Max-Planck-Institut für Kernphysik Heidelberg

Cooling Ions using Electrons

or

"Sympathetic cooling of highly charged ions in a Penning trap using a self-cooled electron plasma"

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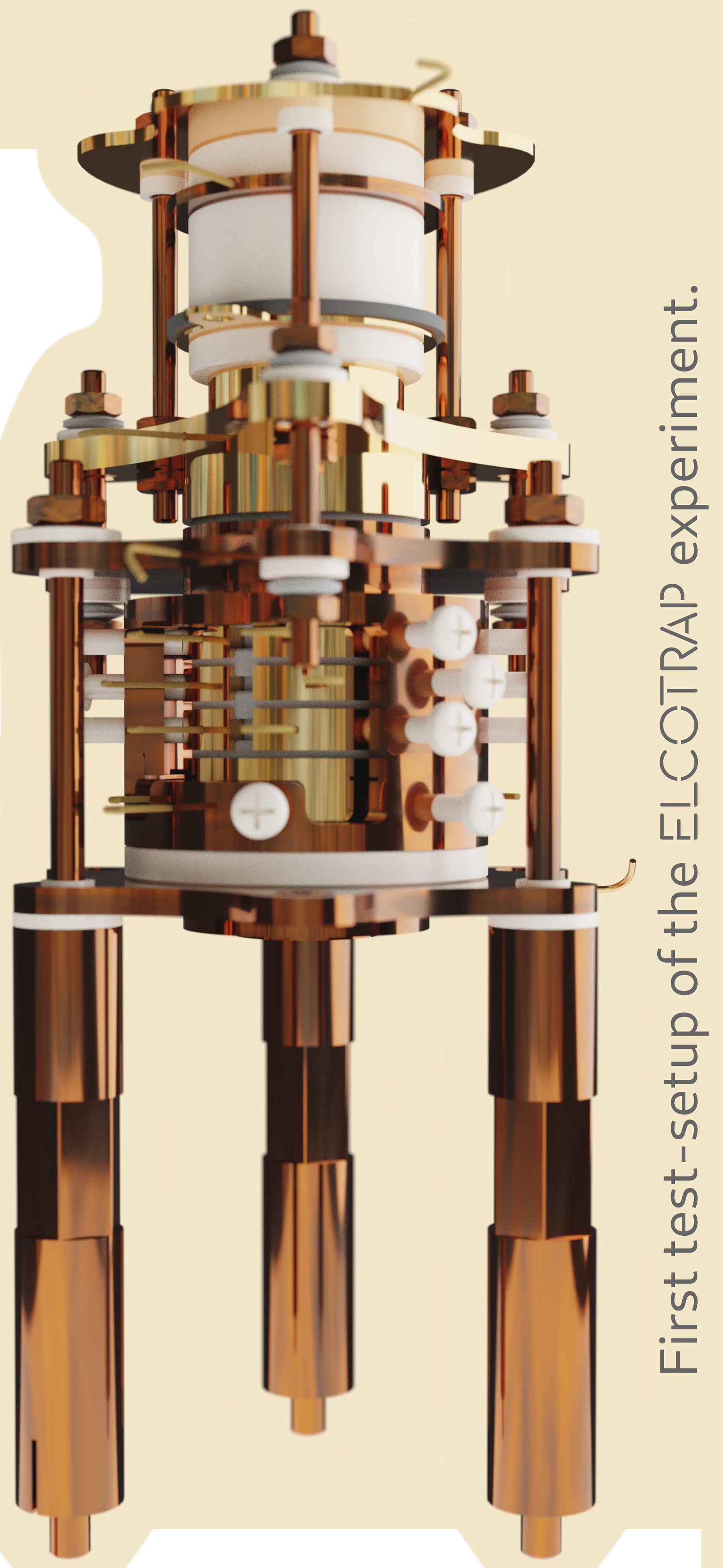


First test-setup of the ELCOTRAP experiment.

MOTIVATION

Penning traps are used to store charged particles for fundamental research e.g. in the following applications:
- **Mass** measurements [1]
- **Magnetic moment** measurements [2, 3, 4]
- **Quantum** technology [5]

Efficient particle cooling is essential to all of these experiments. A new technique uses an electron plasma stored in a Penning trap to cool a single highly charged ion in a **macroscopically distant** Penning trap down to very low temperatures.
This promises significant improvements in precision.

Why cold ions?

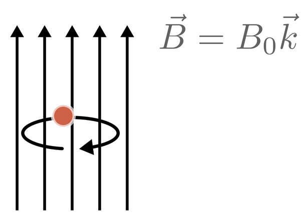
- Smaller relativistic shifts
- Less influence from field imperfections due to smaller oscillation amplitude
- Smaller thermal phase space volume -> Higher precision frequency determination

[1] S. Eliseev, et al., Phys.Rev.Lett., 115, 062501 (2015)
[2] S. Sturm, et al., Phys.Rev.Lett., 107, 023002 (2011)
[3] A. Mooser, et al., Nature, 509,596 (2014)
[4] C. Smorra, et al., Nature, 550, 371 (2017)
[5] Bruzewicz, C. D. et al., Appl. Phys. Rev. 6, 021314 (2019)

PENNING TRAP

Radial confinement

of charged particles using a strong, homogeneous magnetic field:



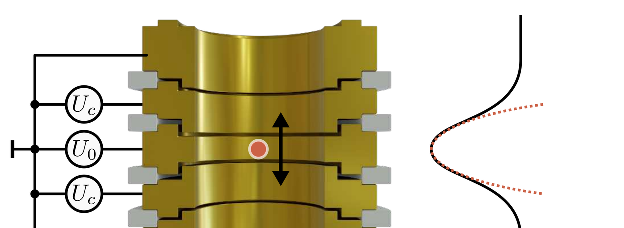
Free cyclotron frequency:

$$\nu_c = \frac{q}{2\pi\, m} B_0$$

+

Axial confinement

using an harmonic electrostatic potential:



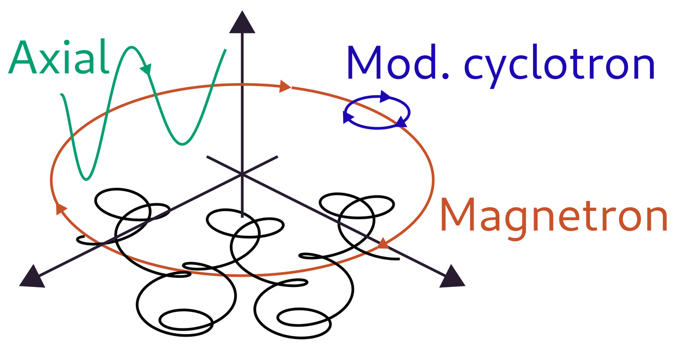
Axial frequency:

$$\nu_z = \frac{1}{2\pi}\sqrt{\frac{2qC_2U_0}{m}}$$

→

Superposition of fields

leads to three independent eigenmotions:



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

ELECTRON COOLING

1. Cyclotron cooling

- Up to 10^3 electrons are stored in a dedicated Penning trap.
- Due to their very high cyclotron frequency of approx. 195 GHz at B_0=7 T, their cyclotron modes dissipate energy due to **cyclotron radiation**.

Cooling time constant
$\tau_+ = 50\,\mathrm{ms}$

Equilibrium temperature
$T_+ = 4.2\,\mathrm{K}$

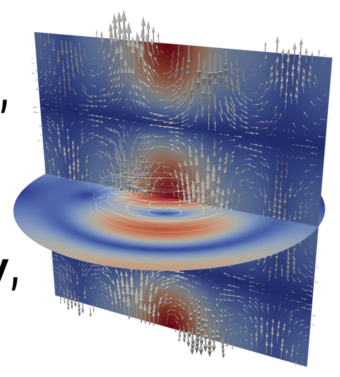
Average Landau level
$\langle n_+ \rangle = 0.45$

2. Sideband coupling

A quadrupolar RF-field at $\nu_{RF}=\nu_+-\nu_z$ couples and **thermalizes the axial mode** of the electrons with their well cooled cyclotron mode.

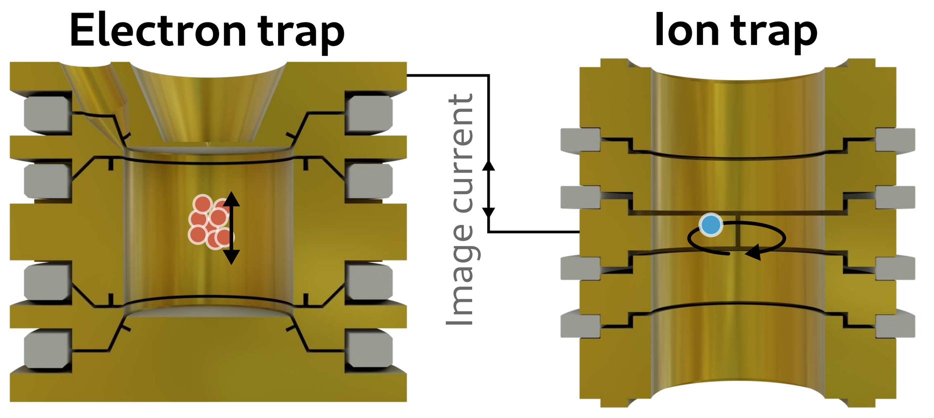
$$\langle n_z \rangle = 0.45 \qquad T_z = T_c\frac{\nu_z}{\nu_+} = 0.5\,\mathrm{mK}$$

The wavelength of the sideband drive is 1.5 mm, which is on the order of the trap dimensions. The trap acts like a **cavity**, whose modes must be carefully planned.



3. Coupling to ion

- A single highly charged ion is stored in a **separate Penning trap**.
- Interconnecting certain electrodes leads to **coupling** of the electron-axial and ion-cyclotron motion due to induced **image currents**.
- Potential depth of electron trap can be tuned so that ν_z of electrons precisely math ν_+ of ion.



$$T_{+,\mathrm{ion}} = 0.5\,\mathrm{mK}$$

The ion ends up mostly cooled down to its motional ground-state*

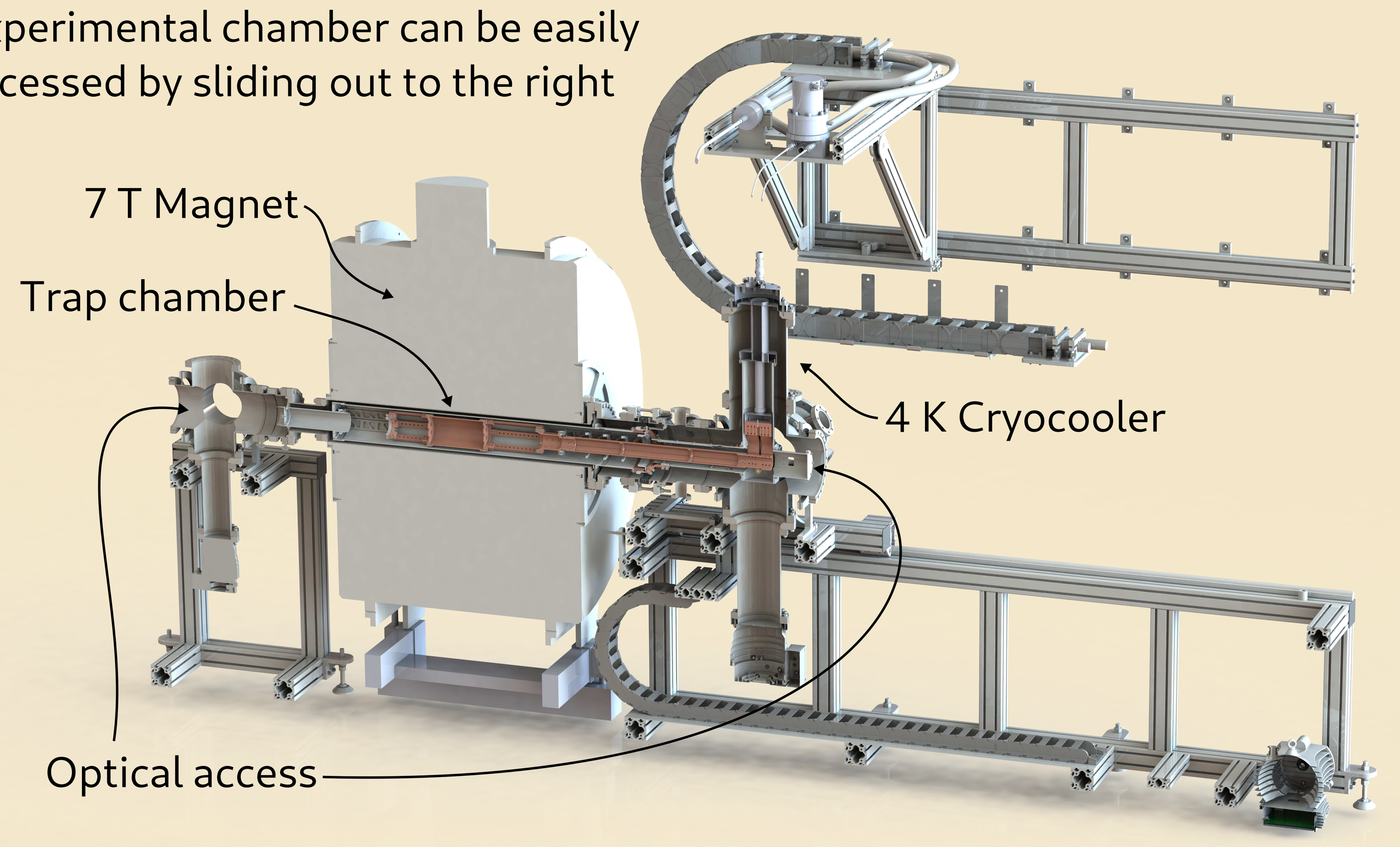
$$\langle n_+ \rangle_{\mathrm{ion}} = 0.45$$

*ideally

NEW PENNING-TRAP EXPERIMENT

- Dedicated to realizing electron cooling
- Optimized for **rapid design iterations**
- Experimental chamber can be easily accessed by sliding out to the right

ELCOTRAP



NEW SIMULATION FRAMEWORK

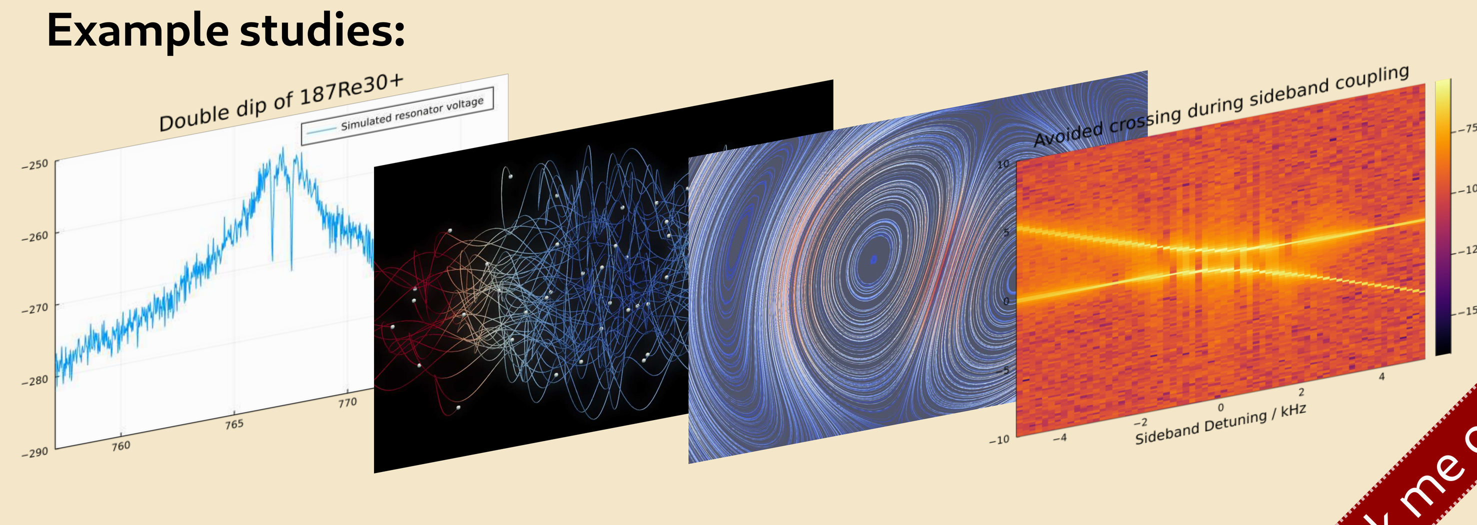
github.com/jherkenhoff/**Penning.jl**

Motivation:
- Simulating the electron-cooling technique from first principles.

Features:
- Symplectic integration
- Integrated circuit simulator
- N Body simulations with interactions
- Multiple interconnected Penning traps
- Arbitrary excitation fields

Written entirely in julia

Example studies:



Fork me on GitHub