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Penning traps for spectroscopy of highly charged ions

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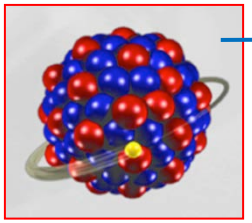
QED in Highly Charged Ions (HCI)

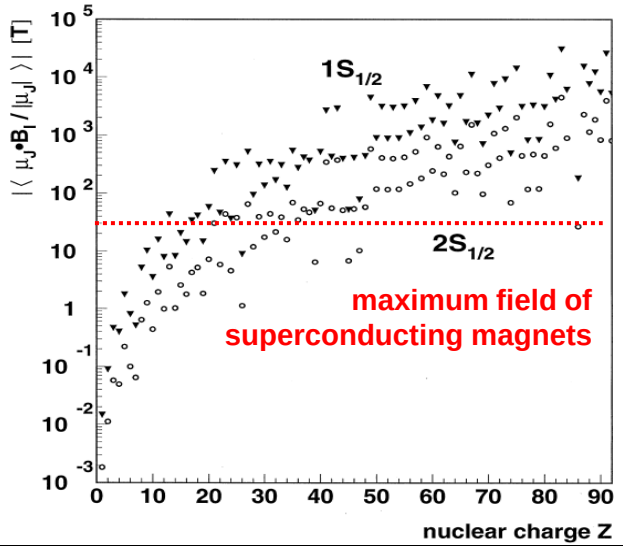
"Quantum electrodynamics is the most precise theory in physics..."

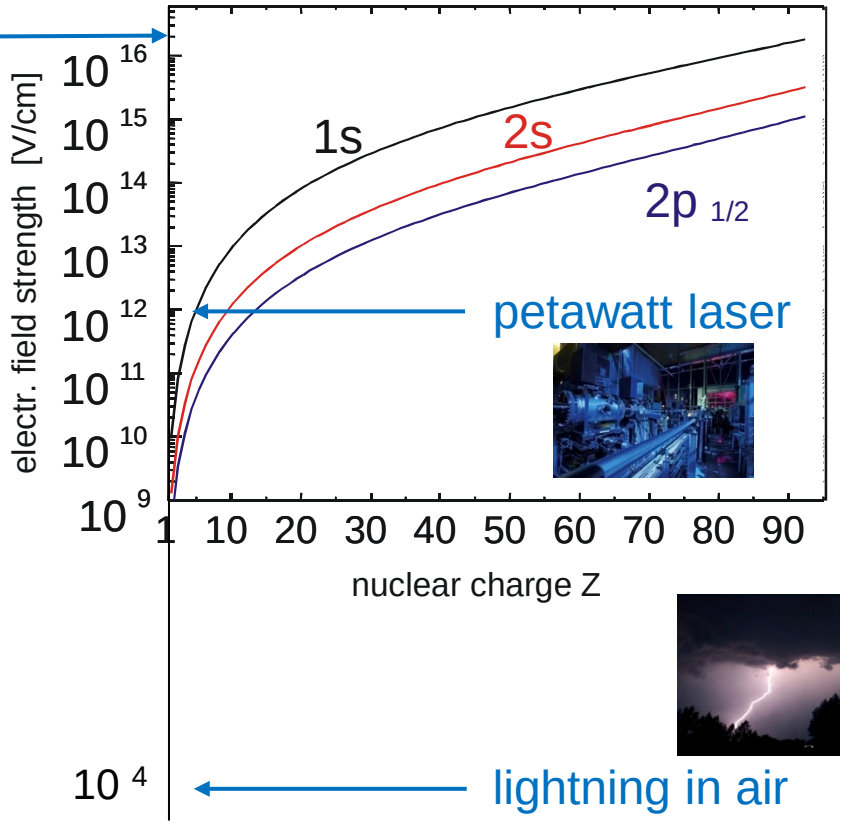
...but it has been rigorously tested only in weak fields

e⁻ in Hydrogen



e⁻ in a H-like HCI





T. Beier, Phys. Rep. 339 (2000) 79

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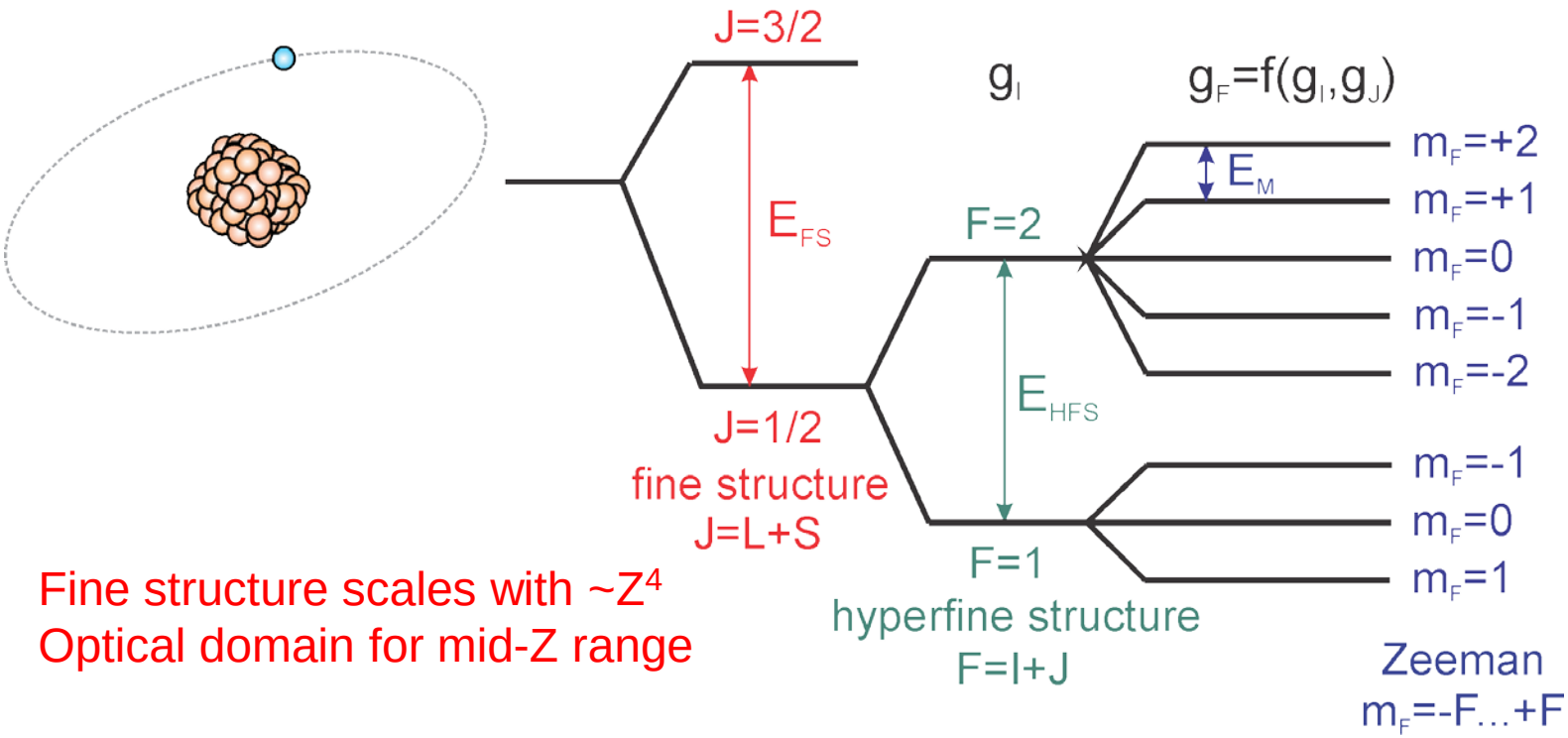
Forbidden transitions in HCI



Fine structure scales with ~Z^4
Optical domain for mid-Z range

Hyperfine structure scales with ~Z^3
Optical domain for high-Z range

Zeeman effect scales with magnetic field
Microwave domain for a few T

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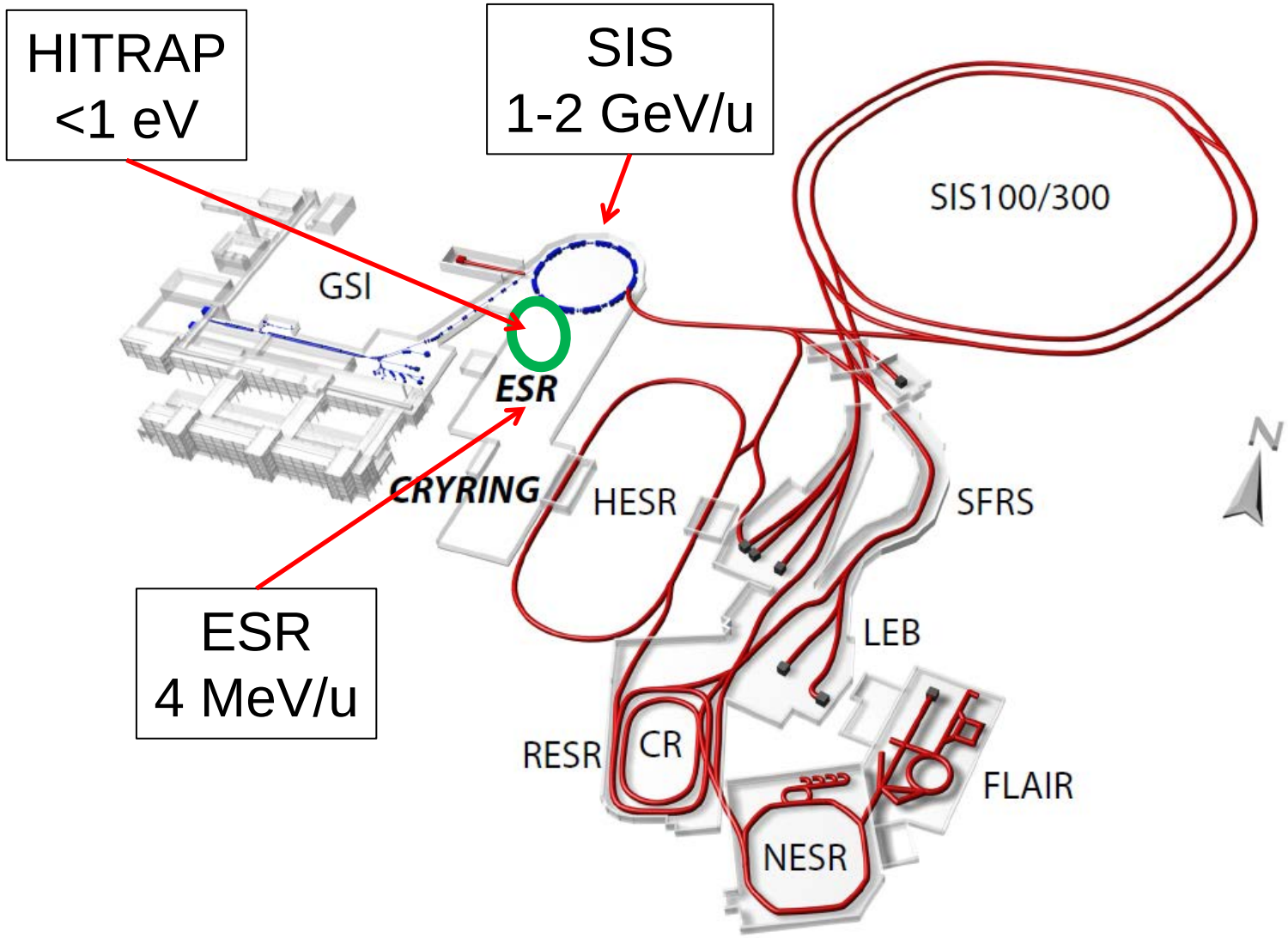
Production of cold HCI



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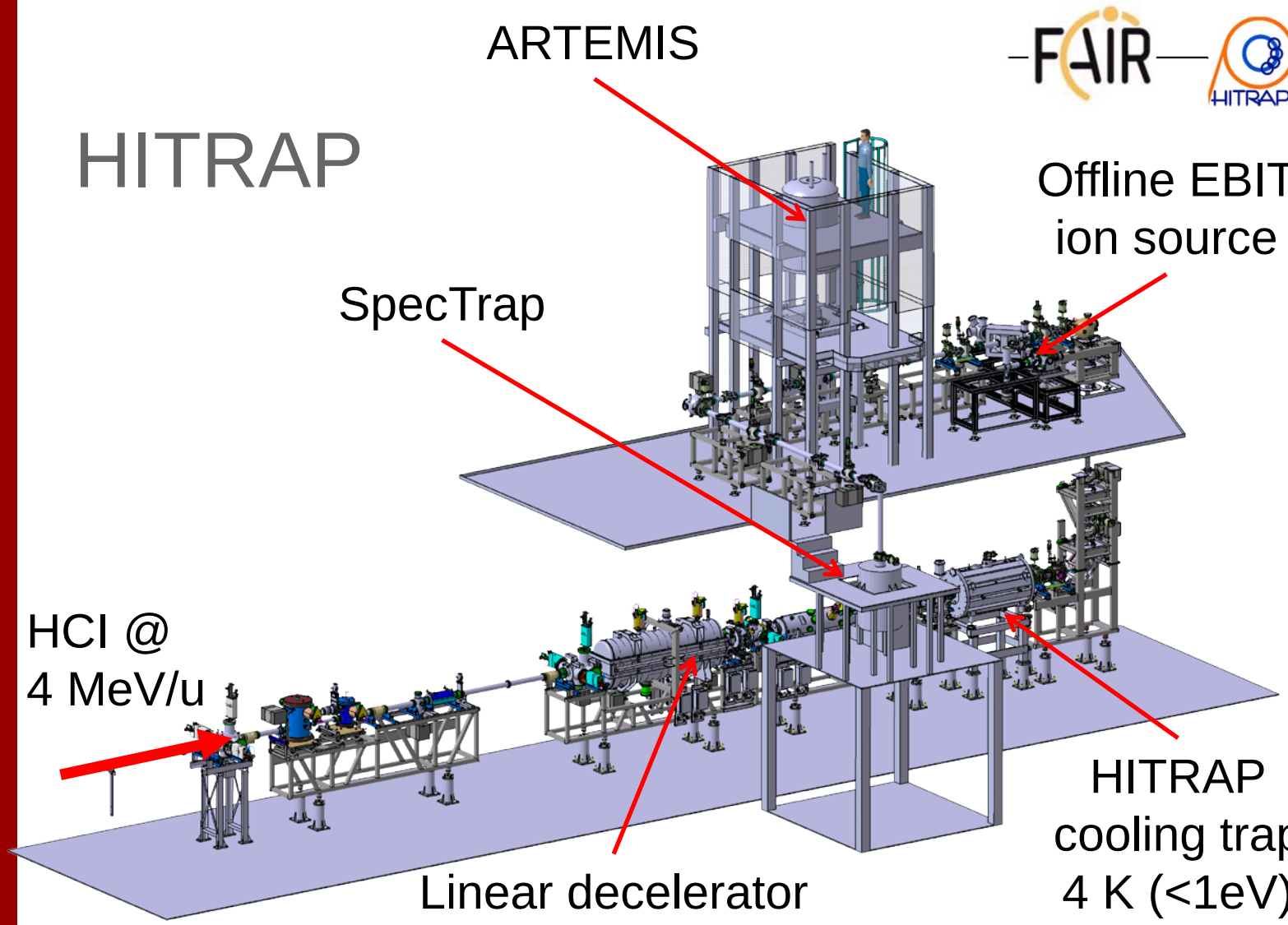
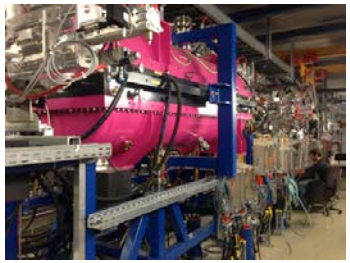
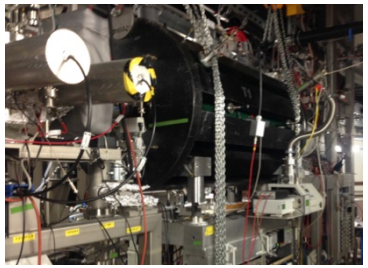
HITRAP







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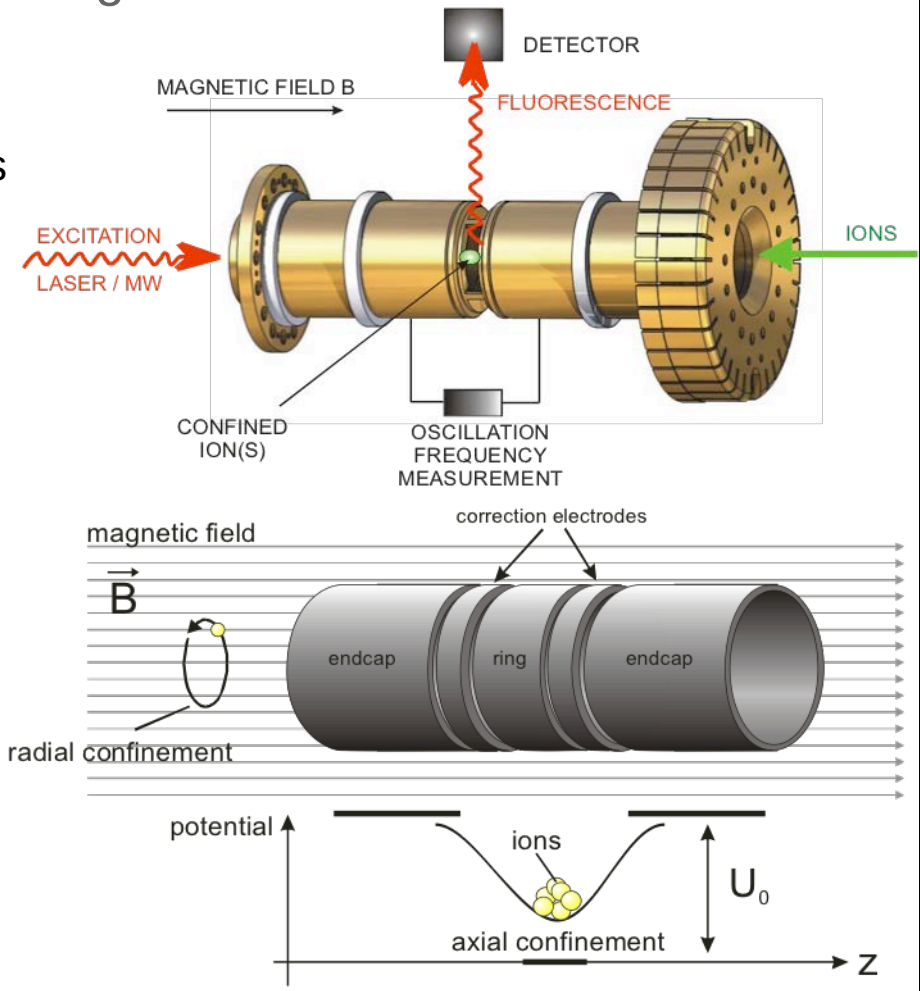
SpecTrap

Ground state hyperfine splitting in HCI

- Aim to measure small corrections to the energy levels from
  - the Bohr-Weisskopf effect
  - QED-contributions
- Ions need to be extremely cold to reduce the Doppler width and increase the signal.
- HCI will be sympathetically cooled by laser cooled Mg^+ ions.
- Excite with spectroscopy laser and record florescence spectrum.
- Detection is challenging due to difficult wavelengths and low signal rates



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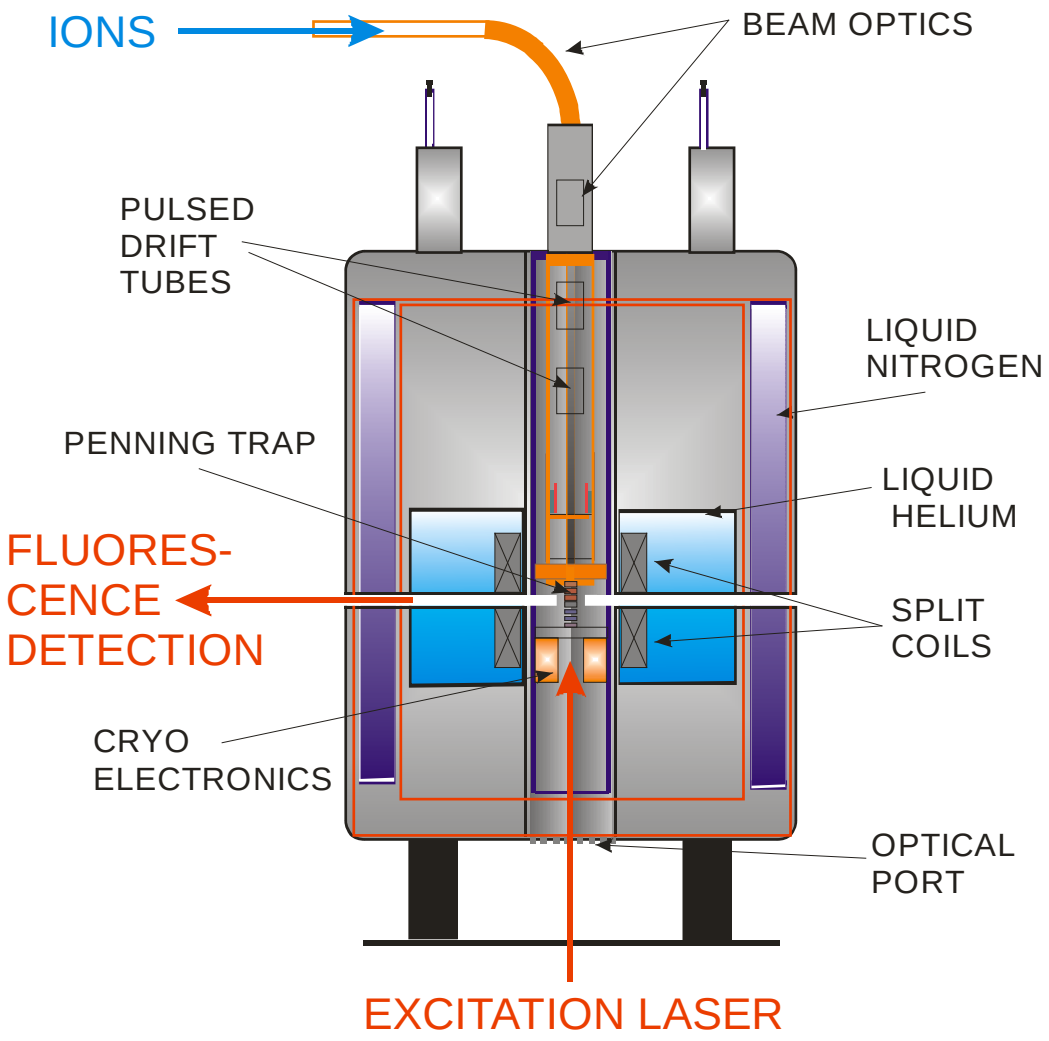
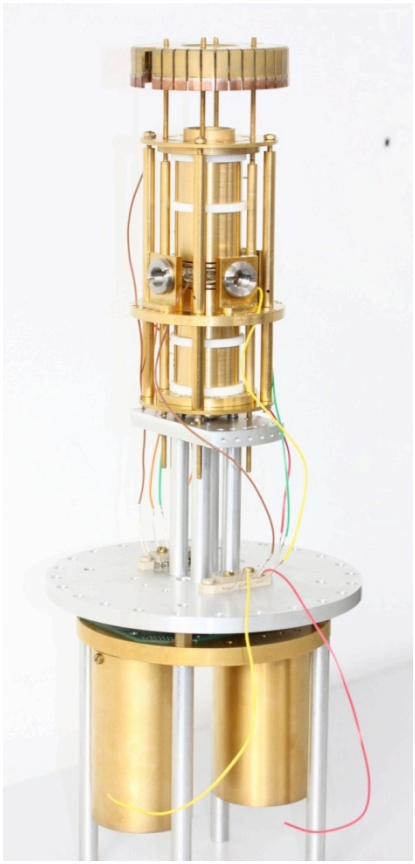
The SpecTrap setup





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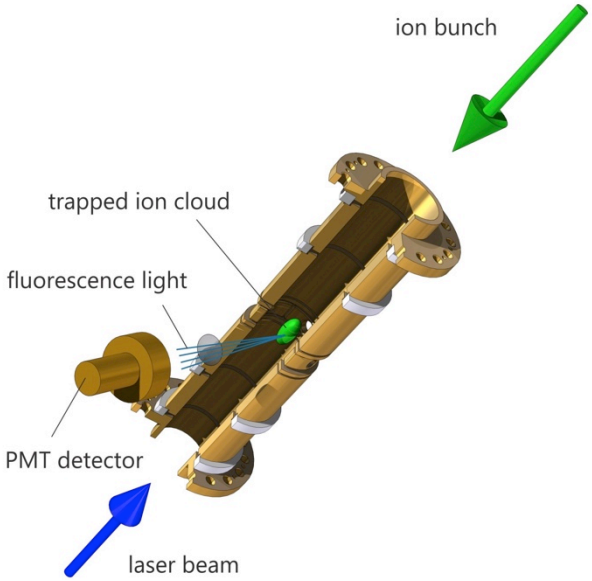
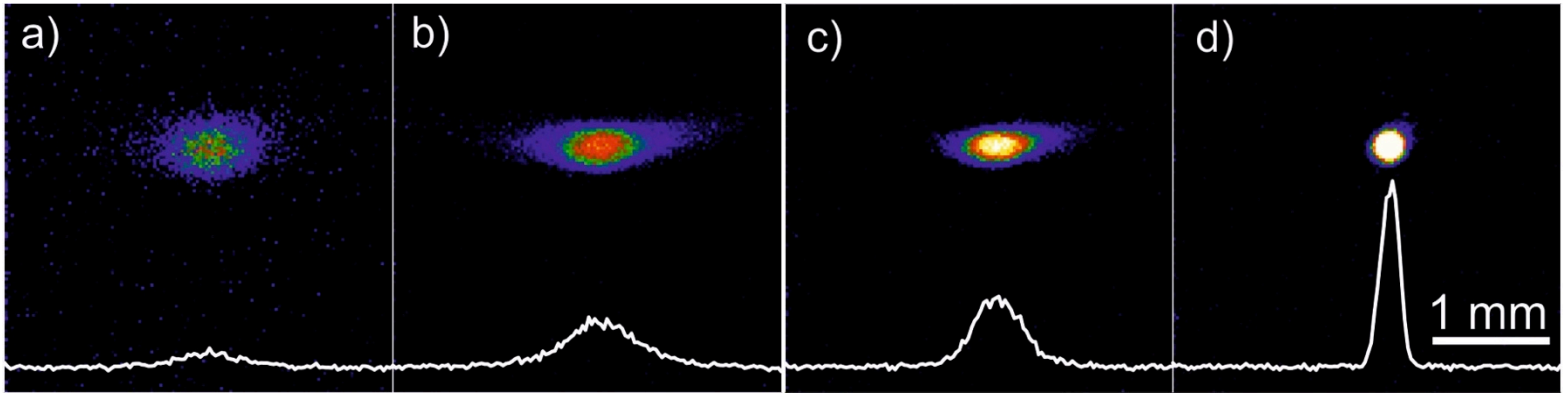
Cooling of Mg^+ ions

- Resistive cooling of Mg^+ down to 4 K successfully demonstrated.
- Laser cooling of Mg^+ below 60 mK successfully demonstrated.
- HCI (Ar^{13+}) from an EBIT successfully loaded and sympathetically cooled.





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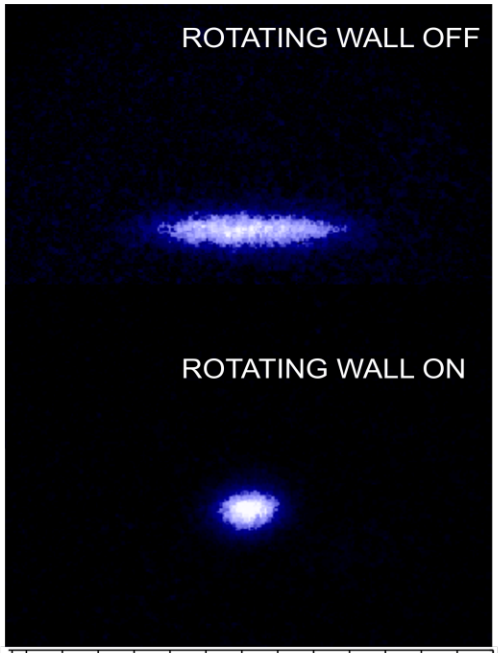
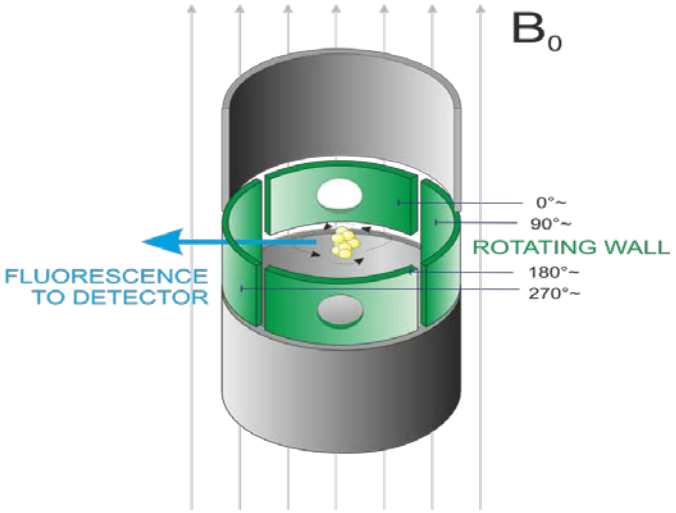
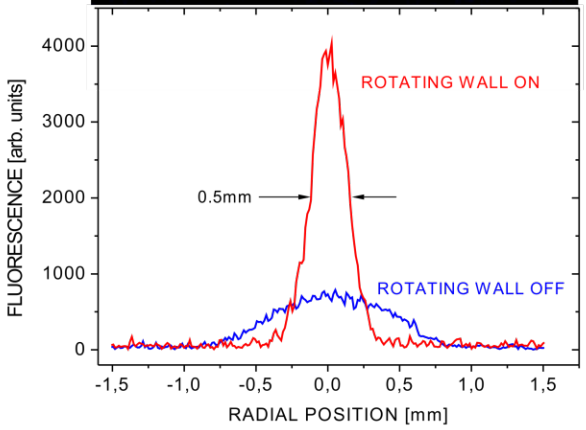
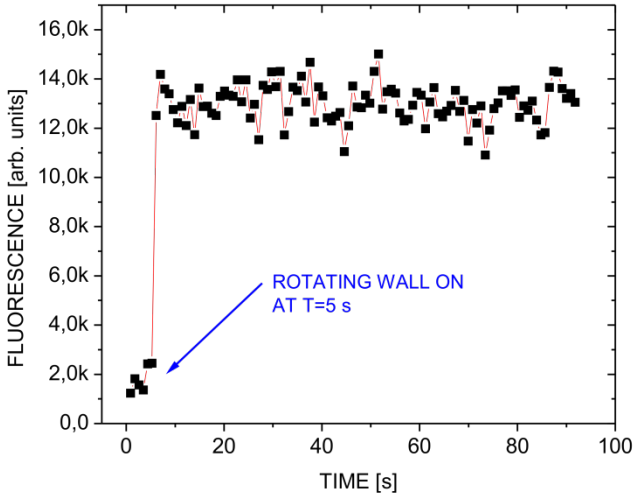
Ion cloud compression by rotating wall









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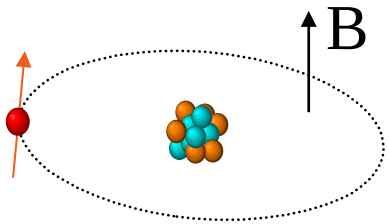
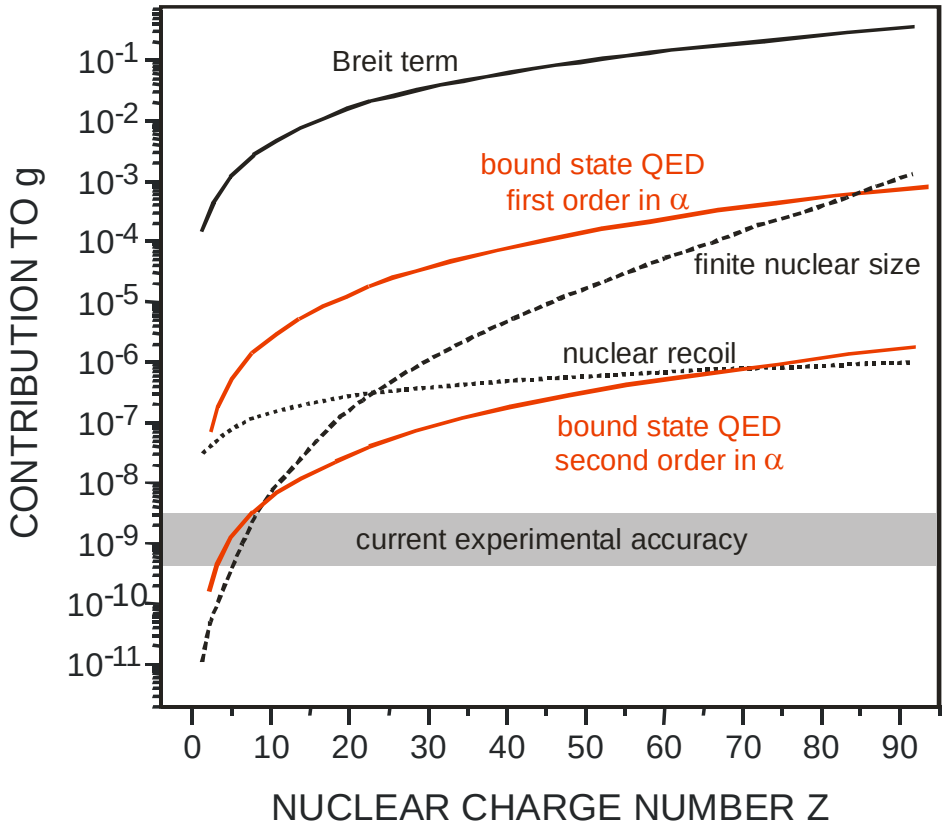
g_J-factor of the bound electron in a hydrogen-like ion



$$g_J = 2 \cdot \frac{\omega_L^{\,e}}{\omega_c^{\,ion}} \cdot \frac{m_e}{M_{ion}} \cdot \frac{Q^{ion}}{e}$$



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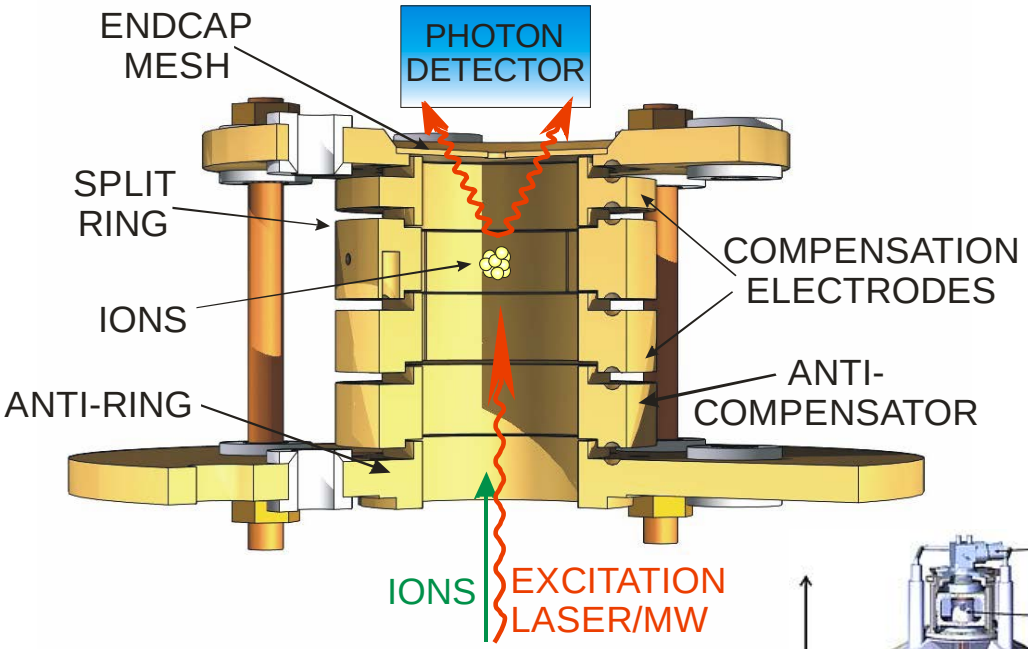
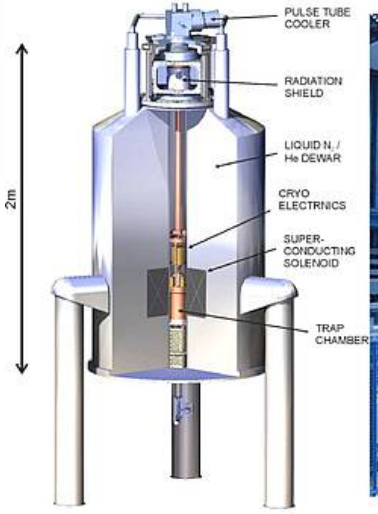
ARTEMIS

A Half-open Penning trap for laser-microwave double resonance spectroscopy





- **Optical transition energies**
- **g-factors**
- **Atomic lifetimes**

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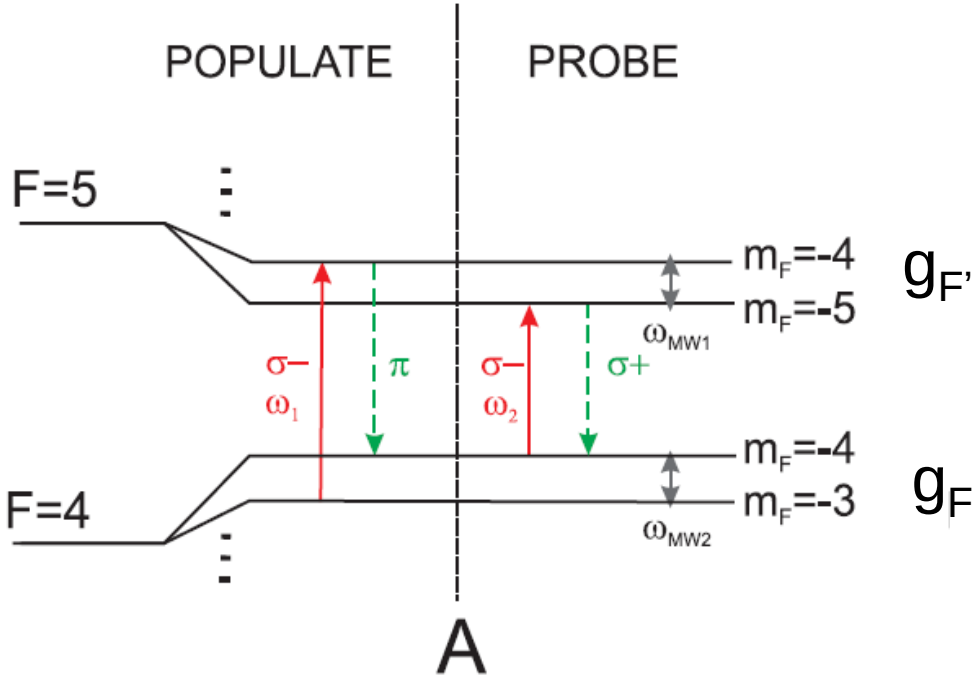
Laser-microwave double resonance spectroscopy for bound electron g-factor measurements in hydrogen-like ions

Principle:
use the light from the optical transition as a probe for the Zeeman transitions.



From g_F and $g_{F'}$ it is possible to simultaneously and independently derive:

- g_J for comparison with QED calculations.
- g_I independent of diamagnetic shielding, i.e. shielding effects can for the first time be measured and theory can be tested.

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Penning trap advantages

Ions can be cooled nearly to rest
⇒ Small Doppler shift and broadening

Ions are well-localized
⇒ Laser irradiation is easy

Many ions in a dense ion cloud can be investigated at the same time
⇒ High fluorescence signal

Extended time for measurement, stable conditions
⇒ Makes life easier, allows slow transitions

Thank You

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Extra

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Limitations of present superconducting magnet

- Small solid angle for light collection
  - Small windows
  - High stray magnetic field
  - In total ~1% / window
- Very high LHe consumption (~30 L/day)
  - Running time only 20 days/year
- Damaged in the transportation
  - He leak into the vacuum system
  - Ion storage deteriorate over time
  - Not suitable for HCI

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New SUper conducting MAgnet

- New SUMA for SpecTrap: ~300 k€
  - Increased solid angle by a factor of 10.
  - Significantly lower LHe consumption
  - Improved vacuum

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UNIVERSITY OF GOTHENBURG — Ingvar Lindgren

Wolfgang Quint et al.
GSI-Darmstadt

Manuel Vogel et al.
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V. Hannen et al.
Universität Munster

Richard Thompson et al.
Imperial Collage London

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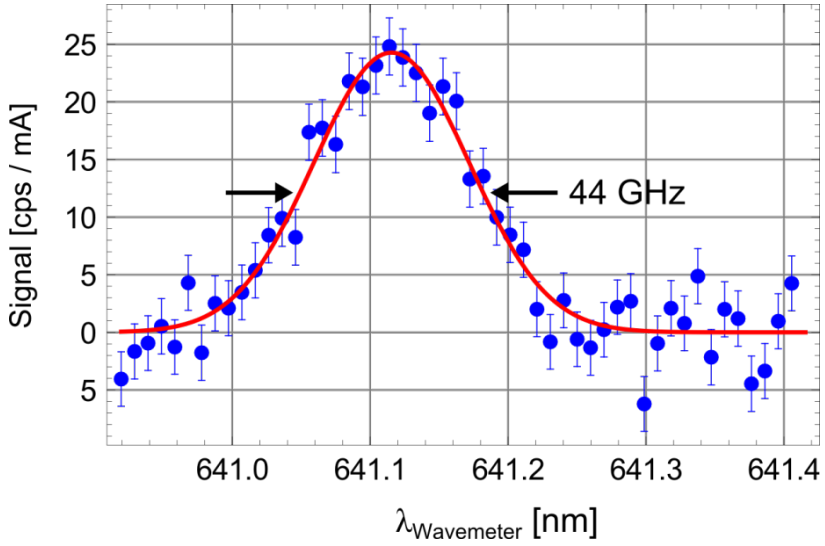
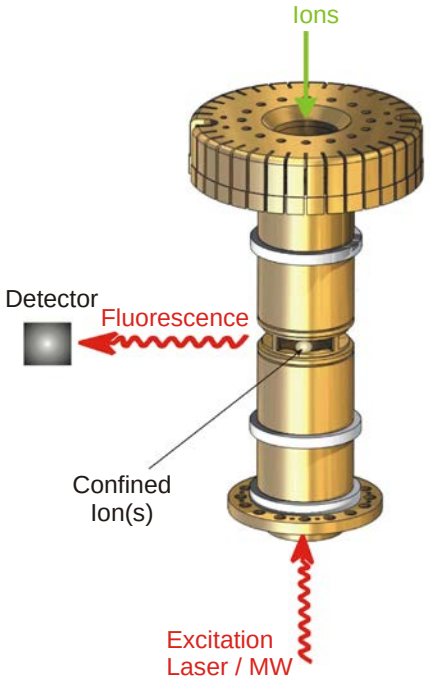
Comparison with stored beam measurements





- In the storage ring
  - Velocity is very high
    - Doppler shifts to a visible wavelength
    - Doppler shift is hard to calibrate
  - Line is broad (many GHz)

- In the trap
  - Velocity is very low
    - Wavelength inconvenient
    - No Doppler shift
  - Line is narrow (tens of MHz)
  - Signal is weak