Quantum Information Using Microwave Manipulation of Laser Cooled Ionic Spin Chains

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Motivation

Strings of laser cooled ions stored in linear Paul traps have promising potential in the fields of quantum information and simulation [1, 2]. They provide a system which can be efficiently screened from a decoherence inducing environment, accurately prepared in a large variety of states and manipulated with high accuracy. Furthermore, state detection can be achieved with almost unit efficiency.

Spin-Spin Coupling

The Hamiltonian of linearly trapped ions exposed to a magnetic gradient can be described as [4-5]

$$H = H_{int} + H_{ext} - \frac{\hbar}{2}\sum_{n<l}^{N} J_{nl}\sigma_{z,n}\sigma_{z,l}$$

This Hamiltonian describes a linear ion chain, where every ion represents an individually addressable qubit with a characteristic resonance frequency. N is the number of ions and J_{nl} is the coupling constant of ion l with ion n. The last term in the Hamiltonian describes the pair-wise coupling between ions. This term is analogue to the well known spin-spin coupling within molecules, which is used in NMR-experiments. Hence, the linear ion chain can be considered as an N-qubit molecule, with adjustable coupling constants. Adjusting the coupling constants can be achieved by global means (modifying the trap frequency or gradient strength) or locally by tailoring the individual ion separations in segmented traps.

We expose Ytterbium ions to a magnetic field gradient. The spatial dependent Zeeman shift allows us to address the ions in the frequency space [3].

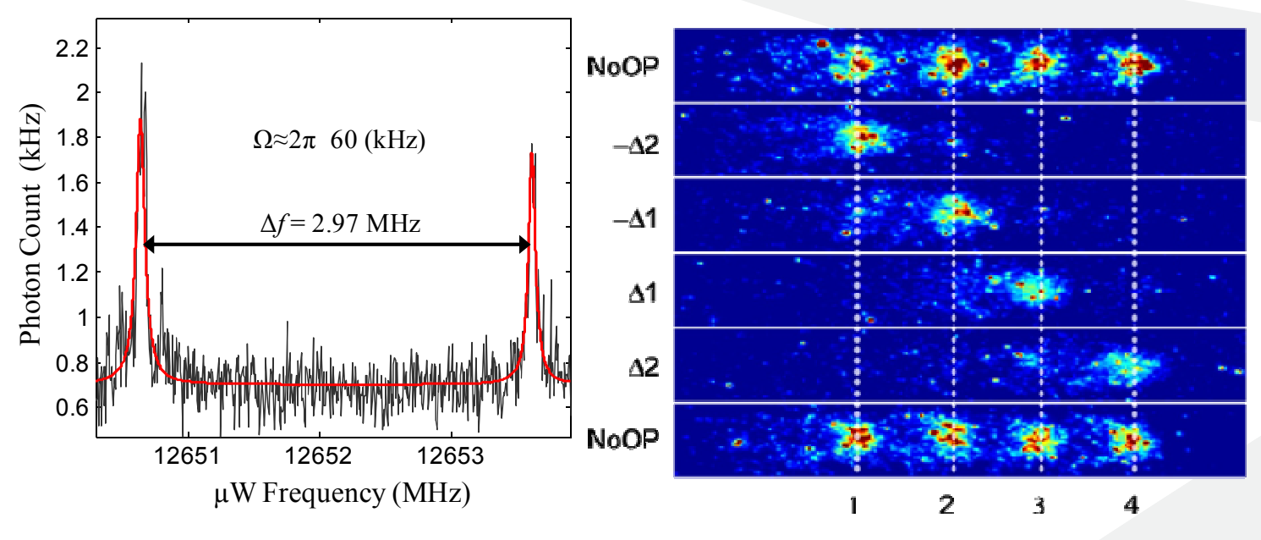


Fig. 1: Addressing a string of ions by rf radiation. The ions are optically pumped into a dark state. The rf field resonantly brings ions back into the detection cycle [6].

Due to the spin dependent force the internal state couples to the motional state. The coupling is described by an effective Lamb-Dicke-parameter. The conventional LDP is vanishingly small.

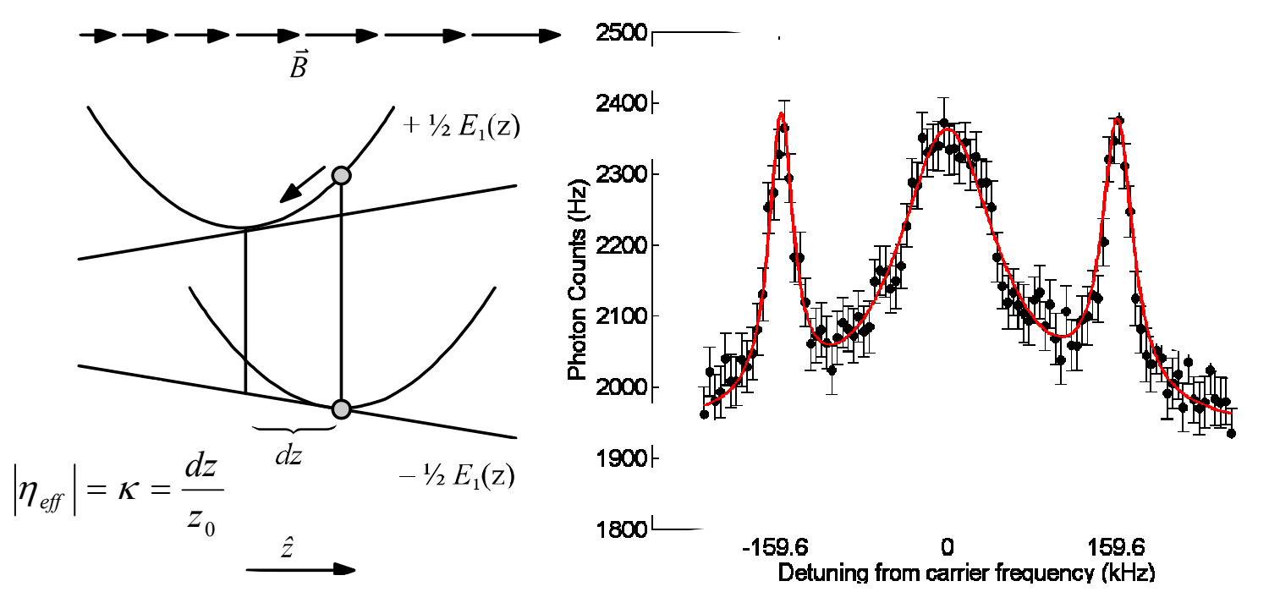


Fig. 2: A change of the internal state leads to a new equilibrium position and mimics a momentum kick (left) apparent as motional sidebands in the microwave absorption spectrum (right, measured in a macroscopic linear trap under conditions comparable to those envisaged for the trap discussed here).

As a third effect the internal state is coupled to the equilibrium positions of all other ions, mediated by Coulomb repulsion. This can be understood as a long range spin-spin σ_z coupling of the ions' internal states induced by the gradient, which is proportional in strength to the square of the magnetic gradient [4]. The spin-spin coupling is useful for building a quantum computer and for quantum simulations, e.g., for studying quantum phase transitions.

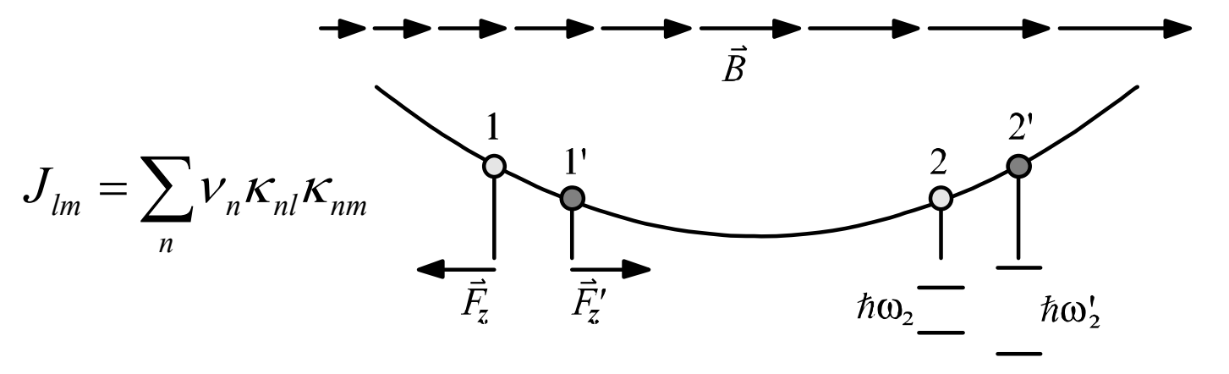


Fig. 3: A changing equilibrium position of any ion affects the positions of all other ions, mediated by Coulomb repulsion

Magnetic Gradient Induced Coupling (MAGIC) is, to first order, insensitive to thermal excitation of motional states and avoids several difficulties often associated to laser manipulation (lifetime, spontaneous decay, pointing-, amplitude- and frequency-stability).

We measured the spin spin coupling in a two ion string stored in a macroscopic Paul trap using a Ramsey phase method with intermittent Spin echo pulses to cancel unwanted coupling to the environment or drifts of the resonance frequency due to changing magnetic fields.

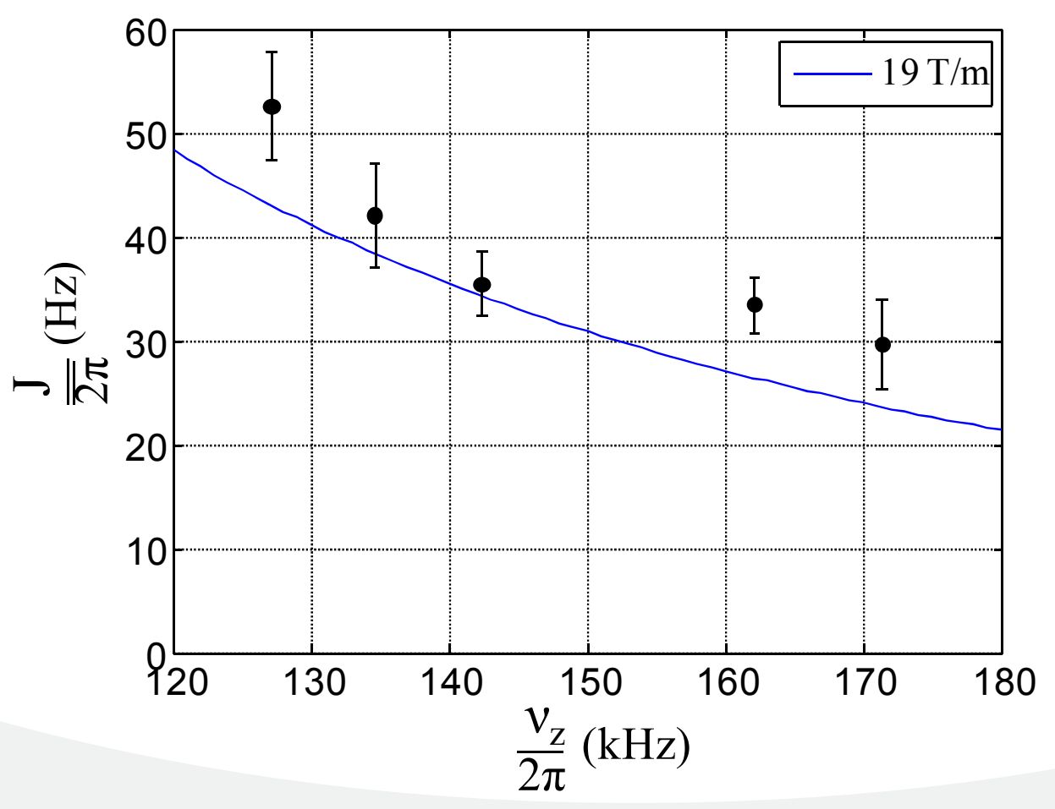


Fig. 4: Measured spin-spin coupling as a function of axial trap frequency (data points) and theoretical prediction (blue curve)

The segmented Gradient Microtrap

A large magnetic gradient results in both large frequency separation and coupling constants. Therefore we developed a coil design which was optimized with respect to gradient per dissipated heat.

Segmented Trapping

Our trap is a three layer design. The two outer layers were designed, simulated and implemented by the group of Schmidt-Kaler, University of Mainz.

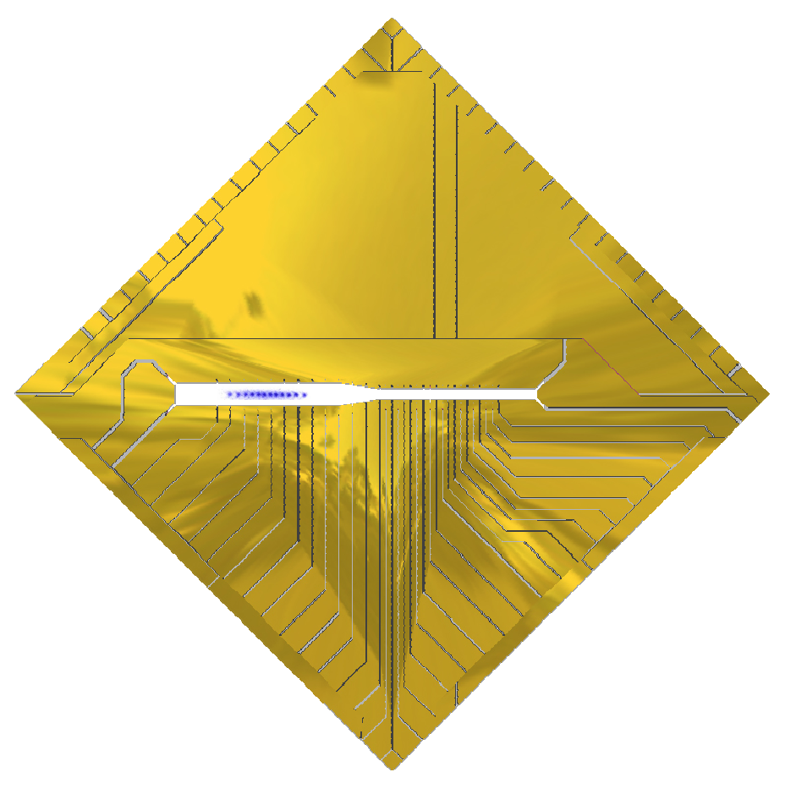


Fig. 5: The segmented microtrap features a wide trapping zone and a narrow experimenting zone, in which a magnetic gradient can be created by a anti-Helmholtz-coil

The outer layers are made of 125 μm thick Al_2O_3, and provide RF electrodes for radial trapping and 32 segmented DC electrodes for tailoring arbitrary axial trapping potentials in a wide (500 μm) trapping zone and a narrow (250 μm) experiment zone.

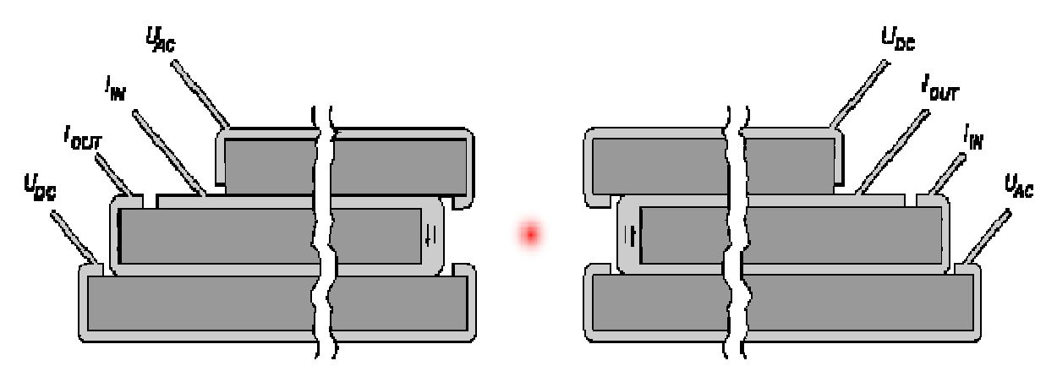


Fig. 6: Three layer structure which provides trapping (outer layers) and the magnetic gradient (central layer)

Miniature Anti-Helmholtz-Coils

The middle layer was designed by our group to form an inhomogeneous magnetic field. This is realized by the electric current flowing around the gold plated inner edges of the Al_2O_3 middle layer. We form an Anti Helmholtz pair by two of these geometries with opposite current flow.

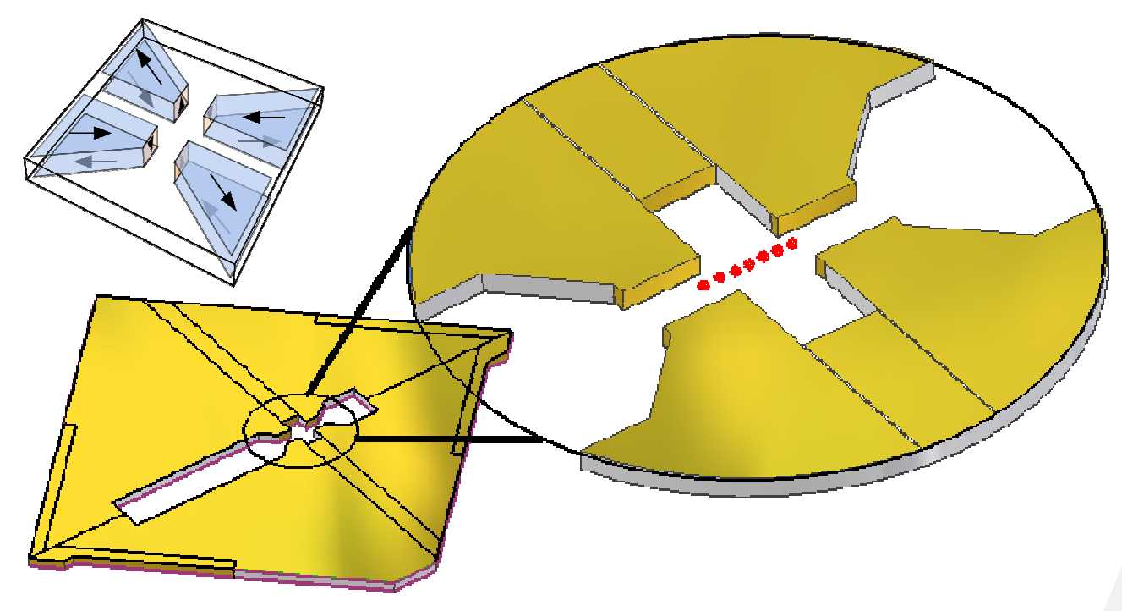


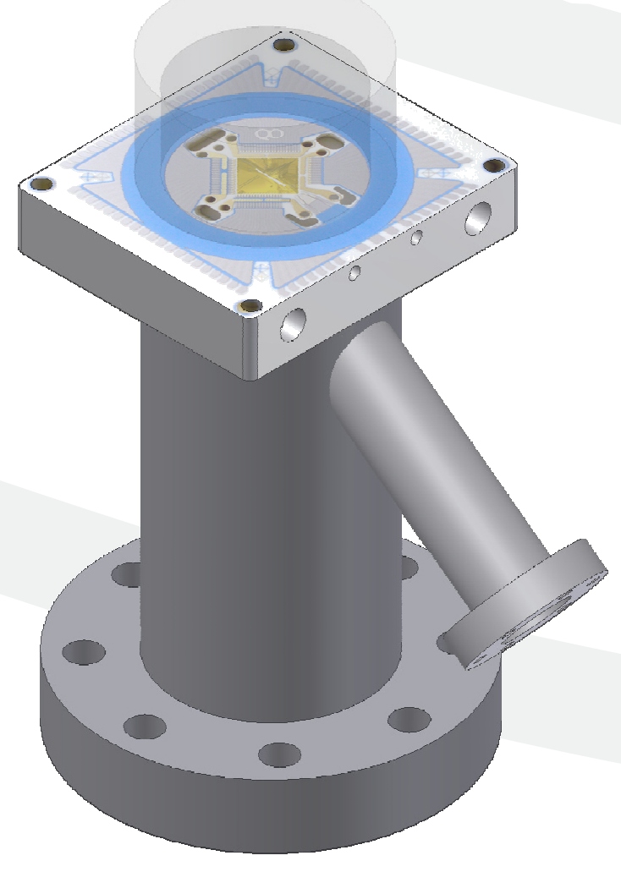
Fig. 7: Gold plated middle layer featuring an Anti-Helmholtz pair for gradient creation

Experimental Status

The chip carrier is also made of Al_2O_3 and was designed and built in cooperation with the Detector Physics group at Siegen (Prof. Walenta). It acts as a mechanical support and electrical vacuum interconnect with very short separation to the low pass filters on a connected PCB board. All wires are printed with thick film hybrid technology; thermal excess power is removed by heatpipes.

The system is assembled and under UHV. The round-trip coil resistances of the gradient coils are around 1 Ohm, permitting up to 5 A steady state current (corresponding to ca. 5 T/m), and potentially a factor of 10 more when pulsed. We are currently setting up the system, check for neutral atom fluorescence, and attempt trapping.

Fig. 8: Chip carrier as interconnect and part of the vacuum system



Outlook

Once up and running, the experiment opens up a wide range of possibilities to create tailored interaction for quantum simulations and quantum information. As one application, we proposed an efficient implementation to create cluster states [7] which are interesting for example in the one way quantum computer [8].

Nuclear Spin Qubits

We propose to encode qubits in both electronic and nuclear spins of trapped atomic ions for QC and quantum simulations. We consider quantum logic operations on ions in the Paschen- Back regime with qubits encoded in nuclear spins I and auxiliary qubits in electron spins S = 1/2. This combines the long decoherence time of nuclear spins with efficient manipulation and readout using electron spins.

Quantum information is stored in nuclear spins and is only swapped into electronic spins for single-qubit gates and conditional quantum dynamics with two and more ions. Thus, quantum information remains well protected from ambient noise fields that otherwise would give rise to decoherence.

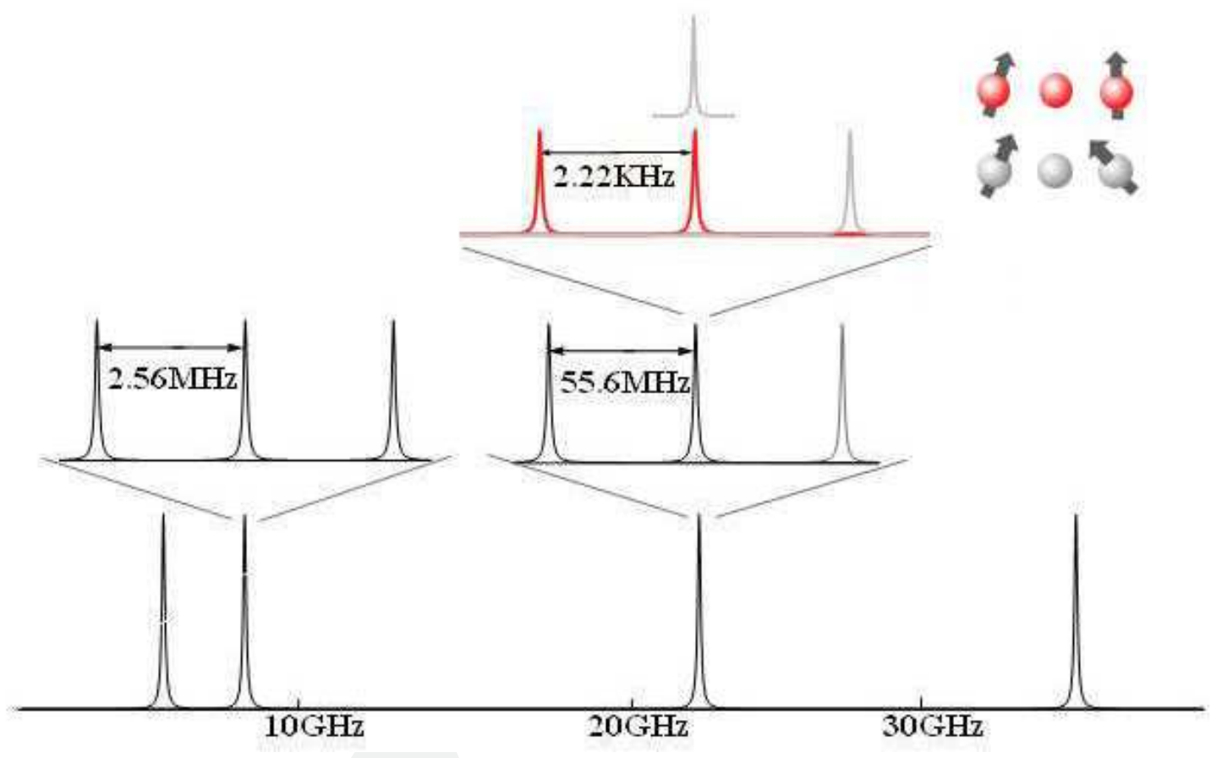


Fig. 9: Simulated spectrum of $^{171}Yb^+$ in a a strong magnetic field (1 T) and gradient (500 T/m). Swapping gate frequencies and qubit rotation frequencies are clearly separated in frequency space.

To achieve both high magnetic offset fields and gradients we propose the combination of surface traps and a Halbach magnet. While the first allows to create a high and switchable gradient, the latter uses permanent magnets to create static magnetic fields exceeding the flux density of the permanent magnets.

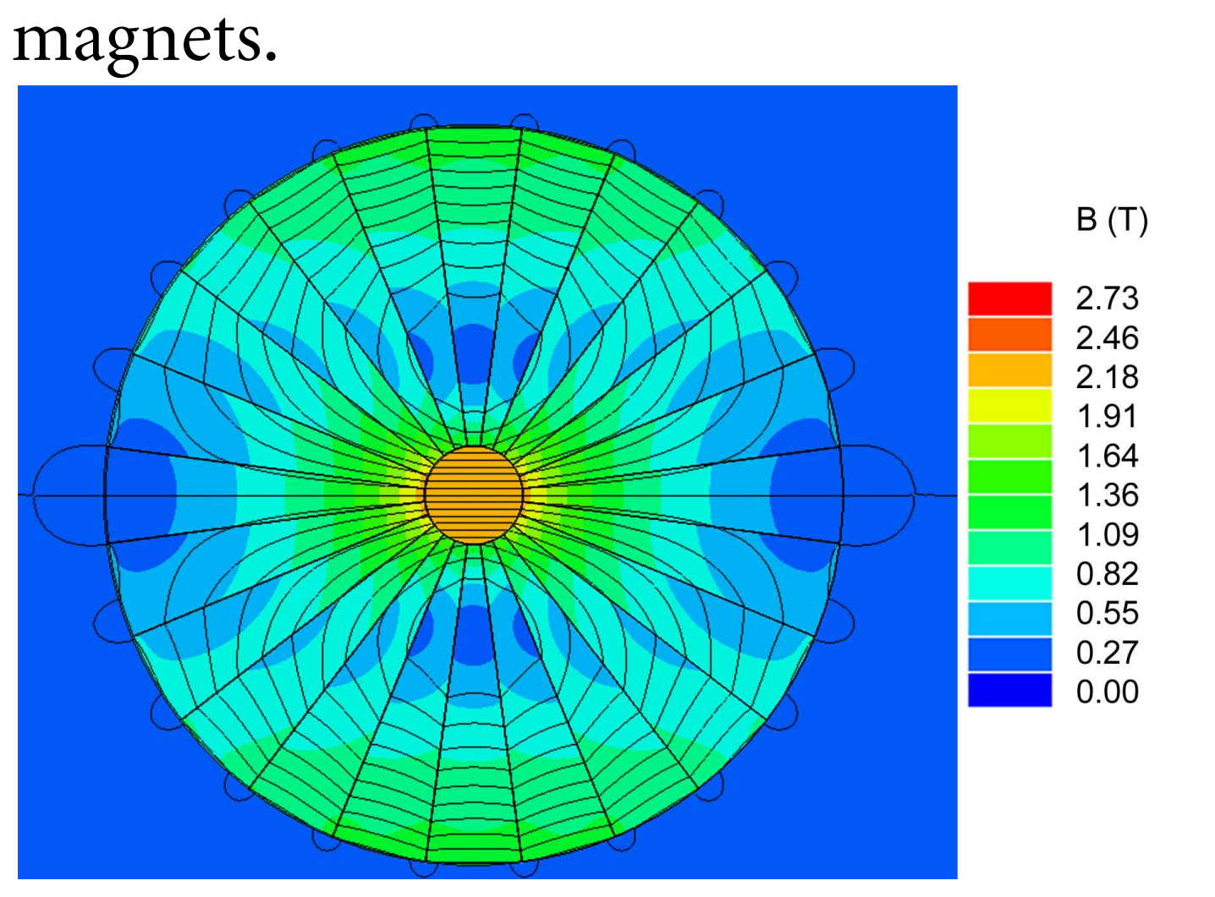


Fig. 9: Simulated flux density of a Halbach ring, composed of 24 permanent magnets with 1.3 T remanence. The total field in the center clearly exceeds this and quickly drops to zero outside of the ring.

Literature

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