WEAN2: Particle accelerator spin-transparent storage rings for beyond state-of-the-art science

MC8.U09 – Applications of Accelerators, Technology Transfer, Industrial Relations, and Outreach

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Thomas Jefferson National Accelerator Facility

Outline

- Spin transparency and figure-8 storage rings

- Applications:

  1. Measurement of Electric Dipole Moments of free electron and proton

  2. Search for axions

  3. Quantum computing

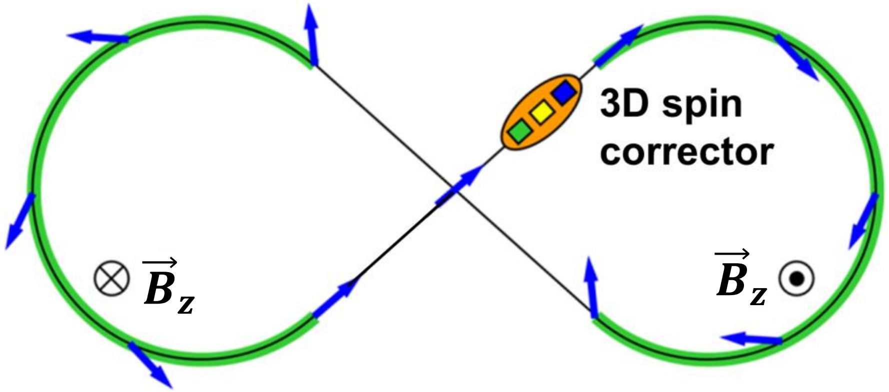
- Summary

Spin Transparency

- Any spin direction repeats after a particle turn along periodic orbit in spin-transparent storage ring
- Best example of spin-transparent storage ring is a figure-8 ring; here global spin tune (precession) is zero independent of particle energy – spin-echo effect

https://doi.org/10.1103/PhysRevLett.124.194801

https://doi.org/10.3390/sym13030398



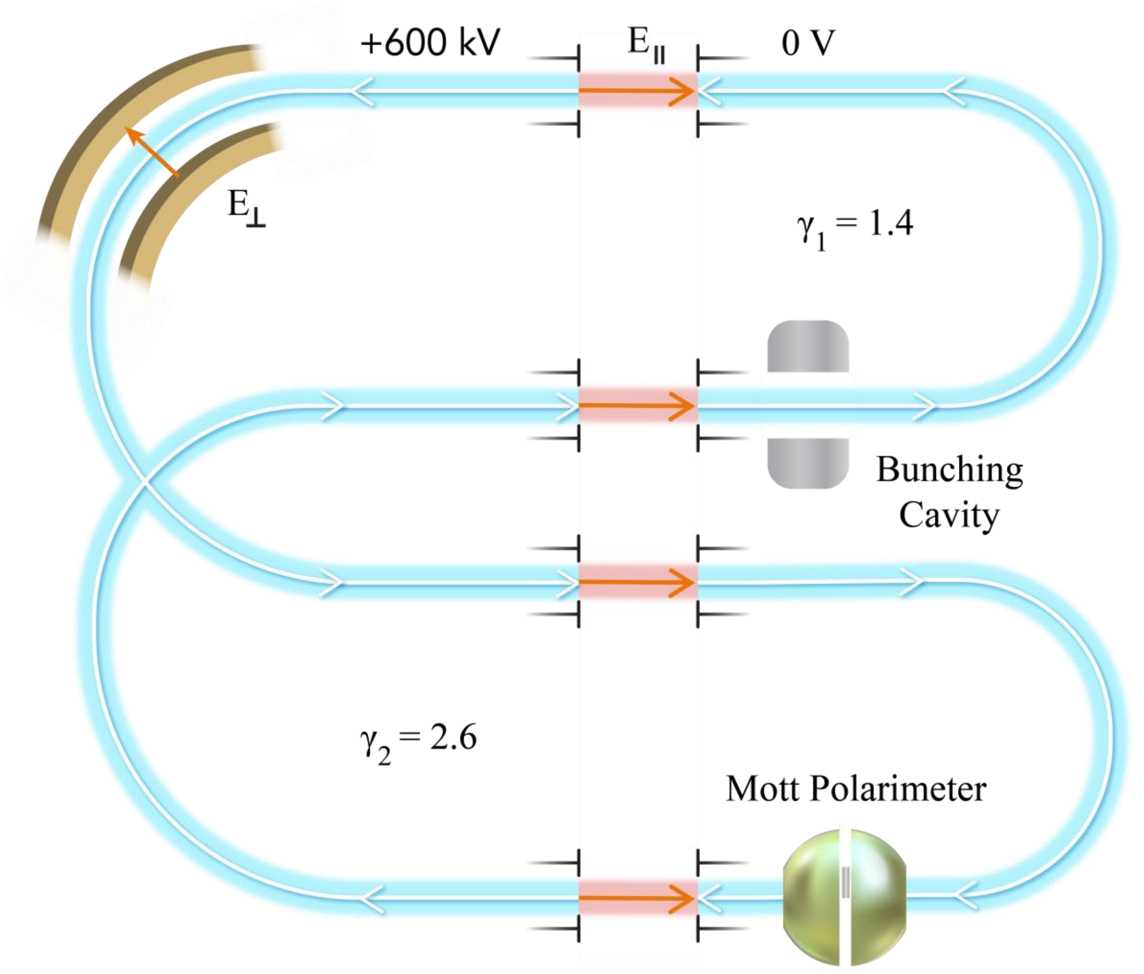
- Remaining challenge is to compensate for spin decoherency due to imperfections (e.g., misalignments) and beam emittances

Spin Coherence Time

- Any real spin-transparent storage ring has imperfections distorting its closed orbit in relation to ideal design orbit
- Imperfection spin effects can be measured and suppressed by a local 3D spin corrector consisting of weak magnets
- Particles undergo betatron and synchrotron oscillations about closed orbit due to beam transverse and longitudinal emittances
- Application of compensation measures combined with error control provides long spin coherence times of many hours – ultimately limited by beam emittances

I. Measurement of Electric Dipole Moment (EDM) of Free Electron

- EDM is very sensitive to physics beyond Standard Model and new sources of Charge-conjugation and Parity (CP) violation – such CP violation could signal presence of new physics and explain puzzle of matter-antimatter asymmetry in Universe
- Current electron EDM upper limit ($d_e < 4.1 \times 10^{-30}$ e · cm) has been extracted from measurement using HfF^{+} ions
- Any measurement of EDM relies on measuring spin precession rate in an electric field of a particle's rest frame, $\frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B}_{rest} + \vec{d} \times \vec{E}_{rest}$
- Magnetic Dipole Moment (MDM) effect is naturally suppressed at any energy due to spin-transparent ring topology and symmetry
- All-electric design with no magnetic fields to allow for two counter-rotating electron beams (CRA and CRB) – only one beam shown in right figure) to circulate concurrently
- EDM ST ring consists of two low-energy and two high-energy arcs connected by longitudinal static electric field sections – they preserve suppression of MDM effect but remove degeneracy of EDM spin precession



Projected Electron EDM Statistical Limit

- Build-up of vertical component of electron beam polarization due to spin precession from longitudinal to vertical caused by EDM can be measured using a conventional Mott polarimeter

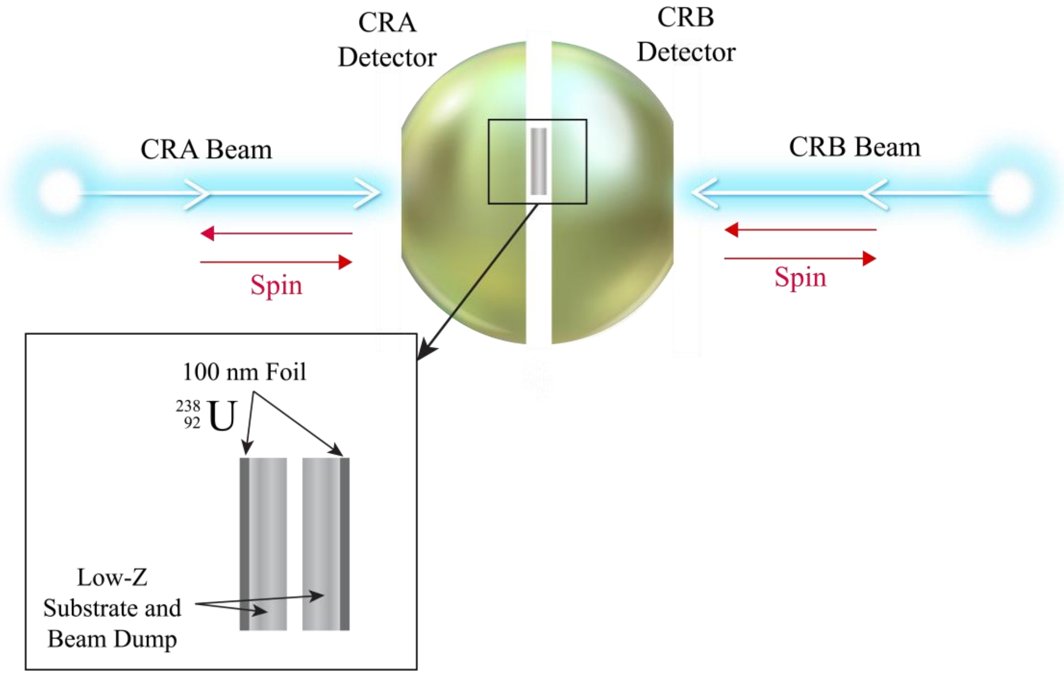
- Statistical uncertainty of EDM measurement per fill:

$$2.5 \times 10^{-28}\ \mathrm{e \cdot cm}$$

- After five years of data taking, projected statistical limit:

$$5.8 \times 10^{-30}\ \mathrm{e \cdot cm}$$

with expectation that further optimization and improvements will lower this limit.



Riad Suleiman, Vasiliy S. Morozov and Yaroslav S. Derbenev, "High precision fundamental physics experiments using compact spin-transparent storage rings of low energy polarized electron beams", Physics Letters B, Volume 843, 2023, 138058, ISSN 0370-2693, https://doi.org/10.1016/j.physletb.2023.138058

Measurement of EDM of Free Proton

In collaboration with Bogdan Wojtsekhowski

- Fully electric or magnetic figure-8 ring $\Rightarrow$ Both MDM and EDM rotations suppressed
- **Alternating** electric and magnetic arcs in figure-8 ring $\Rightarrow$ MDM suppressed, **EDM rotation is not!**
- EDM rotation

$$\frac{\partial^2|\psi|}{\partial\eta\partial N} = 4\left|\frac{\omega_{EDM}^E}{\omega_{MDM}^E} - \frac{\omega_{EDM}^B}{\omega_{MDM}^B}\right|\left|\sin\frac{\Theta_B}{2}\sin\frac{\Theta_E}{2}\right|$$

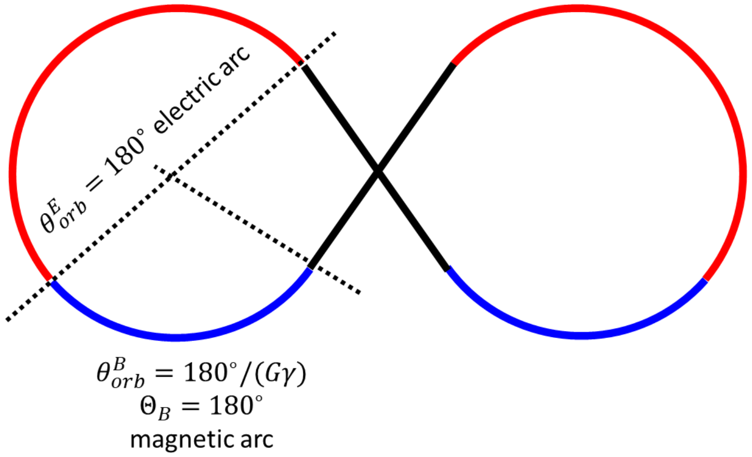
$$\frac{\omega_{EDM}^E}{\omega_{MDM}^E} = \frac{\eta}{2}\frac{\gamma^2\beta}{1-G\gamma^2\beta^2}, \qquad \frac{\omega_{EDM}^B}{\omega_{MDM}^B} = -\frac{\eta\beta}{2G}$$

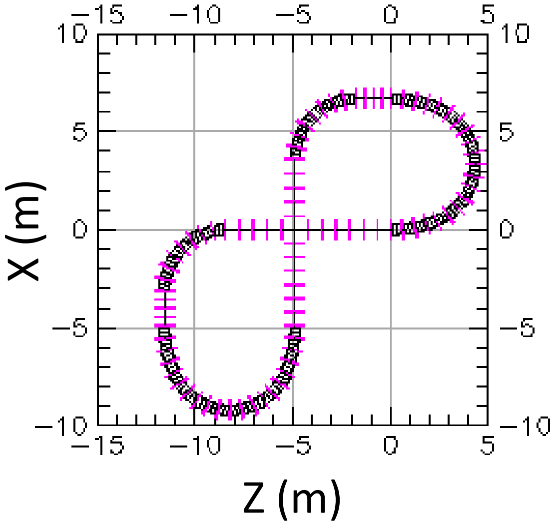
$$\Theta_E = -\frac{1-G\gamma^2\beta^2}{\gamma}\theta_{orb}^E, \qquad \Theta_B = G\gamma\theta_{orb}^B$$

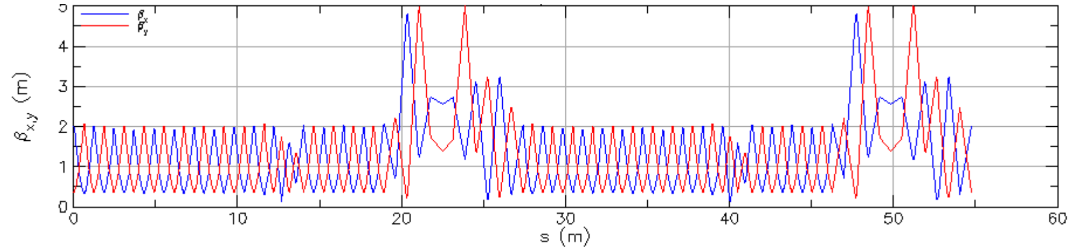
- $p = 100$ MeV/c, $d_p = 2\times10^{-27}$ e · cm ($\eta = 3.8\times10^{-13}$) $\Rightarrow \psi = 0.337\eta = 1.28\times10^{-13}$ rad/turn
- Extract signal through proton velocity dependence by measuring at several different β's:

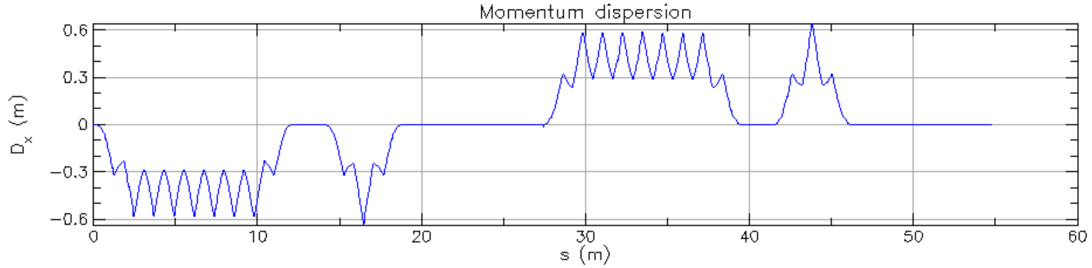
$$\frac{\partial P}{\partial t} \propto C_1 G\beta + C_2\eta\beta^2 + C_3\beta^3$$

- Proton EDM can also be measured at magic energy (232.8 MeV) [arXiv:1912.07881, PhysRevD.105.032001]



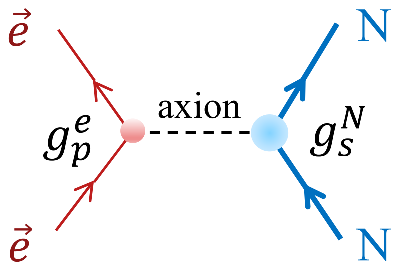






II. Search for Axions

- Axions:
  - Axion is a new particle beyond Standard Model that can explain strong CP problem of Quantum Chromodynamics (QCD), so called "QCD axion" – no CP-violation has ever been seen in any experiment involving only strong interaction in spite of fact that Standard Model as a whole violates this symmetry
  - Axions are also a viable candidate for dark matter which dominates mass of Universe
- Search for axions:
  - Spin precession due to interaction of Milky Way's dark matter axions with electrons: https://doi.org/10.1016/j.physletb.2023.138058
  - Spin precession due to axion-mediated nucleon-electron forces from Earth or test mass – next slide



- Spin-transparent storage rings:
  - Same as electron EDM ring, or
  - All-electric and one-energy (300 keV) ring – both MDM and EDM are suppressed

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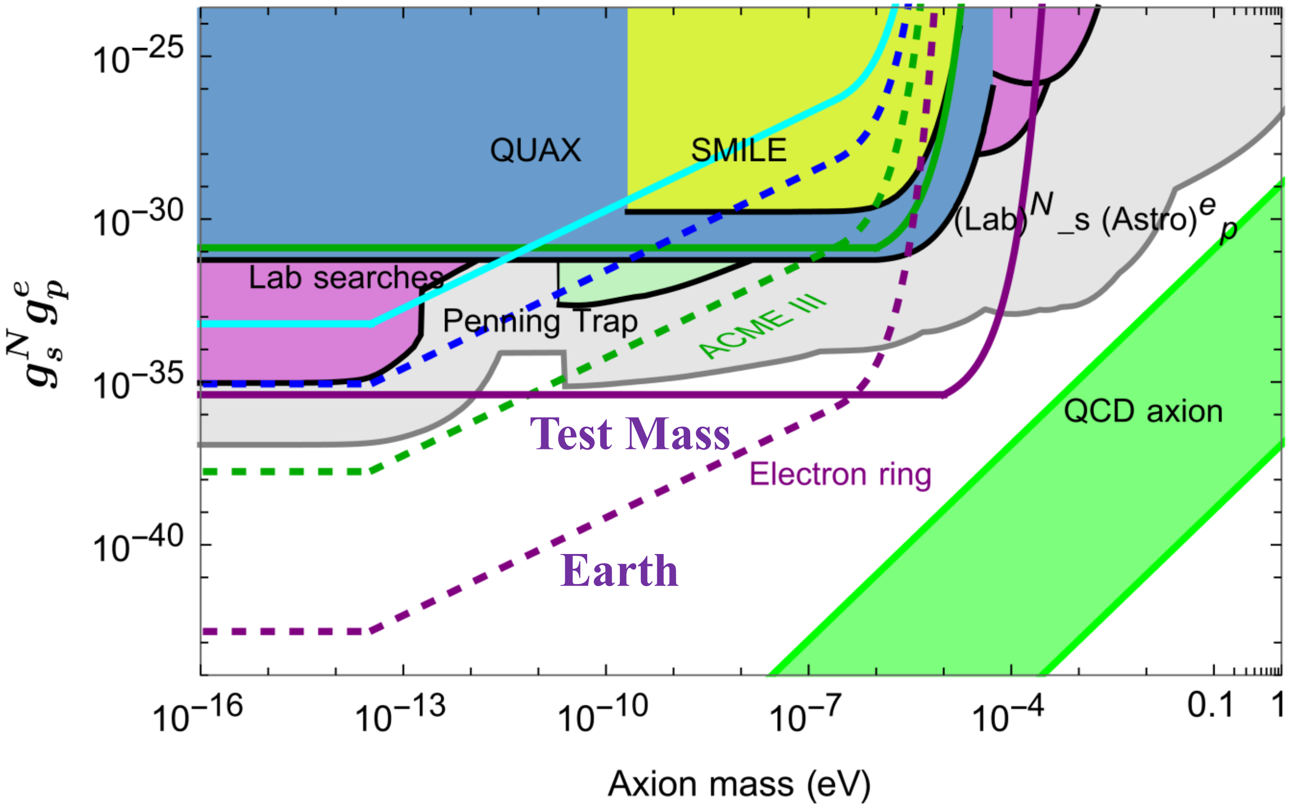
Experimental Bounds on Axion-mediated Forces

- Spin-transparent ring can measure nHz (10^{-9} Rad/s) spin precession frequency

- Axion sources:
  1. **Earth** – produces vertical axion coherent field
  2. **Test Mass** (e.g. lead bricks around ring) – produces radial axion coherent field

- Spin-transparent ring would surpass any existing or near-future search by several orders of magnitude

Xing Fan and Mario Reig, https://doi.org/10.48550/arXiv.2310.18797 and private communication



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III. Quantum Computing

- Quantum computers utilize fundamental principles of quantum mechanics of superposition, entanglement, and interference to deliver a huge leap forward in computation to advance certain applications, such as cryptography, machine learning, and pharmacology to name a few

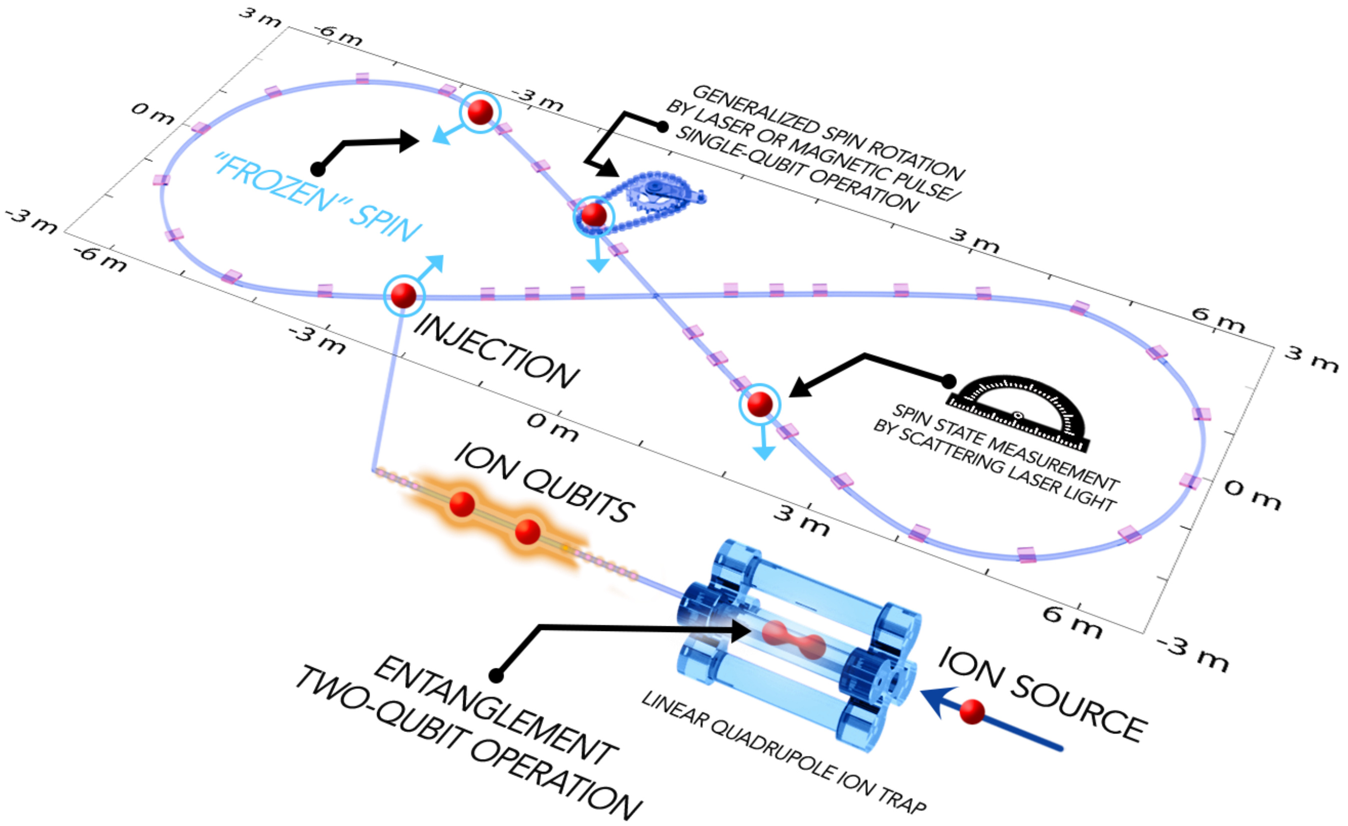
- Two of greatest challenges involved with constructing quantum computers are:
  1. Preserving quantum coherence: loss of coherence in qubit comes from its interactions with external world and fluctuations of control parameters in quantum operations. Ultimately, ratio of coherence time to gate time – time it takes to perform an operation on one or more qubits – determines maximum achievable algorithmic complexity of device.
  2. Implementing scalability: scalability is measure of a quantum system's ability to increase number of qubits without an exponential increase in cost of resources (such as time, space, or energy).

  ➢ Device that can provide long coherence times for large, scalable systems of qubits is needed

Viability of Spin-transparent Storage Rings for Quantum Computing

- Spin-transparent storage rings can be used in conjunction with ion traps to increase quantum coherence times and enhance scalability of ion quantum computing
- State-of-the-art ion traps: Quantinuum H2 system has 32 qubits and IonQ Forte has 36 qubits – both have coherence time of > 100 s

Ion	**$^{171}Yb^{+}$**
Kinetic energy	10 keV
Velocity (β)	3.54×10^{-4}
Electric bending field	17.3 kV/m
Longitudinal temperature	<200 K
Transverse temperature	232 K
Ring circumference	33.5 m
Circulation frequency	3.17 kHz
Time separation of qubits	95.7 ns
Number of qubits	**3,300**
Quantum coherence time	**> 3 hours**



Summary

- Spin-transparent storage rings have many exciting applications:

  1. Measurement of EDMs of free electron and proton
  2. Search for axions
  3. Quantum computing

- Advantages of spin-transparent storage ring for quantum computing:
  1. Can store large number of qubits
  2. Long quantum coherence times of up to several hours
  3. Long storage lifetimes
  4. Operates at room temperature

Thank you