

Globally driven superconducting quantum computing architecture

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We propose a platform for implementing a universal, *globally driven* quantum computer based on a 2D ladder hosting three different species of superconducting qubits. In stark contrast with the existing literature, our scheme exploits the always-on longitudinal ZZ coupling. The latter, combined with specific driving frequencies, enables the reach of a blockade regime, which plays a pivotal role in the computing scheme.

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Introduction. Superconducting circuits have demonstrated exceptional performance in executing precise control and measurement operations, thus making them a preferred choice for quantum computing (QC) architectures [1–7]. Nevertheless, notwithstanding their remarkable properties, these platforms are still afflicted by a serious drawback. It is indeed widely recognized that the scalability of superconducting (and other solid-state) architectures faces a hurdle because of the need for *localized* control of each logical qubit [8–11]. This challenge, often dubbed the “wiring problem”, arises from the necessity of multiple control signals for each qubit in standard QC architectures, leading to a wiring overload [1,12,13]. In view of this fact, maintaining high gate fidelity while scaling up the number of qubits within a single processor presents a significant hurdle [14]. While state-of-the-art superconducting QC platforms can achieve single-qubit operation fidelities as high as 99.99% [15,16], reducing errors in two-qubit gates remains challenging. To our knowledge, the associated error rates for these operations persist at around 0.1% [17–21]. Incidentally, one of the main limiting factors to enhance two-qubit gate fidelity in superconducting platforms is the “residual” longitudinal ZZ interaction between neighboring qubits. While recent research endeavors have showcased methods to alleviate [22–25] and even leverage ZZ coupling [26–28] for implementing two-qubit gates, such interaction remains generally undesirable within conventional quantum superconducting QC frameworks.

To offer a solution to these daunting issues, we present a universal superconducting QC architecture where, exploiting the presence of always-on ZZ coupling terms, local driving

of each individual qubit is replaced by *global* pulses that control *collectively* a large collection (roughly one third) of the memory registers of the model, hence drastically reducing the total number of wires necessary to run the computation.

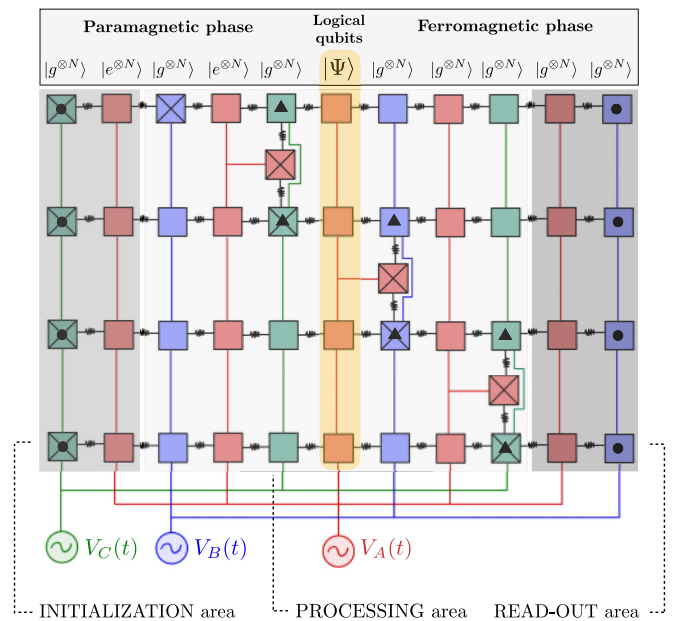


FIG. 1. Architecture for a globally driven superconducting quantum computer. Three groups, A, B, C of superconducting qubits (red, blue, and green squares, respectively) occupy the horizontal rows of a 2D ladder. Black springs, colored continuous lines, crosses, filled circles, and triangles are defined in the main text. Electrical wires depicted as continuous red, blue, and green lines connect all elements within each group, facilitating global control through independent classical electrical pulses. During the computation, the logical information is encoded in the qubits of one of the columns of the processing area (enlightened in yellow in the figure): qubits on the left (right)-hand side of such information carrier column are in a “paramagnetic” (“ferromagnetic”) *geg* (*ggg*) phase. The illustration pertains to a $N = 4$ logical qubit quantum computer.

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Historically, a pioneering global scheme of QC was first proposed by Lloyd [29]. Soon after, several other proposals for QC based on global control were put forward [30–32]. However, these failed to reach the readiness level necessary to be competitive with models based on local control. Our scheme is inspired by a recent disruptive advancement that was made by Cesa and Pichler [33], who presented a universal quantum computer based on globally driven Rydberg atoms. In this QC platform [34,35], two nearby atoms in an excited Rydberg state interact so strongly that their simultaneous excitation is forbidden (“Rydberg blockade” [36]). Building on this effect, the authors of Ref. [33] demonstrated that by arranging *two* different species of (N^2) Rydberg atoms in an almost-regular rectangular lattice, one can implement globally driven QC on N qubits.

Here, we propose a generalization of the results of Ref. [33] to a solid-state, superconducting platform. Readers will immediately understand that this is far from trivial since the aforementioned blockade effect does not come “for free” in our platform. Below, we show how to *dynamically* induce blockade into a lattice of superconducting qubits. Additionally, we use *three* rather than *two* species of qubits, which, as we argue below, significantly reduces (with respect to Ref. [33]) the number of physical qubits that are needed to implement a universal quantum computer. Last but not least, we propose a different initialization scheme with respect to that of Ref. [33], which helps us reducing the size of the initialization area of our solid-state quantum computer with respect to the Rydberg one. In our model, quantum information is always localized in the N superconducting qubits of one of the vertical columns that form the ladder (see Fig. 1), referred to as the “information carrier column” (ICC) in the following, while the remaining qubits are kept in a reference (separable) configuration. Quantum computation proceeds through sequences of control pulses that operate collectively on one or more of three species of qubits. These pulses serve to rigidly shift the position of the ICC in the ladder and activate single- and two-qubit gates on its elements at specific locations in the device, both enabled by the *blockade interactions* that connect the qubits. In our device, such interactions are implemented via the unwanted ZZ coupling mentioned above. As we will discuss below, by exploiting the fact that ZZ interactions can alleviate some of the degeneracies in the energy spectra of neighboring superconducting qubits, we selectively impede specific energy transitions, effectively emulating Rydberg blockade [33] on a superconducting platform.

Model. We propose the quantum computing architecture depicted in Fig. 1, which consists of a 2D ladder with N parallel rows. The ladder contains $2N + 3$ columns, each housing a distinct type of superconducting qubits chosen among three possible species A , B , and C (represented, respectively, by red, blue, and green squares in the figure), organized in the

$$\underbrace{CABA}_{\text{row 1}} \underbrace{CABA}_{\text{row 2}} \underbrace{CABA}_{\text{row 3}} \cdots \quad (1)$$

pattern. The first (last) two columns on the left (right) boundary of the ladder serve as dedicated areas for the initialization (read-out) stage of quantum computation. The central portion of the scheme, encompassing $2N - 1$ columns, represents instead the processing area of the model where the quantum

computation takes place. In this area, starting from the third column, each of the B - and C -type columns also incorporates an additional A -type qubit. This A -type qubit acts as a “coupler” between adjacent rows of the ladder, enabling two-qubit logic gates [37]. All qubits within a group share the same level spacing: $\hbar_A$ for A -type qubits, $\hbar_B$ for B -type qubits, and $\hbar_C$ for C -type qubits. Exceptions to this rule, marked with a black circle or triangle in Fig. 1, have level spacings slightly detuned from the nominal values to compensate for the “anomalous” (i.e., different) number of nearest-neighboring ZZ interacting elements (see the next paragraphs for details). In our model, qubits within the same row are interconnected via nearest-neighbor ZZ coupling, with uniform strength $\hbar\zeta$, depicted as black springs in the figure. This interaction also links additional intrarow coupler A -type qubits with adjacent B or C elements in the same column. Crucially, all A -type qubits are collectively driven by a *single* time-dependent external electrical signal, $V_A(t)$, via a continuous red line. Similarly, all B -type [C -type] qubits, including those with a black circle or triangle, are collectively driven by signal $V_B(t)$ [$V_C(t)$] through a dedicated blue [green] line. Finally, the crossed qubits in the device identify a subset of superconducting qubits A , B , or C that, while maintaining their nominal level spacings, couple with the external electrical signals $V_A(t)$, $V_B(t)$, or $V_C(t)$ at augmented Rabi frequencies. As shown in the figure, crossed elements of the same type never appear in the same row or column. Additionally, the pattern (1) ensures that any two columns that contain crossed elements of the same type B or C are always separated by a sequence of *three* columns that contain no crossed qubits of that same type. We point out that this feature, which is crucial for implementing single-qubit and two-qubit gates, can be engineered *at the level of circuit fabrication* and needs no extra control (see the Supplemental Material, SM [38]).

The total Hamiltonian of the ladder in Fig. 1 can be written as $\hat{H}(t) := \hat{H}_0 + \hat{H}_{\text{drive}}(t)$, where

$$\hat{H}_0 := \sum_{\chi \in \{A,B,C\}} \sum_{i \in \chi} \frac{\hbar}{2} \hat{\sigma}_i^{(z)} + \sum_{\langle i,j \rangle} \frac{\hbar\zeta}{2} \hat{\sigma}_i^{(z)} \otimes \hat{\sigma}_j^{(z)} \quad (2)$$

describes the local energy contribution of the superconducting qubits and their always-on ZZ interactions, while

$$\hat{H}_{\text{drive}}(t) := \sum_{\chi \in \{A,B,C\}} \sum_{i \in \chi} \hbar\Omega_\chi(t) \sin(\omega_{\chi} t + \phi_\chi(t)) \hat{\sigma}_i^{(y)} \quad (3)$$

represents the time-dependent driving owing to the classical control lines. In Eqs. (2) and (3), $\hat{\sigma}_i^{(x,y,z)}$ represent the Pauli matrices acting on the Hilbert space of the i th qubit, expressed in the local energy basis $|g_i\rangle := (0, 1)^T$, $|e_i\rangle := (1, 0)^T$. The summation in the second term on the right-hand side of Eq. (2) runs over all nearest-neighbor qubits. The parameter ω_{χ} denotes the oscillation frequency of the driving pulse $V_\chi(t)$, while $\Omega_\chi(t)$ and $\phi_\chi(t)$ define the time-dependent Rabi frequency and phase of such control. For simplicity, in writing Eq. (2), we have not specified that when i identifies a blue [green] qubit with a black circle, the corresponding qubit’s level spacing becomes $\hbar(\hbar_B - \zeta)$ [resp. $\hbar(\hbar_C - \zeta)$] instead of $\hbar_B$ [$\hbar_C$], and when it identifies a blue [green] qubit with a black triangle, it becomes $\hbar(\hbar_B + \zeta)$ [resp. $\hbar(\hbar_C + \zeta)$] instead of $\hbar_B$ [$\hbar_C$]. Similarly, whenever in Eq. (3) i identifies

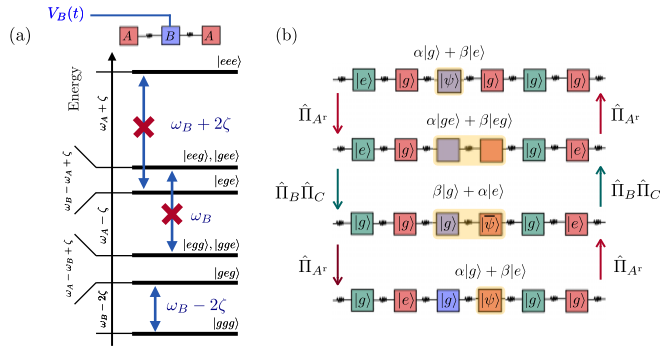


FIG. 2. (a) Energy spectrum of three qubits ABA coupled via nearest-neighbor ZZ couplings as in $\hat{H}_0$: a driving pulse of frequency $\omega_{d,B} = \omega_B - 2\zeta$ acting on the central B -type element can only activate transitions between the two lowest energy levels. The energy spectrum for the qubit triplet ACA is analogous to the one shown. In this case, the driving pulse must have a frequency $\omega_{d,C} = \omega_C - 2\zeta$. The same argument holds for the CAB triplet (C - and B -type qubits are driven at the same time thus they can be seen as the same species in this context) where the driving pulse is now $\omega_{d,A} = \omega_A - 2\zeta$. A generalization of this scheme for a $ABACA$ qubit chain is shown in the SM [38]. (b) Analysis of the sequence $\hat{U}_{\text{shift}} = \hat{\Pi}_{A^r} \hat{\Pi}_B \hat{\Pi}_C \hat{\Pi}_{A^r}$ that induces a collective motion of the interface for the case of a single ($N = 1$) row.

a crossed qubit, $\Omega_\chi(t)$ is replaced by $2\Omega_\chi(t)$. Apart from these local adjustments, which must be implemented once and for all at fabrication level, it is important to note that $\Omega_\chi(t)$, $\phi_\chi(t)$, and $\omega_{d,\chi}$ are independent of the index i , indicating that they represent a control acting *globally* on all qubits of type χ .

Blockade regime via ZZ interactions. Throughout our analysis, we assume that two ZZ -coupled nearest-neighbor qubits are never simultaneously driven [39]. Furthermore, in the time intervals where the control $V_\chi(t)$ is active, we shall assume the corresponding $\Omega_\chi(t)$ and $\phi_\chi(t)$ values to be constant. Under these driving conditions, there exists a particular choice of $\omega_{d,\chi}$, which allows us to implement a dynamical blockade regime. A physical insight into the origin of this effect can be obtained considering the energy spectrum of the Hamiltonian $\hat{H}_0$ for the simplified case where one has three alternating qubits, say the ABA triplet shown in Fig. 2(a), arranged in a single row. A generalization of Fig. 2(a) to a qubit chain $ABACA$ is provided in the SM [38]. In the ABA case, which capture the essential physics, one notices that, in the rotating wave approximation (RWA), if we apply a pulse $V_B(t)$ of frequency $\omega_{d,B} := \omega_B - 2\zeta$ to the central element, only the transition between states $|ggg\rangle$ and $|geg\rangle$ is activated, while other transitions are not allowed since they are off-resonance. In other words, whenever at least one of the “external” qubits of the triplet resides in the excited state $|e\rangle$, the system remains unaffected by the specified control pulse [40]. A generalization of this result to the full ladder can be obtained by describing the system’s evolution in the time-dependent reference frame defined by the controls. In particular, it is possible to show (see the SM [38]) that applying the unitary transformation $\hat{U}_{\text{rf}}(t) := e^{i\hat{\sigma}_i^{(z)} \omega_{d,i} t/2}$ in the realm of the RWA, the

Hamiltonian of the model reduces to

$$\hat{H}_{\text{rf}}(t) \simeq \sum_{\chi \in \{A,B,C\}} \sum_{i \in \chi} \frac{\hbar \Omega_\chi(t)}{2} [e^{i\phi_\chi(t)} |g_i\rangle \langle e_i| + \text{H.c.}] + \sum_{(i,j)} 2\hbar \zeta |e_i e_j\rangle \langle e_i e_j|. \quad (4)$$

If the dimensionless parameter $\eta_{\text{BR}} := |\zeta/\Omega_\chi| \gg 1$ (i.e., if the ZZ coupling is the largest energy scale), $\hat{H}_{\text{rf}}(t)$ exactly mimics the effective Rydberg-blockade Hamiltonian employed in Ref. [33]. We here stress that this Hamiltonian applies to *all* the qubits of the scheme, including the off-detuned elements indicated by black triangles or circles in Fig. 1.

Dynamics and quantum computation. The evolution induced by $\hat{H}_{\text{rf}}(t)$ can be expressed as ordered products of the form

$$\hat{U}_{\text{tot}} = \hat{U}_{\chi_\ell}^{(\ell)} \dots \hat{U}_{\chi_2}^{(2)} \hat{U}_{\chi_1}^{(1)}, \quad (5)$$

where $\hat{U}_{\chi_\ell}^{(\ell)}$ is the unitary operator associated with the ℓ th time window, where $V_{\chi_\ell}(t)$ is active. Each unitary operator $\hat{U}_\chi$ can be described as $\hat{U}_\chi := e^{-i\hat{H}_\chi \tau_\chi/\hbar}$, with $\hat{H}_\chi = \hat{H}_{\text{rf}}(\tau_\chi)$. Restricting ourselves to the blockade $\eta_{\text{BR}} \gg 1$ regime, we can consider the interaction term of $\hat{H}_\chi$ as a constraint that prevents any dynamical evolution on χ -type qubits unless both of their nearest-neighbor $\bar{\chi}$ -type qubits [41] are in the ground state $|g\rangle$. This implies that Eq. (5) reduces to a product of identical *control-unitary* operations [42], where each qubit of the χ type is controlled by its first neighboring sites of $\bar{\chi}$ type. One can prove (see the SM [38]) that, by using sequences (5) that only involve a finite set of $\hat{U}_\chi$ activated by the same control line $V_\chi(t)$, we can induce arbitrary evolutions of the form

$$\hat{W}_\chi(\theta', \mathbf{n}'; \theta'', \mathbf{n}'') := \hat{W}_{\chi^r}(\theta', \mathbf{n}') \hat{W}_{\chi^\times}(\theta'', \mathbf{n}''), \quad (6)$$

where χ^r ($\chi^\times$) is the subset of χ that includes all its regular (crossed) elements. For $\xi \in \{\chi^r, \chi^\times\}$, $\hat{W}_\xi(\theta, \mathbf{n})$ is a control-unitary transformation that applies to all qubits in ξ , a uniform, single-qubit rotation $\mathbb{R}_i(\theta, \mathbf{n}) := e^{-i\frac{\theta}{2} \mathbf{n} \cdot \hat{\sigma}_i}$ parametrized by the 3D unit vector $\mathbf{n}$ and the angle $\theta \in [0, 2\pi]$. Of particular relevance are the unitaries (6) where only one of the parameters θ' , θ'' differs from zero, which correspond to transformations that selectively operate on either χ^r or $\chi^\times$. This allows for the individual addressing of both regular and crossed qubits using only global pulses.

Following Ref. [33], we encode the quantum information on the 2D ladder by placing one logical qubit per row. As indicated in Fig. 1, at each computational step, these qubits reside on a single column of the processing area of the device. Such ICC can be formed either by A -, B -, or C -type qubits. However, if the ICC is formed by B - or C -type qubits, the red-crossed elements in Fig. 1, which act as intrarow couplers, are not involved in the encoding but will always remain into the ground state $|g\rangle$ of their local Hamiltonian.

The ICC is positioned at the interface between two strings of qubits: a “ferromagnetic” phase ($|gggg\dots\rangle$) on the right, and a “paramagnetic” phase ($|\dots gegeg\rangle$) on the left. Assuming that at a given computational step a (possibly entangled)

state $|\Psi\rangle$ of the N -logical qubit is located in the k th column of the ladder, the global quantum state of the model is described by *well-formed* vectors of the form

$$|\Psi; k\rangle := (\cdots |g^{\otimes N}\rangle_{k-3} \otimes |e^{\otimes N}\rangle_{k-2} \otimes |g^{\otimes N}\rangle_{k-1}) \otimes |\Psi\rangle_k \\ \otimes (|g^{\otimes N}\rangle_{k+1} \otimes |g^{\otimes N}\rangle_{k+2} \otimes |g^{\otimes N}\rangle_{k+3} \cdots), \quad (7)$$

where, for $k = 1, \dots, 2N + 3$, the ket $|\cdots\rangle_k$ refers to the state of the k th column of the device. As shown in the SM [38], starting from a fully ferromagnetic phase, where all the qubits of the device are in the ground state $|g\rangle$, a specific control pulse $V_C(t)$ can promote the first C -type column of the initialization area of Fig. 1 in $|e^{\otimes N}\rangle$. Formally, this produces a vector $|\Psi; k\rangle$ where the ICC is located in the first B -type column of the processing area, and a logical state $|\Psi\rangle := |g^{\otimes N}\rangle$. Thanks to Eq. (7), one can show that, under $e - e$ blockade conditions, there exist control unitary evolutions (5) that enable universal QC. The key ingredients that make this feasible are: (a) the ability to *rigidly* move the ICC at any position in the ladder (including the last column of the read-out area where measurements can be performed at the end of the computation); (b) the possibility to implement arbitrary single-qubit gates on the crossed element of the B - or C -type column where the ICC is located, while leaving the rest of the qubits unaffected; and (c) the ability to activate a nontrivial two-qubit entangling gate (e.g., a control- Z operation) between the j th and $(j + 1)$ th logical qubits when the ICC is located in the B - or C -type column that contains the crossed A -type qubit, which acts as a coupler between the j th and $(j + 1)$ th rows of the ladder.

To achieve task (a), we identify a sequence $\hat{U}_{\text{shift}}$ [43] of transformations (6) that shifts the horizontal position of the ICC without affecting its internal state, i.e., $\hat{U}_{\text{shift}}|\Psi; k\rangle = |\Psi; k + 1\rangle$, see Fig. 2(b).

In the case in which the ICC is located in a χ -type column with $\chi \in \{B, C\}$, the operations needed for implementing the single-qubit gates of point (b) can be realized by composing sequences of the form $\hat{Z}_{A'}^{\text{tot}} \hat{W}_{\chi \times}(\theta/2, -\mathbf{n}_{\perp}) \hat{Z}_{A'}^{\text{tot}} \hat{W}_{\chi \times}(\theta/2, \mathbf{n}_{\perp})$ with $\mathbf{n}_{\perp}$ orthogonal to $\mathbf{z}$ and $\hat{Z}_{A'}^{\text{tot}}$ obtained from (6) for $\theta' = 2\pi$ and $\theta'' = 0$ (see the SM [38]). Indeed, thanks to the fact that the crossed χ -type qubits are located on columns, which are at least three columns apart from each other, when acting on $|\Psi; k\rangle$ the above transformation will effectively correspond to the application of the single-qubit rotation $\hat{R}(\theta, \mathbf{n}_{\perp})$ on the crossed element of the ICC [44]. Finally, once the ICC is aligned with a two-qubit gate, we only need to use a single $\hat{Z}_{A \times}^{\text{tot}}$ evolution obtained by setting $\theta' = 0$ and $\theta'' = 2\pi$ in Eq. (6), which leaves unchanged every regular A -type qubit and induces conditional-phase shift [42] on the crossed ones.

Discussion. Exploiting ZZ interactions, we achieved universal QC on N logical qubits through external *global* pulses that act on a ladder of $N_{\text{tot}} = 2N^2 + 4N - 1$ physical qubits [37]. In contrast with the Rydberg-atom proposal [33], which relies on the use of two different species of physical qubits, our scheme uses three species. This choice allows us to roughly halve the total number of physical qubits of the device, which for the two-species model [33] scales as $N_{\text{tot}} \simeq 4N^2$ for $N \gg 1$. As discussed above, the condition $\eta_{\text{BR}} \gg 1$

is crucial for our device's operation. Numerical checks in the SM [38] confirm that ζ must be at least on the order of $5\Omega_{\chi}$. The largest values of ζ that have been experimentally achieved [45] are on the order of 100 MHz, while typical Rabi frequencies can reach values as small as 5 MHz [46], suggesting that the blockade regime is fully within reach in current superconducting-qubit platforms.

In order to achieve a fault-tolerant quantum computation, error-correction (EC) schemes are necessary. Since our machine is universal, any standard fault-correction procedure can be implemented. In particular, regarding, e.g., surface codes [47] or qLDPC codes [48,49], we mention that while our proposal uses only nearest-neighbor couplings, nothing prevents us from introducing long-range couplings between logical qubits in order to reach 2D connectivity requirements. This can be experimentally carried out, for example, by following the approaches of Refs. [50,51]. We finally mention that existing EC schemes for globally controlled quantum computers have been studied in the past [52–56]; however, globally driven EC codes for our machine will be subject of future research. Moreover, a significant challenge of our architecture is the impact of inhomogeneities in SC qubit frequencies and coupling strengths on protocol fidelity. Although a detailed noise analysis is beyond the scope of this Letter, we remark that systematic fabrication errors could be treated as standard dynamical errors within error correcting schemes, as shown in Ref. [57], thus allowing the strategies discussed above to be applied. An alternative strategy involves a *hybrid* “bottom-up mitigation approach”, where global control is applied to small qubit patches or chiplets (with fabrication inhomogeneities below a set tolerance). These patches will be then connected to each other [58,59]. For instance, suppose that in order to have N logical qubits, we need to build k patches with inhomogeneities below the above mentioned tolerance, each encoding M logical qubits. For each patch we have (1) control lines. By coupling the k chiplets we still have (k) wires with $k \sim N/M$. This configuration would still significantly reduce the number of control lines required for universal QC. The calculation of the tolerance required is left for future work. Another potential challenge is that qubit state readout is currently limited to the rightmost column of the ladder, complicating the individual qubit tune-up typically required for gate calibration. To address this, flip-chip technology could be employed, for example by coupling the computational chip to a top readout chip that performs individual readout of the qubits inside the ladder [60].

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- $N_{\text{tot}} = (2N + 3)N + N - 1 = 2N^2 + 4N - 1$, while the total number of columns is $N_{\text{column}} = 2N + 3$.
- [38] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevResearch.7.L012065> for a wealth of additional technical details.
- [39] More specifically at any given time, either the control pulse $V_A(t)$ is active while $V_B(t)$ and $V_C(t)$ are not, or, if either $V_B(t)$ or $V_C(t)$ is active, then $V_A(t)$ is not i.e., $\Omega_A(t) \neq 0 \Rightarrow \Omega_B(t) = \Omega_C(t) = 0$, and $\Omega_B(t) \neq 0$ or $\Omega_C(t) \neq 0 \Rightarrow \Omega_A(t) = 0$.
- [40] Depending on the circuit design, indeed, the longitudinal ZZ-coupling ζ in Eq. (2) can be either positive [22,24,27,28] or negative [23,26]. However, its sign does not influence the blockade effect. Indeed, the ZZ interaction detunes the $|eg\rangle \rightarrow |ee\rangle$ and $|ge\rangle \rightarrow |ee\rangle$ transitions with respect to the non-interacting case, effectively “blocking” these transitions and making the $|ee\rangle$ state inaccessible with the external pulses that we use. Also, we remark that $\zeta \sim \text{kHz} - \text{MHz}$ while the natural frequency of the qubits is $\chi \sim \text{GHz}$. Thus, for a two-qubit system, the $|ee\rangle$ state is the highest in energy even in the presence of interactions.
- [41] Here, the symbol $\bar{\chi}$ denotes a species that is distinct from χ .
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- [43] This can be done through three different types of π pulses: one that acts only on the non-crossed elements of A [i.e., $\hat{\Pi}_{A'} := \hat{W}_{A'}(\pi, \mathbf{x})$], and the others on the full set of B - and C -type qubits [i.e., $\hat{\Pi}_B := \hat{W}_B(\pi, \mathbf{x}; \pi, \mathbf{x})$, $\hat{\Pi}_C := \hat{W}_C(\pi, \mathbf{x}; \pi, \mathbf{x})$]. Specifically, if the ICC of $|\Psi; k\rangle$ is of B or C type, we take $\hat{U}_{\text{shift}} = \hat{\Pi}_{A'} \hat{\Pi}_B \hat{\Pi}_C \hat{\Pi}_{A'}$, while if it is of A type we use $\hat{U}_{\text{shift}} = \hat{\Pi}_B \hat{\Pi}_C \hat{\Pi}_{A'} \hat{\Pi}_B \hat{\Pi}_C$. Notice that, since in both scenarios the action of $\hat{U}_{\text{shift}}$ on the well-formed state coincides (up to a global phase) with its own inverse (see the SM [38]), the same operation can also be used to induce a collective motion of the interface in the opposite direction, i.e., $\hat{U}_{\text{shift}}|\Psi; k+1\rangle = |\Psi; k\rangle$, see Fig. 2(b).
- [44] The key observation here is that when the k th column of $|\Psi; k\rangle$ is made of B -type qubits, the unitary $\hat{Z}_{A'}^{\text{tot}}$ defined at the end of the previous section is equivalent to the application of a $\hat{\sigma}^{(z)}$ gate to each of the element of the ICC, i.e., $\hat{Z}_{A'}^{\text{tot}}|\Psi; k\rangle = |(\hat{\sigma}^{(z)})^{\otimes N} \Psi; k\rangle$. Notably, the same property holds also when we replace the $|g^{\otimes N}\rangle$ state of a ferromagnetic B -type column of $|\Psi; k\rangle$ with a generic N -qubit state. Exploiting this effect it then follows that, given a unit vector $\mathbf{n}_{\perp}$ orthogonal to $\mathbf{z}$, the sequence $\hat{Z}_{A'}^{\text{tot}} \hat{W}_{B \times}(\theta/2, -\mathbf{n}_{\perp}) \hat{Z}_{A'}^{\text{tot}} \hat{W}_{B \times}(\theta/2, \mathbf{n}_{\perp})$ maps $|\Psi; k\rangle$ into a new state $|\Psi'; k\rangle$ with a new ICC vector $|\Psi'\rangle$ obtained from $|\Psi\rangle$ via the application of the single-qubit rotation $\hat{\sigma}^{(z)} \hat{\mathbb{R}}(\theta/2, -\mathbf{n}_{\perp}) \hat{\sigma}^{(z)} \hat{\mathbb{R}}(\theta/2, \mathbf{n}_{\perp}) = \hat{\mathbb{R}}(\theta, \mathbf{n}_{\perp})$ on the crossed element of the column. Analogous considerations apply also to the case in which the ICC is of C type.
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