Scalable imaging of trapped ions

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Theory collaborators:

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- Prof Harry Quiney (U Melb)
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Experimental team:

- Dr Erik Streed
- Dr Andreas Jechow
- Dr Till Weinhold (U Qld)
- Benjamin Norton
- Matthew Petrasiunas
- Valdis Blums

Griffith UNIVERSITY

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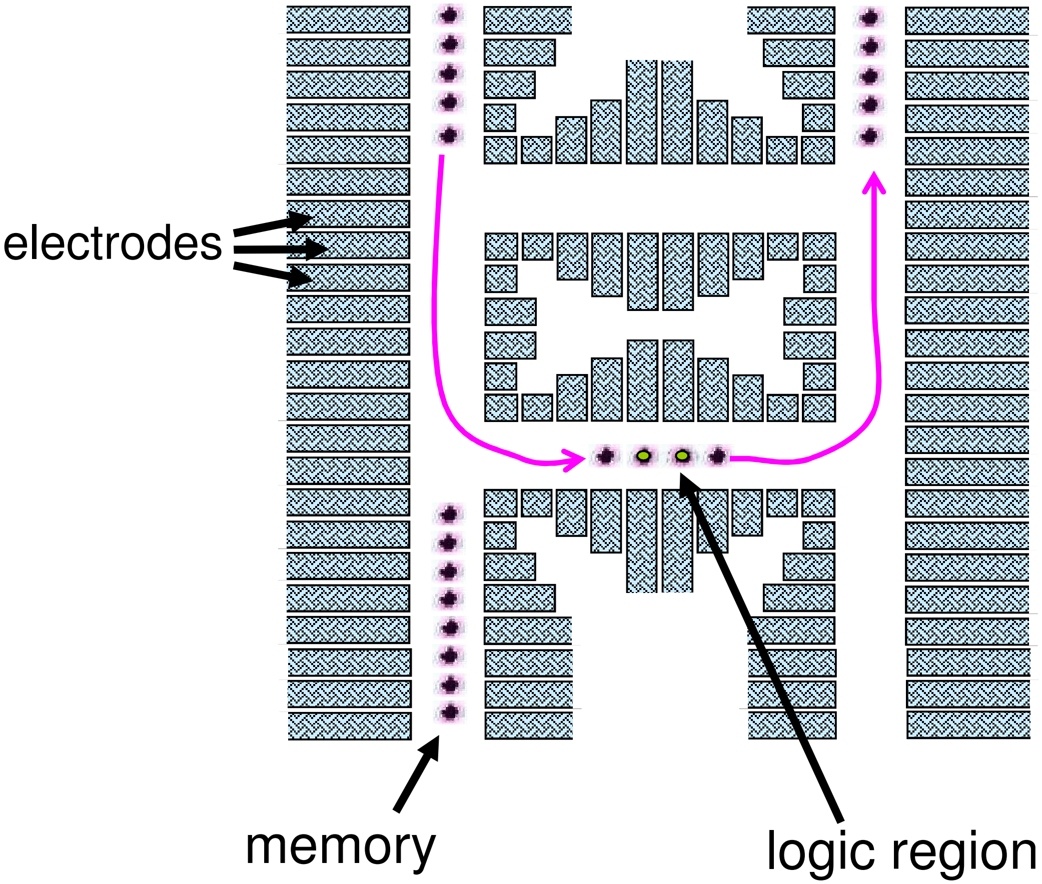
Australian Government
Australian Research Council

“Quantum CCD”

Kielpinski, Monroe, Wineland, *Nature* **417**, 709 (2002)



Large numbers of ions are hard to control!

How to scale up?
Modular architecture

shuttle ions around

Highly parallel imaging

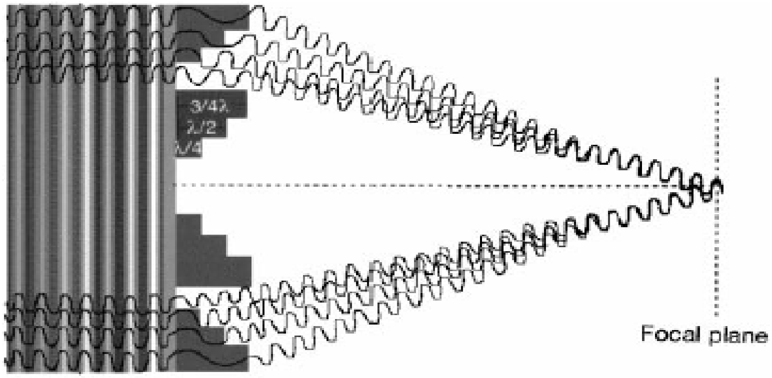
Streed, Norton, Chapman, Kielpinski, *Quant Inform Comp* 9, 0203 (2009)

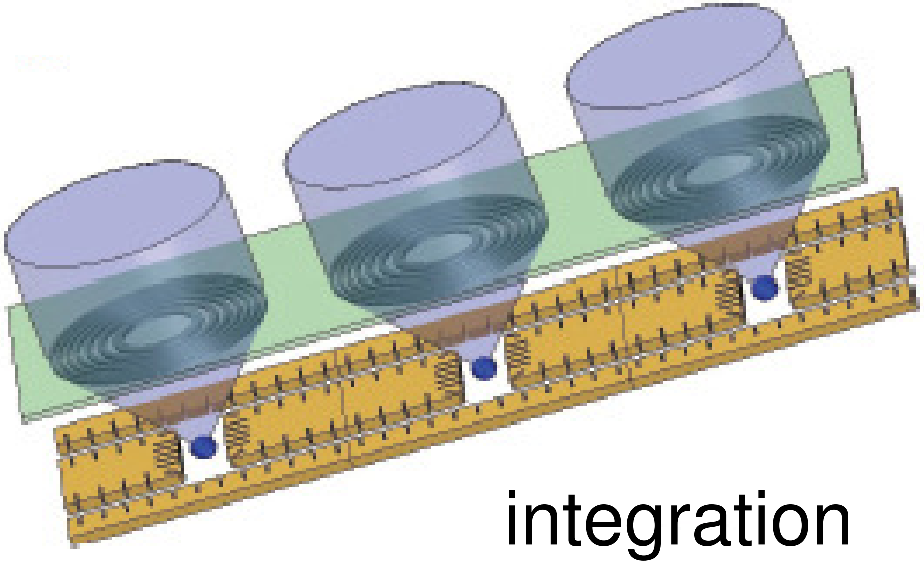
Fault-tolerance: parallel error correction
rate-limiting step: *ion readout*
efficient, scalable light collection

Quantum communication:
match to single-mode fiber
imaging, not just collection

Traditional multi-element lens: bulky, complex, inefficient

Fresnel lens: engineer surface directly
Up to 32% solid angle
(20x better than lens)
Microfabricated lens arrays





integration
with trap array

Fresnel lens design and fabrication

Simple two-level lens design:

trenches with square x-section, depth = π phase shift

trench spacing: phase profile of perfect lens

Fabrication: e-beam lithography on fused silica substrate

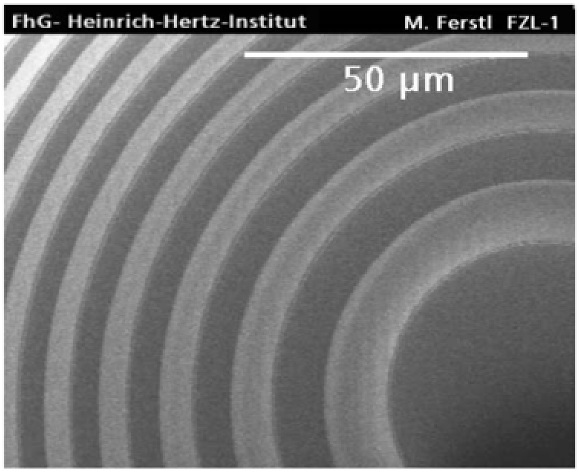
focal length = 3 mm, diameter = 5 mm

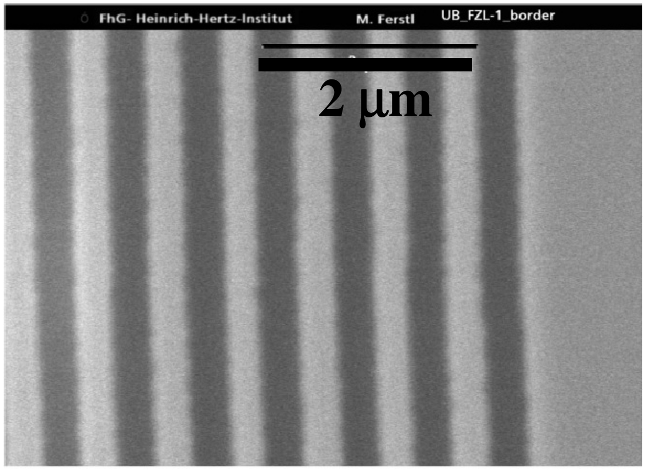
12% of total solid angle (0.12 × 4π steradians)

fabrication: M. Ferstl

HHI

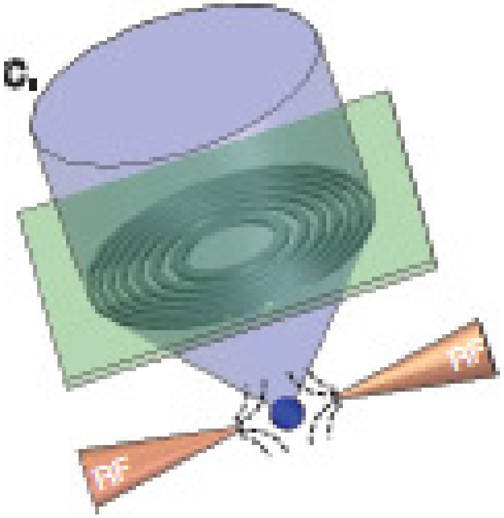
Fraunhofer
Institut
Nachrichtentechnik
Heinrich-Hertz-Institut

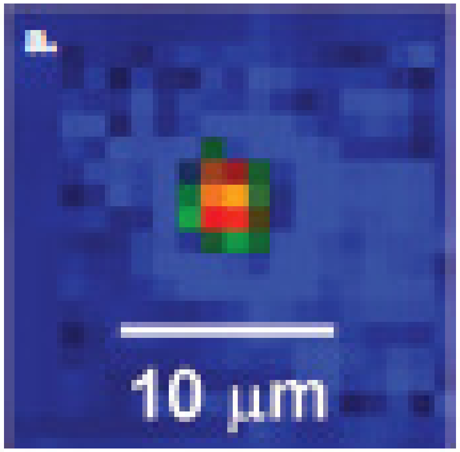




Scalable ion imaging

Streed, Norton, Jechow, Weinhold, Kielpinski
PRL 106, 010502 (2011)





$^{174}Yb^{+}$

λ = 369 nm

Imaging at standard detection wavelength of 369.5 nm

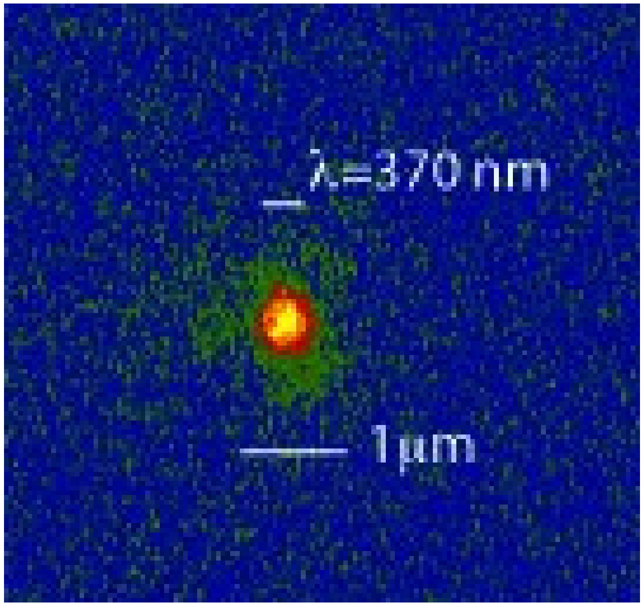
4% collection efficiency (30% diffraction)

140 μm field of view, signal = 23×background

Scalable with performance similar to other systems

Imaging at the wavelength scale

Jechow, Streed, Norton, Petrasiunas, Kielpinski, arXiv:1101:4403 (2011)



Record resolution for imaging an isolated atom: 440 nm FWHM

20% larger than wavelength

Est. 36x higher entanglement rate

aberration-free imaging volume

only a few µm on a side

nanopositioning becomes crucial!

Ideal resolution at our numerical aperture: 294 nm FWHM

Temperature should not limit resolution for Doppler cooling

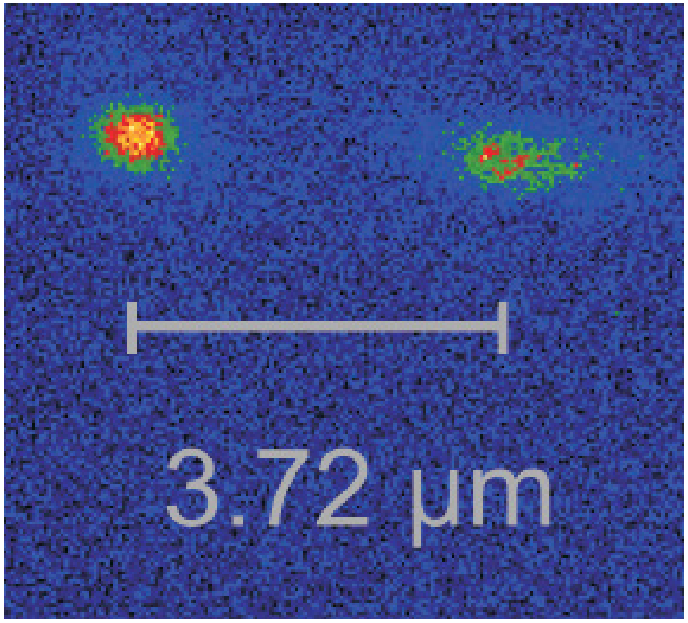
Need to locate aberration-free volume better? Vibration issues?

Applications of high resolution

Laser addressing

Low-crosstalk fiber coupling

Smaller traps
(stray light not a problem!)

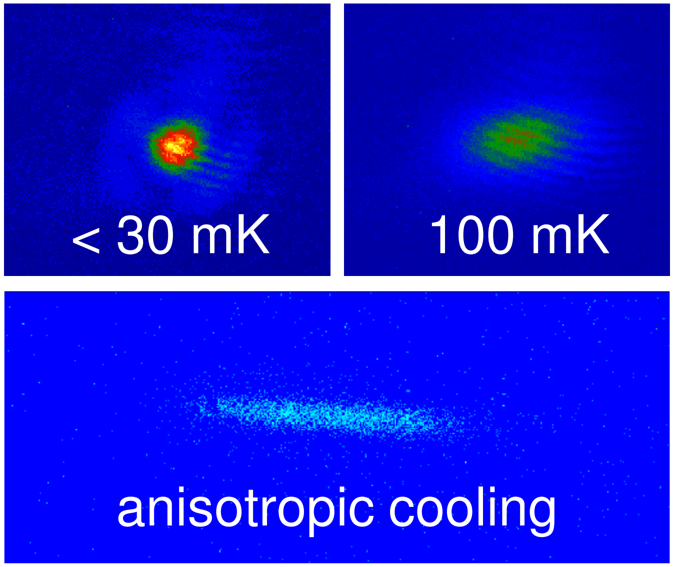


Spatial thermometry

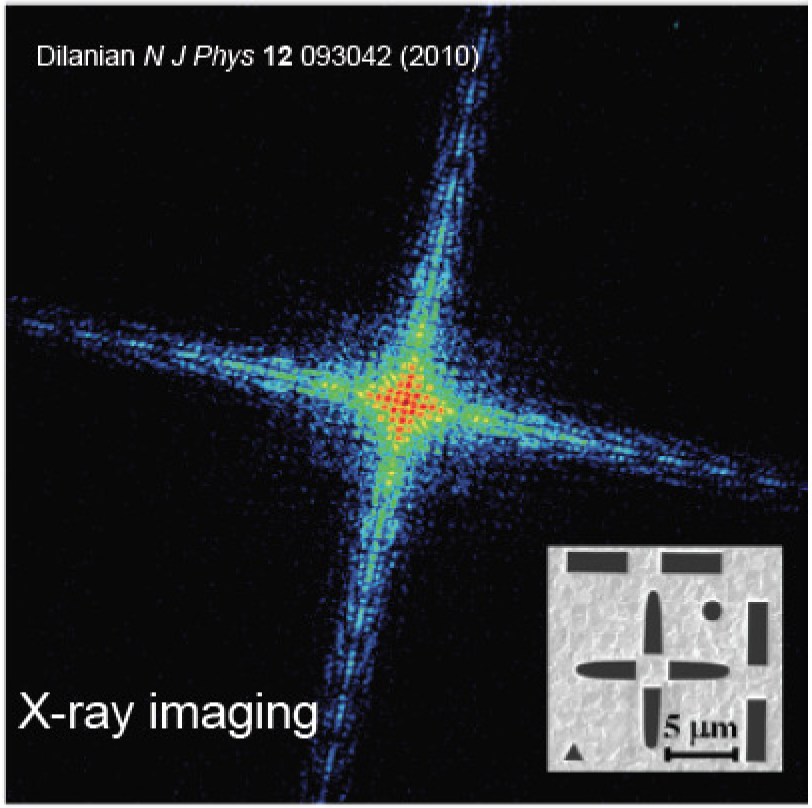
0.3 mK resolution, 15 mK accuracy

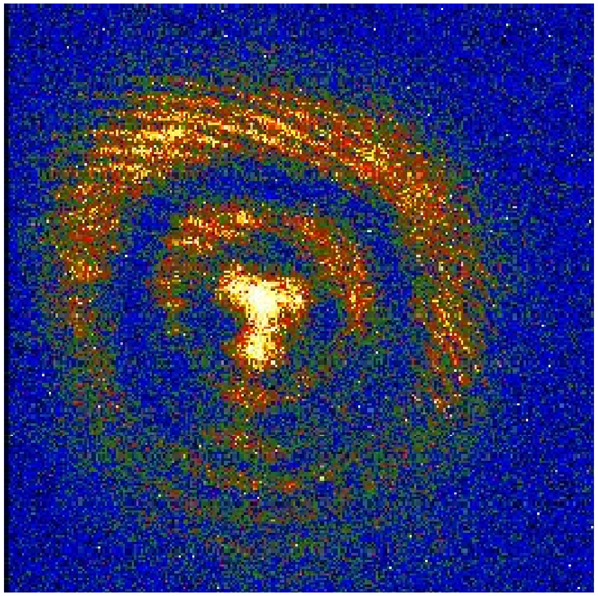
Equilibrium technique
(unlike spectral thermometry)

Novel laser cooling dynamics



Spatial wavefunction of ion photons


Dilanian *N J Phys* **12** 093042 (2010)


Series of defocused ion images

Assume Fresnel diffraction between images

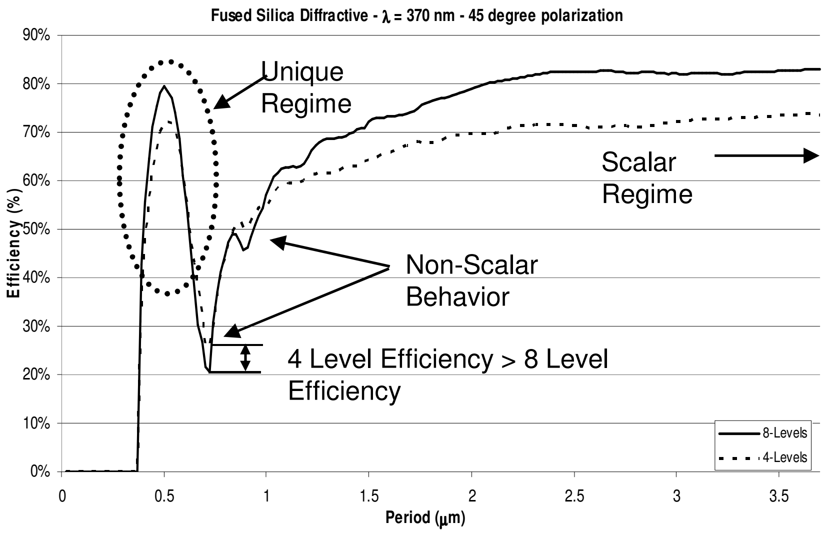
Reconstructs amplitude and phase of wavefront

Improving Fresnel lenses

80% diffraction efficiency

Use more complex groove profile

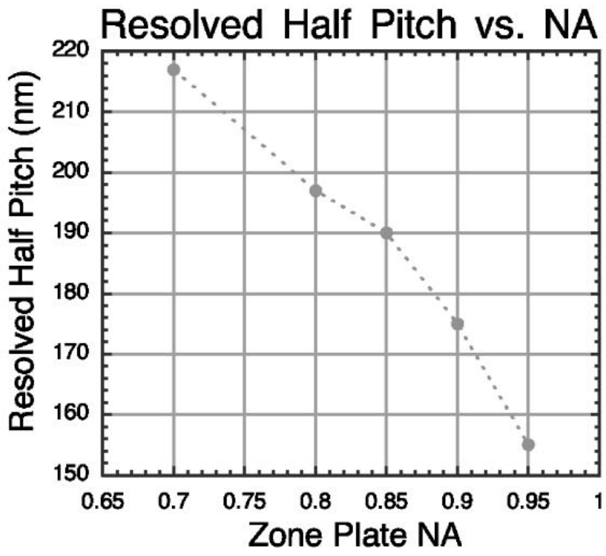
Sandia / Griffith, Proc. SPIE 6482, 648209 (2007)



28% solid angle coverage

(diameter = 4 x focal length)

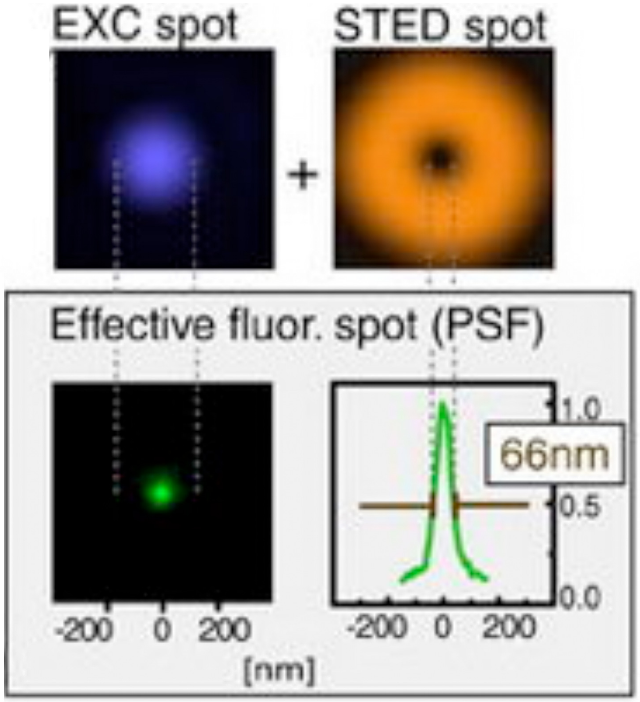
Gil et al., J. Vac. Sci. Technol. B 20, 2597 (2002)



22% collection efficiency, 200 nm resolution, diffraction-limited

x 2500 increase in ion-ion entanglement rate

Superresolution imaging of ions



Superresolution microscopy: beat the wavelength limit

Example: STED (stimulated emission depletion) microscopy

Scanned vortex beam with dark spot << λ

Simple for ions!

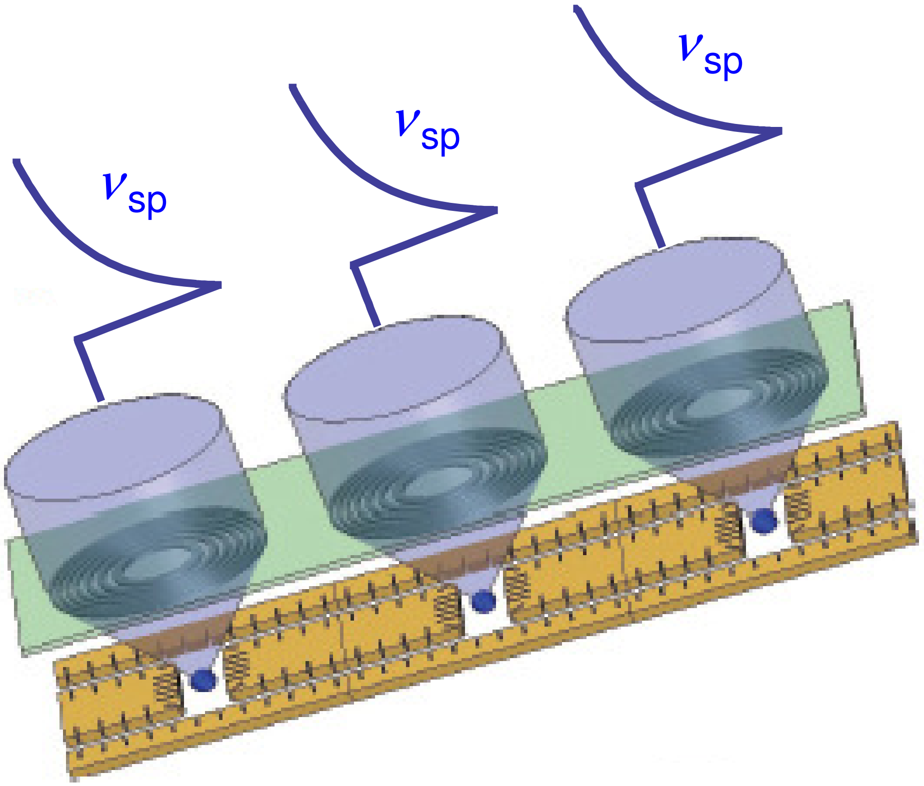
- STED: λ/60 = 6 nm resolution (scan laser beam)
- Resolve quantized motion by fluorescence
- Quantum feedback on motional state
- Application to BEC imaging?

Quantum repeaters with trapped ions

Long-distance quantum communication:

extend range of quantum light pulses using quantum repeaters

key capability: entangle ion qubit with quantum light pulse



Dipole coupling limits bandwidth to << 1 GHz (even with cavity)

Spontaneous emission: single-sided exponential

Fixed wavelength

Interface to telecom networks?

Fiber telecommunications:

short pulses (tens of ps for optimum use of DWDM)

smooth pulses (dispersion management)

many wavelength slots in 1550-1650 nm band

How to interface with ion light pulses?

Current lines of research:

Nonlinear wavelength conversion of single photons

Narrowband SPDC engineering (match to quantum emitter)

Try to speed up ion photon… still limited to 1 GHz

Quantum optical waveform conversion

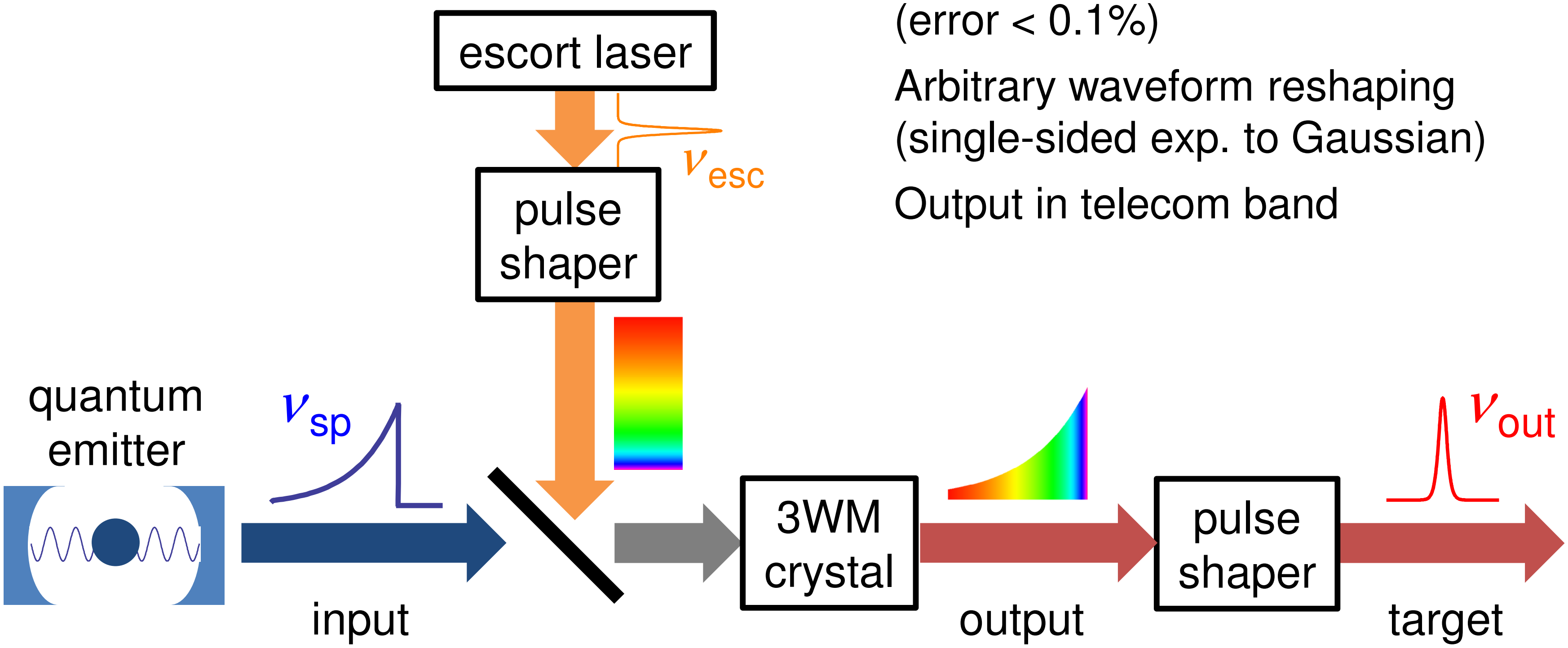
Access full time-bandwidth product of telecom link

Kielpinski, Corney, Wiseman, arXiv:1010.2104, accepted to PRL

Preserves quantum coherence (error < 0.1%)

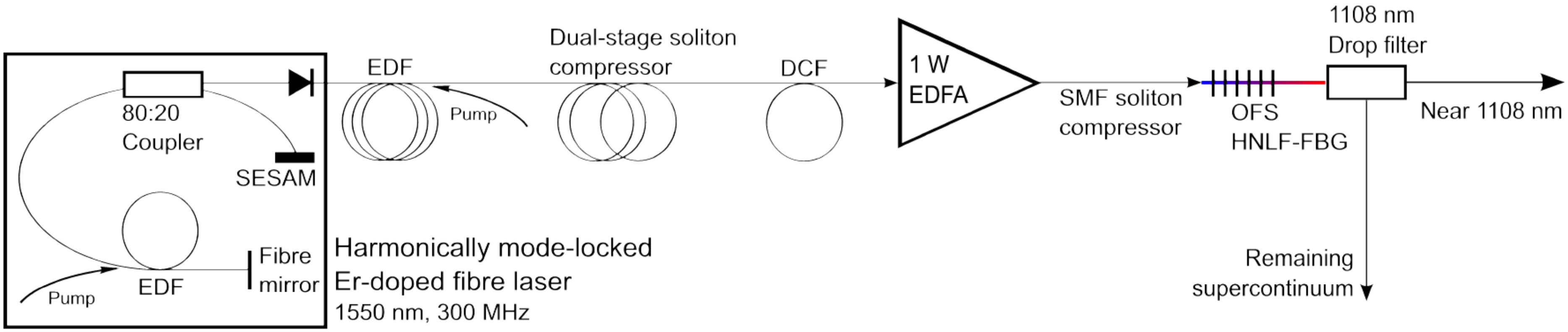
Arbitrary waveform reshaping (single-sided exp. to Gaussian)

Output in telecom band



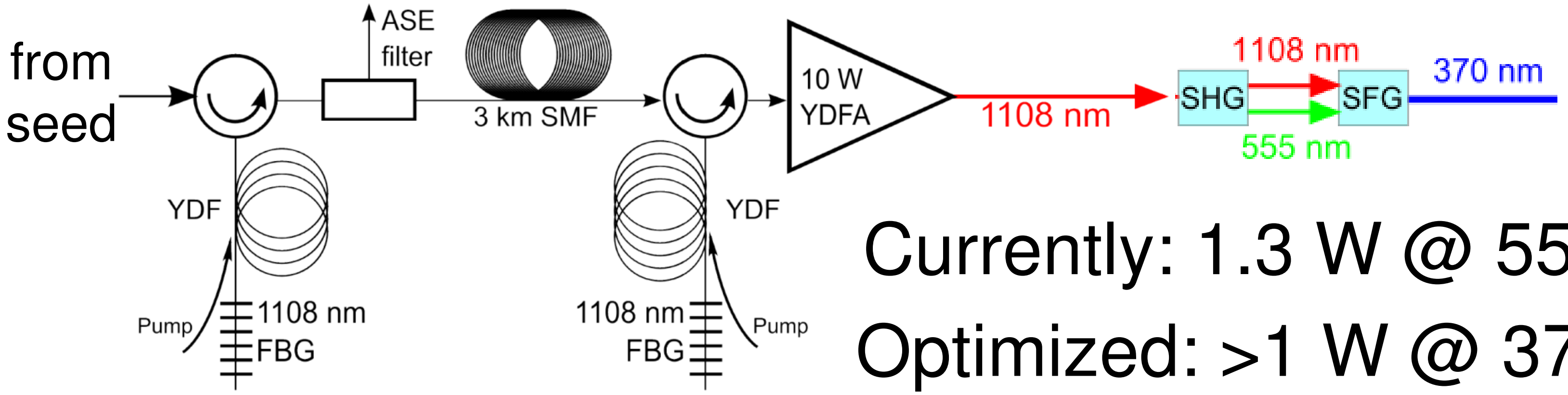
Ultrafast all-fiber lasers for fast gates

Tunable seed with scalable repetition rate (300 MHz)



Harmonically mode-locked
Er-doped fibre laser
1550 nm, 300 MHz

Power amplification and upconversion



Currently: 1.3 W @ 555 nm

Optimized: >1 W @ 370 nm

Conclusions

Fresnel lens imaging of trapped ions

- efficient, low-aberration collection into single mode
- should increase ion-photon entanglement rate
- clear path to highly parallel operation

Quantum optical waveform conversion

- compress and reshape fluorescence photon waveform
- negligible error in state transfer

Ultrafast lasers for fast gates

Telecom-compatible quantum repeaters
with fast quantum logic


AC/DC