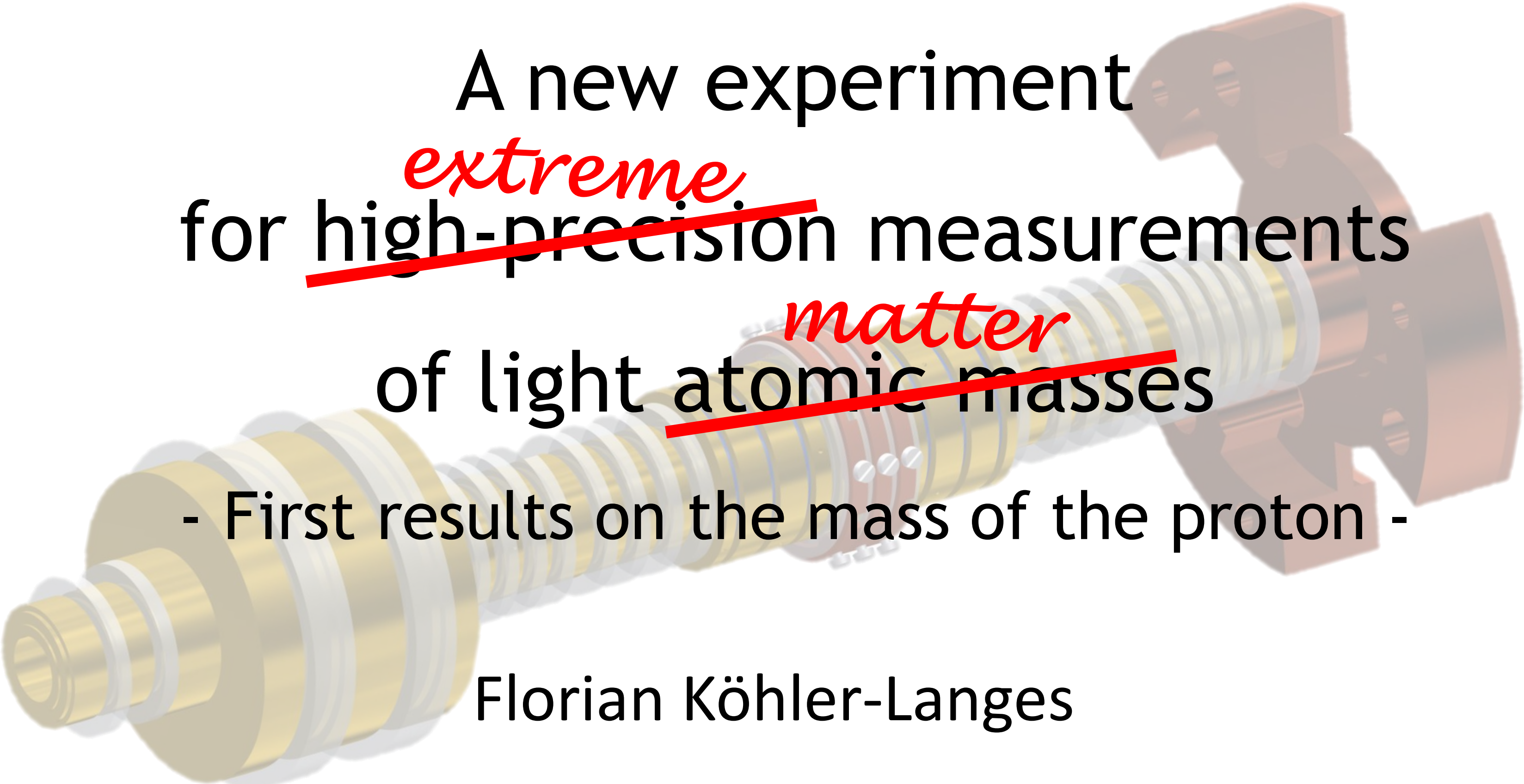
A new experiment for ~~high-precision~~ *extreme* measurements of light ~~atomic masses~~ *matter*



- First results on the mass of the proton -

Florian Köhler-Langes

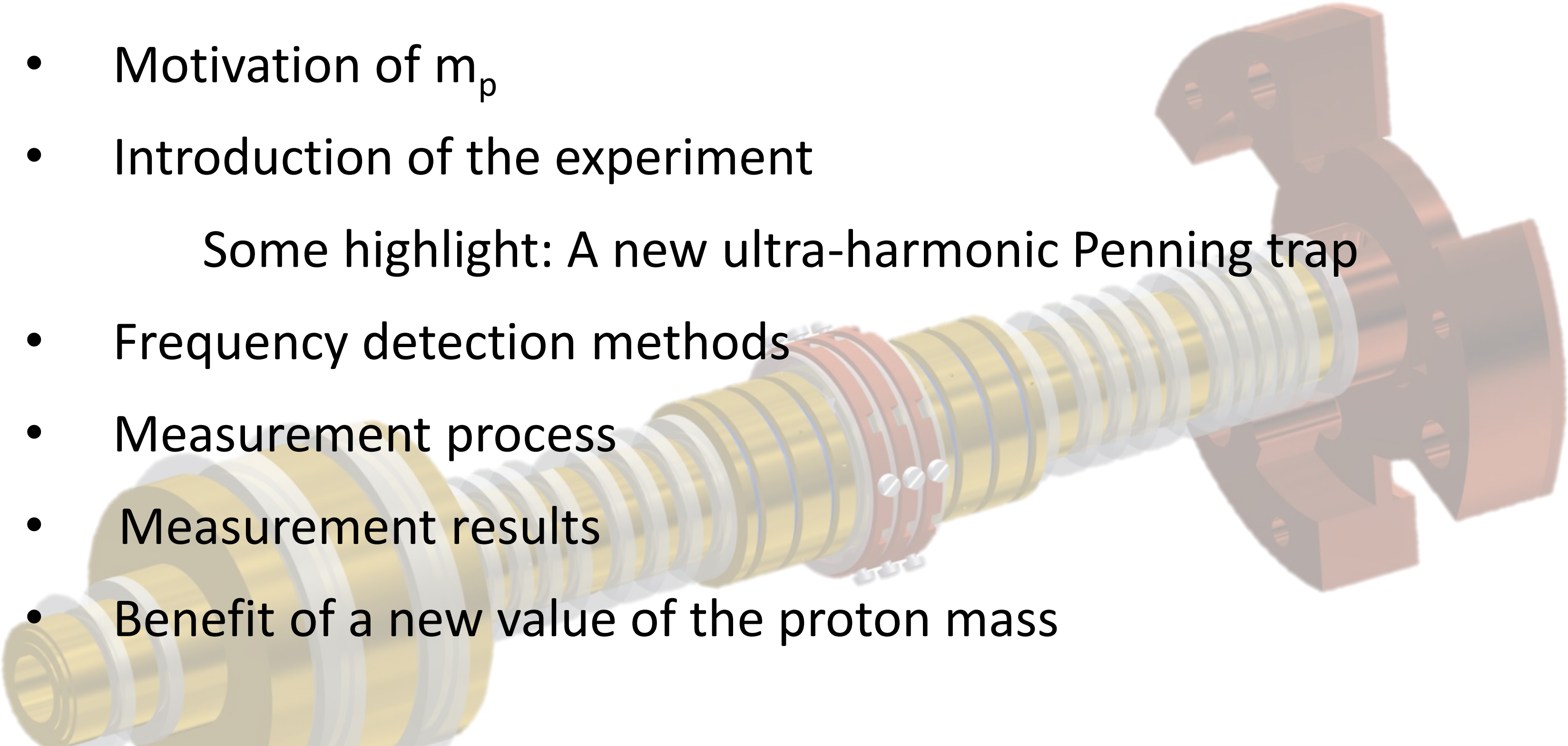
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

EMMI Physics Day 2017

November 28, 2017

GSI Darmsatdt

Towards ppt … an Outline



Part I: An improved proton mass

- Motivation of m_p
- Introduction of the experiment

  Some highlight: A new ultra-harmonic Penning trap

- Frequency detection methods
- Measurement process
- Measurement results
- Benefit of a new value of the proton mass

Part II: What's next?

- Towards most precise mass measurements ($<10^{-11}$)

  Reduction of dominant uncertainties

- Next measurement campaigns

Motivation
The Proton’s Atomic Mass…

- is a fundamental property of one of the basic building blocks of matter.

100 years ago …

!! Observation of long range scintillations as those by hydrogen atoms !!

In December 1917, Rutherford to Bohr:

"I am detecting and counting the lighter atoms set in motion by α particles and the results, I think, throw a good deal of light on the character and distribution of forces near the nucleus." [Stuewer, Roger H. (1986). "Rutherford's satellite model of the nucleus," *Historical Studies in the Physical Sciences 16*, 321-352.]

Publication two years later:

Rutherford found it …

… difficult to avoid the conclusion that these long-range atoms arising from the collision of alpha particles with nitrogen are not nitrogen atoms ***but probably charged atoms of hydrogen****, … we must conclude that the nitrogen atom is disintegrated under the intense forces developed in close collision with a swift α particle,* ***and that the hydrogen atom which is liberated formed a constituent part of the nitrogen nucleus.***

[Rutherford, Ernest (1919). "Collision of α particles with light atoms, IV: An anomalous effect in nitrogen," *Philosophical Magazine 37*, 581-587]

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But the story went on …

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But the story went on …

Rutherfords idea: ~~$^{14}N + {}^{4}He \rightarrow {}^{13}C + {}^{4}He + {}^{1}H$~~

In 1925 Patrick Blacket:

After study 23000 photos with 420000 tracks of alpha particles …

→ He found 8 events with alpha-nitrogen disintegration

BUT emerging two and NOT three tracks

Blackets idea: $^{14}N + {}^{4}He \rightarrow {}^{17}O + {}^{1}H$

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Bonne anniversaire nuclear structure!

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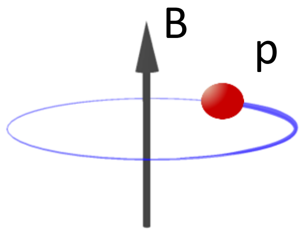
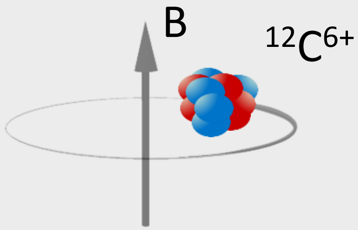
Motivation
The Proton's Atomic Mass…

- is a fundamental property of one of the basic building blocks of matter.
- is an important input parameter for hydrogen spectroscopy and thus impacts the value of the Rydberg constant.
- is needed for a precision CPT test.
  [S. Ulmer *et al.*, Nature **524**, 196 (2015)]
- can help to understand the discrepancies between light atomic mass measurements
  [E. Myers *et al.*, PRL **114**, 013003 (2015)]
  [S.L. Zafonte and R.S. Van Dyck, Metrologia **52**, 280 (2015)]

Basic Measurement Principle

Direct measurement of the atomic mass of the proton:





$$\nu_c(p) = \frac{1}{2\pi}\frac{e}{m_p}B$$

$$\nu_c(^{12}C^{6+}) = \frac{1}{2\pi}\frac{6e}{m(^{12}C^{6+})}B$$

$$m_p = \frac{1}{6}\frac{\nu_c(^{12}C^{6+})}{\nu_c(p)}m(^{12}C^{6+})$$

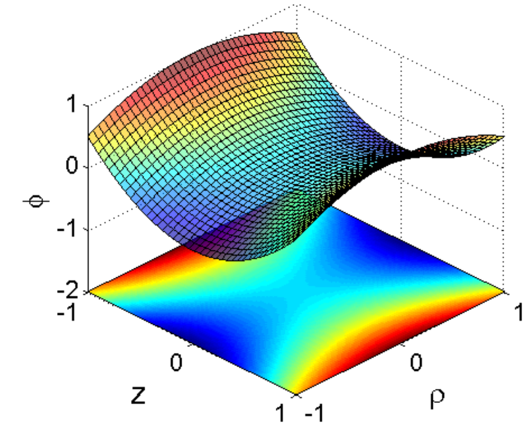
$\delta m/m(^{12}C^{6+})<8\cdot 10^{-14}$

$$R \equiv \frac{\nu_c(^{12}C^{6+})}{\nu_c(p)}$$

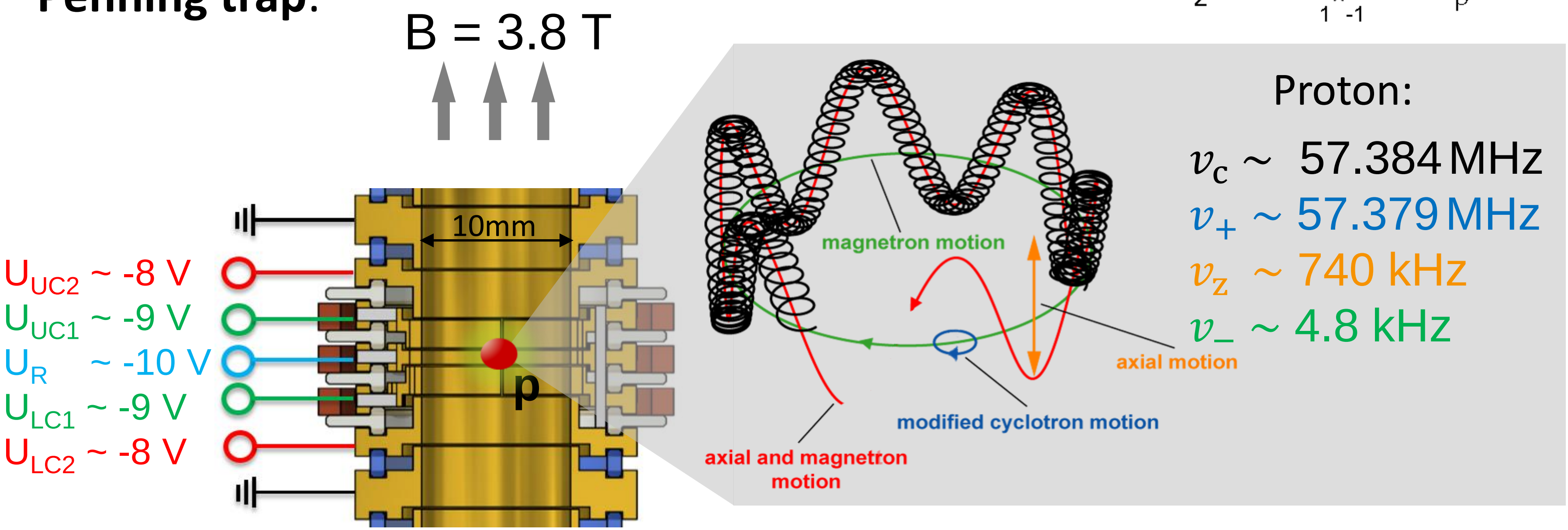
Particular challenge: m_p /$m(^{12}C^{6+})$ is not a mass doublet nor a q/m doublet!

Our Experimental Tool

- **Measurement of cyclotron frequency:**
  → Homogeneous & static magnetic field
  → Electrostatic quadrupole potential for trapping



- **Penning trap**:



- **Cyclotron frequency via the invariance theorem:**

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

$$\nu_c \approx \nu_+ >> \nu_z >> \nu_-$$

[L.S. Brown & G. Gabrielse, PRA **25**, 2423 (1982)]

A New Ultra-Harmonic Trap

Ideal world:

$$U(z) = \frac{1}{2} U_r \left(C_0 + C_2 \frac{z^2}{d_{char}^2} \right)$$

A New Ultra-Harmonic Trap

Real world:

$$U(z) = \frac{1}{2}U_r\left(C_0 + C_2\frac{z^2}{d_{char}^2} + C_4\frac{z^4}{d_{char}^4} + C_6\frac{z^6}{d_{char}^6} + C_8\frac{z^8}{d_{char}^8} + C_{10}\frac{z^{10}}{d_{char}^{10}} + \cdots\right) = \frac{1}{2}U_r\sum_{i=0,2,\ldots}^{\infty} C_i\frac{z^i}{d_{char}^i}$$

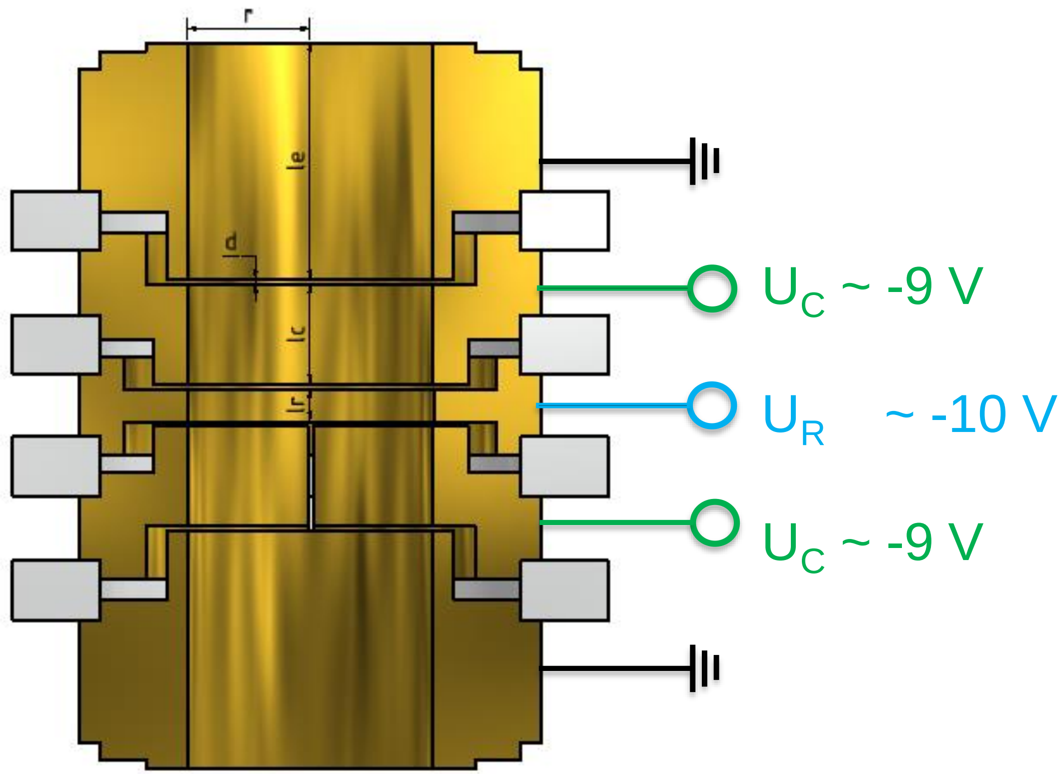
So far:

Degrees of freedom: l_R, l_C, U_C

Optimized parameters:

C_4=C_6=0 (compensated)

ν_z indep. of U_c (orthogonal)



A New Ultra-Harmonic Trap

Real world:

$$U(z) = \frac{1}{2}U_r\left(C_0 + C_2\frac{z^2}{d_{char}^2} + C_4\frac{z^4}{d_{char}^4} + C_6\frac{z^6}{d_{char}^6} + C_8\frac{z^8}{d_{char}^8} + C_{10}\frac{z^{10}}{d_{char}^{10}} + \cdots\right) = \frac{1}{2}U_r\sum_{i=0,2,\ldots}^{\infty} C_i\frac{z^i}{d_{char}^i}$$

New trap (additional pair of correction electrodes)

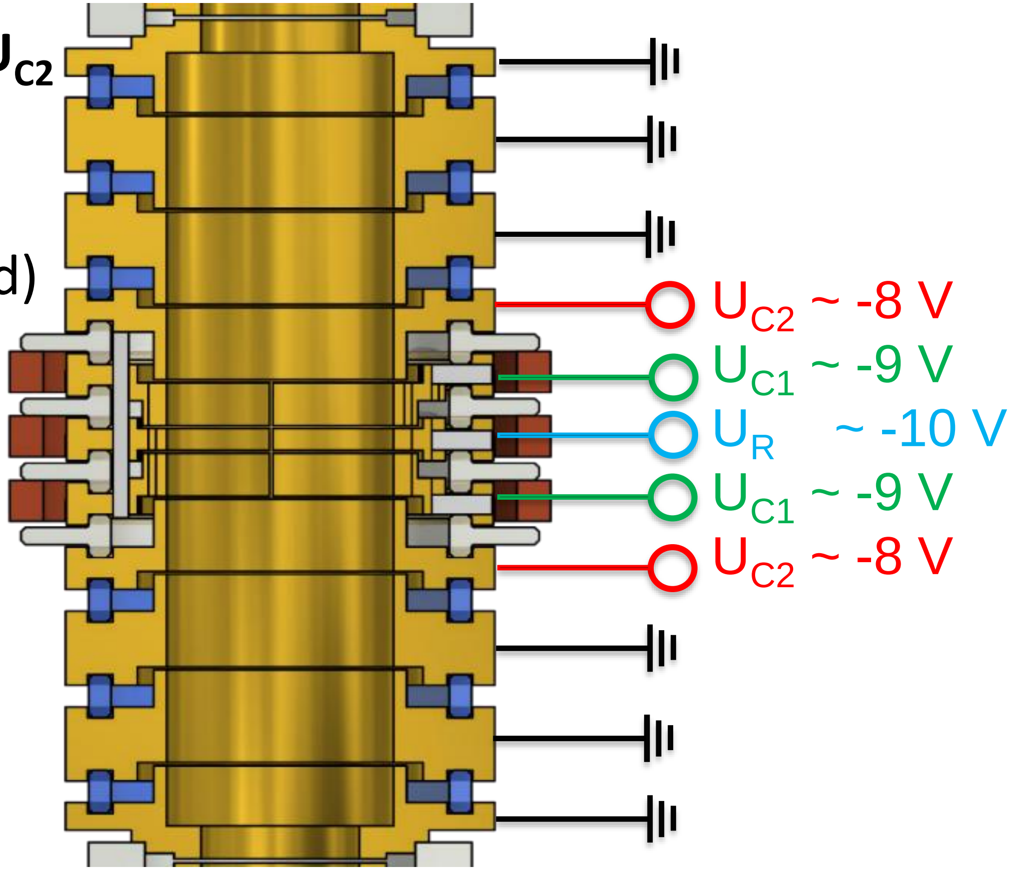
Degrees of freedom: l_R, l_{C1}, U_{C1}, $\mathbf{l_{C2}}$, $\mathbf{U_{C2}}$

Optimized parameters:

$C_4=C_6=C_8=C_{10}=0$ (compensated)

ν_z indep. of same scaling of U_{C1} and U_{C2}

(combined orthogonality)



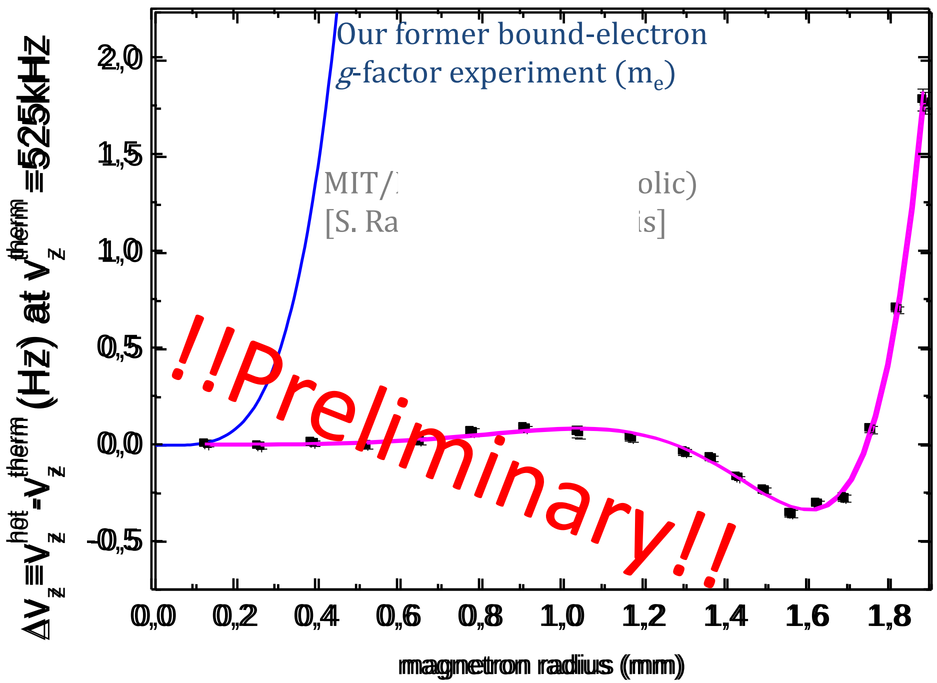
A New Ultra-Harmonic Trap - Performance

Optimization of the electric potential in a running experiment:

DOFs: U_{C1} and U_{C2} → Optimize: C_4=C_6=0

Study shifts of axial frequency due to magnetron bursts:

$$\frac{\Delta\nu_z}{\nu_z} = -\frac{3}{2}\frac{C_4}{d_{char}^2 C_2} r_-^2 + \frac{15}{8}\frac{C_6}{d_{char}^4 C_2} r_-^4 - \frac{35}{8}\frac{C_8}{d_{char}^6 C_2} r_-^6 + \cdots$$

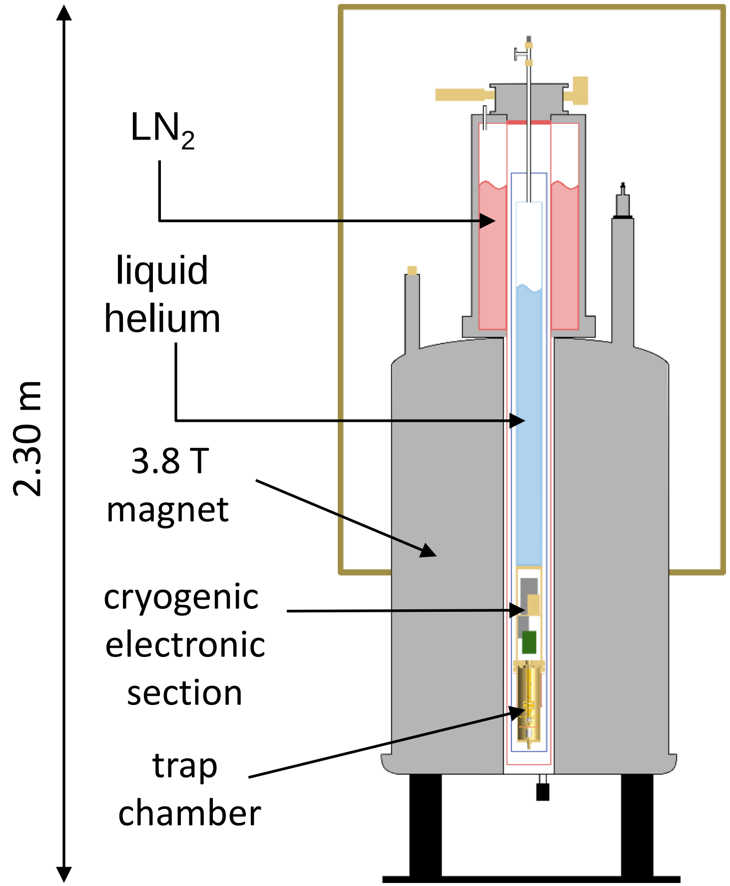


	new experiment	our former experiment
C_4	$0.07(1.27)\cdot10^{-6}$	$0(1)\cdot10^{-5}$
C_6	$-4.0(4.3)\cdot10^{-6}$	$-1.6(1)\cdot10^{-2}$
C_8	$9.2(61.0)\cdot10^{-5}$	-
C_{10}	0.0105(38)	-

C_6 a factor of 4000 smaller

It seems that a 7 electrode cylindrical trap is more harmonic than existing hyperbolic traps (at least for $z_0/r_{trap} \leq 0.4$)

The Setup



Experimental conditions:

- stable 3.8 T magnetic field
- cryogenic temperatures (4.2 K)
- closed trap chamber
  → mEBIS
- vacuum (within trap chamber):
  $p < 10^{-16}$ mbar

→ **Storage times: ~ months**

Magnet and cryostat from former bound-electron *g*-factor experiment:

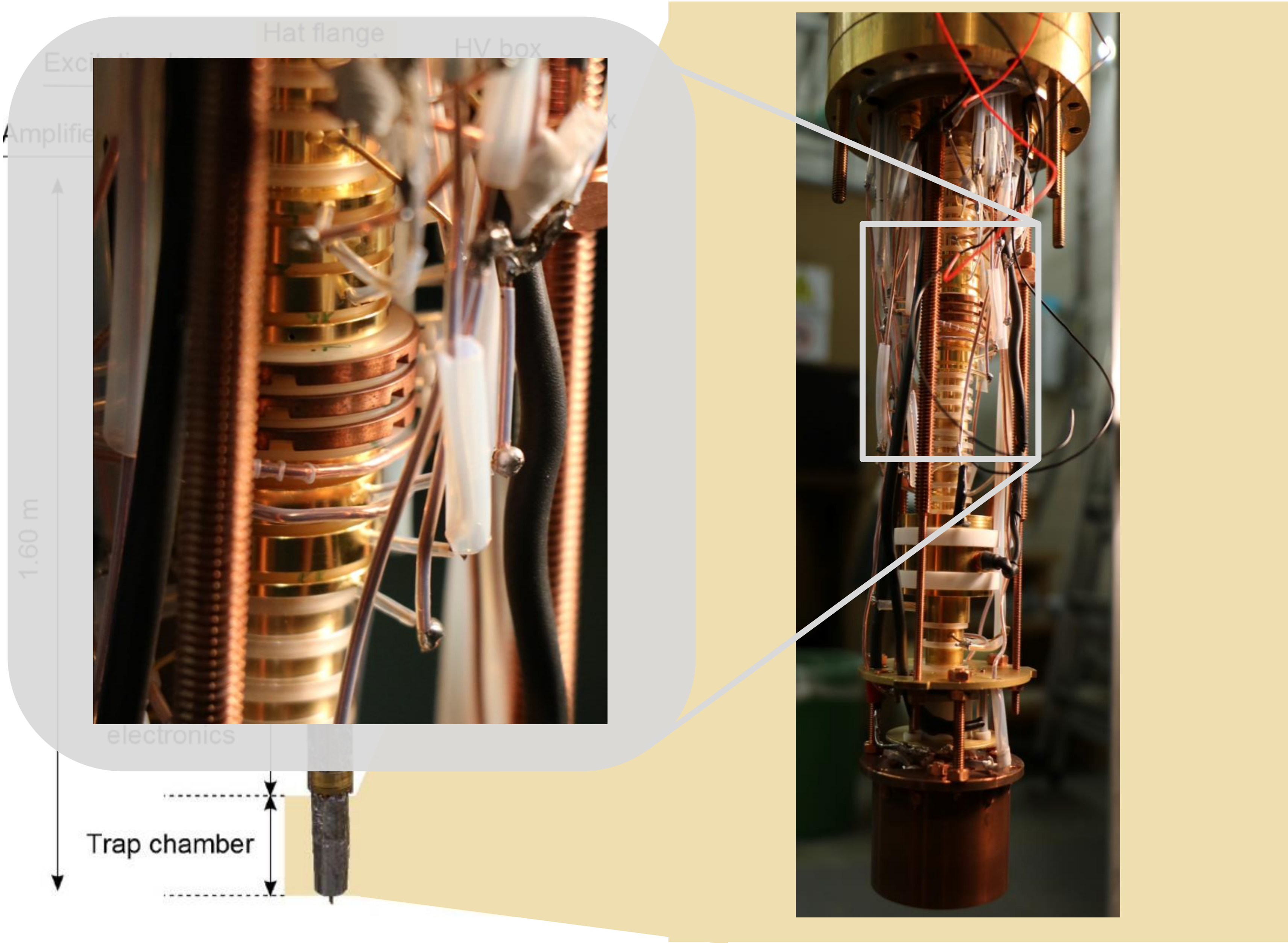
BS-QED tests: $g(^{28}Si^{13+})$ [S. Sturm et al., PRL **107**, 2 (2011)]

$g(^{28}Si^{11+})$ [A. Wagner *et al.*, PRL **110**, 033003 (2013)]

$g(^{40,48}Ca^{17+})$ [F. Köhler-Langes *et al.*, Nature Comm. **10246** (2016)]

Electron mass: $g(^{12}C^{5+})$ [S. Sturm *et al.*, Nature **506**, 467-470 (2014)]

Some Pictures



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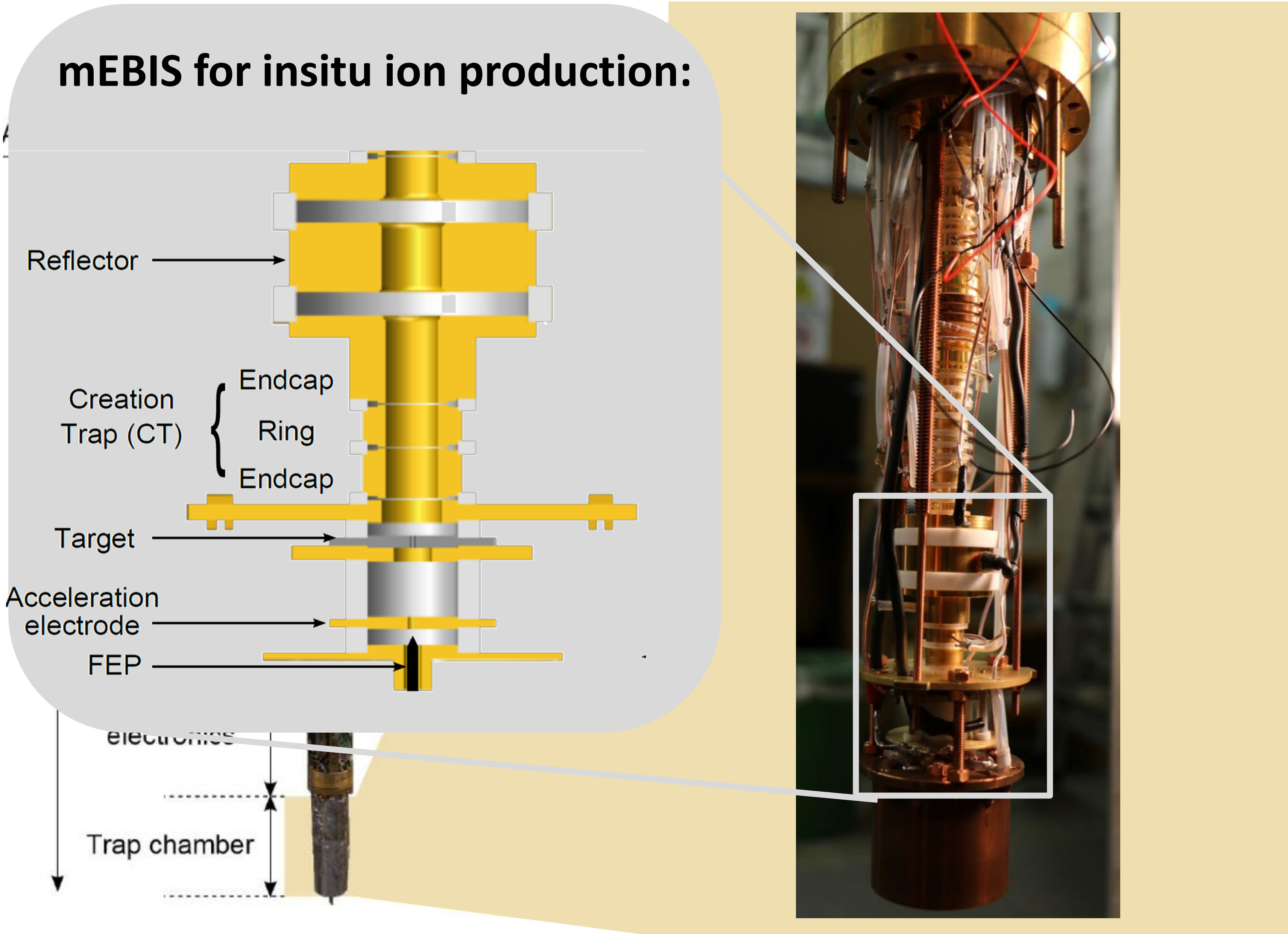
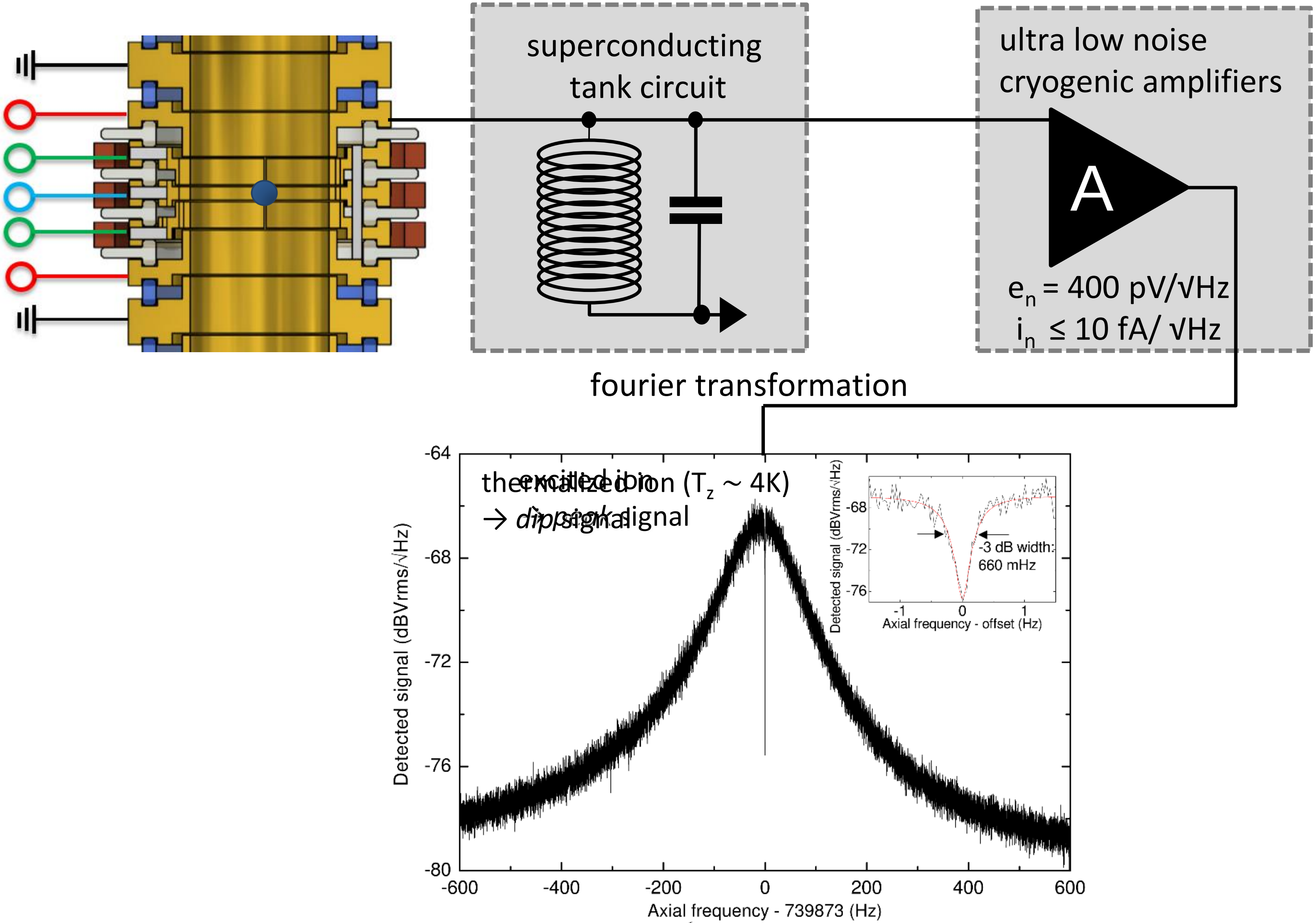


Frequency Detection Techniques

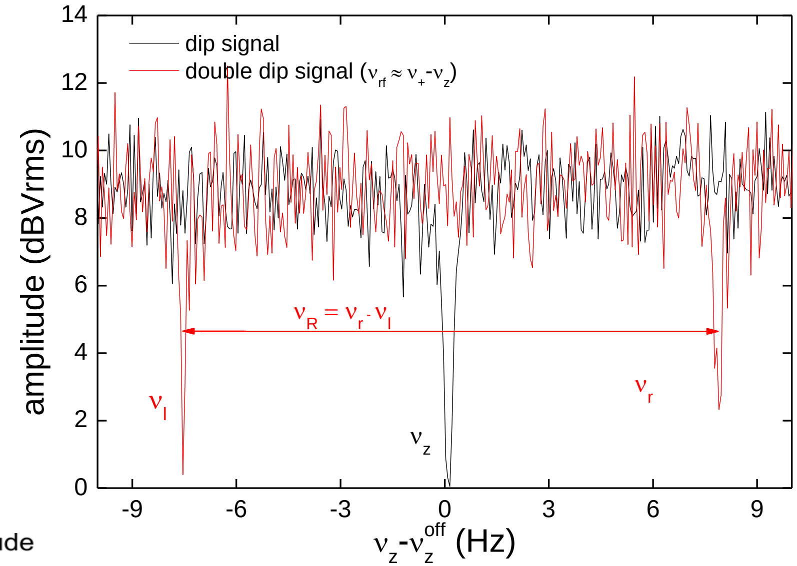
Eigenfrequency Detection

Measurement of induced image currents (~ fA) on trap electrodes



Eigenfrequency Detection II

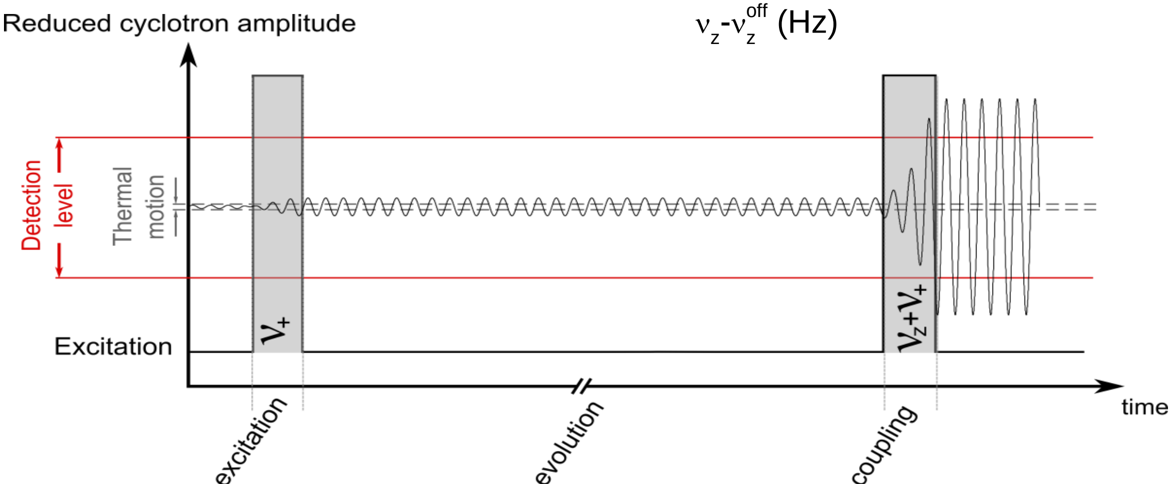
Radial motions can be detected via sideband coupling at e.g. $\nu_{rf} \sim \nu_+ - \nu_z$.
Then, *axial dip* splits into a *double dip*:



$$\nu_+ = \nu_{rf} - \nu_z + \nu_l + \nu_r$$

Phase-sensitive measurement of ν_+ via PnA-method:

S. Sturm et al., PRL 107, 143004 (2011)



- Rapid measurement time (~10 s instead of ~ 3 min for *double dip*)
  → **Reduction of impact of B-field fluctuations**
- Small radial kinetic energies during phase evolution
  → **Small magnetic and relativistic shifts**

Measurement Cycle

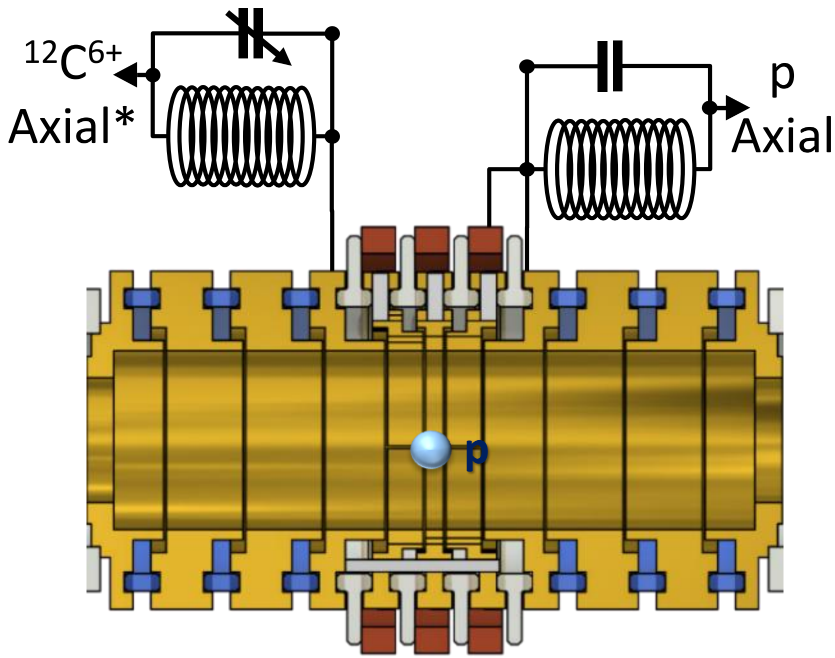
Two Tuned Detection Systems

To guarantee identical position use the exactly same electric field configuration!

$$\nu_z = \frac{1}{2\pi}\sqrt{\frac{q}{m}\frac{C_2}{d_{\mathrm{char}}^2}U_r}$$

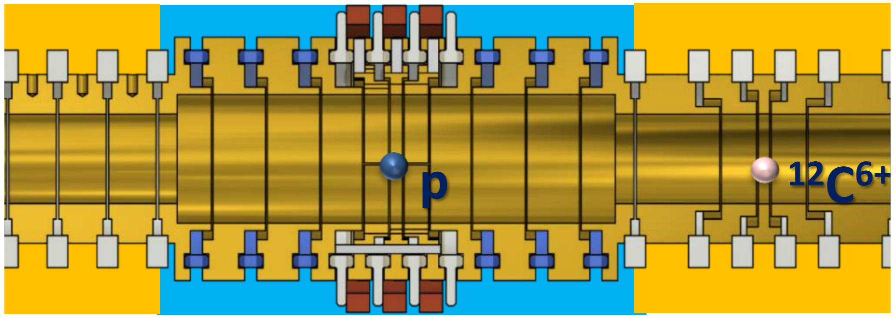
@U_r=-9.812V:
$\nu_z(p)$ = 740kHz
$\nu_z(^{12}C^{6+})$ = 525kHz

→ **Two independent superconducting axial resonators!**



*Resonator fine tuned with a varactor diode

Masurement Cycle



Both ions at the same time within the trap chamber

(I) $\nu_c(p)$ in MT

(II) $\nu_c(^{12}C^{6+})$ in MT

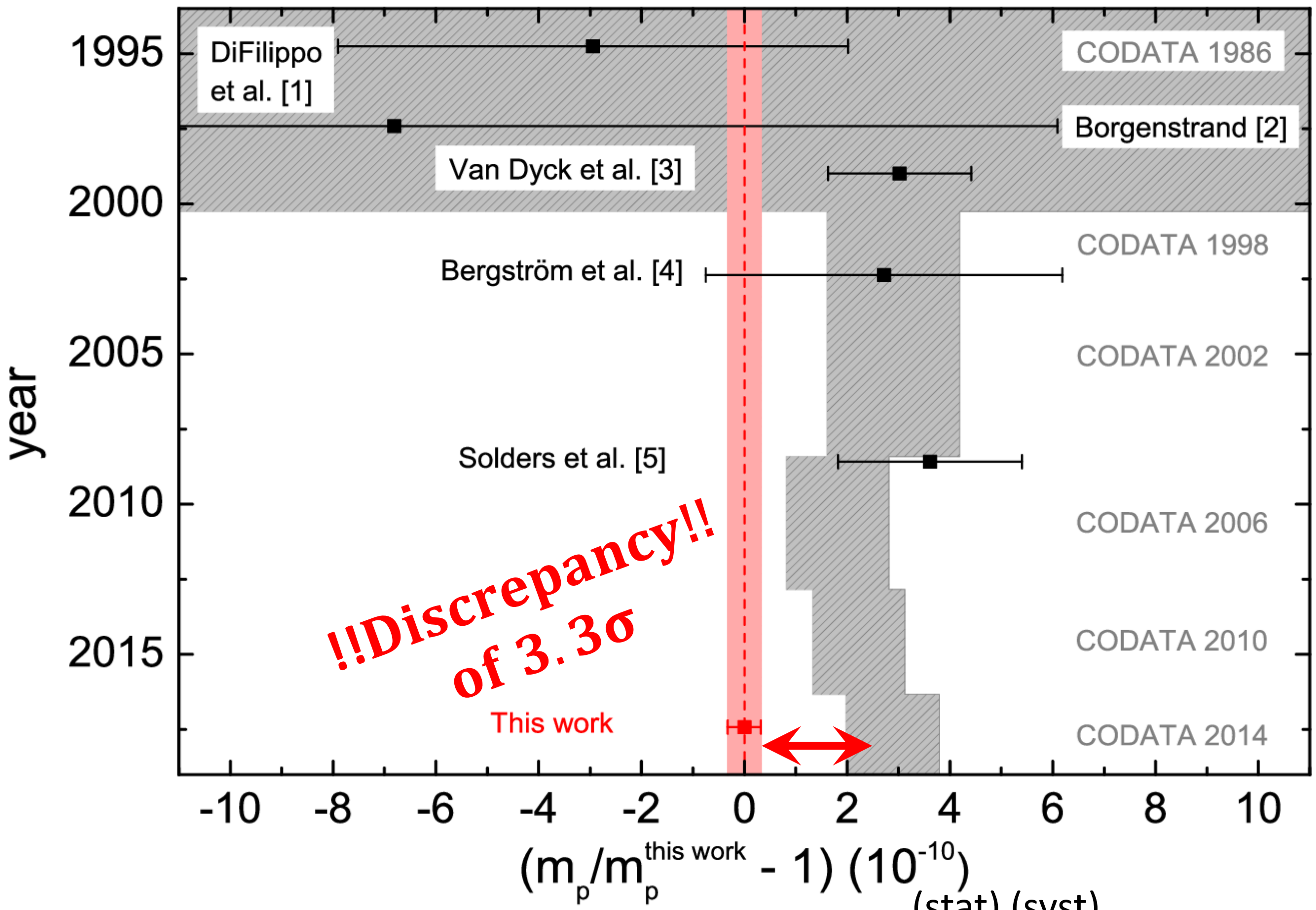
$$R \equiv \frac{\nu_c(^{12}C^{6+})}{\nu_c(p)}$$

Time between ν_+ measurements: LESS THAN 3 MINUTES

→ **Reduction of impact of magnetic field fluctuations compared to former measurements**

→ **Each cycle (48min) gives a frequency ratio R with $\delta R/R = 1.8 \cdot 10^{-10}$**

Results



(stat) (syst)

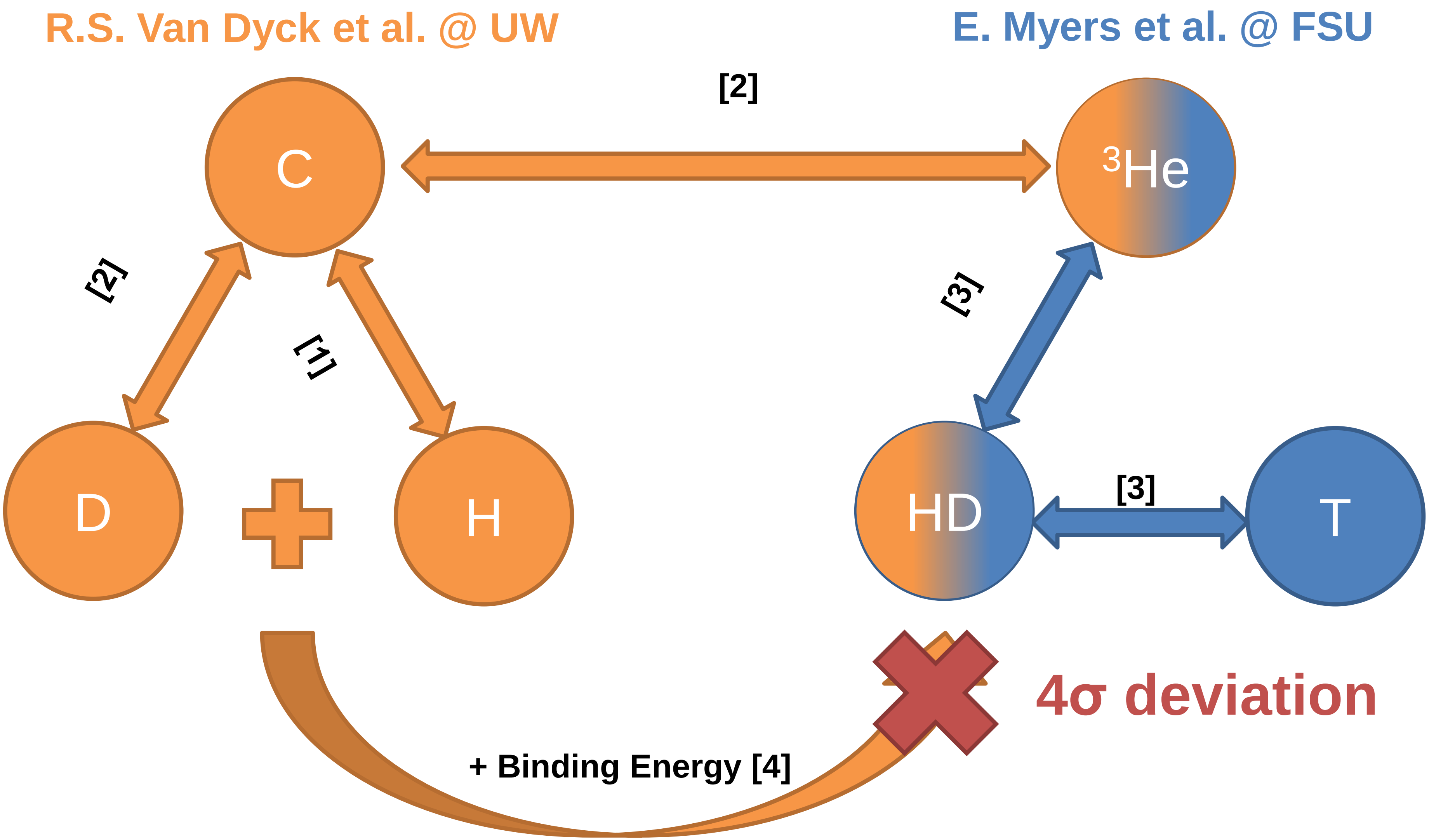
$$m_p = 1.007\,276\,466\,583\,(15)(29)\,u \qquad \frac{\delta m_p}{m_p} = 3.2 \cdot 10^{-11}$$

→ **Improvement by a factor of 3**

[1] PRL **73**, 1481 (1994). [2] Ph.D. thesis, Stockholm University (1997).
[3] AIP Conf. Proc. **457**, 101 (1999). [4] Phys. Scr. **66**, 201 (2002). [5] PRA **78**, 2514 (2008).

[PRL **119**, 033001 (2017)]

Puzzle of light atomic masses



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[2] Metrologia **52**, 280 (2015)
[3] PRL **114**, 013003 (2015)
[4] Yan et al, PRA **67**, 062504 (2003)

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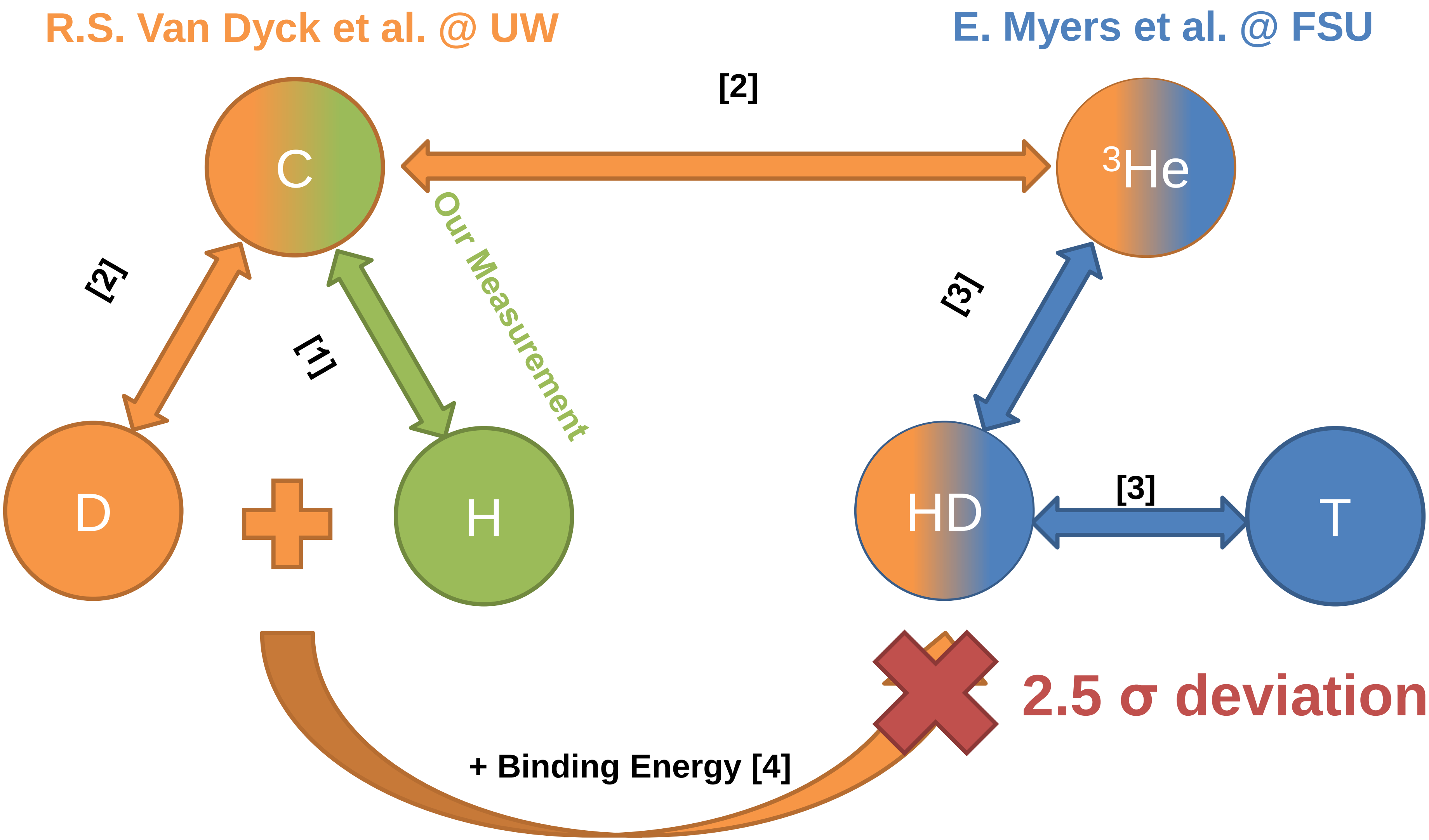

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What's next?

How to beat dominant uncertainties?

Systematic Shifts and Limitations in Our Proton Measurement

Effect	Rel. syst. shift of ν_c (10^{-11})	Rel. syst. shift of R_0 (10^{-11})	Uncertainty (10^{-11})
r_+^{exc} for p / $^{12}C^{6+}$ (μm)	9/14	0/ 0	0/0
Image charge	0.83/9.94	9.10	0.46
Image current	-0.14/-0.33	-0.19	0.03
Residual magnetostatic inhomogeneity	4.43/0.14	-3.95	2.75
Residual electrostatic anharmonicity	$\ll 0.01/\ll 0.01$	$\ll 0.01$	$\ll 0.01$
Special relativity	7.23/3.45	-1.14	0.71
Lineshape model[a]	-0.03/0.14	0.27	0.30
Magnetron frequency uncertainty	0.01/0.06	0	0.06
Total	12.33/13.40	3.82	2.89

[a] The typical value varies slightly between measurement sets due to different detunings of the axial resonators.

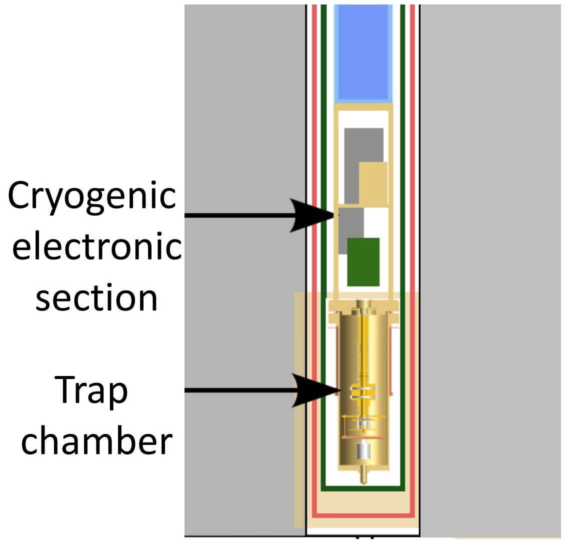
[PRL **119**, 033001 (2017)]

Magnetic inhomogeneity:

$B(z)=B_0+B_1z+B_2z^2+\dots$
$\langle B\rangle=B_0+B_2\langle z_0^2\rangle/2$

B_2=-0.27(2)T/m²
B_1=0.92(1)mT/m

→ Superconducting B1/B2-shim coils



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$B_2=-0.27(2)\,T/m^2$
$B_1=0.92(1)\,mT/m$

→ Superconducting B1/B2-shim coils

Special relativity:

dominated by thermal energy in the proton's cyclotron mode

→ cooling via cyclotron resonator

Image charge:

→ recent measurement campaign and new simulations

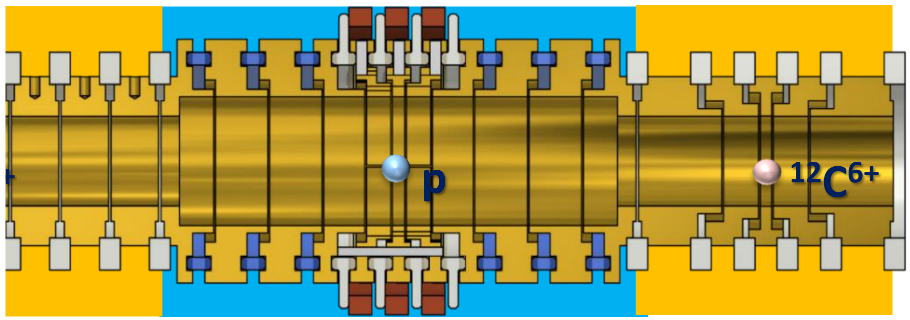
Improving Statistics

Statistics limited by magnetic field fluctuations

→ Introduce an additional trap with a third, single and highly-charged ion

reference trap (RT)

measurement trap (MT)



storage trap 2 (ST2)

storage trap 1 (ST1)

!SIMULTANEOUS! measurements of cyclotron frequencies:

(I) $\nu_c(^{28}\mathrm{Si}^{13+})$ and $\nu_c(\mathrm{p})$

$$R_1 = \frac{\nu_c(\mathrm{p})}{\nu_c(^{28}\mathrm{Si}^{13+})}$$

(II) $\nu_c(^{28}\mathrm{Si}^{13+})$ and $\nu_c(^{12}\mathrm{C}^{6+})$

$$R_2 = \frac{\nu_c(^{12}\mathrm{C}^{6+})}{\nu_c(^{28}\mathrm{Si}^{13+})}$$

$$\frac{R_1}{R_2} = \frac{\nu_c(\mathrm{p})}{\nu_c(^{12}\mathrm{C}^{6+})}$$

→ Cancelation of the impact of common mode magnetic field fluctuations

Next Measurement Campaigns

The Mass of the Neutron

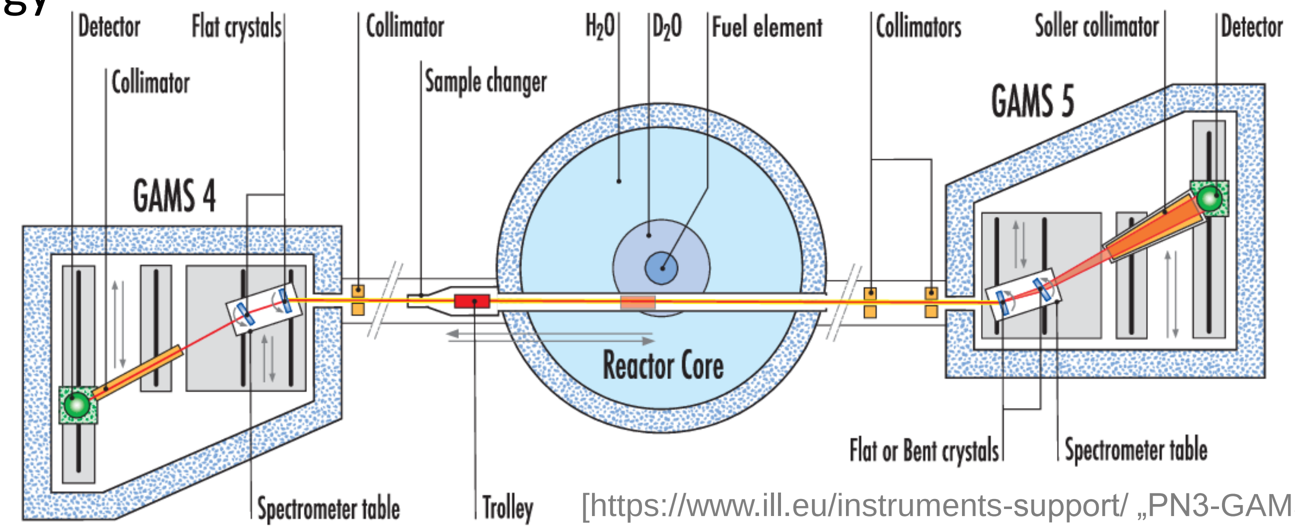
Apply proton measurement scheme to the deuteron

→ Extract the neutron mass:

$$m_{\mathrm{n}} = m_{\mathrm{d}} - m_{\mathrm{p}} + E_{\gamma}/c^2$$
$$E_{\gamma}/c^2 = 2.388\,170\,07\,(42) \times 10^{-3}\mathrm{u}$$

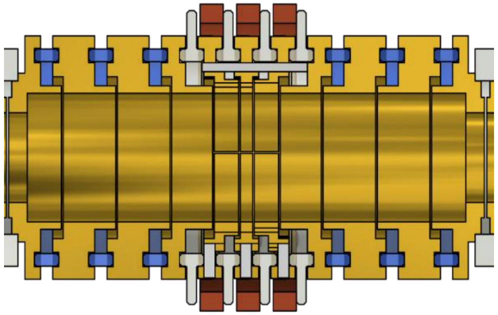
[E.G. Kessler et al. PLA **255**, 221-229 (1999)]

Improved binding energy needed, currently measured at the ILL in France



[https://www.ill.eu/instruments-support/ „PN3-GAMS“]

Summary

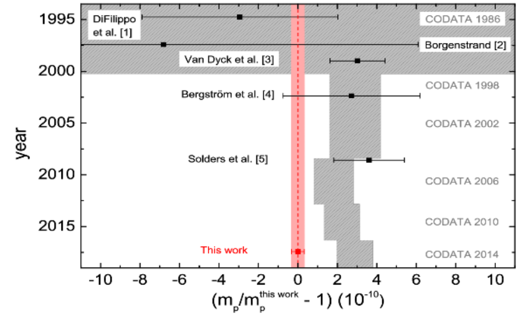


First phase: A new value of the proton mass

- Experimental setup
  New seven electrode Penning trap

- Dedicated frequency detection techniques / Measurement process

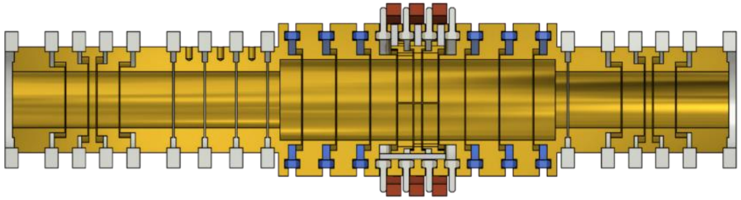
- First results on the atomic mass of the proton
  (3-fold improvement and 3σ deviation)



Second phase:

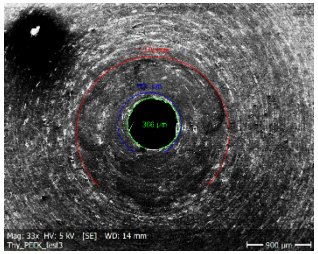
- Reduce dominant systematic uncertainties
  (B2, Image charge shift)

- Reference Trap



Next measurement campaigns:

- The mass of deuterium / neutron



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[1]*Division of Stored and Cooled Ions at MPIK, Heidelberg*

[2]*Atomic Physics Division at GSI Helmholtzzentrum, Darmstadt*

[3]*MATS group within QUANTUM at the Institut für Physik, Mainz*

[4]*RIKEN Ulmer Initiative Researcher Unit, Wako, Saitama 351-0198, Japan*

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GSI

JGU JOHANNES GUTENBERG UNIVERSITÄT MAINZ

RIKEN

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erc

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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Max Planck Institute for Nuclear Physics

RIKEN

RIKEN Incentive Research FPR Funding

Thank you for your attention! Questions?