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A Lamb-Shift Polarimeter for the BOB Experiment

27.11.2018

by Ralf Engels

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Introduction

Part 1: The Lamb-shift polarimeter and his components

Part 2: How to identify the single hyperfine-substates

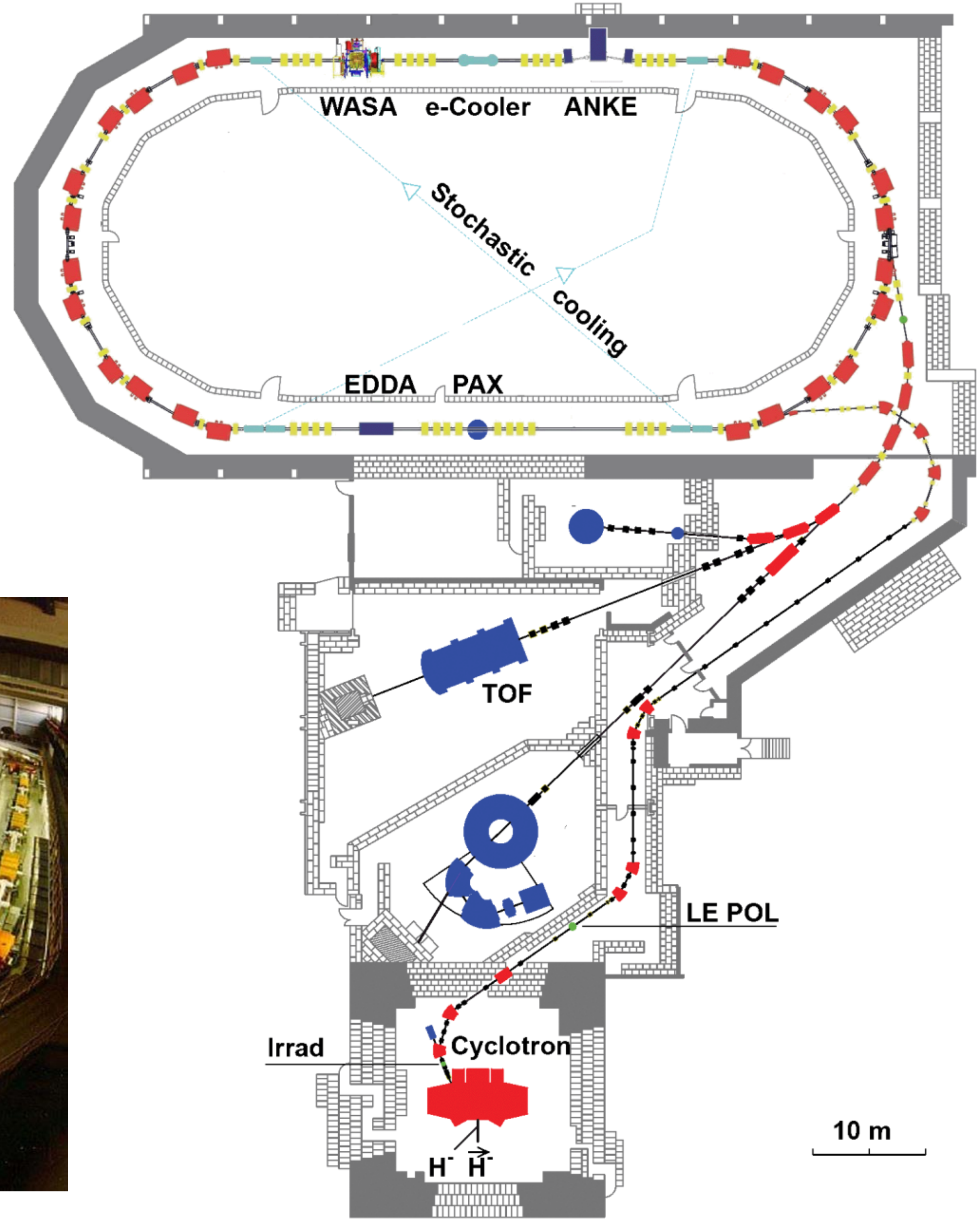
with a Lamb-shift Polarimeter

COSY (Cooler Synchrotron)

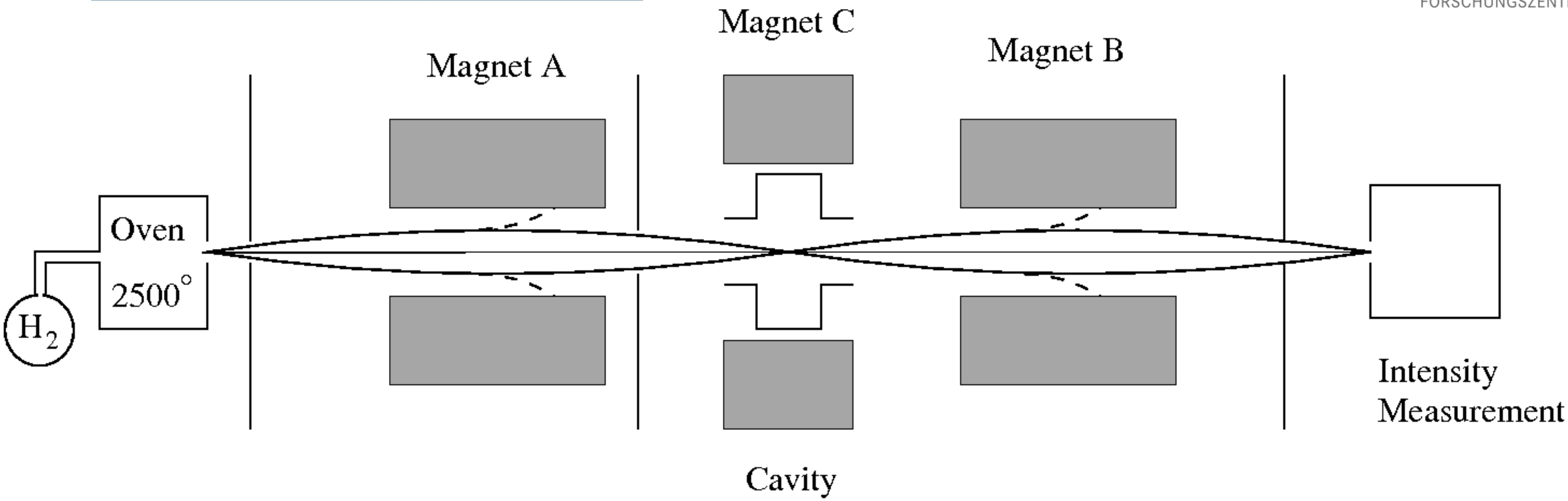
$p, \vec{p}, d, \vec{d}$

with momenta up to 3.7 GeV/c

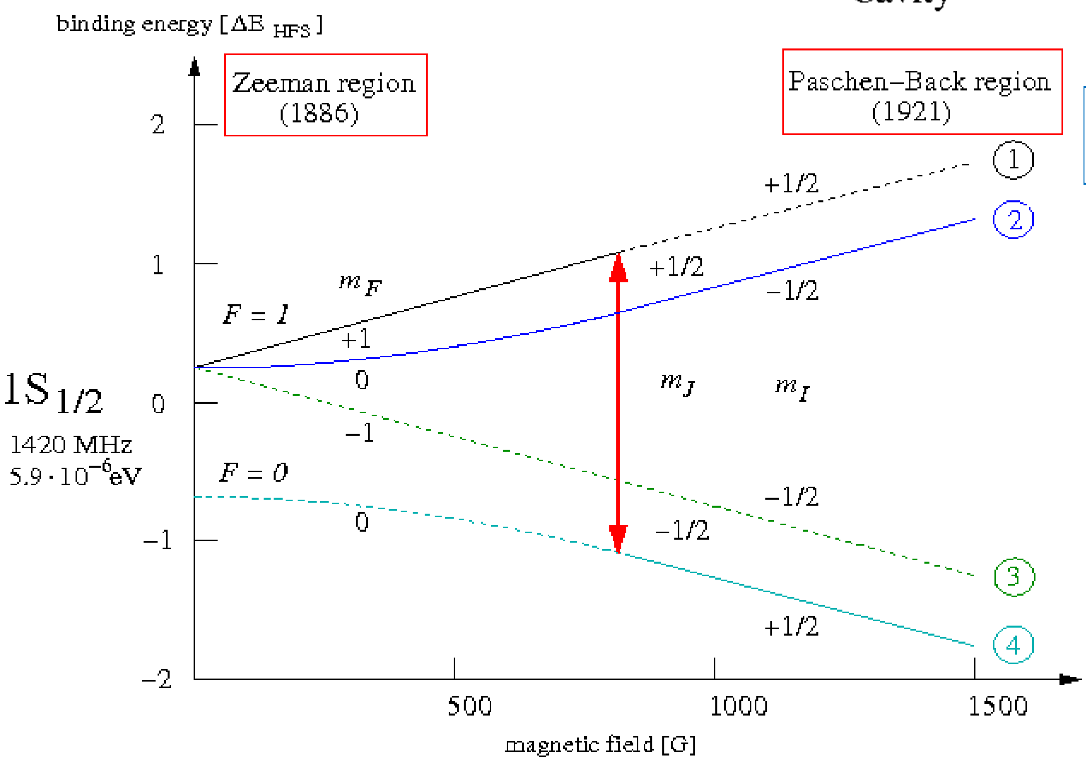
- **internal experiments** – with the circulating beam
- **external experiments** – with the extracted beam



The Rabi Apparatus



The Breit-Rabi Diagram



The Tools: Atomic Beam Source (ABS)

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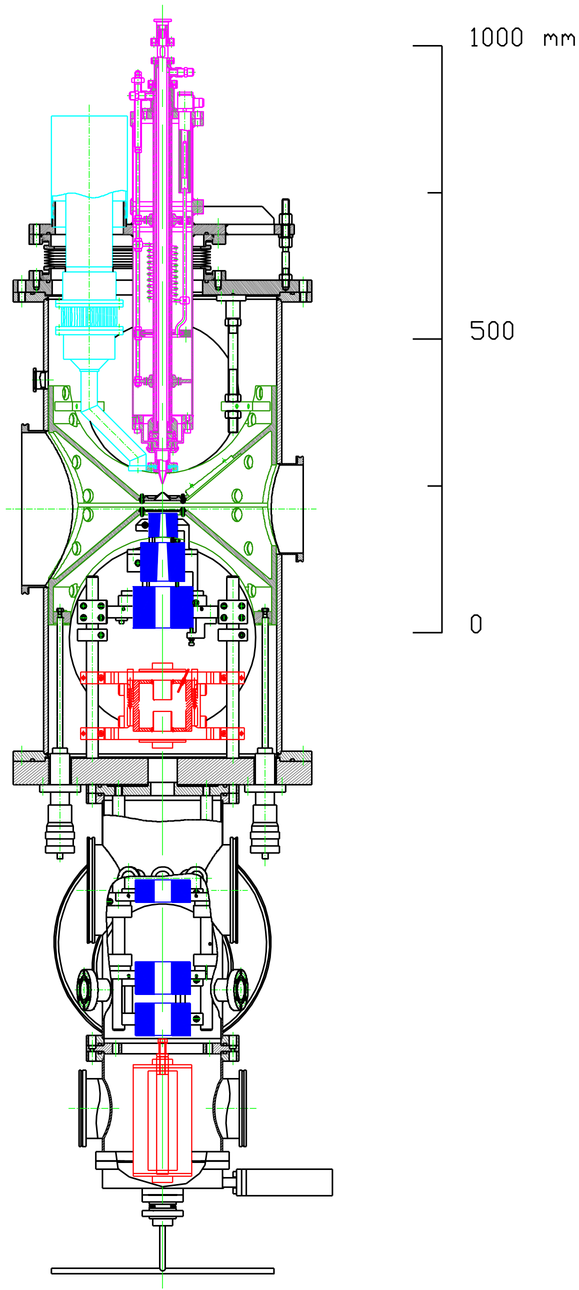

1. Dissoziator: $H_2 \rightarrow 2\ H$
2. Nozzle Cooling: ~ 70 K
3. Stern-Gerlach Magnets (up to 1.7 T)
4. Transition unit
5. Stern-Gerlach Magnets
6. Transition Unit
7. Storage Cell

PIT @ ANKE/COSY

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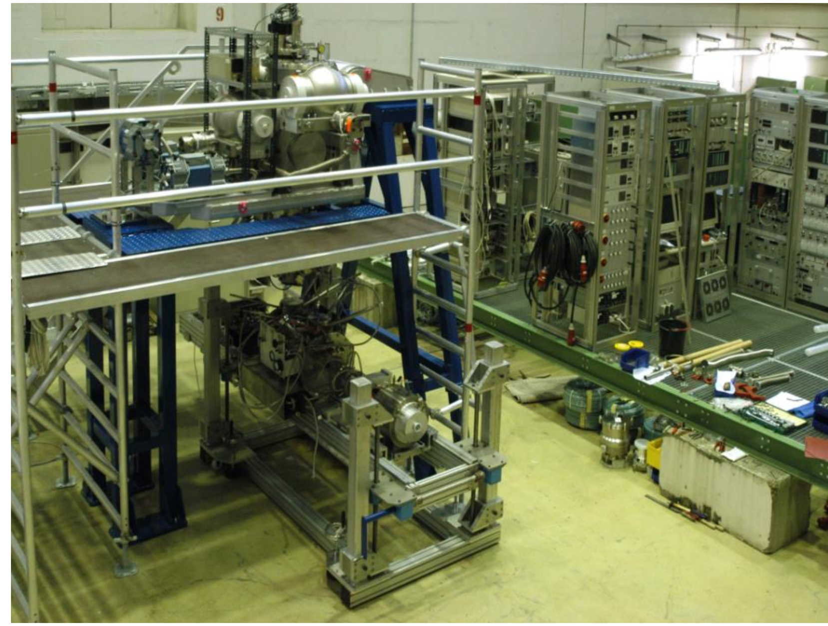
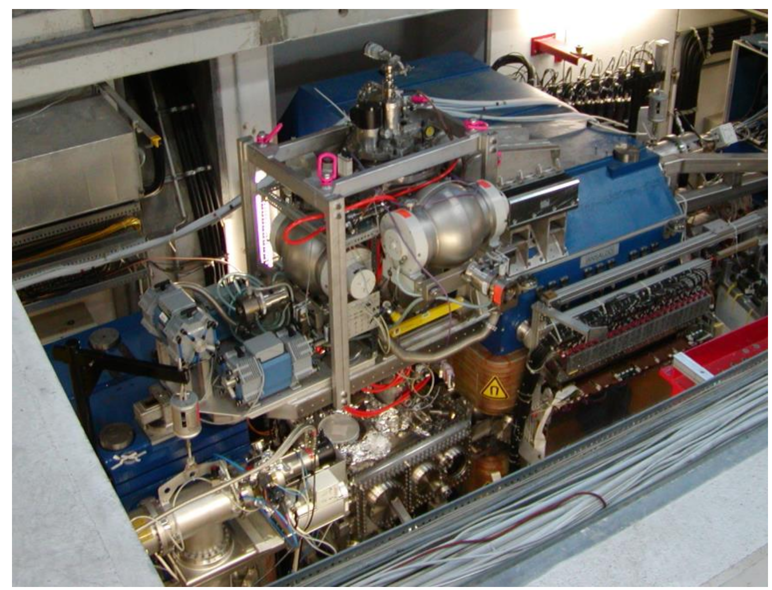


Main parts of a PIT:

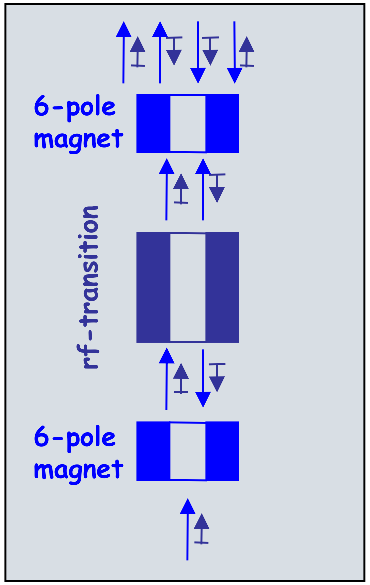
- Atomic Beam Source
  - Target gas
    hydrogen or **deuterium**
  - H beam intensity (2 hyperfine states)
    $\mathbf{8.2 \cdot 10^{16}}$ **atoms / s**
  - Beam size at the interaction point
    $\boldsymbol{\sigma = 2.85 \pm 0.42}$ **mm**
  - Polarization for hydrogen atoms
    $\mathbf{P_Z = \ \ 0.89 \pm 0.01}$ **(HFS 1)**
    $\mathbf{P_Z = -0.96 \pm 0.01}$ **(HFS 3)**

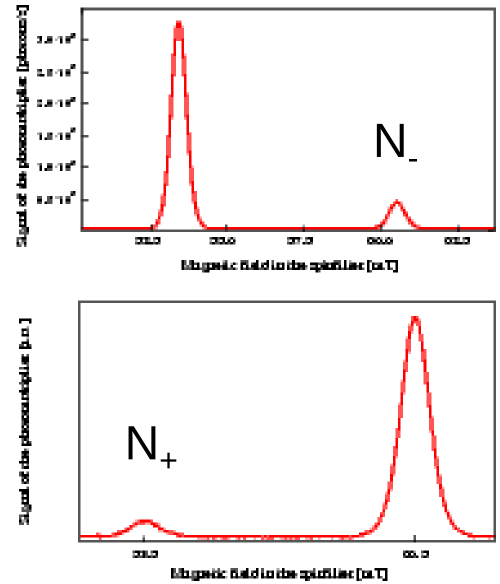
- Lamb-Shift Polarimeter
- Storage Cell

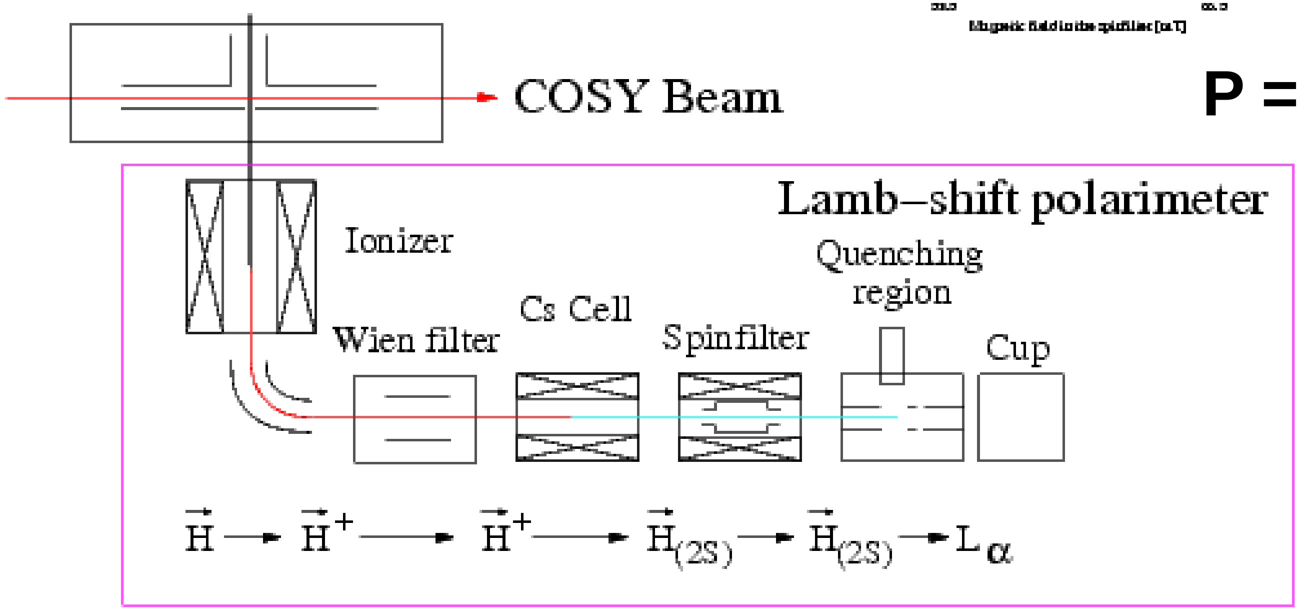


M. Mikirtychyants et al.; NIM A **721** (0) 83 (2013)

ABS and Lamb-shift polarimeter



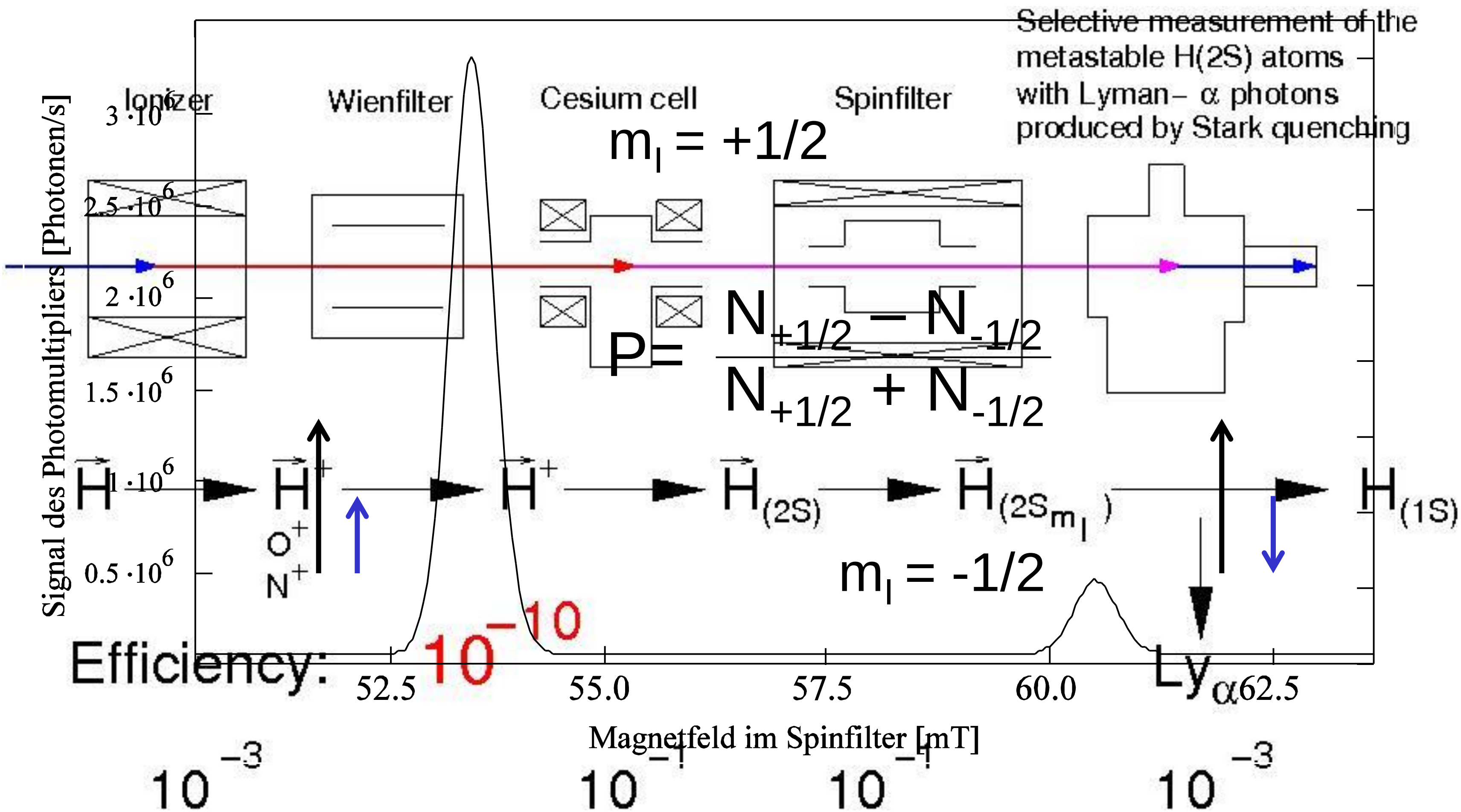




$$P = \frac{N_+ - N_-}{N_+ + N_-}$$

The experimental Setup

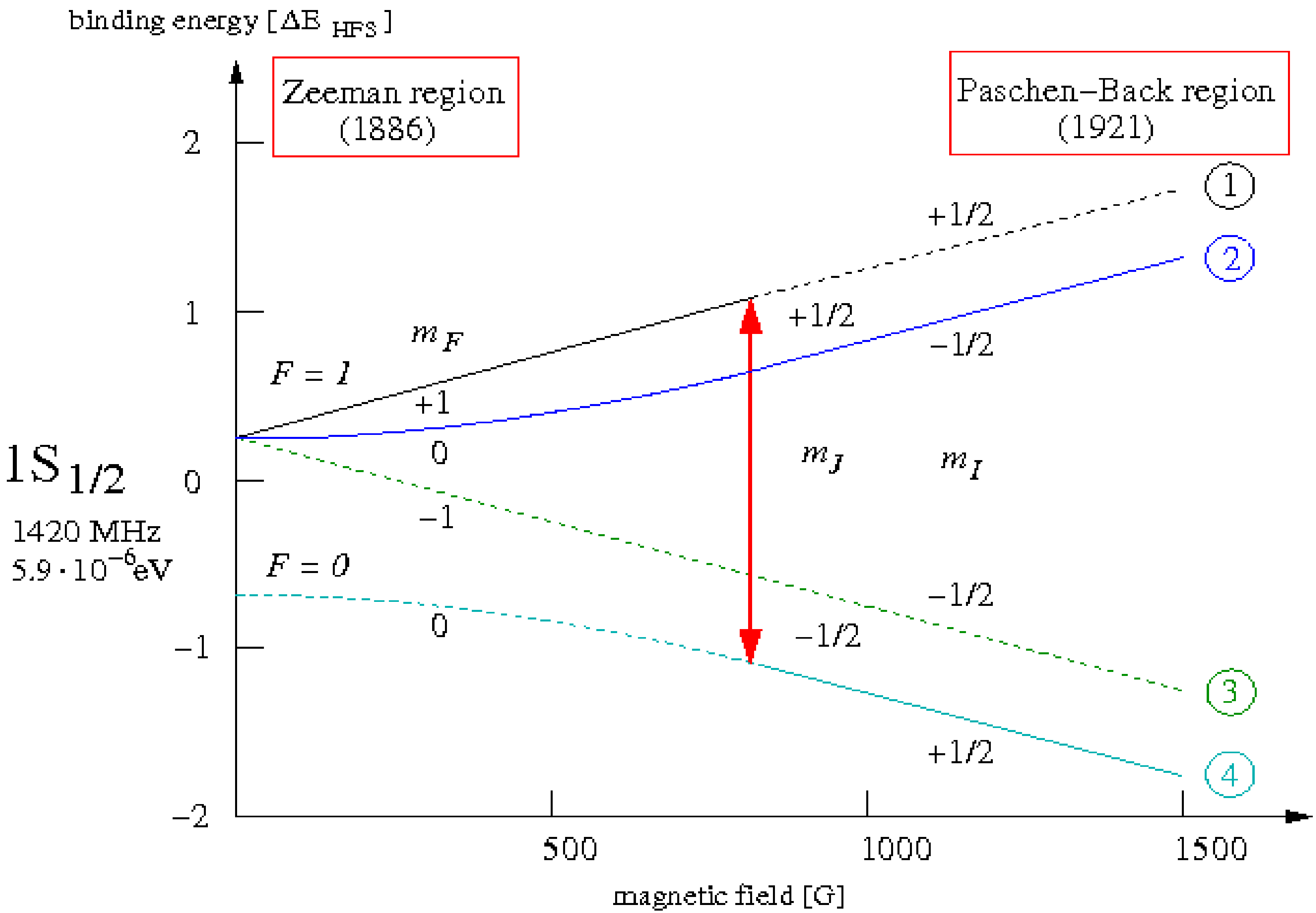
The Lamb-shift Polarimeter



R. Engels et al., Rev. Sci. Instr. **74** 4607 (2003)

R. Engels et al., Rev. Sci. Instr. **85** 103505 (2014)

The Breit-Rabi Diagram: $1S_{1/2}$



Breit and Rabi

$$\chi = 1 \longrightarrow B_c \sim \frac{\Delta E_{HFS}}{2\mu_B} = 50.7\ \text{mT}$$

Zeeman region		Paschen–Back region
$\vert F, m_F>$	$B \to 0$ $<$ B_c $<$ $B \to \infty$	$\vert m_J, m_I>$

$$1 \quad |1,+1> \longleftrightarrow |m_J = +1/2, m_I = +1/2> \longleftrightarrow |+1/2, +1/2>$$

$$2 \quad |1,0> \longleftrightarrow \frac{1}{\sqrt{2}}\left[\sqrt{1+a}\,|+1/2,-1/2> + \sqrt{1-a}\,|-1/2,+1/2>\right] \longleftrightarrow |+1/2, -1/2>$$

$$3 \quad |1,-1> \longleftrightarrow |m_J = -1/2, m_I = -1/2> \longleftrightarrow |-1/2, -1/2>$$

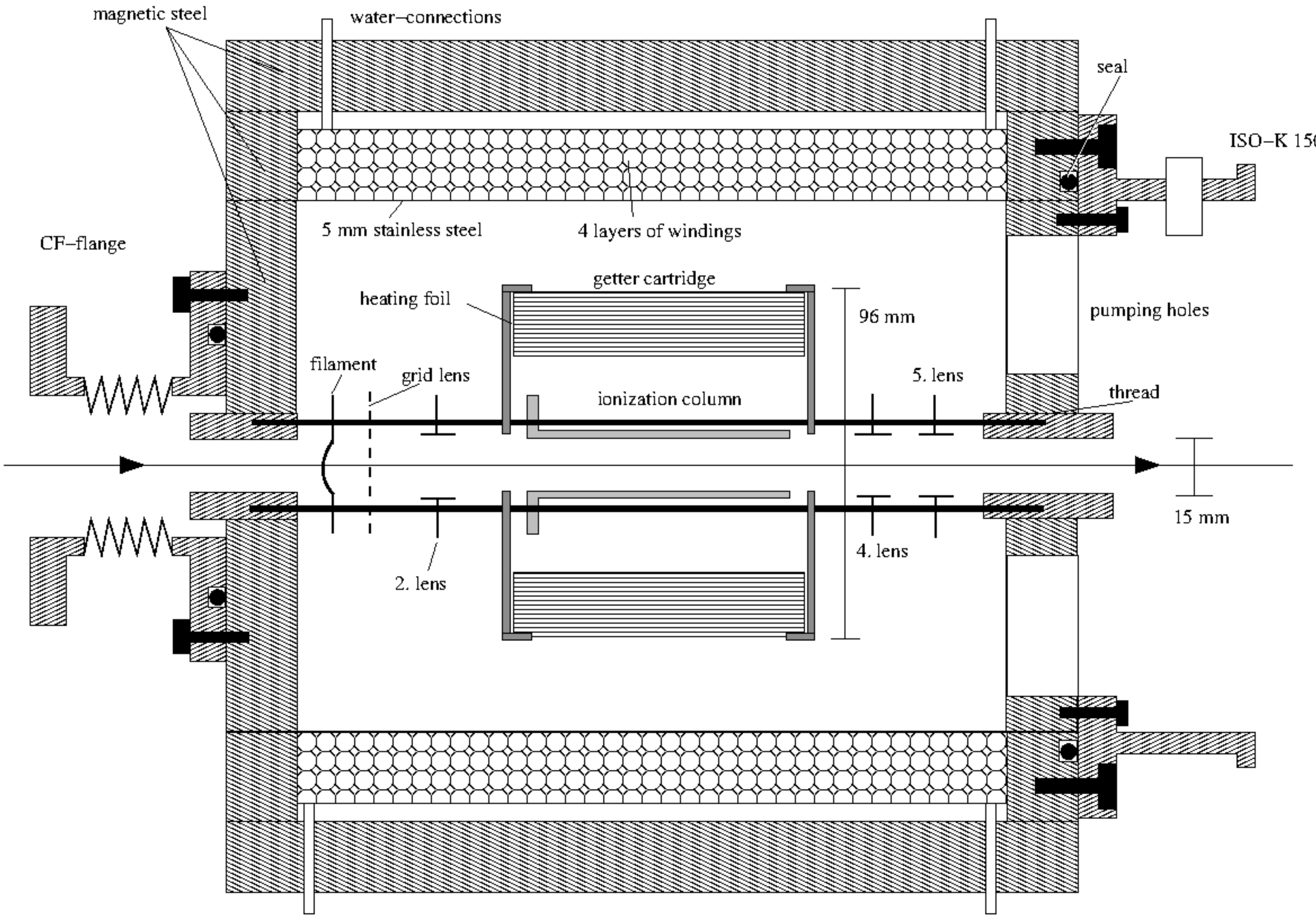
$$4 \quad |0,0> \longleftrightarrow \frac{1}{\sqrt{2}}\left[\sqrt{1-a}\,|+1/2,-1/2> - \sqrt{1+a}\,|-1/2,+1/2>\right] \longleftrightarrow |-1/2, +1/2>$$

$$a_{(B)} = \frac{B/B_c}{\sqrt{1+(B/B_c)^2}}$$

$P_{(HFS\ 4)} = a_{(B)}$

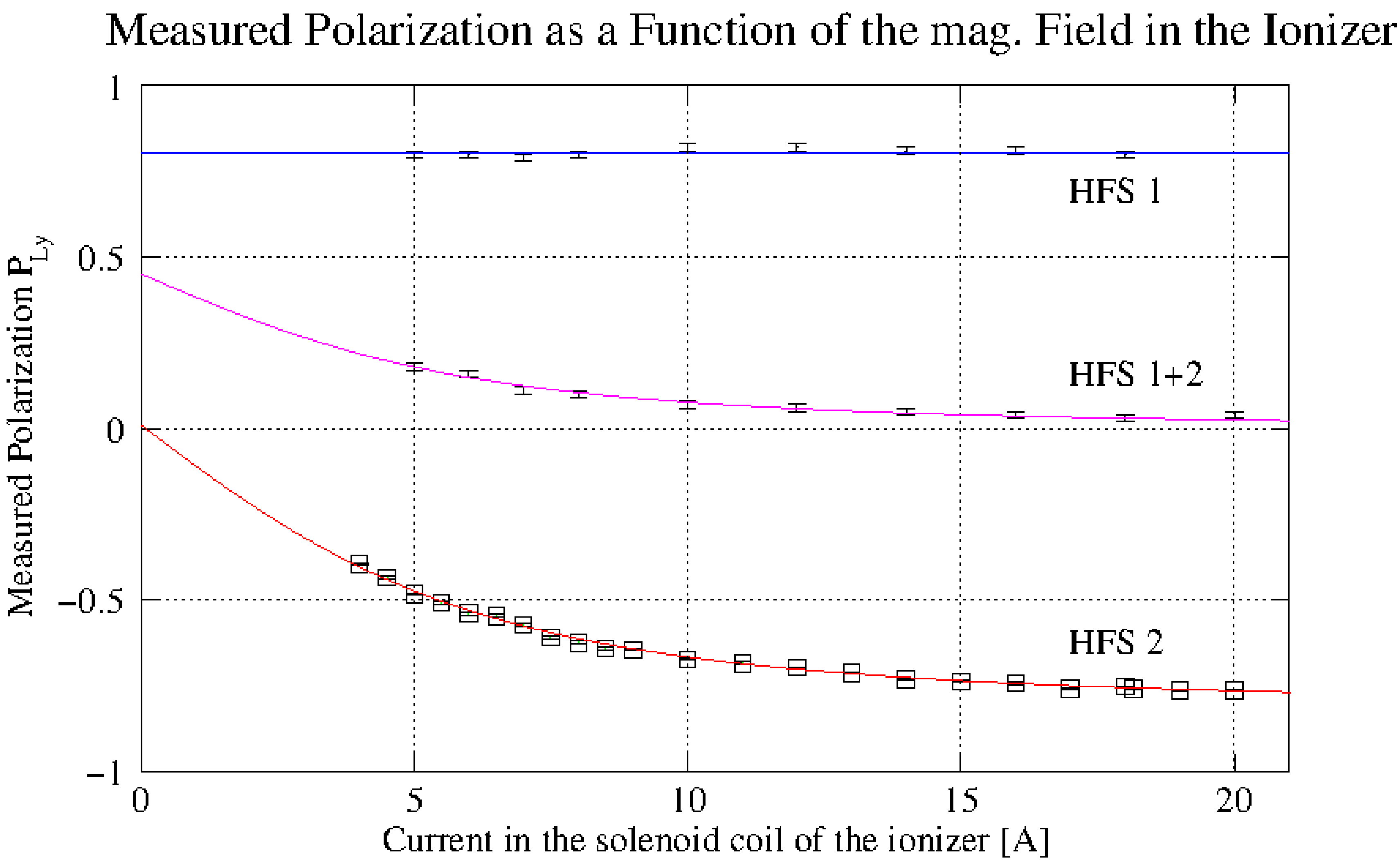
$P_{(HFS\ 2)} = -\ a_{(B)}$

The Ionizer



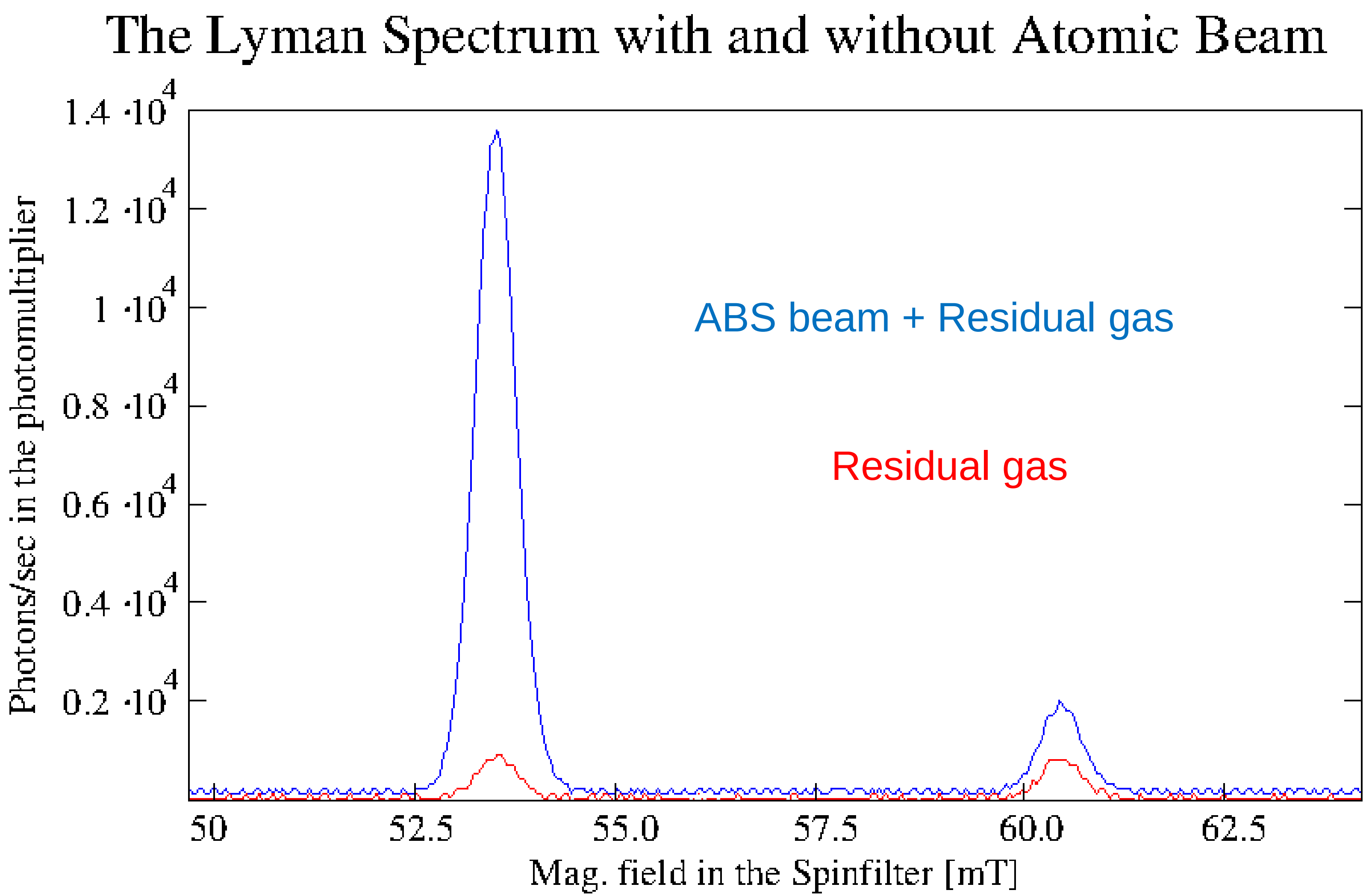
magnetic steel
water–connections
seal
ISO–K 150
CF–flange
5 mm stainless steel
4 layers of windings
getter cartridge
heating foil
96 mm
pumping holes
filament
grid lens
5. lens
thread
ionization column
15 mm
4. lens
2. lens

The Ionizer



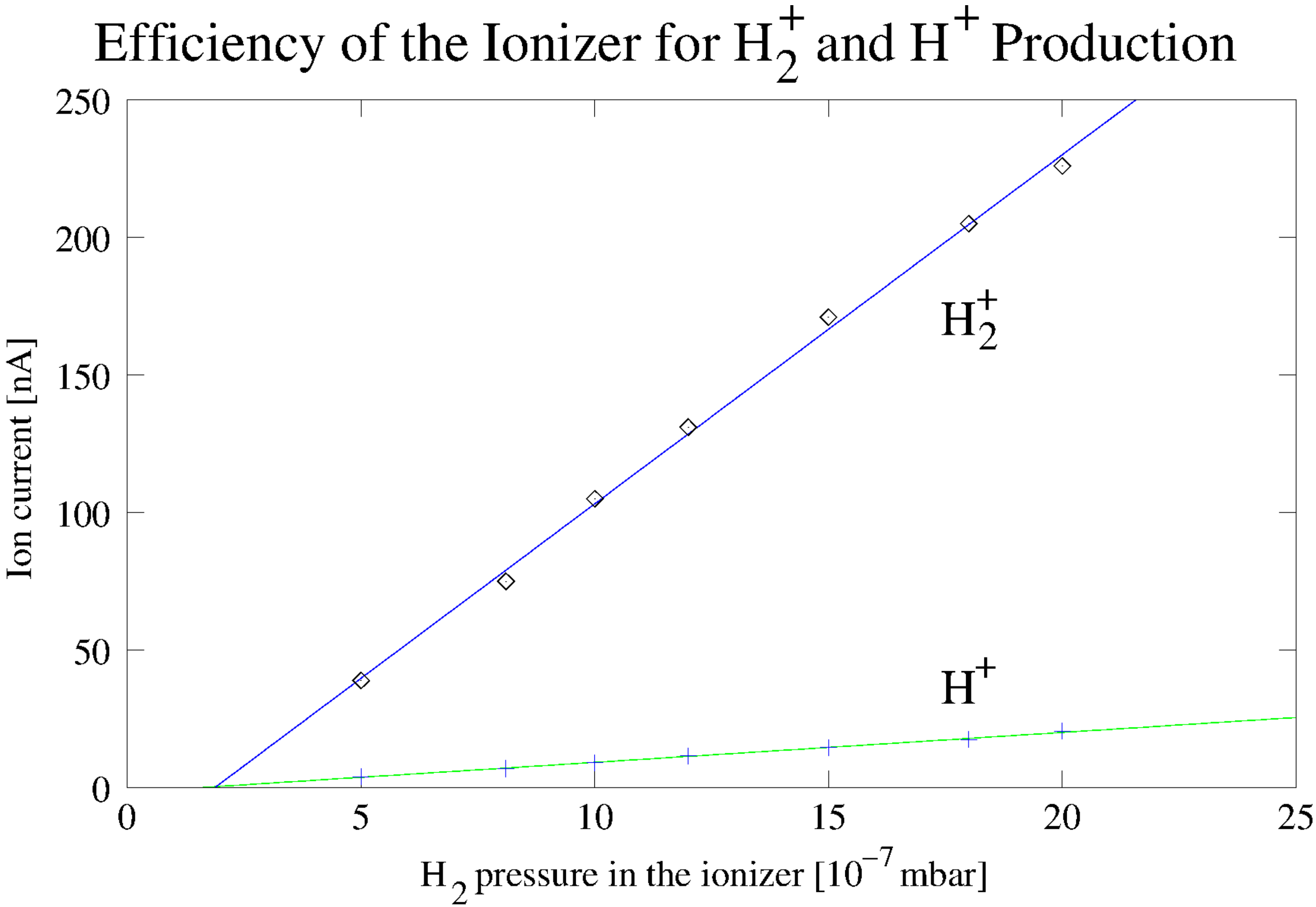
Measured Polarization as a Function of the mag. Field in the Ionizer
Measured Polarization P_{Ly}
Current in the solenoid coil of the ionizer [A]
HFS 1
HFS 1+2
HFS 2
1
0.5
0
−0.5
−1
0
5
10
15
20

The Ionizer

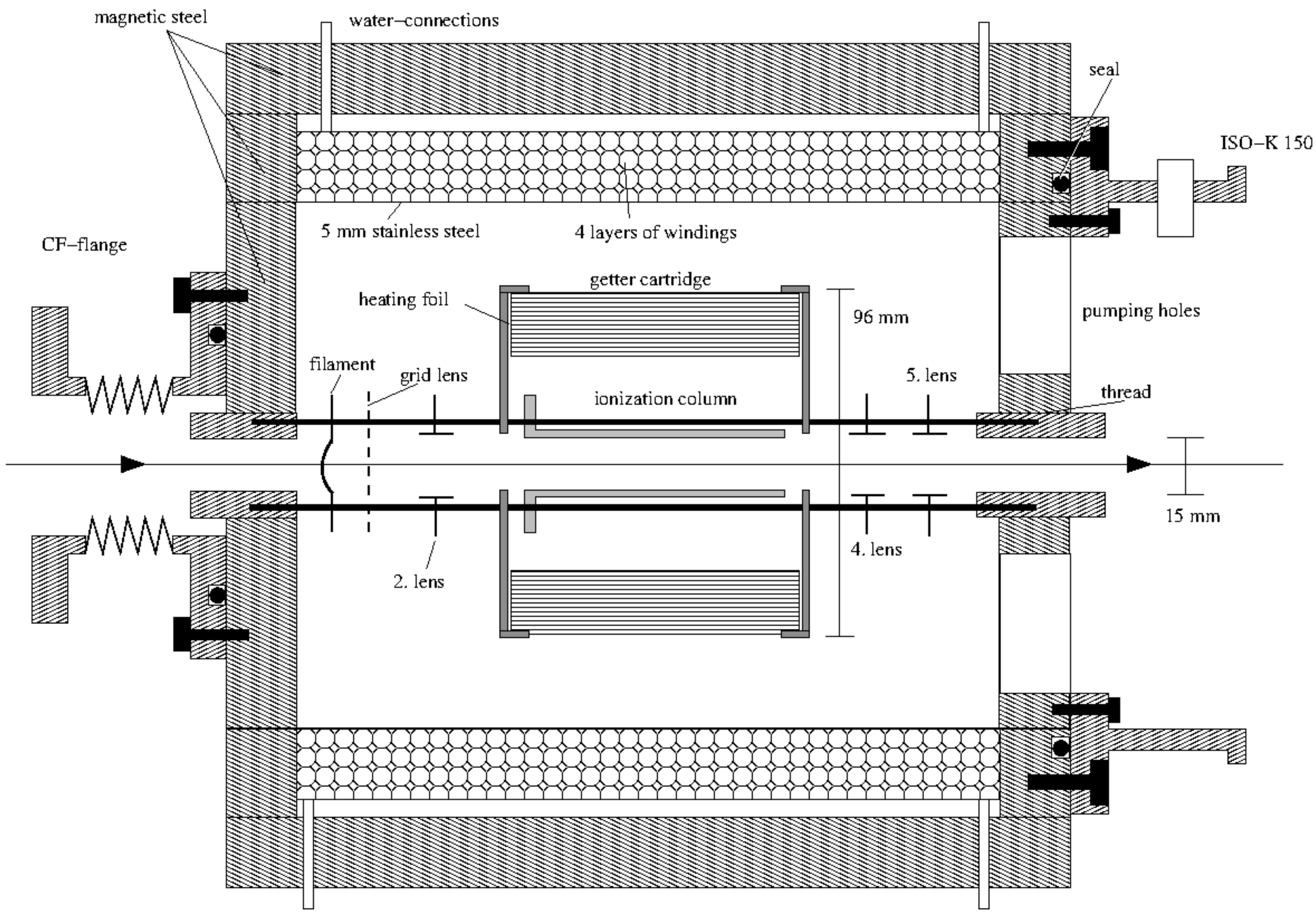


The Lyman Spectrum with and without Atomic Beam
1.4 ·10^4
1.2 ·10^4
1 ·10^4
0.8 ·10^4
0.6 ·10^4
0.4 ·10^4
0.2 ·10^4
Photons/sec in the photomultiplier
50
52.5
55.0
57.5
60.0
62.5
Mag. field in the Spinfilter [mT]
ABS beam + Residual gas
Residual gas

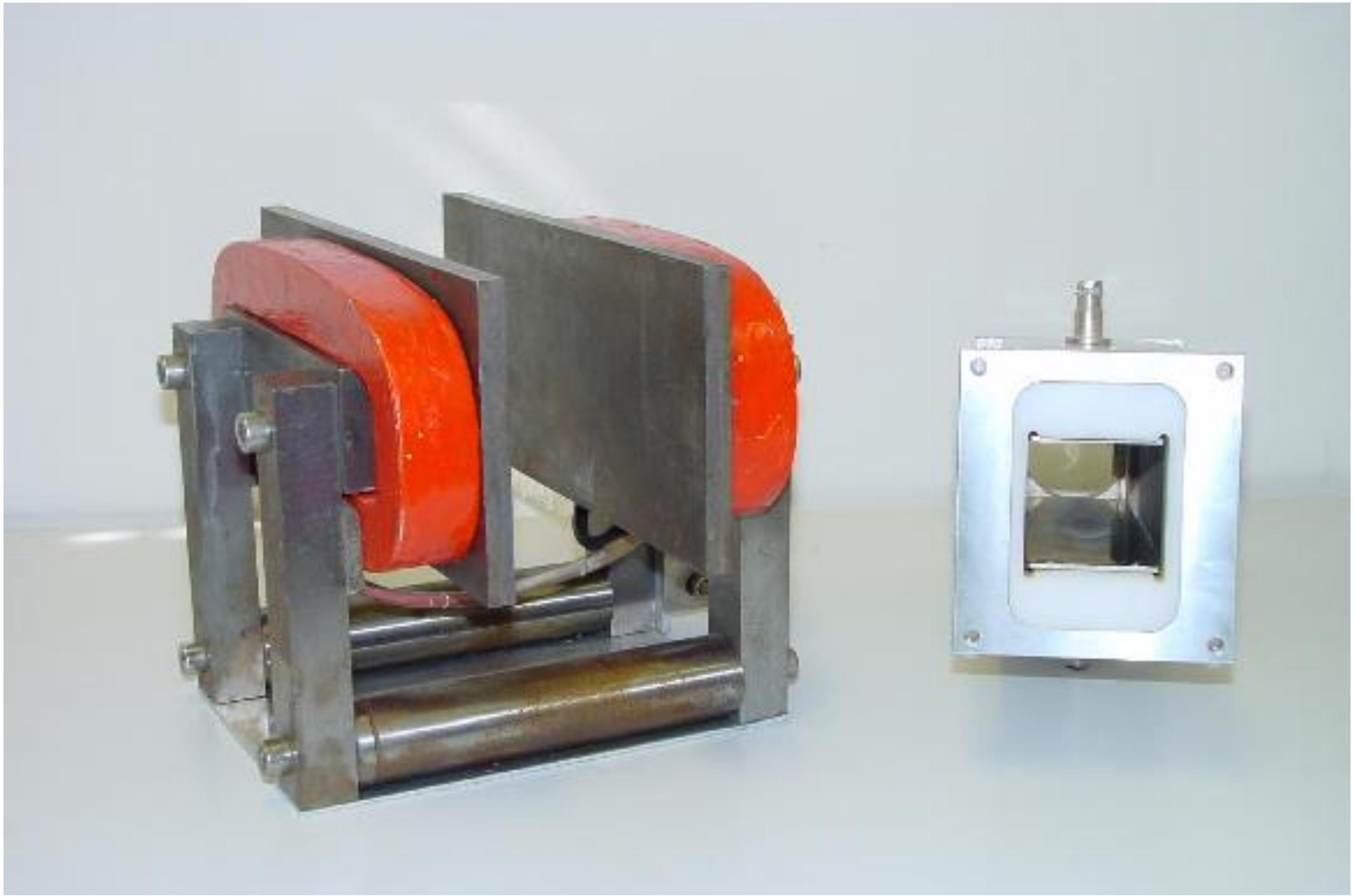
The Ionizer


Efficiency of the Ionizer for H_2^+ and H^+ Production
Ion current [nA]
0
50
100
150
200
250
0
5
10
15
20
25
H_2^+
H^+
H_2 pressure in the ionizer [10^{-7} mbar]

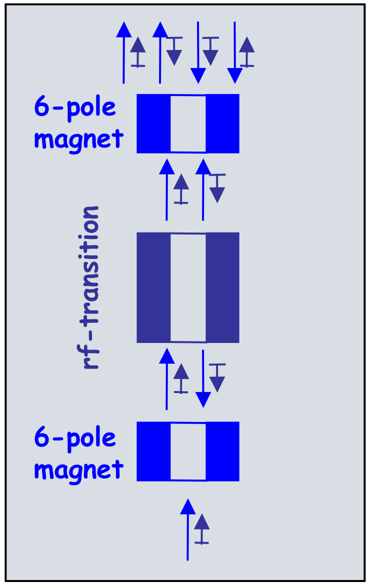
The Ionizer

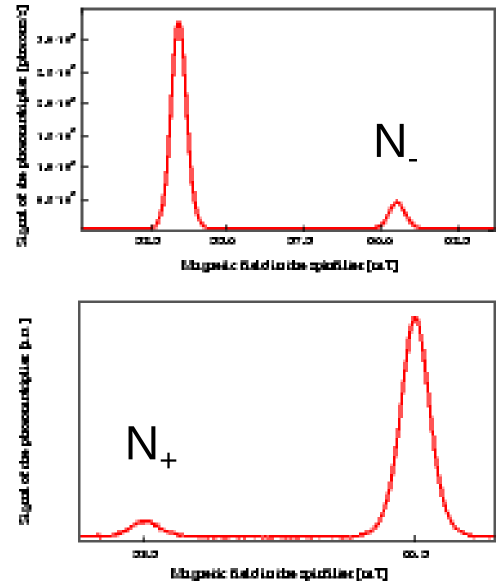

magnetic steel
water–connections
seal
ISO–K 150
CF–flange
5 mm stainless steel
4 layers of windings
getter cartridge
heating foil
96 mm
pumping holes
filament
grid lens
5. lens
thread
ionization column
15 mm
4. lens
2. lens

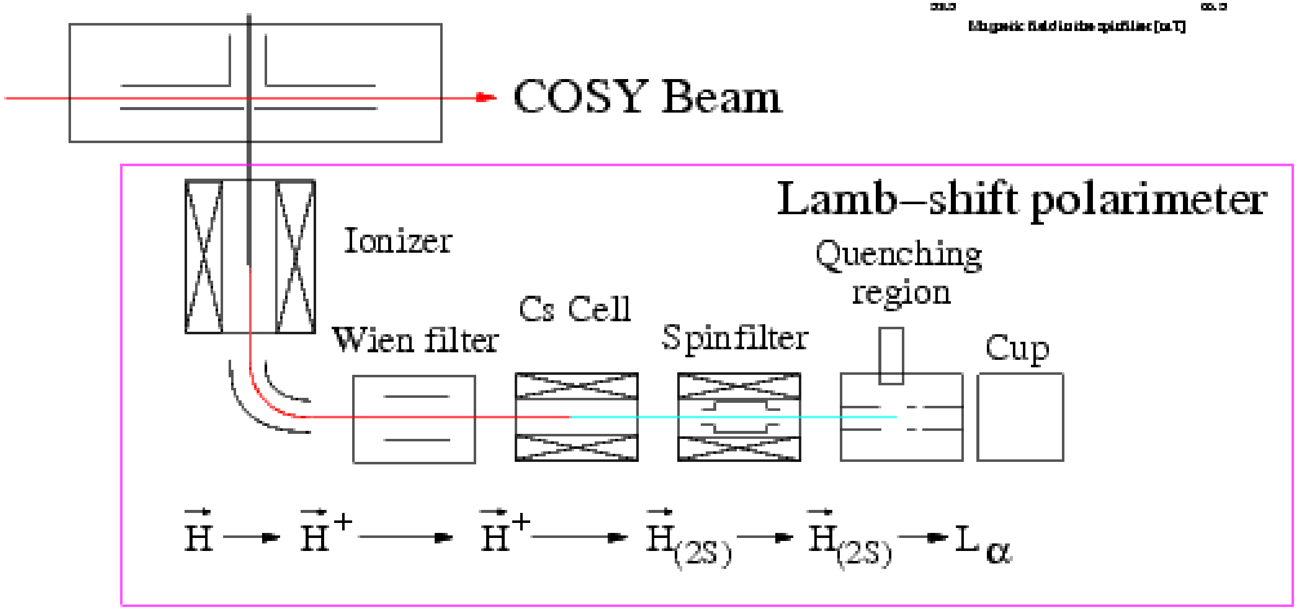
The Wienfilter



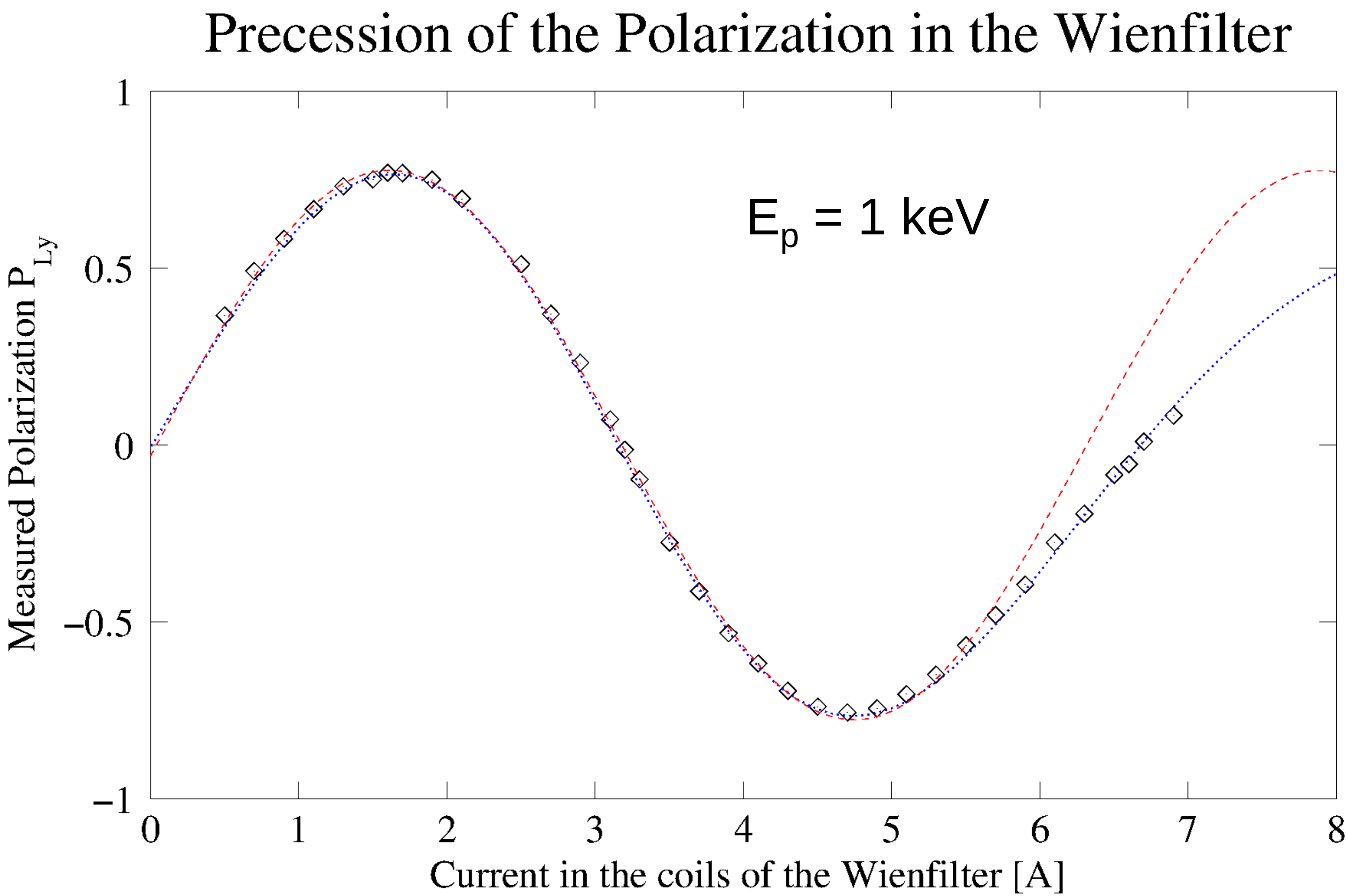
ABS and Lamb-shift polarimeter



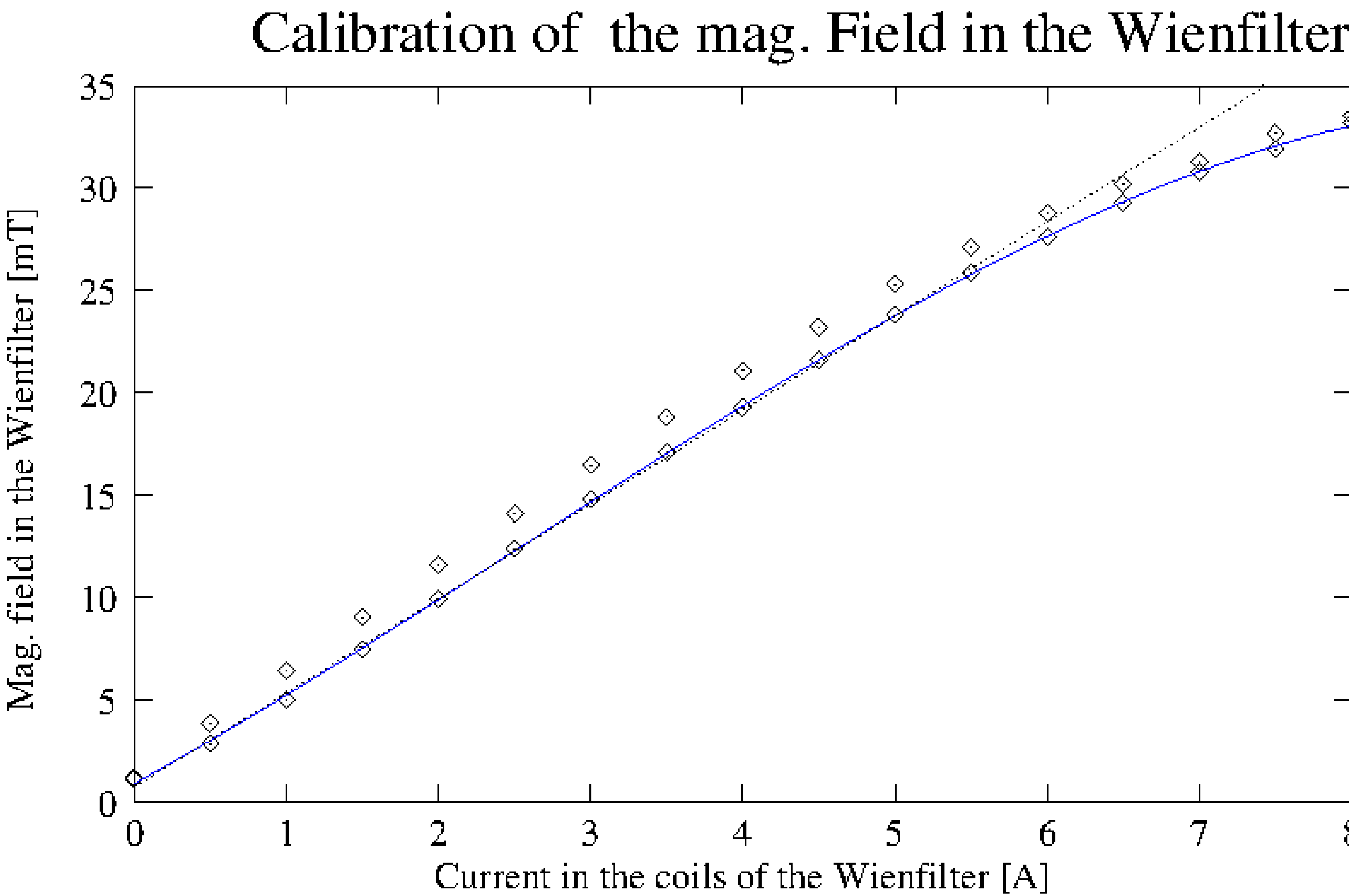




The Wienfilter

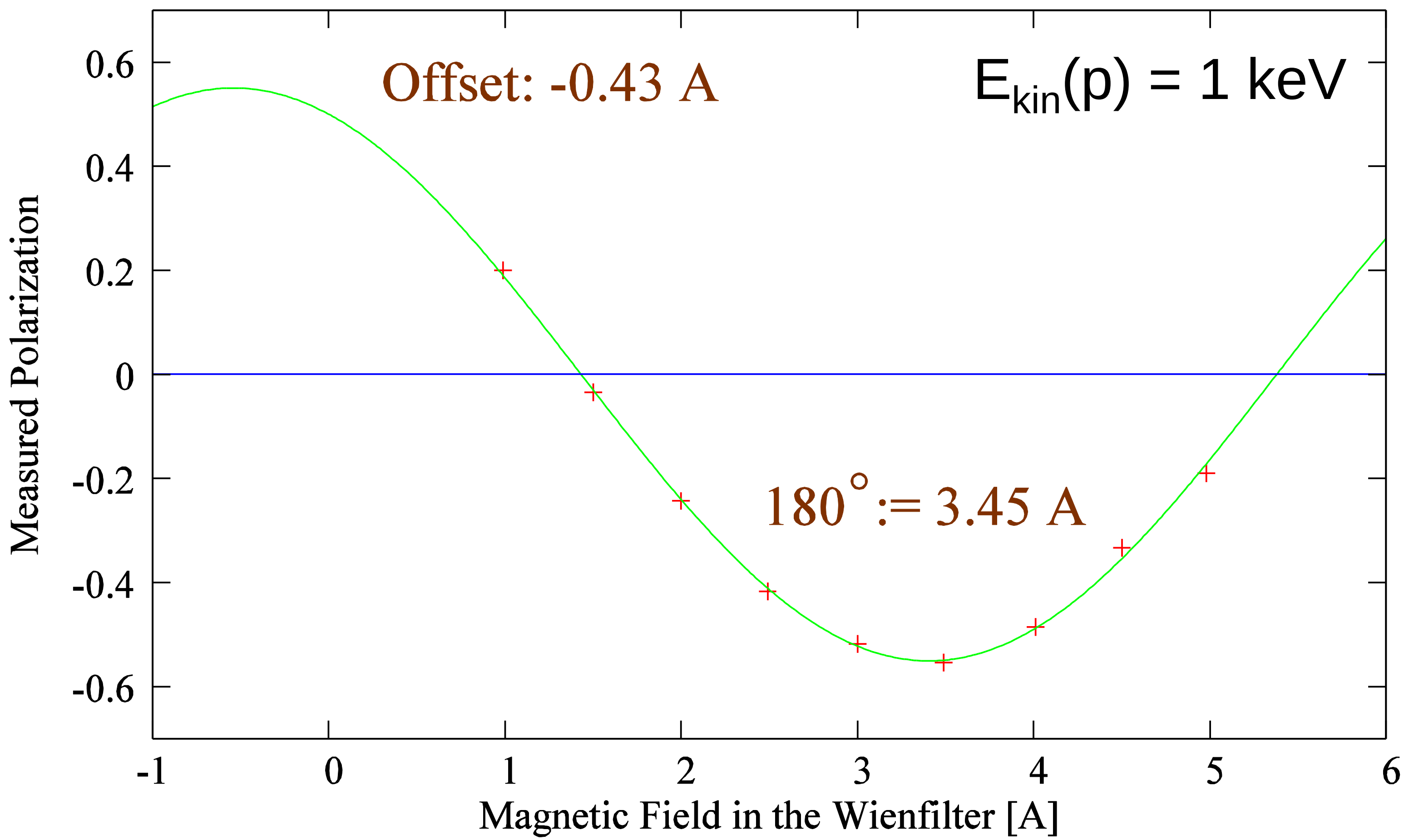


The Wien filter



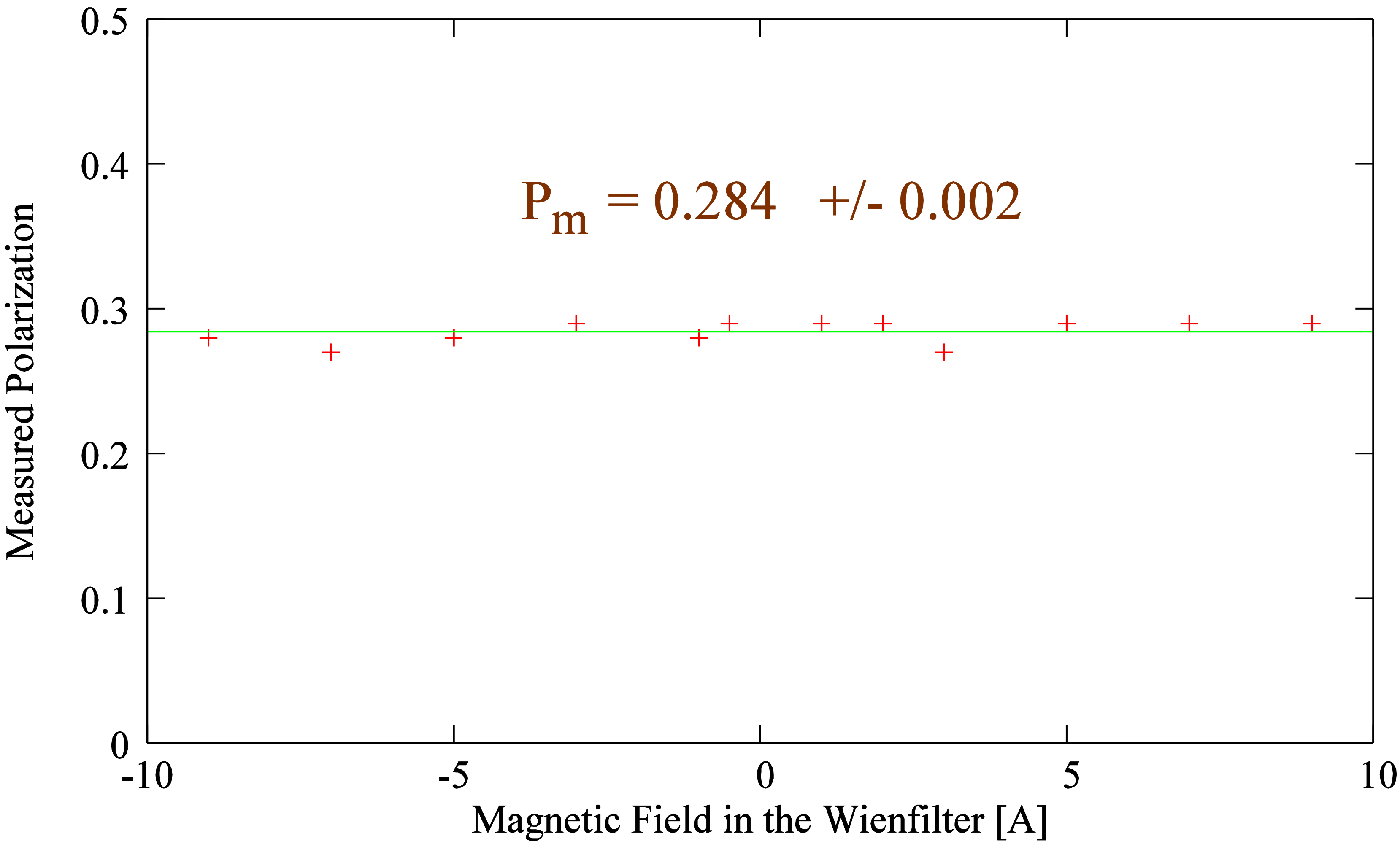
Experimental results

Wienfilter function of the protons in the LSP

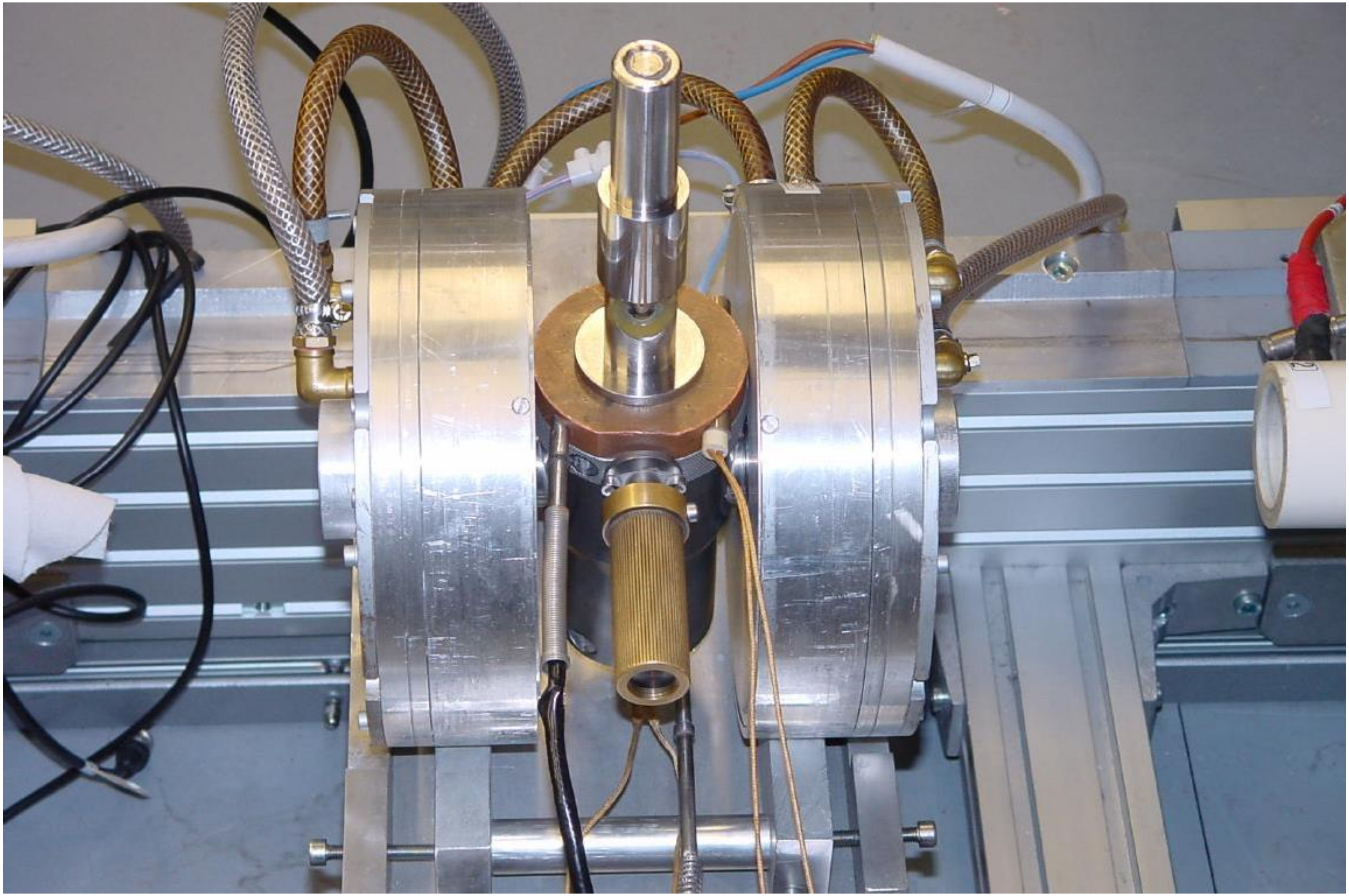


The Wien filter

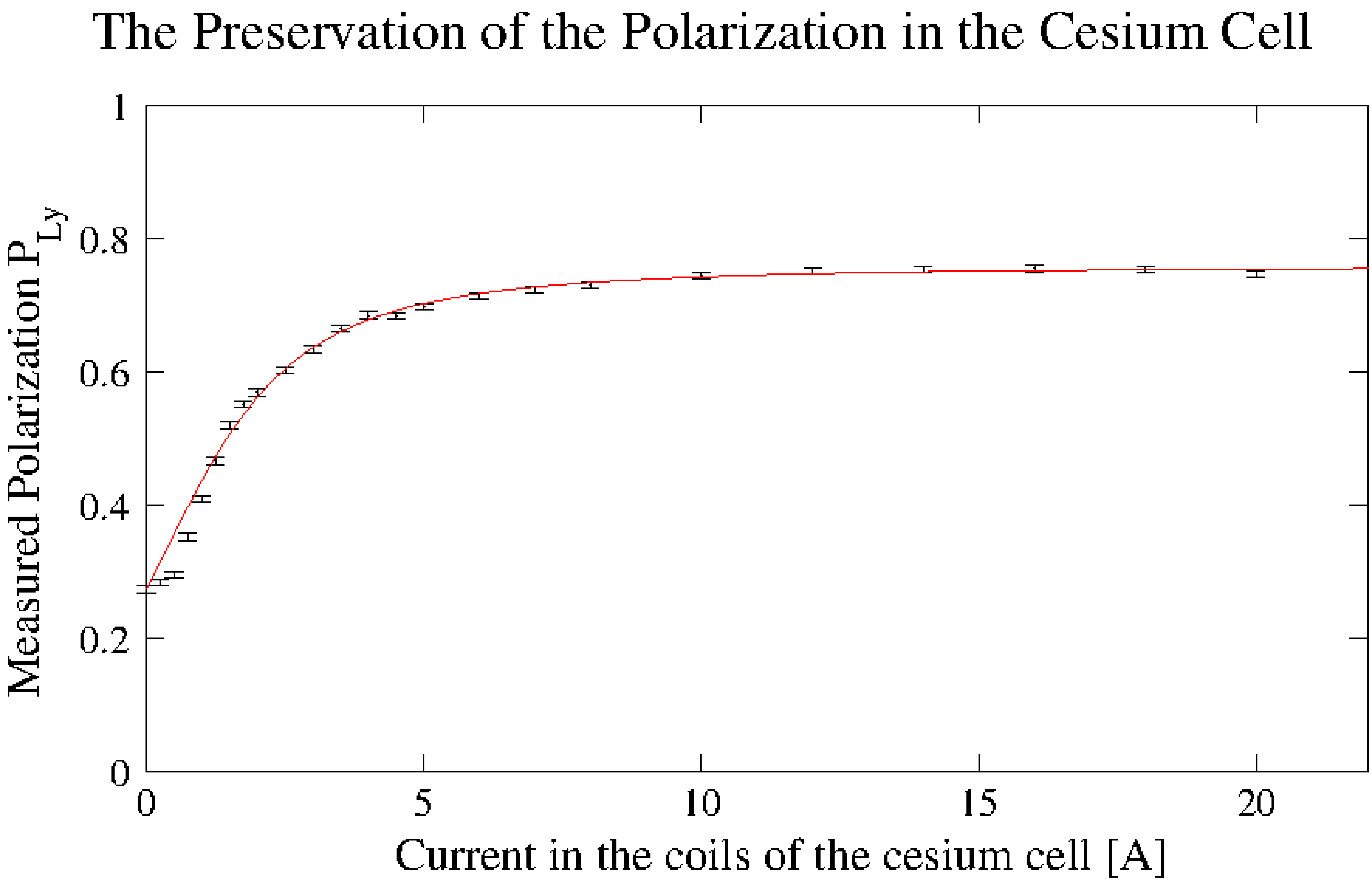
Wienfilter function of the H_2^+ in the LSP



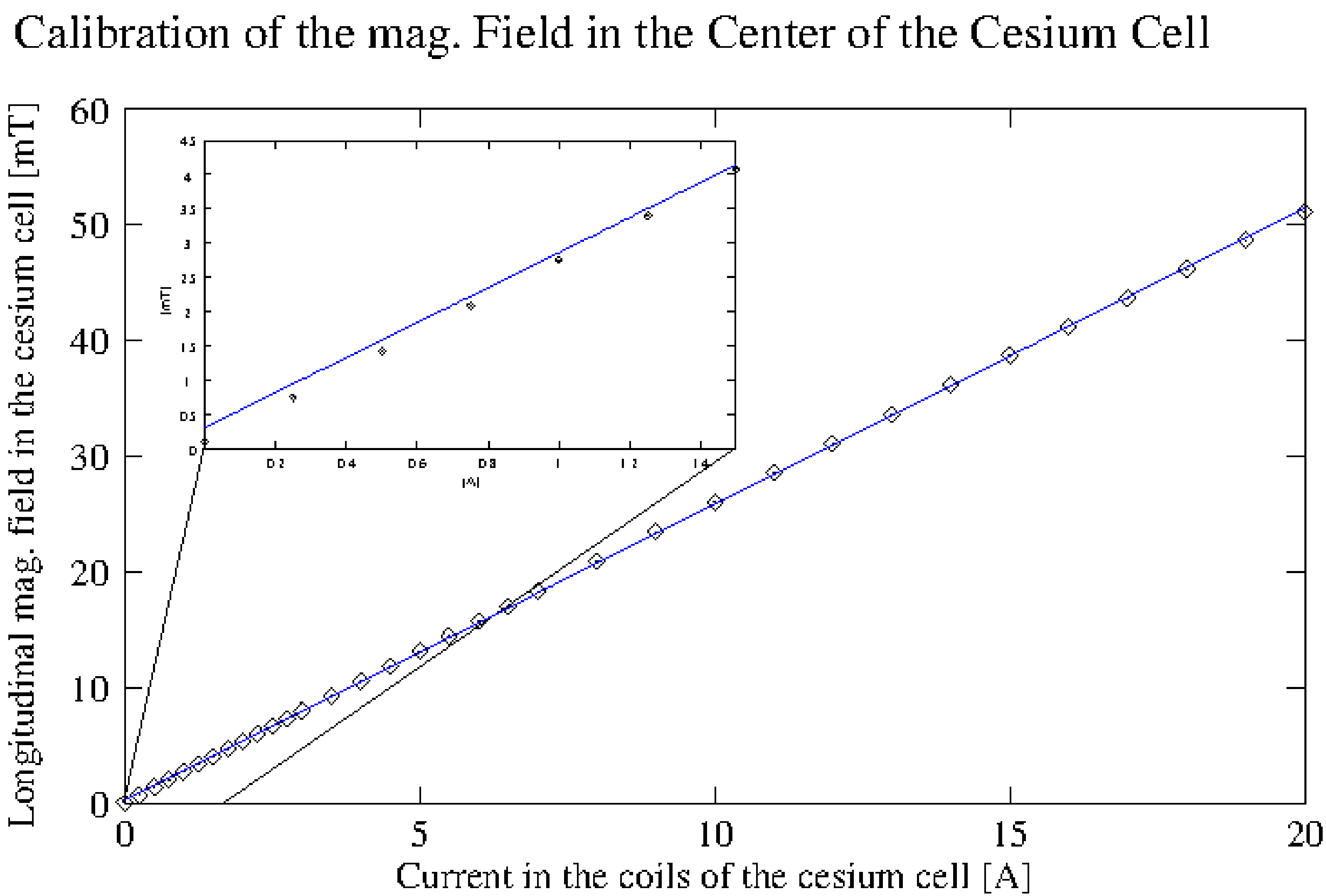
The Cesium Cell



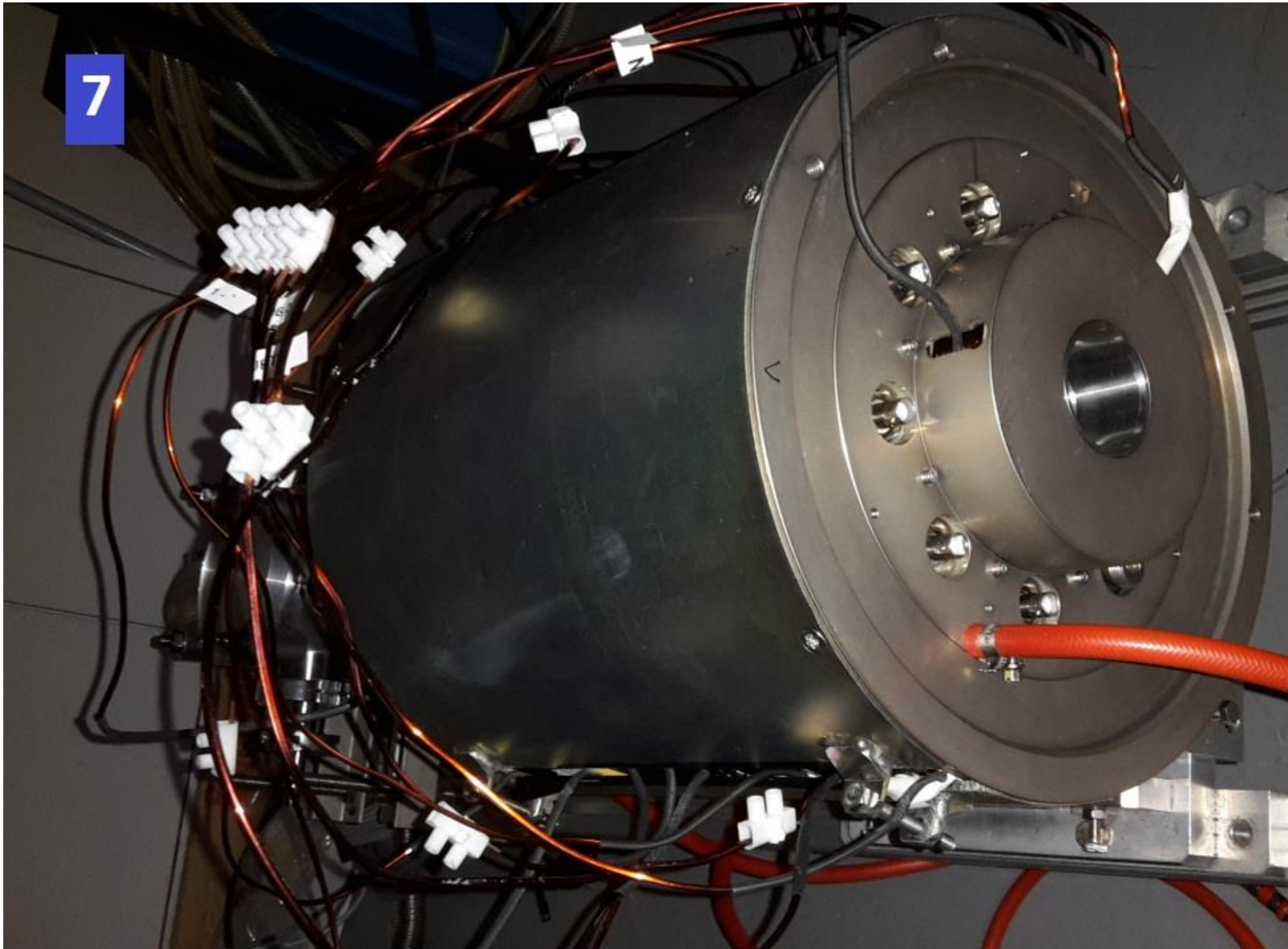
The Cesium Cell



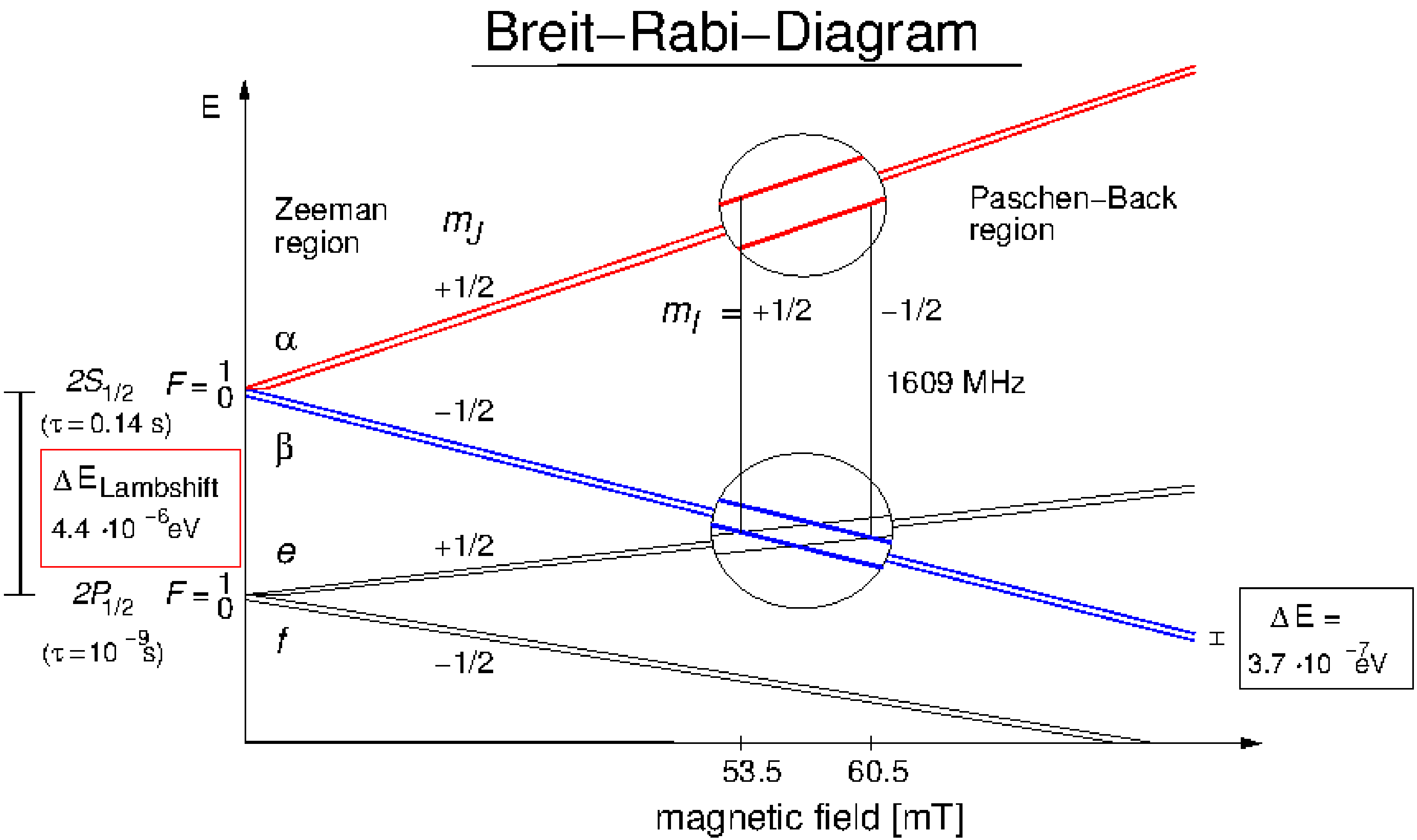
The Cesium Cell



The Spinfilter



The Spinfilter



The Spinfilter

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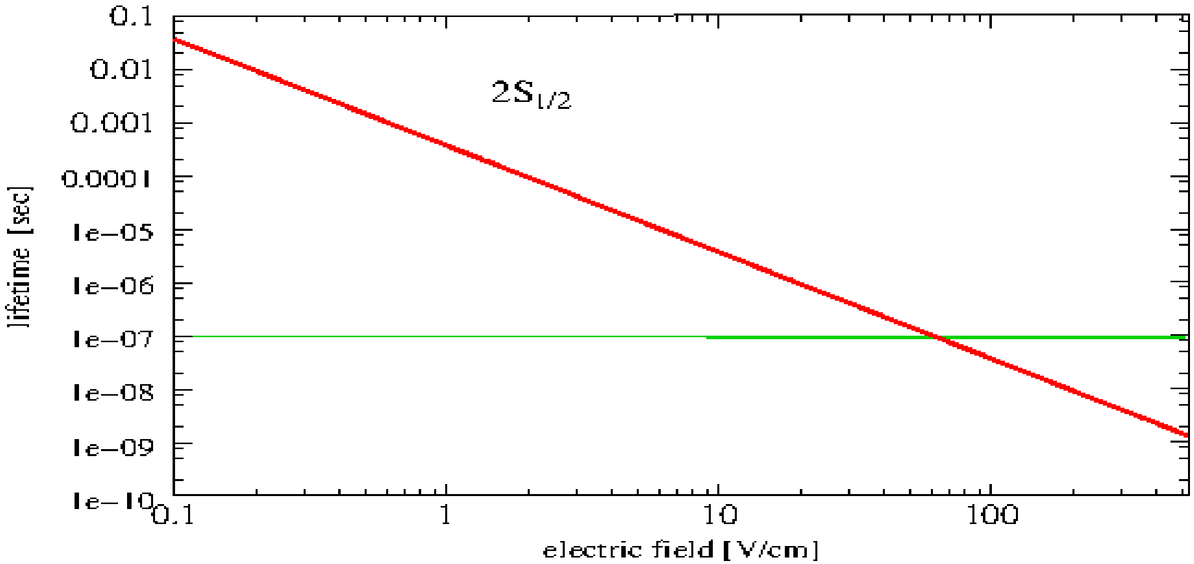
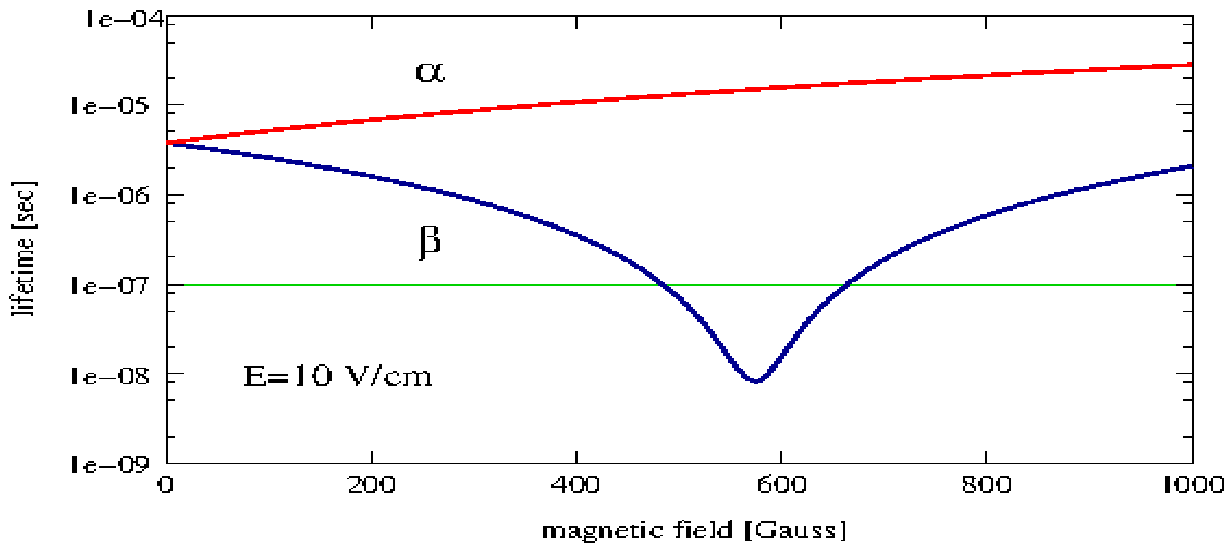
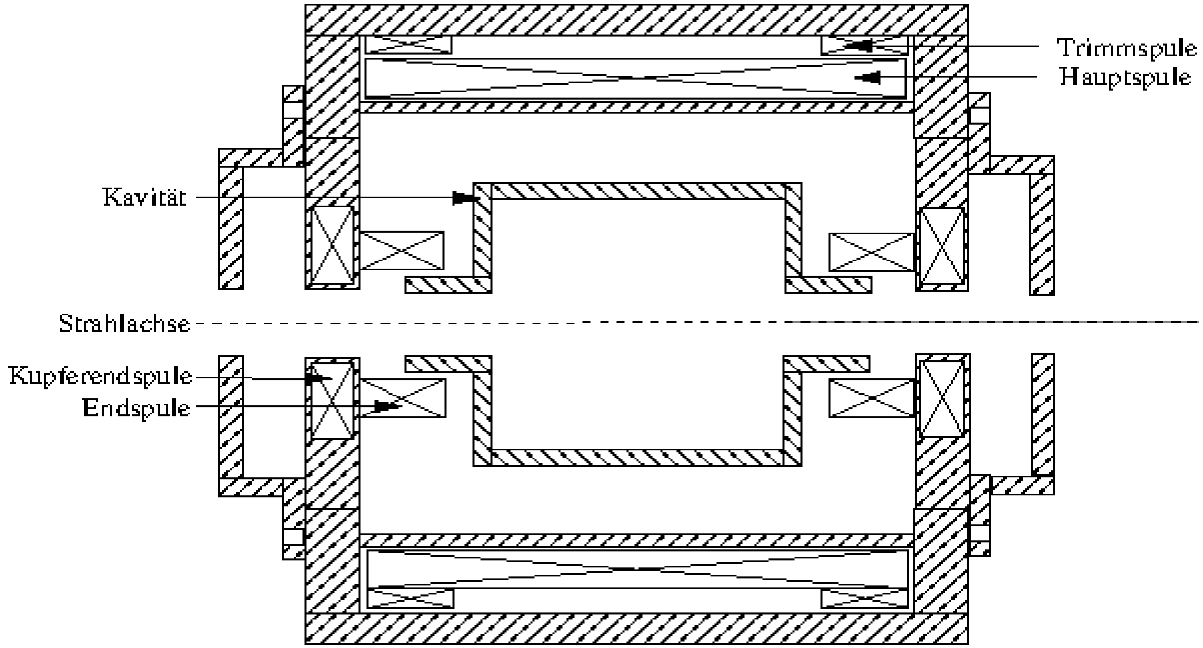
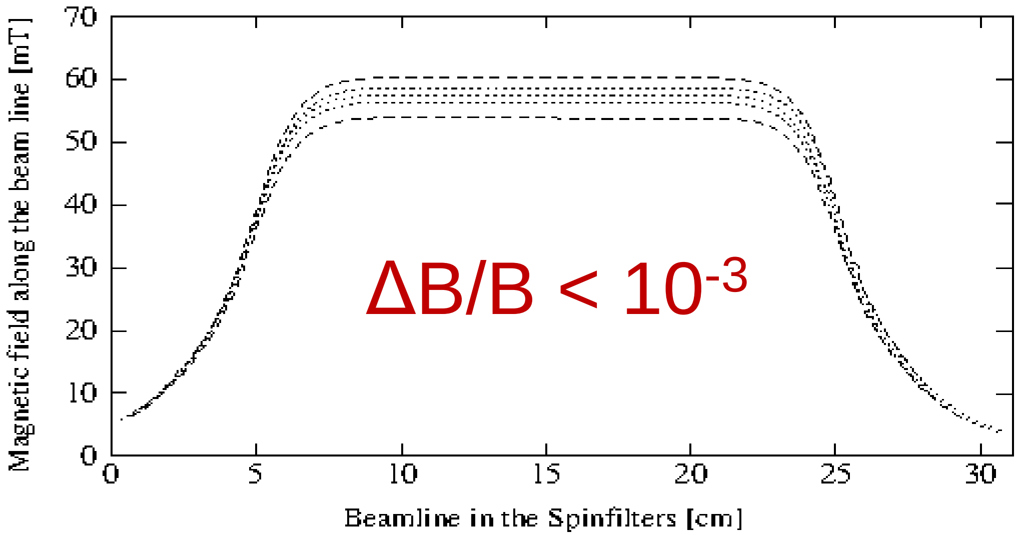


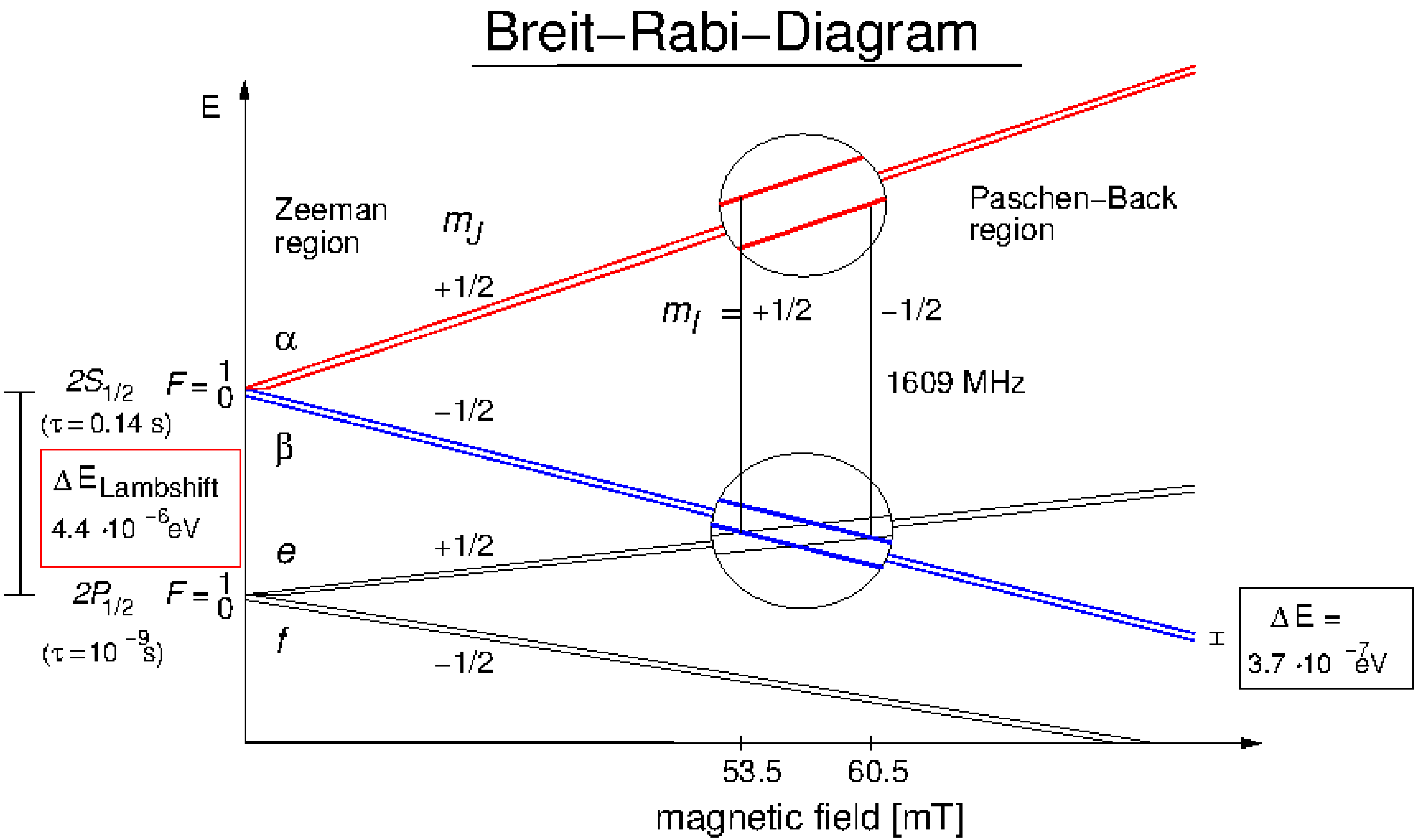


The Spinfilter





The Spinfilter



The Spinfilter

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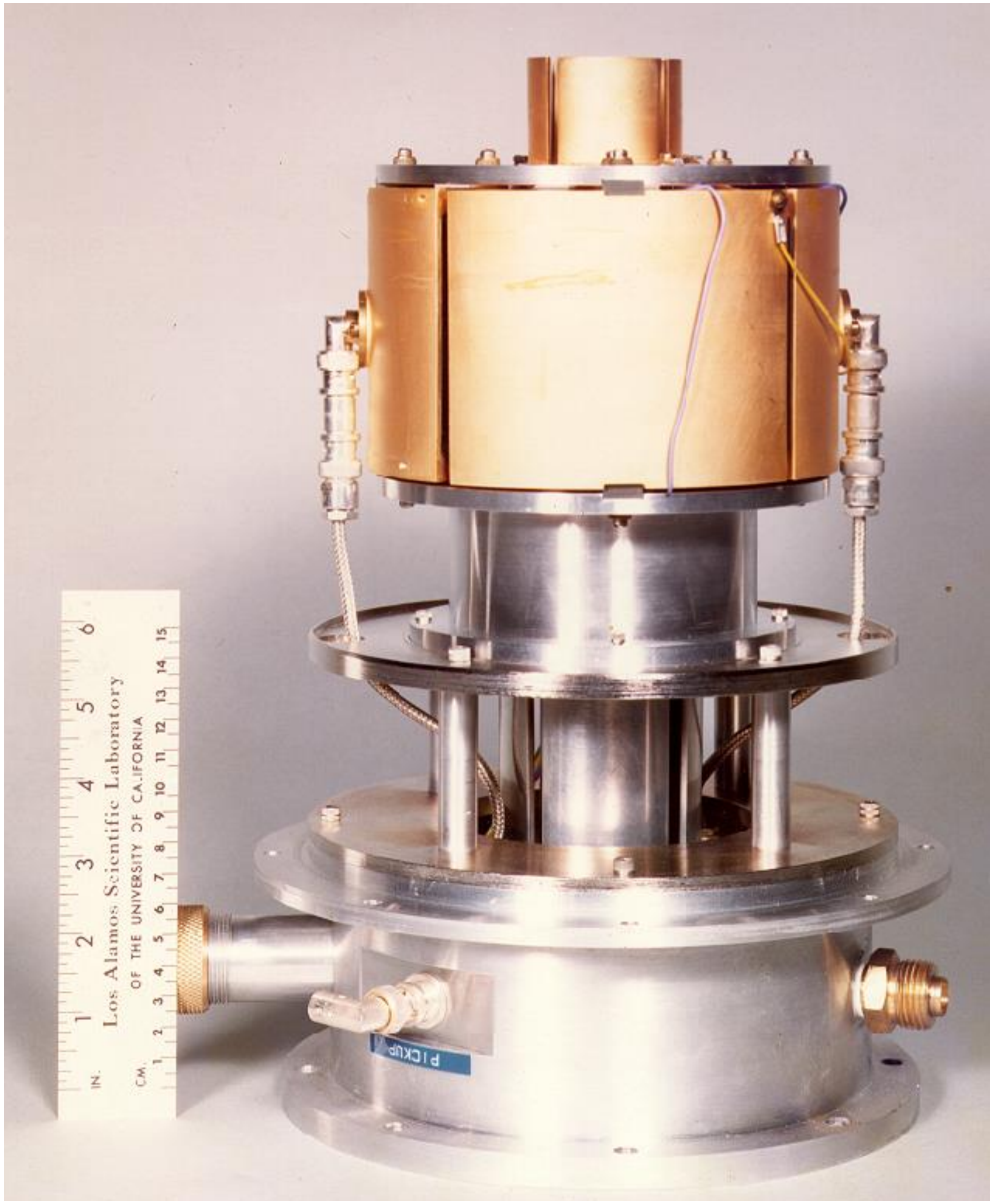
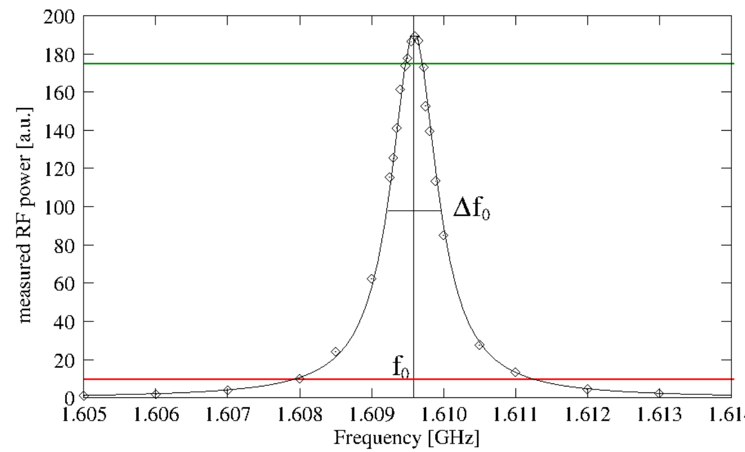
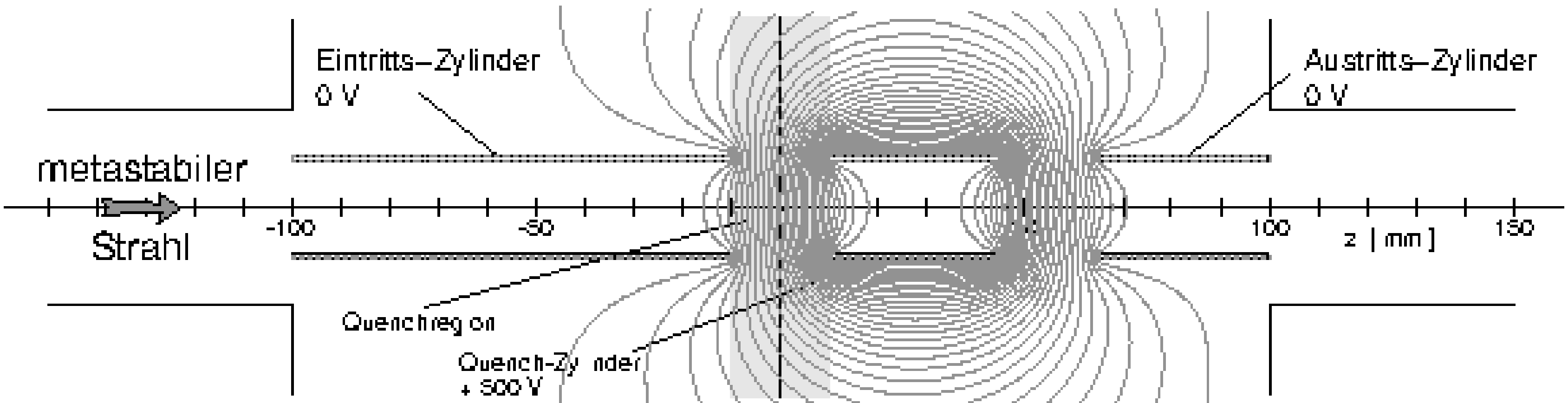




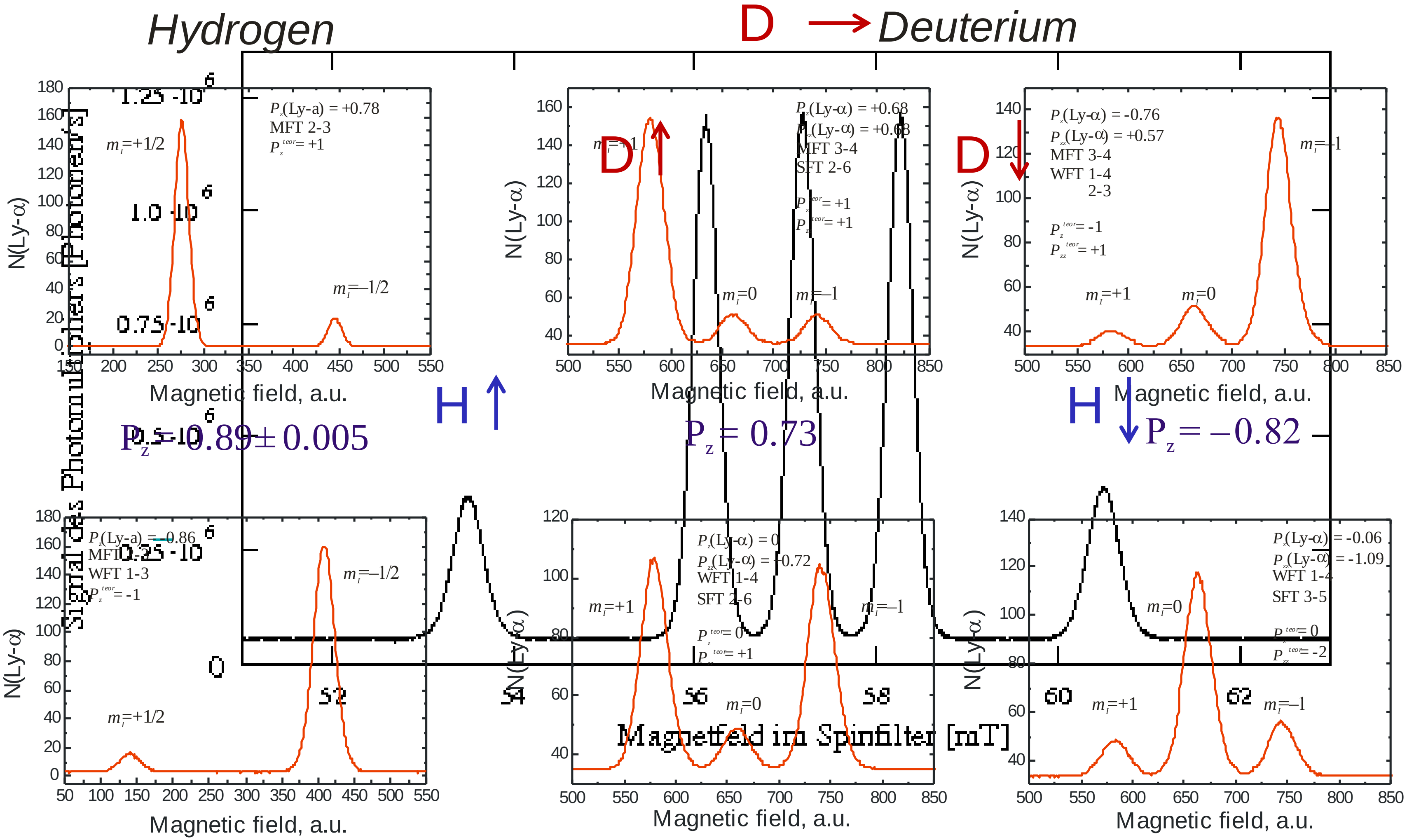
$f/\Delta f > 1600$

The Quenching Chamber

Photomultiplier



The Lyman-α Spectra



$P_z = 0.89 \pm 0.005$

$P_z = 0.73$

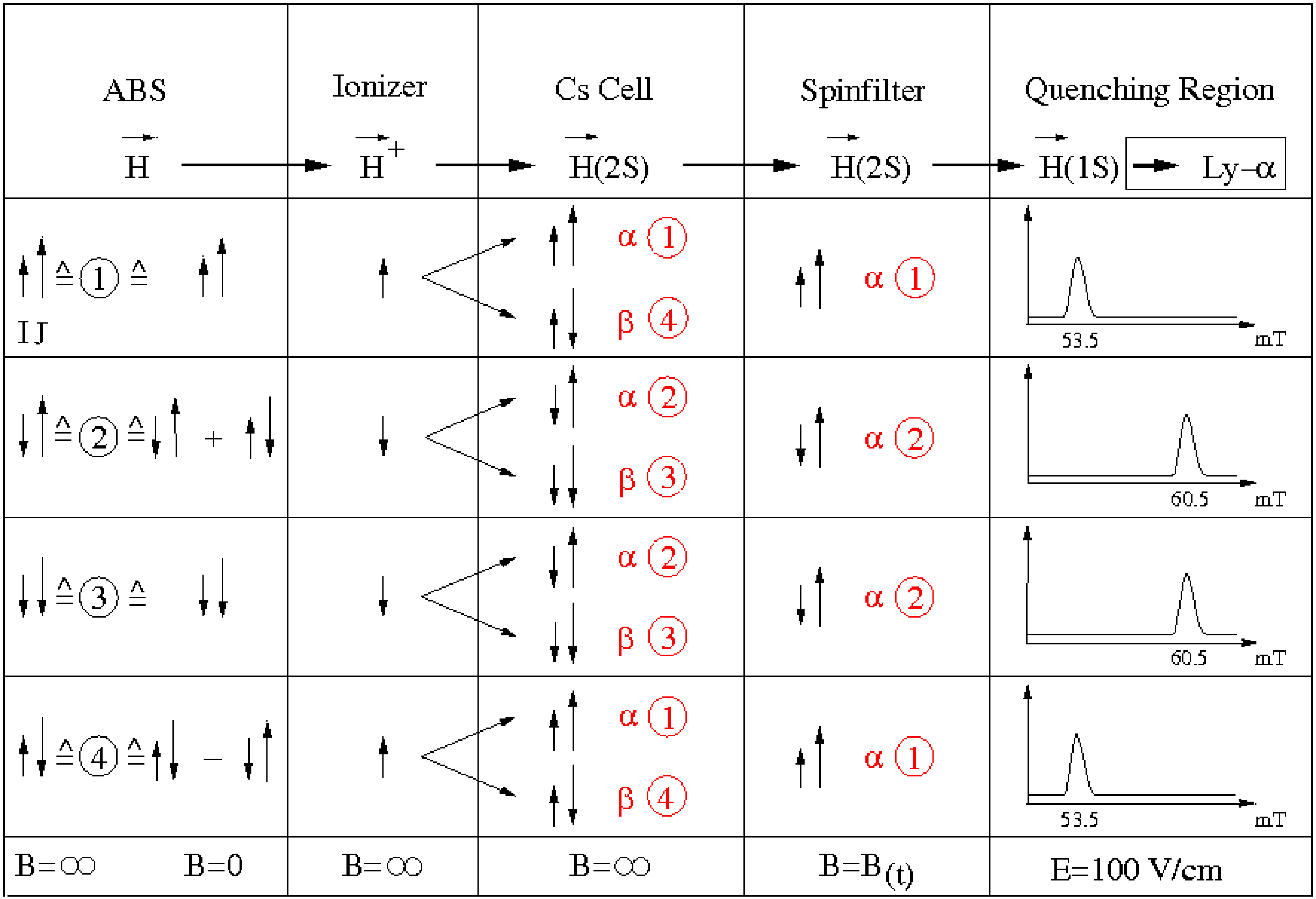
$P_z = -0.82$

$P_z = -0.96 \pm 0.005$

$P_{zz} = 0.77$

$P_{zz} = -1.17$

Lamb-Shift Polarimeter



Summary

The Lamb-shift polarimeter can measure:

1.) The nuclear polarization of protons/deuterons (E ~ keV)

2.) The occupation numbers of the HFS of H/D atoms

3.) The nuclear polarization of H_2^+, D_2^+ and HD^+ molecular ions

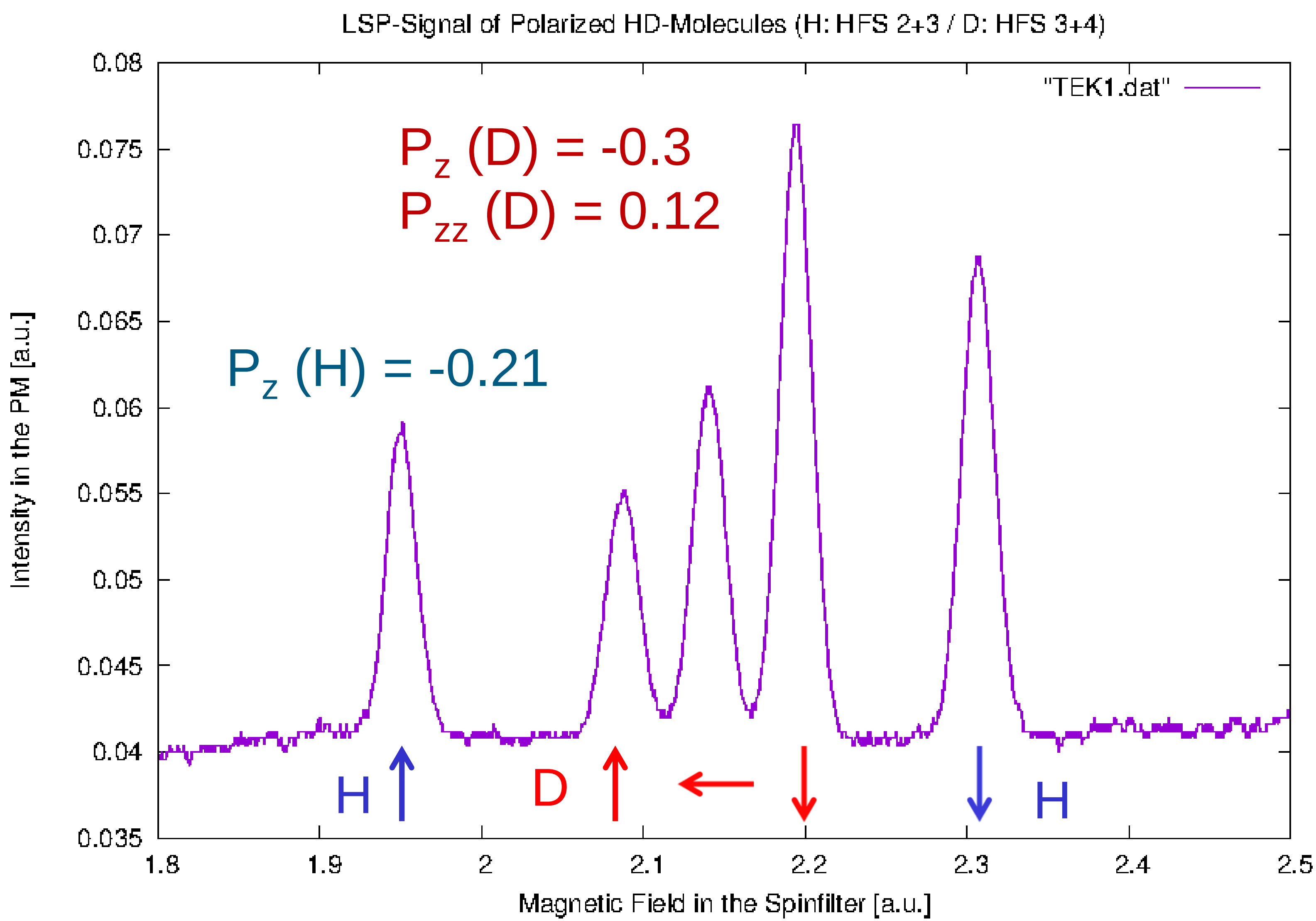
4.) The nuclear polarization of H_2, D_2 and HD molecules

5.) The nuclear polarization of H_3^+ ions (D_3^+ not tested up to now)

6.) The nuclear polarization of H^-, D^- ???

Summary

(Surface: Gold / T = 80 K / B = 0.528 T / E = 2 keV)



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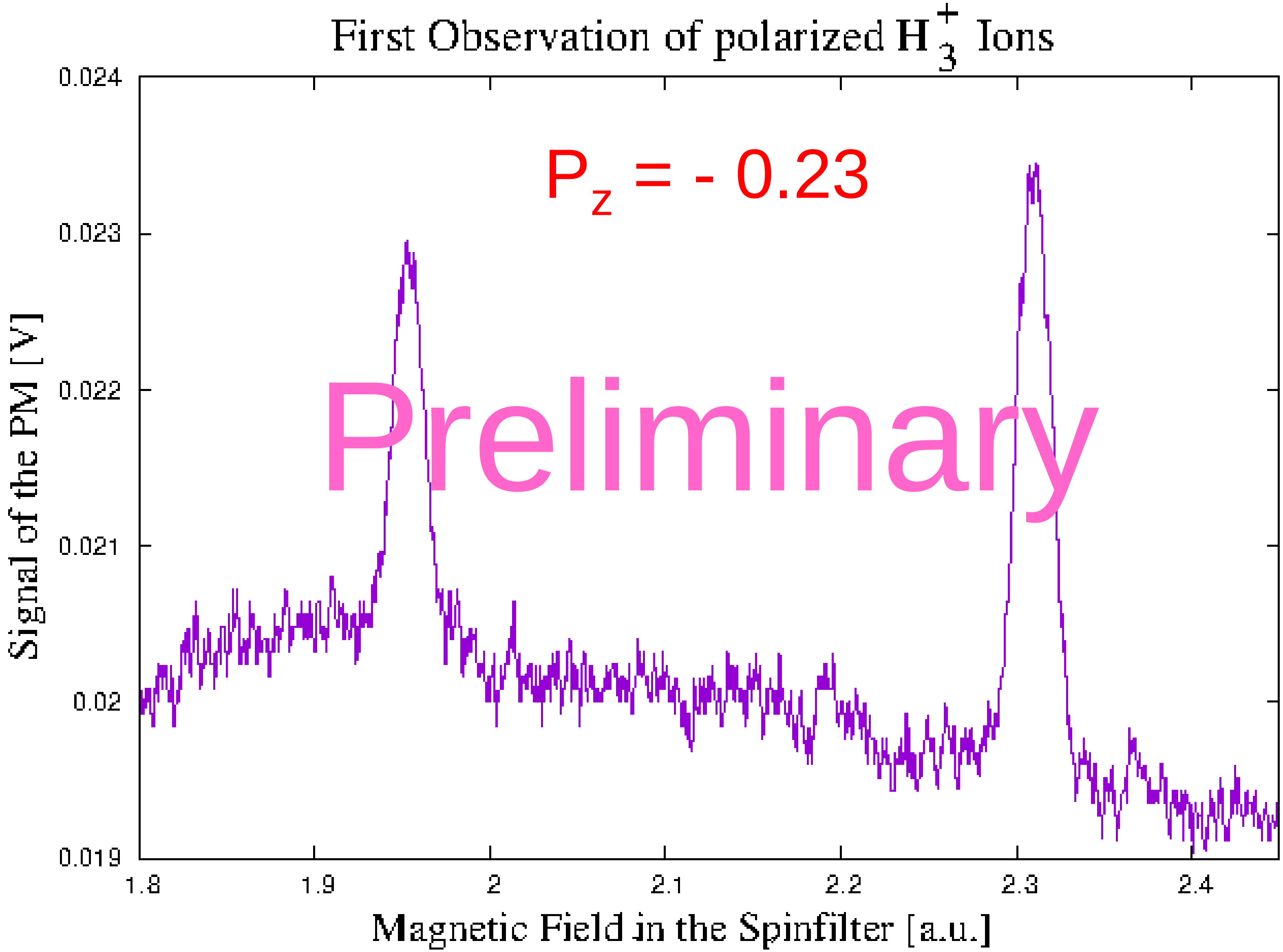
Summary



First Observation of polarized H_3^+ Ions
P_z = - 0.23
Preliminary
0.024
0.023
0.022
0.021
0.02
0.019
Signal of the PM [V]
1.8
1.9
2
2.1
2.2
2.3
2.4
Magnetic Field in the Spinfilter [a.u.]

Summary

Lamb-shift polarimeter are used in different projects

1.) Polarized Target at ANKE/COSY (in collaboration with PNPI)

2.) Polarized Proton/Deuteron Source at COSY

3.) Production of hyperpolarized Molecules (in collaboration with PNPI)

4.) Measurement of the Helicity of the $\bar{\nu}_e$ (BOB/Tech. Uni. Munich)

5.) Polarized Molecular Beam Source (BINP/Novosibirsk)

6.) Spin Dependence of the d-d Fusion reactions (PNPI)

7.) New Type of Laser-pumped Polarized p/d Source (starting)

8.) Measurement of the weak coupling constants (design studies)

….

The Bound Beta Decay (BOB)

$$n \longrightarrow p + e + \bar{\nu}_e$$

Efficiency: $4 \cdot 10^{-6}$

$$n \longrightarrow H_{(1S)} + \bar{\nu}_e$$

$Q_H = 325.7$ eV

Efficiency: $\sim 10^{-1}$

$$n \longrightarrow H_{(2S)} + \bar{\nu}_e$$

$Q_H = 325.7$ eV

L.L. Nemenov,
Sov. J. Nucl. Phys. **31** (1980)

The Bound Beta Decay (BOB)

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Helicity of the Antineutrino: right-handedness

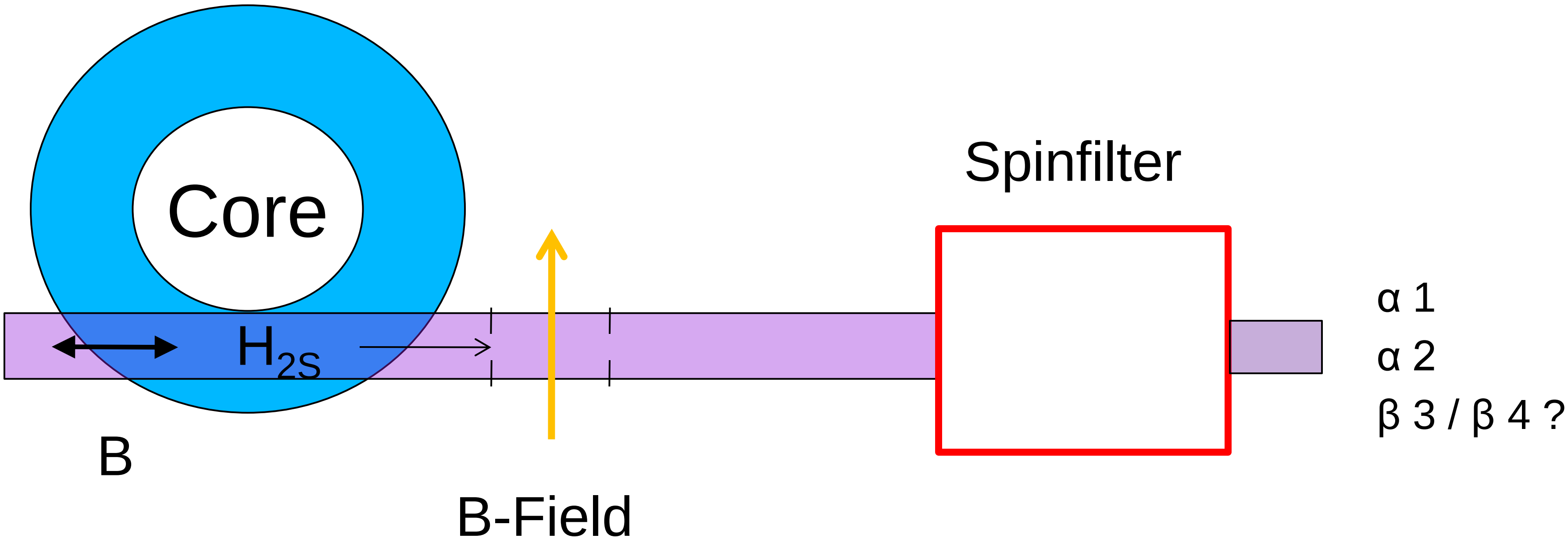
$\bar{\upsilon}$	n	p	e^-	W_i (%)	F	mF	HFS
←	←	←	→	44.14	0,1	0	α_2, β_4
←	←	→	←	55.24	0,1	0	β_4, α_2
←	→	→	→	0.62	1	1	α_1
→	←	←	←	0	1	-1	β_3
→	→	→	←	0	0,1	0	β_4,α_2
→	→	←	→	0	0,1	0	α_2,β_4

→ left handed admixtures ?

→ scalar or tensor contributions to the weak force ?

The Bound Beta Decay (BOB)

Reactor: FRM II



The Hyperfine Substates

α 1: $|F=1, m_F=+1\rangle = |m_J=1/2, m_I=1/2\rangle$

α 2: $|1,0\rangle = \frac{1}{\sqrt{2}}\left[\sqrt{1+a}\,|+1/2,-1/2\rangle + \sqrt{1-a}\,|-1/2,+1/2\rangle\right]$

β 3: $|1,-1\rangle = |-1/2,-1/2\rangle$

β 4: $|0,0\rangle = \frac{1}{\sqrt{2}}\left[\sqrt{1-a}\,|+1/2,-1/2\rangle - \sqrt{1+a}\,|-1/2,+1/2\rangle\right]$

$$a_{(B)} = \frac{\frac{B}{B_c}}{\sqrt{1+\left(\frac{B}{B_c}\right)^2}}$$

$B_c = 6.34$ mT

B → 0: a → 0

B → ∞: a → 1

The Hyperfine Substates

$|m_J=+1/2,\ m_I\ -1/2>$: $\left(\frac{1+a}{2}\right)$ α2 V $\left(\frac{1-a}{2}\right)$ β4

$|m_J=-1/2,\ m_I=+1/2>$: $\left(\frac{1-a}{2}\right)$ α2 V $\left(\frac{1+a}{2}\right)$ β4

B ~ 0: (a = 0)

|+1/2, -1/2> : 44,14 % /2 α2 44,14 % /2 β4

|-1/2, +1/2> : 55,24 % /2 α2 55,24 % /2 β4

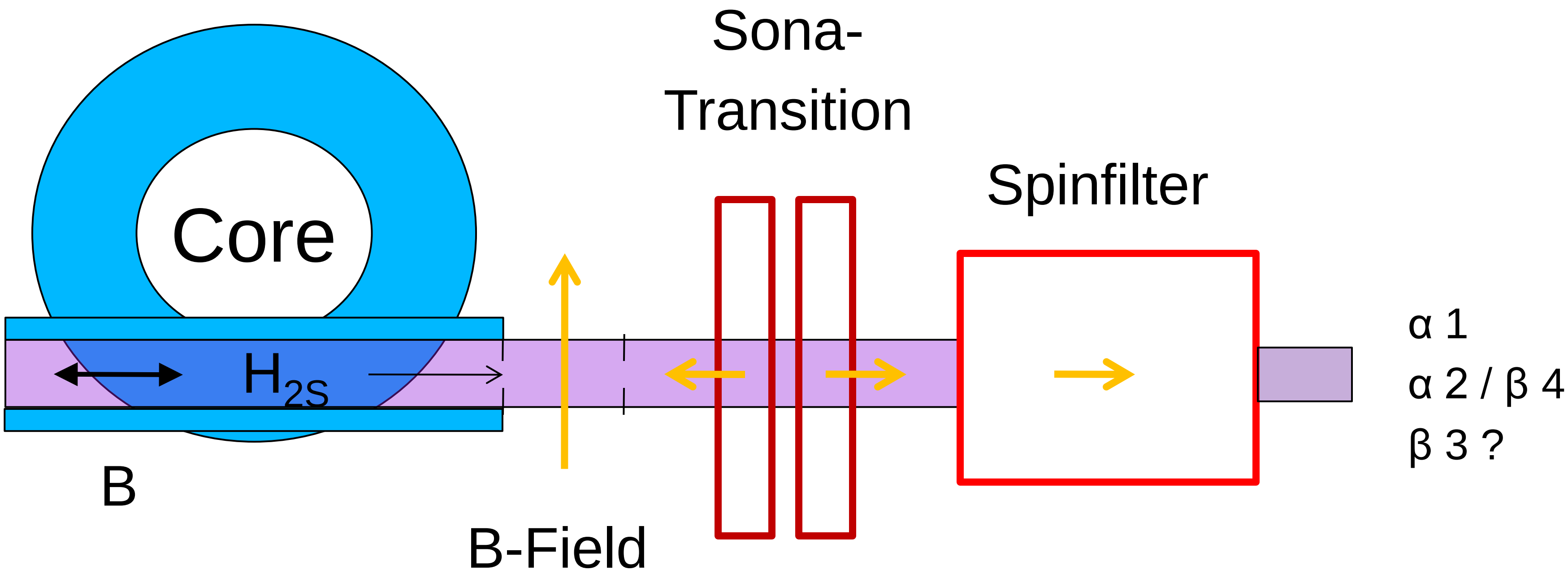
49,69 % α2 49,69 % β4

B → ∞: (a = 1)

|+1/2, -1/2> : 44,14 % α2 |-1/2, +1/2> : 55,24 % β4

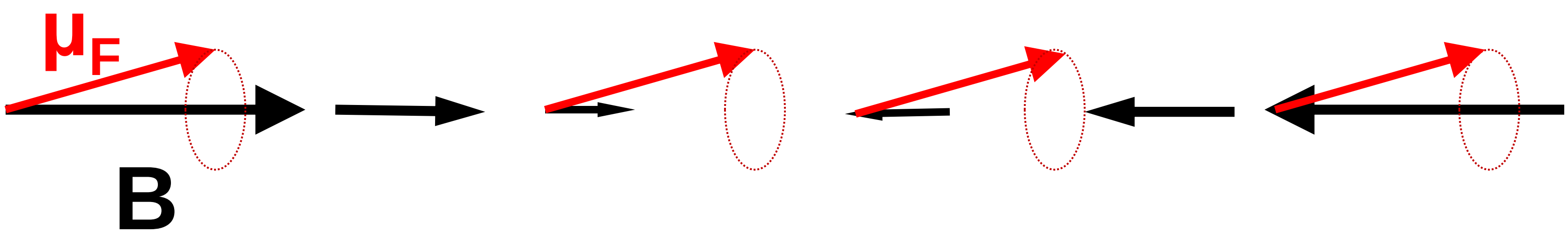
The Bound Beta Decay (BOB)

Reactor: FRM II



The Principle of a Sona Transition Unit

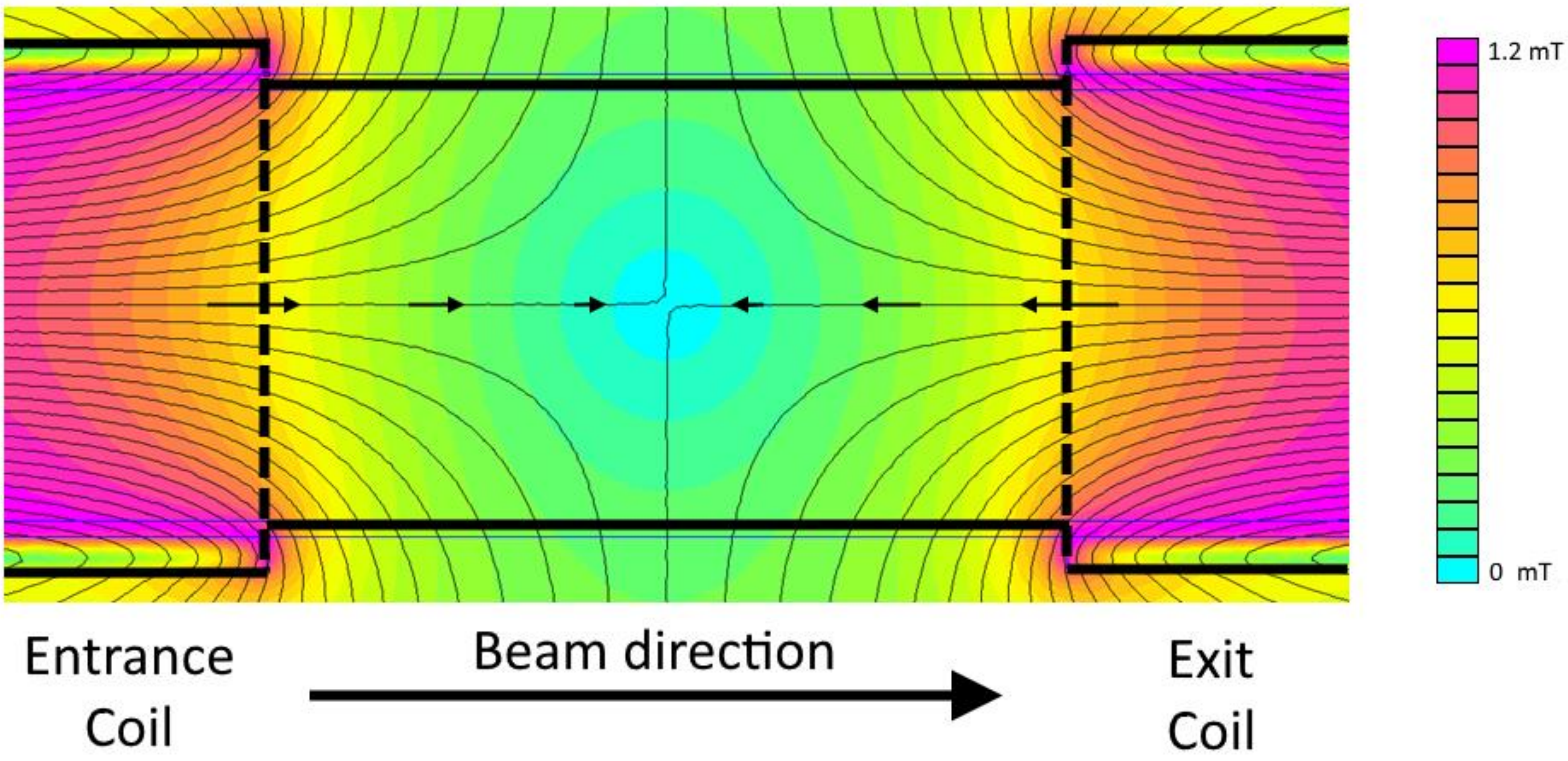
The ideal case:



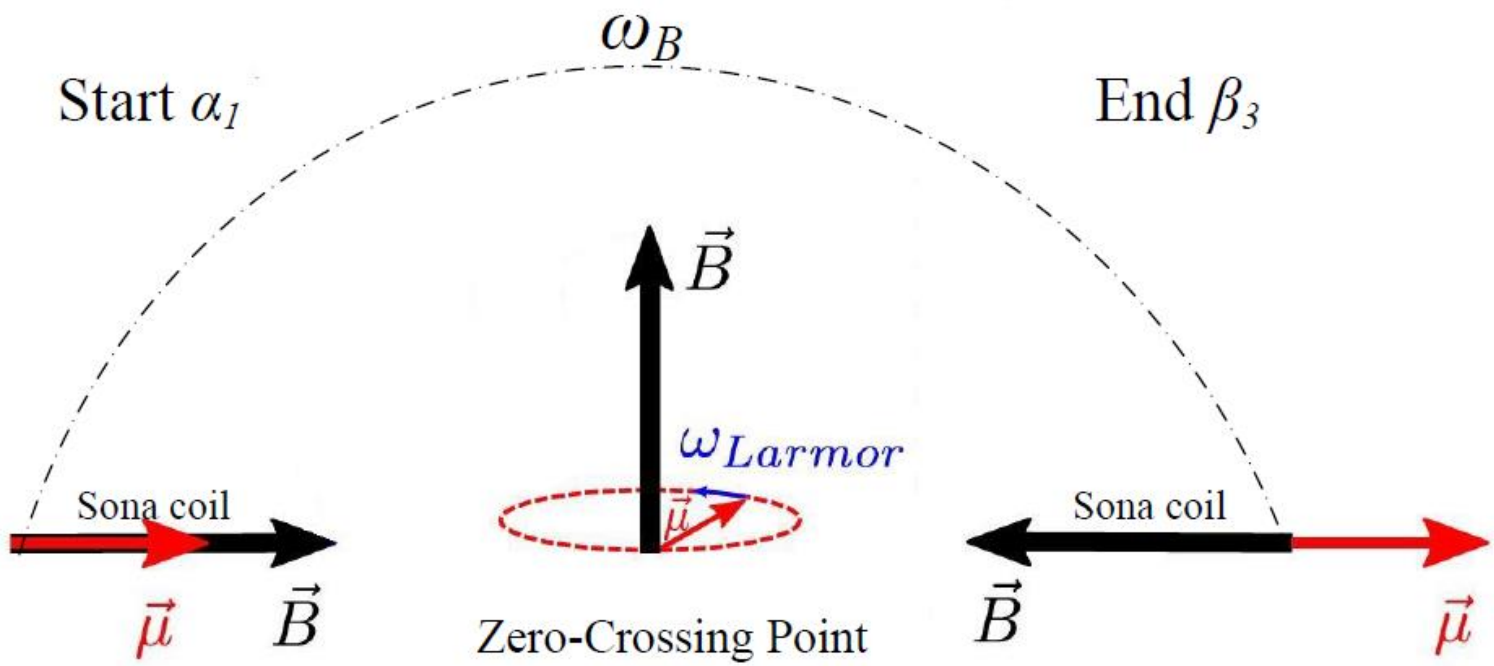
w_L > w_L

α1 → β3

The Magnetic Field of opposite Coils



Principle of a Sona Transition

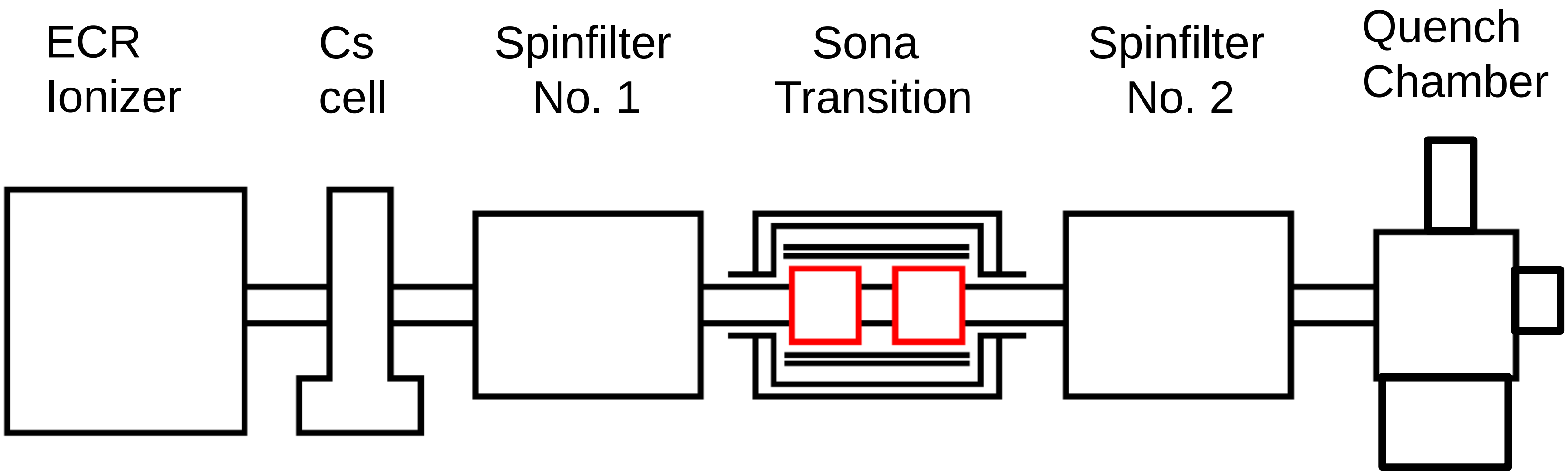


Ideal Case: On Axis are no radial component of B

Real Case: $B_{rad.}(r) = (dB_{long.}/dr) \cdot r/2$ -> **induced Lamor-Precession**

P. Sona, "A new method proposed to increase polarization in polarized ion sources of H^- and D^-", Energia Nucleare, **14**(5), May 1967.

The Experimental Setup



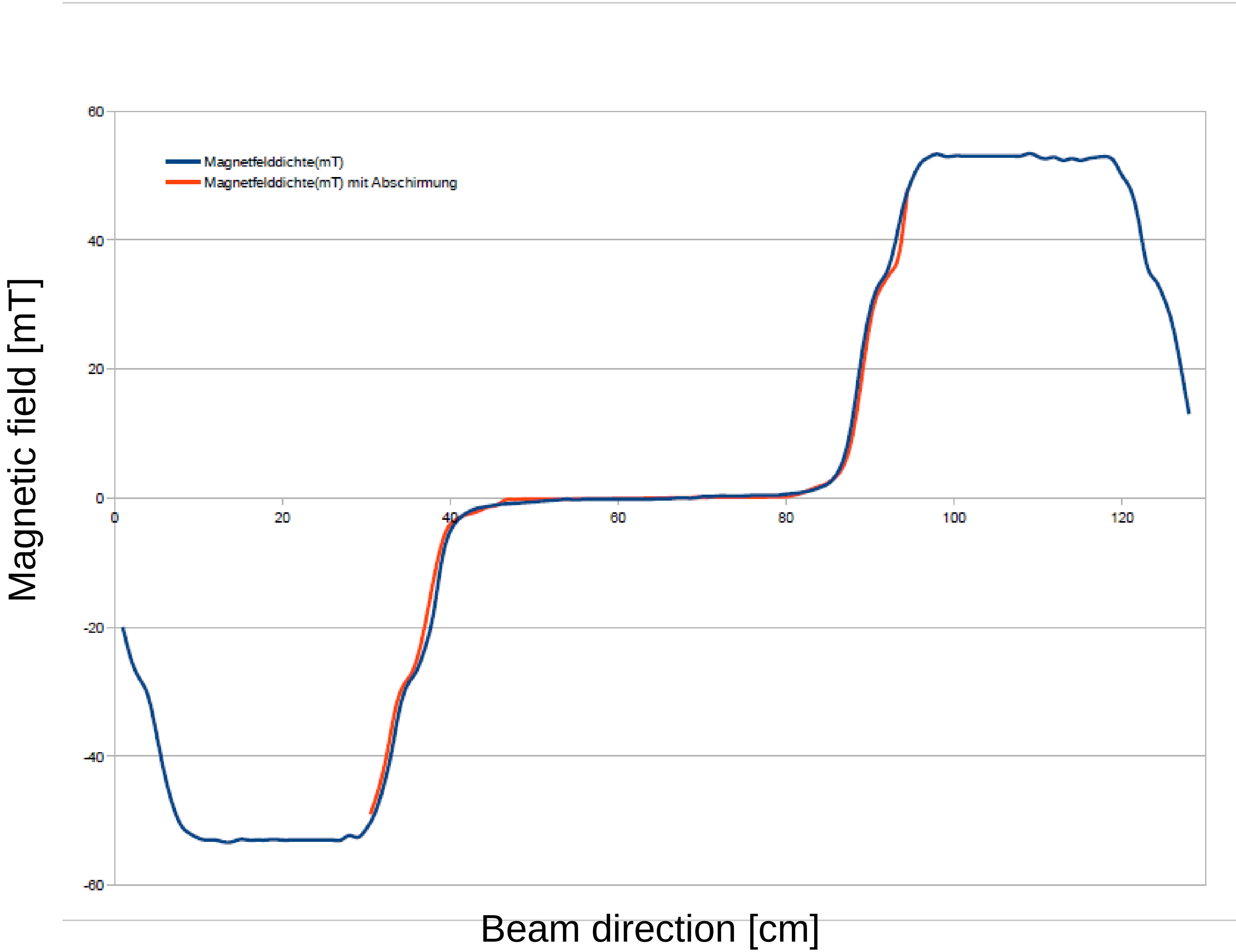
Ideal: $p \rightarrow H_{2S} \rightarrow \alpha 1 \rightarrow \beta 3 \rightarrow H_{1S} \rightarrow$ ~~Ly~~

Possible: $p \rightarrow H_{2S} \rightarrow \alpha 1 \rightarrow \alpha 1 \rightarrow \alpha 1 \rightarrow$ Ly

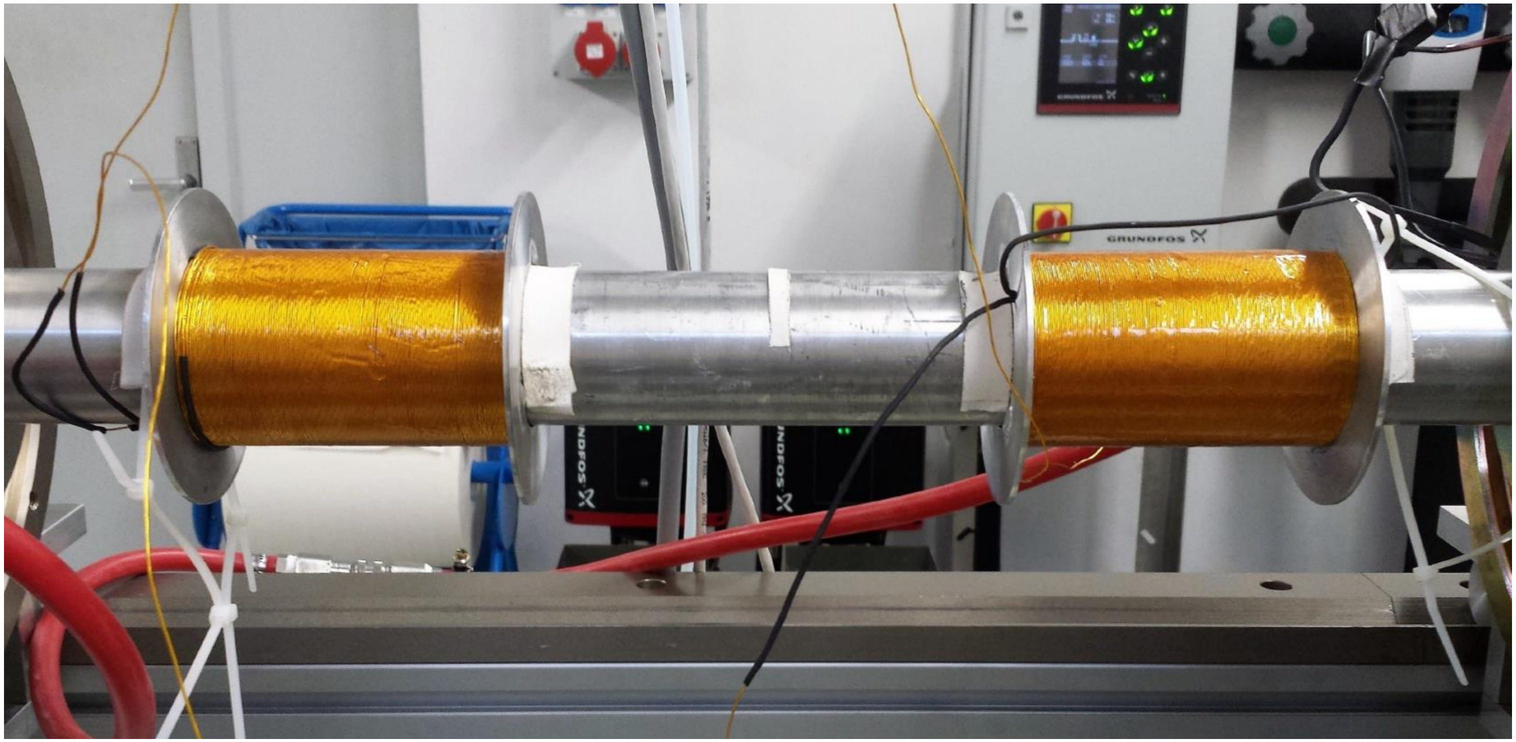
Possible: $p \rightarrow H_{2S} \rightarrow \alpha 1 \rightarrow \alpha 2 \rightarrow \alpha 2 \rightarrow$ Ly

Ideal: $p \rightarrow H_{2S} \rightarrow \alpha 2 \rightarrow \alpha 2 \rightarrow \alpha 2 \rightarrow$ Ly

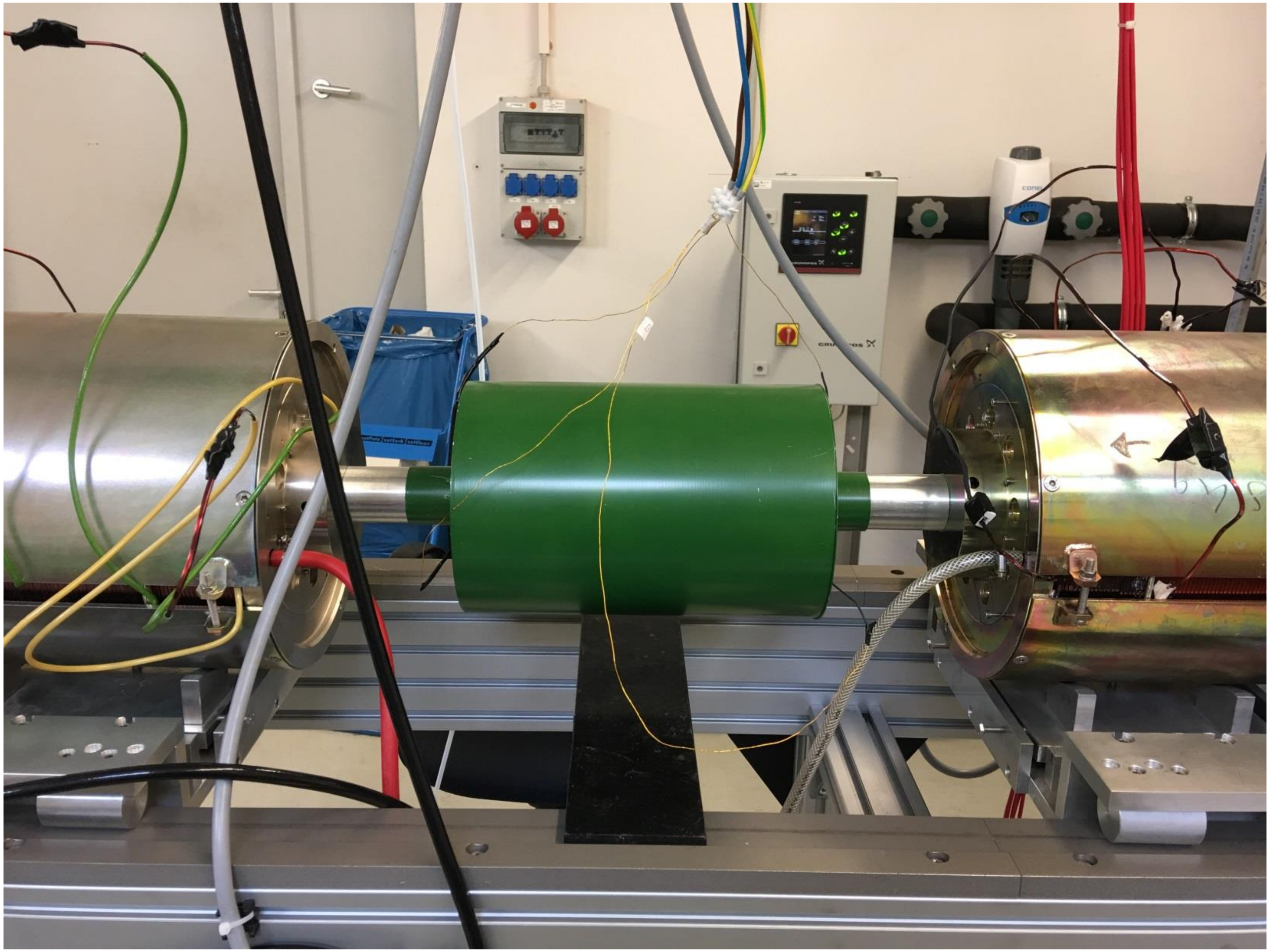
The longitudinal Magnetic Field



The Sona Transition Unit



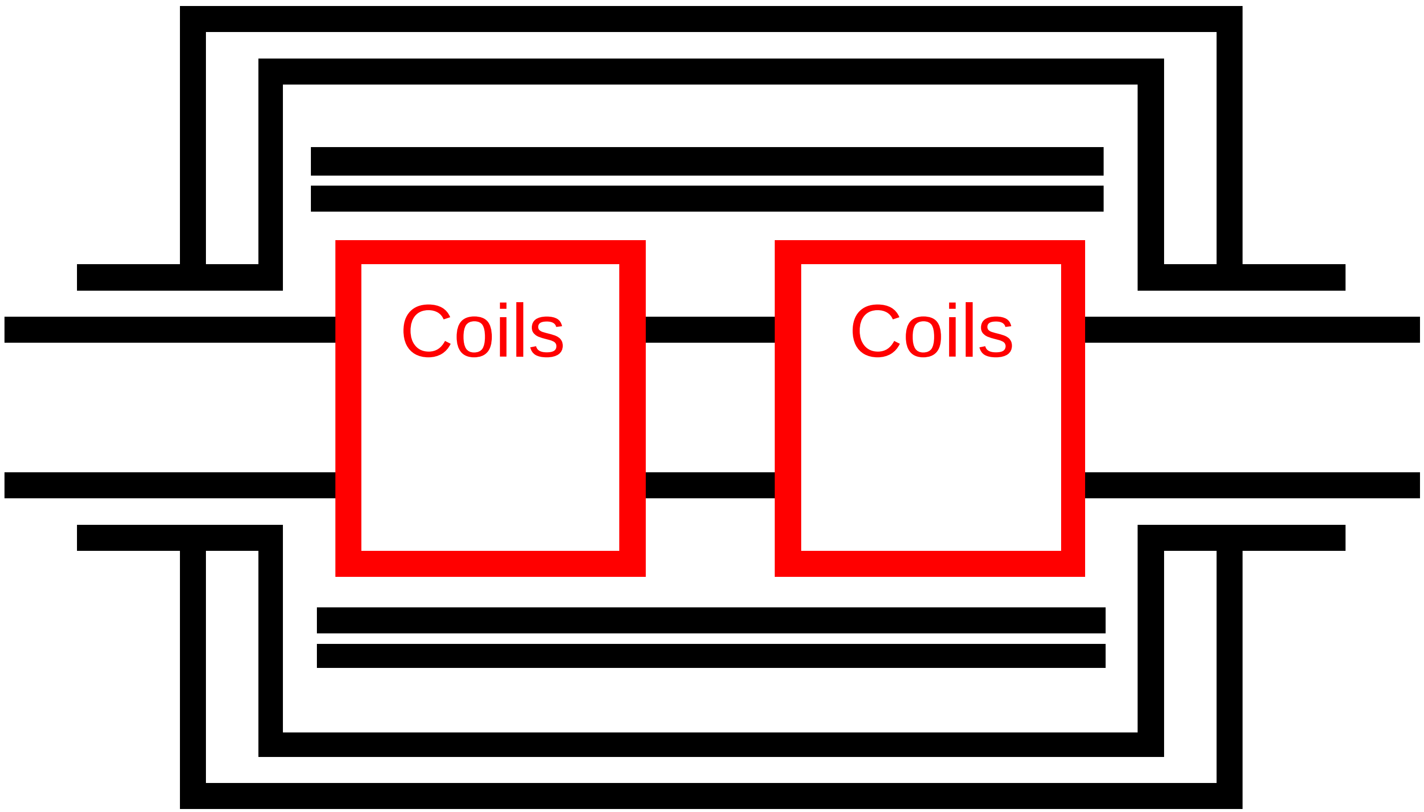
The Sona Transition Unit



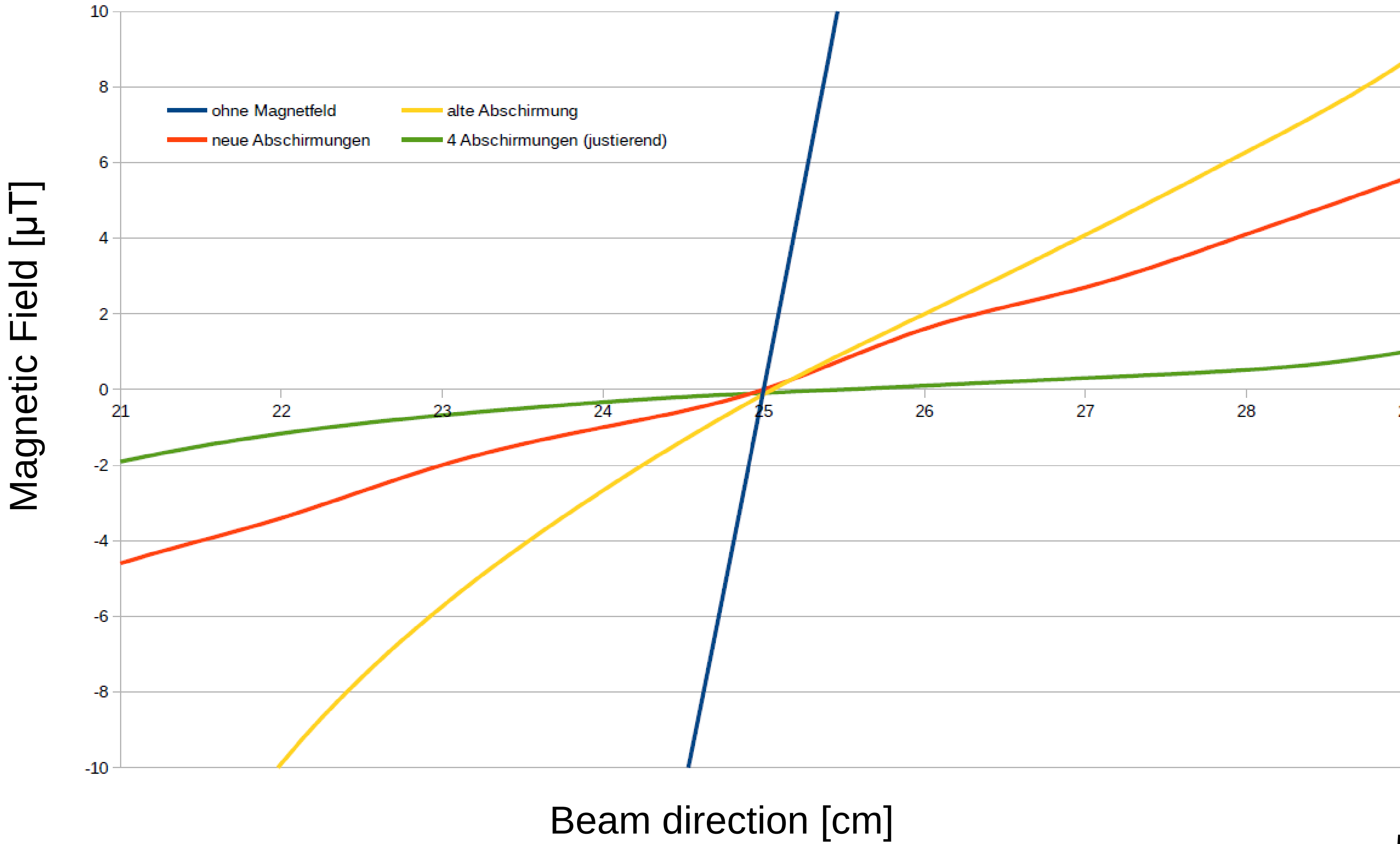
Bachelor Thesis: Yuchen Gan, FH Aachen, University of Applied Science, Jülich Campus

The Sona Transition Unit

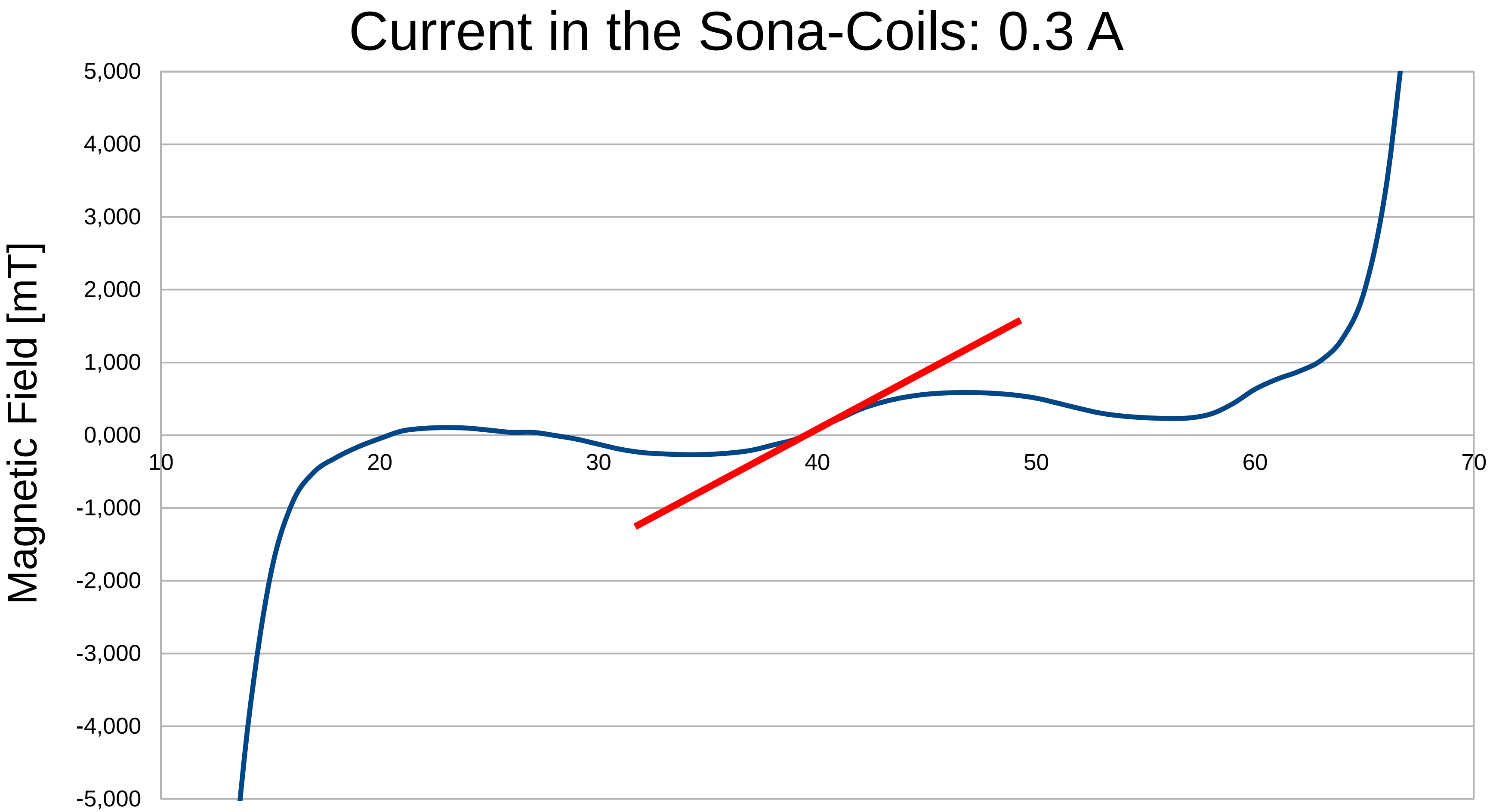
μ-metall shieldings



The Magnetic Field at the Zero Crossing

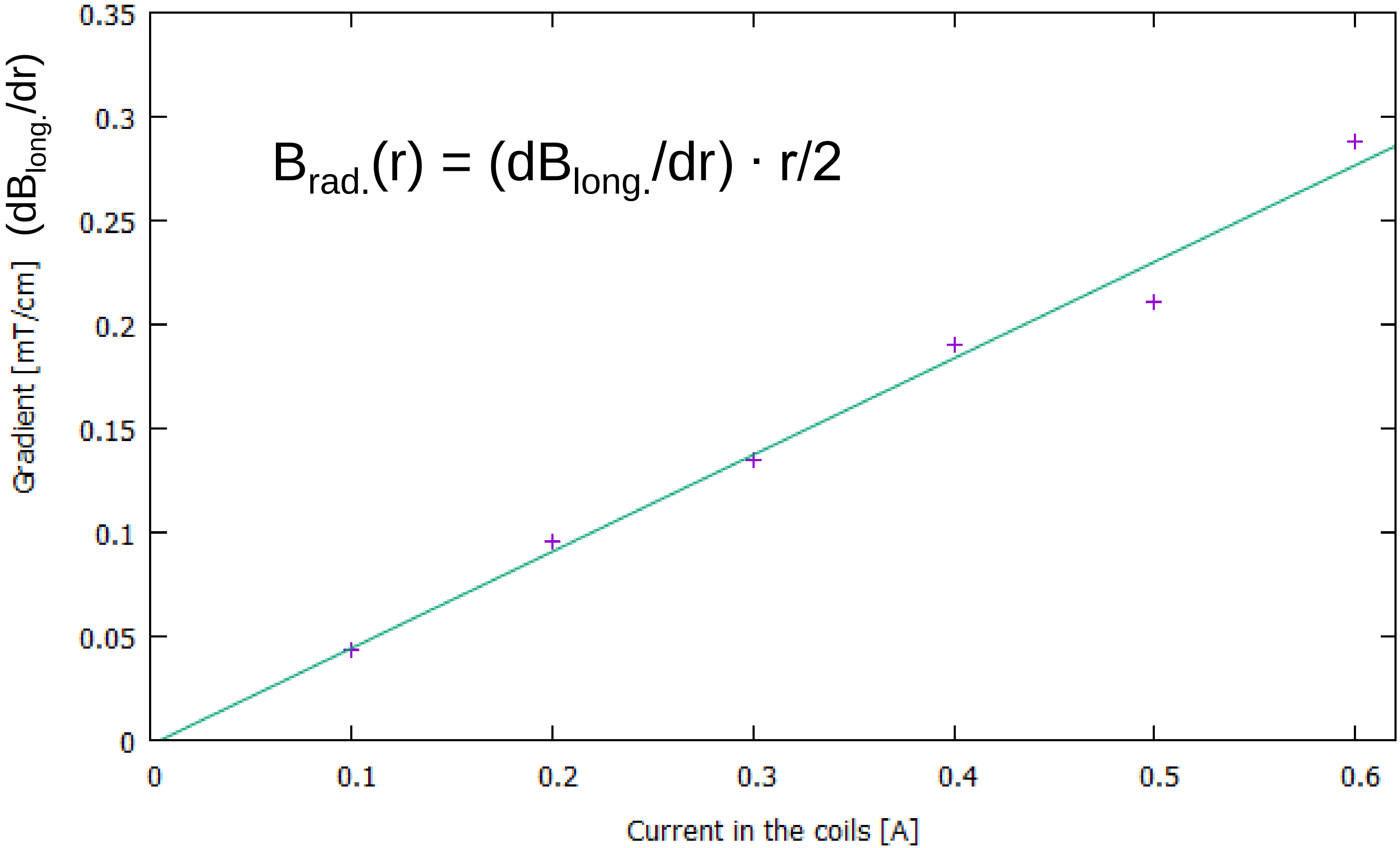


The Sona Transition Unit



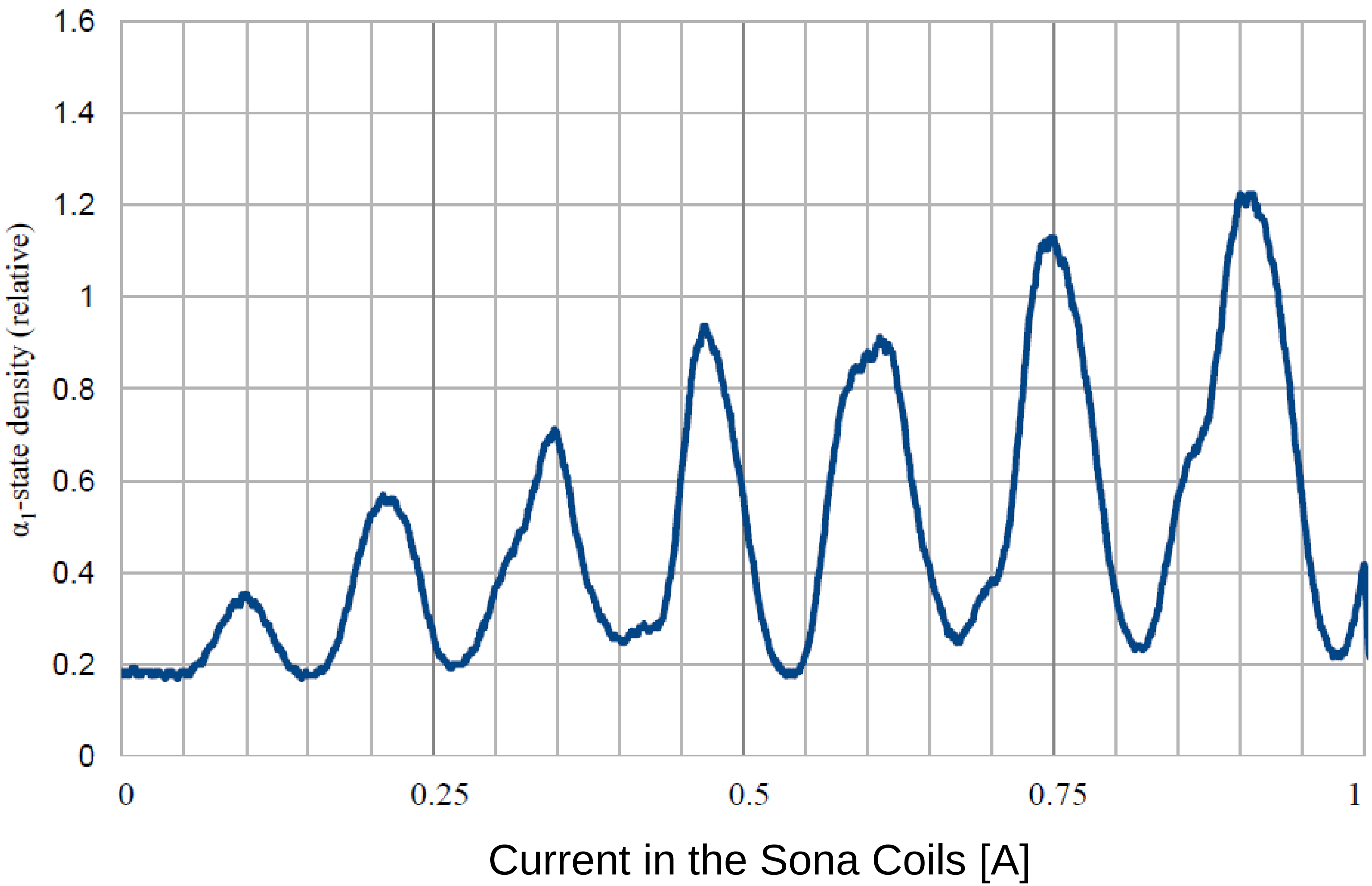
Gradient: 135 µT/cm

The Sona Transition Unit



First Results

1. SF: α1 -> Sona Transition -> 2. SF: α1



Outline of the BOB Experiments

3 Steps are needed for the full experiment

1.) Verifying the rare neutron decay into a hydrogen atom

$H_{1/2S}$ → Argon cell to get H^- → velocity separation via:
- counter field method
- BN gates
- mag. Spectrometer

2.) Measurement of the HFS ratio of α1 ↔ α2 and α2 ↔ β4

H_{2S}(+ B Field) → Spinfilter → Identification of the meta. Atoms:
- Argon cell (+ acceleration)
- Lyman-α photons
- ?

3.) Measurement of the forbidden state β3

Measurement of the ratios α2 ↔ β3 with SONA transition