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SPIN-TRANSPARENT STORAGE RINGS FOR QUANTUM COMPUTING*

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Abstract

Spin-transparent storage rings, in which any spin orientation returns to its original state after a full revolution, offer a promising new platform for quantum computing when combined with ion traps. These rings present several key advantages: they can store large numbers of qubits, enable long quantum coherence times – lasting up to several hours – support long storage lifetimes, and operate at room temperature. Such characteristics make spin-transparent rings an attractive and scalable solution for implementing complex quantum algorithms that require deep circuit depths and high qubit counts. Moreover, the extended coherence time makes this technology well-suited for applications in quantum sensing and quantum memory.

SPIN-TRANSPARENT STORAGE RING

A spin-transparent (ST) storage ring [1] is designed to make the spin dynamics degenerate, that is, the spin transformation in one turn around the ring is an identity transformation. The spin-transparency property of such a ring holds regardless of the precise geometry, provided the ring is flat and the net bending angle over one turn is zero. The most natural ST topology is a figure-8 ring configuration. A conventional magnetic ring has a distinct spin direction $\vec{n}_0$ where the spins of all particles precess around. The rate of this precession is called a spin tune ν. In the conventional magnetic ring, $\vec{n}_0$ is in the vertical direction. All the spins precess about the vertical magnetic fields of the bending dipoles. Since the spins precess about magnetic field $G\gamma$ times faster than momentum, where G is the particle's anomalous gyro-magnetic ratio and γ is the relativistic factor, the spin makes $G\gamma$ revolutions about the vertical direction in one particle turn around a conventional circular ring ($\phi = G\gamma \oint d\theta = 2\pi G\gamma$ and $\nu = G\gamma$).

The spin components perpendicular to $\vec{n}_0$ decohere in the conventional ring. The main cause of this decoherence is the spread in ν due to the spread in the particle energies $\Delta\gamma$, which is always present in a particle beam: $\Delta\nu = G\Delta\gamma$. For practical beam parameters, total polarization decoherence occurs in several thousand turns.

The ST ring configuration offers a universal solution to this decoherence problem. Clearly, since the bending angle $\int d\theta$ in one turn is zero, the spin rotation in one turn is also identically zero, independent of the particle energy ($\phi = G\gamma \oint d\theta = 0$). For a particle of any given energy, the spin rotation in one arc is completely compensated by an equal but opposite rotation in the other arc. This compensation mechanism is analogous to the spin-echo effect observed in NMR, where opposing spin rotations cancel out over a cycle.

In an ideal ST ring, any initial spin orientation remains unchanged after one complete revolution around the ring. This means the spin state is preserved from turn to turn, regardless of its initial direction – effectively "freezing" the spin configuration. However, in real-world rings, several effects lead to deviations from this ideal behavior. The primary source of deviation arises from imperfections in the ring, which distort the actual closed orbit relative to the ideal design orbit. A secondary source of deviation comes from particle betatron and synchrotron oscillations about the closed orbit. These oscillations influence on spin dynamics is of higher order compared to the dominant effect from closed orbit distortions.

In the context of closed-orbit distortion, vertical orbit distortion is of primary concern because it leads to a net spin rotation over one full turn around the ring. This vertical distortion is mainly caused by misalignments of vertical quadrupole magnets and the roll of dipole magnets. The sensitivity of the spin to such errors can be effectively evaluated using the spin response function formalism for ST rings [2]. This effect has been investigated particularly in the context of GeV rings. Both theoretical analysis and simulations have shown that the imperfection spin effect can be measured and mitigated using a local 3D spin corrector, consisting of weak magnetic elements [3]. The implementation of such compensation measures, combined with precise control of alignment errors, is essential for achieving the required spin coherence time.

The strengths of ST ring technology include its exceptionally long coherence times – lasting several hours – and its capacity to store a large number of particles. To scale beyond the current maximum number of stored particles, one possible approach is the use of multiple rings.

QUANTUM COMPUTING

Quantum computers [4] have the potential to make significant impact in the fields of cryptography [5], machine learning [6], and pharmacology [7] owing to their ability to execute critical algorithms with dramatically increased computational efficiency compared to classical systems. A wide range of physical platforms are currently under development for quantum computation, spanning much of modern physics. However, it remains uncertain which technology

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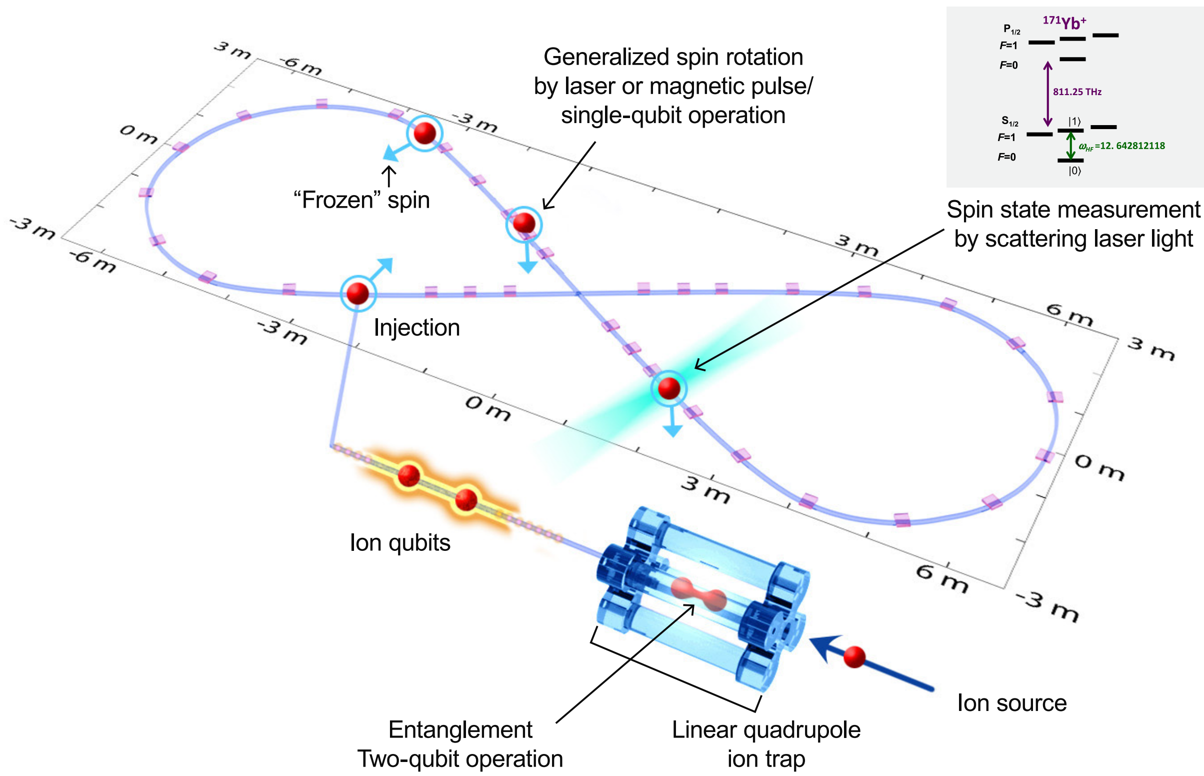

Figure 1: Schematic of the proposed quantum computing platform based an ST ring and an ion trap.

will ultimately overcome the many challenges involved and emerge as the most viable.

Among the most critical challenges in building quantum computers are the preservation of quantum coherence and the implementation of scalability. Qubit coherence is typically lost due to interactions with the environment and fluctuations in control parameters during quantum operations. The key metric governing a system's computational capacity is the ratio of coherence time to gate time – this ratio determines the maximum algorithmic complexity that can be executed reliably.

Scalability, on the other hand, refers to a quantum system's ability to increase the number of qubits without incurring exponential growth in resource demands, such as time, space, or energy. Therefore, the development of a quantum platform that combines long coherence times with efficient scalability is essential for the realization of practical and powerful quantum computers.

Ytterbium Ion Qubit

Ion traps [8] can be combined with the ST ring to greatly enhance both quantum coherence time and scalability. The spins of the nuclei of these ions, such as $^{171}\mathrm{Yb}^{+}$, couple to the spins of the outer-shell atomic electrons through the hyperfine interaction [9]. The qubits are represented by the two hyperfine ground states: $|F=0, m_F=0\rangle$ and $|F=1, m_F=0\rangle$.

Polarized $^{171}\mathrm{Yb}^{+}$ can be prepared in the ion trap by optical pumping of $^{171}\mathrm{Yb}^{+}$ atoms into a single hyperfine state, which are then injected into the ring. The ion trap is used to prepare the single-ion qubits and the entangled ion qubits. The $^{171}\mathrm{Yb}^{+}$ atomic ion is highly suitable for use as a qubit in a ring because of its long-lived hyperfine qubit, which has been demonstrated in radio-frequency Paul traps. The spin of the $^{171}\mathrm{Yb}^{+}$ qubit can be measured using state-dependent resonant fluorescence, where the $^{171}\mathrm{Yb}^{+}$ ion interacts with a laser beam and fluoresces photons when it is in only one hyperfine spin state. This fluorescence method provides an efficient and robust readout mechanism of the qubit in the ring.

Ring Design

The layout of the ring, shown in Fig. 1, is designed to store about three thousand $^{171}\mathrm{Yb}^{+}$ ions and fits in a 12 m by 6 m footprint. Qubit motion is transversely stabilized by alternating focusing. A radio-frequency (RF) bunching cavity provides longitudinal confinement of the individual ions. The maximum number of stored qubits is determined by their minimum longitudinal separation sufficient for their independent manipulation – chosen to be about 1 cm, so that the fringe fields of pulsed elements, such as the injection kicker, do not overlap the adjacent ions.

The ring design is electrostatic. It is necessary to preserve its spin transparency feature for ions. Unlike an elementary particle, an ion is a compound particle, and its

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Table 1: ST Ring Parameters for ^{171}Yb$^+$ Ion

Kinetic energy, K	10 keV
Momentum, p	56.4 MeV/c
Velocity, β	3.54×10^{-4}
Relativistic γ	$1 + 6.27 \times 10^{-8}$
Relative longitudinal momentum offset, $\Delta p_\parallel / p$	$< 10^{-3}$
Longitudinal temperature, $T_\parallel = mc^2\beta^2(\Delta p_\parallel/p)^2/k_B$	< 200 K
Angular deviation, $\Delta\theta_\perp$	1 mrad
Transverse temperature, $T_\perp = mc^2\beta^2\gamma^2(\Delta\theta_\perp)^2/k_B$	232 K
Ring circumference, L	33.5 m
Circulation frequency, f_c	3.17 kHz
No. of qubits / RF harmonic number	3, 300
Time separation of qubits, Δt	95.7 ns
Electric bending field, E	17.3 kV/m
Integrated magnetic / electric field of 10 mrad injection / extraction kick	1.9 T·mm / 200 V

anomalous gyro-magnetic ratio is a function of the applied magnetic [10] and electric fields. The field dependence is such that the spin phase advance is not necessarily zero for zero integrated magnetic field while it is zero for a zero integrated electric field. Some of the ring parameters are listed in Table 1.

The limit on the maximum transverse and longitudinal offsets of a stored particle comes not from the spin coherence or ring acceptance but from the Doppler shift of the state transition frequencies. Unlike techniques relying on quantization of the orbital motion [11, 12], the spin-based qubit states are robust. The spin state is practically decoupled from the orbital motion. Once set, aside for resonant situations, the spin state is stable to external factors. However, deviation of the particle momentum from the design value results in a Doppler shift of its transition frequency. If the shift is greater than the difference in frequency between the states, the two states cannot be discerned. Despite being the major limitation, this constraint still allows for momentum offsets of hundreds of Kelvin in terms of the transverse and longitudinal beam temperatures.

Storage Lifetime

The storage lifetime of the beam is determined by the interaction of ^{171}Yb$^+$ ions with the residual gas in the ring. The vacuum in the storage ring is expected to be lower than 10^{-12} Torr. This extreme high vacuum can be achieved with high temperature bake-outs of vacuum components such as electrodes and beam pipes and providing sufficient pumping. For such a vacuum system, the residual gas in the ring is mainly hydrogen molecules. The interaction of the ^{171}Yb$^+$ ion in the ring is dominated by the charge-exchange (or electron-capture) reaction, that is, $^{171}\mathrm{Yb}^+ + \mathrm{H}_2 \rightarrow {}^{171}\mathrm{Yb} + \mathrm{H}_2^+$. The cross-sectional values for this reaction can be written as

$$\sigma_{q\to q-1} = Cq^a E_0^b \tag{1}$$

where $C = 1.43 \times 10^{-12}$, $a = 1.17$, $b = -2.76$, and $E_0 = 15.426$ eV is the ionization energy of the hydrogen molecule. The above cross section does not depend significantly on the ion energies below 100 keV. For 10 keV ^{171}Yb$^+$ ions, the cross section is $\sigma \approx 7.5 \times 10^{16}$ cm^2. Under these conditions, the expected storage lifetime for the ST ring, with the design parameters shown in Table 1, is slightly longer than one hour.

Small-Scale Prototype

The ring in Fig. 1 is already fairly compact. Nevertheless, all of its relevant quantum features can be demonstrated by building an even smaller prototype. The ring size is primarily driven by the required number of qubits and the spatial qubit separation chosen. Although there is a limit on how small the separation can be, an initial proof-of-principle experiment can be done with a much smaller number of qubits than assumed for Fig. 1. The bending electric field requirements allow us to reduce the prototype ring size to a convenient circumference of several meters. Up to several MV/m electrostatic bending field strengths are possible while we estimated that a 0.0173 MV/m is needed for the full ring as listed in Table 1. Thus, as an initial step, we propose to build a cost-effective, small-scale prototype ST ring and use it to demonstrate all of the relevant quantum features expected of a full-size ring.

SUMMARY

We propose a new platform for quantum computing based on polarized particles stored in ST rings. ST rings offer several compelling advantages: they can store a large number of qubits, maintain quantum coherence times of several hours, enable long storage lifetimes, and operate at room temperature. These features make ST rings a promising candidate for scalable quantum computing, particularly for implementing complex algorithms requiring many quantum operations and high qubit counts.

We further propose integrating ST rings with ion trap systems to enhance both scalability and coherence times in ion-based quantum computing architectures. The long coherence times of qubits in ST rings also make them well-suited for applications in quantum sensing and quantum memory.

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