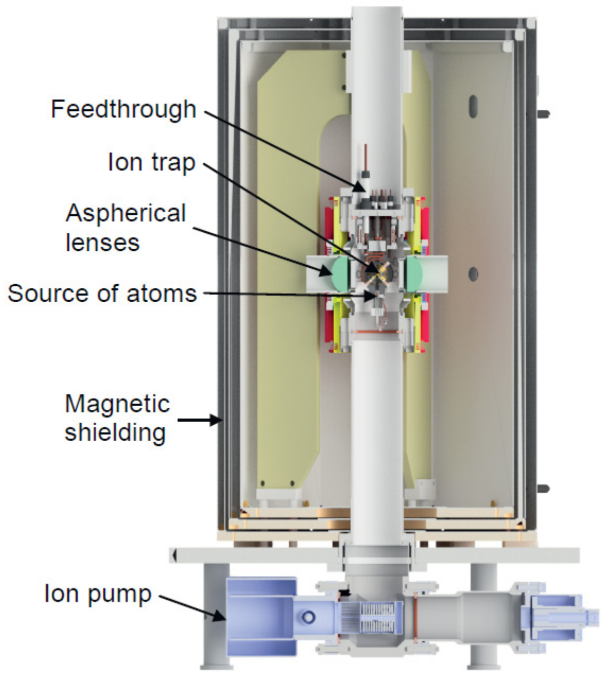


Fig. 5. Entire assembly cross-section view.

### D. *Coils for generating magnetic field*

The traditional way to generate a homogeneous magnetic field in the ion trap's centre is to use one pair of Helmholtz coils for each axis. This arrangement requires a larger space, increasing the dimension of surrounding magnetic shielding and decreasing the interrogation lasers' optical access.

In our case, the magnetic field is generated by 3 pairs of coils, 1 pair of Helmholtz coils, and 2 pairs of saddle coils (Fig.3). The saddle coils allow us to minimize their size as their shape follows the shape of the vacuum chamber [2] [3]. With this arrangement, we can independently control the magnetic field on each axis. Simulations were used to determine the minimum distance between the coils and the shielding to ensure that the field homogeneity was not significantly affected.

### E. *Source of atoms*

To ensure a sufficient source of atoms for the ion trap, we use a combination of techniques that allow the efficient generation of calcium and aluminium ions. As a first source of calcium atoms, we use a resistively heated oven that is designed for high electric current-driven calcium evaporation. This method allows controlled heating and evaporation of calcium, generating a beam of calcium atoms that are subsequently ionized in an ion trap.

A laser ablation method is used to extend the atom generation capabilities. Unlike the resistively heated oven, this method also allows the generation of aluminium atoms, which would be difficult to generate by the first method due to the high evaporation temperature of aluminium. This method uses an intense laser beam to vaporize the material from the target surface. The method focuses on generating calcium and aluminium atoms by laser ablation, where targets comprise pure calcium and aluminium materials. The determined parameters of the laser beam, such as power and pulse repetition frequency, are adjusted to allow efficient ablation of the material and the generation of atoms, which are then trapped and manipulated in an ion trap.

## III. MAGNETIC FIELD SIMULATIONS

A magnetic field simulation is a key tool for analysing and optimizing the magnetic properties of our apparatus. When properly configured for their dimensions, both types of coils (Helmholtz and saddle coils) produce a homogeneous magnetic field in the region between the coils on an axis passing through the centre of the coils.

The computed simulation showed us the magnetic field strength on the axis passing through the centres of the coils, as shown in Fig. 7. The homogeneity in the region of trapped ions is important for experiments. By optimizing the coil parameters, sufficient homogeneity in the required area can be achieved, as shown in Fig. 8

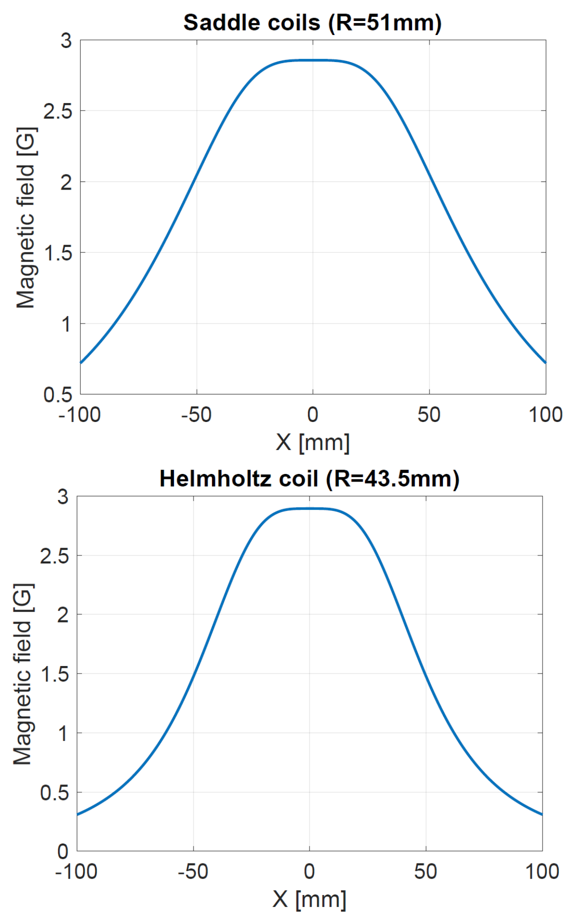


Fig. 6. Simulation of a magnetic field of Helmholtz and saddle coils. In ion trapping area is achieved a homogeneous magnetic field.

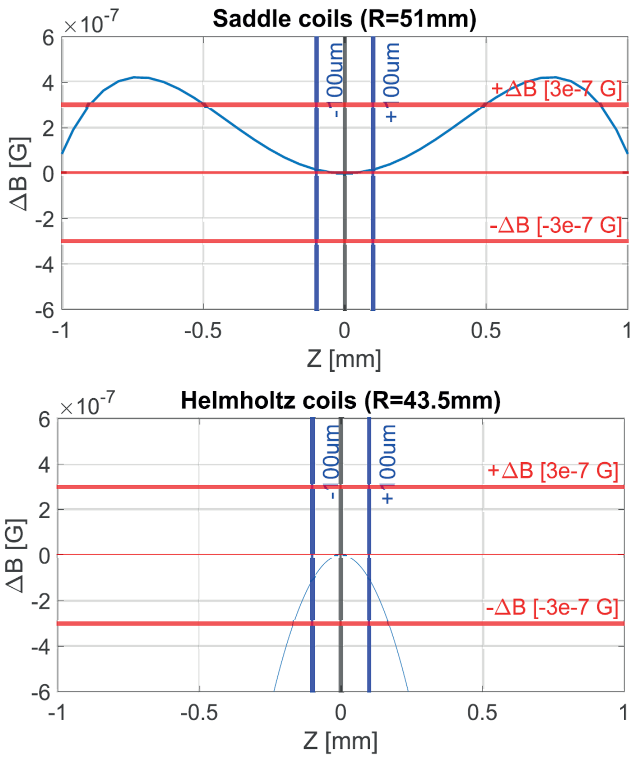


Fig. 7. Detail of magnetic field in the ion trapping area. The calculation was made with the positions of the designed coil threads.

## IV. Conclusions

We have designed a compact assembly for trapping $Ca^+$ and $Al^+$ ions, consisting of a vacuum chamber, a linear quadrupole trap, a magnetic shield, coils and other important components. The vacuum chamber has been designed to achieve the lowest possible pressure, which is crucial to ensure optimal conditions for ion trapping and accurate ion measurement.

An important part of our development was in computational simulations that allowed us to optimize the characteristics of the magnetic field inside the chamber. The simulations provided important information about the magnetic field distribution. It allowed us to optimize the arrangement of the coils and magnetic shielding to achieve a homogeneous and stable magnetic field.

Some parts of the apparatus have already been fabricated and tested, particularly tests to achieve ultra-high vacuum. The remaining parts are already in production and are about to complete the whole experimental apparatus.


## Acknowledgment

The work has been performed within the project 20FUN01 TSCAC. Project 20FUN01 TSCAC both have received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme. The research was also supported by the project: CZ.02.1.01/0.0/0.0/164026/0008460 (MEYS CR).


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