R&D Theme

Research and development for photonic interconnects of ion traps

Progress until FY2022

1. Outline of the project

To realize a large-scale quantum computer using ion traps, this theme pursues quantum photonic interconnects of ion traps. The core of this project is the development of a device that integrates a micro-optical cavity and a linear ion trap. The micro-optical cavity is required for coupling ions and photons, while the linear ion trap is for trapping multiple ions in an array (Fig. 1). Quantum photonic interconnects will be possible only when these are realized simultaneously in a single device.

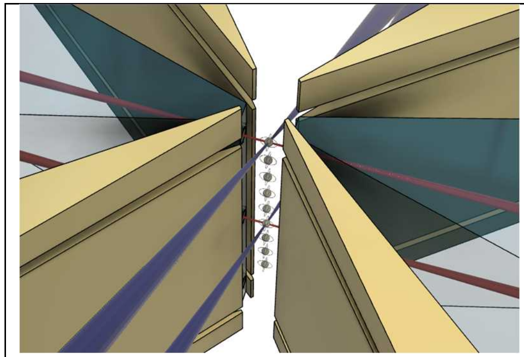


Fig.1 Schematic for an optical cavity-integrated ion trap

We also work on other themes such as enhanced ion-photon coupling using Ba^+ ions and development of an optical cavity using semiconductor mirrors.

2. Outcome so far

A three-dimensional linear ion trap was fabricated using a technique called selective laser etching (SLE). The SLE is a laser-based 3D printing technique that can be used to cut arbitrary three-dimensional structures out of glass. An electrode was created by depositing metal on the surface of the glass structure created in this way, and the ion trap was completed (Fig. 2).

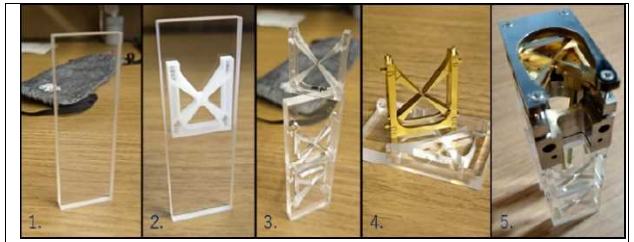


Fig.2 Fabrication of an ion trap using SLE

With an ion trap fabricated in this way, we successfully trapped and laser-cooled a string of ions (Fig. 3).

For the experiment using Ba^+ ions, we evaluated the performance of high-reflectivity mirrors at a wavelength of 493 nm which is the transition wavelength of Ba^+. It was reported that mirrors in the UV and visible ranges would degrade over time in vacuum. By constructing an optical cavity at 493 nm in vacuum and measuring its finesse for a long period of time, we confirmed that such degradation does not happen.

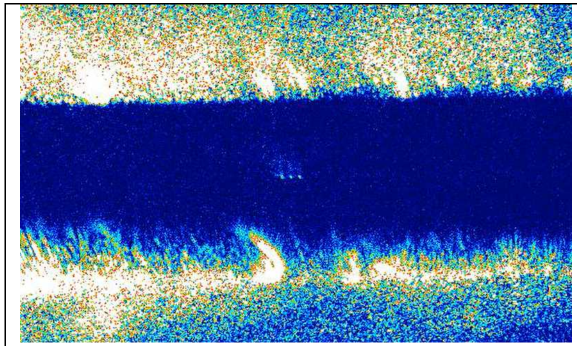


Fig.3 Image of trapped ions in the SLE-made ion trap

The use of semiconductors is expected to avoid the deposition of stray charges on the mirror surface. We have established a technique to form patterned metal electrodes on a semiconductor mirror (Fig. 4)

Fig.4 Patterned electrodes on semiconductor DBR

3. Future plans

We integrate optical cavities in ion traps and aim to couple single ions to the optical cavities.

R&D Theme

Superconducting circuit ion traps with low-vibrational cryostat

Progress until FY2022

1. Outline of the project

Ion trap quantum computers are based on uniform qubits prepared in vacuum and ultra-precise manipulations have been achieved. However, even higher precision must be achieved for the fault-tolerance. In this theme, we will develop superconducting-circuit ion traps. Ion trapping at cryogenic temperatures has been studied as a stage for high-performance ion traps due to improvements in electrical noise and vacuum. Furthermore, by incorporating superconducting microwave circuit technology, we will construct a high-performance ion trap system that combines low power consumption and high-precision operation.

2. Outcome so far

1. Basic technologies required for cryo-ion trap

We first developed a low-vibration refrigerator, whose vibrations were evaluated to be less than 100 nm relative to an optical table. An imaging system was also developed to microscope the ions inside the refrigerator from the outside with multiple radiation shielded windows.

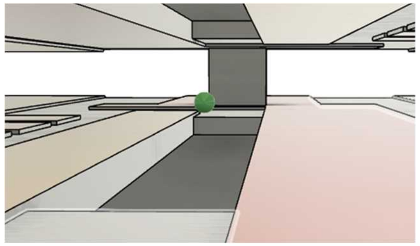
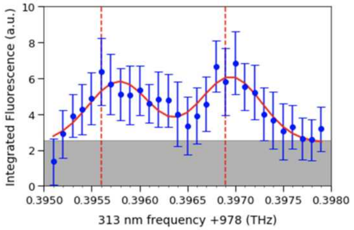


Fig. 1 Microfabricated superconducting ion trap



Fig, 2 Beryllium ion spectrum with laser ablation

2. Stable atomic source with a laser ablation

low-heat atomic sources based on laser ablation have been used for cryo-ion trap. However, it is difficult to achieve stable atomic flux with laser ablation. We achieved a stable atomic source of beryllium using a nanosecond ultraviolet laser and beryllium oxide. Figure 2 shows the spectrum of beryllium ions produced by this atomic source.

3. Superconducting circuit for ion traps

We have developed a compact superconducting circuit for microwave control of trapped ion qubits with followed characteristics:

a. Low impedance resonator with large capacitance
b. Small footprint for the integration into trap electrodes
c. High Q-value at 4-6K

Figure 3 shows a interdigit superconducting Nb circuit.

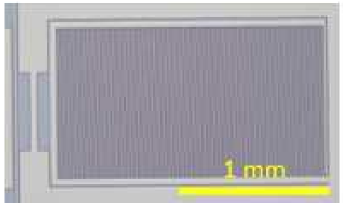


Fig. 3 Low impedance superconducting circuit

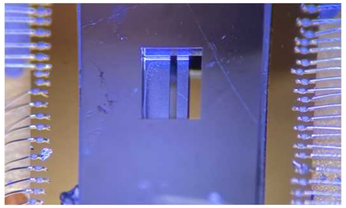


Fig. 4 Flip-chiped circuits

4. Flip-chip integration

Superconducting circuits are integrated two-dimensionally on a silicon substrate. We use flip-chip method to achieve strong confinement of ions and a strong microwave field with a 2D circuit. We have developed substrate fabrication and assembly techniques for this purpose. Figure 4 shows a flip-chip mounted superconducting circuit.

3. Future plans

We will realize a cryo-ion trap and to integrate the various technologies to realize a superconducting-circuit ion trap. By applying a large magnetic field gradient to ions in a superconducting circuit, ultra-precise quantum state manipulation can be achieved without the use of lasers. Furthermore, we will identify and overcome the implementation issues by integrating the ion trap optical connection technology developed in other themes.

R&D Theme

Quantum Error Correction Using the Phononic DoF

Progress until FY2022

1. Outline of the project

The realization of error-corrected logical qubits and operations between them is the key to performing useful quantum computation. The system of vibrational modes in ions is a good candidate for the realization of logical qubits. Using stimulated Raman transition to realize beam-splitter interactions between collective vibrational phonon modes and thereby realizing quantum entanglement between phonon modes are important steps to realize operations between logical qubits. Such entanglement manipulations for multiple modes and squeezed states can be used to generate continuous-variable cluster states. Furthermore, by preparing bosonic codes as vibrational states of ions and utilizing the beam-splitter interaction described above, it is possible to implement gate operations across multiple modes.

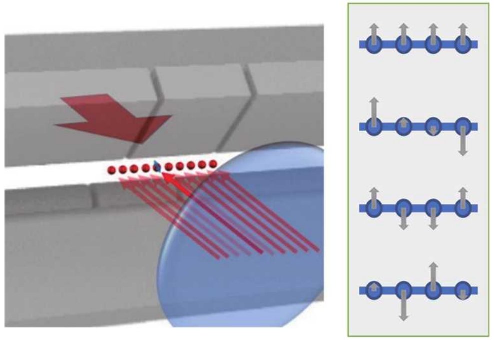


Fig. 1: (left) Excitation of radial vibration modes by counter-propagating laser beams, (right) radial collective vibration modes of an ion array.

2. Outcome so far

To generate states that can be used for error correction in vibrational modes, experiments were conducted to generate vibrational squeezed states using reservoir engineering (Figs. 2 and 3). Figure 2 shows the blue-side band Rabi oscillation results for the squeezing parameter $r = 0.00$, i.e., no squeezing at all (vibrational ground state), and shows the shape of a damped oscillation. On the other hand, Figure 3 shows the experimental results for the squeezing parameter $r=0.86$, which reflects the characteristics of blue-sideband Rabi oscillation for the squeezed state.

In this regard, improvement of the vibrational state coherence is considered necessary to obtain even higher fidelity. In addition, we have already realized a beam-splitter interaction between vibration modes, and it is considered necessary to improve the vibrational state coherence in the same way to improve the fidelity of the beam-splitter interaction. In this study, we evaluated the vibrational state coherence and obtained a value of 1.5 ms as the decay time of the vibrational state Ramsey interference. In the future, it will be necessary to improve this value by about one order of magnitude, and possible measures include improving the accuracy of AC voltage amplitude stabilization for trapping in the radial direction, using modes other than the center-of-mass mode, and using an axial vibration mode. We are currently preparing for these measures.

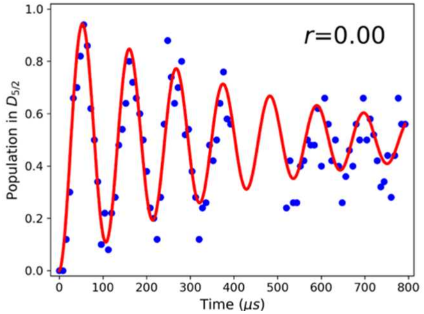


Fig. 2: Results of blue-sideband Rabi oscillation measurements for the squeezing parameter r=0.00.

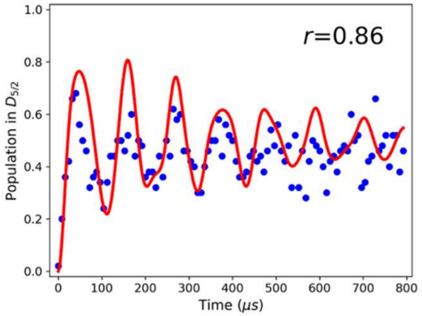


Fig. 3: Results of blue-side band Rabi oscillation measurements for the squeezing parameter r=0.86.

3. Future plans

We will realize EPR (Einstein-Podolsky-Rosen) type quantum entangled states by mixing squeezed states prepared between multiple vibrational modes through beam-splitter interactions. In addition, we will encode a single qubit for a single vibrational mode with a bosonic code. We will also prepare code states for multiple vibrational modes and apply beam-splitter interactions between modes to achieve quantum gate operations for bosonic codes spanning multiple modes.

R&D Theme

Fabrication and evaluation techniques of high-performance ion traps

Progress until FY2022

1. Outline of the project

To realize ion-trap modules for photonically-interconnected ion-trap quantum computing novel approaches have to be implemented to ion traps. The approaches include ion-photon quantum interconnect, microwave-based qubit control and quantum encoding to phonons. The goal of our R&D theme is to develop ion-trap fabrication and evaluation techniques to enable these approaches. We also try to join other ion-trap research groups in Japan to the development cycle of the fabrication and evaluation by distributing more versatile trap samples and by obtaining feedbacks.

2. Outcome so far

While 3D ion traps provide stronger ion confinement and immunity to field disturbances by mirrors for the ion-photon interconnect, planar traps have an advantage of accommodating complex functions such as junctions. We are developing both traps in parallel.

A 3D ion trap consisting of AlN substrates has been fabricated successfully. The trap is expected to suppress heating of phonon modes due to excellent thermal conductivity. It was found, however, in a more detailed inspection that some electrodes facing the ions contact neighboring ones. The problem has been solved by improving the fabrication process, and the improved trap is ready for evaluation with ions (Fig. 1).

Planar traps fabricated with silicon substrates have successfully trapped ions. To simplify their assembling by users we have fabricated a vacuum package which enables plug and play assembling of trap chips in a collaboration with another project and Japanese companies. It will be available to user inside and outside of the project soon.

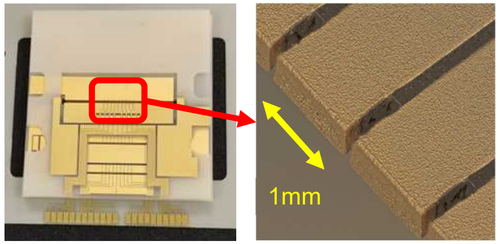


Fig.1 3D trap fabricated with AlN substrates.

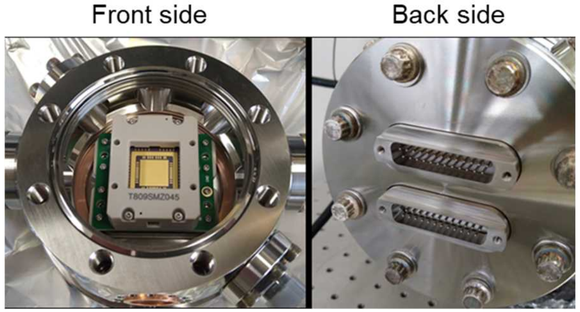


Fig. 2 Planar trap vacuum package.

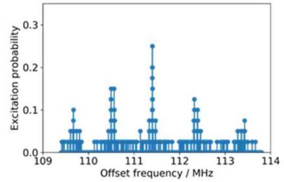


Fig.3 Excitation spectrum of the clock transition of a single $^{174}\mathrm{Yb}^+$

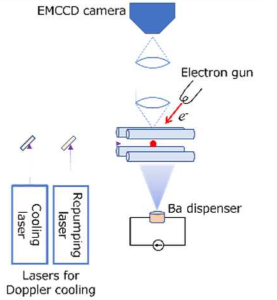


Fig.4 Planar trap evaluation testbed with Ba^+ under development.

Two groups have jointed our R&D theme to accelerate the trap development cycle. The first group uses Yb^+ to test 3D traps. Cooling near to the Lamb-Dicke regime has been achieved (Fig.3). The second uses Ba^+ for the planar trap evaluation (Fig.4).

3. Future plans

The fabricated traps will be supplied to the project groups for trap performance test. The vacuum package will be updated with an extended collaboration with Japanese companies to supply to groups inside and outside of the project. In the Yb^+ trap evaluation $^{171}\mathrm{Yb}^+$ will be deployed as a qubit. In the planar trap evaluation with Ba^+ basic performances of the supplied trap will be investigated. Our goal is to develop fabrication and evaluation techniques to realize ion-trap modules for ion-trap quantum computing in collaboration with project groups and companies in Japan.

国立研究開発法人
科学技術振興機構
Japan Science and Technology Agency

R&D Theme

R&D for Cloud Quantum Computing

Progress until FY2022

1. Outline of the project

We will implement automation and remote operation technologies that are essential for the cloud computing of ion trap quantum computers and create an environment where small-scale quantum computers can be used remotely by educational institutions and other organizations. To this end, we will greatly improve the reliability of basic ion control technology and enable all series of operations in experiments (e.g., ion loading, laser cooling, gate operation, etc.) to be performed remotely. Furthermore, we will realize a quantum computer with a relatively small number of ions (on the order of 10) using established ion internal state qubits and provide an environment in which these can be operated remotely. In addition, as fundamental technology development to improve the performance of the cloud-based ion trap quantum computer, we will conduct ion transport experiments to integrate the ion trap module and two-dimensional ion array experiments to expand the number of qubits.

2. Outcome so far

For the cloud-based ion trap quantum computer, we set up the ion trap system. For the ion trap system used for laser cooling, a machined 3D linear trap, an atomic oven, and other equipment were installed in the vacuum chamber (Fig. 1), and the entire vacuum system was baked and the optics and optical components for cooling were placed on the optical table (Fig. 2). Frequency stabilization of the semiconductor laser source (935 nm) for cooling was also performed. Using an optical frequency comb generator as a reference for frequency stabilization and evaluating the frequency with an optical wavelength meter, we found that the fluctuations were within 1.6 MHz during 40 h of operation. This indicates that the continuous operation time and stability are sufficient to withstand operation in cloud computing for more than 24 hours. In addition, we have designed and installed optics for stimulated Raman excitation, stabilized the repetition rate of a picosecond pulsed laser, which is necessary for stable qubit control using the stimulated Raman transitions, and succeeded in phase-locking a beat signal around 1 GHz. In the future, we will modify the pulsed laser to perform phase locking on beat signals corresponding to hyperfine structure spacing (around 13 GHz).

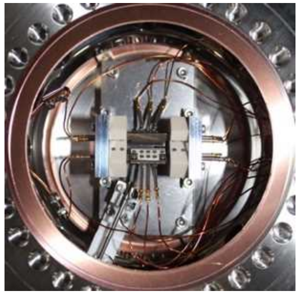


Fig. 1: Machined 3D linear trap installed in a vacuum

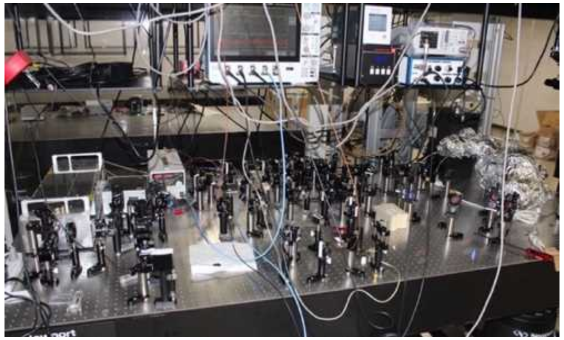


Fig. 2: Optical setup for cooling and stimulated Raman excitation.

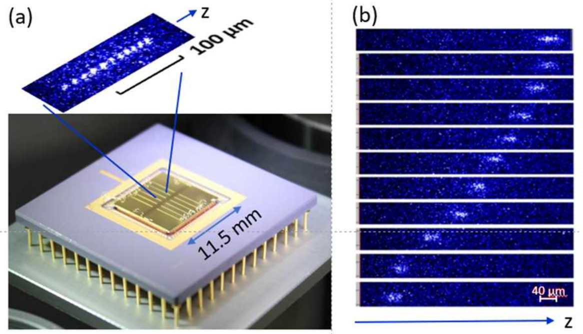


Fig. 3: (a)Surface-electrode trap and image of calcium ions trapped 200 μm above the electrode surface. (b) Results of ion transportation by varying applied voltages.

We perform experiments of ion transportation using a surface-electrode trap which consists of multiple trapping regions as shown in Fig. 3 (a). We manipulate the trapping potential by varying voltages applied to these electrodes. We have derived appropriate voltages by use of a method for solving optimization problems so that we move the ion position with maintaining the potential curve around the ions. Figure 3 (b) shows one of the experimental results. Around the starting (ending) position, we accelerate (decelerate) the ions slowly to avoid heating ions.

3. Future plans

We will implement a quantum gate, improve its accuracy, and implement a relatively simple algorithm so that the quantum gate algorithm experiment can be operated. Ion transportation technique is of significance because it determines the computation time of quantum computers. We will develop the faster transportation technique based on the above-mentioned results.

R&D Theme

Research and development on integrated optical circuits for ion trapping

Progress until FY2022

1. Outline of the project

Many kinds of lasers are utilized in trapped-ion quantum technology. Conventional implementations of light sources are free-space optical circuits with many optical elements mounted on a rigid optical table. However, our R&D project aims at replacing previous system with a photonic circuit fabricated on a tiny chip, which leads to the realization of a “photonically integrated ion trap.” Such a technological development can drastically promote the compact and stable implementation of a trapped-ion quantum node, and facile reproduction of it is indeed necessary for a photonically interconnected ion-trap quantum computer.

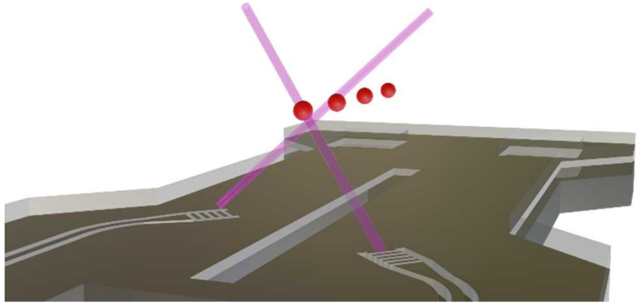
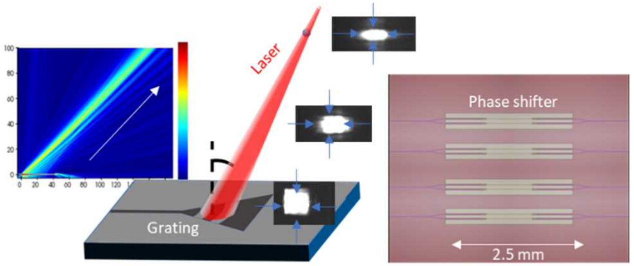


Fig. 1 Schematics of photonically integrated ion trap

2. Outcome so far

We are developing an integrated optical circuit to advance quantum computing technology in the ion trap device. Our focus is on introducing a variety of pump lasers into an ion trap, a critical component for this purpose. The integrated optical circuit we have developed has a wide range of wavelengths, from the visible to the near-infrared. This circuit incorporates silicon-based waveguides that not only have a wide bandwidth, but also have exceptional light integration capabilities. To further improve our on-chip integrated system, we are actively working on the fabrication of small footprint and efficient phase shifter devices. Ultimately, our goal is to implement the advances in the ion trap device being developed at the University of Tokyo.



Fig, 2 Development of photonic circuit elements

We are also developing a method to integrate a photonic chip or photonic elements described above, and in parallel, we are constructing ion-trapping apparatus for a proof-of-concept integration of them in a real trapped-ion quantum node. System constructions are almost completed and ion-trapping is now close at hand.

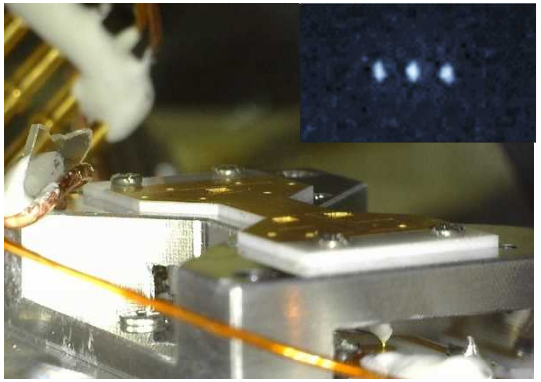


Fig. 3 Constructed ion-trapping apparatus

3. Future plans

By completing first designs of photonic elements and testing them in an ion-trapping experiment, we are demonstrating that we have a test bed for photonically integrated ion trap with photonic elements with additional functionalities, such as nanophotonic modulators. We are pushing up the frontline of a novel field between the ion trap and photonics for better reproducible quantum nodes, and also expecting that we are actually diving into a new field in photonics which aims at “slow but precise” photonics.

R&D Theme

Arranging individual trapped ions with junction traps

Progress until FY2022

1. Outline of the project

We reviewed the research and development status of 2-dimensional and 3-dimensional microfabricated ion traps used for quantum information processing. 2-dimensional ion traps are superior for handling many ions. On the other hand, when photon is used for transmitting quantum states, the number of ions manipulated in each trap can be reduced and extensive transportation of ions is no longer necessary. In addition, in transmitting photons from ions, it is very important to firmly determine the position of the ion traps in order to couple them with the fiber at a high efficiency. For this purpose, a 3-dimensional trap is preferable. In this research, we are developing a trapping device using 3 dimensional microfabricated electrodes that can simultaneously trap and array different elemental ions (Ca and Sr) in a 3-dimensional trap for sympathetic cooling.

2. Outcome so far

In designing the microelectrodes for the ion trap, we examined electric field analysis software capable of performing numerical calculations and selected the software to be used. Using this software, we considered the shape of the junction based on the microelectrode technology that could be fabricated.

We conducted a close examination of software required for numerical analysis of electric fields. Specifically, we created 3-dimensional ion traps in three software packages that can calculate ion trajectories in AC electric fields and confirmed their usability.

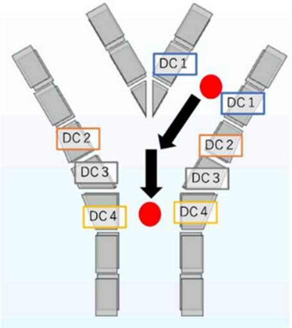


Figure 1: Ion transport model in junction 3-dimensional microfabricated trap

Of these, the software C is a general integrated simulation software based on the finite element method, which is compatible with high-frequency RF and allows different mesh sizes to be set for microfabricated and non-microfabricated areas, so it suitable for the calculation of microfabricated electrodes. We also confirmed that the software has been used in previous studies, which is preferable for constructing our calculation models. Since it is compatible with high-frequency RF and does not require long computation time even for models with microstructures, we decided to use the software C in this research.

Numerical analysis was conducted to quantitatively evaluate the electrode configuration and applied voltage that would allow ions to move through the two-way junction shown in Figure 1. Ions were transported from the red circle of DC1 to the red circle of DC4 in the junction shown in Figure 1 on the various conditions of electrode configurations. Figure 2 shows an example of the ion trajectory results.

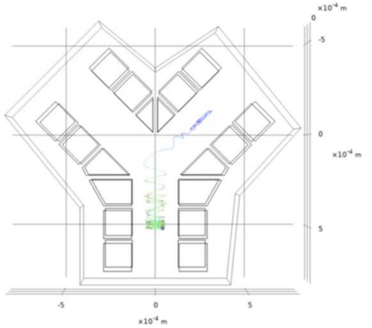


Figure 2: Ion orbitals in the transport of junctions

It is now possible to set the temporal variation of the DC voltage setting to allow transport of ions depending on the angle of the junction.

We prepared the vacuum system, electric field drive system, observation system, optical system, laser source system, etc. to set up the apparatus required for the trap and laser cooling of Ca and Sr ions.

3. Future plans

We will fabricate a prototype of a 3D microfabricated electrode and first aim to observe Ca ions by ion trapping and laser cooling. Once the ions can be observed, we will work on ion transport by changing the DC electrode as calculations. We will trap and observe Sr ions for simultaneous trapping and observation of multiple elements and ion manipulation in an arbitrary order using junctions.

R&D Theme

Development of quantum interfaces between ions and atoms

Progress until FY2022

1. Outline of the project

Linking remote ion-trap modules is key ingredient for scaling the number of ion qubits towards large-scale fault-tolerant quantum computation. A technology for coupling a single ion to a different quantum system is indispensable for this purpose. In this research project, we develop a quantum interface for ions and neutral atoms based on Rydberg excitation. We aim to use ultracold atoms as a mobile qubit transmitter which enables connection between remote ion qubits. We expect that such a quantum interface for a hybrid quantum system offer a novel strategy for scaling the ion qubits in a more efficient and flexible way.

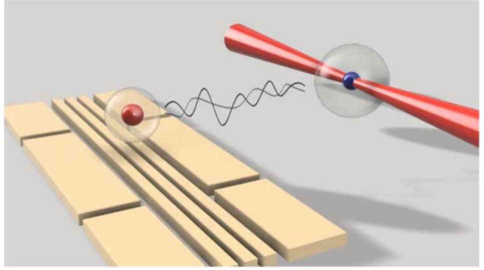


Fig.1. A quantum interface for atoms and ions

2. Outcome so far

We developed an apparatus for simultaneous capturing of ions and atoms (Sr ions and Sr atoms). First, we designed and built a linear Paul trap, which has a three-dimensional structure with segmented electrodes, and the trap is assembled in a vacuum chamber as found in Fig.2. This trap enables tight confinement of trapped ions into a Lamb-Dicke regime. Combined with a subsequent laser cooling, the ions can be initialized in the motional ground state. This is an important step for coherent control of the ion's internal and vibrational degrees of freedoms, i.e., qubit states.

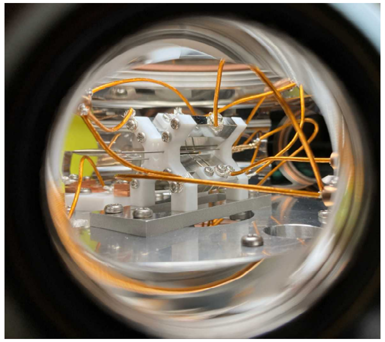


Fig.2. An image of the assembled linear trap

In parallel, we designed a vacuum system for trapping ultracold atoms (Fig.3). A hot beam of Sr atoms from an atomic oven is initially laser cooled via the Zeeman slowing section. The atoms are subsequently captured and further cooled in a magneto-optical trap (MOT) in a main chamber. Combined with a narrow-line MOT, the atom temperature at this stage reaches a sub-millikelvin regime. The design includes a set of electrodes and a micro-channel plate for ionization and detection of atoms in a Rydberg state. The field electrodes are also useful for nulling the excess electric field at the atom-trap center, which enables stable trapping of Rydberg atoms. We are currently working on trapping experiment of ions and atoms with this setup.

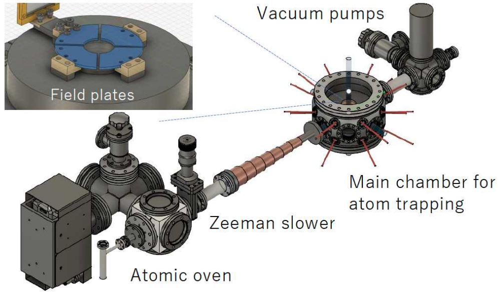


Fig.3. CAD design for atom-trapping apparatus

3. Future plans

We first plan to establish a stable trapping of a single ions and an ensemble of ultracold atoms. Performing Rydberg spectroscopy is also desired to characterize the level structure of the highly excited states. Such spectroscopic information is important to predict the target Rydberg state for exploring a strong atom-ion interaction. At the final stage of the project, we plan to demonstrate Rydberg-blockade gates in an atom-ion hybrid system. This opens an opportunity for utilizing neutral atoms as supportive qubits in ion-based quantum devices.