White Paper on the future of Rydberg Atoms Quantum computing infrastructure in Europe

This White Paper represents the position of the consortium partners of the EuRyQa project (Horizon Europe programme HORIZON-CL4-2021-DIGITAL-EMERGING-01-30 via the project 101070144) on the future of neutral atom quantum computing in Europe. It aims at providing input into the next EU program for research and innovation and the Quantum Act.

It presents the ***outcomes*** *of the project, the* ***vision*** *for the future of the research in this field and* ***recommendations*** *for policy makers stakeholders.*

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Executive Summary

Today's prototype quantum systems are capable of performing specific computational tasks at the limits of what is possible using classical computers, but there remains a long way to go before achieving full-fledged quantum computers. However, 2025 — the International Year of Quantum Science and Technology — marked a decisive transition: quantum technologies have begun entering the era of efficient quantum error correction and fault tolerance, heralding a new phase of quantum computation that promises unambiguous quantum advantage across areas of societal and strategic importance for the EU. EuRyQa ("European Infrastructure for Rydberg quantum computing") is the Quantum Flagship program competitively selected to develop digital, programmable quantum computers based on neutral atoms. Thanks to key results from EuRyQa and international laboratories, all requirements for fault tolerance have now been demonstrated for neutral atom quantum computing technology. This technology is currently the best platform for scaling up to millions of well-controlled qubits in a single quantum computing node and for designing flexible architectures for quantum error correction and Fault Tolerant Quantum Computing (FTQC). This is based on a unique combination of features which include all-to-all and dynamical qubit couplings, native high-fidelity and fast multi-qubit gates, all-optical controls, etc. As a result, neutral atoms are among the most promising, and fastest improving, platforms for Fault Tolerant Quantum Computing.

EuRyQa provides a tightly focused EU program for quantum computing. It is built on a close collaboration among nationally selected quantum computing platforms, academic research centers and leading companies in quantum hardware, control electronics and software, providing Europe with a well-coordinated and focused effort to develop a full stack quantum computer.

This white paper expresses the key technical requirements and needs to achieve large scale FTQC with neutral atoms. It also provides a vision of how the European Union could develop such a program, via a competitive long-term research and development program, built on partnerships between private and public sectors, with clearly stated strategy goals, the necessary funding, goal-oriented decision-making and periodic review.

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Chapter 1 EuRyQa: Digital neutral atom quantum computers from NISQ to FTQC

Quantum computing is widely recognized as a strategic technology with the potential to transform fields such as chemistry, materials science, optimization, and machine learning, with far-reaching impacts on energy, mobility, healthcare, and artificial intelligence. Europe has therefore identified quantum computing as a key pillar for long-term technological sovereignty and economic competitiveness.

Among the different hardware platforms under development, neutral atoms manipulated with optical tweezers and interacting through Rydberg states have emerged as a leading approach. Neutral atoms offer exceptional isolation from the environment, long coherence times, and interactions that can be switched on and controlled optically. In addition, optical tweezer arrays allow atoms to be dynamically arranged in large, programmable geometries, providing a level of architectural flexibility impossible to achieve in other platforms.

Even before the start of the EuRyQa program – before 2021 –, neutral-atom systems had already demonstrated most of the fundamental ingredients required for quantum computing. In particular, they satisfied the key criteria commonly used to evaluate quantum computing platforms: the ability to initialize and read out qubits, perform coherent single-qubit control, realize controllable interactions between qubits, and scale to large numbers of qubits. However, an important limitation remained: the fidelity of two-qubit gates was not yet high enough for useful digital quantum computation, especially on large qubit arrays – a situation typical of the so-called *noisy intermediate scale quantum* (NISQ) era. As a result, neutral-atom platforms were used predominantly for analog quantum simulation, where large arrays of interacting atoms could emulate complex many-body quantum systems.

The EuRyQa network was created to overcome these limitations by bringing together leading European academic groups and industrial partners across the full digital quantum computing stack, from atomic physics and quantum control to electronics, firmware, software, and cloud integration. Through coordinated efforts, EuRyQa has enabled major advances in hardware, control protocols, and system integration. In particular, the development of optimized control techniques and improved experimental architectures has significantly increased the fidelity of Rydberg-based entangling gates — historically the main bottleneck of the platform.

These advances have transformed neutral-atom systems from powerful quantum simulators into a viable architecture for general-purpose quantum computing, strengthening Europe’s position in the global race toward scalable and fault-tolerant quantum technologies.

Building on these achievements, as EuRyQa we recognize that new requirements must now be established for any quantum computers operating in the fault-tolerant regime, as presented below.

Chapter 2 Neutral atoms for FTQC: technical assessment

1) Requirements for FTQC – demonstration

Achieving fault-tolerant quantum computing (FTQC) requires more than incremental advances over today's NISQ devices; it will require a fully integrated technology stack linking hardware, control, architecture, and algorithms into coherent and scalable systems. At the physical level, this entails realizing large-scale qubit arrays with high connectivity, fast and accurate multi-qubit gates, and coherence times sufficient to sustain active quantum error correction. It requires innovation regarding quantum error correcting codes and fault-tolerant gate implementations with resource overheads that remain manageable as the system scales. And it also requires sophisticated software and control systems that can manage compilation, calibration, syndrome extraction and real-time classical decoding to sustain fault-tolerant operation over long timescales.

In practical terms, the requirements for FTQC, independent of the precise hardware modality, can be framed around four core criteria:

Scalable, high-quality qubits and gates — physical qubits and multi-qubit operations achieving sub-threshold error rates (below ~0.03, depending on the error correcting code), and a credible path toward million-qubit-scale systems with high connectivity

Quantum error-correcting codes and logical memory — demonstration of long-lived, actively protected logical qubits with error suppression below physical rates over many correction cycles.

Universal fault-tolerant logical gates — a complete set of logical gates for fault-tolerant logical qubits implemented with acceptable space–time overheads, ideally highly adapted to the underlying hardware architecture.

Integrated classical co-processing — a mature software and hardware stack enabling real-time syndrome extraction, fast decoding, and seamless compilation of fault-tolerant quantum algorithms across the full system.

2) European position in neutral atom quantum computing

European efforts have placed neutral-atom quantum computing on a clear trajectory from few-qubit demonstrators towards processors that meet the stringent requirements of fault-tolerant quantum computing. While several of the largest current hardware demonstrations originate from US-based teams, European groups and companies have been pivotal in shaping the architectures, control methods, and error-correction strategies that will determine which platforms ultimately scale to the mega- and gigaquop regimes. In particular, work coordinated through programmes such as EuRyQa has driven advances in large-register scalability, high-fidelity Rydberg-gate design, realistic noise and threshold analysis, and the co-development of hardware with a mature classical and software stack. In what follows, we discuss the state of the art in neutral-atom quantum computing, with an emphasis on Europe along the four key FTQC requirements: scalable high-quality hardware, quantum error correction and protected logical memory, universal fault-tolerant gate sets, and classical co-processing and software.

Scalable, high-quality qubits and physical gates

Before 2021 – the start of EuRyQa –, two-qubit gate fidelities in neutral-atom quantum computers based on Rydberg blockade interactions had reached the mid- to high-90% range in leading experiments. By 2019–2021, groups such as at Harvard University and University of Wisconsin–Madison in the US demonstrated controlled-phase and CNOT-type gates with fidelities around ~97–98% in optical tweezer arrays . These results verified high-quality entanglement in scalable atom arrays, but fidelities generally remained below threshold for practical fault-tolerant error correction. **EuRyQa has transformed the field** by proposing new time-optimal and robust protocols for two-qubit and multi-qubit gates that have allowed achieving two-qubit gate fidelities ≳99.7 % in platforms based on many different types of atoms, such as Rb, Cs, Yb, and Sr. The limitations of the currently best two-qubit gate fidelities are well understood and can be improved beyond 99.9 %, for example with better suppression of laser phase noise and faster gate speeds. Combined with rapidly growing array sizes, this puts the neutral atoms platform in a leading position for combining high-fidelity entanglement, massive parallelism and flexible connectivity—three ingredients that any scalable, error-corrected architecture must provide. For example, programmable neutral-atom arrays have crossed the thousand-qubit frontier and currently hold the record for the largest coherent and programmable qubit array of 6100 Cs qubits [Nature 647, 60–67 (2025)]. Moreover, ^{171}Yb experiments have demonstrated flexible qubit encoding with coherent mapping and entanglement across Rydberg, metastable and clock qubits within the same device [arXiv:2506.13632 (2025)]. Because a single laser can address hundreds to thousands of atoms at once, the classical and optical control overhead can grow much more slowly than the qubit number . Together, these results bring neutral-atom hardware into the regime where meaningful demonstrations of logical qubits become realistic. As a result, since 2024, these achievements have paved the way for increasingly advanced **demonstrations of practical quantum error correction in neutral atoms**, with capabilities on par with, or even exceeding, those of other quantum computing platforms.

Quantum error correction and long-lived logical memories

Quantum error correction (QEC) is essential for scaling quantum computers beyond the noisy intermediate-scale regime. To date, the **surface code** has been the workhorse architecture because it tolerates relatively high error rates and operates under generic noise models with local stabilizers. Several experimental platforms have now demonstrated logical qubits and even sub-threshold performance using surface-code–type architectures, including with neutral atoms [Nature 649, 39–46 (2026)]. However, the large **space overhead** of these codes—requiring many physical qubits per logical qubit—has become a central bottleneck for scalable quantum computation.

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As physical gate fidelities approach QEC thresholds, the field is shifting toward **more resource-efficient codes and noise-aware error-correction strategies**. High-rate quantum LDPC codes promise dramatically improved encoding efficiency, while tailored noise models—such as erasure-biased channels—can significantly raise fault-tolerance thresholds and reduce overhead. Neutral-atom platforms are particularly well positioned in this landscape due to their large programmable arrays, flexible connectivity, and the possibility of converting dominant physical errors into **detectable erasures and doing continuous, mid-circuit correction for atom-losses**, which substantially relaxes QEC requirements.

The **EuRyQa** program targets precisely this next stage of quantum error correction by co-designing hardware, noise models, and codes for neutral-atom processors. Experiments with metastable ^{171}Yb have already demonstrated **mid-circuit erasure detection**, converting a large fraction of gate errors into flagged erasures while leaving surrounding qubits unaffected. This capability enables error-correction schemes such as XZZX surface codes to operate at significantly higher effective thresholds than under standard depolarizing noise.

In parallel, EuRyQa partners are developing **high-rate qLDPC codes tailored to neutral-atom architectures**. UNISTRA has designed families of 2D-local LDPC constructions compatible with programmable Rydberg interactions, achieving encoding rates far above the surface code while maintaining practical connectivity requirements. Circuit-level simulations indicate that these codes can achieve substantially lower logical error rates once two-qubit gate errors reach the 10^{-3}–10^{-2} regime. Complementary work explores implementations on **reconfigurable atom arrays**, where atom rearrangement and long-range interactions enable efficient stabilizer measurement with reduced qubit overhead.

These efforts extend across the full QEC stack within EuRyQa. Code development and simulation frameworks quantify realistic thresholds and logical-gate performance; architecture proposals integrate long-lived data qubits with fast measurement ancillas for non-destructive stabilizer readout; and noise engineering strategies exploit erasure-biased channels natural to alkaline-earth–like atoms. Together, these advances position neutral-atom arrays as a promising platform for **high-threshold, hardware-tailored quantum error correction**, with a clear path toward long-lived logical qubits and scalable fault-tolerant processors.

Universal fault-tolerant logical gate sets with acceptable overhead

Before 2021, no clear experimental roadmap existed toward resource-efficient, fault-tolerant quantum computation. Scalable demonstrations of quantum-error-corrected memories were still lacking, and implementing logical gates within fully protected code spaces remained a long-term objective. On the theoretical side, the Eastin–Knill theorem (Phys. Rev. Lett. 102, 110502 (2009)) established a fundamental constraint: no quantum error-correcting code supports a universal gate set implemented entirely through transversal operations. As a result, implementing a universal gate set typically relies on resource-intensive procedures such as magic-state injection and distillation, leading to large space- and time-overheads. In conventional two-dimensional surface-code architectures with strictly local connectivity, each logical operation requires multiple rounds of stabiliser extraction and substantial routing overhead, while magic-state factories dominate both qubit counts and runtime for algorithms with deep non-Clifford layers. Furthermore, beyond surface and color codes, systematic strategies enabling transversal Clifford gates while preserving addressability in advanced codes such as high-rate quantum low-density parity-check (qLDPC) codes remained largely unexplored.

Experiments across several platforms have recently demonstrated key milestones, including surface code memories with repeated cycles above threshold (Nature 605, 669–674 (2022)) and quantum error correction below the surface code threshold with superconducting qubits (Nature 638 920-926 (2025)) universal logical gates with magic-state injection in trapped-ion systems (Nature 605, 675–680 (2022)), first logical operations in reconfigurable neutral-atom arrays (Nature 604, 451–456 (2022)), and logical magic-state distillation directly in a neutral-atom processor (Nature 645, 620–625 (2025)). Together, these results confirm that fault-tolerant logical primitives (Nature 649, 39–46 (2026)) can be realised experimentally and provide a foundation for architectures designed to minimise overhead.

Within this rapidly evolving context, EuRyQa focuses on exploiting the unique capabilities of neutral-atom systems to implement hardware-efficient logical gates and scalable error-corrected architectures. Reconfigurable atom arrays enable "geometry-on-demand" connectivity: ancilla qubits or entangled blocks can be coherently moved across the processor to mediate interactions between distant code patches, allowing transversal-style Clifford operations and logical entangling gates without extensive routing. Native multiqubit Rydberg interactions allow direct measurement of high-weight stabilisers and logical parities, avoiding long sequences of two-qubit gates and reducing the number of entangling layers required per error-correction cycle. Recent demonstrations of collective Rydberg operations and time-optimal multiqubit gates provide the physical primitives required for these approaches.

EuRyQa advances these capabilities along two complementary directions. First, it develops **hardware-tailored logical-gate constructions** based on long-range and multiqubit Rydberg interactions, enabling efficient logical entangling gates between separated surface-code or qLDPC patches and fast stabiliser measurements in one or a few entangling layers. Second, the project develops **dedicated compilation and synthesis tools** that explicitly incorporate the neutral-atom interaction graph, multiqubit gate set, and noise characteristics—particularly erasure-biased error channels arising in metastable alkaline-earth-like encodings. These tools map logical Clifford and non-Clifford operations to minimal-depth physical gate sequences while coordinating decoding strategies that exploit erasure information to improve fault tolerance.

At the same time, complementary theoretical developments—including improved magic-state distillation protocols, logical code-switching approaches for non-Clifford gates, and hybrid schemes combining transversal operations with correlated decoding—suggest that the time overhead of fault-tolerant quantum computation can, in principle, be reduced to a constant factor (Nature 646, 303–308 (2025); Nature 649, 39–46 (2026)).

Together, these achievements position EuRyQa at the forefront of efforts to transform fault-tolerant quantum computing from a theoretical construct into a realistic, resource-efficient technology. By combining programmable neutral-atom hardware, multiqubit Rydberg operations, advanced compilation techniques, and new theoretical approaches to non-Clifford resource generation, the project establishes a credible roadmap toward scalable quantum processors capable of running large-scale algorithms with practical overheads.

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Integrated classical co-processing, compilation, and decoding

Fault-tolerant quantum computing places demanding requirements not only on the quantum hardware but also on the surrounding classical infrastructure. Practical systems must coordinate low-latency hardware control, scalable compilation and scheduling, and real-time decoding of stabiliser measurements, all while maintaining manageable calibration overheads (Quantum Sci. Technol. 9, 033001, 2024). Neutral-atom quantum processors are particularly favourable in this respect. Their gate speeds and coherence times allow stabiliser measurements, decoding, and classical feedback to operate on compatible timescales without requiring highly specialised classical hardware. This “goldilocks zone” makes neutral atoms a strong candidate platform for large-scale fault-tolerant quantum computing, even as systems scale toward thousands of qubits.

Recent work has begun to formalise the classical co-processing requirements associated with such systems. In particular, latency-based benchmarks for controller–decoder architectures have shown that classical processing can become a limiting factor for fault-tolerant circuits if decoding and feed-forward operations are not executed sufficiently quickly. Experiments and simulations of non-Clifford error-correction circuits demonstrate that decoding-dependent feedback may become the dominant bottleneck when classical latency exceeds the timescale set by stabiliser cycles and gate operations (Tan et al., Quantum 8, 1281, 2024). These results highlight the need for tightly integrated classical–quantum stacks capable of **sustaining high-throughput stabiliser processing and adaptive circuit execution**.

The state of the art already combines high-performance control electronics with specialised compilation frameworks. Modern quantum-control stacks typically rely on FPGA-based controllers capable of nanosecond-scale timing, real-time feedback, and flexible waveform generation for complex multi-qubit gate sequences (Quantum Sci. Technol. 9, 033001, 2024). Neutral-atom platforms have developed control systems that can orchestrate Rydberg excitation pulses, mid-circuit measurements, and atom rearrangement across large arrays, supporting the first demonstrations of logical-qubit operations that already depend on nontrivial classical processing. In parallel, a rapidly expanding ecosystem of **neutral-atom–specific compilation tools** is emerging. These include design-automation frameworks for neutral-atom processors, optimal and satisfiability-modulo-theory (SMT) based layout synthesis for dynamically field-programmable qubit arrays, heuristic and graph-based compilers for reconfigurable atom arrays, and architecture-aware compilation strategies that minimise atom movement while exploiting global Rydberg pulses. More recently, machine-learning and reinforcement-learning approaches have begun to treat compilation as a sequential decision problem, training agents to learn efficient movement and layout strategies tailored to neutral-atom architectures.

Within EuRyQa, major progress is being made toward integrating these classical capabilities into a **coherent fault-tolerant quantum computing stack.** On the control side, TUE has developed FPGA-based infrastructure capable of nanosecond-scale timing and complex pulse scheduling across large neutral-atom arrays. This system supports optimised Rydberg pulse sequences, mid-circuit measurements, and conditional operations on timescales compatible with Rydberg coherence and gate durations, enabling real-time adaptive quantum circuits. In parallel, Qruise has developed differentiable digital-twin models of neutral-atom devices that capture motional dynamics, control-transfer functions, and non-Markovian noise processes. These models enable gradient-based pulse optimisation, noise-aware compilation, and hybrid calibration routines that significantly reduce the experimental measurement budget while maintaining high-fidelity operations. By allowing new gate protocols to be prototyped and optimised in simulation before deployment on hardware, these tools accelerate development cycles and improve device stability during extended experimental runs.

At the system level, EuRyQa partners are beginning to assemble integrated compilation and decoding pipelines tailored to the distinctive characteristics of neutral-atom processors. These workflows explicitly incorporate hardware constraints, such as atom movement and programmable connectivity, while accounting for platform-specific noise processes including erasures and atom loss. Logical-gate synthesis, decoding strategies, and classical feedback protocols are co-designed with the available multiqubit Rydberg operations and control infrastructure, ensuring that classical processing remains compatible with stabiliser-cycle timing and large-scale array operation. Complementary work has also advanced hardware-aware compilation schemes in which equivalent circuit representations are optimized using platform-specific error models, thereby opening a route toward quantum-assisted compiler modules for fidelity-aware circuit optimization.

Together, these developments demonstrate that neutral-atom quantum processors can be supported by a **scalable and efficient classical co-processing layer**. By combining high-performance control electronics, advanced compilation frameworks, machine-learning–assisted optimisation, and hardware-aware decoding strategies, EuRyQa is laying the foundations for a fully integrated classical–quantum architecture capable of supporting large-scale fault-tolerant quantum computation.

Challenges for FTQC with neutral atoms

Fault-tolerant quantum computing presents major challenges across all leading hardware platforms—including superconducting circuits, trapped ions, and neutral atoms. Achieving practical quantum advantage requires sustained improvements in gate fidelities beyond 99.9% together with scaling to processors containing more than 10,000 qubits. Neutral-atom quantum processors have made rapid progress toward these targets, but several scientific and engineering challenges must still be addressed to translate current demonstrations into large-scale fault-tolerant systems.

A first priority is the **continued improvement and scalable deployment of high-performance quantum gates**. State-of-the-art neutral-atom two-qubit gates currently reach fidelities of about 99.7%, with well-understood limitations arising from laser phase noise, atomic motion, and control imperfections. These limitations can be mitigated through improved laser stability, faster gate protocols, and advanced pulse-engineering techniques. However, these fidelities have so far been demonstrated primarily in relatively small systems. Future fault-tolerant processors will require maintaining similar performance across arrays of thousands to tens of thousands of atoms while minimizing crosstalk, suppressing state-preparation-and-measurement (SPAM) errors, and ensuring reliable local addressing.

Another key challenge is **atom loss and long-term operational reliability**. Neutral-atom arrays rely on trapping individual atoms in optical potentials, and stochastic atom loss during long experimental sequences can limit error-correction performance. Mitigation strategies include continuously loaded atom arrays, rapid reloading techniques, improved vacuum and trapping conditions, and error-correction protocols designed to tolerate erasures. Continuous loading architectures—where lost atoms are replaced without interrupting the computation—are particularly promising but remain technically complex, often requiring additional subsystems and atom-transfer mechanisms. Further engineering and industrialisation of such solutions will be required to support truly continuous operation in large processors.

Maintaining stable **hardware performance over long experimental runs** is another central challenge. Neutral-atom systems are sensitive to drifts in control parameters, including laser power, polarization, alignment, and background electromagnetic fields. Although laser frequencies and powers can in principle be stabilised precisely, monitoring and controlling all relevant parameters directly at the atom position remains difficult due to the complexity of optical setups. In practice, current systems interleave computation with calibration routines to compensate for such drifts. While effective, this approach introduces time overhead and reduces overall computational throughput. Moving toward continuous calibration and feedback will therefore be important. One promising direction is to exploit error-correction syndrome measurements themselves as diagnostic signals that can feed back into hardware control. Machine-learning approaches, such as reinforcement learning linking syndrome data to control adjustments, may offer scalable ways to stabilise system parameters during operation.

Neutral atoms offer a distinctive advantage through dynamic qubit connectivity: atoms can be rearranged during computation, enabling flexible interaction graphs and efficient distribution of entanglement across the processor. This capability has already enabled demonstrations of programmable connectivity and key elements of quantum error correction. However, **atom rearrangement and qubit readout** remain slower than single- and two-qubit gate operations and may become bottlenecks in deep error-correction cycles. Fault-tolerant quantum computing requires repeated cycles of syndrome measurements and feedback, making fast, reliable measurement and reset operations essential. Reducing cycle times—particularly for initialization, measurement, and atom movement—will therefore be critical. Approaches under exploration include faster shuttling techniques, dual-species architectures, using quantum buses connecting distant atoms, zone-based readout schemes, and alternative error-correction strategies that reduce reliance on frequent measurements.

Scaling neutral-atom processors also requires advances in the supporting hardware infrastructure. Large-scale systems depend on complex optical architectures involving multiple stabilised laser sources, beam-delivery networks, and optical modules capable of addressing large arrays with high precision. Future processors will require **compact, robust, and scalable laser and optical systems together with highly parallel control electronics** capable of driving thousands of qubits simultaneously with nanosecond-level timing accuracy. Parallel control and modular optical systems will be key to maintaining performance as system sizes grow.

Equally important is the tight **integration of hardware and software**. Fault-tolerant quantum processors require sophisticated compilers, decoders, and classical-control systems that map logical circuits onto hardware operations while accounting for connectivity constraints, noise characteristics, and atom movement. Efficient classical co-processing is essential to maintain low-latency feedback during stabiliser cycles and to optimise gate scheduling and qubit layouts. As system sizes increase, scalable compilation pipelines and decoding algorithms must be co-designed with the hardware to avoid classical bottlenecks.

Understanding and mitigating error sources will also be crucial for accelerating technological progress. As systems grow larger and more complex, identifying the dominant contributors to gate errors and algorithmic failures becomes increasingly difficult. While analytical models can describe simple one- or two-qubit systems, realistic fault-tolerant subsystems require detailed numerical modelling of larger systems and advanced experimental design methods. Digital-twin models and data-driven approaches can help quantify the relative importance of different error processes, guiding research and development toward the most impactful improvements.

Understanding how the **energy consumption of quantum processors** scales with the number of quits is essential for assessing whether large-scale fault-tolerant quantum computers can become viable computational resources. The potential for a quantum energy advantage exists. The energy efficiency of Rydberg-atom platforms has only begun to be investigated very recently [Quantum Sci. Technol. **8** 025001, 2023], but early results are promising. Recent findings [arXiv:2601.03141] show that baseline costs – mainly those associated with the optical traps – dominate, but are substantially lower than those of other quantum computing platforms, which rely on energetically-demanding cryogenic systems. This suggests that the neutral-atom platforms may offer a potential energy advantage over alternative quantum computing implementations. Another work [arXiv:2511.20388] analyzed the energetic consumption of a Rydberg-atom processor performing analogue quantum simulations, showing that neutral-atom devices can deliver comparable or superior performance compared to classical approaches, with significantly reduced energy consumption. However, a truly comprehensive study of the energetics of quantum computation remains an outstanding, highly nontrivial task. It should also establish benchmarks to evaluate energetic performance and to enable meaningful comparisons across different setups and platforms, and between classical and quantum machines.

Finally, the successful development of large-scale neutral-atom quantum computers depends on building a strong **interdisciplinary skills base**. Progress requires coordinated expertise in atomic physics, laser and optical engineering, electronics, control systems, computer science, and quantum information theory. Strengthening this ecosystem—across academia, startups, and industrial partners—will be essential to sustain rapid technological development.

Chapter 3 Strategic Recommendations

Neutral-atom quantum computing has progressed at an extraordinary pace over the past decade. What was largely a laboratory technology ten years ago has evolved into a leading platform for scalable quantum processors, with demonstrations now approaching the first elements of fault-tolerant quantum computing. Despite this progress, even an optimistic scaling of neutral-atom systems to around one million physical qubits will not automatically outperform modern high-performance computing (HPC) centres for many practical workloads. **Achieving practical quantum advantage will therefore require not only continued engineering improvements but also disruptive conceptual advances emerging from fundamental research. Sustaining the current technological momentum demands a coordinated European initiative that accelerates both hardware scaling and the development of fundamentally new approaches to quantum architectures, algorithms, and error correction.**

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Europe is uniquely positioned to lead such an effort. The continent combines world-class academic research groups, a rapidly growing ecosystem of quantum-technology startups, and globally competitive industrial partners in optics, lasers, and photonics. The latter sector in particular has demonstrated Europe's ability to dominate technologically demanding global markets. These capabilities are directly relevant to the scaling challenges of neutral-atom quantum computing.

Neutral-atom platforms offer a particularly compelling cost-to-performance ratio compared with other quantum hardware approaches. Unlike superconducting circuits, which require extensive cryogenic infrastructure, or semiconductor-based quantum processors that depend on advanced fabrication facilities, neutral-atom systems rely primarily on optical and vacuum technologies. These systems typically require minimal cryogenic support, leverage standardized optical and vacuum subsystems, and can operate with relatively modest shared infrastructure. As a result, they enable scientific innovation and technological competitiveness without the massive initial capital investments often required by alternative platforms. Furthermore, the minimal cryogenic requirements of neutral-atom platforms make them particularly favourable also from an energy consumption perspective.

Nevertheless, scaling neutral-atom processors toward fault-tolerant systems will still require substantial investment in infrastructure and enabling technologies. Future systems will depend on continued progress in several critical areas, including high-performance and ultra-stable laser systems, scalable optical architectures, modular control electronics, and advanced computing architectures for control and decoding. In addition, flexibility in exploring different atomic species—such as alkali and alkaline-earth atoms—will remain important for optimizing and benchmarking performance and enabling new capabilities. Although neutral-atom processors typically operate at or near room temperature, cryogenic technologies may become beneficial in the long term to suppress environmental noise (thermal radiation) and achieve ultra-high-fidelity qubit gates. **These developments further motivate strong academic–industrial partnerships and coordinated investment by both the public and private sectors.**

A central recommendation is therefore **to establish a large-scale European initiative** that encourages **ambitious, high-risk, and high-impact research directions** while maintaining a **clear technological roadmap**: fostering a spirit of constructive and friendly competition among European teams pursuing different technological approaches, as exemplified by the EuRyQa consortium, can be a powerful strategy at this stage. **Encouraging diversity in technical pathways and open comparison of results will help identify the most promising routes toward the next generation of quantum computers**, especially where new strategies and optimal hardware choices are still evolving. Such an initiative should build on existing structures, in particular the European Quantum Flagship and its coordination with Quantum Chips pilot lines, while expanding the scale and ambition of collaborative projects focused on neutral-atom technologies. The goal should be to develop a fully integrated European ecosystem spanning fundamental research, enabling technologies, and industrial deployment.

Strong and sustained development of public infrastructure alongside private investment should form the core of this strategy. **The experience gained in the EuRyQa consortium has demonstrated the value of close collaboration between universities, startups, and technology companies.** Industrial partners benefit from early access to cutting-edge research developments, while academic groups gain insight into engineering constraints and scalable system design. This model of co-development should be expanded, enabling joint exploration of new hardware modalities, architectures, and error-correction strategies specifically tailored to neutral-atom platforms. This would boost innovation, enhance cooperation across

Europe and feed into successful commercial exploitation without over-reliance on one or a few technology providers.

Future initiatives should also emphasize **focused, mission-oriented projects**. Rather than distributing resources across many loosely connected objectives, funding programmes should support long-term collaborations centred on clearly defined technological themes. Examples include the development of next-generation sources of atoms, scalable optical and laser infrastructures, modular quantum processor architectures, and new quantum error-correcting codes designed to exploit the connectivity and noise characteristics of neutral-atom arrays.

In parallel, **sustained support for fundamental research** remains essential. Academic laboratories continue to play a critical role in exploring new concepts and technologies that may later become key components of industrial quantum systems. Basic research efforts should therefore be supported across the full spectrum of neutral-atom quantum technologies, including quantum computing, quantum simulation, and quantum sensing and metrology.

Strategic programmes should also define **clear technological targets** to guide research and investment over the coming decade. Examples of such goals include the demonstration of neutral-atom quantum processing units capable of supporting more than 100 logical qubits under active quantum error correction, the development of practical and scalable quantum error-correction codes adapted to neutral-atom architectures, and the realization of robust and scalable processor designs capable of supporting both digital and analog quantum simulation of strongly correlated many-body systems.

A second strategic priority is the development of a **robust European supply chain for neutral-atom quantum technologies**. Scaling to large quantum processors will require specialised lasers, optical components, control electronics, and photonic subsystems at levels of stability and integration not currently available off-the-shelf. Coordinated European investment could accelerate the industrialisation of these components, ensuring technological sovereignty and reducing dependence on non-European suppliers. In particular, securing access to state-of-the-art enabling technologies—such as advanced laser systems, optical modulators, modular architectures, and reliable atomic sources—will be essential for long-term competitiveness.

Another important recommendation is the creation and long-term support of **joint industry–academia competence centres** at national and European levels. These centres should function as technology clusters with strong engineering capabilities, facilitating the transition from laboratory-scale demonstrations to industrially deployable systems. By bringing together physicists, engineers, computer scientists, and industrial partners, such clusters would help accelerate technology transfer, support workforce development, and strengthen Europe's overall quantum ecosystem.

Finally, **funding levels and programme structures must reflect the scale of the challenge.** Achieving globally competitive quantum technologies will require sustained investment comparable to major international initiatives. Large, multi-year programmes—combining fundamental research funding with technology-development support—should be implemented to ensure continuity and enable the construction of advanced experimental infrastructures.

Neutral-atom quantum technologies are now a mature and strategically vital part of the global quantum landscape. Europe has developed a strong leadership position supported by a unique combination of academic excellence, innovative startups, industrial partners, and national research infrastructures. Consolidating this leadership will require continued investment in fundamental science, long-term strategic planning toward specific technological targets, and strong engagement from both public and private stakeholders.

This moment therefore represents a unique opportunity to establish Europe as a global leader in the next generation of quantum technologies.

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