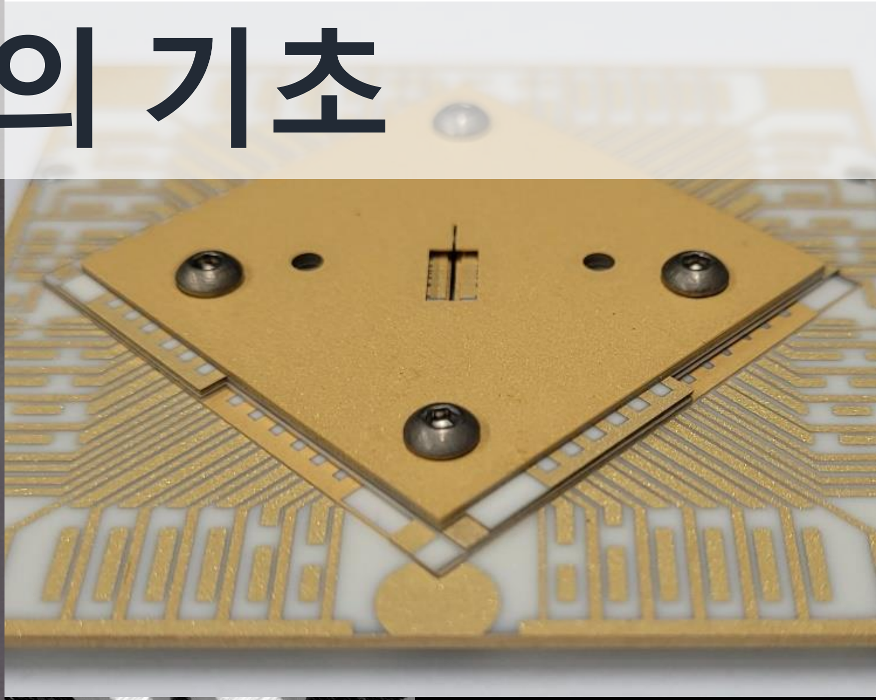
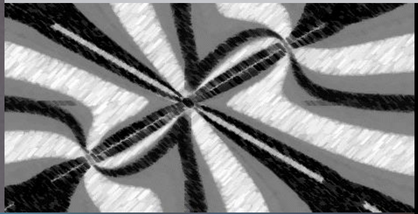
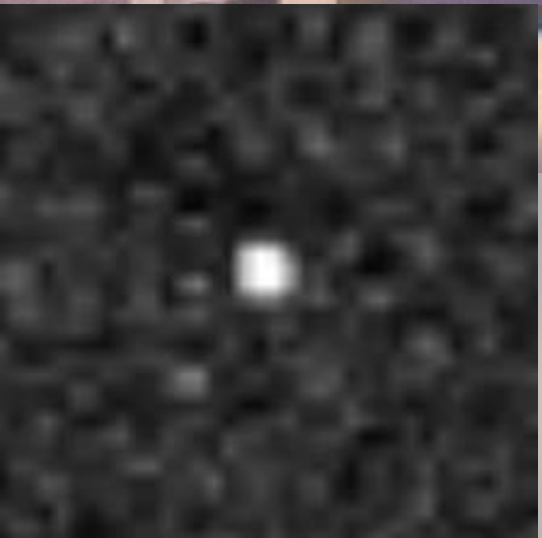
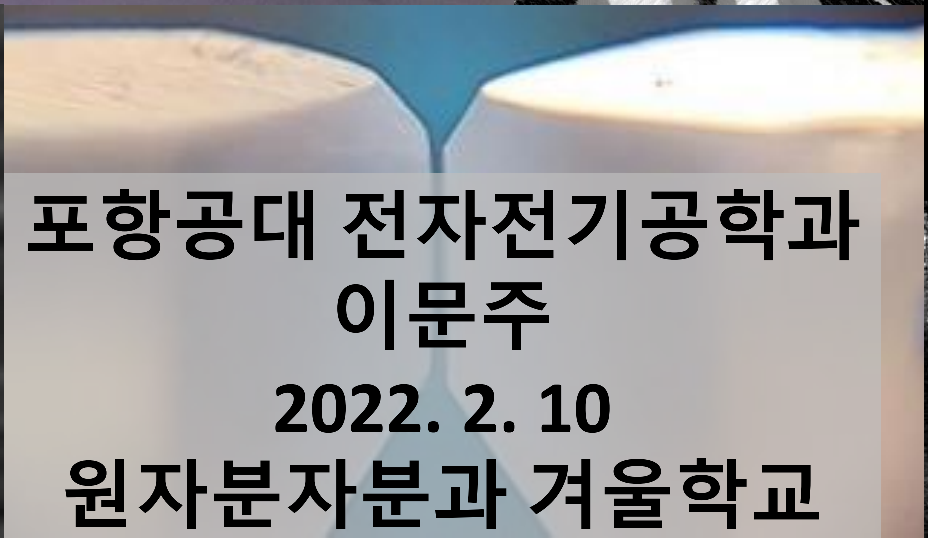
이온 트랩의 기초

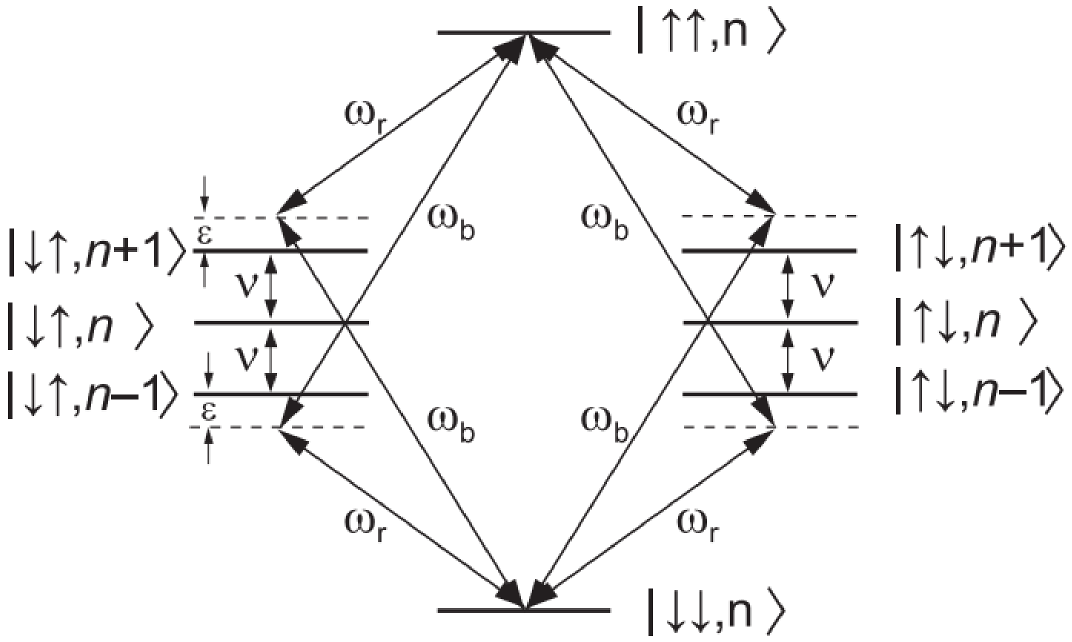




포항공대 전자전기공학과
이문주
2022. 2. 10
원자분자분과 겨울학교

목표

$$\hat{H}_{\mathrm{LD}}(t) = (\hbar/2)\Omega_0\sigma_+\{1 + i\,\eta(\hat{a}e^{-i\nu t} + \hat{a}^\dagger e^{i\nu t})\}e^{i(\phi - \delta t)} + \mathrm{H.c.}$$



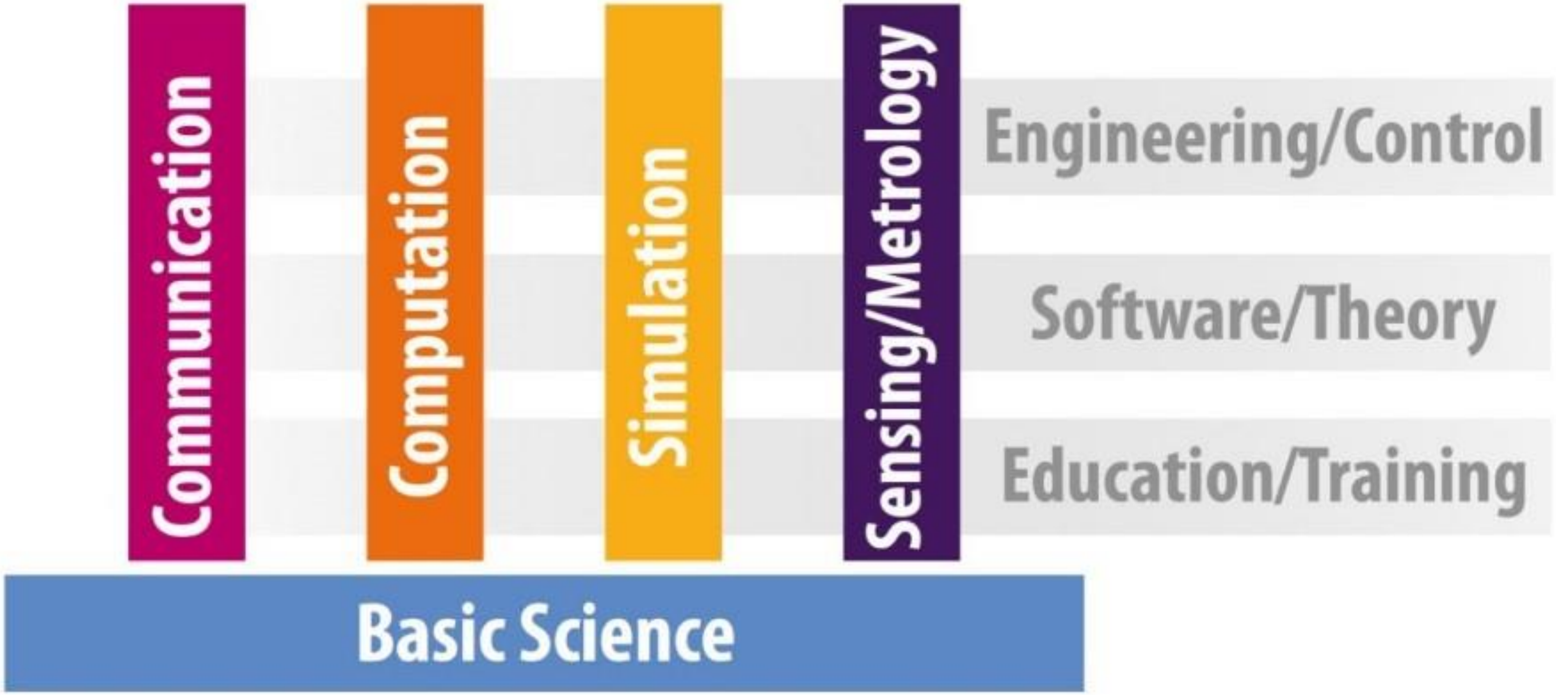
목차

- 양자컴퓨터 분야 동향 소개
- 이온 트랩 특징 및 소개
- 이온 트랩 기본 계산
- 이온 얽힘 발생 소개
- 포항공대 이온 트랩 연구 소개

Quantum technology: 4 pillars

US National Quantum Initiative: >$1.275 Billions in 5 years

European Quantum Flagship: >€1 Billion in 10 years

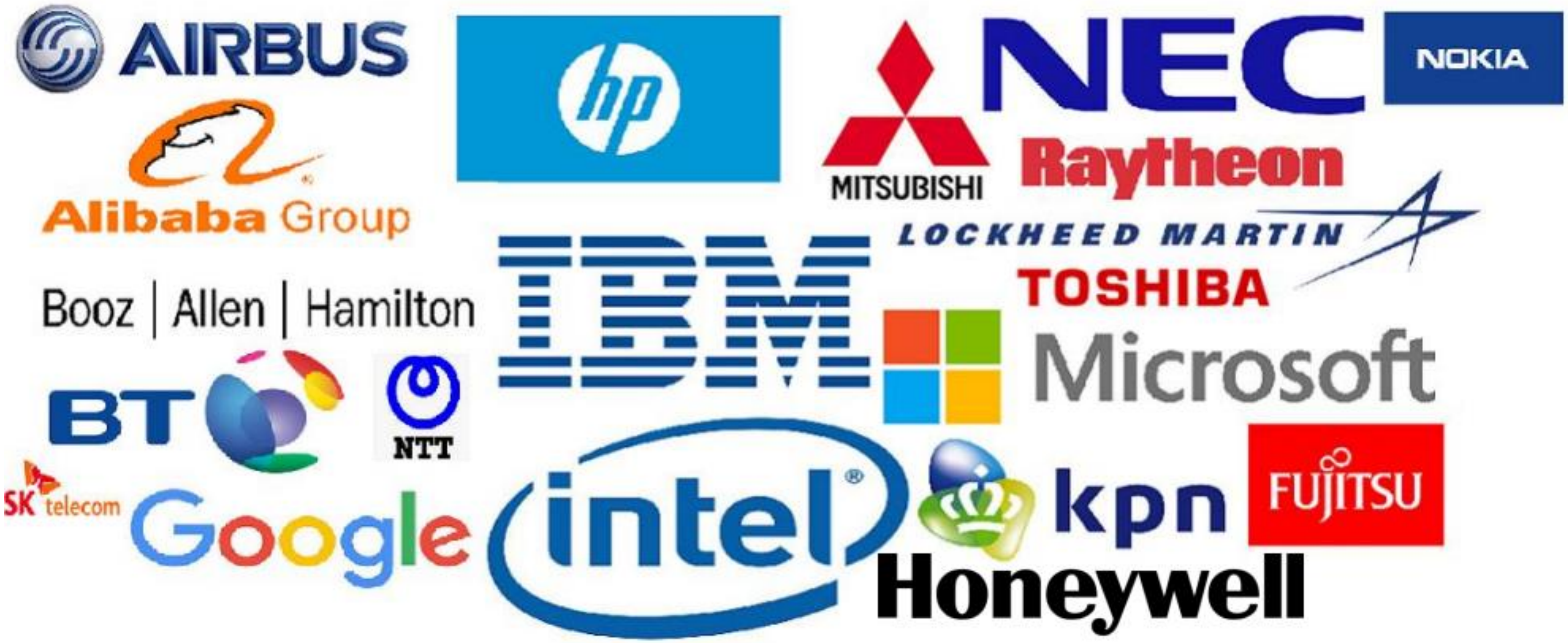


Quantum projects started at 2019 in Korea

NRF national quantum computing project: $xxx M in next years

NRF 2022년 800억 이상 투자

Investment from private sectors



In Korea: Samsung, SK Telecom, KT, IDQuantique, …

삼성종기원에서 초전도 큐비트 연구 중

양자컴퓨팅 하드웨어

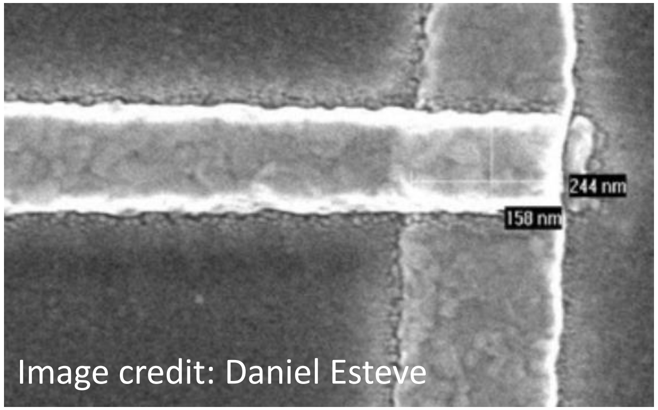


Image credit: Daniel Esteve

Josephson junction을 이용한 초전도 회로

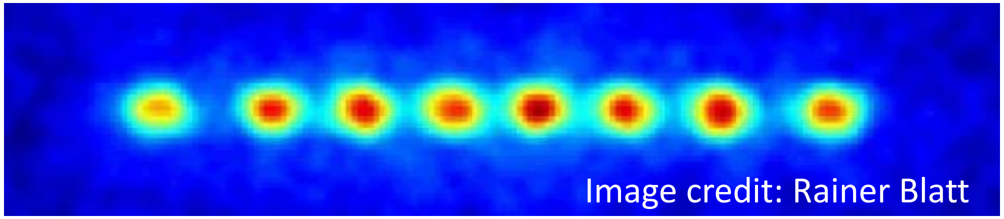
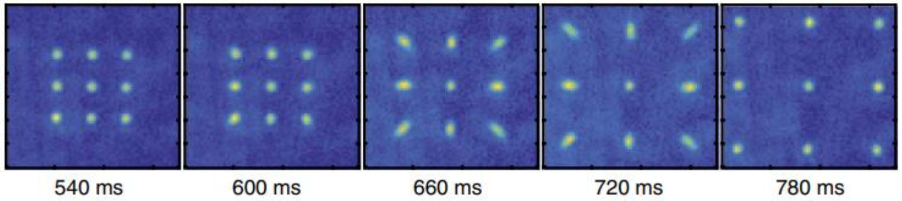
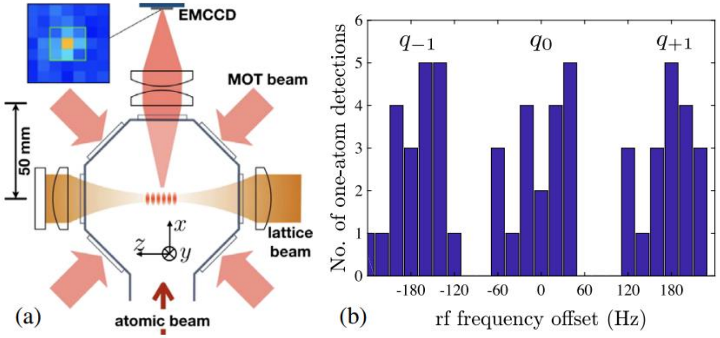


Image credit: Rainer Blatt

이온 트랩



Nat. Commun. 7, 13317 (2016)
KAIST 안재욱 교수님 그룹



Phys. Rev. Lett. 122, 133201 (2019)
고려대 조동현 교수님 그룹

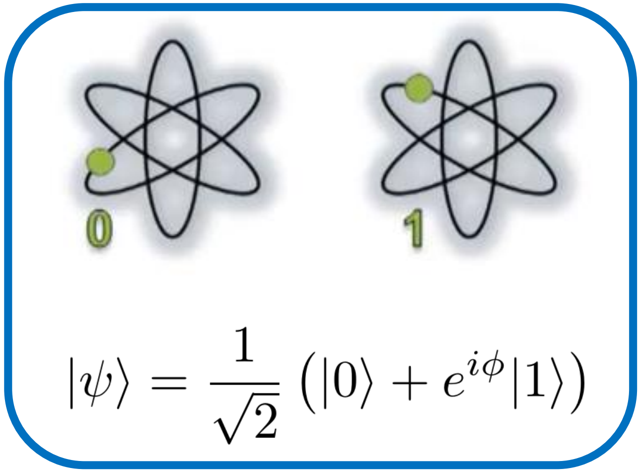
Rydberg interaction/optical lattice를 이용한 중성 원자

Three small pieces of physics

1. **Qubit**
2. **Entanglement**
3. **Cavity**

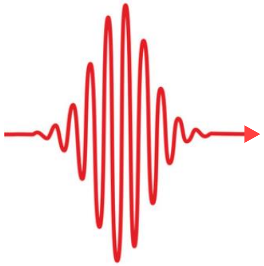
1. Quantum bit (qubit)

Superposition of 0 and 1

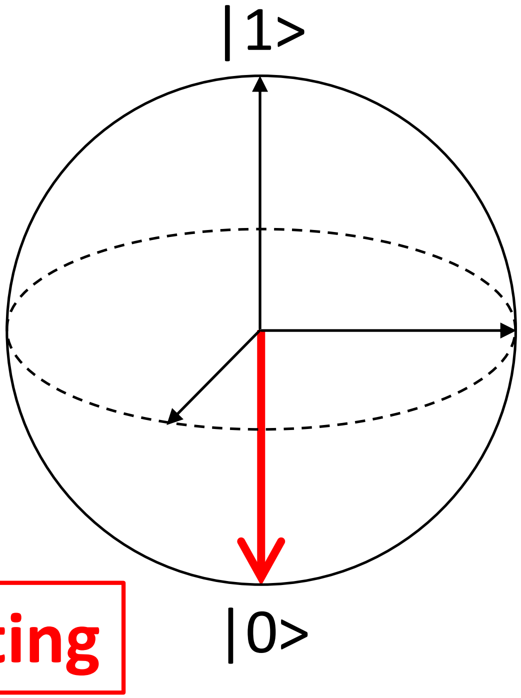


$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle + e^{i\phi}|1\rangle\right)$$

Laser or microwave pulse



Bloch sphere



computing

Stationary

Neutral atoms, **trapped ions**, **superconducting qubits**, quantum dots, **nitrogen-vacancy (NV) centers** …

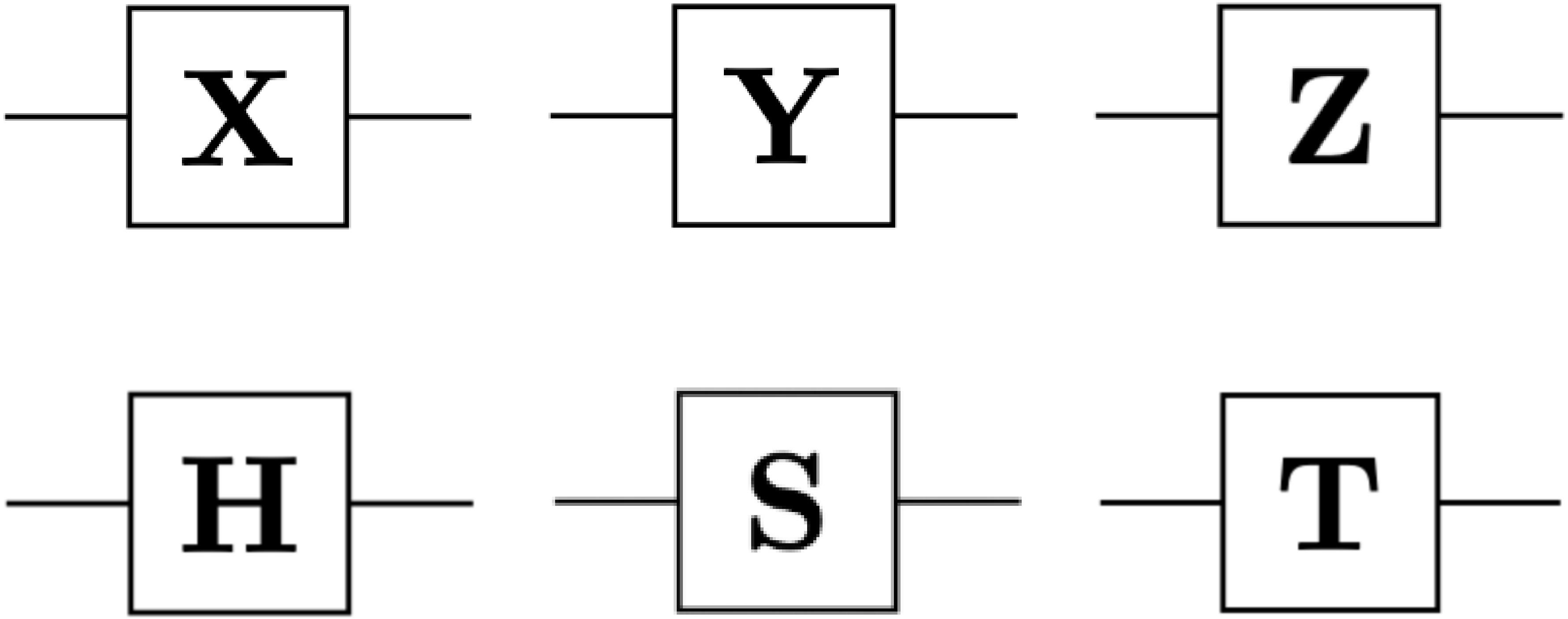
sensing & networking

Flying

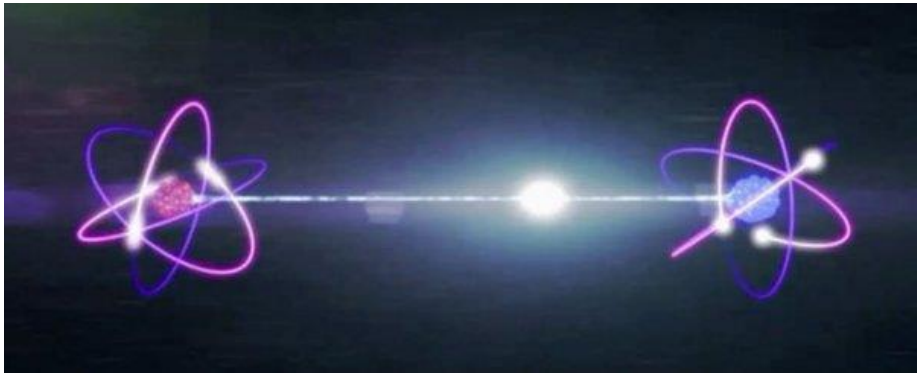
Photons (mostly with polarizations)

communication

Single-qubit gates



2. Entanglement



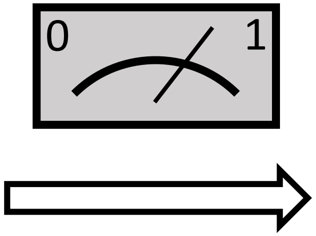
correlation without wire

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle|0\rangle + |1\rangle|1\rangle)$$

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle|0\rangle|0\rangle + |1\rangle|1\rangle|1\rangle)$$

$$\cdots$$

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle|0\rangle...|0\rangle + |1\rangle|1\rangle...|1\rangle)$$



measurement

$$|0\rangle|0\rangle$$

$$|0\rangle|0\rangle|0\rangle$$

$$\cdots$$

$$|0\rangle|0\rangle...|0\rangle$$

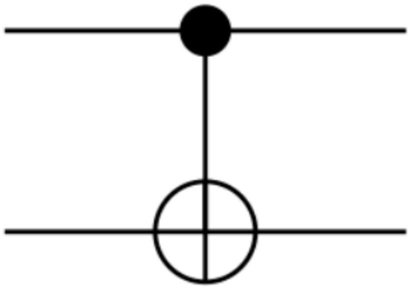
$$|1\rangle|1\rangle$$

$$|1\rangle|1\rangle|1\rangle$$

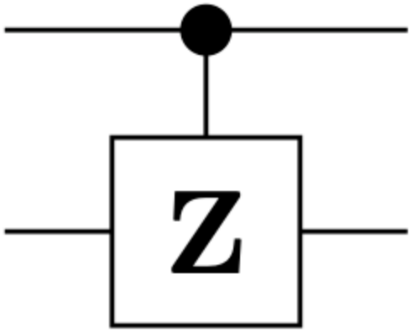
$$\cdots$$

$$|1\rangle|1\rangle...|1\rangle$$

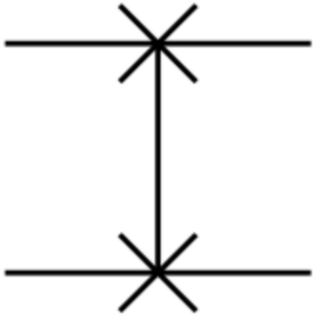
Two- and multi-qubit gates



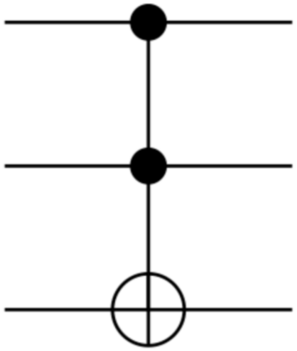
CNOT gate



Controlled Z gate

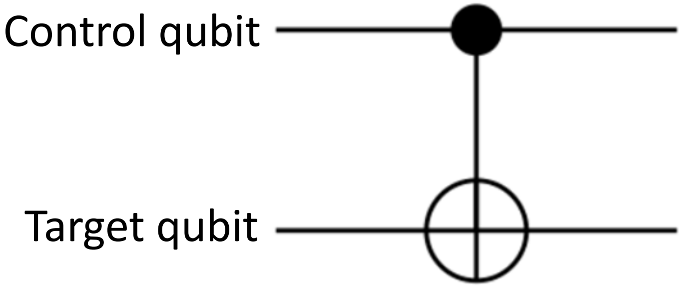


SWAP gate



Toffoli gate

CNOT gate



$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$|00\rangle = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad |01\rangle = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}$$

$$|10\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} \qquad |11\rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

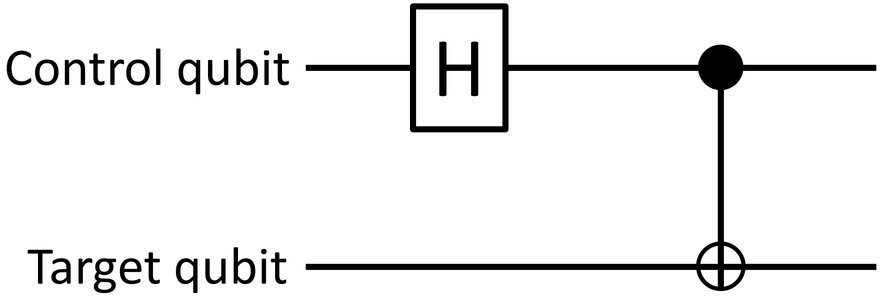
$|00\rangle \rightarrow |00\rangle$

$|01\rangle \rightarrow |01\rangle$

$\boxed{|10\rangle \rightarrow |11\rangle}$

$\boxed{|11\rangle \rightarrow |10\rangle}$

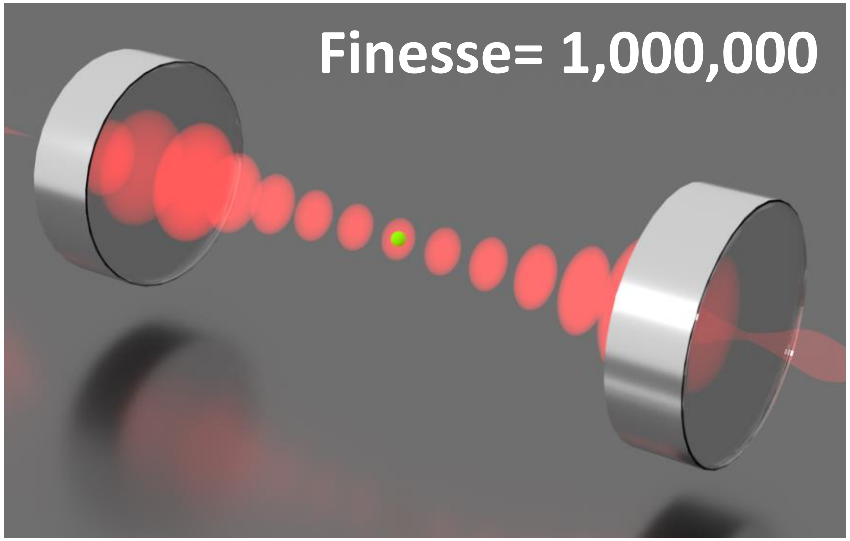
CNOT gate

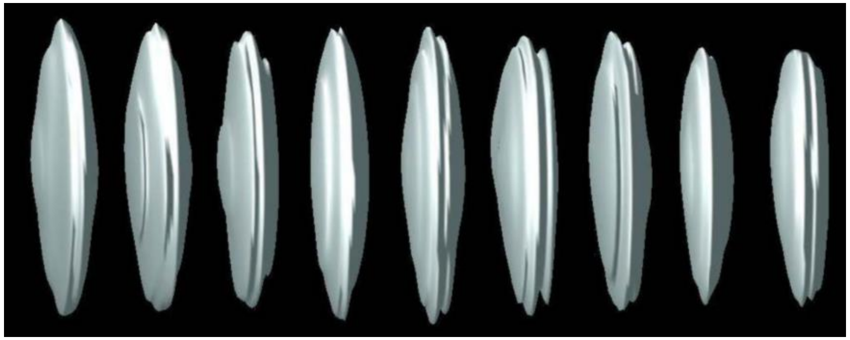


$$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \otimes |0\rangle \rightarrow \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

- Hadamard/T gate와 CNOT gate 만 있으면 모든 양자 연산 가능
- 양자 CNOT gate는 결국 entangling gate
- **High-fidelity entanglement를 만드는 것이 양자컴퓨팅의 핵심: 가장 중요하며 가장 어려움**

3. Cavity (=resonator)



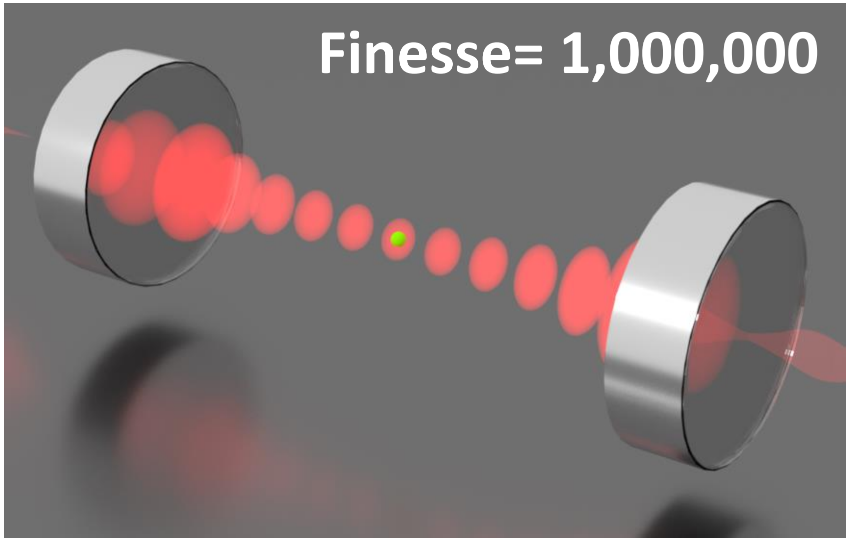


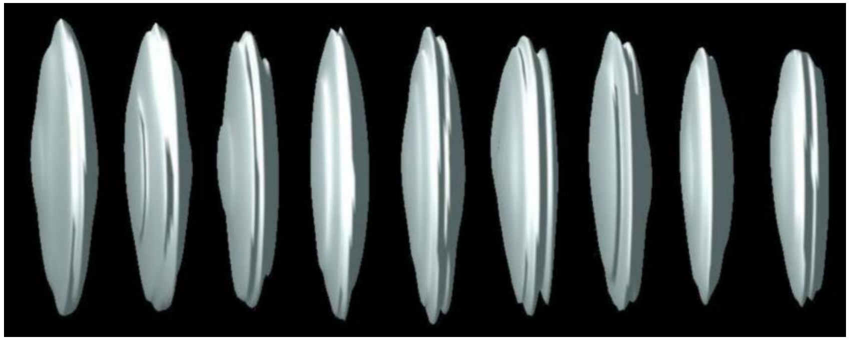
M. Lee et al., Nat. Commun. 5, 3441 (2014)

- Atom-photon interaction at the single photon level
- High-photon collection efficiency (near 100%)
  With high-NA lenses: ~20%
- Optical domain: cavity quantum electrodynamics (QED)
- Microwave domain: circuit QED
  superconducting qubits

Haroche & Raimond, Exploring the Quantum, Oxford Univ. Press (2006)

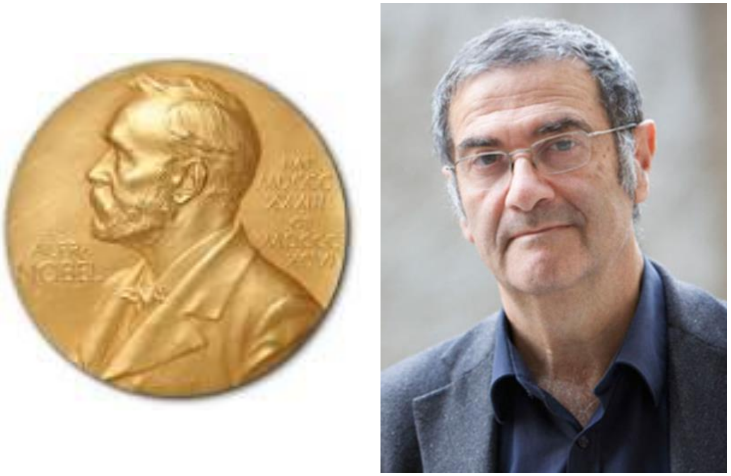
3. Cavity (=resonator)





M. Lee et al., Nat. Commun. 5, 3441 (2014)

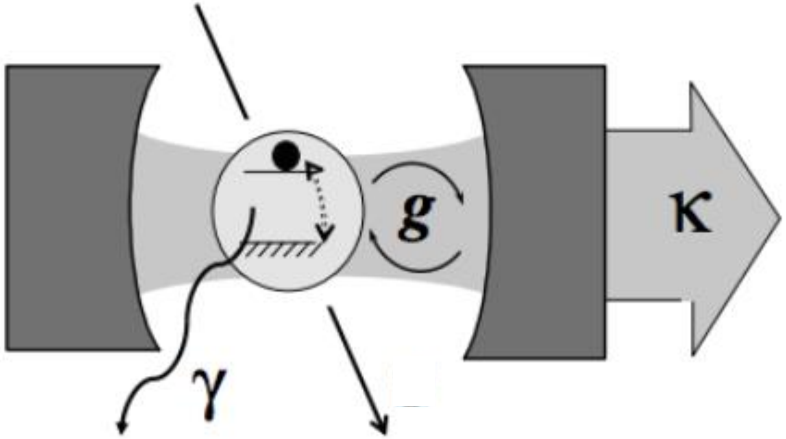
- Atom-photon interaction at the single photon level
-
- um
- Microwave domain: circuit QED **superconducting qubits**



Serge Haroche
Nobel Prize in Physics 2012

Haroche & Raimond, Exploring the Quantum, Oxford Univ. Press (2006)

Jaynes-Cummings Hamiltonian

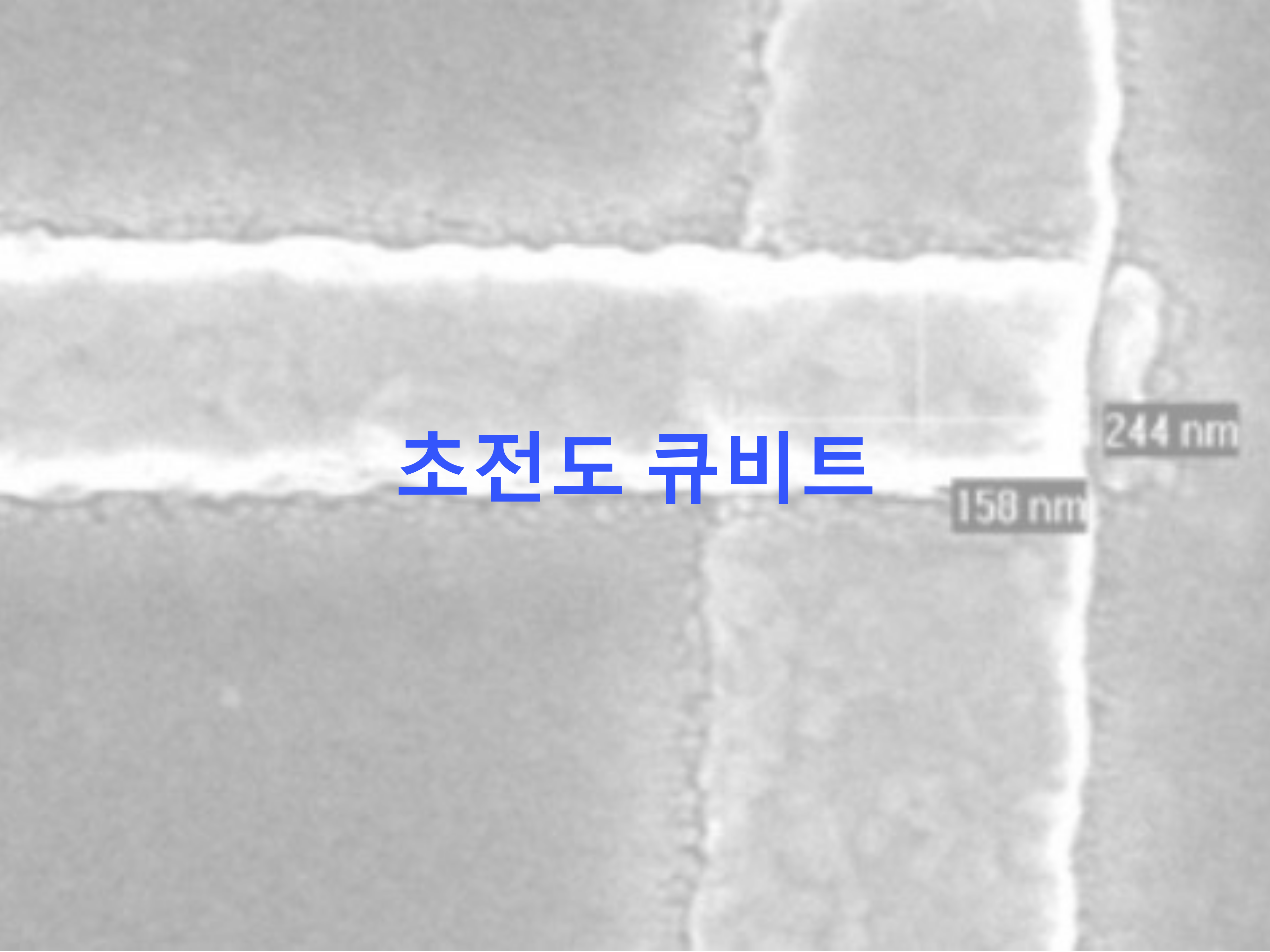


g: atom-photon coupling rate
γ: atomic decay rate
κ: cavity decay rate

$$H = \hbar\omega_c a^\dagger a + \frac{1}{2}\hbar\omega_a \sigma_z + \hbar g(a^\dagger \sigma_- + a\sigma_+)$$

Atom-cavity system / superconducting qubit-LC resonator system 모두 완벽하게 기술함

초전도 큐비트

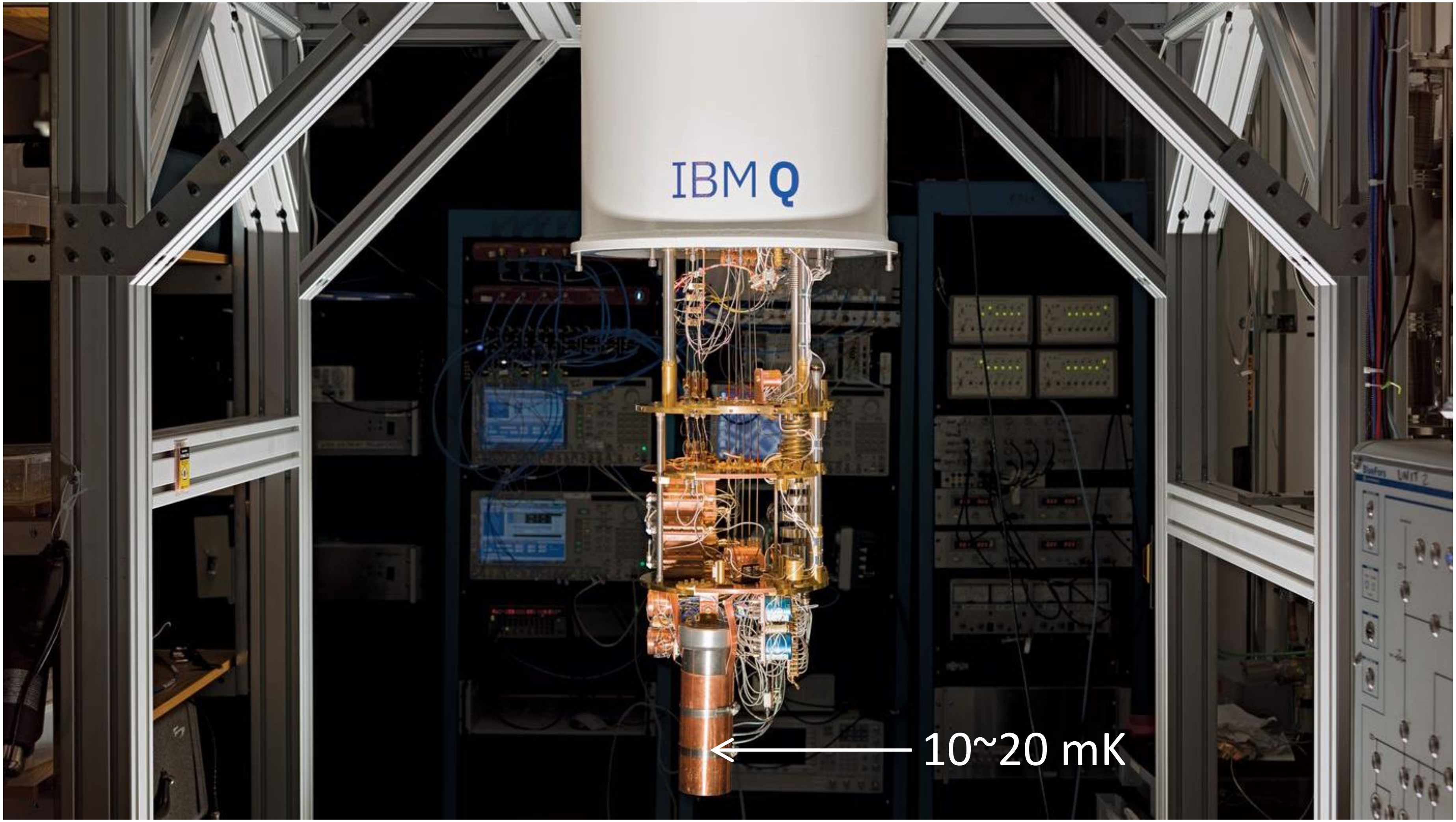


초전도 큐비트

Dilution refrigerator

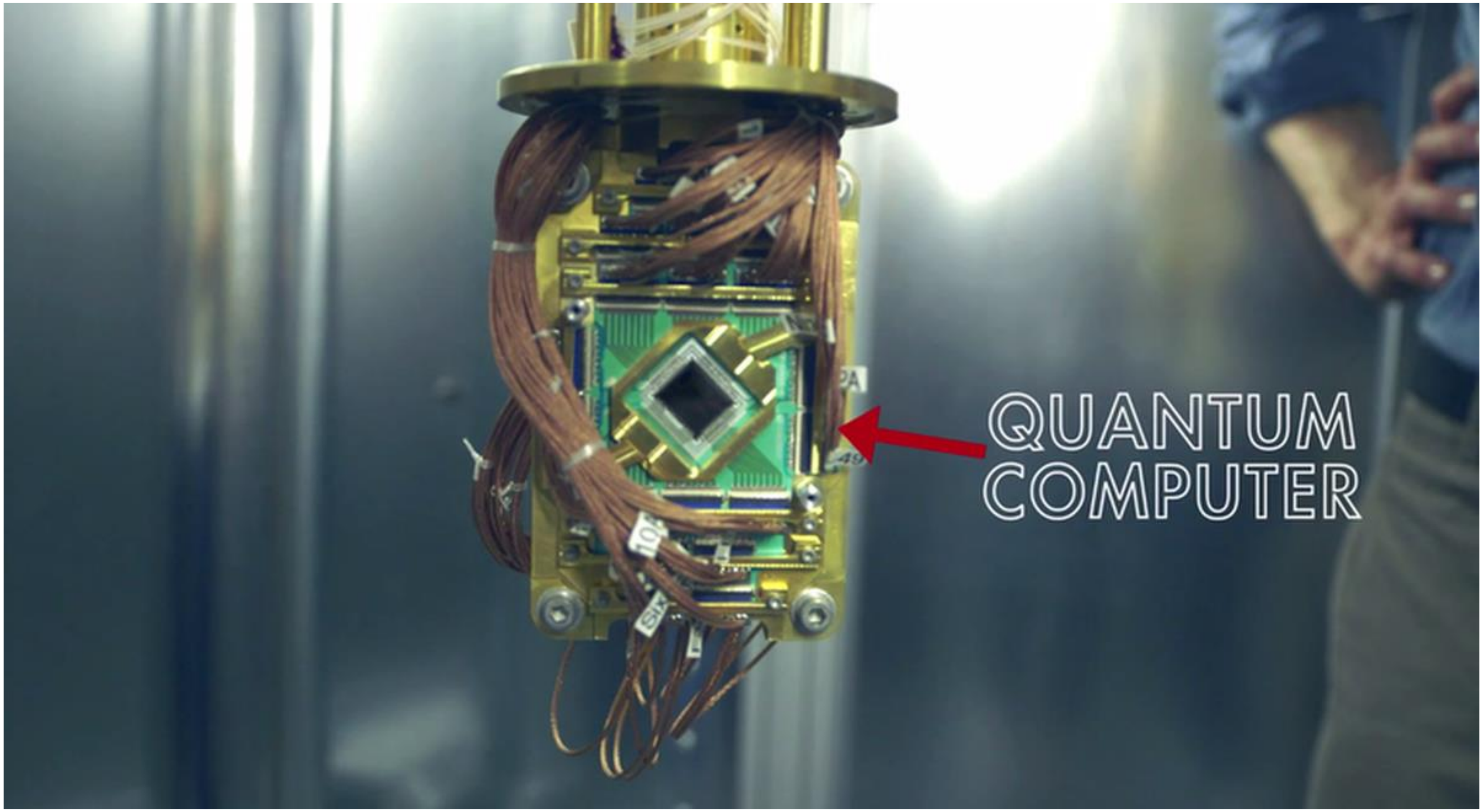
초전도 큐비트

초전도 큐비트

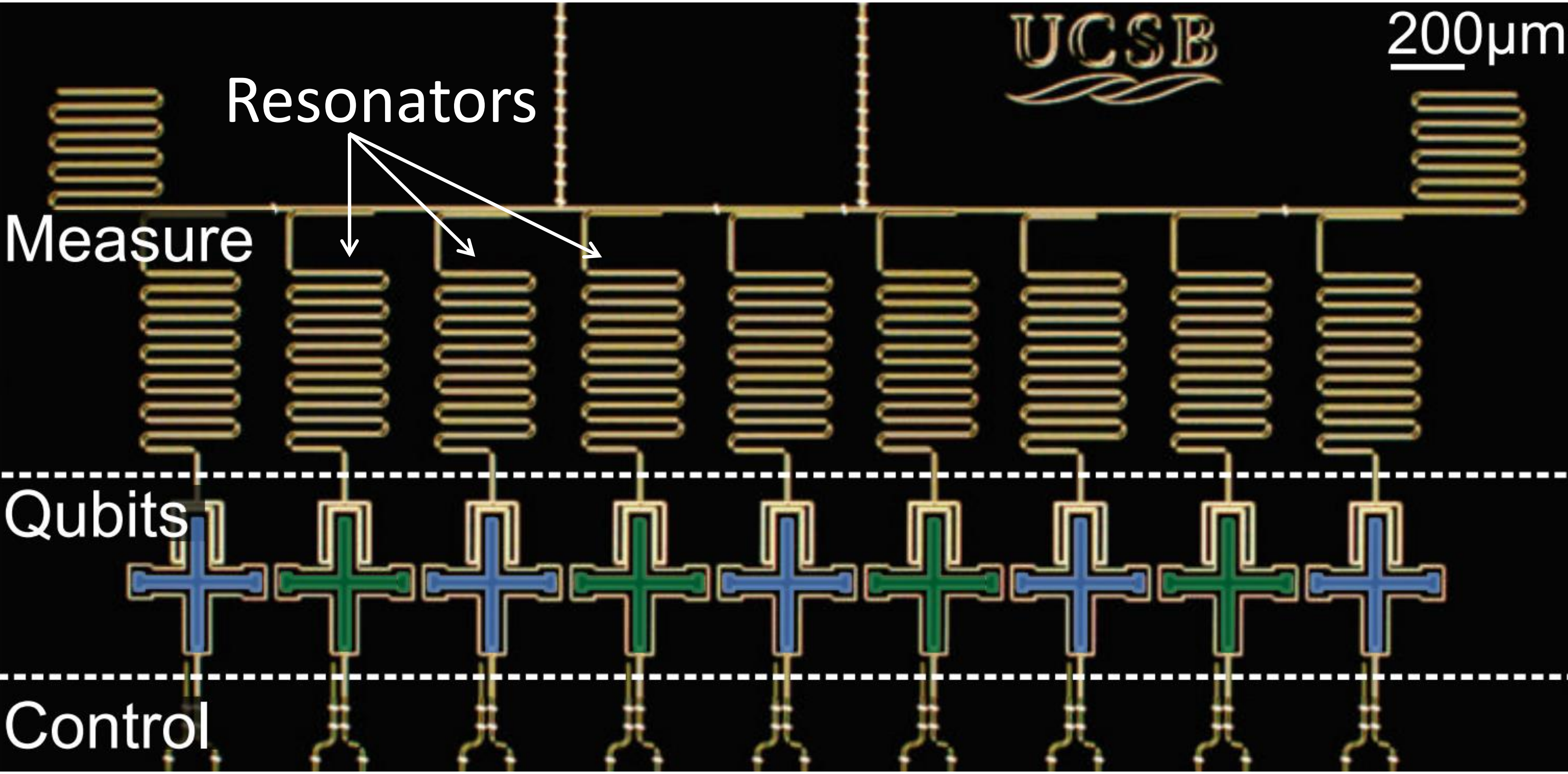


RF connections, circulators, cooling lines…

초전도 큐비트

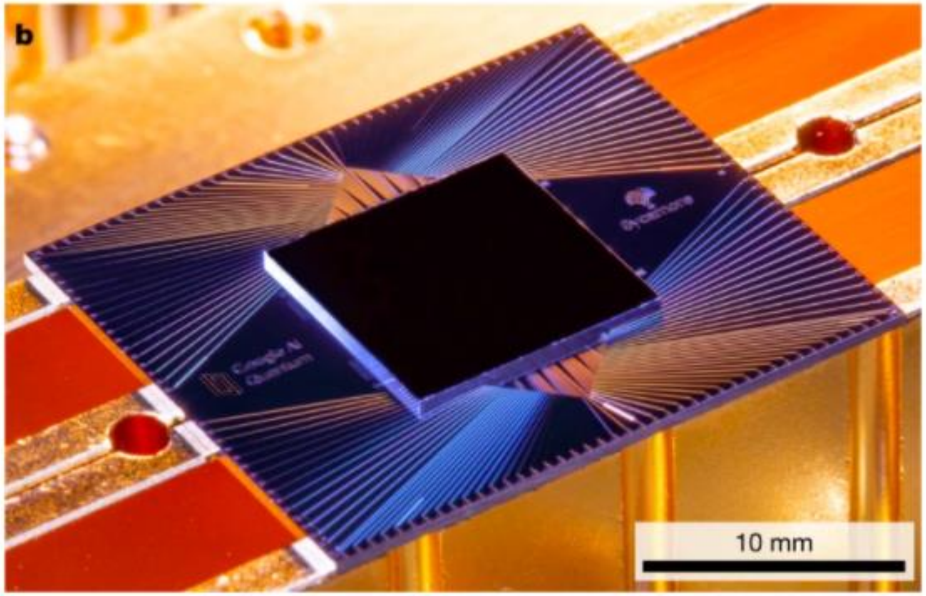


Superconducting-qubit-based quantum computer

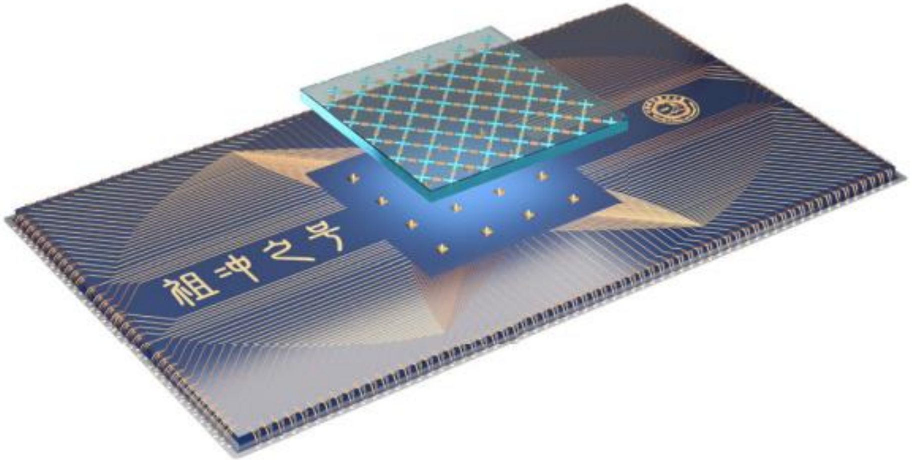


Quantum computer hardware = Connected atom-cavity systems

초전도 기반 양자컴퓨터 현황



미국 구글 양자컴퓨터 칩
`Sycamore(시카모어)’
53개 큐비트
2019년 10,000년 → 200초



중국 양자컴퓨터 칩
`주중츠’
66개 큐비트
슈퍼컴퓨터보다 1천만배 빠르게 계산

목차

- 양자컴퓨터 분야 동향 소개
- 이온 트랩 특징 및 소개
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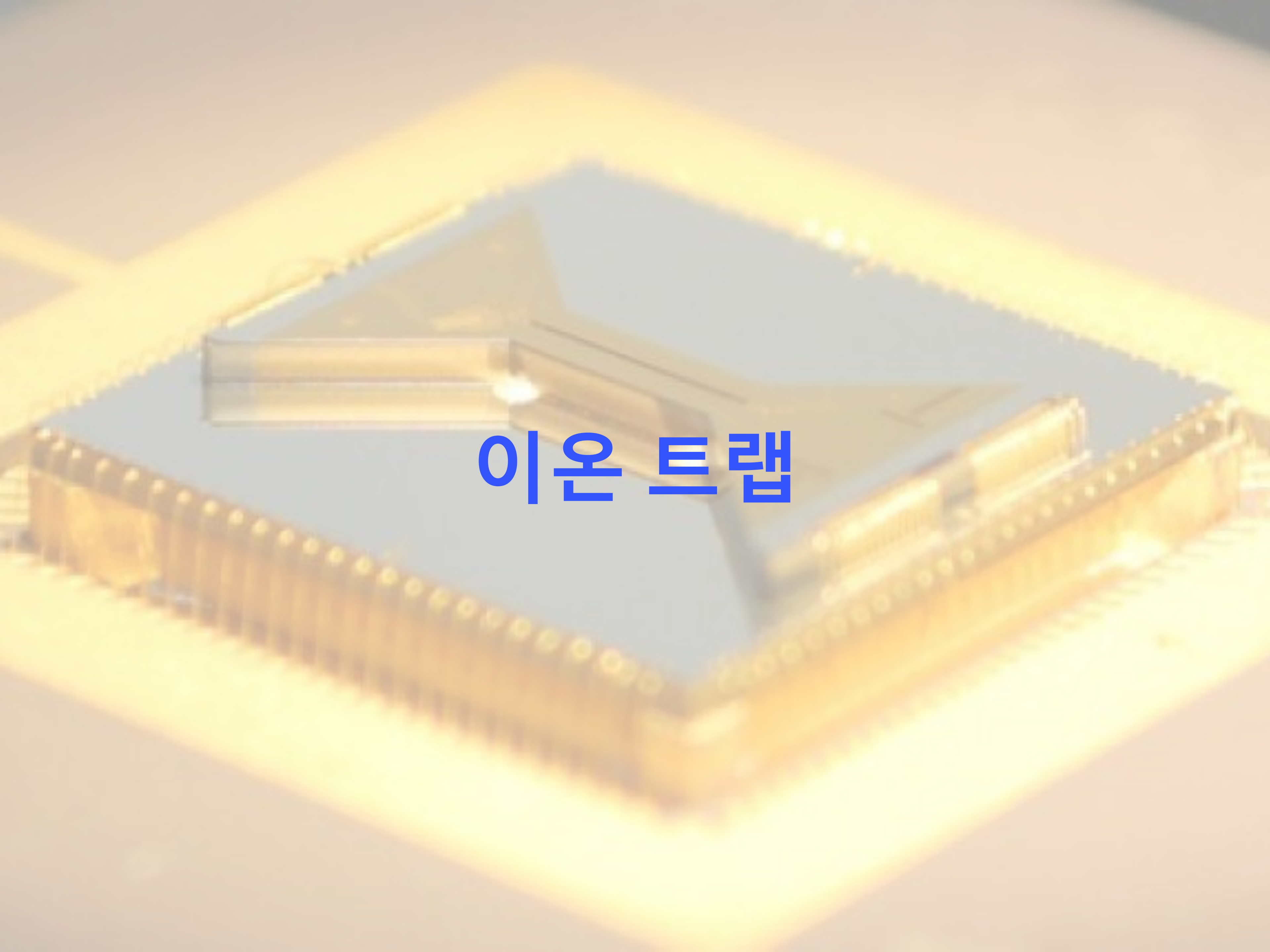
- 이온 얽힘 발생 소개
- 포항공대 이온 트랩 연구 소개



이온 트랩

Trapped ions: in principle

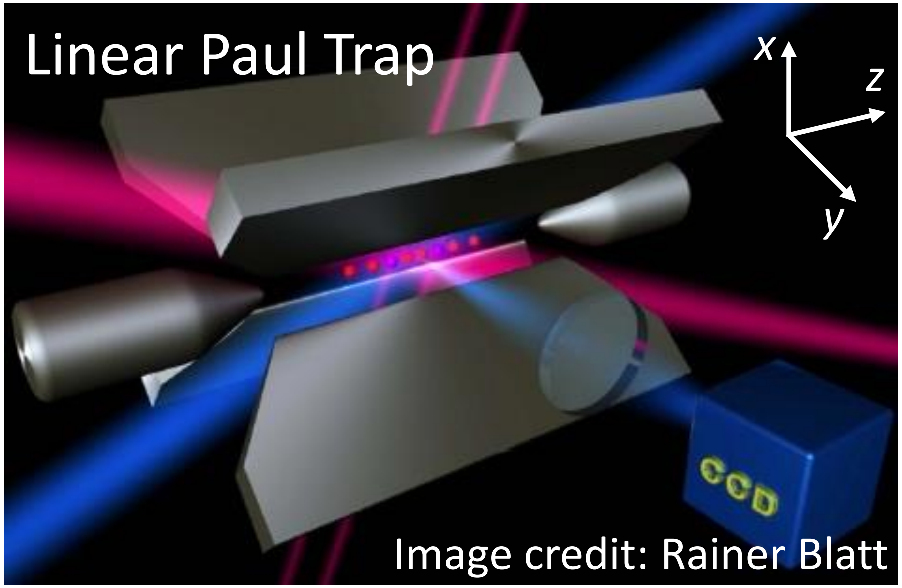
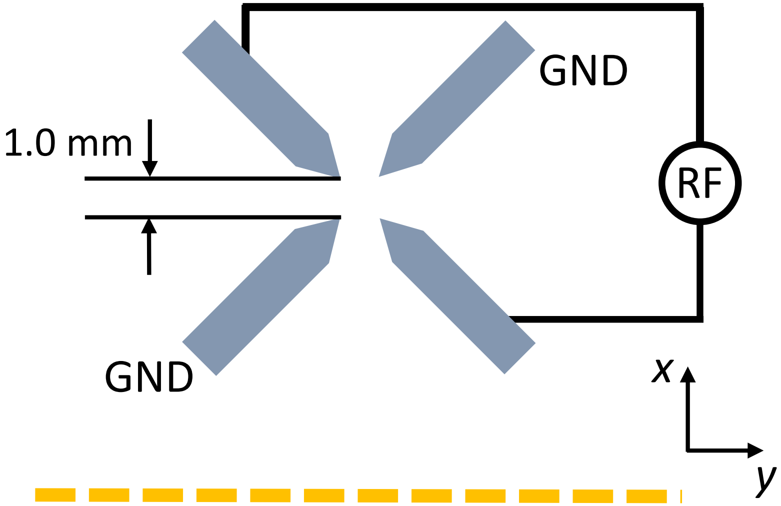
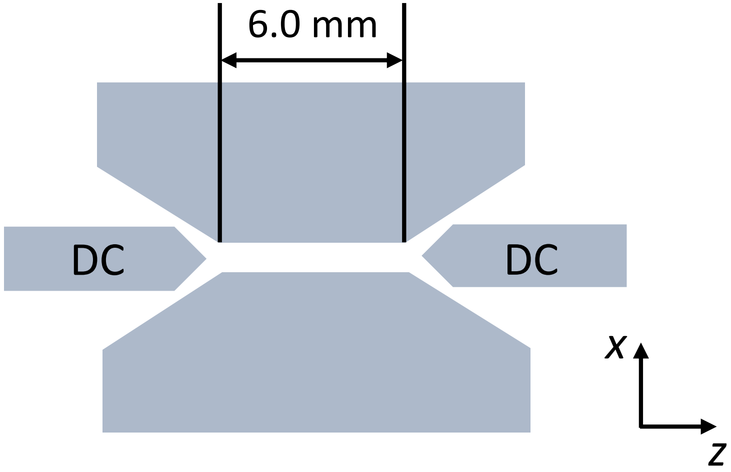
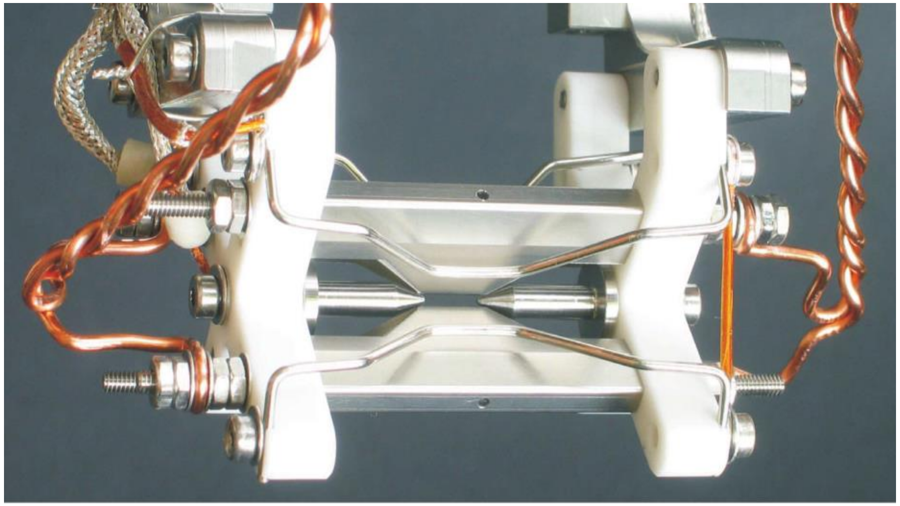


Image credit: Rainer Blatt



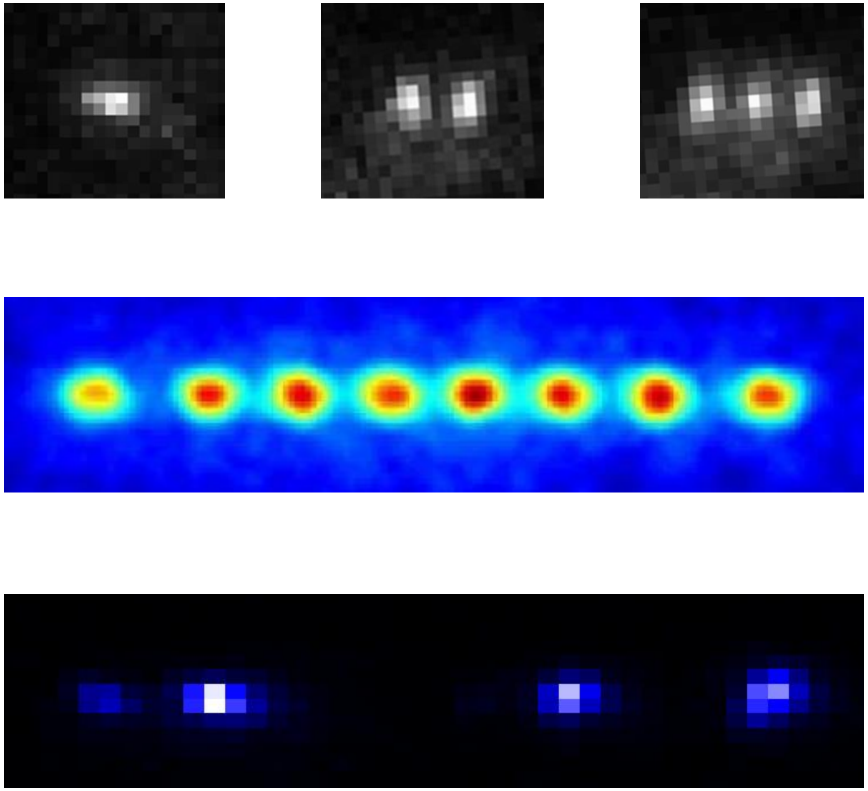




- *xy* directions : RF (20-30 MHz) & GND
- *z* direction: DC

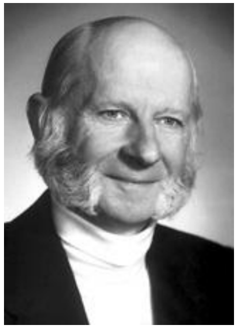
→ Create 3D potential energy

Trapped ions: in practice



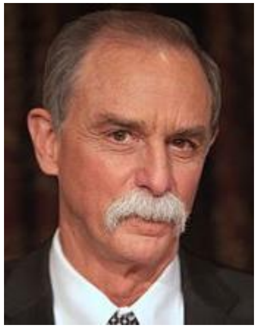
Nobel Prize in Physics 1989

W. Paul

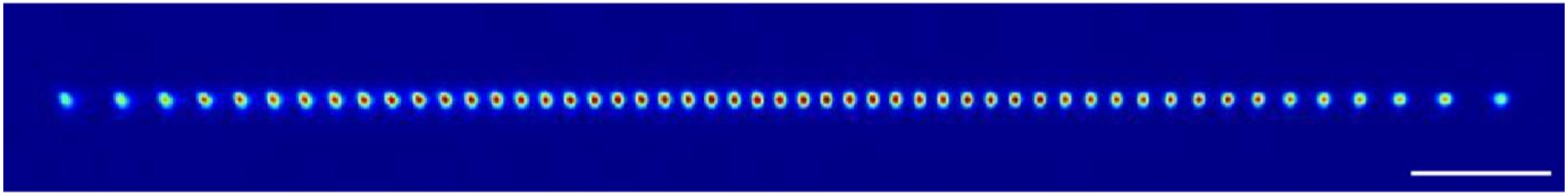


H. Dehmelt

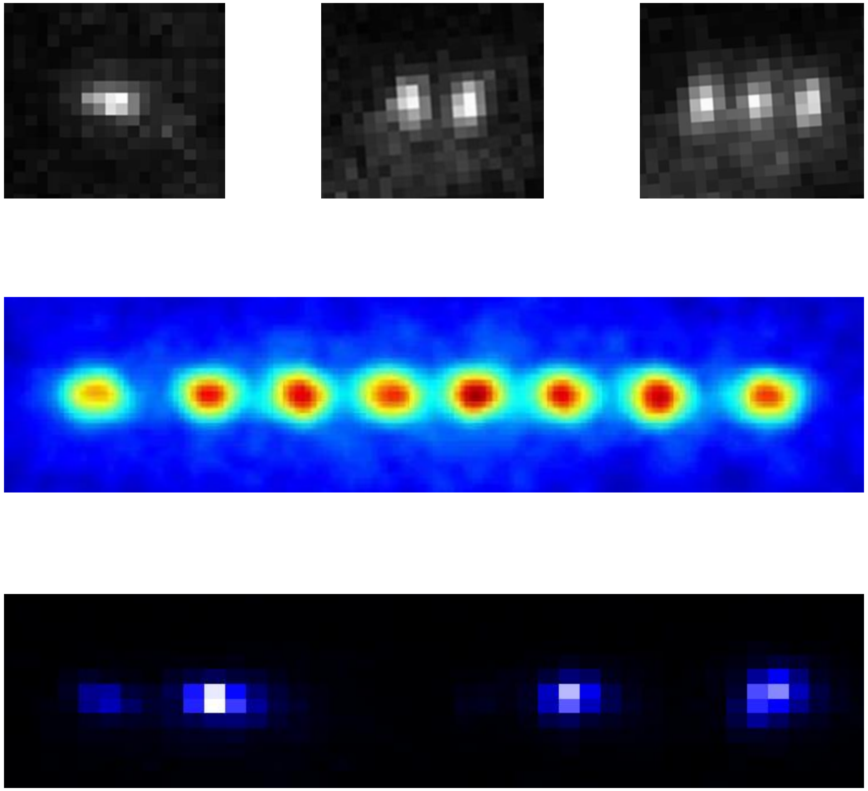
2012

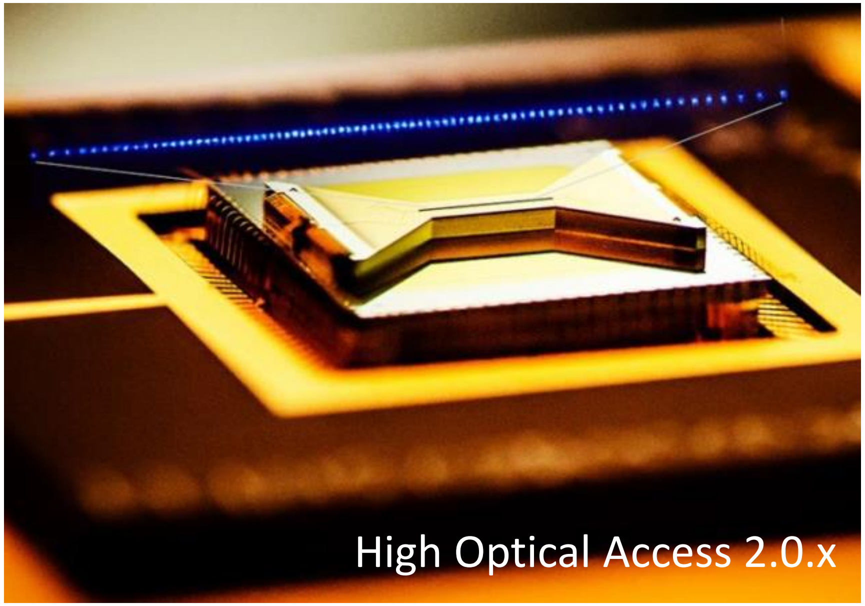


D. Wineland



Trapped ions: in practice





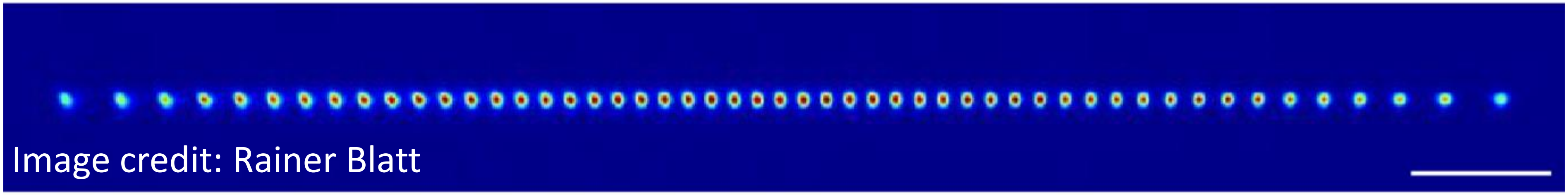


Image credit: Rainer Blatt

전 세계 이온 트랩 그룹

World map of ion trapping groups (updated August 04, 2020). https://quantumoptics.at/en/links/ion-trapping-worldwide.html

1	Argentina		Buenos Aires	University of Buenos Aires	Laboratory of Cold Ions and Atoms	Christian Schmiegelow
2	Australia	New South Wales	Sydney	University of Sydney	Quantum Control Laboratory	Mike Biercuk
3	Australia	Queensland	Brisbane	Griffith University	Ion-trap Quantum Computing Laboratory	Eric Streed, Mirko Lobino
4	Austria		Innsbruck	University of Innsbruck	Quantum Optics and Spectroscopy	Rainer Blatt
5	Austria		Innsbruck	University of Innsbruck	Quantum Interfaces Group	Tracy Northup
6	Austria		Innsbruck	[Company]	AQT	Thomas Monz
7	Canada	British Columbia	Burnaby	Simon Fraser University	Haljan Group	Paul Haljan
8	Canada	Ontario	Ottawa	NRC	Measurement science and standards	John Bernard, Alan Madej
9	Canada	Ontario	Waterloo	IQC, University of Waterloo	Quantum Information with Trapped Ions	K. Rajibul Islam
10	Canada	Ontario	Waterloo	IQC, University of Waterloo	Crystal Senko Group	Crystal Senko
11	China	Anhui	Hefei	University of Science and Technology of China	Key Laboratory of Quantum Information	Guang-Can Guo
12	China	Beijing	Beijing	Tsinghua University	Center for Quantum Information	Kihwan Kim
13	China	Beijing	Beijing	Tsinghua University	Center for Quantum Information	Luming Duan
14	China	Beijing	Beijing	Tsinghua University	Joint institute for Measurement Science	Li-Jun Wang
15	China	Hubei	Wuhan	Huazhong University of Science and Technology	MOE Key Laboratory	Ze-Huang Lu
16	China	Hubei	Wuhan	Wuhan Institute of Physics and Mathematics	Ion Optical Frequency Standard	Xue-Ren Huang
17	China	Hubei	Wuhan	Wuhan Institute of Physics and Mathematics	Mercury Ion Microwave Frequency Standard	Jiaomei Li
18	China	Hubei	Wuhan	Wuhan Institute of Physics and Mathematics	Quantum Information and Trapped Ion Physics	Mang Feng
19	China	Hubei	Wuhan	Wuhan Institute of Physics and Mathematics	Trapping of Cold Ions	Ke-Lin Gao
20	China	Hunan	Changsha	National University of Defense Technology	Department of Physics	Pingxing Chen
21	Czech Republic		Olomouc & Brno	Palacký University & ISI	Quantum Optics Lab	Radim Filip, Lukáš Slodička
22	Denmark		Aarhus	Aarhus University	Ion Trap Group	Michael Drewsen
23	Finland		Helsinki	Aalto University	MIKES Time and Frequency Group	Mikko Merimaa
24	France		Besançon	FEMTO-ST	Compact Optical Atomic Clock	Clément Lacroûte
25	France		Marseille	Aix-Marseille University	Ion Trapping and Laser Manipulation Group	Martina Knoop, Caroline Champenoi
26	France		Paris	LKB	Trapped Ions Group	Laurent Hilico
27	France		Paris	Université Paris Diderot	Trapped Ions and Quantum Information	Luca Guidoni, Samuel Guibal
28	Germany		Bonn	University of Bonn	Experimental Quantum Physics	Michael Köhl
29	Germany		Braunschweig	PTB	Quantum Logic Spectroscopy Group	Piet Schmidt
30	Germany		Braunschweig	PTB	Multi-Ion Clocks	Tanja Mehlstäubler
31	Germany		Braunschweig	PTB	Trapped-Ion Quantum Engineering	Christian Ospelkaus
32	Germany		Braunschweig	PTB	Optical Clocks with Trapped Ions	Ekkehard Peik
33	Germany		Düsseldorf	University of Düsseldorf	Quantum Optics and Relativity	Stephan Schiller
34	Germany		Erlangen	MPI for the Science of Light	Leuchs Division	Gerd Leuchs
35	Germany		Freiburg	University of Freiburg	Schaetz Division	Tobias Schaetz
36	Germany		Garching	MPQ	Trapped Ions Group	Thomas Udem, Ted Hänsch
37	Germany		Hannover	Leibniz University	Trapped-Ion Quantum Engineering	Christian Ospelkaus
38	Germany		Heidelberg	MPI für Kernphysik	Highly Charged Ion Dynamics	José Ramon Crespo López-Urrutia
39	Germany		Kassel	University of Kassel	Light-matter interaction	Kilian Singer
40	Germany		Mainz	Mainz University	Cold Ions and Experimental Quantum Information	Ferdinand Schmidt-Kaler
41	Germany		Saarbrücken	Saarland University	Quantum Photonics Group	Jürgen Eschner
42	Germany		Siegen	University of Siegen	Quantum Optics Research Group	Christof Wunderlich
43	Germany		Ulm	Ulm University	Institute of Quantum Matter	Johannes Hecker Denschlag
44	India		Bangalore	Raman Research Institute	Quantum Interactions	Sadiq Rangwala
45	Israel		Rehovot	Weizmann Institute	Trapped-Ions Lab	Roee Ozeri
46	Israel		Rehovot	Weizmann Institute	Molecular Physics Group	Daniel Zajfman
47	Japan		Kobe	NICT	Quantum ICT Laboratory	Kazuhiro Hayasaka
48	Japan		Kyoto	Kyoto University	Quantum Optical Engineering	Masao Kitano
49	Japan		Osaka	Osaka University	Mukaiyama Laboratory	Takashi Mukaiyama
50	Japan		Tokyo	University of Tokyo	Hasegawa Laboratory	Shuichi Hasegawa
51	Netherlands		Amsterdam	University of Amsterdam	Hybrid atom-ion Quantum Systems	Rene Gerritsma
52	Netherlands		Amsterdam	VU Amsterdam	HD+ spectroscopy team	Jeroen Koelemeij

	Country	State	City	Institution	Group	Head
53	Netherlands		Amsterdam	VU Amsterdam	Ultrafast Laser Physics and Precision Metrology Group	Kjeld Eikema
54	Netherlands		Groningen	University of Groningen	Research Group Ions	Klaus Jungmann
55	Singapore		Singapore	CQT	Microtraps Group	Murray Barrett
56	Singapore		Singapore	CQT	Trapped molecular ions	Dzmitry Matsukevich
57	Singapore		Singapore	CQT	Cold Ion Group	Manas Mukherjee
58	South Africa		Stellenbosch	Stellenbosch University	Trapped Ion Quantum Control	Hermann Uys
59	South Korea		Pohang	Pohang University of Science and Technology	Quantum Computing and Quantum Network	Moonjoo Lee
60	South Korea		Seoul	Seoul National University	Nano/Micro system & controls Lab	Dan Cho
61	South Korea		Seoul	Seoul National University	Quantum Information and Quantum Computing Lab	Taehyun Kim
62	Spain		Granada	Universidad de Granada	Molecules Atoms Ions Nuclei	Daniel Rodríguez
63	Sweden		Stockholm	Stockholm University	Trapped Ion Quantum Technologies	Markus Hennrich
64	Switzerland		Basel	University of Basel	Willitsch Group	Stefan Willitsch
65	Switzerland		Zurich	ETH	Trapped Ion Quantum Information	Jonathan Home
66	United Kingdom		Brighton	University of Sussex	Ion Quantum Technology Group	Winni Hensinger
67	United Kingdom		Brighton	University of Sussex	ITCM Group	Matthias Keller
68	United Kingdom		London	Imperial College	Ion Trapping Group	Richard Thompson
69	United Kingdom		Oxford	University of Oxford	Ion Trap Quantum Computing Group	David Lucas, Andrew Steane
70	United Kingdom		Oxford	University of Oxford	Softley Research Group	Tim Softley
71	United Kingdom		Teddington	NPL	Strontium Ion Optical Frequency Standard	Alastair Sinclair, Patrick Gill
72	United Kingdom		Teddington	NPL	Ytterbium Ion Optical Frequency Standard	Rachel Godun
73	USA	California	Berkeley	UC Berkeley	Ion Trap Group	Hartmut Häffner
74	USA	California	Los Angeles	UCLA	Hudson Lab	Eric Hudson
75	USA	California	Los Angeles	UCLA	Campbell Lab	Wes Campbell
76	USA	Colorado	Boulder	NIST	Ion Storage Group	John Bollinger
77	USA	Colorado	Broomfield	[Company]	Honeywell Quantum Solutions	Tony Uttley
78	USA	Connecticut	Storrs	University of Connecticut	Atomic and Molecular Spectroscopy Group	Winthrop Smith
79	USA	Georgia	Atlanta	Georgia Tech	Chapman Research Lab	Michael Chapman
80	USA	Georgia	Atlanta	GTRI	Quantum Systems group	Alexa Harter
81	USA	Illinois	Evanston	Northwestern University	Molecular Ion and Atom Trapping Group	Brian Odom
82	USA	Indiana	Bloomington	Indiana University	Richerme Lab	Phil Richerme
83	USA	Maryland	UMD College Park	JQI (UMD / NIST)	Trapped Ion Quantum Information	Chris Monroe
84	USA	Maryland	UMD College Park	JQI (UMD / NIST)	Linke Lab	Norbert Linke
85	USA	Maryland	UMD College Park	Army Research Lab, JQI	Quraishi Group	Qudsia Quraishi
86	USA	Maryland	UMD College Park	Army Research Lab, JQI	Trapped Ion Lab	Joe Britton
87	USA	Maryland	UMD College Park	[Company]	IonQ	Peter Chapman, Jungsang Kim, Chris Monroe
88	USA	Massachusetts	Amherst	Amherst College	Hanneke Ion Trap Lab	David Hanneke
89	USA	Massachusetts	Cambridge	MIT Center for Ultracold Atoms	Experimental Atomic Physics Group	Vladan Vuletic
90	USA	Massachusetts	Cambridge	MIT Center for Ultracold Atoms	Quanta Group	Ike Chuang
91	USA	Massachusetts	Lexington	MIT Lincoln Laboratory	Lincoln Laboratory	John Chiaverini
92	USA	Massachusetts	Williamstown	Williams College	Doret Group	Charlie Doret
93	USA	New Mexico	Albuquerque	Sandia National Labs	Microsystems Engineering, Science and Applications (MESA)	Dan Stick, Peter Maunz, Matt Blain
94	USA	North Carolina	Durham	Duke University	Brown Lab	Kenneth Brown
95	USA	North Carolina	Durham	Duke University	MIST Group	Jungsang Kim
96	USA	Ohio	Granville	Denison University	Ion Quantum Optics	Steven Olmschenk
97	USA	Oregon	Eugene	University of Oregon	Oregon Ions	David Allcock, Dave Wineland
98	USA	Vermont	Middlebury	Middlebury College	Ion Trapping Lab	Paul Hess
99	USA	Washington	Seattle	University of Washington	Trapped Ion Quantum Computing	Boris Blinov

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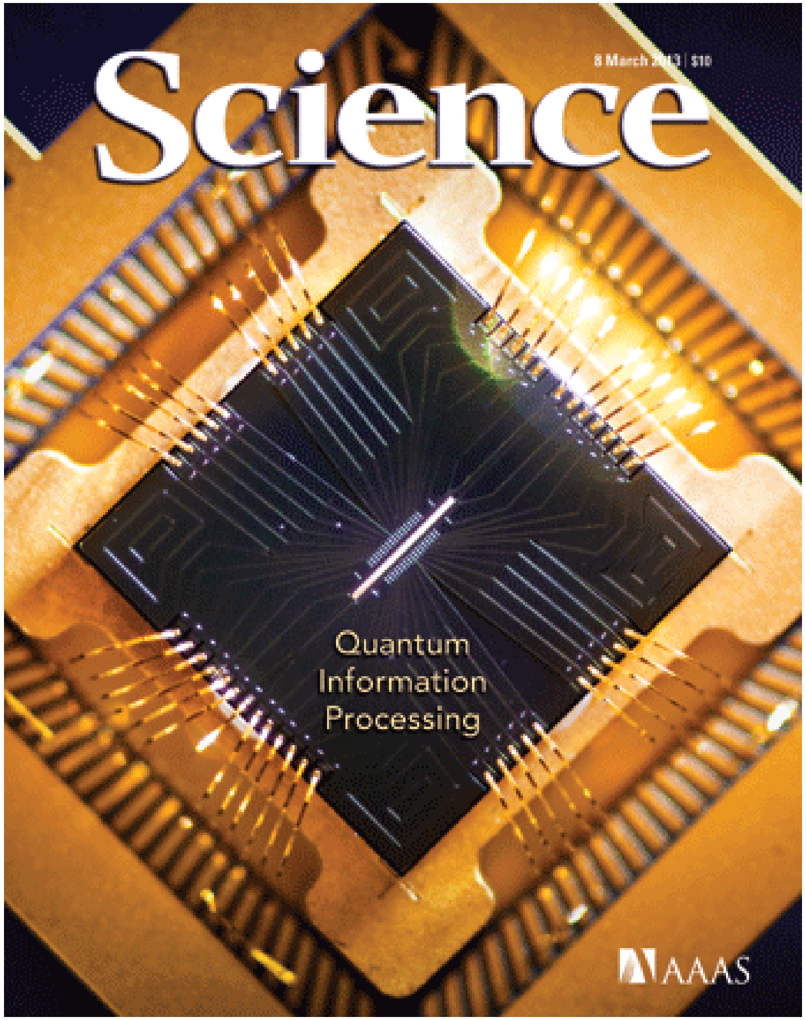
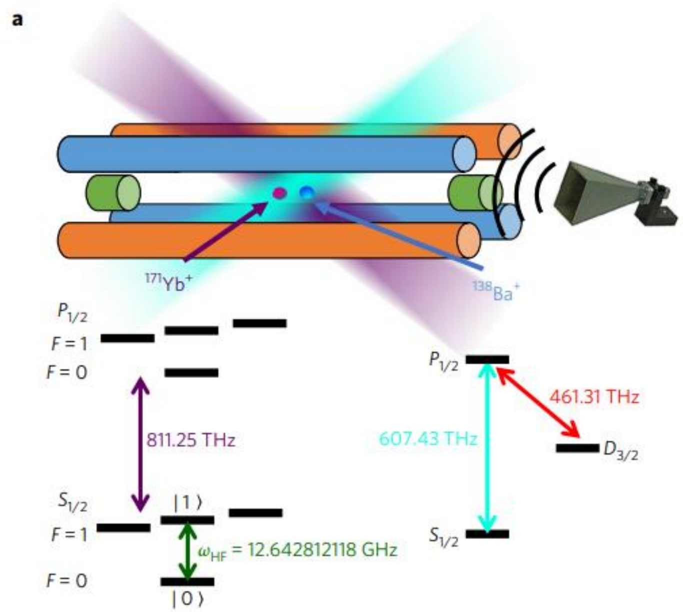


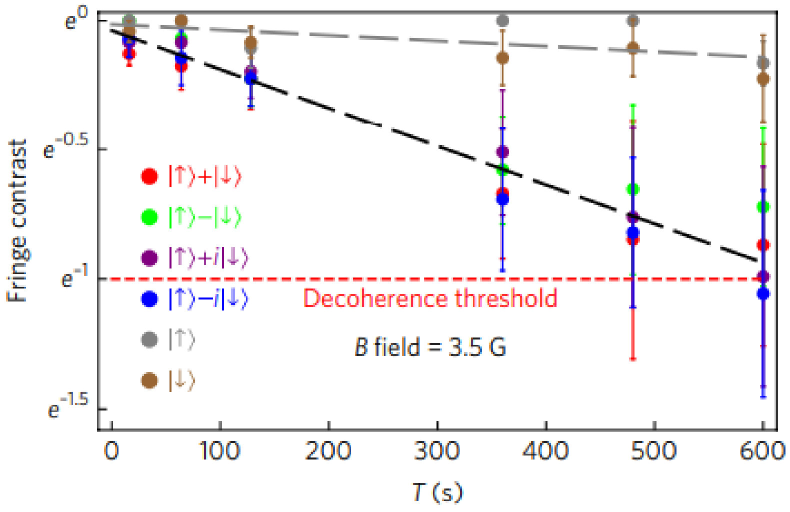
Monroe & Kim, Science (2013)

LETTERS
DOI: 10.1038/s41566-017-0007-1
nature photonics
Corrected: Author correction

Single-qubit quantum memory exceeding ten-minute coherence time

Ye Wang[1], Mark Um[1], Junhua Zhang[1], Shuoming An[1], Ming Lyu[1,3], Jing-Ning Zhang[1], L.-M. Duan[1,2], Dahyun Yum[1*] and Kihwan Kim[1*]





2017년 발표
^{138}Ba$^+$을 이용한 Sympathetic cooling

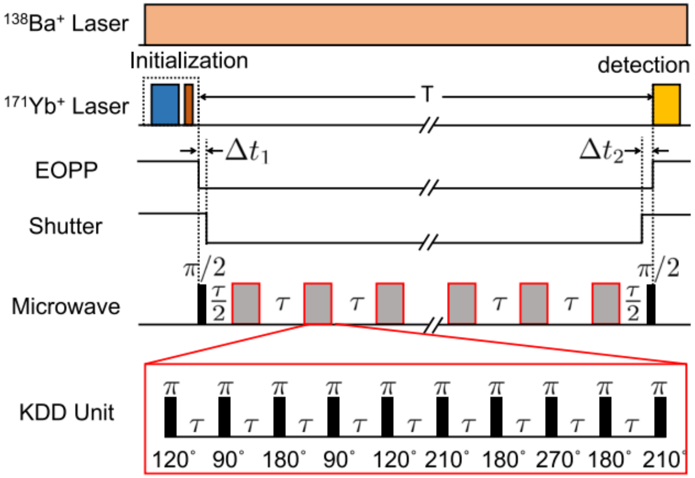
nature COMMUNICATIONS

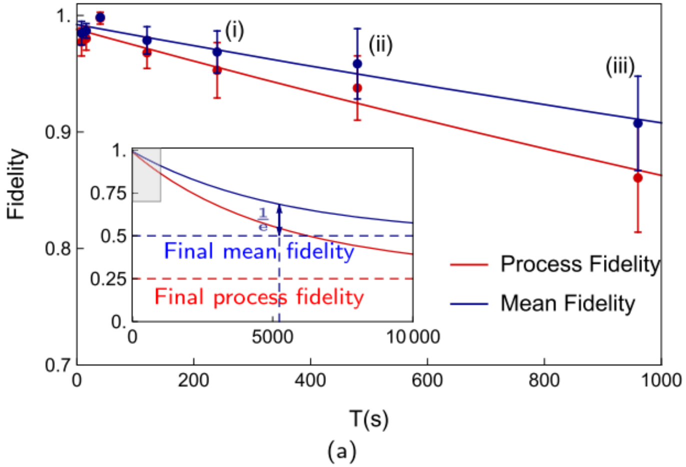
ARTICLE

https://doi.org/10.1038/s41467-020-20330-w OPEN

Single ion qubit with estimated coherence time exceeding one hour

Pengfei Wang [1]✉, Chun-Yang Luan [1], Mu Qiao[1], Mark Um[1], Junhua Zhang[1,2], Ye Wang [1,3], Xiao Yuan [4,5], Mile Gu[6,7,8], Jingning Zhang [9] & Kihwan Kim [1]✉

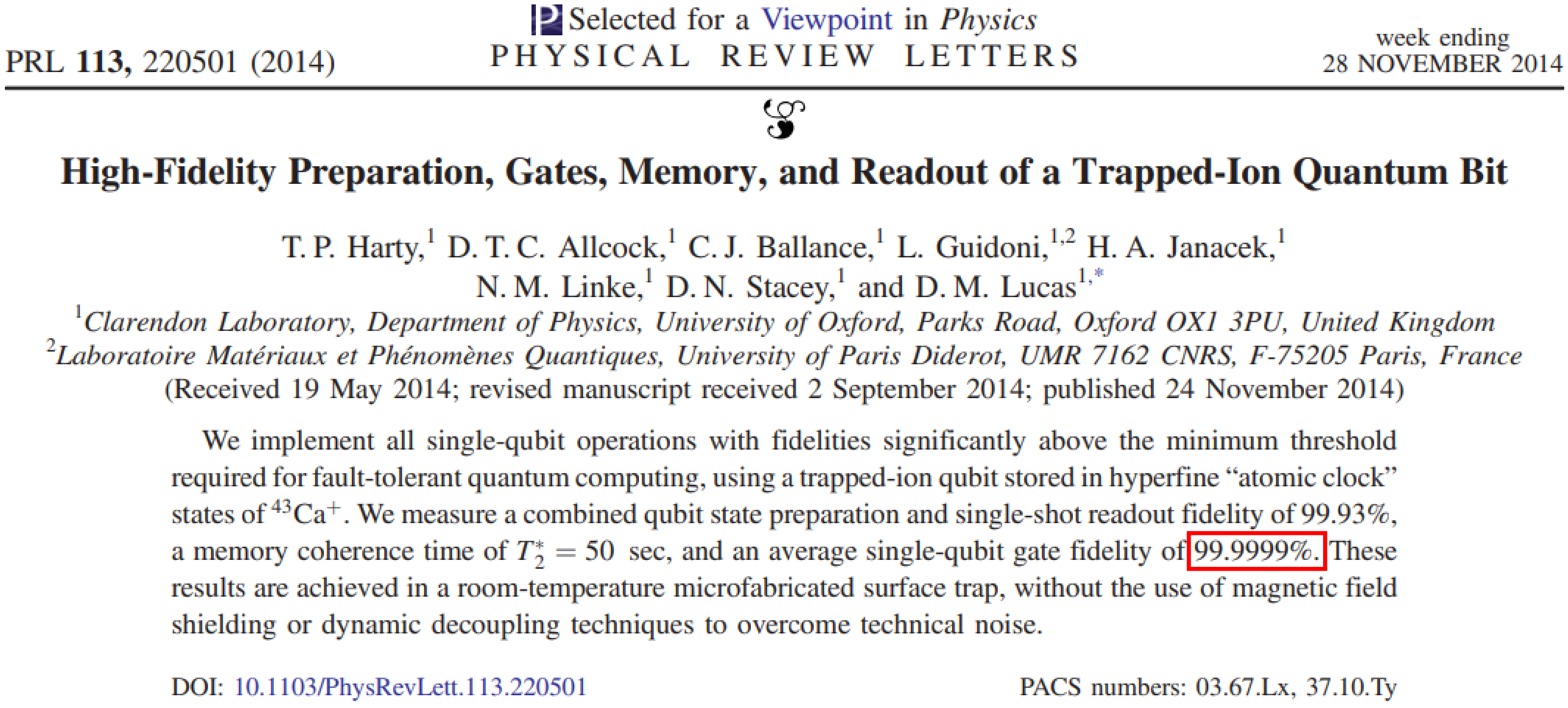




(a)

2021년 발표
자기장 stray field등 기타 noise source 차폐

Single-qubit gate fidelity record: 99.9999%



Selected for a Viewpoint in *Physics*
PRL **113,** 220501 (2014) PHYSICAL REVIEW LETTERS week ending 28 NOVEMBER 2014

High-Fidelity Preparation, Gates, Memory, and Readout of a Trapped-Ion Quantum Bit

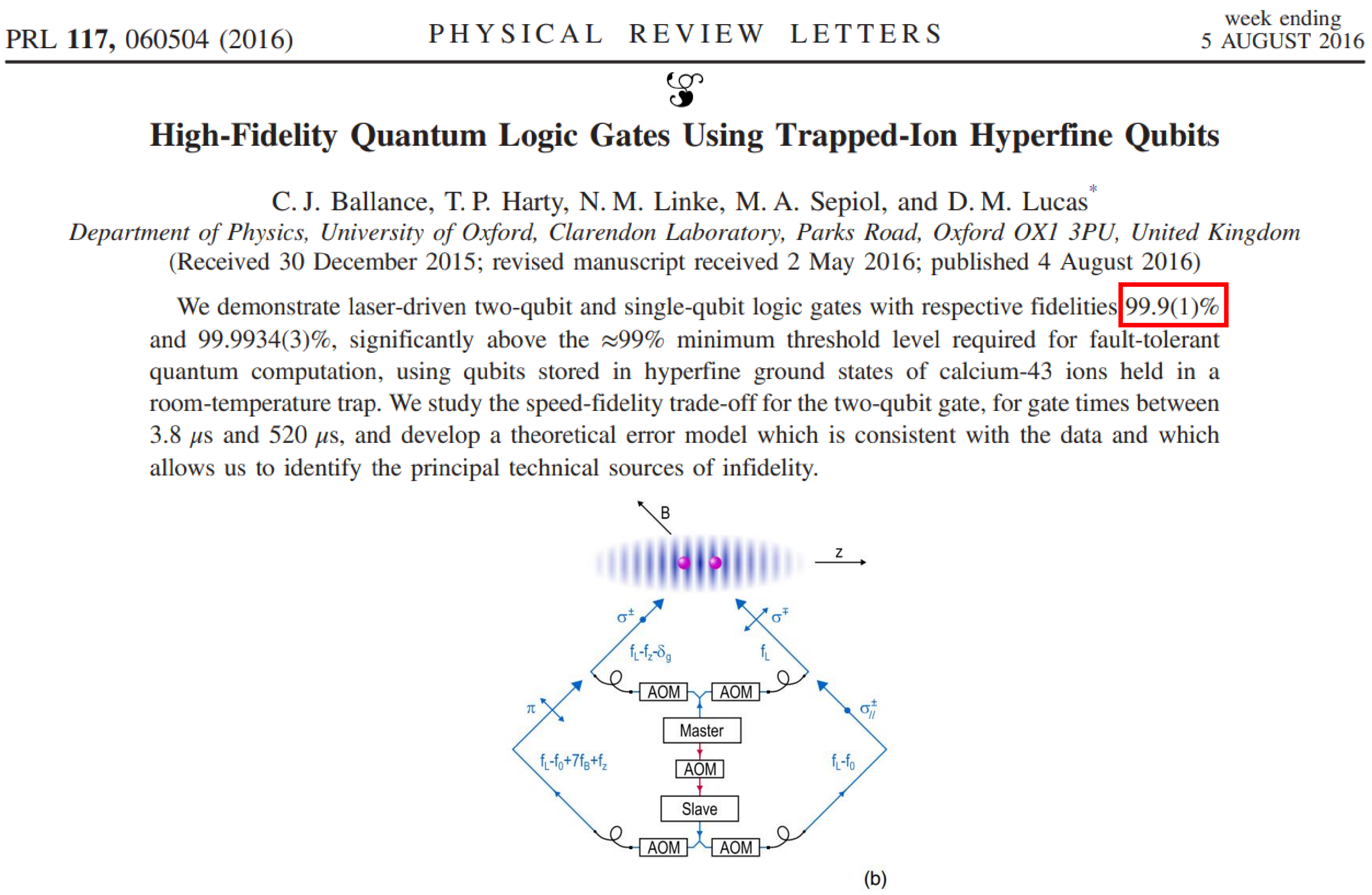
T. P. Harty,[1] D. T. C. Allcock,[1] C. J. Ballance,[1] L. Guidoni,[1,2] H. A. Janacek,[1]
N. M. Linke,[1] D. N. Stacey,[1] and D. M. Lucas[1,*]
[1]*Clarendon Laboratory, Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom*
[2]*Laboratoire Matériaux et Phénomènes Quantiques, University of Paris Diderot, UMR 7162 CNRS, F-75205 Paris, France*

(Received 19 May 2014; revised manuscript received 2 September 2014; published 24 November 2014)

We implement all single-qubit operations with fidelities significantly above the minimum threshold required for fault-tolerant quantum computing, using a trapped-ion qubit stored in hyperfine "atomic clock" states of $^{43}\mathrm{Ca}^+$. We measure a combined qubit state preparation and single-shot readout fidelity of 99.93%, a memory coherence time of $T_2^* = 50$ sec, and an average single-qubit gate fidelity of 99.9999%. These results are achieved in a room-temperature microfabricated surface trap, without the use of magnetic field shielding or dynamic decoupling techniques to overcome technical noise.

DOI: 10.1103/PhysRevLett.113.220501 PACS numbers: 03.67.Lx, 37.10.Ty

Two-qubit gate fidelity record: 99.9999%



PRL **117,** 060504 (2016) PHYSICAL REVIEW LETTERS week ending
5 AUGUST 2016

High-Fidelity Quantum Logic Gates Using Trapped-Ion Hyperfine Qubits

C. J. Ballance, T. P. Harty, N. M. Linke, M. A. Sepiol, and D. M. Lucas[*]
Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, United Kingdom

(Received 30 December 2015; revised manuscript received 2 May 2016; published 4 August 2016)

We demonstrate laser-driven two-qubit and single-qubit logic gates with respective fidelities 99.9(1)% and 99.9934(3)%, significantly above the ≈99% minimum threshold level required for fault-tolerant quantum computation, using qubits stored in hyperfine ground states of calcium-43 ions held in a room-temperature trap. We study the speed-fidelity trade-off for the two-qubit gate, for gate times between 3.8 μs and 520 μs, and develop a theoretical error model which is consistent with the data and which allows us to identify the principal technical sources of infidelity.

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days to weeks

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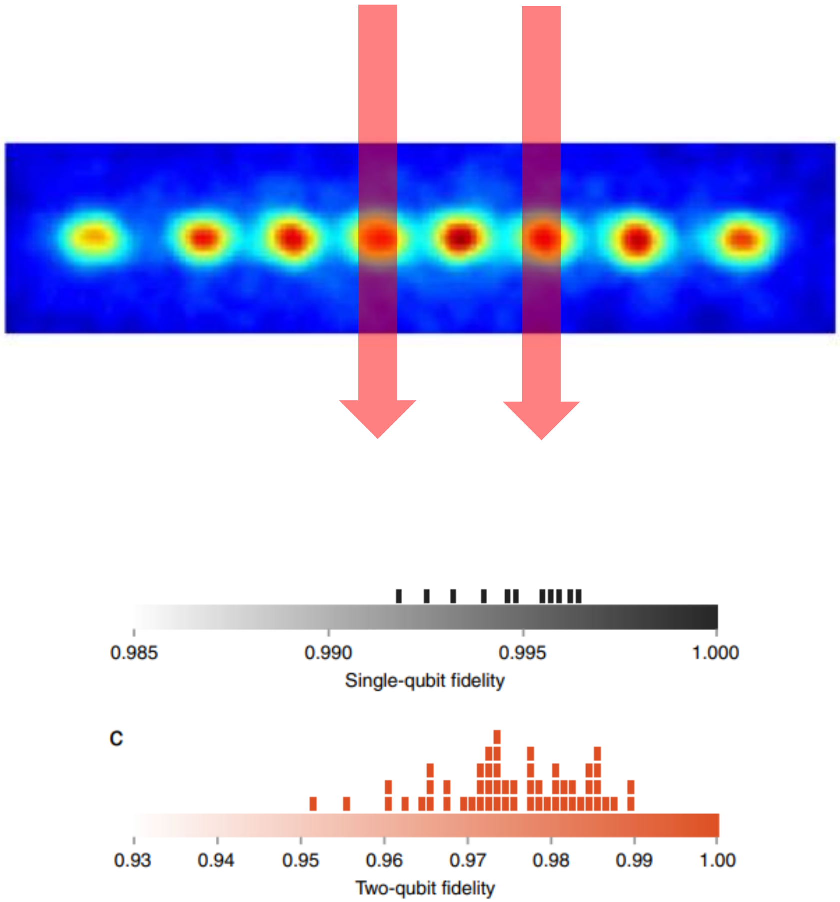

<u>Full connectivity!</u>
Wright et al., Nat. Commun. (2019)

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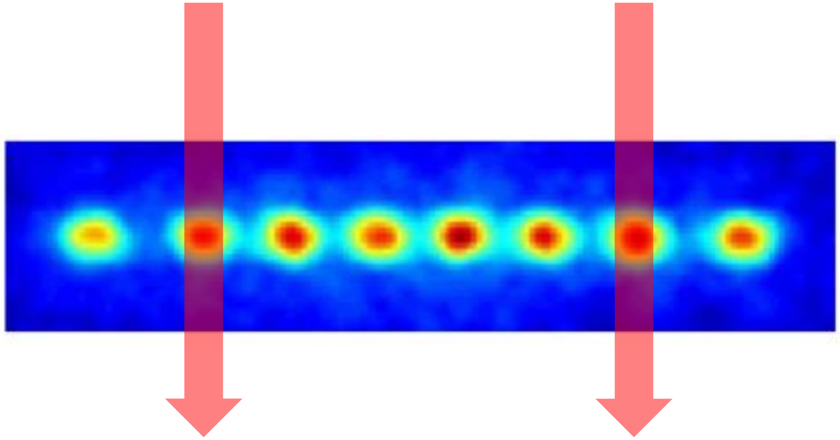

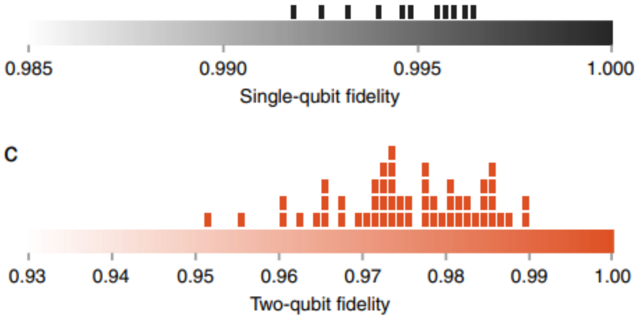

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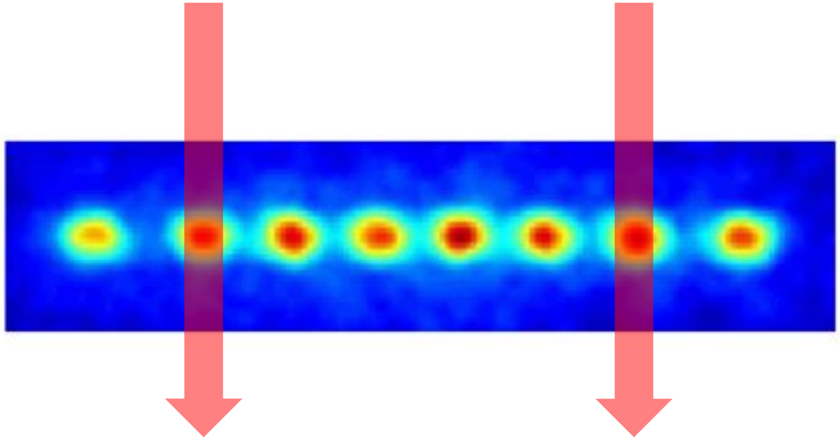
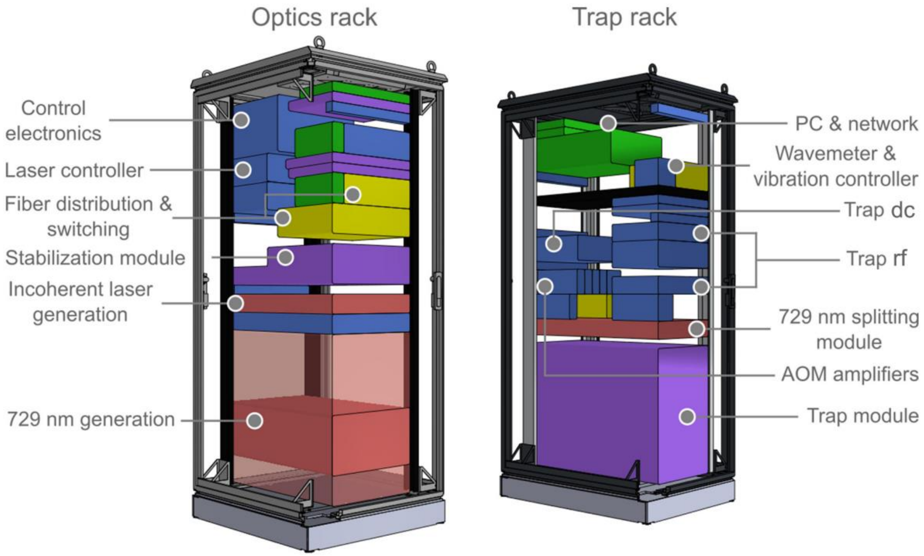
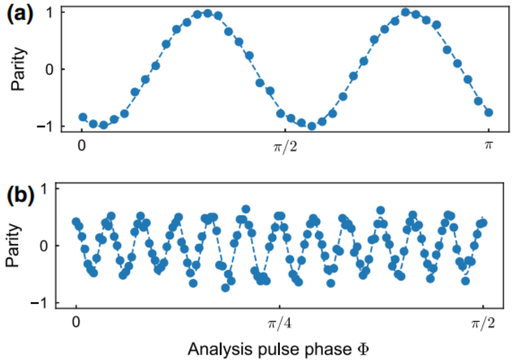


이온트랩 양자컴퓨터 현재 성능
포획: 100~150개 까지 가능
Two-qubit gate: 15개 정도 ion chain에서 fidelity 약 99%

Full connectivity!
Wright et al., Nat. Commun. (2019)

Ion trap in two racks





Entanglement of 24 ions, GHZ state

Pogorelov et al., PRX Quantum 2, 020343 (2021)

Trapped ions at Wall Street

Opening bell ceremony
at New York Stock Exchange

주식 시장 요약 > IONQ Inc

12.28 USD

+1.76 (16.73%) ↑ 오늘

폐장: 10월 27일 오후 7:55 GMT-4 · 면책조항

폐장 후 12.43 +0.15 (1.22%)

NYSE: IONQ

시가	10.45	시가총액	23.64억	52-주 최고	15.39
최고	12.85	주가수익률	-	52-주 최저	7.07
최저	10.45	배당수익률	-		

주식 시장 요약 > IONQ Inc

16.67 USD

−1.90 (10.23%) ↓ 오늘

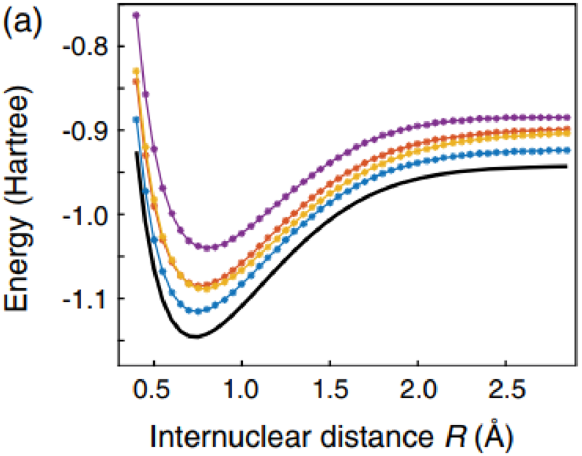
폐장: 12월 13일 오후 7:59 GMT-5 • 면책조항

폐장 후 16.71 +0.040 (0.24%)

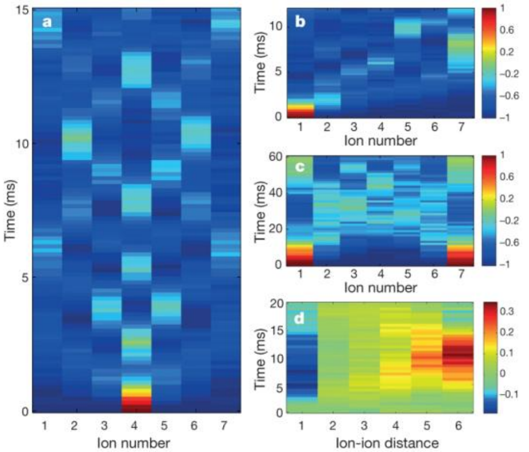
NYSE: IONQ

시가	18.57	시가총액	32.09억	52-주 최고	35.90
최고	19.23	주가수익률	-	52-주 최저	7.07
최저	16.61	배당수익률	-		

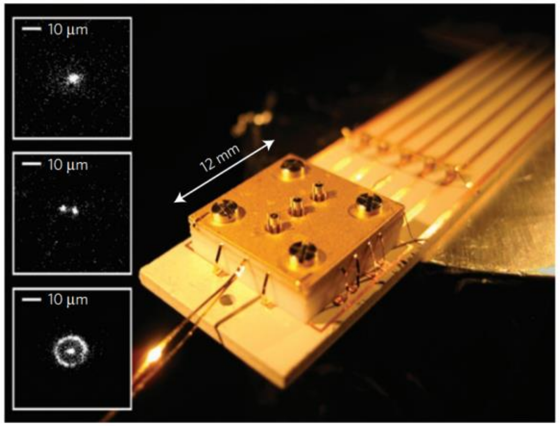
Ion trap everywhere



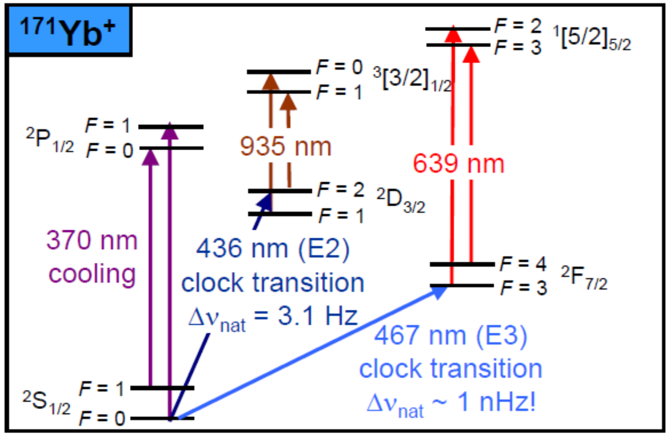
Quantum computing
Hempel et al., PRX 2016



Quantum simulation
Jurcevic et al., Nature 2014



Quantum sensing
Maiwald et al., Nat. Phys. 2009



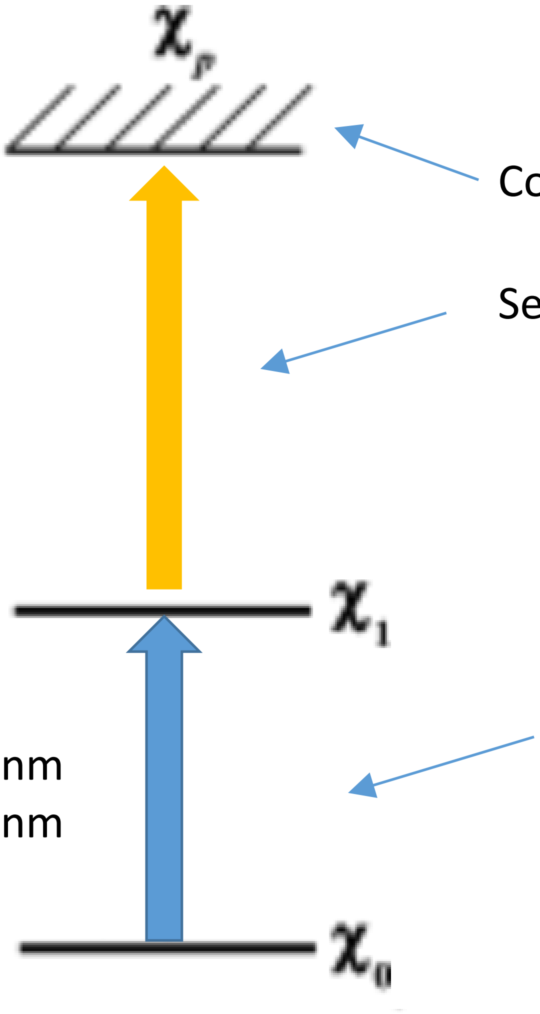
Quantum metrology
Ludlow et al., RMP 2015

목차

- 양자컴퓨터 분야 동향 소개
- 이온 트랩 특징 및 소개
- 이온 트랩 기본 계산
- 이온 얽힘 발생 소개
- 포항공대 이온 트랩 연구 소개

이온을 만드는 방법: two-photon ionization

두 색깔의 레이저를 이용함



Continuum state라고 부름

Second step: 여기서 electron이 떨어져 나감

First step: 여기는 중성 원자 neutral atom의 전이선 excitation
(electron orbital excitation)

Yb$^+$: 399/369 nm
Ca$^+$: 422/355 nm

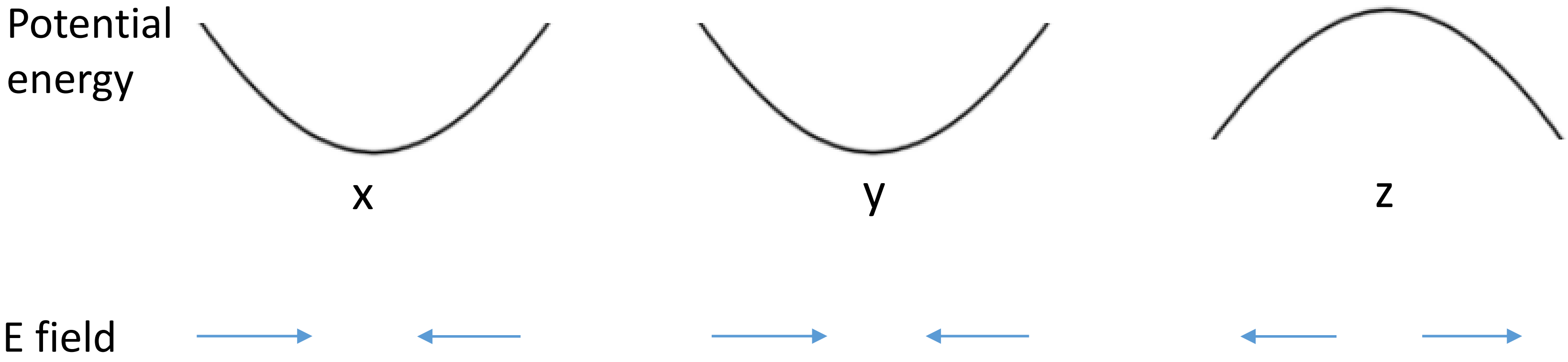
Single excitation으로 할 수도 있으나 xUV 필요

Earnshaw's theorem

- 왜 RF voltage가 필요한가?
- → refer 가우스 법칙

$$\nabla \cdot E = 0 \qquad \frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z} = 0$$

- Static (DC) 전압만으로는 3차원 포획이 불가능
- 예를 들어 포텐셜이 x, y 방향이 concave형태이면 z 방향은 convex 형태여야 함 → z 방향으로 이온이 빠져나감

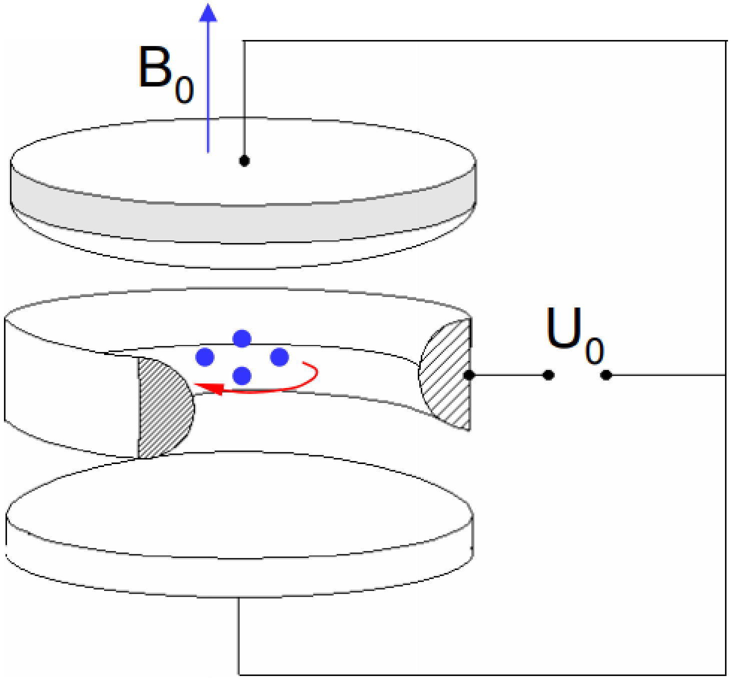


Solution 1: Penning trap:

$$q\Phi \propto U_0 \, [2z^2 - x^2 - y^2]$$

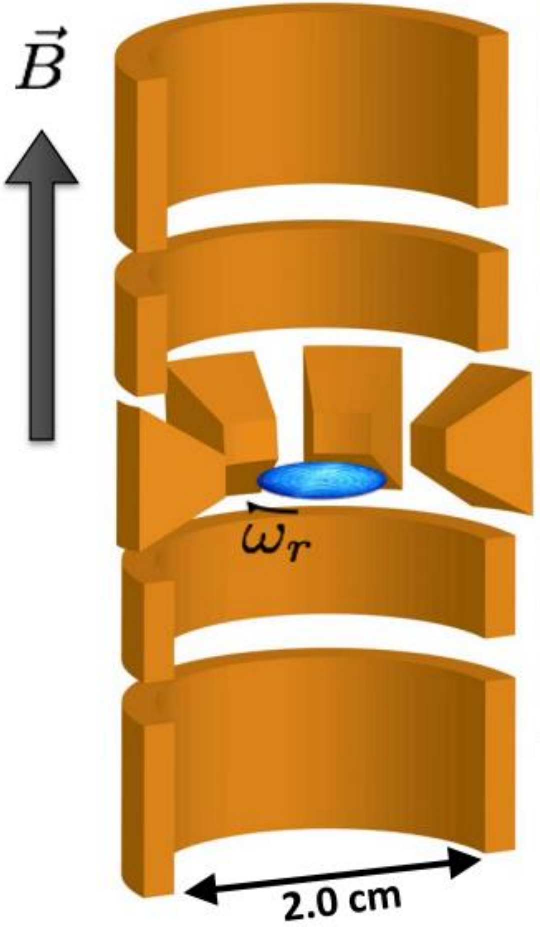
Difficult to accomplish individual ion addressing.

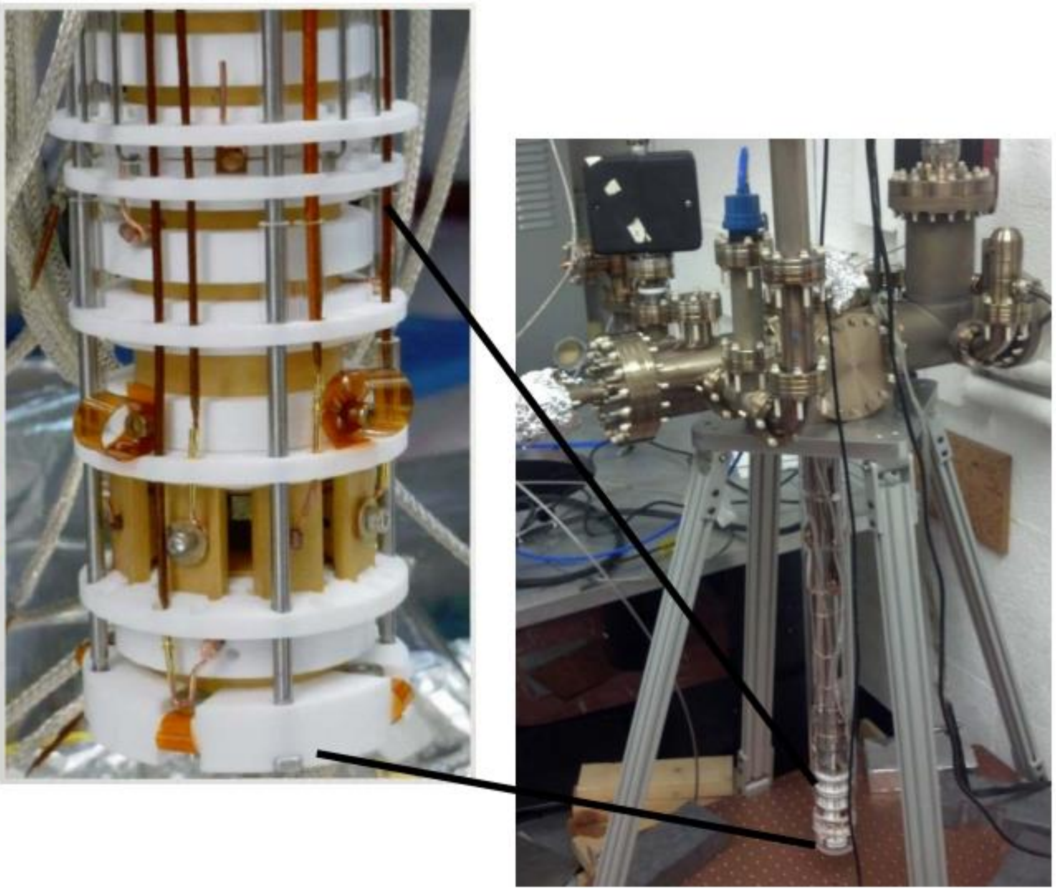
(However, see: Ciaramicoli, Marzoli, Tombesi, PRL **91**, 017901 (2003))



- Static 전압 U_0를 가하여 axial 방향의 포텐셜을 가함
- Z 축으로 자기장을 가하여 Lorenz force를 이용해 회전 시킴
- 2차원 형태로 많은 수의 이온이 포획됨 2D Coulomb crystal
- Control이 매우 어려움; 특정 시점마다 imaging함.

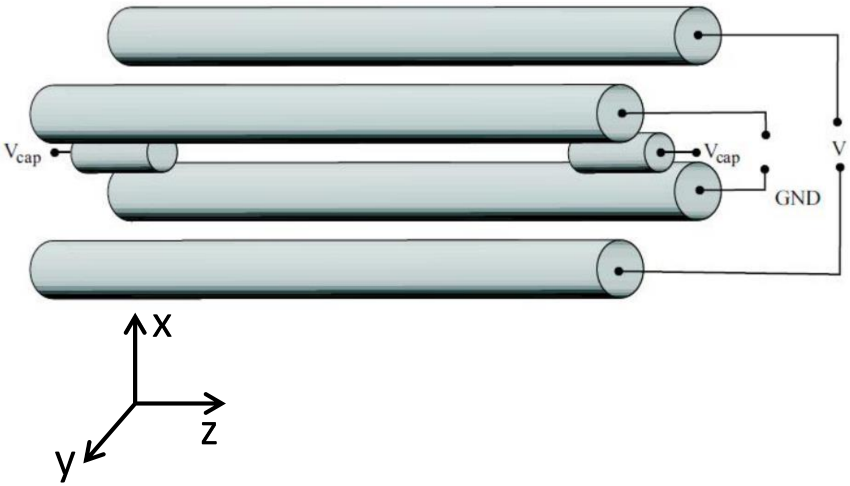
NIST Penning trap

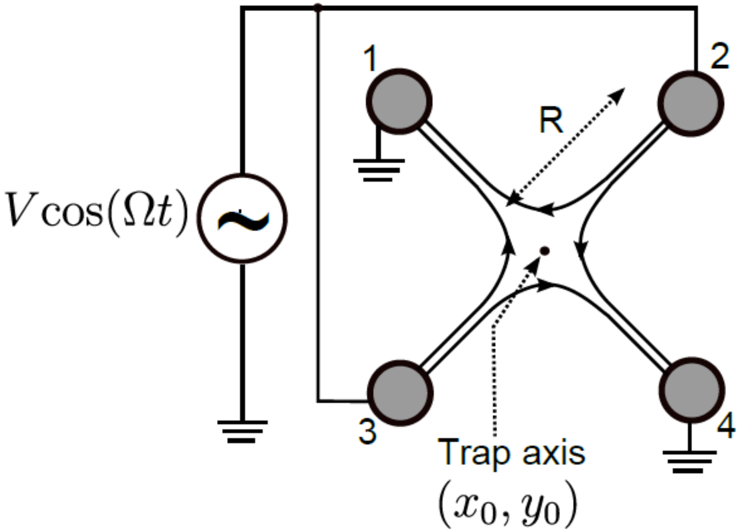




^{9}Be$^+$, B_0 = 4.5 T, $\frac{\Omega_c}{2\pi} \sim$ 7.6 MHz, $\frac{\omega_z}{2\pi} \sim$ 1.6 MHz, $\frac{\omega_m}{2\pi} \sim$ 160 kHz

Solution 2: RF-Paul trap:





PhD thesis Debnath
Univ. Maryland (2016)

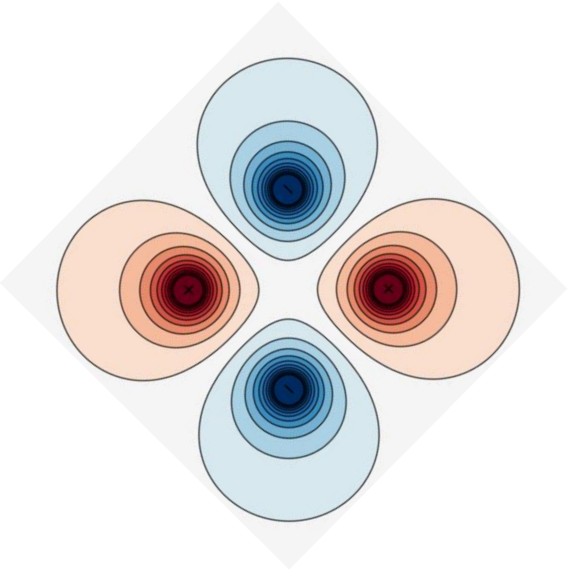
- RF quadrupole field (4개의 pole)

→ 2개는 RF, 2개는 gnd

- Center 부근에서는potential이 아래와 같이 주어짐

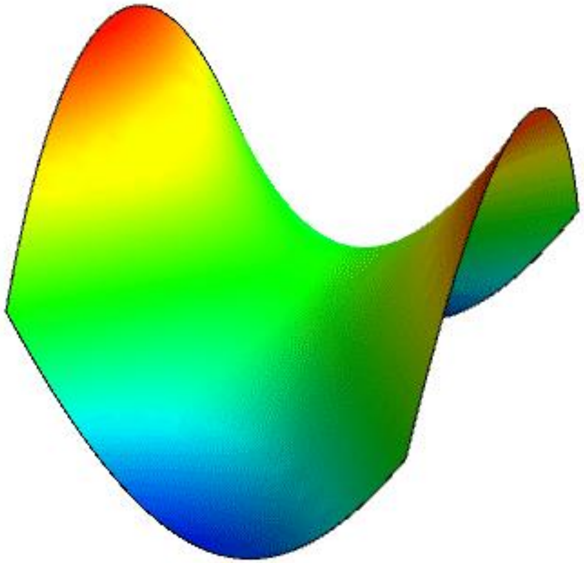
$$\Phi = \frac{(x^2 - y^2)}{2R^2} V_0 \cos \Omega_T t$$

이 sign때문에 Earnshaw's theorem 만족함



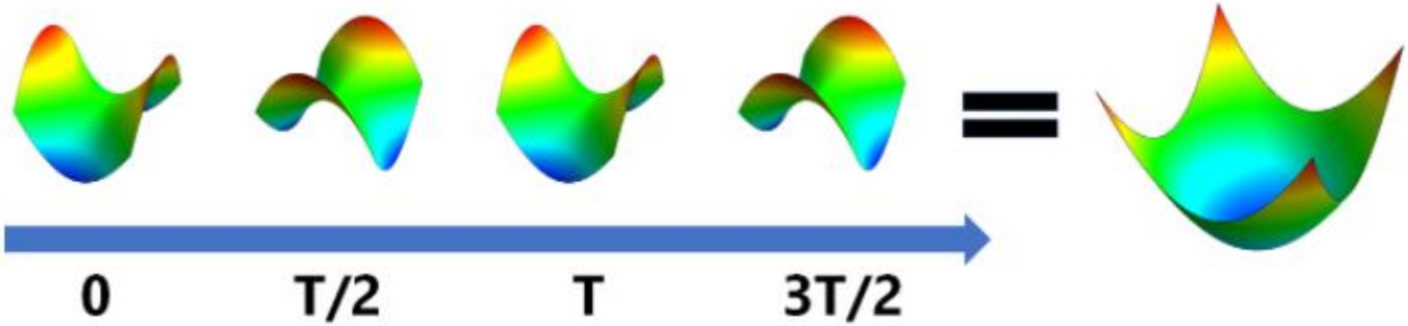
Given t에서 equipotential surface

RF quadrupole field

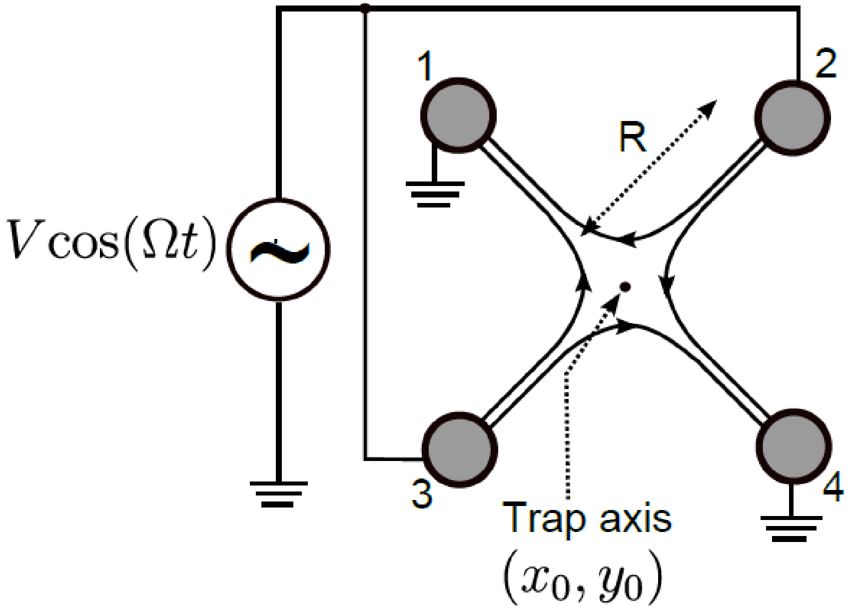


이온의 움직임 보다 훨씬
빠르게 potential이 움직임
→ Ion은 time-average된
potential을 봄

https://doooob.tistory.com/64



Ion trap potential



RF quadrupole field (4개의 pole)
→ 2개는 RF, 2개는 gnd

Center 부근에서는potential이
아래와 같이 됨

$$\Phi = \frac{(x^2 - y^2)}{2R^2} V_0 \cos \Omega_T t$$

Electric field

$$\bar{E}(x,y,t) = -\bar{\nabla}\phi(x,y,t)$$

$$\bar{E}(x,y,t) = -\bar{\nabla}\phi(x,y,t) = -\frac{V}{R^2}(x\hat{x} - y\hat{y})\cos(\Omega t) = \bar{E}_0(x,y)\cos(\Omega t).$$

→ Earnshaw's theorem 만족함

Ion trap potential

$$m\ddot{x} = e\bar{E}_x = -\frac{eV}{R^2}\cos(\Omega t)x$$

$$m\ddot{y} = e\bar{E}_y = +\frac{eV}{R^2}\cos(\Omega t)y$$

시간에 대해 적분을 하는 데 x를 상수로 근사함 (x의 변위가 매우 작음)

Variation of $x(y)$ is small → variation of spatial electric field $eVx(y)/R^2$ is negligible

이온이 움직이는 변위에 대해 전기장 amplitude는 그대로임

➡

$$x(t) - x_0 = \frac{eV}{m\Omega^2 R^2}\cos(\Omega t)x$$

$$y(t) - y_0 = -\frac{eV}{m\Omega^2 R^2}\cos(\Omega t)y$$

이제 이온이 받는 시간에 대해 평균된 힘을 구함

Ion trap potential

(x_0, y_0) 근처에서의 전기장:

$$\bar{E}_0(x,y,t) = \bar{E}_0(x_0,y_0)\cos(\Omega t) + \frac{\partial E}{\partial x}\Big|_{x0}(x(t)-x_0) + \frac{\partial E}{\partial y}\Big|_{y0}(y(t)-y_0)$$

$$x(t) - x_0 = \frac{eV}{m\Omega^2 R^2}\cos(\Omega t)x$$

$$y(t) - y_0 = -\frac{eV}{m\Omega^2 R^2}\cos(\Omega t)y$$

시간 t에서의 힘:

$$\bar{F}(x,y,t) = e\left[\bar{E}_0(x_0,y_0)\cos(\Omega t) - \frac{eV^2}{m\Omega^2 R^4}\cos^2(\Omega t)x\hat{x} - \frac{eV^2}{m\Omega^2 R^4}\cos^2(\Omega t)y\hat{y}\right]$$

Ion trap potential

시간에 대해 평균된 힘:

$$\bar{F}(x,y) = -\frac{e^2V^2}{2m\Omega^2R^4}x\hat{x} - \frac{e^2V^2}{2m\Omega^2R^4}y\hat{y}$$

Restoring force $F(r) = -m\omega^2 r$ 가 가해지는

Harmonic potential안에서 운동과 같아짐

$$\omega = \frac{eV}{2^{1/2}m\Omega R^2}$$

DC: hundreds of volts

Trap frequency or secular frequency

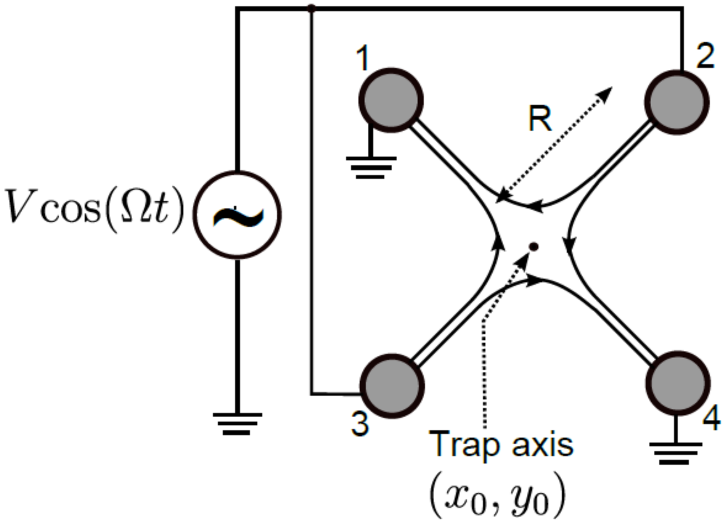
- ω/2π ~ (3, 3, 1) MHz

Trap drive

- Ω/2π ~ 20~30 MHz

RF가 주는 potential을 pseudopotential, ponderomotive potential이라고 부름

Micromotion



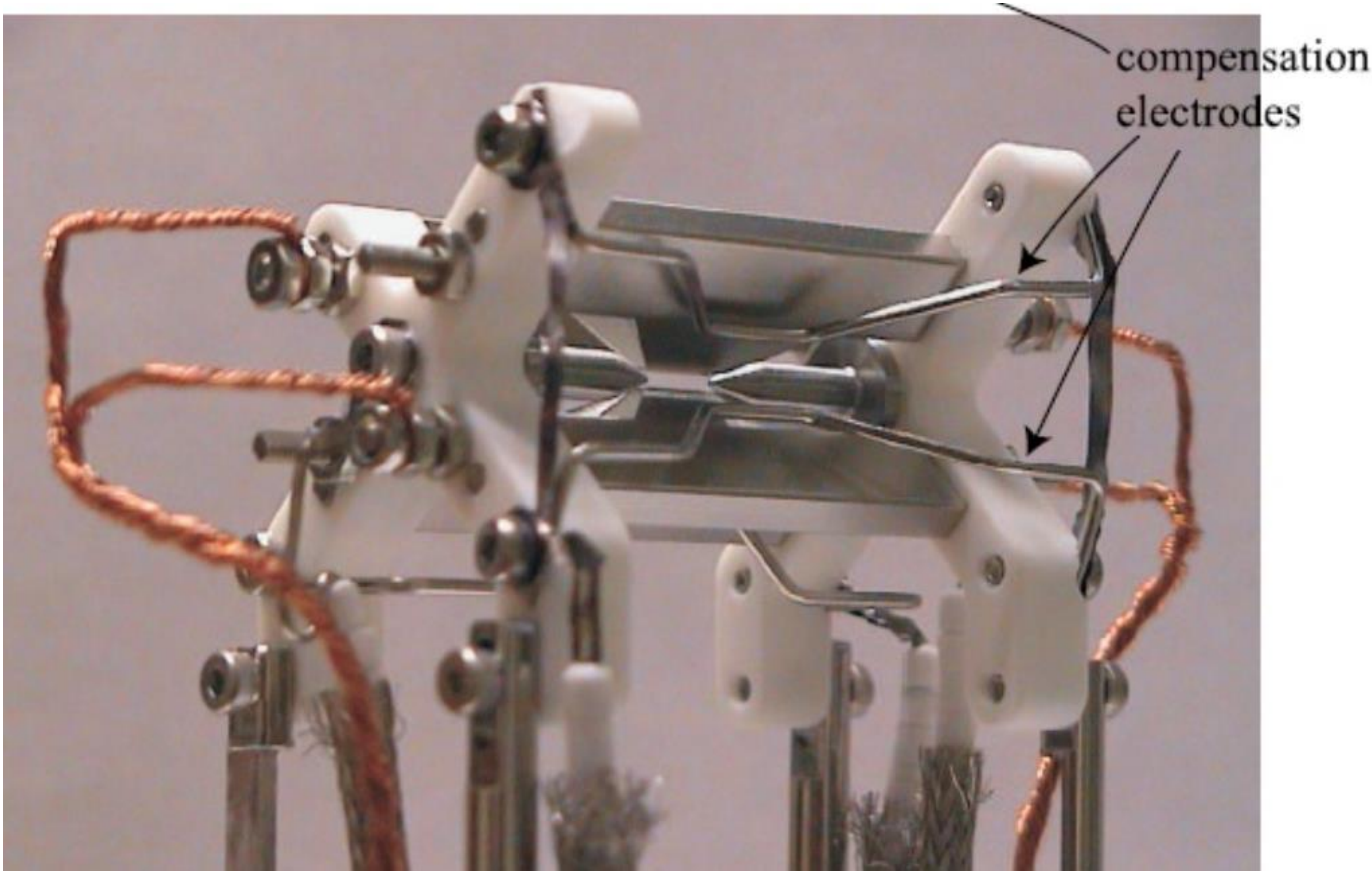
실제로 ion이 겪는 potential은 RF + stray field DC

RF potential minimum에 이온이 존재하지 않고 좀 빗겨난 위치에 있는 경우가 많음

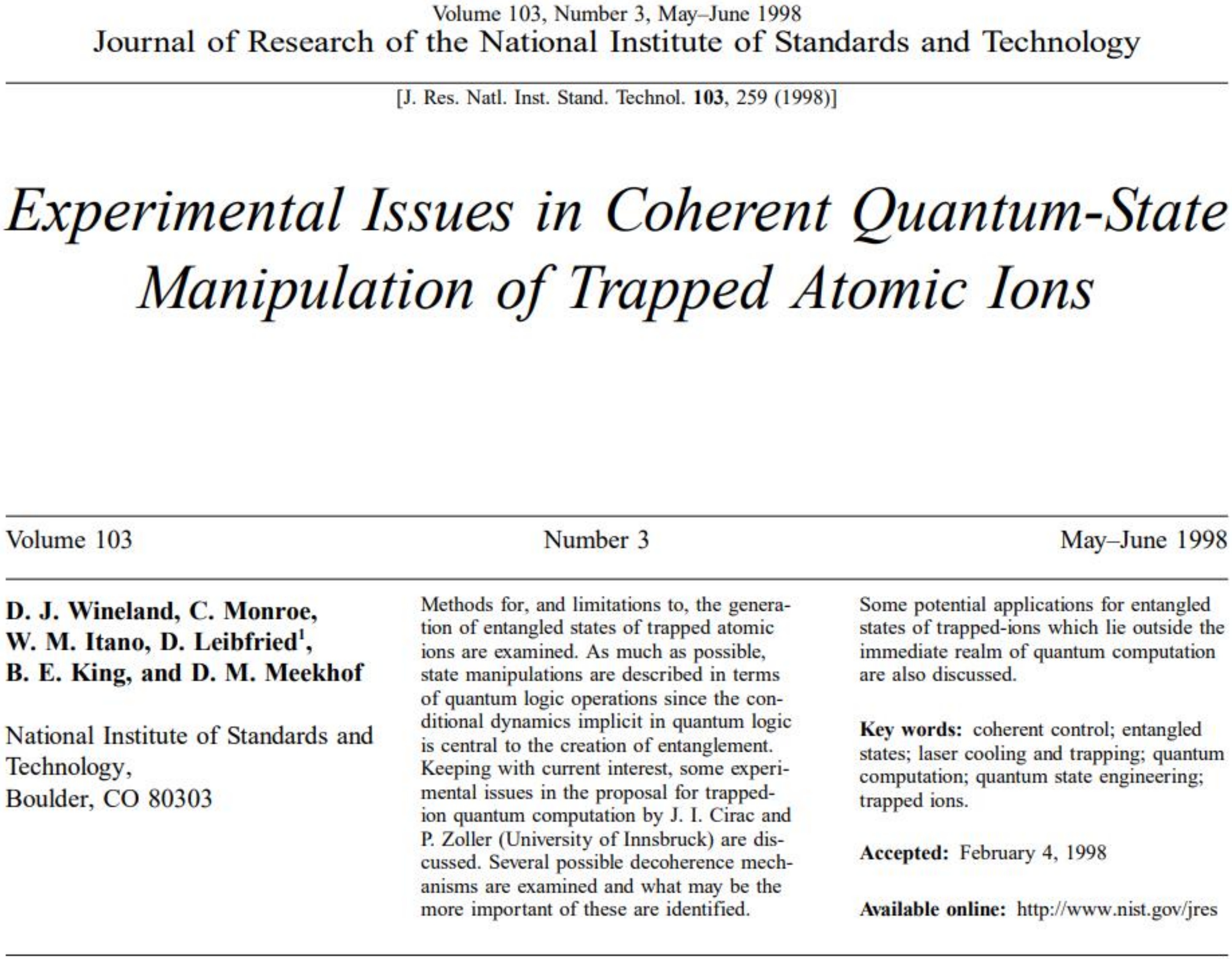
→ 이온이 RF field를 겪으며 진동함 → micromotion이라고 함

→ 주변에 추가적인 전극을 달아 RF null로 이온을 보내어 micromotion compensation함

$$x_i(t) \simeq \underbrace{X_{i0}\cos\omega_i t}_{\text{“secular” motion}} + \underbrace{\left[X_{i0}\cos\omega_i t\right]\frac{q_i}{2}\sin\Omega_T t}_{\text{“micromotion”}}$$



PhD thesis, Gulde, University of Innsbruck (2003)



Volume 103, Number 3, May–June 1998
Journal of Research of the National Institute of Standards and Technology

[J. Res. Natl. Inst. Stand. Technol. **103**, 259 (1998)]

Experimental Issues in Coherent Quantum-State Manipulation of Trapped Atomic Ions

Volume 103 Number 3 May–June 1998

D. J. Wineland, C. Monroe, W. M. Itano, D. Leibfried[1], B. E. King, and D. M. Meekhof

National Institute of Standards and
Technology,
Boulder, CO 80303

Methods for, and limitations to, the generation of entangled states of trapped atomic ions are examined. As much as possible, state manipulations are described in terms of quantum logic operations since the conditional dynamics implicit in quantum logic is central to the creation of entanglement. Keeping with current interest, some experimental issues in the proposal for trapped-ion quantum computation by J. I. Cirac and P. Zoller (University of Innsbruck) are discussed. Several possible decoherence mechanisms are examined and what may be the more important of these are identified.

Some potential applications for entangled states of trapped-ions which lie outside the immediate realm of quantum computation are also discussed.

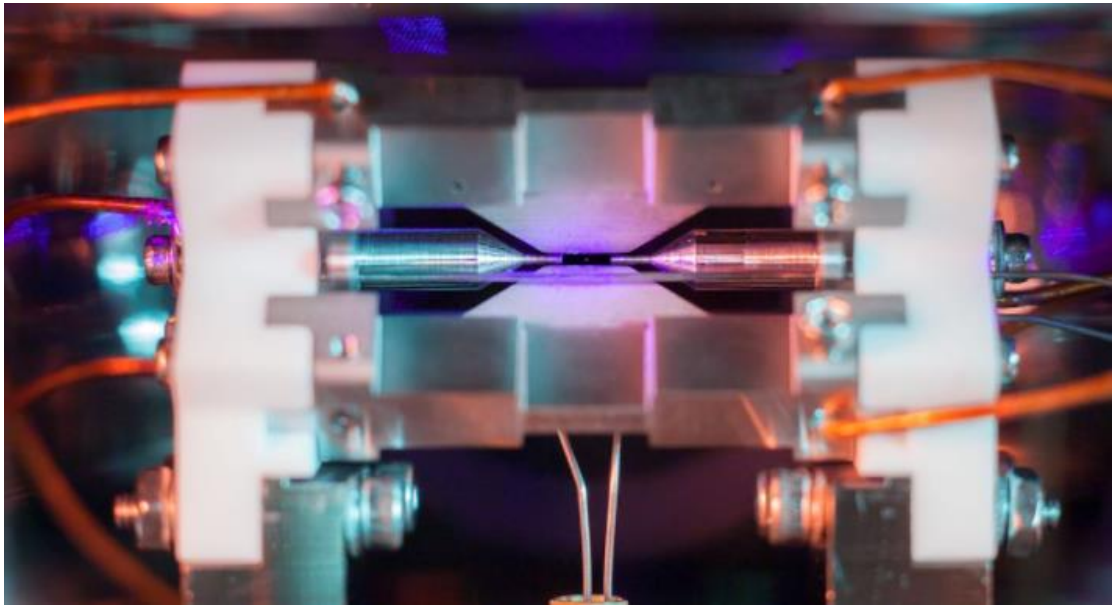
Key words: coherent control; entangled states; laser cooling and trapping; quantum computation; quantum state engineering; trapped ions.

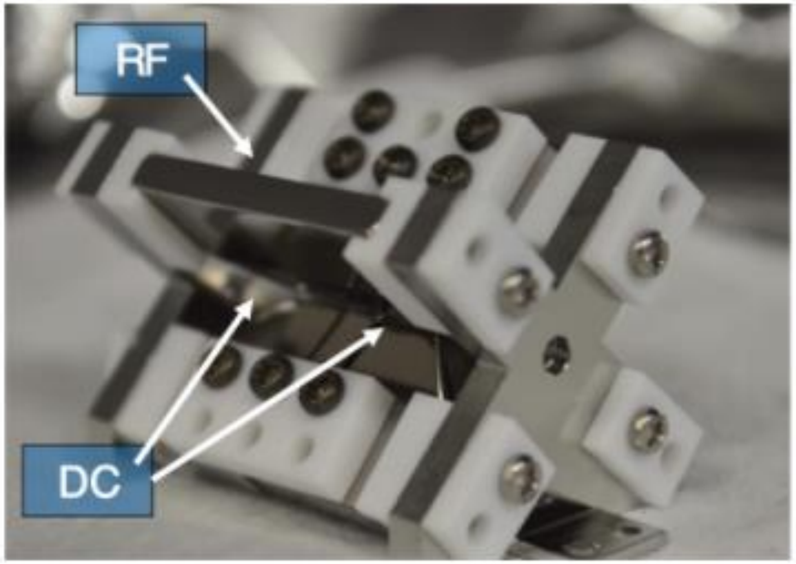
Accepted: February 4, 1998

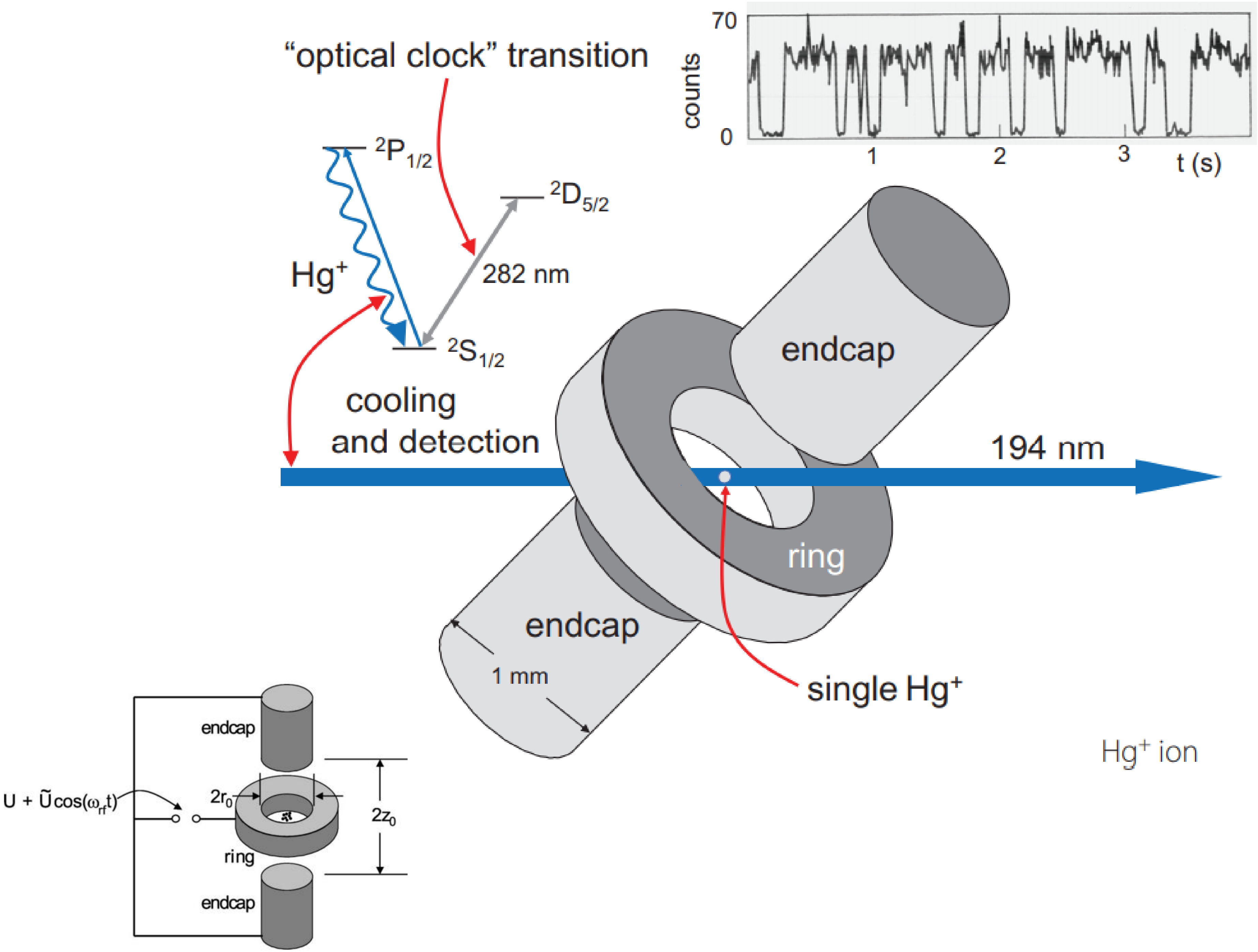
Available online: http://www.nist.gov/jres

전공자들을 위한 추천 논문 (약 70페이지)

다양한 trap 구조물

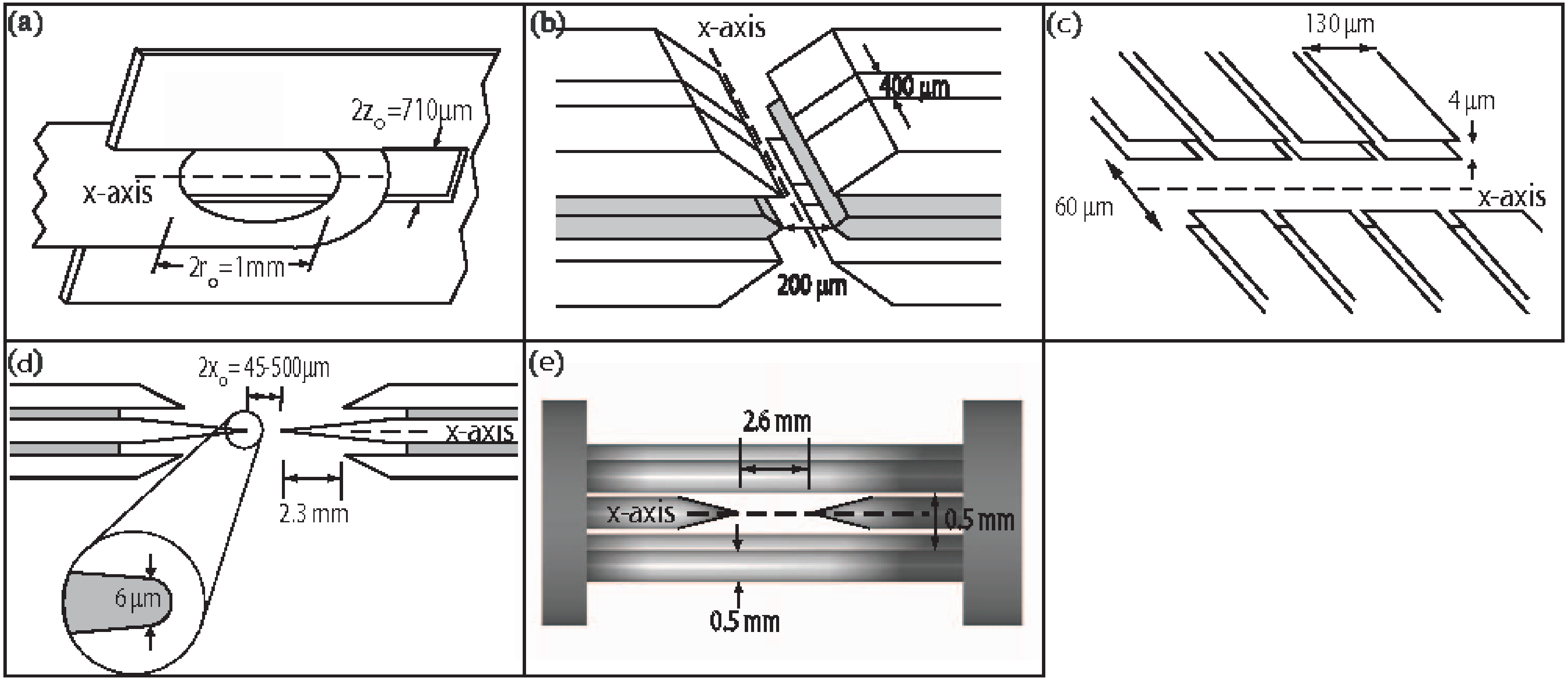




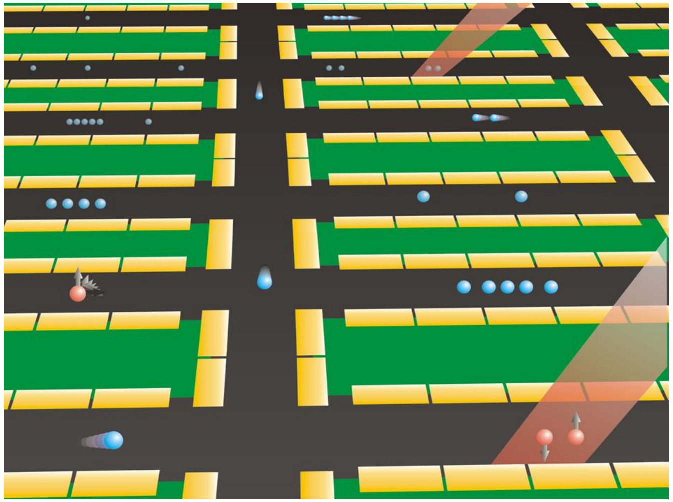

"optical clock" transition
70
0
counts
1
2
3
t (s)
${}^2P_{1/2}$
${}^2D_{5/2}$
Hg$^+$
282 nm
${}^2S_{1/2}$
cooling
and detection
endcap
194 nm
ring
endcap
1 mm
single Hg$^+$
endcap
$U + \tilde{U}\cos(\omega_{rf}t)$
$2r_0$
$2z_0$
ring
endcap

Hg$^+$ ion

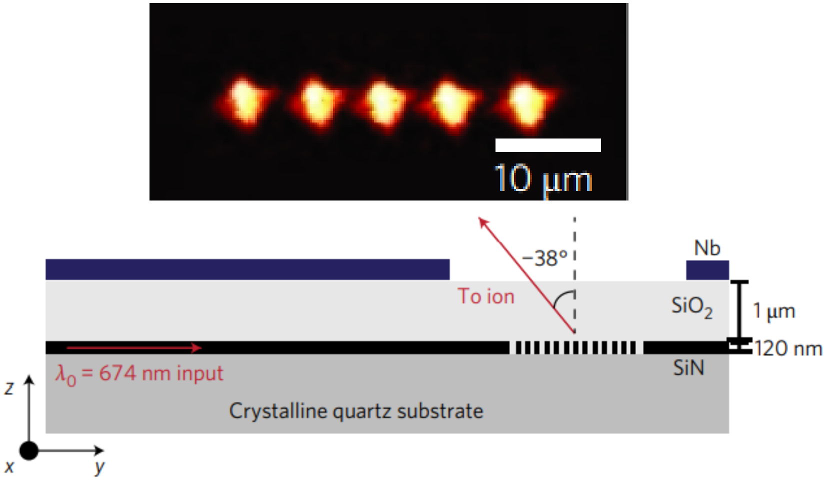
다양한 trap 구조물


(a)
2z$_o$=710µm
x-axis
2r$_o$=1mm
(b)
x-axis
400 µm
200 µm
(c)
130 µm
4 µm
60 µm
x-axis
(d)
2x$_o$=45-500µm
x-axis
2.3 mm
6 µm
(e)
2.6 mm
x-axis
0.5 mm
0.5 mm

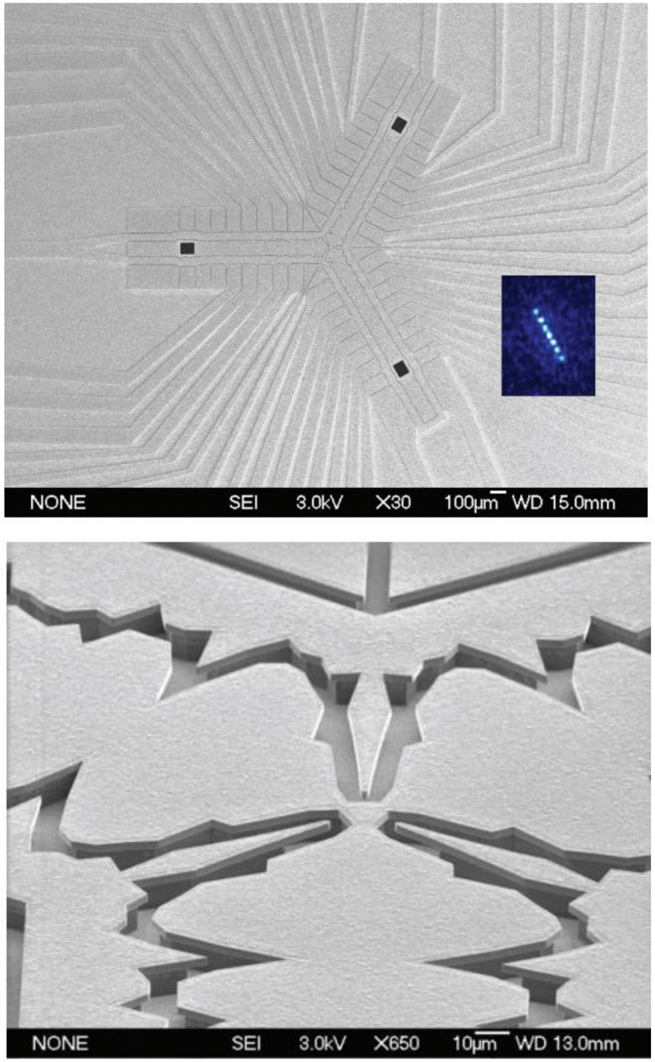
Cutting edge ion-trap architectures



Kielpinski et al, Nature (2002)

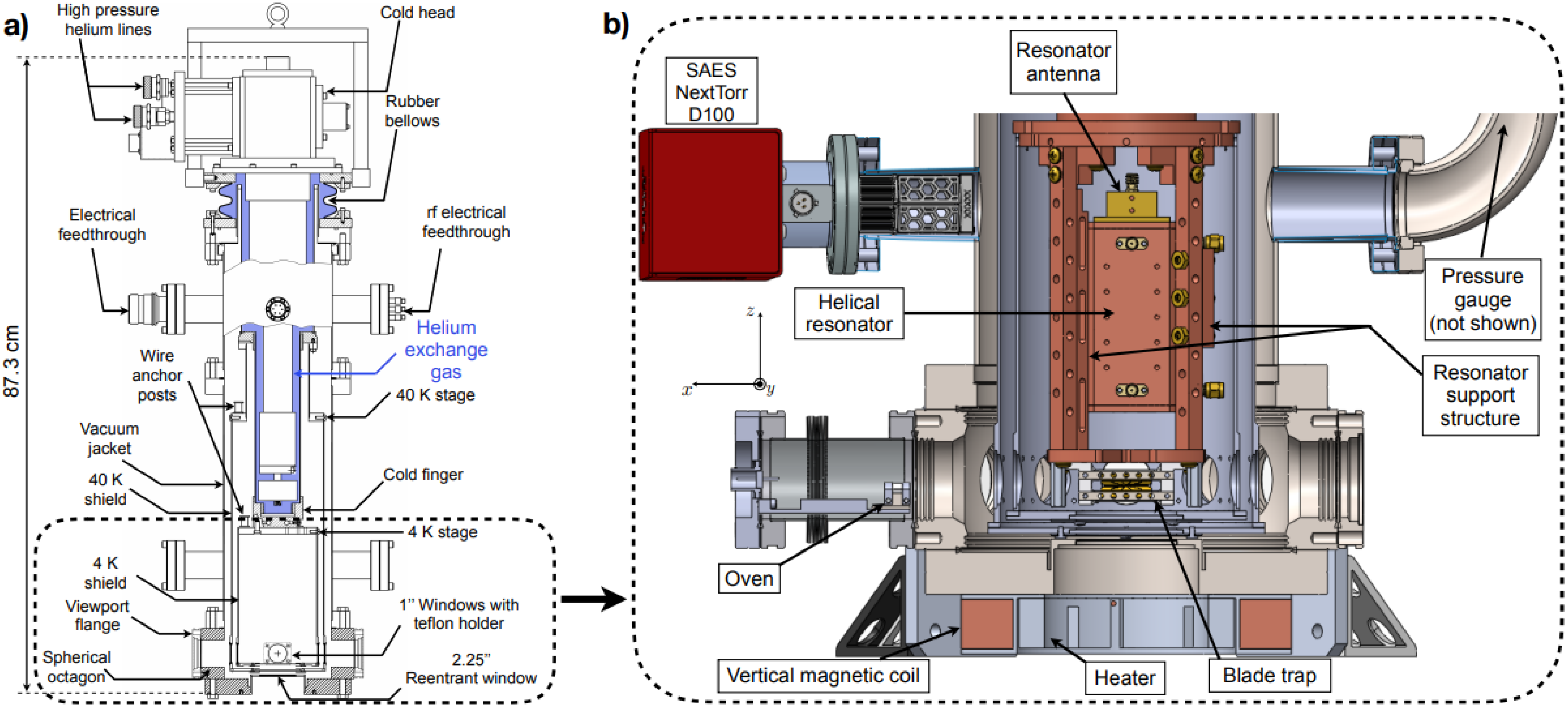


Mehta et al., Nat. Nanotechnol. (2016)



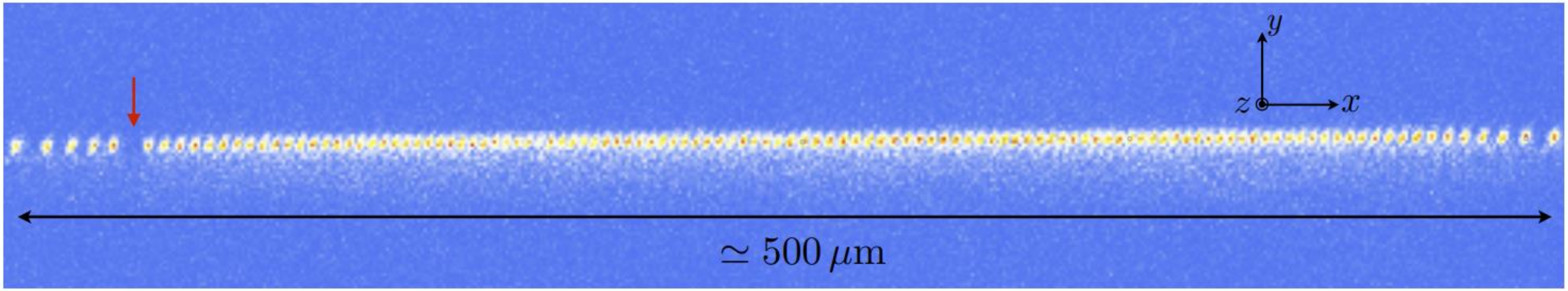
Moehring et al., New J. Phys. (2011)

Ion trap at cryogenic temperatures



- Background gas collision
- Electric field noise

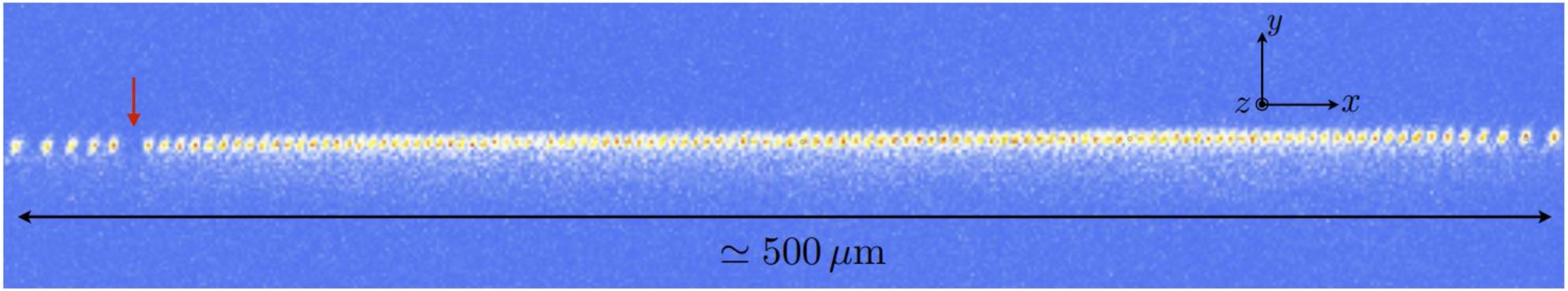
$^{171}Yb^{+}$ ion crystal at 4K



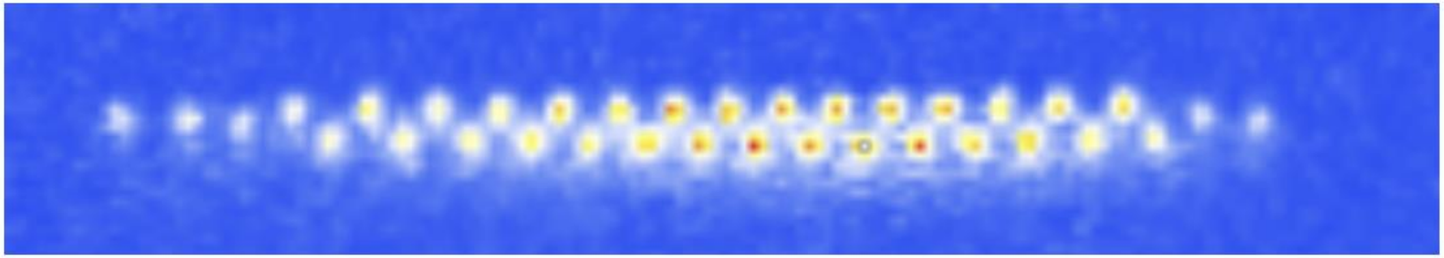
Ion string with 127 ions
Dark ions do not jump around

Pagano et al., Quantum Sci. and Technol. 4, 014004 (2019)

$^{171}Yb^{+}$ ion crystal at 4K



Ion string with 127 ions
Dark ions do not jump around



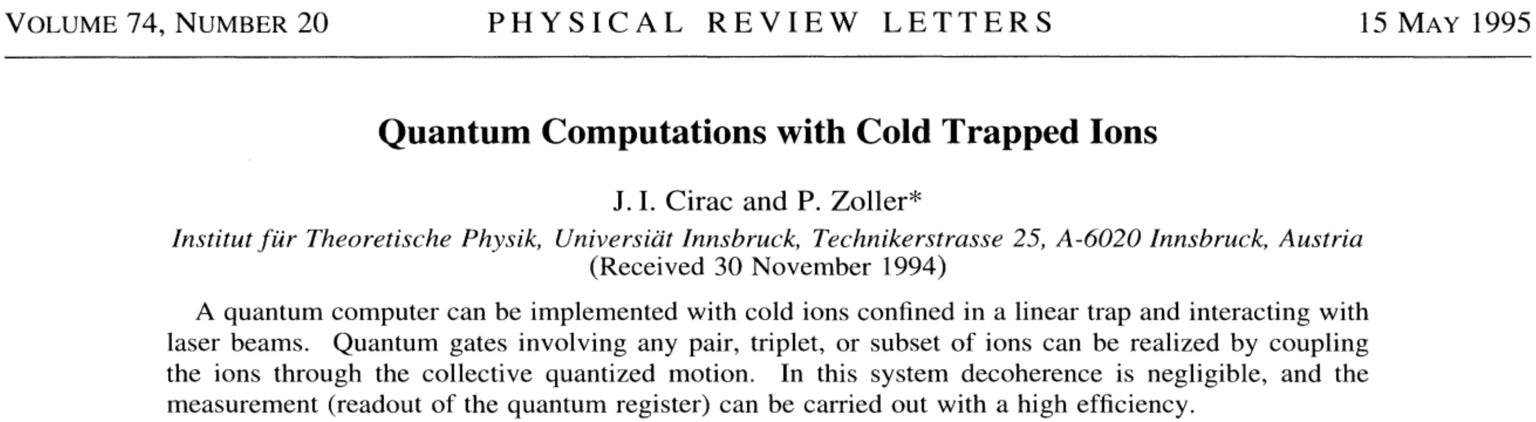
Zig-Zag ion chain

Pagano et al., Quantum Sci. and Technol. 4, 014004 (2019)

목차

- 양자컴퓨터 분야 동향 소개
- 이온 트랩 특징 및 소개
- 이온 트랩 기본 계산
- 이온 얽힘 발생 소개
- 포항공대 이온 트랩 연구 소개

Cirac-Zoller gate



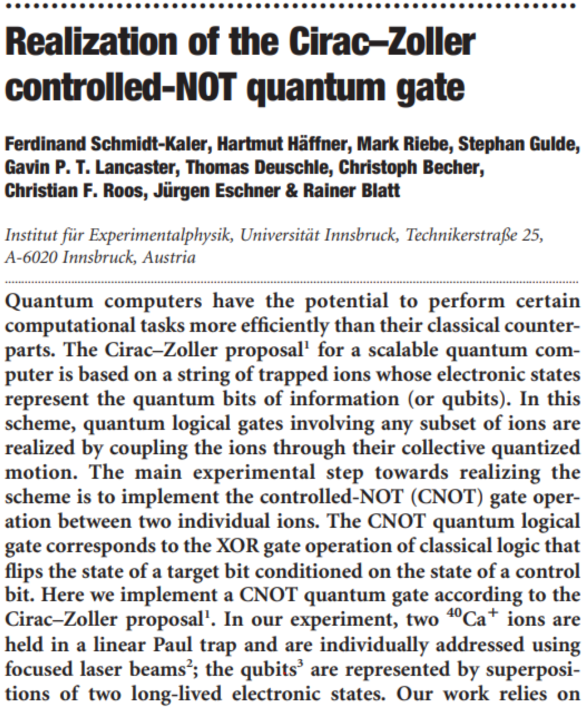
VOLUME 74, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 1995

Quantum Computations with Cold Trapped Ions

J. I. Cirac and P. Zoller*
Institut für Theoretische Physik, Universiät 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.

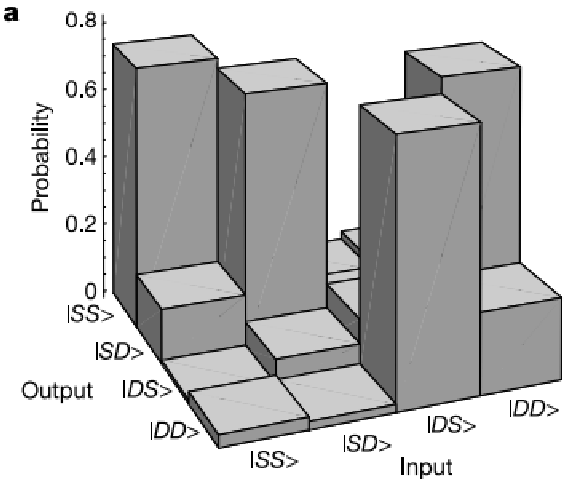


Realization of the Cirac–Zoller controlled-NOT quantum gate

Ferdinand Schmidt-Kaler, Hartmut Häffner, Mark Riebe, Stephan Gulde, Gavin P. T. Lancaster, Thomas Deuschle, Christoph Becher, Christian F. Roos, Jürgen Eschner & Rainer Blatt

Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25, A-6020 Innsbruck, Austria

Quantum computers have the potential to perform certain computational tasks more efficiently than their classical counterparts. The Cirac–Zoller proposal[1] for a scalable quantum computer is based on a string of trapped ions whose electronic states represent the quantum bits of information (or qubits). In this scheme, quantum logical gates involving any subset of ions are realized by coupling the ions through their collective quantized motion. The main experimental step towards realizing the scheme is to implement the controlled-NOT (CNOT) gate operation between two individual ions. The CNOT quantum logical gate corresponds to the XOR gate operation of classical logic that flips the state of a target bit conditioned on the state of a control bit. Here we implement a CNOT quantum gate according to the Cirac–Zoller proposal[1]. In our experiment, two $^{40}\mathrm{Ca}^+$ ions are held in a linear Paul trap and are individually addressed using focused laser beams[2]; the qubits[3] are represented by superpositions of two long-lived electronic states. Our work relies on



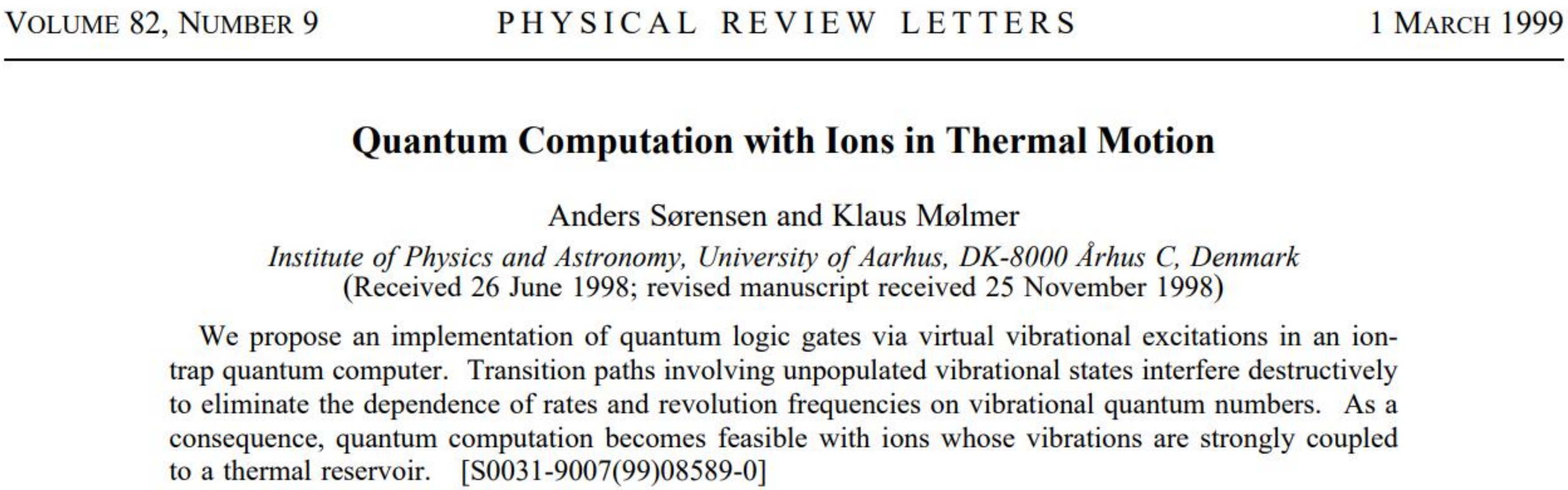
Nature 2003

단점

여러 개의 laser 펄스

Individual addressing이 필요함

Mølmer-Sørensen gate



VOLUME 82, NUMBER 9 PHYSICAL REVIEW LETTERS 1 MARCH 1999

Quantum Computation with Ions in Thermal Motion

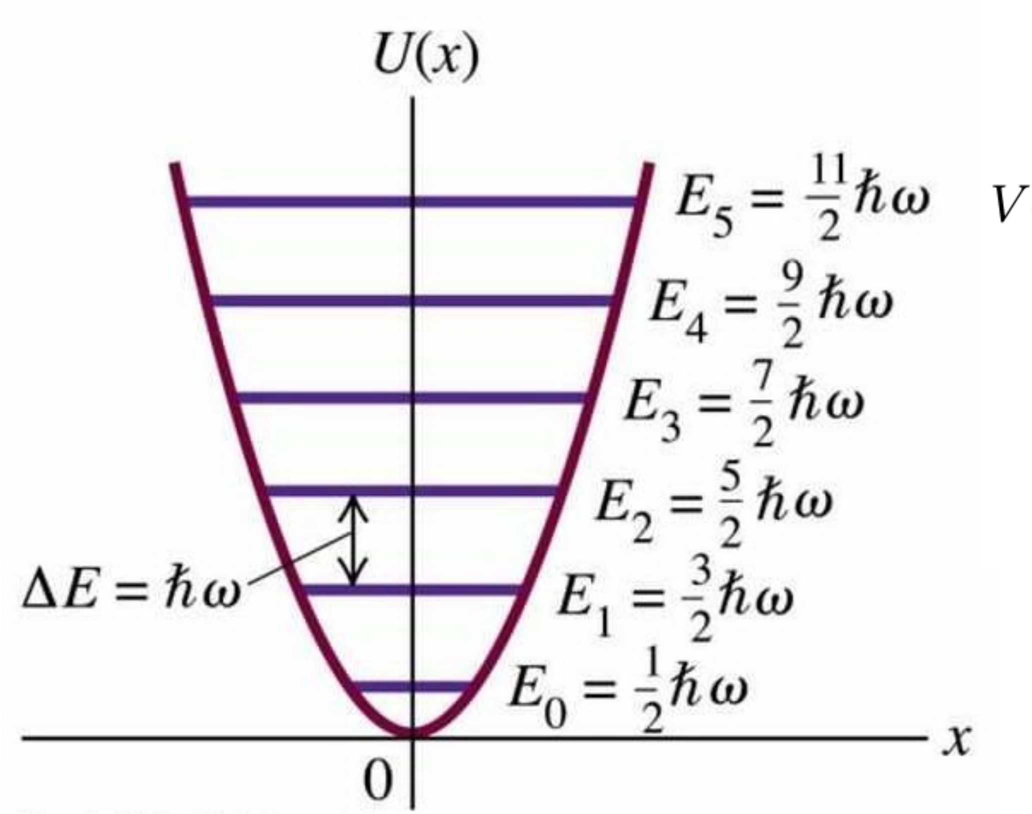
Anders Sørensen and Klaus Mølmer
Institute of Physics and Astronomy, University of Aarhus, DK-8000 Århus C, Denmark
(Received 26 June 1998; revised manuscript received 25 November 1998)

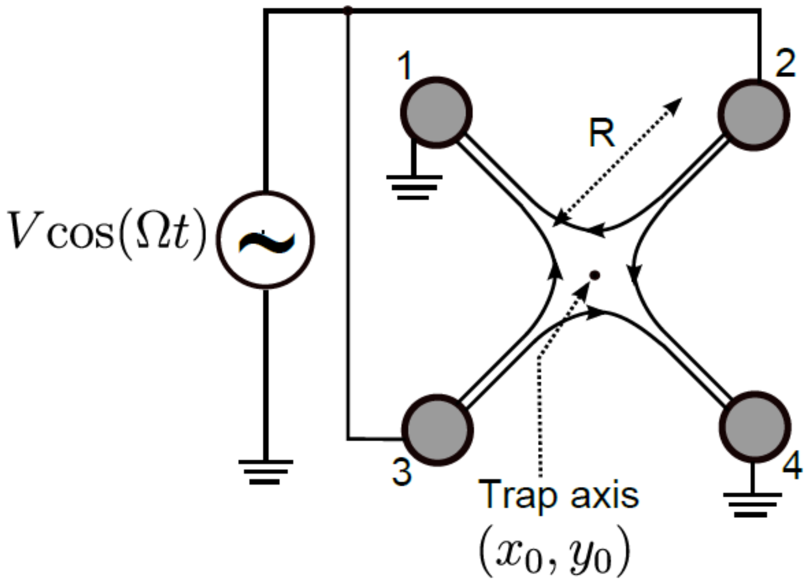
We propose an implementation of quantum logic gates via virtual vibrational excitations in an ion-trap quantum computer. Transition paths involving unpopulated vibrational states interfere destructively to eliminate the dependence of rates and revolution frequencies on vibrational quantum numbers. As a consequence, quantum computation becomes feasible with ions whose vibrations are strongly coupled to a thermal reservoir. [S0031-9007(99)08589-0]

See also: Cirac-Zoller gate PRL 1995,
Geometric phase gate Nature 2003

한 번의 laser pulse (two frequencies)
Individual addressing 필요 없음

Vibrational mode of single ion

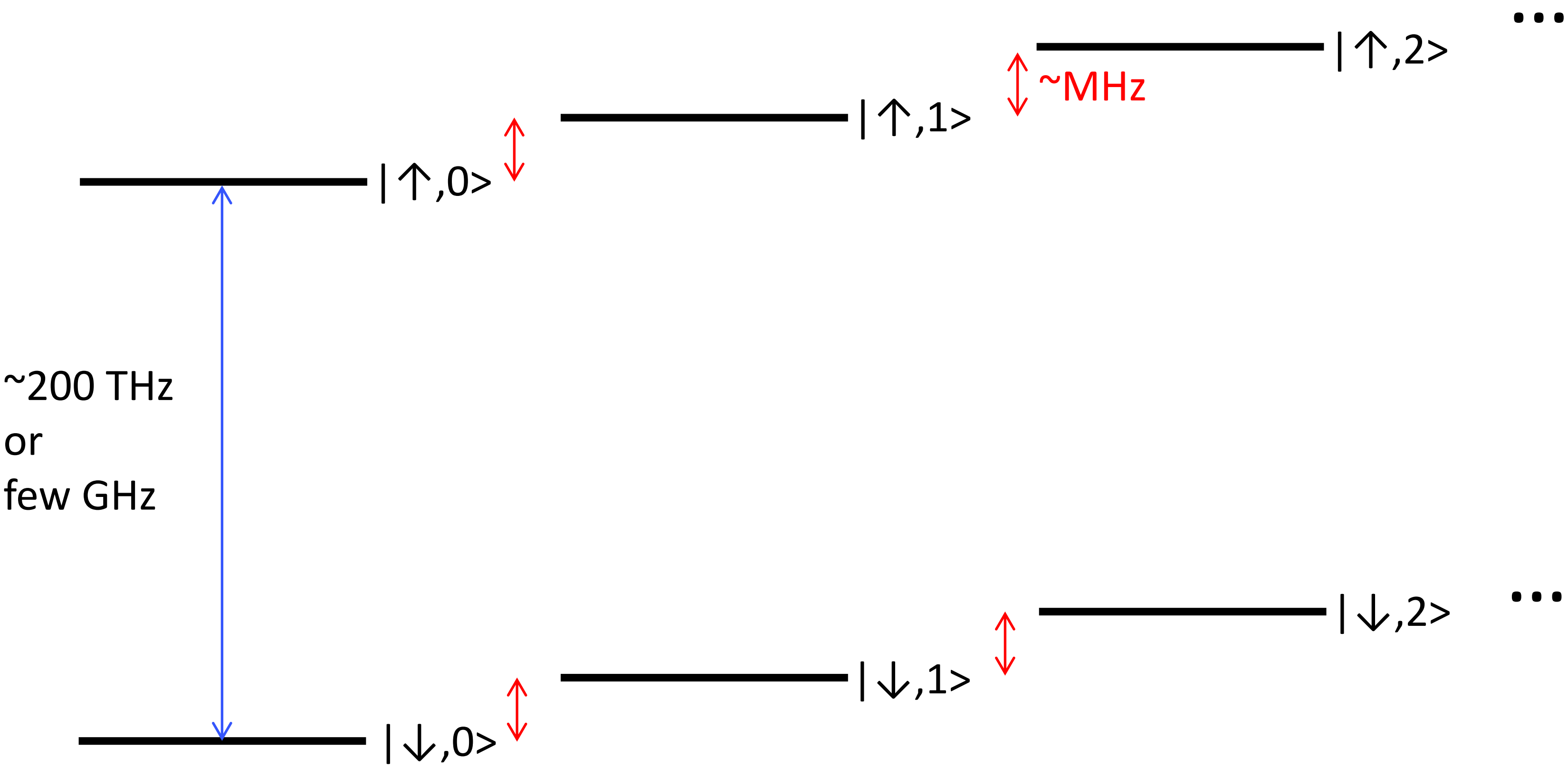




$$\boxed{\omega = \frac{eV}{2^{1/2} m \Omega R^2}}$$

Two radial motional modes and one longitudinal mode
Ion 1개 → motional mode 3개

Vibrational mode of single ion



Motional ladder appear in all three motional modes.
Laser fields can drive individual motional transitions.

REVIEWS OF MODERN PHYSICS, VOLUME 75, JANUARY 2003

Quantum dynamics of single trapped ions

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(Published 10 March 2003)

Single trapped ions represent elementary quantum systems that are well isolated from the environment. They can be brought nearly to rest by laser cooling, and both their internal electronic states and external motion can be coupled to and manipulated by light fields. This makes them ideally suited for quantum-optical and quantum-dynamical studies under well-controlled conditions. Theoretical and experimental work on these topics is reviewed in the paper, with a focus on ions trapped in radio-frequency (Paul) traps.

Hamiltonian: one ion in monochromatic field

$$\hat{H} = \hat{H}^{(m)} + \hat{H}^{(e)} + \hat{H}^{(i)},$$

$$\hat{H}^{(m)} = \hbar\nu\left(\hat{a}^{\dagger}\hat{a} + \frac{1}{2}\right)$$

➡ motion

$$\hat{H}^{(e)} = \hbar\frac{\omega}{2}\sigma_z$$

➡ internal energy

$$\hat{H}^{(i)} = (\hbar/2)\Omega(|g\rangle\langle e| + |e\rangle\langle g|)\,[e^{i(k\hat{x}_S - \omega t + \phi)} + e^{-i(k\hat{x}_S - \omega t + \phi)}].$$

➡ ion in traveling wave; interaction Hamiltonian

$$|e\rangle\langle g| \mapsto \hat{\sigma}_+ = 1/2(\hat{\sigma}_x + i\hat{\sigma}_y),$$
$$|g\rangle\langle e| \mapsto \hat{\sigma}_- = 1/2(\hat{\sigma}_x - i\hat{\sigma}_y).$$

Hamiltonian: one ion in monochromatic field

→ Go to interaction picture

$$\hat{H}_0 = \boxed{\hat{H}^{(m)}} + \hat{H}^{(e)}$$

→ 교과서의 two-level atom + laser field에는 motion무시

$$\hat{U}_0 = \exp[-(i/\hbar)\hat{H}_0 t]$$

$$e^{\alpha A} B e^{-\alpha A} = B + \alpha[A, B] + \frac{\alpha^2}{2!}[A, [A, B]] + \ldots,$$

$$\hat{H}_{\text{int}} = \hat{U}_0^{\dagger} \hat{H}^{(i)} \hat{U}_0$$

$$= (\hbar/2)\Omega e^{(i/\hbar)\hat{H}^{(e)}t}(\sigma_+ + \sigma_-)\, e^{-(i/\hbar)\hat{H}^{(e)}t}$$

→ Rotation with internal energy

$$\times e^{(i/\hbar)\hat{H}^{(m)}t}[e^{i(k\hat{x}-\omega t+\phi)} + e^{-i(k\hat{x}-\omega t+\phi)}]e^{-(i/\hbar)\hat{H}^{(m)}t}$$

→ Rotation with motional energy

↓

$$= (\hbar/2)\Omega(\sigma_+ e^{i\omega_0 t} + \sigma_- e^{-i\omega_0 t})$$

$$\times\ e^{(i/\hbar)\hat{H}^{(m)}t}[e^{i(k\hat{x}-\omega t+\phi)} + e^{-i(k\hat{x}-\omega t+\phi)}]e^{-(i/\hbar)\hat{H}^{(m)}t}.$$

→ Rotation with motional energy

Hamiltonian: one ion in monochromatic field

$$= (\hbar/2)\Omega(\sigma_+ e^{i\omega_0 t} + \sigma_- e^{-i\omega_0 t})$$

$$\times\ e^{(i/\hbar)\hat{H}^{(m)}t}[e^{i(k\hat{x}-\omega t+\phi)} + e^{-i(k\hat{x}-\omega t+\phi)}]e^{-(i/\hbar)\hat{H}^{(m)}t}.$$

⇨ Rotation with motional energy

Using $k\hat{x}(t) = \eta\{\hat{a}u^*(t) + \hat{a}^\dagger u(t)\}$

⇩ rotate

$$\hat{H}_{\text{int}}(t) = (\hbar/2)\Omega\hat{\sigma}_+ \exp(i\{\phi + \eta[\hat{a}u^*(t) + \hat{a}^\dagger u(t)] - \delta t\}) + \text{H.c.}$$

⇩ 정리, 정리, 정리…

$$\hat{H}_{\text{int}}(t) = (\hbar/2)\Omega_0\sigma_+ \exp\{i\eta(\hat{a}e^{-i\nu t} + \hat{a}^\dagger e^{i\nu t})\}e^{i(\phi-\delta t)} + \text{H.c.}$$

⇩ Lamb-Dicke limit

$$\boxed{\hat{H}_{\text{LD}}(t) = (\hbar/2)\Omega_0\sigma_+\{1 + i\eta(\hat{a}e^{-i\nu t} + \hat{a}^\dagger e^{i\nu t})\}e^{i(\phi-\delta t)} + \text{H.c.}}$$

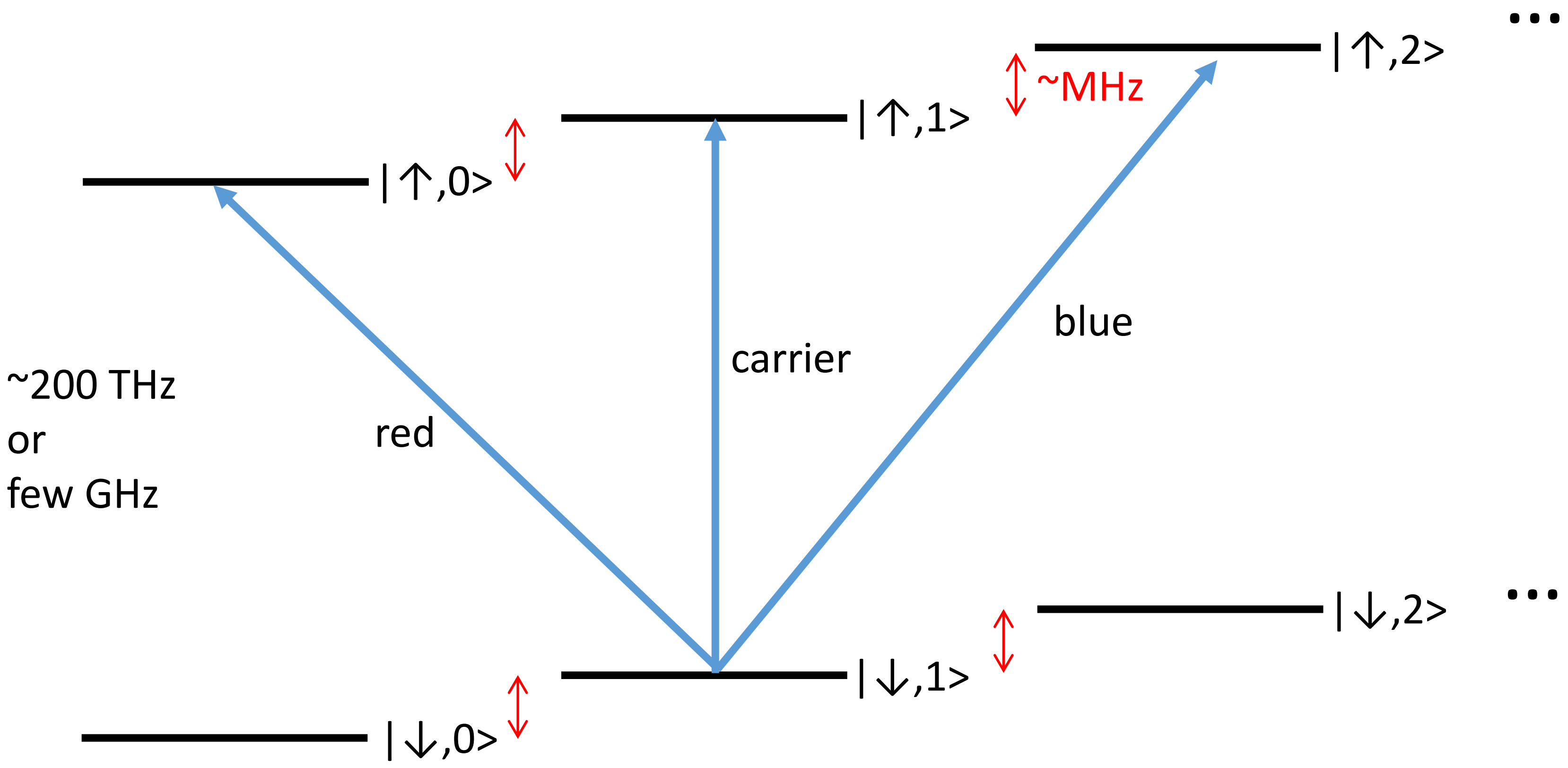
Lamb-Dicke parameter

$$\begin{aligned}\eta &= k \cdot x_0 \\ &= 2\pi\frac{x_0}{\lambda} \\ &= 2\pi\frac{\sqrt{\frac{\hbar}{2m\nu}}}{\lambda}\end{aligned}$$

→ η=0 → 교과서
원자+레이저 상호작용

→ Excitation of carrier,
blue/red sidebands

Vibrational mode of single ion



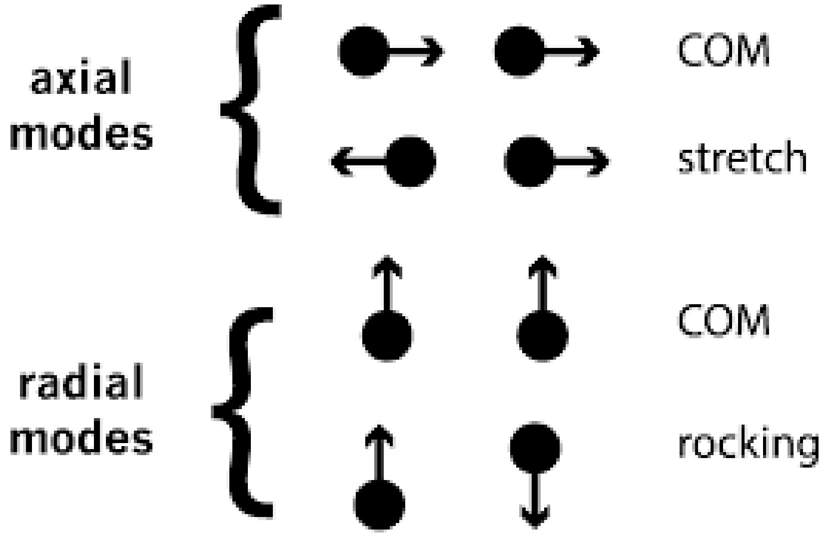
$$\boxed{\hat{H}_{\mathrm{LD}}(t)=(\hbar/2)\Omega_0\sigma_+\{1+i\,\eta(\hat{a}e^{-i\nu t}+\hat{a}^\dagger e^{i\nu t})\}e^{i(\phi-\delta t)}+\mathrm{H.c.}}$$

State vector: $|\psi\rangle = \sum_n |g,n\rangle + |e,n\rangle$

→ η=0 → 교과서
원자+레이저 상호작용

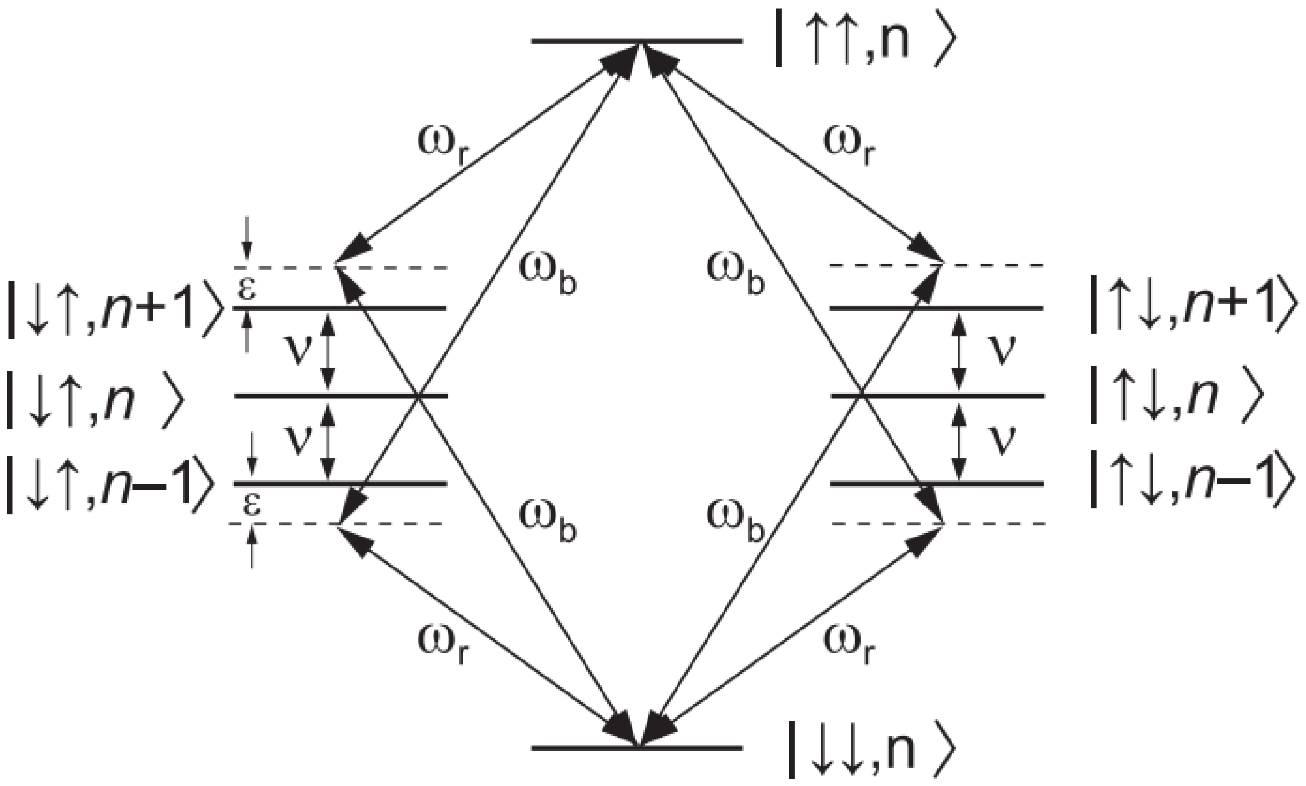
→ Excitation of carrier,
blue/red sidebands

Vibrational mode of two ions



Ion 2개 → motional mode 6개
Any collective motional modes can be driven to generate an ion-ion entanglement.

`Bichromatic' laser drive



Two ions are driven with a laser field of two frequencies ω_r, ω_b.
The ions at |↓↓> are excited to |↑↑> via motional states.

두 ion의 collective motion을 `살짝' excite하며 얽힘 상태 발생시킴

Hamiltonian: two ions in bichromatic fields

$$H_0 = \hbar\nu(a^\dagger a + 1/2) + \frac{\hbar\omega_{eg}}{2}\left(\sigma_z^{(1)} + \sigma_z^{(2)}\right)$$

Interaction picture

$$H(t) = \hbar\Omega(e^{-i\delta t} + e^{i\delta t})e^{i\eta(ae^{-i\nu t} + a^\dagger e^{i\nu t})}(\sigma_+^{(1)} + \sigma_+^{(2)}) + h.c.$$

Lamb-Dicke limit

$$\boxed{H(t) \approx -\hbar\eta\Omega(a^\dagger e^{i\epsilon t} + ae^{-i\epsilon t})S_y}$$

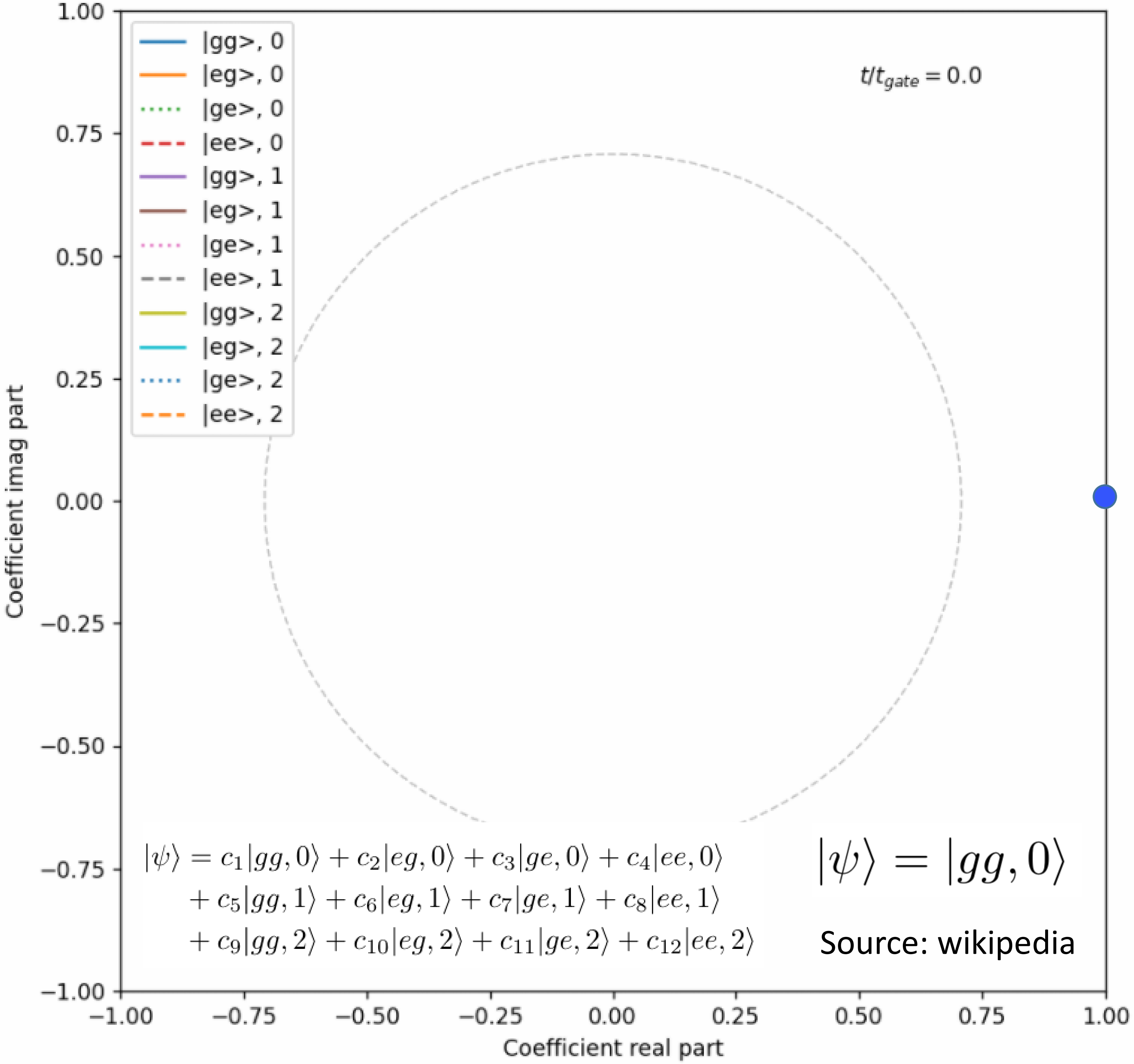
$$t_{gate} = 2\pi/\epsilon$$

$$\epsilon = \nu - \delta,\ S_y = \sigma_{1y} + \sigma_{2y}$$

$$|e\rangle\langle g| \mapsto \hat{\sigma}_+ = 1/2(\hat{\sigma}_x + i\hat{\sigma}_y),$$

$$|g\rangle\langle e| \mapsto \hat{\sigma}_- = 1/2(\hat{\sigma}_x - i\hat{\sigma}_y).$$

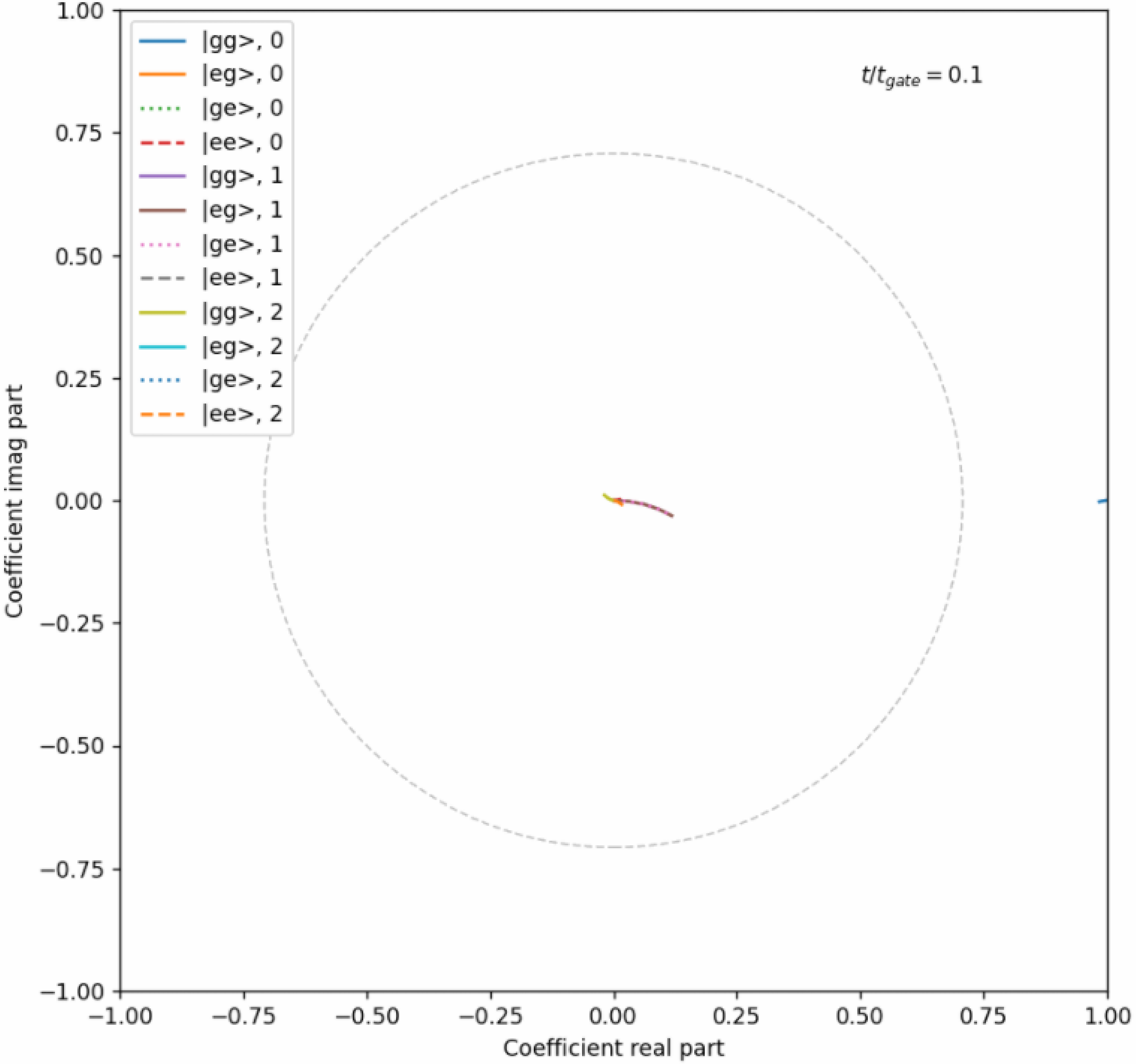
$$\boxed{\begin{aligned}|\psi\rangle &= c_1|gg,0\rangle + c_2|eg,0\rangle + c_3|ge,0\rangle + c_4|ee,0\rangle\\ &+ c_5|gg,1\rangle + c_6|eg,1\rangle + c_7|ge,1\rangle + c_8|ee,1\rangle\\ &+ c_9|gg,2\rangle + c_{10}|eg,2\rangle + c_{11}|ge,2\rangle + c_{12}|ee,2\rangle\end{aligned}}$$

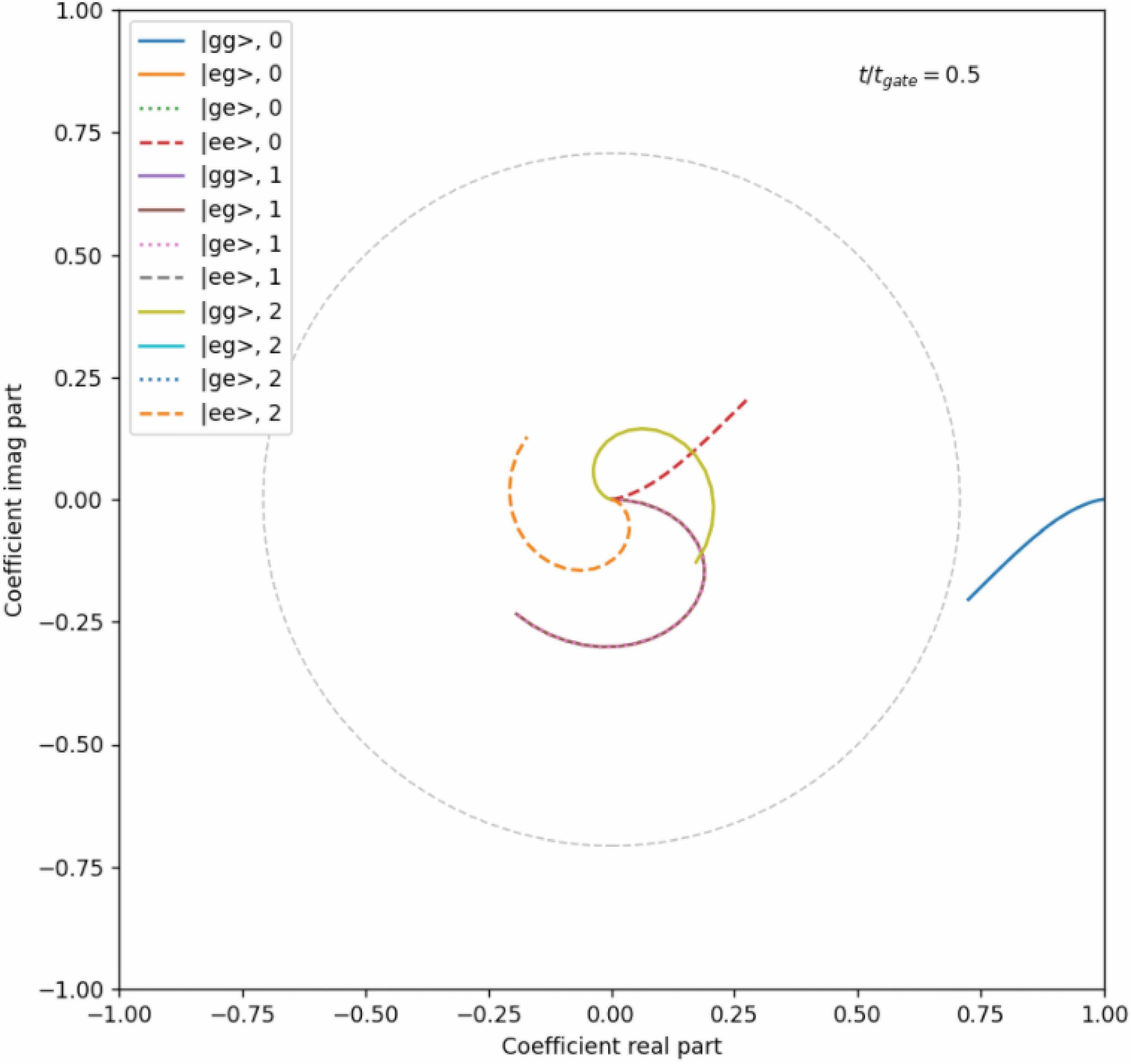


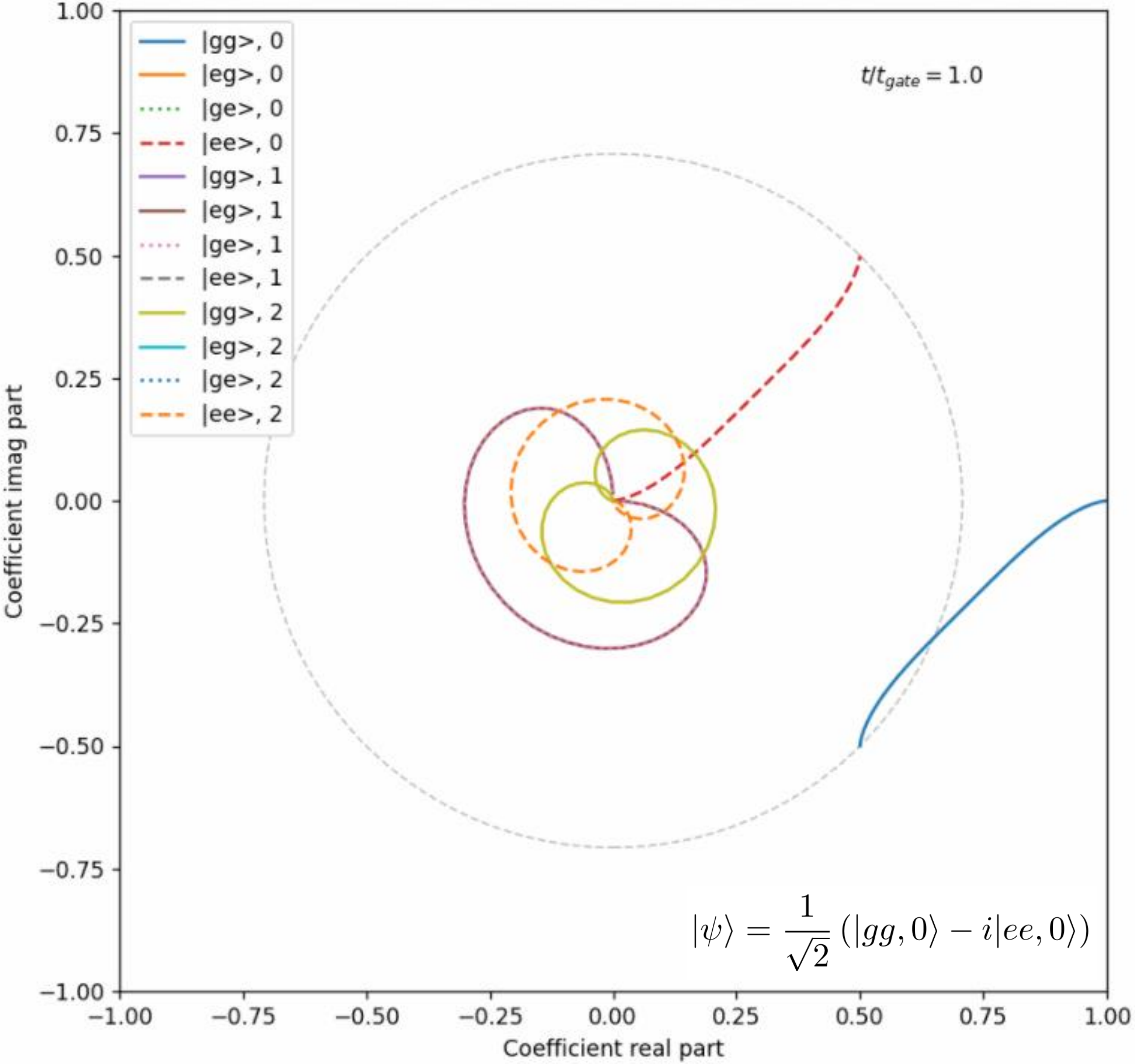
$$
\begin{aligned}
|\psi\rangle = {} & c_1|gg,0\rangle + c_2|eg,0\rangle + c_3|ge,0\rangle + c_4|ee,0\rangle \\
& + c_5|gg,1\rangle + c_6|eg,1\rangle + c_7|ge,1\rangle + c_8|ee,1\rangle \\
& + c_9|gg,2\rangle + c_{10}|eg,2\rangle + c_{11}|ge,2\rangle + c_{12}|ee,2\rangle
\end{aligned}
$$

$$|\psi\rangle = |gg,0\rangle$$

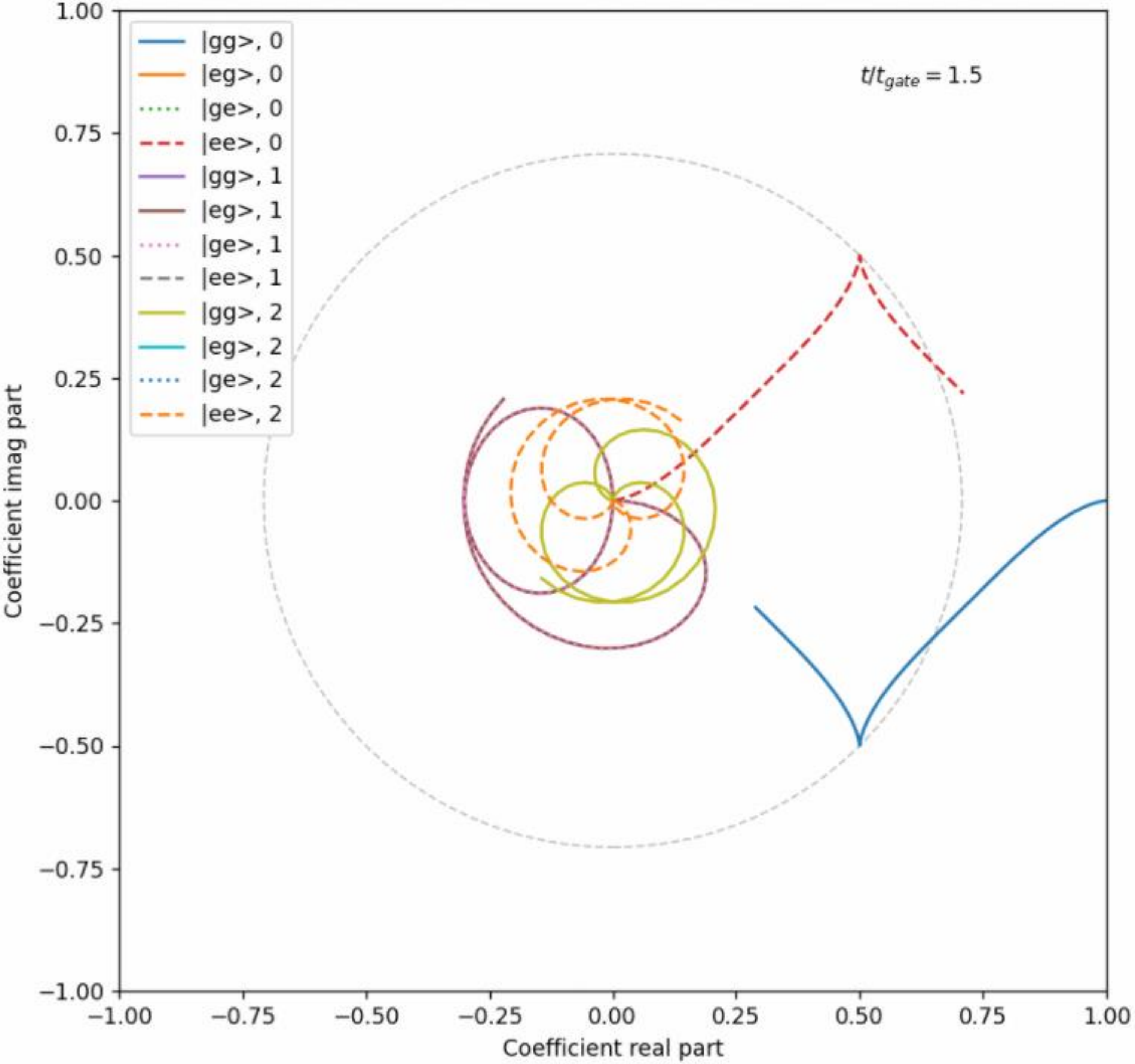
Source: wikipedia
]

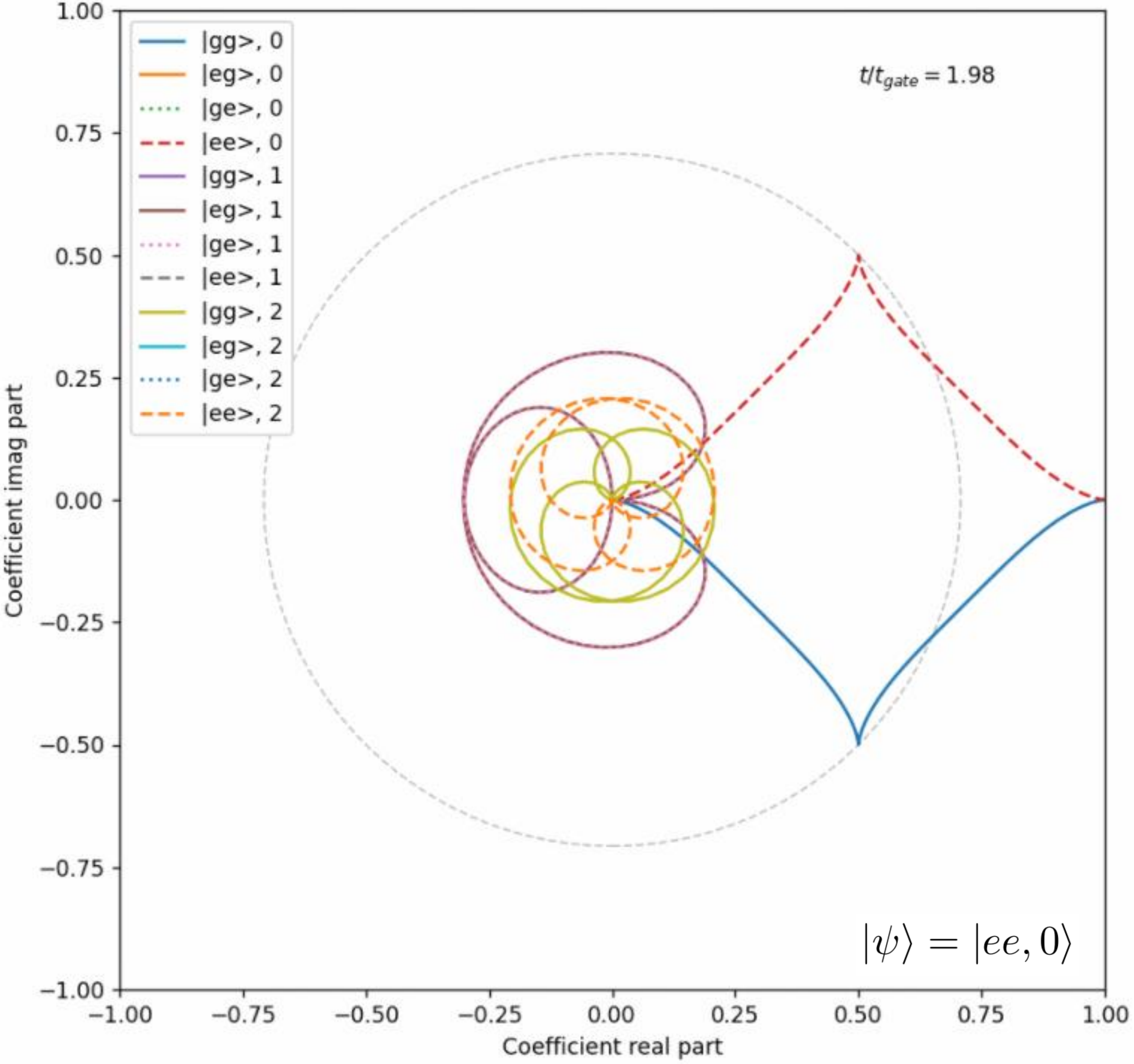

|gg>, 0
|eg>, 0
|ge>, 0
|ee>, 0
|gg>, 1
|eg>, 1
|ge>, 1
|ee>, 1
|gg>, 2
|eg>, 2
|ge>, 2
|ee>, 2
$t/t_{gate} = 0.1$
Coefficient imag part
Coefficient real part
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00


|gg>, 0
|eg>, 0
|ge>, 0
|ee>, 0
|gg>, 1
|eg>, 1
|ge>, 1
|ee>, 1
|gg>, 2
|eg>, 2
|ge>, 2
|ee>, 2
$t/t_{gate} = 0.5$
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
Coefficient imag part
Coefficient real part



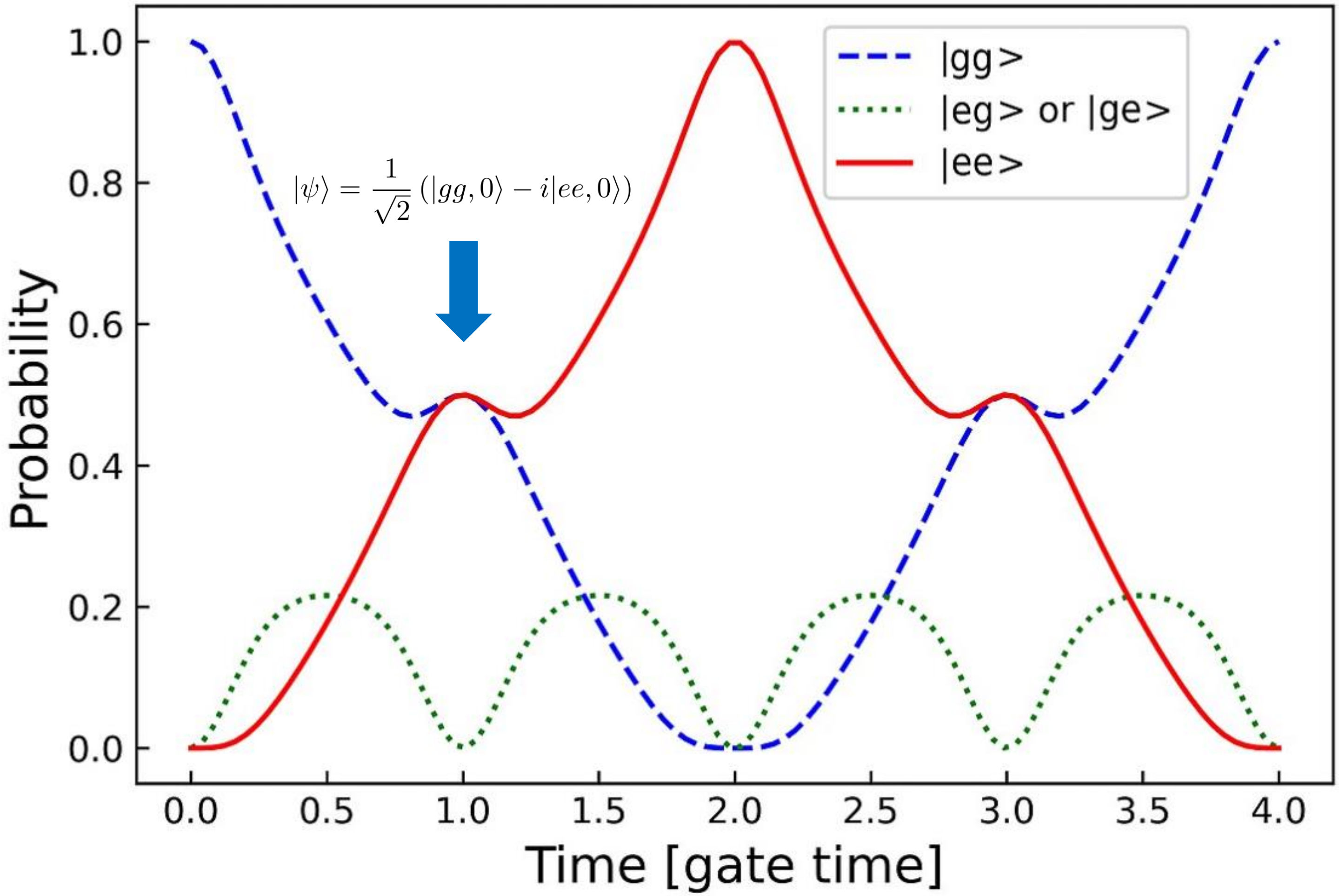
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|gg,0\rangle - i|ee,0\rangle\right)$$


|gg>, 0
|eg>, 0
|ge>, 0
|ee>, 0
|gg>, 1
|eg>, 1
|ge>, 1
|ee>, 1
|gg>, 2
|eg>, 2
|ge>, 2
|ee>, 2
$t/t_{gate} = 1.5$
Coefficient imag part
Coefficient real part
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00



$|\psi\rangle = |ee, 0\rangle$

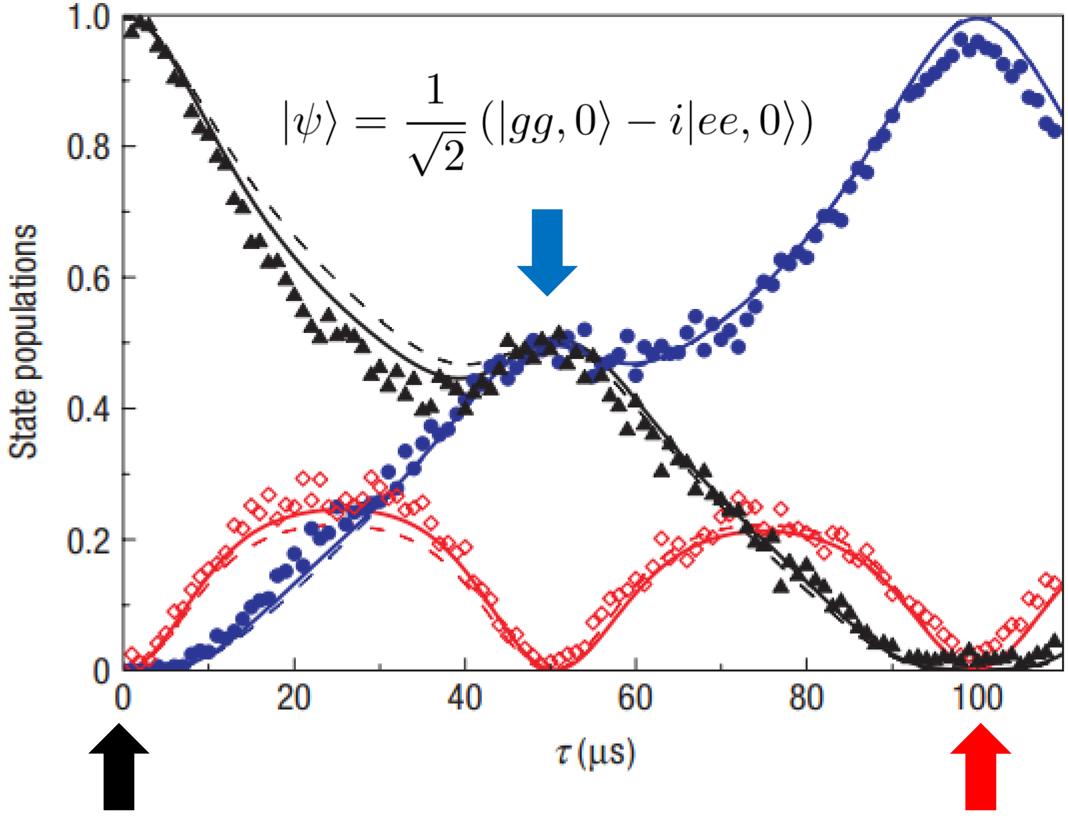
Evolution of population



$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|gg,0\rangle - i|ee,0\rangle\right)$$

`Rabi oscillation of entangled state’

Ion-ion entanglement



$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|gg,0\rangle - i|ee,0\rangle\right)$$

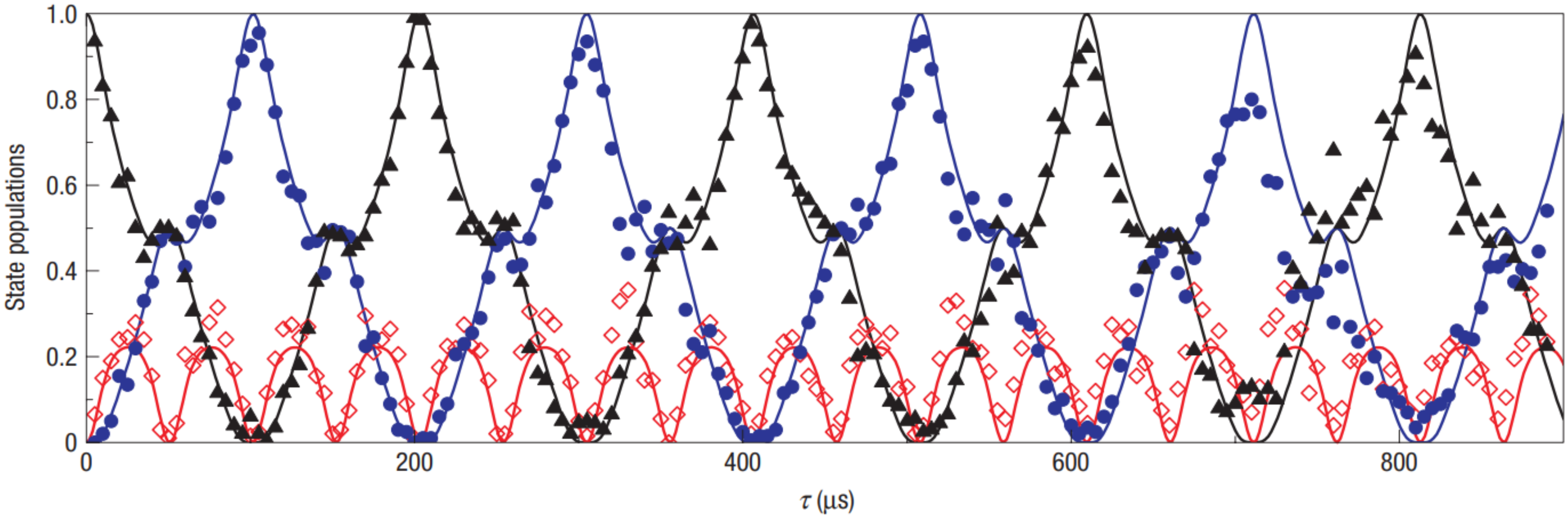
$$|\psi\rangle = |gg,0\rangle$$

$$|\psi\rangle = |ee,0\rangle$$

Axial mode, optical qubit $^{40}\mathrm{Ca}^{+}$

Benhelm, Kirchmair, Roos, Blatt, Nat. Phys. 4, 463 (2009)

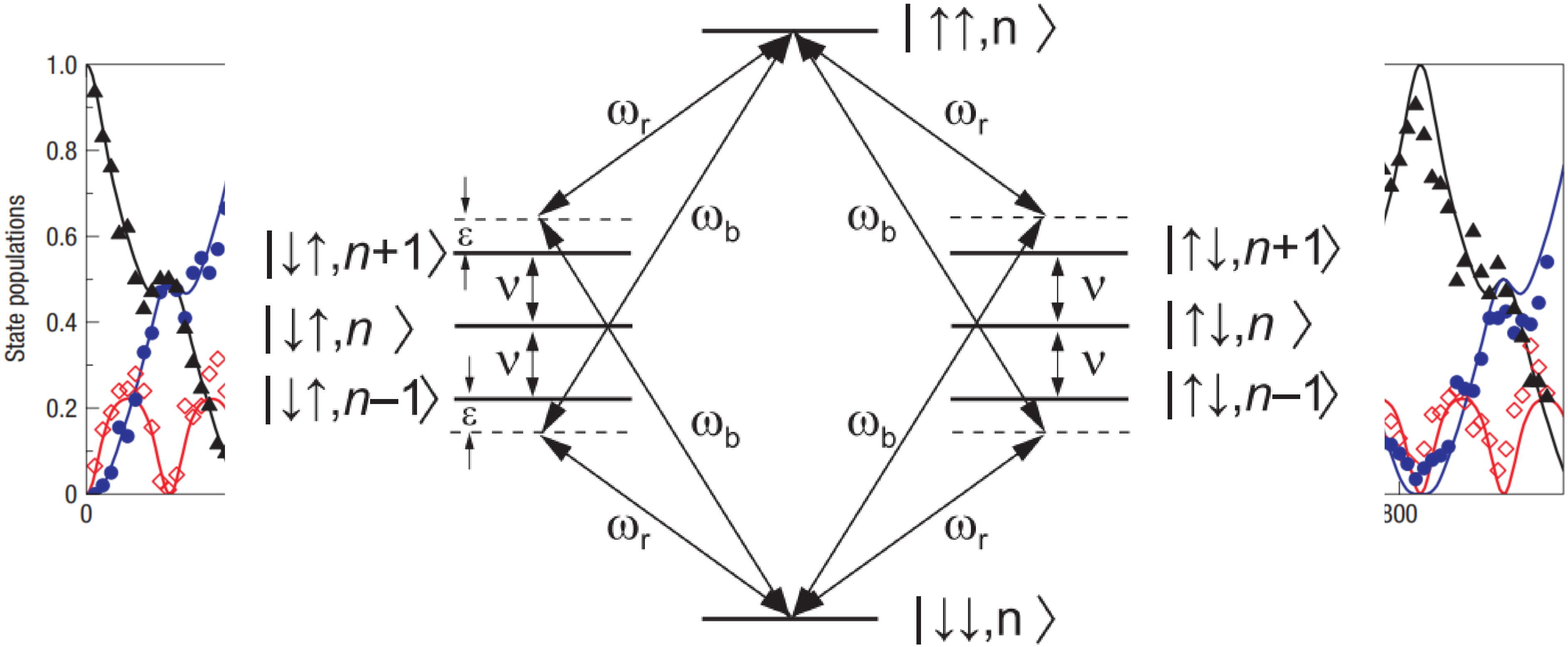
Ion-ion entanglement



Axial mode, optical qubit $^{40}\mathrm{Ca}^+$
Benhelm, Kirchmair, Roos, Blatt, Nat. Phys. 4, 463 (2009)

Radial mode, hyperfine qubit $^{171}\mathrm{Yb}^+$
See also: Kim et al., PRL 2009, Choi et al., PRL 2014

Ion-ion entanglement



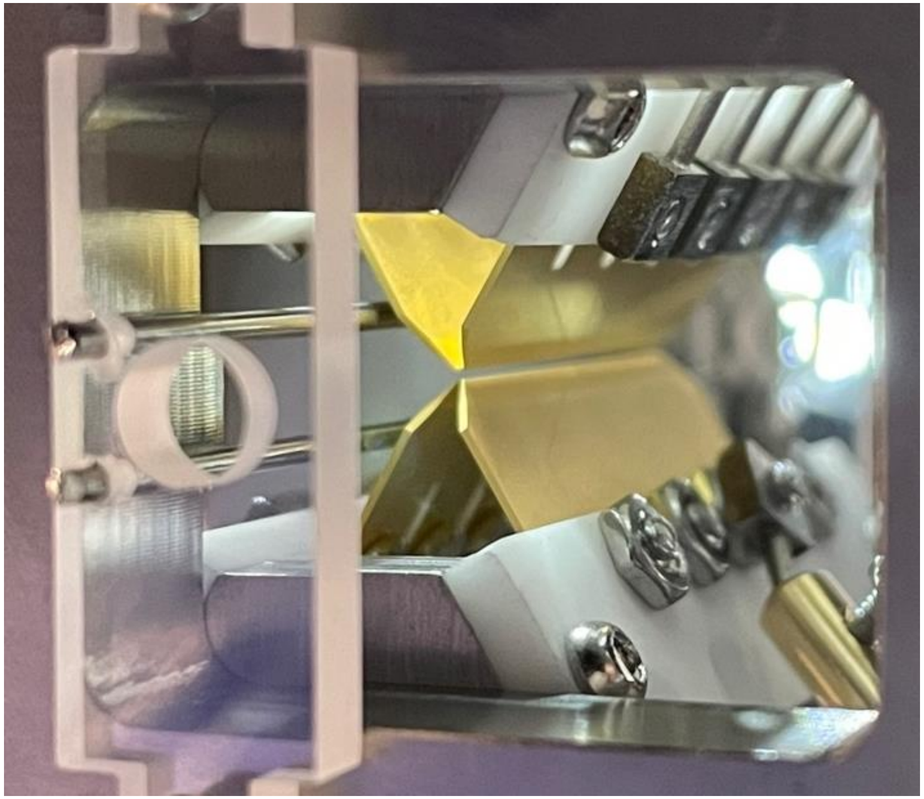
Benhelm, Kirchmair, Roos, Blatt, Nat. Phys. 4, 463 (2009)

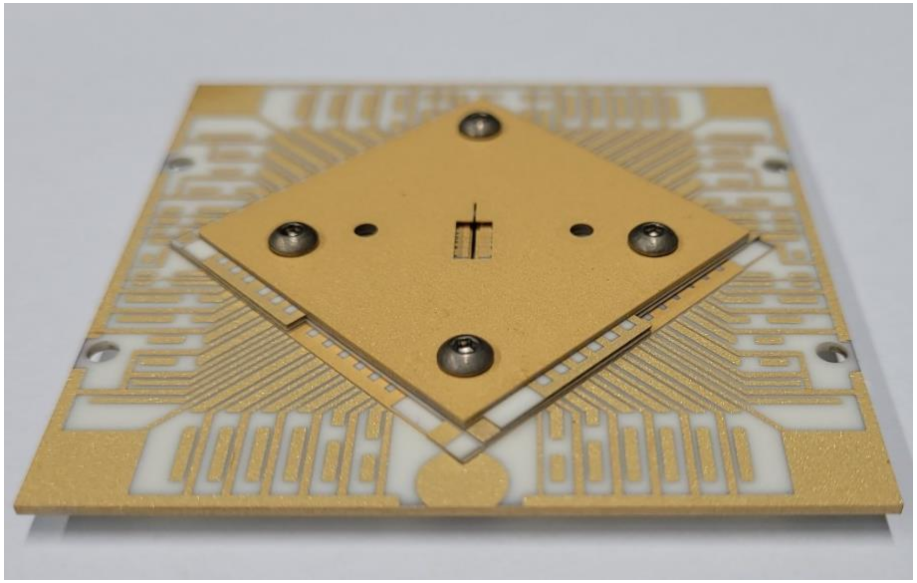
Radial mode, hyperfine qubit ^{171}Yb$^+$
See also: Kim et al., PRL 2009, Choi et al., PRL 2014

목차

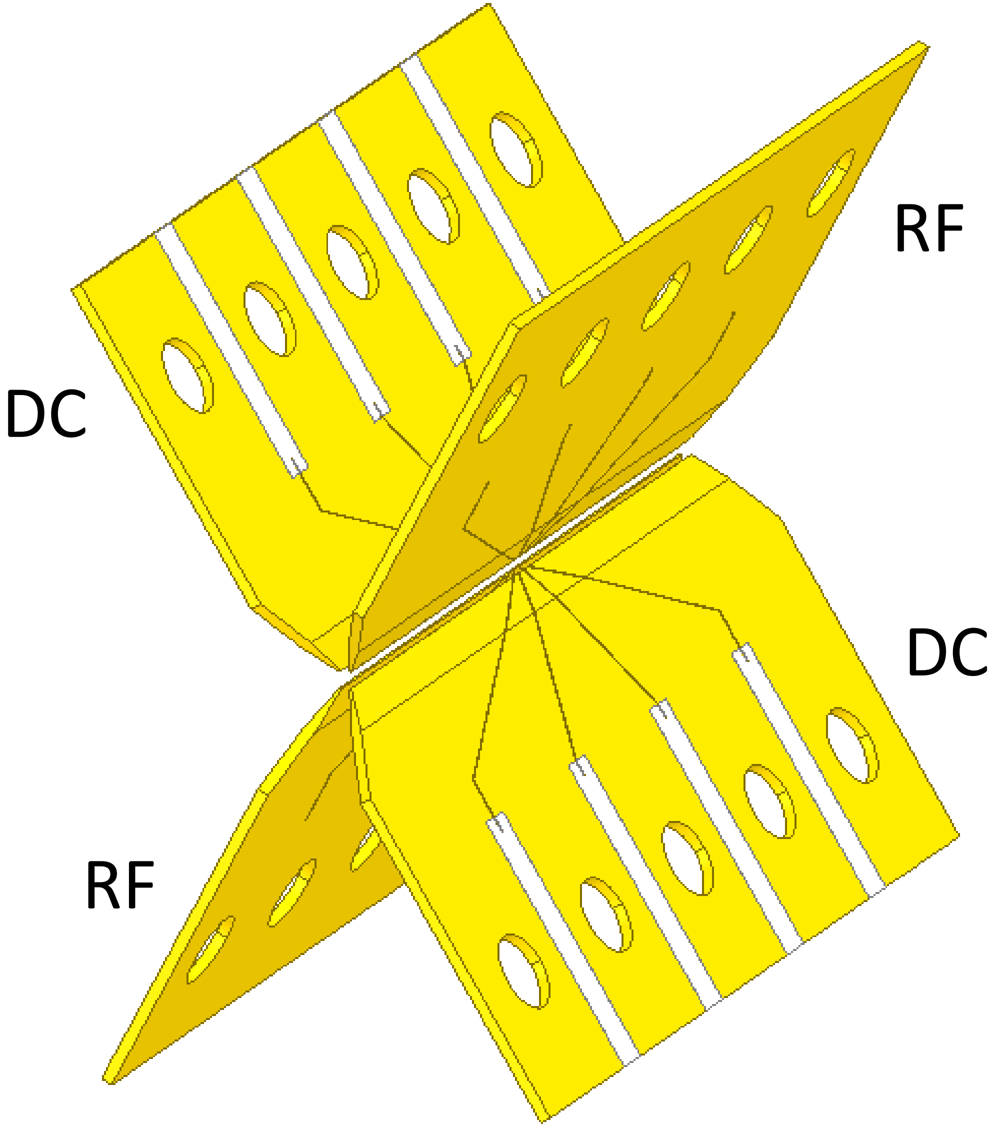
- 양자컴퓨터 분야 동향 소개
- 이온 트랩 특징 및 소개
- 이온 트랩 기본 계산
- 이온 얽힘 발생 소개
- 포항공대 이온 트랩 연구 소개

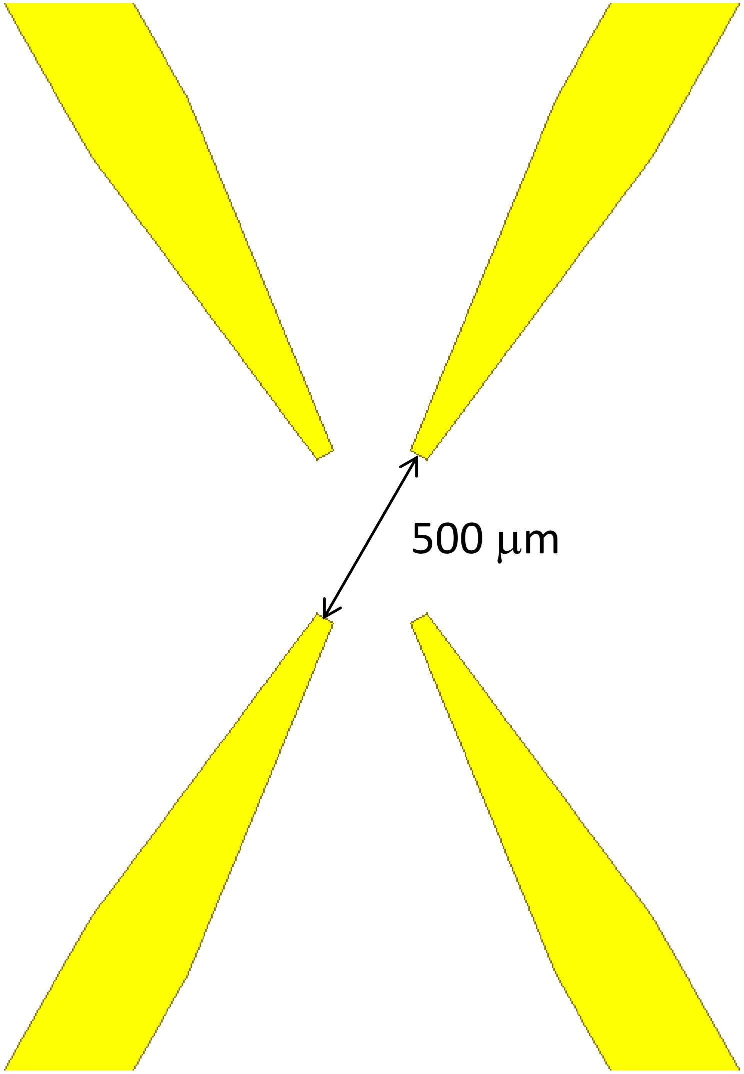
포항공대에서 개발 중인 이온 트랩





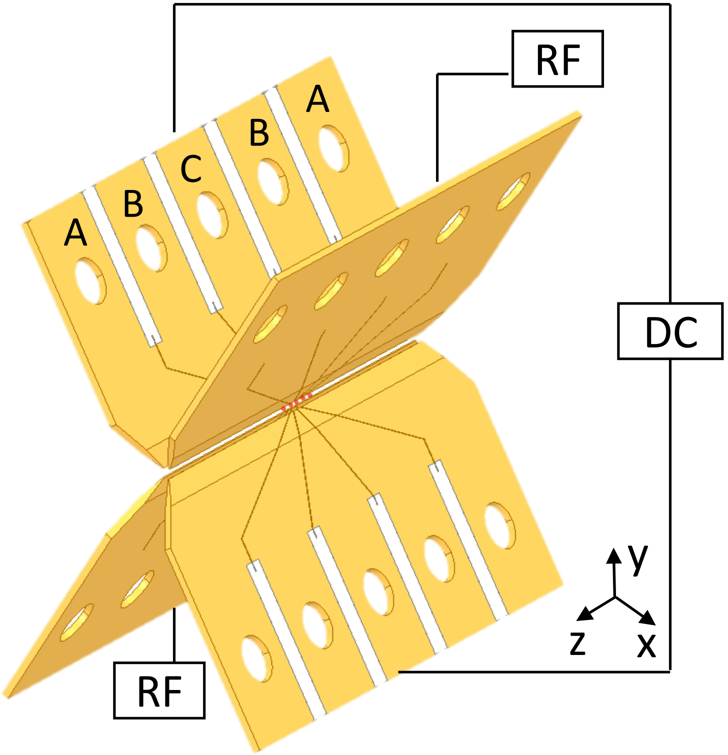
Segmented blade trap

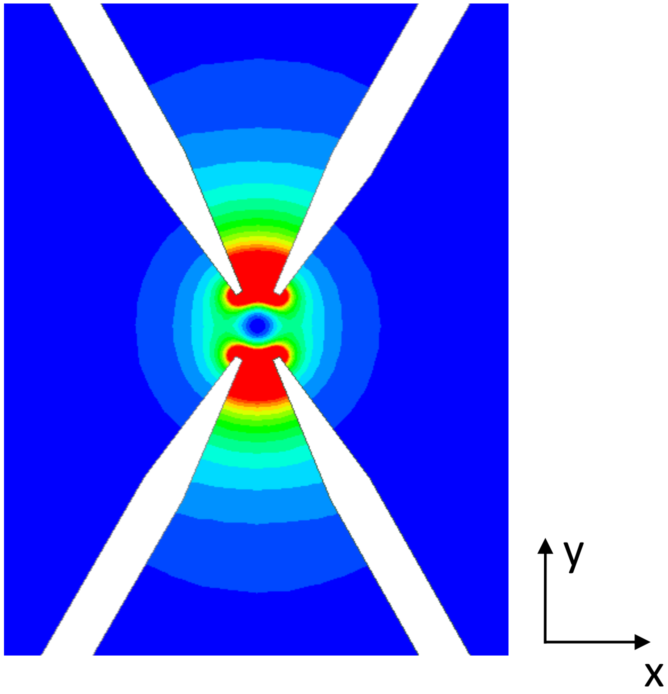


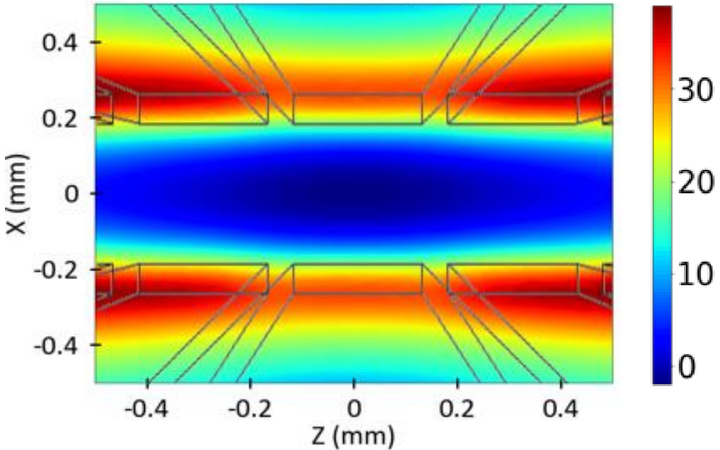


Numerical aperture > 0.38

Trapping potential simulation







- RF amplitude 600 V, 22.5 MHz
- DC voltage
  - A : 15V
  - B : 3V
  - C : -10V

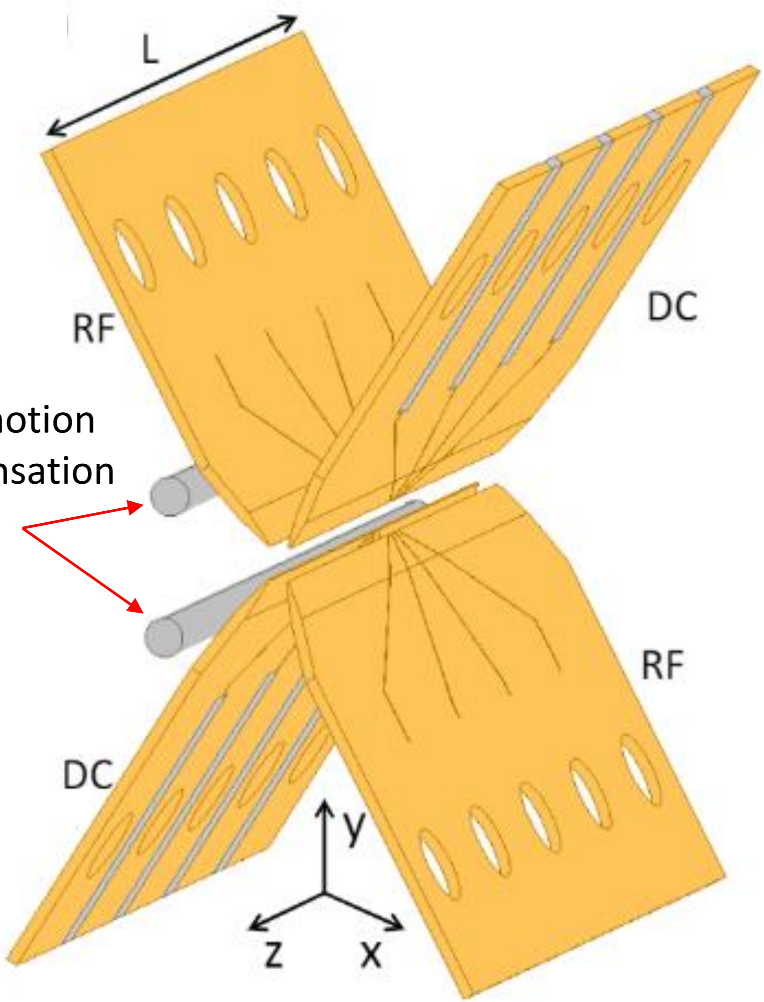
$^{171}\text{Yb}^{+}$

Secular frequency

(3, 3, 1) MHz

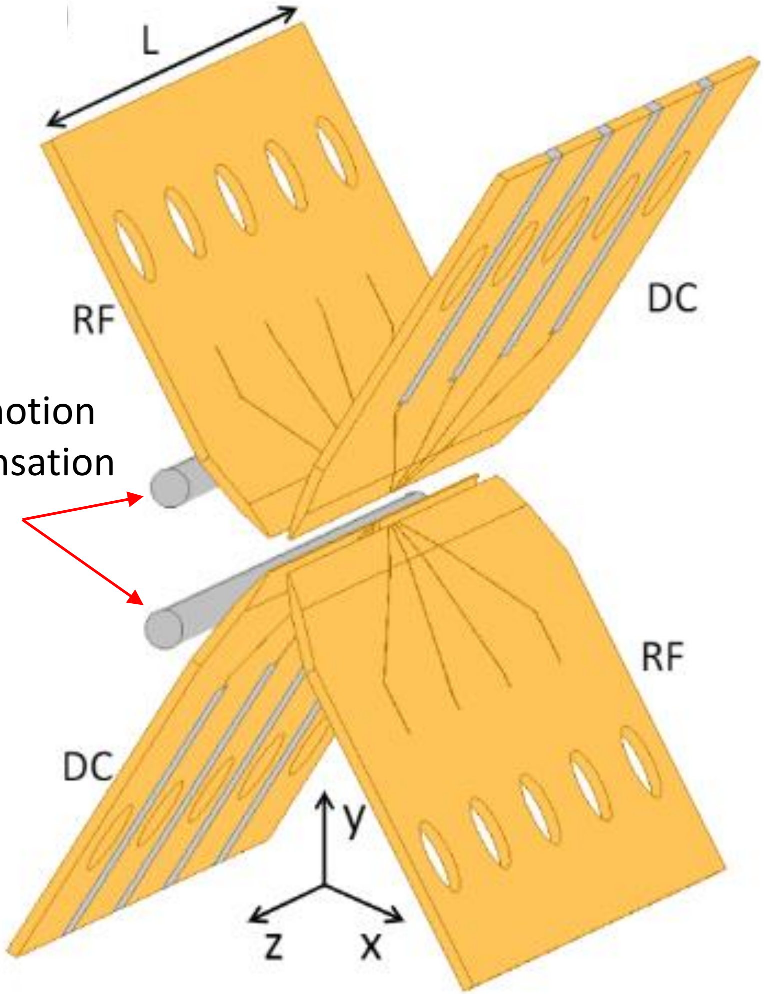
ANSYS Electronics Desktop 2020 R1

We have two new features

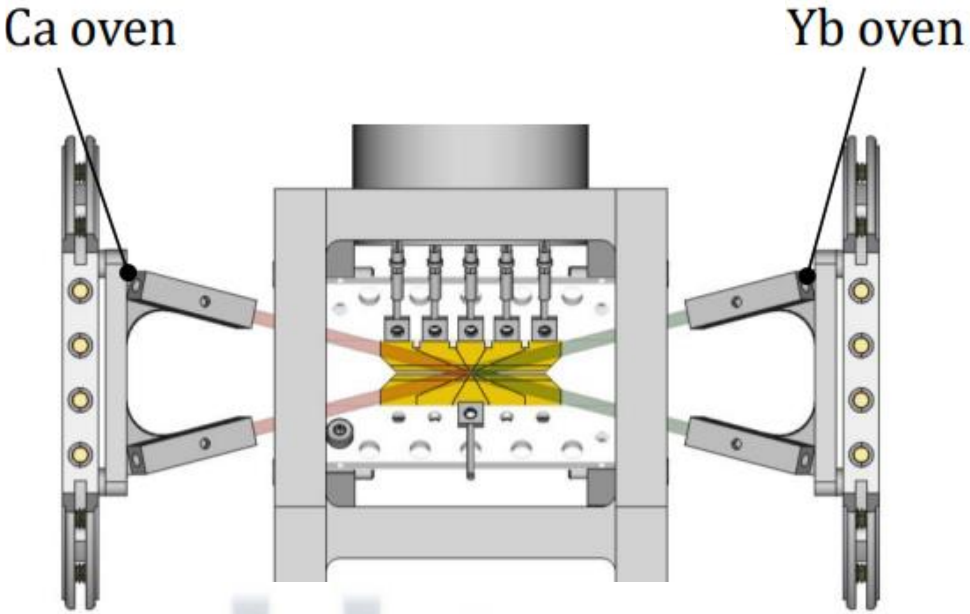


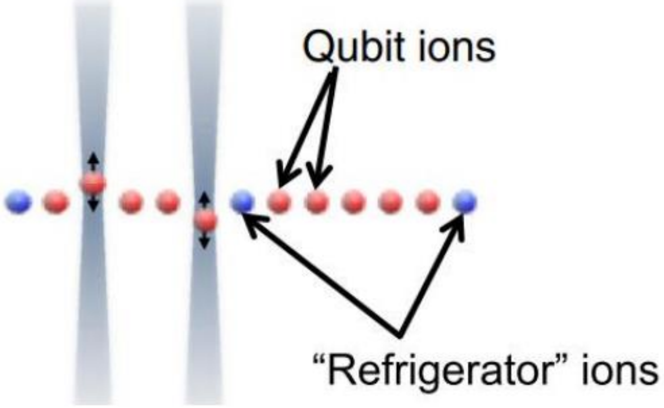
Micromotion compensation rods

We have two new features



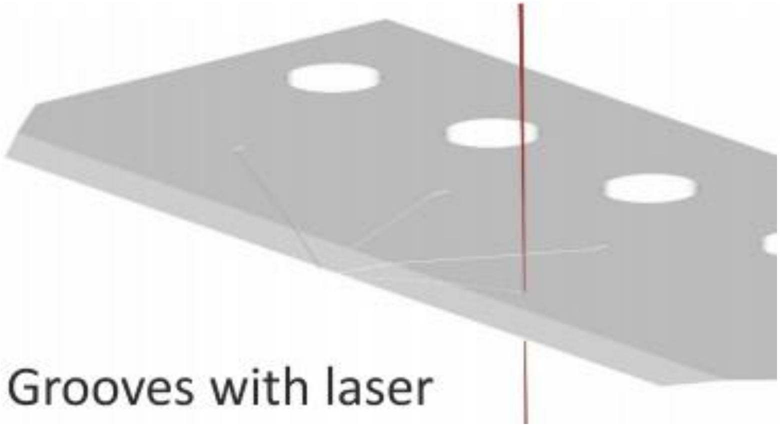
Micromotion compensation rods

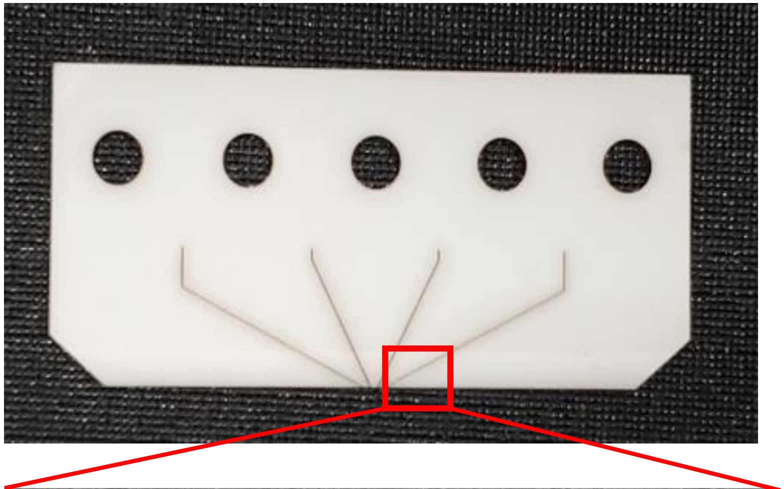


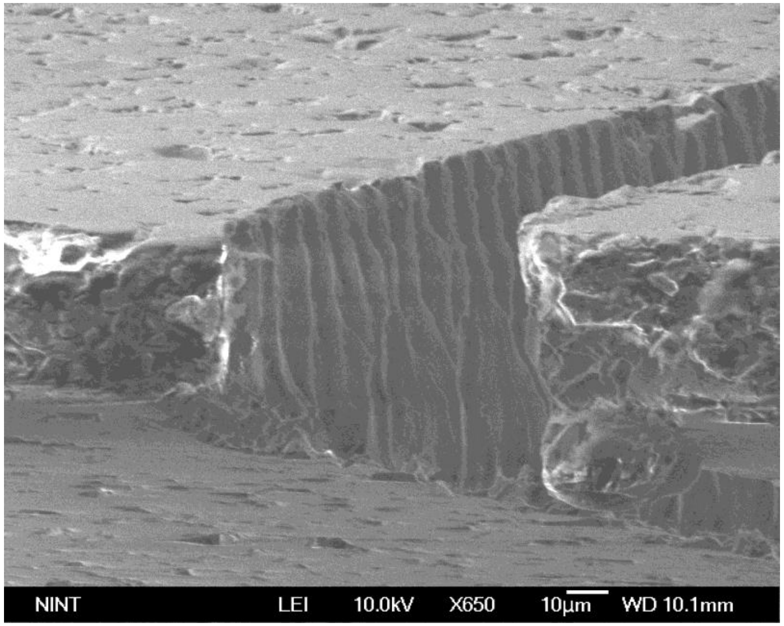


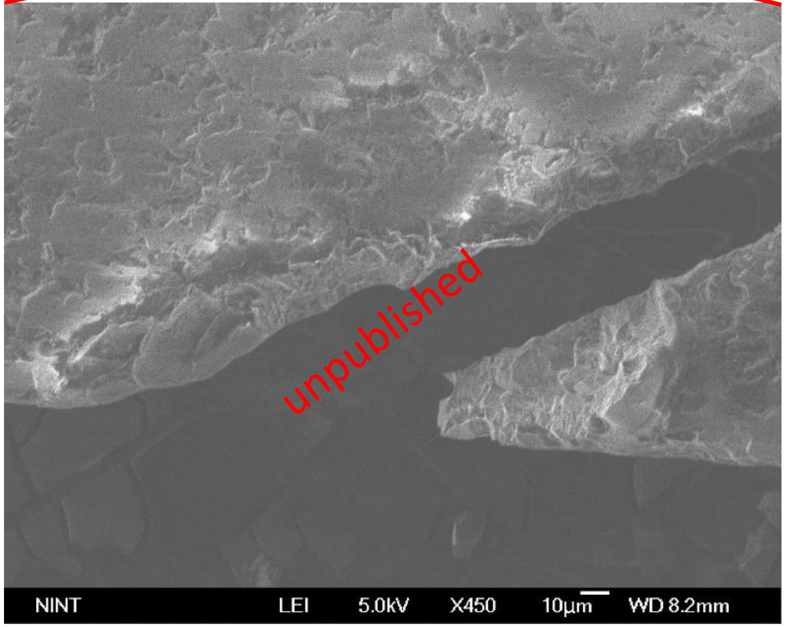
Mixed crystal: sympathetic cooling, no crosstalk…

1) Laser micromachining



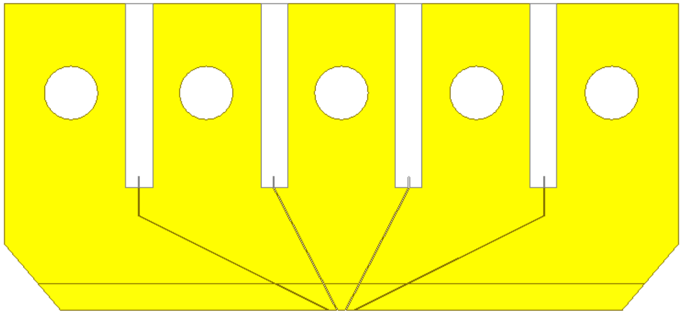






21th century, Inc., Korea
300-µm thick Al_2O_3

2) Gold sputtering

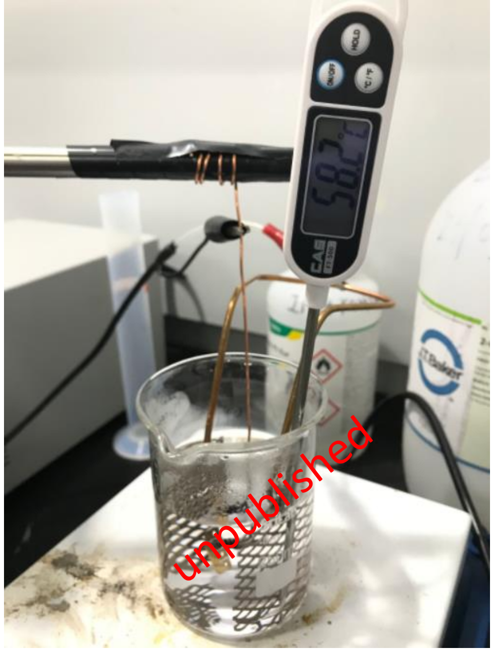


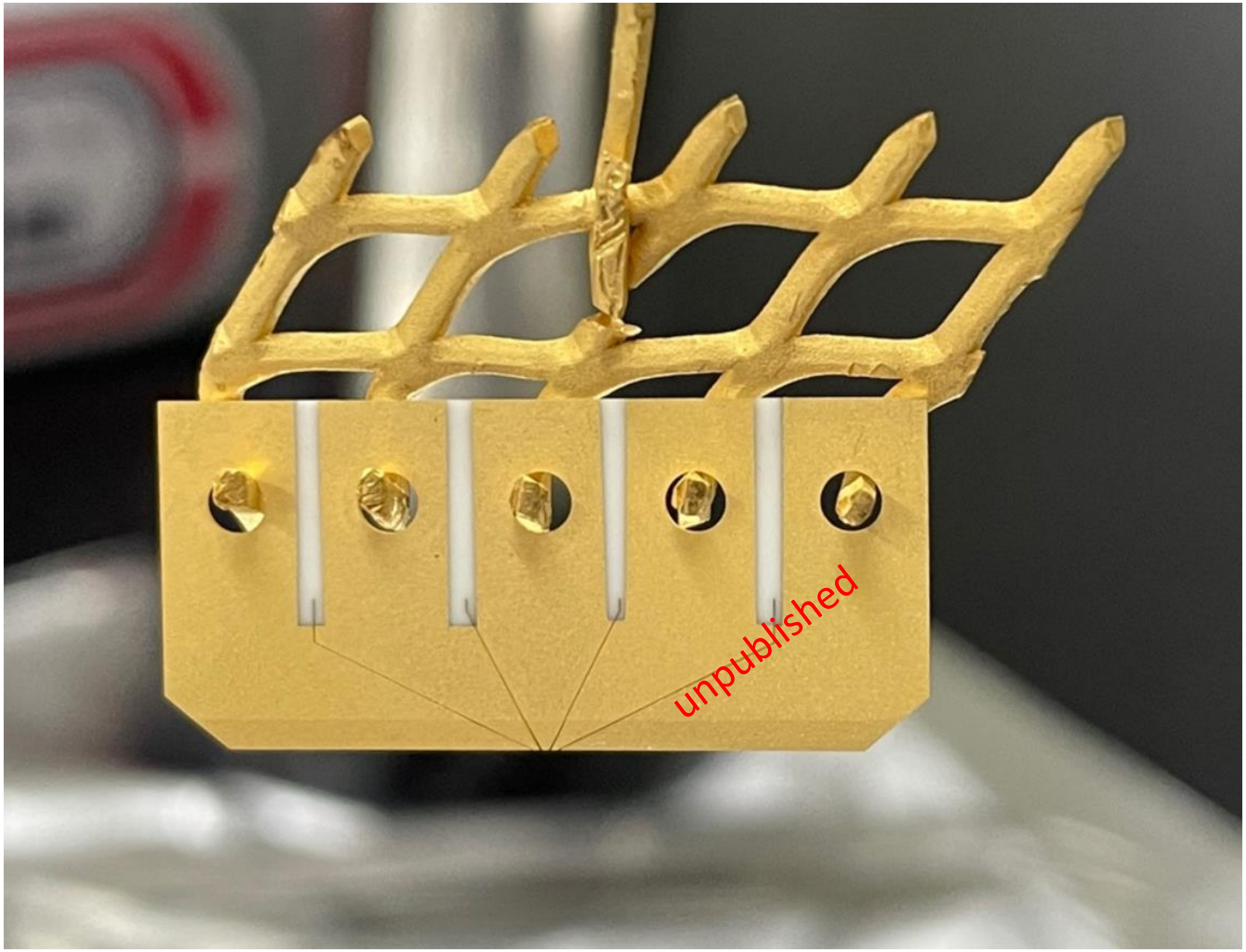
Metal mask

sputtering

- 100-nm thick Au

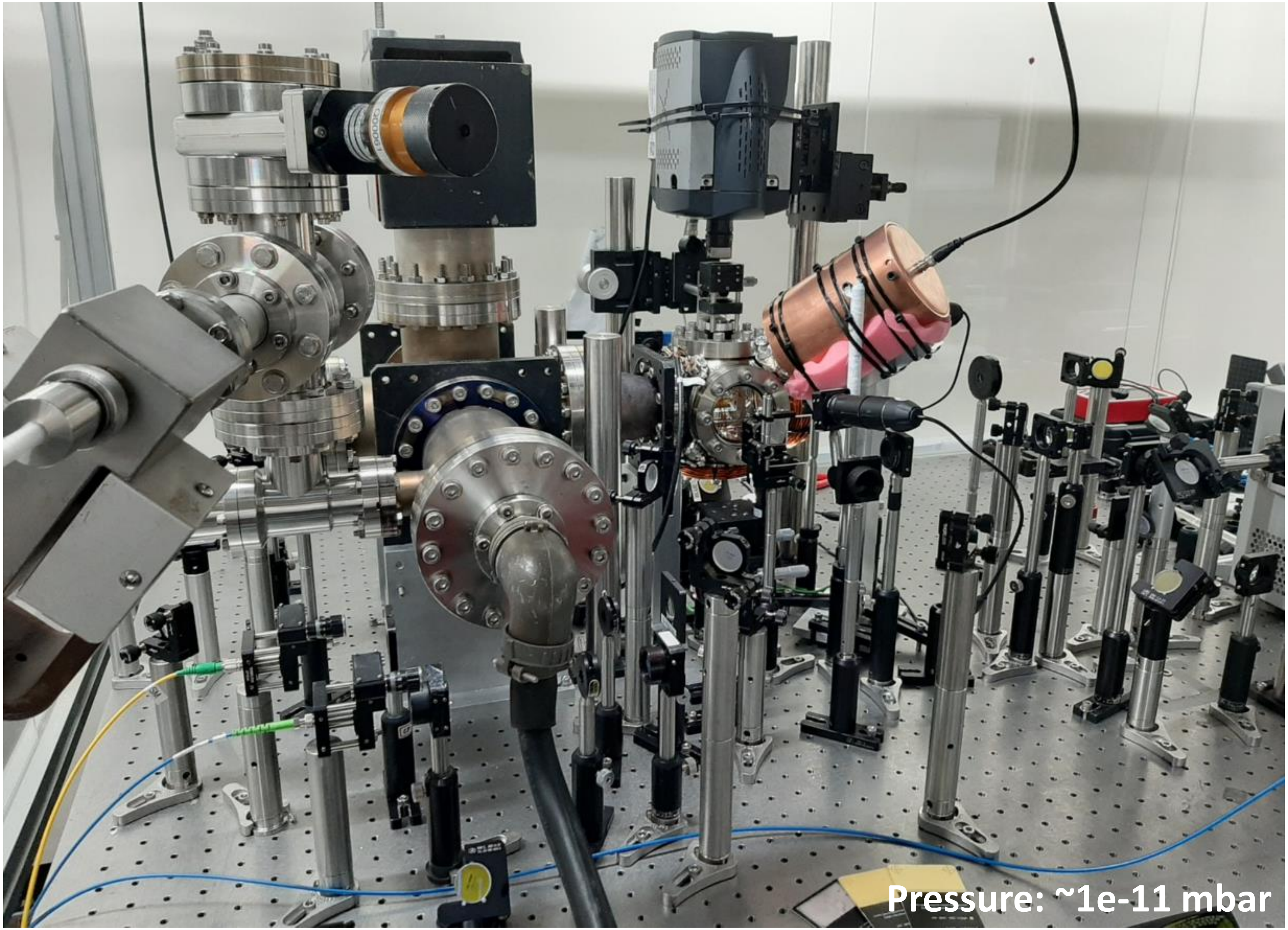
3) Gold electroplating





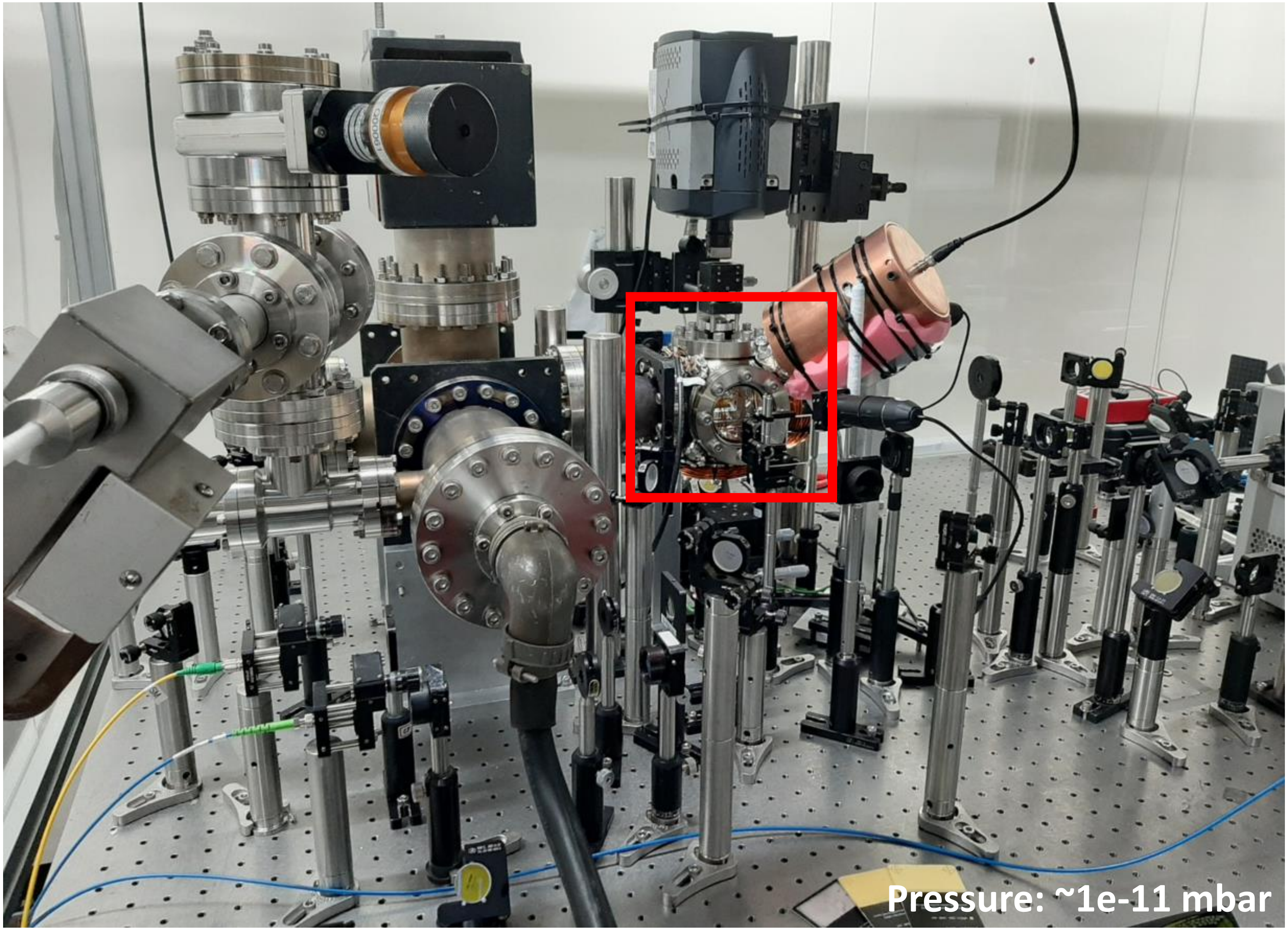
- Au thickness of ~3 μm

Vacuum chamber and optics



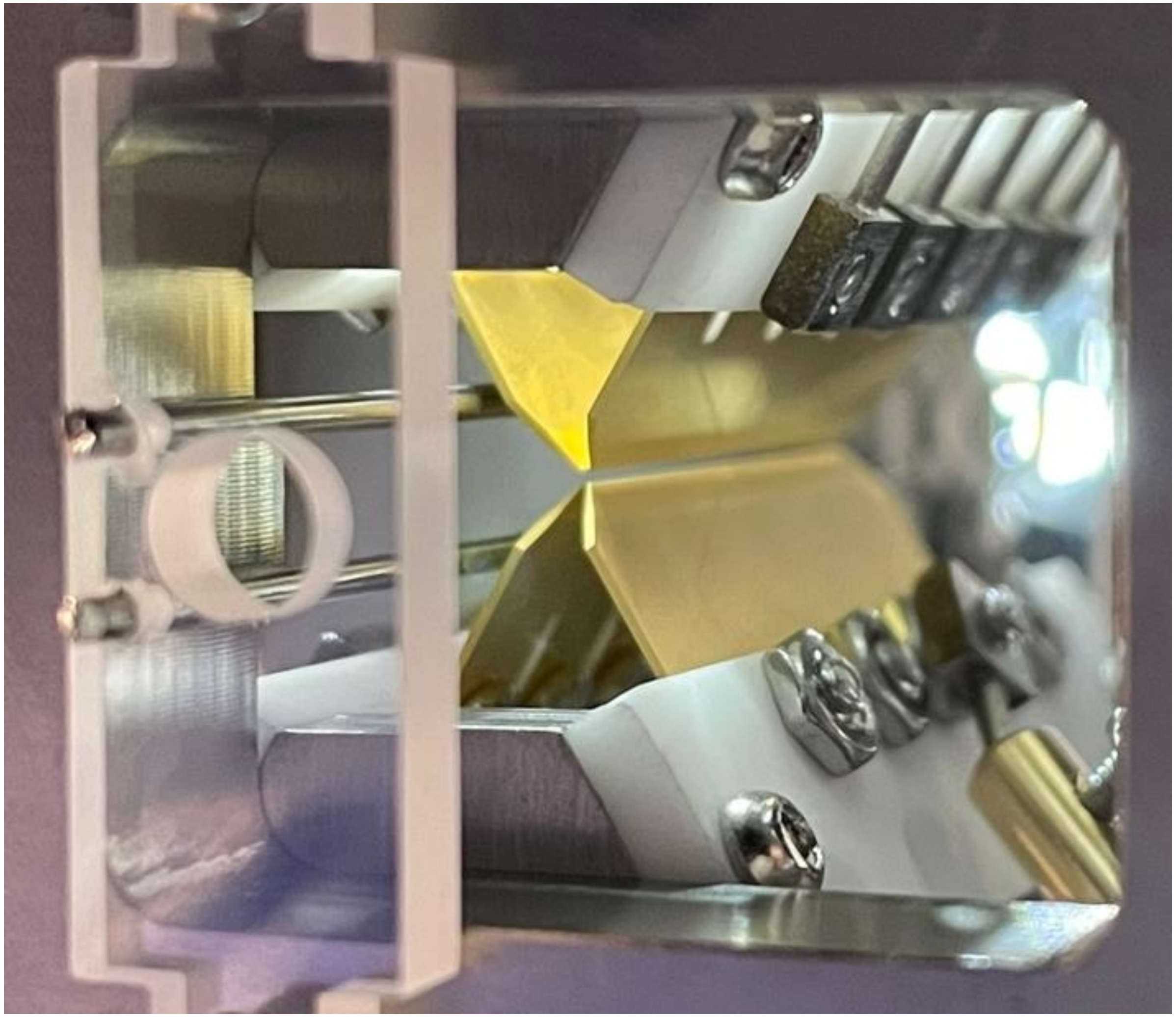
Pressure: ~1e-11 mbar

Vacuum chamber and optics

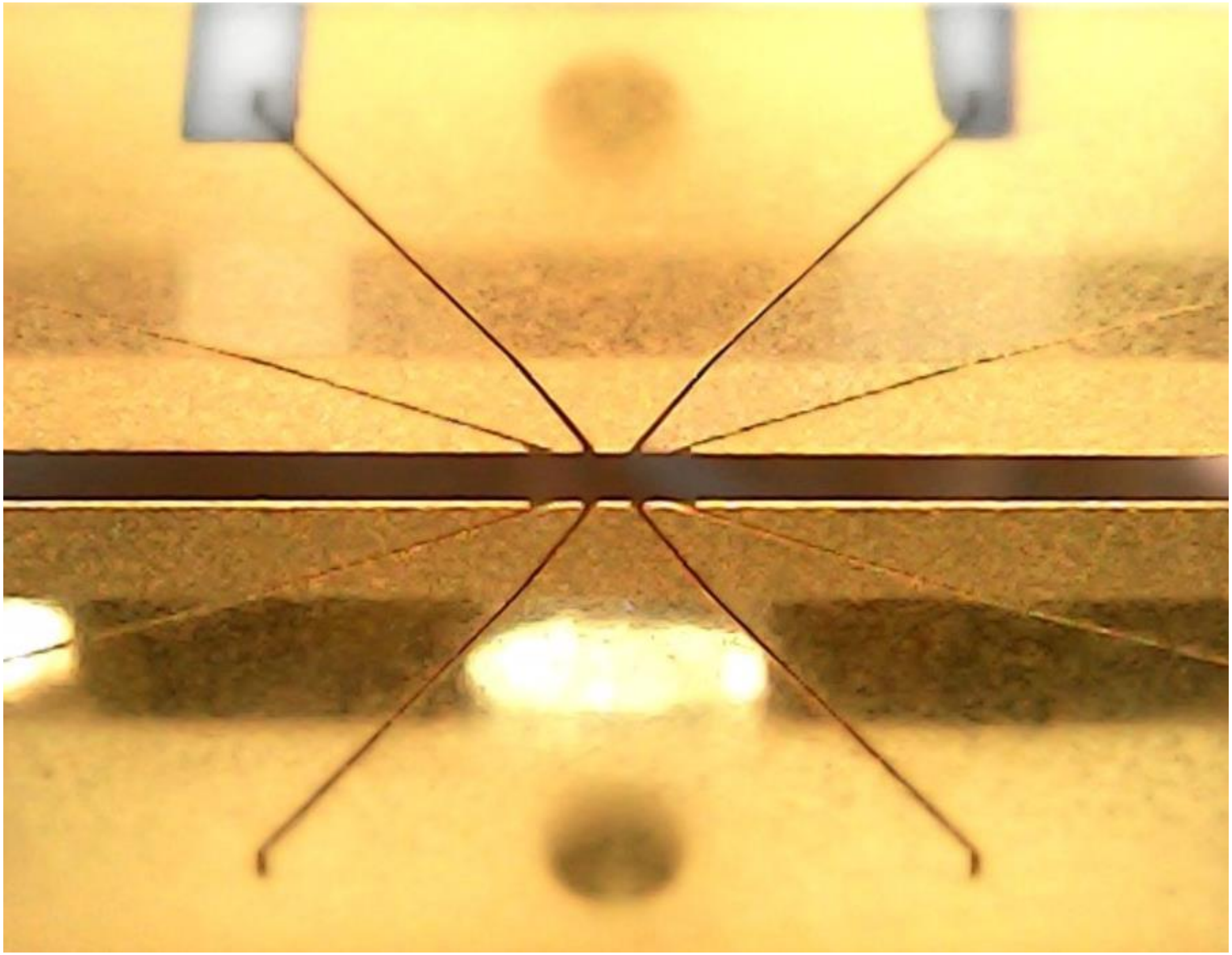


Pressure: ~1e-11 mbar

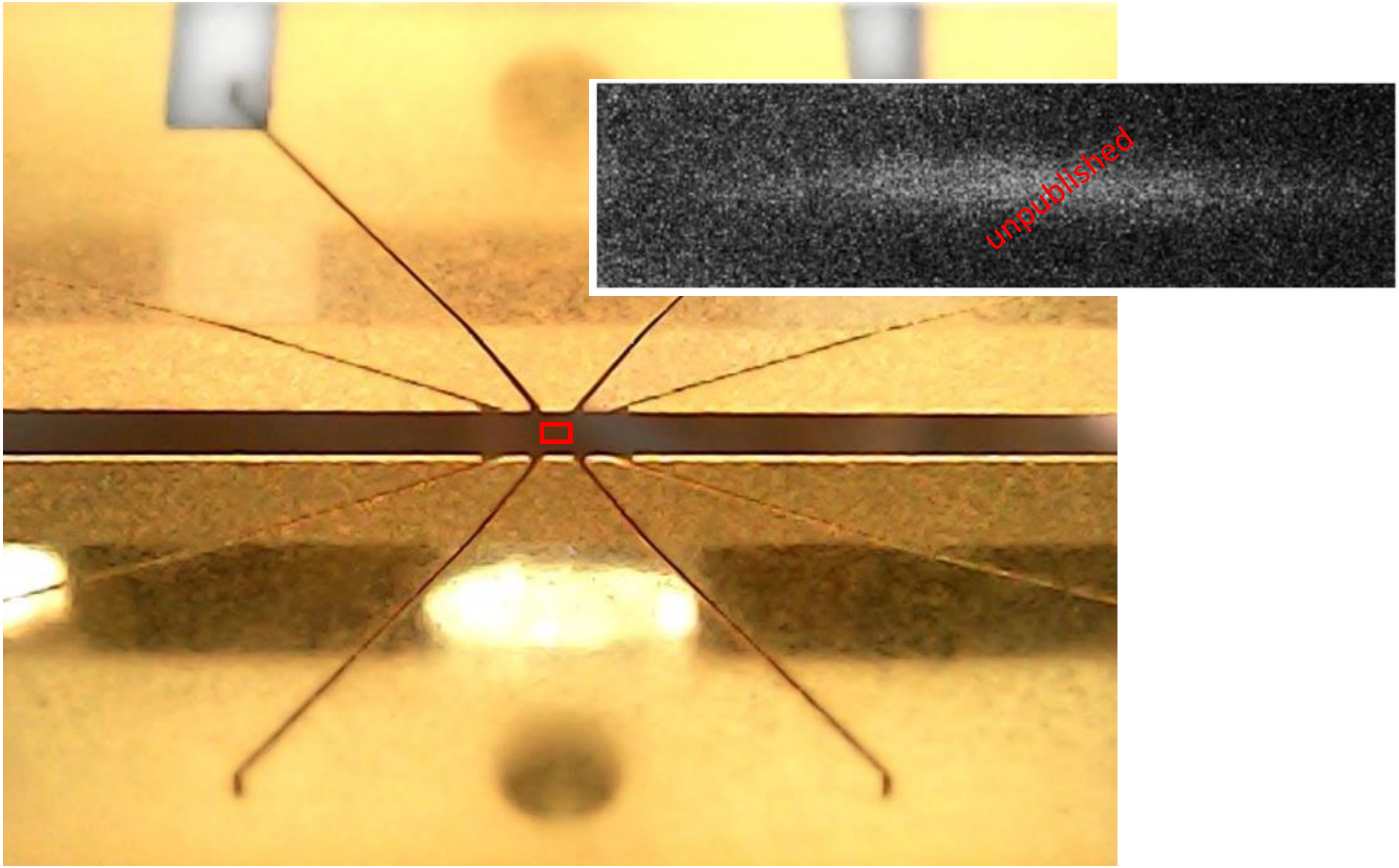
Our trap



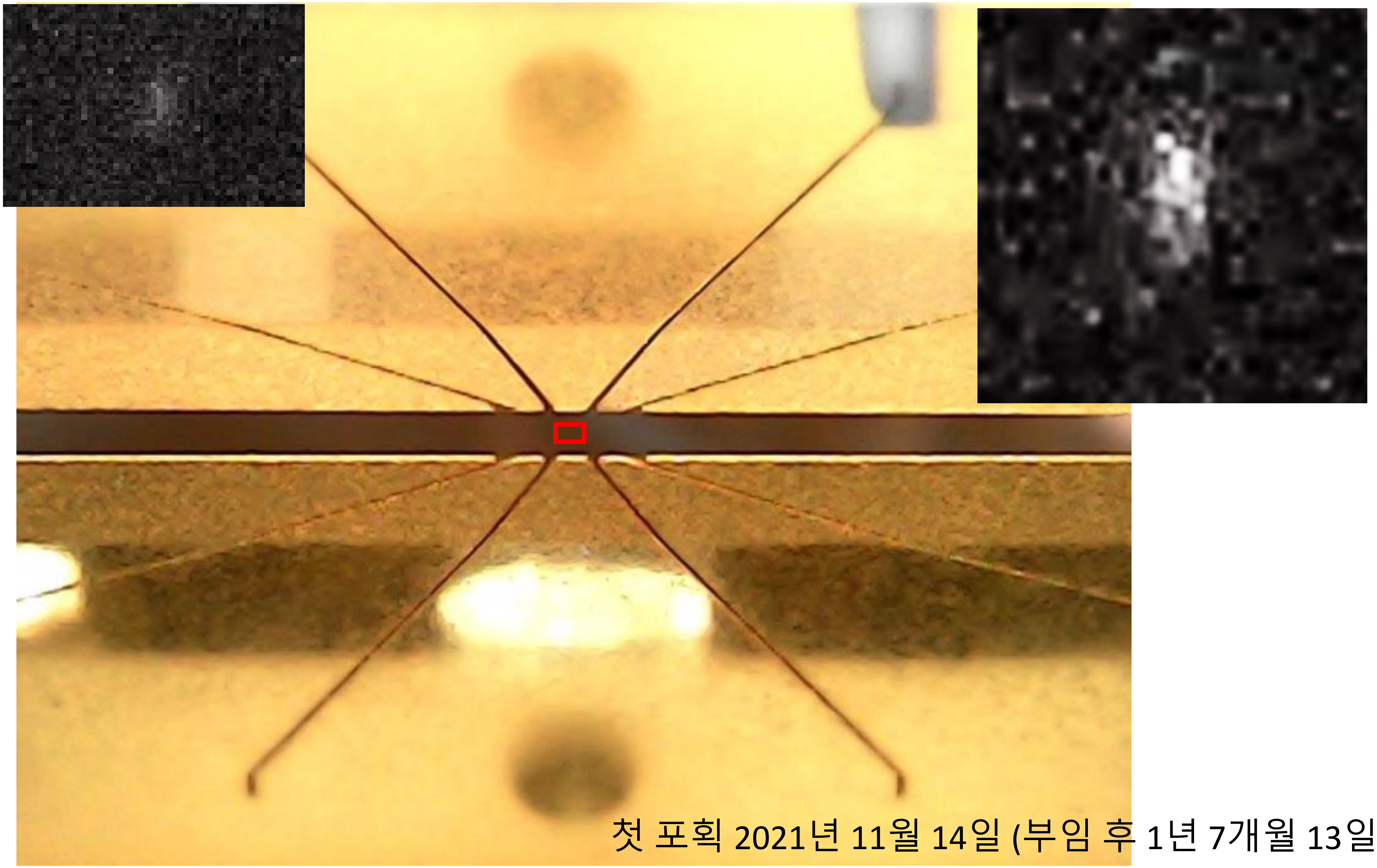
Our trap and status: $^{174}\mathrm{Yb}^{+}$



Our trap and status: $^{174}\mathrm{Yb}^{+}$

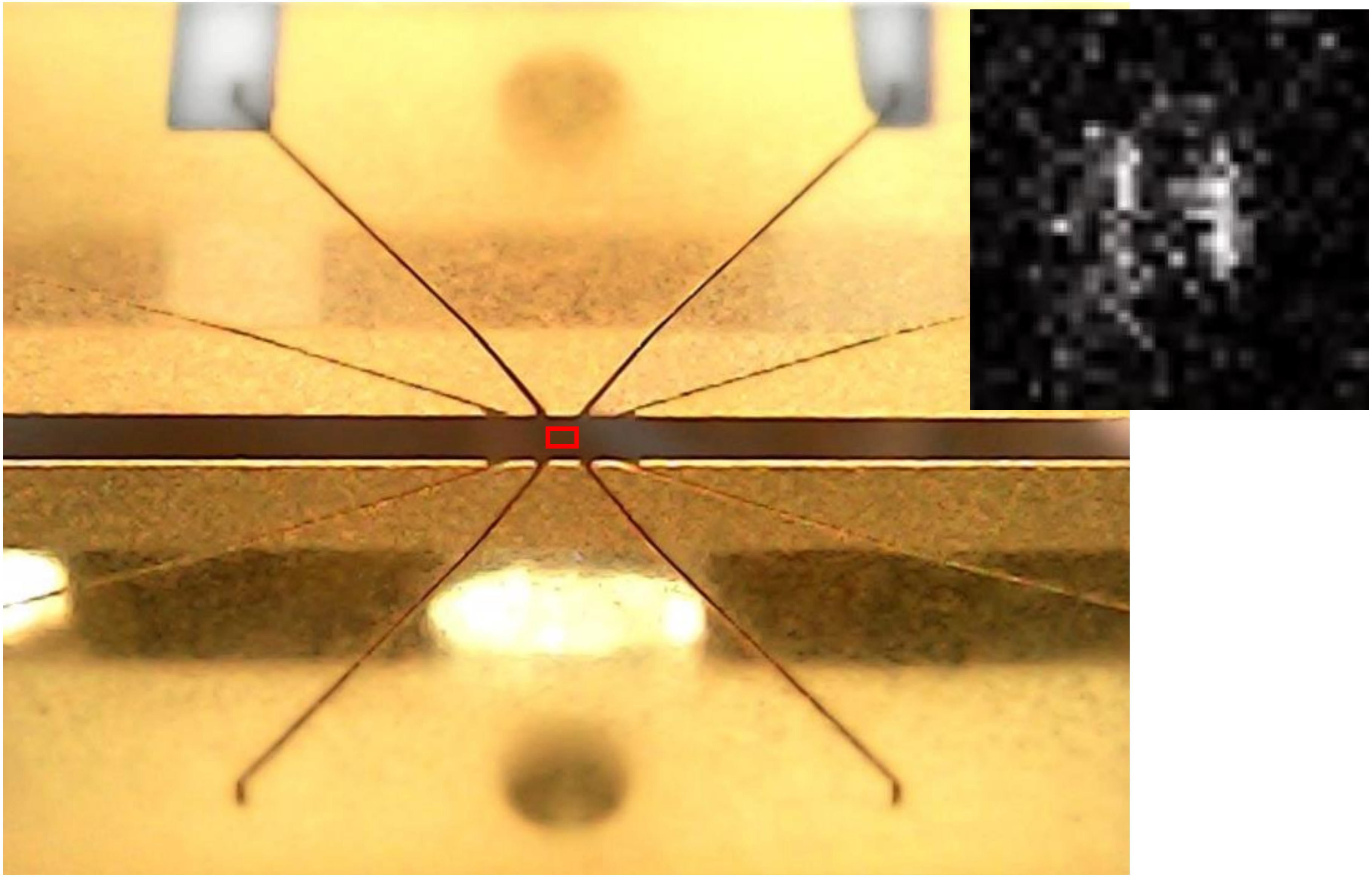


Our trap and status: $^{174}Yb^{+}$

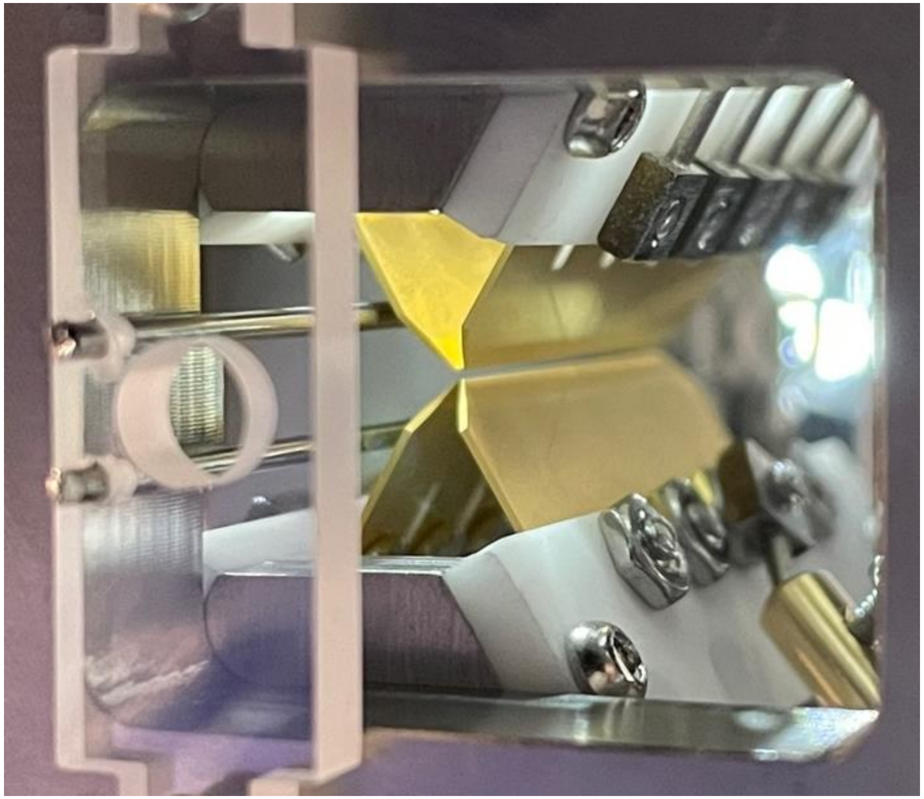


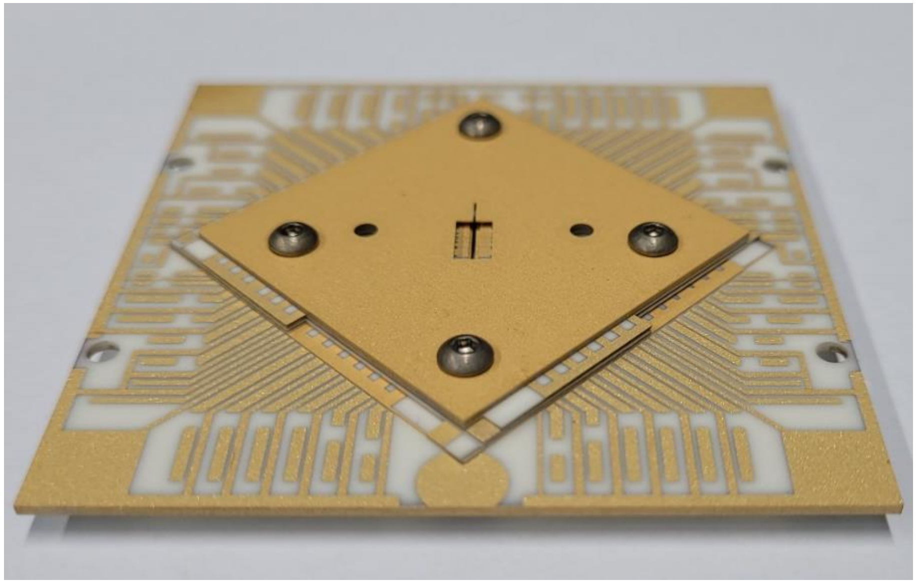
첫 포획 2021년 11월 14일 (부임 후 1년 7개월 13일)

Our trap and status: $^{174}\mathrm{Yb}^+$

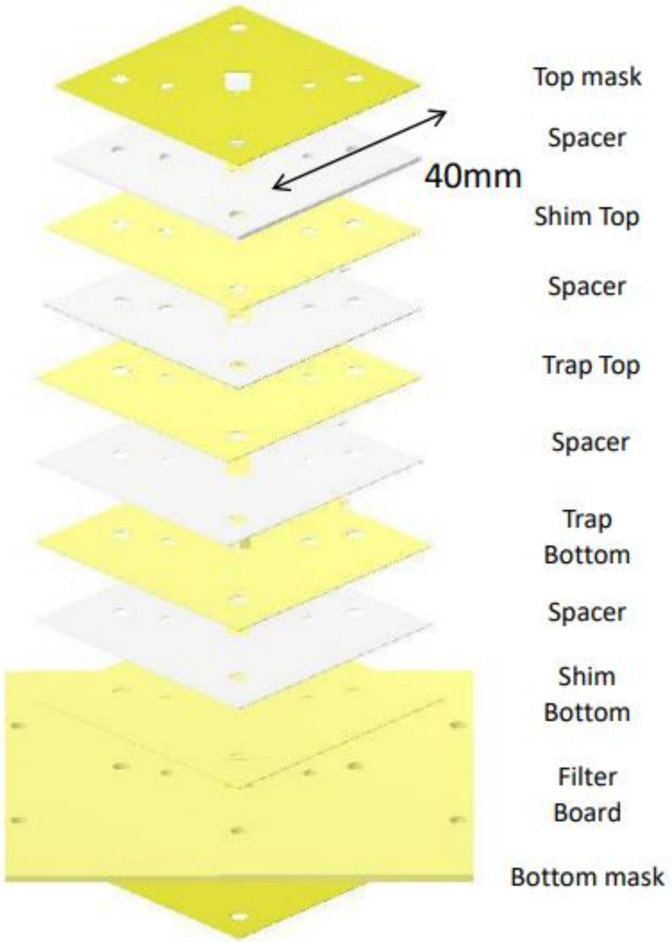


포항공대에서 개발 중인 이온 트랩



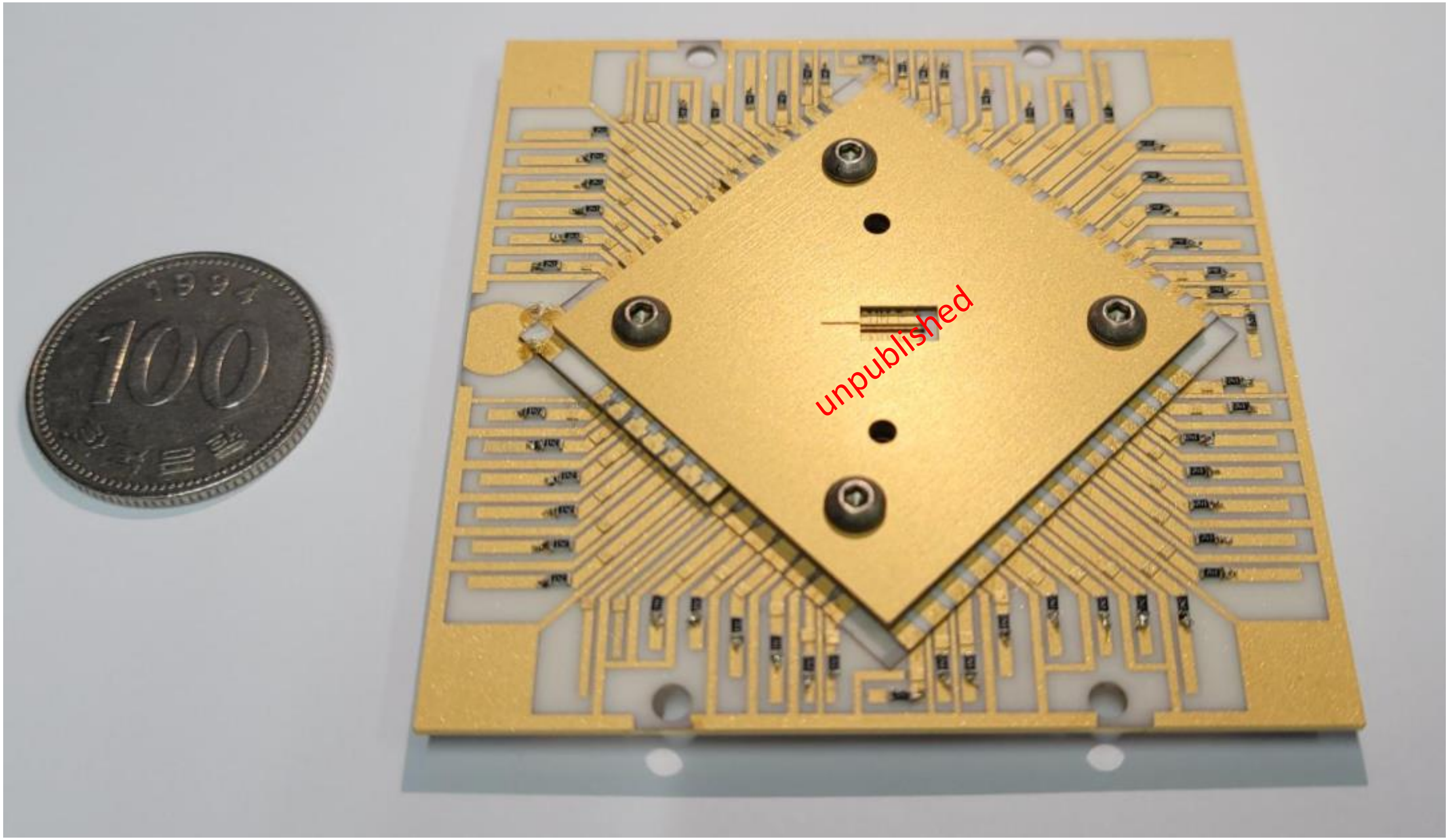


POSTECH ION2: multi-layer trap

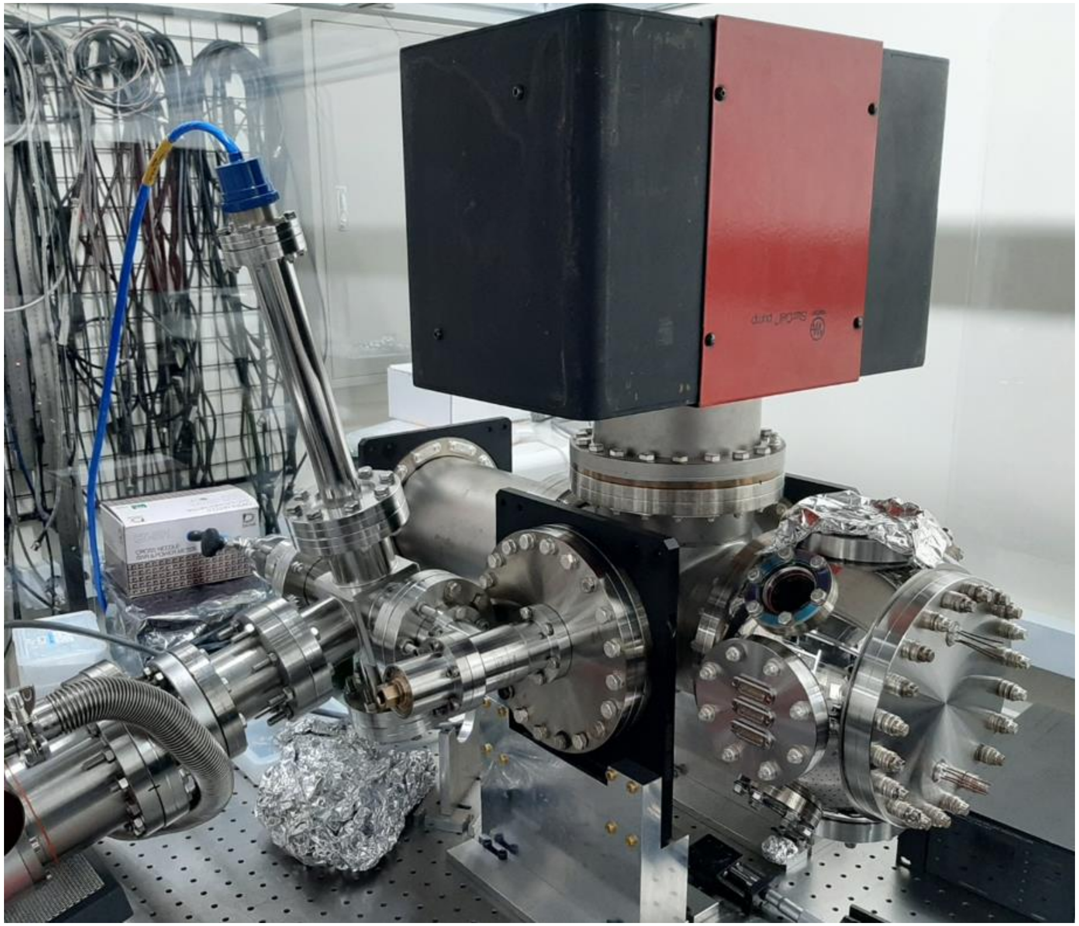


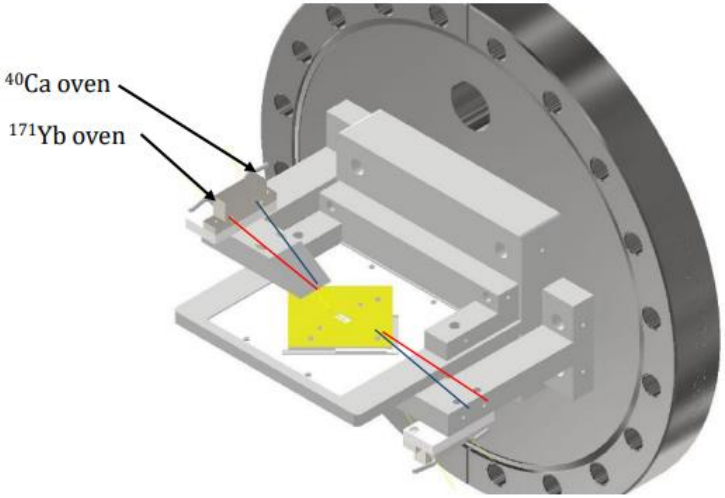
See also: NIST, Mainz, ETH Zurich…

Status of our chip

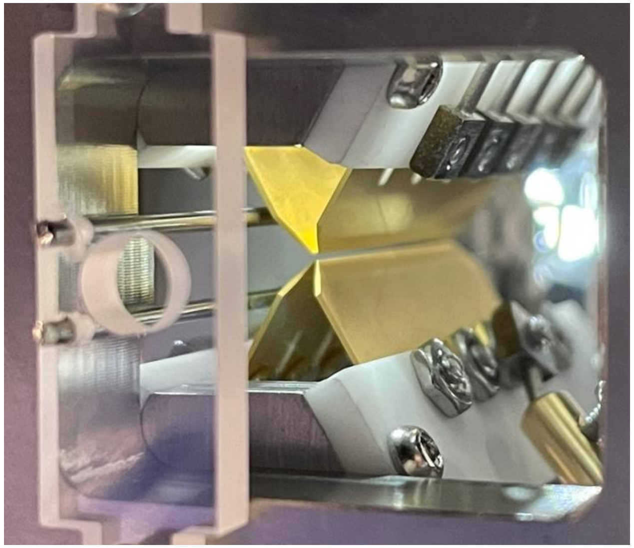


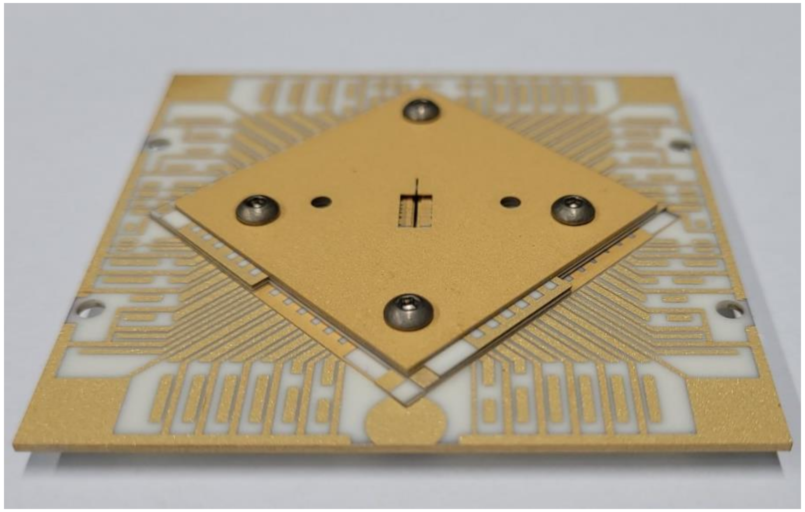
Vacuum chamber ready

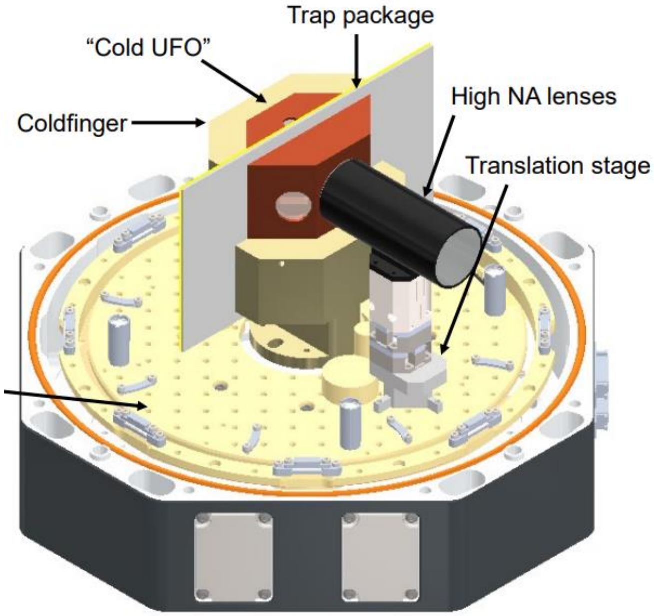




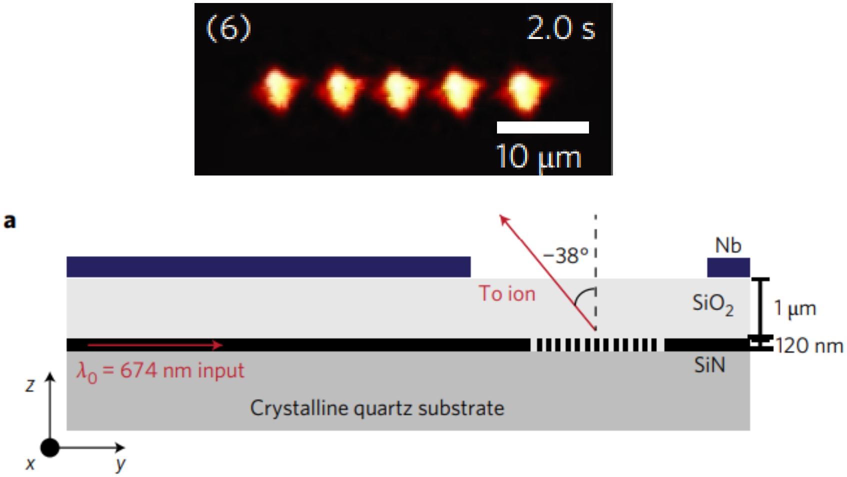
포항공대에서 개발 중인 이온 트랩





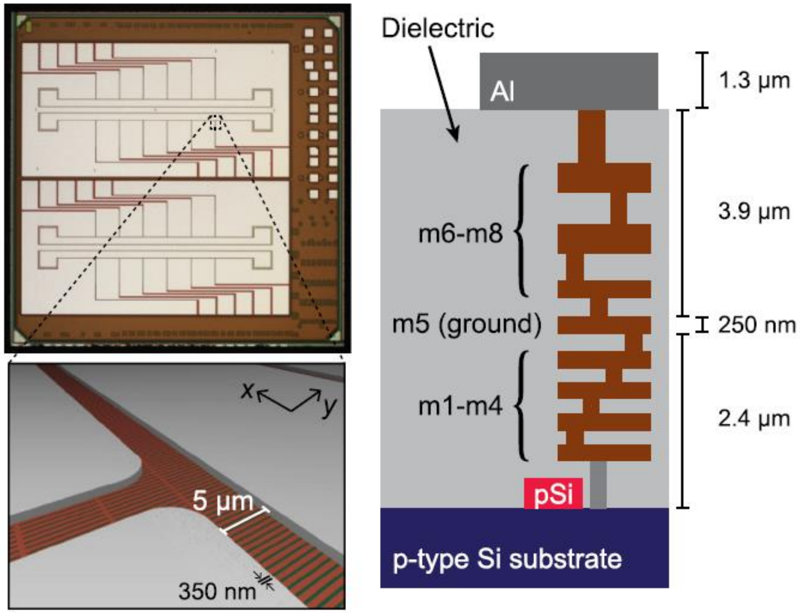


Integrated circuit meets ion trap



Mehta et al., Nat. Nanotechnol. (2016)

Chip fabrication in CMOS foundry

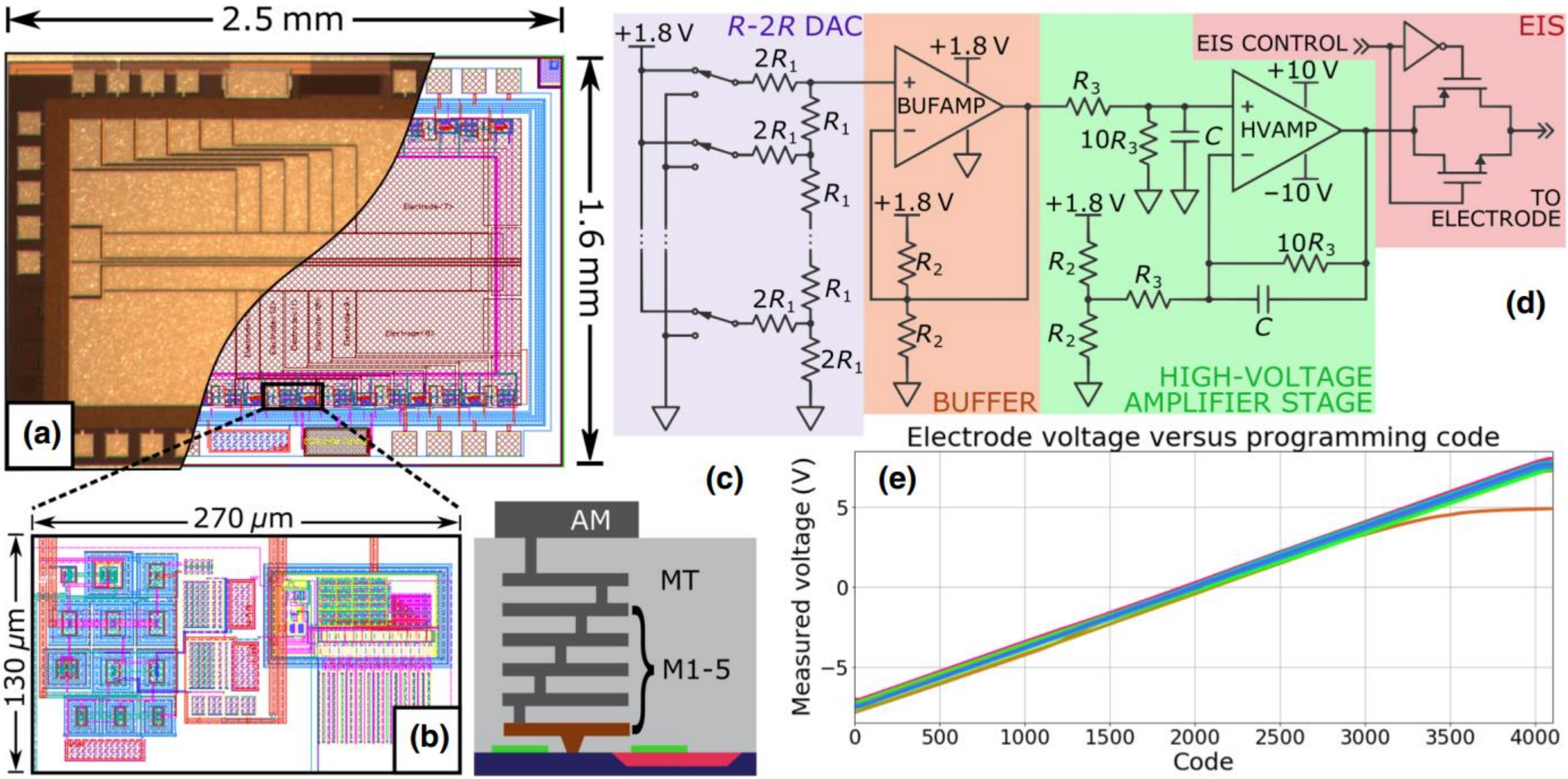


Mehta et al., Appl. Phys. Lett. (2014)

- CMOS foundry를 이용한 reproducible한 chip 제작 가능

Integrated circuit layout

In collaboration with 심재윤 교수님



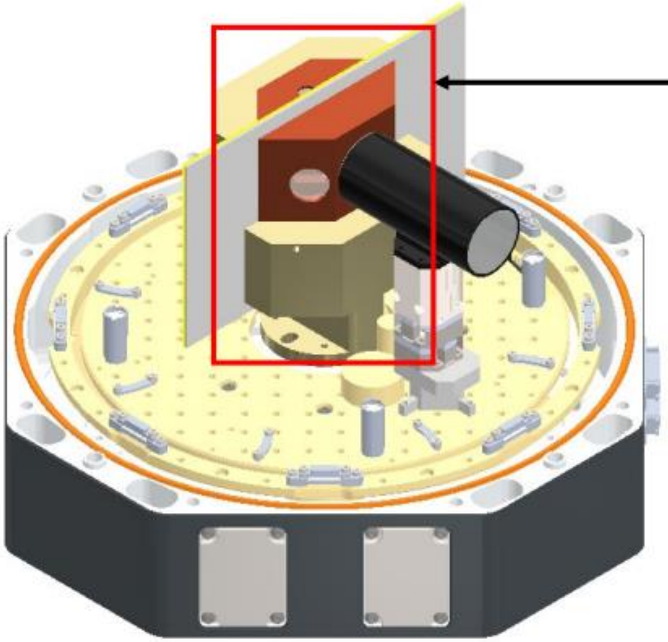
Stuart et al., Phys. Rev. Applied (2019)

POSTECH ION3: cryogenic trap

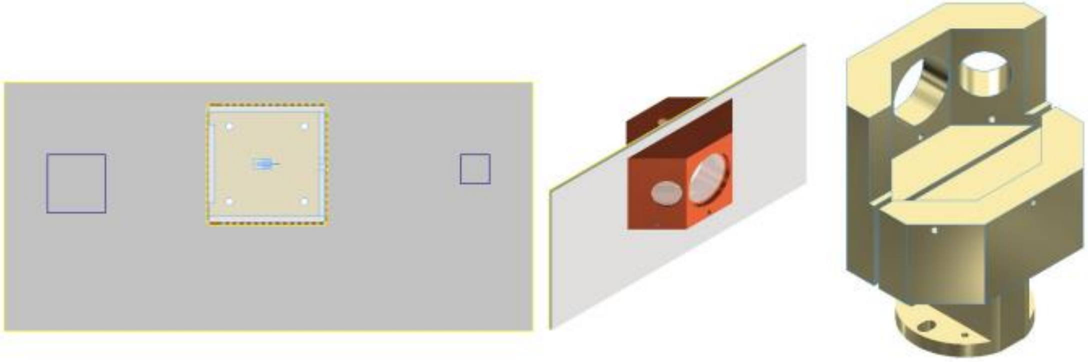
Montana Instruments Inc., S200

POSTECH ION3: cryogenic trap

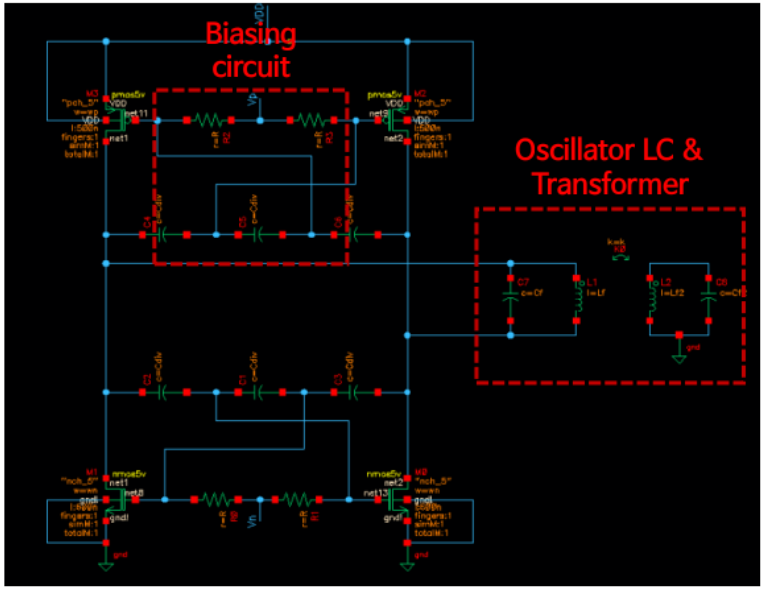
POSTECH ION3: cryogenic trap

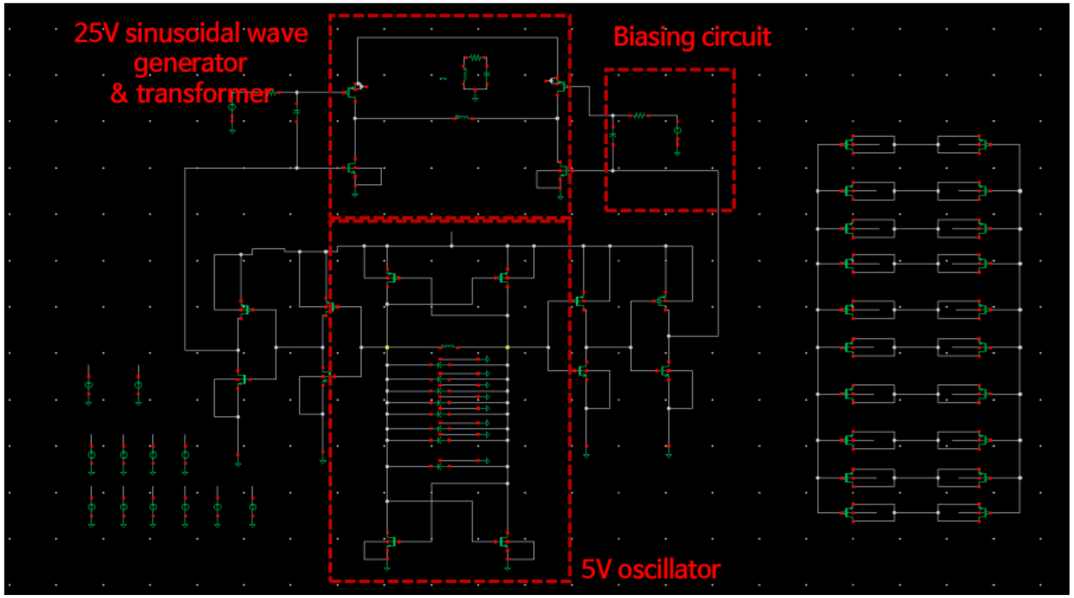


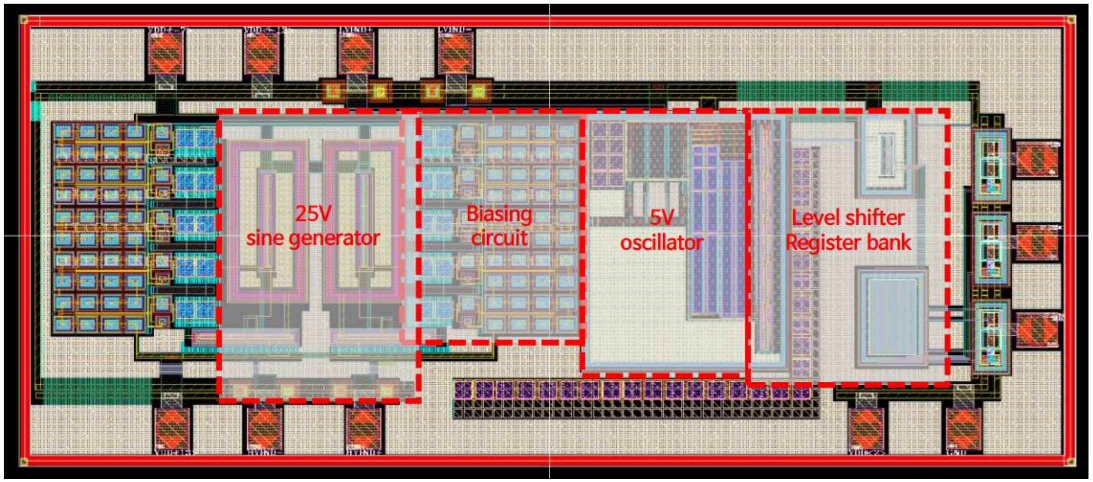
- Temperature of all parts of refrigerator ≠ 4 K
- Only Coldfinger connected to cryo-cooler: 4 K
- Temperature of other parts: 40 K ~ 90 K
- Higher vacuum at 4 K than other
- So we need cold UFO and coldfinger and package for our chip



DC and RF sources are on chip

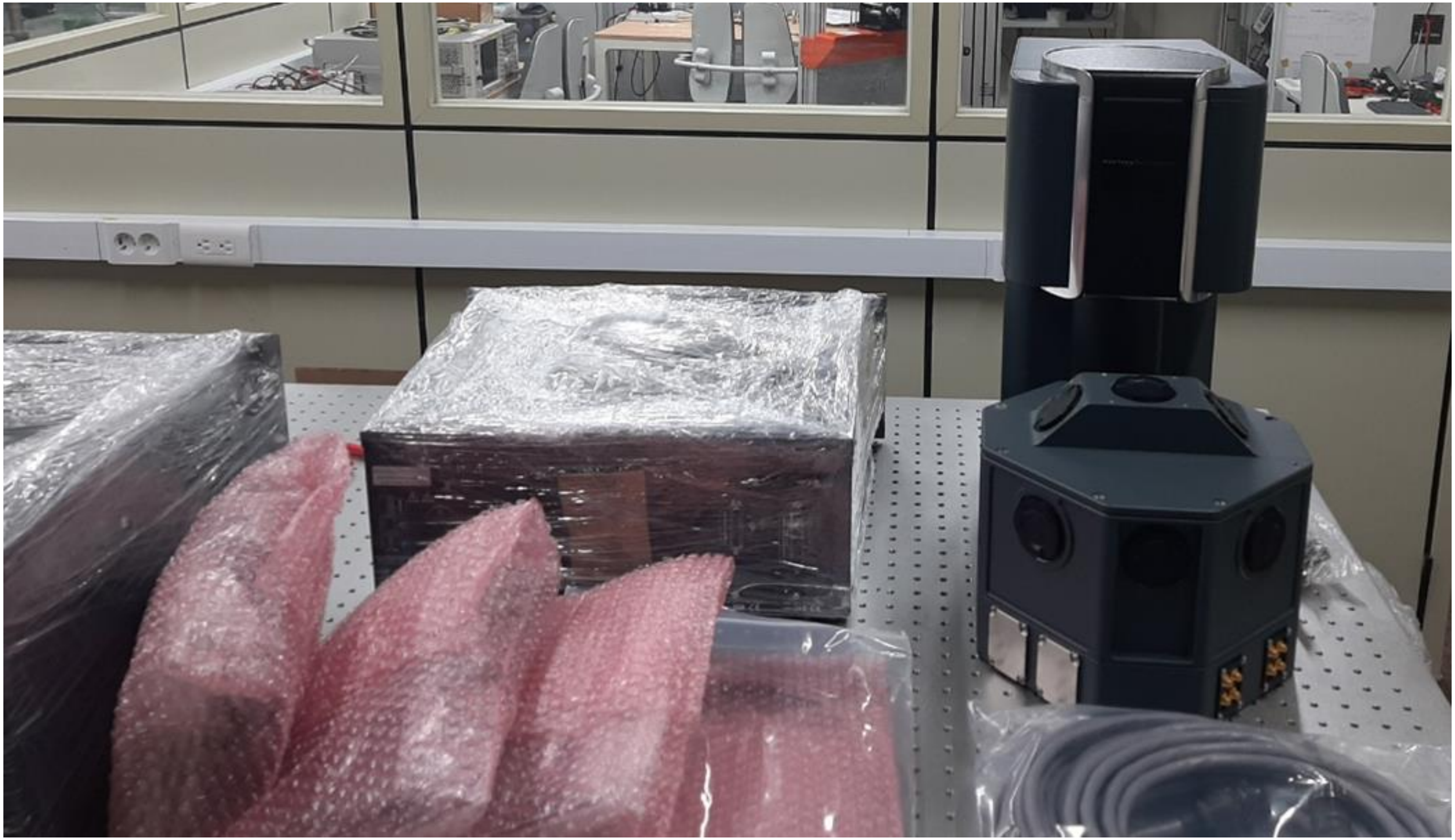




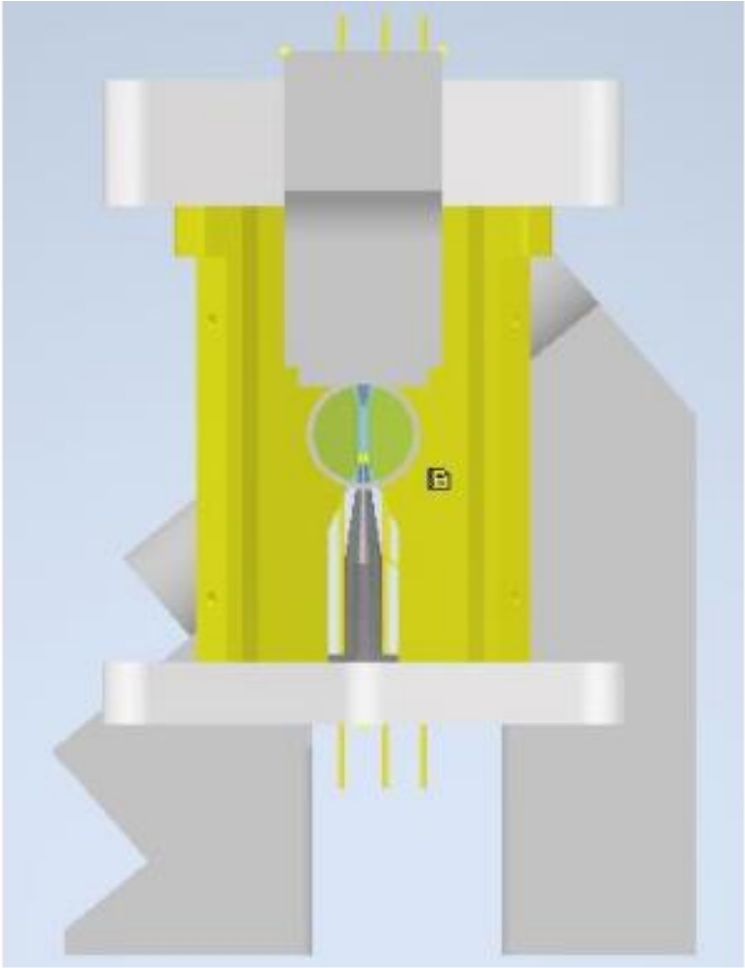


- 심재윤 교수님 연구실에서 칩 설계 완료 → 현재 TSMC에서 제작 중
- 저발열 DC voltage source
- DC source는 ion trap chip에 integration된 적 있으나 RF source는 최초

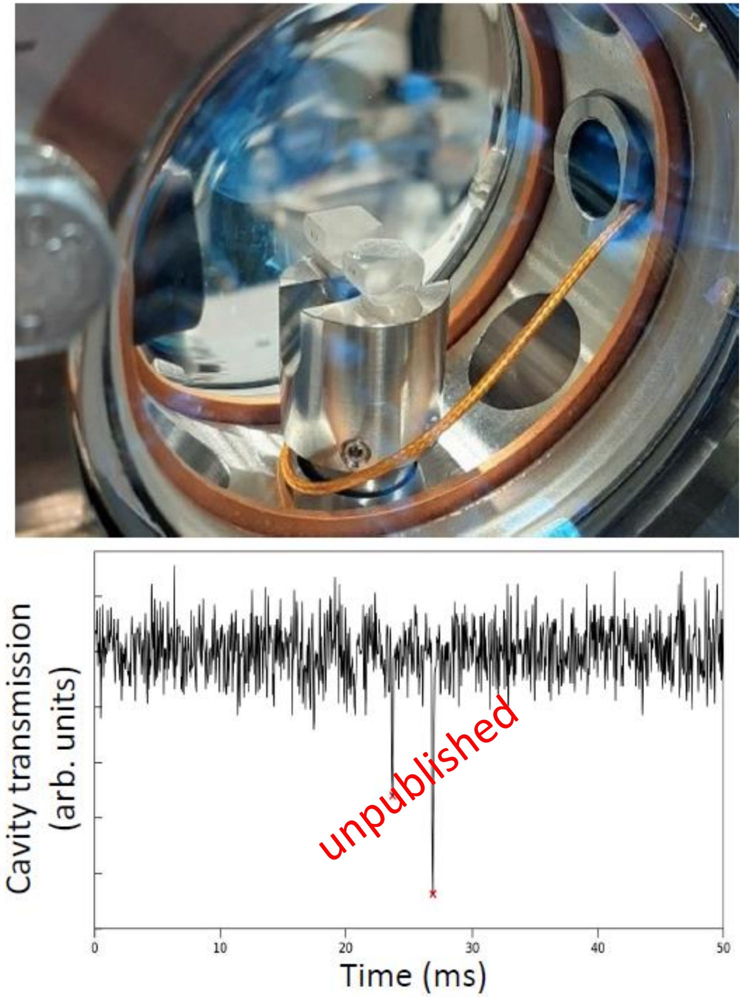
Montana cryostat arrived at POSTECH



Other projects: $^{40}Ca^+$, ^{87}Rb



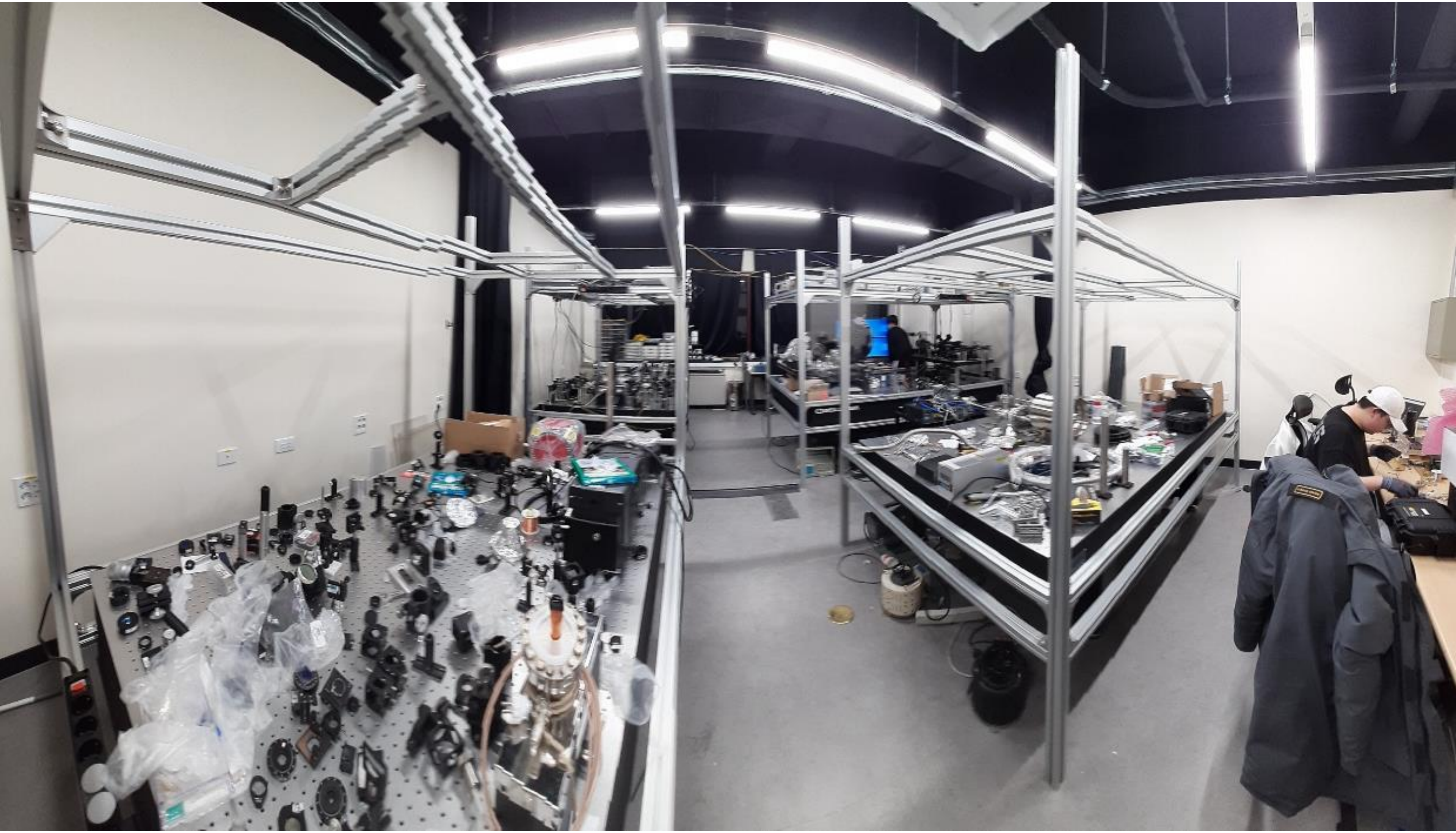
Ion-cavity experiment
삼성미래기술육성재단



Atom-cavity experiment
NRF 보호연구지원사업

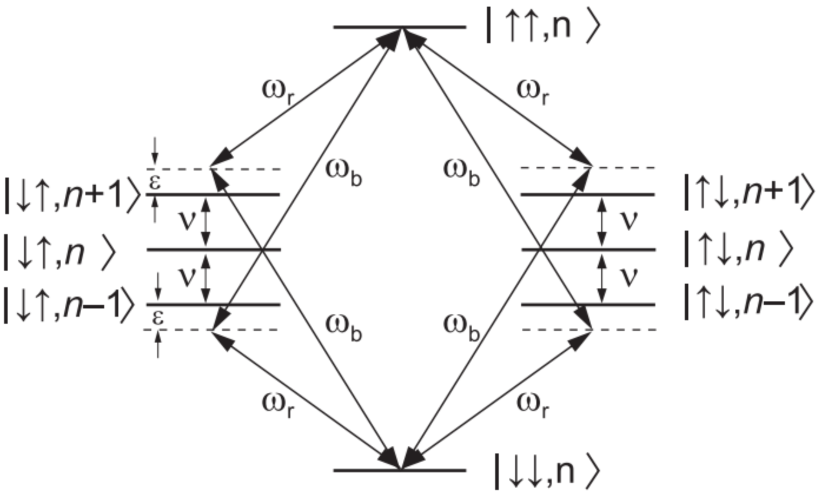
Lab 1 : 포항공대 제2공학관 506호

Lab 2 : 포항공대 제2공학관 502-2호



요약

$$\hat{H}_{\mathrm{LD}}(t) = (\hbar/2)\Omega_0\sigma_+\{1 + i\eta(\hat{a}e^{-i\nu t} + \hat{a}^\dagger e^{i\nu t})\}e^{i(\phi-\delta t)} + \mathrm{H.c.}$$



대학원생 7명 (+1명, 9월 부터)
Postdoc 1명 (+1명, 3월 부터)
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