**Roadmap for rare-earth quantum computing**

Kinos et al, [arXiv:2103.15743](https://arxiv.org/abs/2103.15743) (2021)

**Collaboration (SQUARE):**
Lund, Karlsruhe, Paris, Aarhus, Barcelona, Stuttgart, Thales, Attocube

**Background**

Many combinations of rare-earth ions + hosts:

- Eu for long coherence times
- Er for telecom wavelength
- Pr for gates (simplicity)
- Yb, Nd, Ce, Er for single ion detection

For QC, one single system is needed

... but can still make use of multiple spieces for different roles!

**Purpose**

- Describe *one* complete REQC
- Analyze strength/weaknesses
- Identify path(s) forward

**Goals**

- Give numbers for current estimates
- Act as reference work for future upgrades
- May allow more focused progress
Roadmap for REQC – Overview

**Single qubit operations**
- Two-color optical pulses drive spin qubits
- Including crosstalk, realistic fidelity errors of $\sim 10^{-4}$

**Readout**
- Cavity enhanced readout ion (e.g. Nd or Er)
- Expected detection of $\sim 10^7$ photons/s for a cavity Q of $\sim 10^7$.

**Two-qubit gates**
- Entanglement via dipole interaction
- Including crosstalk, realistic fidelity error of $\sim 10^{-3}$

**NISQ processor node**
- Frequency selection of ions with $\sim 1\text{GHz}$ bandwidth per ion (Eu).
- $\sim 100$ qubit processor with $\sim 10$ connections per qubit

**Scaling with multi-node architecture**
- Connecting many NISQ’s together
- Scalable materials with e.g. high $T_2$ thin films or milled cavities

**Optical interface**
Roadmap for REQC – Readout

Potential species:
- Nd – Strong signal
- Er – Strong signal, telecom wavelength
- Pr – Moderate signal, no electron spin

Purcell enhancement by micro-cavity

(Fixed nano-beams/WGM disc/scanning open)

Advantages:
- Can use different spatial locations
- Material/wavelength versatility

Main challenge:
- More sensitive to vibrations

Readout duration and fidelity
- cavity Q of $\sim 10^6 - 10^7$ (Nd and Er)
- Mode volume $\sim 1 - 10 \lambda^3$

- Najer et al, Nature 575, 622 (2019)
  $\rightarrow \sim 10^7$ photons/s, $T_{1,enh} \sim 100$ ns

- Bayesian method uses each detector click
  - Debnath et al, PRA 103, 043705 (2021)
  $\rightarrow$ Fid $\sim 95\%$ after 10 $\mu$s

  Limited by excited state decay (2 ms)

- Use one qubit as buffer stage, 3 times
  - Walther et al, PRA 92, 022319 (2015)
  $\rightarrow$ Fid $\sim 99.9\%$ after 40 $\mu$s
Roadmap for REQC – Single qubit operations

Challenges

- Short pulse to avoid decay
  - High bandwidth
- Avoiding overlap with other levels (internal crosstalk)
- Avoid exciting other frequencies (external crosstalk)
- Built in robustness?
  - Not needed if carefully calibrated

Simulations results

- Eu:YSO
- Including all crosstalk channels
- Adam Kinos (manuscript in preparation)

High fidelity required for quantum error correction

Cut Gaussian:

\[ |e\rangle \]
\[ |g_1\rangle = |0\rangle \]
\[ |g_2\rangle = |1\rangle \]
Roadmap for REQC – Two qubit operations

Dipole ion-ion interactions:

| Control | Target |
|---------|--------|
| $|e\rangle$ | $|e\rangle$ + $\delta\nu$ |
| $|0\rangle$ | $|0\rangle$ |
| $|1\rangle$ | $|1\rangle$ |

- Blockade gate
- Interaction gate
  - simultaneous excitation + wait time
  - = conditional phase shift on $ee$

Simulations results

- Eu:YSO
- Including all crosstalk channels
- Adam Kinos (manuscript in preparation)
- Bandwidth usage per qubit $\sim$ 1 GHz (Eu)

Shift scales as $\frac{1}{r^3}$ $\rightarrow r \sim 2 - 10$ nm
Roadmap for REQC – NISQ processor node

- Use dipole interaction to map out controlling ions
- Search qubit channels to switch off fluorescence
- Remove overlapping channels (optical pumping)
- Two search paths (Kinos, manuscript in prep):
  - Always switch off the previous qubit
  - Exhaust switch-off on the first qubit

Early results – Interaction gates should increase this!

100 GHz Laser limited
Roadmap for REQC – Connecting multiple nodes

Main idea:
- Best protocol still under investigation
- Share ideas with many other platforms for QC
- Closest ions in each NISQ node entangled
  - Debnath et al, PRA 103, 043705 (2021)
- Distillation ensures high fidelity
- Entanglement within nodes by gates

Optical integration a strength of the RE platform
- Many wavelengths, including telecom
- Nano-structures allow efficient coupling
- Nano-structures may allow integrated photonics
  → polished down bulk crystals ensures long $T_2$
  - Merkel et al, PRX 10, 041025 (2020)

Dynamic switching est ~ few μs:
- Casabone et al, arXiv:2001.08532 (2020)

Still many ideas to improve all components
- Now the improvements have a context
Thank you for your attention!

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