Precision spectroscopy of highly charged ions and exotic nuclei using the ion trapping facility **HITRAP**

Peter Micke

Helmholtz Institute Jena

GSI Helmholtz Center for Heavy Ion Research, Darmstadt

Friedrich Schiller University Jena

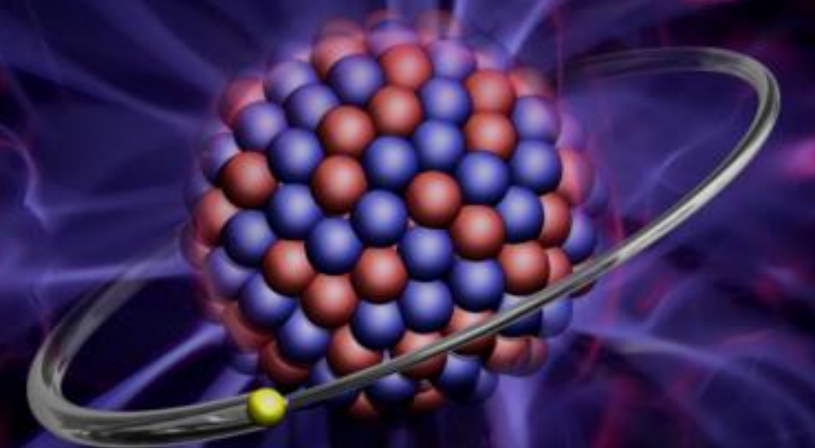
MML Matter

FROM MATTER TO MATERIALS AND LIFE

MT DTS

MATTER AND TECHNOLOGY

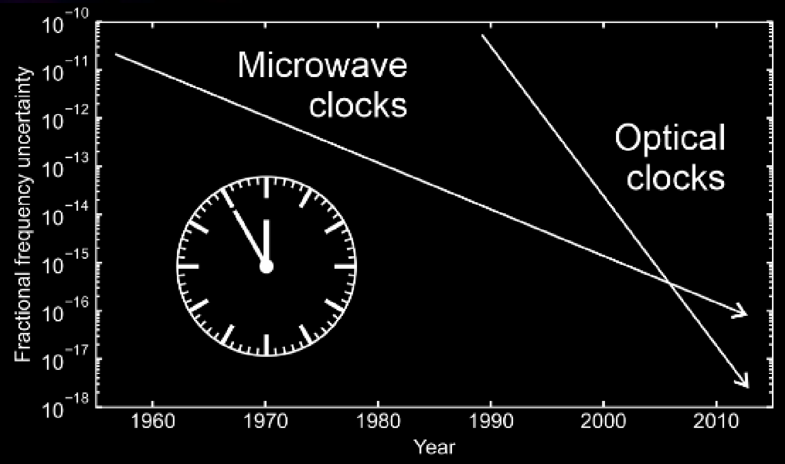
Trapped ions as quantum sensors



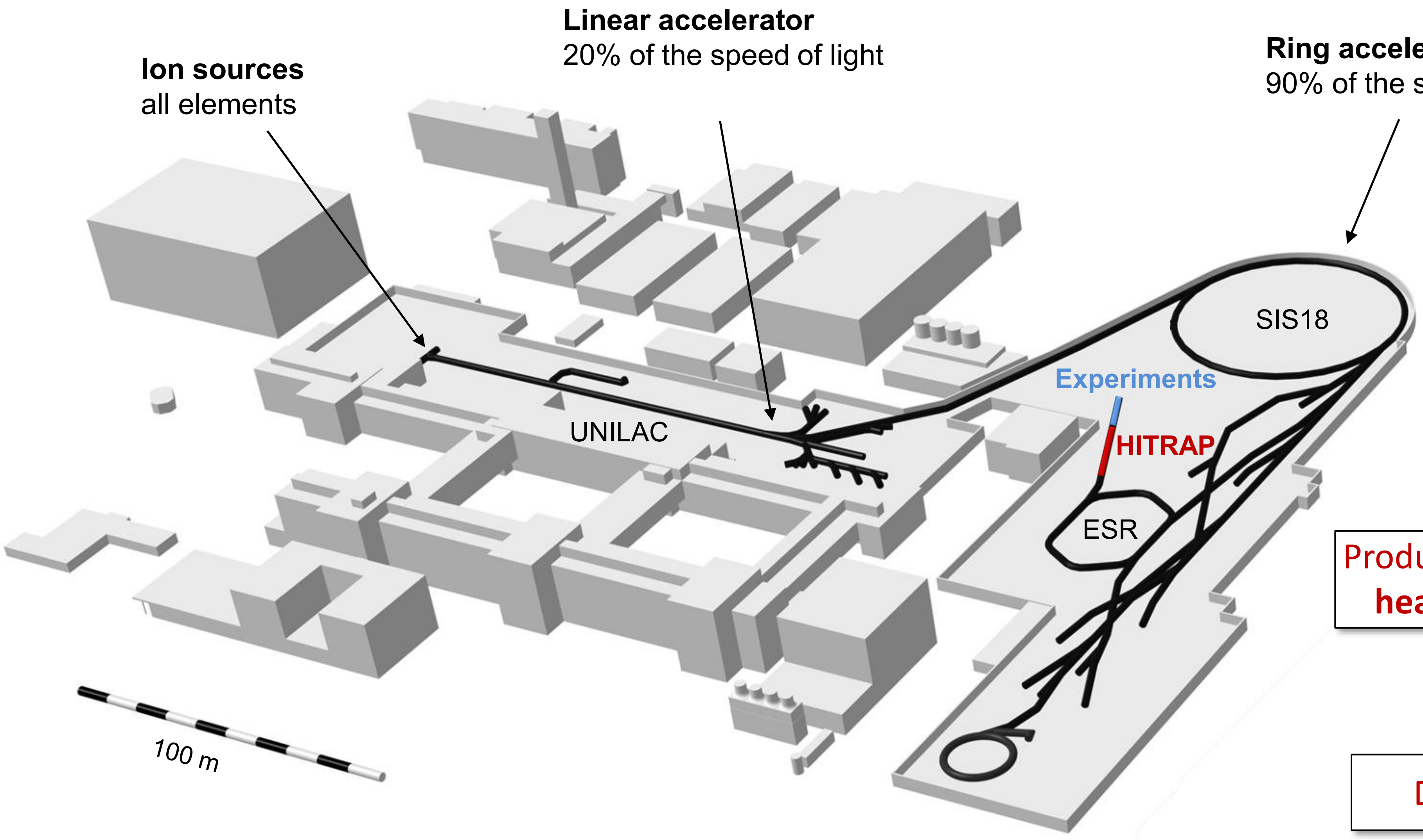
Highly-charged (heavy) ions

- **Simple** structure ⇒ accurate prediction of properies
- **Extreme** electromagnetic fields
  - **Highly sensitive** to fundamental physics
  - **Robust** against external perturbations

- Sensor itself is **quantum**
- Quantum properties used for sensing / as probes
  - Quantum transition
  - *g*-factor
  - ...
- Fundamental physics / BSM
  - Fundamental constants
  - Dark matter
  - Fifth force
  - QED
- Atomic and nuclear physics



GSI Helmholtz Center for Heavy Ion Research

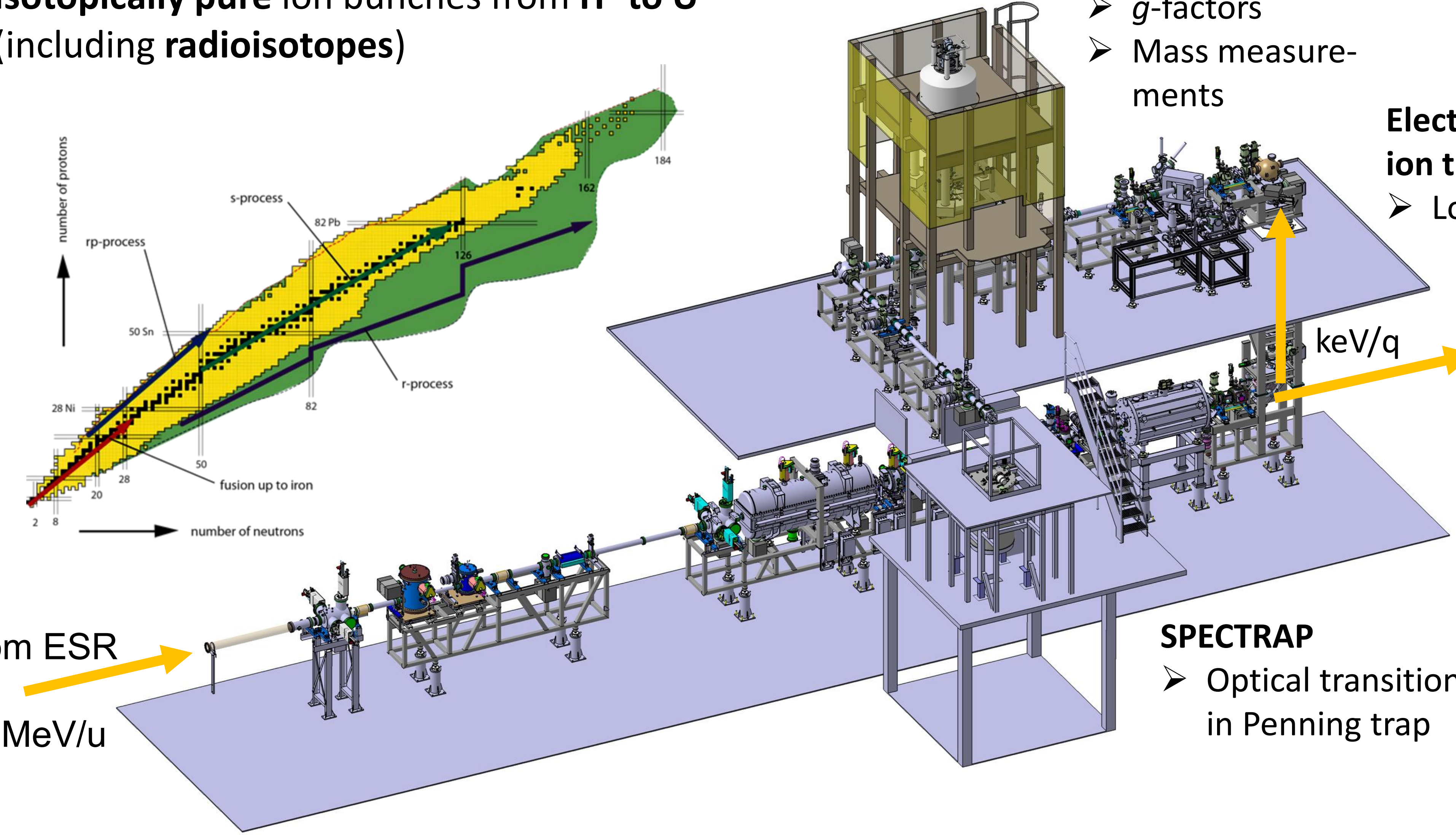


Production of **highly-charged heavy ions** at 400 MeV/u

Deceleration to rest

HITRAP facility

Isotopically pure ion bunches from **H^{+} to U^{92+}** (including **radioisotopes**)



ARTEMIS
- *g*-factors
- Mass measure-ments

Electron beam ion traps
- Local ion sources

keV/q

Quantum logic laser laboratory
- Optical transitions in Paul trap

from ESR

4 MeV/u

SPECTRAP
- Optical transitions in Penning trap

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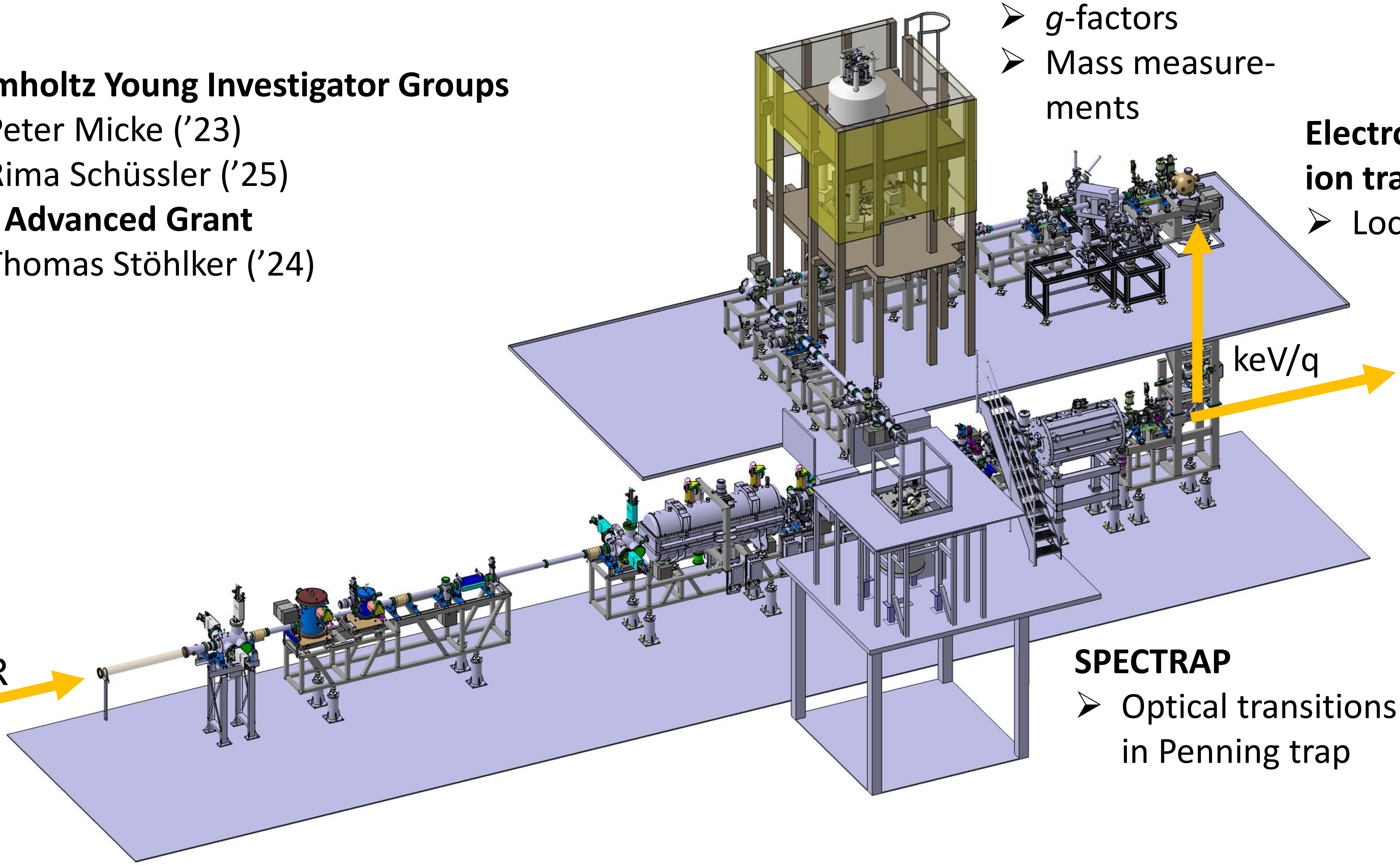
HITRAP facility

- **2 Helmholtz Young Investigator Groups**
  - ➢ Peter Micke (’23)
  - ➢ Rima Schüssler (’25)
- **1 ERC Advanced Grant**
  - ➢ Thomas Stöhlker (’24)

ARTEMIS
- ➢ *g*-factors
- ➢ Mass measure-ments

Electron beam ion traps
- ➢ Local ion sources

Quantum logic laser laboratory
- ➢ Optical transitions in Paul trap



from ESR

4 MeV/u

SPECTRAP
- ➢ Optical transitions in Penning trap

Stockholm EBIT: Ion source for HITRAP

Super-EBIT as a source for highly charged ions: Stand-alone operation of HITRAP

Provided by Stockholm University and HI Jena. Currently, limited to 10 kV operation voltage.

Sonja Bernitt

Design Parameter	S-EBIT II
Type	Cryogenic (LHe free)
Magnetic field	4T
Electron beam energy	260 keV
Electron beam current	250 mA
Electron beam radius	37 µm
Trap length	2 cm
Ions per pulse	10^6-10^7
Characteristic	Electron gun/ collector + trap on HV-platforms

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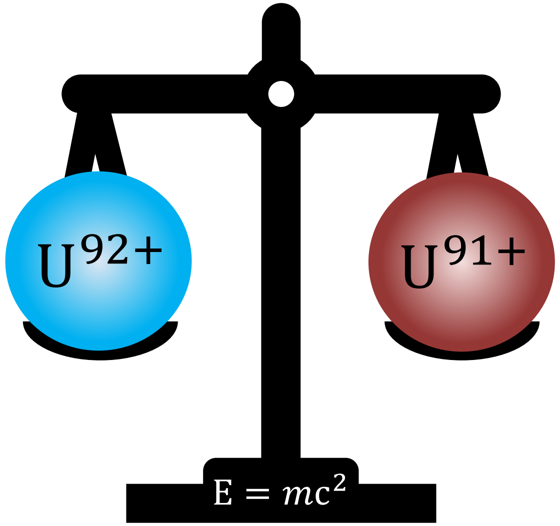
HYIG: Rima X. Schüssler

Host institute: **Helmholtz Institute Jena**

University partner: **Friedrich Schiller University Jena**



$$\Delta E_B = m(\mathrm{U}^{91+}) - m(\mathrm{U}^{92+}) - \mathrm{m_e}$$

Cyclotron frequency $\boxed{\omega_c = \frac{qB}{m}}$

2026 2027 2028 2029 2030

Start

Strong homogeneous magnetic field

ARTEMIS magnet

Penning traps

Test QED through **binding energy** measurement based on **mass measurements** with $\delta m/m \approx 10^{-12}$

$<$ 1 eV precision:
Isotope shift
Nuclear properties
2nd order QED

Current best precision with storage rings $\approx$ 5 eV

HYIG: Peter Micke

Helmholtz Young Investigator Groups

SUPPORTED BY THE HELMHOLTZ INITIATIVE AND NETWORKING FUND

HELMHOLTZ

Host institute: **Helmholtz Institute Jena**

University partner: **Friedrich Schiller University Jena**

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GSI

FRIEDRICH-SCHILLER-UNIVERSITÄT JENA

Abbe Center of Photonics | JENA Friedrich-Schiller-Universität

Hiroshi Hayakawa | Peter Micke | Lukas Kau | Nadine Homburg

2023 2024 2025 2026 2027 2028

Start

Universal QLS platform for **highly-charged heavy ions**

→ **Fundamental, atomic,** and **nuclear** studies

Additional support by

GSI Atomic, Quantum & Fundamental Physics

Thomas Stöhlker
Rima Schüssler
Manuel Vogel
Wolfgang Quint
…

Network outside Helmholtz

PTB

Piet O. Schmidt
Fabian Wolf
…

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

José R. Crespo Lopéz-Urrutia
Vera M. Schäfer
…

CERN BASE

Stefan Ulmer
Christian Smorra
…

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Highly-charged heavy ions for optical clocks

PRL **98,** 180801 (2007) PHYSICAL REVIEW LETTERS week ending 4 MAY 2007

Hydrogenlike Highly Charged Ions for Tests of the Time Independence of Fundamental Constants

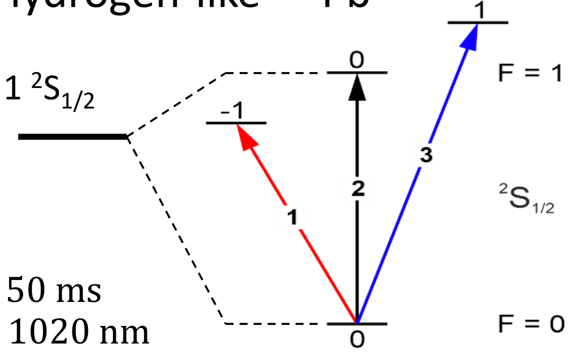
S. Schiller

Institut für Experimentalphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany
(Received 18 October 2006; published 30 April 2007)

Hyperfine transitions in the electronic ground state of cold, trapped hydrogenlike highly charged ions have attractive features for use as frequency standards because the majority of systematic frequency shifts are smaller by orders of magnitude compared to many microwave and optical frequency standards. Frequency measurements of these transitions hold promise for significantly improved laboratory tests of local position invariance of the electron and quark masses.

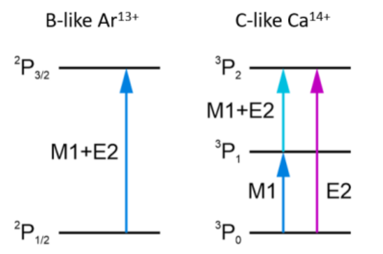
DOI: 10.1103/PhysRevLett.98.180801 PACS numbers: 06.20.Jr, 06.30.Ft, 31.30.Gs, 32.30.Dx

Hydrogen-like $^{207}Pb^{81+}$



$\tau = 50$ ms
$\lambda = 1020$ nm

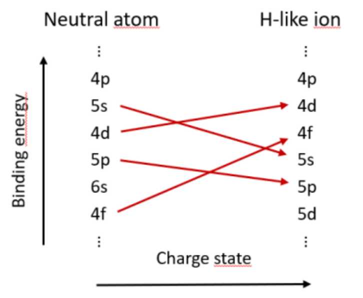
Fine-structure transitions



☑

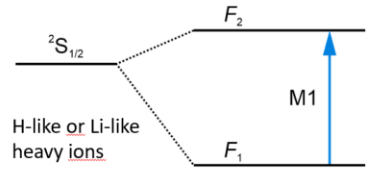
Micke et al., Nature **578** (2020)

Level-crossing transitions



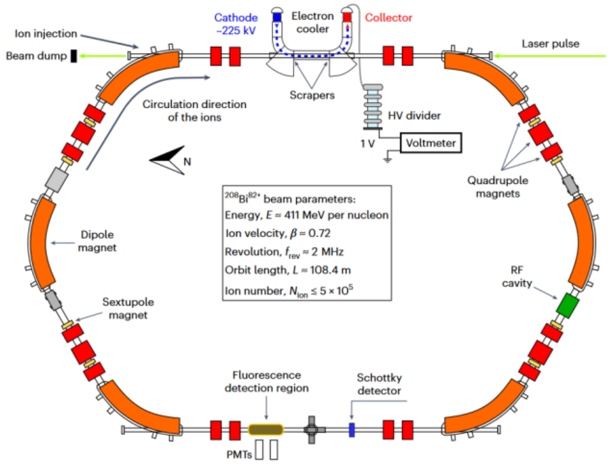
☐

Hyperfine-structure transitions



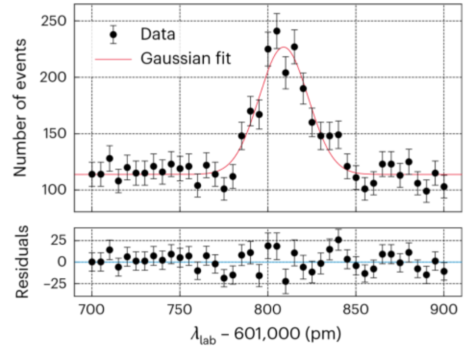
H-like or Li-like heavy ions

☐



➡

Collinear laser spectroscopy



Horst et al., Nat. Phys. **21** (2025)

ESR

Uncertainty of about 10^{-5}

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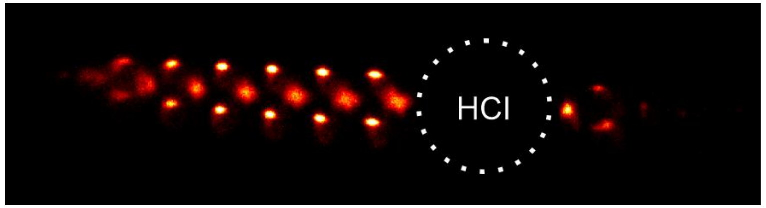
Enabling toolbox

Capture of highly-charged heavy ion in Paul trap

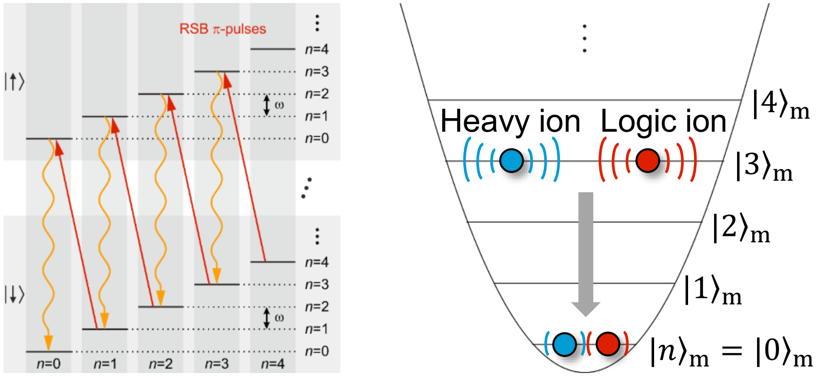


HCI: Highly charged heavy ion

Two-ion crystal preparation

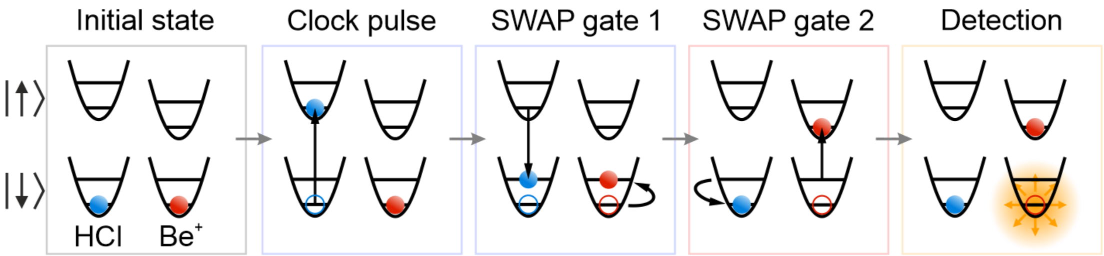
Be^{+}: Logic ion

Cooling to quantum-mechanical ground state of motion



Coldest possible state

Quantum logic spectroscopy

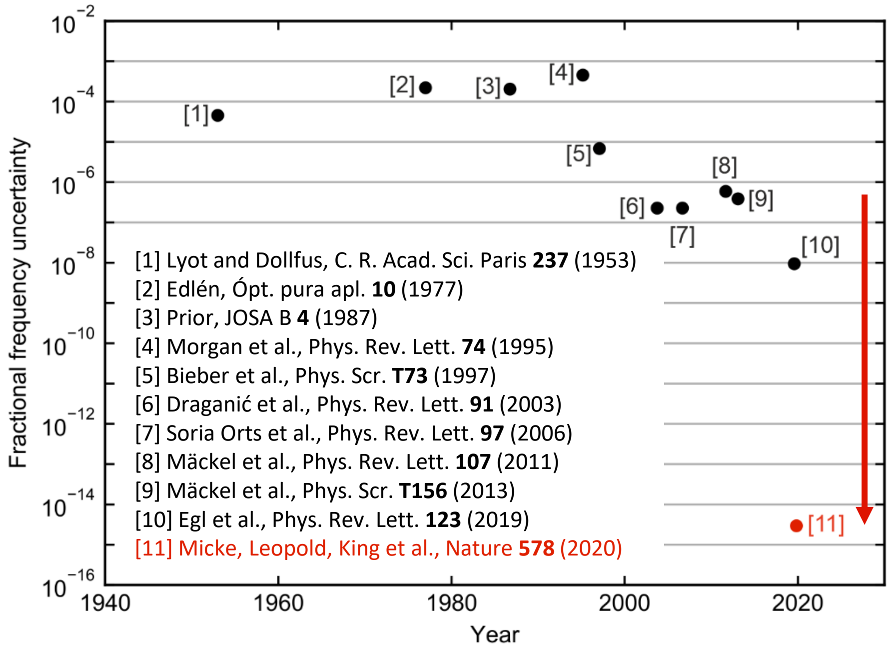


Quantum logic achievements

(1) Al^+ ion cock

(2) Molecular ions

(3) Highly charged ions



nature

Micke et al., Nature **578**, 60–65 (2020)

(1)

PHYSICAL REVIEW LETTERS **123**, 033201 (2019)

Editors' Suggestion | Featured in Physics

$^{27}Al^+$ Quantum-Logic Clock with a Systematic Uncertainty below 10^{-18}

S. M. Brewer,[1,2,*] J.-S. Chen,[1,2,†] A. M. Hankin,[1,2,‡] E. R. Clements,[1,2] C. W. Chou,[1] D. J. Wineland,[1,2,3] D. B. Hume,[1] and D. R. Leibrandt[1,2,§]
[1]*Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305, USA*
[2]*Department of Physics, University of Colorado, Boulder, Colorado 80309, USA*
[3]*Department of Physics, University of Oregon, Eugene, Oregon 97403, USA*

(2)

LETTER

doi:10.1038/nature22338

Preparation and coherent manipulation of pure quantum states of a single molecular ion

Chin-wen Chou[1], Christoph Kurz[1], David B. Hume[1], Philipp N. Plessow[2], David R. Leibrandt[1,3] & Dietrich Leibfried[1]

(3)

Article

Coherent laser spectroscopy of highly charged ions using quantum logic

https://doi.org/10.1038/s41586-020-1959-8

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P. Micke[1,2,4*], T. Leopold[1,4], S. A. King[1,4], E. Benkler[1], L. J. Spieß[1], L. Schmöger[1,2], M. Schwarz[1,2], J. R. Crespo López-Urrutia[2] & P. O. Schmidt[1,3*]

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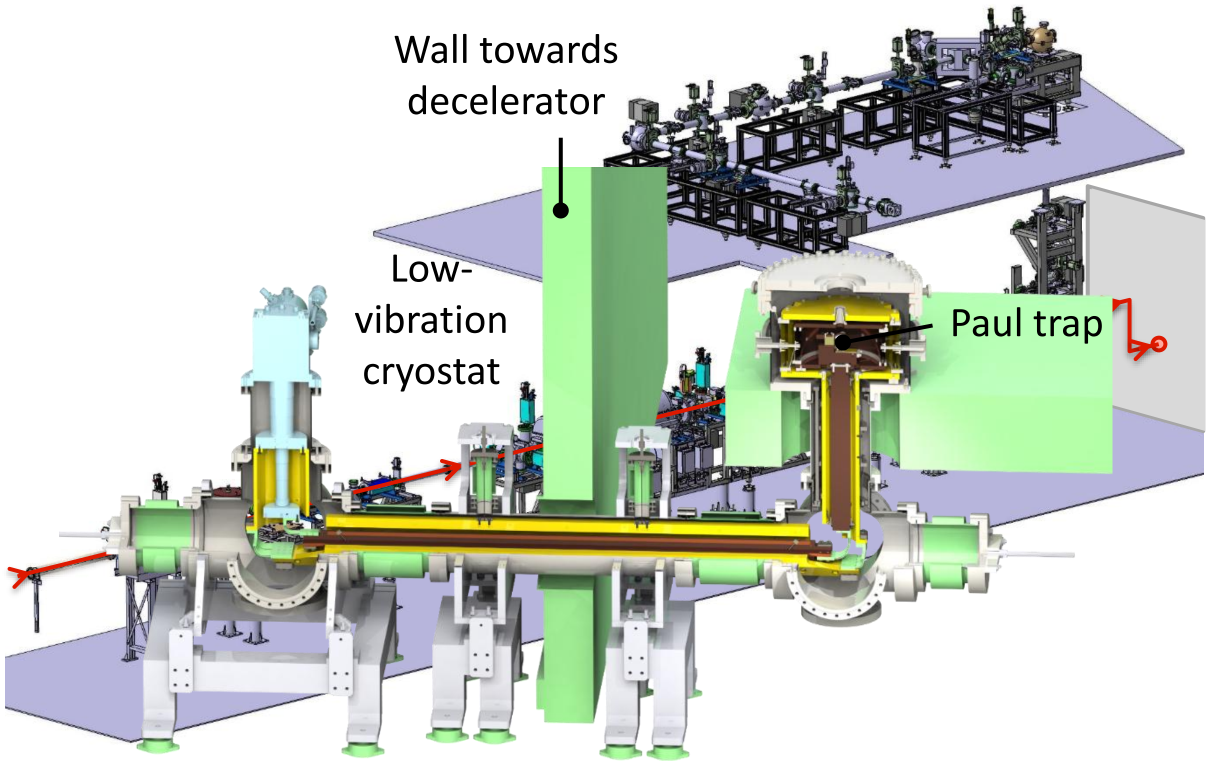
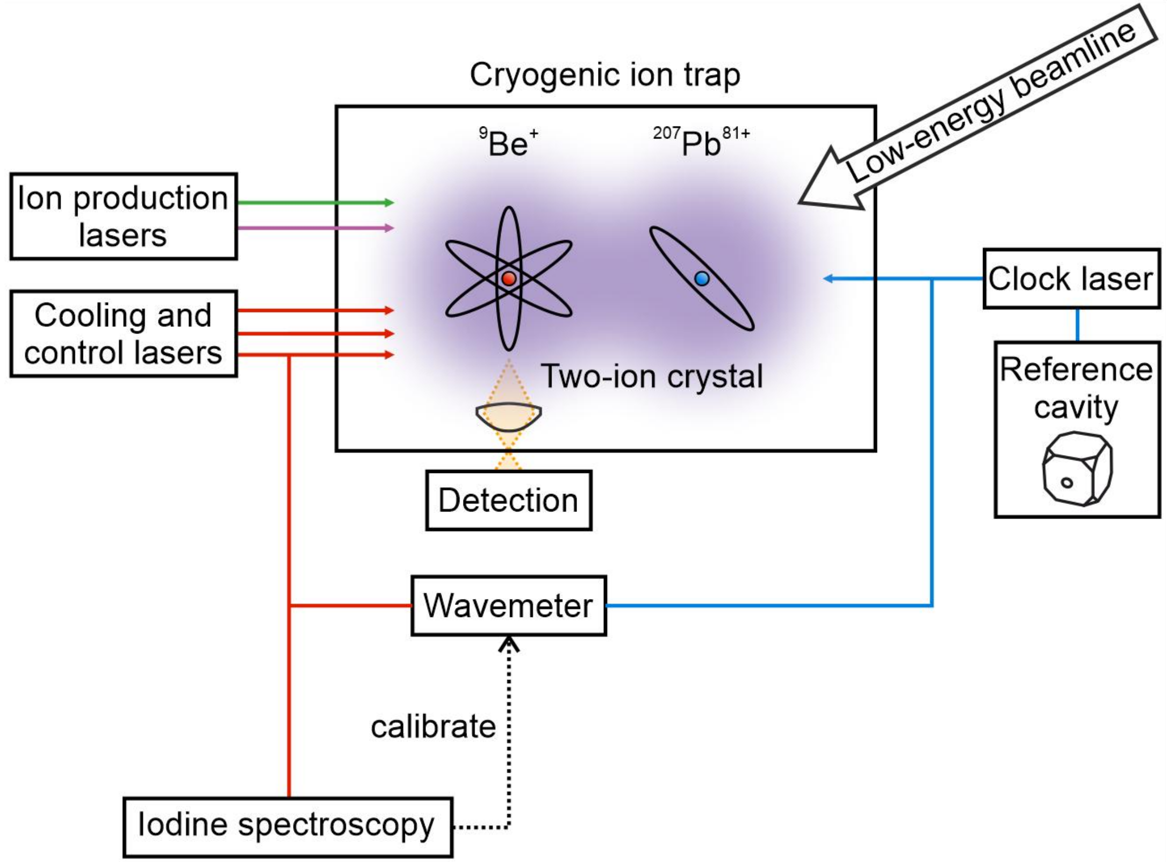
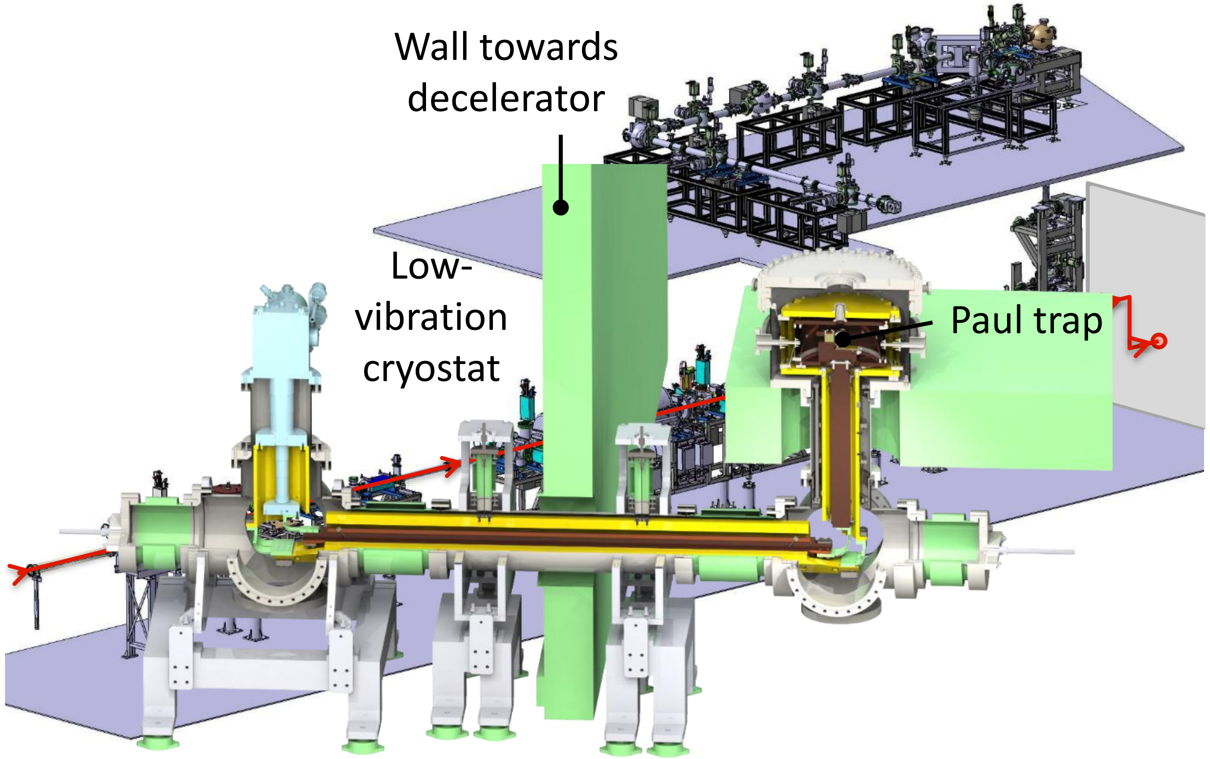
Implementation at HITRAP



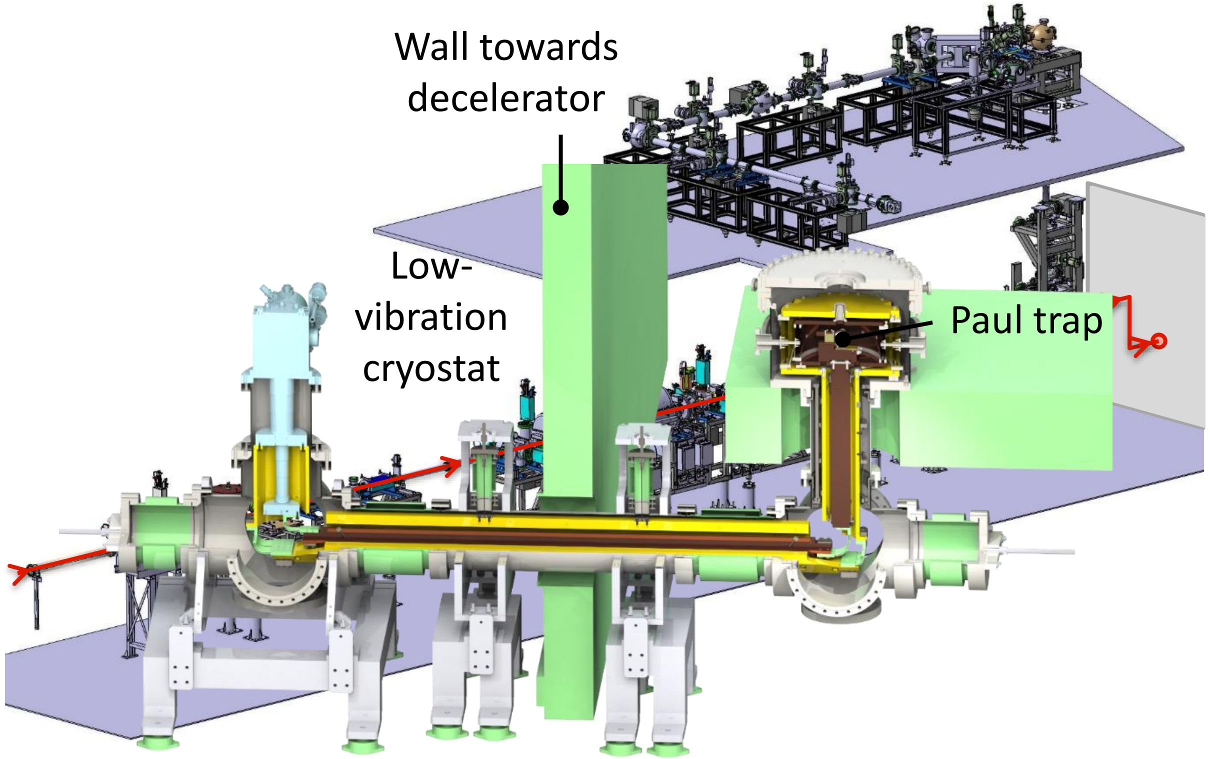


Improvement: 10^4

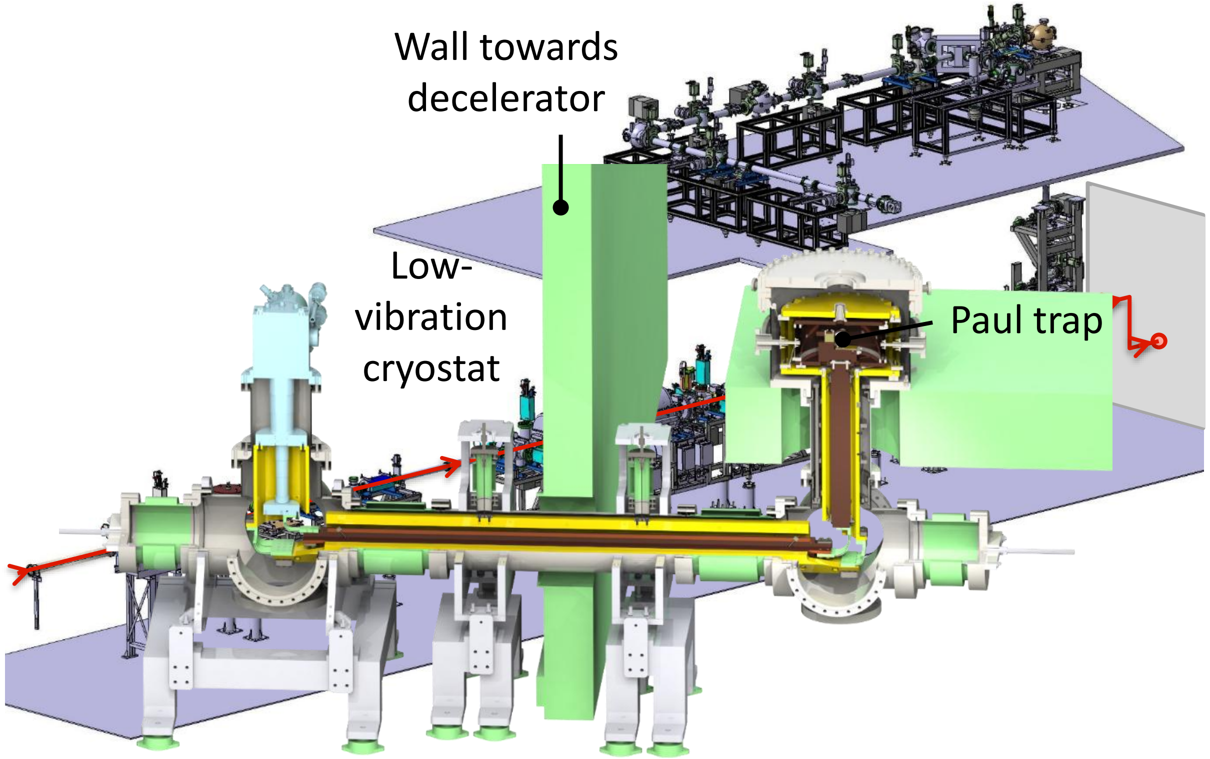
Implementation at HITRAP

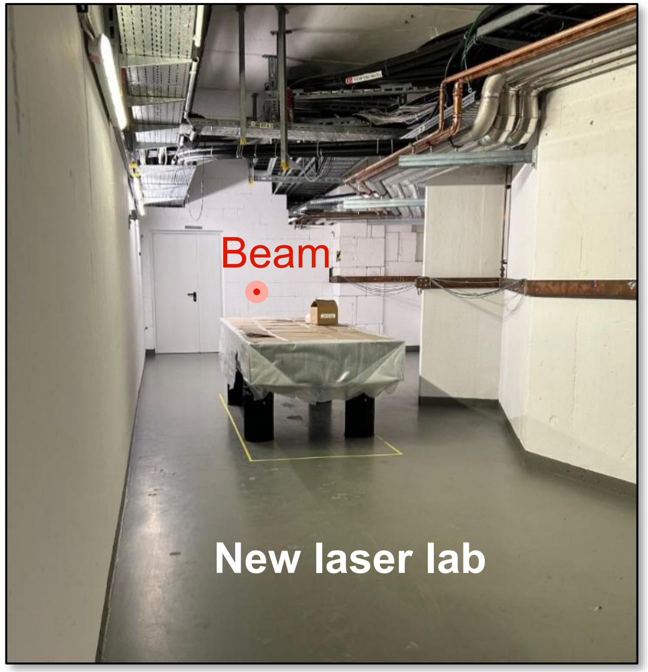


Implementation at HITRAP

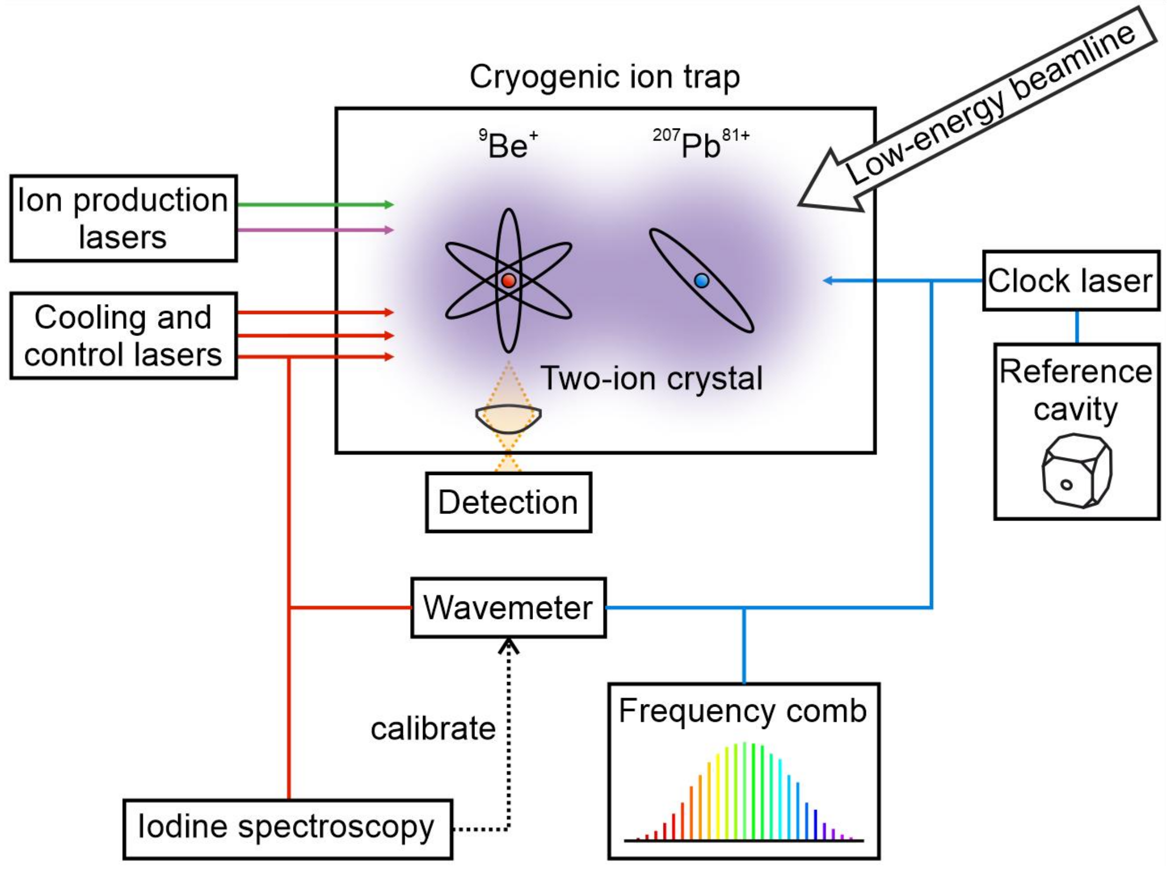


Implementation at HITRAP





Towards a quantum logic clock

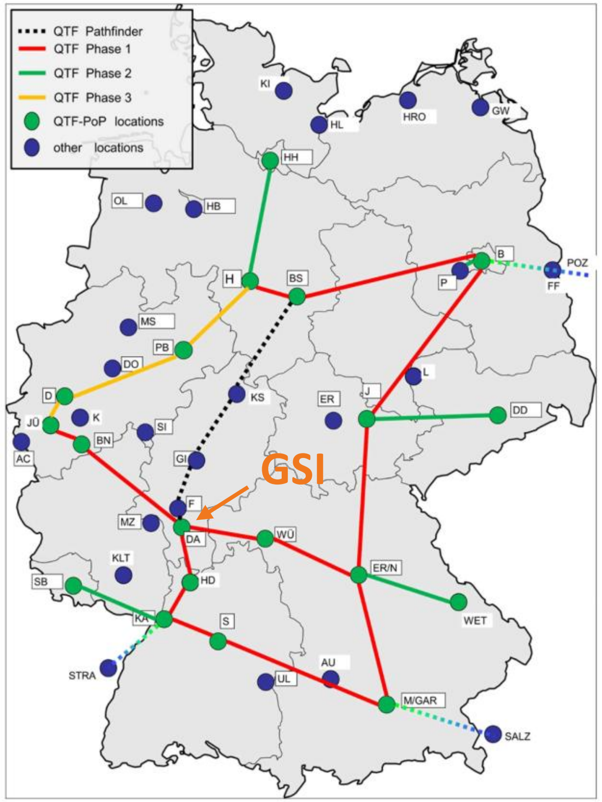


Upgrade 1:

- Frequency comb

Improvement:
10^8 … 10^9

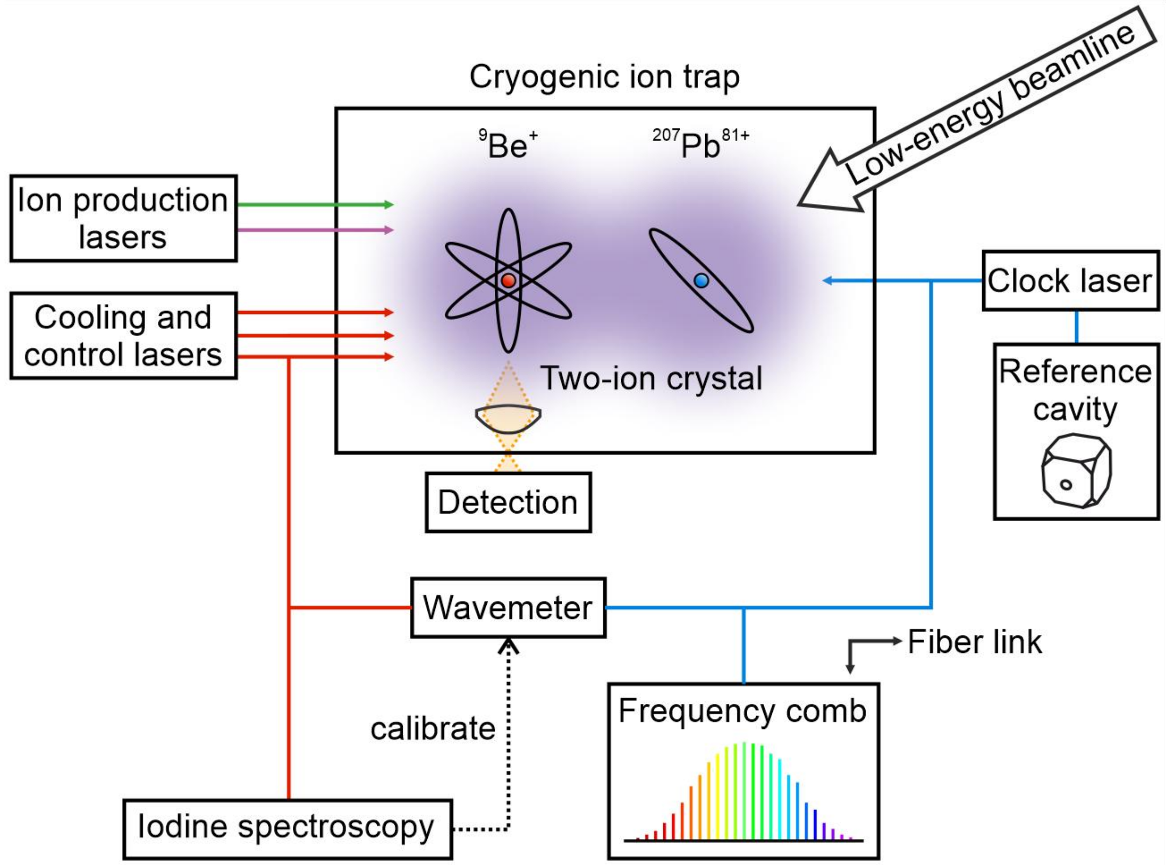
Towards a quantum logic clock



QTF-Backbone
für die Quantenzukunft

www.ptb.de/cms/
qtf-de-backbone

Glass-fiber link to Germany's national metrology institute **Physikalisch-Technische Bundesanstalt** (Braunschweig) will enable highest level of precision and **clock comparisons**

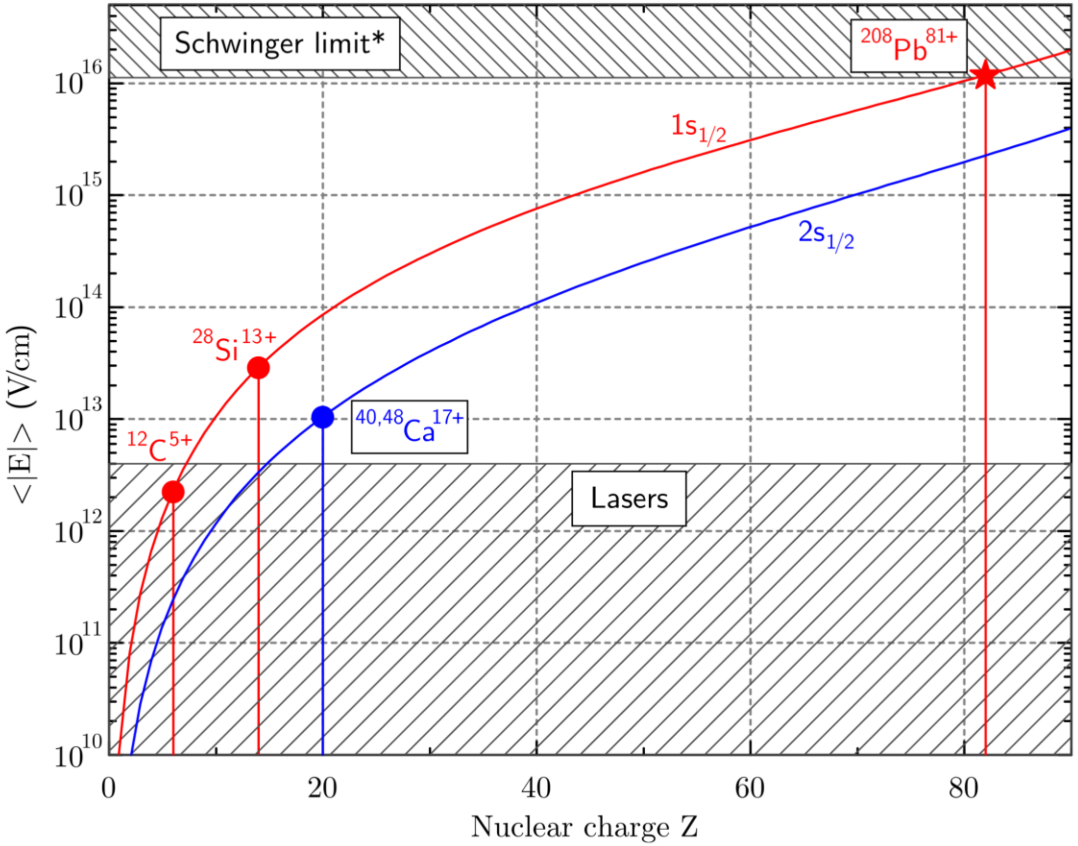


Upgrade 2:

- Link to another optical clock

Improvement:
10^{10} … 10^{12}

Science cases



Sturm et al., EPJ **227**, 1425–1491 (2019)

Tests of **QED** in **strongest fields**:

Studies of *Specific Difference* of H-like and Li-like ions for which nuclear contributions cancel

Shabaev et al., PRL **86**, 3959–3962 (2001)
Horst et al., Nat. Phys. **21**, 1057–1063 (2025)
Morgner et al., PRL **134**, 123201 (2025)
Morgner et al., Science **388**, 945-949 (2025)

Studies of **nuclear properties/physics** by assuming QED to be correct

Searches for **physics beyond the Standard Model**, e. g.

- Fifth force
- Dark matter
- Variation of fundamental constants,

Quint et al., arXiv:2506.03274v1 (2025)

Kozlov et al., Rev. Mod. Phys. **90**, 045005 (2018)
Lange et al., PRL **126**, 011102 (2021)

sensitivity to:

– $\dot{\alpha}$
– $\dot{\left(m_e/m_p\right)}$
– $\dot{\left(m_q/\Lambda_{QCD}\right)}$

average light-quark mass

QCD energy scale

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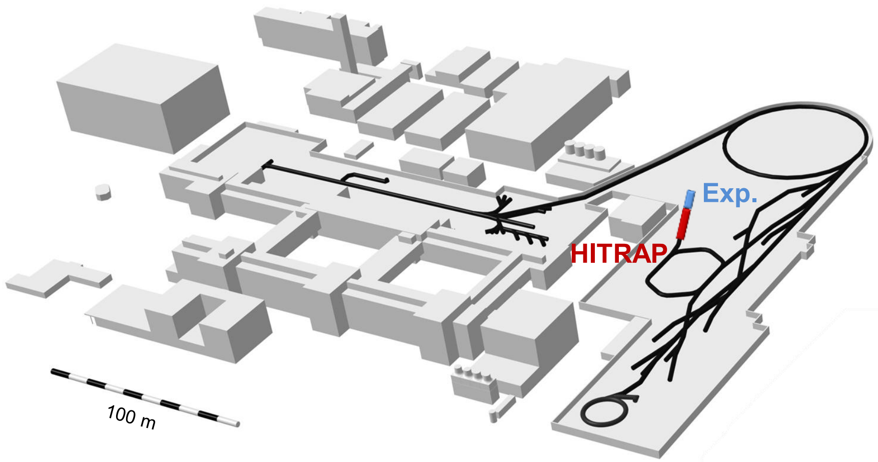
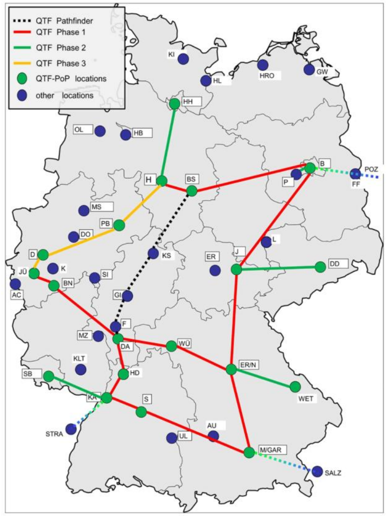
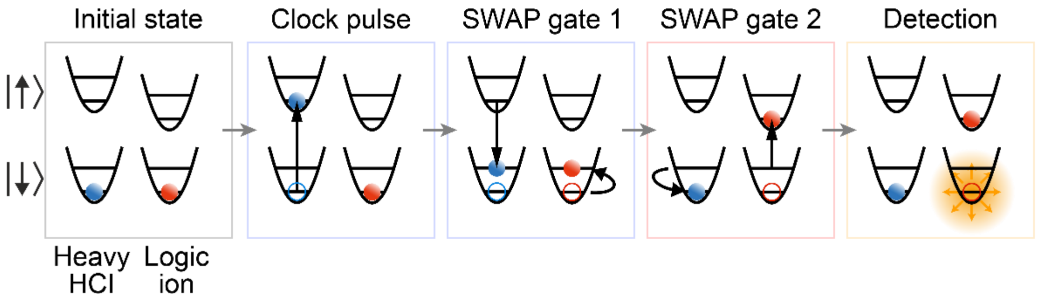
Summary

- **Trapped ions** as quantum sensors for studies of **fundamental, atomic,** and **nuclear** physics
  - Universal ion production
  - Variety of ion traps
    - Electron beam ion traps
    - Penning traps
    - Paul trap
      - Optical clock

Bright future with unique setting







Thank you very much!