

# Trapped Ion Architecture for Multi-Dimensional Quantum Simulations

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**A rich and powerful toolbox for individually trapped atomic ions is available for quantum information processing, including quantum metrology and quantum simulation, demonstrating control with highest fidelities. Building on this success, a novel architecture for analog quantum simulations aims at setting up fully controlled and reconfigurable quantum lattices by individually trapped ions in multi-dimensional arrangements. In this article, an overview of recent developments and demonstrations of prototype operations is given. The features and limitations of the architecture are discussed and crucial steps toward mid and long-term simulation applications are laid out.**


## 1. Introduction

In the early 1980s the idea arose to realize a quantum simulator to study specific dynamics of complex and otherwise intractable quantum systems.<sup>[1–3]</sup> In general, requirements on experimental platforms to build an analogue quantum simulator (AQS) are considered to remain less demanding compared to those to realize a universal quantum computer (QC).<sup>[4]</sup> On the one hand, being universal, the latter might run any algorithm, including any digital quantum simulation. On the other hand, operating digitally, it will require unprecedented operational fidelities to reduce the related tremendous overhead, required to feature quantum error correction. AQS are predicted to be less prone to errors potentially addressing physics of interest before a universal QC might become available.<sup>[5]</sup> Driven in parts by the tremendous progress in many different experimental platforms working toward universal QC and quantum metrology, many different approaches toward AQSs are under development.<sup>[6–8]</sup> As a consequence of non-universality, each approach remains suited for a specific set of tasks only. Still, some generic requirements can be formulated. Cirac and Zoller state on the prospects for

experimental quantum simulation in their commentary of *Nature Physics* that, in any platform, at least one class of Hamiltonians should be addressable that cannot be simulated (at present) with numerical techniques.<sup>[4]</sup> They further remark that 1D systems can be treated very efficiently by established methods, for example, by the density matrix renormalization group technique.<sup>[9]</sup> Only if the dynamics in the system is in focus, even 1D systems can become intractable. Moreover, they state that 2D systems are different, although

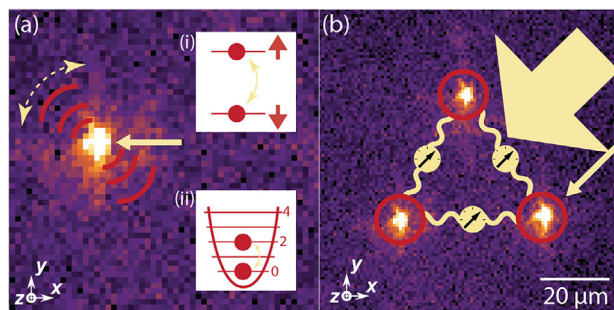
many of those problems could still be accessed by powerful numerical methods, for example, by projecting the physics to (lower) one-dimensionality, as done, for example, by the projected entanglement pair states approach.<sup>[9]</sup> To reach beyond the capabilities of current numerical techniques and to permit accessing many intriguing open questions on systems in equilibrium, the complexity of the quantum system in two dimensions has to be complemented by interactions at long-range. In combination, this puts a premium on experimental simulator platforms. A set of criteria for a suitable AQS can be summarized by four key elements:<sup>[4]</sup> i) A lattice of many fermions and/or bosons, ii) initialization into a fiducial system state, iii) engineering of local and global interactions with tunable strengths, and iv) performance of local or global measurements on the system. Ideally single-shot experiments need to be repeated several times for identical parameter settings to infer statistical distributions of measured observables.<sup>[10]</sup> Ultimately, the verification of results remains problematic. It requires that simulator platforms can be benchmarked thoroughly and that results from different platforms can be compared. The importance of interaction at a long range in this list is generic.<sup>[4,5,11]</sup> It is evidenced, for example, by the tremendous efforts in the field of optical lattices, trying to extend this established platform beyond current nearest neighbor interaction. Seminal proposals and first experiments on trapping Rydberg atoms<sup>[12]</sup> and dipolar molecules<sup>[13]</sup> provide encouraging proof-of-principle results. In addition, neutral atoms might get sufficiently close to assist their interaction by Casimir-Polder forces in vicinity of surfaces, as recently proposed.<sup>[14]</sup> In contrast, trapped ions naturally provide long-range interaction by their direct Coulomb interaction and present already a powerful simulator platform in linear arrangements with seminal demonstration experiments.<sup>[15–23]</sup> However, scaling cannot directly build on the approach of multiplexing for QC, where ions get separated, shuttled, and recombined in a network of 1D, concatenated traps.<sup>[24–26]</sup> To realize AQS, a multi-dimensional ensemble has to evolve as a whole and a suitable architecture has to

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**Figure 1.** Prototype of a versatile quantum array for multi-dimensional simulation based on individual and locally controlled atomic ions. a) In each site, single (or multiple) trapped atomic ions are located. Here, a false-color image of the fluorescence light of a single trapped  $\text{Mg}^+$  ion is shown. Local control fields allow for initialization, coherent manipulation, and detection of engineered quantum degrees of freedom. Ions host (pseudo) fermionic (spin-1/2) degrees of freedom in the internal, electronic states (inset i) while the three external, motional directions correspond to bosonic degrees of freedom (inset ii). Technical developments for the control of ions in a single potential are driven by a variety of applications, for example, atomic clocks and quantum information processing. b) Fluorescence image of three ions in our basic triangular array with three micro trapping sites. Sites can be deterministically loaded with a selection of ions of the identical or different species. A combination of global and local control fields enable realtime control of each quantum degree of freedom and tunable inter-site couplings establish coherent long-range interactions within the array, evidenced by interference effects between all sites.<sup>[37,38]</sup>

be developed.<sup>[27–32]</sup> Multiple review articles compare features of alternative experimental platforms<sup>[6,8]</sup> and introduce the toolbox of trapped ions for experimental simulations.<sup>[33,34]</sup>

In our paper, we highlight ongoing research on building a versatile multi-dimensional simulator platform with tunable, long-range interactions based on arrays of individually trapped and controlled atomic ions. After an assessment of features and limitations, we present a possible next generation array and discuss addressable physics goals.

## 2. Design Features and Prototypes

Systems of single (or few) atomic ions trapped in linear arrangements are well known for their high level of control. The seminal work of Wineland and others leading to this reputation has been rewarded with a share of the 2012 Nobel prize in physics.<sup>[35]</sup> In corresponding experiments, ions are trapped under ultra-high vacuum conditions in so-called Paul traps using a combination of radio-frequency (rf) and static electric fields,<sup>[36]</sup> see an image of the fluorescence light from a single ion in **Figure 1a**. Trap depths on the order of a few eV (thousands of Kelvin) and trapping durations on the order of hours or days can be achieved in these conventional linear trap geometries. Multiple laser beams address ions and are used to manipulate the internal, electronic states via optical pumping and the external, motional states via laser cooling. In this way, fiducial initial states are prepared with close to unit fidelity within less than a millisecond.<sup>[24,39]</sup> Coherent control to generate superposition and entangled (electronic and motional) states can be performed via lasers or microwave fields, typically with operation durations of a few microseconds

to a few milliseconds.<sup>[40–42]</sup> Since first implementations of multi-qubit gates<sup>[43]</sup> and effective spin–spin interactions,<sup>[15]</sup> common modes of motion are employed as an information bus and, today, fidelities exceeding 99.95% are achievable for all operations.<sup>[44,45]</sup> Noise field amplitudes can be strongly mitigated in these experiments to achieve coherence durations of electronic (motional) superposition states on the order of minutes<sup>[40,46]</sup> (few hundred milliseconds), enabling, for example, atomic clocks with a fractional frequency uncertainty of  $< 10^{-18}$ .<sup>[47]</sup> Final state detection, including full state tomography, of electronic and motional degrees of freedom is (again) based on sequences of coherent control pulses and concluded by counting the number of photons resulting from resonantly induced fluorescence of the ions.<sup>[24,39]</sup> Sequences are repeated hundreds of times for identical parameter settings to record statistical distributions of final states, for example, to distinguish pure (quantum) from mixed (thermal) states.<sup>[24,39]</sup>

Applications of these techniques in the context of quantum simulations are persistently extended by increasing the number of constituents forming a strongly coupled linear crystalline structure trapped in a common potential.<sup>[15–23]</sup> While for specific trapping conditions ions crystallize in multi-dimensional structures, it becomes increasingly challenging to apply the control techniques (used in linear arrangements) in this domain, but efforts in this direction are in progress.<sup>[48–50]</sup> Notably, experiments performed on 2D ion crystals controlled in so-called Penning traps present intriguing demonstrations toward high-fidelity quantum control of hundreds of ions.<sup>[31,51]</sup> In such configurations, focused laser beams enable local control that may even include the tuning of inter-ion couplings.<sup>[52]</sup>

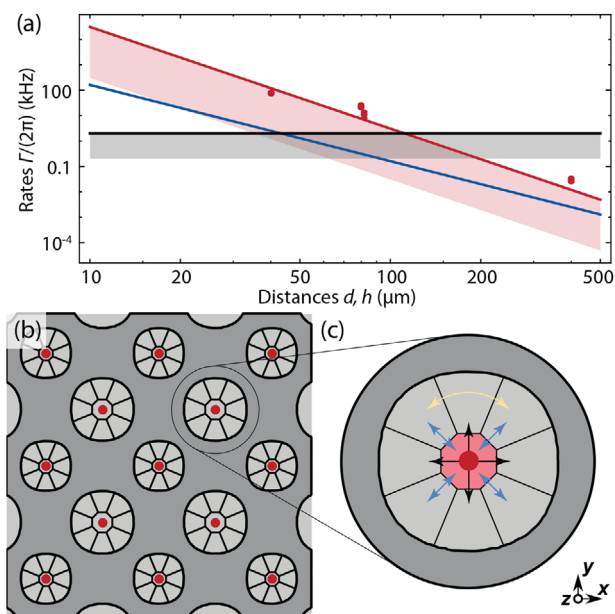
Alternatively, many of the technical control aspects of the aforementioned single ion systems can be readily applied in arrays of micro traps. However, here the challenging key ingredient is a suitable and powerful trap architecture. Its development was initiated almost 15 years ago with the demonstration of microfabricated surface-electrode traps,<sup>[53,54]</sup> where a linear chain of ions is trapped at a distance  $h$  from a chip surface. Using such architecture, the exchange of a single quantum of motion, as well as entangling spin–spin interactions have been reported—still, in a linear arrangement of two micro traps.<sup>[55,56]</sup> In this context, a crucial figure of merit is the inter-site distance  $d$  as it sets timescales for required inter-site interactions  $\propto d^3$ .<sup>[27,55–57]</sup> Many research groups realized different geometries and followed different design principles to provide an increasing density of micro traps with  $d \approx 1500$ ,<sup>[58]</sup> 500,<sup>[59]</sup> 270  $\mu\text{m}$ ,<sup>[60]</sup> and 80 to 40  $\mu\text{m}$ .<sup>[57]</sup> The latter two arrays generate a landscape of the potential featuring three micro traps that form a basic equilateral triangular array with  $d \approx h$  and control structures embedded into the chip enable local control of each site. In **Figure 1b**, we show an image of the fluorescence light of individually trapped  $\text{Mg}^+$  in each of the three sites. In these cases, the shapes of rf electrodes (generating the overall potential landscape) are optimized by a linear-programming algorithm that yields electrode shapes with low fragmentation, which minimizes corresponding classical control overhead.<sup>[57,61,62]</sup>

In a first series of experiments, we demonstrated individual control of the electronic and motional degrees of freedom in each micro site, including the preparation of a fiducial initial state with ion motion close to the quantum mechanical ground state.<sup>[57]</sup> As

a result, confirming that state-of-the-art control techniques of linear ion systems can be applied in these novel trap architectures. In a second series of experiments, we showed tunable inter-site couplings that steered in real time the classical interference effects of coupled motional dynamics in all sites.<sup>[37]</sup> Here, we were additionally able to show that local parametric modulations of detuned trapping potentials can be used to control the strength, and phase of inter-site couplings.<sup>[38]</sup> Two main technical limitations are currently preventing us from demonstrating high-fidelity inter-site couplings on the single quantum level: i) motional mode stability (motional dephasing) and ii) the so-called anomalous heating rate (motional decoherence). i) Amplitude variations of our potential landscape translate to a significant dephasing rate (on the order of the inter-site coupling strength) over the course of several hundred sequence repetitions. In future, we can actively stabilize the potential amplitude and expect a tenfold improvement.<sup>[63]</sup> ii) In addition, noise fields originating (most likely) from contaminations of the electrode surface lead to decoherence effects within single sequences. This kind of decoherence effect is known to scale approximately with  $h^{-4}$  and can be mitigated.<sup>[64,65]</sup> In **Figure 2a**, we summarize these findings for our currently accessible experimental parameter regime, that is, atomic mass and mode frequencies and identify a suitable regime for  $d \simeq h \simeq 30$  to  $80 \mu\text{m}$  (more on this in Section 3).

To design micro trap lattices of other periodicity or, even, non-periodic arrays, the same algorithm can be used to yield globally optimal electrode shapes for an arbitrary number of sites. In **Figure 2b**, we present a unit cell of an optimized periodic electrode structure that generates a bilayer square lattice of micro trapping sites, that is, even more than 2D arrangements can be anticipated.<sup>[61]</sup> To keep the demonstrated local tuneability of each site, it is required to feature control electrodes near each micro trap as illustrated in **Figure 2b**. These additional electrodes enable controlling the local electric fields for stray field compensation (fine tuning of the site location) and tuning of the second order curvatures of the trapping potential, that is, matching the neighboring mode frequencies and orientations (manipulating inter-site couplings). In total, this demands eight control electrodes (for each site) for the classical control of the motional degrees of freedom. In the future, even control components for local initialization, manipulation, and detection of the electronic (and motional) degrees of freedom can be integrated into the chip.<sup>[66–72]</sup> However, to calibrate and operate the vast number of experimental parameters in real time, highly integrated control hardware, methods of efficient automatization, and optimal control techniques have to be implemented. Here, the demand on classical control capabilities are quite similar to those encountered for quantum computing and metrology applications and first joint efforts have been initiated.<sup>[73]</sup>

Most practically, we can tackle some of these demanding developments with a next generation chip, outlined in **Figure 3**. The blueprint includes 46 control electrodes grouped into four islands near the micro sites to enable additional tuning of anharmonic contributions of trapping potentials. Structure sizes and routing complexity required for such an array are comparable to the prototype basic triangular array. Here, control structures are optimized with adapted design rules via machine-learning algorithms to yield minimal voltage amplitudes for operation,<sup>[74]</sup> while aiming at increasing trap depths and corresponding ion



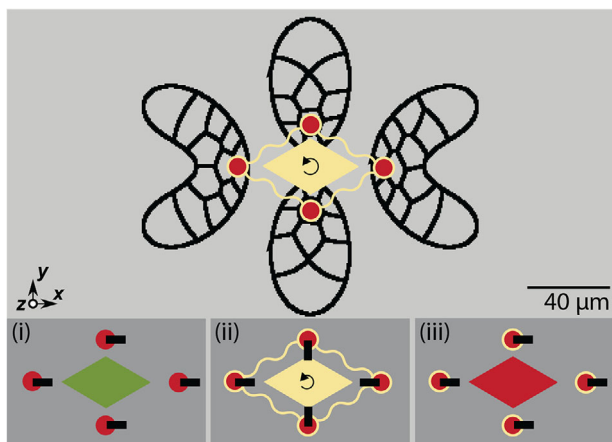
**Figure 2.** Key properties of surface-electrode trap chips for large-scale arrays. a) Inter-site coupling (blue), motional dephasing (black), and decoherence/anomalous heating (red) rates as a function of inter-site  $d$  and ion-surface  $h$  distance for  $^{25}\text{Mg}^+$  and a motional mode frequency of  $2\pi \times 1.5$  MHz. Red data points represent measured heating rates for different traps in our laboratory. Shaded areas indicate required improvements of conditions that have been demonstrated in comparable setups. This indicates a best working regime near  $d \simeq h \simeq 30$  to  $80 \mu\text{m}$ . b) Sectional view of an infinite lattice pattern with multiple micro sites (red dots) in a bilayer arrangement. Optimal radio-frequency electrode structure (dark gray) enables a global potential landscape and segmented regions (light gray) within the chip plane are available for integration of local control elements. c) Close-up view of a single site illustrating integrated control electrode structures. Essential are eight segmented control electrodes (light gray) that allow for local tunings of motional state properties and, in turn, are required to establish tunable, coherent inter-site couplings. In the future, each site may even be equipped with additional control components (red) for initialization, manipulation, and detection of the ions.

storage durations. The designed array sets up a rhombic ladder, a prototype of concatenated plaquettes, that enables to experimentally study, for example, Aharonov–Bohm physics, and transport and thermalization processes under fully controlled conditions (see Section 3). Generally, these type of experiments require high-fidelity realtime playback of pre-calibrated system configurations, for example, for initialization, inter-site coupling, and detection (see insets of **Figure 3**) that are repeated hundred of times within a few seconds to measure observables (and their statistical distributions) with sufficiently low systematic disturbances.

### 3. Discussion

We identify two critical steps to judge future prospects of the trapped-ion array architecture:

1. Understanding and decreasing noise field contributions to reach high operation fidelities on the single quantum level.



**Figure 3.** Next generation micro trap array with four sides forming a plaquette structure for simulation of synthetic gauge fields. Sectional view of the optimized electrode structure (gray) including 46 control electrodes (grouped into four islands) required to fine-tune the potential landscape of the four micro trapping sites (red dots). Gaps between electrodes (black) are about 2  $\mu\text{m}$ . State of the art micro-fabrication techniques and three metal layers are required to build this structure. (Insets) Basic experimental sequence including global inter-site coupling. i) A combination of global and local control fields (including multiple laser beams aligned parallel to the chip surface) enable the deterministic initialization into a fiducial array state while inter-site couplings are turned off. ii) Simultaneous realtime control of motional states in each site engages coherent inter-site couplings to implement a synthetic gauge field. The coupling strengths and efficiencies are tunable via mode parameters and the inter-site phonon dynamics can be steered by Floquet-engineering.<sup>[38]</sup> iii) The final state of the array can be reconstructed when inter-site couplings are turned off and local detection of all quantum states is concluded. Typically, such sequences are repeated 100 to 1000 times for identical parameter settings within a few seconds of data taking.

2. Scaling arrays to tens or hundreds of sites to trigger further developments and initiate first benchmarks of (already) powerful numerical approaches and of their underlying approximations.

Step (1), the dominating technical noise contribution, currently disrupting experiments on the single quantum level in the vicinity of the surface, is suspected to stem from surface contaminations that also limit other platforms and precision experiments.<sup>[64,65]</sup> Although the resulting anomalous heating rate can be reduced by established techniques,<sup>[64,75]</sup> underlying microscopic mechanisms need to be understood in more detail to routinely reduce or even fully avoid these technical limitations of coherence times. Promisingly, in linear rf-surface traps, operating at similar ion-surface distances and secular frequencies as our basic triangular array, heating rates have been reduced by more than two orders of magnitude.<sup>[64,75]</sup> The possibility of combining surface cleaning procedures and operation at cryogenic temperatures is under investigation and may yield an even greater reduction. Applying these techniques successfully to arrays will decrease heating rates to orders of magnitude below direct inter-site coupling rates and enable deterministic exchange of single phonons between sites,<sup>[55,76]</sup> since initialization of near-ground states in individual sites has been shown.<sup>[57]</sup> However, it is important to emphasize that the

direct coupling strength (via resonant Coulomb interaction) exceeds the strengths of synthesized couplings, such as effective spin-spin interactions mediated by phonons according to perturbation theory (see below).<sup>[77]</sup> Consequently, after reduction of noise fields it may be beneficial to decrease the structure sizes (with required  $h/d \approx 1$ ) on the chip even further to increase the inter-site coupling strength  $\propto d^{-3}$ , limited by increasing heating rates (empirically found to scale approx. with  $\propto h^{-4}$ ). Alternatively, exploiting additional ions per site can allow for sympathetic assistance<sup>[78]</sup> and increase the coupling.<sup>[76]</sup> Generation of squeezed, initial states of the motional degrees can boost effective interaction strengths even further.<sup>[79]</sup> In this way, it should be possible to complete the quantum control toolbox in a single experimental apparatus and enable the creation of deterministic entanglement within an entire array. Further engineering anharmonicities by accessing higher order terms of the trapping potential might allow for novel tools, such as realizing motional mode mixing and on-site phonon-phonon coupling.<sup>[77]</sup>

During step (2), platform scaling to tens or hundreds of sites in two dimensions may ultimately enable deeper insight into physics of interest. Here it is still possible to rely on established fabrication technologies, such as CMOS and MEMS processes<sup>[80,81]</sup> with parameter regimes similar to the proof-of-principle devices.<sup>[57]</sup> Since micro arrays can be filled deterministically and sequentially with ions, the complexity of AQS (build up ion by ion) can be tuned and used to investigate the correlations of scaling, complexity and residual experimental limitations. Moreover, as mentioned above, an additional layer of micro sites can be accessed to extend simulations into the third dimension. This has already been realized for ancilla traps above our basic triangular array, exploited to assist loading, and to transfer ions via control voltages, opening transport channels between individual sites.<sup>[57]</sup> While it will still take years until an experimental quantum simulator based on any platform will challenge or outperform state-of-the-art and continuously improved numerical methods on quantum effects of interest, this may be the only access to highly entangled quantum systems.<sup>[4]</sup> Definitely, it will remain advantageous to further propel numerical approximations and experimental simulators in parallel, for example, to allow for benchmarking, and improving models, and their approximations in well-controlled many-body systems.

In the following, we concentrate on mid- and long-term quantum simulation goals that can be addressed by fully controlled multi-site lattices and discuss three examples, i) quantum spin Hamiltonians, ii) artificial gauge fields, and iii) transport phenomena: i) Here, the goal will be to address quantum spin Hamiltonians in square and triangular lattices and the phenomenon of degenerate ground states, in particular, studying the increase of complexity by increasing size, interaction strength, as well as interaction range. Some examples are stated in ref. [82], considering dipolar interactions between spins in spin-ice materials giving rise to emergent magnetic monopoles,<sup>[83]</sup> effective long-range magnetic interactions between zigzag edges in graphene,<sup>[84]</sup> spin-frustration,<sup>[4,14]</sup> as well as the instantaneous transmission of correlations after local quenches.<sup>[21,22]</sup> ii) Artificial gauge fields and the related Aharonov-Bohm physics in rhombic ladders, launching a change of paradigm where phonons are exploited directly (in quantum information processing based on trapped ions, phonons have been restricted to

mediate interactions). Here, the ions are located in a potential array representing lattice sites and phonons tunneling between these sites simulate hopping, charged particles.<sup>[85,86]</sup> The amplitude and phase of the vibrational couplings between sites can be controlled via Photon-Assisted-Tunneling (PAT). For neutral atoms this has been exploited to provide effective gauge fields. We can achieve PAT by parametrically modulating the individual confinements of detuned trapping sites—in contrast to a shaking of the entire lattice that is accompanied by fundamental heating effects.<sup>[87]</sup> Analogue to the Aharonov–Bohm effect, the phonons pick up geometric phases, proportional to the area the loops enclose on the surface pierced by an external field. Depending on the phases of different pathways, constructive and destructive interference rule the dynamics. The latter can cause coupled modes of the system to become localized and vibrational bands (onset for ten sites), where nonzero energy modes correspond to the so-called Aharonov–Bohm cages, while edge states get exponentially localized around the boundaries (onset for seven sites).<sup>[86,88]</sup> We stress that arbitrary fluxes can be attained, even reaching one flux quantum per unit cell—a regime inaccessible in solid-state materials for realistic magnetic fields. Furthermore, applying two-photon stimulated Raman transitions permits adding state-dependent Stark shifts to incorporate state-dependent tunneling and an effective spin–spin interaction, respectively. iii) Quantum dynamics in crystalline or even non-periodic micro arrays might also permit studying complex transport and thermalisation processes. For example, featured by quantum walks,<sup>[16,17,89–91]</sup> transport phenomena,<sup>[92–96]</sup> their expiration due to many-body localization<sup>[97]</sup> and equilibration/thermalization in 2D in open/closed quantum systems.<sup>[98–101]</sup> In addition, dependent on the density of the ensemble, it may be necessary to include boundary electrode structures to compensate for the overall Coulomb repulsion,<sup>[61]</sup> that is, mimicking infinite lattices. In this context, creating periodic boundary conditions in ring-traps might become possible.<sup>[102]</sup> When individual control along the ring is provided, the traps of the array could get linked to form an orbit and accelerate ions to form crystalline beams<sup>[103–105]</sup> and still allowing for pulsed coherent control of electronic and motional degrees of freedom.<sup>[106,107]</sup> First promising results demonstrate the treatment of angular momentum of rotating ions in the quantum regime.<sup>[108,109]</sup> In summary, such first generation studies may fully exploit the 2D architecture and its tunable interactions at long range, while, in principle, preserving most of the unique operational fidelities of single and few ion systems. We judge the architecture of individual atomic ions controlled in micro trap arrays, potentially combined with optical lattices,<sup>[110,111]</sup> to be a promising platform that may contribute to future applications and developments. However, John Preskill recently coined the term Noisy Intermediate-Scale Quantum-era<sup>[112]</sup> to describe the current status of the research field and reported about his personal view of a roadmap that covers upcoming decades. Relying on these timescales, experts are trying to assess the future relevance and potential impact of experimental quantum simulations on industry.<sup>[113]</sup> However, the general assumption that experimental quantum simulators might be intrinsically more robust than digital quantum computers might have to be carefully analyzed considering each individual application.<sup>[5]</sup> In addition, experimentally controlled quantum systems can reach a large size in Hilbert space that seemingly turns them numerically

intractable—if exact diagonalization is required. While it is, generally, a complex task to derive the size of a quantum system that is (currently) numerically intractable, we consider the following example: Assume an fully loaded array of  $N_{\text{sites}} = N_{\text{ions}} = 10$  sites (single ions in each site), where the ions' pseudo spin states and  $N_{\text{modes}} = 2$  of their modes of motion (enabling coherent inter-site couplings) are relevant in the dynamics. In this case, a numerical estimation (via exact diagonalization) of dynamics involves  $N = 2^{N_{\text{ions}}} \times n_c^{(N_{\text{modes}} \times N_{\text{ions}})} > 2^{41}$  eigenstates, when truncating the motional (Fock-) states to  $n_c = 3$ . To follow the dynamics, a Matrix of  $N^2$  has to be handled and dependent on the relevant timescales of the problem leaves numerical tractability. Yet, a lack of complexity might well allow for numerical approximations providing sufficiently small and derivable errors. In any case, gaining in isolation and coherent control in complex systems will be key to reach toward applications of academic and industrial interest. Concluding, we share the opinion of John Preskill: “Because quantum computing technology is so different from the information technology we use now, we have only a very limited ability to glimpse its future applications, or to project when these applications will come to fruition.”<sup>[112]</sup>

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## Conflict of Interest

The authors declare no conflict of interest.

## Keywords

quantum simulations, quantum technology hardware platform, surface-electrode trap arrays, trapped atomic ions

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