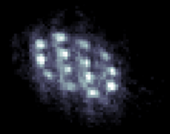
Experimental techniques behind the scenes of ion trapping experiments: status, challenges and developments.

Christian Schmiegelow

Departamento de Físcia e Instituto de Físcia de Buenos Aires, UBA-CONICET



Research Techniques Seminar FERMILAB, January 2021

LIAF Laboratorio de Iones y Átomos Fríos

Departamento de Física, Universidad de Buenos Aires
Instituto de Física de Buenos Aires, CONICET

Local Founding Team

Juan Pablo Paz

Miguel Larotonda

Augusto Roncaglia

Christian Schmiegelow

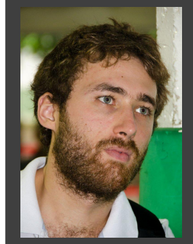
External Founding Partner

Ferdinand Schmidt-Kaler
Universität Mainz

Objective:

setup a lab aimed at research in quanum physics and applications

2016



Martín
Drechler
Doctorado

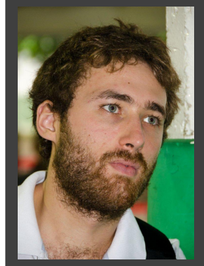
Noelia
Fernandez
Licenciatura

Ulises
López
Laboratorio 6y7

Luis
Biaus
Laboratorio 6y7

Matías
Cveczilberg
Licenciatura

2017



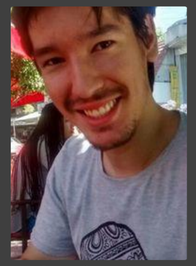
Martín
Drechler
Doctorado

Matías
Cveczilberg
Licenciatura

Patricio
Grinberg
Investigador

Diego
Espejo
Labo 6y7

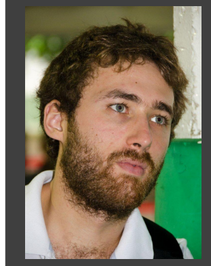
Lucas
Martin
Labo 6y7



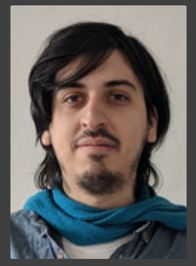
Christian
Reartes
Labo 6y7

Julian
Ruffinelli
Labo 6y7

2018



Martín
Drechler
Doctorado

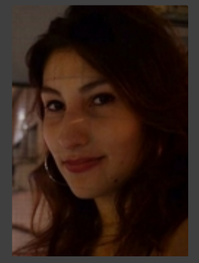


Nicolás
Nuñez Barreto
Doctorado

Patricio
Grinberg
Investigador

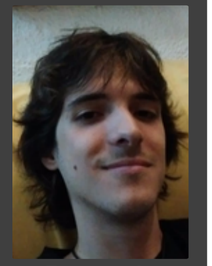
Ulises
López
Licenciatura

Lautaro
Filgueira
Pasante



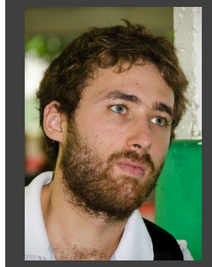
Leila
Prelat
Labo 6y7

Facundo
Rost
Labo 6y7

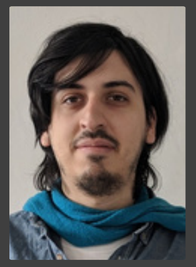


Fernando
del Rio
Labo 6y7

2019



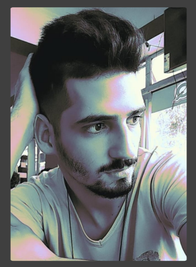
Martín
Drechler
Doctorado



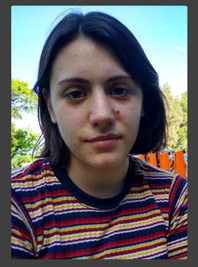
Nicolás
Nuñez Barreto
Doctorado

Patricio
Grinberg
Investigador

Lautaro
Filgueira
Licenciatura



Florencia
Zapata
Laboratorio 6y7

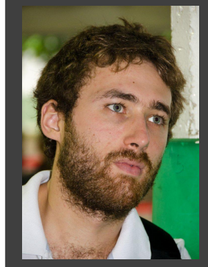


Federico
Winkel
Laboratorio 6y7

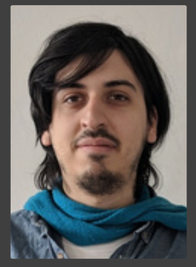
Muriel
Bonetto
Laboratorio 6y7

Julieta
Wenger
Laboratorio 6y7

2020



Martín
Drechler
Doctorado



Nicolás
Nuñez Barreto
Doctorado

Patricio
Grinberg
Investigador

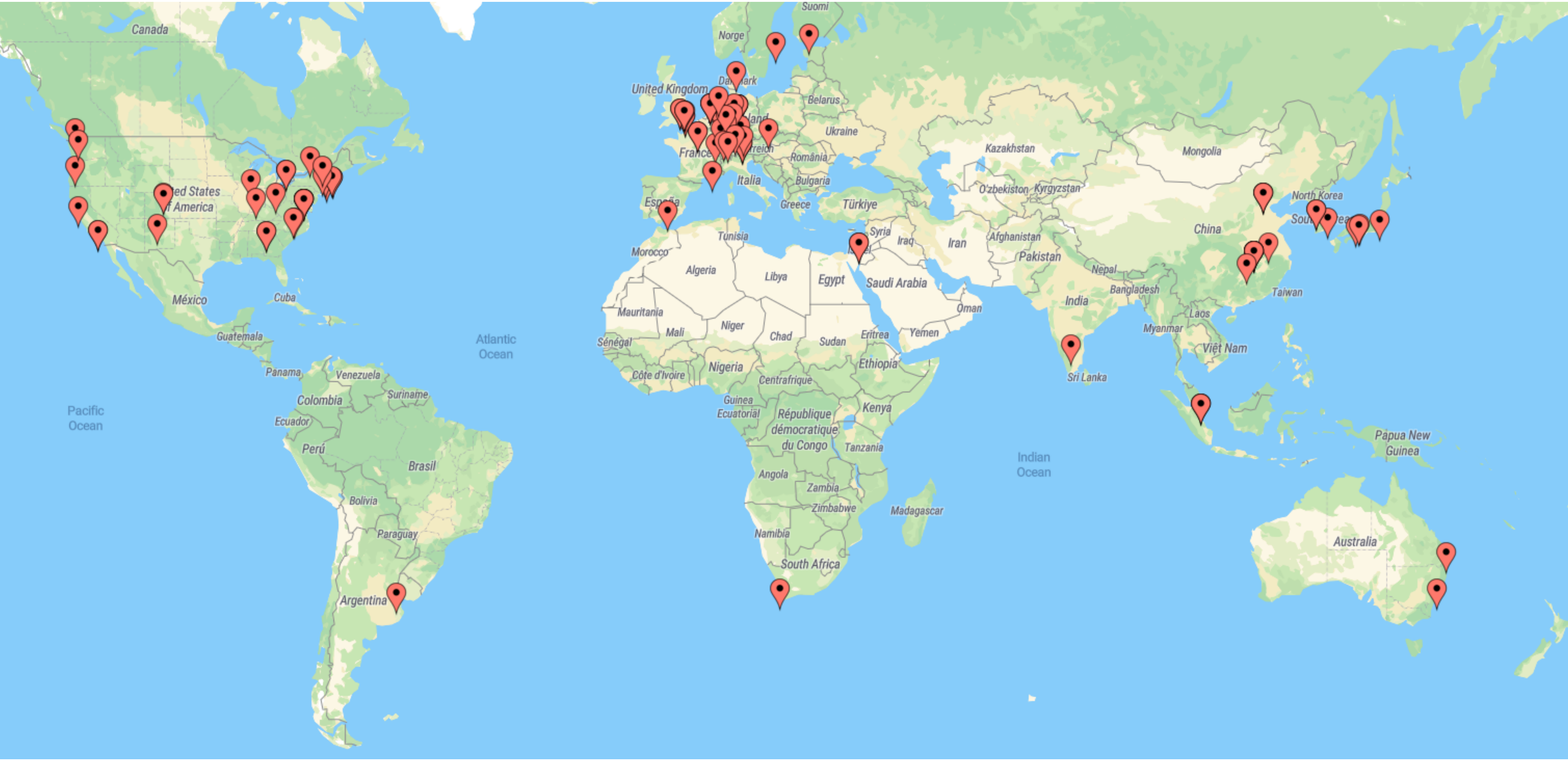
Lautaro
Filgueira
Doctorado

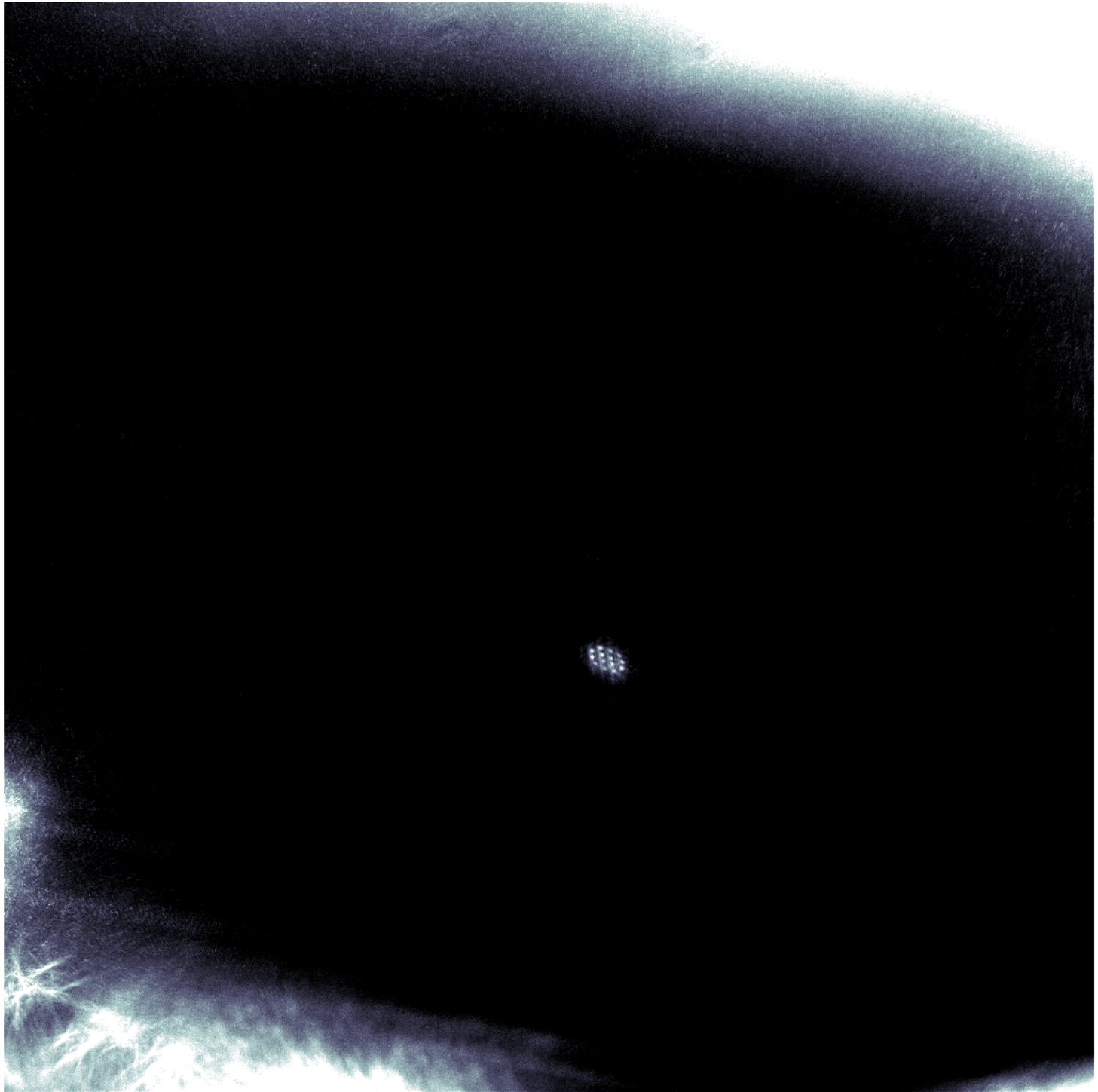
Muriel
Bonetto
Laboratorio 6y7

Julieta
Wenger
Laboratorio 6y7

Milton
Katz
Licenciatura

Lucas
Mendicino
Licenciatura


Canada
Norge
Suomi
United Kingdom
Belarus
Ukraine
France
Italia
Bulgaria
Greece
Türkiye
Kazakhstan
Mongolia
O'zbekiston
Kyrgyzstan
North Korea
China
Tunisia
Morocco
Algeria
Libya
Egypt
Syria
Iraq
Iran
Afghanistan
Pakistan
Saudi Arabia
Nepal
Bangladesh
India
Taiwan
Oman
Mauritania
Mali
Niger
Chad
Sudan
Eritrea
Yemen
Laos
Myanmar
Sénégal
Nigeria
Ethiopia
Côte d'Ivoire
Centrafrique
Guinea Ecuatorial
République démocratique du Congo
Kenya
Tanzania
Angola
Zambia
Zimbabwe
Madagascar
Namibia
South Africa
Sri Lanka
Việt Nam
Papua New Guinea
Australia
Atlantic Ocean
Pacific Ocean
Indian Ocean
México
Cuba
Guatemala
Panama
Venezuela
Colombia
Suriname
Ecuador
Perú
Brasil
Bolivia
Paraguay
Argentina



Outline

- Uses of ion traps
- Ion trapping 101
- Typical ion trapping experiments
- Multi ion experiment challenges
- Outlook of ion trapping
- Corolary: Skipper CCDs

Uses of ion traps

very incomplete review

- Atomic-optical clocks
-- New second
-- Geodesy
-- Dark matter and new physics search

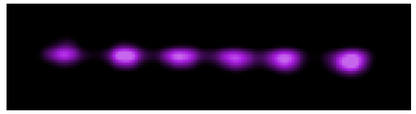
- Quantum Infomration Procesosrs
-- Quantum Computers
-- Quantum Simulators

- Fundamental Physics
-- Quantum-Classical transistion, quantum thermodynamics, etc.
-- Measurement of fundamental constants and atomic properties

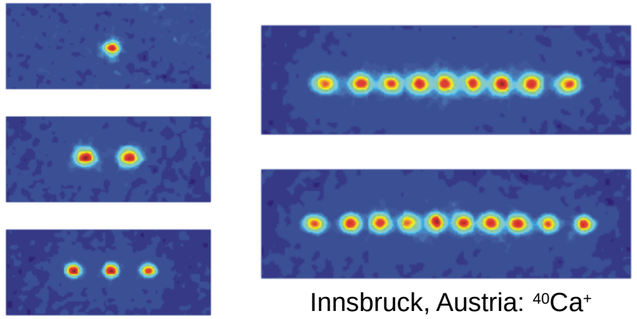
Why ion traps?

the main points

- low temperatures (mK to uK)
- environment isolation
- atom by atom control

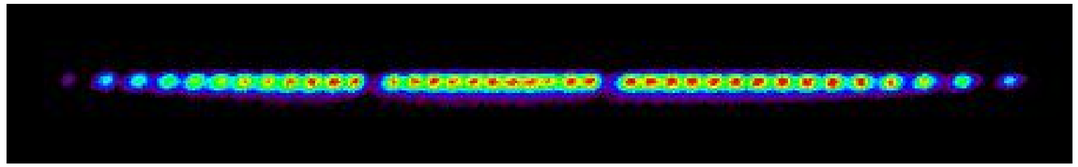


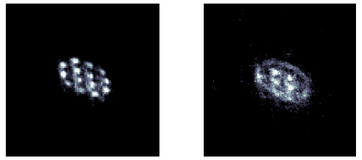
Oxford, England: $^{40}Ca^{+}$



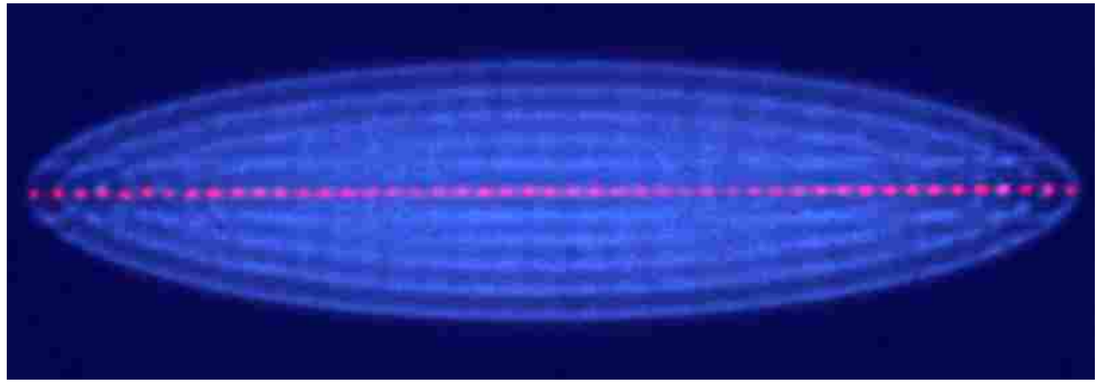
Innsbruck, Austria: $^{40}Ca^{+}$

Boulder, USA: Hg^{+}





LIAF, Buenos Aires, Argentina



Aarhus, Denmark: $^{40}Ca^{+}$ (red) and $^{24}Mg^{+}$ (blue)

Ion trapping 101

-) **Vacuum chamber**, deep UHV P < 10^-11 mbar

-) **Trap.** Radiofrequency Paul/quadrupole trap

-) **Atomic source.**

-) **Ionization mechanism**

-) **Cooling**

-) **Observation / Detection**

Ion trapping 101

-) **Vacuum chamber**, deep UHV P < 10^-11 mbar

Preparation
--) Backing, days or weeks
--) Prepump + Turbo Pump
Tech advance:
--) Oil pre-pumps -> dry prepumps

Manitenace
--) Only "storing" pumps.
Typically before 2010
--) Ion getter + titanium sublimation
Typically now
--) Ion getter + NEG (non evaporative getter)

Ion trapping 101

-) **Trap.** Radiofrequency Paul/quadrupole trap
(a lot to say here)

Trends
-) miniaturization
-) segmentation
-) embeding optics and detection

Ion trapping 101

-) **Atomic source.**

from **ovens** to **laser ablation targets**

Ion trapping 101

-) **Ionization mechanism**

from **electron imact ionization** to **photoionization**

Ion trapping 101

-) **Cooling**

Various steps laser cooling.

mK Range.
ubicuous Doppler cooling

uK Range.
sideband cooling
coherent population trapping cooling
polarization gradient cooling
etc... ongoing!

Ion trapping 101

-) **Observation / Detection**

--) Microscope
- typicaly x10 or x20 magnification
- NA - vacuum chalenge.

--) Detector
- mirror image charges
- **PMTs (photo multiplier tubes)**
- Human eye
- MCP + CCDs (multi cannel plates + charge coupled divices)
- **eMCCDs (electron multiplier CCD)**
- sCMOS (scientific complementary metal-oxide-semiconductor
- ... PMT arrays, fiber bundles, etc.
- ... APDs (avalanche photodiode)
- ... skipper-CCDs?

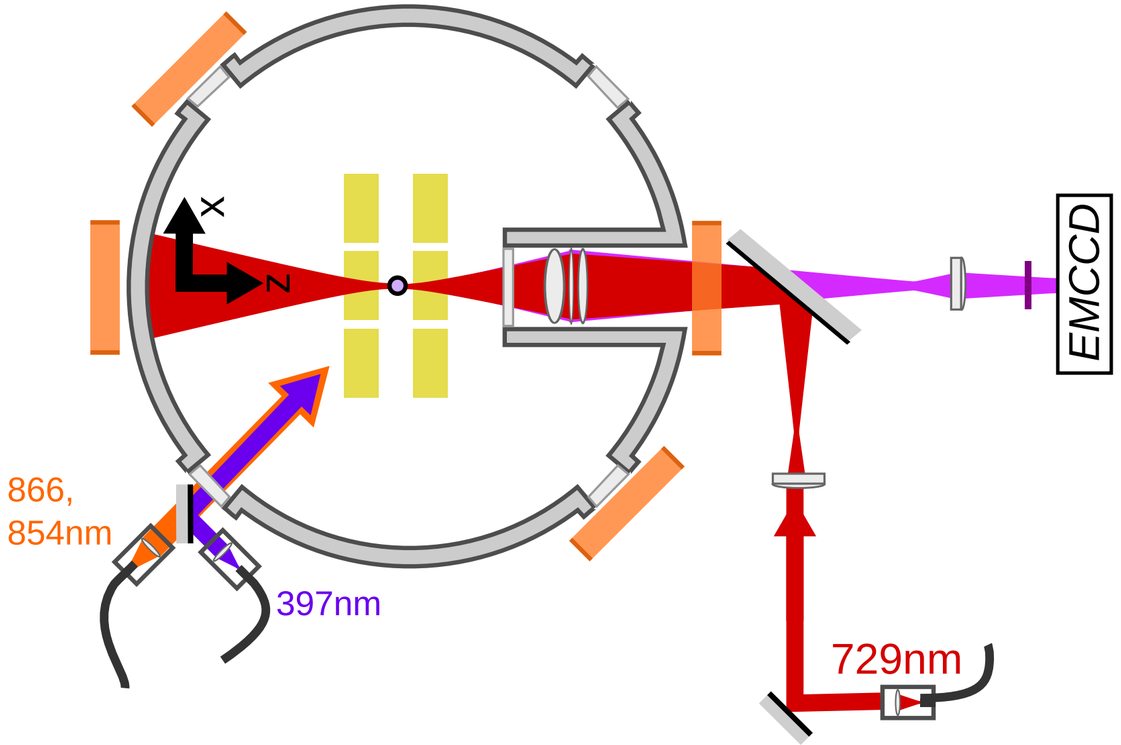
A typical experiment

-) **Laser Coolling** ~ 100-1000 μs

-) **Optical Pumping** ~ 10 μs

-) **Coherent Manupulation** ~ 1-500 μs or even s

-) **Detection** 500-1000 μs



A typical experiment

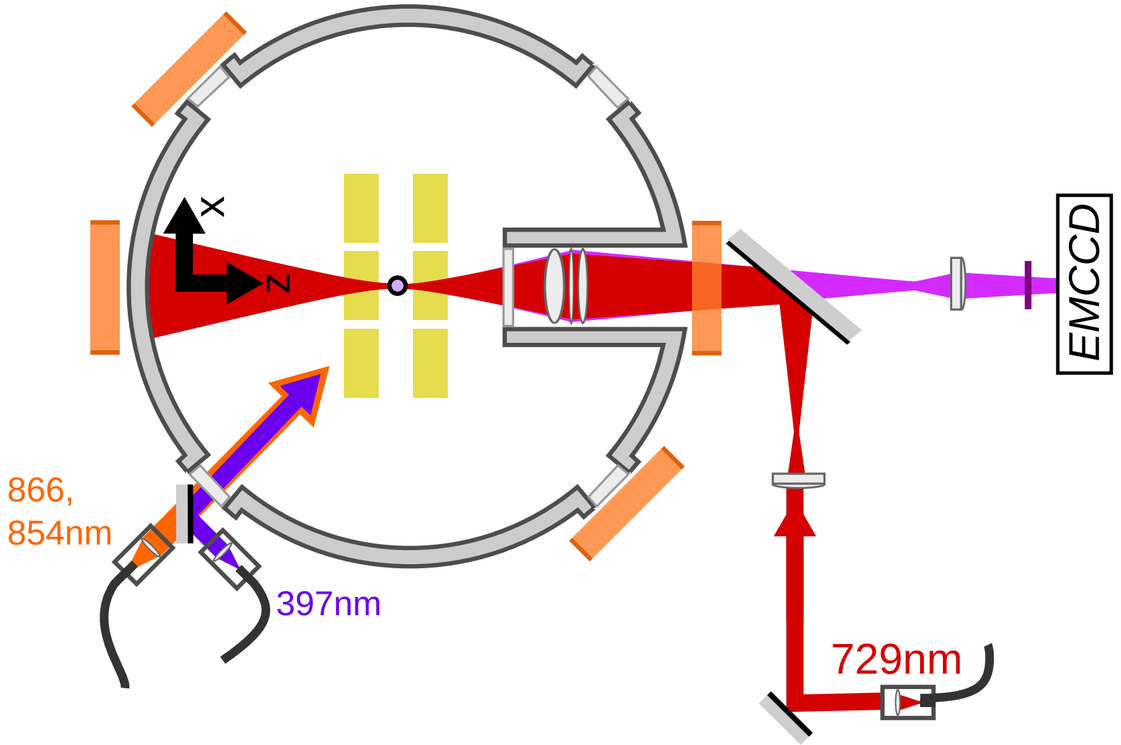
-) **Laser Coolling** ~ 100-1000 μs

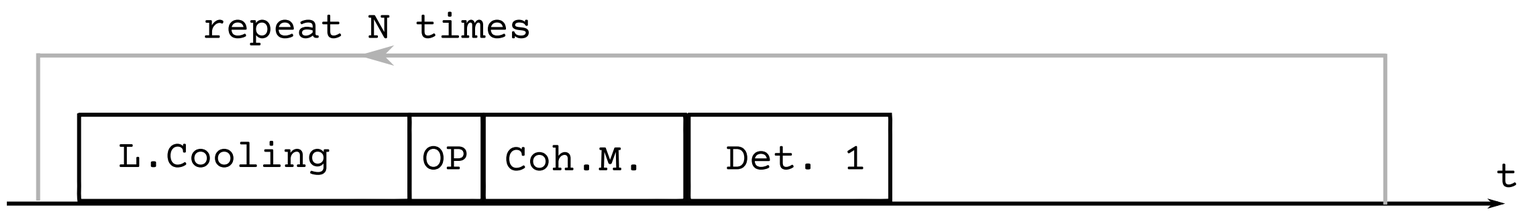
-) **Optical Pumping** ~ 10 μs

-) **Coherent Manupulation** ~ 1-500 μs or even s

-) **Detection** 500-1000 μs

(-) Iteration logic





A typical experiment

-) **Laser Coolling** ~ 100-1000 μs

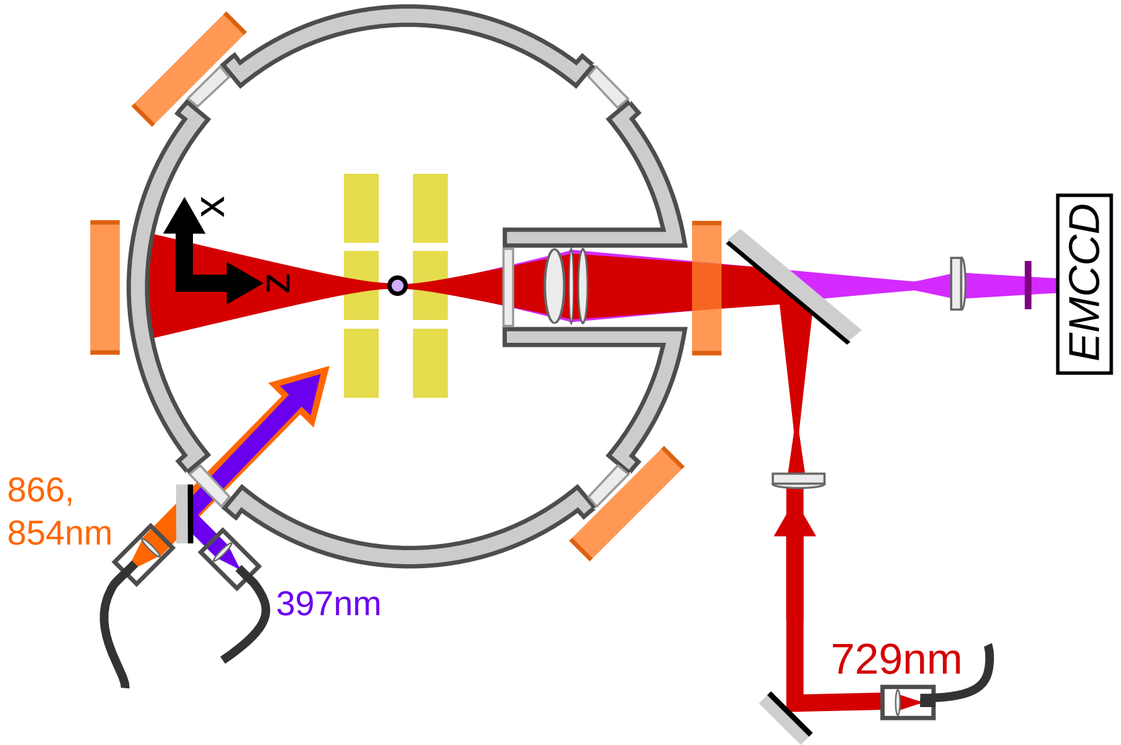
-) **Optical Pumping** ~ 10 μs

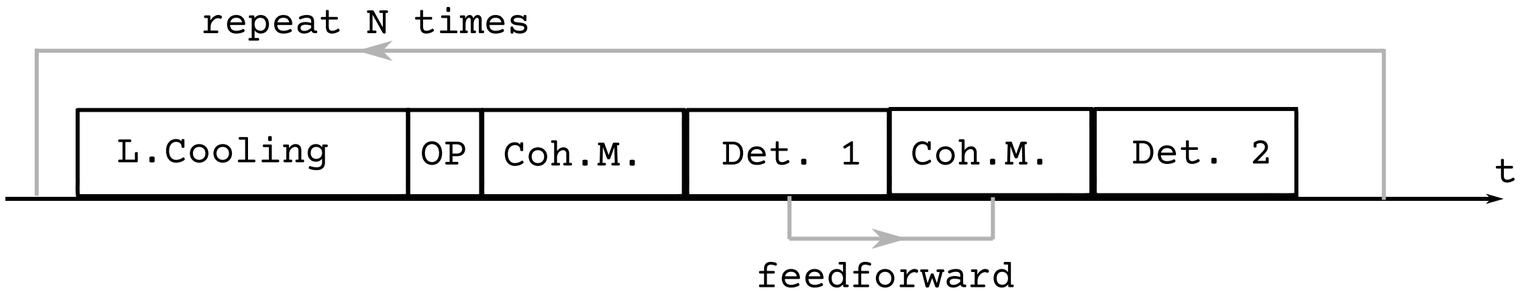
-) **Coherent Manupulation** ~ 1-500 μs or even s

-) **Detection** 500-1000 μs

(-) Iteration logic

(-) Feedforward

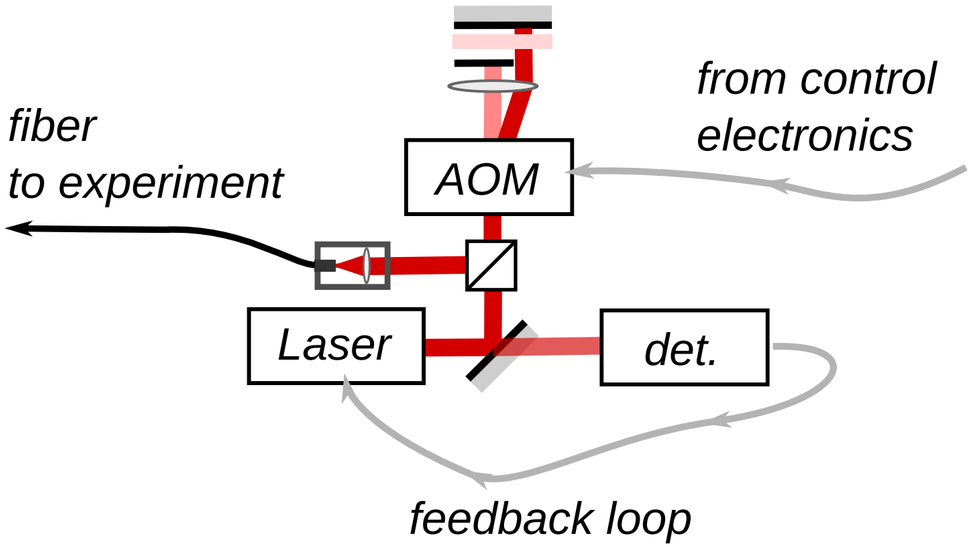




Laser systems + control electronics

Lasers
-) Tunable lasers
-) Frequency stabilization
-) Frequency, amplitde and polarization control

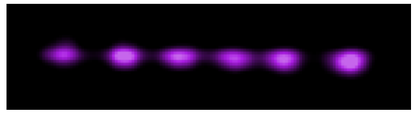
Contol electronics
-) FPGAs
-) DSPs (MHz and GHz w/ phase control)
-) ADCs and DACs.



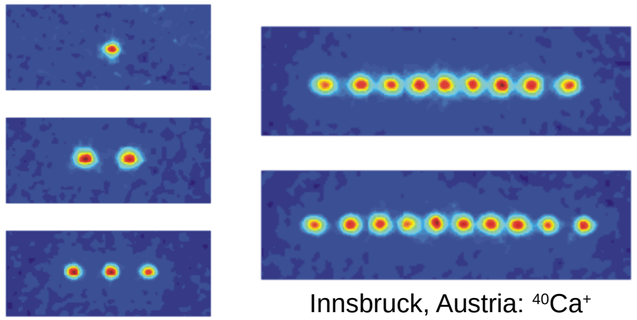
A multi ion experiment

challenges

-) ion addressing
-) mode cramping
-) ion loss

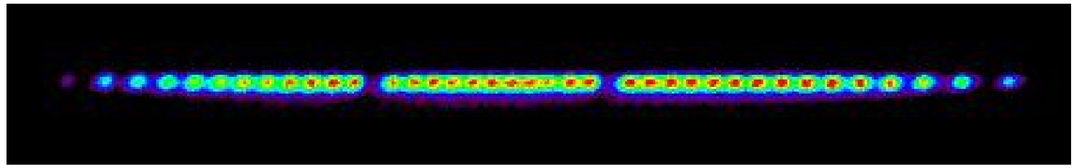


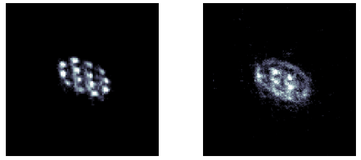
Oxford, England: $^{40}Ca^{+}$



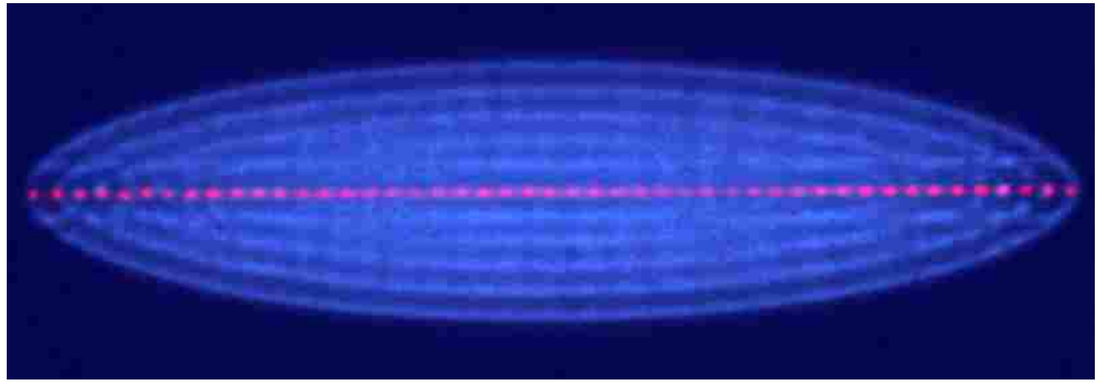
Innsbruck, Austria: $^{40}Ca^{+}$

Boulder, USA: Hg^{+}





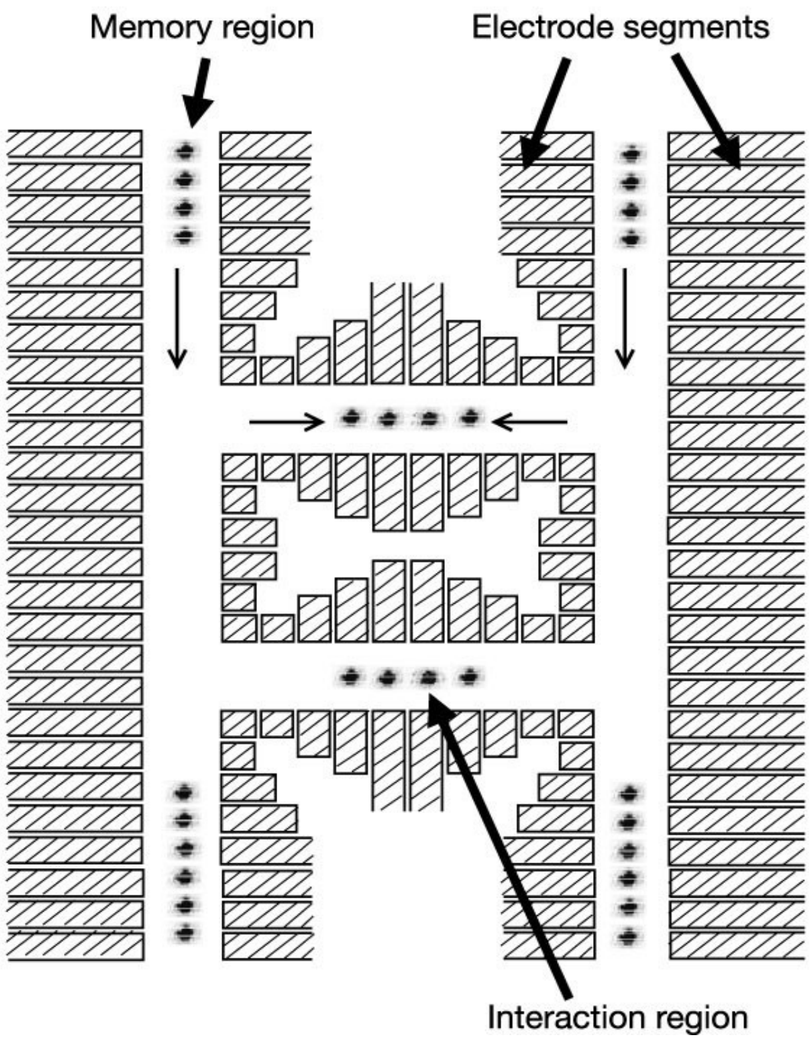
LIAF, Buenos Aires, Argentina



Aarhus, Denmark: $^{40}Ca^{+}$ (red) and $^{24}Mg^{+}$ (blue)

A multi ion experiment

the ion trap CCD solution



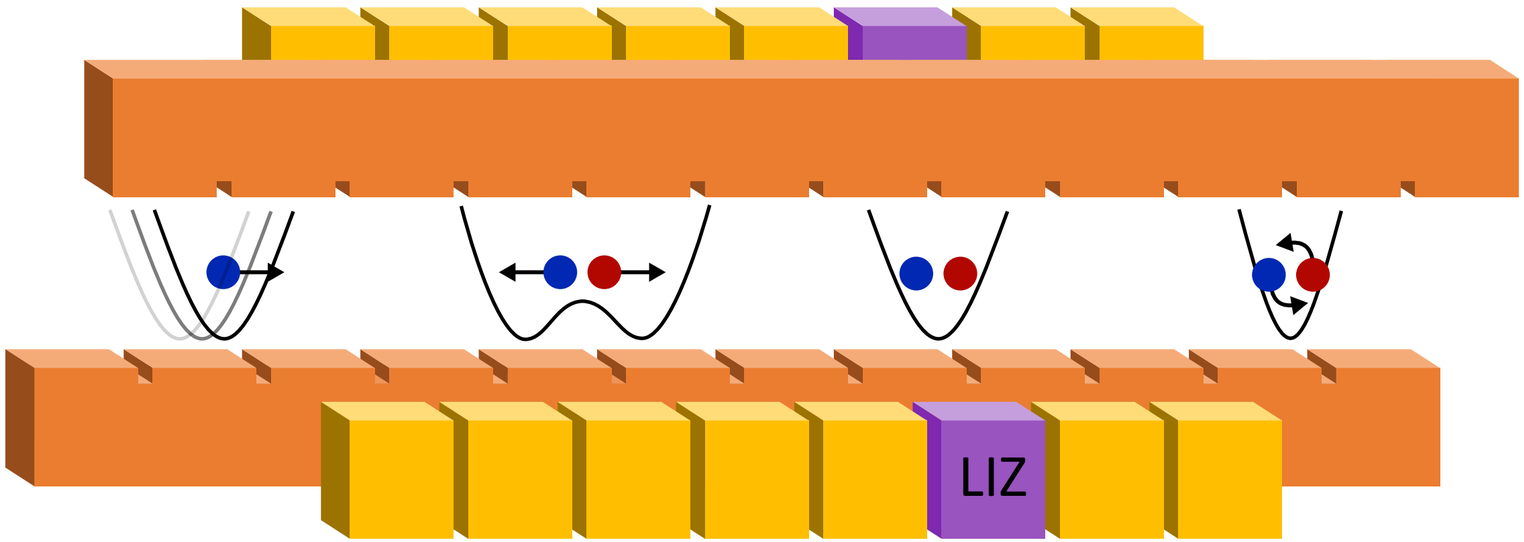
new challenges

-) ions near surfaces: heating and noise
-) high voltages and minutarization
-) integration

D. Kielpinski, C. Monroe & D. J. Wineland, Nature 417, 709(2002)

Mainz QIP platform

the ion Meeenzer ion CCD

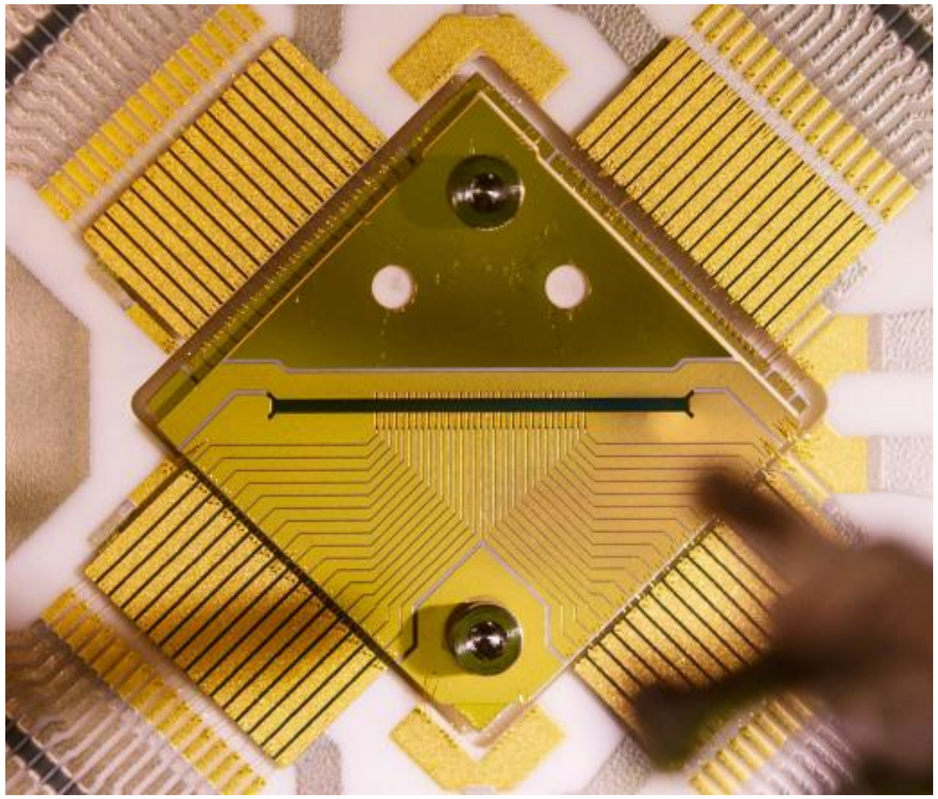


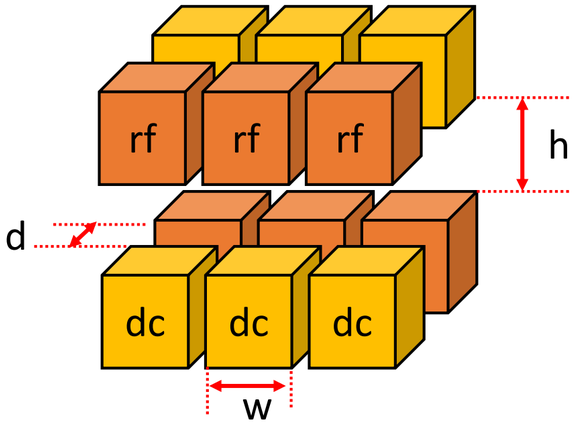
Team leader U. Poschinger, PI F Schmidt-Kaler

AVS Quantum Sci. 2, 014101 (2020); doi: 10.1116/1.5126186

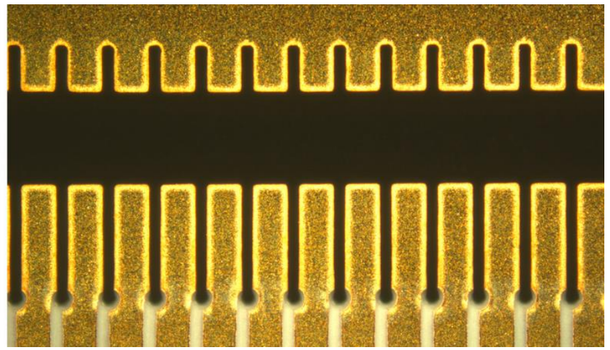
Mainz QIP platform

dimensions and overlook





w = 150 µm
d = 254 µm
h = 400 µm

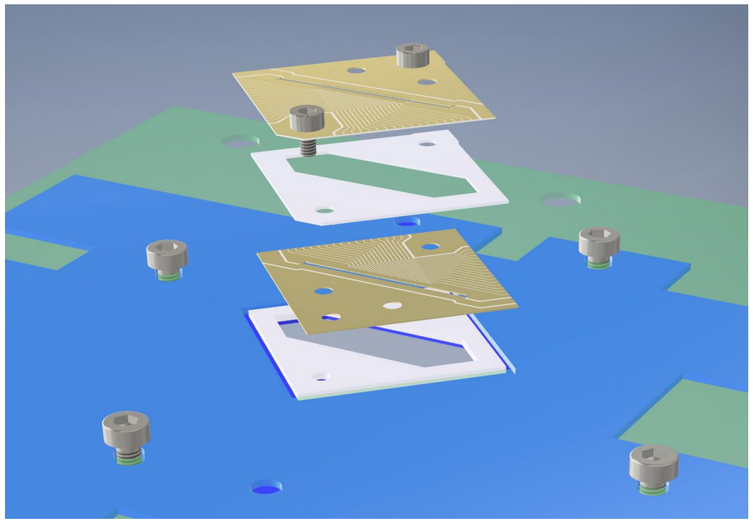


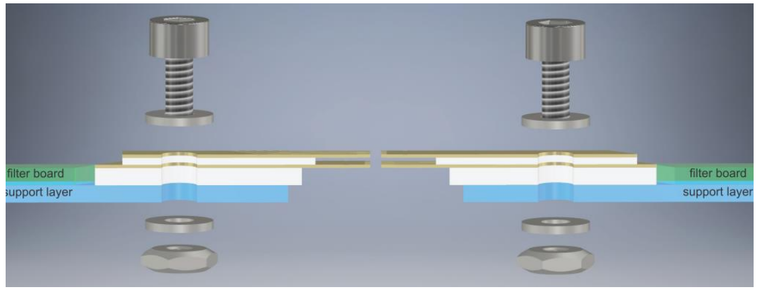
Team leader U. Poschinger, PI F. Schmidt-Kaler

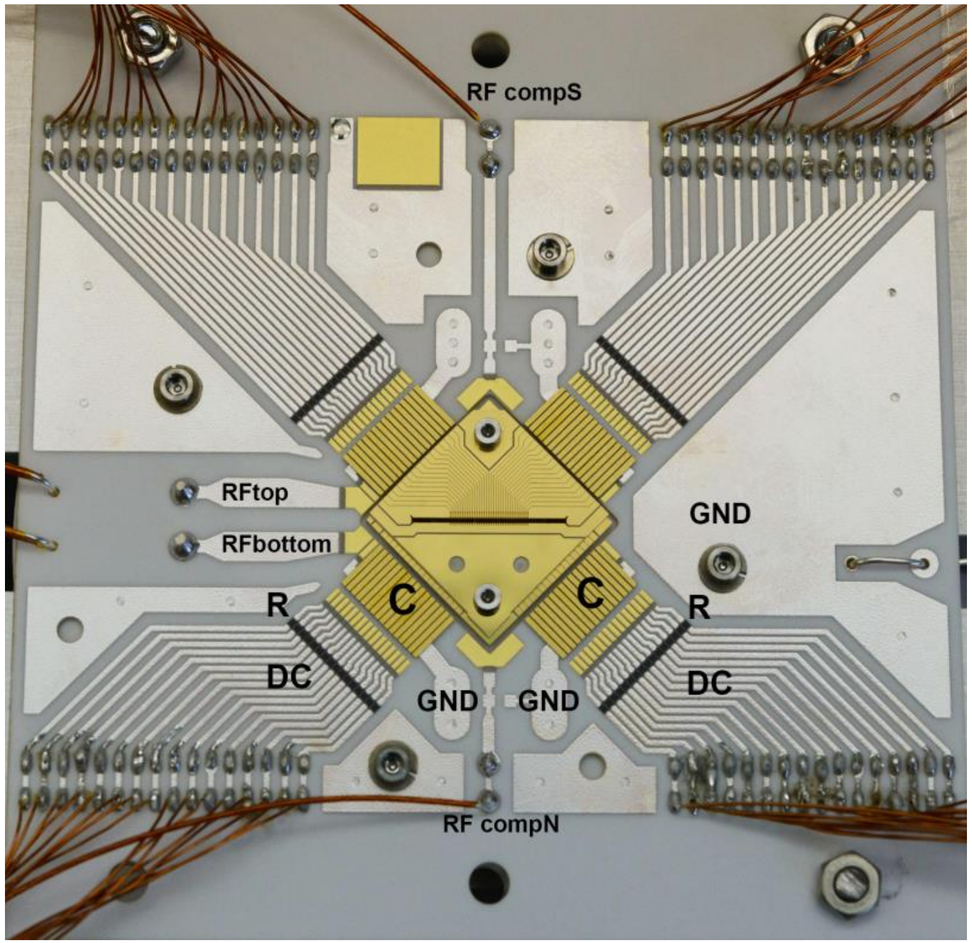
AVS Quantum Sci. 2, 014101 (2020); doi: 10.1116/1.5126186

Mainz QIP platform

assembly







Team leader U. Poschinger, PI F. Schmidt-Kaler

AVS Quantum Sci. 2, 014101 (2020); doi: 10.1116/1.5126186

Mainz QIP platform

main features

Trap
-) laser-cur, gold-coated alumina wafers

Filter/holder board
-) thick film printing on alumina wafers
-) capacitor arrays

Team leader U. Poschinger, PI F. Schmidt-Kaler

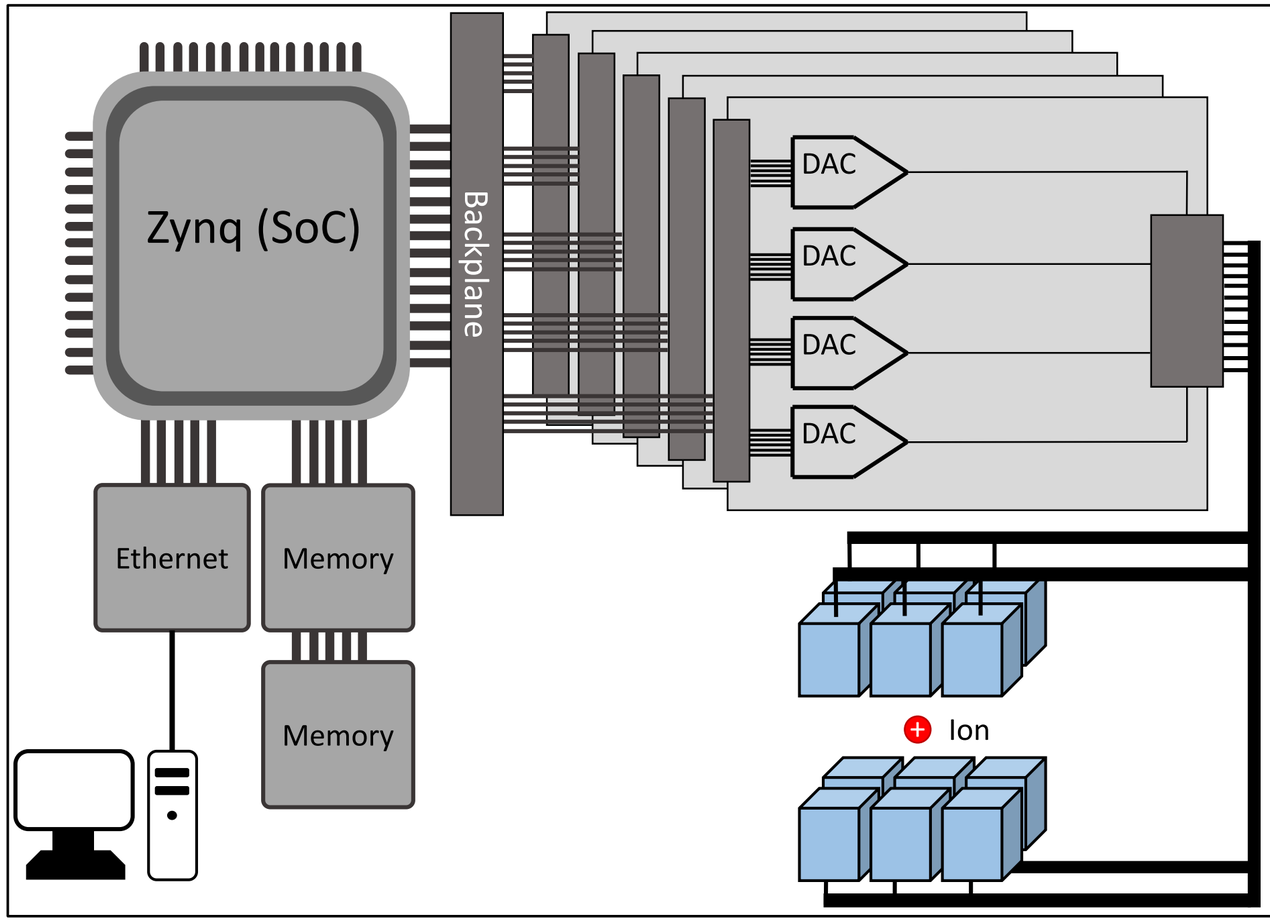
AVS Quantum Sci. 2, 014101 (2020); doi: 10.1116/1.5126186

Mainz QIP platform

electronics: FPGA+DACs

Table I. Important performance specifications of the Mainz mAWG.

Characteristic	Value	Unit
Max. data transfer rate	730	MBit/s
Sequence memory	900	MB
Max. internal clock rate	400	MHz
Signal clock rate	50	MHz
Sample hold time resolution	20	ns
Min. analog sample update time	360	ns
Max. number of analog channels	80	
Output voltage range	± 40	V
Min. analog resolution	1.2	mV
Slew rate	~ 20	$V/\mu s$
Noise floor	<100	$\mu V/\sqrt{Hz}$

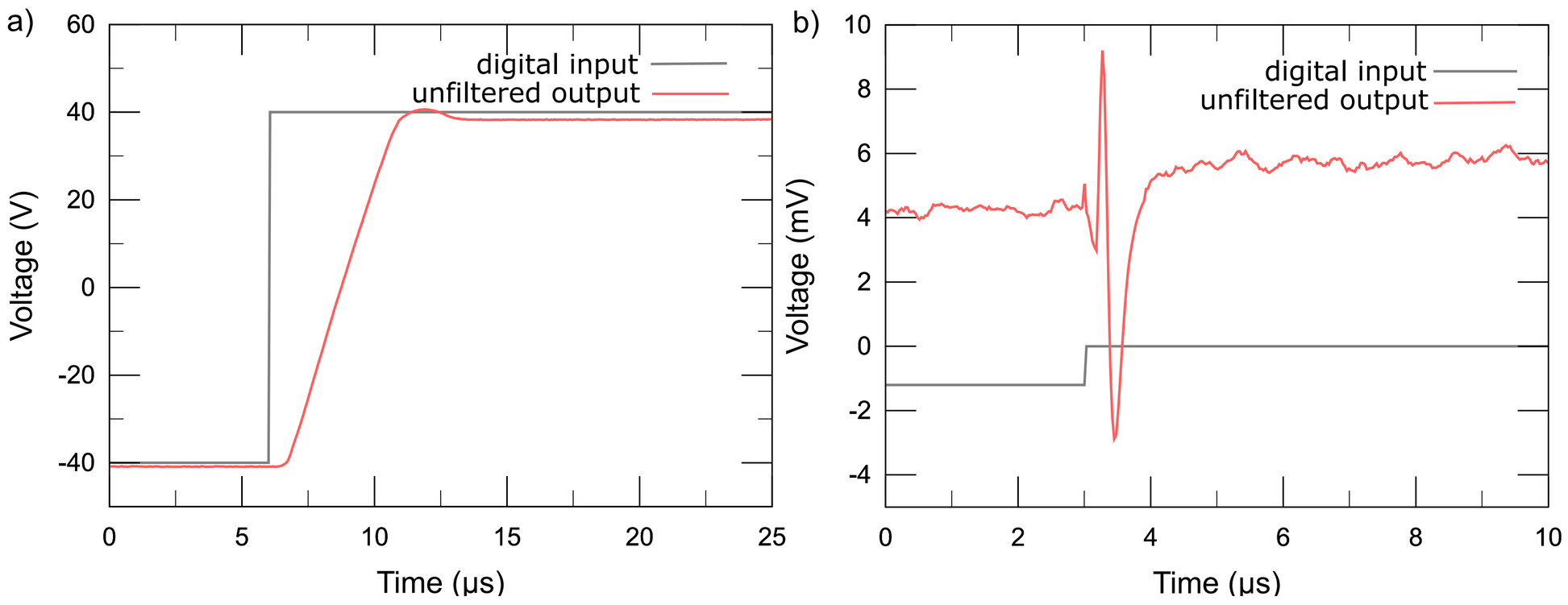


Team leader U. Poschinger, PI F. Schmidt-Kaler

AVS Quantum Sci. 2, 014101 (2020); doi: 10.1116/1.5126186

Mainz QIP platform

limitations: slew rate and glitches



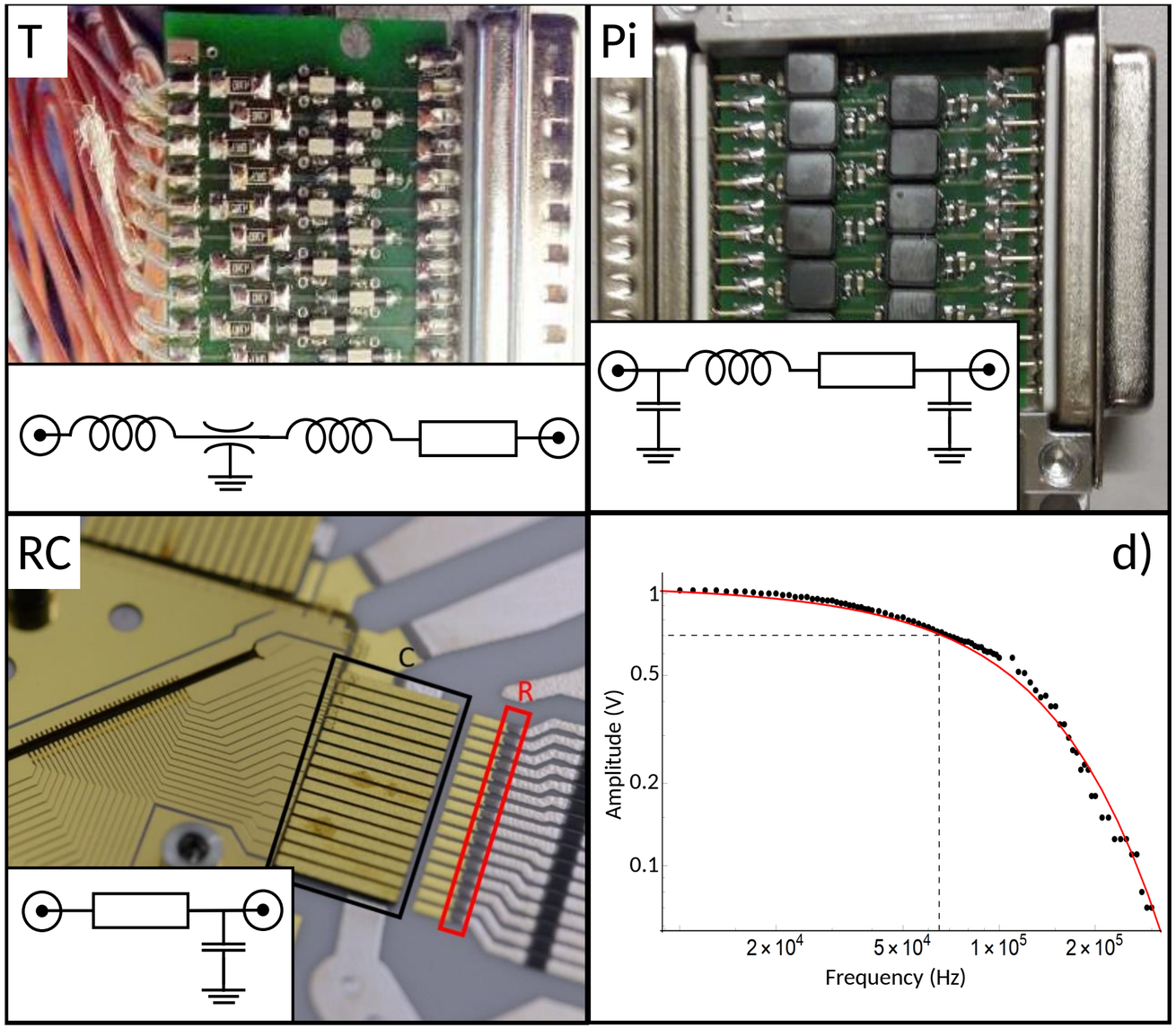
Team leader U. Poschinger, PI F. Schmidt-Kaler

AVS Quantum Sci. 2, 014101 (2020); doi: 10.1116/1.5126186

Mainz QIP platform

filtering: trap RF and DAC noise

- crosstalk
- cutoff and slope

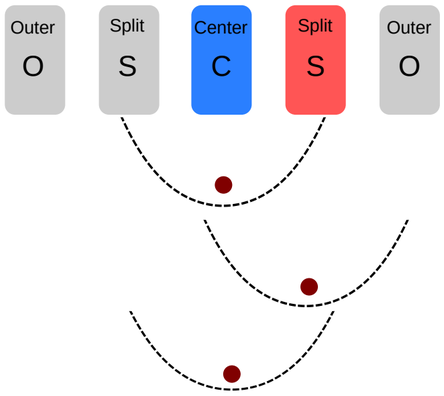


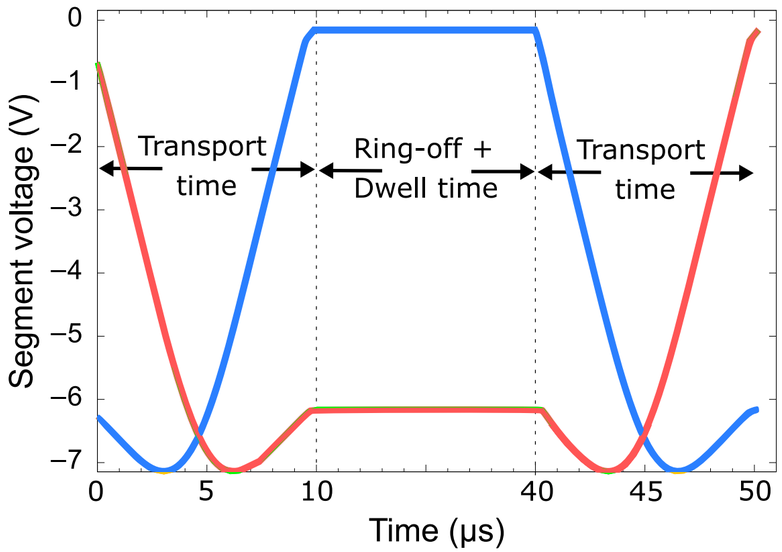
Team leader U. Poschinger, PI F. Schmidt-Kaler

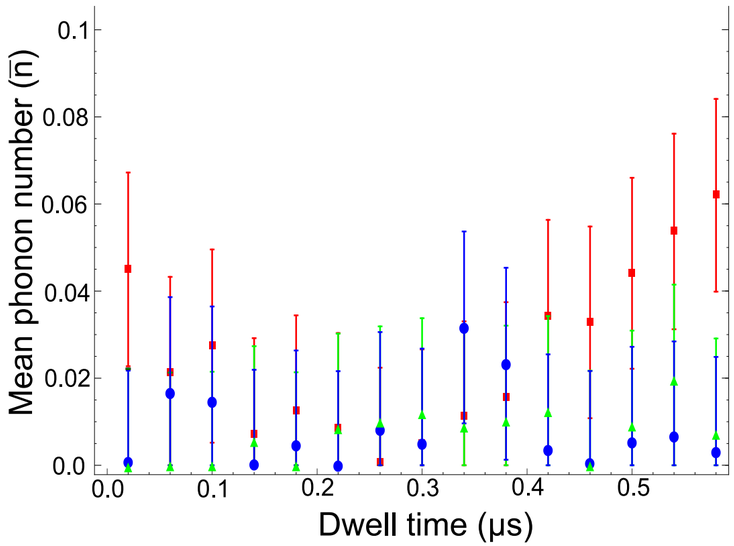
AVS Quantum Sci. 2, 014101 (2020); doi: 10.1116/1.5126186

Mainz QIP platform - experiments

transport





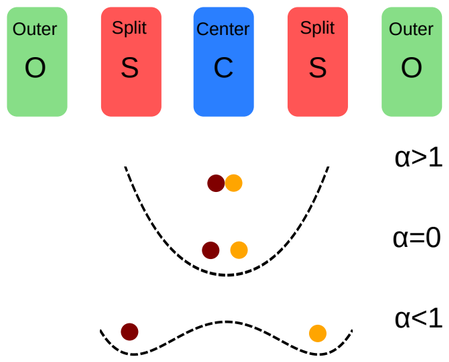


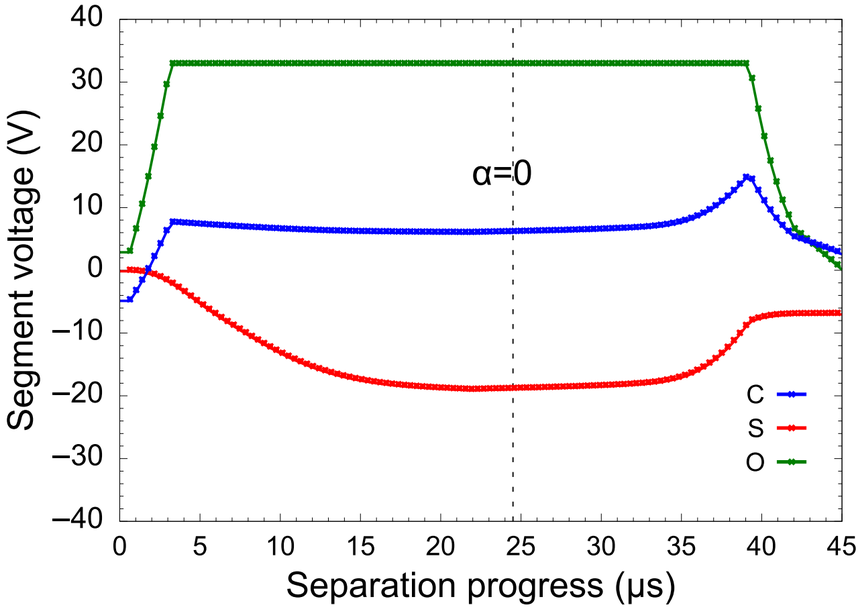
Team leader U. Poschinger, PI F. Schmidt-Kaler

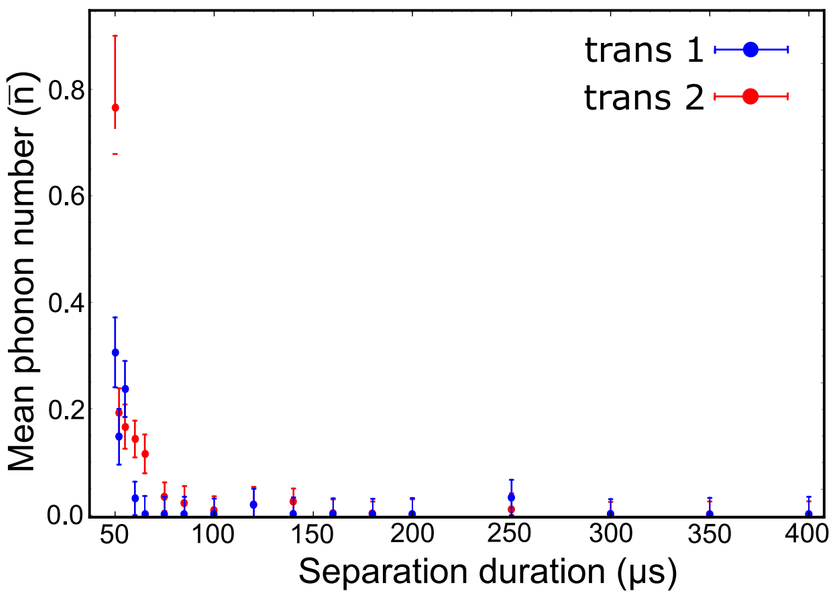
Phys. Rev. Lett. 109, 080501 (2012)

Mainz QIP platform - experiments

splitting







Team leader U. Poschinger, PI F. Schmidt-Kaler

Phys. Rev. Lett. 109, 080501 (2012)

Mainz QIP platform - experiments

rotation

18 µs

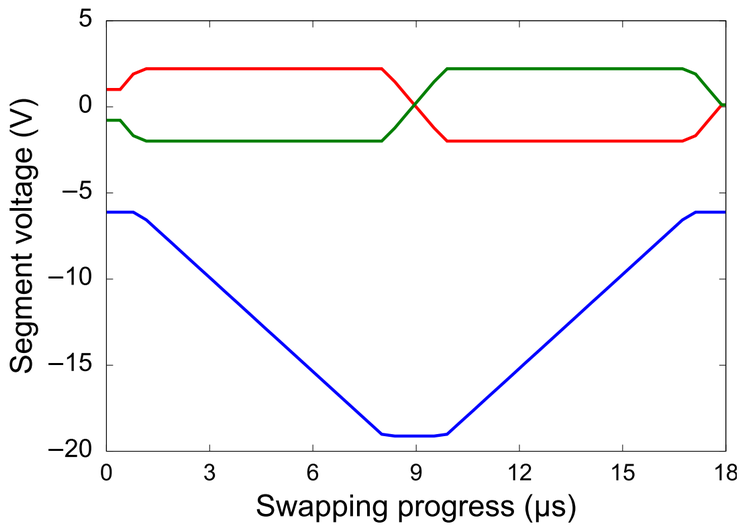


Table III. Motional excitation in mean phonon number induced by a single rotation operation on a two-ion crystal. The values are obtained from averaging red sideband excitation with respect to probe time, see Sec. VII B.

Secular mode	Secular frequency/2π (MHz)	Lamb-Dicke (η)	$\bar{n}$ after swapping	Increase
axial:com	1.49	0.16(1)	0.36(2)	0.10(3)
axial:str	2.58	0.11(1)	0.28(2)	0.08(2)
trans1:com	3.81	0.06(1)	0.34(2)	0.01(3)
trans1:rocking	3.49	0.06(1)	0.37(2)	0.12(3)
trans2:com	4.63	0.065(3)	0.25(2)	0.04(2)
trans2:rocking	4.37	0.065(3)	0.23(2)	0.01(2)

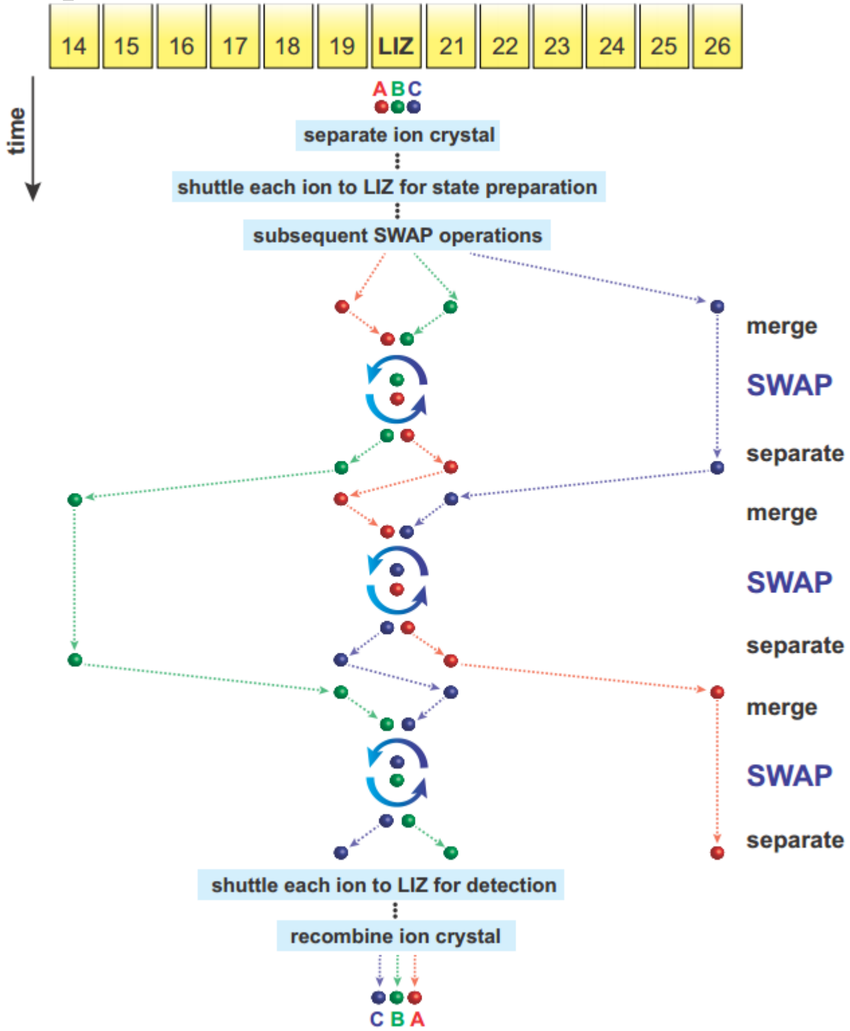
Team leader U. Poschinger, PI F. Schmidt-Kaler

Phys. Rev. Lett. 109, 080501 (2012)

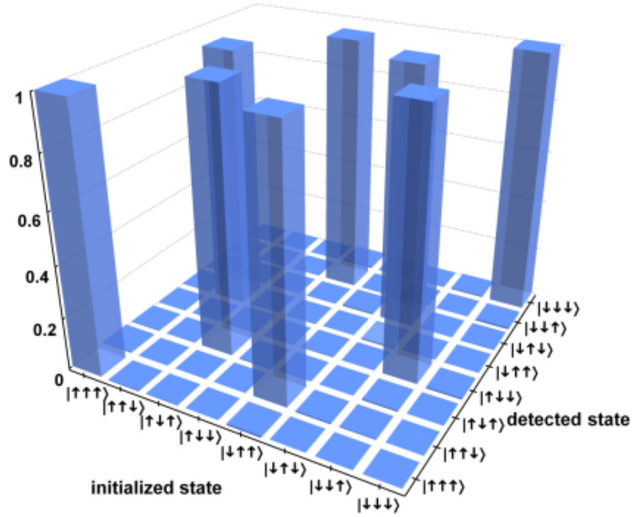
Mainz QIP platform - experiments

Fast ion swapping for quantum-information processing

Main sequence



Switching truth table



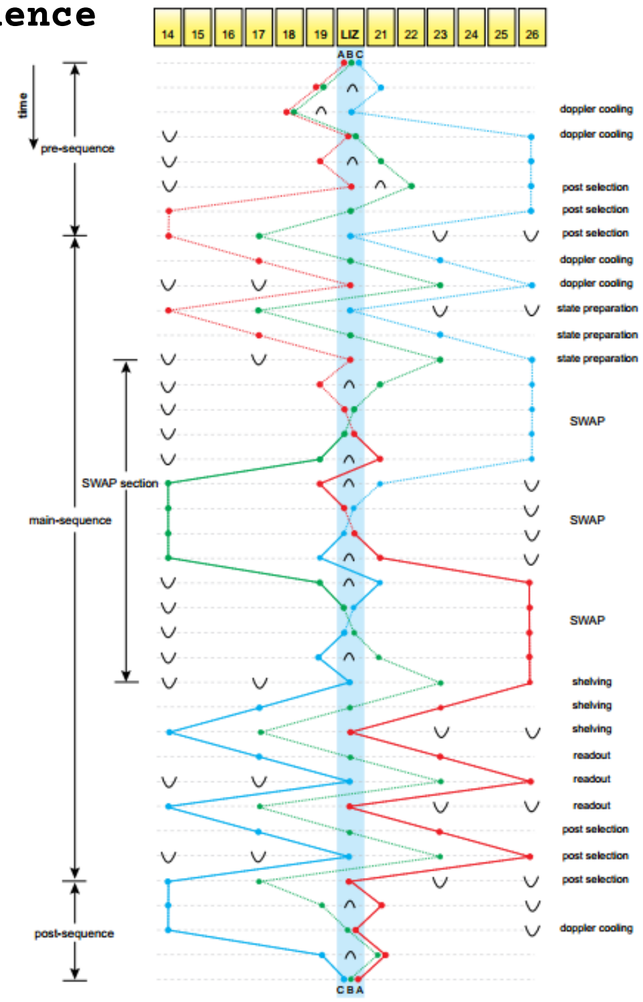
Team leader U. Poschinger, PI F. Schmidt-Kaler

Phys. Rev. Lett. 109, 080501 (2012)

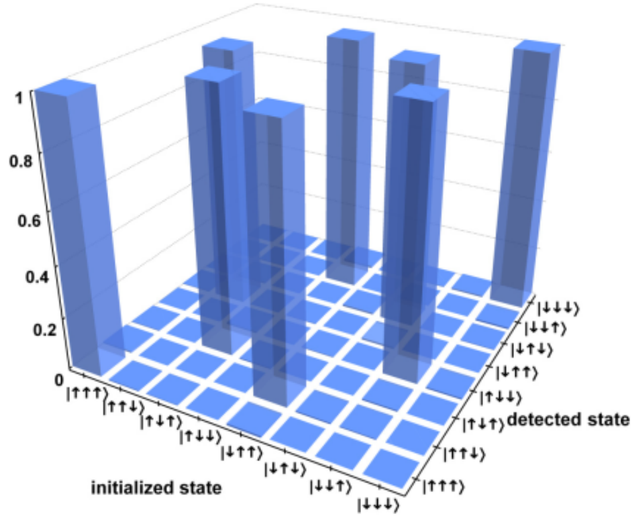
Mainz QIP platform - experiments

Fast ion swapping for quantum-information processing

Full sequence



Switching truth table



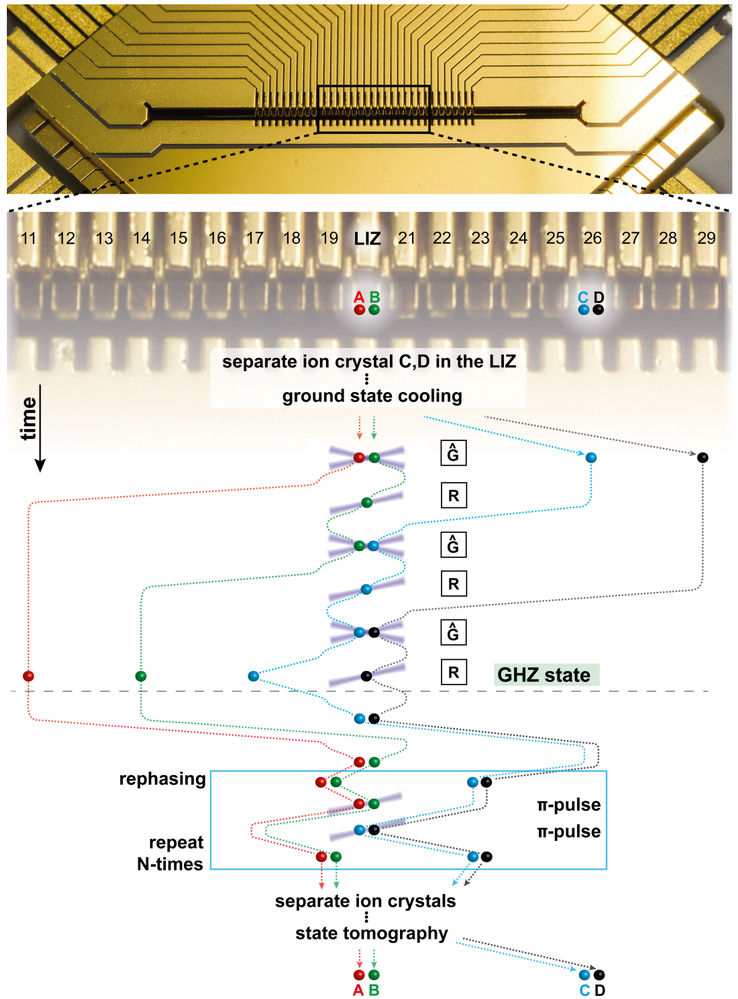
Team leader U. Poschinger, PI F. Schmidt-Kaler

Phys. Rev. Lett. 109, 080501 (2012)

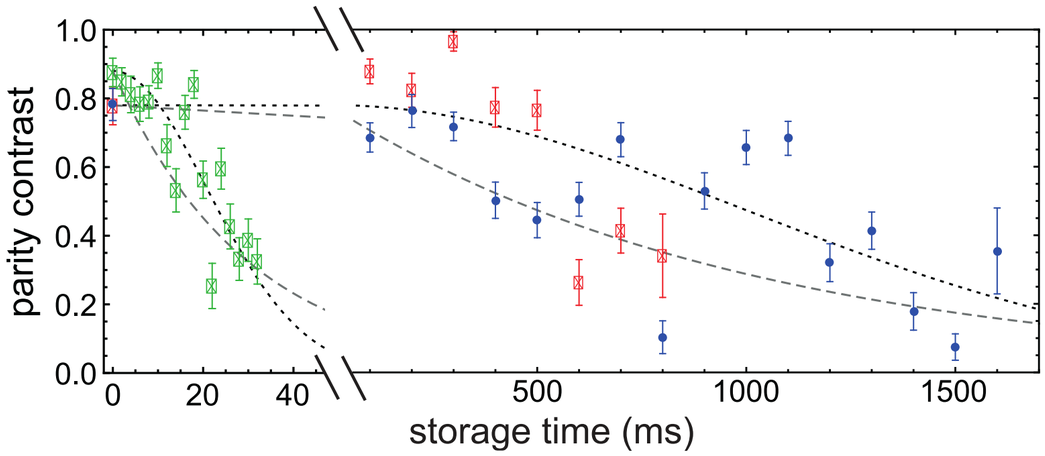
Mainz QIP platform - experiments

Scalable Creation of Long-Lived Multipartite Entanglement

Main sequence



Entanglement protection for long times.



Team leader U. Poschinger, PI F. Schmidt-Kaler

Phys. Rev. Lett. 109, 080501 (2012)

thank you for your attention