Linear Ion Trap Array Coupled to an Optical Resonator

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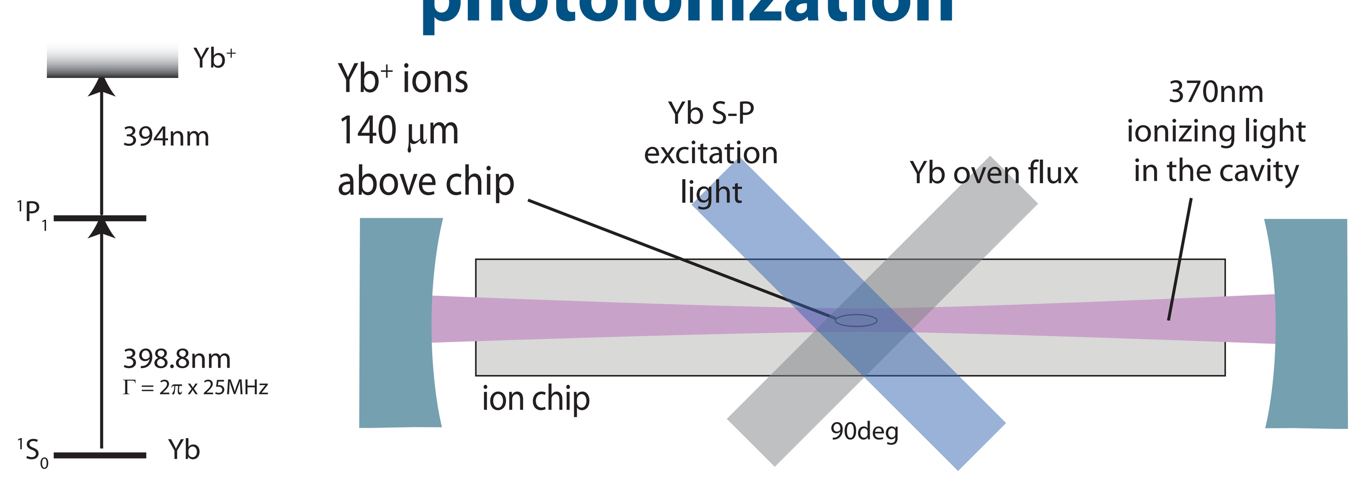
Introduction

Photonic memories based on collective excitation of atomic ensembles experience decoherence due to atomic motion and loss, limiting their storage time. The interaction between the atoms is also weak, making gates between stored excitations difficult.

We are developing a system to realize a photonic memory based on an ensemble of Yb^+ ions. Strong ion confinement in the Lamb-Dicke regime, together with the use of F=0 and F=1, m_F=0 magnetic field insensitive hyperfine states promises long storage times. Individual ion addressability in our system enables Coulomb interaction between the ions to be used for controlled operations between the individual stored excitations.

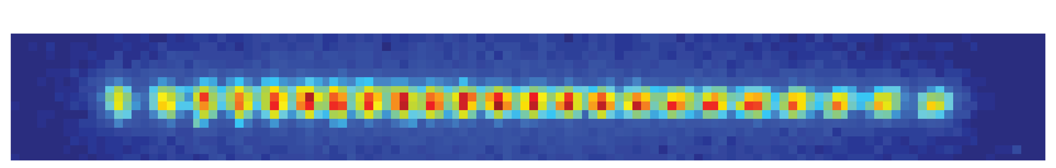
Trap loading via resonator-aided photoionization



To load a large number of ions into an array of small, deep traps while not contaminating the trap structure by the atom flux requires efficient ionization of atoms in the trapping region. We accomplish this by using the experimental cavity to build up high light intensities for a two step ionization process for Yb.

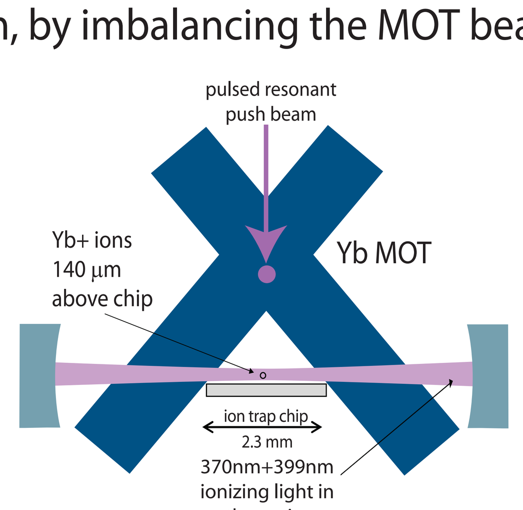
We place an effusive thermal neutral Yb oven with ~0.5mm apperture 3cm away from the trapping region and angle it 20deg upwards relative to the trap surface. We excite the Yb atoms in the tails of the oven flux close to the chip with 1W/cm² of 399nm light tuned to the S-P transition in neutral Yb. Atoms excited inside the resonator mode are then ionized with ~100W/cm² of 370nm light circulating inside the resonator.

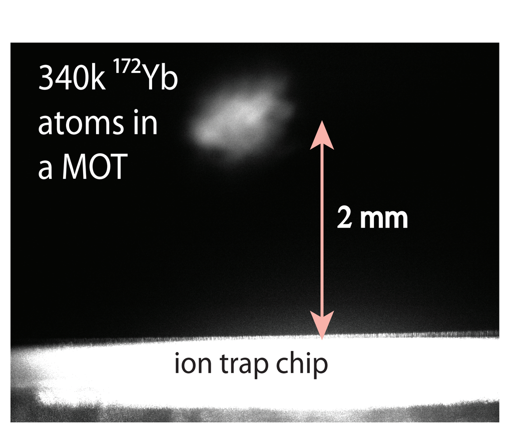
Using this scheme, we are able to load ~2 $^{174}Yb^+$ ions /s with ~90% isotopic purity. Below is an image of a 23 ion chain of the $^{74}Yb^+$ isotope prepared with 100% purity:



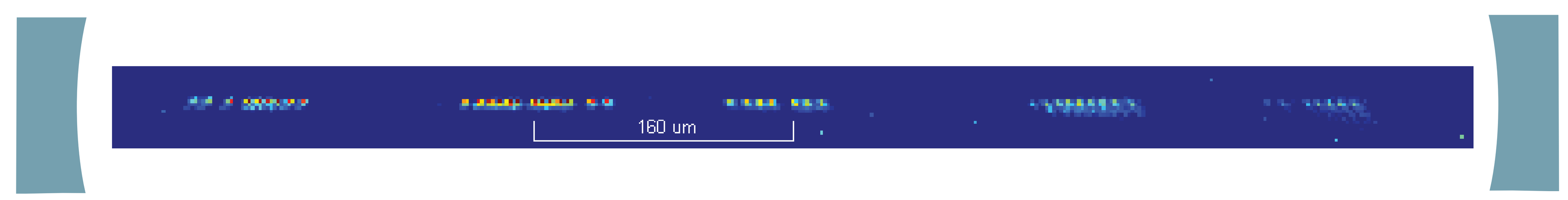
Future: Loading via a MOT

We have built a magneto-optical trap (MOT) for Yb atoms. This allows loading of the ion trap with the isotope of choice selected by the MOT detuning. Atoms can be pushed from the MOT towards the ion trap by a resonant push beam, by imbalancing the MOT beams or by shifting the magnetic field zero.





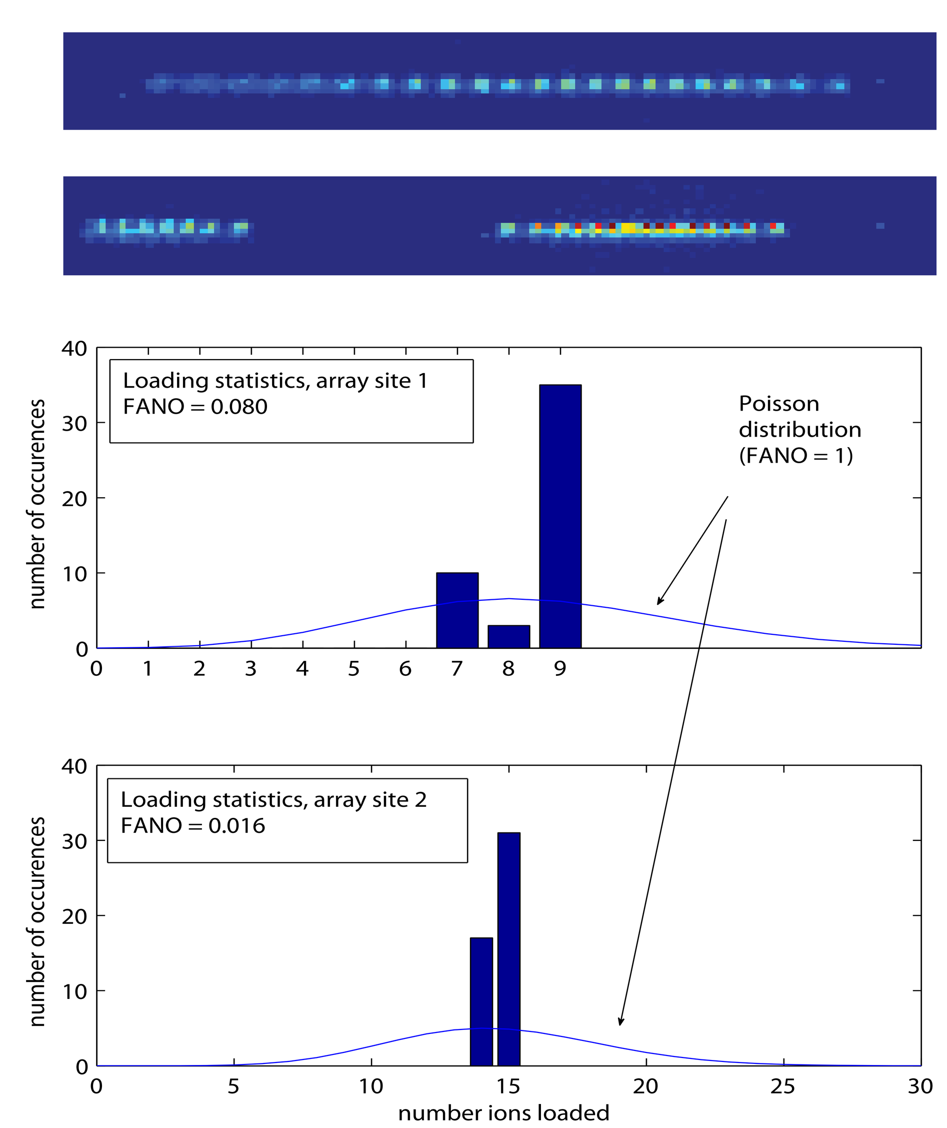
$^{174}Yb^+$ ion chains excited via an optical resonator



Ion-ion repulsion limits the density of ions in an ensemble. To achieve a high optical depth for interaction with photons, one can use many ions in a bulk Coulomb crystal. However, the close spacing of a crystal's vibrational modes and the difficulty of optically resolving individual ions makes controlled ion-ion gates difficult.

To achieve high optical depth while preserving optical and motional addressability of individual ions, we place a linear array of RF Paul traps along the mode of a medium-finesse optical resonator.

Reversible sub-Poisson splitting of ion chains

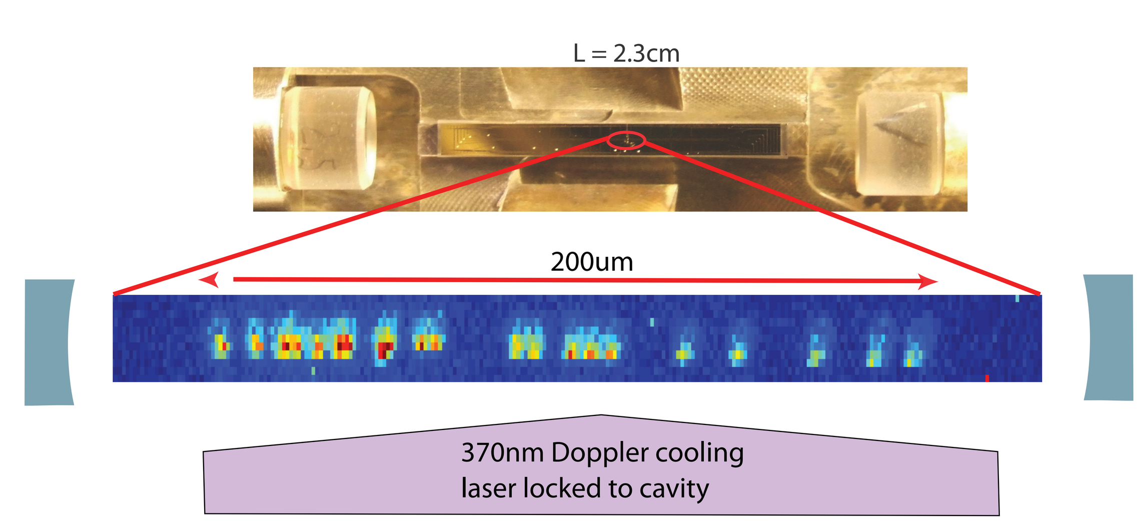


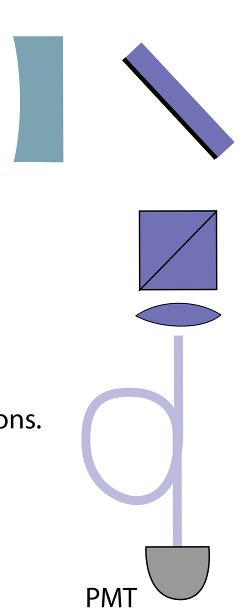
Starting with an isotopically pure chain of $^{174}Yb^+$ ions, we ramp up the periodic DC potential, splitting the chain between the array sites. The number of ions loaded in each site in such a manner is repeatable. For the sample shown, we perform 50 ramps and observe the chain splitting between two sites with highly sub-Poissonian statistics.

We quantify the ion statistics in each site by FANO = ratio of observed variance in ion number in each site relative to Poisson distribution for the same number of ions. We obtain Fano factors of 1.6% and 8.0%, deep in the sub-Poisson regime.

Such deterministic loading is promising for scalable quantum information processing using ion motional modes for operations in each array site and cavity-based coupling between array sites.

Cavity as ion fluorescence detector





cavity finesse =3,600
cavity mode waist = 38 um
λ = 369.5nm

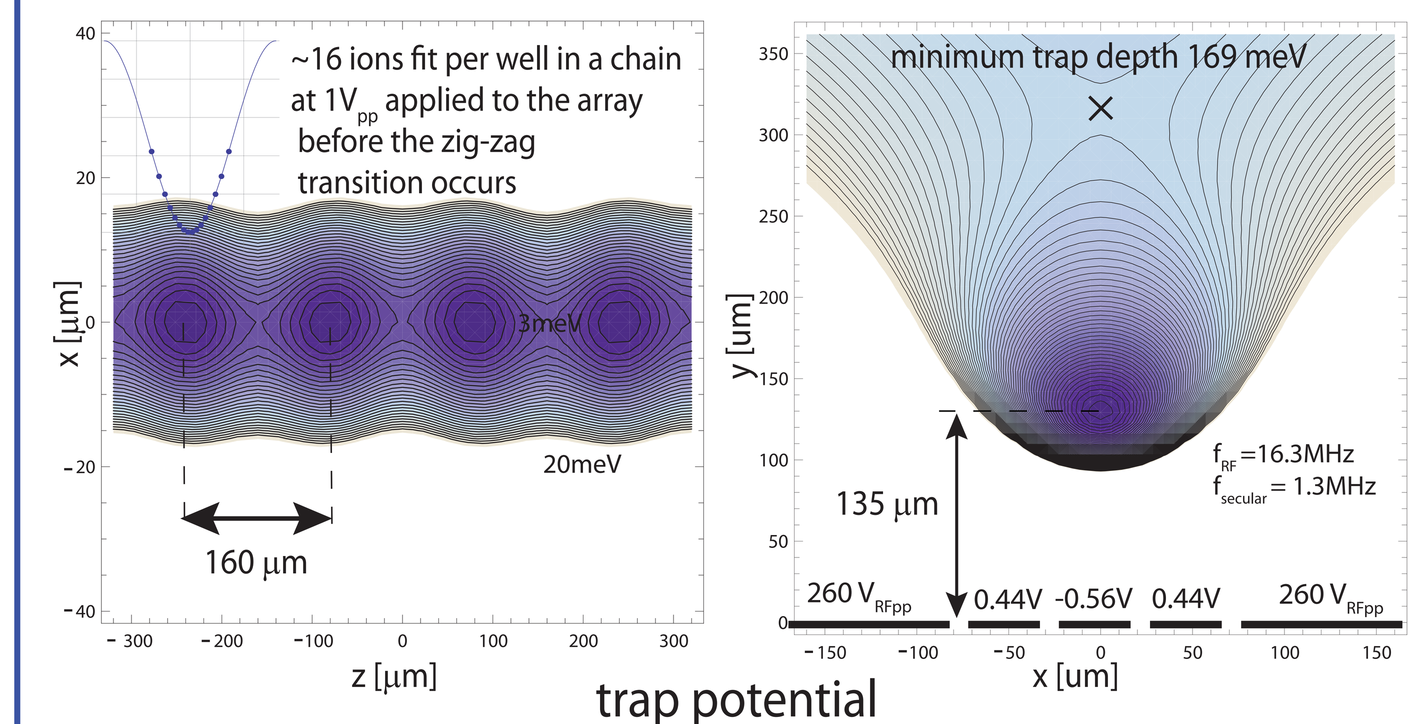
saturated ion fluorescence	$6x10^7$/s
theoretical max. cavity collection efficiency	4.4%
node-antinode average	0.5
two-sided cavity	0.5
polarization selection	0.5
ion saturation	0.25
broadening due to residual radial micromotion	0.5
fiber coupling	0.3
PMT QE	0.19
loss (estimate)	0.6
optical pumping (estimate)	0.5
max. predicted PMT counts	700/s
measured PMT counts / ion	200/s

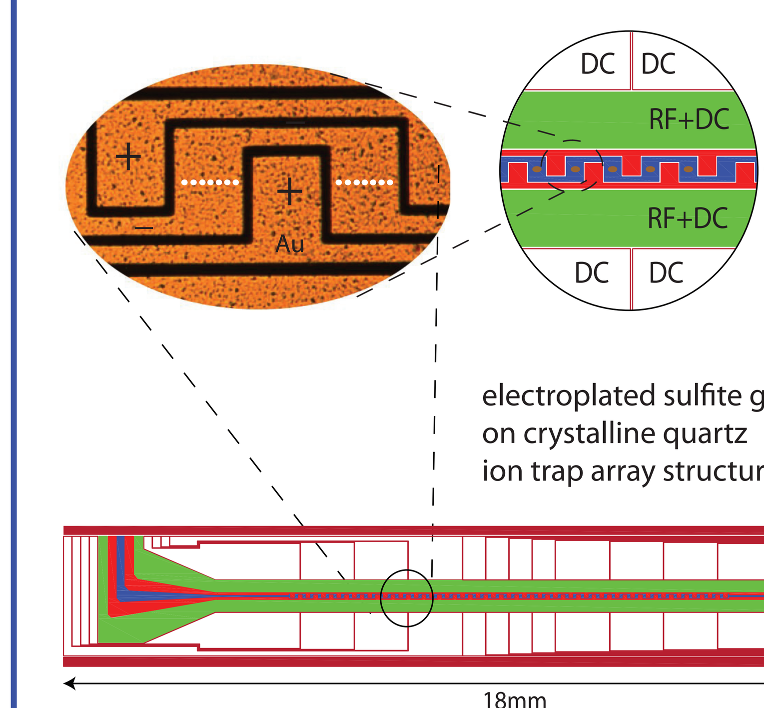
We use a transfer cavity setup to stabilize the optical resonator relative to a 369.5nm ion cooling laser.

We Doppler cool the ions from the side and use the cavity to collect the scattered photons.

Preliminary results give 100-200 PMT counts/s/ion, corresponding to 0.5% probability for a cold, well-localized ion to emit into the single cavity mode -- promising for probabilistic entanglement of individual ions or single photon generation via the DLCZ protocol (Duan et al, Nature 414, 2001).

Lithographic linear DC trap array

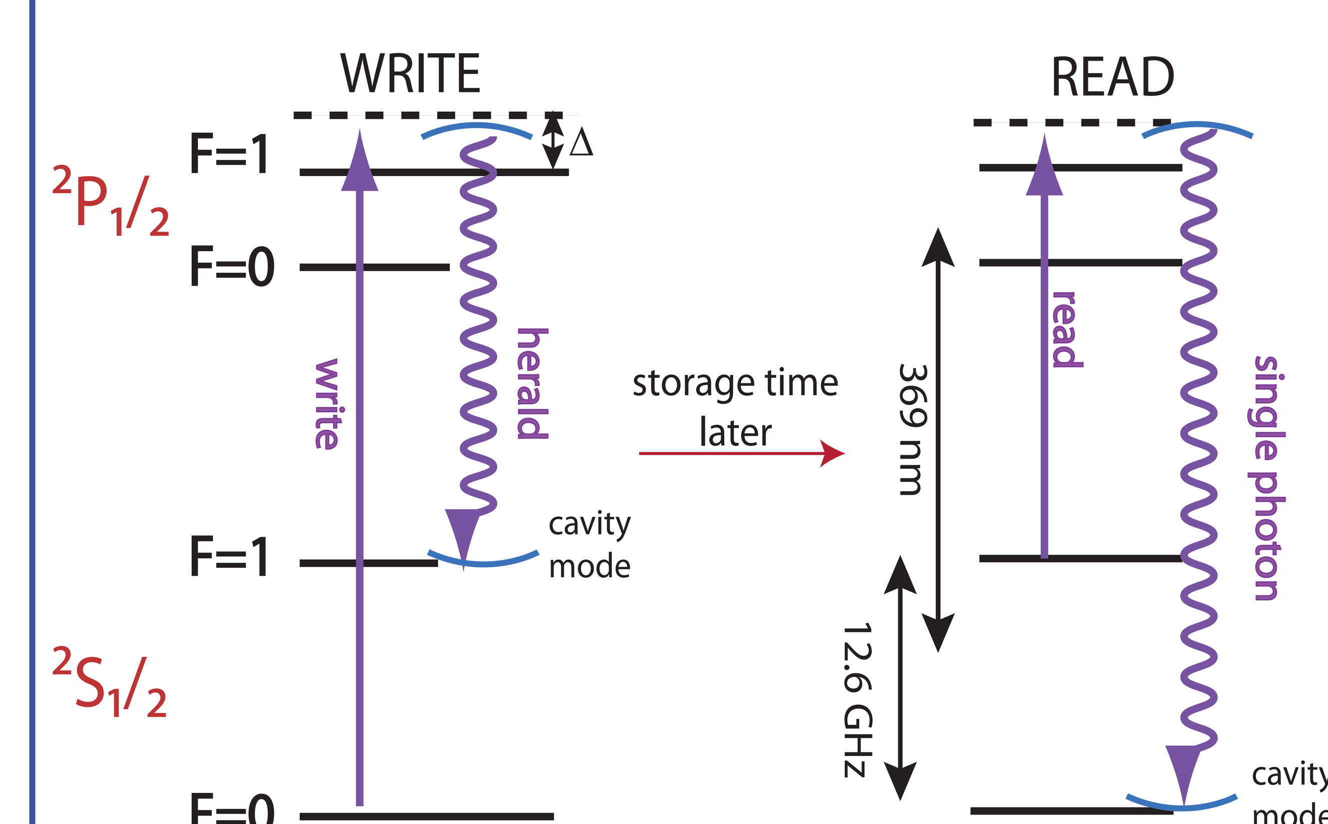




The array of traps is produced by a DC bias applied to a meandering periodic electrode. Up to 50 array sites are available this way.

24 independent DC electrodes are also available for micromotion compensation across the array and for arbitrary potential shaping.

Future: Photon storage in $^{171}Yb^+$ ions



Single excitations can be written into the ionic ensemble by driving the F=0 to F=1 transition with a weak 'write' beam and detecting an indivudal Raman photon scattered into the cavity resonant with the F=1 to F=0 transition. This projects the ion ensemble onto a W-state of the form:

$$\frac{1}{\sqrt{N}}\left(e^{i\phi_1}\left|\uparrow\downarrow\downarrow..\downarrow\right\rangle + e^{i\phi_2}\left|\downarrow\uparrow\downarrow...\downarrow\right\rangle + ... + e^{i\phi_N}\left|\downarrow...\downarrow\uparrow\right\rangle\right)$$

The stored photonic state has an enhanced probability to emit into the cavity when driven by a 'read' beam satisfying an appropriate four-wave phase-matching condition. The superradiant enhancement scales with the number of ions participating in the W state. With ~100 ions in the cavity mode we project order-unity photon recovery efficiencies.