Annual Report 2018

Stefan Ulmer

RIKEN

2019 / 01 / 22

Programs for Junior Scientists

MAX-PLANCK-GESELLSCHAFT

東京大学
THE UNIVERSITY OF TOKYO

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

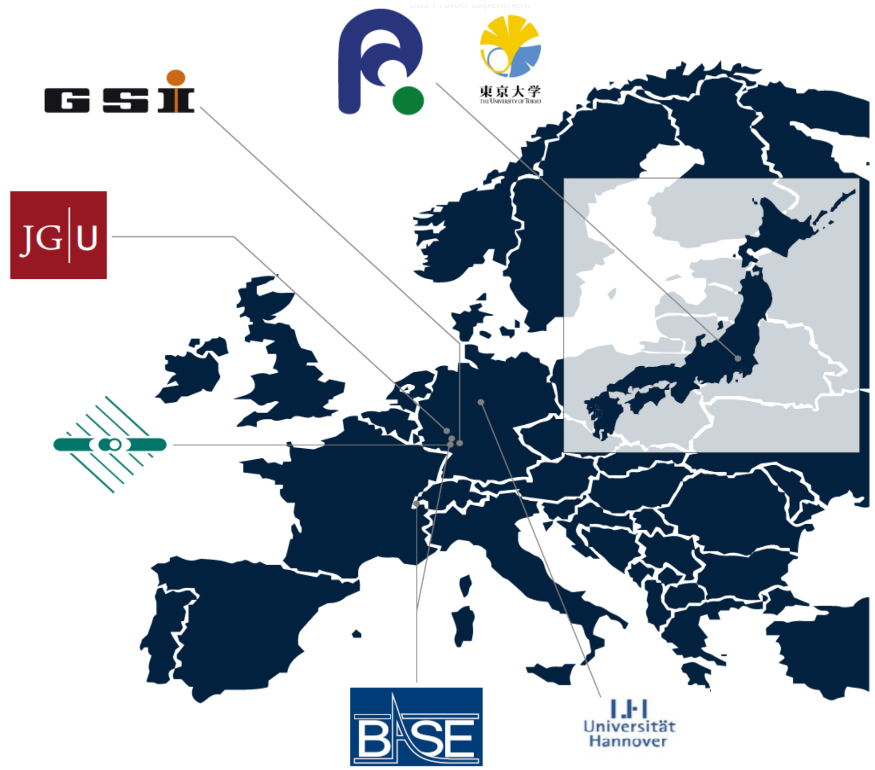
GSI

Leibniz Universität Hannover

PTB

BASE – Collaboration

- **Mainz:** Measurement of the magnetic moment of the proton (Mooser, Ulmer, Blaum, Walz, Quint).
- **CERN-AD:** Measurement of the magnetic moment of the antiproton and proton/antiproton q/m ratio (Ulmer, Smorra, Yamazaki, Blaum, Matsuda).
- **Hannover/PTB:** QLEDS-laser cooling project (Ospelkaus, Ulmer)




BASE

Experiment of the moment

The BASE collaboration at CERN has measured the antiproton magnetic moment with extraordinary precision, offering more than 100-fold improved limits on certain tests of charge–parity–time symmetry.

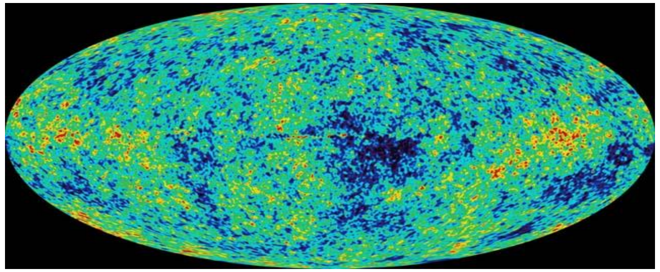
The BASE setup at CERN's Antiproton Decelerator.

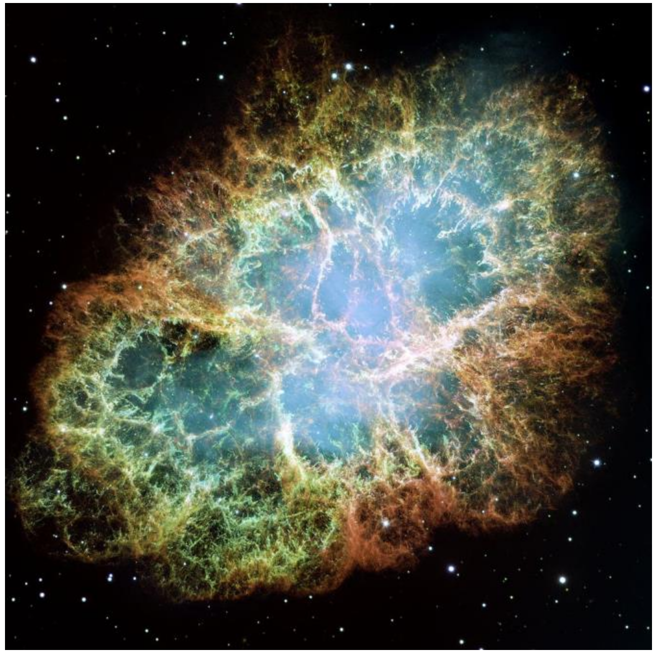
Non-destructive physics

Institutes: RIKEN Ulmer IRU, RIKEN APL, Max Planck Society, CERN, University of Mainz, Tokyo University, GSI Darmstadt, University of Hannover, PTB Braunschweig

C. Smorra et al., EPJ-Special Topics, The BASE Experiment, (2015)

What inspires AD experiments?





1. Big Bang scenario supported by
   1. Hubbles law
   2. Discovery of **CMWB with a black body spectrum of 2.73(1)K, by far too intense to be of stellar origin**.
   3. BBN scenario **describes exactly the observed light element abundances as found in «cold» stellar nebulae**.

2. Using the models which successfully describe 1., 2. and 3.:

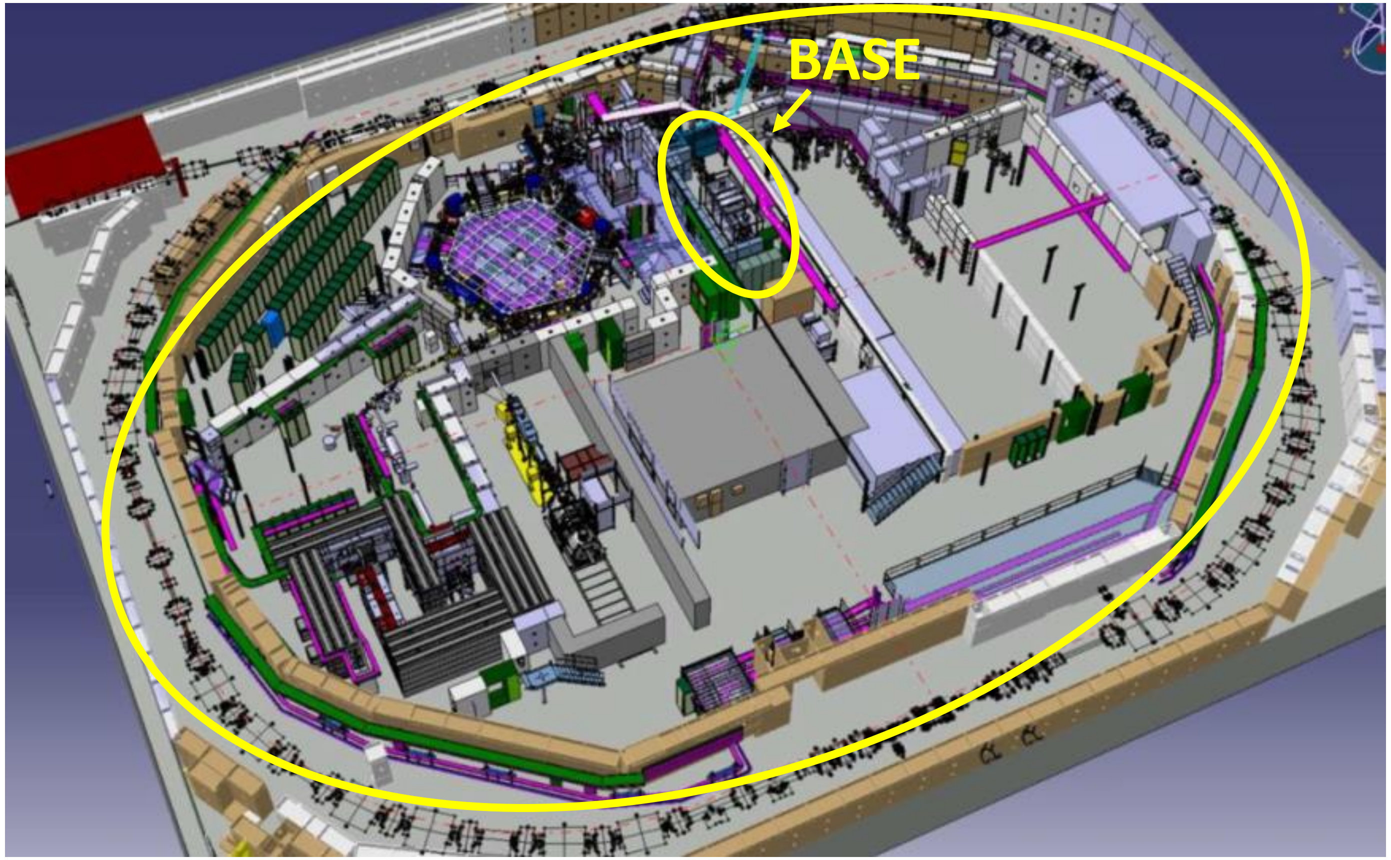
Prediction	
Baryon/Photon Ratio	10^{-18}
Baryon/Antibaryon Ratio	1

Observation	
Baryon/Photon Ratio	10^{-9}
Baryon/Antibaryon Ratio	10000

Following the current Standard Model of the Universe our predictions of baryon to photon ratio are **wrong by about 9 orders of magnitude** while our baryon/antibaryon ratio is **wrong by about four orders of magnitude**.

BASE in the AD Facility

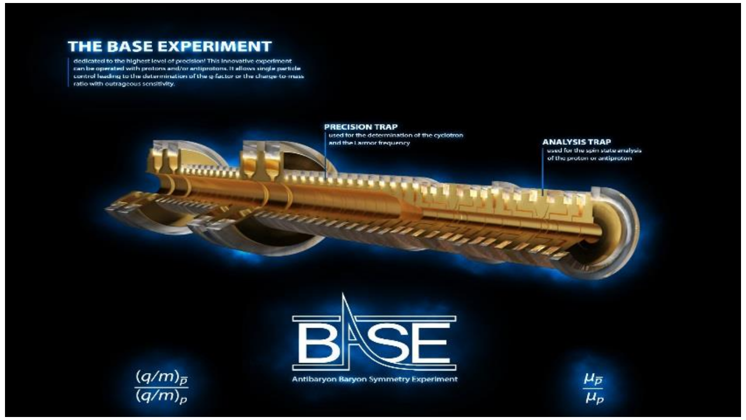
- AD statistics 2018
  - AD-physics hours: 2950
  - Particles delivered: $4.4*10^{10}$
- BASE 2018 consumption
  - AD-beam hours: 24 (three full shifts, **THANKS 2 ALPHA !**)
  - Particles consumed: $3.6*10^{8}$ (0.8%)
  - **BASE-physics hours: 7450**



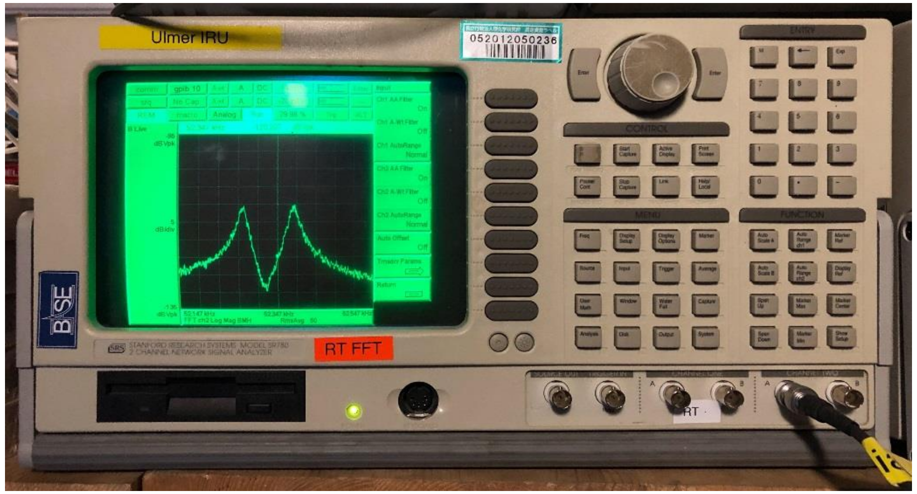
thanks to our reservoir trap

A Special Place – the BASE Reservoir Trap

- We have
  - a vacuum of 5e-19 mbars
    - best characterized vacuum on earth,
    - comparable to pressures in the interstellar medium
  - antiproton storage times of several 10 years.
  - not more than 3000 atoms in a vacuum volume of 0.5l
  - order 100 to 1000 trapped antiprotons
  - a local inversion of the baryon asymmetry



BASE ANTIMATTER INVERSION	
local volume	0.0001^3 m^3
Baryons in local trap volume	$1.65*10^{-7}$
Antibaryon in local trap volume	100
Antibaryon/Baryon Ratio	**$5.9*10^{8}$**
Ratio Inversion	**$3.8*10^{12}$**

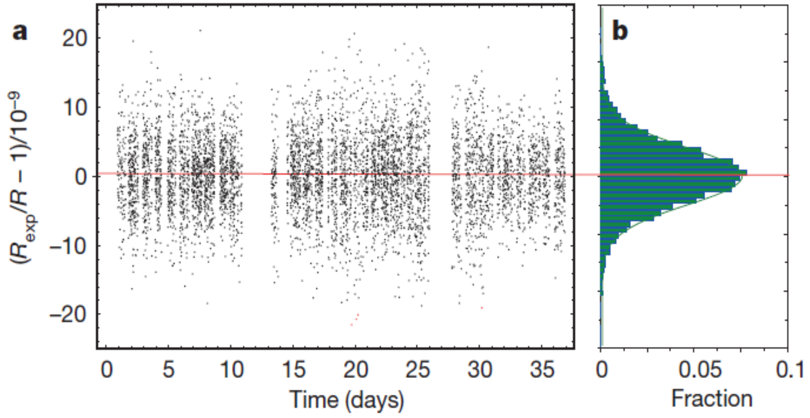


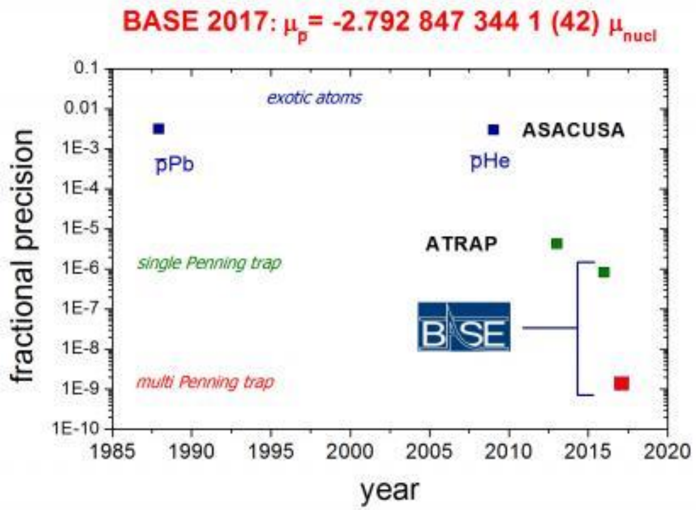
With this instrument we investigate the properties of antiprotons very precisely

Goals and Status of BASE Measurements

$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g_{\bar{p}}}{2}\frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$





$R_{exp,c}$ = 1.001 089 218 755 (69)

g/2 = 2.792 847 344 1 (42)

69 p.p.t (2mHz)

1500 p.p.t (120mHz)

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

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

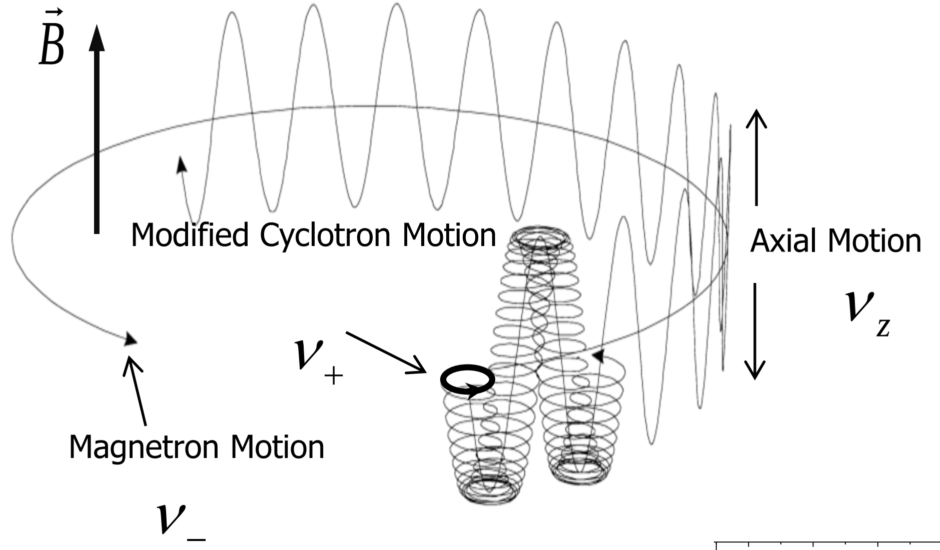
This Talk: Report on Activities in 2018

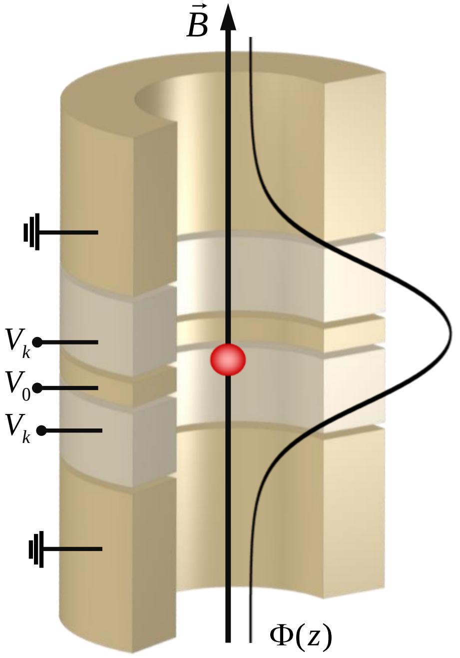
??? WHY ARE WE NOT DOING MUCH BETTER ???

Reminder - Main Tool: Penning Trap

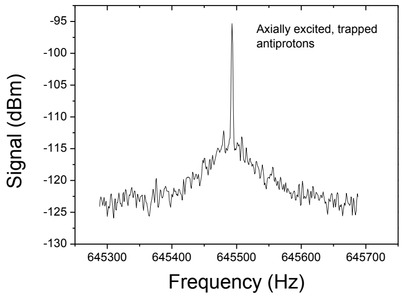
radial confinement: $\vec{B} = B_0 \hat{z}$

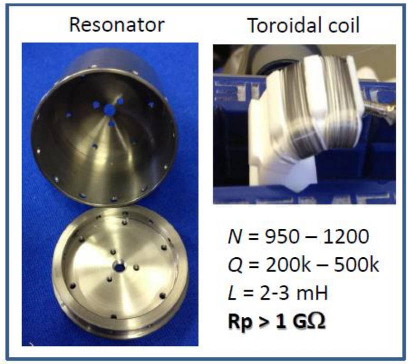
axial confinement: $\Phi(\rho, z) = V_0 c_2 \left(z^2 - \frac{\rho^2}{2} \right)$





Axial	600 kHz
Magnetron	7 kHz
Modified Cyclotron	30 MHz





H. Nagahama et al., Rev. Sci. Instrum. 8, 14084 (2017).

Invariance-Relation

J. Brown, G. Gabrielse, PRA 25, 2423 (1982)

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

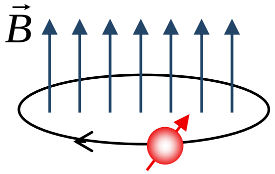
Cyclotron Frequency

$$\nu_c = \frac{1}{2\pi} \frac{q_{ion}}{m_{ion}} B$$

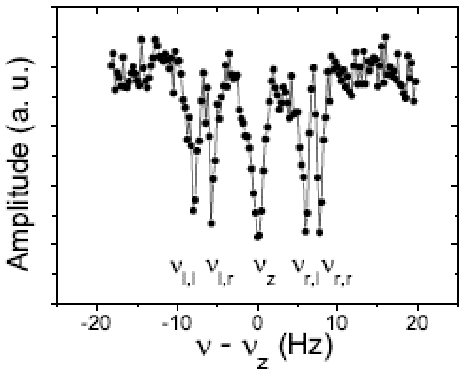
Cyclotron frequency connects measurable quantity to fundamental properties of trapped charged particle

Measurements in Penning traps

Cyclotron Motion



simple



S. Ulmer, A. Mooser *et al.* PRL 107, 103002 (2011)

g: mag. Moment in units of nuclear magneton

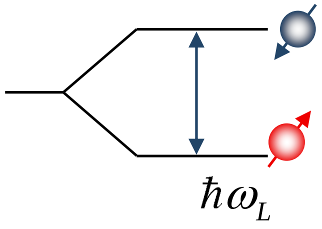
$$\omega_c = \frac{e}{m_p} B$$

$$\omega_L = g \frac{e}{2m_p} B$$

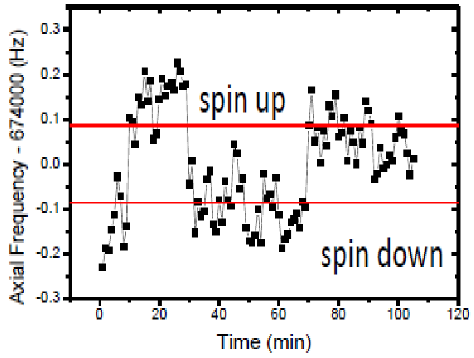
$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g_{\bar{p}}}{2} \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$

$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

Larmor Precession



difficult



S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

Determinations of the q/m ratio and g-factor reduce to measurements of frequency ratios -> in principle **very simple** experiments –> **full control, (almost) no theoretical corrections required.**

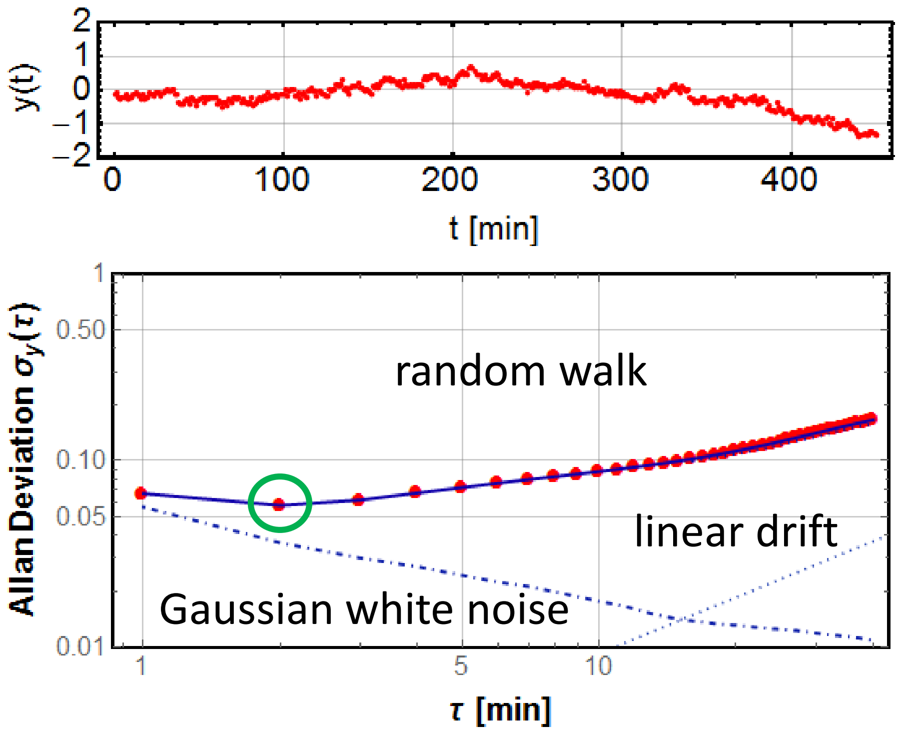
Limits: Magnetic Field Stability

- General idea of measurements in Penning traps

$$\omega_c = \frac{e}{m_p} B \qquad \frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

$$\omega_L = g \frac{e}{2m_p} B \qquad \frac{\mu_{\bar{p}}}{\mu_N} = \frac{g_{\bar{p}}}{2} \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$

Perform measurements such that magnetic field cancels out



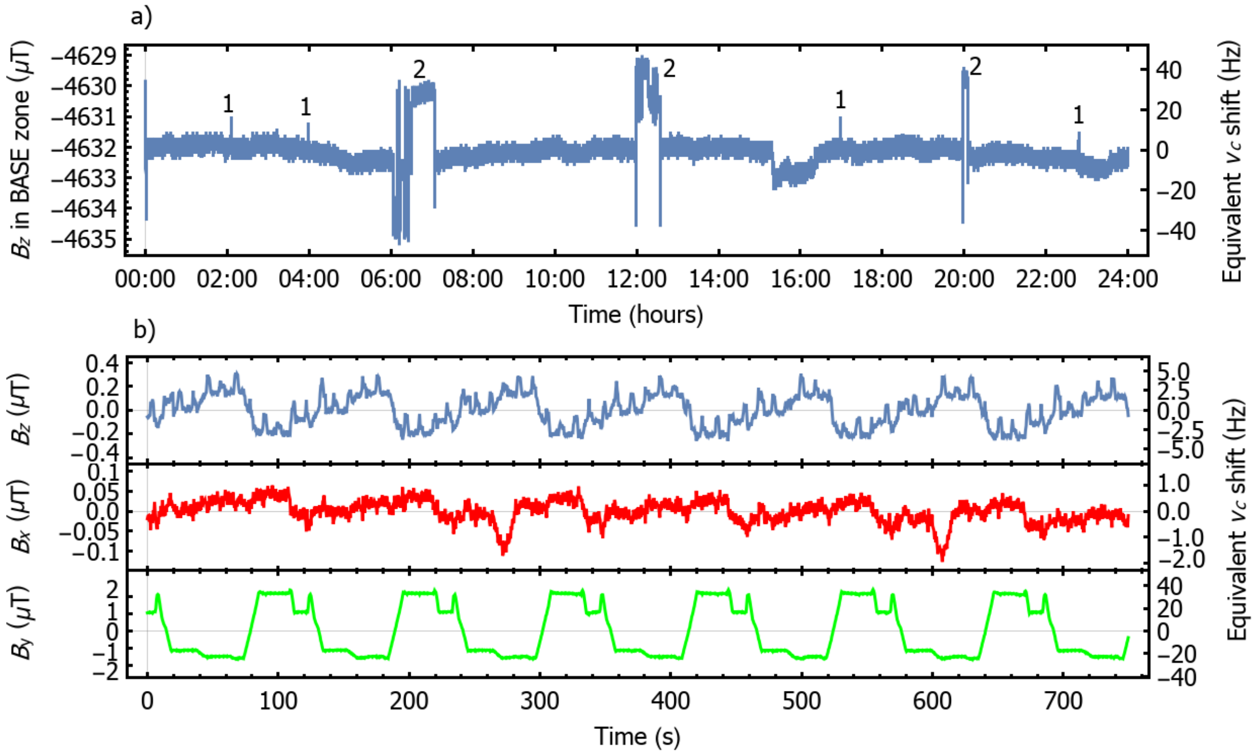
magnetic field fluctuations convolve into the ratios and lead to line broadening

Effects on ratio measurements: e.g. given this example, the best possible ratio scatter would be at 2 p.p.b.

To do better all aspects of the given **noise contributions** need to be **detected, analysed, understood and improved.**

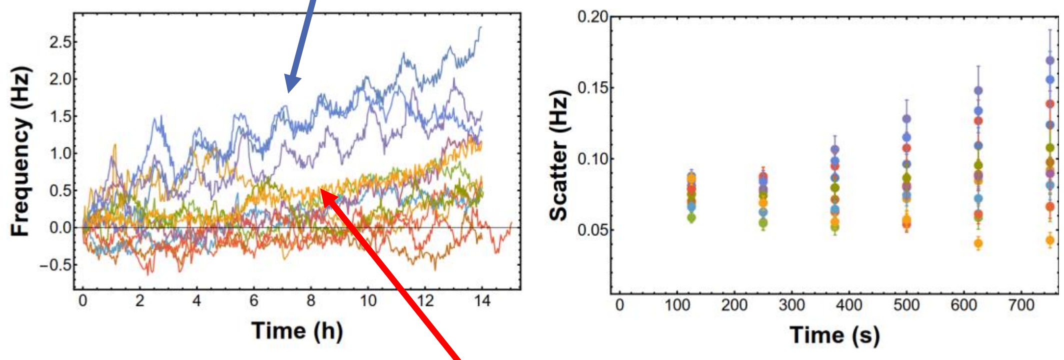
Welcome to the AD

- If you need to define an example for a place where you would never want to setup a precision Penning trap experiment, **use the AD facility as a role model.**



- Magnetic field fluctuations induced by the AD air conditioning system

thermalization platforms "in phase"



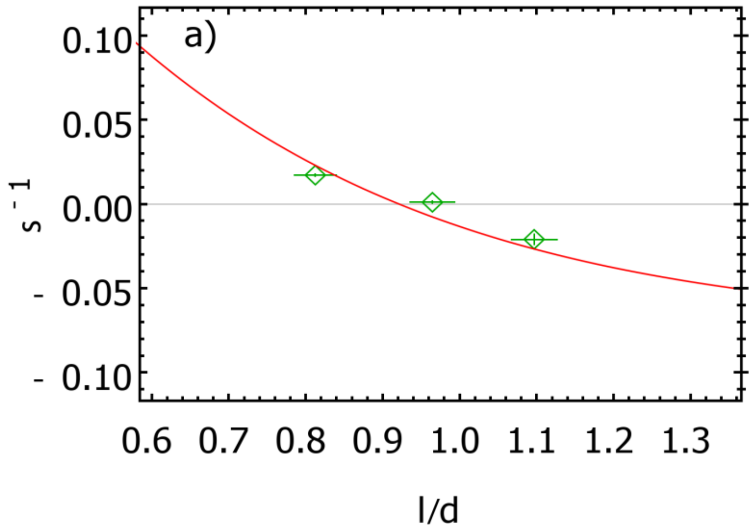
thermalization platforms "out of phase"

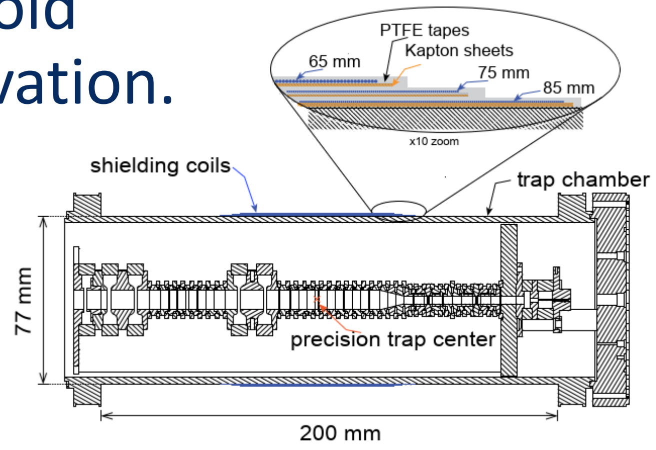
- Magnetic field fluctuations induced by the AD cycle and the overhead crane

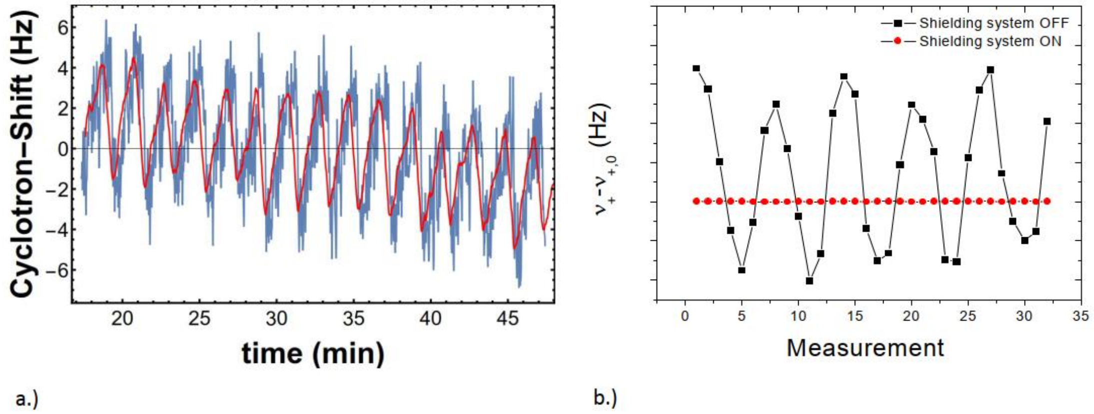
- Note: BASE frequency measurements require precision on the 100uHz (ratio) to 50 mHz (moment) level!

New Magnetic Shielding System

- Considerable upgrade based on self-shielding solenoid idea: Tuneable shielding factors based on new innovation.







- Need to improve our frequency measurement methods to be able to characterize the new shielding system.
- Estimate of shielding factor

50 < S < 500

J. Devlin
RIKEN

E. Wursten
CERN / RIKEN

compare G. Gabrielse and J. Tan, J. Appl. Phys. 63, 5143 (1988)

Other Limits in Frequency Measurements

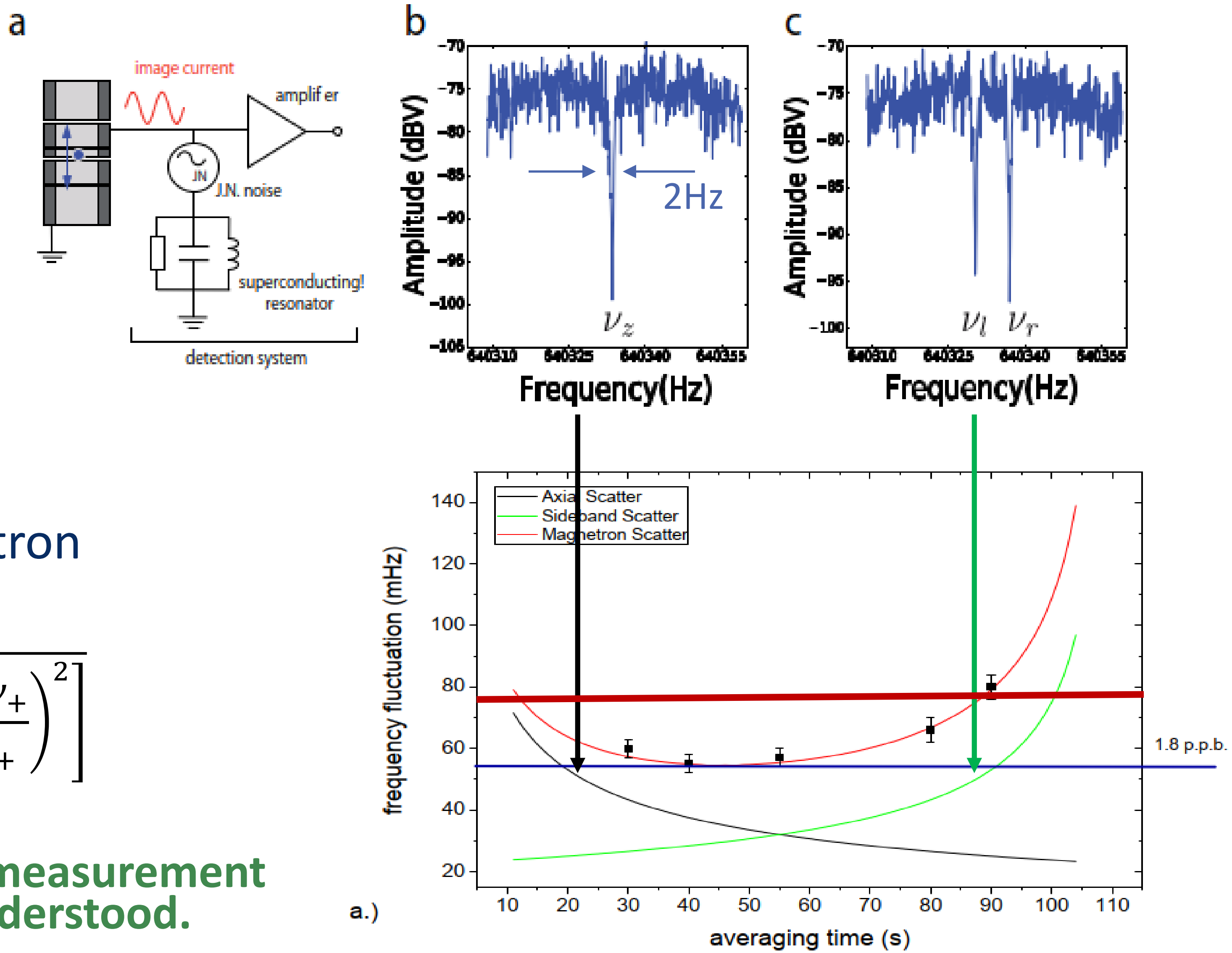
- Recipe: use image current detection
  - Measure axial
  - Measure sideband frequencies
  - **Obtain modif. cyclotron frequency**

$$\sigma(\nu_+) = \sqrt{3} \cdot \sigma(\nu_+)$$

- Test basic systematics using magnetron frequency measurements

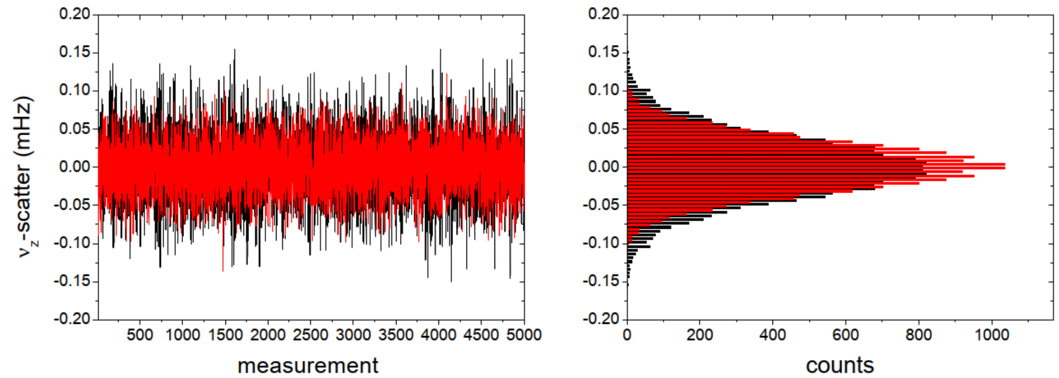
$$\sigma(\nu_-) = \nu_- * \sqrt{\left[2\left(\frac{\Delta\nu_z}{\nu_z}\right)^2 + \left(\frac{\Delta\nu_+}{\nu_+}\right)^2\right]}$$

Basic frequency stability at standard measurement parameters (1 AD cycle) is well understood.



Magnetic Inhomogeneities…

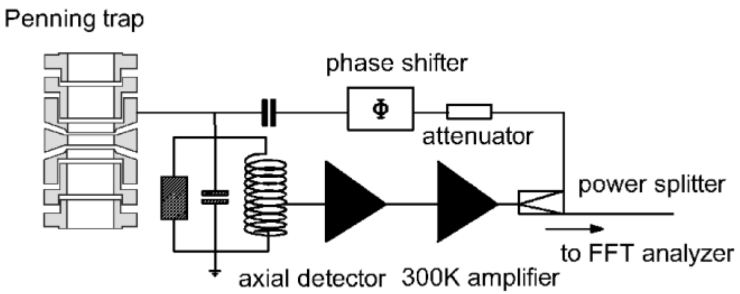
- …add scatter

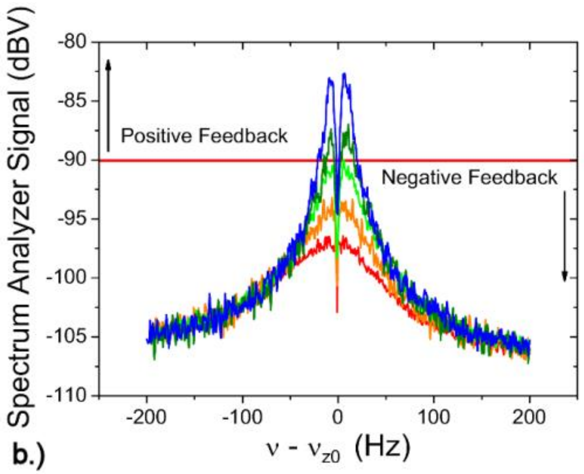


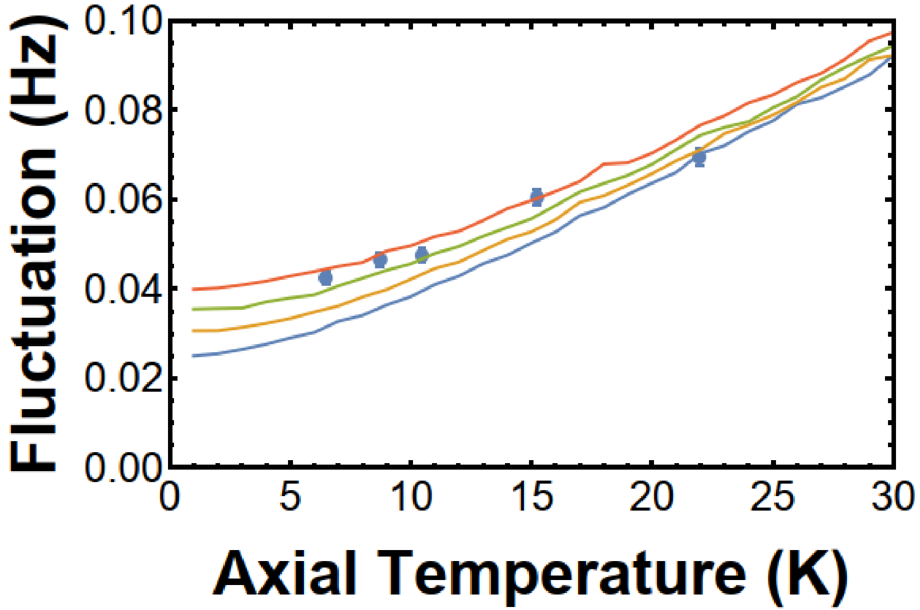
- mechanism:

$$\frac{\Delta\nu_z}{\nu_z} = \frac{1}{4\pi^2 m_p \nu_z^2}\frac{B_2}{B_0}E_+$$

- …introduce feedback cooling





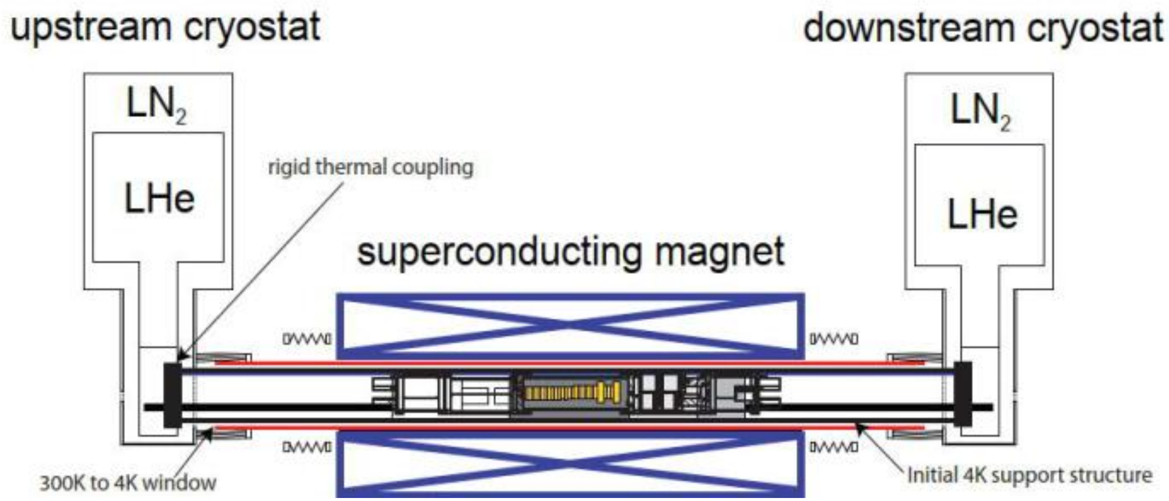


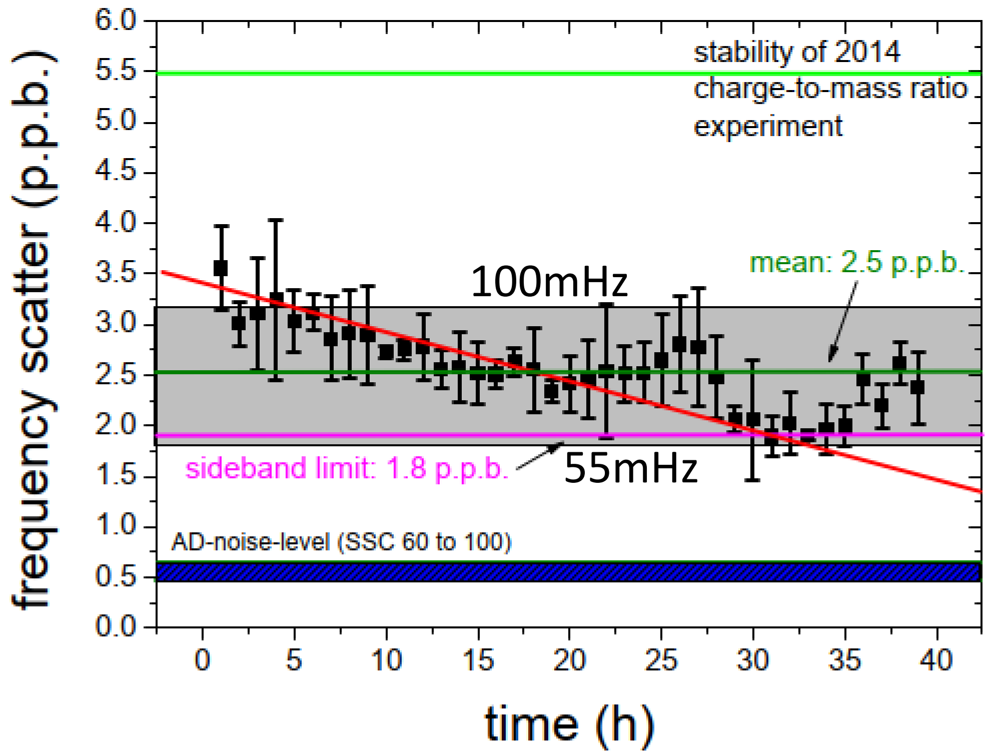
achieved a cyclotron-rms-scatter of 2.4 p.p.b. while we expect 1.8 p.p.b.

Cryoliquids

- Magnetic field fluctuations induced by boiling of cryoliquids
  - boiling shakes on the apparatus…
  - …this induces eddy currents…
  - …and thus, magnetic field fluctuations.

- Rough amplitude estimate: **40um**.

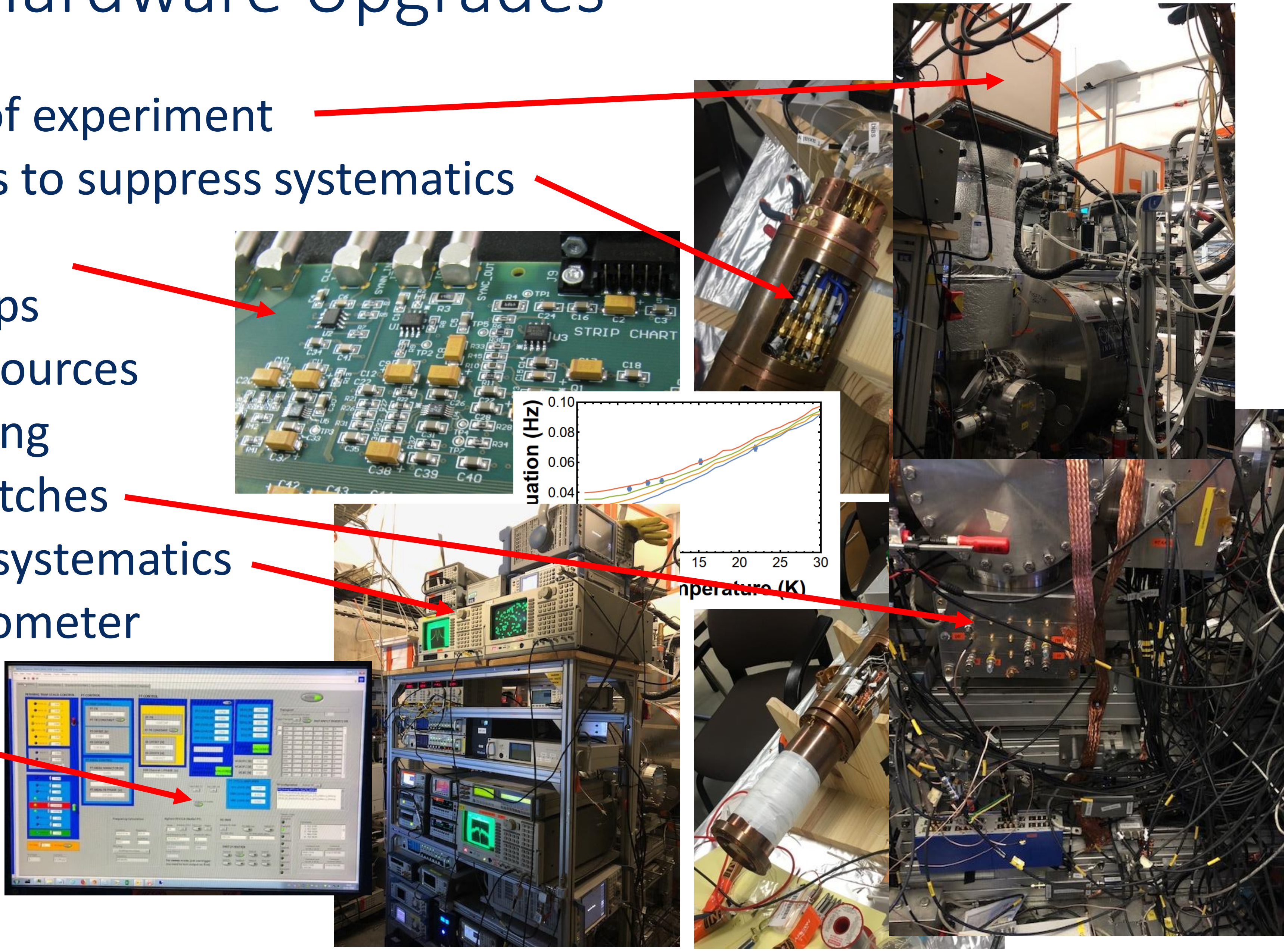




Still, this experiment is > 2 times more stable than the 2014 apparatus.

Additional Hardware Upgrades

- New thermal isolation of experiment
- Tuneable axial detectors to suppress systematics
- New SSB converters
- SSB based feedback loops
- Battery biased voltage sources
- Voltage reference tracking
- New high insulation switches
- Parallel FFT-routing for systematics
- Superconducting seismometer
- New logger system
- Revised control system
- …etc….



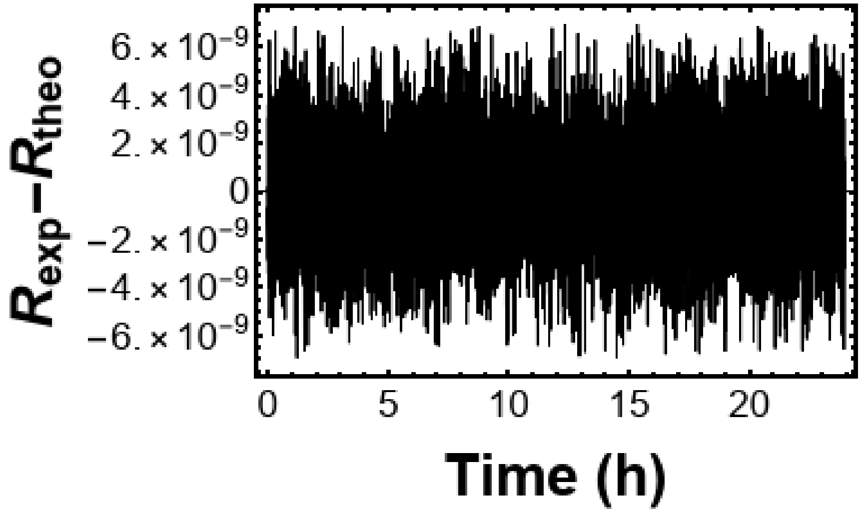
Some Preliminary Results

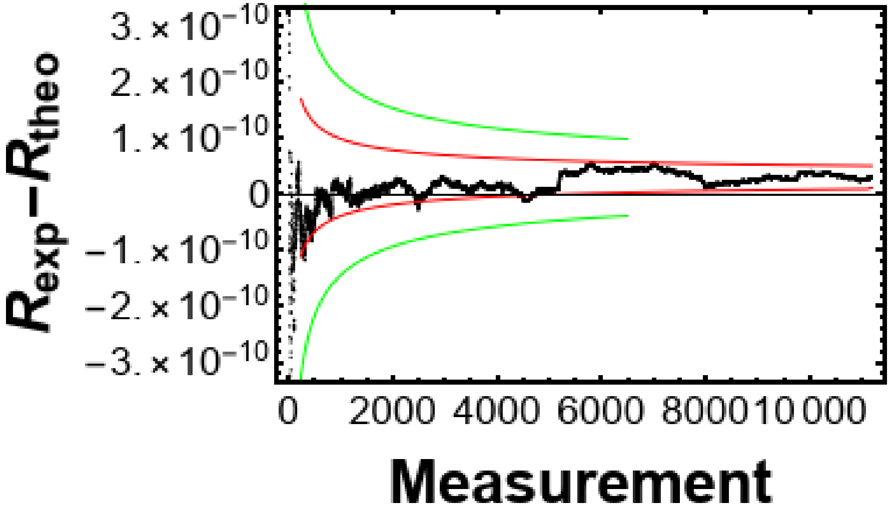
- Data-set:
  - 11500 measurements in 6 weeks
  - average scatter: 2.4 p.p.b.

  Naïve statistical precision: 22.4 p.p.t (660uHz)
  Systematics: in progress.

- Requires detailed analysis and careful systematic studies (on going).

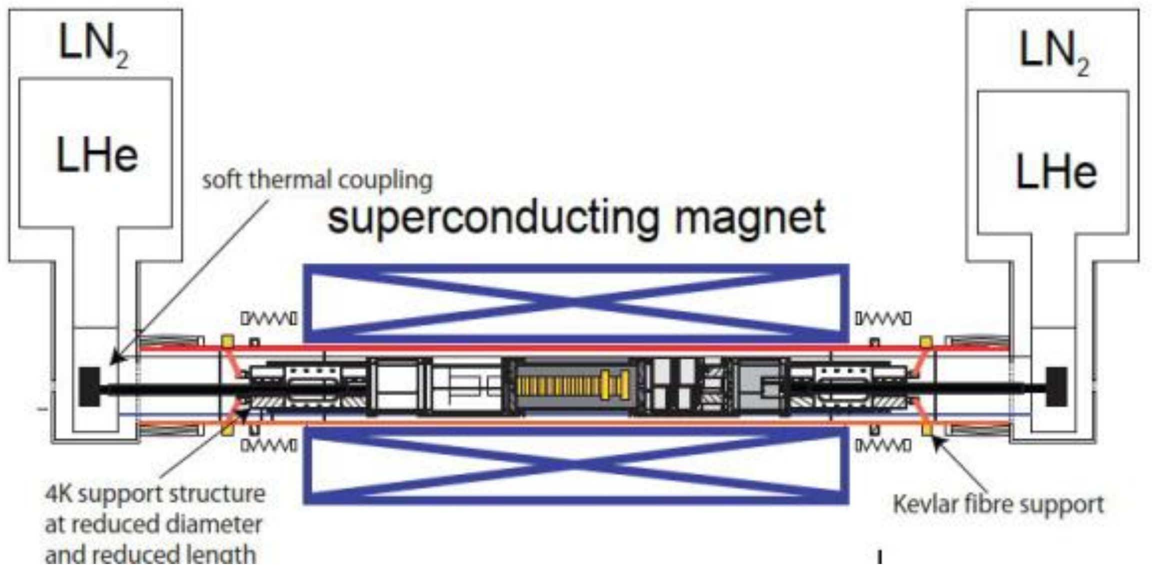
Compare to 7000 ratios at 5.5 p.p.b. in 2014 run.

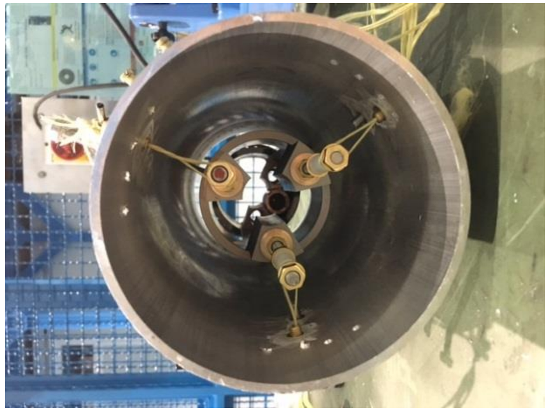




J. Harrington
MPIK/RIKEN

Mechanical Upgrade of the Apparatus

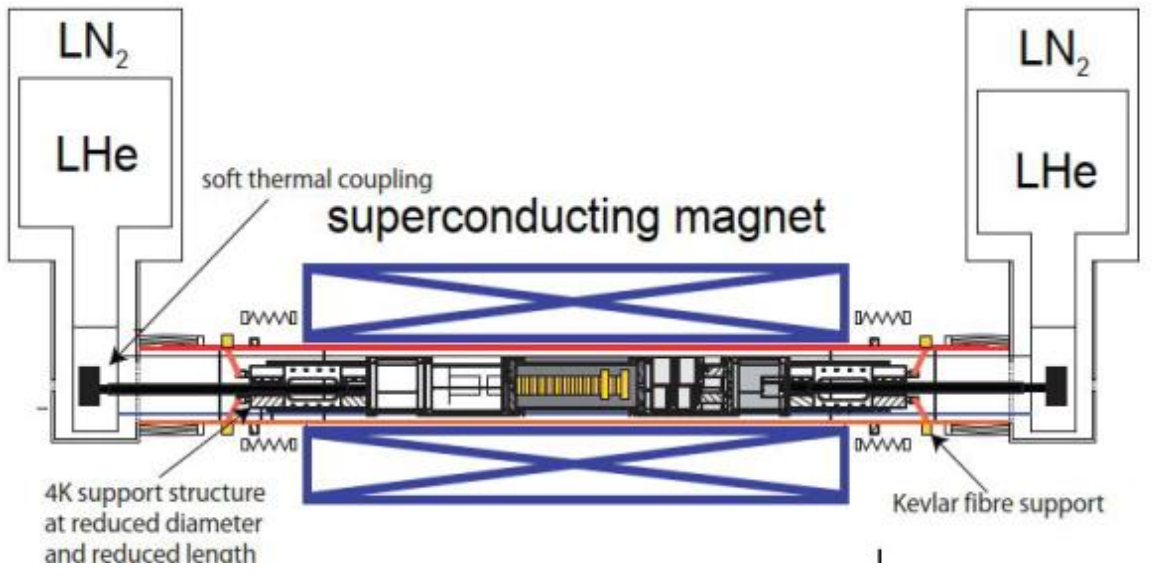


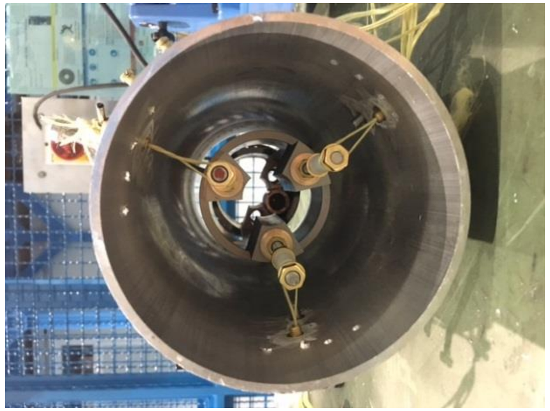


High Risk ! – High Gain ?

- Idea:
  - Reduce the surface of the 4K stage.
  - Support apparatus inside the magnet using Kevlar fibres.
  - Get rid of 300K to 4K windows
- Intention
  - Reduce boil-off rate
  - Decouple trap from cryostats

Mechanical Upgrade of the Apparatus





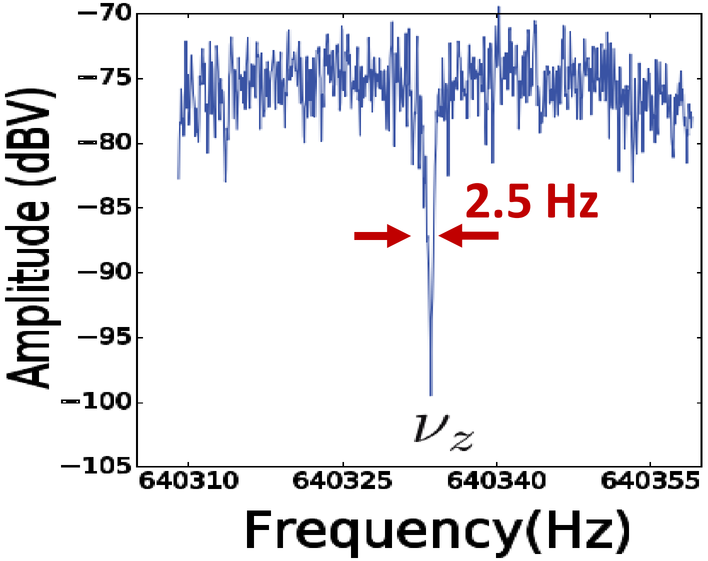
Results

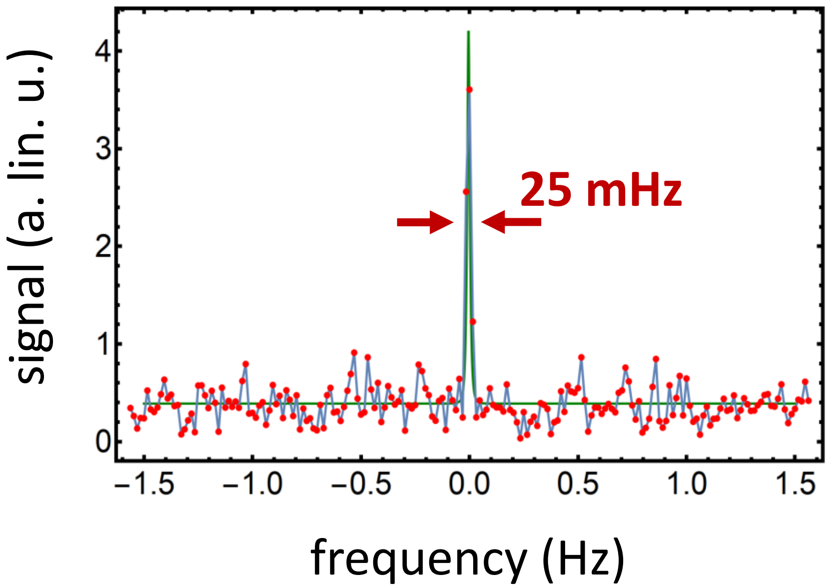
- Cryoliquid consumption rate reduced by a factor of > 2.
- Temperature of experiment reduced from 6.2K to 4.8K.
- Reduces the power of the mechanism which is driving the vibrations.

How about the cyclotron frequency stability ?

"Re-Discovered" Cyclotron Peak Measurement Method

Need new measurement method to resolve improved frequency scatter, used peak method applied in "old" Penning trap experiments (Dehmelt / Werth / Gabrielse / …others)



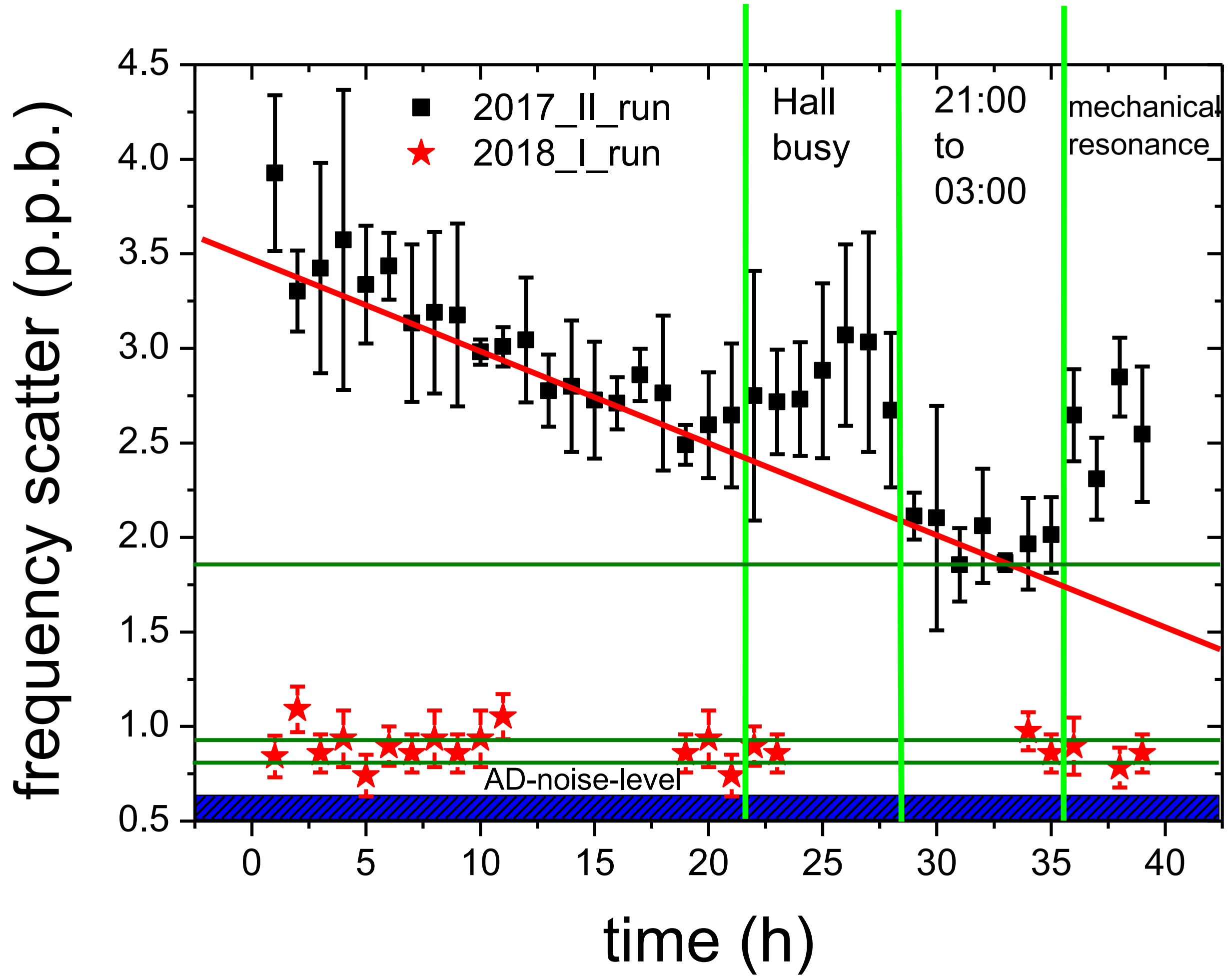


- Low shot-to-shot resolution (2 p.p.b.)
- Low systematics

- High shot-to-shot resolution (0.2 p.p.b.)
- Considerable systematics (1eV – 1 p.p.b.)

Find methods to use this technique

Improved Frequency Scatter



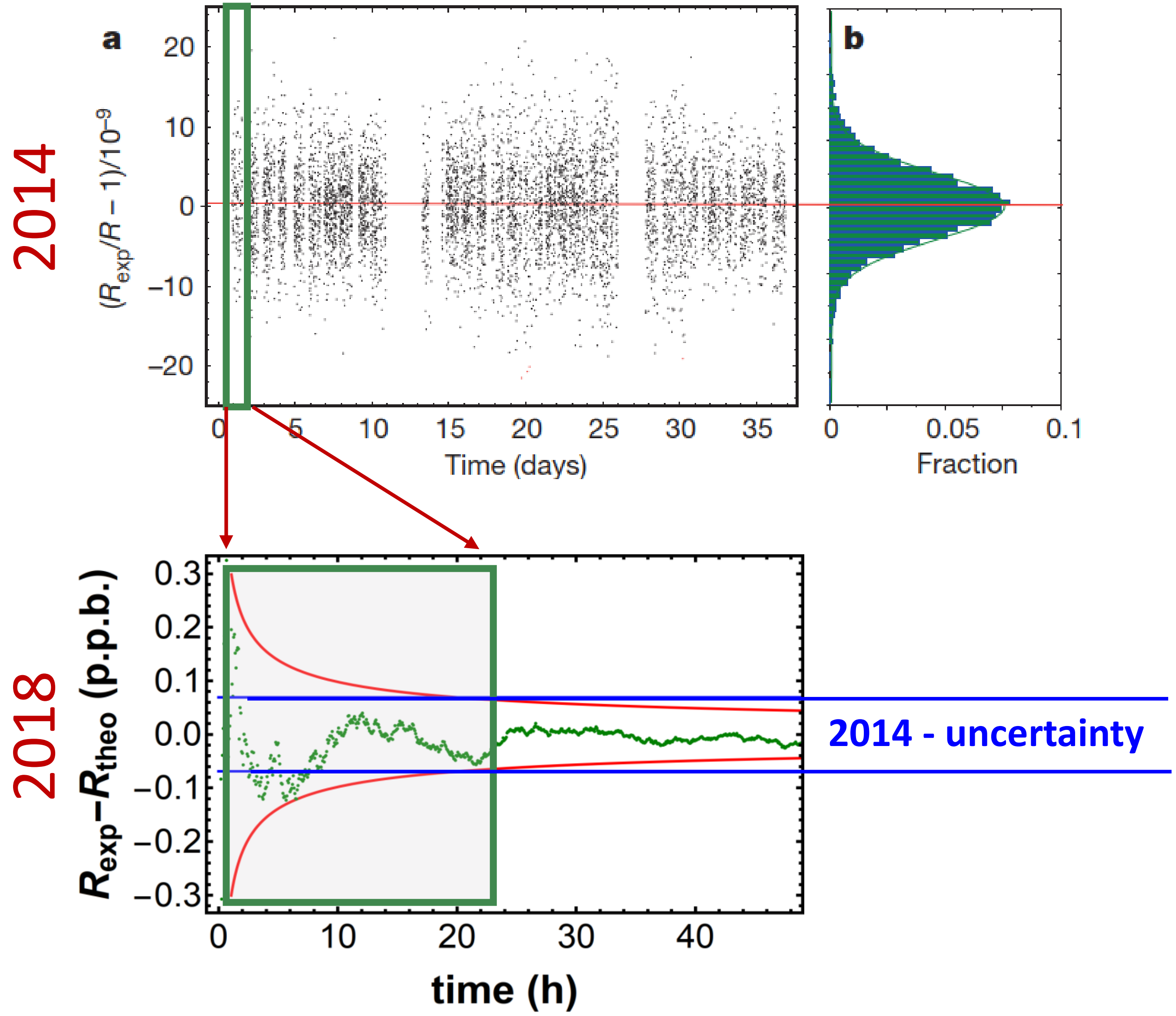
Drastically reduced scaling with cryostat filling level.

Clearly reduced frequency fluctuation

(being between 0.6 p.p.b. and 1.25 p.p.b., currently under invstigation)

Comparably **risky strategy paid back**, BASE has never been in better shape

Comparison 2014 run / 2018 run

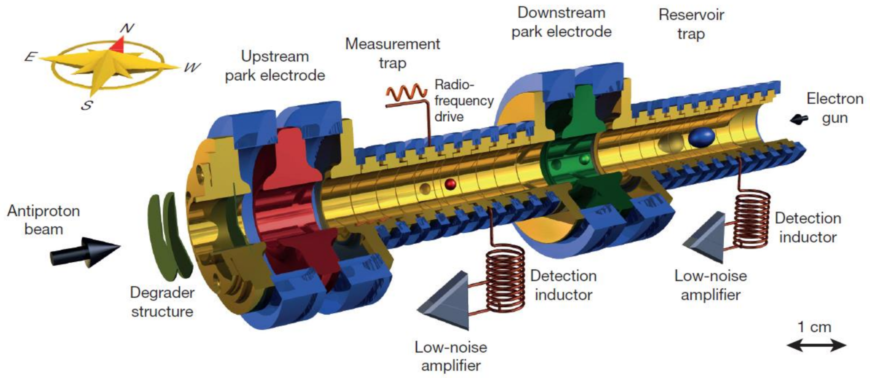


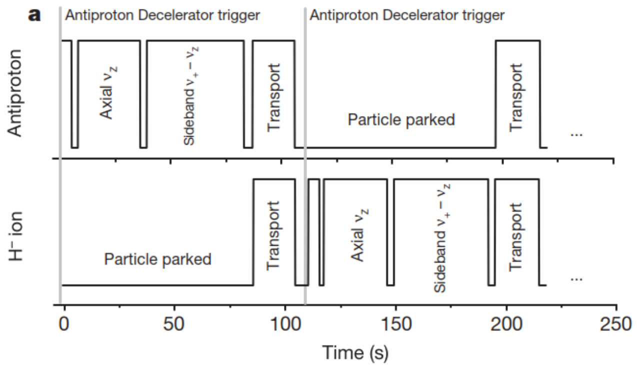
- **In practical experimental units:** statistical precision of 2014 measurement (40 days) is now reached within 24h of data accumulation

- **Current projects:** Investigate and understand frequency stability at this improved resolution **to come up with a considerably improved instrument after LS2**

Peak Method Useful for BASE?

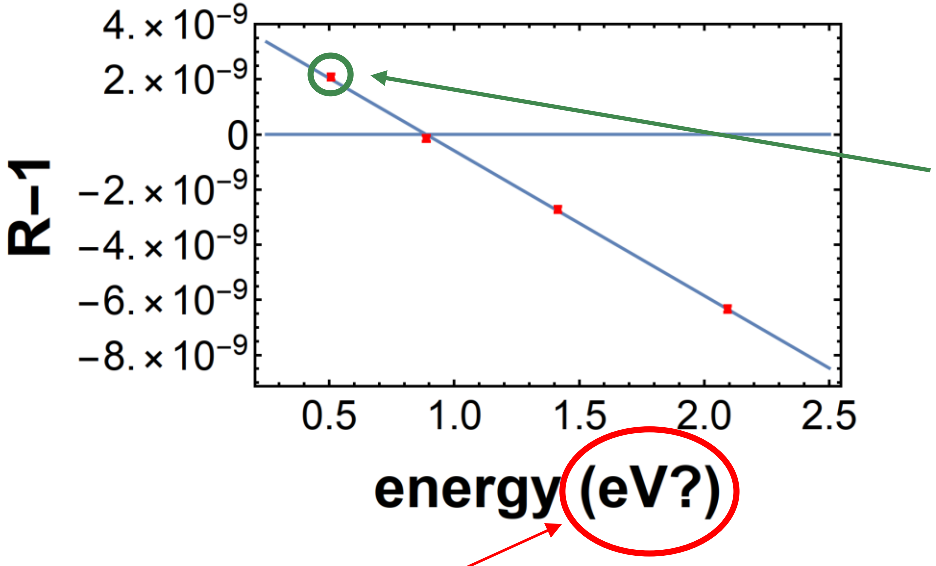
- Method has been used in previous trap experiments by Dehmelt / Werth / Gabrielse…
- Can we combine this method with the special features and advantages of BASE?





Strength of BASE: We sample about 50 times faster than almost all other mass spectrometers.

Use identical particles and measure ratio as a function of energy.

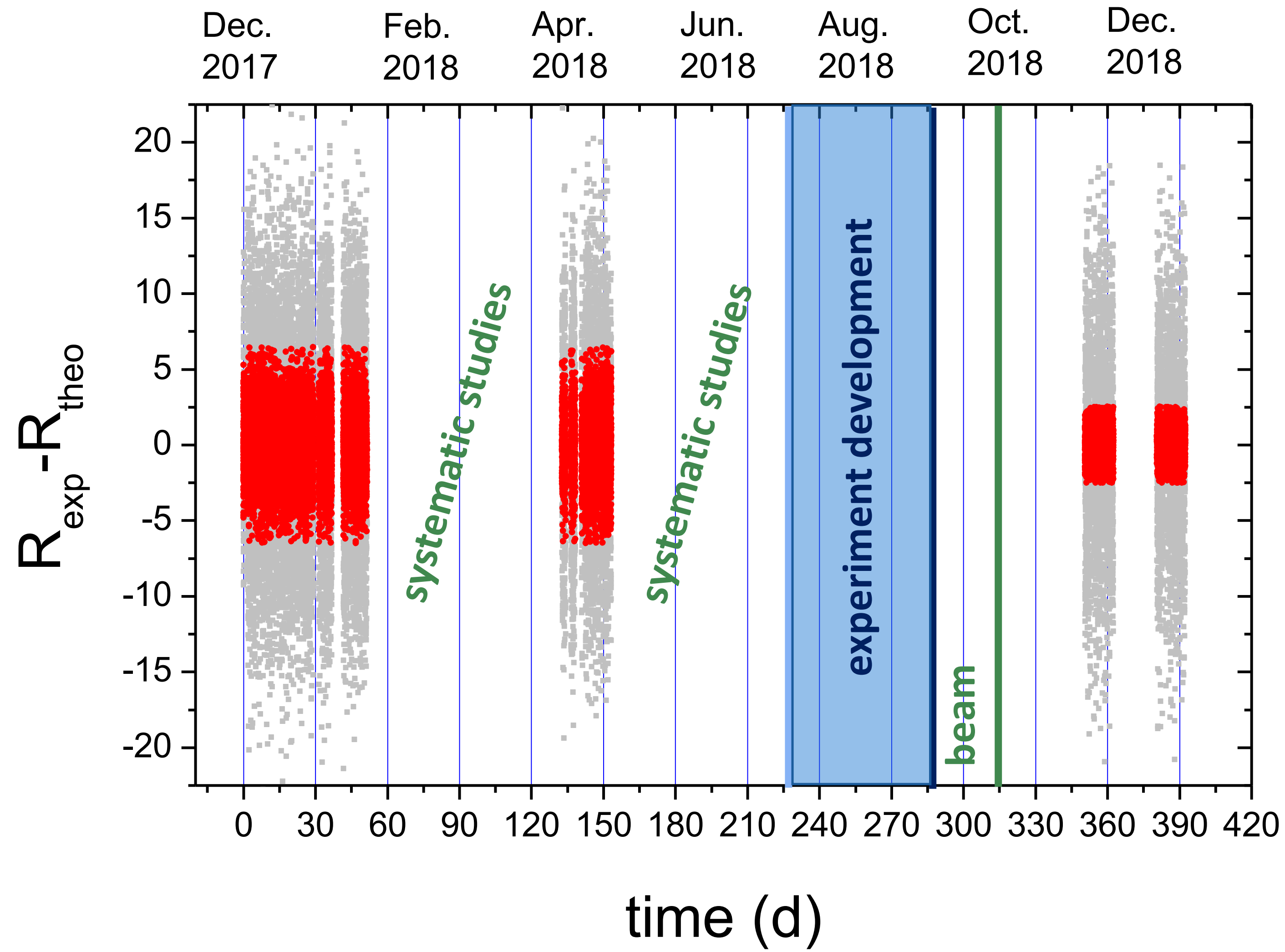


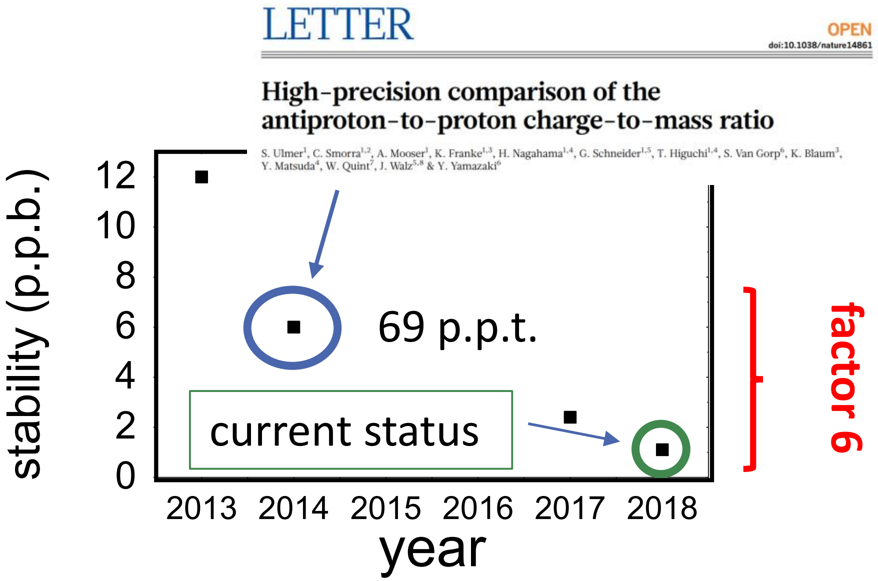
each of these points has a fractional resolution better than 70 p.p.t.

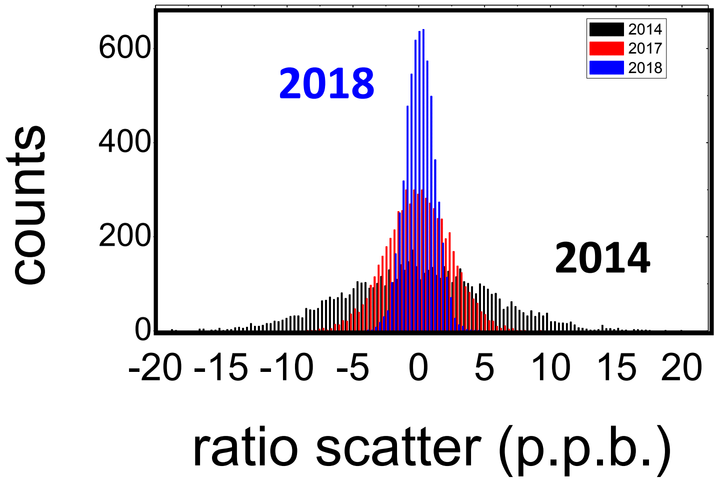
Need to get that resolved and under control.

Green light for next measurement campaign.

BASE 2018 – 80% of all Available Data



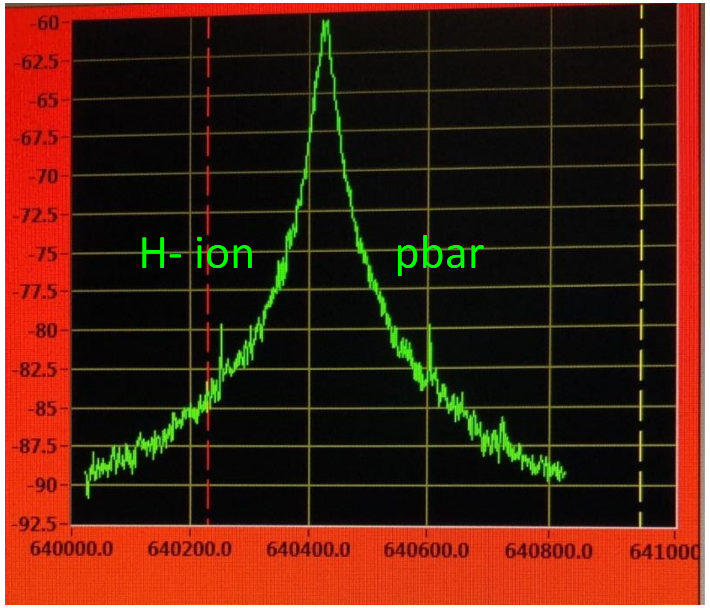




Plan to finalize the data analysis and systematic studies before 2019/06.

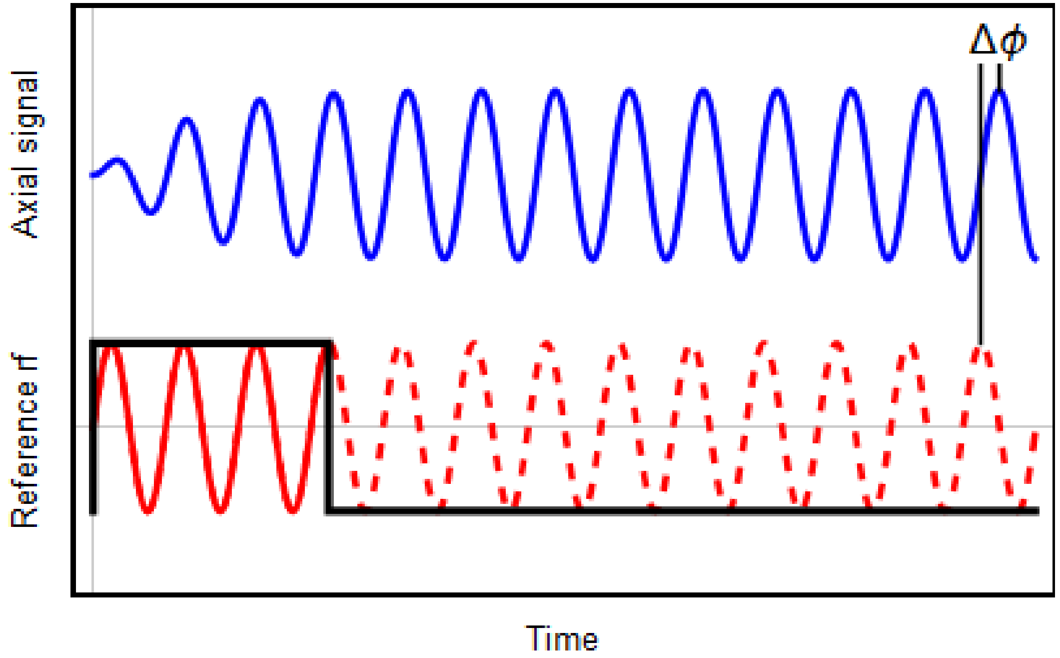
What's next?

- Work on simultaneous measurements on two particles in one trap.



- Magnetic field fluctuations cancel.
- Adds other systematics.
- Fun method, but obviously challenging.

- Implement phase sensitive detection methods.

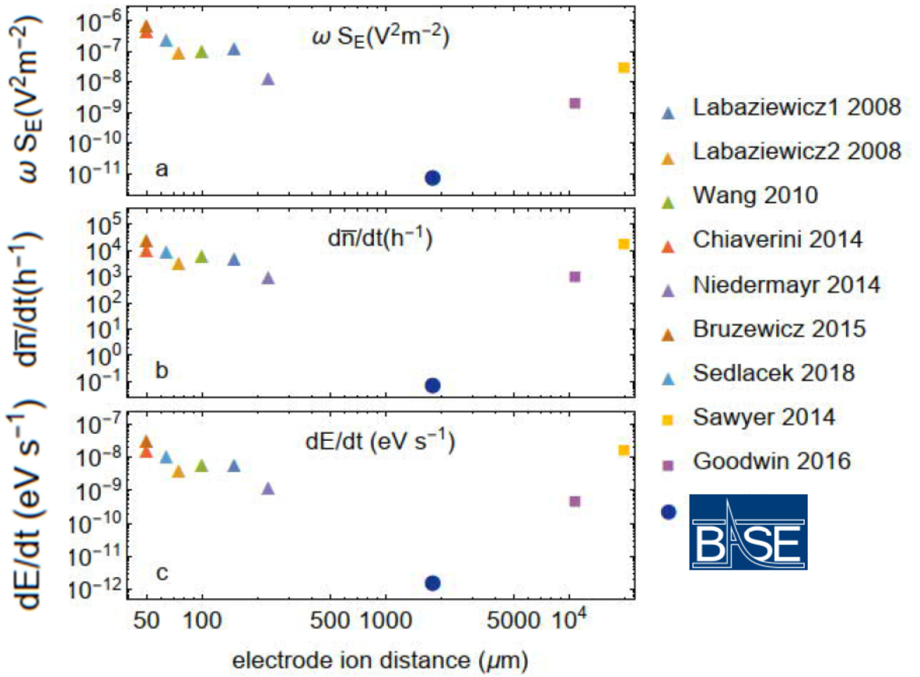


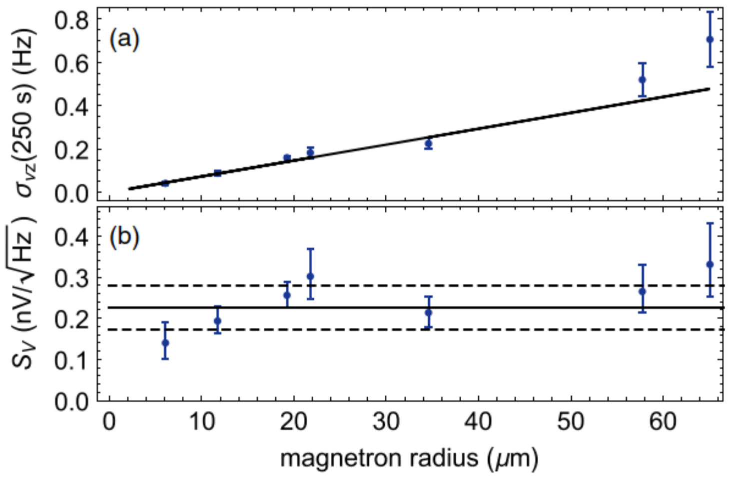
- Frequency scatter in phase methods scales as 1/T (rather than $T^{-0.5}$)
- Phase resolution will likely be limited by trap errors – new trap design in the pipe.

Sideproject – Heating Rate Measurements in BASE

- Relevance: Parasitic heating in traps…
  - … induces decoherence in ion-based quantum computers
  - … reduces detection fidelities in spin-flip experiments

- **Our motivation:** Understand scaling law of heating rate and translate this to further improve spin state detection fidelity.





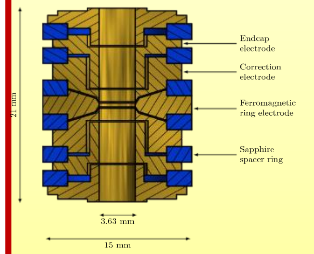
- **Our conclusion:** Improve spin-flip electronics.
- Expect drastically improved temperature acceptance in future runs

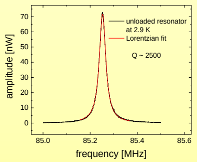
M. Borchert
Hannover/RIKEN

M. Borchert, accepted manuscript (2019)

Other Projects Developed in Parallel

Implementation of a Cooling Trap for Improved Moment Measurements

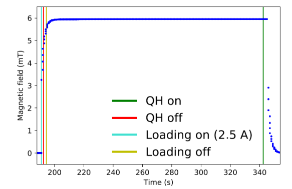




10-fold faster moment measurement cycles

P. Blessing
GSI & RIKEN

Development of Local Tuning Magnets for measurement at Higher Presision

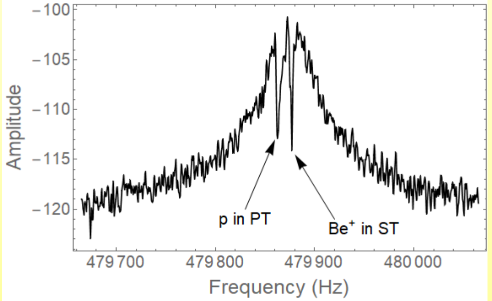


Persistent mode coils deveoped, charging switches finalized

Full gradient compensation demonstrated

J. Hansen
RIKEN

Be/p trapping in Mainz Laser Experiment Demonstrated

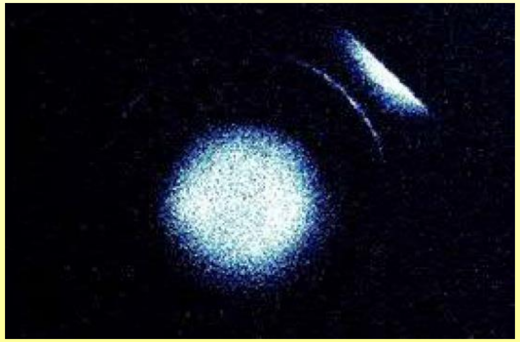


C. Smorra
RIKEN

M. Bohman
RIKEN/MPIK

M. Wiesinger
RIKEN/MPIK

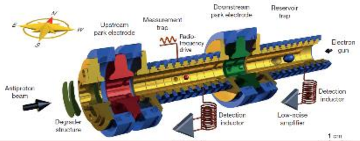
Be trapping in Hannover Experiment Demonstrated

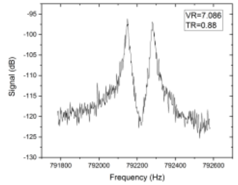


For Quantum Logic Spectroscopy on Single trapped Protons and Antiprotons

Clear Strategy for developments in LS2 to Perform Measurements at Improved Precision After LS 2

Summary BASE - Timeline 2018





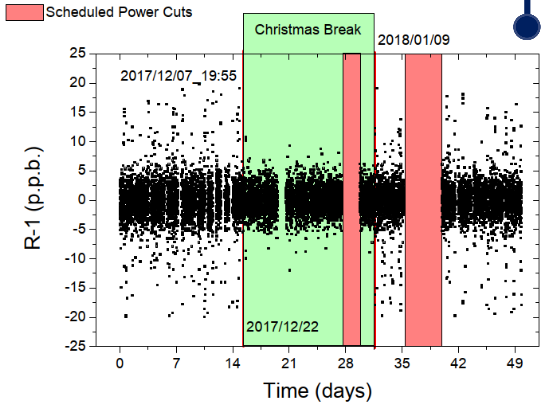
Centre for Time, Constants and Fundamental Symmetries
APPROVED

New Method

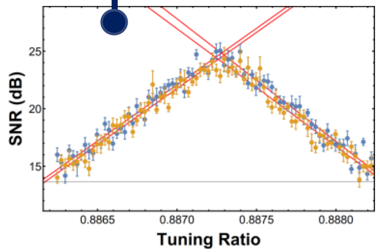
beam

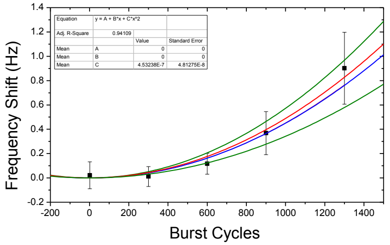
Preparation	Measurement Campaign	Systematics	Measurement	Software Upgrade	Experiment Upgrade	Systematics	Measurement Campaign

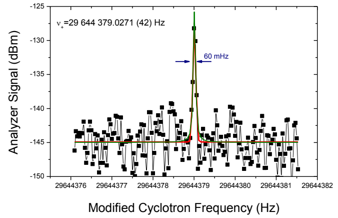
17/10 — 18/01 — 18/03 — 18/06 — 18/09 — 18/12 — 19/01

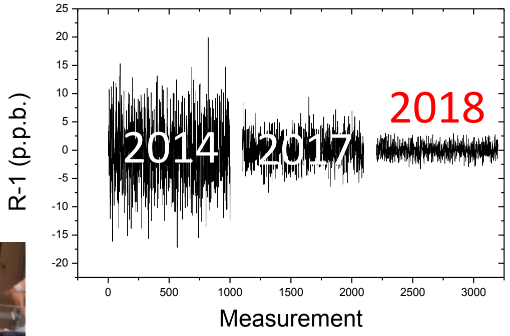


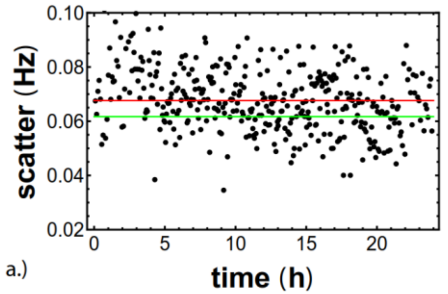
R_{exp}-R_{theo}=0.000 000 000 023 (19)

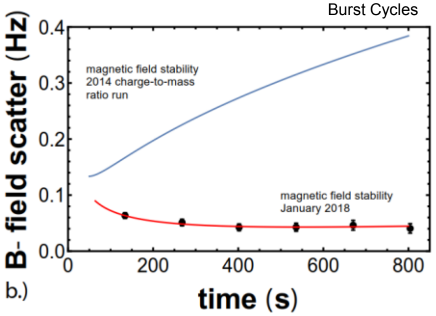


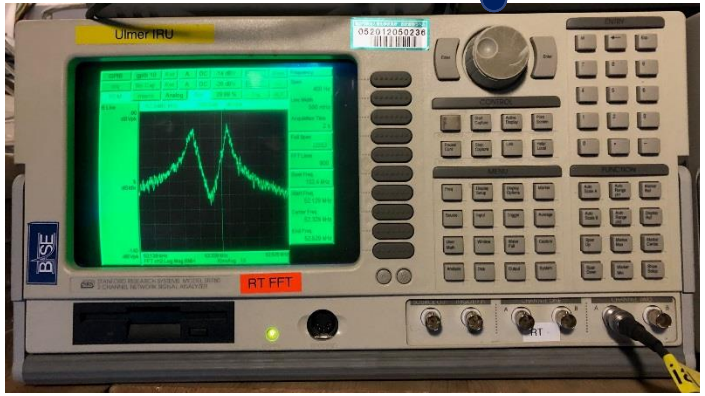






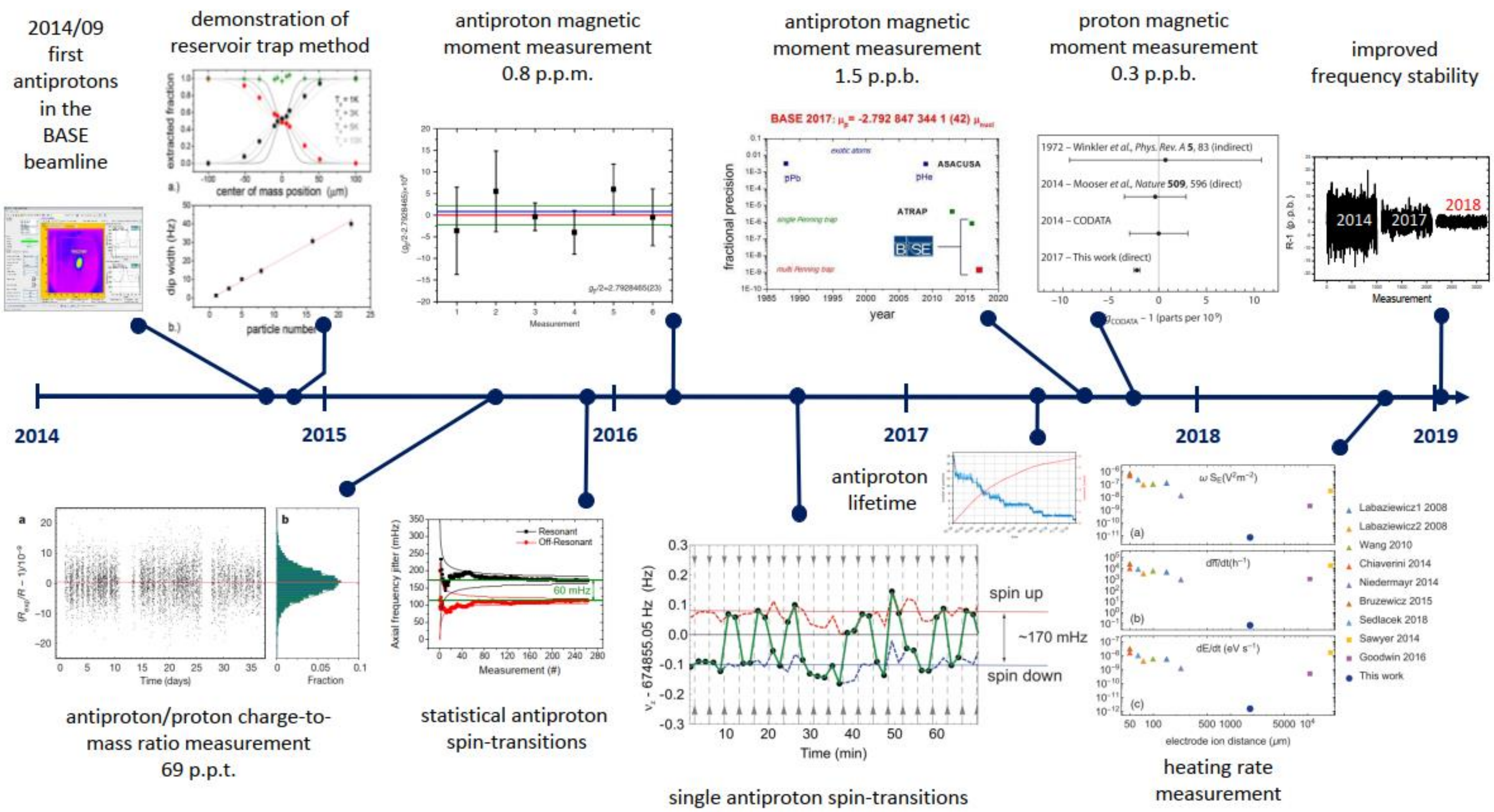






Summary LS1 to LS2 window

- BASE was approved in 2013 and took first beam in 2014, first shot after LS2



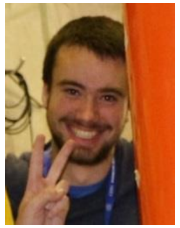
Thanks for your attention!


S. Ulmer
RIKEN


J. Devlin
RIKEN


E. Wursten
CERN / RIKEN


J. Harrington
RIKEN & MPIK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P. Blessing
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J. Hansen
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J. Morgner
Hannover / RIKEN


C. Nguyen
RIKEN/Hannover


C. Smorra
RIKEN


M. Bohman
RIKEN/MPIK


M. Wiesinger
RIKEN/MPIK

RIKEN

Programs for Junior Scientists

MAX-PLANCK-GESELLSCHAFT

CERN

東京大学 THE UNIVERSITY OF TOKYO

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

PTB

Leibniz Universität Hannover

GSI

Thanks very much to CERN for supporting us with two research fellowships (Devlin & Wursten)

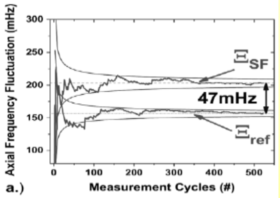
K. Blaum, Y. Matsuda,
C. Ospelkaus, W. Quint,
J. Walz, Y. Yamazaki

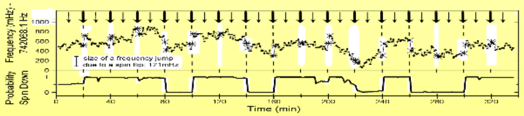
Previous Achievements

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

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

Observation of spin flips with a single trapped proton

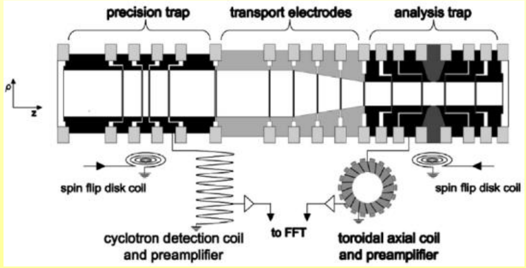




S. Ulmer, et al., **PRL 106, 253001 (2011)**

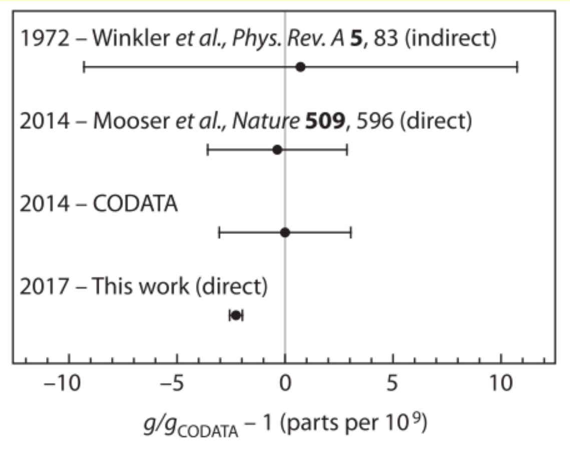
A. Mooser, et al., **PRL 110, (2013)**

Application of the double Penning-trap technique



A. Mooser, et al., **PLB 723, 78 (2013)**

Most precise proton g-factor measurment



g/2 = 2.792 847 350 (9)

A. Mooser *et al.*, Nature **509**, 596 (2014).

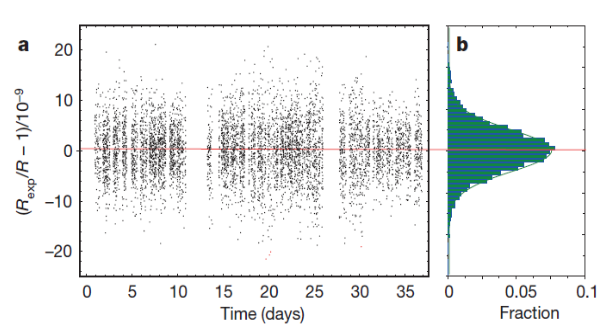
First direct high precision measurement of the proton magnetic moment.

g/2 = 2.792 847 344 62 (82)

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

Precise CPT test with baryons

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

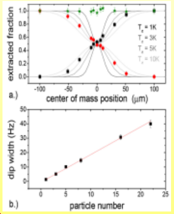


$$1+\frac{(q/m)_{\bar{p}}}{(q/m)_{p}} = 1(69)\times 10^{-12}$$

$R_{exp,c}$ = 1.001 089 218 755 (64) (26)

To be improved by another factor of 10 to 100

Reservoir trap for antiprotons



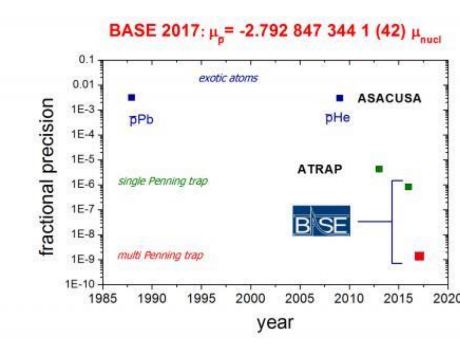
C. Smorra, et al., **Int. Journ. Mass Spec. 389, 10 (2015).**

Idea: Enable operation with antiprotons independent of accelerator run times.

Most precise antiproton g-factor measurment

H. Nagahama, et al., Nature Comms. **8, 14084 (2017)**

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



g/2 = 2.792 846 5 (23)

Sixfold improvement compared to previous measurement

g/2 = 2.792 847 344 1 (42)

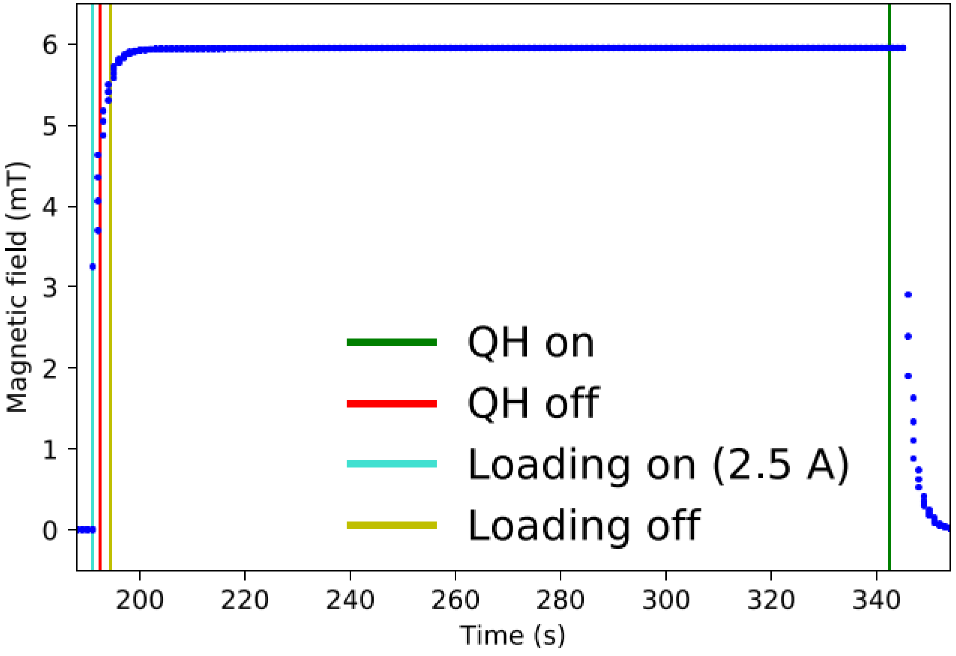
350-fold improvement compared to previous measurement

Also see poster by **M. Wiesinger** and related talk by **A. Mooser**

Partly comparable work by J. DiSciacca, G. Gabrielse et al.. (ATRAP/TRAP collaboration)

Local Magnets

- future measurements will target p.p.t. level.
- In that case: need local B-field tuning for systematic studies



–	E_+/K	E_z/K	E_-/K
SR Shift Cyclotron	-9.18426×10^{-14}	-4.59213×10^{-14}	-4.28689×10^{-17}
SR Shift Axial	-4.59213×10^{-14}	-3.4441×10^{-14}	-1.07172×10^{-17}
SR Shift Magnetron	4.28689×10^{-17}	1.07172×10^{-17}	5.00242×10^{-21}

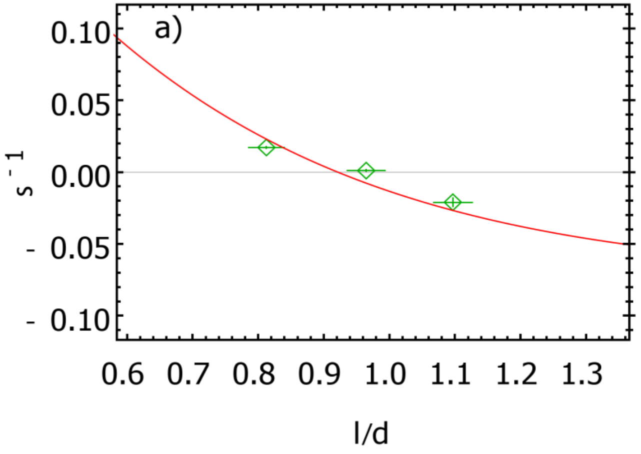
–	E_+/K	E_z/K	E_-/K
B2 Shift Cyclotron	3.26746×10^{-14}	-7.00022×10^{-11}	1.40004×10^{-10}
B2 Shift Axial	-7.00022×10^{-11}	0	-7.00022×10^{-11}
B2 Shift Magnetron	1.40004×10^{-10}	-7.00022×10^{-11}	1.40004×10^{-10}

–	$E_+/(K*mUnit)$	$E_z/(K*mUnit)$	$E_-/(K*mUnit)$
C4 Shift Cyclotron	-1.15388×10^{-14}	4.94417×10^{-11}	-9.88835×10^{-11}
C4 Shift Axial	4.94417×10^{-11}	-5.29622×10^{-8}	2.11849×10^{-7}
C4 Shift Magnetron	9.88835×10^{-11}	-2.11849×10^{-7}	2.11849×10^{-7}

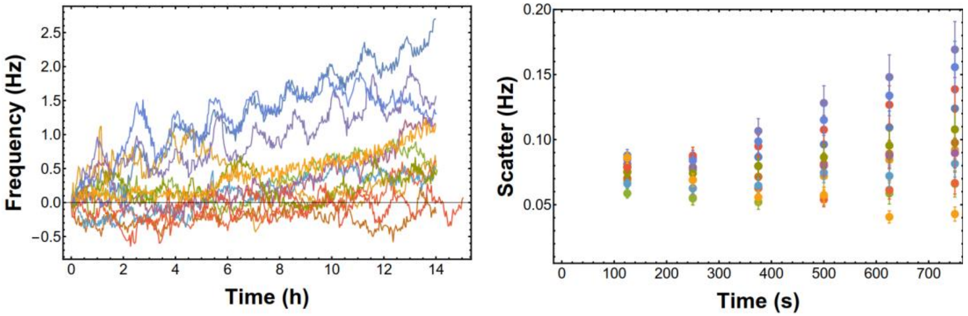
- developed methods to reliably produce persistent joints and
- methods to produce superconducting to normal conducting loading transitions

J. Hansen
RIKEN

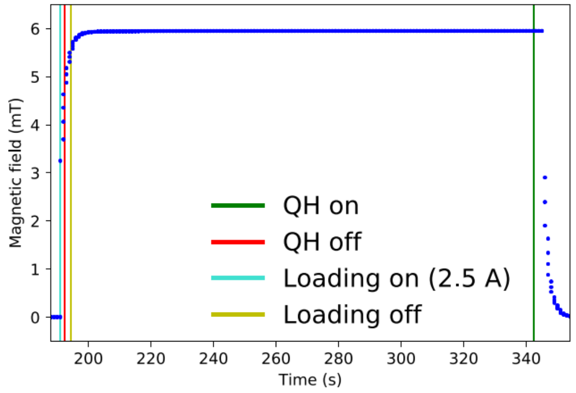
Clear Strategy for developments in LS2



Based on 2018 measurements with tunable coil system: develop an improved magnetic shielding system.

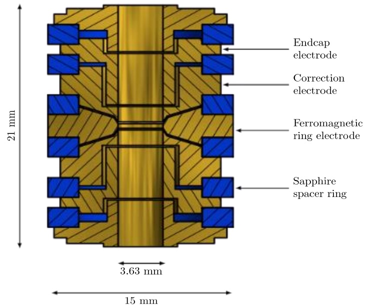


- Further decouple BASE from the AD hall.
- Long term: Move out of the hall

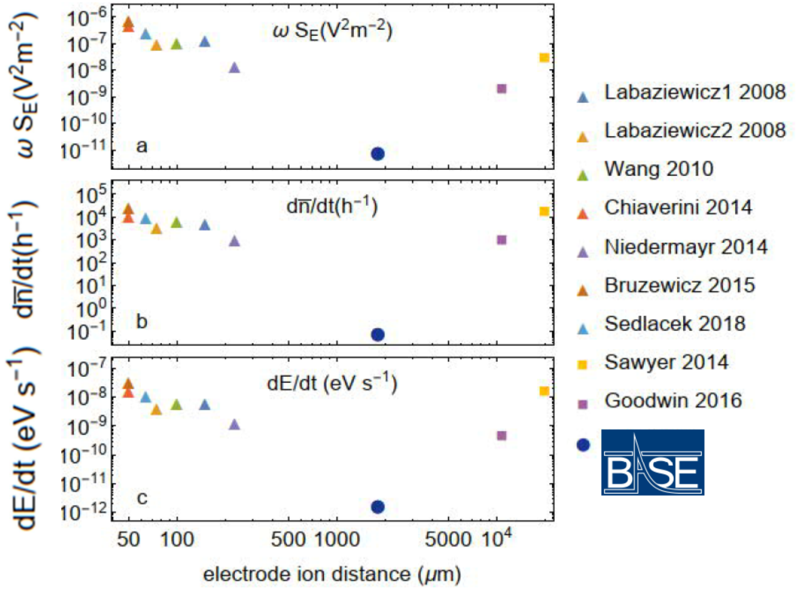


- For measurements at p.p.t. precision: Implement local tuning coils.

- Improved concept for spin state detection



- Will get new and improved traps prepared (CT / 7-pole PT / 2-g-AT) to focus on p.p.t. level after LS2



Center for Time, Constants, and Fundamental Symmetries

Directors of Center

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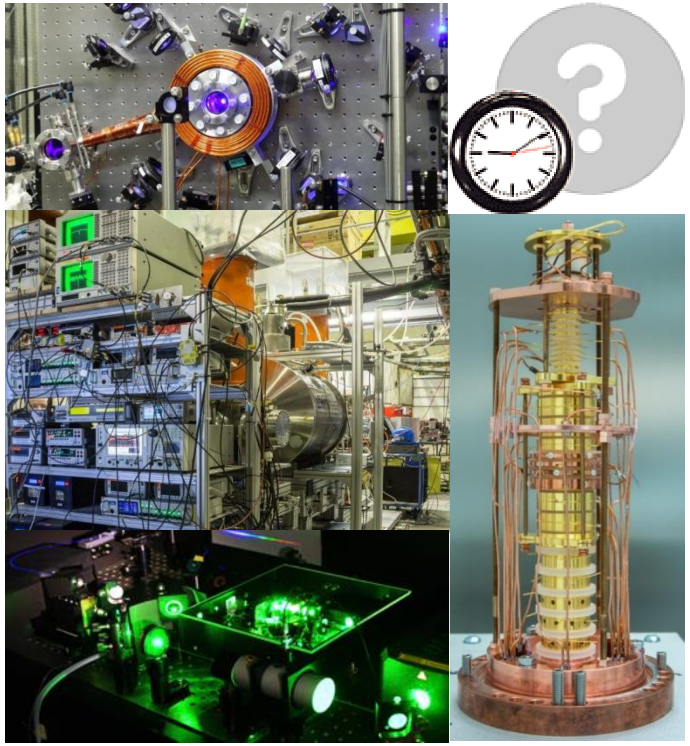
RIKEN
„Quantum Metrology Laboratory“

Dr. Stefan Ulmer
RIKEN
„Fundamental Symmetries Laboratory“

Prof. Dr. Klaus Blaum
MPI for Nuclear Physics
„Stored and Cooled Ions“

Prof. Dr. Dr. h.c. mult. Theodor Hänsch
MPI for Quantum Optics
„Laser Spectroscopy & Quantum Physics“

PD Dr. Ekkehard Peik
PTB
„Time and Frequency“



RIKEN – MAX PLANCK
JOINT RESEARCH CENTER

- **BASE achievements critically important in the approval procedure**
- Secures funds for BASE to
  - develop **transportable antiproton traps**
  - implement **sympathetic cooling** experiment by coupling antiprotons to laser-cooled Be ions

&

PRECISION MEASUREMENT

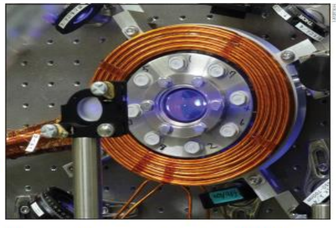
German–Japanese centre to focus on precision physics

On 1 January a new virtual centre devoted to some of the most precise measurements in science was established by researchers in Germany and Japan. The Centre for Time, Constants and Fundamental Symmetries will offer access to ultra-sensitive equipment to allow experimental groups in atomic and nuclear physics, antimatter research, quantum optics and metrology to collaborate closely on fundamental measurements. Three partners – the Max Planck Institutes for nuclear physics (MPI-K) and for quantum optics (MPQ), the National Metrology Institute of Germany (PTB) and RIKEN in Japan – agreed to fund the centre in equal amounts with a total of around €7.5 million for five [illegible] of matter and antimatter, namely C, P and T invariance, which have not yet shown up, even though such differences intrinsically must exist, otherwise the universe would consist of almost pure radiation. Closely related to these tests of fundamental symmetries is the search for physics beyond the Standard [illegible]. The broad research portfolio also includes the development of novel optical clocks based on atoms, nuclei and highly charged ions.

[illegible] fascinating that nowadays manageable laboratory experiments make it possible to investigate such fundamental questions in physics and cosmology by means of their high precision", says Klaus Blaum of MPI-K.

Stringent tests of fundamental interactions and symmetries using the protons and antiprotons available at the BASE experiment at CERN are another key aspect of the German–Japanese initiative, explains Stefan Ulmer, co-director of the centre, chief scientist at RIKEN, and spokesperson of the BASE experiment: "This centre will strongly promote fundamental physics in general, in addition to the research goals of BASE. Given this support we are developing new equipment to improve both the precision of the proton-to-antiproton charge-to-mass ratio as well as the proton/antiproton magnetic moment comparison by factors of 10 to 100."

To reach these goals, the researchers intend to develop novel experimental techniques – such as transportable antiproton traps, sympathetic cooling of antiprotons by laser-cooled beryllium ions, and optical clocks based on highly charged ions and thorium nuclei – which will outperform contemporary methods and enable measurements at even shorter time scales and with improved sensitivity. "The combined precision-physics expertise of the individual groups with their complementary approaches and different methods using traps and lasers has the potential for substantial progress," says Ulmer. "The low-energy, ultra-high-precision investigations for physics beyond the Standard Model will complement studies in particle physics."



On time *A lattice clock at RIKEN, one of the partners of the new Centre for Time, Constants and Fundamental Symmetries.*

CERN COURIER JANUARY/FEBRUARY 2019 11