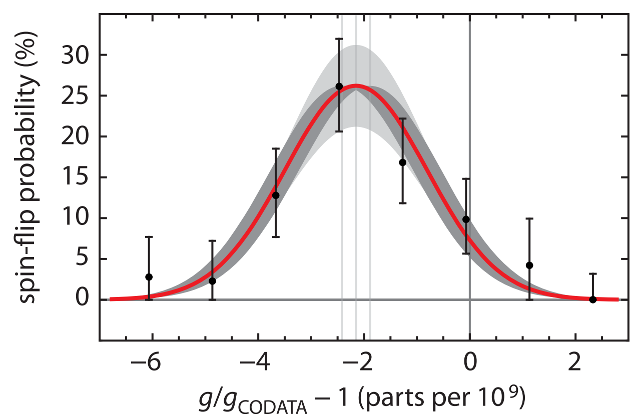
Outline

- BASE: *g*-Factors and Charge-to-Mass Ratio
- Cryogenic Detection Systems I:
  Image Current Detectors
- Cryogenic Detection Systems II:
  Single Photon Sensors for Fluorescence Detection
- Cryogenic Detection Systems III:
  A single laser-cooled Be+ ion as a quantum sensor

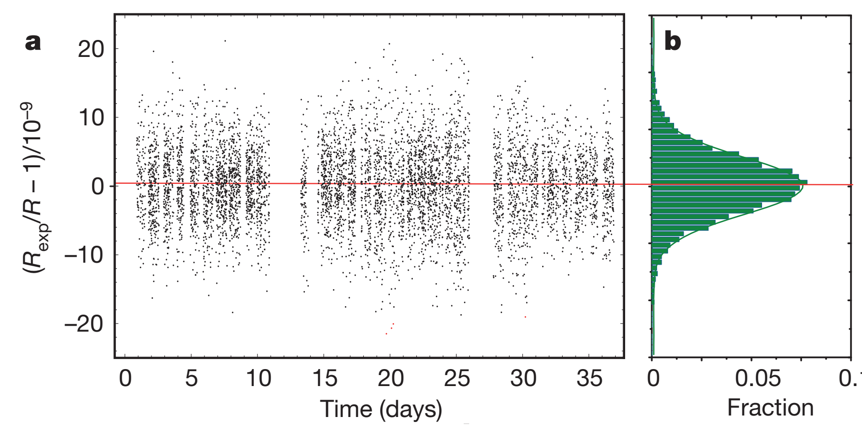
The BASE Collaboration

Proton g-Factor



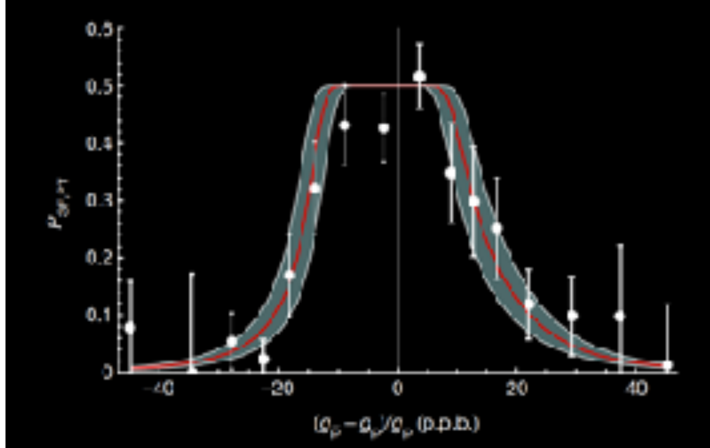
$$\frac{g_p}{2} = 2.792\,847\,344\,63(75)(34)$$

Proton-Antiproton Charge-to-Mass Ratio



$$\frac{(q/m)_{\overline{p}}}{(q/m)_p} = 1.000\,000\,000\,001(64)(26)$$

Antiproton g-Factor



$$\frac{g_{\overline{p}}}{2} = -2.792\,847\,344\,1(4\,2)$$

in Mainz

at CERN

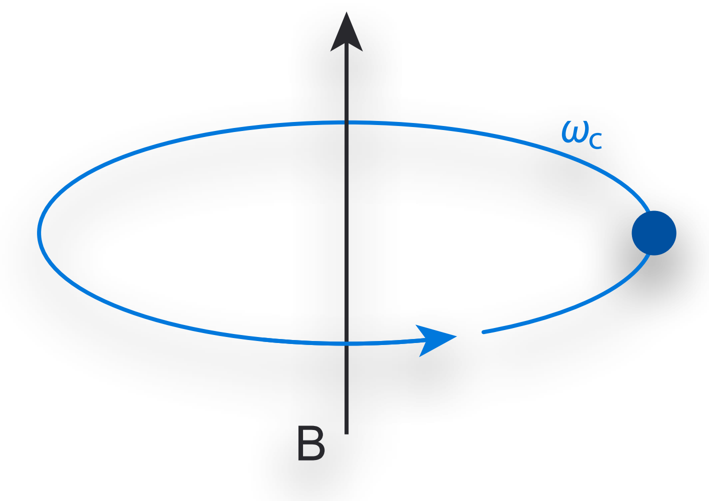
Schneider, G. *et al*. Science **358**, 1081 (2017)

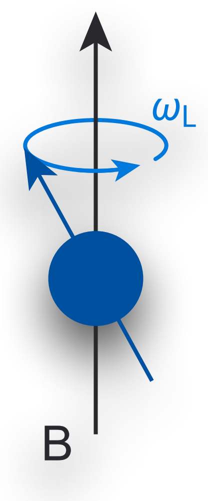
Ulmer, S. *et al*. Nature **524**, 196 (2015)

Smorra, C. *et al*. Nature **550**, 371 (2017)

BASE Mainz - The Proton *g*-Factor

- frequencies of a single proton in a magnetic field:





cyclotron frequency

$$\omega_c = \frac{qB}{m}$$

Larmor frequency

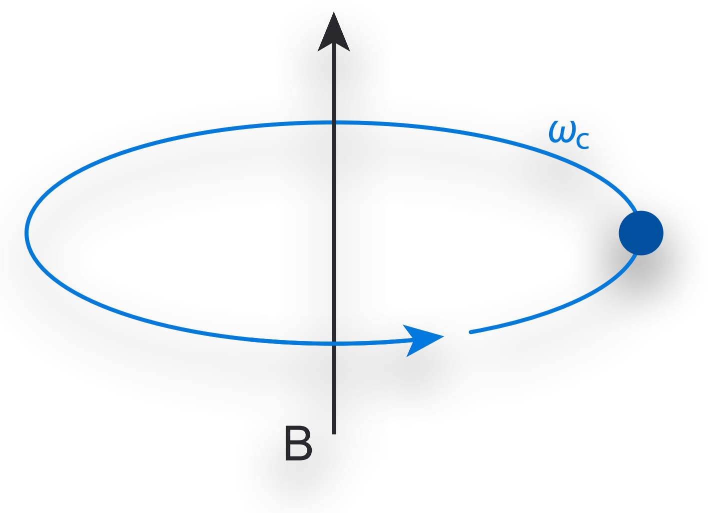
$$\omega_L = \frac{g}{2}\frac{qB}{m}$$

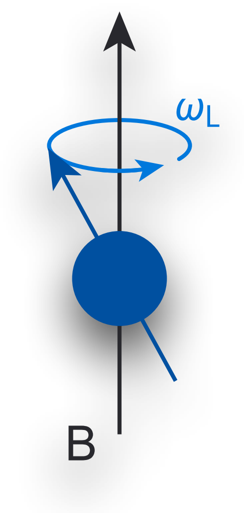
- *g*-factor of the proton:

$$\frac{g}{2} = \frac{\omega_L}{\omega_c}$$

BASE Mainz - The Proton *g*-Factor

- frequencies of a single proton in a magnetic field:





cyclotron frequency

$$\omega_c = \frac{qB}{m}$$

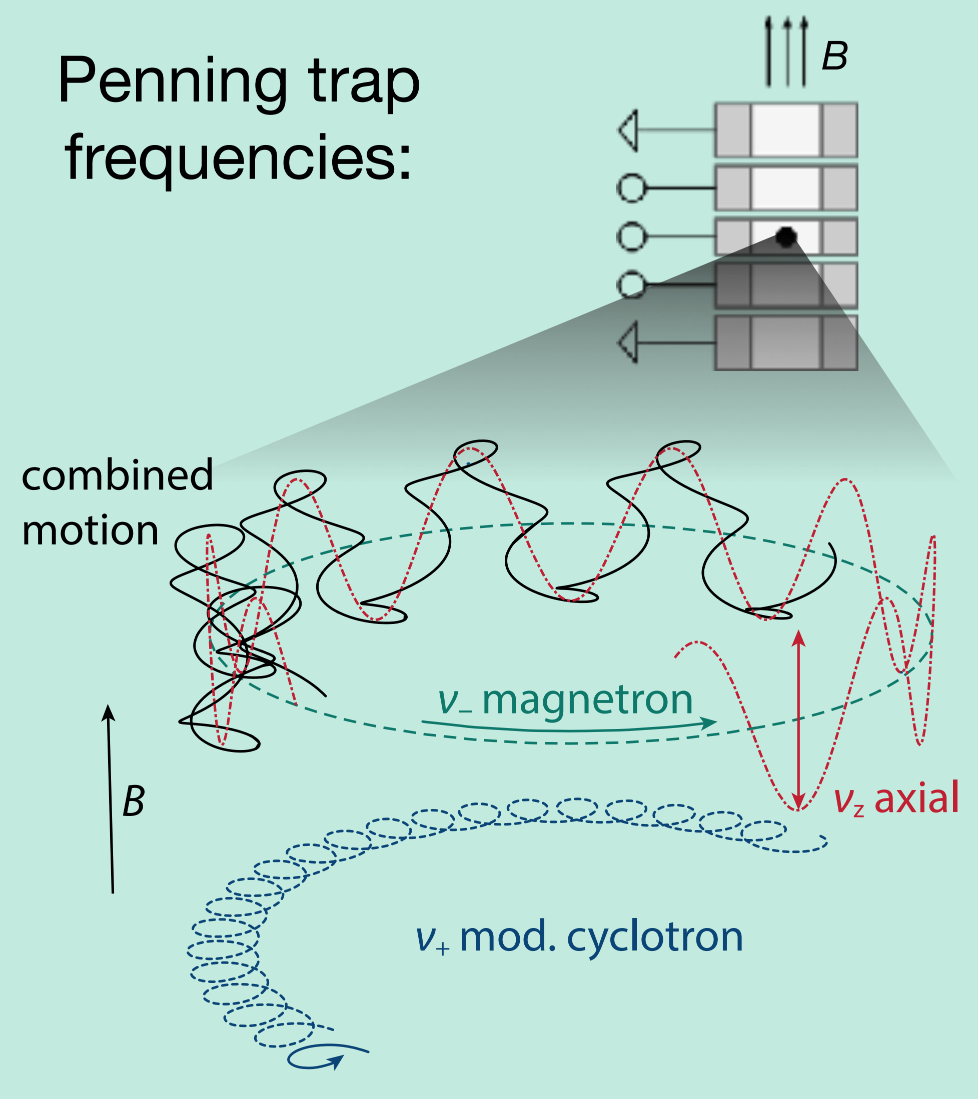
Larmor frequency

$$\omega_L = \frac{g}{2}\frac{qB}{m}$$

- *g*-factor of the proton:

$$\frac{g}{2} = \frac{\omega_L}{\omega_c}$$

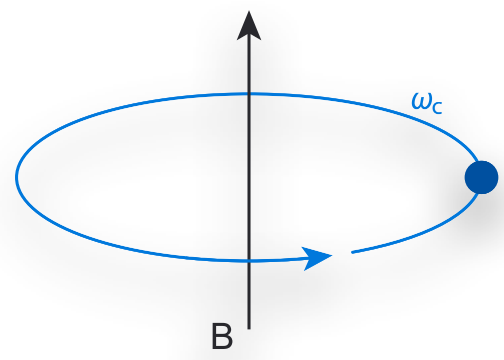
Penning trap frequencies:



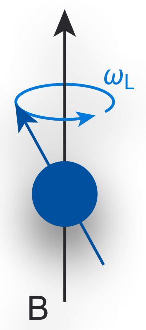
$$\nu_c{}^2 = \nu_+{}^2 + \nu_z{}^2 + \nu_-{}^2$$

BASE Mainz - The Proton *g*-Factor

- frequencies of a single proton in a magnetic field:



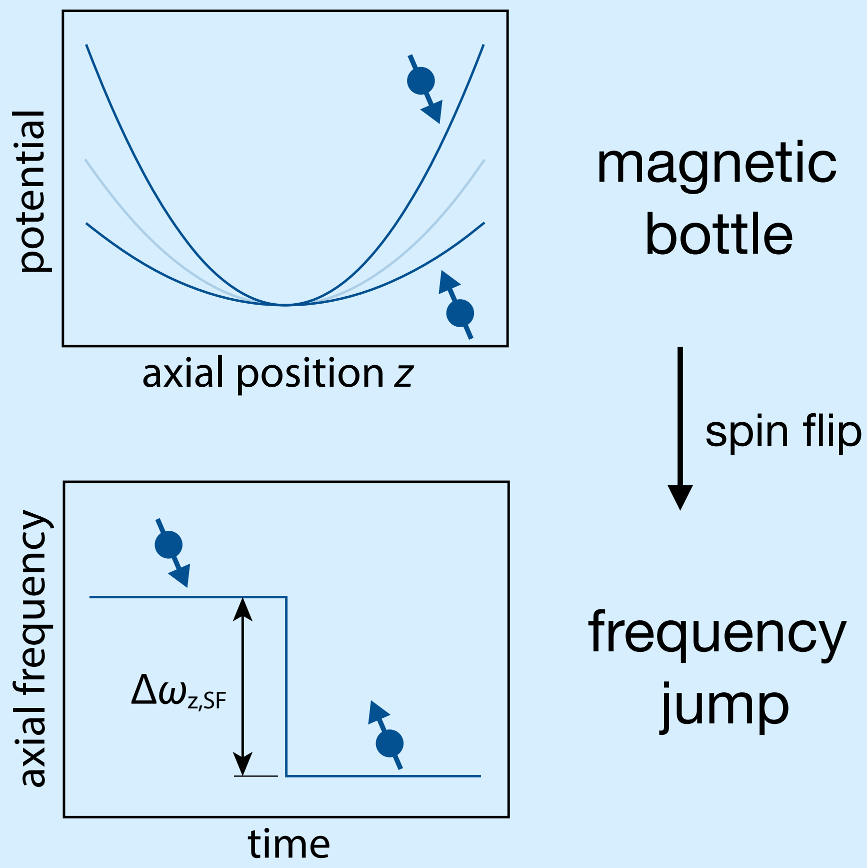
$$\omega_c = \frac{qB}{m}$$



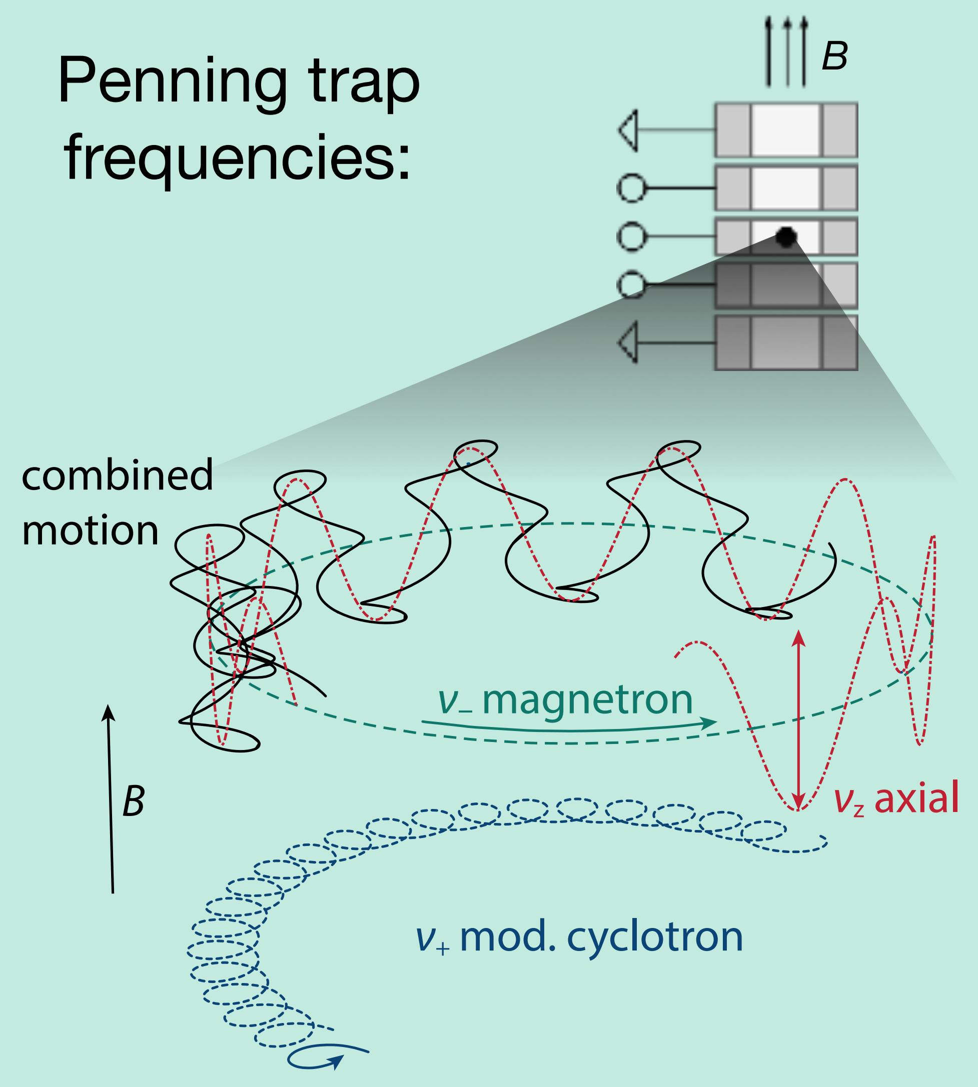
$$\omega_L = \frac{g}{2}\frac{qB}{m}$$

continuous Stern-Gerlach effect:

$$E_{pot} = -\vec{\mu}\cdot\vec{B} = \pm\frac{g_p}{2}\mu_K B_2 z^2$$

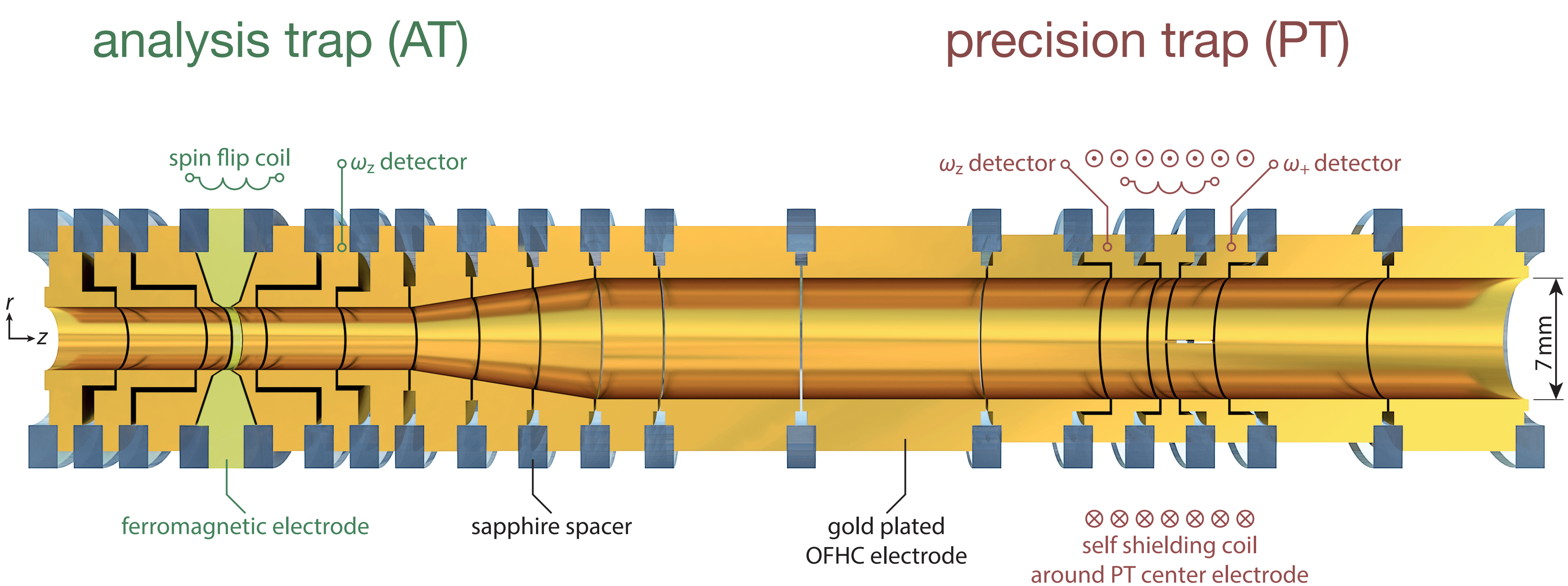


Penning trap frequencies:

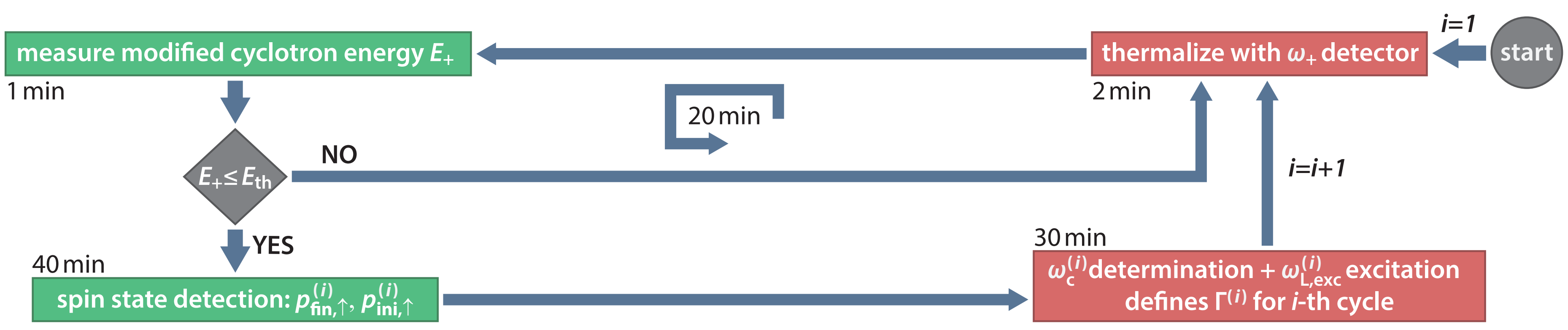


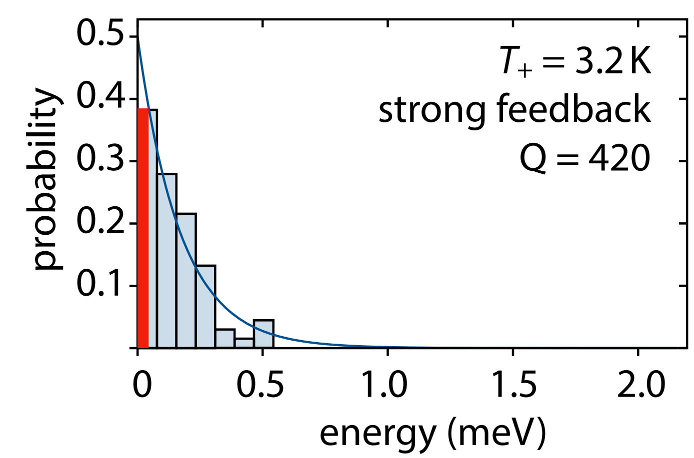
$$\nu_c{}^2 = \nu_+{}^2 + \nu_z{}^2 + \nu_-{}^2$$

The Double Penning Trap Method



sub-thermal cooling:





threshold: 0.05 meV

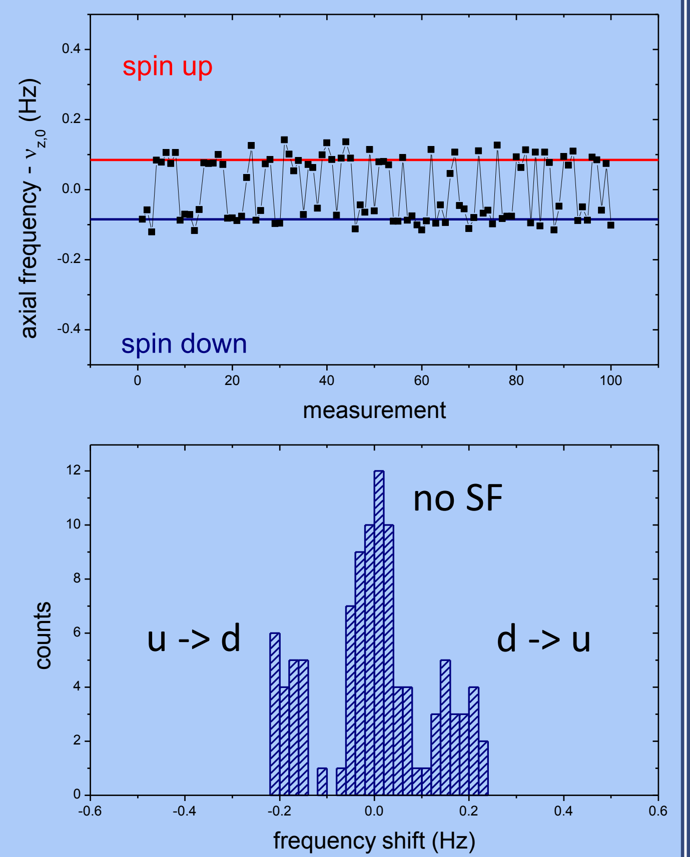
(0.6 K)

→ the cooling process is very time-consuming

Schneider, G. *et al*. Science **358**, 1081 (2017)

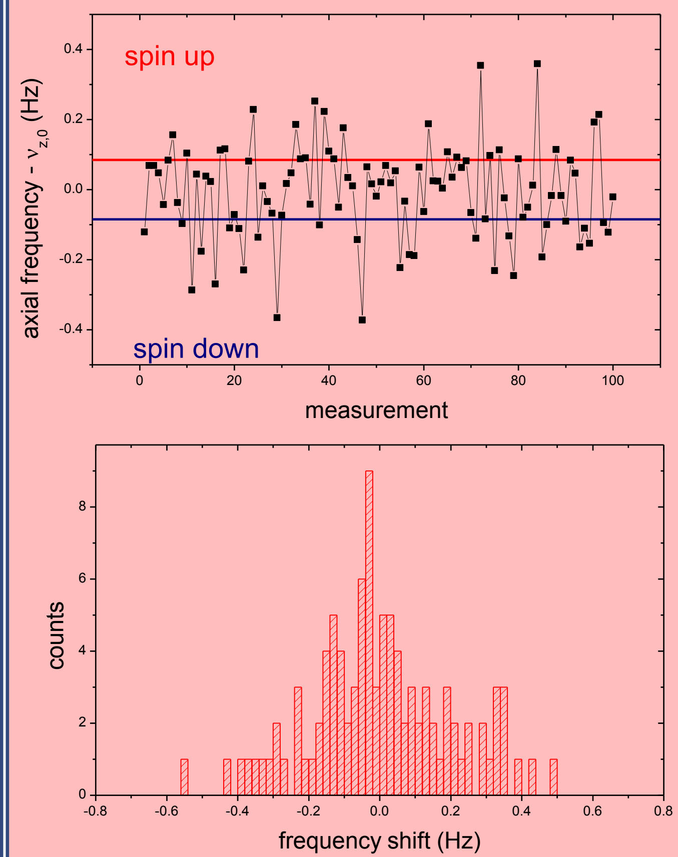
Single Spin-Flip Resolution and Particle Temperature

cold particle (50mK)



high-fidelity spin state resolution

hot particle (1K)



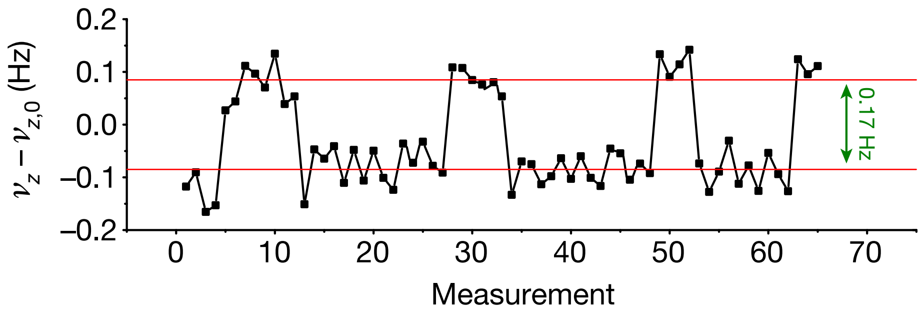
fidelity at 65%, not useful for measurements

- RF noise → cyclotron quantum transitions
- transition rate proportional to cyclotron quantum number

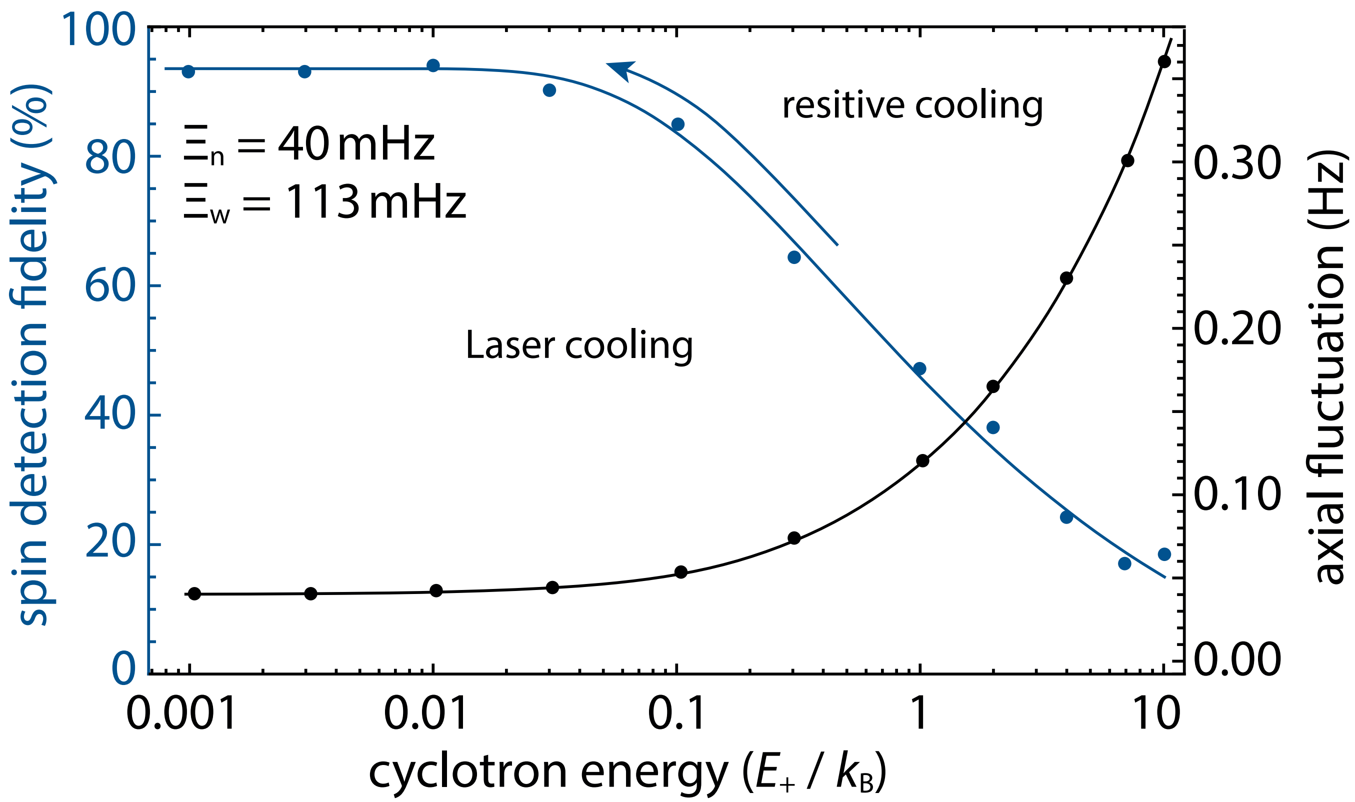
$$\frac{\mathrm{d}n_+}{\mathrm{d}t} \propto n_+$$

- ultra-cold particles (0.1K) are required for high fidelity spin-flip detection
- problem: temperature after cyclotron frequency measurement: 300K

Single Spin-Flip Resolution and Particle Temperature

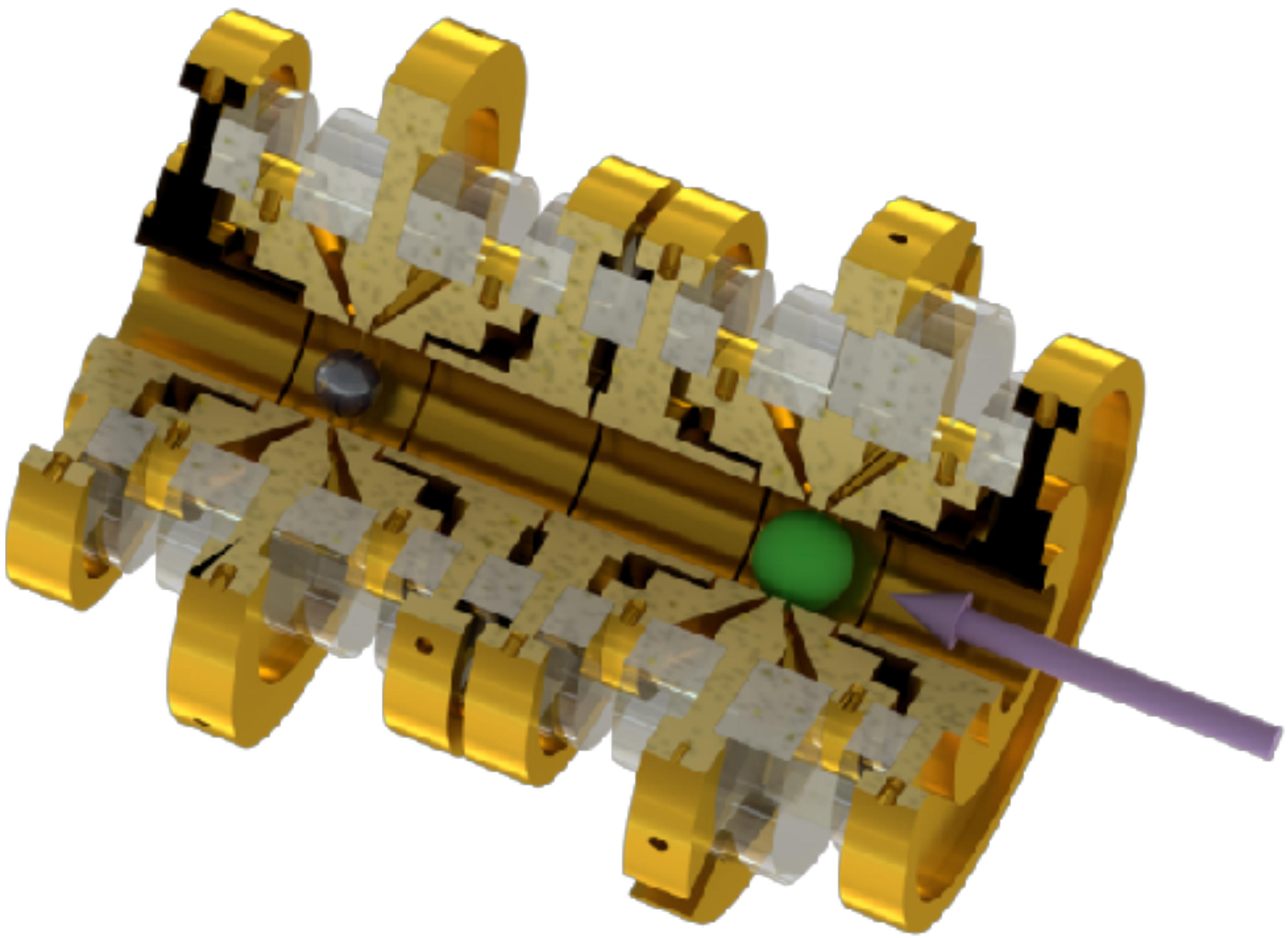


- ultra-cold particles (0.1K) are required for high fidelity spin-flip detection
- laser cooling can provide temperatures in the mK range

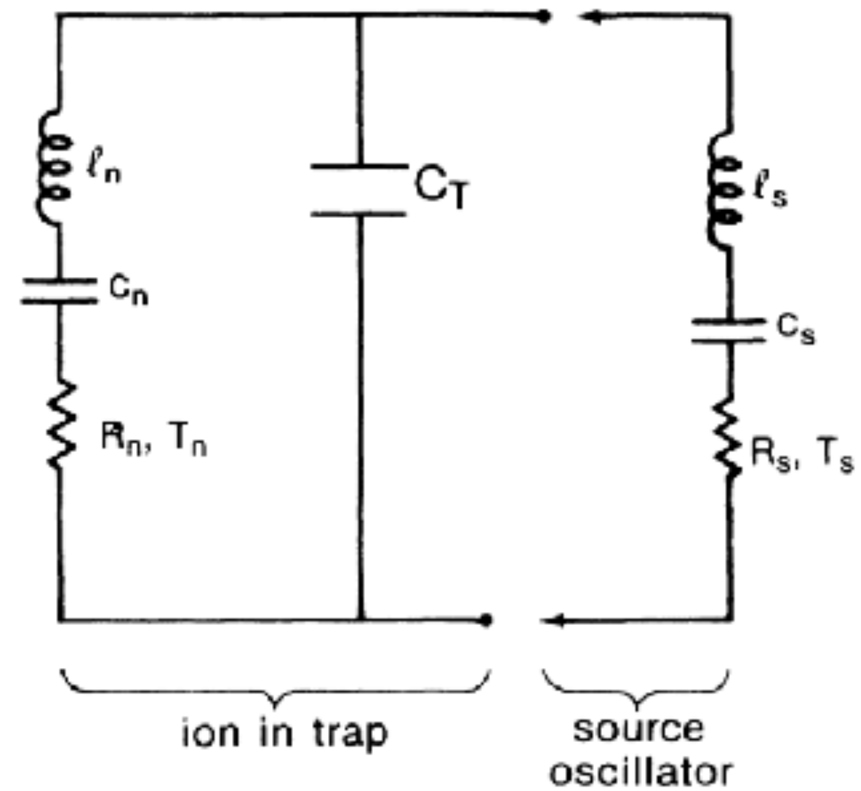


Sympathetic Cooling via Coupled Traps

- cloud of N trapped and laser cooled Be ions is used as refrigerator for the proton



- trap design minimises C_T and therefore the coupling time τ:



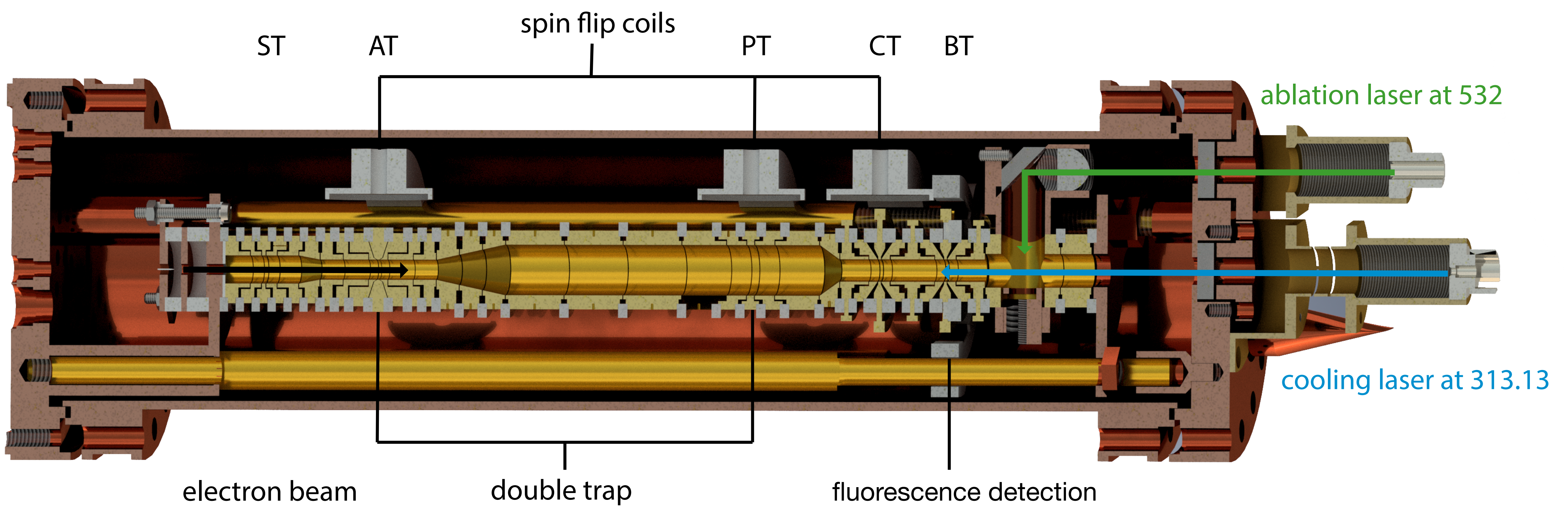
- coupling time τ on the order of 55 s:

$$\tau = \pi \omega_z d^2 C_T \frac{\sqrt{m_p m_{Be}}}{e^2} \frac{1}{\sqrt{N}}$$

Heinzen, D. J. & Wineland, D. J., Phys. Rev. A, **42**, 2977 (1990)

Bohman M. *et al.*, J. Mod. Opt. (2017)

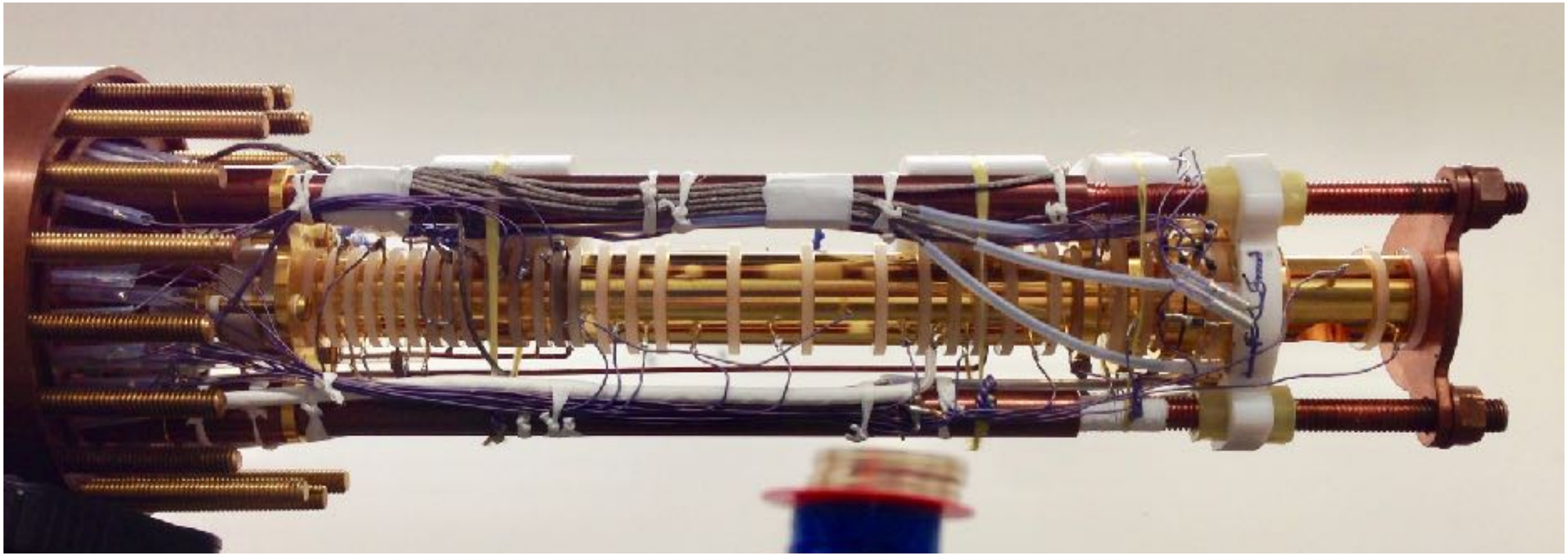
The Apparatus



- double trap for *g*-factor measurements
- coupling traps for sympathetic cooling

Bohman M. *et al.*, J. Mod. Opt. (2017)

The Apparatus



- double trap for *g*-factor measurements
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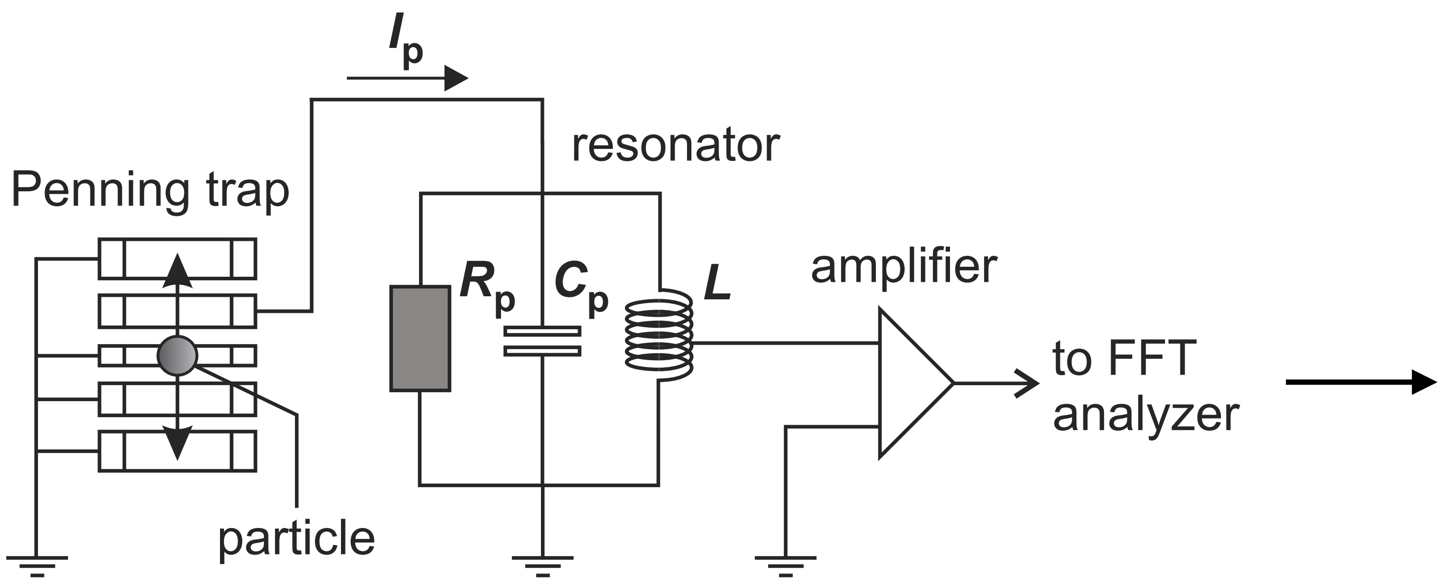
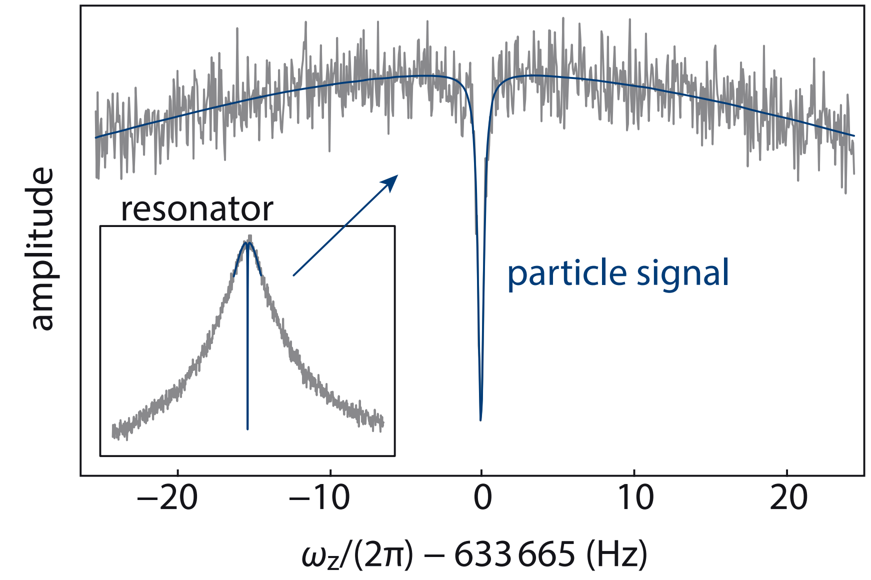
Bohman M. *et al.*, J. Mod. Opt. (2017)

Cryogenic Detection Systems I

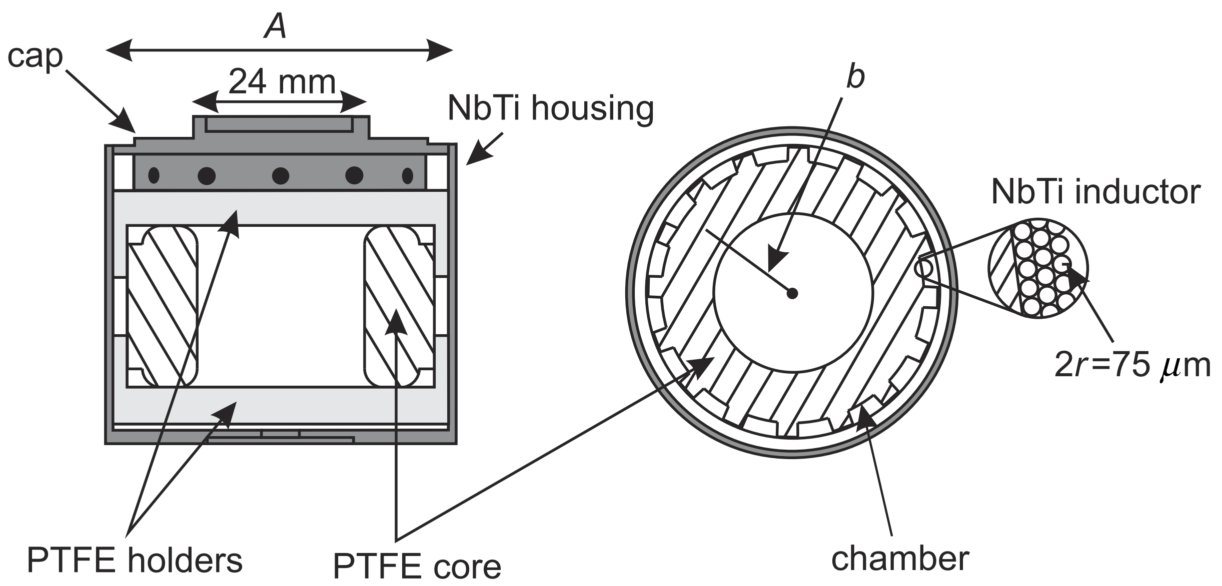
Image Current Detectors

Axial Frequency Detection System



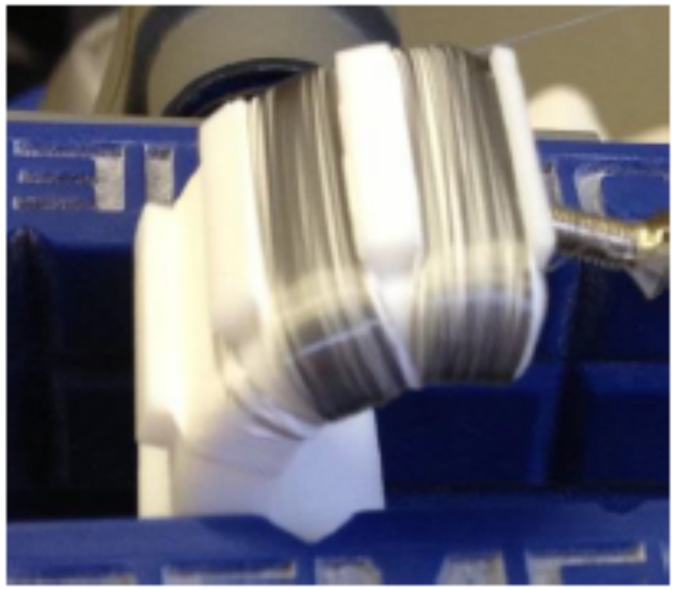


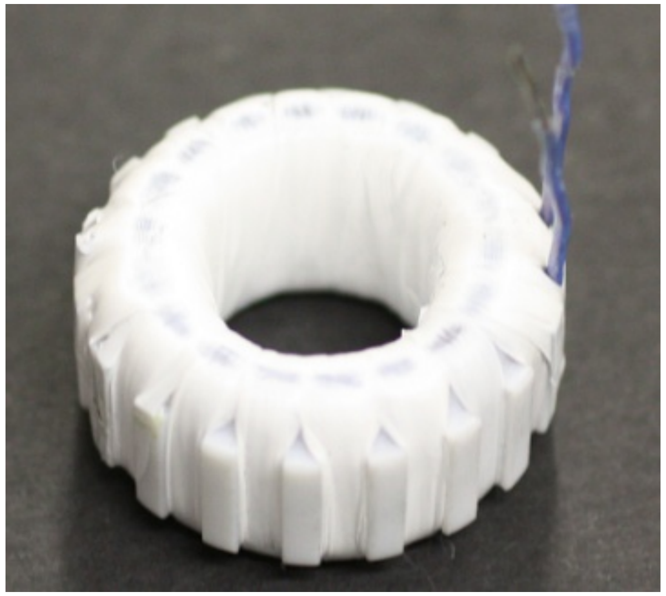
- toroidal coils
- inductivity ~ 3 mH
- crucial: materials
- resonance frequency ~ 500 kHz



Nagahama, H. *et al*. Rev. Sci. Instrum. **87**, 113305 (2016)

Axial Frequency Detection System





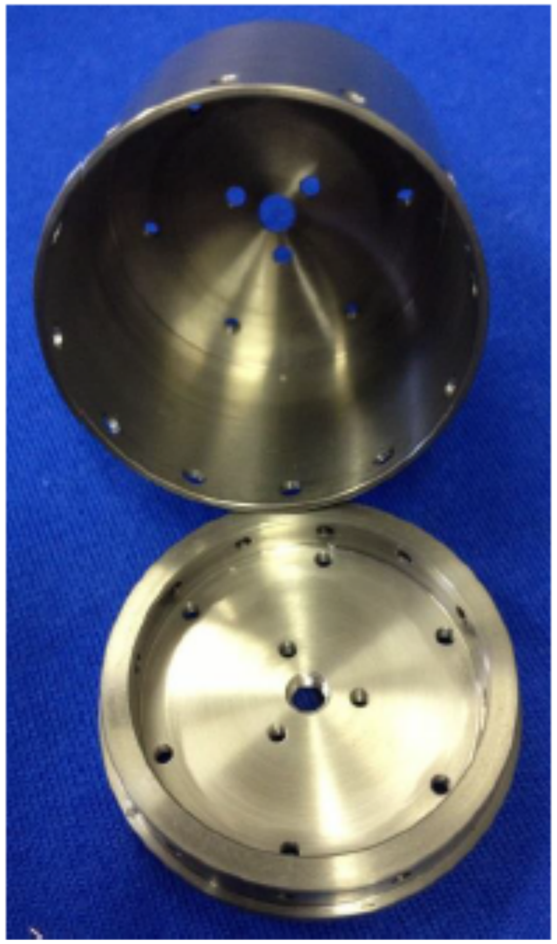
N = 950 - 1200

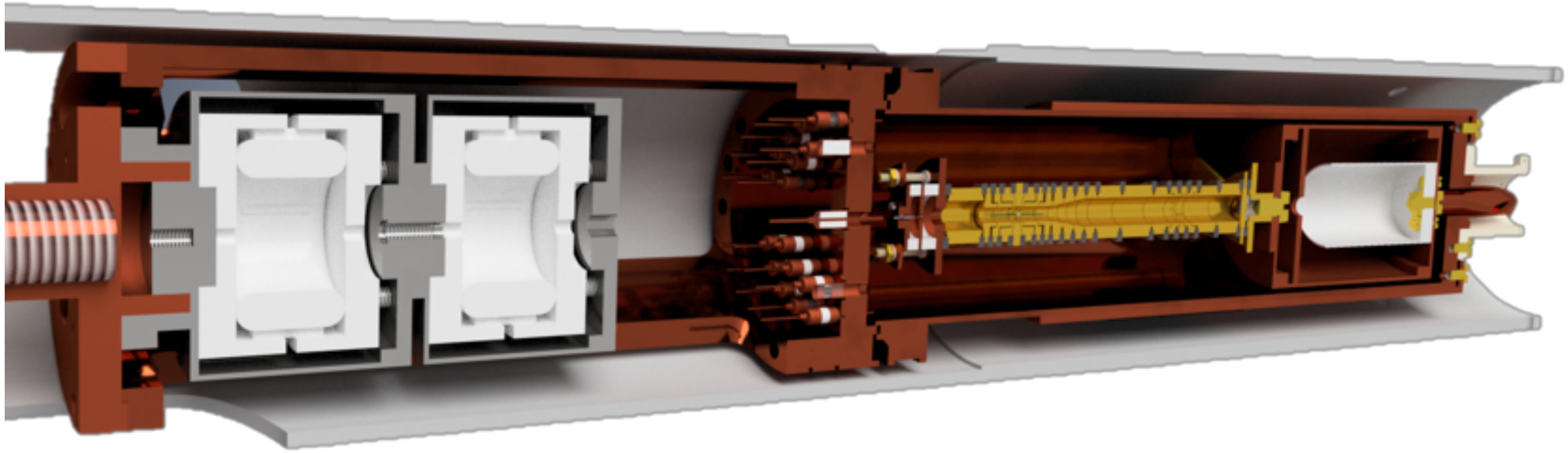
Q = 200k - 500k

L = 2-3 mH

ν_z = 400-800 kHz

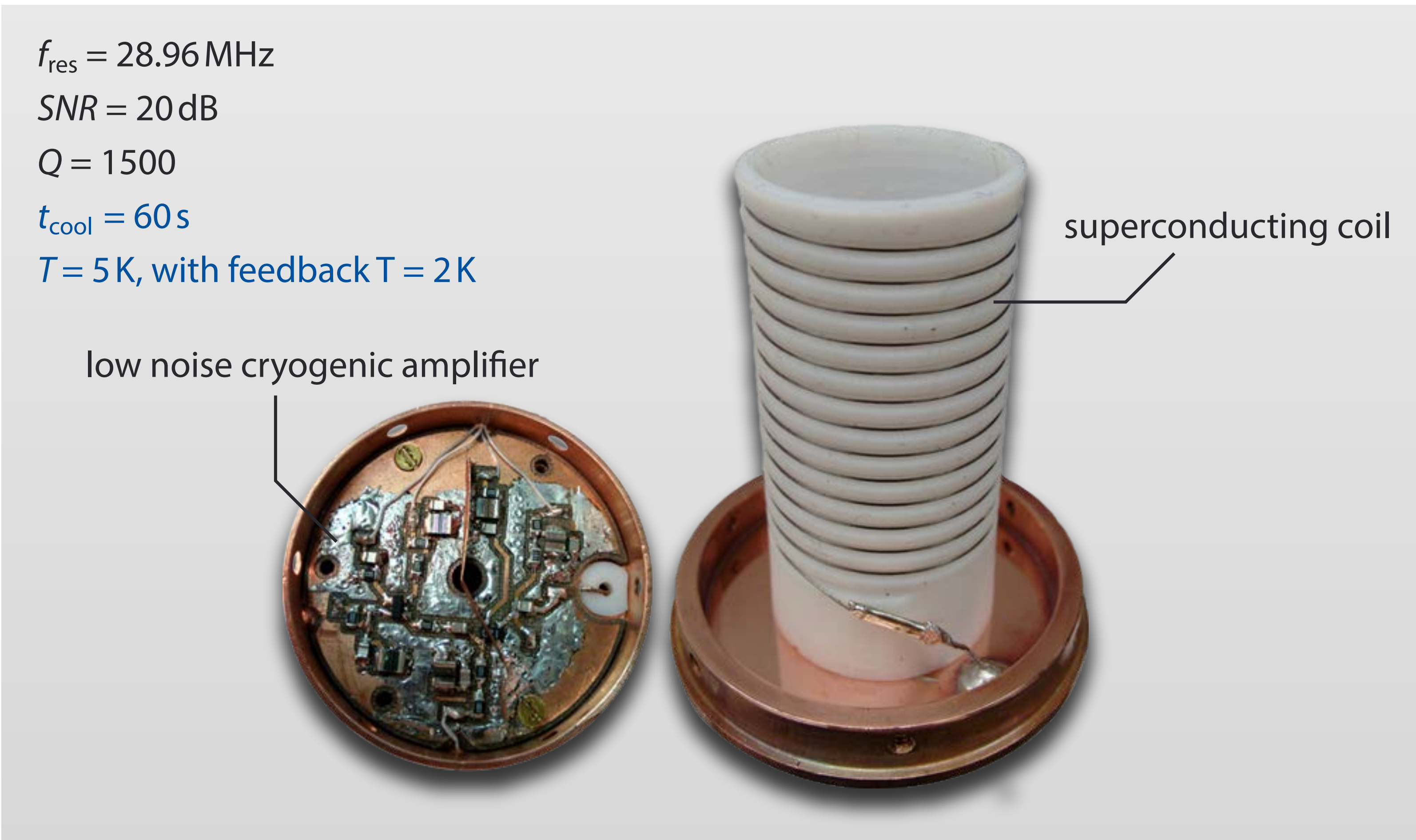
Rp > 1GΩ

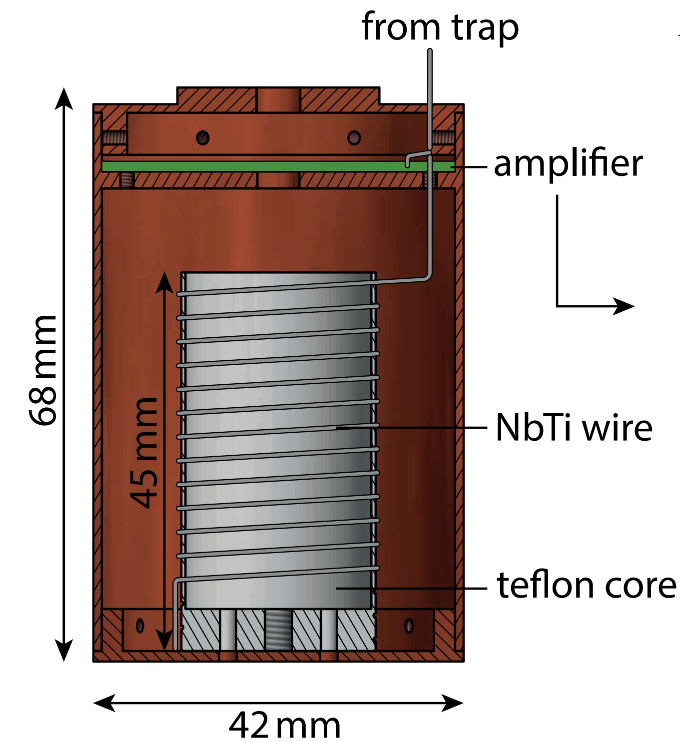




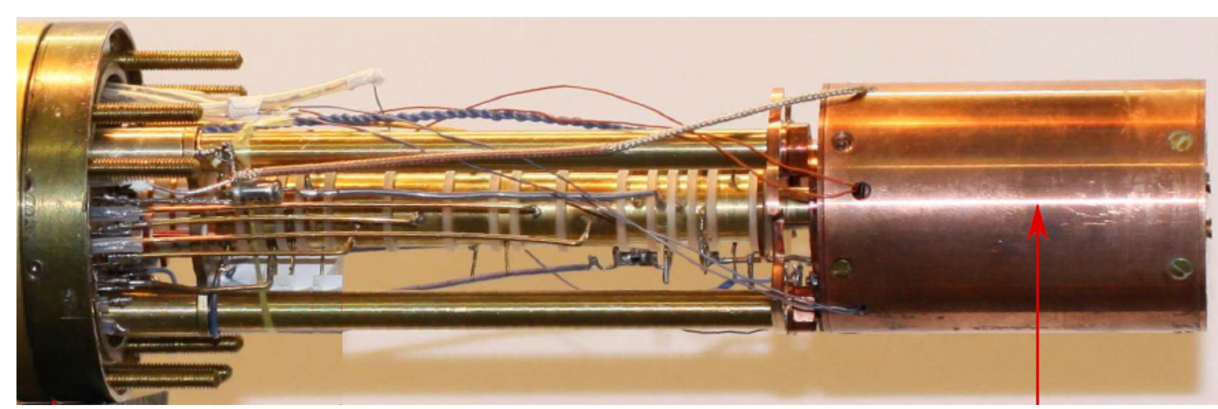
Nagahama, H. *et al*. Rev. Sci. Instrum. **87**, 113305 (2016)

Modified Cyclotron Frequency Detection System





- split electrodes necessary
- crucial: choice of materials



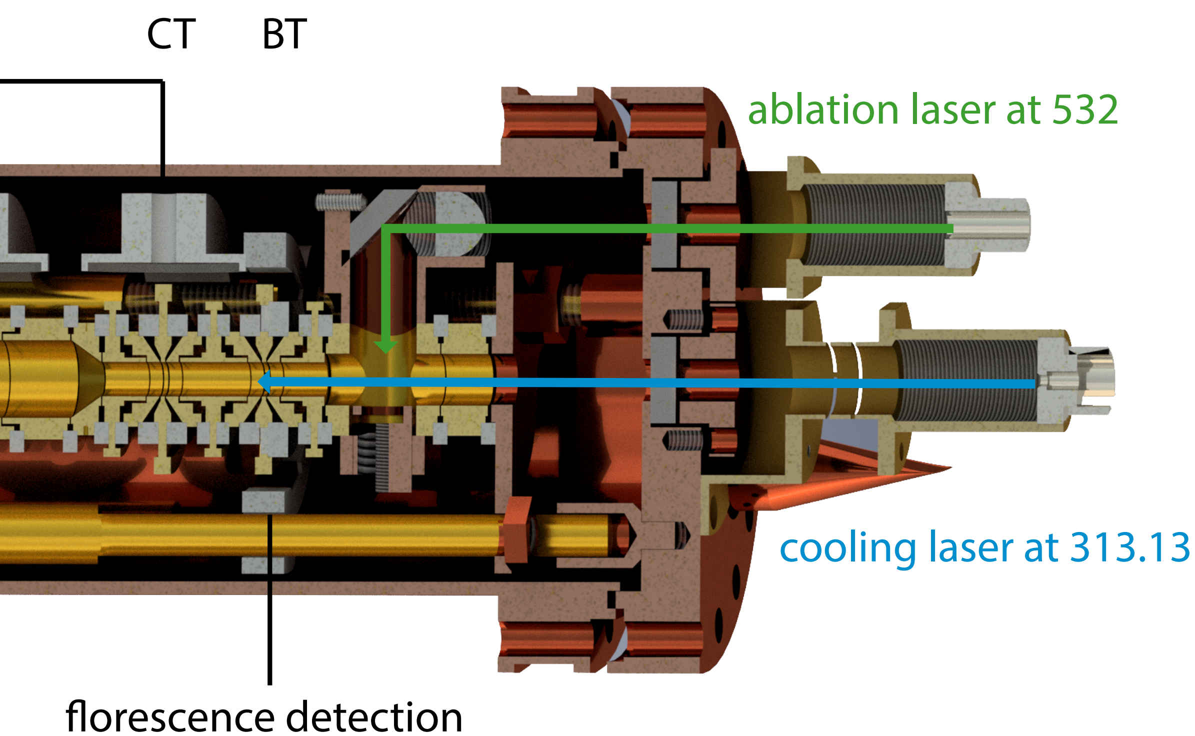
Schneider, G. Doctoral Thesis (2018)

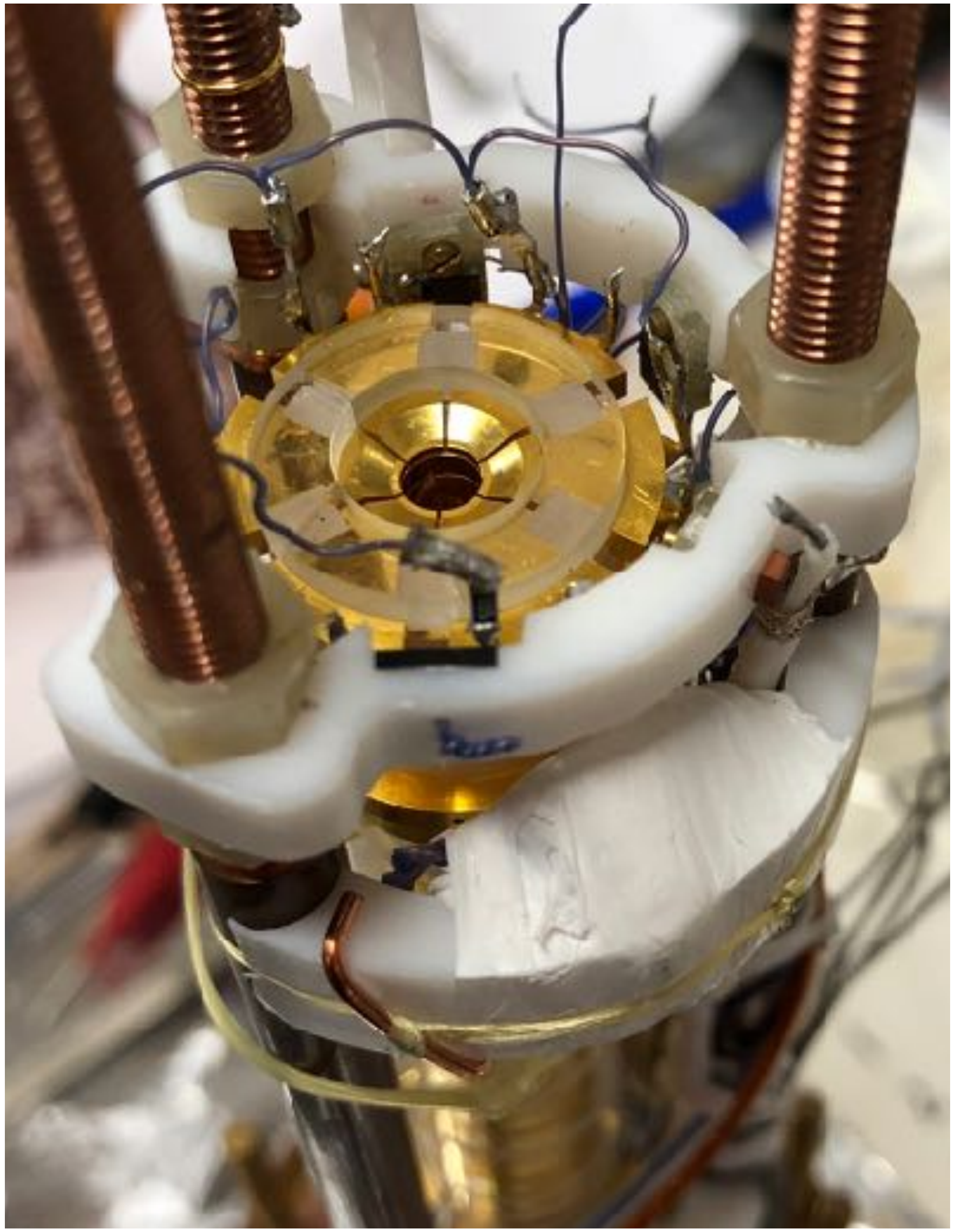
Cryogenic Detection Systems II

Single Photon Sensors for Fluorescence Detection

Fluorescence Detection

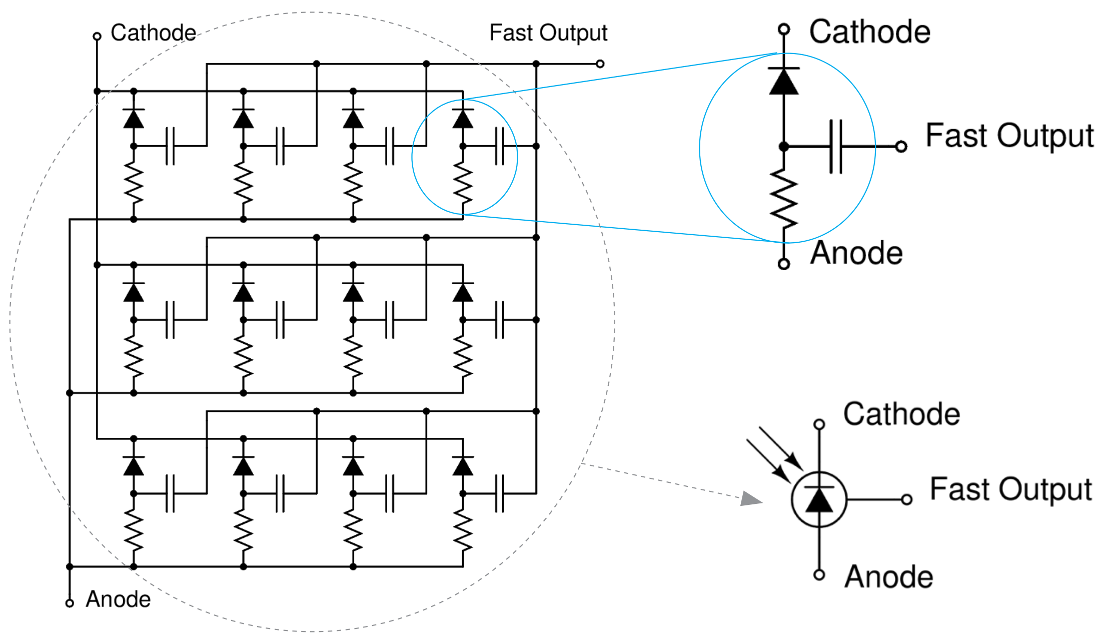
- BT ring electrode:
  - features 6 slits
  - application of rotating wall drive
  - allows detection of fluorescence light

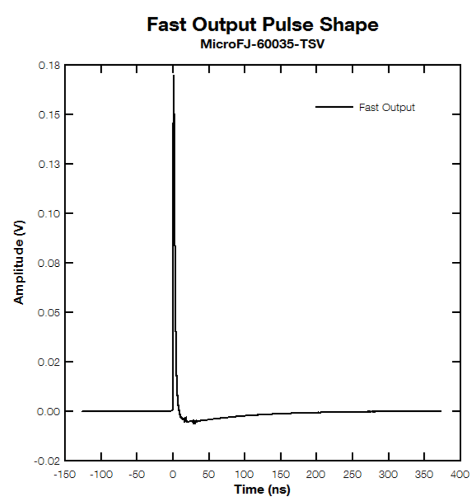


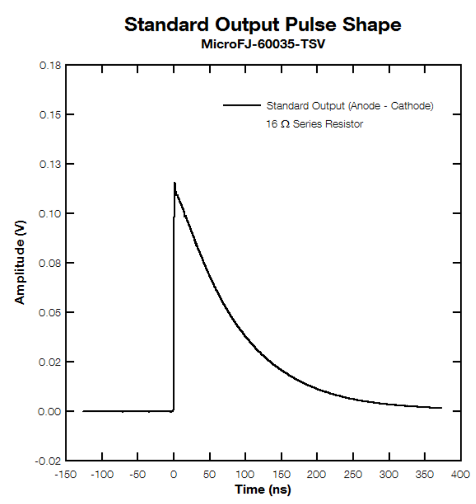


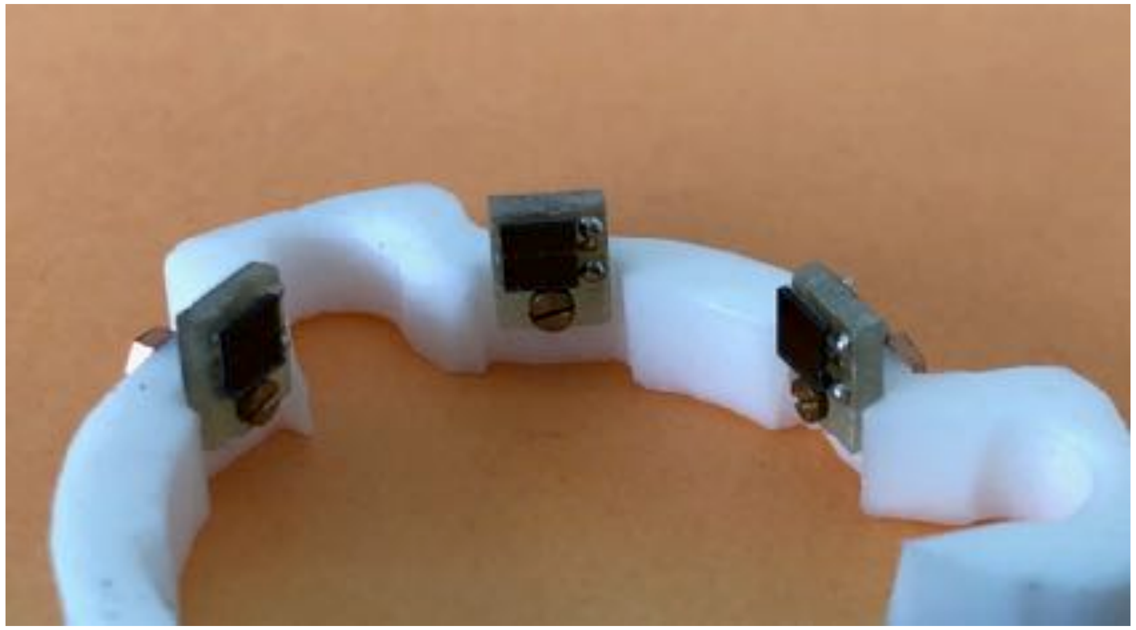
The SiPM Sensor

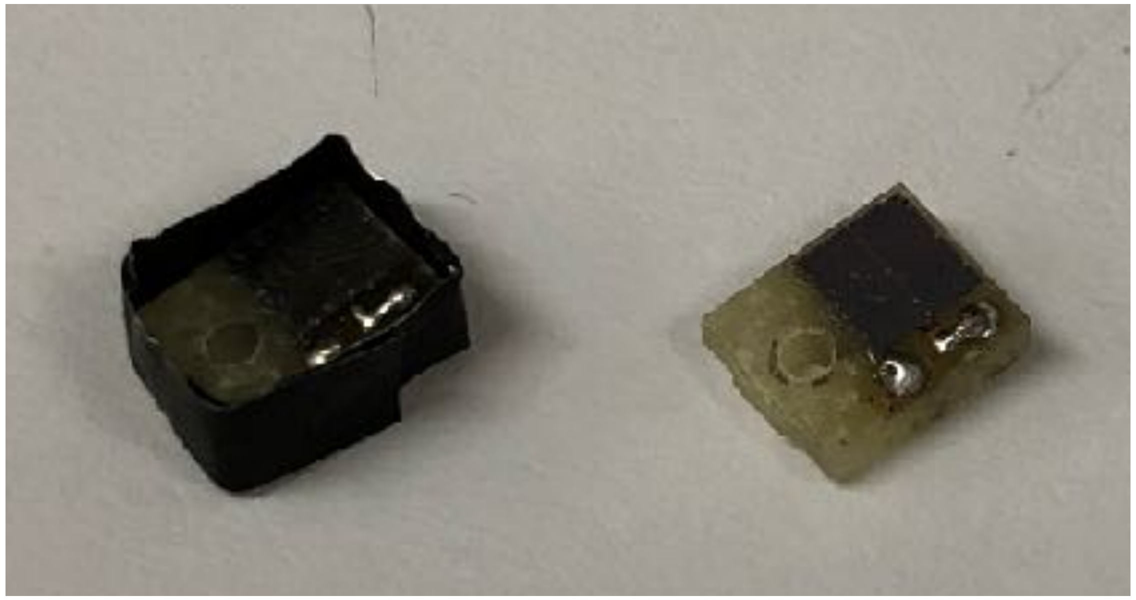
5676 cells





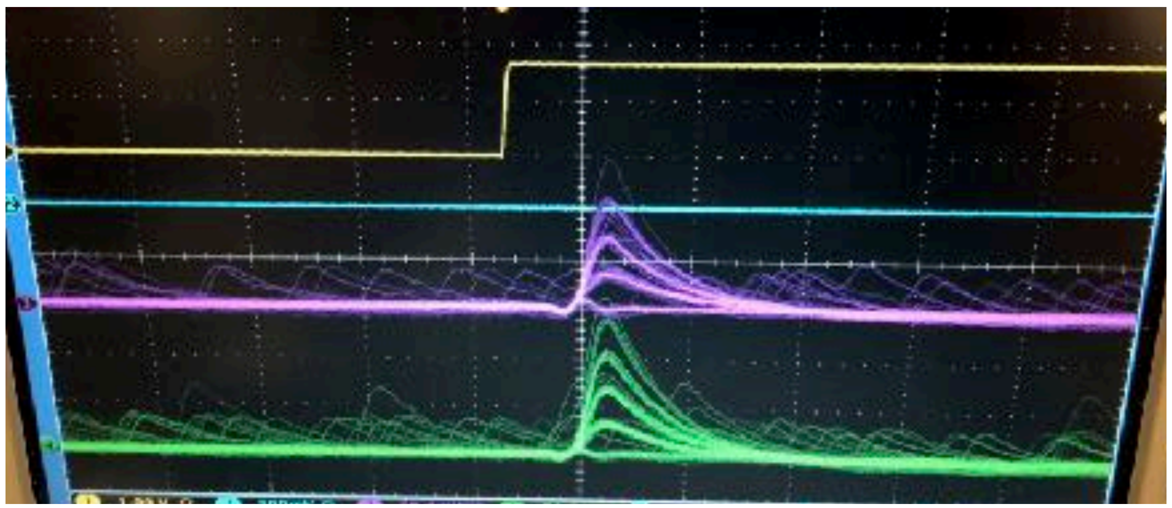




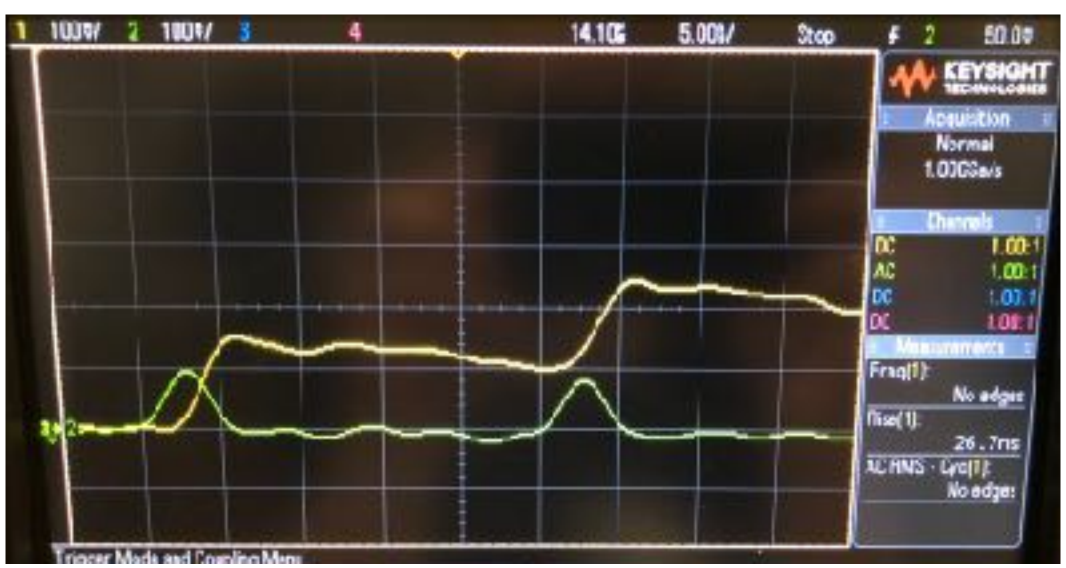


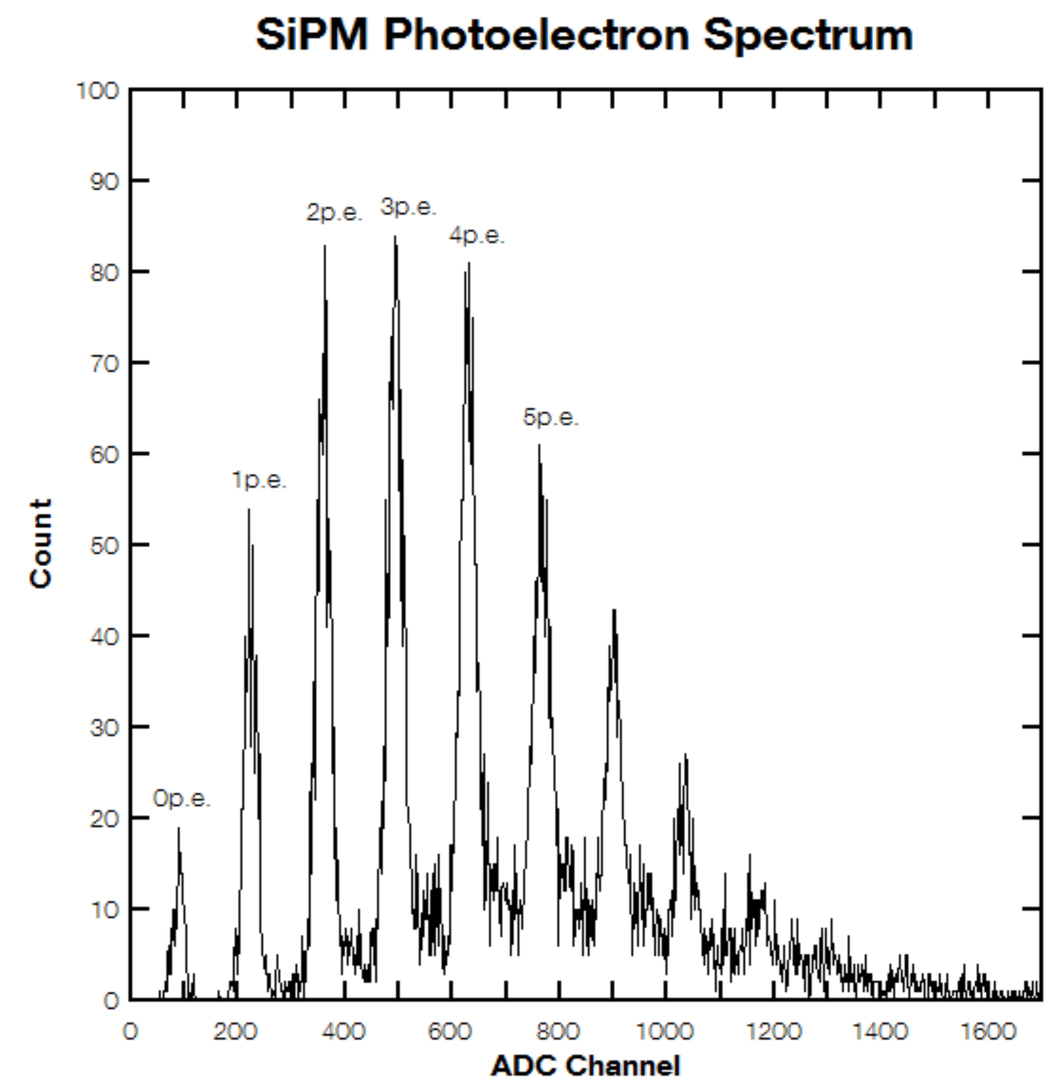
Test Setup

- multiple photons:



- fast vs. slow signal:





Fluorescence Detection Progress

- ✅ test in the cryostat at 4K
- ✅ test with 315±5 nm light
- ✅ cables:
  - ❌ cryo coax
  - ❌ twisted pair
  - ❌ shielded twisted pair
  - ❌ low noise cryo coax
  - ✅ small diameter kapton insulated copper coaxial cable (but 55 mW heat load)
- ✅ test in the apparatus

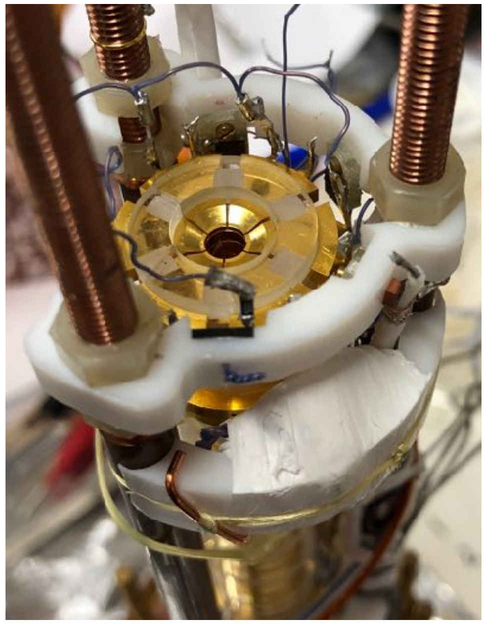
we are working on:

readout

cables: semi-rigid coaxial cable made of BeCo/SS or SS/SS

Recent Results

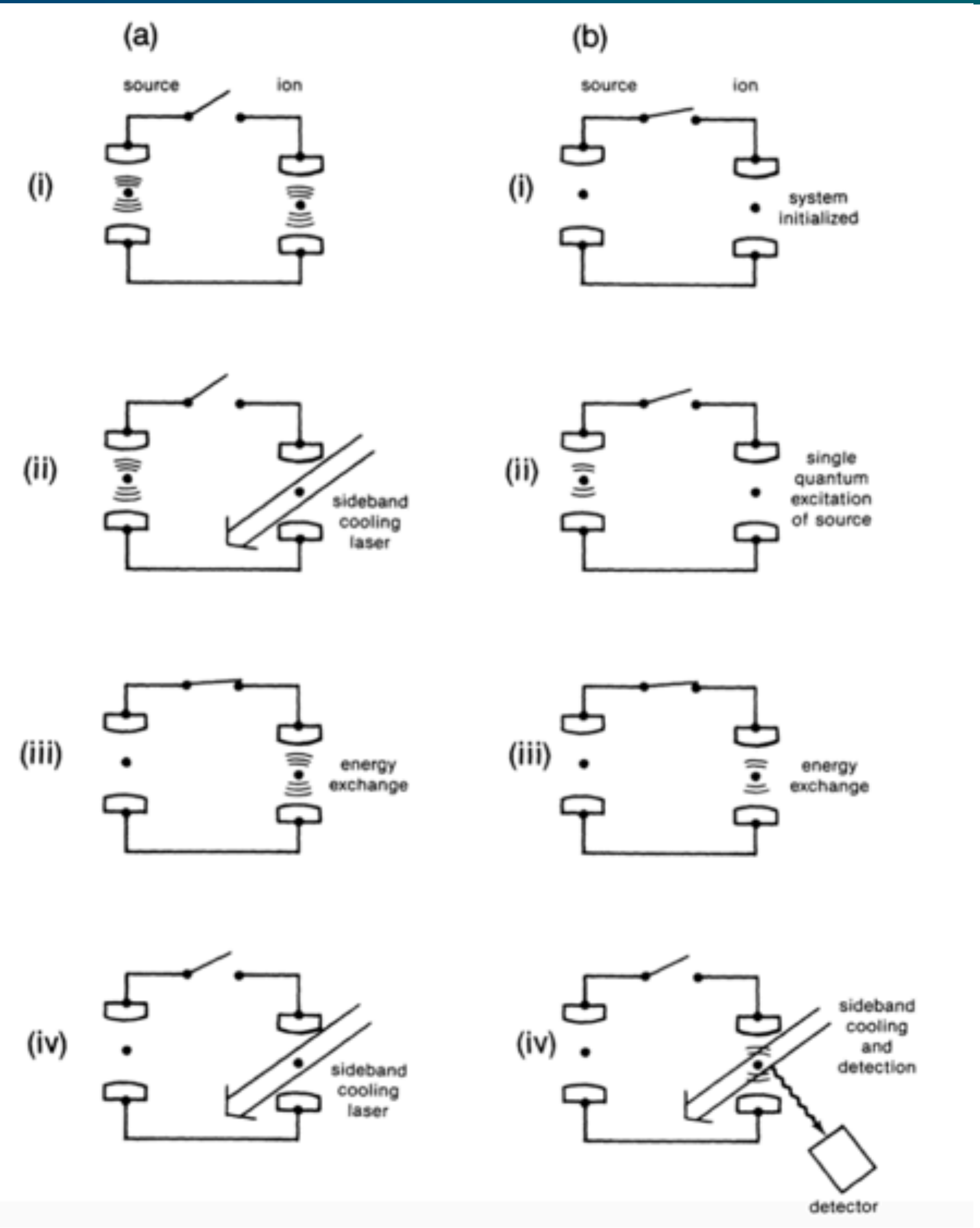
- Tests of the SiPM in the apparatus at 4K:
  - excellent background count rate: < 1 Hz
  - laboratory lights background: 1000 Hz
  - 313 nm cooling laser background: 60 kHz
- estimated fluorescence signal: > 10 kHz



Cryogenic Detection Systems III

A single laser-cooled Be^{+} ion
as a quantum sensor

Laser cooled Be+ as quantum sensor



Heinzen, D. J. & Wineland, D. J., Phys. Rev. A, **42**, 2977 (1990)

a) cooling of a source to the ground state of motion

b) detecting single quantum excitations of the source

BASE

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG

Cryogenic Detection Systems for Low-Energy Particles in a Penning Trap

JG|U

GSI

HIM
HELMHOLTZ
Helmholtz-Institut Mainz