THE ANTIMATTER EXPERIMENT
Gravity | Interferometry | Spectroscopy

AEgIS

CERN

5 laser beams

100 million antiprotons

AEgIS

THE WEIGHT OF ANTIMATTER

UNIVERSITY OF LIVERPOOL

TIFPA Trento Institute for Fundamental Physics and Applications

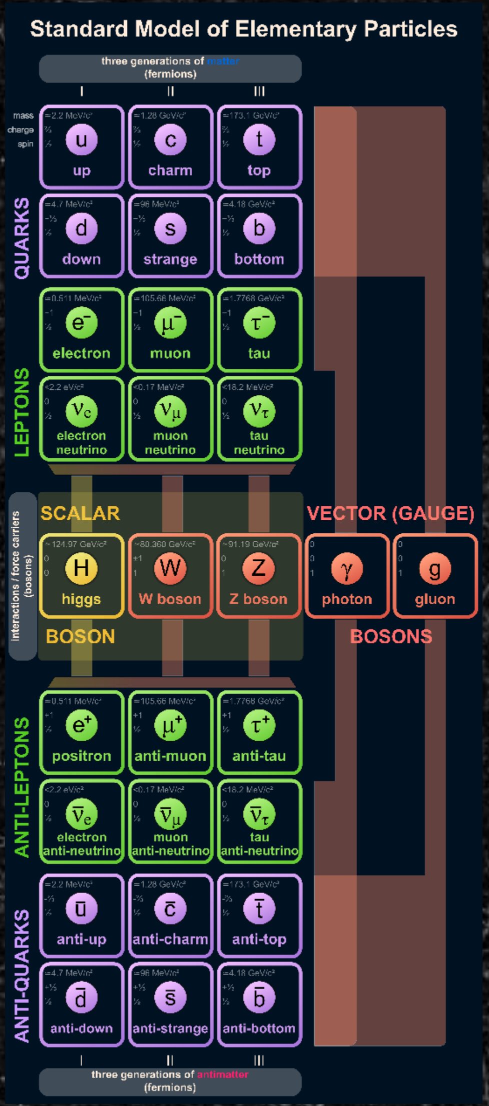
NICOLAUS COPERNICUS UNIVERSITY IN TORUN

NTNU

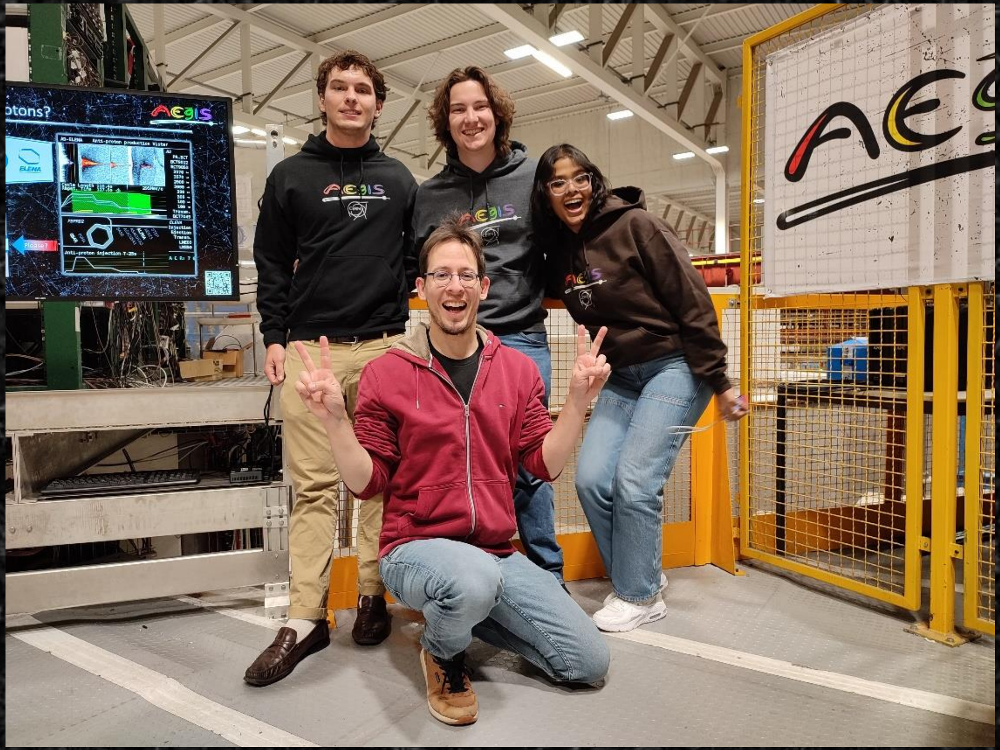
1 billion positrons

50 collaborators

Basics about antimatter



2024 SIT students (and mentor)



Measuring the weight of antihydrogen

Moiré deflectometer

- A **pulsed** antihydrogen source is required!
- **Timing** is defined by the Ps **excitation** and **velocity** profile
- O(10) μm shift <-> 1% of $\bar{g}$

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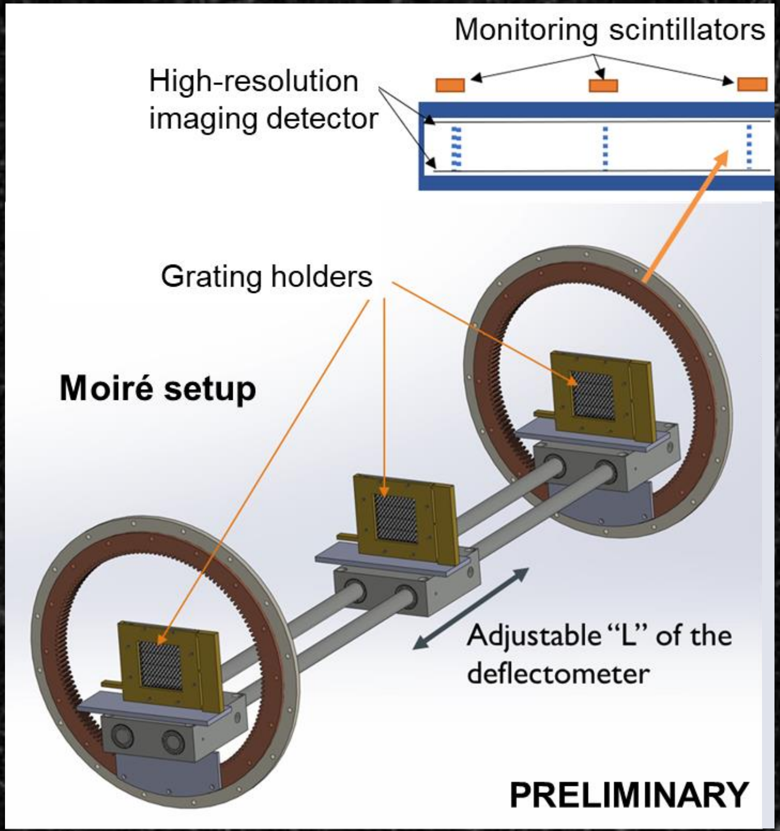
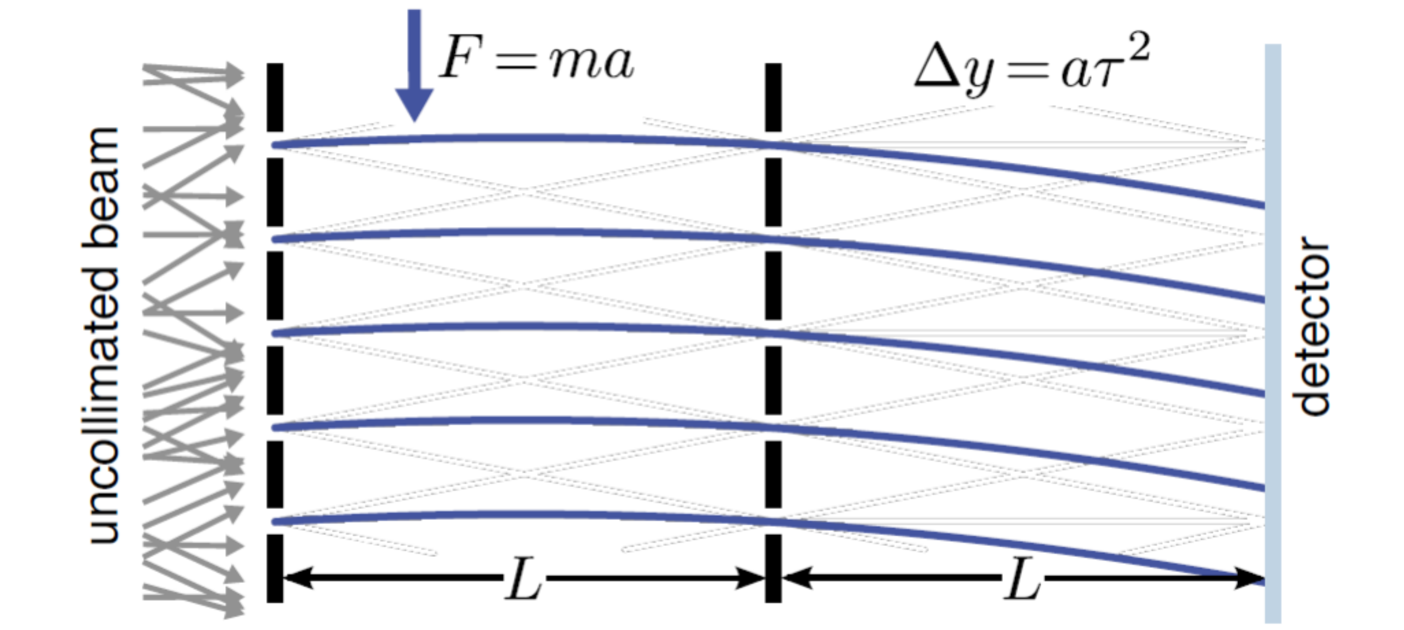
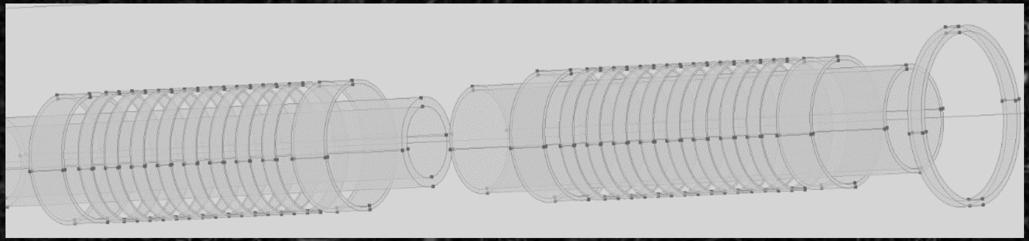
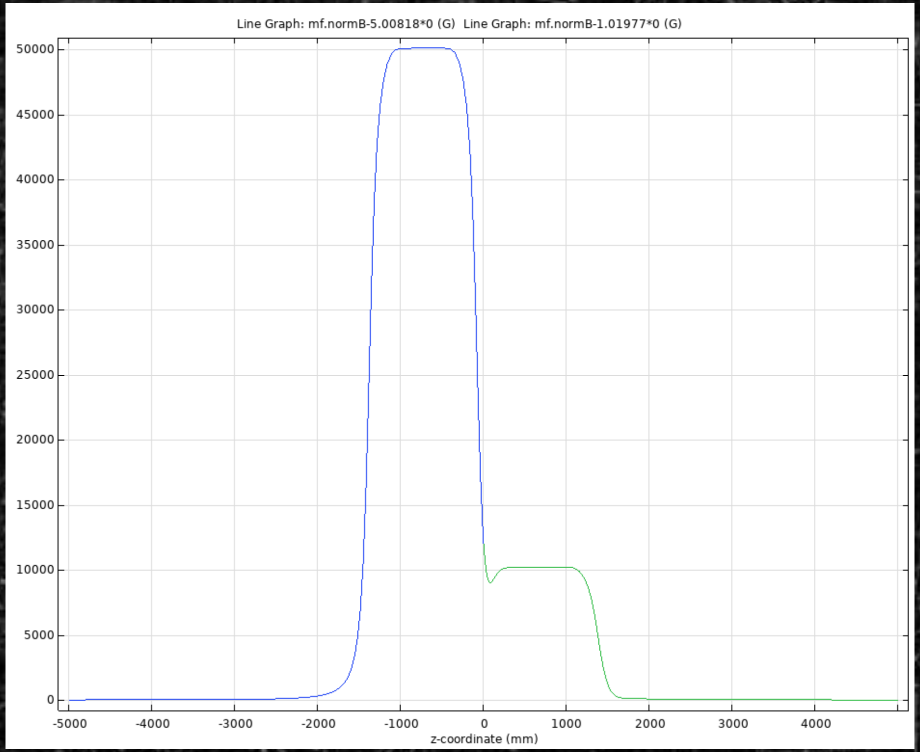
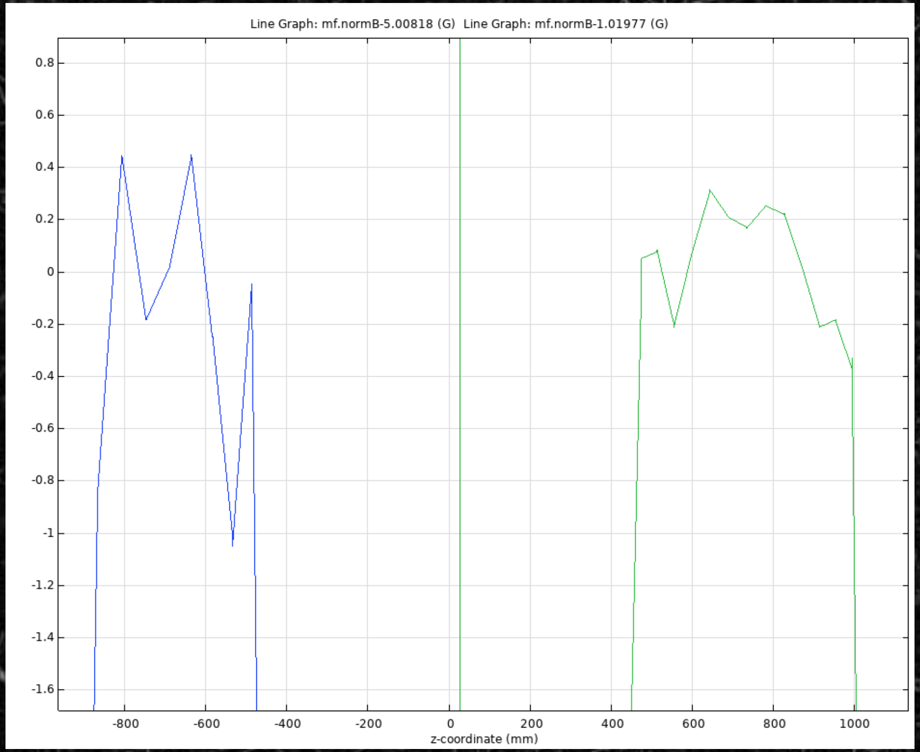




COMSOL: magnetic field simulation







COMSOL: magnetic field simulation

MAGNETIC MOMENT IN EXTERNAL MAGNETIC FIELD — 13/02/2024

1) Energy of the magnetic moment in external magnetic field

$$V(\vec{r}) = -\vec{\mu}\cdot\vec{B}(\vec{r})$$

2) Force

$$\vec{F}(\vec{r}) = -\nabla V(\vec{r}) = \nabla\left(\vec{\mu}\cdot\vec{B}(\vec{r})\right)$$

So:

$$(*)\begin{cases} F_x(\vec{r}) = \frac{\partial}{\partial x}\left(\mu_x B_x(\vec{r}) + \mu_y B_y(\vec{r}) + \mu_z B_z(\vec{r})\right) \\ F_y(\vec{r}) = \frac{\partial}{\partial y}\left(-\,''\,-\right) \\ F_z(\vec{r}) = \frac{\partial}{\partial z}\left(-\,''\,-\right) \end{cases}$$

3) Note that one can rewrite this to a more familiar form using Maxwell equation (no currents)! $\nabla\times\vec{B}(\vec{r}) = 0$

$$\vec{F}(\vec{r}) = \nabla\left(\vec{\mu}\cdot\vec{B}(\vec{r})\right) = (\vec{\mu}\cdot\nabla)\vec{B} + \vec{\mu}\times\underbrace{(\nabla\times\vec{B})}_{\to 0}$$

$$= (\vec{\mu}\cdot\nabla)\vec{B}(\vec{r})$$

So:

$$F_x(\vec{r}) = \mu_x\frac{\partial B_x(\vec{r})}{\partial x} + \mu_y\frac{\partial B_x(\vec{r})}{\partial y} + \mu_z\frac{\partial B_x(\vec{r})}{\partial z}$$

It is equivalent to (*) since!

$$\nabla\times\vec{B} = 0 \Rightarrow \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} = 0 \text{ etc.}$$

1) $F_x(\vec{r}) = \mu_x\cdot\frac{\partial B_x(\vec{r})}{\partial x} + \mu_y\frac{\partial B_x(\vec{r})}{\partial y} + \mu_z\frac{\partial B_x(\vec{r})}{\partial z}$

"x-force on particle at position $\vec{r}$"

2) $\vec{\mu} = \begin{pmatrix}\mu_x\\ \mu_y\\ \mu_z\end{pmatrix}$; $|\vec{\mu}|^2 = \mu_x^2 + \mu_y^2 + \mu_z^2$

$\mu_z' = \mu_B\cdot g_j\cdot m_j$ // $\vec{B} = \begin{pmatrix}B_x\\ B_y\\ B_z\end{pmatrix}$

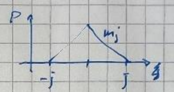
$|\vec{\mu}'| = \mu_B\cdot g_j\cdot\sqrt{j(j+1)} \overset{!}{=} |\vec{\mu}|$

$\Rightarrow \sqrt{\mu_x'^2 + \mu_y'^2} = \mu_B\, g_j\cdot\sqrt{j(j+1) - m_j^2} = \mu_s'$

3) $s = \frac{1}{2}$; $l \in [0; n-1]$; $j \in [|l-s|; l+s]$

$m_j \in [-j; j]$

Example: $n = 30$



4) $\vec{B} = \begin{pmatrix}B_x\\ B_y\\ B_z\end{pmatrix}$ $\vec{n}_{B_1} = \begin{pmatrix}-B_y\\ B_x\\ 0\end{pmatrix}$ $\vec{n}_{B_2} = \begin{pmatrix}-B_x B_z\\ -B_y B_z\\ (B_x^2 + B_y^2)\end{pmatrix}$

$\vec{B} \perp \vec{n}_{B_1} \perp \vec{n}_{B_2}$

5) $\mu_y' = \mu_s'\cdot\cos\varphi\cdot\frac{\vec{n}_{B_1}}{|\vec{n}_{B_1}|}$ "align with $\vec{n}_{B_1}$"

$\mu_z' = \mu_B\cdot g_j\cdot m_j\cdot\frac{\vec{B}}{|\vec{B}|}$ "align with $\vec{B}$"

$\mu_x' = \mu_s'\cdot\sin\varphi\cdot\frac{\vec{n}_{B_2}}{|\vec{n}_{B_2}|}$ "align with $\vec{n}_{B_2}$"

$\varphi \in [0; 2\pi]$

6) Exploit Cartesian rules to get μ_x, μ_y, μ_z!

$$\mu_x = \mu_B\cdot g_j\cdot m_j\cdot\frac{B_x}{|\vec{B}|} - \mu_s'\cdot\cos\varphi\cdot\frac{B_y}{|\vec{n}_{B_1}|} - \mu_s'\cdot\sin\varphi\cdot\frac{B_x B_z}{|\vec{n}_{B_2}|}$$

$$\mu_y = \mu_B\cdot g_j\cdot m_j\cdot\frac{B_y}{|\vec{B}|} + \mu_s'\cdot\cos\varphi\cdot\frac{B_x}{|\vec{n}_{B_1}|} - \mu_s'\cdot\sin\varphi\cdot\frac{B_y B_z}{|\vec{n}_{B_2}|}$$

$$\mu_z = \mu_B\cdot g_j\cdot m_j\cdot\frac{B_z}{|\vec{B}|} + \mu_s'\cdot\sin\varphi\cdot\frac{(B_x^2 + B_y^2)}{|\vec{n}_{B_2}|}$$

We can express $\vec{\mu} = (\mu_x, \mu_y, \mu_z)$ only with the terms $\vec{B}, m_j, \varphi$

Question: Which statistical statements can be made with respect to m_j and φ?

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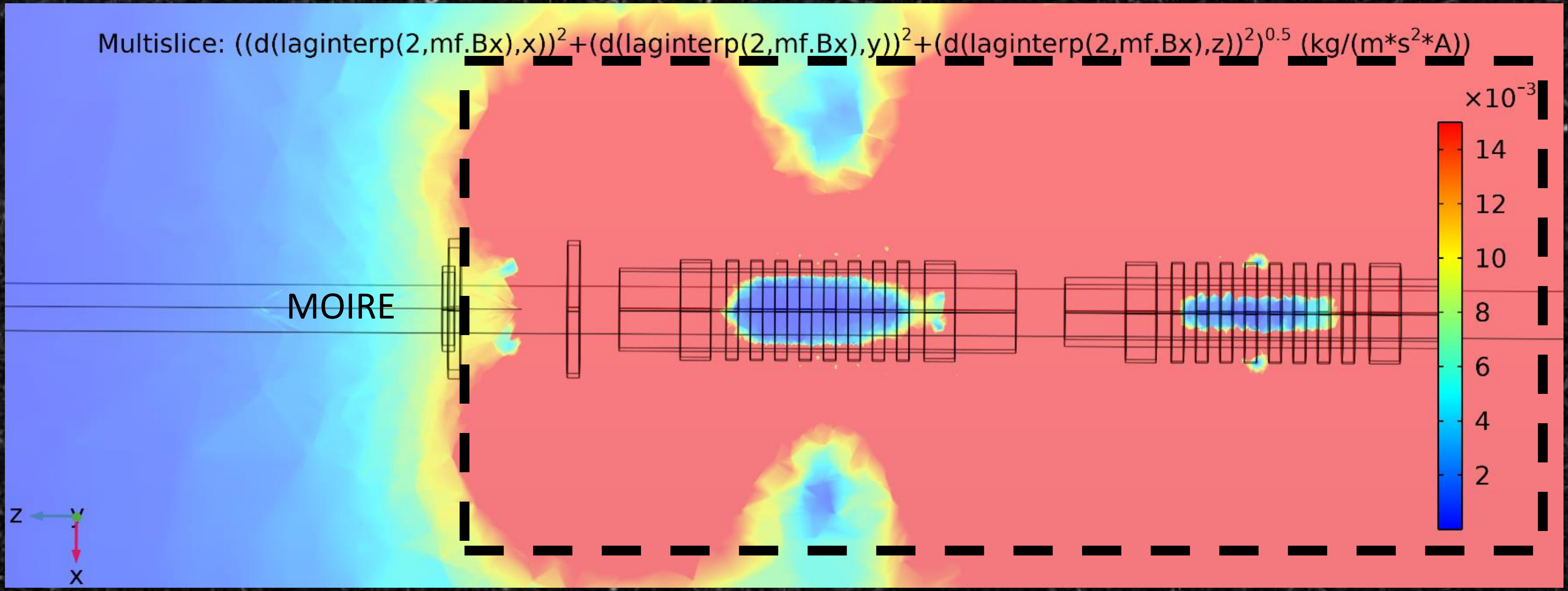

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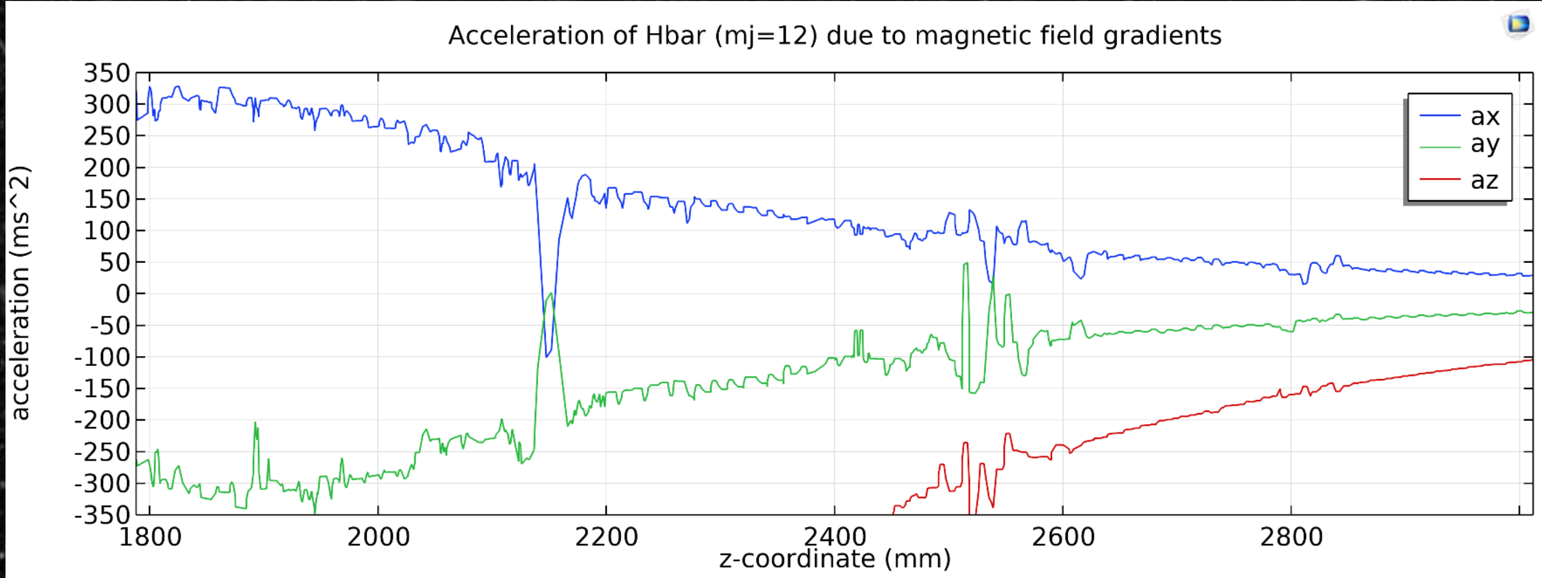
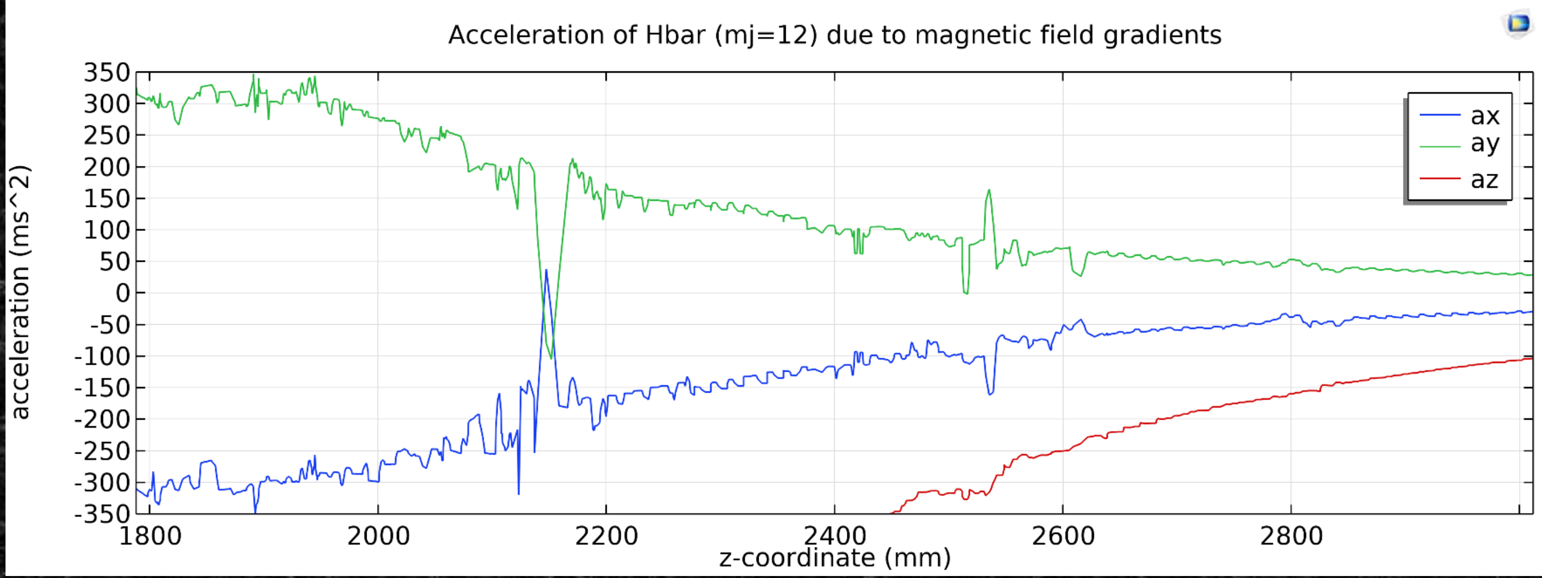


$m_j = 12, j = 15, \varphi = \pi$



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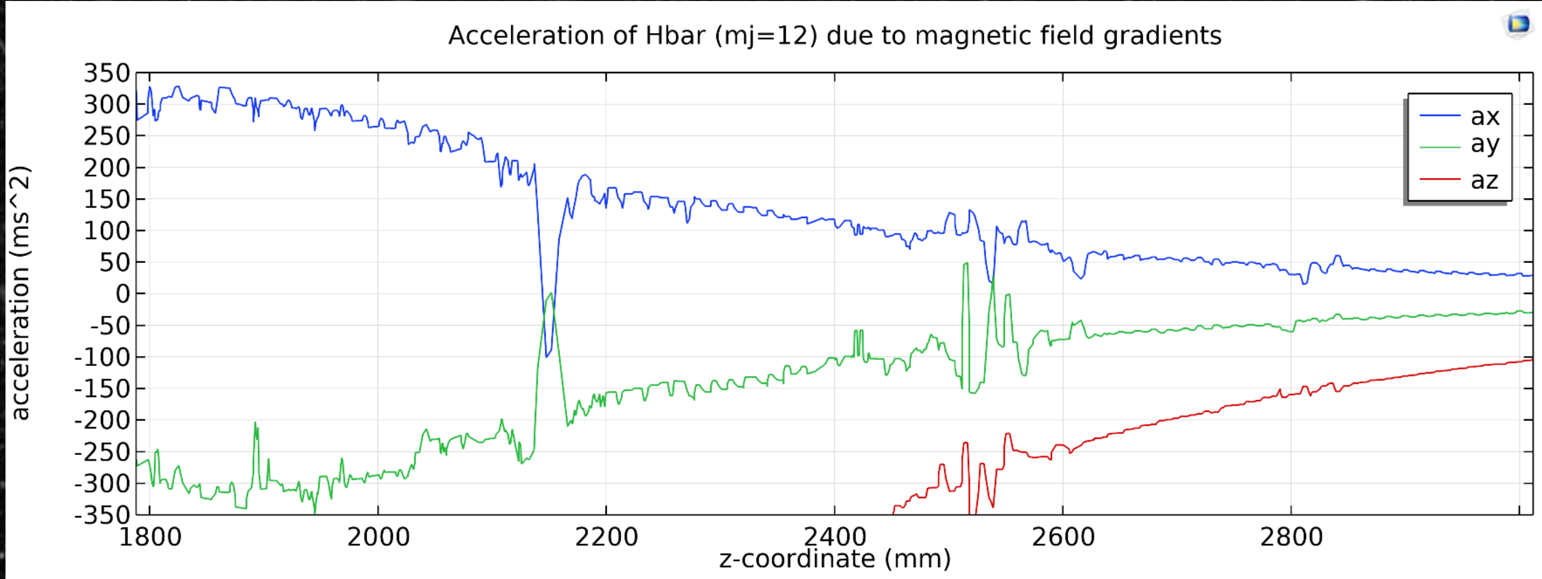
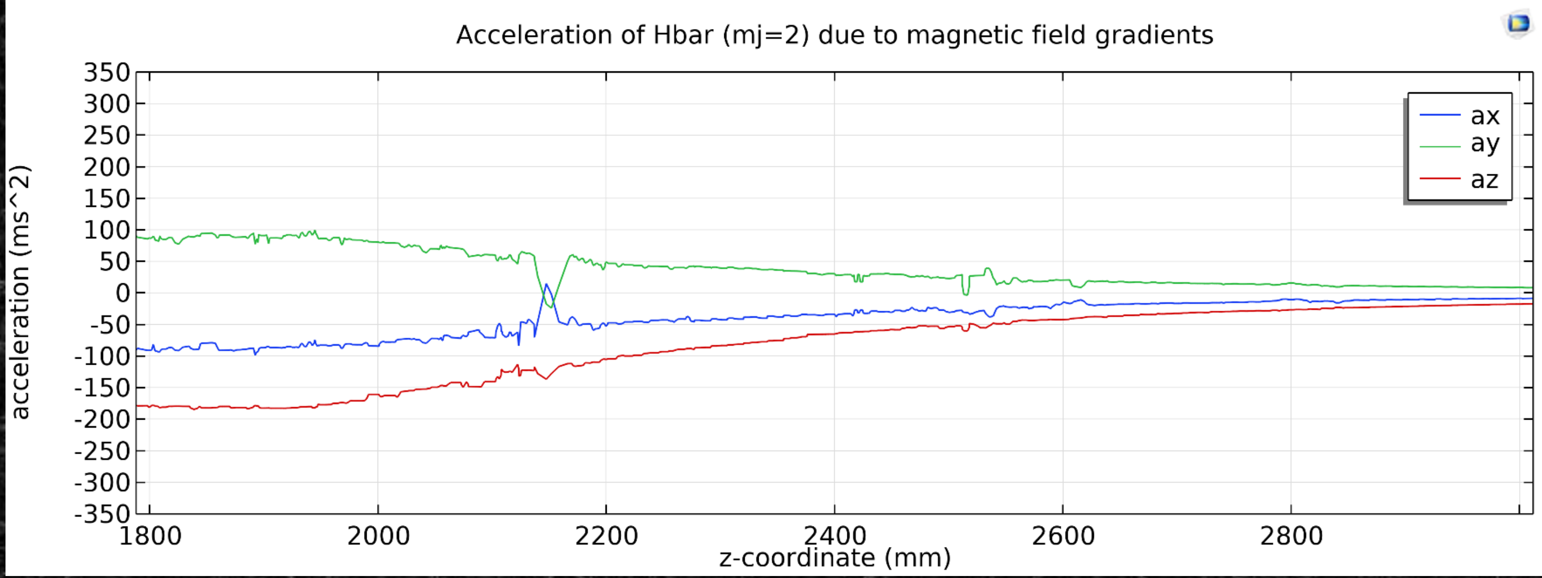
COMSOL: magnetic field simulation

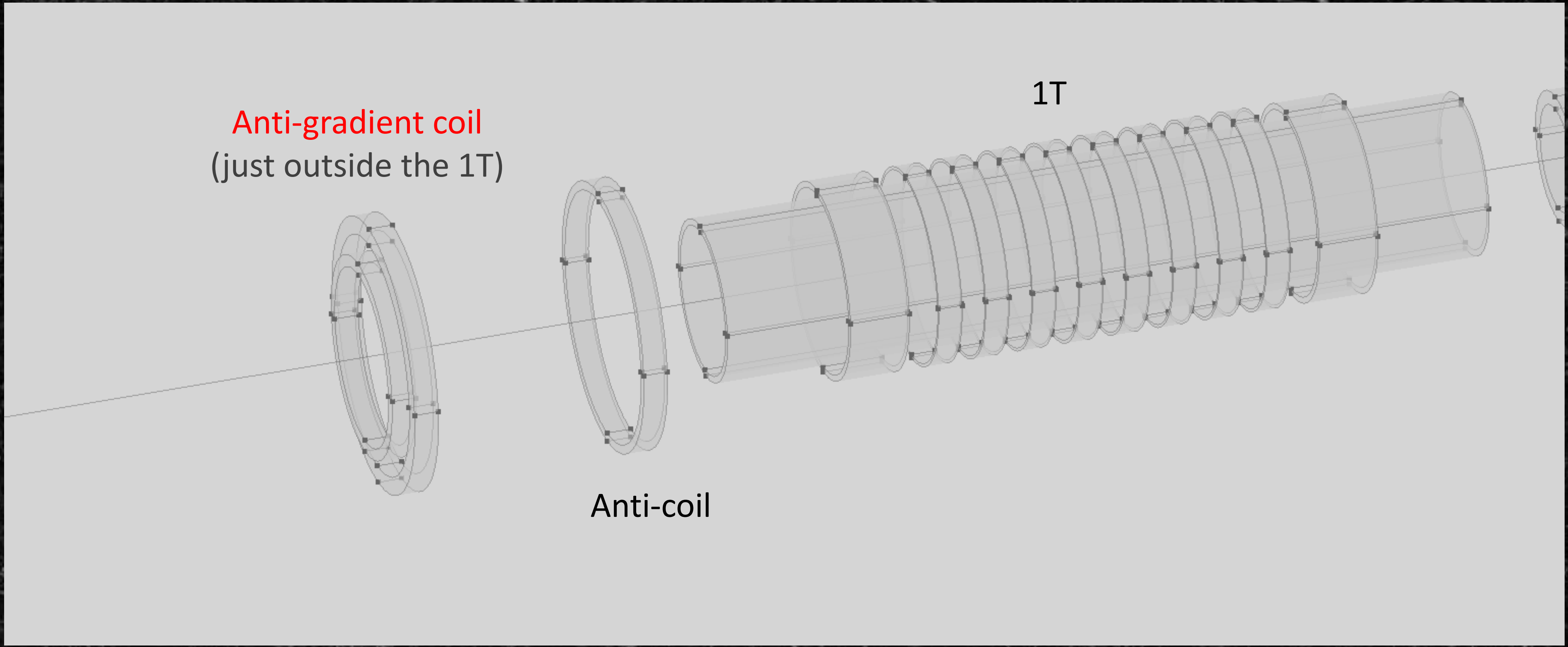


$m_j = 12, j = 15, \varphi = 0$

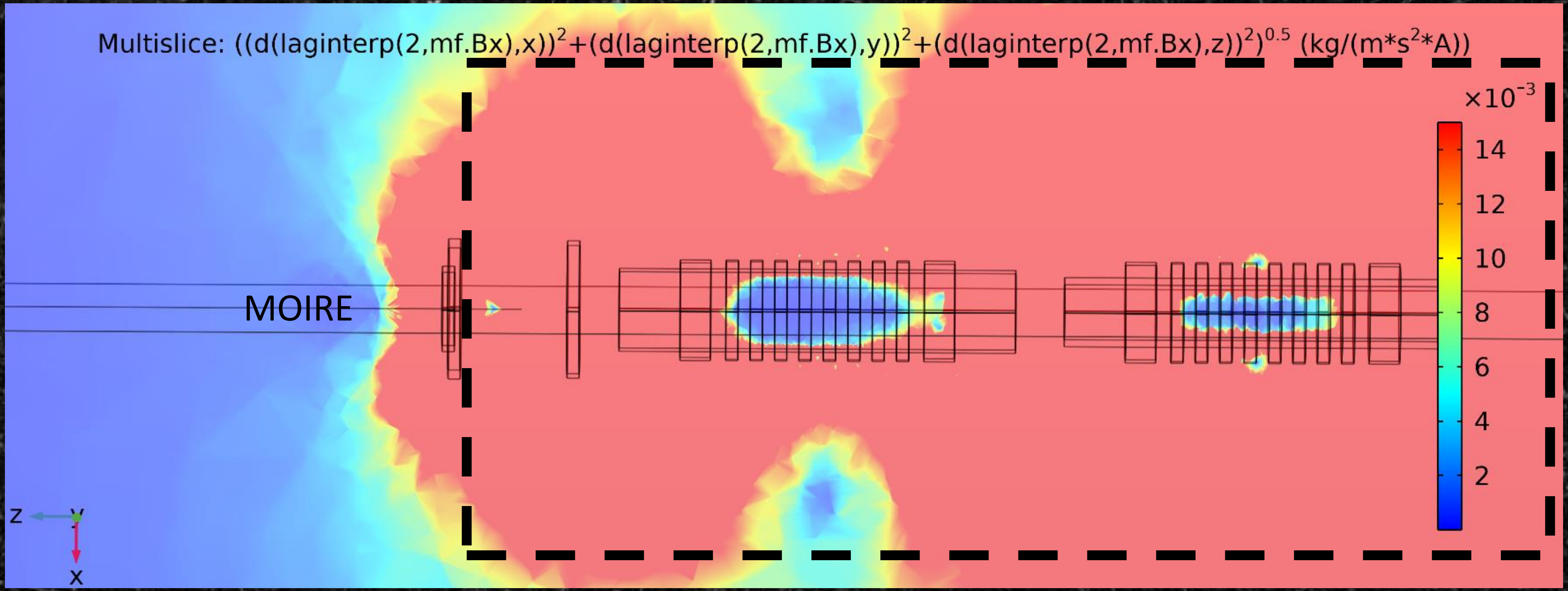


$m_j = 2, j = 3, \varphi = 0$

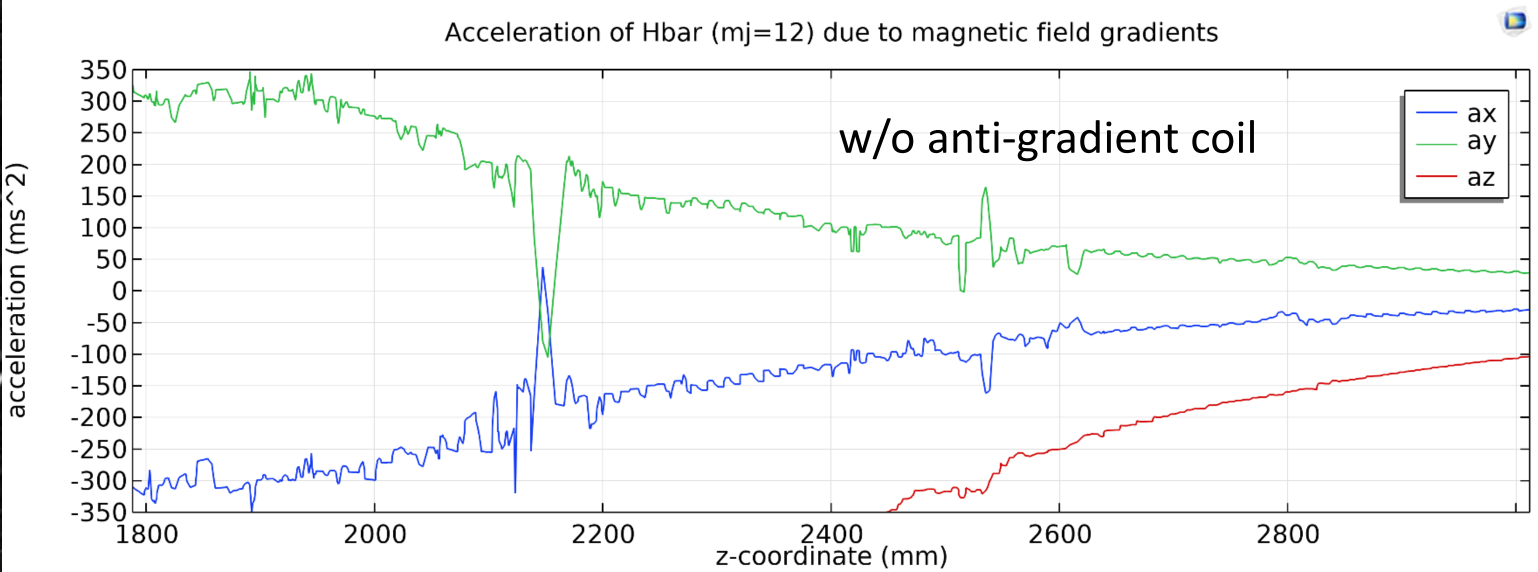
COMSOL: magnetic field simulation



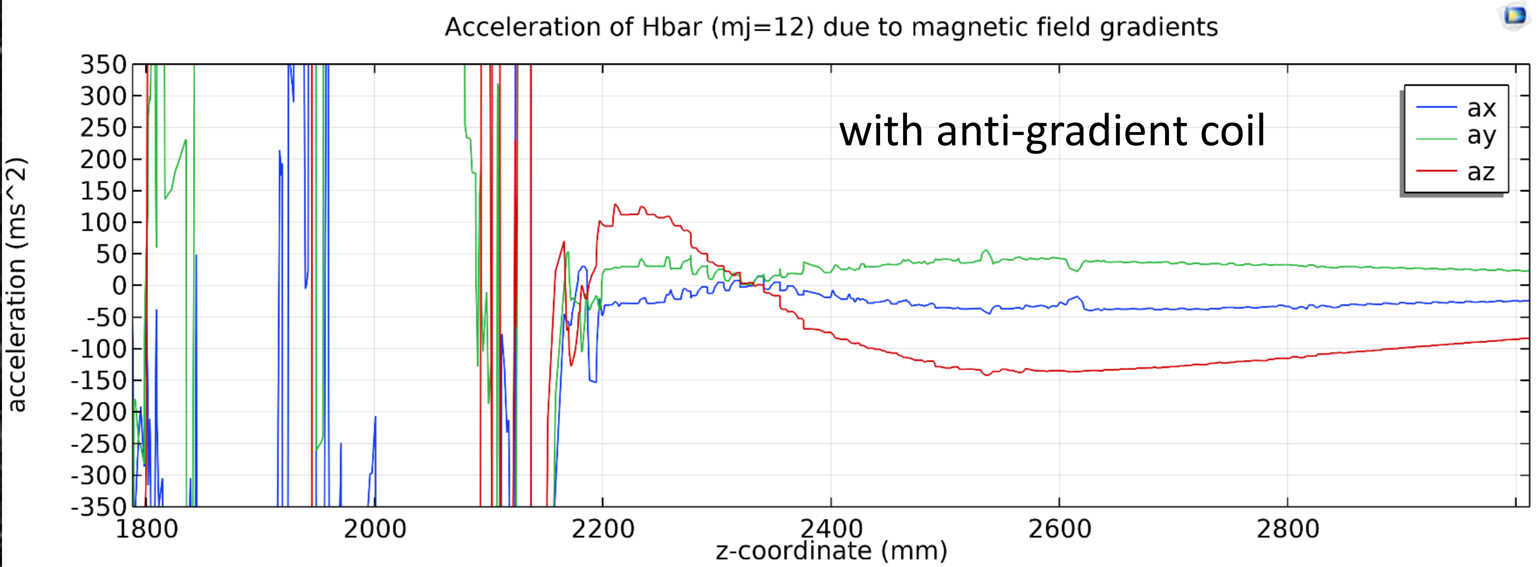
COMSOL: magnetic field simulation



COMSOL: magnetic field simulation



$m_j = 12, j = 15, \varphi = 0$



$m_j = 12, j = 15, \varphi = 0$