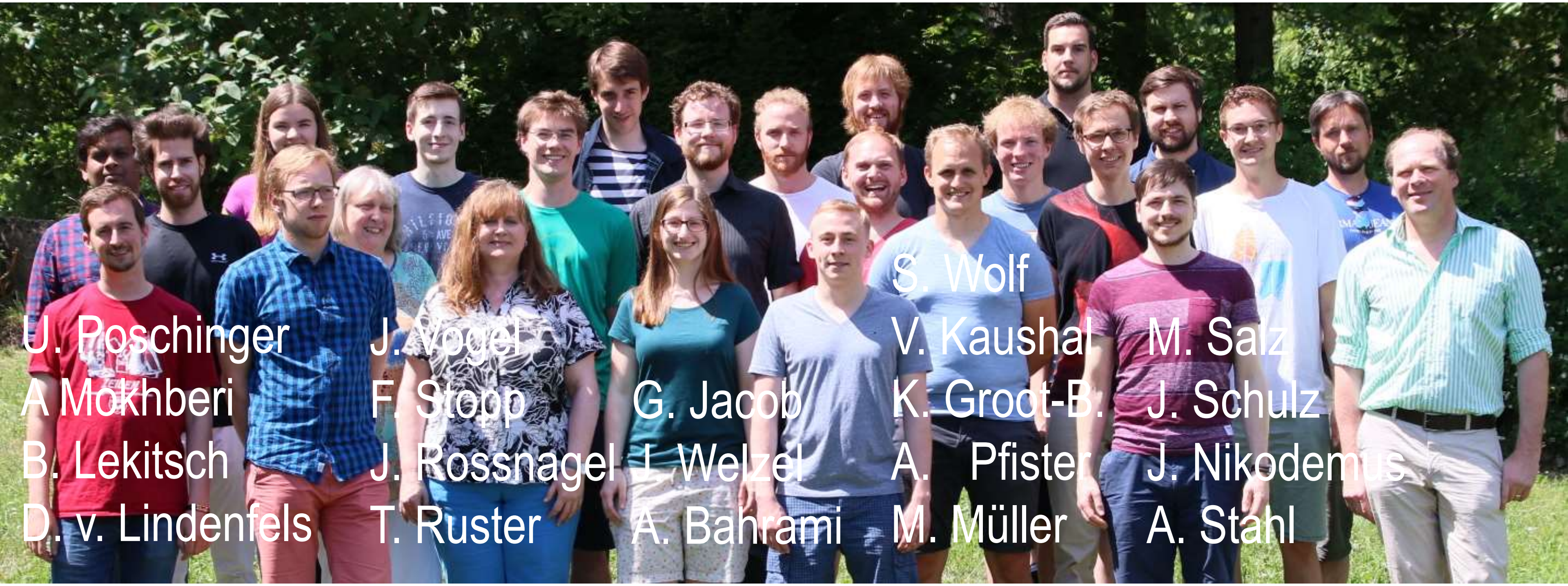
The team

www.quantenbit.de



Folman @Be'er Sheva
Retzker @Jerusalem
Zoller, Blatt @Innsbruck

Budker, Walz @Mainz
Lesanowski @Nottingham
Wrachtrup @Stuttgart

Zanthier, Lutz @Erlangen
Plenio, Jelezko, Calacro@Ulm
Jamieson @Melburne

DFG Deutsche Forschungsgemeinschaft

QUANTUM FLAGSHIP

RySQ

iRyd

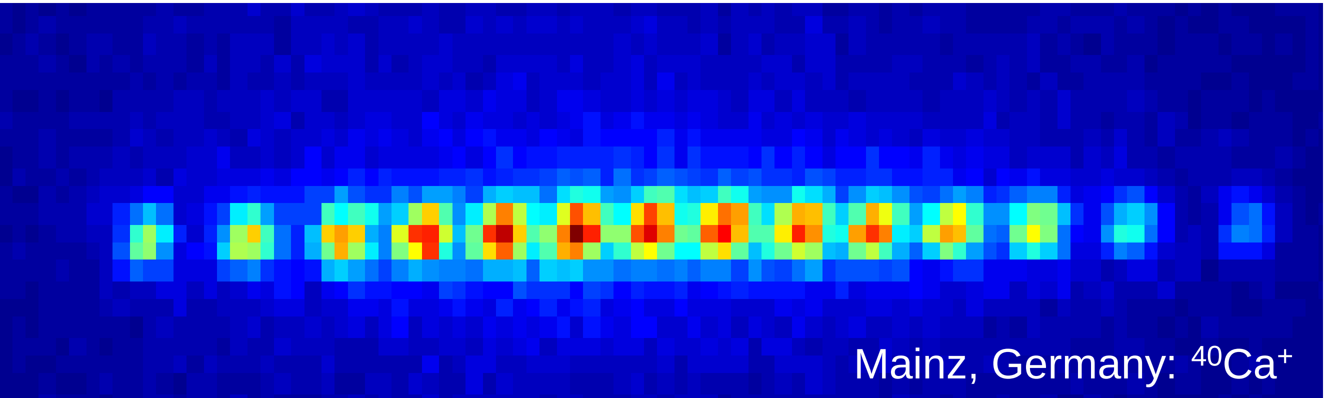
VolkswagenStiftung

BMBF Q.ComQ

FUNDING OPPORTUNITIES from the FUTURE & EMERGING TECHNOLOGIES scheme

Quantum optics and information with trapped ions

- Introduction to ion trapping and cooling
- Trapped ions as qubits for quantum computing and simulation
- Qubit architectures for scalable entanglement
- Quantum thermodynamics introduction
- Heat transport, Fluctuation theorems,
- Phase transitions, Heat engines
- Outlook



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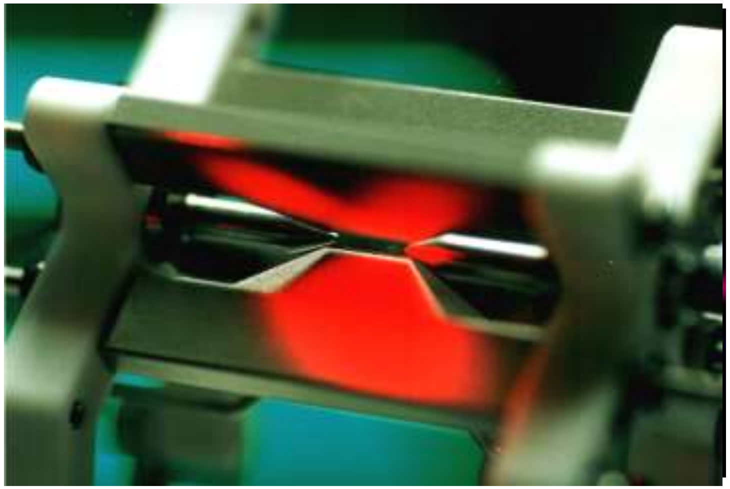
F. Schmidt-Kaler

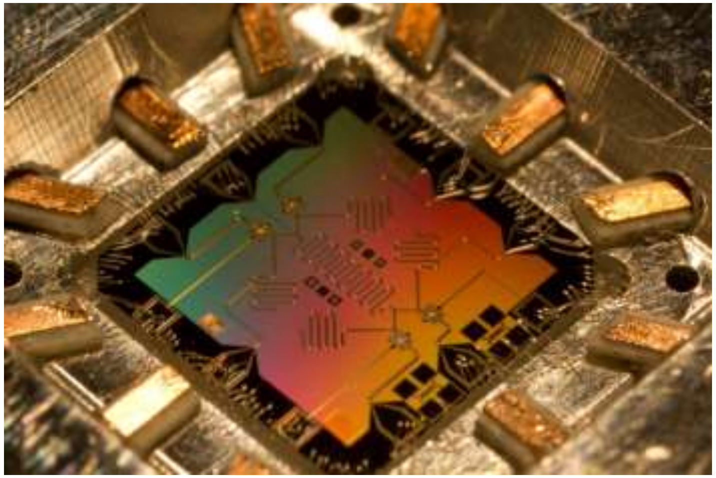
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

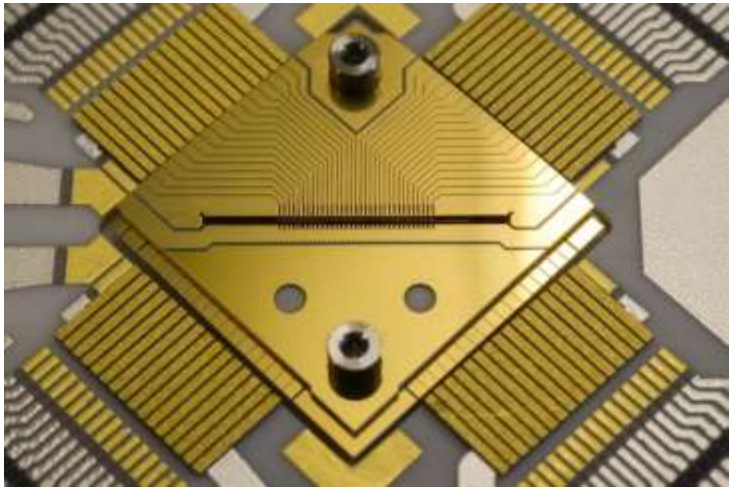
Quantum computing platforms

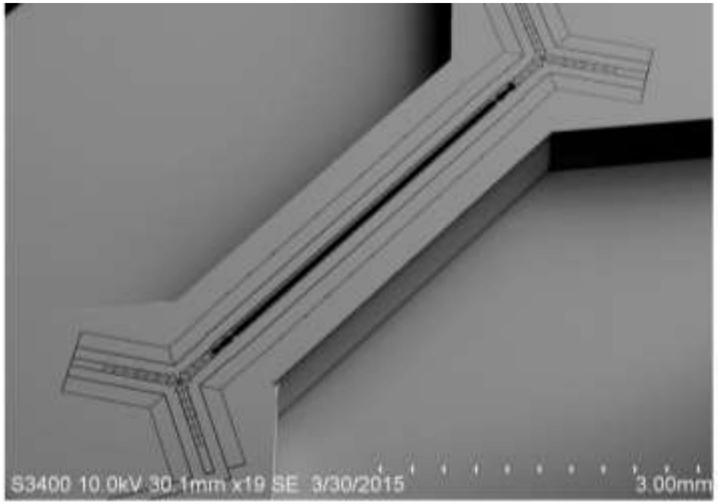
Trapped Ions in Paul traps

Solid state technology: SC qubit circuits & ….









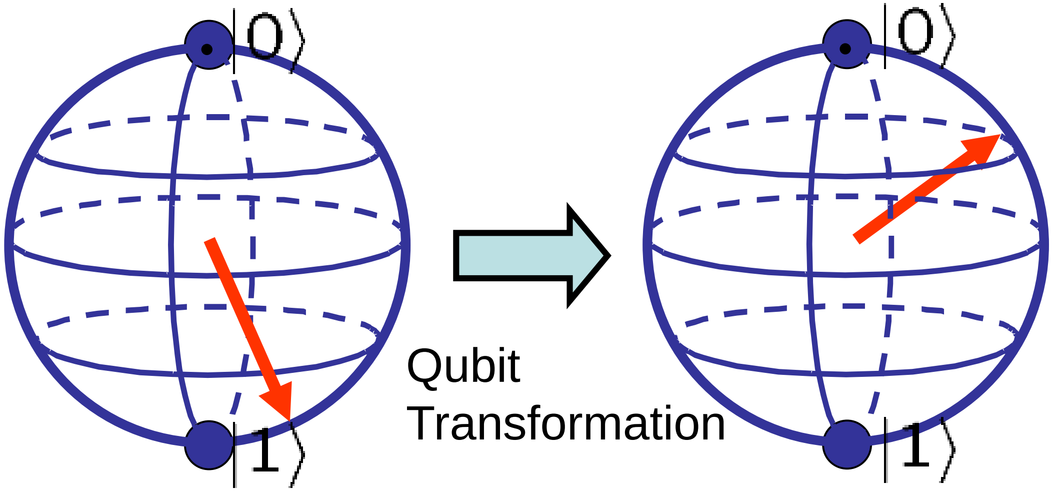
The experimental requirements for quantum computing

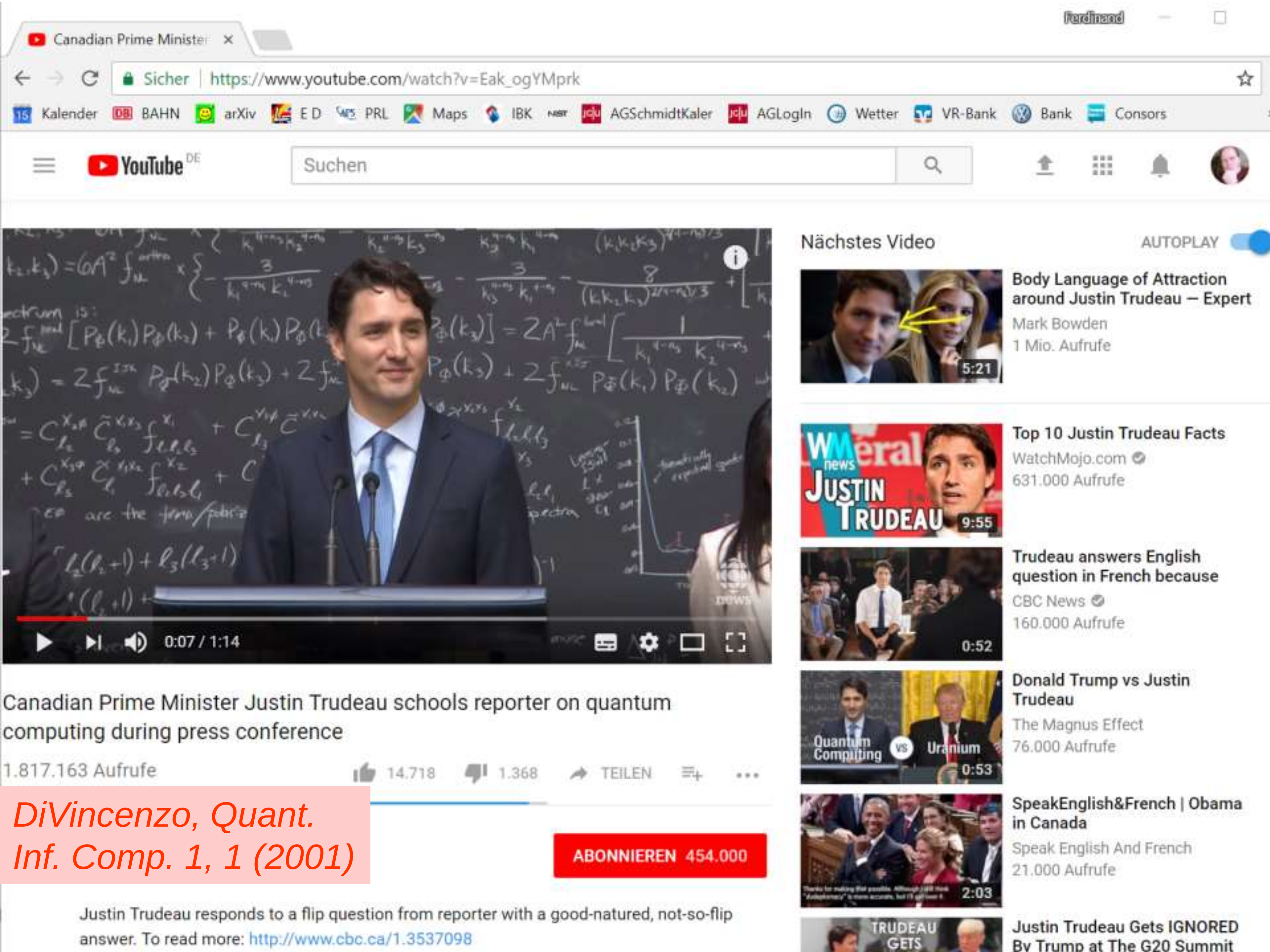
DiVincenzo, Quant. Inf. Comp. 1, 1 (2001)

1. Qubits store superposition information, scalable physical system
2. Ability to initialize the state of the qubits $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$
3. Universal set of quantum gates: Single bit and two bit gates
4. Long coherence times, much longer than gate operation time
5. Qubit-specific measurement capability

6. Qubit connectivity

7. Large distance transmission



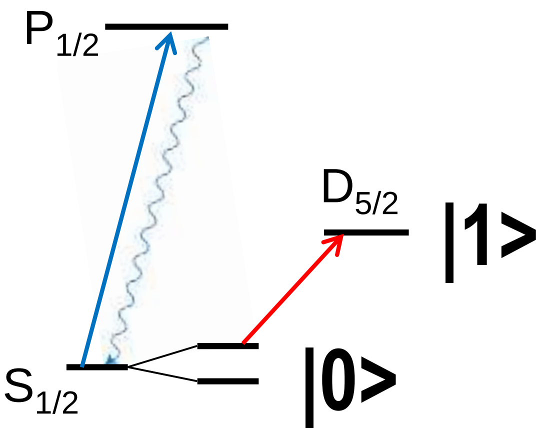


DiVincenzo, Quant. Inf. Comp. 1, 1 (2001)

Ion qubit choice

OPTICAL

$^{40}Ca^+$: UIBK, UCB, ETH, PTB
$^{88}Sr^+$: MIT, Weizmann
$^{128}Ba^+$: UIBK



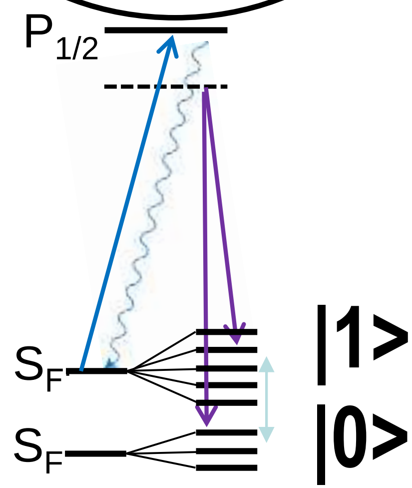
- Best overall performance so far
- Easy readout
- Requires optical phase stability
- Limited by metastable lifetime

HYPERFINE

$^{9}Be^+$: NIST, ETH
$^{25}Mg^+$: NIST, Freiburg
$^{43}Ca^+$: UIBK, Oxford
$^{171}Yb^+$: JQI, Sussex, Siegen, Duke,...

MICROWAVE

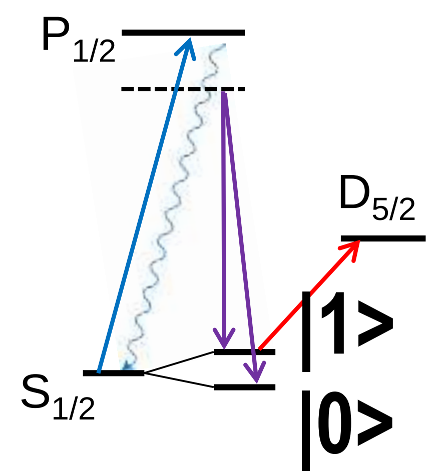
NIST, Hannover, Oxford, Sussex, ...



- Infinite T_1
  only scattering errors
- complicated level scheme

SPIN

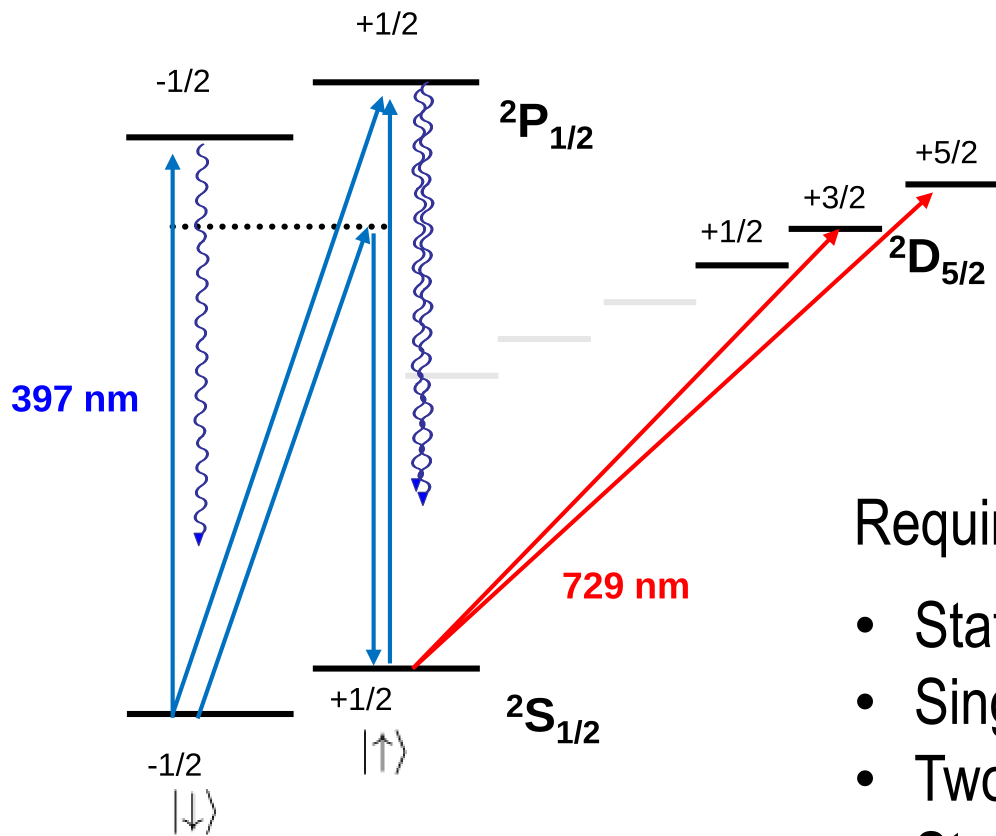
$^{40}Ca^+$: Oxford, UMZ



- Infinite T_1
  only scattering errors
- readout overhead

$^{40}Ca^{+}$ spin qubit

[illegible]lations

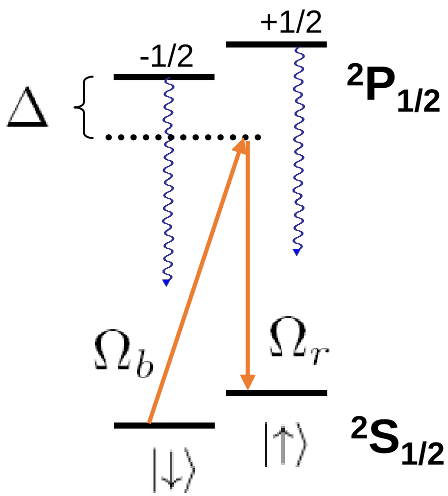


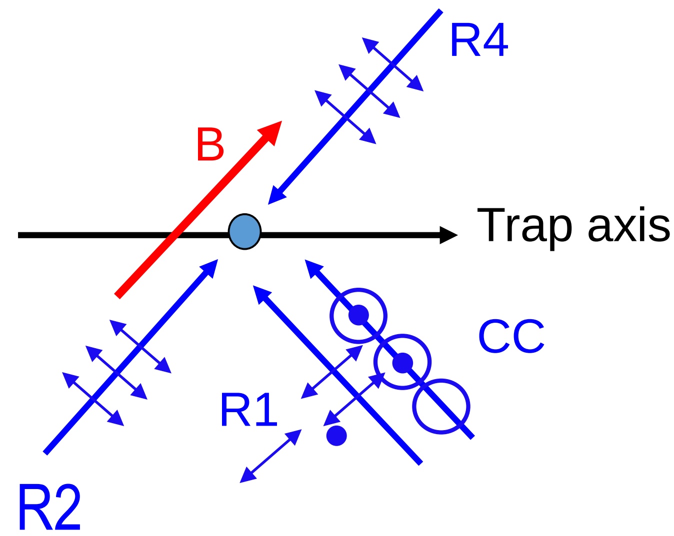
Requirements:

- State preparation
- Single-qubit gates
- Two-qubit gates
- State readout
- Flourescence detection
- Reset

Poschinger et al., J. Phys. B 42 154013 (2009)

Stimulated Raman transitions

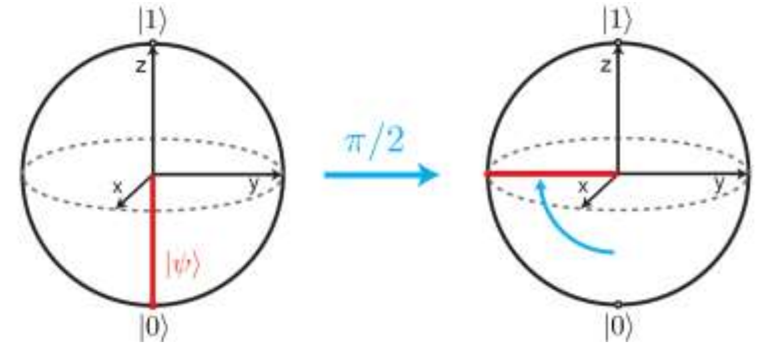


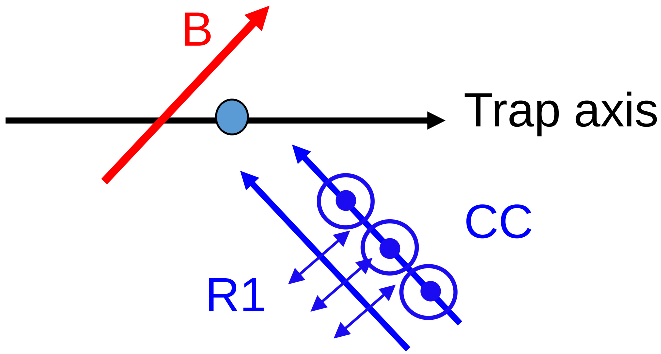


- Single photon detuning Δ much larger than natural linewidth
- Very small spont. scattering rate
- Effective two-level system

Four beams near 397nm used pairwise in different configurations

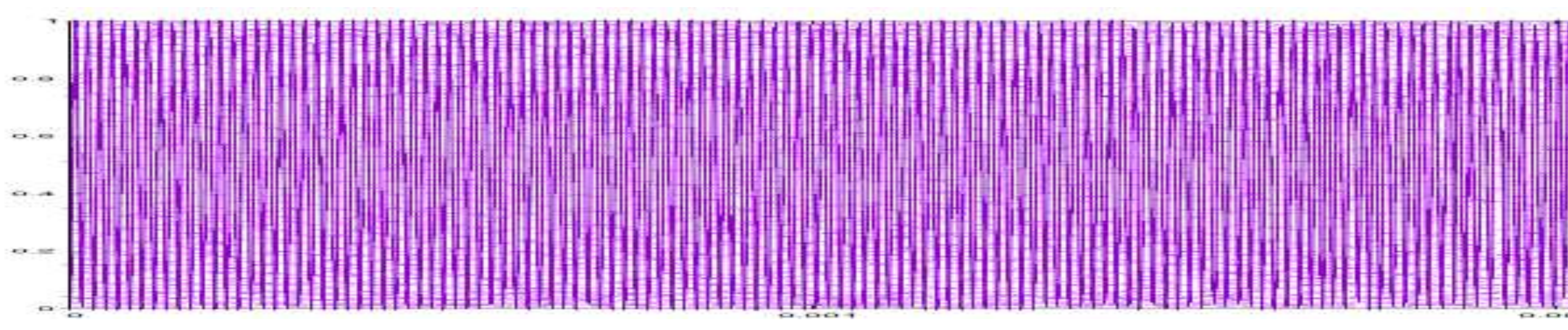
Single qubit rotation





- Copropgating beams
- No effective k-vector
- No coupling to ion motion
- 99,9949(2) % fidelity gates

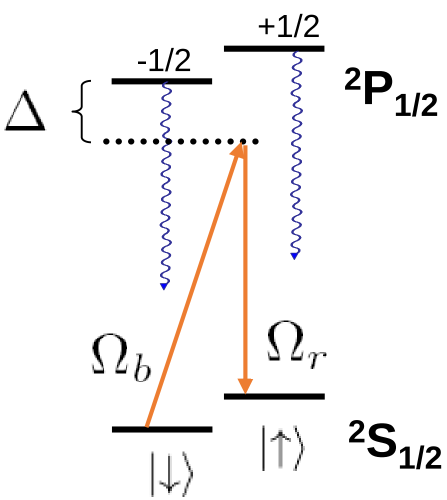
$$\Omega_{Raman} \propto \frac{\Omega_r \Omega_b}{\Delta}$$

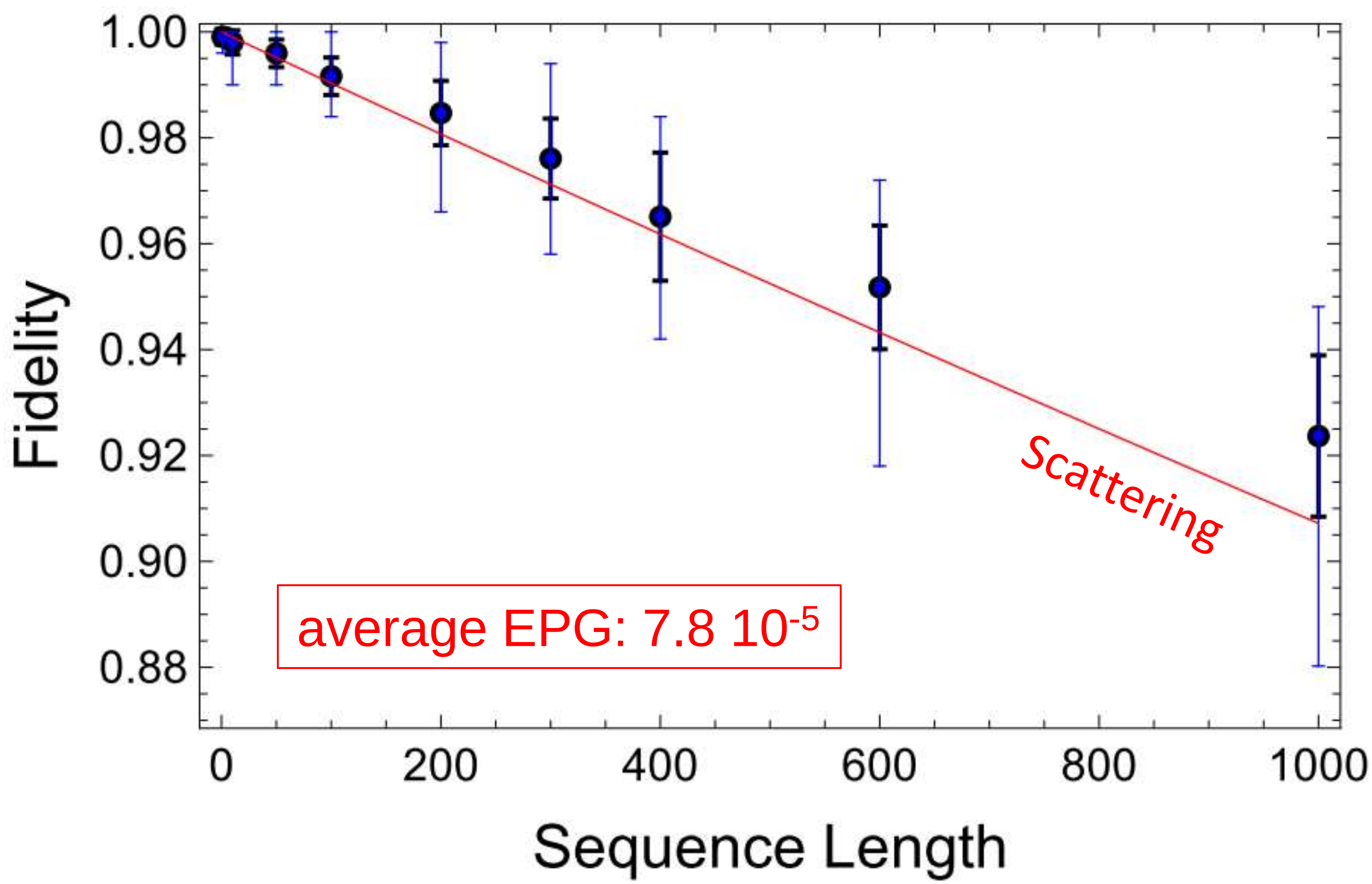


Spin qubit gate operation: Randomized benchmarking

Kaufmann, PhD

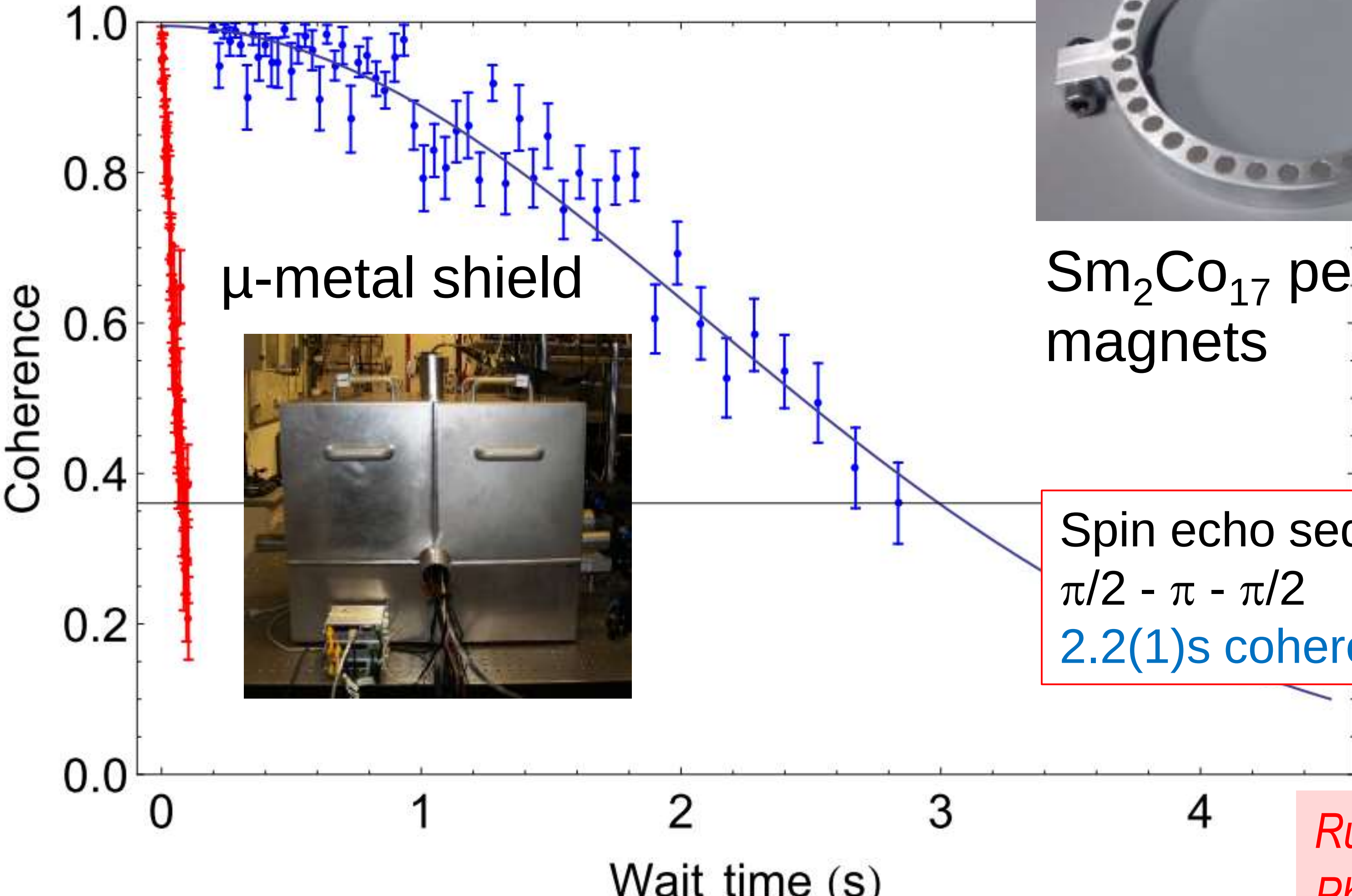
- Blocks of 40 gate sequences
- Gates chosen from $\{I, R_X(\pi/2), R_Y(\pi/2), R_Z(\pi/2), R_X(\pi), R_Y(\pi), R_Z(\pi)\}$, with π-time: 6.2 µs
- 500 repetition per sequence
- Raman detuning: here 300 GHz





Spin qubit coherence

Decoherence only by phase shifts, magnetic field fluctuations dominate



μ-metal shield

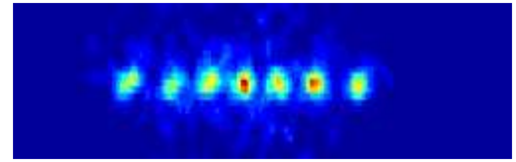
Sm_2Co_{17} permanent magnets

Spin echo sequence:
$\pi/2$ - π - $\pi/2$
2.2(1)s coherence time

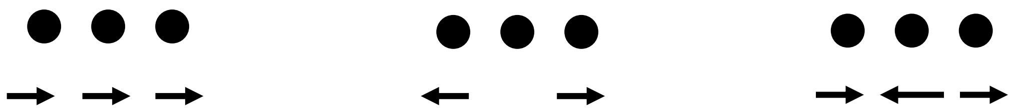
Ruster et al, Appl. Phys. B, 122(10), 1

Designed qubit interactions

Interactions due to coupling to common modes of vibration

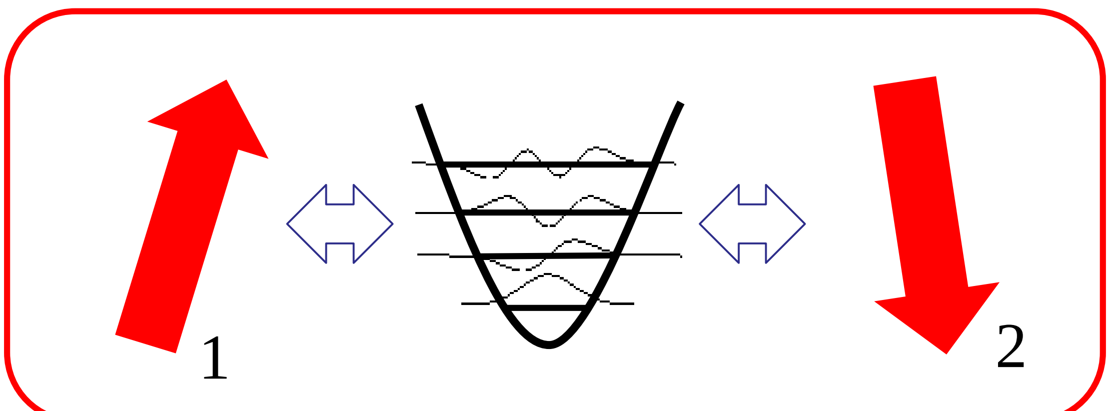


An N-ion crystal has N common modes in axial, radial-x, and radial-y direction



$1\ \omega_{ax}$ $\sqrt{3}\ \omega_{ax}$ $\sqrt{29/5}\ \omega_{ax}$

axial modes for N=3



Spin coupling is mediated by laser light interactions to one or many modes

Advantage: designing

Monroe, et al, Science ***272****, 1131 (1996)*
Leibfried et al., Nature 412, 422 (2003)
McDonnell et al. PRL ***98****, 063603 (2007)*

*Poschinger et al, PRL****105****, 263602 (2010)*

First gate proposal

74, NUMBER 20 4091 PHYSICAL REVIEW LETTERS 15 MAY 1995

Quantum Computations with Cold Trapped Ions

J. I. Cirac and P. Zoller*
Institut für Theoretische Physik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria
(Received 30 November 1994)

A quantum computer can be implemented with cold ions confined in a linear trap and interacting with laser beams. Quantum gates involving any pair, triplet, or subset of ions can be realized by coupling the ions through the collective quantized motion. In this system decoherence is negligible, and the measurement (readout of the quantum register) can be carried out with a high efficiency.

J. I. Cirac P. Zoller

- single bit rotations and quantum gates
- small decoherence
- unity detection efficiency
- scalable

control bit

target bit

$$Controlled-NOT : |\varepsilon_1\rangle|\varepsilon_2\rangle \rightarrow |\varepsilon_1\rangle|\varepsilon_1 \oplus \varepsilon_2\rangle$$

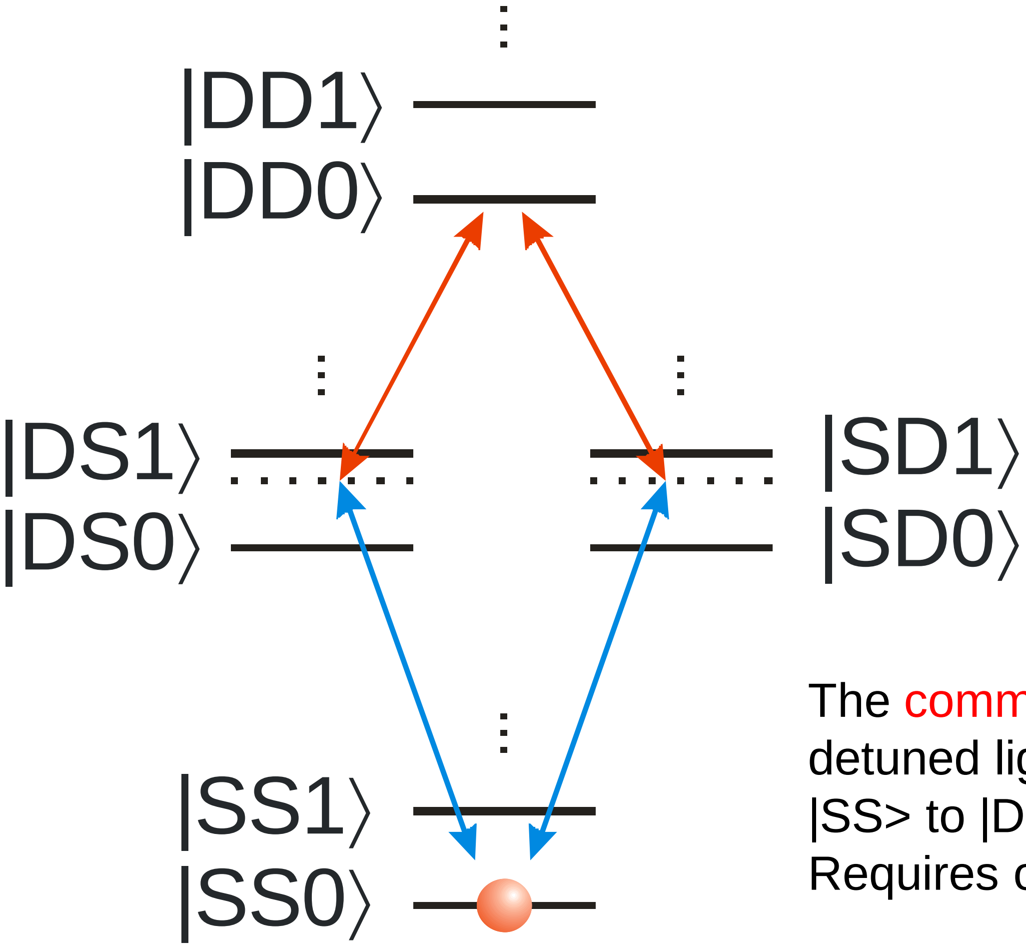
$$|0\rangle|0\rangle \rightarrow |0\rangle|0\rangle$$
$$|0\rangle|1\rangle \rightarrow |0\rangle|1\rangle$$
$$|1\rangle|0\rangle \rightarrow |1\rangle|1\rangle$$
$$|1\rangle|1\rangle \rightarrow |1\rangle|0\rangle$$

F. Schmidt-Kaler et al.,
*Nature **422**, 408 (2003)*
Fidelity : 73%

M. Riebe et al.,
*PRL **97**, 220407 (2006)*
Fidelity : 92,6%

Mølmer-Sørensen gate

Milburn, arXiv:quant-ph/9908037.
Milburn, Schneider, and James, Fortschr. Phys. ***48****, 801 (2000).*
Sörensen and Mölmer, PRL ***82****, 1971 (1999).*
Sörensen and Mölmer, PRA ***62****, 022311 (2000).*

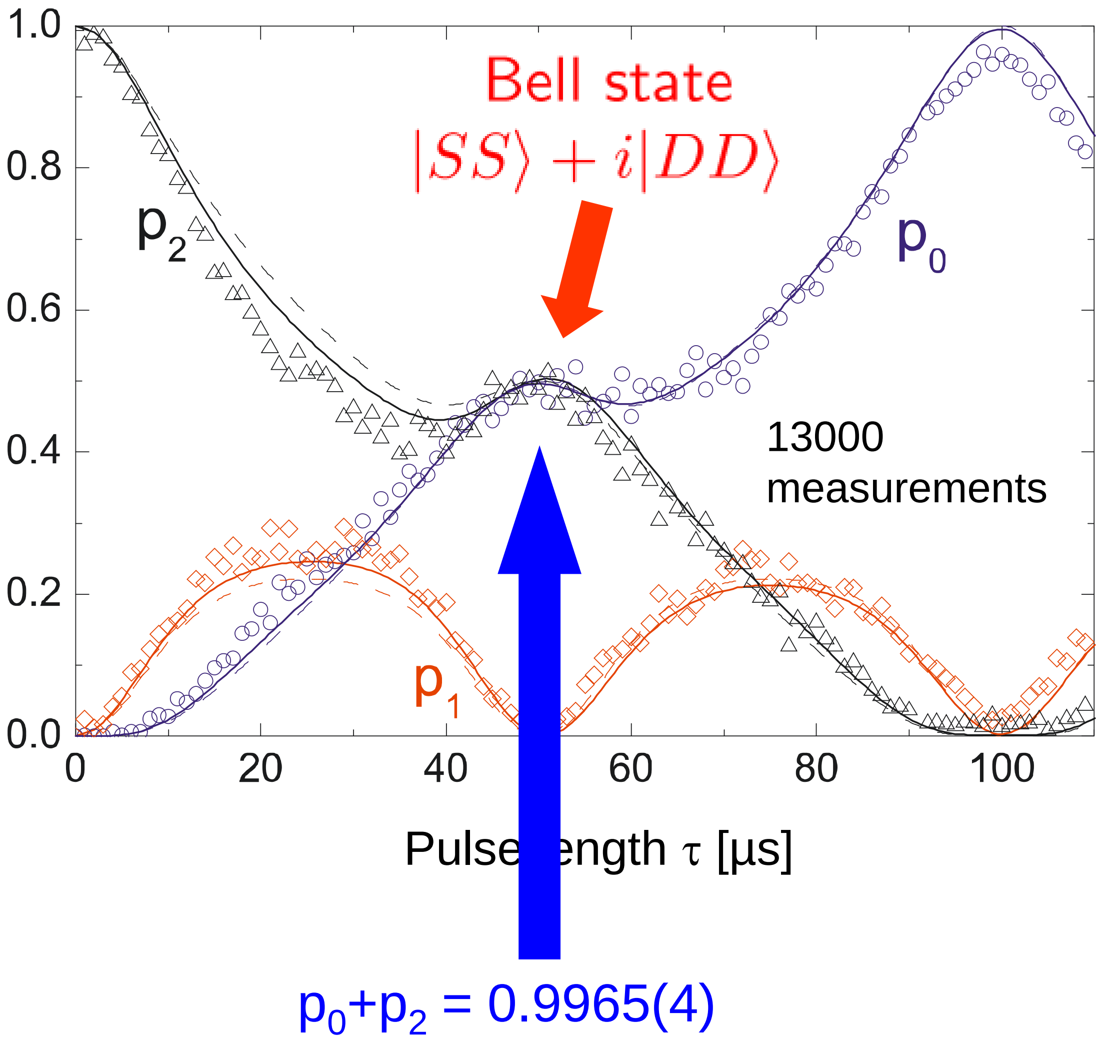


The common absorption of red and blue detuned light leads to a coherent evolution |SS> to |DD>. No excitation of |DS> states. Requires only Lamb Dicke limit $\eta\sqrt{n_{ther.}} << 1$

Bell state with F=83%
Sackett et al., Nature ***406****, 256 (2000)*

Bell state with F=99.3%
Benhelm et al, Nature Phys. 4, 463 (2008)

Mølmer-Sørensen evolution



Probabilities

- $p_0 \equiv p(|DD\rangle)$
- $p_1 \equiv p(|SD\rangle) + p(|DS\rangle)$
- $p_2 \equiv p(|SS\rangle)$

Detuning δ = 20 kHz
→ gate time 50 µs

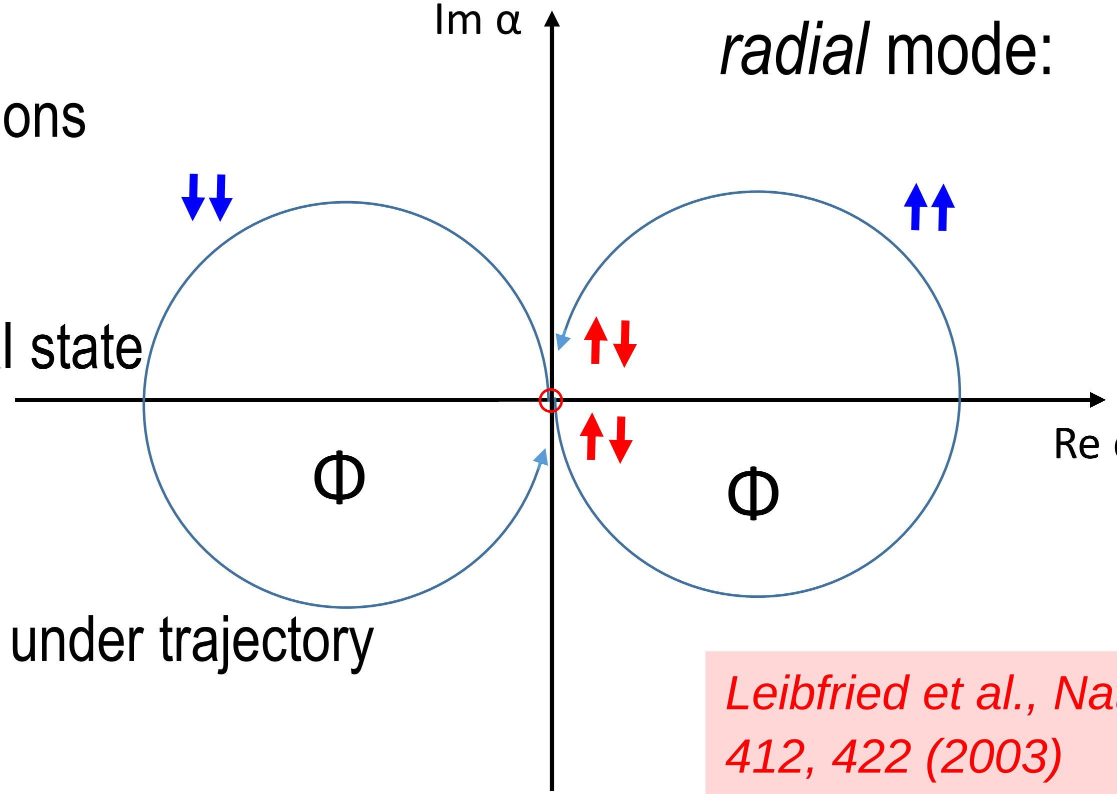
Benhelm, Kirchmair, Roos, Blatt
Nat. Phys. 4, 463 (2008)

Geometric gate

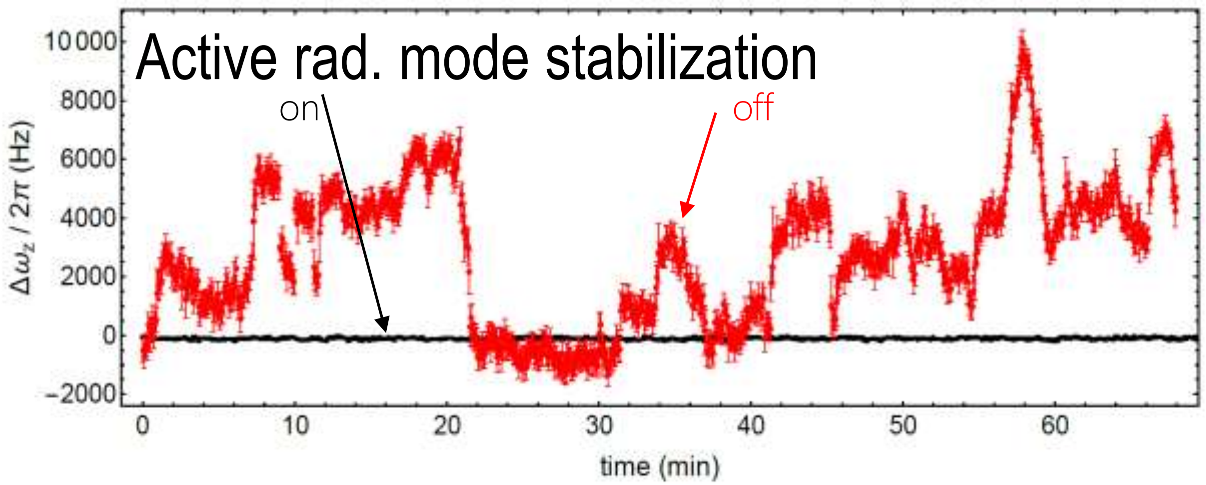
- Only even spin configurations are displaced
- Vibr. mode returns to initial state after time $t_{gate}=2\pi/\delta$
- Only even states pick up geometric phase of Φ : area under trajectory
- Bell state generated
- 99.5(1)% fidelity

rad. mode:
$\Delta n=2.7(9)$/sec
$\Delta\omega=20$ Hz @ 4.4 MHz

Phase space of *radial* mode:



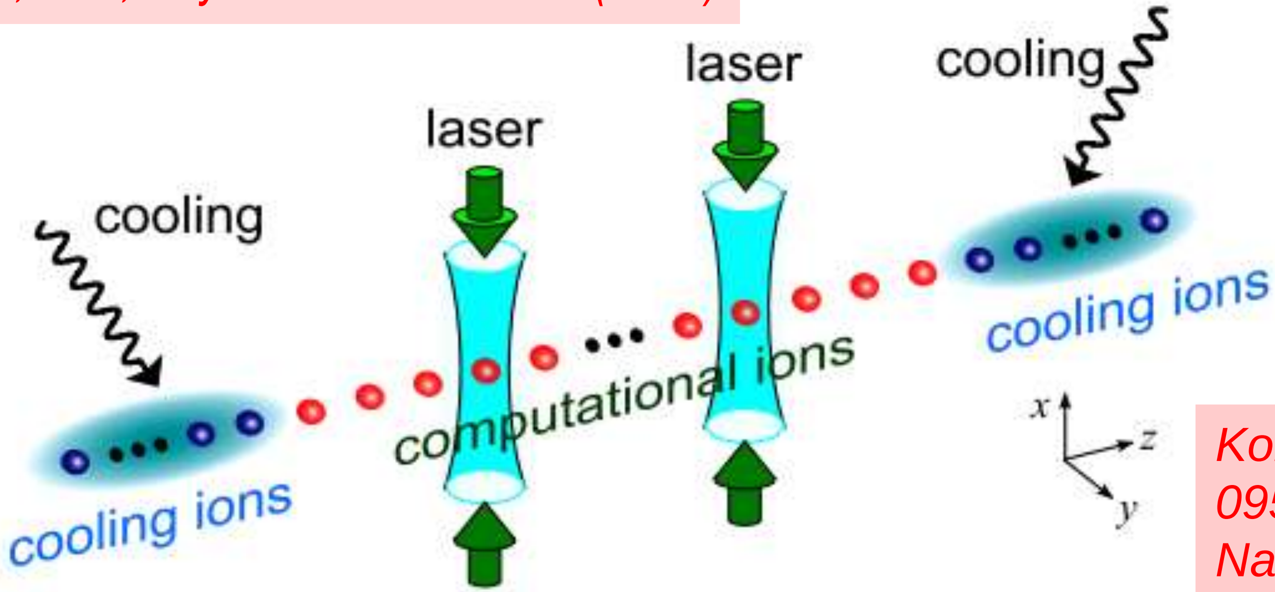
Leibfried et al., Nat. 412, 422 (2003)



Scalable trapped –ion qubit architectures

Long linear crystals & Individual single ion addressing

Nägerl, et al, PRA 60, 145 (1999)
Schindler et al, NJP 15 123012 (2013)
Friis, et al, Phys Rev X. 8 021012 (2018)



Korenblit et al, NJP 14, 095024, Debenath et al, Nature 536, 63 (2016)

Dave Wineland – vision of scalabe QC using shuttles in segmented ion traps

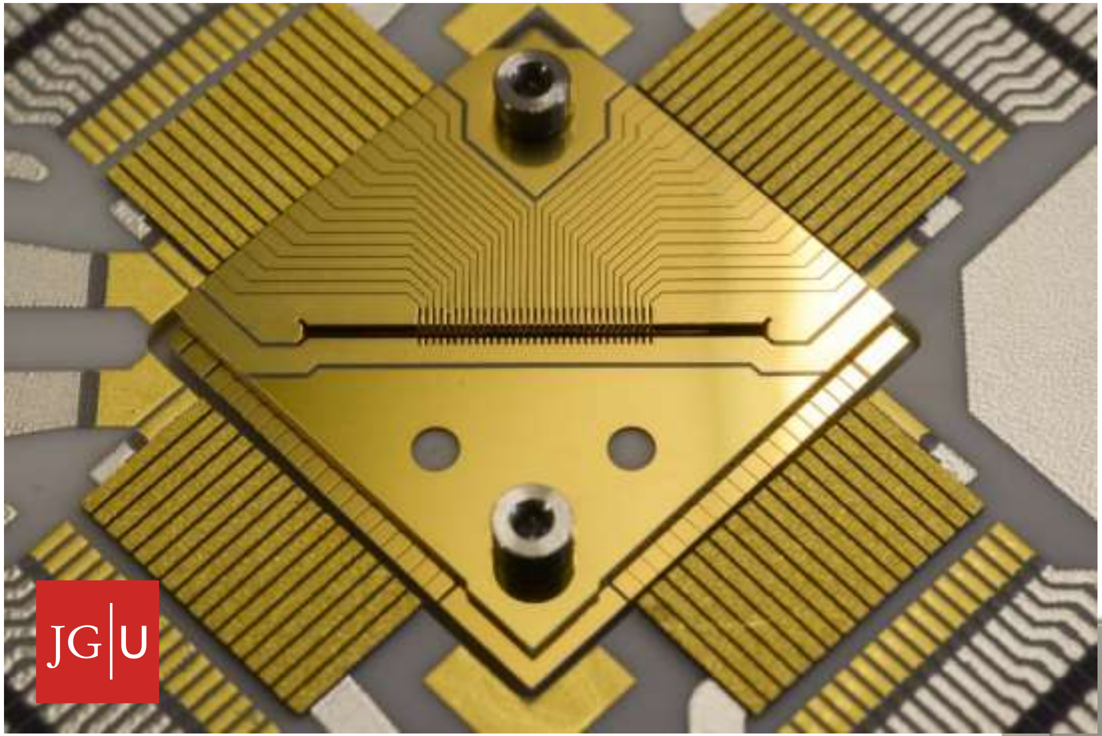
Laser pulses generate entangled states

Segmented Micro trap allows controlling the ion positions

DIVIDE ET IMPERA

Kielpinski et al., Nature 417, 709 (2002)

High performance multi-layer ion trap

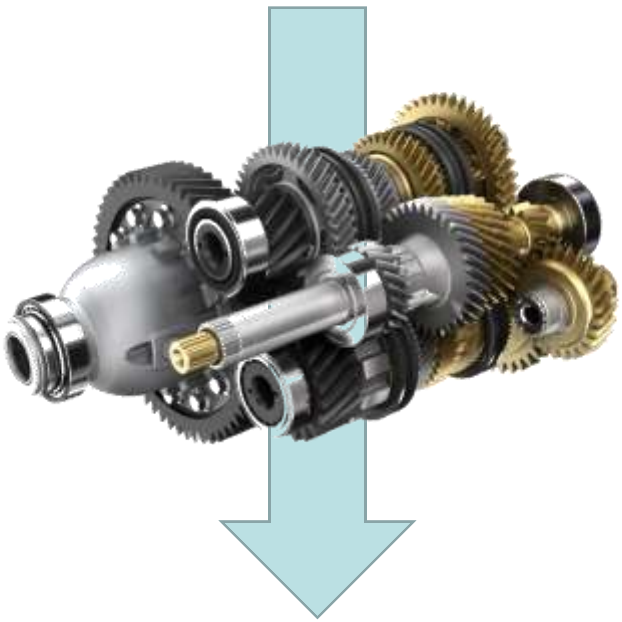


Fabrication
- Laser-cutting of Alumina
- Gold evap./galvoplating
- 32 segment pairs of uniform geometry
- Bonding to capacitor arrays

Performance
- 1.5 MHz axial trap frequency @-6V segment voltage
- Lowest heating rate: 3 phonon/s @ 4 MHz radial trap frequency
- 1 day trapping times

Qubit register reconfiguration control

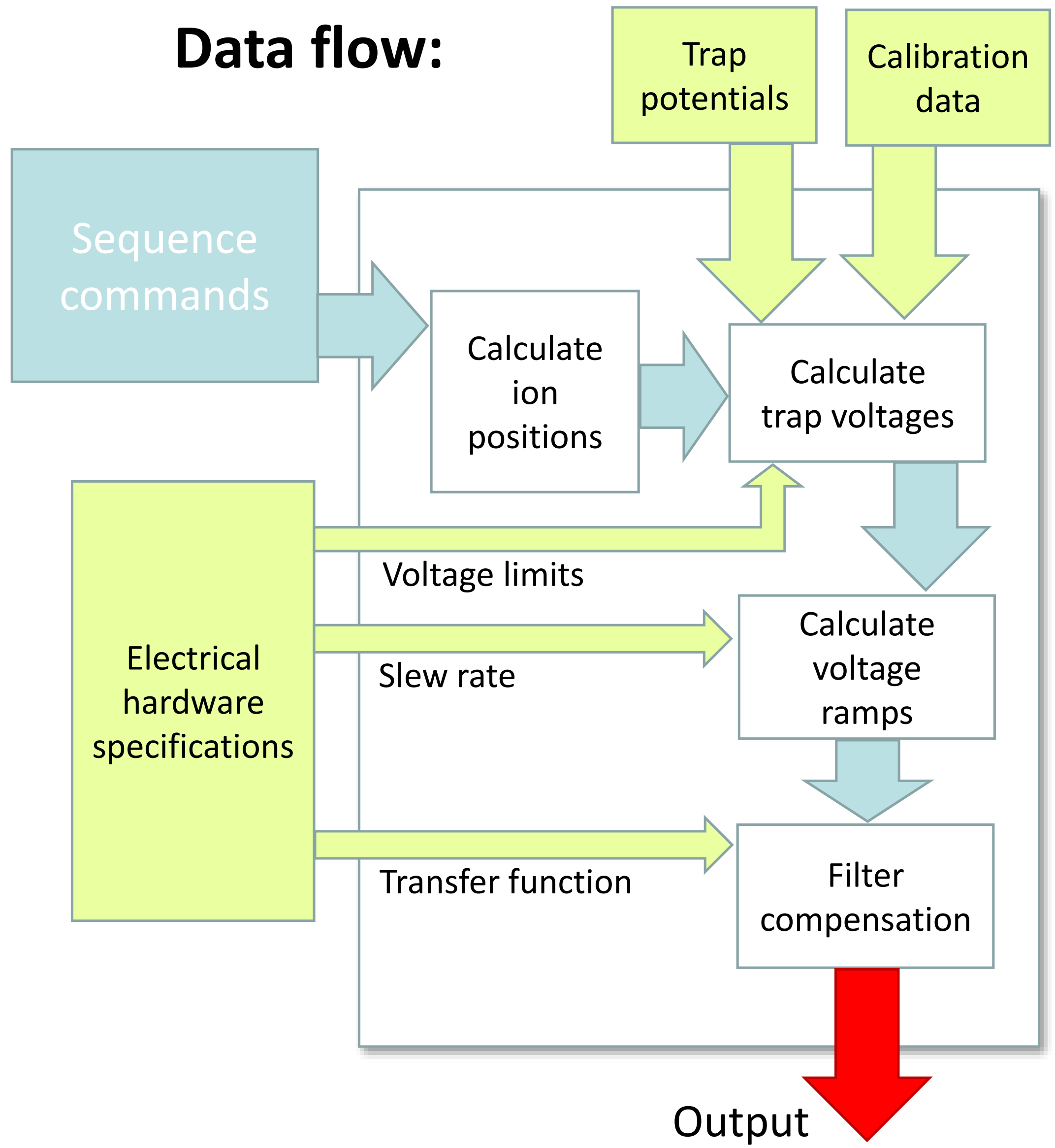
High level QIP command



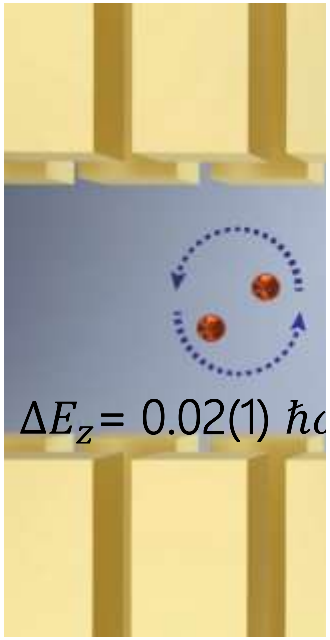
Shuttling voltage ramps

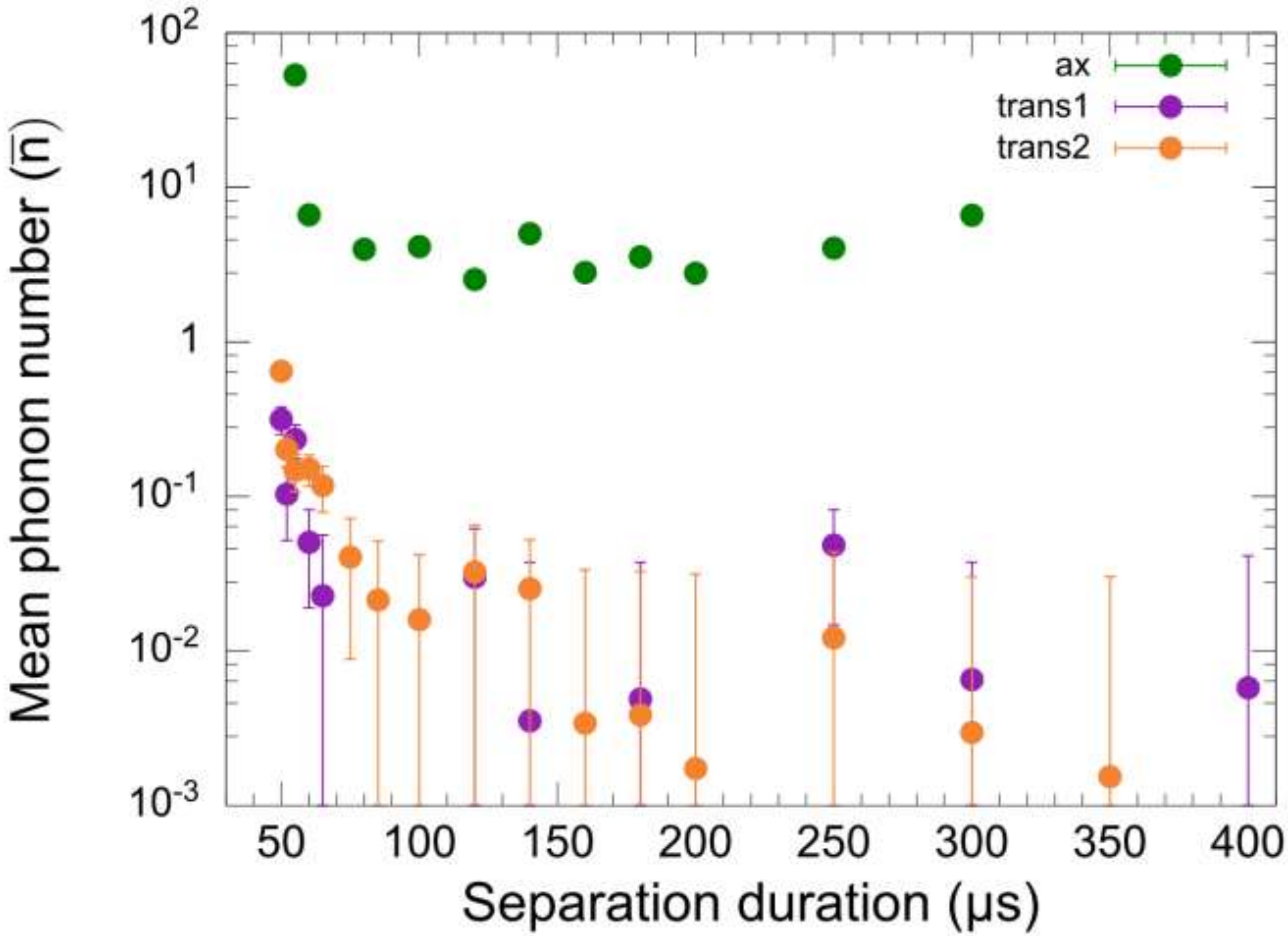
- Technical constraints
- Low motion excitation
- Optimum speed

Data flow:



Ion movement



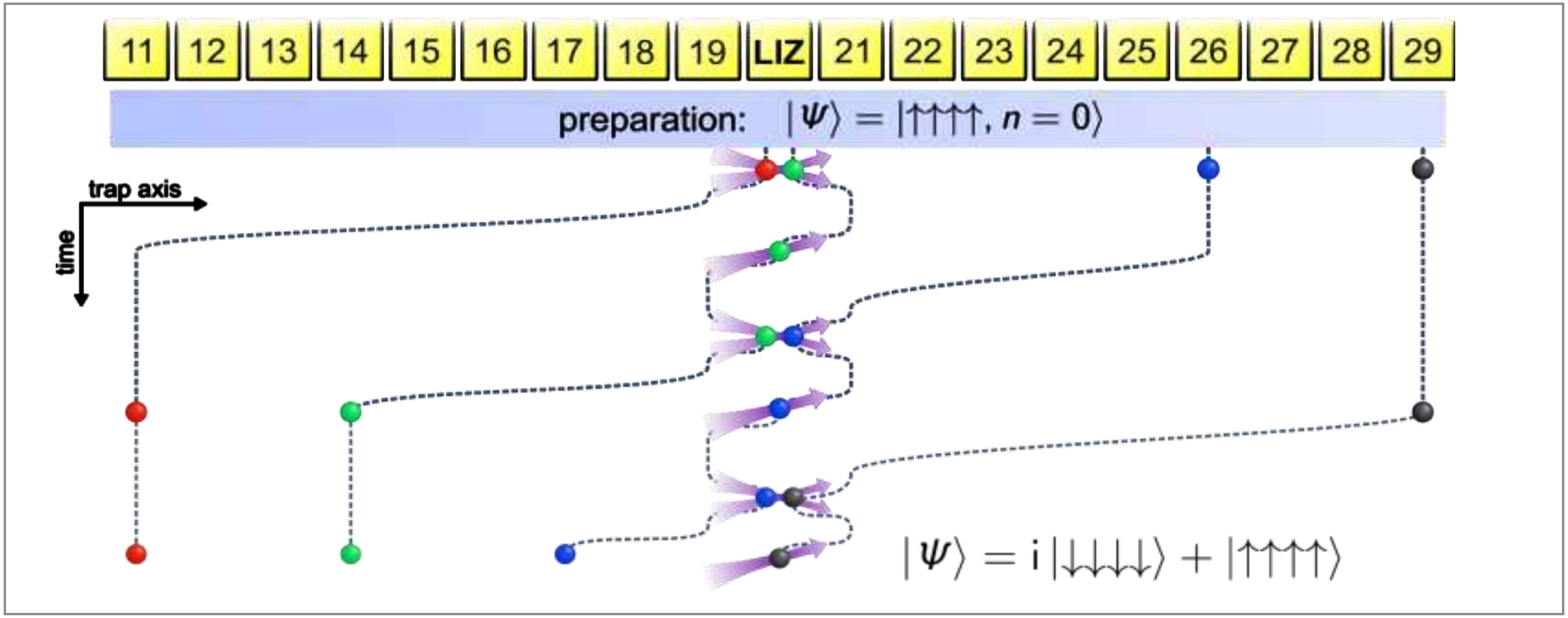


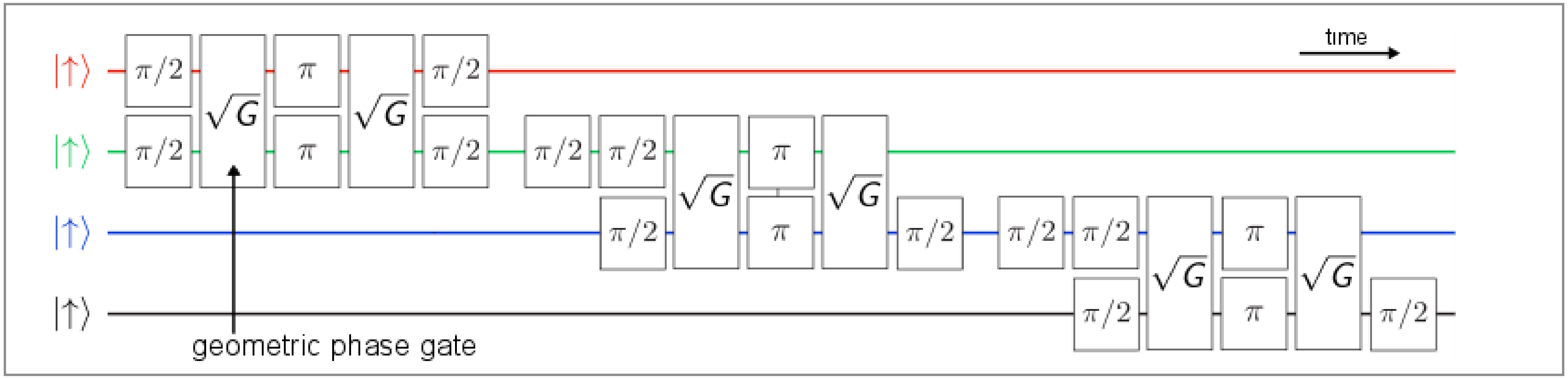
- Shuttle ion crystal
- Separate two-ion crystal
- Merge into two-ion crystal
- Swap ion positions
- Shuttle single ion

Geometric phase gate 99.5(1)% fidelity on **radial** mode

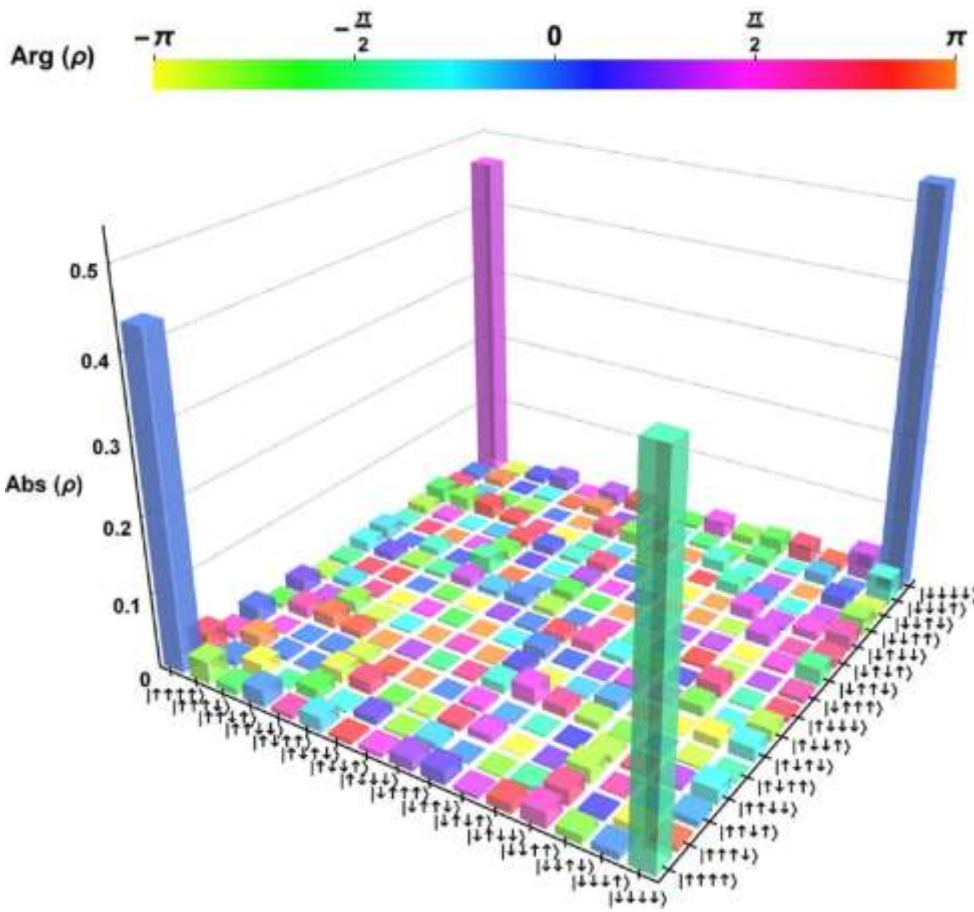
Walter et al., PRL109, 080501 (2012)
Kaufmann et al, NJP 16, 073012 (2014)
Kaufmann et al, RPA 95, 052319 (2017)

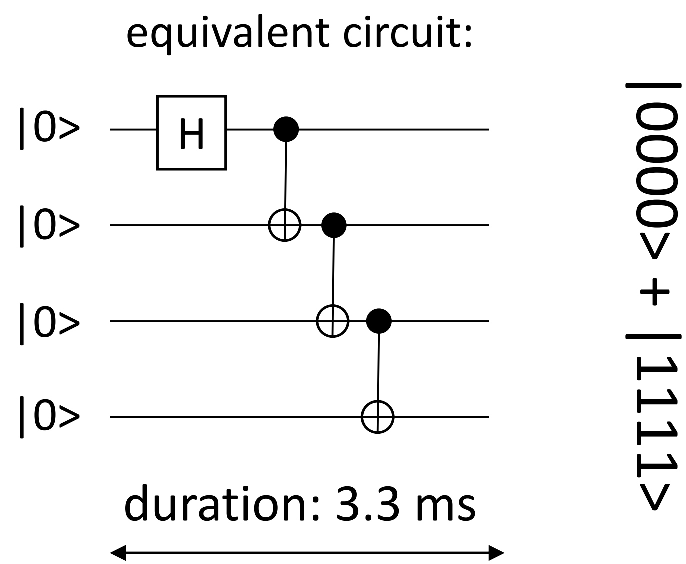
“Knitting together” a 4-ion GHZ state





“Knitting together” a 4-ion GHZ state





Full state tomography yields **94.7 % fidelity** from about 50k measurements.

Experimental sequence uses **> 300 shuttling operations** for SB cooling, state preparation, quantum circuit, state analysis.

Kaufmann et al, PRL 119, 150503 (2017)

Experimental sequence for a 4-ion GHZ state

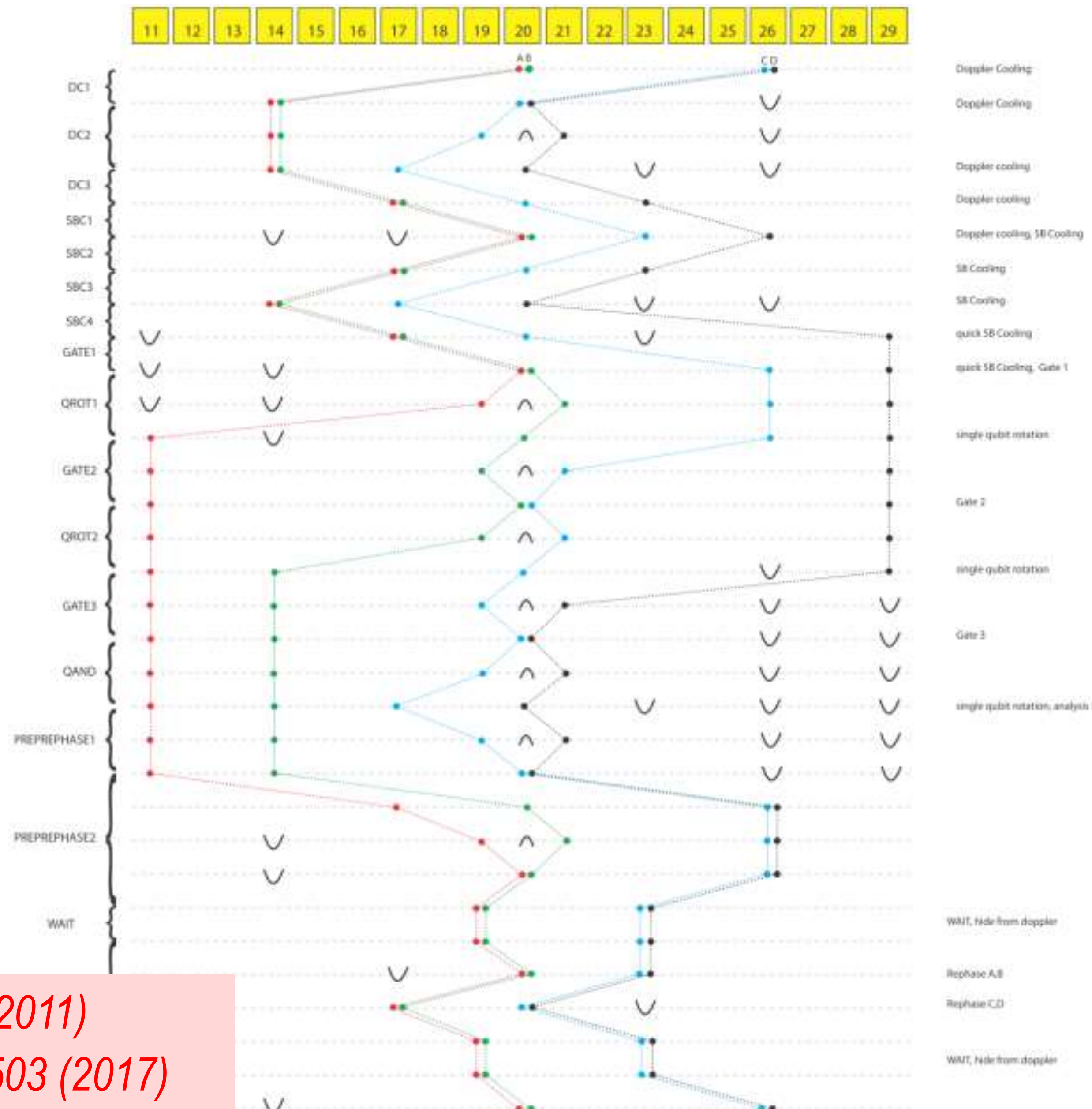
many shuttling op.

- 324 segment to segment transports
- 8 separation/merge operations

+ many gates:

- 12 single qubit gates
- 3 two-qubit gates
- multiple spin echos

0.5 seconds cohernence for |0000> + |1111>

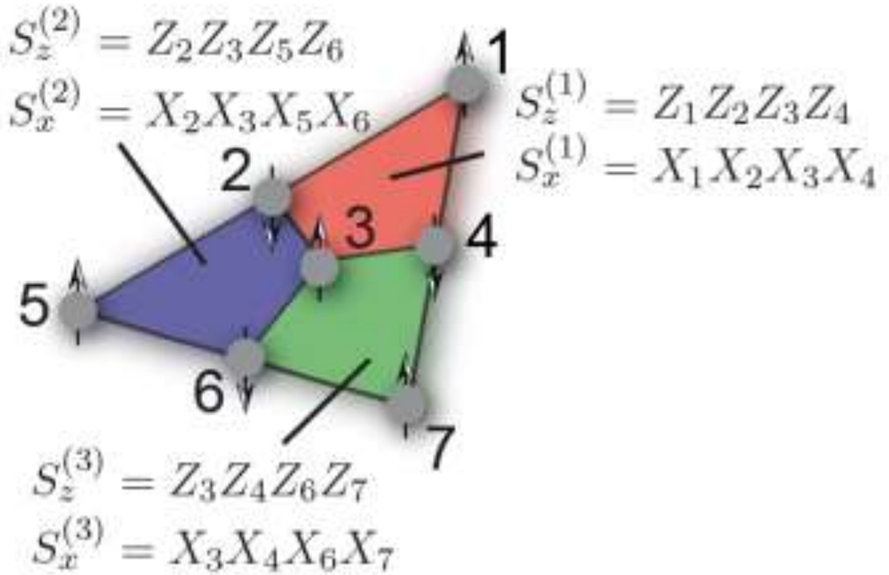


Monz et al, PRL 106, 130506 (2011)
Kaufmann et al, PRL 119, 150503 (2017)

Break-even point for useful QEC ?

Topological quantum error correction, using the reconfigured ion quantum register

- Logical qubit using a 7-qubit color code
- Improve and adapt hardware and software
- Develop strategies to overcome current limitations



Bermudez et al, Phys. Rev. X 7, 041061, Nigg et al., Sci. 234, 302 (2014)

Break-even point for useful QEC ?

$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

Alice perfectly encodes

$|\psi\rangle = \alpha|0\rangle_L + \beta|1\rangle_L$

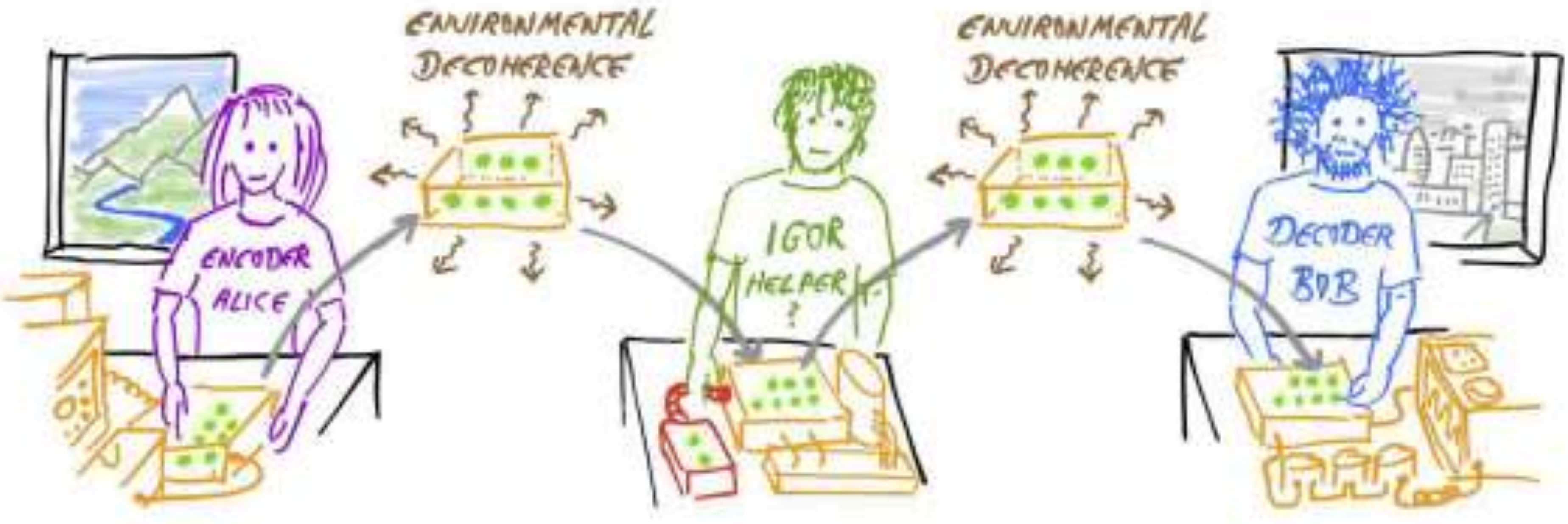
Channel, incl. correlated & coherent noise, and

one round of imperfect QEC by Igor

Bob is asked:

Is it $|\psi\rangle$ or $|\psi\rangle_\perp$?

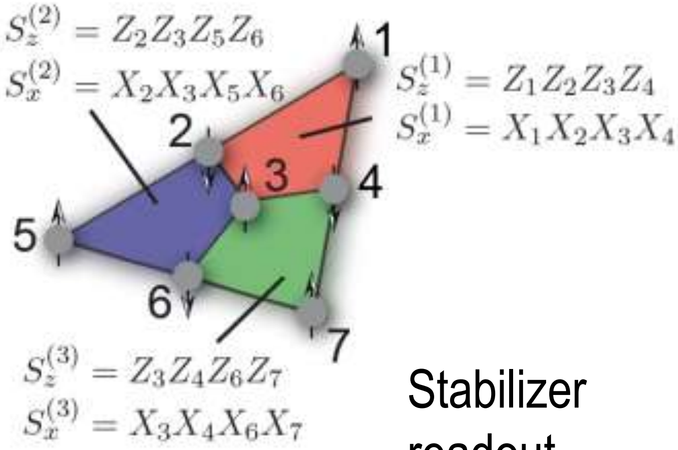
Or, was Igor really a help?



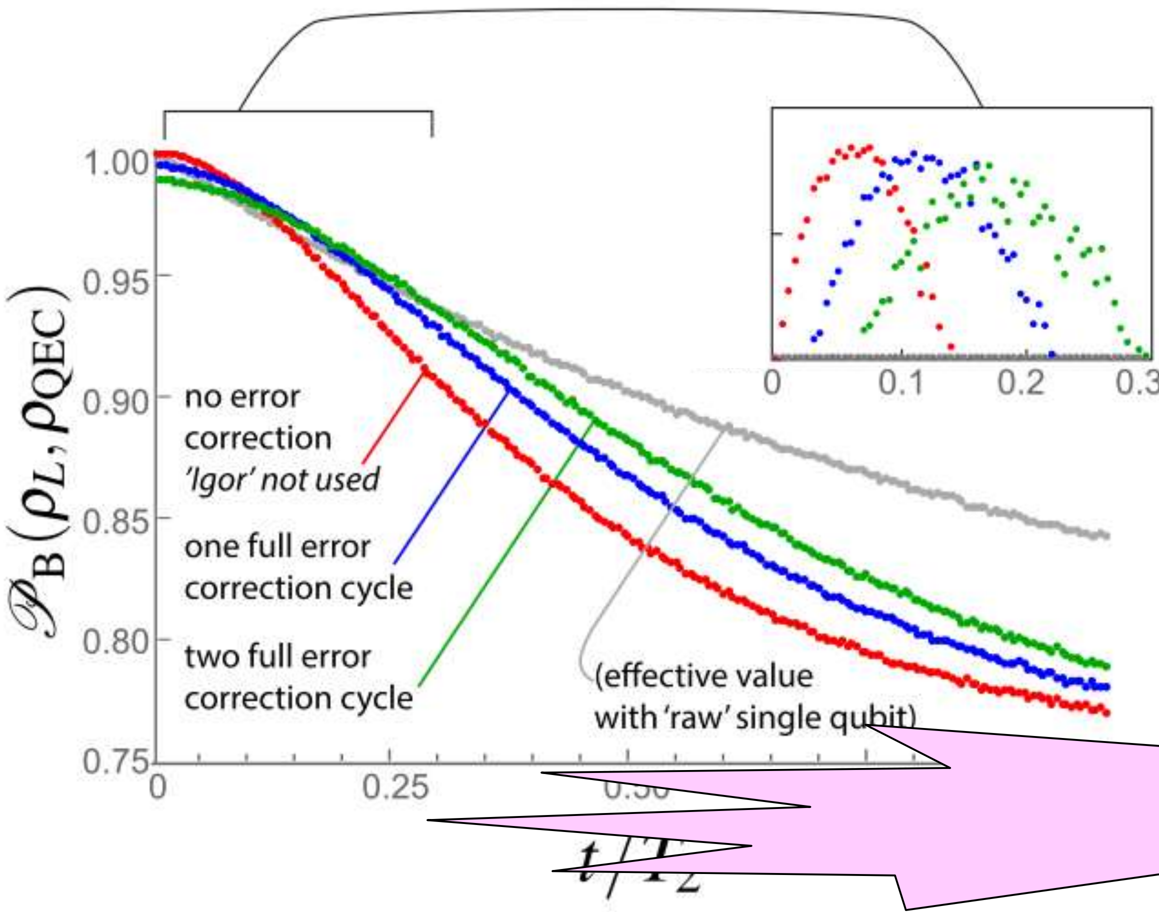
Bermudez et al, Phys. Rev. X 7, 041061

Shuttle based color code QEC

Real-space representation of shuttling-based one-species QEC cycle with multi-qubit MS gates

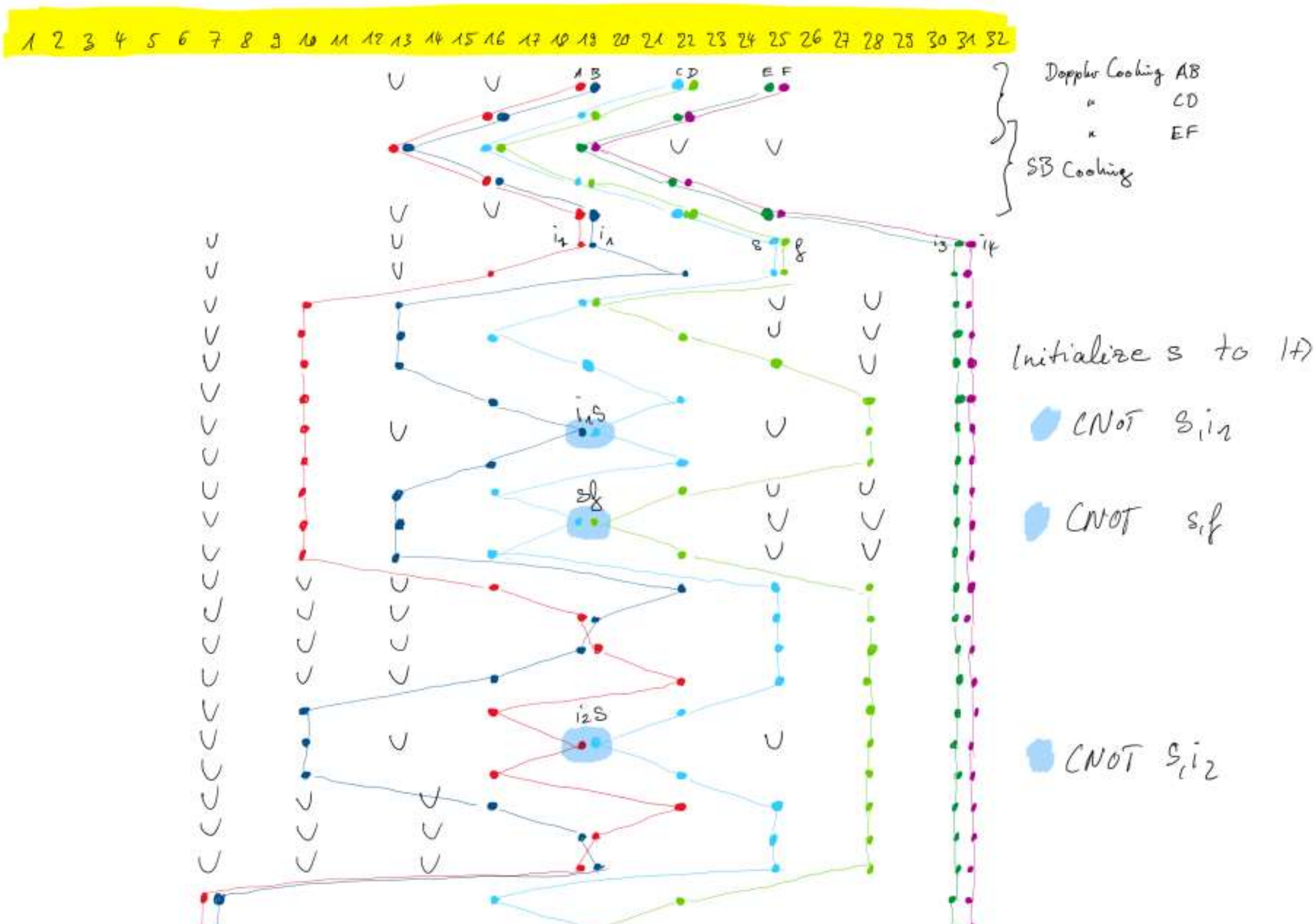


Stabilizer readout



Helpful Igor!

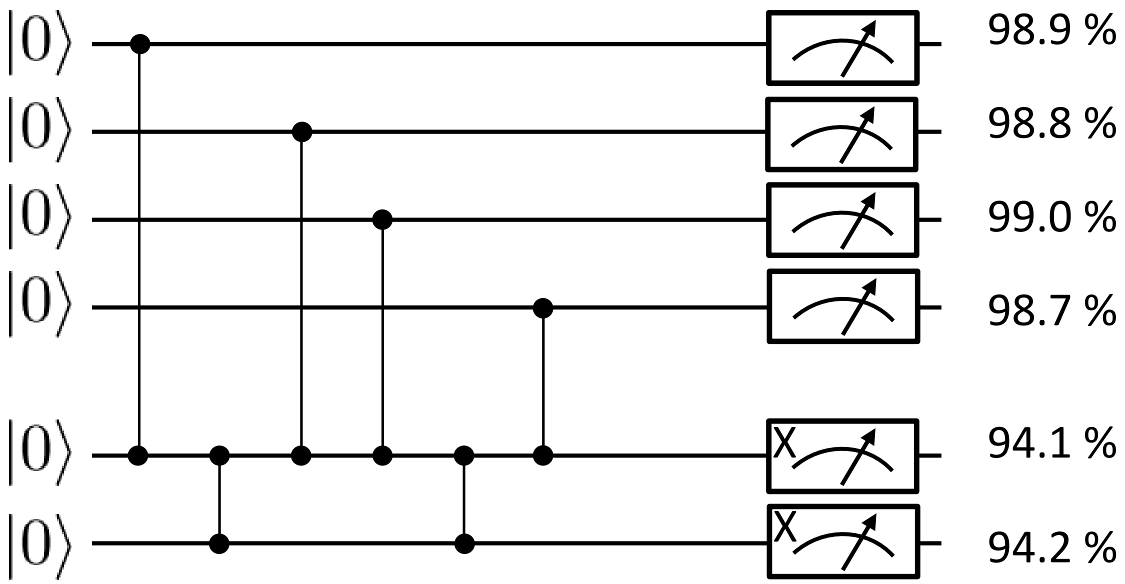
Sequence - Fault tolerant syndrome readout



Readout quality

6 ions:
90 configurations
41 two-ion transports
158 single ion transport
6 two-ion rotation
21 merge/separate
6 two-qubit gates
6 RAP pulses
6 indivdual fluo. det.

'dark' detection probability



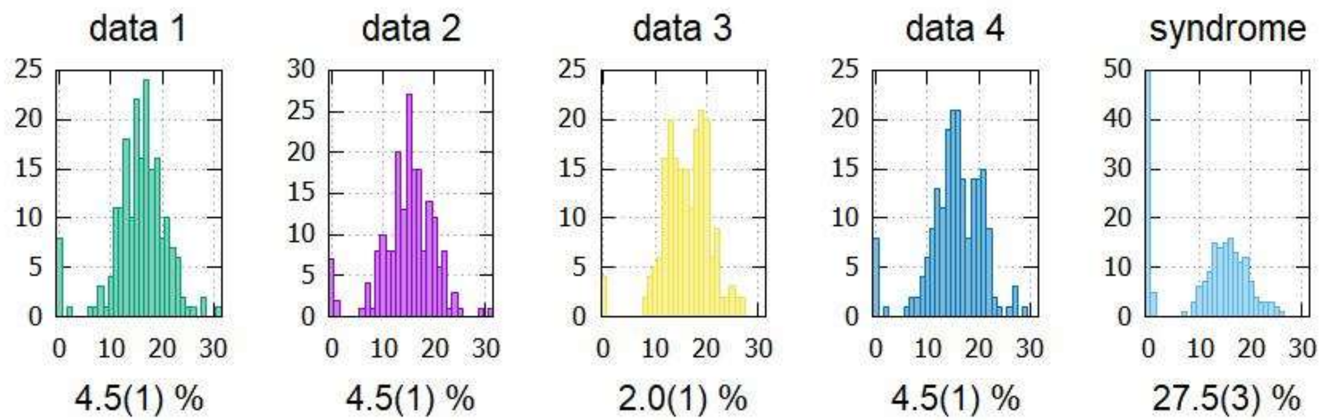
Shelving @729nm for qubit readout affected by shuttling:

- Improve shuttling calibration
- Implement robust shelving
- Reduce η_{729}

Hilder, et al,

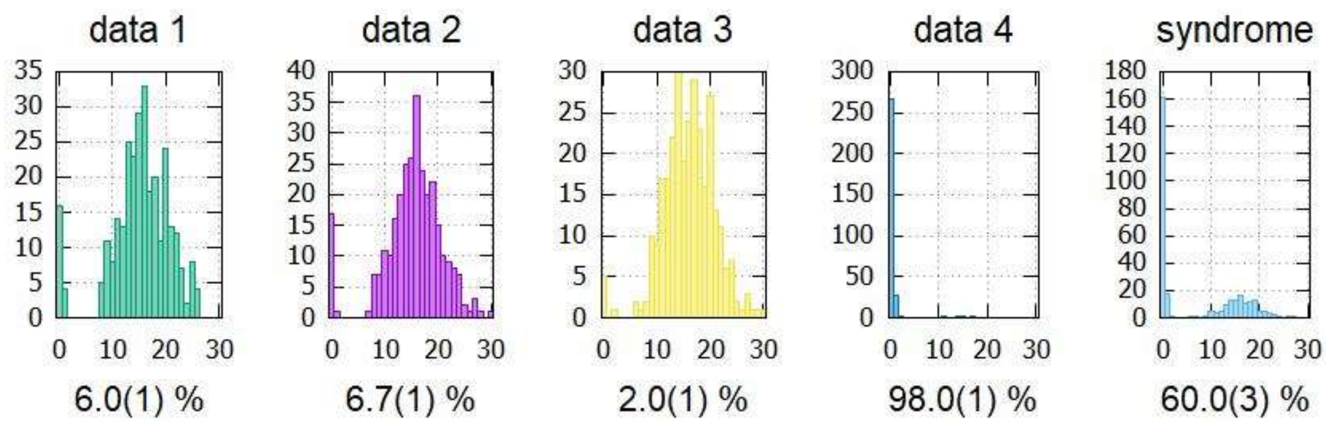
Fault tolerant syndrome – partity readout

|1111> **Even parity**



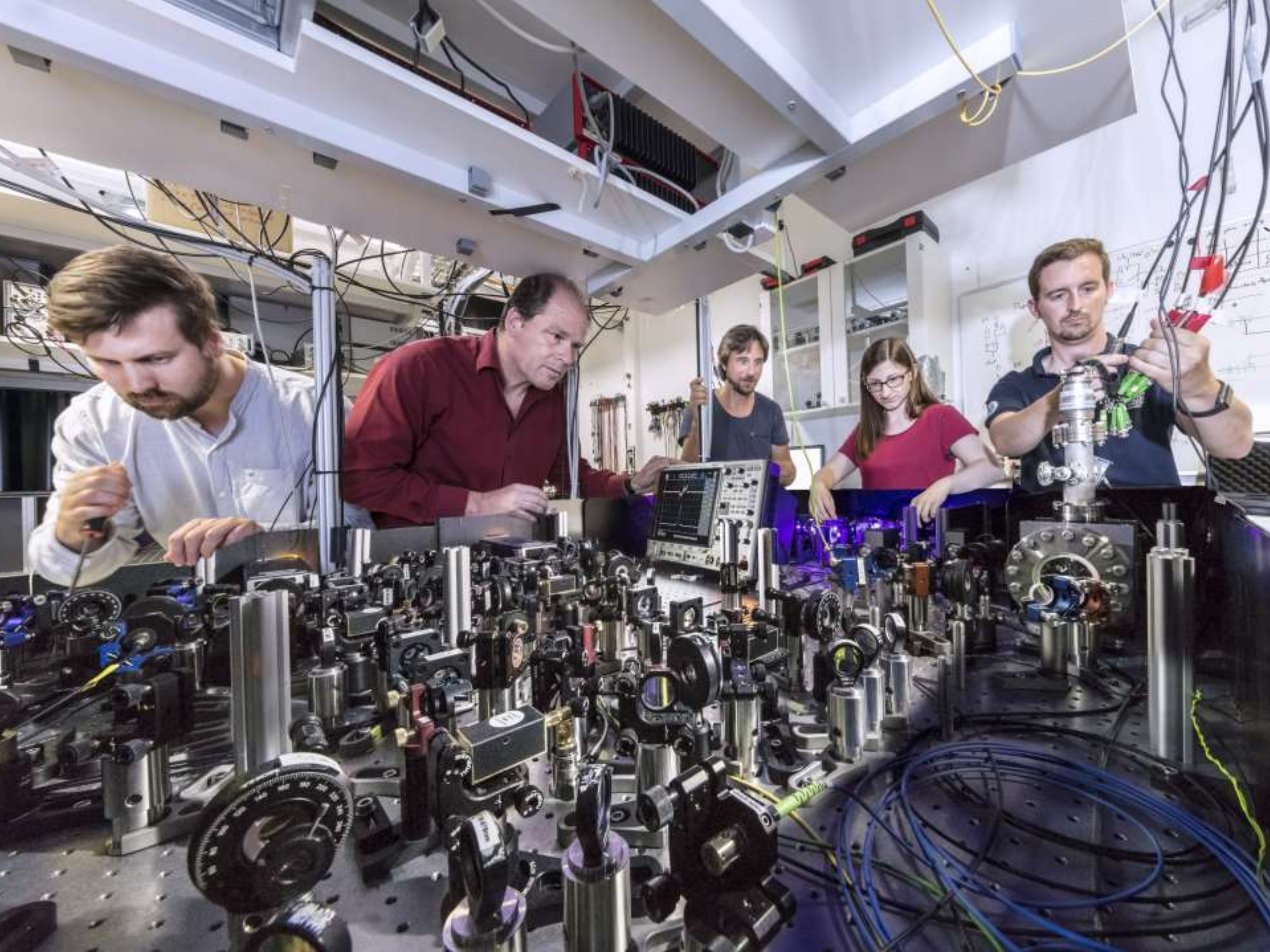
72.5(3)% fidelity

|1110> **Odd parity**

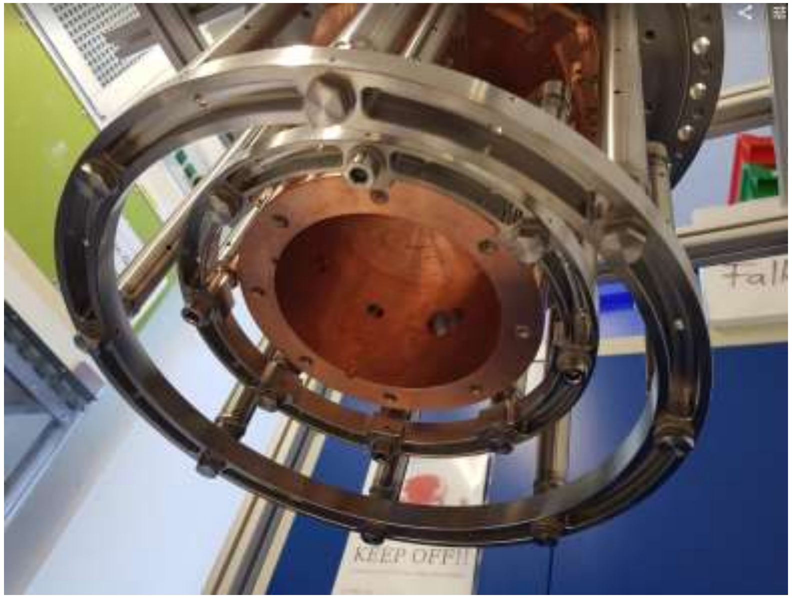


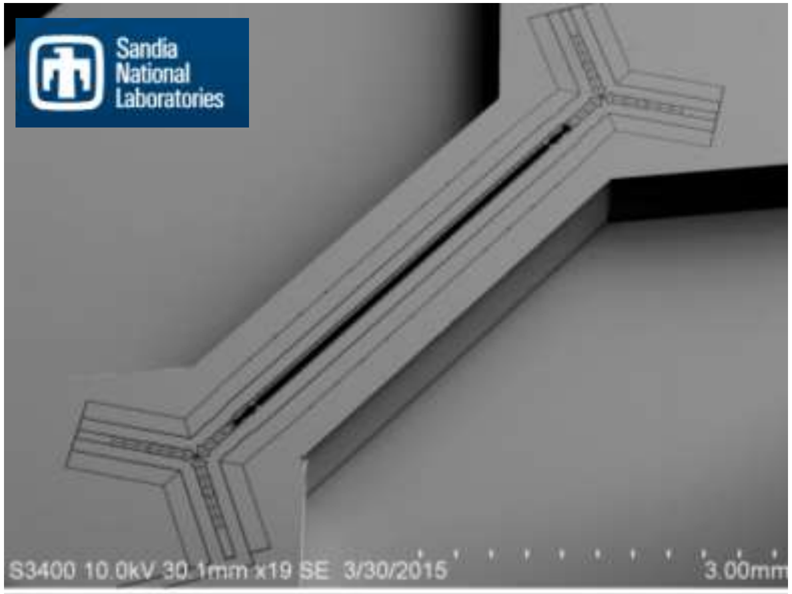
60.0(3)% fidelity

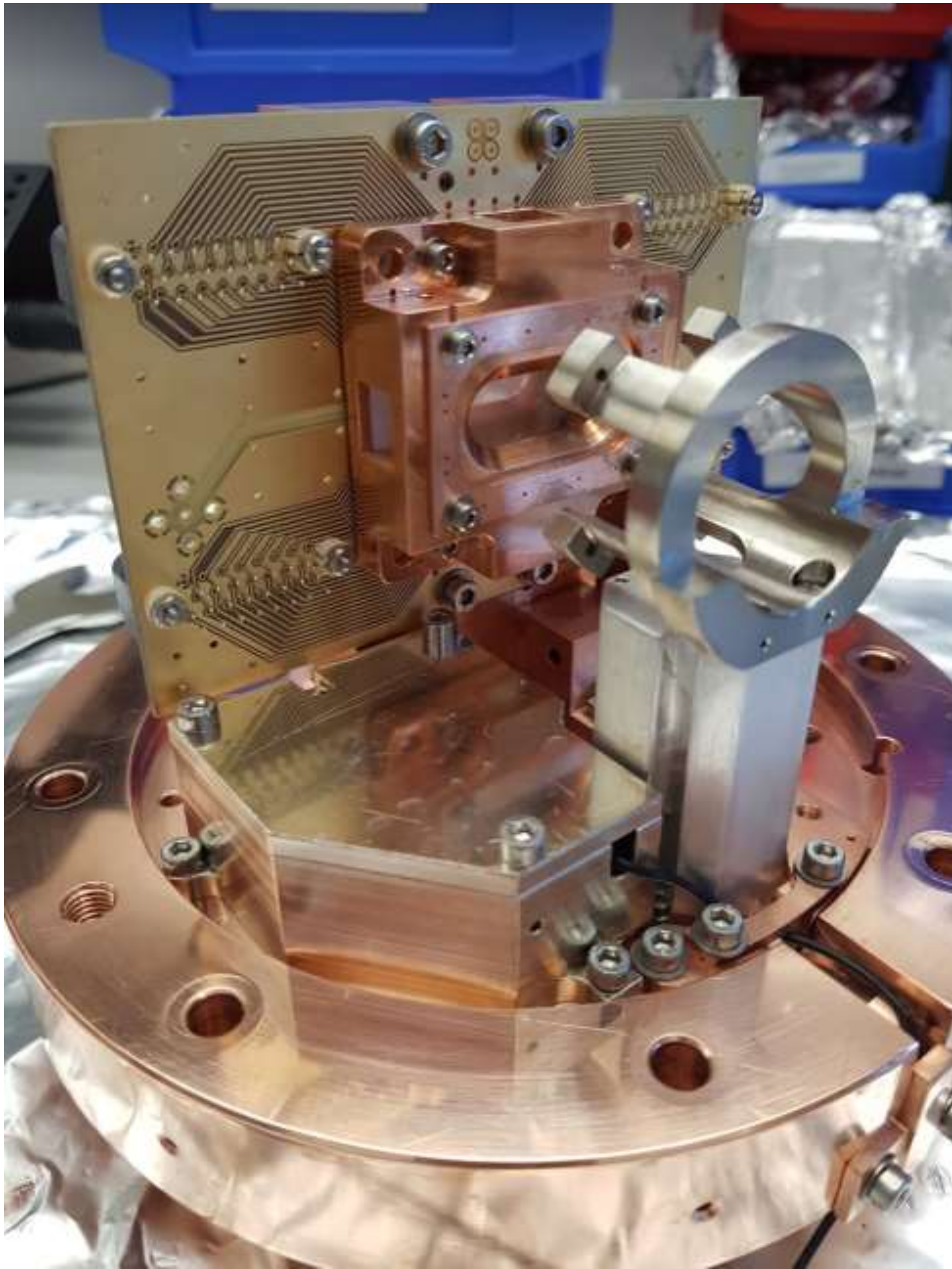
Hilder, et al,



Cryogenic setup







Key figures, now and future, for trapped ion-QC

- Single shot read-out of spin state better $1 - 10^{-4}$
- Single gate fidelity better than $1 - 10^{-4}$….$10^{-5..6}$ mitigating intensity noise, off-resonant excitation, AC Stark shifts
- Two qubit gate fidelity $1 – 10^{-3}$….$10^{-4..5}$ mitigating intensity noise, off-resonant excitation, AC Stark shifts
- Gate operation time ~ 30µs …. ≤10µs using shaped light fields
- Qubit register reconfiguration operations, few µs to 80µs …. ≤1µs optimized electric wave forms
- Long coherence times, up to a few seconds …. ≥ seconds with dynamical decoupling pulse sequences
- Decoherence-free substates, >10s …minutes coherence
- Micro-segmented traps, 30 segments … >100 … 1000 segments
- Cryogenic ion traps, trapping times of days

EU flagship: Advanced QC with trapped ions

AQTION

Our goal: A scalable 50-qubit QC based on scalable industry standards ...

QUANTUM Computing

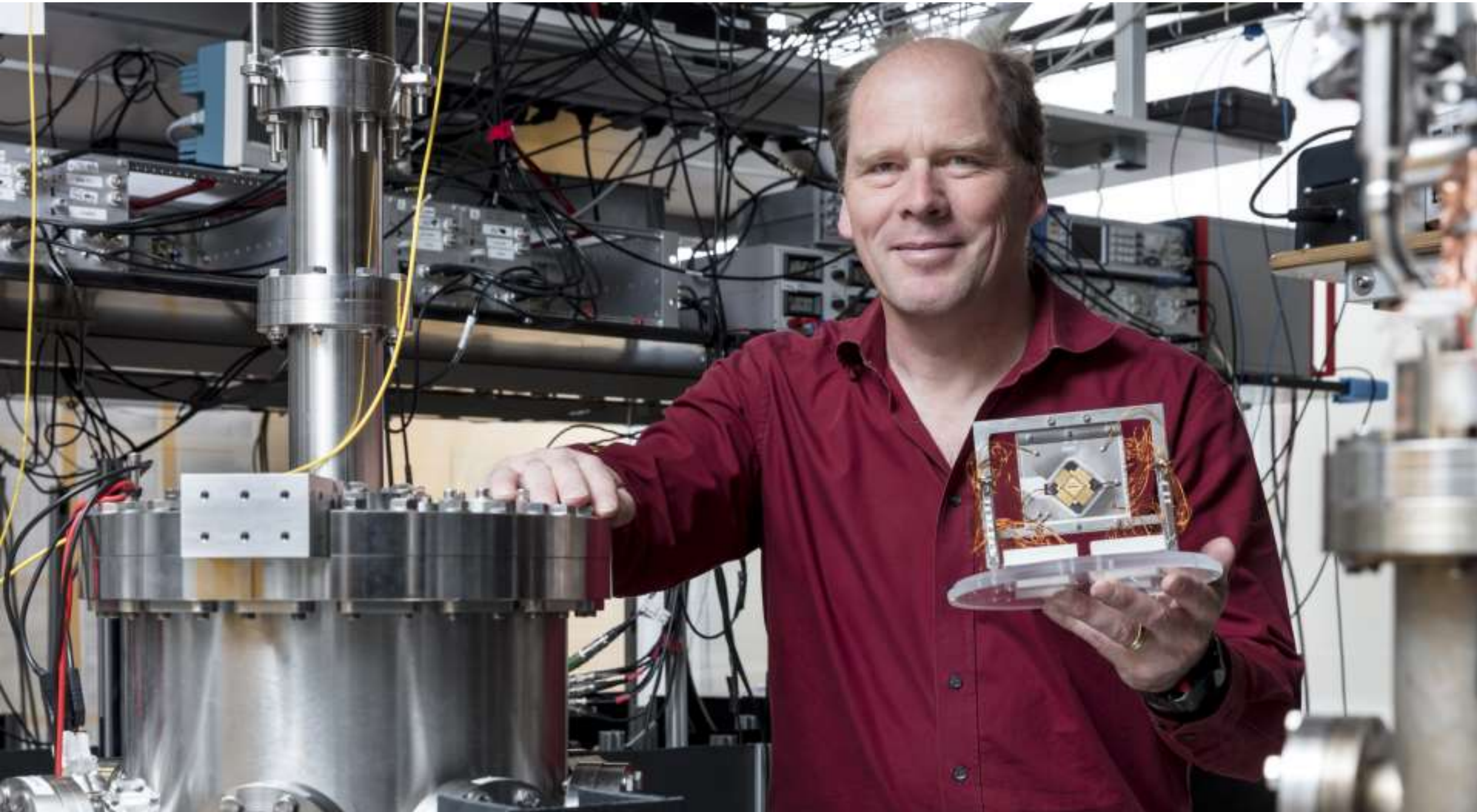
Advanced quantum computing with trapped ions (AQTION)

- Development of a robust and compact ion-trap quantum computing demonstrator
- Scalable quantum hardware and electronics
- Holistic software stack from quantum algorithms to device specific operations
- Scalable verification and validation
- Quantum advantage over classical capabilities
- Quantum processors outside the laboratory

Quantum Flagship, 2018

Quantum information with trapped ions

- Trapped ions as qubits for quantum computing and simulation
- Qubit architectures for scalable entanglement



Quantum thermodynamics with ions

- Quantum thermodynamics introduction
- Heat transport, Fluctuation theorems,
- Phase transitions, Heat engines
- Outlook

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Two-qubit gate operations

Cirac, Zoller, PRL 74, 4091 (1995)

*Schmidt-Kaler et al., Nat. **422**, 408 (2003)*

- Cirac Zoller gate

*Sörensen, Mölmer, PRL **82**, 1971 (1999), PRA **62**, 022311 (2000)*

- Mölmer Sörensen gate

Leibfried et al., Nature 412, 422 (2003)

- Spin-dependent light forces

Khromova et al, PRL 108, 220502 (2012), Warring et al, Phys. Rev. A 87, 013437 (2013)

- Spin-dependent magnetic gradient forces
- Cavity-induced interactions

Li, Lesanowsky, Appl. Phys. B 114, 37 (2014)

- Rydberg excitation & blockade interaction

Vogel, et al, arXiv:1905.05111

- Rydberg ultra-fast electric kick
- Atom-Ion interactions