Microwave-driven two-qubit entangling gate with ^{9}Be$^+$ ions in a scalable microfabricated surface-electrode ion trap

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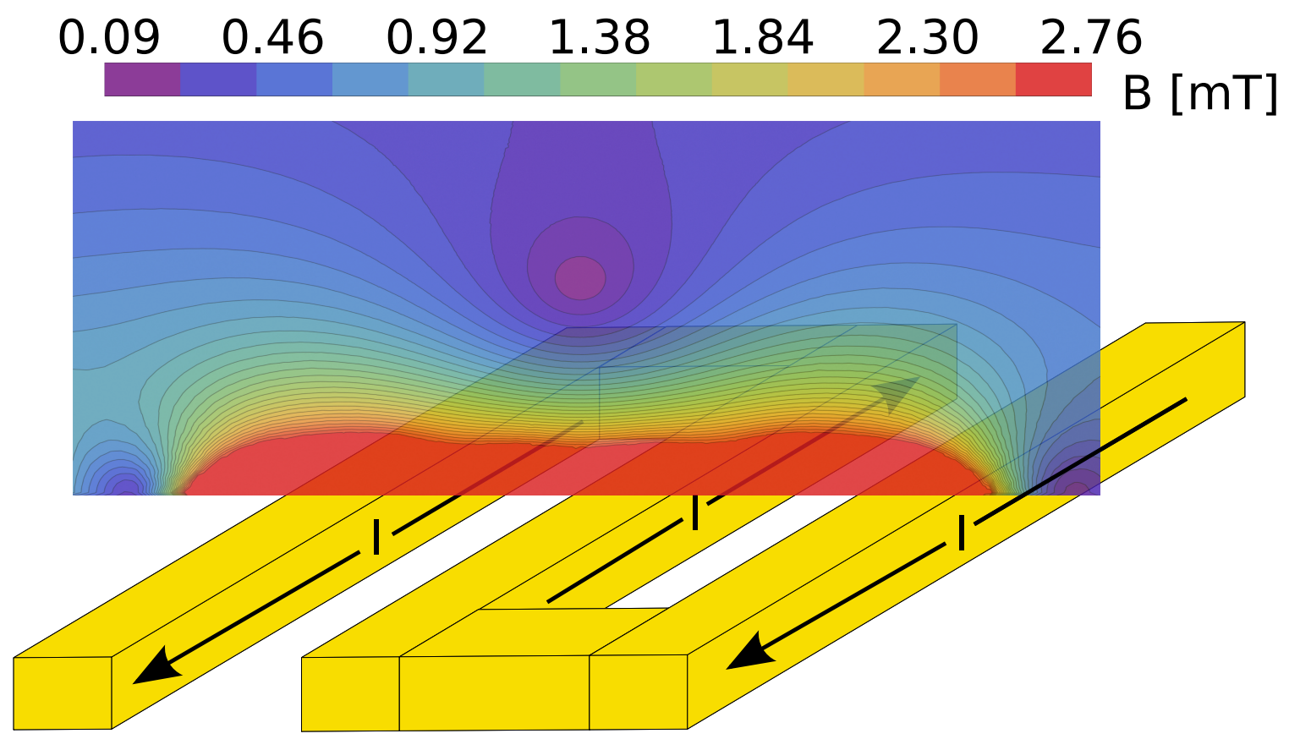
CRC1227
Designed Quantum States of Matter

Microwave near-field approach [1, 2]

Goal
- High-fidelity universal gate set by using microwave fields only

Requirements
- Drive carrier and sideband transitions

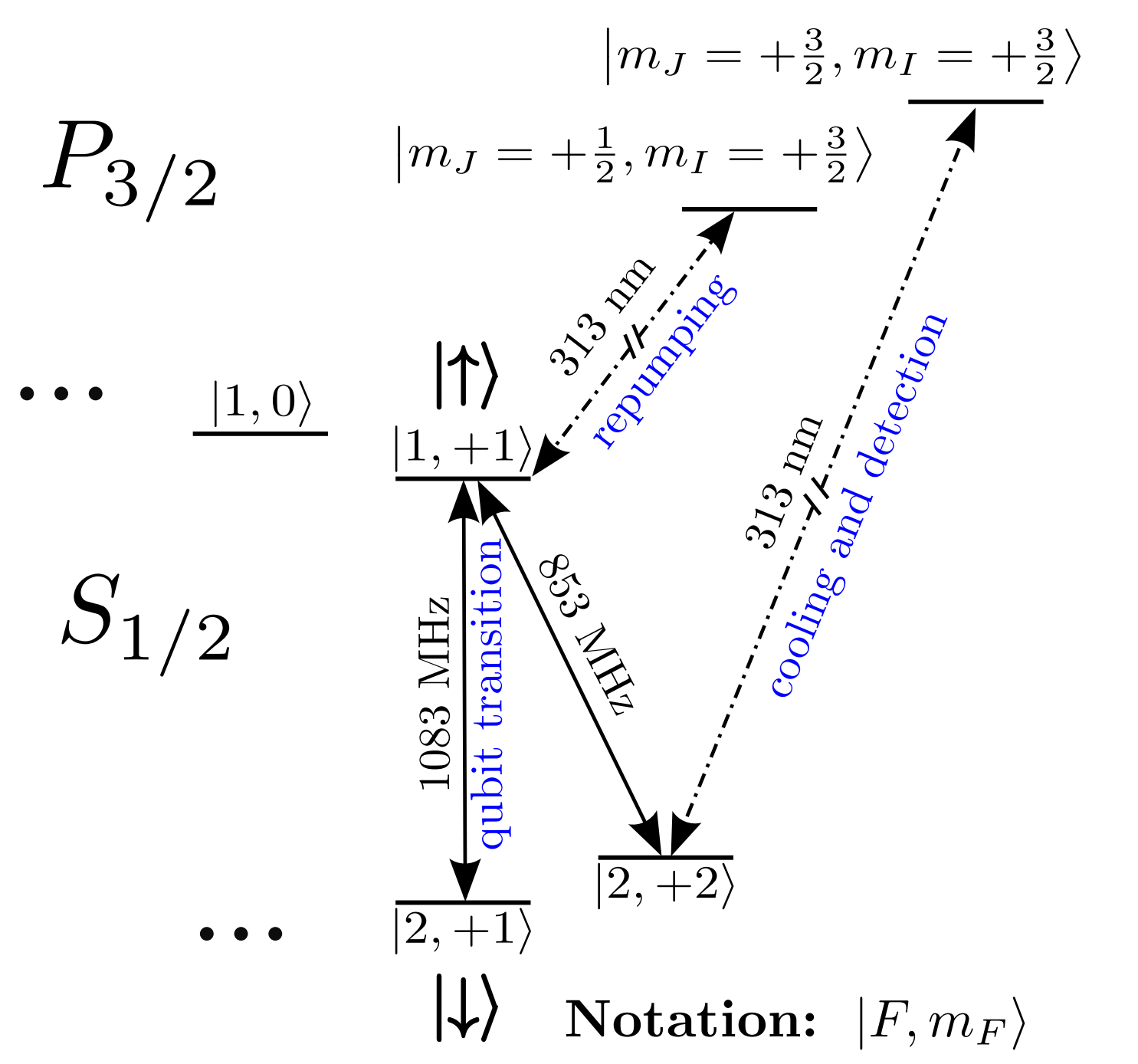
Advantages
- No spontaneous emission
- Less hardware required
- Potentially better scalability



carrier	sidebands
$\Omega_C \propto \tilde{B}\ \langle\downarrow\vert\,\mu_m\vert\uparrow\rangle$ (driven by field)	$\Omega_{SB} \propto x_{wp}\ \tilde{B}'\ \langle\downarrow\vert\,\mu_m\vert\uparrow\rangle$ (driven by gradient)

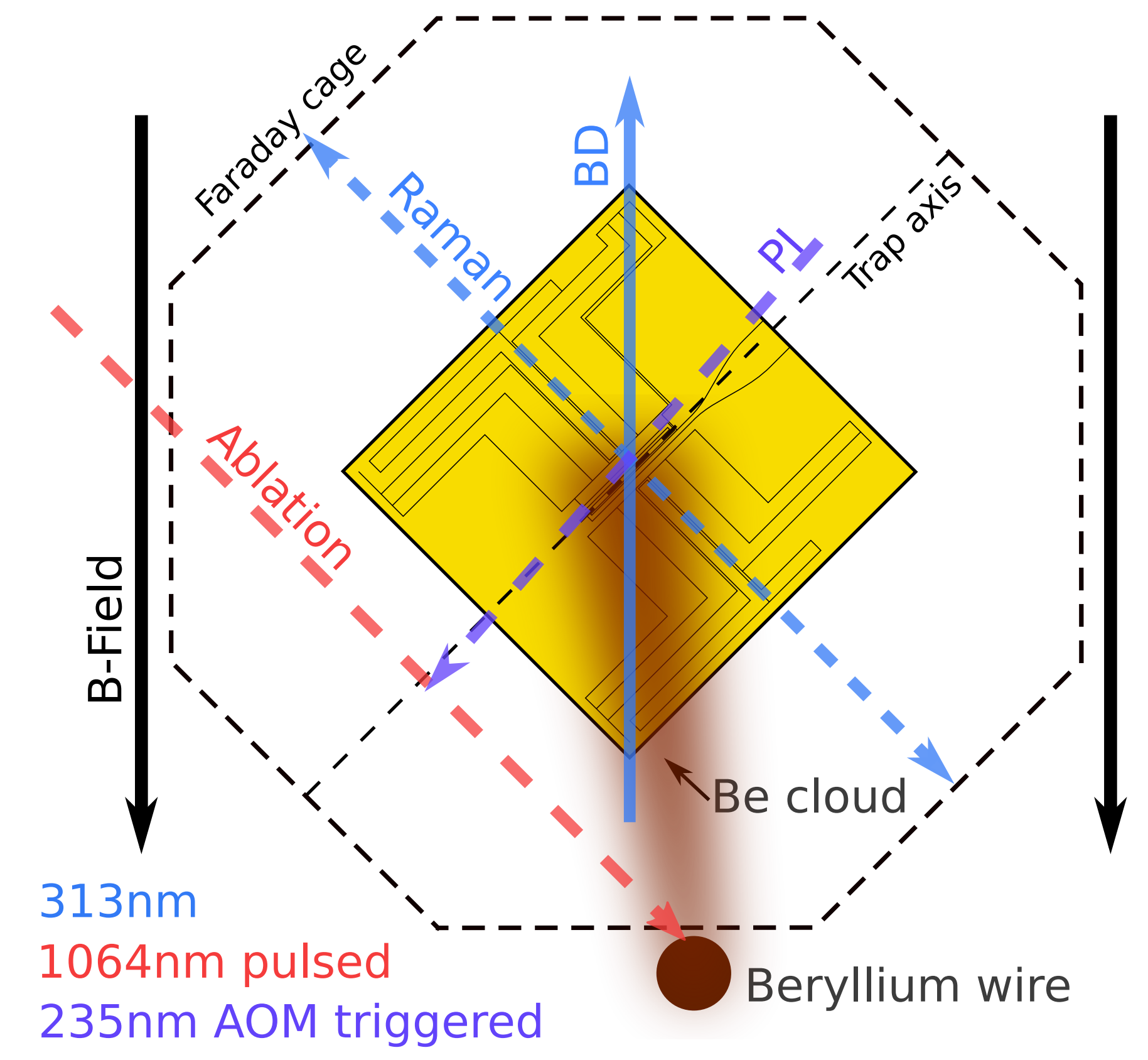
Experimental setup

Atomic transitions of ^{9}Be$^+$

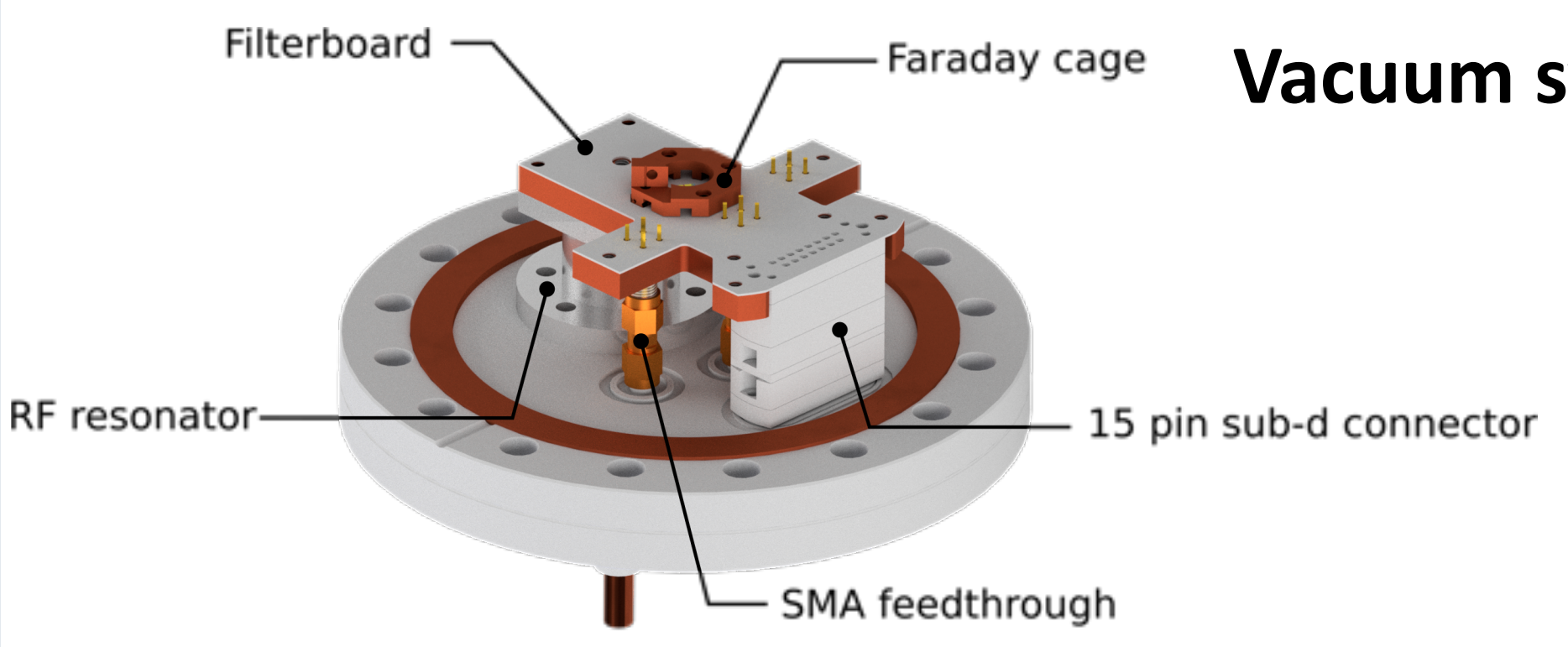


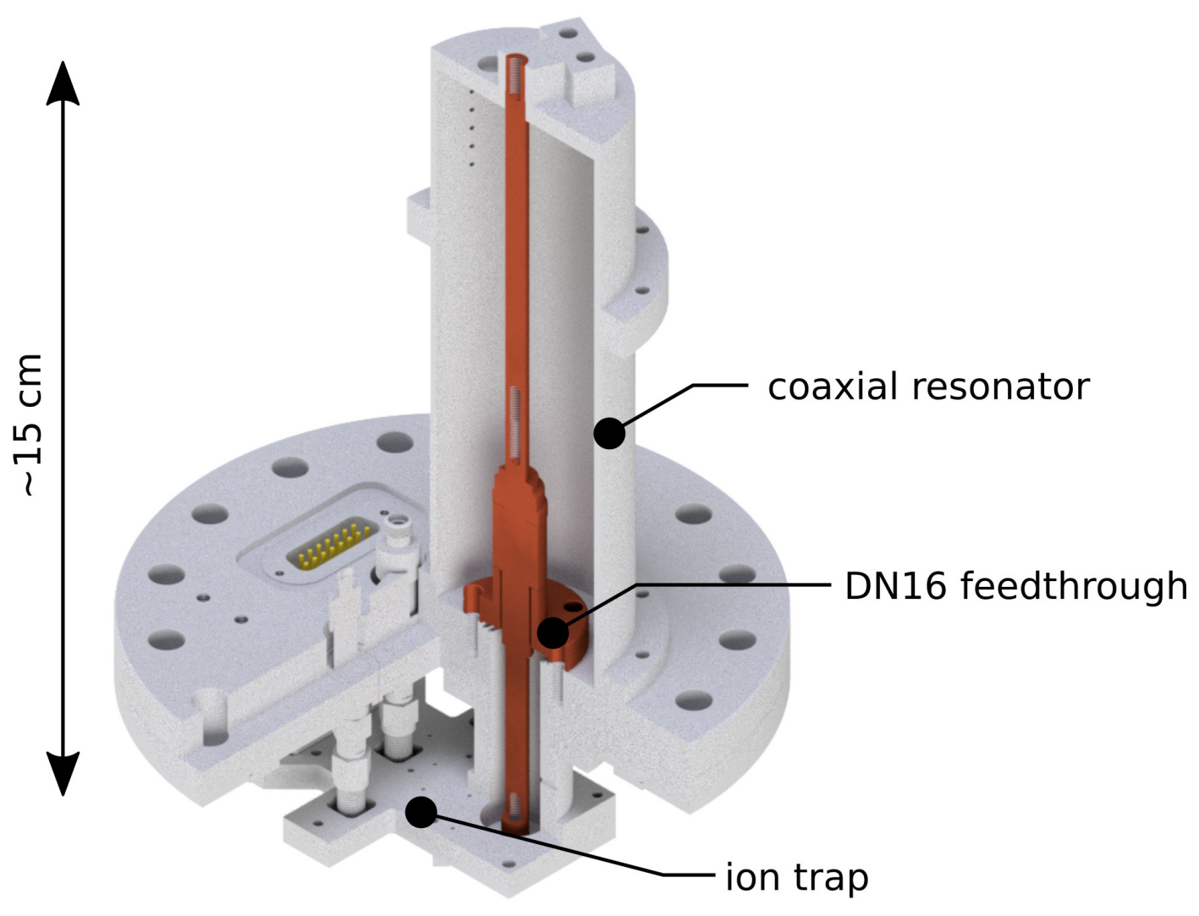
- Qubit to 1st order magnetic-field independent at B_0=22.3 mT

Beam configuration



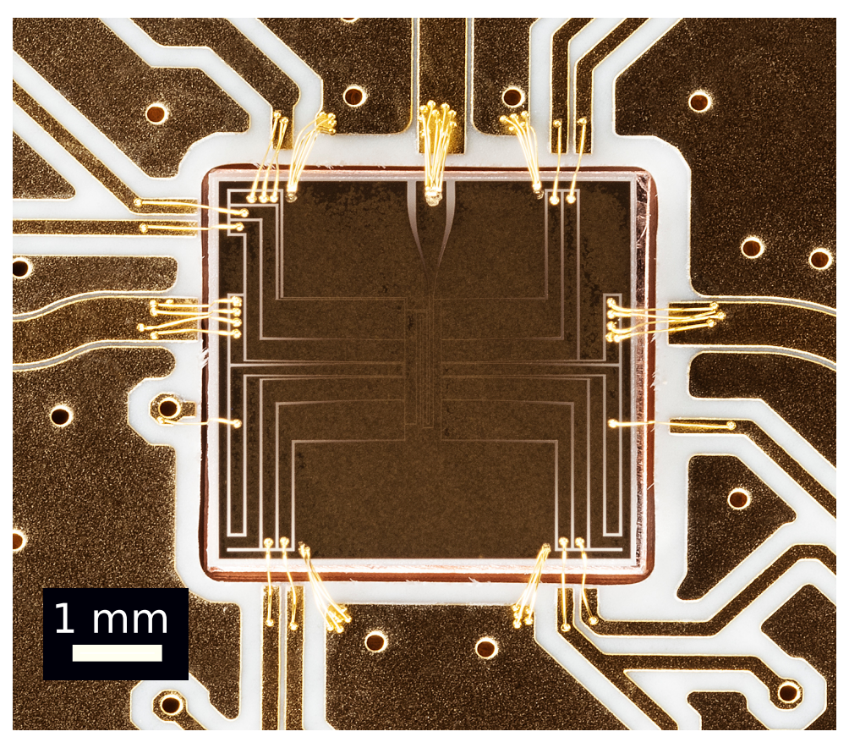
Vacuum system





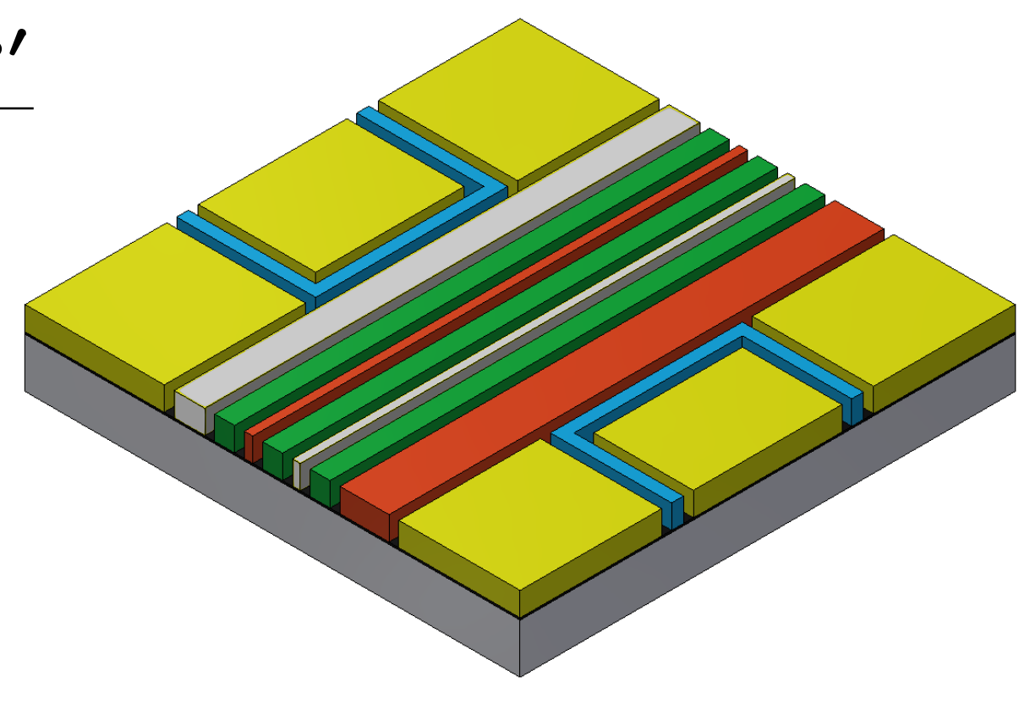
- Modular air and in-vacuum coaxial resonator
- Easy tuning of drive frequency 80-200 MHz
- Permanent magnets (long-coherence times) > 0.5 s

Single layer trap

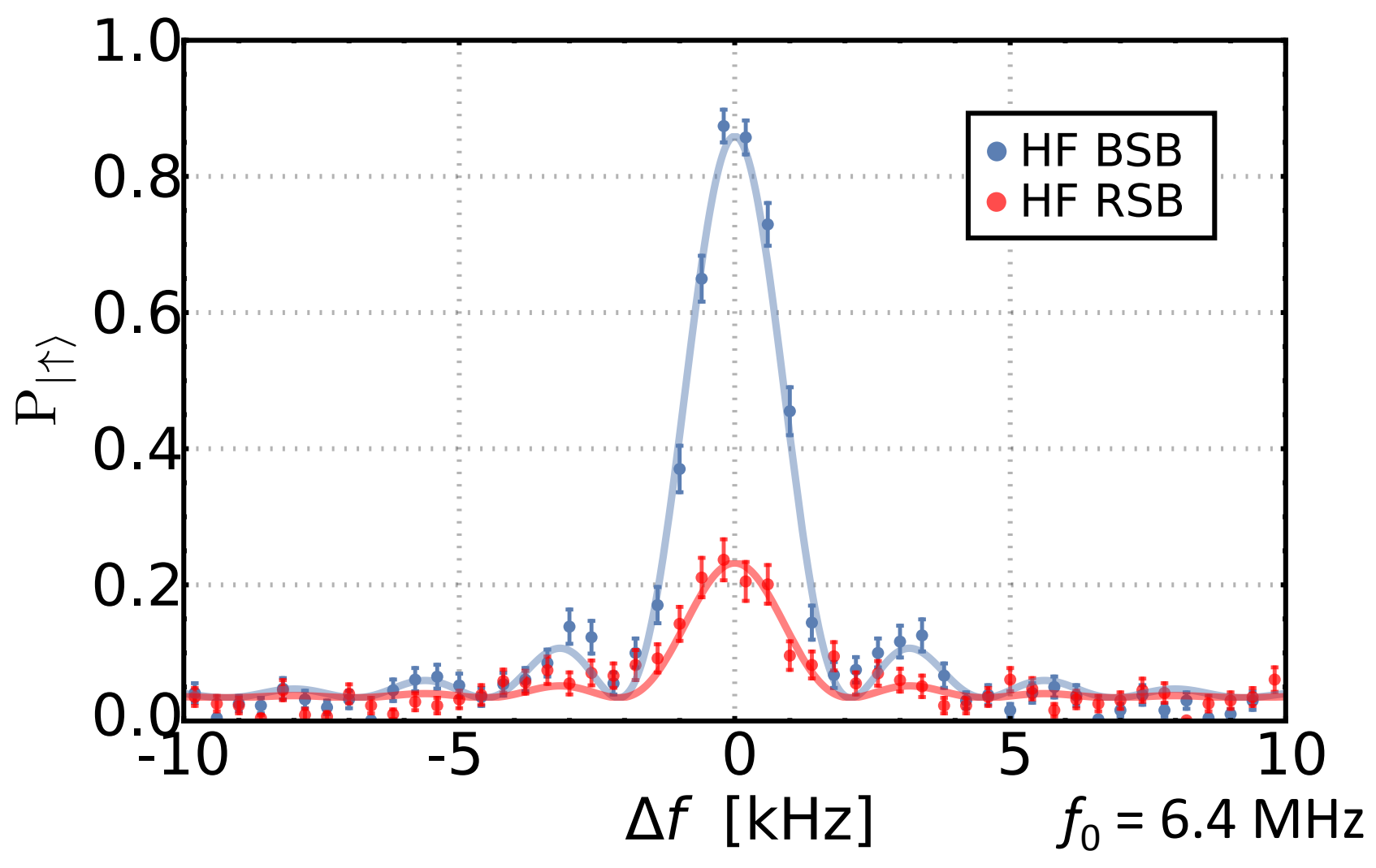


$$FoM = \frac{x_{wp}\,\tilde{B}'}{\tilde{B}}$$

- 🟨 DC
- 🟩 Meander
- 🟦 Carrier
- 🟥 RF



Sideband cooling with MW pulses (1 ion)



Single layer design features

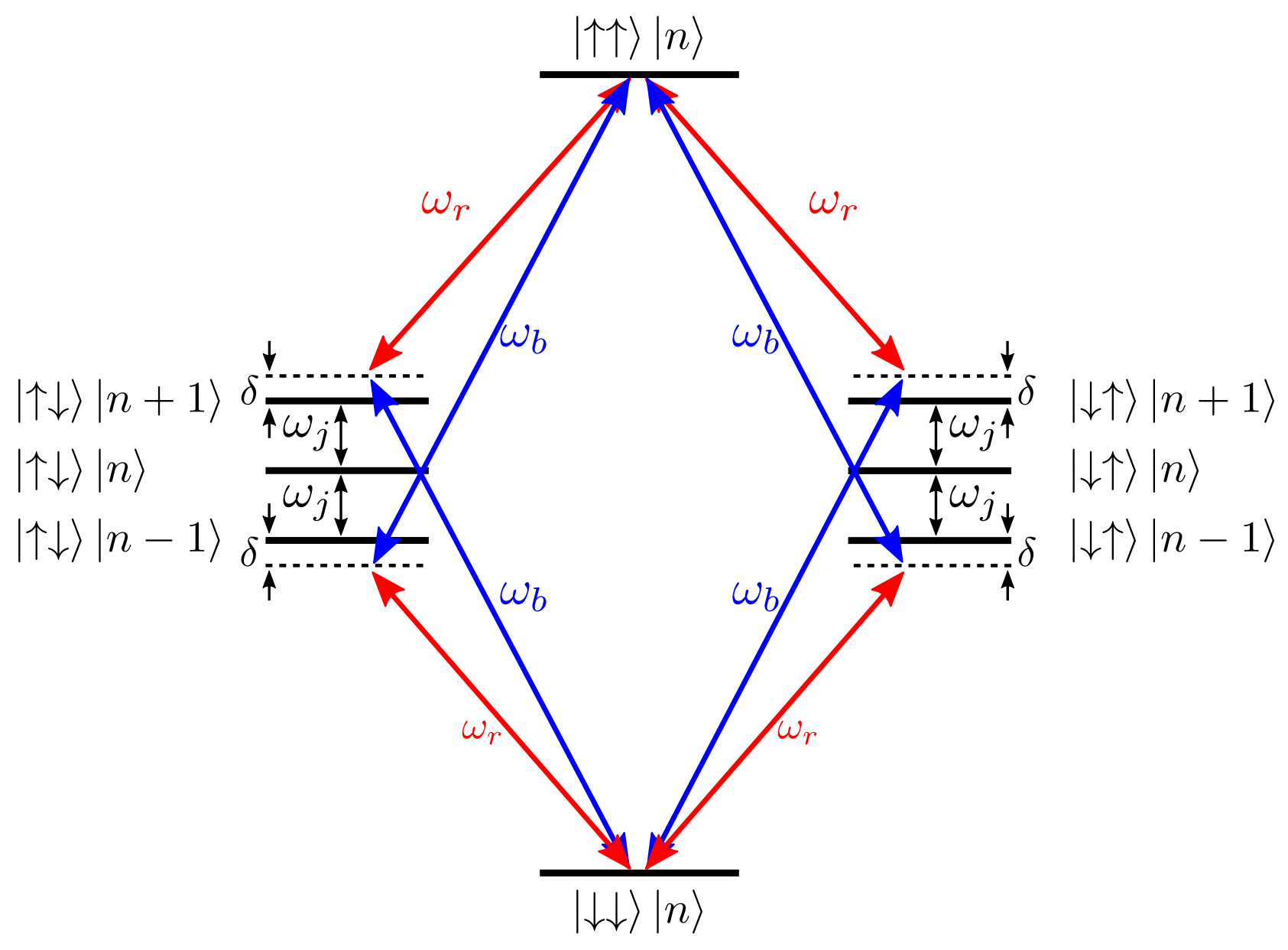
- Substrate: AlN
- Ion-electrode distance: 70 µm
- Figure of Merit: 0.005
- Carrier coupling: -19 dB

Measured heating rates:

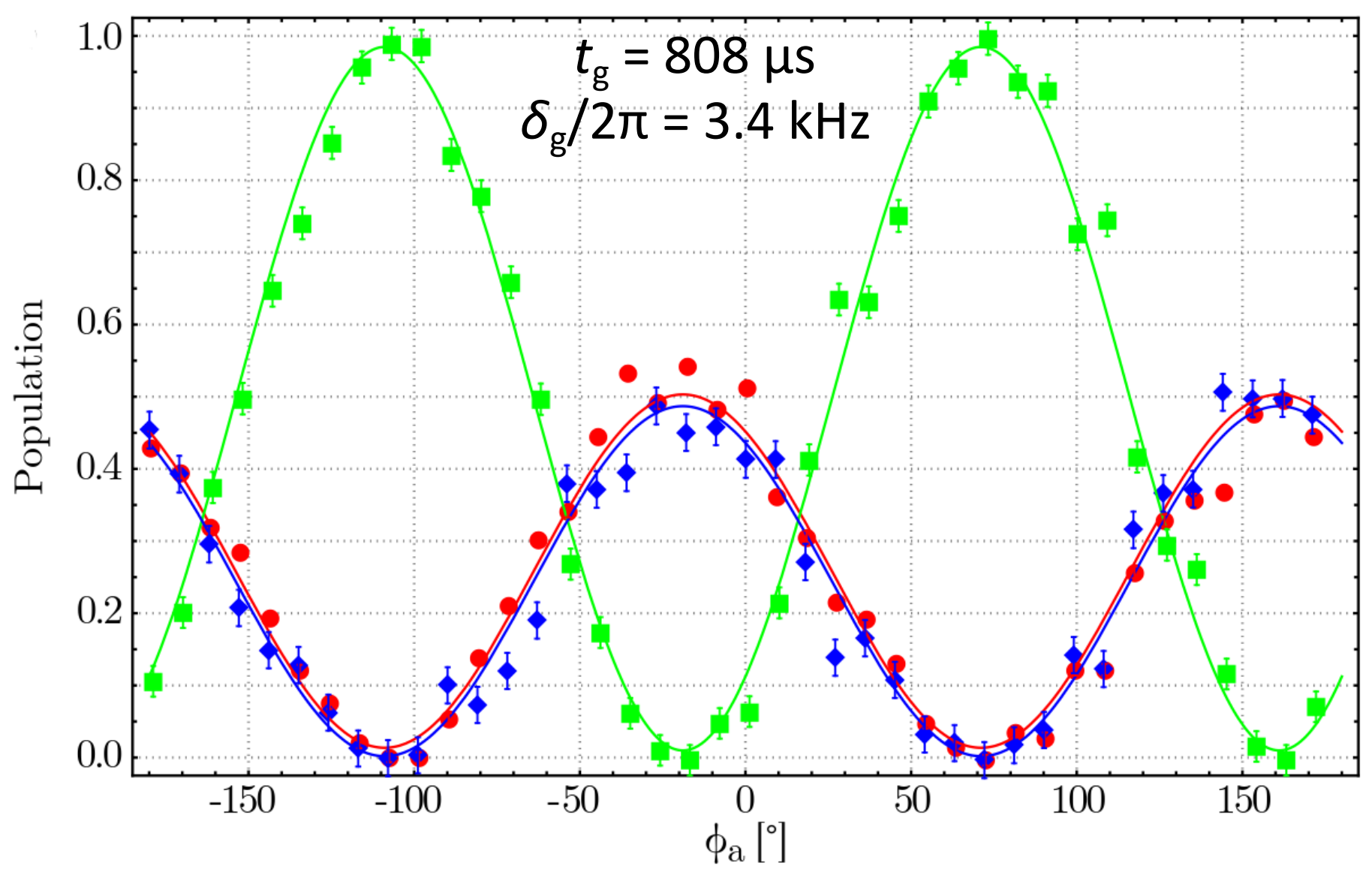
- COM mode, 1 ion:
  $\dot{\bar{n}}_{\mathrm{LF}} \simeq 116 \pm 6\,\mathrm{s}^{-1}$
  $\dot{\bar{n}}_{\mathrm{HF}} \simeq 122 \pm 11\,\mathrm{s}^{-1}$
- Rocking mode, 2 ions:
  $\dot{\bar{n}}_{\mathrm{HF}} \simeq 28 \pm 5\,\mathrm{s}^{-1}$

Standard Mølmer-Sørensen gate [3]

Mølmer–Sørensen gate scheme



Maximally entangled state fidelity: F = 98.2 ± 1.2%

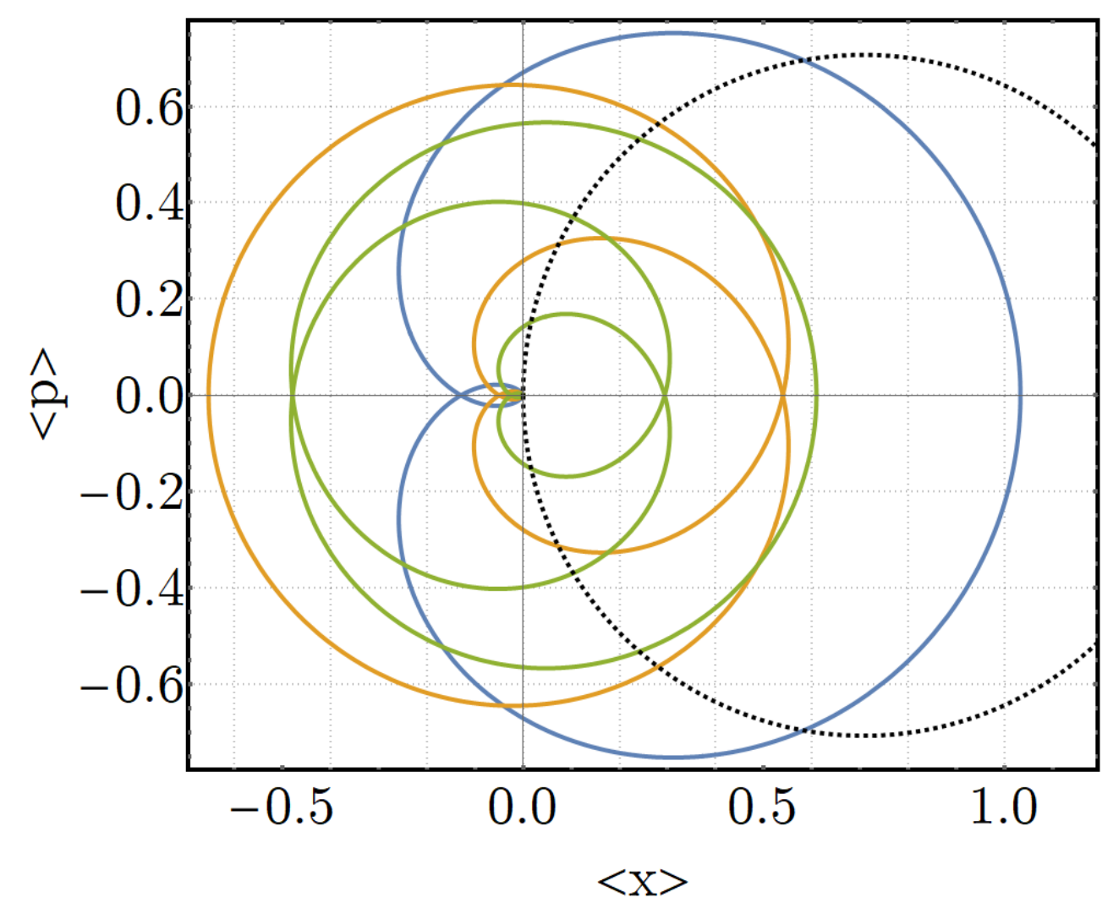


Error budget

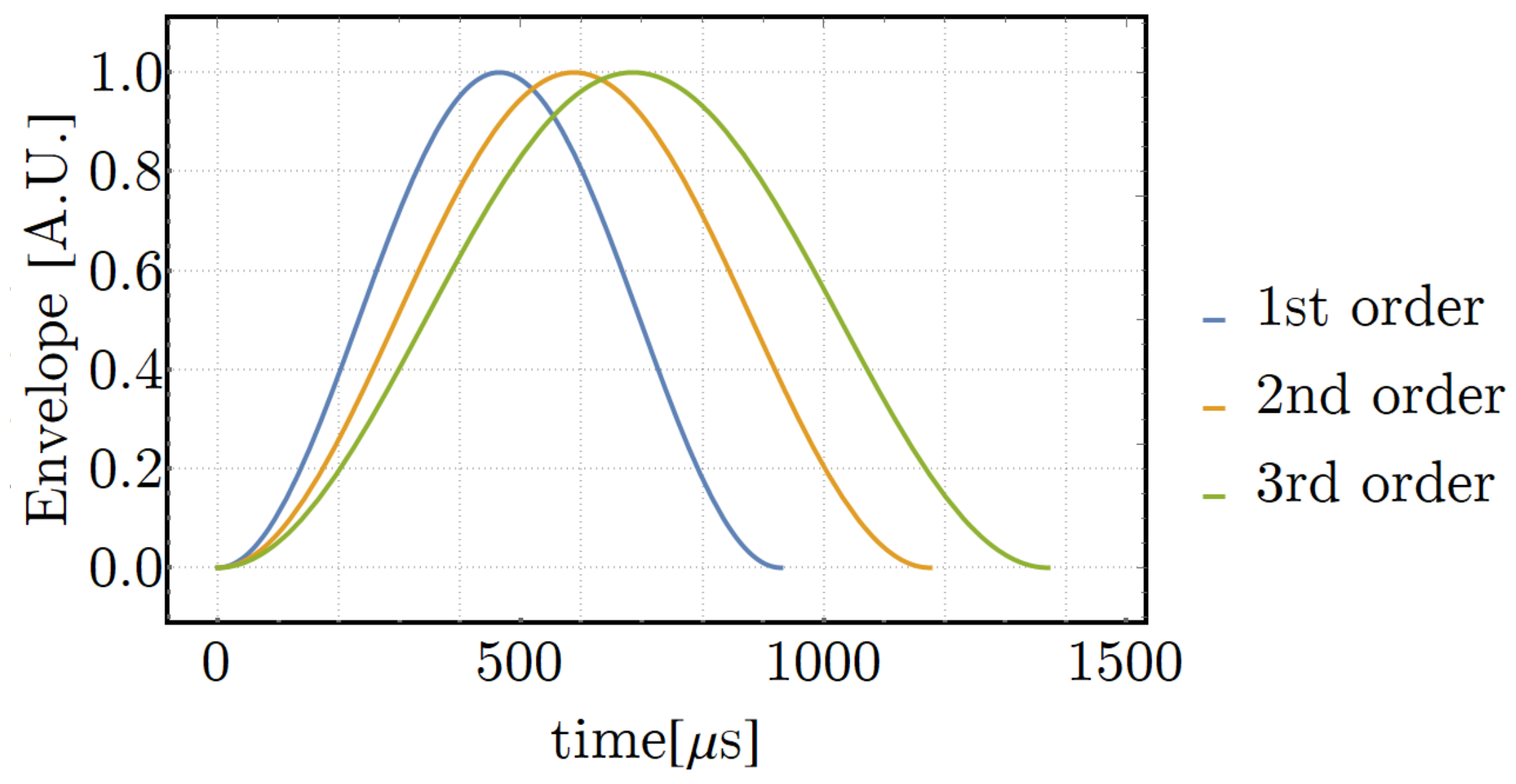
- Motional instability: 1.3%
- Spectator modes: 0.5%
- Heating rate: 0.4%
- Decoherence: <0.1%
- Off-resonant carr. exc. : <0.1%
- Microwave pulse shape : <0.1%

Amplitude modulated MS gate [4]

Phase-space trajectory



Sin^2 modulation

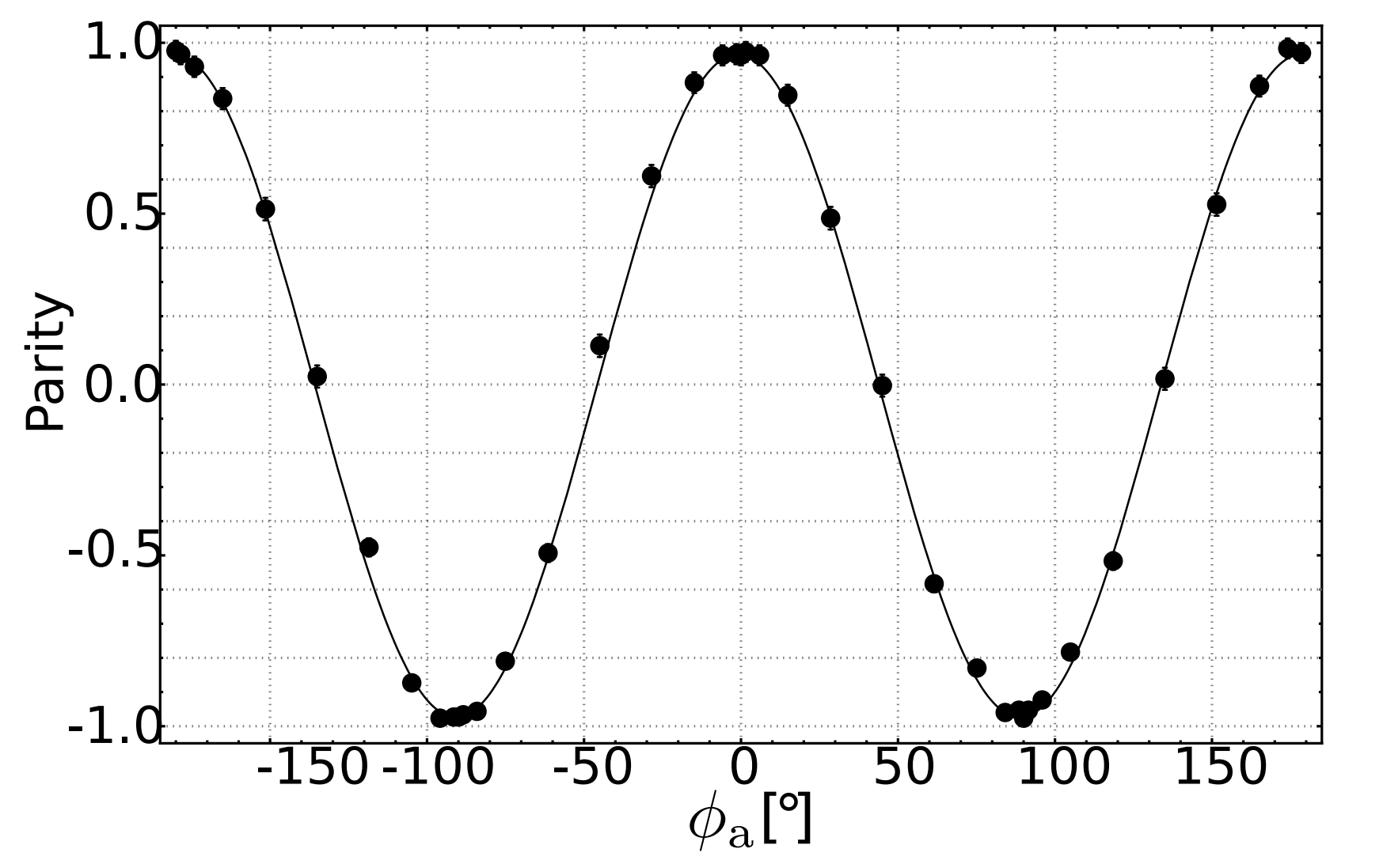


Motivation

Amplitude modulation open the possibility to change the classical circular trajectory in phase space.

- Specific trajectories can be more resistant against residual spin-motion entanglement
- Provides insensitivity against motional mode fluctuations
- Dissipates less energy in the trap microstructures

AM gate with 17th order: F=99.7±0.4%



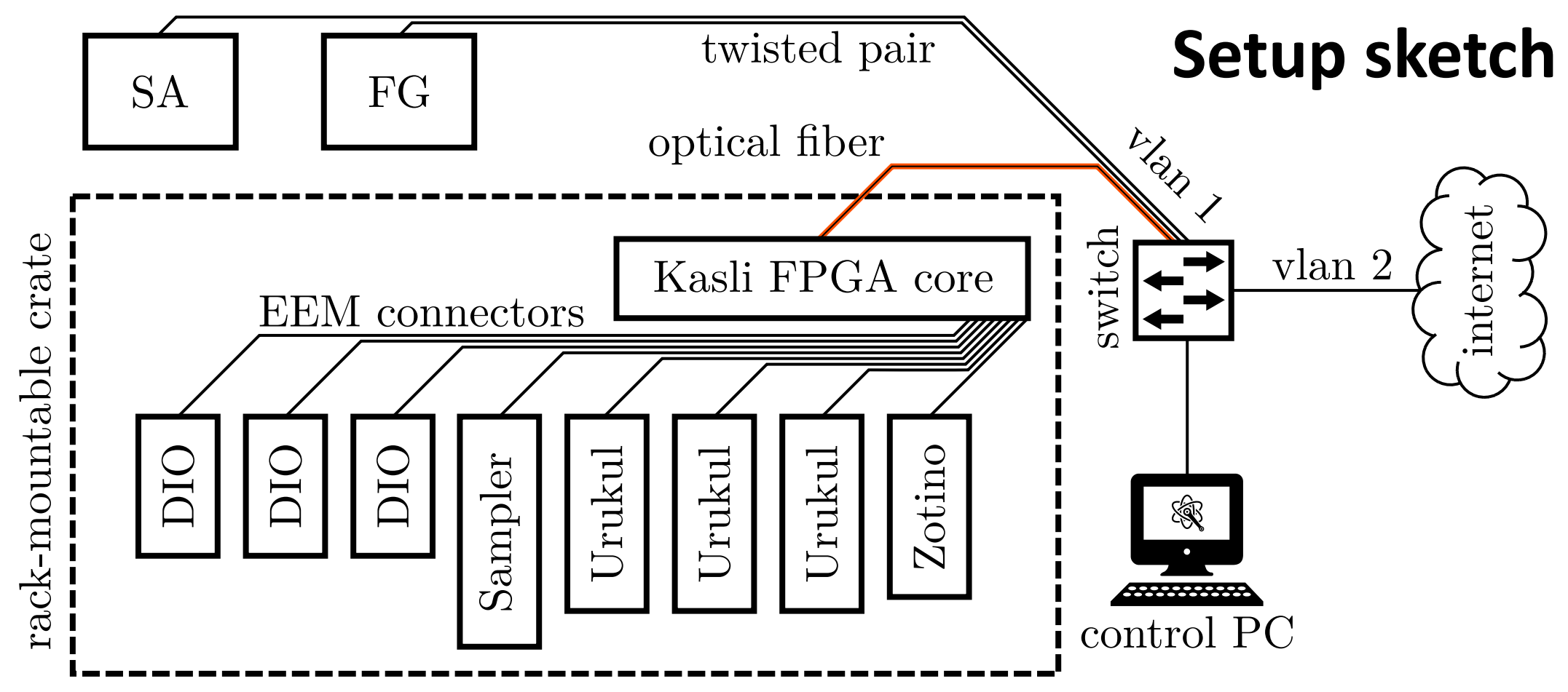
Control system

Motivation

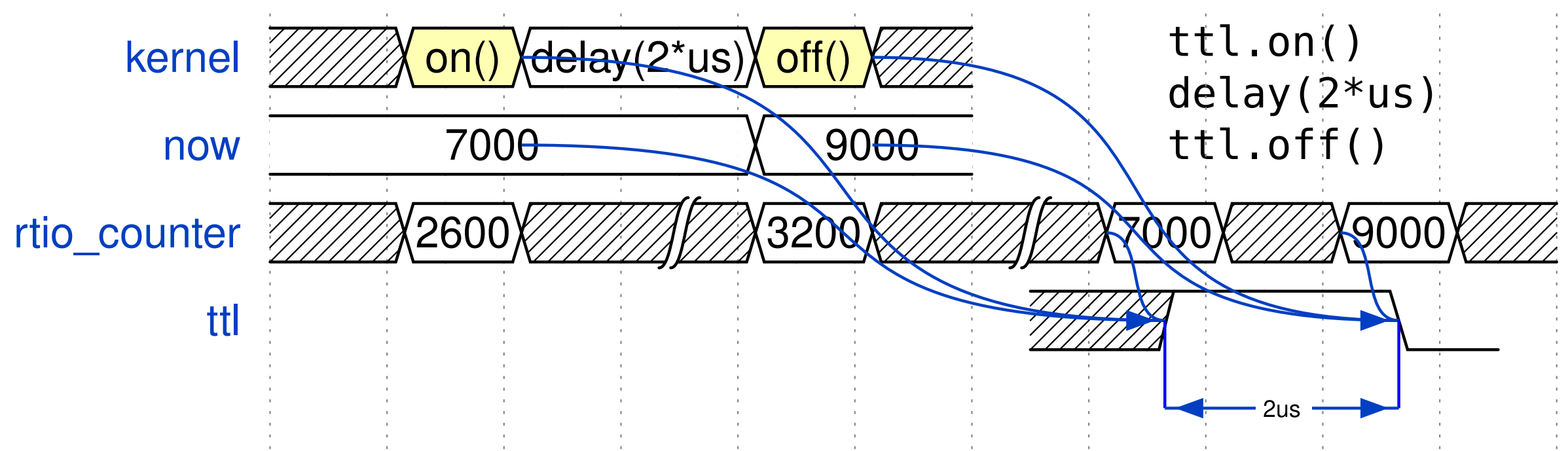
Need a contol system with real-time capability and that enables the description of complex experimental sequences.

ARTIQ [7]
- Simple programming (Python)
- Open source and hardware
- Fully hackable to fit any scenario
- Nanosecond timing resolution (on FPGA)

Setup sketch



Realtime IO



```
ttl.on()
delay(2*us)
ttl.off()
```

automatic timestamping: instructions in the experiment script get a timestamp at compile time

FPGA real time "wall clock"

actual TTL output

Easy paralell programming

```
with sequential:
    with parallel:
        ttl0.pulse(10*us)
        ttl1.pulse(20*us)
    with parallel:
        ttl2.pulse(30*us)
        ttl3.pulse(20*us)
```

Mixing RTIO and RPC calls

```
@kernel
def real_time_on_FPGA():
    ttl0.pulse(10*us)

def asynchronous_on_CPU():
    visa_device.write("some SCPI command")
```

References

[1] C. Ospelkaus *et al*., Nature, 476, 181–184 (2011)
[2] C. Ospelkaus *et al*., PRL 101, 090502 (2008)
[3] H. Hahn, *et al*., NPJ QI 5, 70 (2019)
[4] G. Zarantonello et al., PRL 123, 260503 (2019)
[5] A. Bautista *et al.* New J. Phys. 21, 043011 (2019)
[6] H. Hahn *et al.* Appl. Phys. 125, 154 (2019)
[7] S. Bourdeauducq *et al.* (2016). ARTIQ 1.0. Zenodo. 10.5281/zenodo.51303

Outlook

Future plans
- Simulation of complex quantum systems (i.e. quantum magnetism)
- Multilayer ion traps [5,6] including aspects of the QCCD architecture (i.e. junctions, loading zones, ...)
- Including a second ion species for sympathetic cooling (Ca, Be)

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