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ELECTROMAGNETIC ANALYSIS OF A CIRCULAR STORAGE RING FOR QUANTUM COMPUTING USING Vsim

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Abstract

We discuss design considerations for a circular ion trap based on electromagnetic and particle beam simulations. This is a circular radiofrequency quadrupole (rfq) being designed for quantum information applications. The circular rfq should have good electromagnetic properties to accumulate and store the beam for prolonged times, while providing apertures for laser cooling and lower voltage electrodes to provide control over the beam. We use the electromagnetic and particle-in-cell software VSim, which uses finite difference time-domain and particle-in-cell methods, together with high performance computing tools

INTRODUCTION

Trapped ions are a useful research tool enabled by electromagnetic ion traps [1–3]. Ion traps are devices that use electromagnetic fields and lasers to control and manipulate individual or bunched ions [4]. In the same fashion, storage rings use electromagnetic fields to store beams of charged particles in a closed path. We are building upon the idea of using a compact circular storage ring for quantum computing applications [5]. The storage ring quantum computer (SRQC) is an ion trap concept in a rotating frame. This main difference from most conventional ion traps [1–3] allows to potentially store orders of magnitude more ions, which presents interesting possibilities for quantum information technologies. Together with the unprecedented number of ions that can be stored in a device like SRQC, and the possibility of storing multiple ion chains for parallel quantum computing, the use of ions as qubits allows for longer coherence times. Quantum decoherence is one of the main limitation of the current state of quantum technologies.

Ion Crystals for Quantum Computing

The dynamics of individual ions in the beam is driven by the trap produced fields and by Coulomb forces. For the SRQC application, the beam thermal energy needs to be sufficiently reduced to a level where internal and external quantum states of individual ions can be measured. Once an ion beam is stored in the SRQC, controlled laser pulses can be directed into the device for cooling via Doppler cooling [6]: ions absorb and re-emit photons of specific frequencies, resulting in a lower energy-state of the ion [4]. By sequentially cooling the beam below the Doppler limit, the thermal motion of the beam gets reduced and the Coulomb interaction becomes the dominant inter-ionic force. Ions arrange themselves into a crystalline beam state [7], where they oscillate around their equilibrium positions. If the crystalline beam is further cooled so that phonon modes can be measured, an Ion Coulomb Crystal (ICC) state can be formed. The SRQC concept is based on using the external and internal quantum states of ICC as qubits, where the internal modes are the hyperfine spin states and the external modes are the phonon modes of the ICC [5].

Because of the unprecedented number of ions[1] that can be potentially trapped in the SRQC, the controls engineering concerns need to be studied for SRQC from conception. We recently explored applications of Artificial Intelligence (AI) into the control of an ICC [8], in particular to determining the equilibrium positions of ions in a 1D ICC. We are exploring similar techniques for the accurate timing of laser pulses to the specific cooling needs of the ICC.

The use of a storage ring for trapping an ion crystalline beam was investigated before. The experiment, PAul Laser cooLing Accelerator System (PALLAS), stored beams of $^{24}Mg^{+}$, and cooled it enough to produce a crystalline beam [9]. For the SRQC, we aim at producing Ion Coulomb Crystals.

EM SIMULATIONS WITH VSIM

We use VSim [10, 11] for the electromagnetic analysis of an SRQC trap concept. The SRQC concept has two pairs of inner electrodes to tailor a quadrupolar electric field that

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[1] Conventional ion traps usually manipulate a few dozen ions.

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helps focus the beam transversely. In the longitudinal direction, the beam is not bounded, but radiofrequency potentials can be introduced to break the beam into many parts, opening the possibility to parallel computing [5].

We use VSim to calculate electromagnetic field pattern produced specific trap dimensions. Figure 1 shows the transverse profile of an SRQC concept for preliminary analysis, it shows three main elements, the four main electrodes driving the radiofrequency fields, control conducting rods (gold) and ceramic frame (white) for mechanical support.

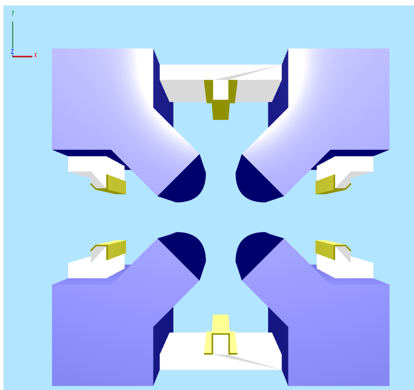

Figure 1: Transverse cross section of the SRQC concept showing the driving electrodes (gray), the control conductors (gold) and ceramic frame (white).

Note the control conductors are shaped such that there is an opening gap in the horizontal plane. This gap is important as it permits the laser pulses to interact with the beam inside the SRQC for cooling and manipulation.

We model the main electrodes and the control rods as perfect electrical conductors. An alternating voltage drives the main electrodes so as to produce the required quadrupolar field. We use 10 V at the control rods to introduce multipolar components into the simulation that can be used for correction and control of the beam. Figure 2 shows the resulting electromagnetic pattern of the SRQC, where the lines indicate equipotentials.

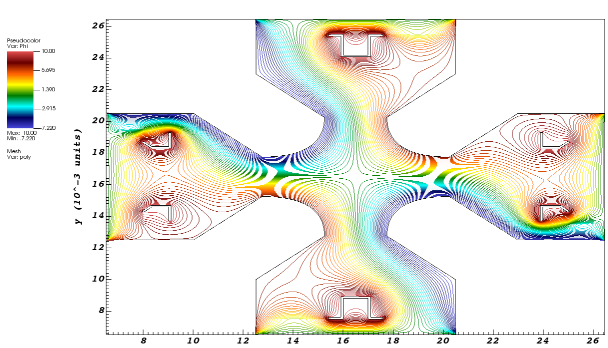

Figure 2: Equipotential map of the SRQC preliminary concept.

COMMENTS

We are exploring multiple aspects of a storage ring quantum computer framework, the applications of AI towards future controls of SRQC and now a preliminary design concept of the SRQC ion trap. Using VSim for electromagnetic and particle simulations, we are optimizing the main geometric dimensions based on expected conditions. We are planning to use beam simulations with VSim to evaluate the stability of the system. Additionally, we are interested in modeling the cooling and formation of the ICC with computational tools. These efforts represent on-going work.

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REFERENCES

[1] W. Paul, "Electromagnetic traps for charged and neutral particles", *Rev. Mod. Phys.*, vol. 62, no. 3, pp. 531-540, Jul. 1990. doi:10.1103/RevModPhys.62.531

[2] D. F. V. James, "Quantum dynamics of cold trapped ions with application to quantum computation", *Appl. Phys. B*, vol. 66, pp. 181-190, 1998. doi:10.1007/s003400050373

[3] L. S. Brown and G. Gabrielse, "Geonium theory: Physics of a single electron or ion in a Penning trap", *Rev. Mod. Phys.*, vol. 58, no. 1, pp. 233-311, Jan. 1986. doi:10.1103/RevModPhys.58.233

[4] C. J. Foot, *Atomic physics*, Oxford, UK: Oxford University Press, 2007.

[5] K. A. Brown and T. Roser, "Towards storage rings as quantum computers", in *Phys. Rev. Accel. Beams*, vol. 23, no. 5, pp. 054701-054716, May 2020. doi:10.1103/PhysRevAccelBeams.23.054701

[6] W. Itano, J. Bergquist, J. Bollinger, and D. Wineland, "Laser Cooling of Trapped Ions", in *Proc. of Enrico Fermi Summer School, Laser Manipulation of Atoms and Ions*, Varenna, Italy, Jul. 1991.

[7] M. Drewsen, "Ion Coulomb Crystals" in *Physica B*, vol. 460, pp. 105-113, Mar. 2015. doi:10.1016/j.physb.2014.11.050

[8] B. Huang *et al.*, "Artificial intelligence assisted design and virtual diagnostic for the initial condition of a storage-ring-based quantum information system", *IEEE Access*, vol. 10, pp. 14350-14358, Feb. 2022. doi:10.1109/ACCESS.2022.3147727

[9] U. Schramm, T. Schätz, M. Bussmann, and D. Habs, "The quest for crystalline ion beams", *Plasma Phys. Controlled Fusion*, vol. 44, pp. 375-387, Nov. 2002.

[10] C. Nieter and J. R. Cary, "Vorpal: A versatile plasma simulation code", *J. Comput. Phys.*, vol. 196, pp. 448-473, May 2004. doi:10.1016/j.jcp.2003.11.004

[11] VSim, https://txcorp.com/vsim/.