

Hybrid single-ion atomic-ensemble node for high-rate remote entanglement generationBenedikt Tissot^{1,*}, Soubhadra Maiti^{2,3}, Emil R. Hellebek¹, and Anders Søndberg Sørensen^{1,†}¹*Center for Hybrid Quantum Networks (Hy-Q), Niels Bohr Institute, University of Copenhagen, Jagtvej 155A, DK-2200 Copenhagen, Denmark*²*QuTech, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands*³*EEMCS, Quantum Computer Science, Delft University of Technology, Mekelweg 4, 2628 CD Delft, The Netherlands*

(Received 17 November 2025; accepted 13 May 2026; published 16 July 2026)

Different quantum systems possess different favorable qualities. On the one hand, ensemble-based quantum memories are suited for fast multiplexed long-range entanglement generation. On the other hand, single-atomic systems provide access to gates for processing of information. Both of those can provide advantages for high-rate entanglement generation within quantum networks. We develop a hybrid architecture that takes advantage of these properties by combining trapped-ion nodes and nodes comprised of spontaneous parametric down-conversion photon-pair sources and absorptive memories based on rare-earth ion ensembles. To this end, we solve the central challenge of matching the different bandwidths of photons emitted by those systems in an initial entanglement-generation step. This enables the parallel execution of multiple probabilistic tasks in the initial stage. As a particular example, we show that our approach can lead to a significant speed-up for the fundamental task of creating ion-ion entanglement over hundreds of kilometers in a quantum network.

DOI: [10.1103/47zq-2h7t](https://doi.org/10.1103/47zq-2h7t)

Introduction. Long-range entanglement generation is central to building a quantum internet [1,2]. Therein, the entanglement can be used for secure communication [3–6], enhanced sensing [7,8], distributed computing [9], as well as fundamental physics experiments like the violation of Bell inequalities [10–14]. While entanglement generation between separate matter systems has been demonstrated in various physical implementations – e.g., between atomic ensembles [15–17], trapped ions [18–20], color centers in solids [21–23], and rare-earth ions [24–26] – high-rate entanglement generation over hundreds of kilometers remains a challenge.

Trapped ions are a favorable candidate for quantum network nodes because they are established computational qubits featuring high fidelity quantum gates [27,28] and long coherence times [29]. Local one- and two-qubit gates allow implementing network protocols, e.g., repeaters, dividing long-distance entanglement into smaller segments to overcome exponential loss in optical fibers [30–32]. An outstanding problem, however, is that the entanglement generation rate is slow over long distances.

To achieve a faster rate, one can employ multiplexing, which boosts the rate of possible entanglement generation attempts of a single qubit from c/L over a distance L with c being the speed of light to Nc/L for N qubits [26,33]. Nodes

combining photon pair sources based on spontaneous parametric down conversion (SPDC) and an absorptive memory using a rare-earth ion doped crystal (SPDC + M) have demonstrated high multiplexing capabilities and feature high duty cycles [24–26,33,34] and long storage durations [35,36]. Single SPDC + M nodes have been shown to support more than 1000 modes [37], which is more feasible and cost effective than trying to link 1000 trapped ions in parallel. Although the high number of memory modes makes ensemble nodes ideal for entanglement generation over an elementary link due to the absence of deterministic gates, information should preferably be transferred to other systems for processing. Repeaters can be implemented using linear optics [31], but in this case, the probabilistic nature of the entanglement swapping (henceforth swap for brevity) limits the entanglement generation rate for long distances [33].

In this Letter, we propose a hybrid architecture tailored towards high-rate long-distance entanglement generation by uniting an SPDC + M backbone (BB) and trapped-ion edge-nodes (EN). Both systems can be entangled with photons with high fidelity [38–41], which can interface the systems. However, this is challenged by the mismatch of the intrinsically narrow bandwidth of photons emitted by ions, and the broadband nature of SPDC photons. One approach to overcome this is photon (re)shaping [42–45] within a final swap between the ion and the memory [46,47]. These approaches rely on reshaping the stored photon, which can introduce additional losses as well as decoherence of the stored photon-photon entanglement. Another option is to replace the SPDC with a photon pair emitter compatible with the atomic system, e.g., Rb atoms both as the atomic system and for photon generation [48].

We propose an approach where we instead use the multi-mode nature of SPDC photon pairs by matching the photon

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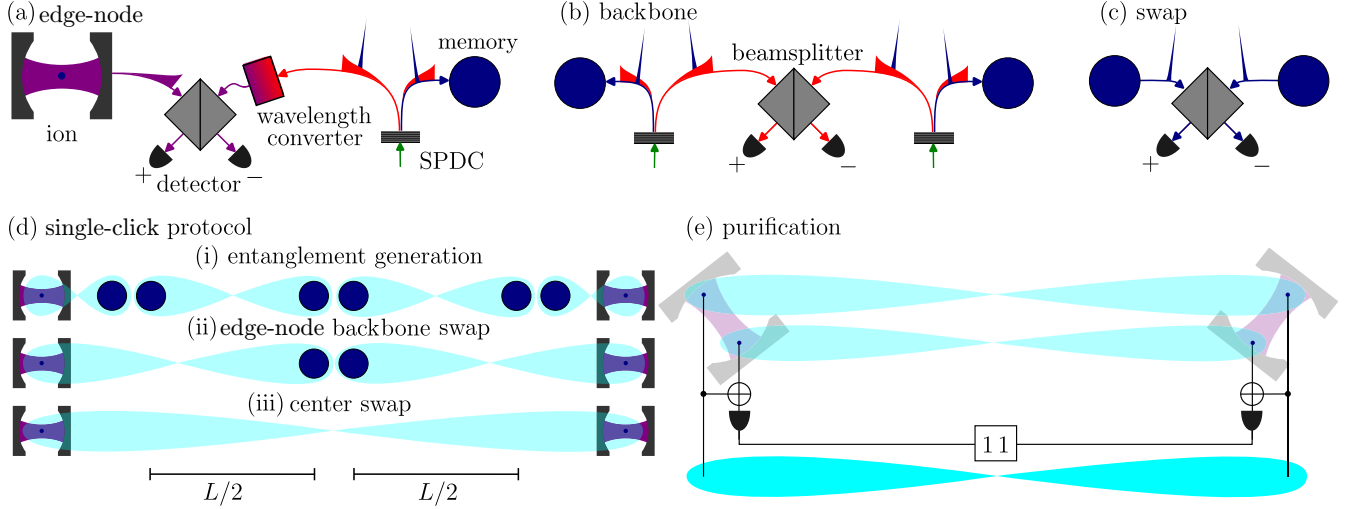


FIG. 1. Sketch of the protocol and extension to long-distance entanglement generation. (a) The proposed scheme to bridge the bandwidth difference of trapped ions and ensemble based memories (M). A SPDC bridges the two systems. After wavelength converting the SPDC photon to match the ion wavelength, the photons are interfered on a beamsplitter (BS) and measured with heralding detectors labeled $\pm$. The hybrid nodes can then be embedded in an ensemble-based quantum network as EN to extend the protocol to long-distance entanglement generation. (b) The long-distance backbone is composed entirely of SPDC + M nodes interconnected by optical fibers and heralding detectors. (c) Memory-memory swaps are also implemented using fiber optics, BS, and heralding detectors. (d) Ion-ion entanglement is generated using a single-click protocol over the long distance L spanned by the backbone network. To this end, (i) backbone and edge-node entanglement is generated in parallel using the setups depicted in (a), (b) and (ii) a swap (c) is performed between the edge-nodes and the closest backbone link. (iii) Finally, a swap in the center links the ions. (e) Performing the single-click scheme twice enables the use of purification. We consider a purification where local CNOTs followed by measurement of both controlled systems in $|1\rangle$ postselects a Bell state of higher fidelity.

correlation time of the SPDC to the broad bandwidth of the quantum memory, while the SPDC is modulated proportional to the slowly varying temporal mode of the photon emitted by the ion. Thereby, we overcome the orders of magnitude different emission timescales (SPDC ~ 100 ns [24] and trapped ions in a cavity ~ 10 μ s [20,49]). Furthermore, our approach exploits short-range connections for the (likely) most inefficient links between the ions and the ensembles. As a result, these links can be generated at a high repetition rate to compensate for the limited probability. The long-range entanglement generation, which has to be performed at a slower rate due to the long communication time, is, however, enhanced by ensemble multiplexing. Performing the matching and long-range generation simultaneously furthermore avoids unnecessary idle time. With this method, rapid long-range entanglement can be established in a full network of links between different trapped ions, see Fig. 1. Local deterministic entanglement swaps between the ions can then further extend the range and complexity of the network. In a companion paper [50] we provide additional theoretical details on modeling the network and compare a single and double-click protocol, while we focus on the idea of the SPDC matching in this Letter and only use the protocols of Ref. [50] to highlight the feasibility of the approach.

SPDC matching. The main step in interfacing the two systems is to generate entanglement between the trapped ion and the BB memory using the setup depicted in Figs. 1(a) and 2. This is achieved by the central idea of our proposal: a method to bridge the different intrinsic timescales of the systems by modulating an SPDC source. To describe this, we model the matter systems using the combined photonic and

matter state immediately after the emission. To implement a single-click protocol [32], we consider the *ions* to emit photons conditioned on the matter state

$$|\Psi_a\rangle = \left[\alpha_0|0\rangle + \alpha_1|1\rangle \int_{\mathbb{R}} dt v(t) a^\dagger(t) \right] |\emptyset_a\rangle, \quad (1)$$

with the matter states $|0\rangle$ and $|1\rangle$, the emission amplitude α_1 ($\alpha_0 = \sqrt{1 - |\alpha_1|^2}$), the photonic creation operator $a^\dagger$ with the channel vacuum state $|\emptyset_a\rangle$, and the normalized

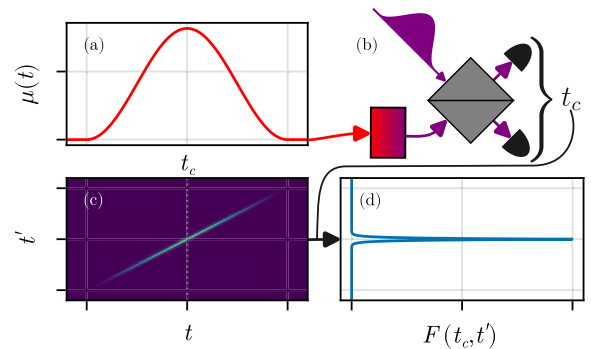


FIG. 2. Matching the SPDC and ion-photon flux within the edge-nodes. (c) The correlation function of the photon pair $\mu(t)F(t, t')$ of all time bins emitted by the SPDC is split into (a) a slowly varying envelope $\mu(t)$ that we can use to (b) match to the atomic photon $v(t)$. Note that (a) and (c) display the combination of all time bins. Conditioned on the heralding click, (d) a short photon is stored within one of the time bins of the multimode (ensemble) memory unless it is lost. For illustration we use $T_a/T_c = 100$.

temporal mode function $v(t)$ of duration T_a . A state of this form can, e.g., be generated using stimulated Raman emission [45,51,52], which was recently used for ion-ion entanglement generation [53].

For (quasi)continuous driving of an SPDC source, successful events are typically defined by the detection of a photon in one arm in a time window defined by the detection time in the other arm. For convenient modeling we divide the time interval into time bins (which is not strictly necessary, but can be understood as the state in the acceptance interval). We take the SPDC + M state within a time bin as the multimodal state

$$|\Psi_b\rangle = \left[\beta_0 + \beta_1 \int_{\mathbb{R}^2} dt dt' \mu(t) F(t, t') b^\dagger(t) c^\dagger(t') \right. \\ \left. + \beta_2 \int_{\mathbb{R}^4} d\vec{t} \mu(t_1) \mu(t_2) G(\vec{t}) b^\dagger(t_1) b^\dagger(t_2) c^\dagger(t_3) c^\dagger(t_4) \right] |\emptyset\rangle, \quad (2)$$

based on the detailed model developed in Ref. [54]. The operator $b^\dagger$ ($c^\dagger$) corresponds to creating a photon in the channel connected with the BS and detectors (the memory), see Fig. 1. Here β_1 (β_2) denotes the single (two) photon emission amplitude within a time bin. The vacuum state $|\emptyset\rangle$ has the amplitude β_0 . The temporal mode μ captures the overall shape of the first detected photon (in the b mode), while the multimodal and multiphoton character is contained in the multitime dependence of the (double) pair correlation function $F(t, t')$ [$G(\vec{t})$]. The correlation time T_c between the photons of a pair corresponds to the width of $F(t, t')$ in the time difference $t' - t$. As the aim is to store most of the photon while avoiding storage of uncorrelated photons, we choose the acceptance interval and therefore the time bin to be a few times the correlation time of $F(t, t')$ (see Fig. 2) but shorter than the much longer ion-photon duration.

For the optical entanglement generation, as well as the probabilistic swaps used for embedding the hybrid nodes in a full network, we consider a setup that combines two input channels using a 50:50 beamsplitter with the two beamsplitter outputs terminating in detectors, see Figs. 1(a)–1(c). For both entanglement generation and swapping we use a single-click to herald success and we model the optics for channels a and b using $a^\dagger \rightarrow \sqrt{\eta/2}(d_+^\dagger + d_-^\dagger) + \sqrt{1-\eta}a_L^\dagger$ and $b^\dagger \rightarrow \sqrt{\eta/2}(d_+^\dagger - d_-^\dagger) + \sqrt{1-\eta}b_L^\dagger$, see Ref. [50] for additional details. Here, the combined efficiencies η and η' account for all losses from emission to the detection of a click and can account for differences in the branches before the beamsplitter, e.g., frequency conversion [49,55] in one of the channels. The operators $d_\pm$ annihilate a photon at one of the detectors and the operators a_L and b_L are annihilation operators of the loss channels. Losses in the memory channel are treated analogously and we denote the efficiency up to detection (after release during a swap) as η_m .

For simplicity we consider a sufficiently narrow temporal resolution and no dead time such that we take the temporal modes as constant within the detection window and the detectors as photon number resolving. Thus, heralding on a single-click ideally corresponds to postselecting on only one detector channel $\pm$ containing a single photon within the detector resolution T around the click time t_c , i.e., a projection of the detector channels onto $\int_{t_c-T/2}^{t_c+T/2} dt a_\pm^\dagger(t) |\emptyset_\pm\rangle |\emptyset_\mp\rangle$ with the

annihilation operator $d_\pm$ and vacuum state $|\emptyset_\pm\rangle$ of detector channel $\pm$. Additionally, we model dark counts as the detection of a click event despite the corresponding detection channel being in vacuum.

While variances of the phase can be accounted for within our model by making the temporal modes complex functions, we assume phase stability or active stabilization of the setup (required by all single-click protocols [31,32,50]) and take the modes as positive functions in the following. Additionally, we calculate the EN state perturbatively to first order in emission probabilities and the ratio of dark count to successful detections. Within the EN links, we use the multimode nature of the SPDC photon pairs before the heralding to match the photon flux to the ion emission, as illustrated in Fig. 2. Slowly modulating the drive strength of the SPDC modulates the photon flux [corresponding to the slow envelopes $\mu(t)$ of the time bins]. This allows matching it to the temporal mode of the ion emission and thereby overcoming the challenge of matching a broadband ensemble system to the ion. Because the SPDCs within the ENs match the longer ion emission timescale, we consider them to be weakly driven and thus to emit uncorrelated pairs [56]. Furthermore, in this regime the slow modulation can be understood analogous to adiabatic modulation, where the operation of the SPDC source is quasicontinuous. The broadband nature of the SPDC emission then leads to a temporally narrow photon stored in the memory upon detection of the heralding click. The click time is used to filter and/or precisely time the release of photons from neighboring memories for entanglement swapping [57–59]. This makes the heralded state insensitive to SPDC photons outside the acceptance interval and allows us to increase the drive strength to suppress part of the effect of losses in the SPDC channel. We therefore propose to place the frequency conversion, required to match the wavelengths of the systems, in the SPDC channel. To this end we express $\eta' = \eta'_0 \eta_{FC}$ with an intrinsic efficiency η'_0 (accounting for intrinsic losses due to, e.g., fiber coupling and detection) and the frequency conversion efficiency η_{FC} .

The state heralded by a single-click in port $\pm$ during the ion-photon duration after tracing out the photon loss and detection channels is

$$\rho_\pm^{\text{EN}} \approx (A_0 |0\rangle \langle 0| + A'_1 |1\rangle \langle 1|) |\emptyset\rangle \langle \emptyset| \\ + A_1 |\varphi_\pm\rangle \langle \varphi_\pm| + A_2 |1\rangle \langle 1| |t_c\rangle \langle t_c|, \quad (3)$$

with the generated target state $|\varphi_\pm\rangle = \cos \theta |1\rangle |\emptyset\rangle \pm \sin \theta |0\rangle |t_c\rangle$ with $\tan^2 \theta = \frac{\eta' \eta_m |\mu(t_c) \alpha_0 \beta_1|^2}{\eta |\nu(t_c) \alpha_1 \beta_0|^2}$. To simplify the target state, we use our assumption of positive temporal modes and positive amplitudes α_k and β_k ($k = 0, 1$); different phases will lead to a phase between the logical states in $|\varphi_\pm\rangle$. We highlight that matching the slowly varying SPDC temporal mode $\mu(t)$ (for all time bins) to the temporal mode $v(t)$ of the ion photon, i.e., $\mu(t) \propto v(t)$, makes θ independent of the click time. The first ket $|k\rangle$ ($k = 0, 1$) denote the atomic state and the second ket the memory photon state in vacuum $|\emptyset\rangle$ or with a single excitation stored in the multimode memory $|t_c\rangle = \int_{\mathbb{R}} dt F(t_c, t) c^\dagger |\emptyset\rangle$ conditioned on the detection of a click at time t_c . To leading order in the emission probabilities the coefficients in the density matrix are given by $A_0 \approx (1 - \eta_m) \frac{\tan^2 \theta}{\eta_m + \tan^2 \theta}$ and $A_1 \approx \eta_m \frac{1 + \tan^2 \theta}{\eta_m + \tan^2 \theta}$ for

the terms with a nonperturbative contribution in magnitude and the remaining elements have a linear leading order contribution $A_2/\eta_m = A'_1/(1 - \eta_m) = (1 - \eta)|\alpha_1|^2 \frac{\tan^2 \theta}{\eta_m + \tan^2 \theta}$. The EN ion-memory state (3) corresponds to a perfect absence-presence entangled matter-photon Bell state in the limit of perfect memory efficiency $\eta_m = 1$, low emission probability $|\alpha_1|^2 \rightarrow 0^+$, and balanced matching $\tan^2 \theta = 1$. A full derivation including higher-order contributions and dark counts, which are used in simulations, is presented in Ref. [50].

The success probability corresponding to the probability of only detecting a single-click at any time t_c during the ion-pulse duration T_a in either detector $\pm$ has the leading contribution

$$\mathbf{P}_{\text{EN}} \approx \eta |\alpha_1|^2 \left(1 + \frac{\tan^2 \theta}{\eta_m} \right), \quad (4)$$

if the slowly varying SPDC envelope ideally matches the ion emission $|\mu(t_c)|^2 = |\nu(t_c)|^2 N$ (for the time bin with support containing t_c). For simplicity, we assume that the ion-pulse duration is divided into N time bins all having the same emission probability $|\beta_1|^2$. This is done to ensure that Eq. (2) is applicable but has no physical meaning.

Entanglement generation. Having discussed the hybrid nodes we now want to investigate their performance within a full protocol. We focus on long-distance entanglement generation and thus consider a single-click scheme, but note that for shorter links or efficient ensemble memories, two-click [31,32,60] or reflection-based [61,62] protocols might be beneficial. The entanglement generation protocol is illustrated in Figs. 1(d) and 1(e), and can be summarized in four steps. It proceeds by (i) simultaneously generating entangled links using single-click heralding between ions and memories locally at ENs [Fig. 1(a)] and between BB memories over a long distance L/n (with the swap level $n - 1 = 1$) [Fig. 1(b)]. (ii) As soon as neighboring BB and EN links are ready, entanglement is swapped between them by heralding on a single-click after releasing the photons from the memories [Fig. 1(c)]. Finally (iii) another optical swap between memories at the central repeater connects the two halves.

We include a repeater in the center of the fundamental link ($n = 2$) because parallelization allows the additional swap to extend the distance without significantly decreasing the success rate [63]. Alternatively, without the central repeater ($n = 1$), a final swap can be performed between the BB and the remaining EN. Upon successfully heralding every step, an ion-ion entangled link is achieved.

The *last part* (iv) is purification to distill two ion-ion links into a single link with enhanced fidelity, see Fig. 1(e). It proceeds by preparing two ion-ion links using the steps above and performing a CNOT gate between the local ions. Measurement of both target ions in state $|1\rangle$ heralds the purification of the ion-ion entanglement, see Fig. 1(e). This postselection helps in suppressing events where the memories do not store any photons while retaining the better scaling of single-click protocols with the (long-distance) fiber losses [31–33,64,65]. Although the single-click protocol inherently relies on phase stability [31,32,50], the purification can reduce the sensitivity

to such fluctuations if the phase is stable between two successful entanglement generation events.

The entanglement generation between the ions and the memories is already described above. The simultaneous multiplexed entanglement generation in the BB is described in multiple works [33,64] and we provide an analogous model for it in Ref. [50]. In short, the SPDC + memory nodes in the BB can be modeled using a state of the form of Eq. (2), but due to the different constraints of the link generation between BB and EN, the SPDC emission probabilities within EN ($|\beta_1|^2$) and BB ($|\beta_1|^2 \rightarrow |\gamma_1|^2$) are chosen independently.

After entanglement generation in the EN and BB links, the generated entanglement can be swapped by reading out neighboring memories, see Fig. 1(c). Ideally, the click times and memory storage are used to re-emit the stored photons simultaneously for the optical swaps. Therefore, we assume the memory photons share the same shape $f(t) = F(0, t)$. As we already included all losses in the generation step of our model to calculate the entanglement swaps, we can straightforwardly apply the same detection model used for the generation step. The first swap (between EN and BB) ideally extends the state $|\varphi_{\pm}\rangle$ to be between the ion and the next memory [see Fig. 1(d)]. Within the perturbative approximation considered here, we find the final density matrix of the ions

$$\rho = (\pm \alpha |0, 1\rangle \langle 1, 0| + \text{H.c.}) + \sum_{k,l=0,1} D_{k,l} |k, l\rangle \langle k, l|, \quad (5)$$

where $\pm$ is the product of all the detectors that click. Ideally, the only nonzero elements are $D_{0,1} = D_{1,0} = \alpha = 1/2$, which corresponds to the Bell states $\sqrt{2}|\Psi_{\pm}\rangle = |0, 1\rangle \pm |1, 0\rangle$. The detailed calculation and density matrix elements $D_{k,l}$ and α , as well as the analysis of the duration of different entanglement generation protocols can be found in Ref. [50], where we account for parallelization of the different entanglement generation steps using results from Refs. [66–68]. We take the ENs timescale to be dominated by the ion-emission and the BBs by the quantum and classical communication time, estimated by two times the light propagation time from the nodes to the heralding station. The BB generation rate is directly enhanced by multiplexing via N_{BB} modes. Additionally, the duration scales with the inverse of the first and second swap probabilities (which are limited by the memory efficiency). In summary, for a single ion-ion link before purification and using a central repeater the average duration is $T_{\text{SL}} = \frac{3}{2} \frac{1}{\mathbf{P}_{\text{S2}}} \frac{1}{\mathbf{P}_{\text{S1}}} \frac{1}{R_{\text{BB}} + R_{\text{EN}}} (1 + \frac{R_{\text{BB}}}{R_{\text{EN}}} + \frac{R_{\text{EN}}}{R_{\text{BB}}})$ with the EN entanglement generation rate $R_{\text{EN}} = \mathbf{P}_{\text{EN}}/\tau_{\text{EN}}$, the trial duration in the EN τ_{EN} , and the swap success probability of the EN-BB swap $\mathbf{P}_{\text{S1}}$ and the final central swap $\mathbf{P}_{\text{S2}}$. The backbone entanglement generation rate R_{BB} has an analogous form to the EN, but is enhanced by the multiplexing capacity N_{BB} and we assume the trial duration $L/(2nc)$ (with swap level $n - 1$) to be determined by the distance between nodes.

The fundamental link generation protocol corresponds to a single-click protocol, which is known to suffer from “vacuum growth” where the memories end up in the joint vacuum state [31,32]. This aligns with our model where in contrast to the “two-photon” component $D_{1,1}$, the “vacuum” component $D_{0,0}$ always appears with a significant probability in the presence of photon loss. The inclusion of a purification step is thus

necessary to limit the “vacuum” component. As discussed above, we propose to follow the generation of two fundamental links, by local CNOTs between the ions of two fundamental links. Postselecting on the controlled ions each being in state $|1\rangle$ heralds success with probability $P_p = 2D_{1,0}D_{0,1} + 2D_{0,0}D_{1,1}$ and the state of the remaining pair takes the same form as Eq. (5). However, purification changes the matrix elements according to $\alpha_{\text{pur}} = \frac{\alpha^2}{P_p}$ and $D_{k,l}^{\text{pur}} = \frac{D_{k,l}D_{1-k,1-l}}{P_p}$, so that both $D_{0,0}^{\text{pur}}$ and $D_{1,1}^{\text{pur}}$ can be reduced by lowering the emission probabilities $|\alpha_1|^2$, $|\beta_1|^2$, $|\gamma_1|^2$ if the dark-count rate p_d/T is sufficiently small since the leading contributions of $D_{1,1}$ are proportional to these. Assuming that the two fundamental links are generated sequentially, the complete average duration including purification is $2T_{\text{SL}}/P_p$.

Performance comparison. With the above model, we evaluate the average duration for the entanglement of ion-ion pairs. We consider a target Bell-state fidelity of $F = 0.99$ and assume the pulses to be matched, constant, and of realistic durations $1/|v(t_c)|^2 = 10/|\mu(t_c)|^2 = 10 \mu\text{s}$ [20,49]. This corresponds to matching the ion with ten time bins and having a time-bin duration of $10T_c$ [24]. In terms of the intrinsic efficiencies we use $\eta = \eta_I = 0.9$, $\eta' = \eta_I^2$ (intrinsic SPDC and frequency conversion), and $\eta_{\text{BB}} = \eta_I \eta_F(L/2n)$ with the fiber transmission efficiency $\eta_F(l) = e^{-l/L_{\text{att}}}$, the swap level $n - 1 = 1$ (0), and the fiber attenuation length $L_{\text{att}} = \frac{10}{0.2 \ln 10} \text{ km}$. We use a memory efficiency of $\eta_m = 0.8$. Optimizing with respect to the emission probabilities $|\alpha_1|^2$, $|\beta_1|^2$, $|\gamma_1|^2$, see Refs. [50,56,69], we find the results shown in Fig. 3.

For comparison, we also include the time for direct ion-ion entanglement. Due to the longer ion pulses, direct generation only works for a shorter distance for the considered dark-count rate. We observe a speedup of around an order of magnitude thanks to the multiplexing of the hybrid architecture compared to direct ion-ion links. While this does not saturate the ideal speedup of the channel capacity due to the additional probabilistic steps and intrinsic losses, it provides a significant speed-up compared to the direct case. For all protocols included in the figure, the entangled state is between ions, and thus the advanced trapped-ion capabilities are available for further processing, including deterministic entanglement swaps. In the absence of dark counts the duration is proportional to $1/(1 - F)$ to leading order. If the target fidelity is relaxed to $F = 0.9$, the proposed protocol including a central multimode memory repeater achieves an average entanglement generation rate exceeding 1 Hz over a distance of 500 km compared to 0.1 Hz for $F = 0.99$.

While we here consider a single-click protocol with purification of the ions, we show in Ref. [50] that, for high memory efficiencies, we can achieve similar rates between using a double-click approach to create spin-photon entanglement between the ion and a dual rail setup. This relaxes the phase stability requirements on the ions and omits the need of an extra purification step. Therefore, we consider this approach more viable in the presence of highly efficient photonic memories, whereas the protocol investigated in this work is more suitable for near-term memories.

Conclusion. We develop a protocol uniting trapped ions with atomic ensemble systems. At the core of our protocol is an approach to link spontaneous parametric down-conversion

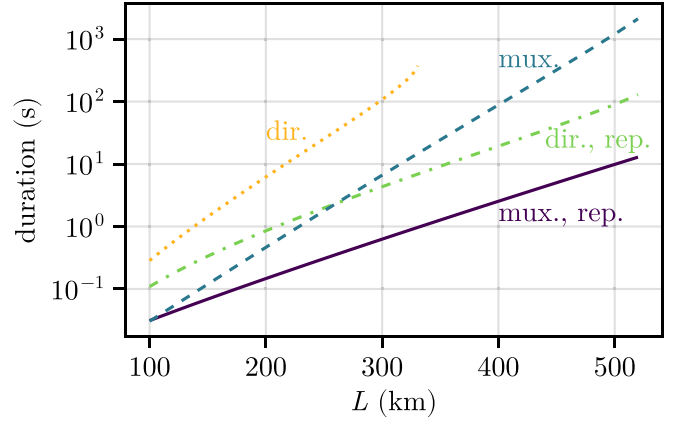


FIG. 3. Duration to prepare a Bell state with 99% fidelity as a function of distance for different protocols. The dotted yellow (dash dotted green) line corresponds to direct ion-ion entanglement generation using a single-click protocol (with an ion node in the center as a repeater). The dashed blue (solid purple) lines correspond to the multiplexed (mux.) protocol proposed in this work without (with) a central multimode repeater (rep.). We take the efficiencies $\eta_m = 0.8$, $\eta = \eta'_0 = \eta_{\text{FC}} = 0.9$, and $\eta' = \eta'_0 \eta_{\text{FC}}$. The BB has $N_{\text{BB}} = 1000$ multiplexing modes and an efficiency $\eta_{\text{BB}} = \eta'_0 \eta_F(L/2n)$ where $\eta_F(l)$ is the fiber transmission efficiency for distance l and an attenuation of 0.2 dB/km and $n = 2$ (1) with (without) a repeater. For direct ion-ion generation the photon efficiency is $\eta_{\text{FC}} \eta_F(L/2n)$. Furthermore, we use a dark-count rate of 10^{-3} Hz , a pulse duration of the ions of $10 \mu\text{s}$, an acceptance window in the backbone of $1 \mu\text{s}$ (i.e., $N = 10$), an SPDC correlation time of 100 ns , a detector resolution of 1 ns , and the speed of light in fiber as $2/3$ the vacuum speed of light.

sources and absorptive memories with trapped ions, i.e., broad-band ensemble systems with single narrow-band quantum emitters. This enables the use of multiplexing of ensemble-based approaches combined with the more advanced gate sets and deterministic entanglement swaps of trapped ions for further processing of the information. Our approach shows a significant speedup and provides better resilience regarding dark counts compared to direct ion-ion entanglement generation. Moreover, the SPDC matching approach can be extended to couple other narrow-band systems to broadband memories, thereby also enabling interconnectivity between those systems.

Acknowledgments. We thank T. E. Northup, H. de Riedmatten, S. D. C. Wehner, M. van Hooft, N. Sangouard, P. Cussonot, B. Grivet, S. Grandi, A. Das, and C. Gustin for fruitful discussions. This work was funded by the European Union’s Horizon Europe Research and Innovation Program under Grant Agreement No. 101102140, QIA Phase 1, Funded by the European Union. The views and opinions expressed are, however, those of the authors only and do not necessarily reflect those of the European Union or European Commission. Neither the European Union nor the granting authority can be held responsible for them. B.T., E.R.H., and A.S.S. acknowledge the support of Danmarks Grundforskningsfond (DNRF Grant No. 139, Hy-Q Center for Hybrid Quantum Networks).

Data availability. The data that support the findings of this article are openly available [69].

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