Max-Planck-Institut für Kernphysik

Towards a Mass-Ratio Measurement of Tritium and Helium-3 at THe-Trap

Tom Segal, IMPRS Seminar, 03.07.2017 Heidelberg

Max-Planck-Gesellschaft

Penning Traps - Motivation

Chemistry: identification of molecules	$10^{-5} - 10^{-6}$
Nuclear physics: shells, sub-shells, pairing	10^{-6}
Nuclear fine structure: deformation, halos	$10^{-7} - 10^{-8}$
Astrophysics: r-process, rp-process, waiting points	10^{-7}
Nuclear mass models and formulas: IMME	$10^{-7} - 10^{-8}$
Weak Interaction studies: CVC hypothesis, CKM unitarity	10^{-8}
Atomic physics: binding energies	QED $10^{-9} - 10^{-11}$
Metrology: fundamental constants	CPT $< 10^{-10}$

Introduction to Penning Traps

The Axial Frequency

$$\omega_z = \sqrt{\frac{qV}{md^2}}$$

The Reduced Cyclotron (+) & Magnetron (-) Frequencies

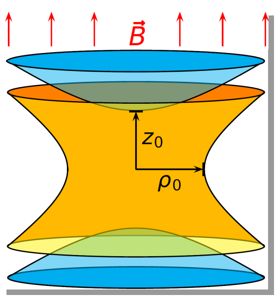
$$\omega_\pm = \frac{\omega_c \pm \sqrt{\omega_c^2 - 2\omega_z^2}}{2}$$

The Invariance Theorem (Brown and Gabrielse, PR 1982)

$$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$$

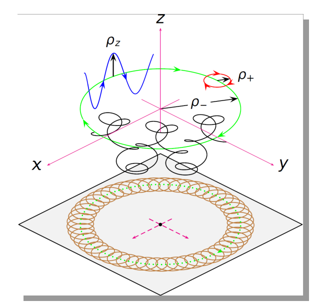
The Cyclotron Frequency

$$\omega_c = \frac{q}{m} B$$



$$\Phi(\rho,z) = \frac{V_0}{Z_0^2 + \frac{1}{2}\rho_0^2}\left(z^2 - \frac{1}{2}\rho^2\right)$$

$$d = \frac{\sqrt{2z_0^2 + \rho_0^2}}{2}$$



q - elementary charge , V - electric potential, m - ion mass ,
z_0 – height parameter , ρ_0 – radius parameter

The Trap:

B = 5.7T, V = -90V, $z_0 \sim \rho_0 \sim d \sim 2.54$mm

$\omega_+ \sim 29MHz$, $\omega_z \sim 4MHz$, $\omega_- \sim 300kHz$,

Real Penning Traps

- Particle Interactions
- B & E misalignment*
- E ellipticity*
- Cylindrically symmetric E and B imperfections.*
- Relativity
- Image charges

* Cancelled out by Gabrielse's Invariance Theorem

Motivation 1 – The Neutrino Mass

Measuring the Q-Value in the beta decay of $^{3}H \rightarrow {}^{3}He^{+}$. This will aid KATRIN [1] in **measuring the electron anti-neutrino's mass** $m_{\bar{\nu}_e}$.

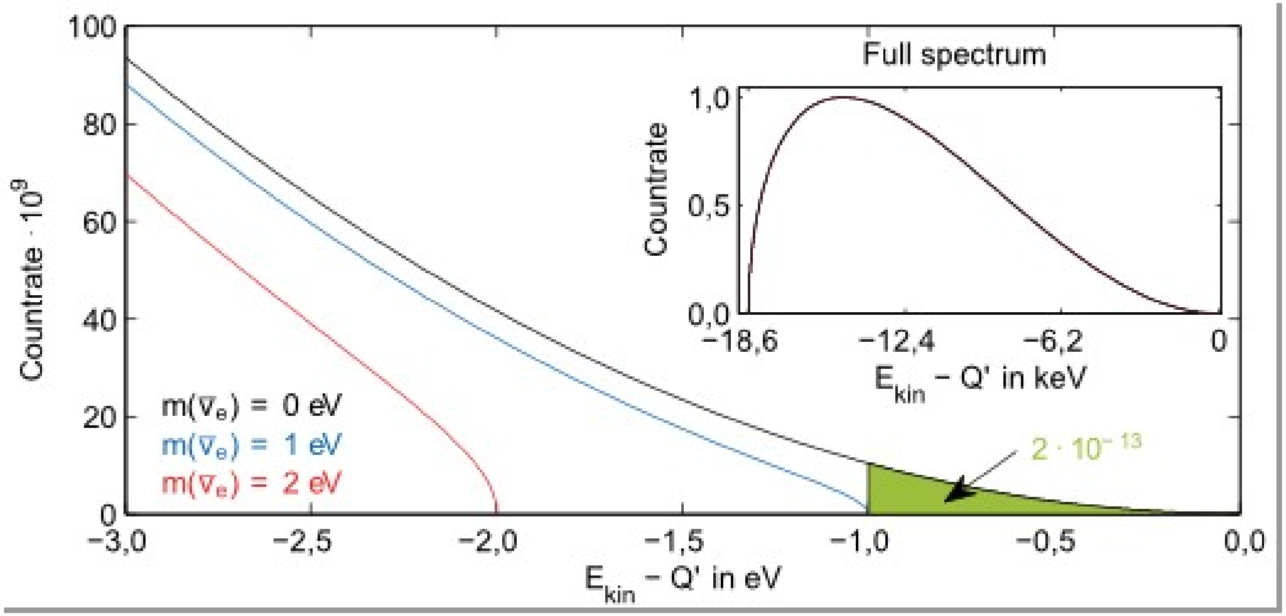
Measuring the Q-Value in the beta decay of $^{3}H \rightarrow {}^{3}He^{+}$. This will aid KATRIN [1] in **measuring the electron anti-neutrino's mass** m.

$^{3}H \rightarrow {}^{3}He^{+} + e^{-} + \bar{\nu}_e$ +Q-value

$Q \approx (m_{3H} - m_{3He}) \cdot c^2 = 18.6\,keV$

$^{3}H \rightarrow {}^{3}He^{+} + e^{-} + $ +Q-value

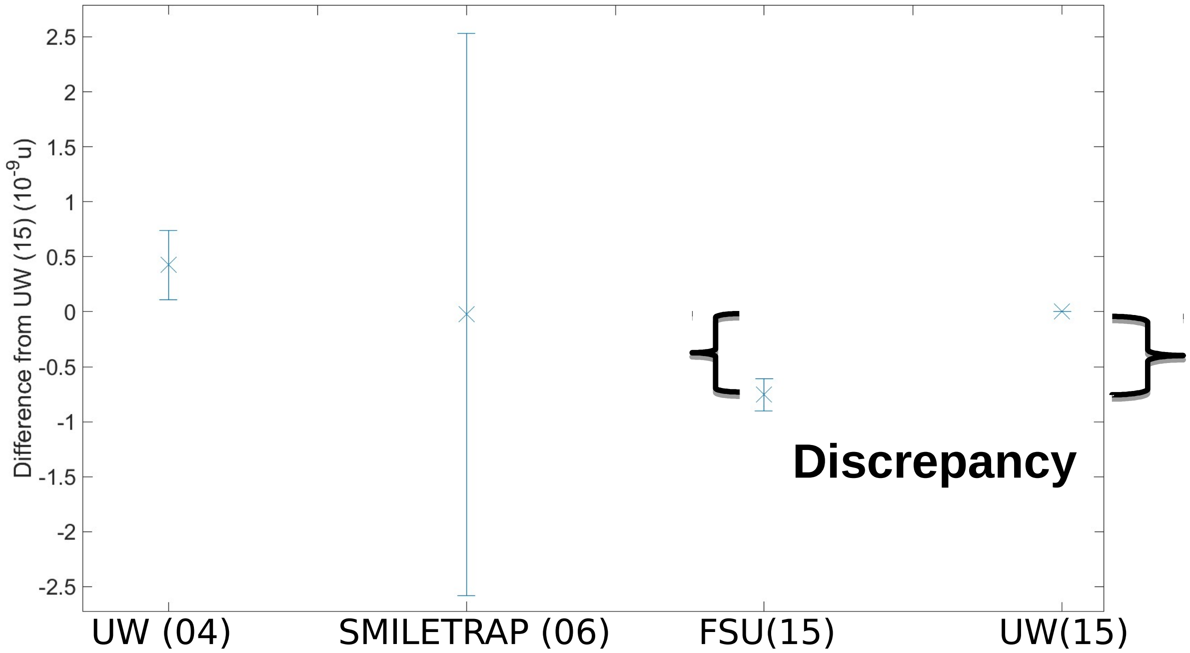
Q ≈ (



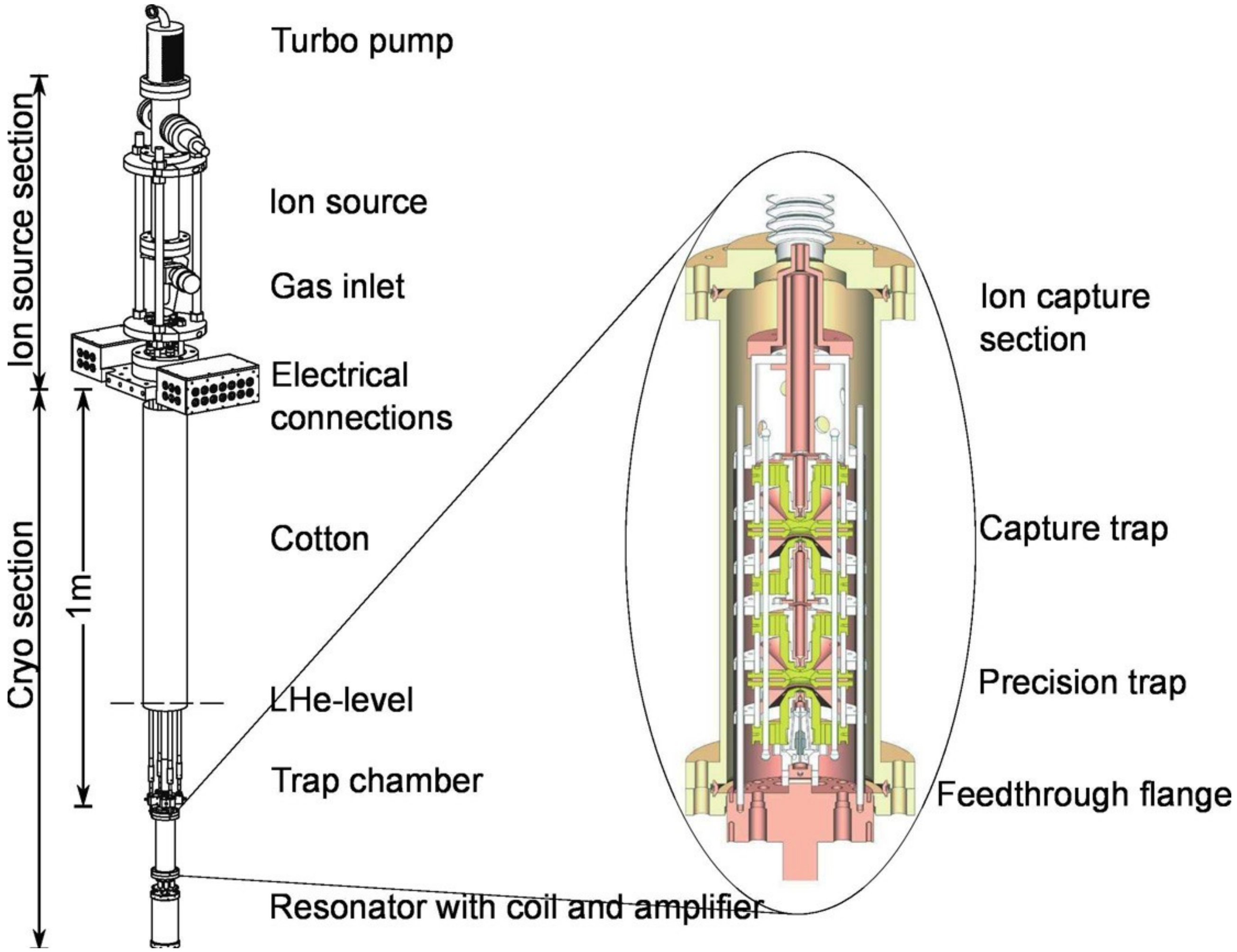
[1] E. W. Otten *et al*., Int. J. Mass Spectrom. 251 (2006) 173–178

Motivation 2 – The Helium Mass

Group	M_{3He}-3.016029000u in 10^{-9}u	Difference from UW (15) in 10^{-9}u	Discrepancy In stds
UW (04)	321.250(0.360)	0.425(0.403)	~1
SMILETRAP(06)	321.700(2.600)	-0.025(2.643)	~0
FSU (15)	322.430(0.190)	-0.755(0.233)	**~3**
UW (15)	321.675(0.043)	0(0)	0

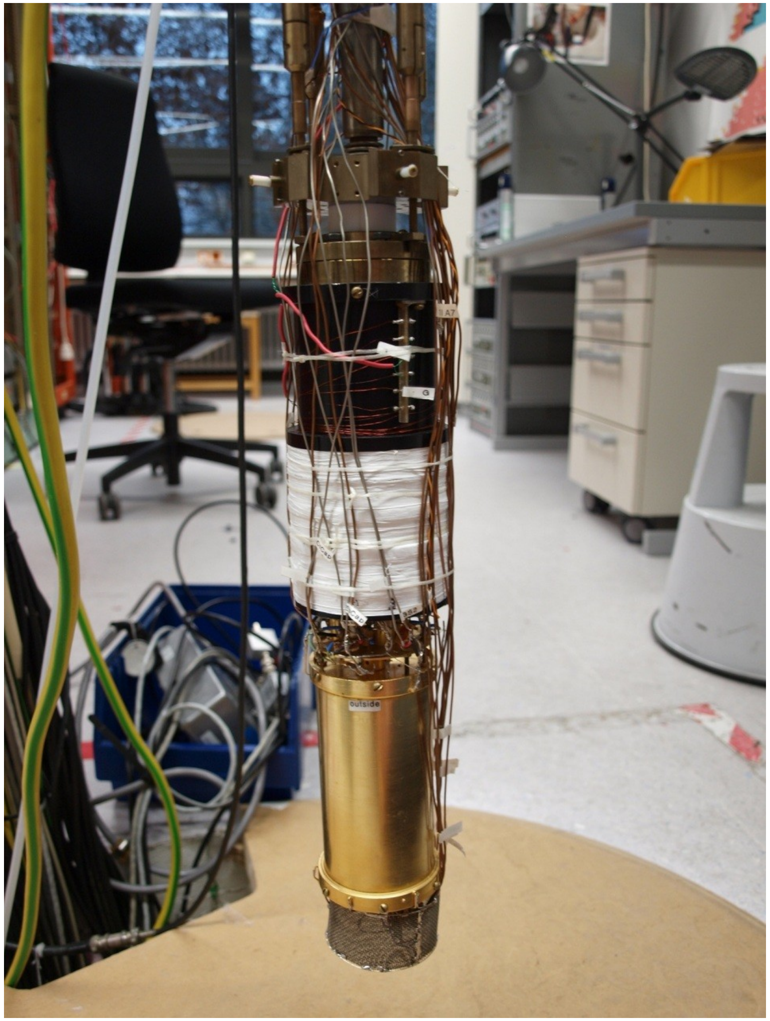


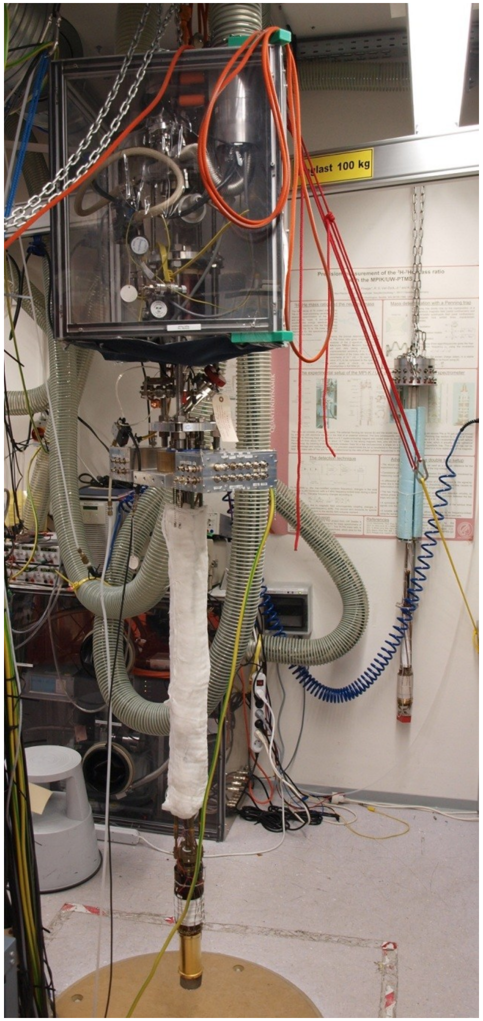
THe-Trap



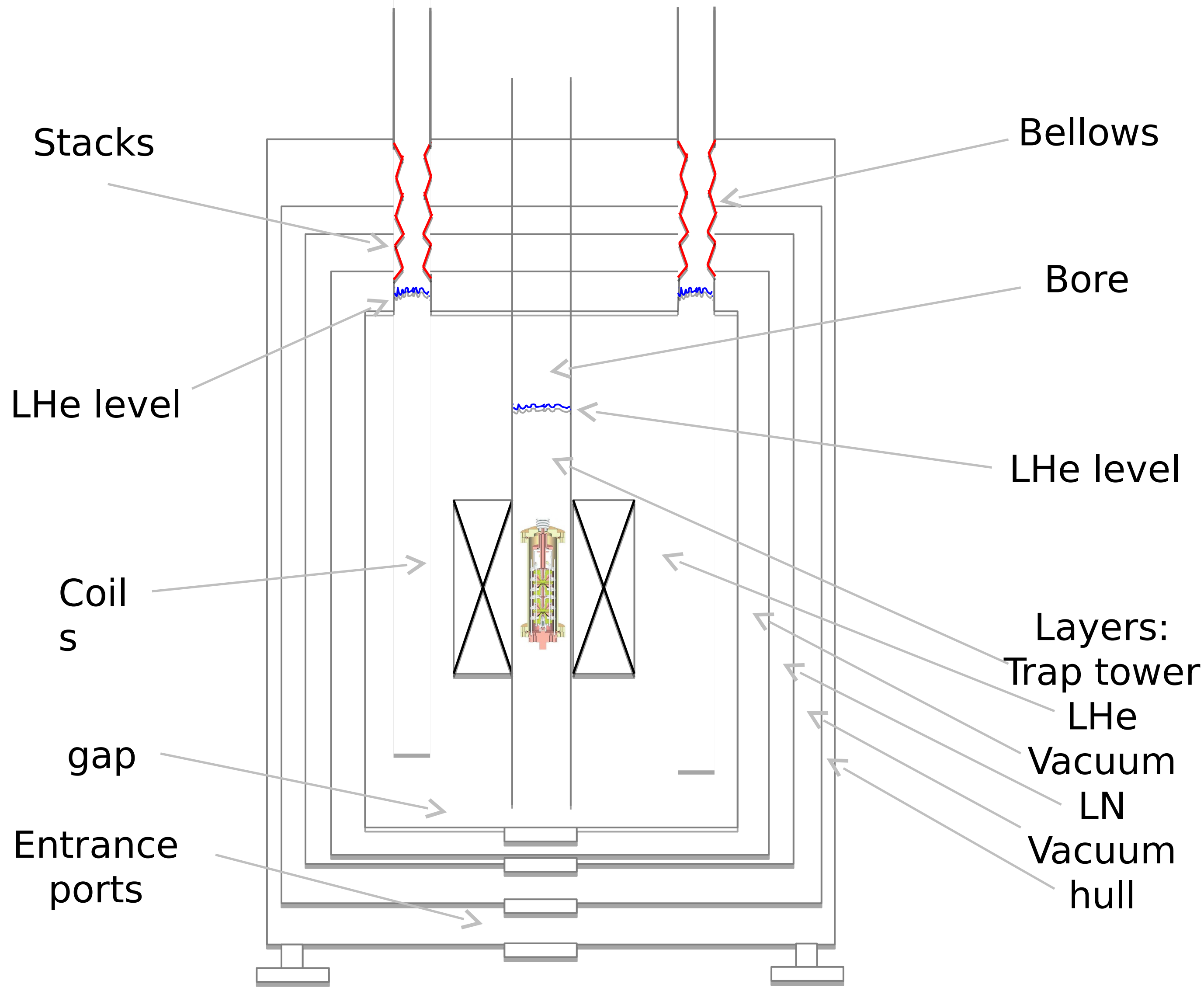
Turbo pump
Ion source
Gas inlet
Electrical connections
Cotton
LHe-level
Trap chamber
Resonator with coil and amplifier
Ion source section
Cryo section
1m
Ion capture section
Capture trap
Precision trap
Feedthrough flange

THe-Trap

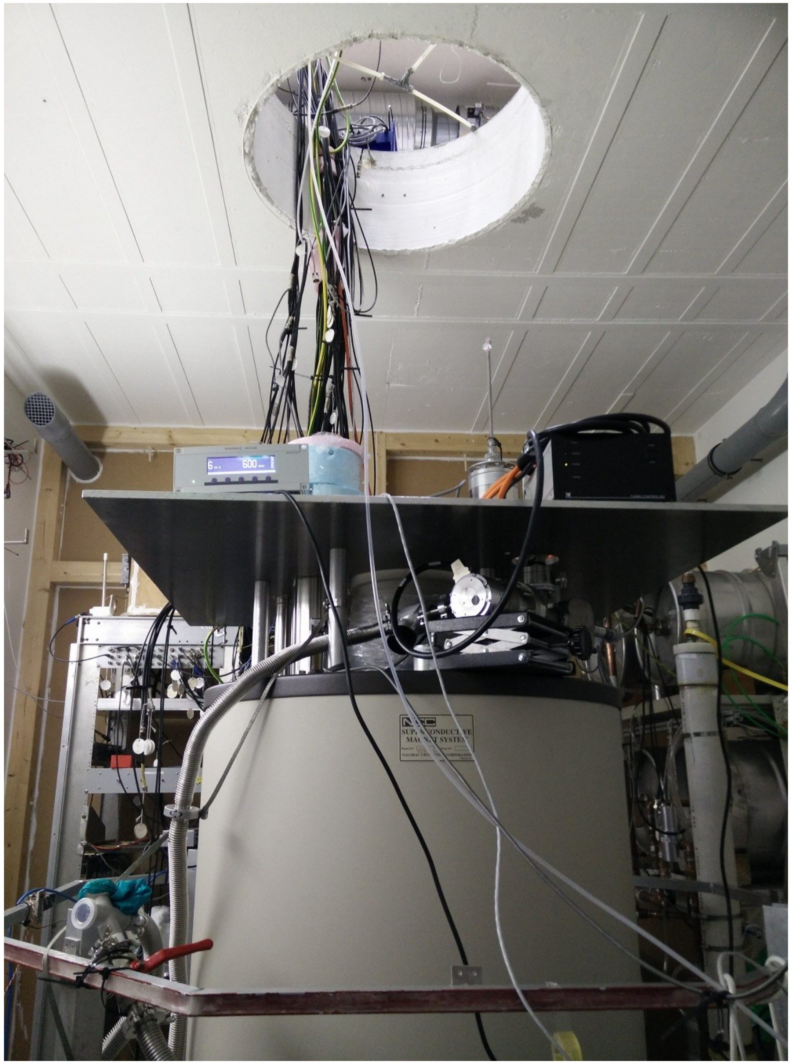




THe Magnet


Stacks
Bellows
Bore
LHe level
LHe level
Coil
s
Layers:
Trap tower
LHe
Vacuum
LN
Vacuum
hull
gap
Entrance
ports

THe Magnet



THe Stabilization System

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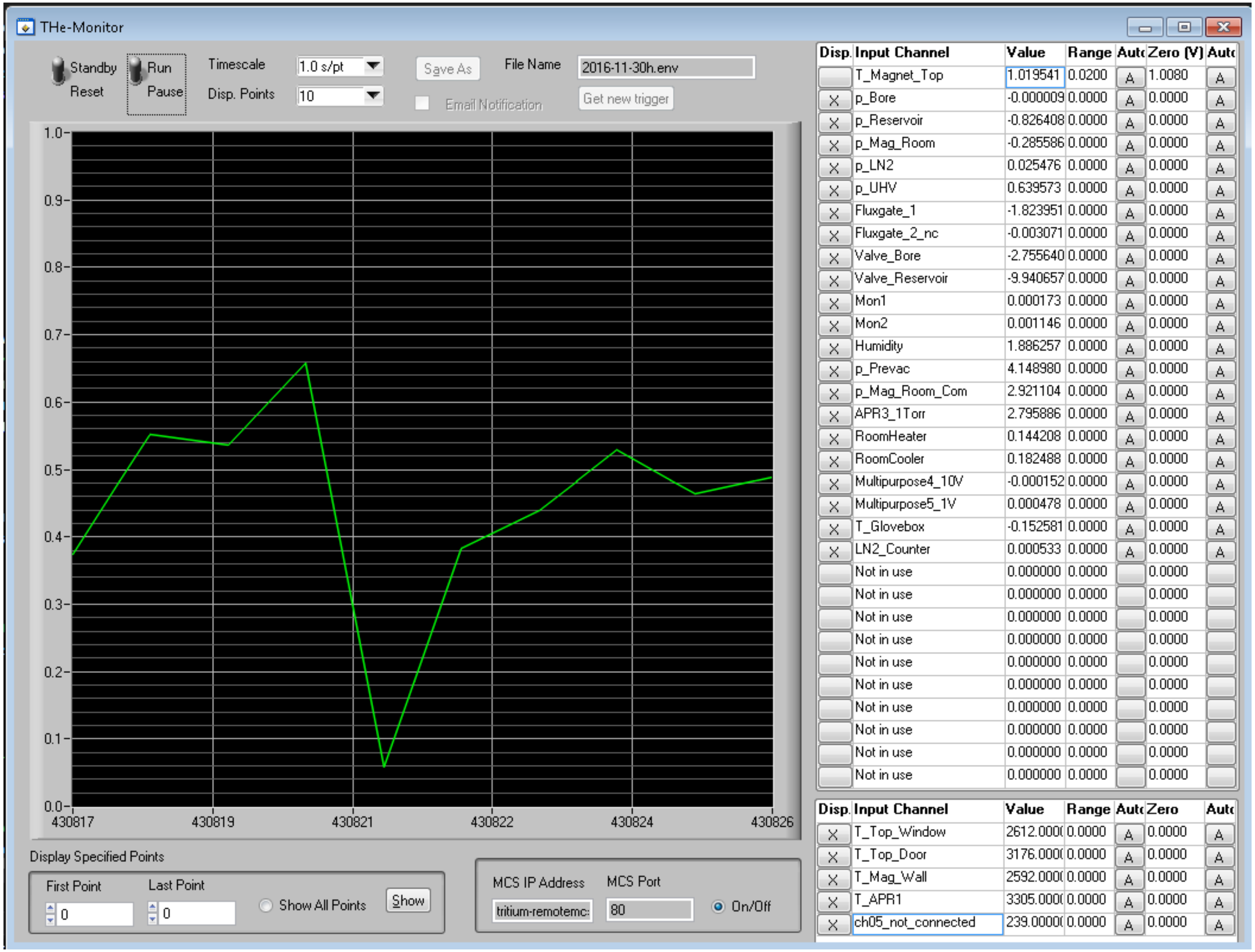
THe Environmental DAQ System



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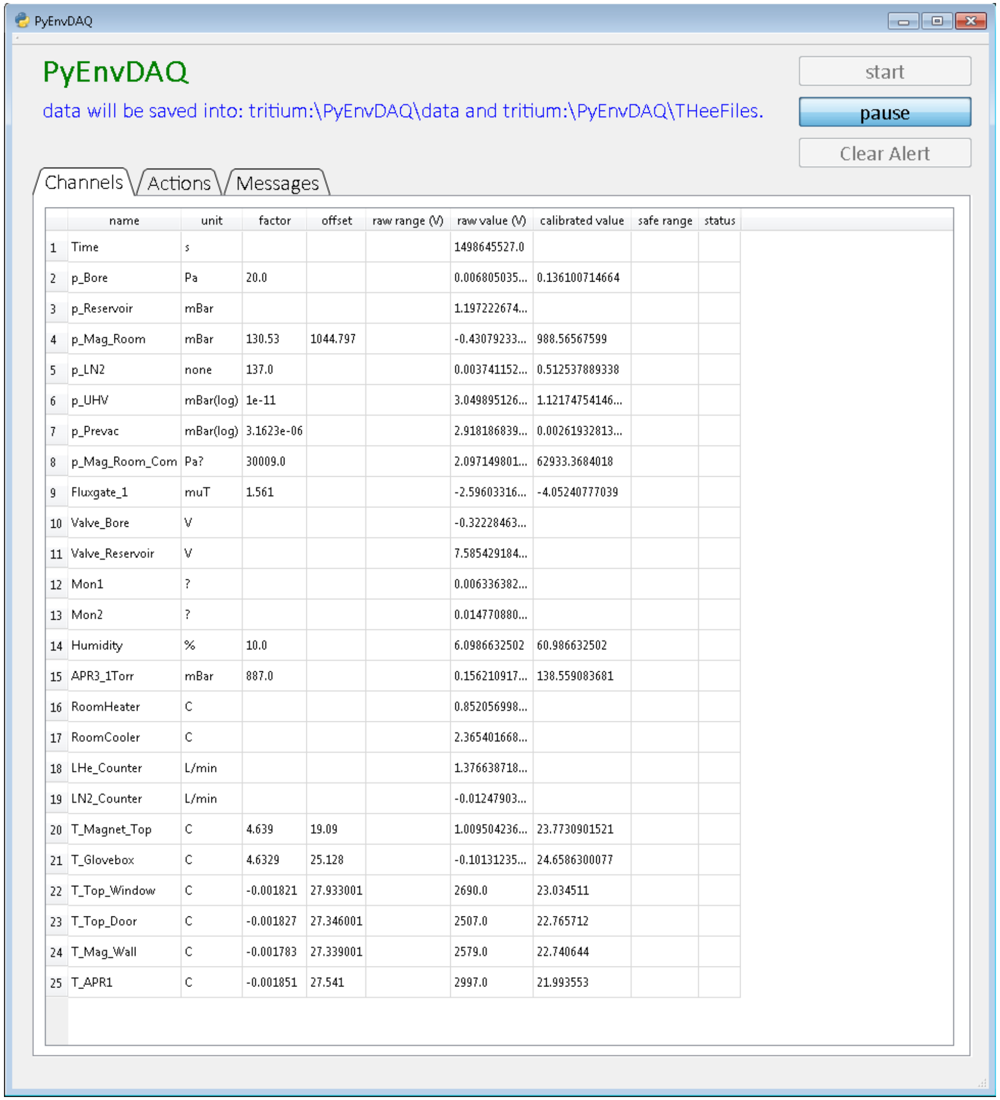
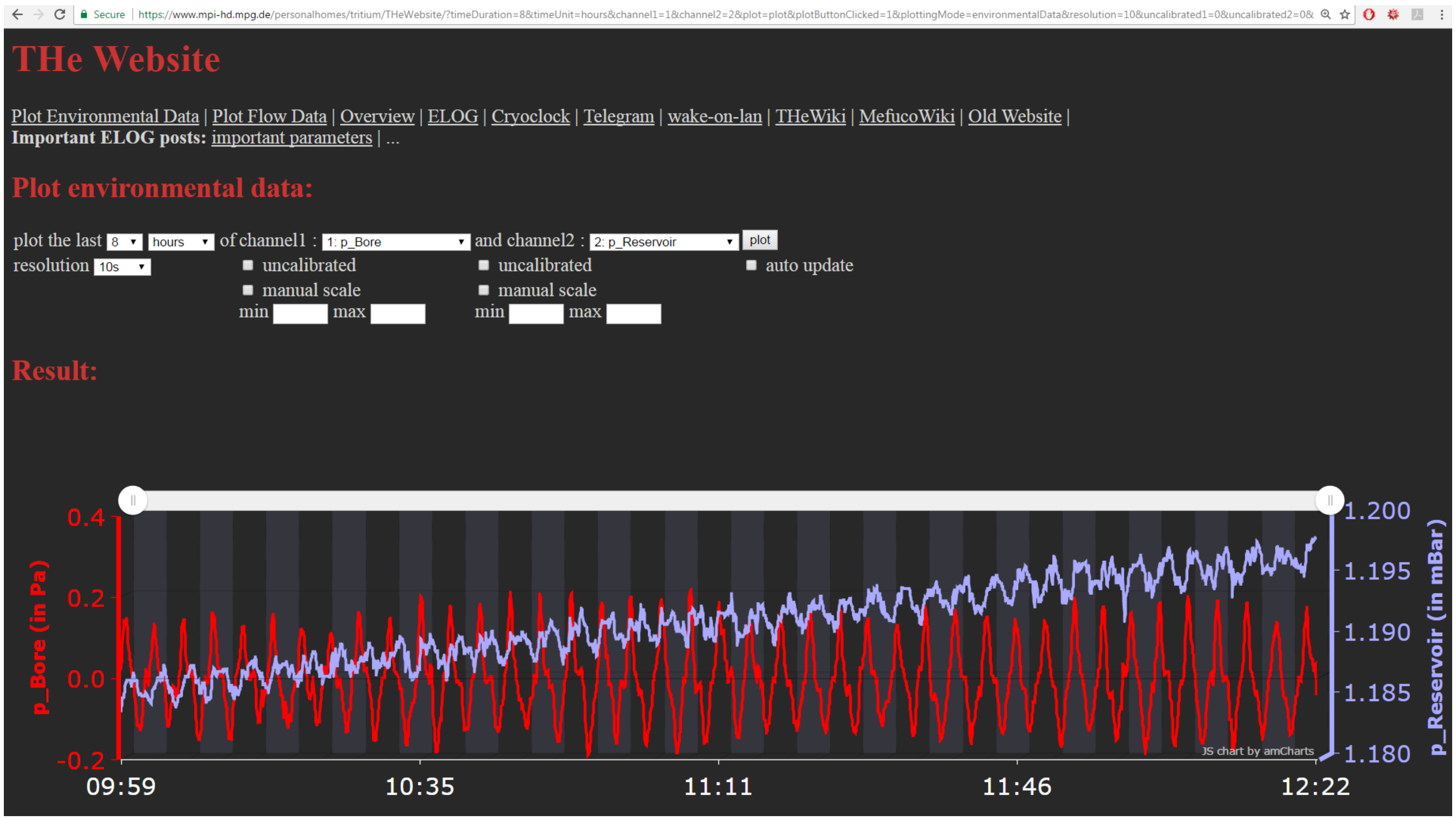
THe Environmental DAQ System



	name	unit	factor	offset	raw range (V)	raw value (V)	calibrated value	safe range	status
1	Time	s				1498645527.0			
2	p_Bore	Pa	20.0			0.006805035...	0.136100714664		
3	p_Reservoir	mBar				1.197222674...			
4	p_Mag_Room	mBar	130.53	1044.797		-0.43079233...	988.56567599		
5	p_LN2	none	137.0			0.003741152...	0.512537889338		
6	p_UHV	mBar(log)	1e-11			3.049895126...	1.12174754146...		
7	p_Prevac	mBar(log)	3.1623e-06			2.918186839...	0.00261932813...		
8	p_Mag_Room_Com	Pa?	30009.0			2.097149801...	62933.3684018		
9	Fluxgate_1	muT	1.561			-2.59603316...	-4.05240777039		
10	Valve_Bore	V				-0.32228463...			
11	Valve_Reservoir	V				7.585429184...			
12	Mon1	?				0.006336382...			
13	Mon2	?				0.014770880...			
14	Humidity	%	10.0			6.0986632502	60.986632502		
15	APR3_1Torr	mBar	887.0			0.156210917...	138.559083681		
16	RoomHeater	C				0.852056998...			
17	RoomCooler	C				2.365401668...			
18	LHe_Counter	L/min				1.376638718...			
19	LN2_Counter	L/min				-0.01247903...			
20	T_Magnet_Top	C	4.639	19.09		1.009504236...	23.7730901521		
21	T_Glovebox	C	4.6329	25.128		-0.10131235...	24.6586300077		
22	T_Top_Window	C	-0.001821	27.933001		2690.0	23.034511		
23	T_Top_Door	C	-0.001827	27.346001		2507.0	22.765712		
24	T_Mag_Wall	C	-0.001783	27.339001		2579.0	22.740644		
25	T_APR1	C	-0.001851	27.541		2997.0	21.993553		

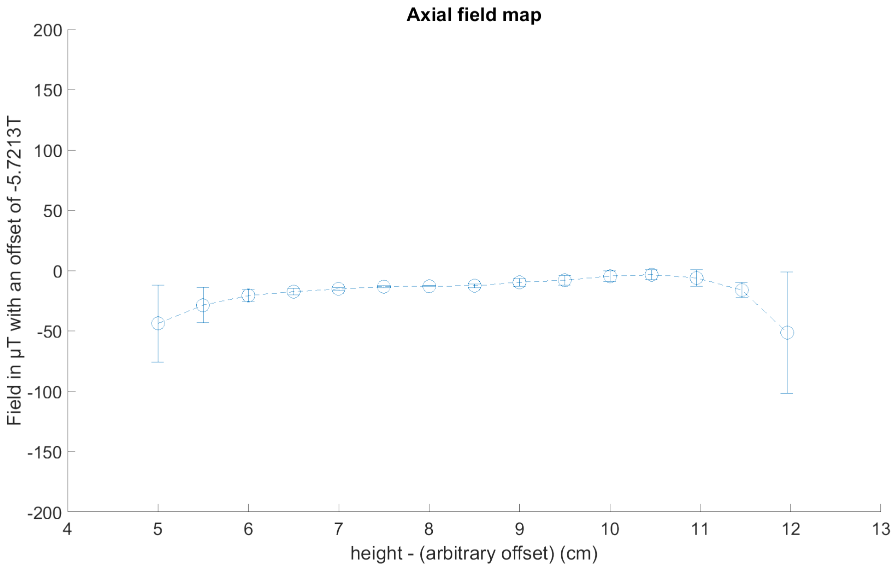
THe Website



Secure | https://www.mpi-hd.mpg.de/personalhomes/tritium/THeWebsite/?timeDuration=8&timeUnit=hours&channel1=1&channel2=2&plot=plot&plotButtonClicked=1&plottingMode=environmentalData&resolution=10&uncalibrated1=0&uncalibrated2=0&
THe Website
Plot Environmental Data | Plot Flow Data | Overview | ELOG | Cryoclock | Telegram | wake-on-lan | THeWiki | MefucoWiki | Old Website |
Important ELOG posts: important parameters | ...
Plot environmental data:
plot the last 8 hours of channel1 : 1: p_Bore and channel2 : 2: p_Reservoir plot
resolution 10s
uncalibrated
uncalibrated
auto update
manual scale
manual scale
min max
min max
Result:
0.4
0.2
0.0
-0.2
p_Bore (in Pa)
1.200
1.195
1.190
1.185
1.180
p_Reservoir (in mBar)
09:59
10:35
11:11
11:46
12:22
JS chart by amCharts

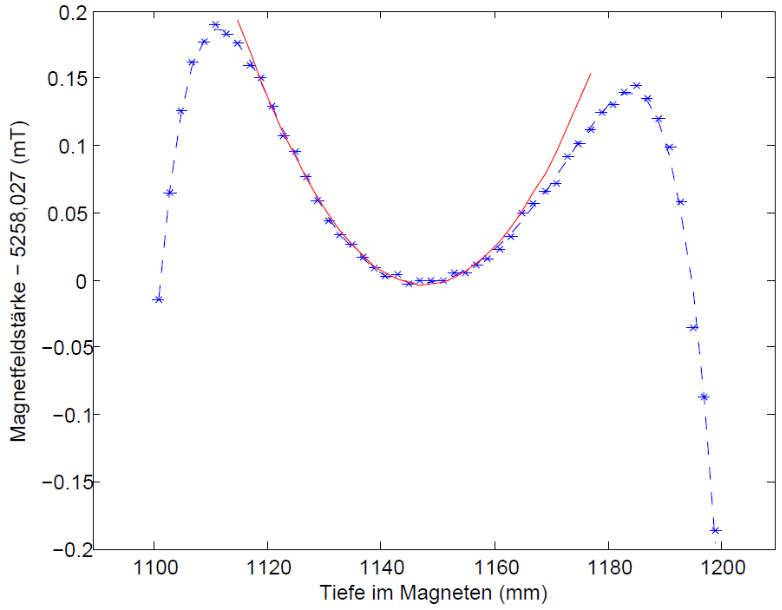
Shimming the magnet

2015



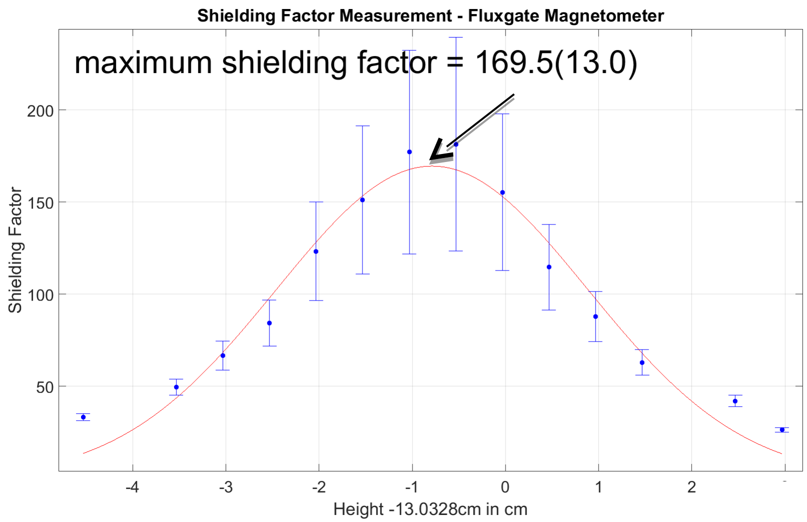
Homogeneity 82 ppb

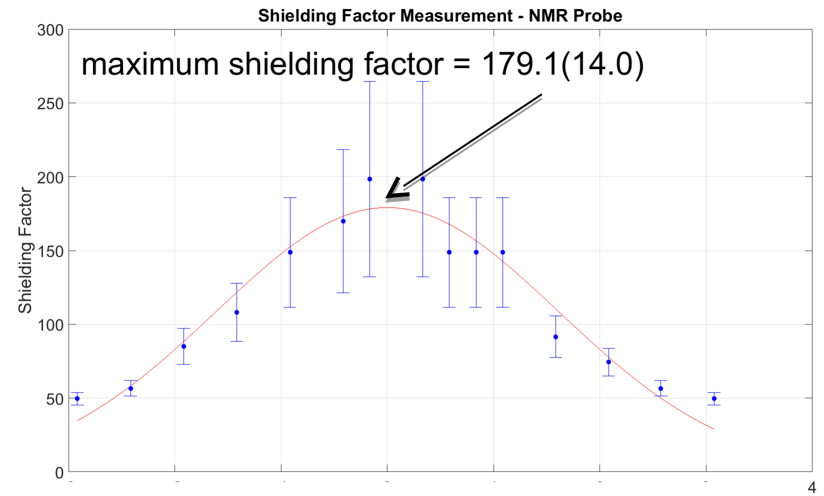
2011

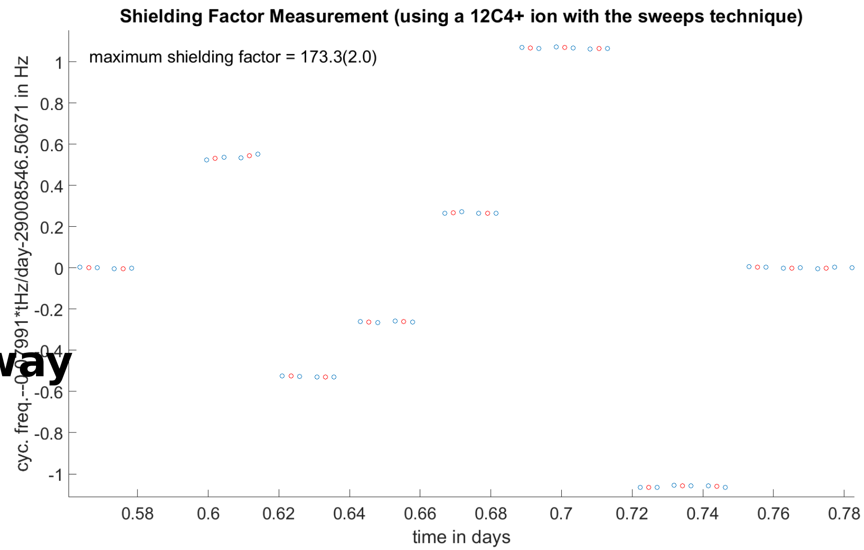


Homogeneity 10 ppm

Shielding Factor





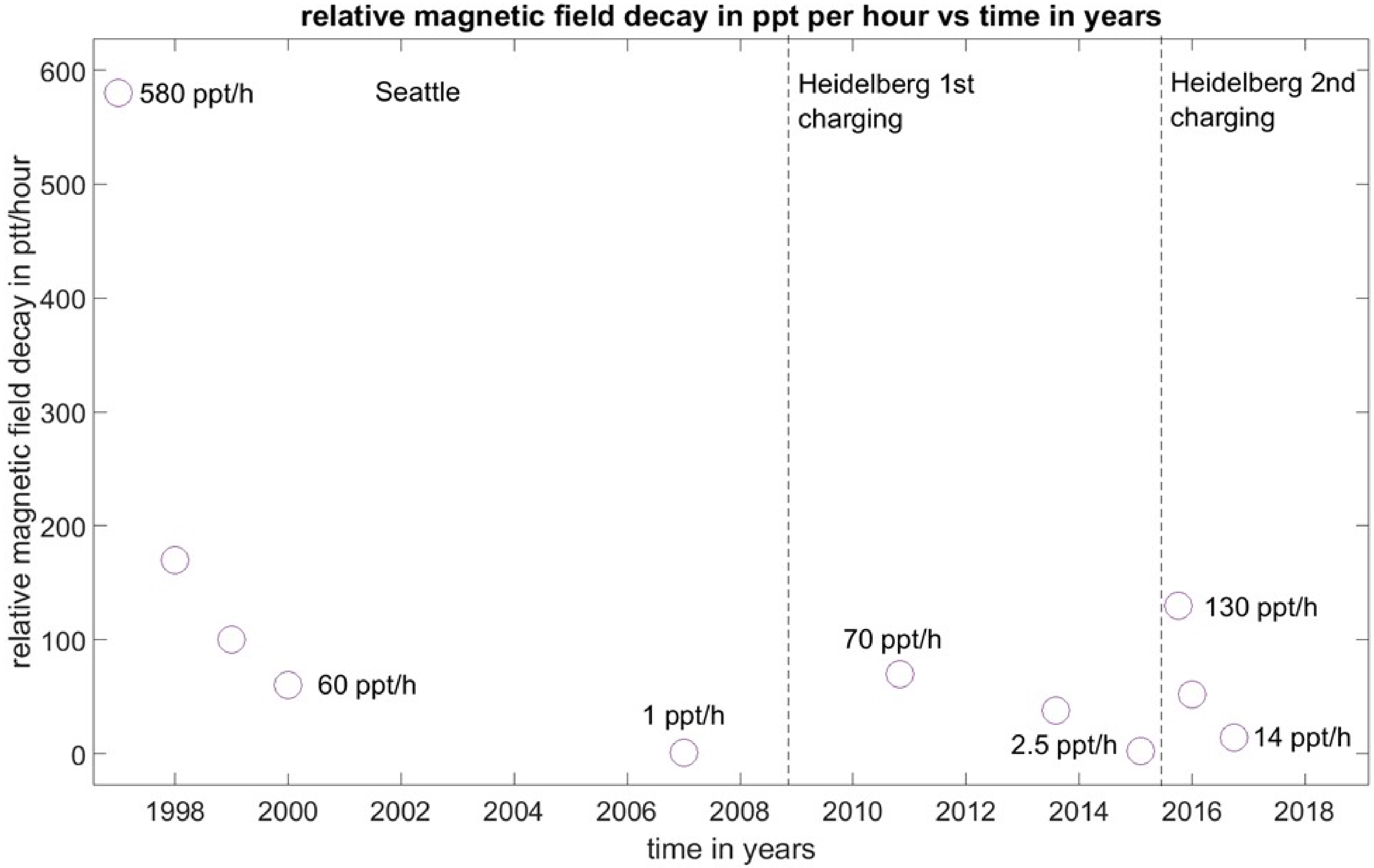


elding Factor measurements:
) (maximum) [2]
.5(13.0) (maximum) fluxgate magnetometer
.1(14.0) (maximum) NMR probe
.3(2.0) 12C4+ ion

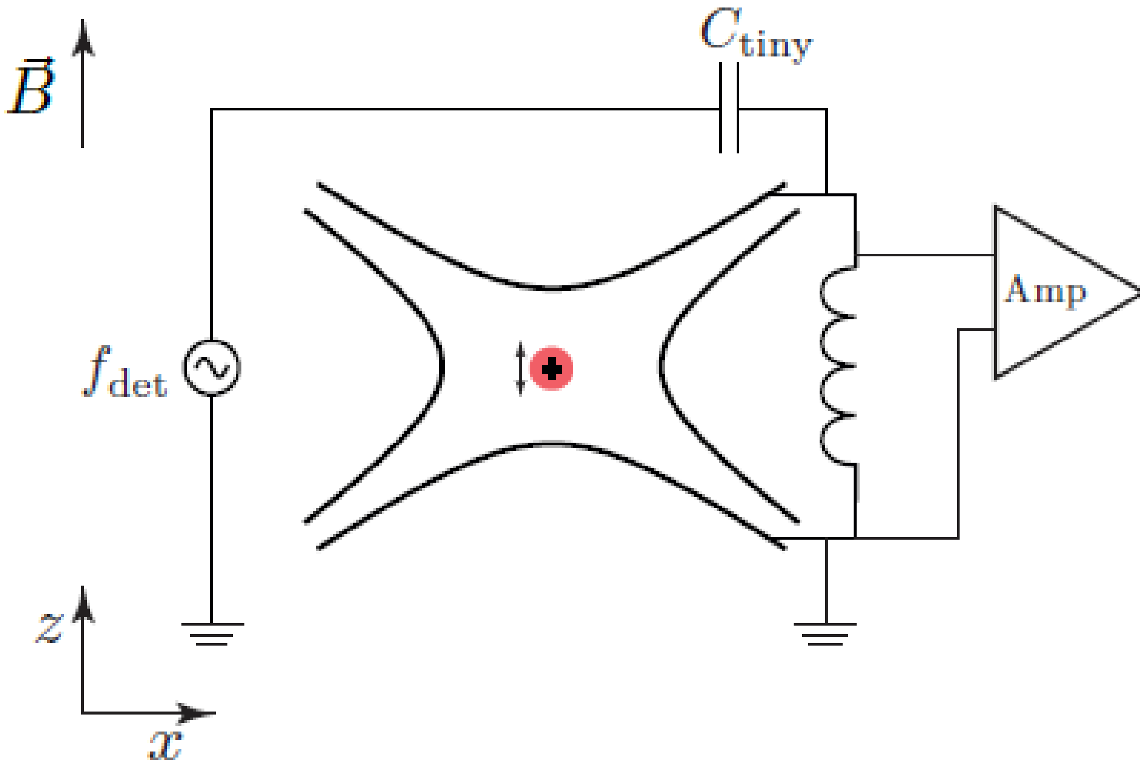
nclusion: The trap is at most mm away from the center.

] Van Dyck *et al*., Rev. Sci. Instrum. **70**, 1665 (1999)

Magnetic Field Drift



Detection Method



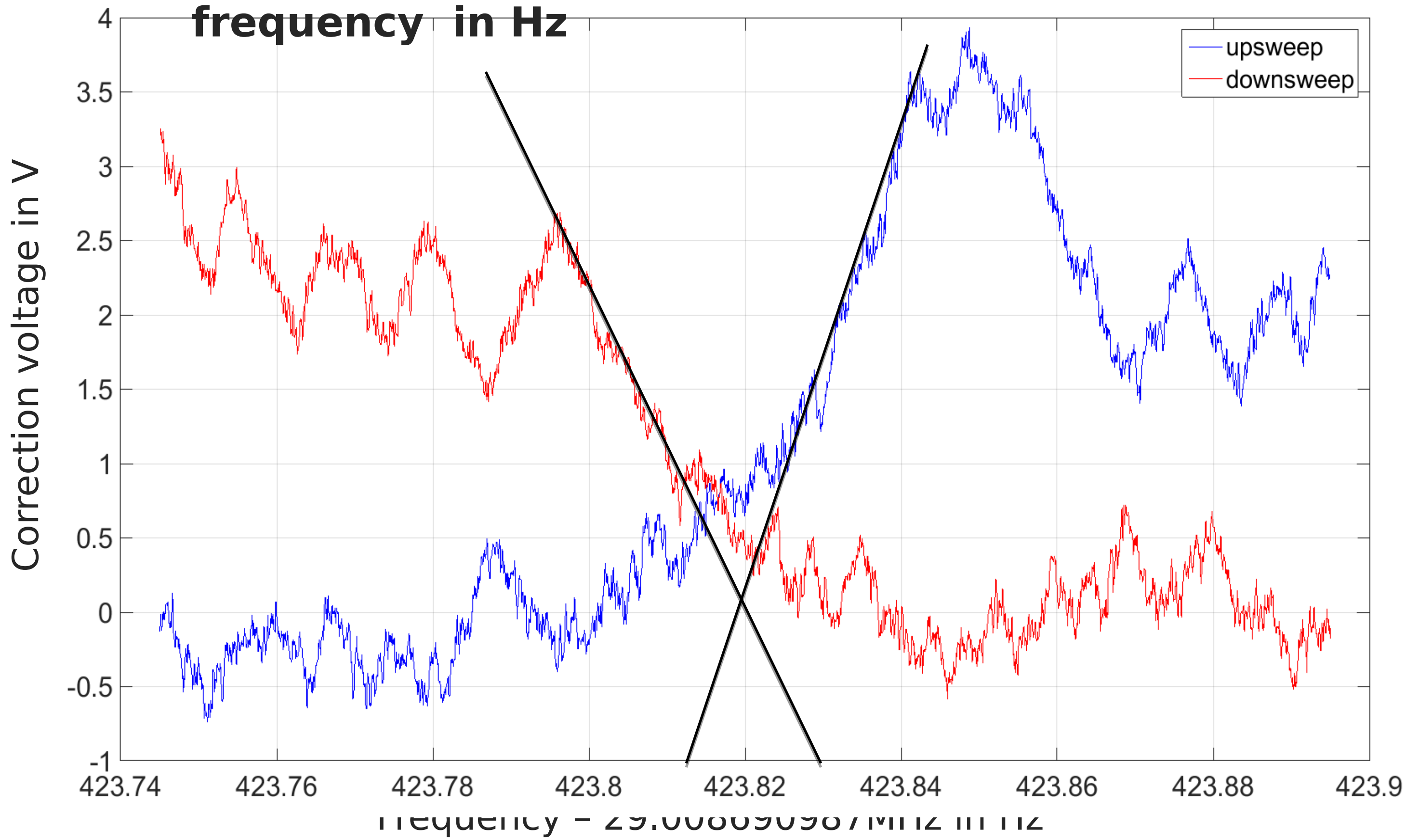
Picture Courtesy of Martin Höcker

Ion Trapping

- **Trap many ions** with a FEP (Field Emission Point)
- **Remove all but one** ion using “brooms” and “ring drops”

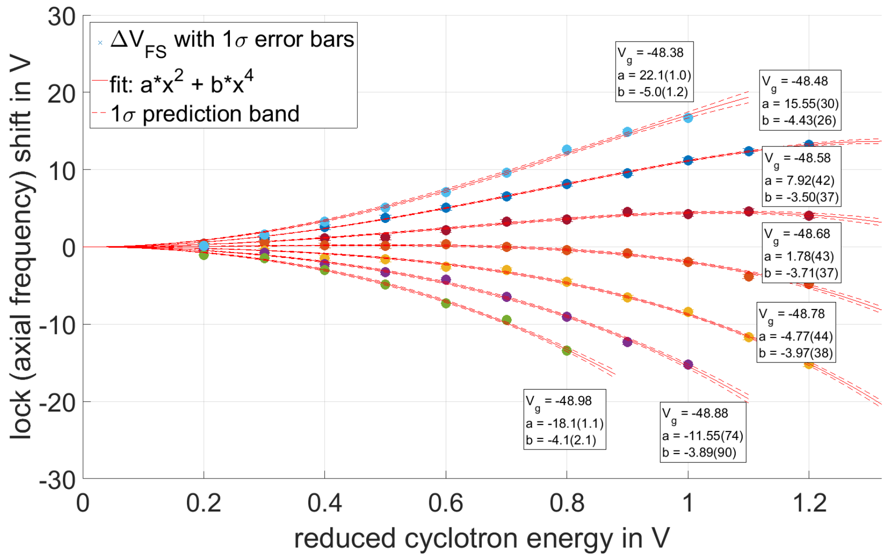
Old Measurement Method – Sweeps

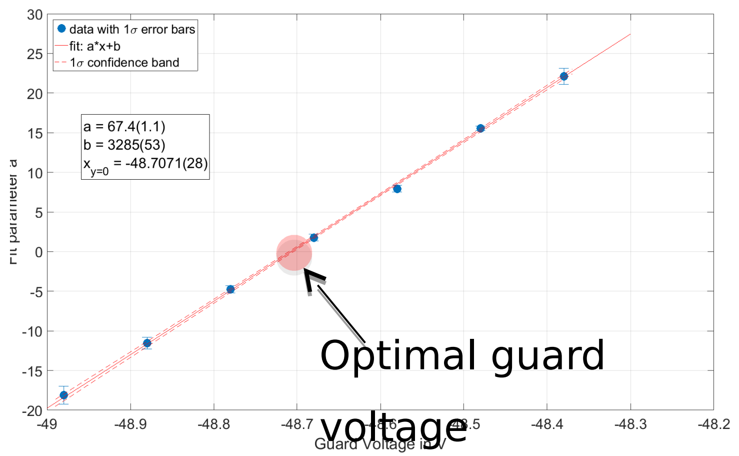
Correction voltage in V vs offsetted excitation frequency in Hz



Reducing The Anharmonicities

1. Measure the axial frequency shift (the lock voltage)
2. Excite reduced cyclotron (or the magnetron) mode
3. Measure the axial frequency shift (the lock voltage)
4. De-energize the reduced cyclotron (or the magnetron)





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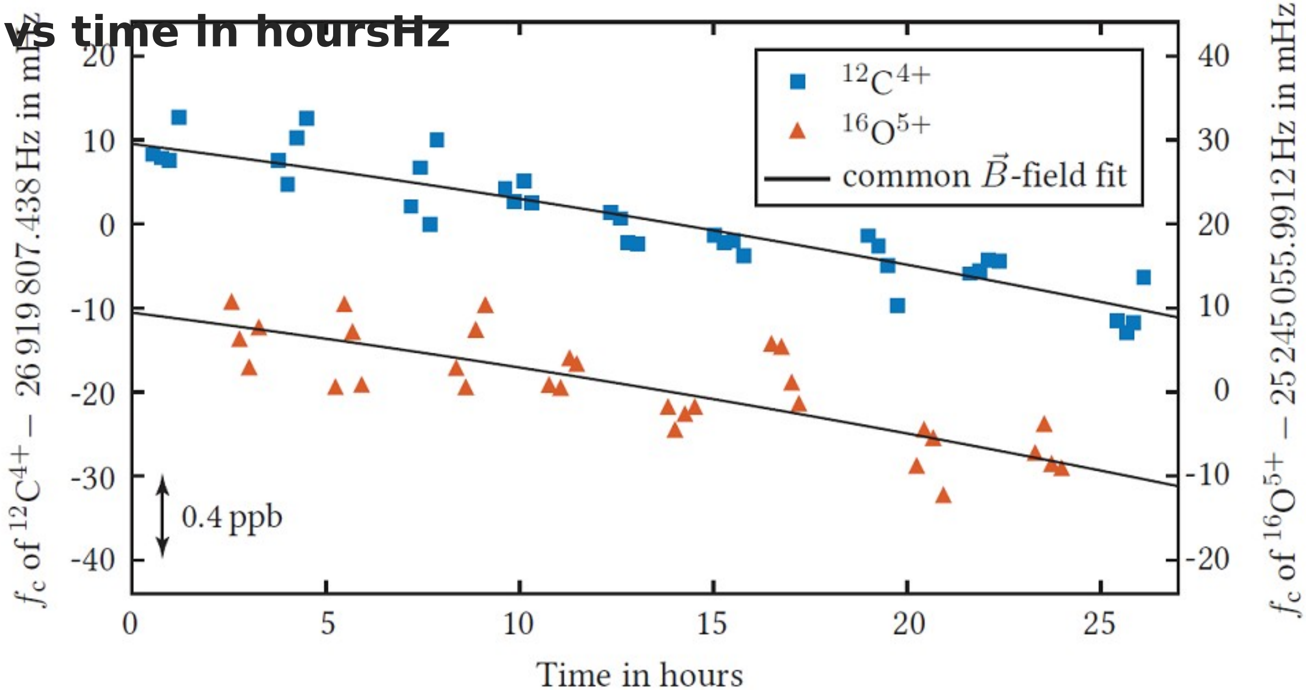
Martin’s Oxygen Measurement

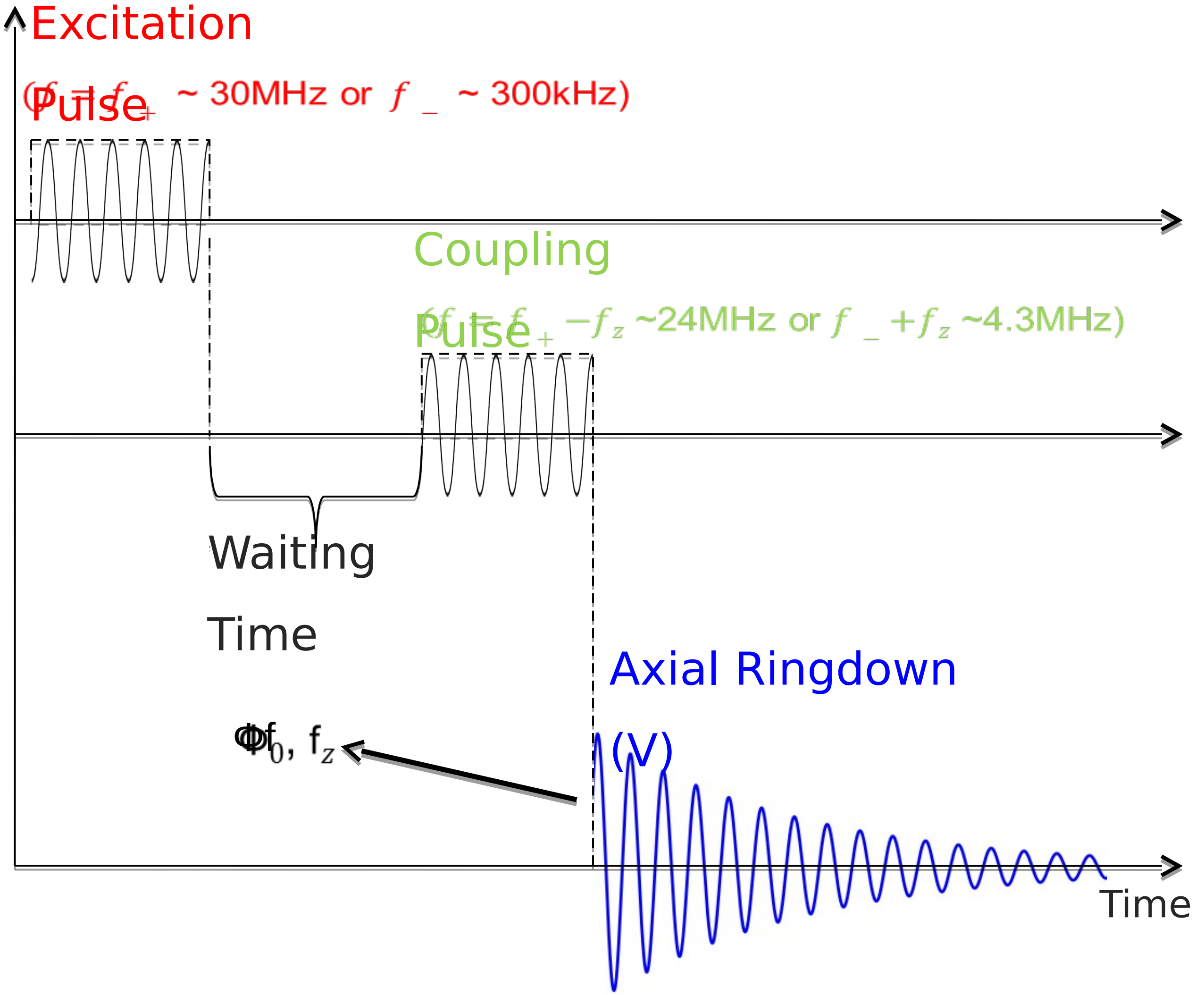
Offsetted cyclotron frequencies of $^{12}C^{4+}$ and $^{16}O^{5+}$ in mHz vs time in hoursHz



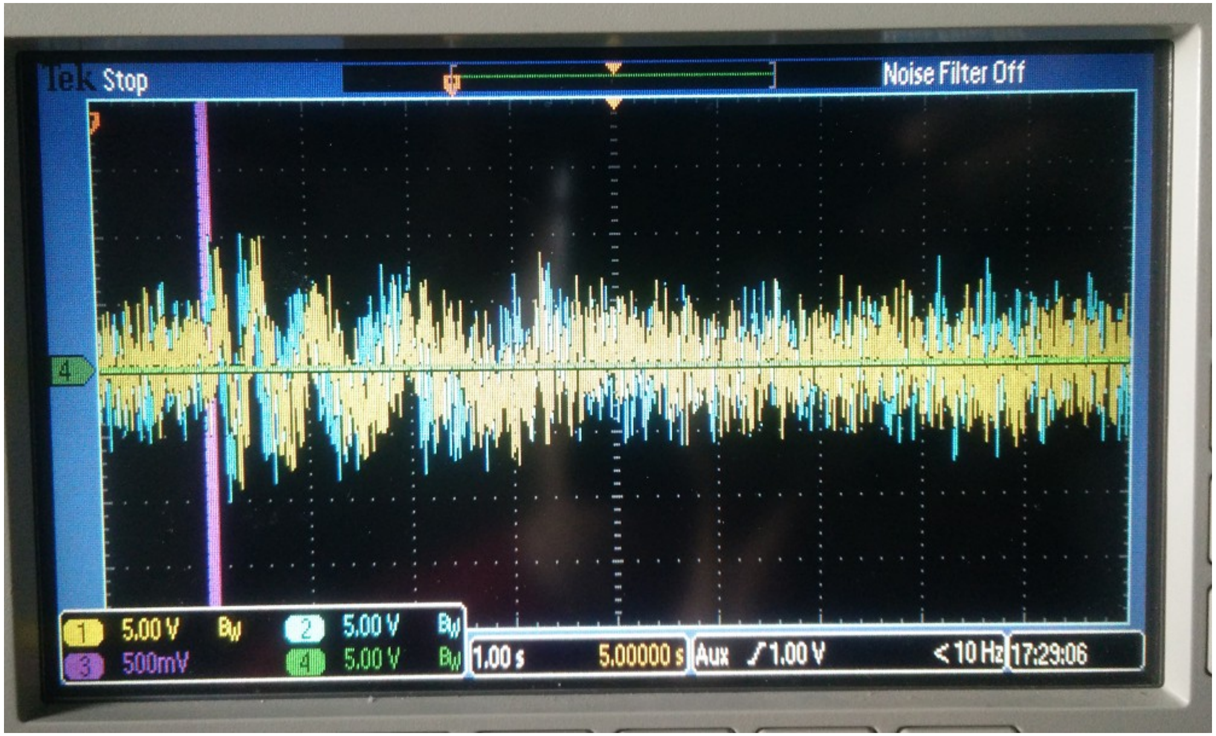
$$\frac{\Delta m(16O^{5+})}{m(16O^{5+})} = \begin{cases} \textbf{THe-Trap: 75 ppt } (17)_{stat}(20)_{syst}(70_{fit}) \text{ [2]} \\ \textbf{Literature: 18 ppt } \text{[3]} \end{cases}$$

[3] M. Höcker’s PhD thesis (2016)
[4] Van Dyck (2006)
Picture taken from M. Höcker’s PhD thesis.

New Measurement Method – Pulse & Phase

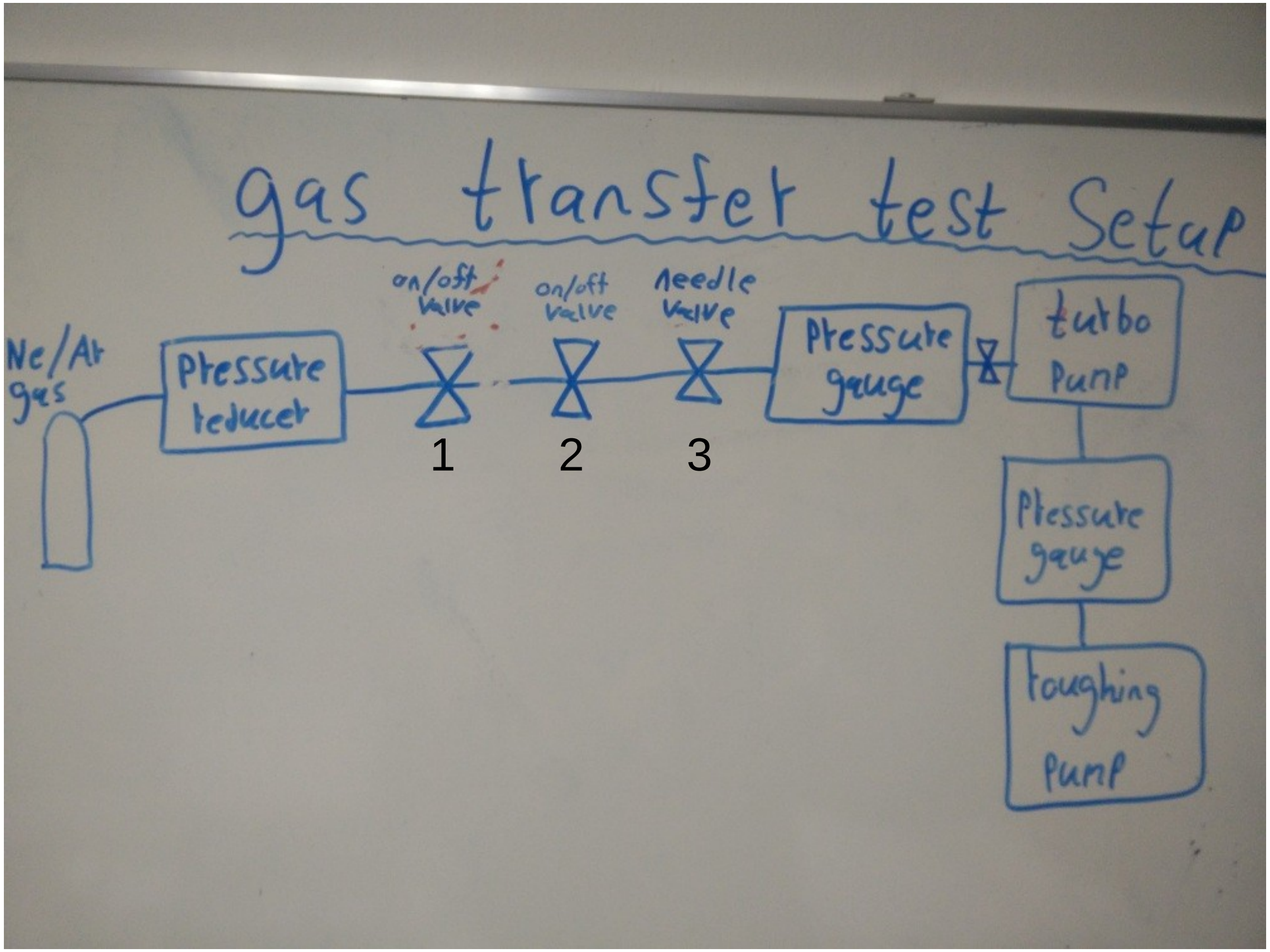


New Measurement Method – Pulse & Phase

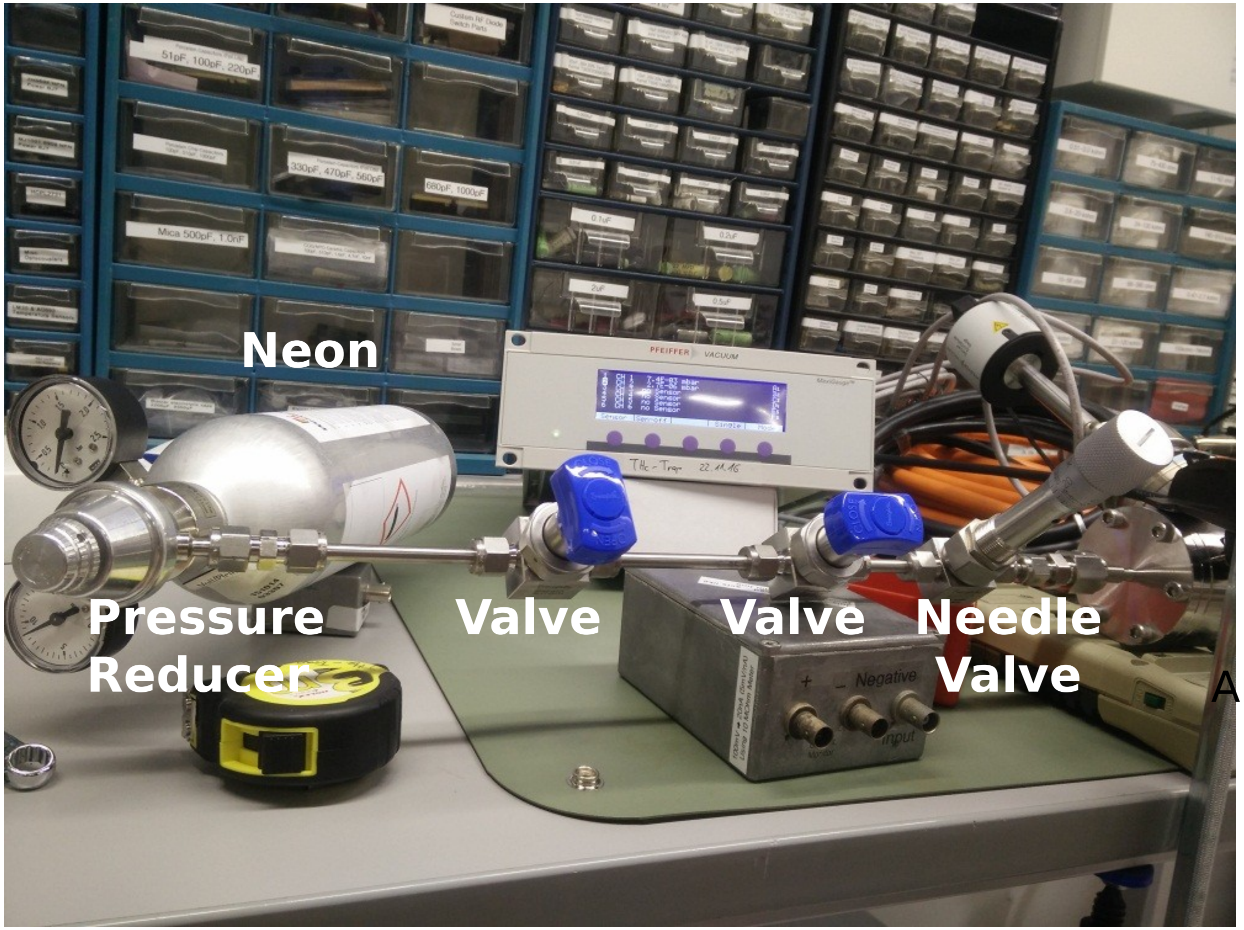


Channels 1 & 2 – x & y ringdown components
Channel 3 – coupling pulse

THe Gas Inlet System

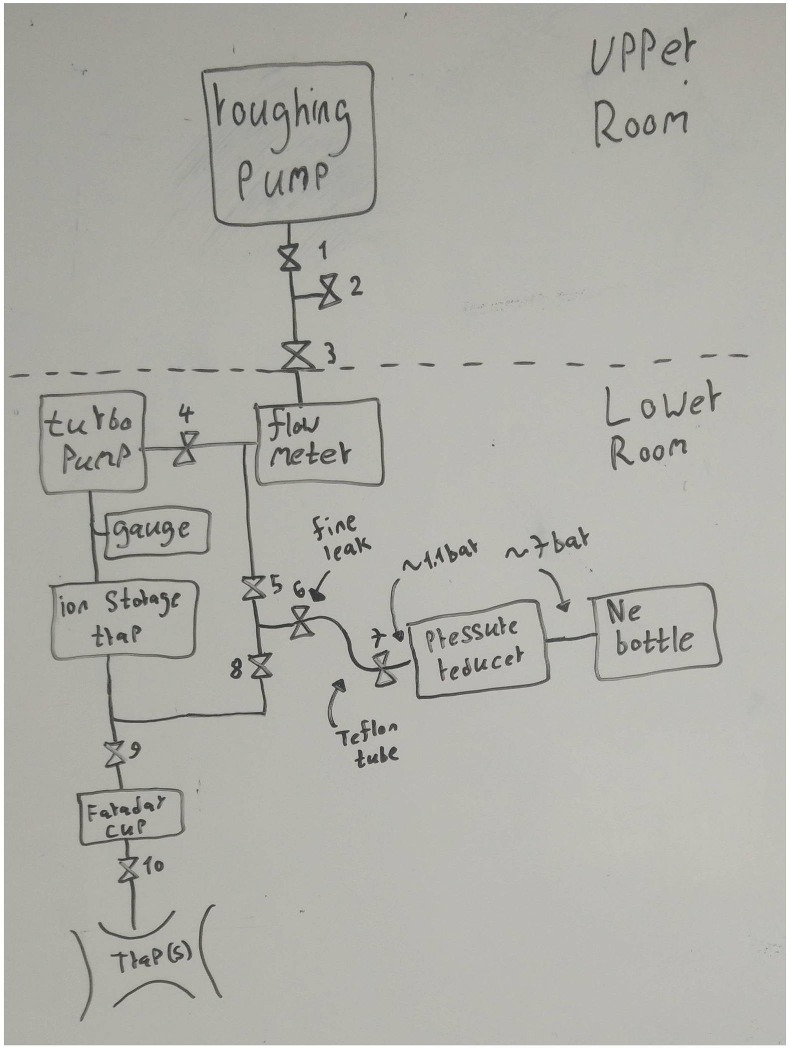


THe Gas Inlet System

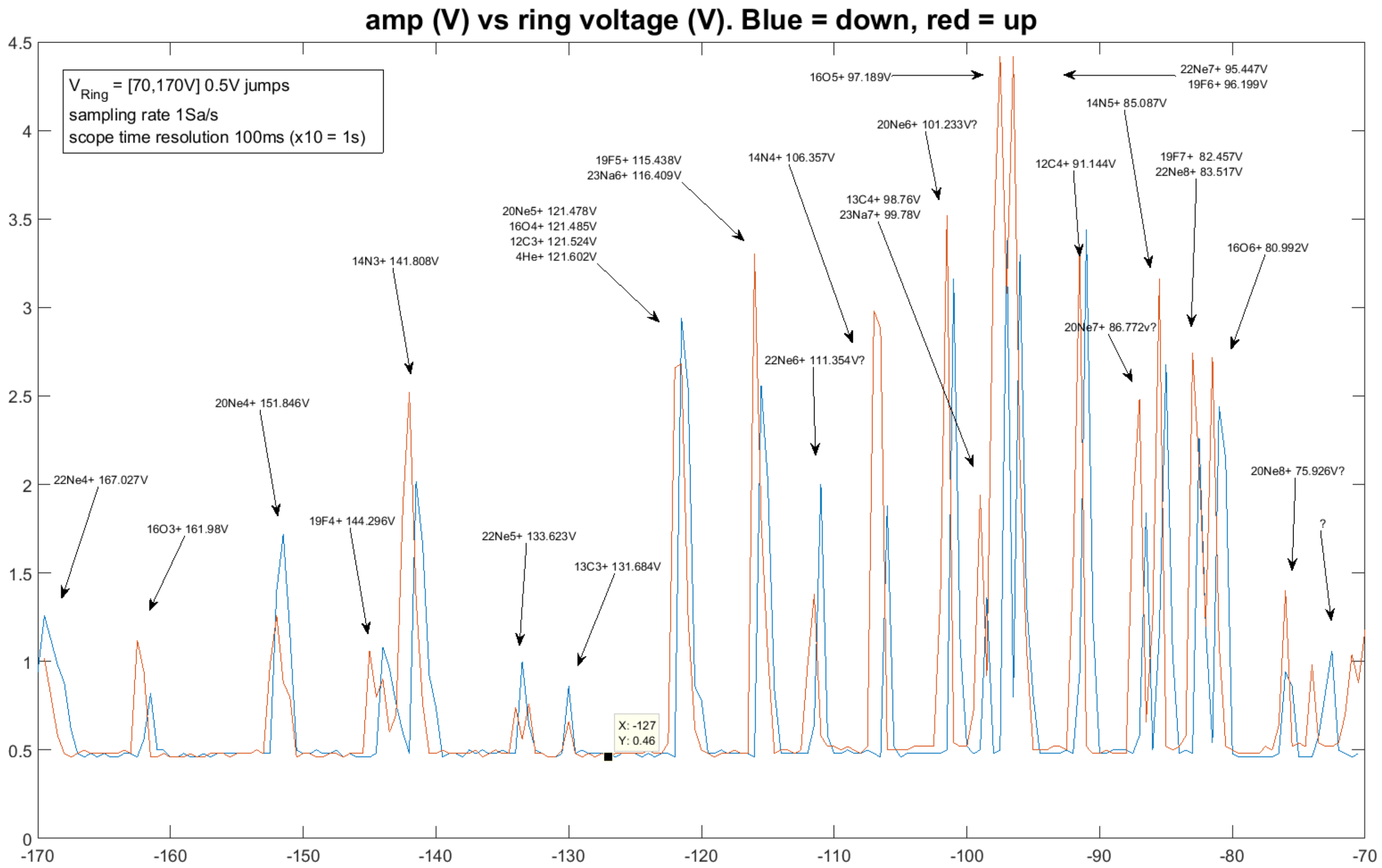


To pumps
And the outside

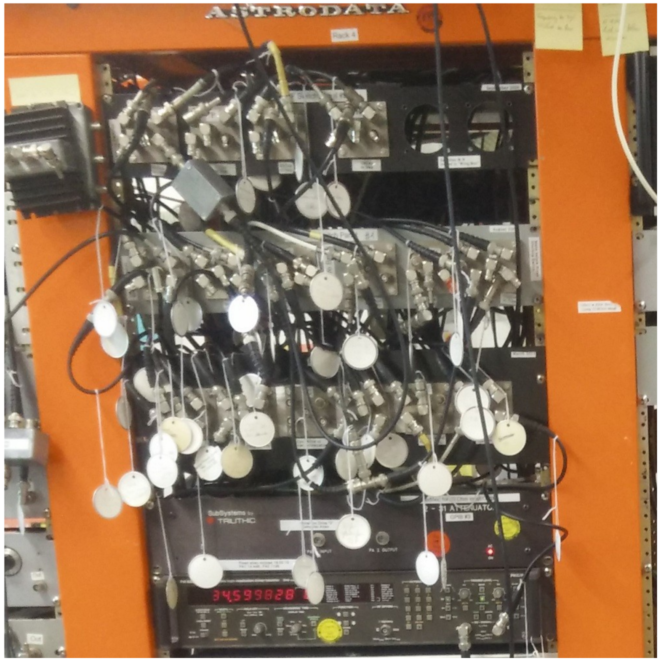
THe Gas Inlet System



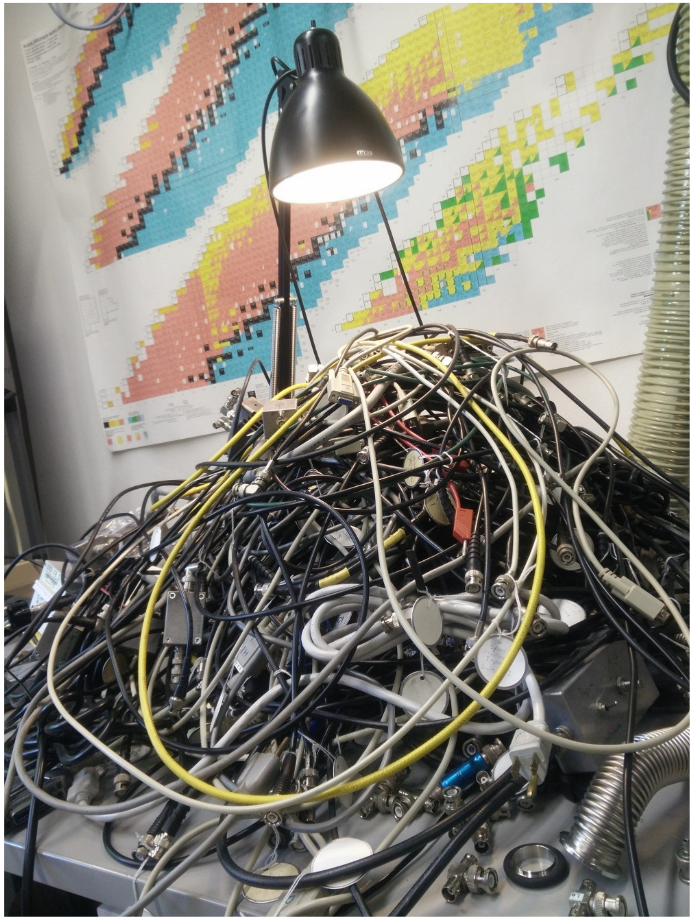
Neon Trapped



Cleaning Up the Lab - Before



Cleaning Up the Lab - After



Future Plans

- Remove noise signals to allow trapping of a single Ne ion
- Perform a mass measurement with Ne (and C?)
- Inject, trap and measure He.

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Danke für eure Aufmerksamkeit