Rydberg antihydrogen dynamics and perspectives towards a first gravity measurement

R. Caravita*
*INFN – TIFPA, Trento (IT)

on behalf of the **AEgIS Collaboration**

PROPOSAL FOR THE AEGIS EXPERIMENT AT THE CERN ANTIPROTON DECELERATOR
(Antimatter Experiment: Gravity, Interferometry, Spectroscopy)

Atom Optical Tools for Antimatter Experiments
Dipl.-Phys. Philippe H. M. Bräunig

Gravity Measurement on $\bar{H}$ in AEḡIS: Numerical Simulation of Perturbative Effects
Andrea Demetrio
Scuola di Scienze M.F.N.
Università di Genova

Limits on a gravity measurement with a non-collimated antihydrogen source
P. Bräunig, A. Demetrio, S. Müller and M. K. Oberthaler
Kirchoff-Institute for Physics, Heidelberg

Feasibility of a gravity measurement on antimatter using a Talbot-Lau interferometer
Put forward by
Andrea Demetrio

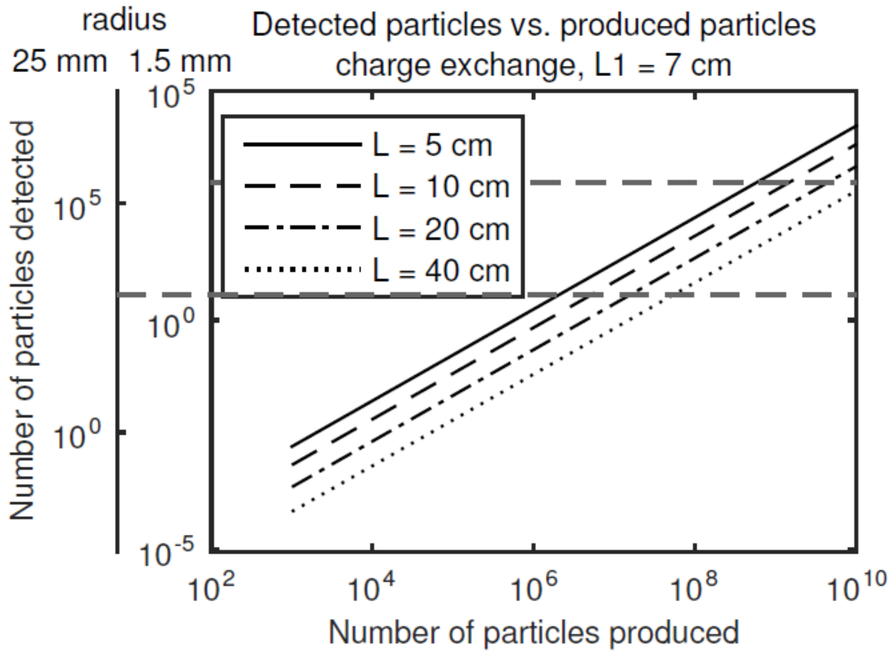
All these studies focused on the use of ground state antihydrogen following the proposal

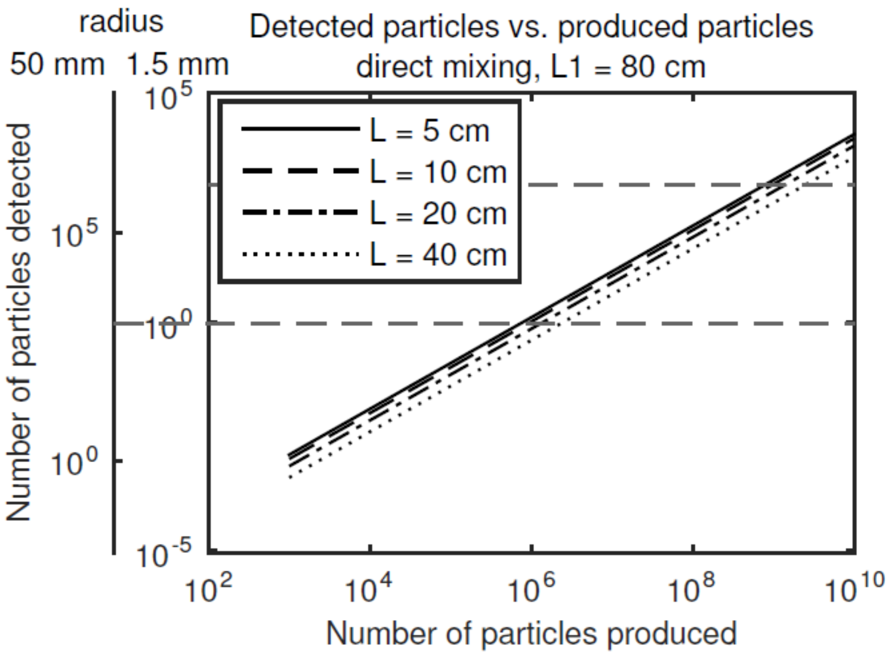
Moire deflectometer sensitivity = **Shot-noise limit** + **Solid angle**

$$a_{\min} = \underbrace{\frac{d}{2\pi \mathcal{V} \eta r}}_{\text{gratings}} \cdot \underbrace{\frac{2(L_{1\text{st}} + 2L)}{L^2}}_{\text{geometry}} \cdot \underbrace{\frac{2\,kT}{m} \frac{1}{\sqrt{N_{\text{prod}}}}}_{\bar{H}\ \text{source}},$$

$$a_{\min} = \frac{d}{2\pi\ \mathcal{V}\ \tau^2 \sqrt{N_{\text{det}}}}.$$

$$N_{\text{det}} = \left(\frac{r}{r_{\bar{\text{H}}}}\right)^2 \cdot \eta^2 \cdot N_{\text{prod}}$$





Moire deflectometer sensitivity

$$a_{\min} = \underbrace{\frac{d}{2\pi \mathcal{V} \eta r}}_{\text{gratings}} \cdot \underbrace{\frac{2(L_{1st} + 2L)}{L^2}}_{\text{geometry}} \cdot \underbrace{\frac{2kT}{m} \frac{1}{\sqrt{N_{prod}}}}_{\bar{H}\ \text{source}},$$

=

Shot-noise limit

$$a_{\min} = \frac{d}{2\pi\ \mathcal{V}\ \tau^2 \sqrt{N_{det}}}\ .$$

+

Solid angle

$$N_{det} = \left(\frac{r}{r_{\bar{H}}}\right)^2 \cdot \eta^2 \cdot N_{prod}$$

The solid angle formula is a good approximation of the geometrical detection efficiency under the assumption of straight linear trajectories (rays)

To what extent is this is this approximation valid for Rydberg antihydrogen atoms?

$$\vec{F}_{|i\rangle} = -m_g\, g\, \hat{y} - \vec{\nabla} U_{|i\rangle}$$

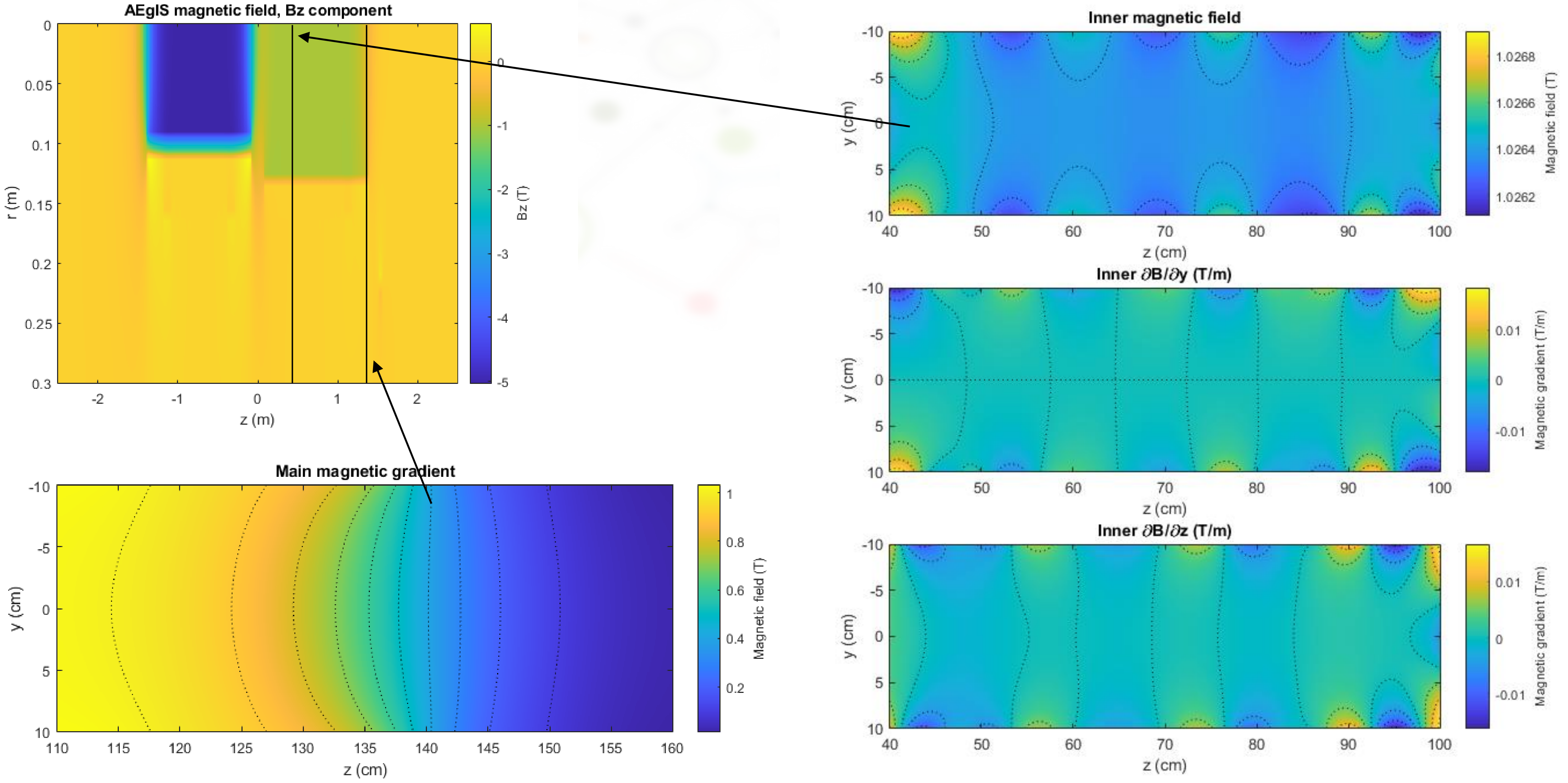
Magnetic potential energy
due to internal level energy shift

$$\vec{\nabla} U_{|i\rangle}(B(\vec{r})) = \frac{dU_{|i\rangle}}{dB} \cdot \vec{\nabla} B(\vec{r})$$

1) magnetic moment of the internal state

2) gradient of magnetic field modulo

AEgIS magnetic field map



$$H_{ij} = \left(\frac{\mu c^2 \alpha^2}{2n^2} + \mu_B \, m \, B \right) \delta_{ij} + \frac{e^2 B^2}{8\mu} H_{ij}^{Q}$$

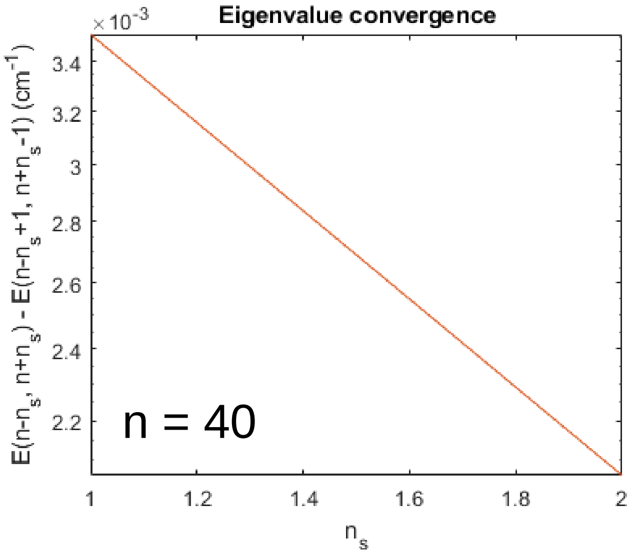
Hydrogen hamiltonian in strong fields including diamagnetism

Garstang R. H. and Kemic, S. B., Astrophys. Space Sci. 31, 103 (1974)

$$H_{ij}{}^{Q} = \langle n, l, m | \, r^2 \, \sin^2\theta \, | n', l', m' \rangle = \langle n, l | \, r^2 \, | n', l' \rangle \cdot \langle l, m | \, \sin^2\theta \, | l', m' \rangle$$

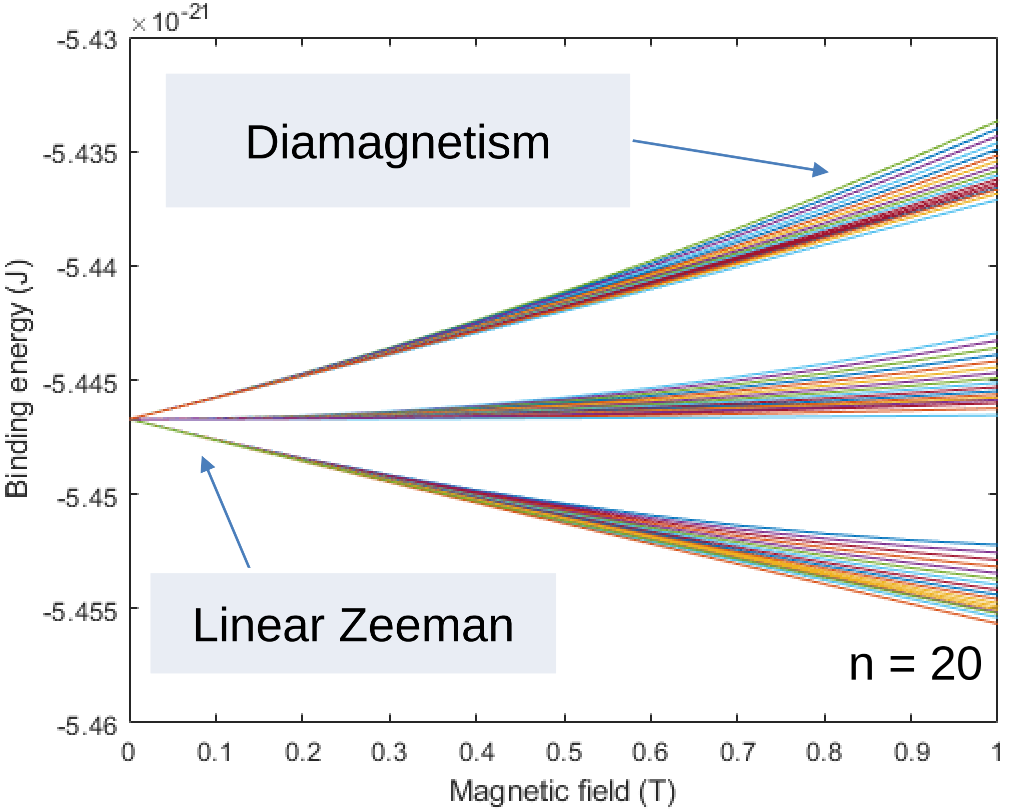
Radial term (numerical)

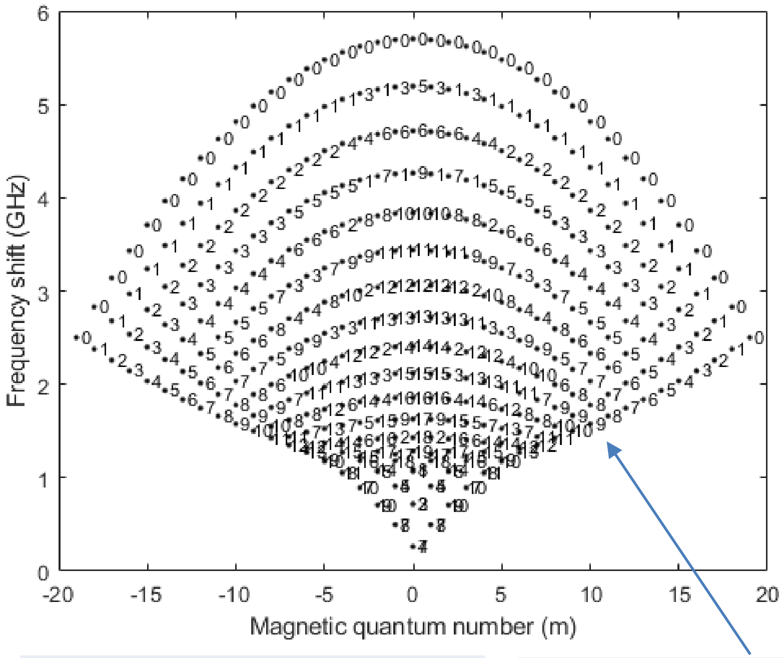
Angular term (analytical)



Numerical diagonalization

An example of diagonalization for a low Rydberg level

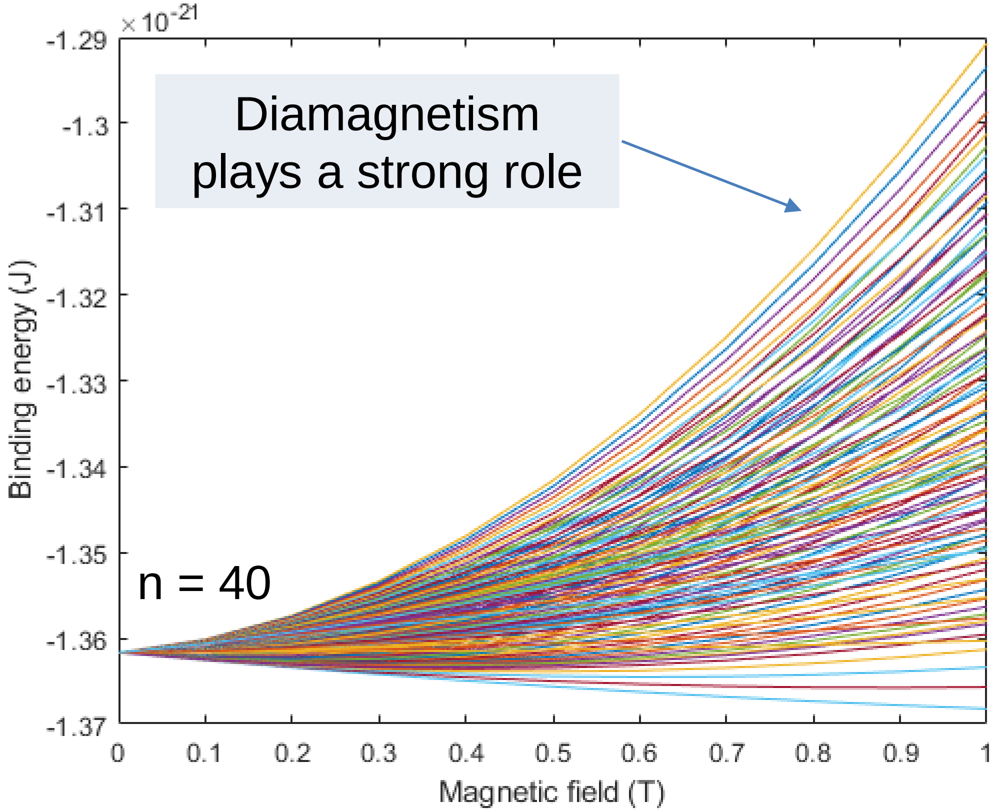


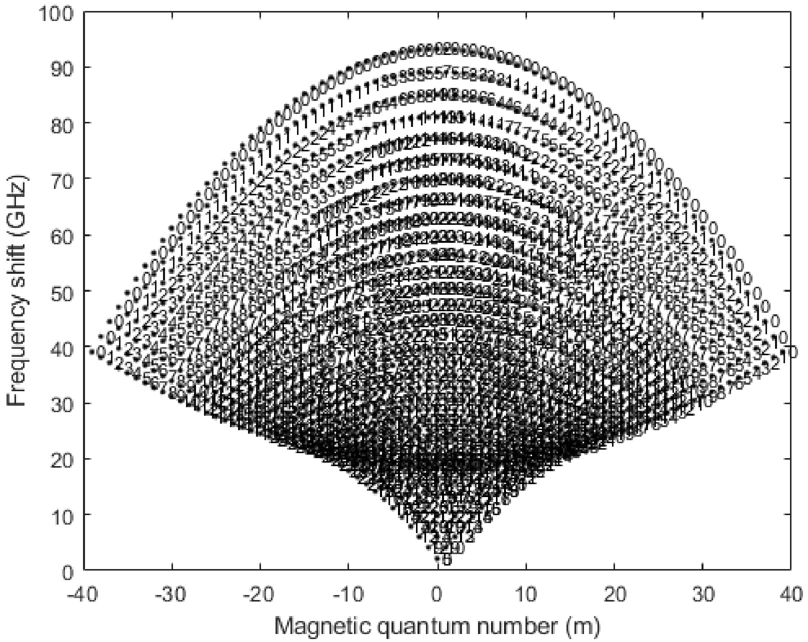


m is still a good quantum number

l is no longer good replaced by k

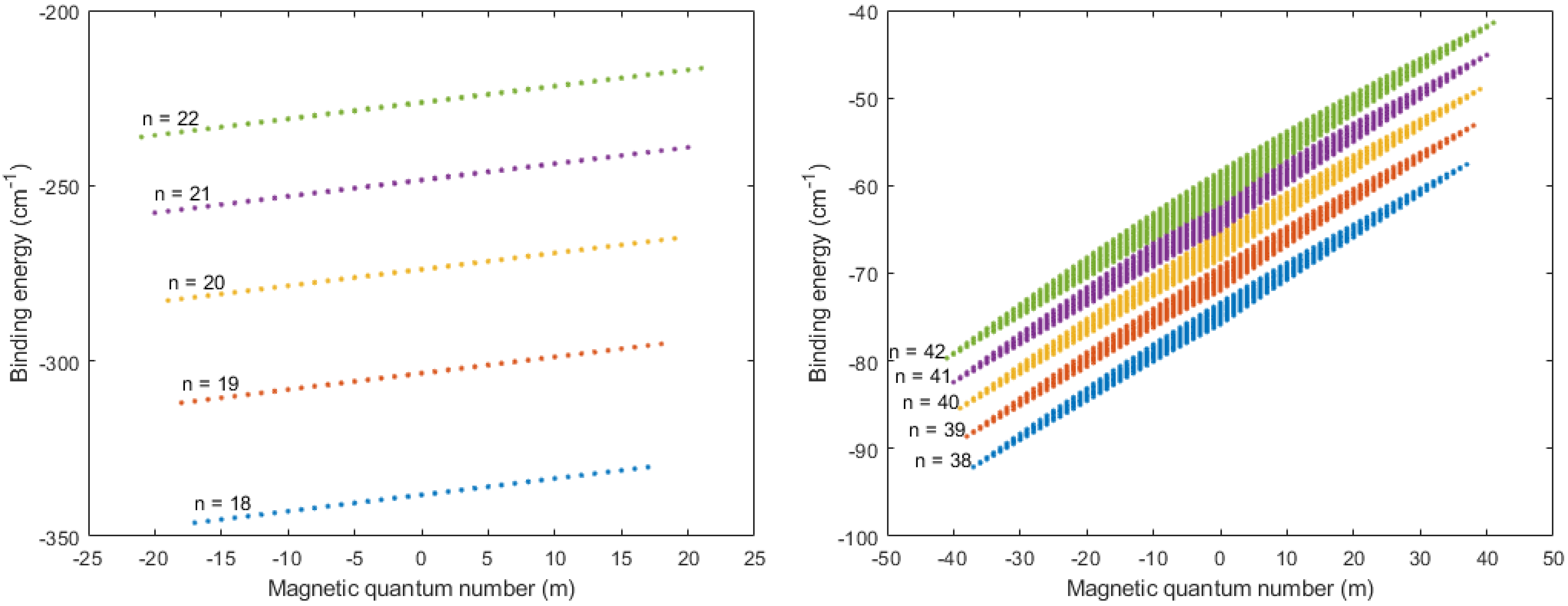
An example of diagonalization for a high Rydberg level



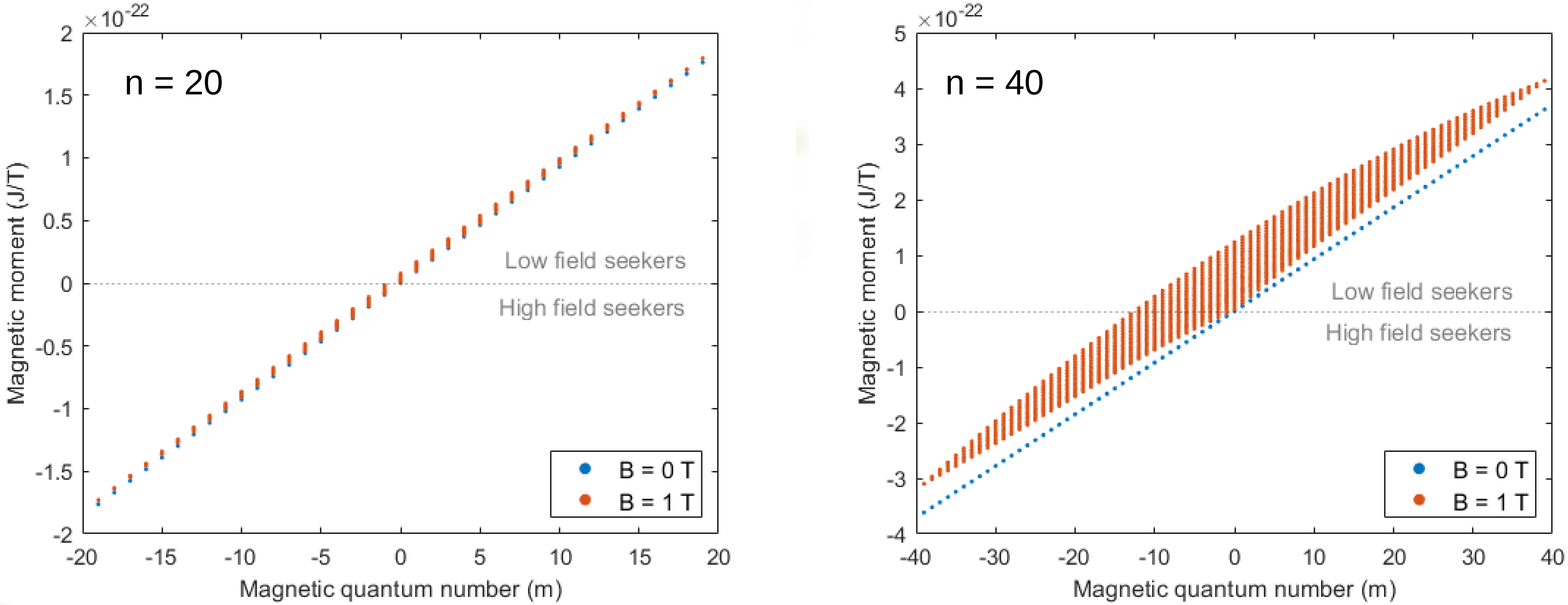


Diamagnetic shifts in the order of 100 GHz

Shell separation plot

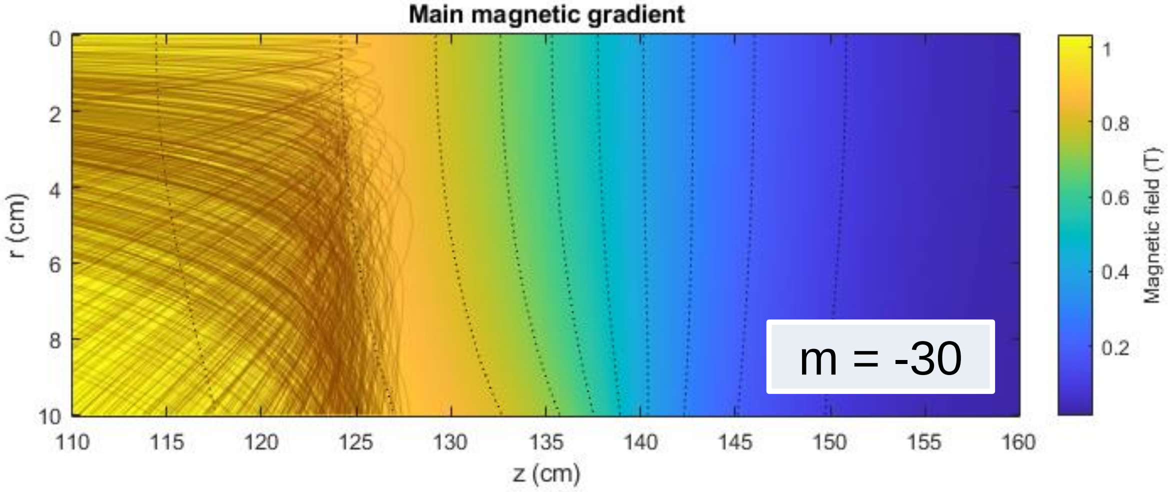


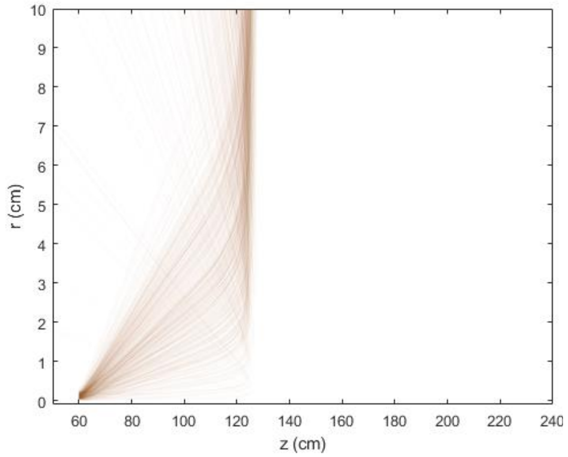
Magnetic moment of high Rybderg antihydrogens

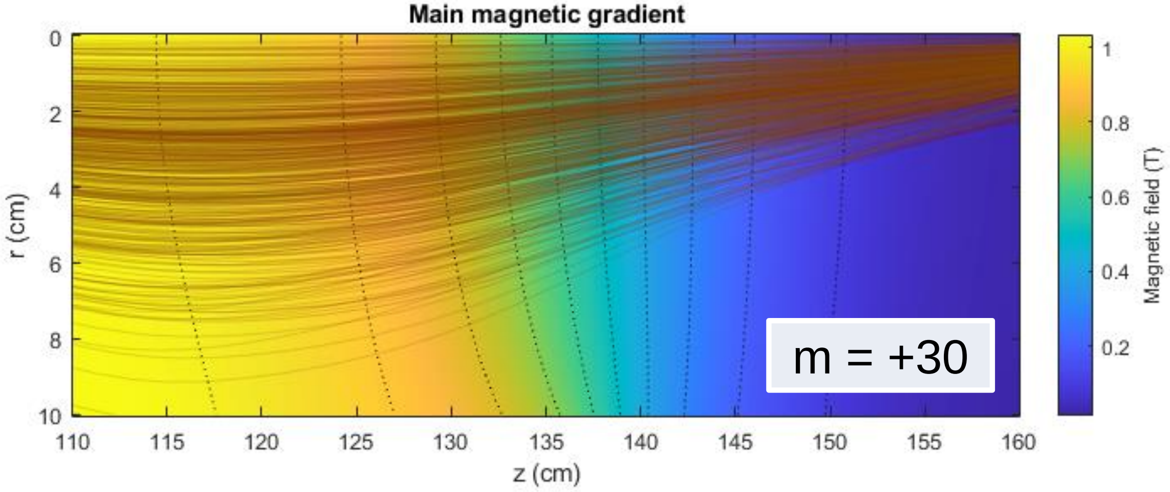


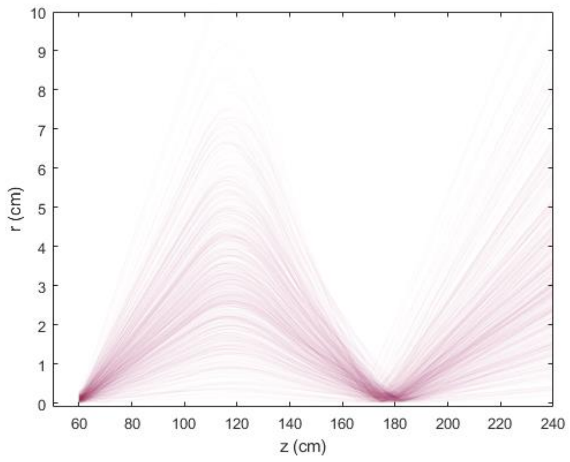
Because of diamagnetism, more sublevels become low field seekers
The higher the n level becomes, the more relevant is diamagnetism

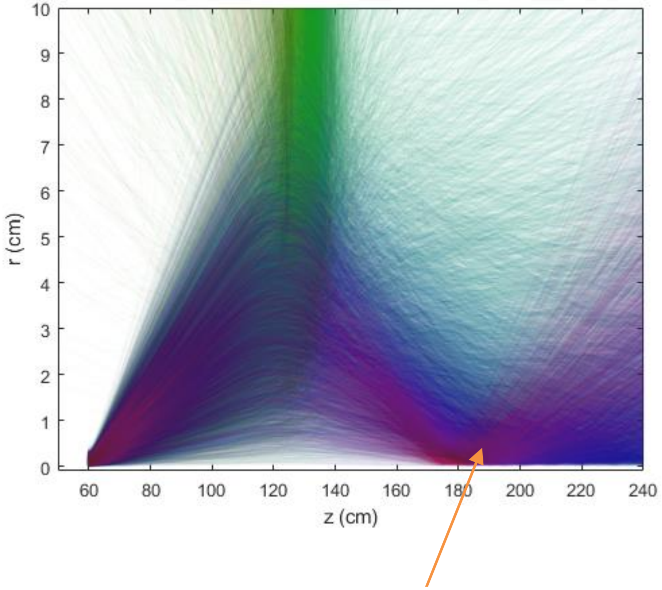
Integration of the equations of motion





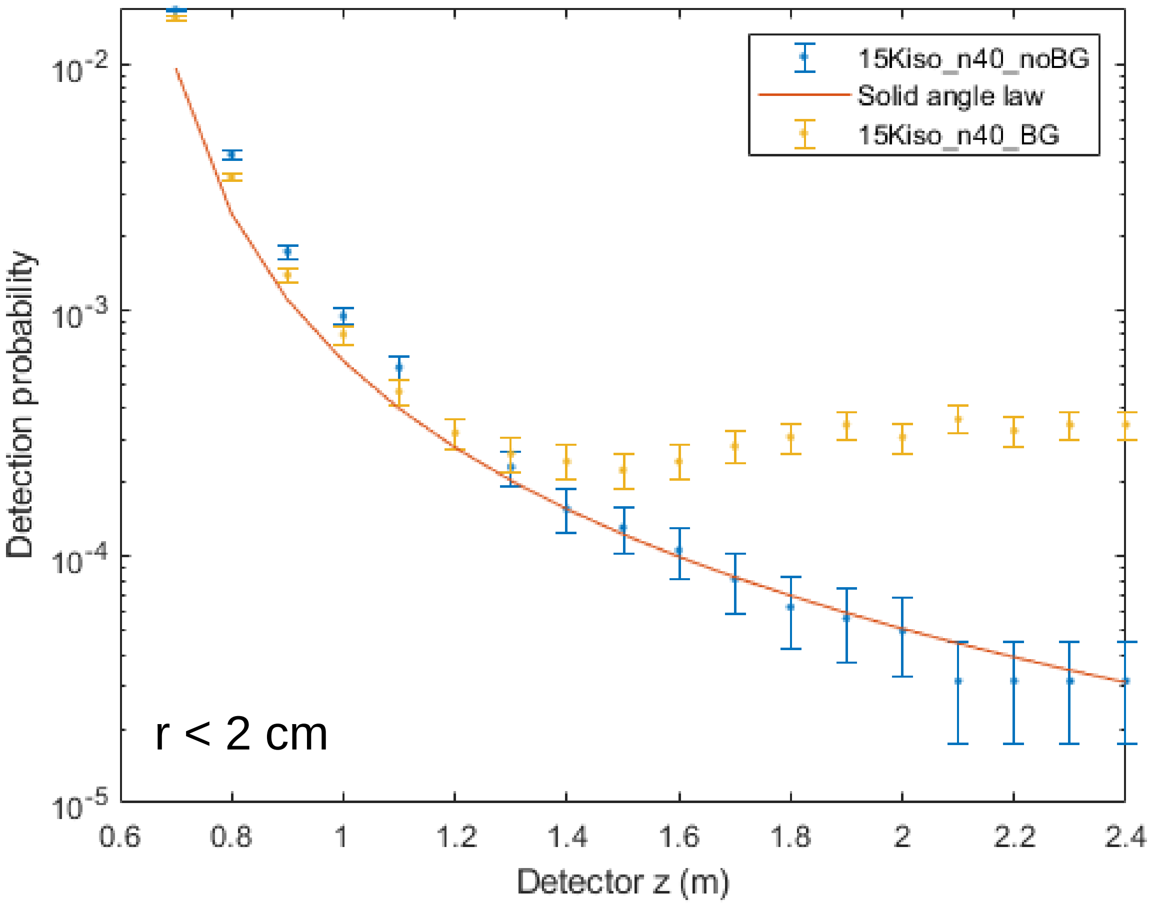






Concentration of atoms in a simil-focus

Violation of the solid angle law



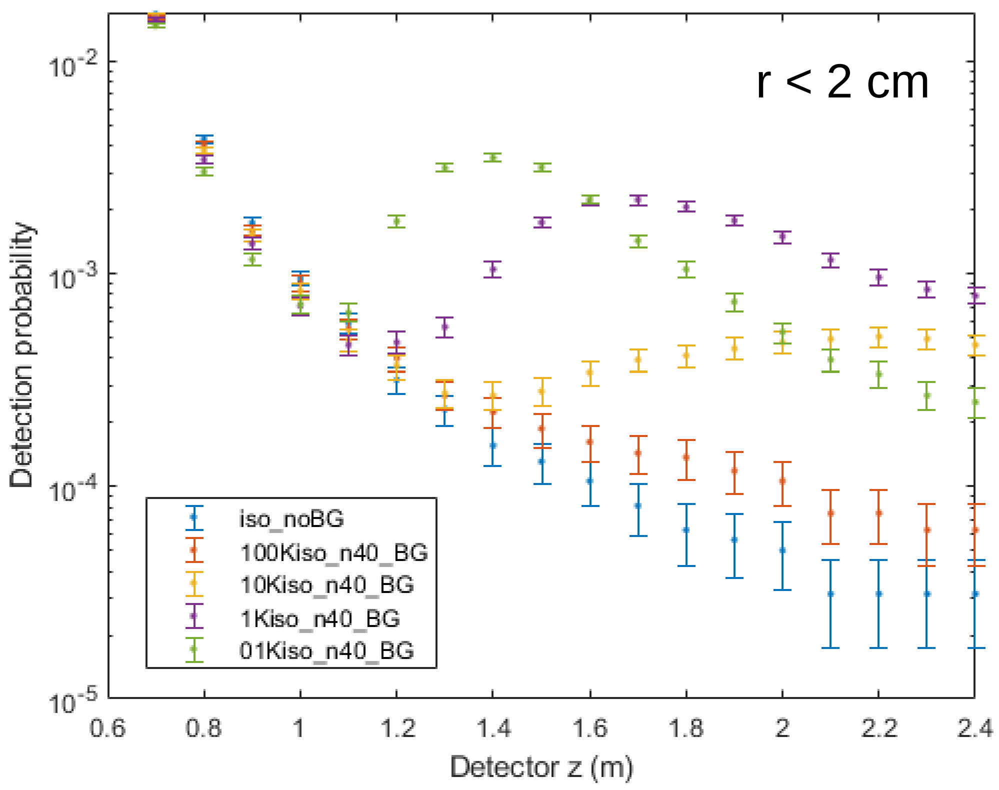
Solid angle law is violated for z > 1.3

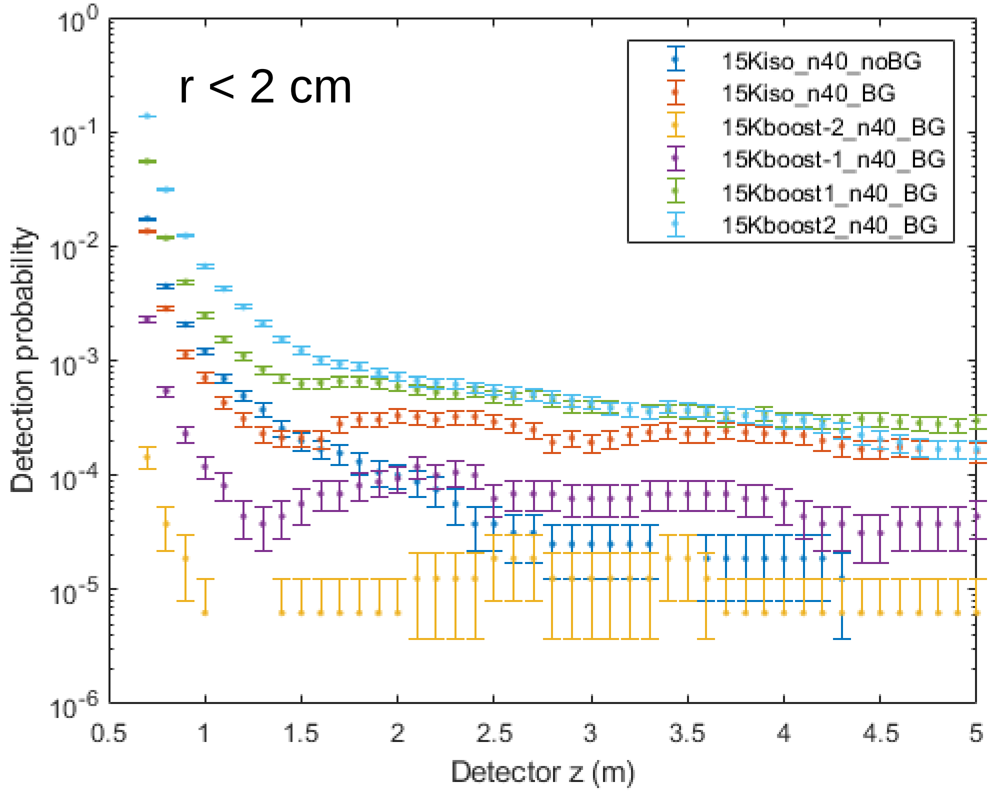
$$N_{\mathrm{det}} = \left(\frac{r}{r_{\bar{\mathrm{H}}}}\right)^2 \cdot \eta^2 \cdot N_{\mathrm{prod}}$$

Moiré sensitivity formula invalid for z > 1.3

$$a_{\min} = \underbrace{\frac{d}{2\pi\,\mathcal{V}\,\eta\,r}}_{\text{gratings}} \cdot \underbrace{\frac{2(L_{1\mathrm{st}} + 2L)}{L^2}}_{\text{geometry}} \cdot \underbrace{\frac{2\,kT}{m}\,\frac{1}{\sqrt{N_{\mathrm{prod}}}}}_{\bar{H}\ \text{source}}\,,$$

Violation of the solid angle law

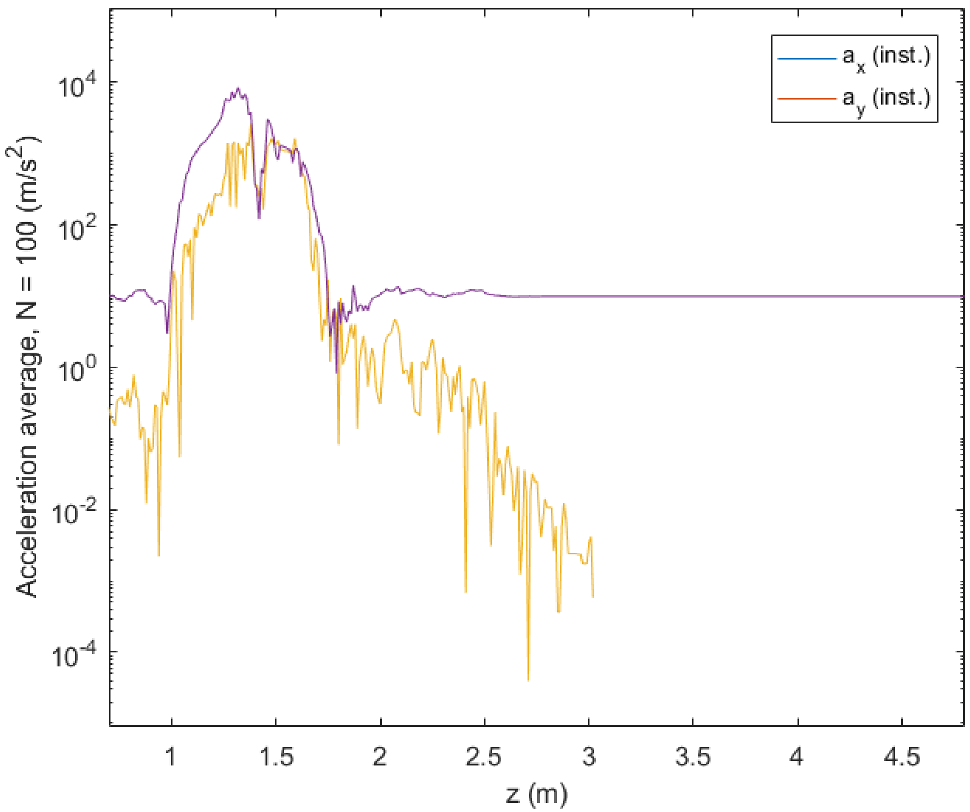


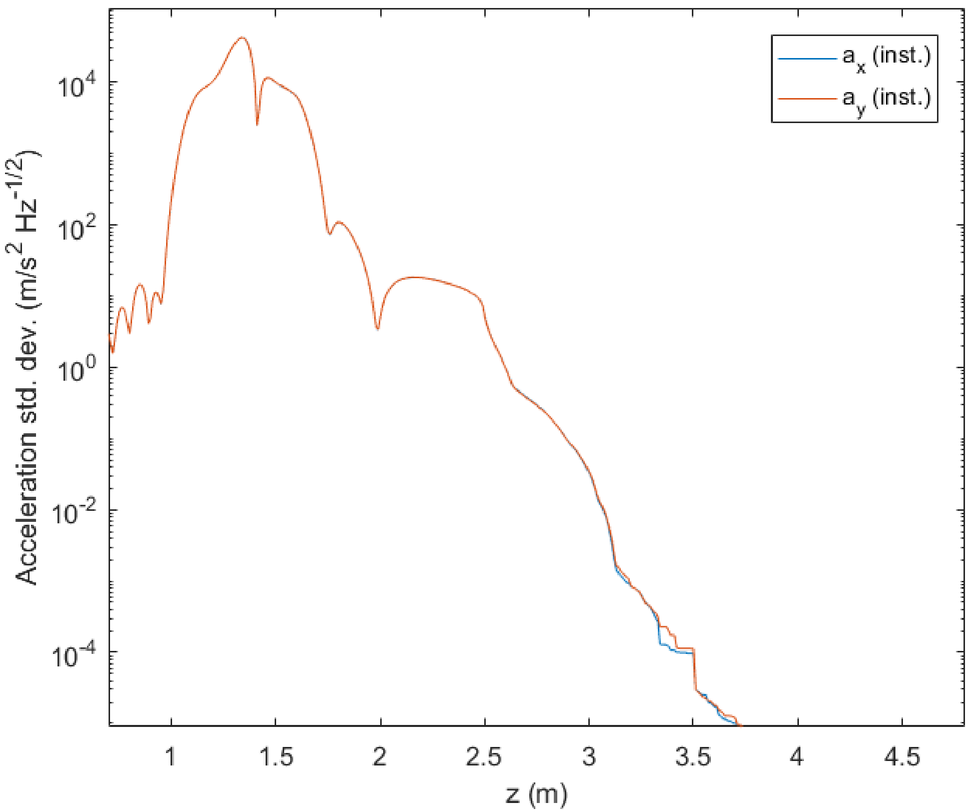


Temperatures of 20 K or better

A boost of $\sqrt{k_b T/m}$ seems optimal

Background magnetic acceleration study

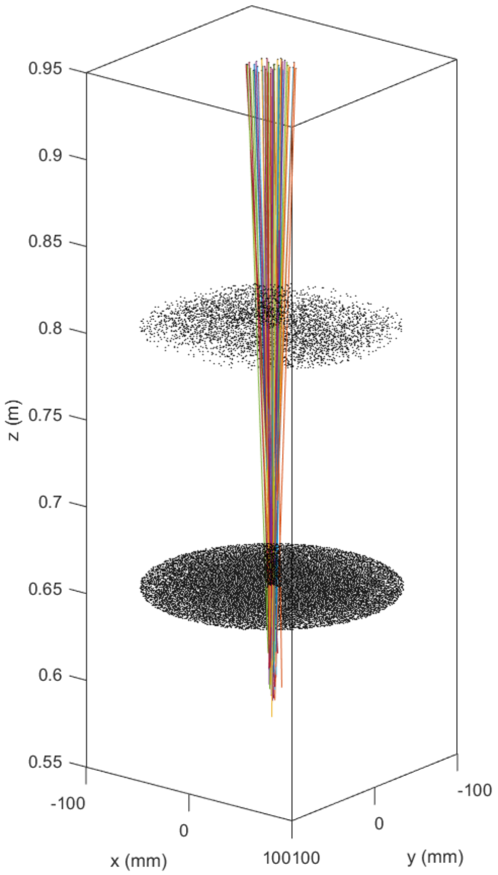


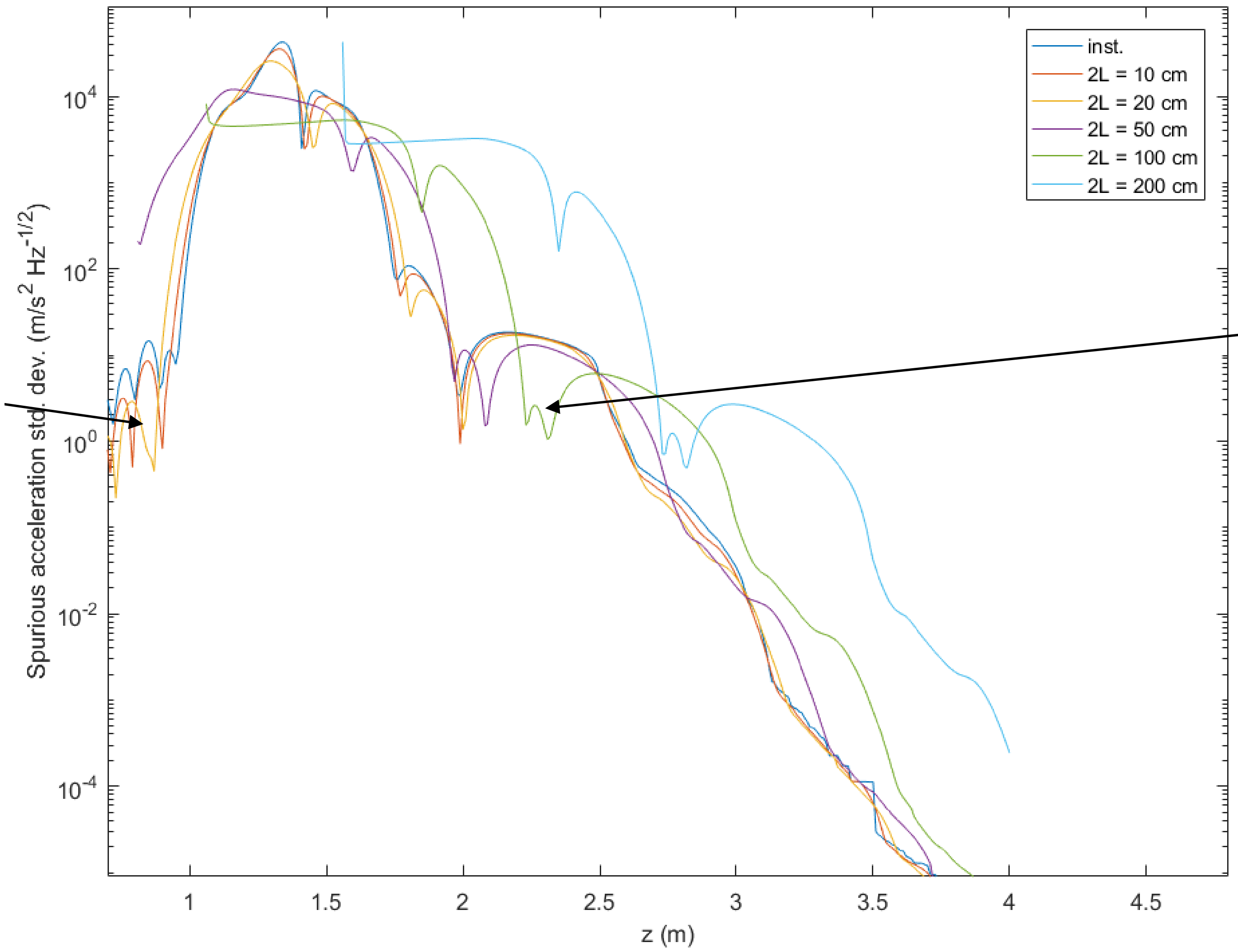


Magnetic force is on average null

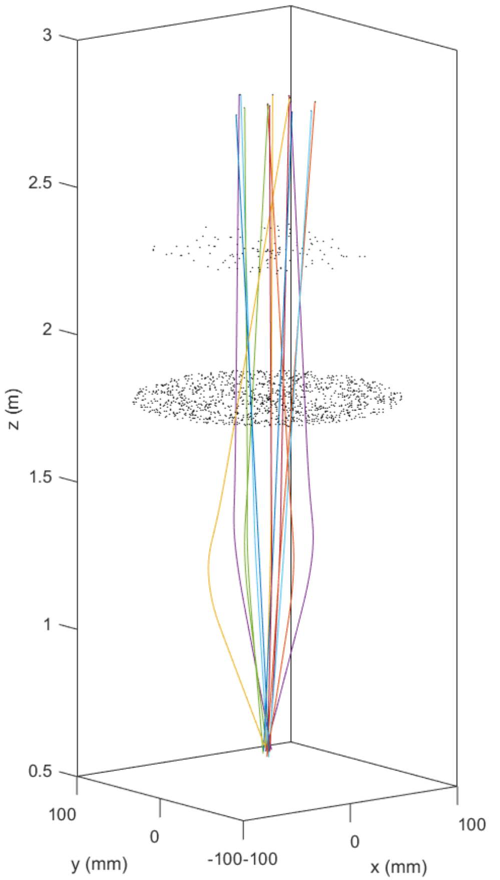
Gravity and magnetic effects can be decoupled rotating the gratings

Inside scenario
2L = 30 cm





Outside scenario
2L = 100 cm



A new perspective for moiré deflectometry outside the magnetic field

Reference source scenario: $T = 15\ K,\ \beta = 1,\ v_z \approx 350\ ms^{-1},\ n = 40$

Inside deflectometer scenario
Grating positions at {0.65, 0.80, 0.95}

1. Deflection of 1.8 um in a L = 15 cm deflectometer
2. Flux $N_{det} = 3.3 \cdot 10^{-3}\ N_{prod}$ in 12.5 cm^2
3. Detected 34 events every 100.000 atoms
4. Shot-noise sensitivity w. 100 atoms: 8.7 m s^{-2}
5. RMS magnetic acceleration $\approx 2\ \mathrm{m\ s^{-1}\ Hz^{-1/2}}$
6. Magnetic shielding possible only < 0.1 T
7. Alignment and zero-reference at cold
8. Blocks the usage of the 1TMCP
9. Requires experiment opening for debugging

Outside deflectometer scenario
Grating positions at {1.8, 2.3, 2.8}

1. Deflection of 20 um in a L = 50 cm deflectometer
2. Flux $N_{det} = 1.7 \cdot 10^{-3}\ N_{prod}$ in 92 cm^2
3. Detected 10 events every 100.000 atoms
4. Shot-noise sensitivity w. 100 atoms: 0.8 m s^{-2}
5. RMS magnetic acceleration $< 2\ \mathrm{m\ s^{-2}\ Hz^{-1/2}}$
6. Allows magnetic termination and shielding
7. Alignment and zero-reference at room temperature
8. Allows the usage of the 1TMCP
9. Can be debugged with experiment cold