Progress on the Design of the Magnetic Field Measurement System for eLISA

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University of Florida, Gainesville

Outline

Top level requirement for LISA

LISA free fall requirement to detect GW

$$S^{1/2}_{\delta a,\mathrm{LISA}}(\omega) \leq 3 \times 10^{-15} \left\{ \left[1 + \left(\frac{\omega/2\pi}{8\ \mathrm{mHz}} \right)^4 \right] \left[1 + \left(\frac{0.1\ \mathrm{mHz}}{\omega/2\pi} \right) \right] \right\}^{\frac{1}{2}} \frac{\mathrm{ms}^{-2}}{\sqrt{\mathrm{Hz}}}$$

$$0.1\ \mathrm{mHz} < \omega/2\pi < 100\ \mathrm{mHz}$$

Internal forces contribution to the total acceleration noise

- **Magnetic effects**
- Charge fluctuations
- Thermal effects
- Brownian motion
- Spacecraft self-gravity
- Laser radiation pressure

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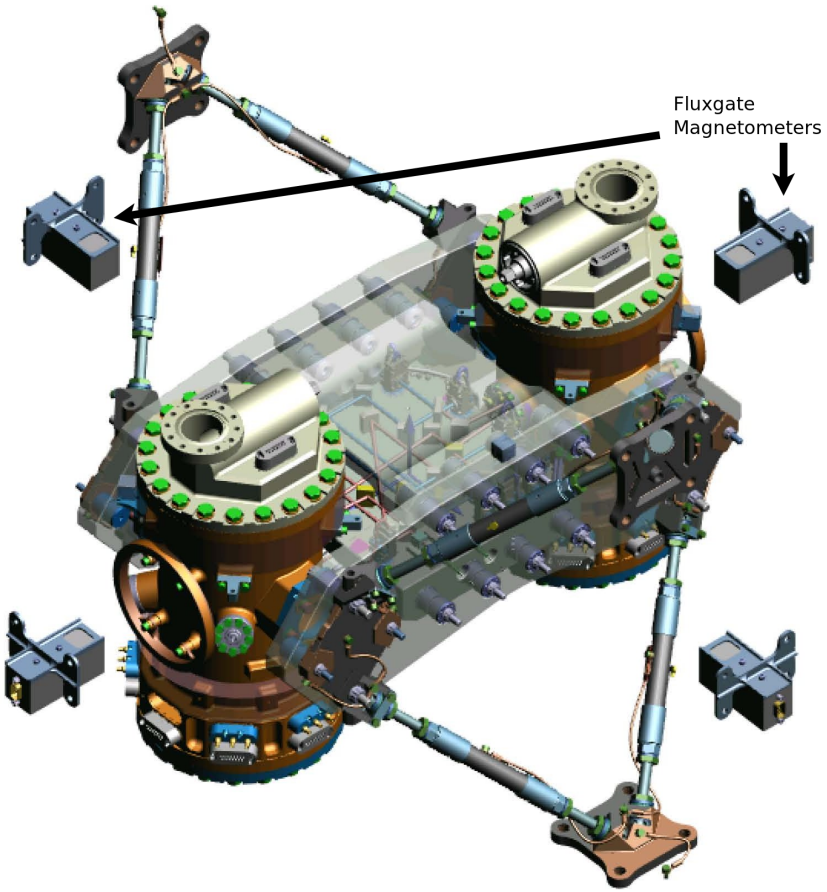
$$0.1\ \mathrm{mHz} < \omega/2\pi < 100\ \mathrm{mHz}$$

Force due to the magnetic effect:

$$\mathbf{F} = \left\langle \left[\left(\mathbf{M} + \frac{\chi}{\mu_0} \mathbf{B} \right) \cdot \nabla \right] \mathbf{B} \right\rangle V$$

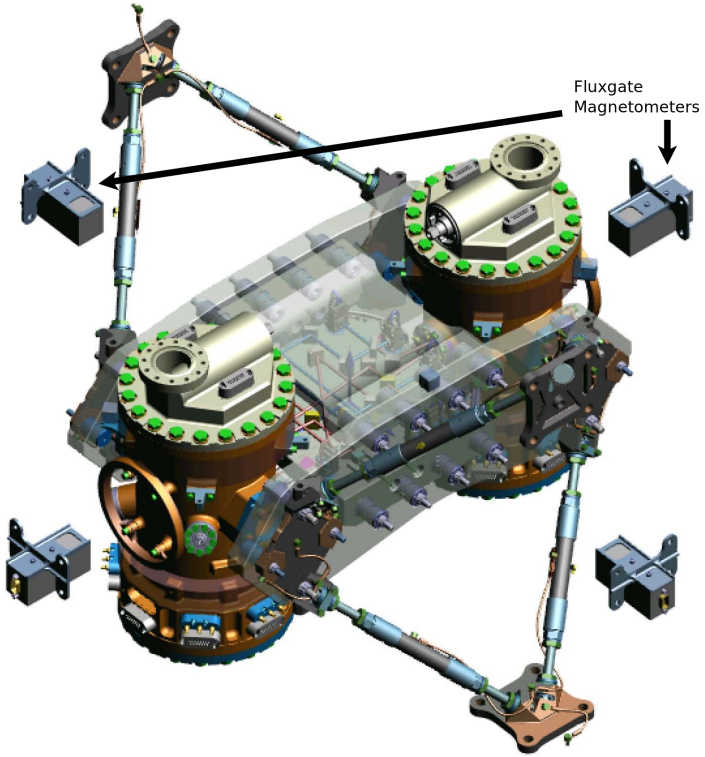
- Magnetic subsystem will assess the magnetic contribution to $S_{\delta a}(\omega)$

In view of eLISA: Main drawbacks in LPF magnetic subsystem



In view of eLISA: Main drawbacks in LPF magnetic subsystem

- Sensors are distant from TMs due to their magnetic back action effect
- Fluxgates are heavy and bulky ($94\,\mathrm{cm}^3$) $\Rightarrow$ less can be placed in the spacecraft
- Classical interpolation methods do not achieve sufficient accuracy
- Noise at lower eLISA frequencies needs to be improved



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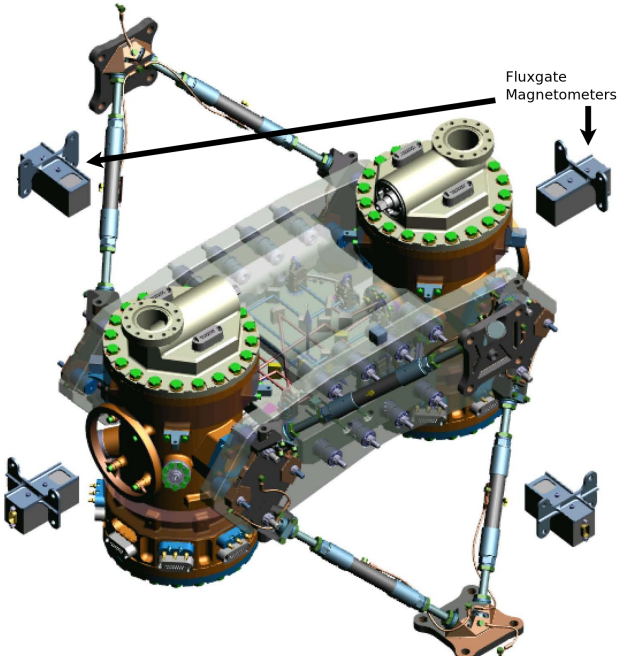

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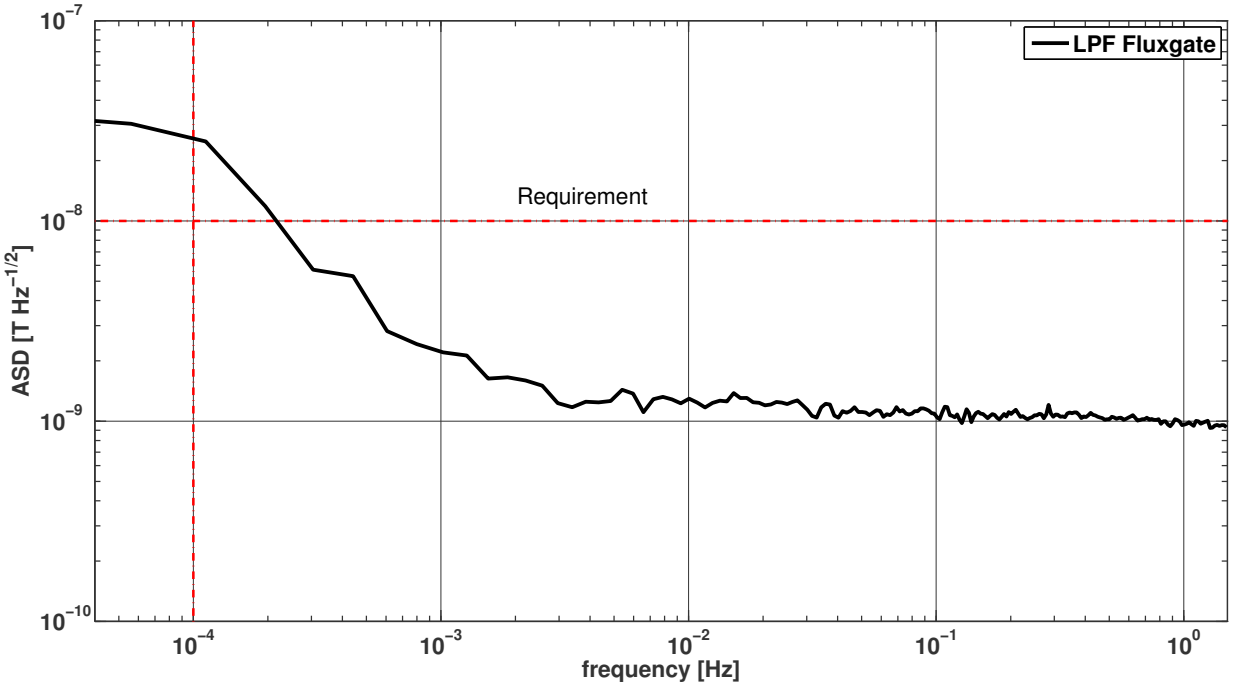
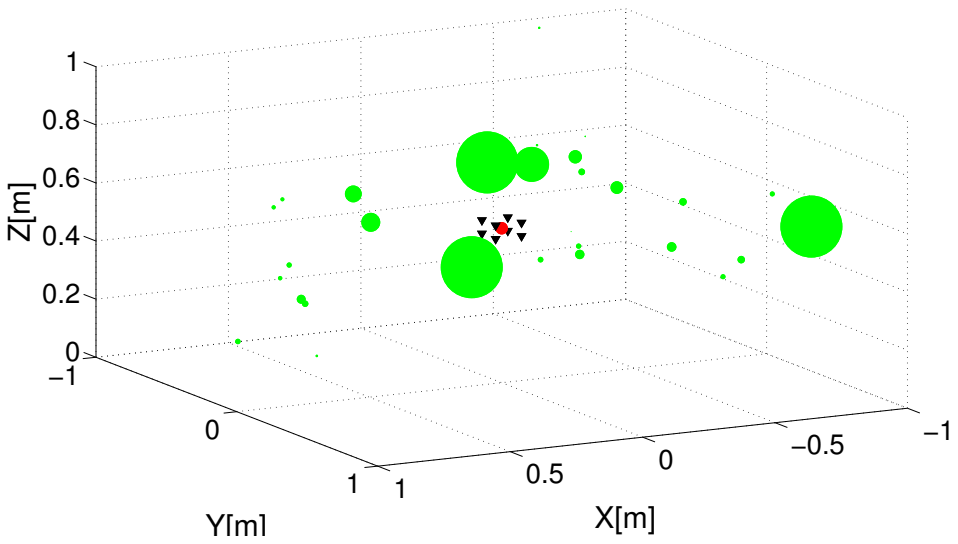
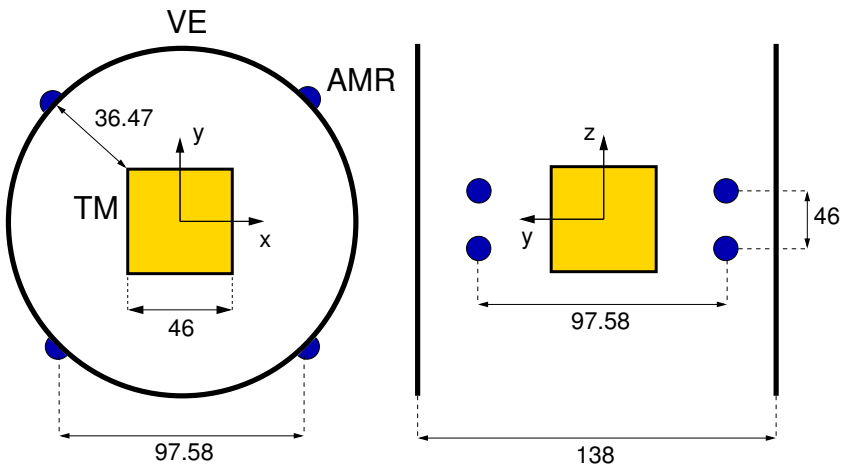


Magnetic sources and sensor location

For a first approach we consider:

- 8 magnetometers layout allocated around the vacuum enclosure.
- The magnitude and location of the magnetic sources measured for LISA Pathfinder.
- A batch of simulated dipoles sources with random orientations to verify the robustness of the interpolation.





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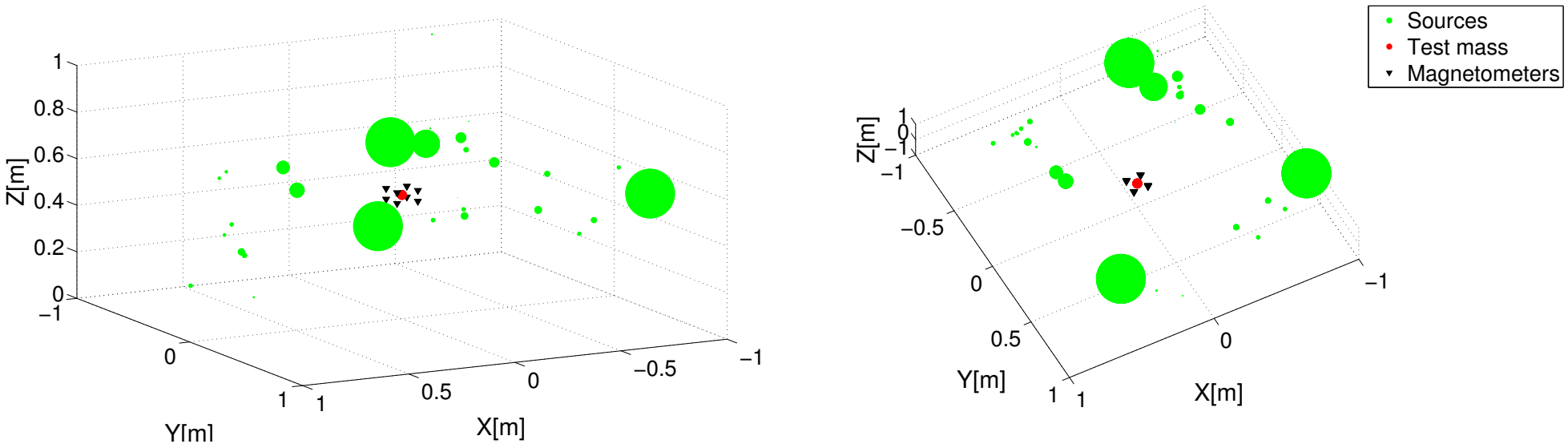


Interpolation method: multipole expansion

The estimated magnetic field measured by an array of N sensors can be expressed as:

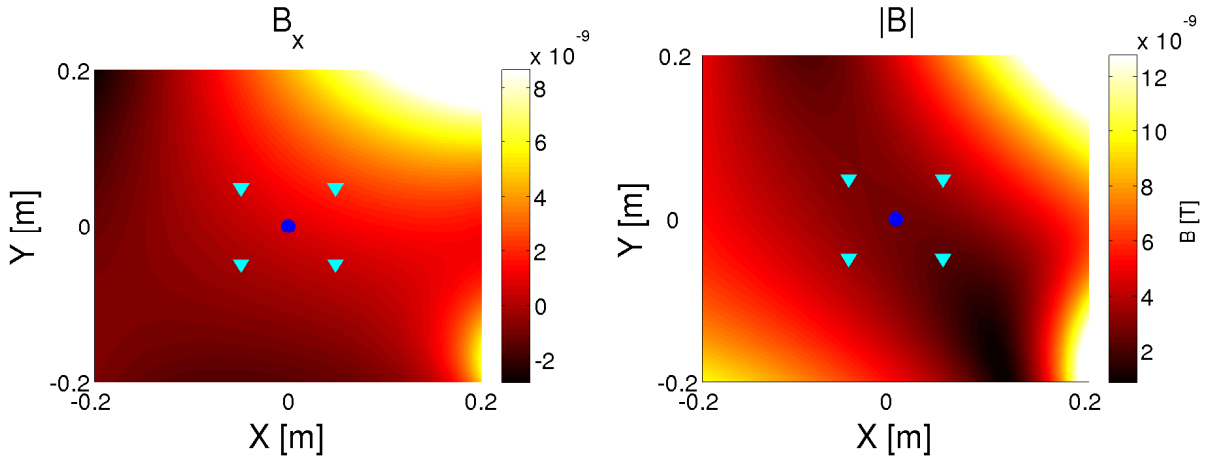
$$\mathbf{B}_{\text{estimated}}(\mathbf{x}, t) = \frac{\mu_0}{4\pi} \sum_{l=1}^{L} \sum_{m=-l}^{l} M_{lm}(t)\, \nabla[r^l\, Y_{lm}(\mathbf{n})]$$

- The number of magnetometers will be defined by the desired multipole order:

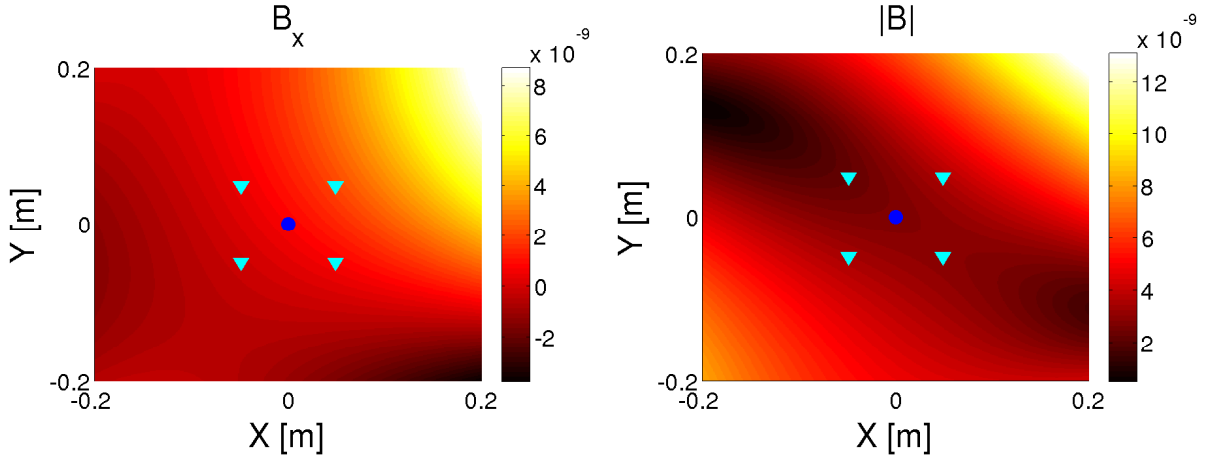
Max. order decomposition L	Equivalent multipole	Terms in expansion [L (L + 2)]	Num. of triaxial magnetometers [N]
1	dipole	3	1
2	quadrupole	8	3
3	octupole	15	5
4	hexadecapole	24	8

Magnetic field reconstruction: 8 triaxial sensors

- **Magnetic field created by the dipolar sources**

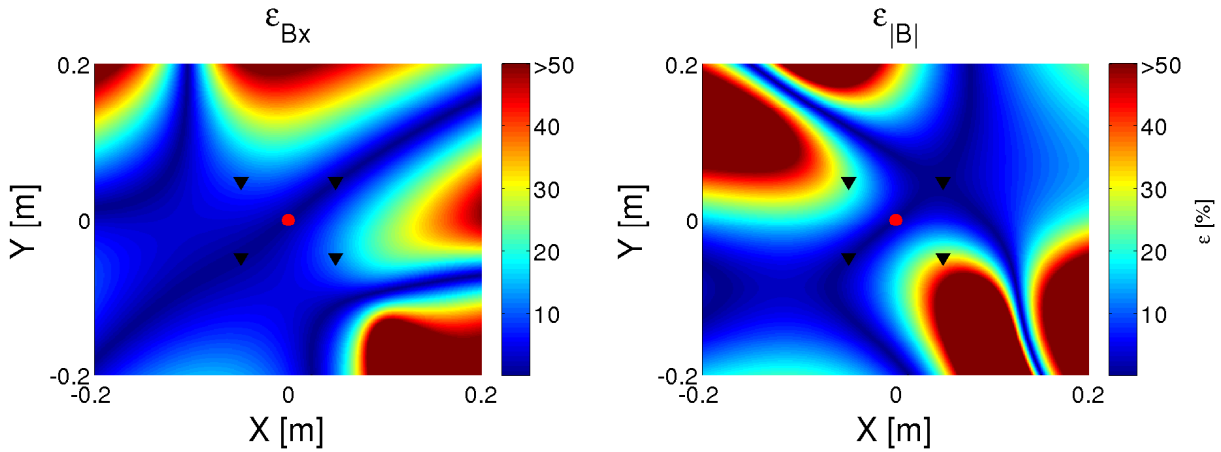


- **Multipole expansion interpolation**

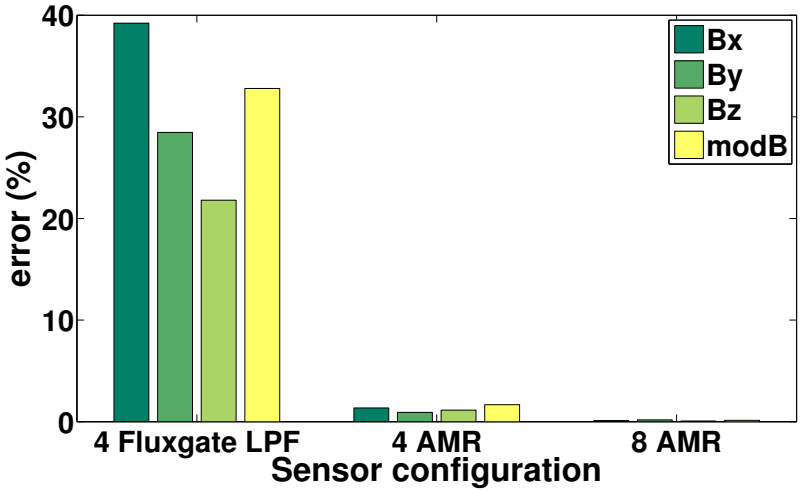


Magnetic field reconstruction: Relative errors

- **Averaged relative errors for multipole expansion**



- **Averaged relative errors at TM's position for different layouts**



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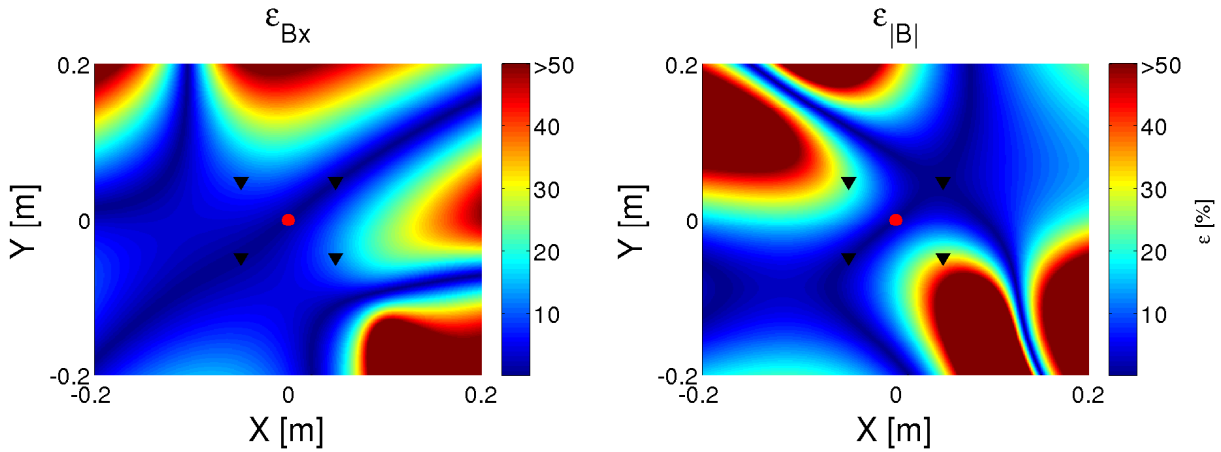

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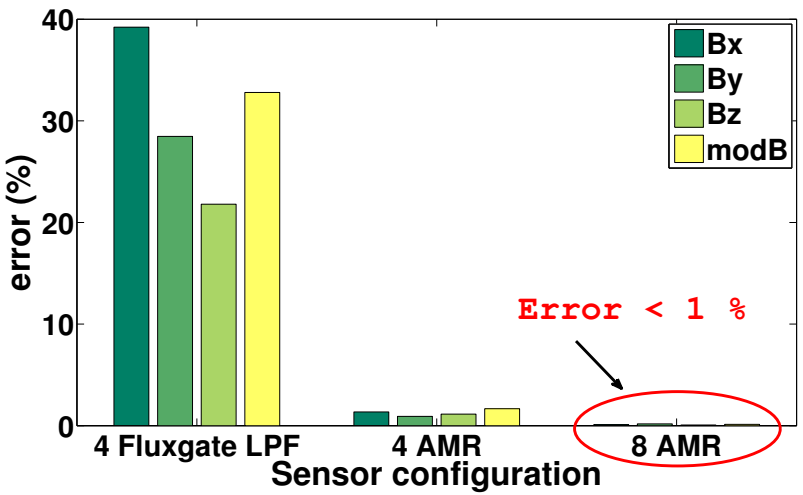

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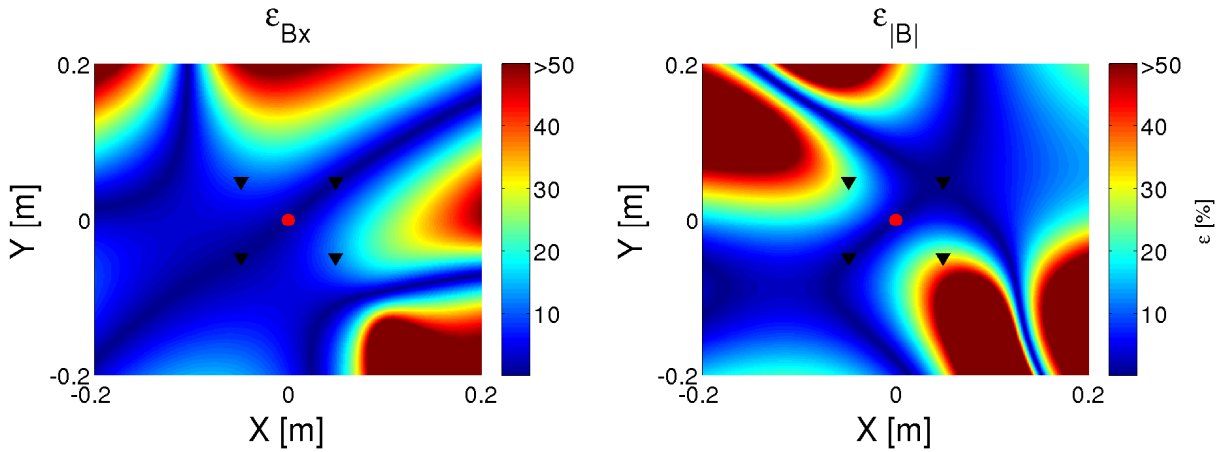

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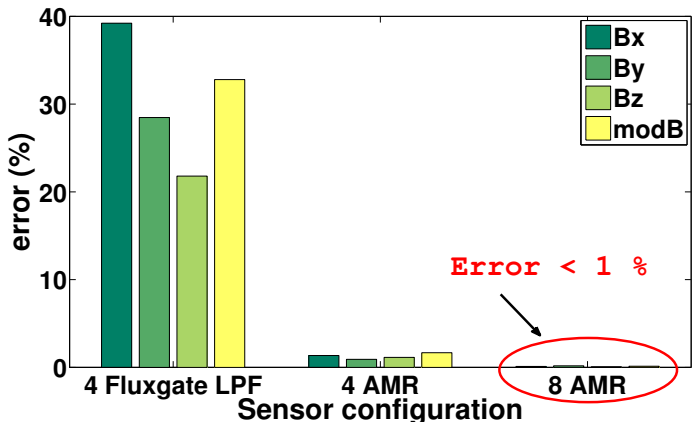
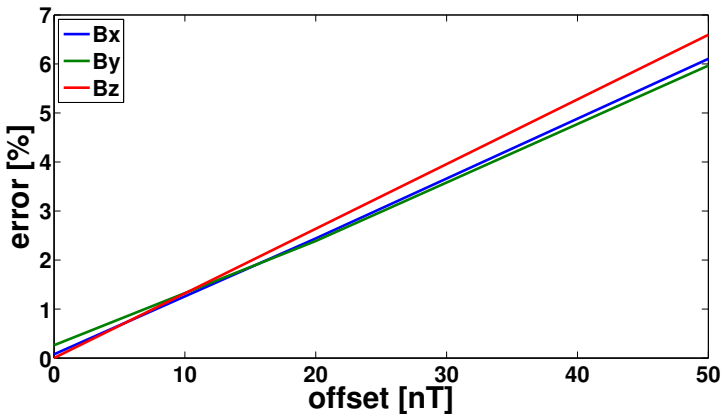
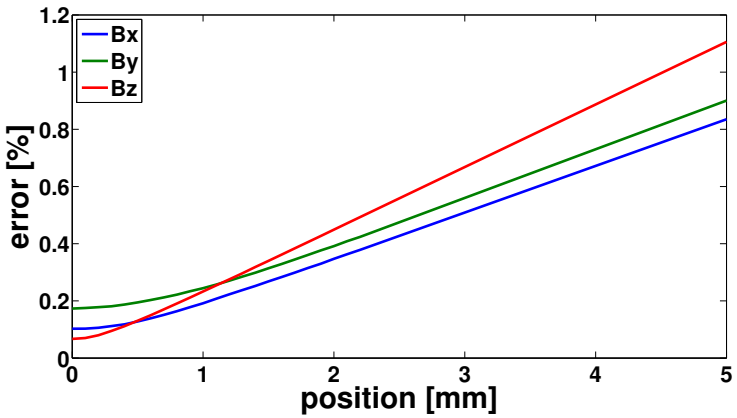


Error (%)	8 AMRs B_x	B_y	B_z	$\lvert\mathbf{B}\rvert$
$\overline{\varepsilon}_{\mathrm{TM}}$	0.1	0.2	0.1	0.1
σ	0.1	0.2	0.1	0.1

Magnetic field reconstruction: Robustness

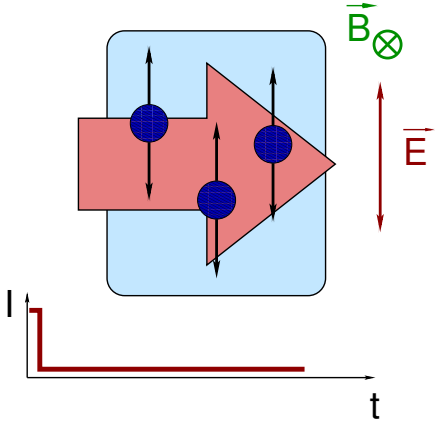
- **Errors due to the offset and position of the sensors**





- AMR's offset can be measured in flight. Fluxgate magnetometers may suffer from unpredictable offsets due to launch stresses ($< 10\,\mathrm{nT}$).
- Spatial resolution will be determined for the size of the sensor head. $\Delta_{\mathrm{AMR}} < 1\,\mathrm{mm}$ and $\Delta_{\mathrm{Fluxgate}} < 4\,\mathrm{mm}$.

Principle of operation



Pump pulse creates alignment in the medium along $\vec{E}$

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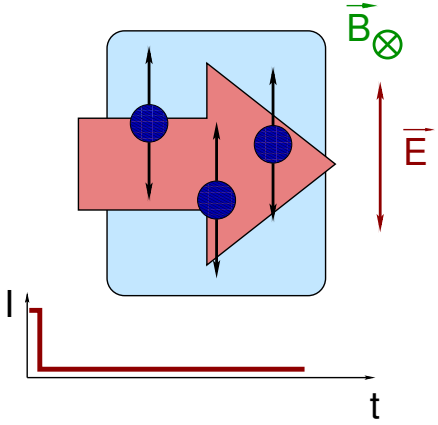

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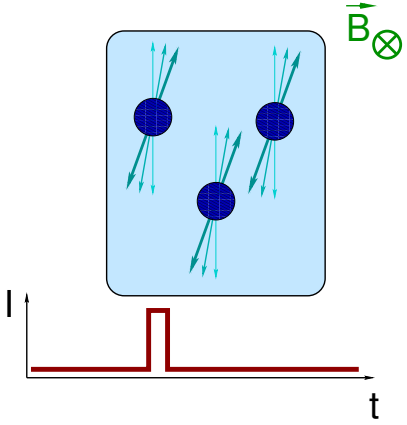

Atomic moments precess about $\vec{B}$ at the Larmor frequency

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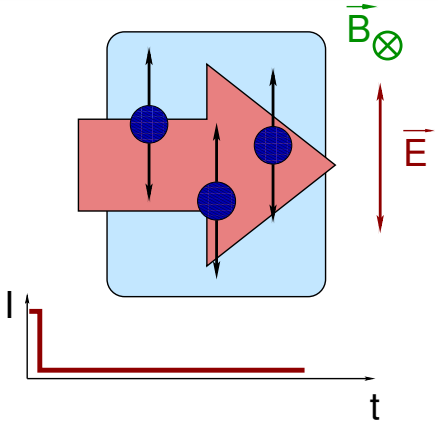

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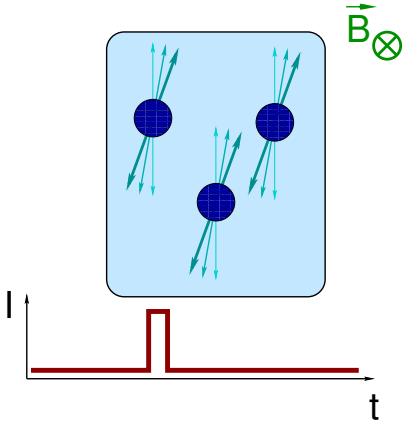

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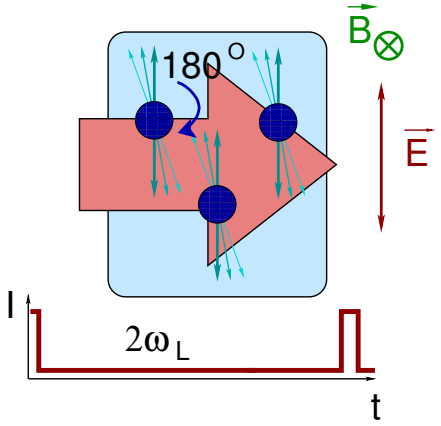

Pump pulses are synchronized and reinforce the macroscopic moments

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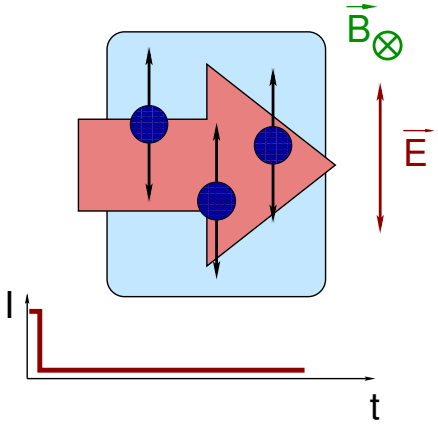

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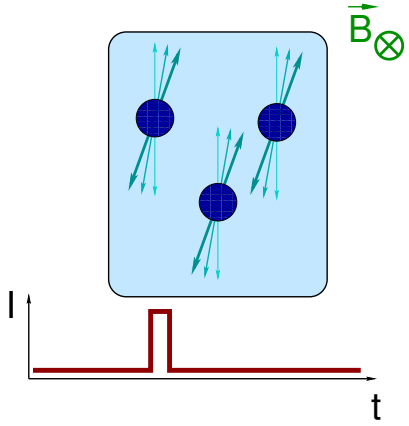

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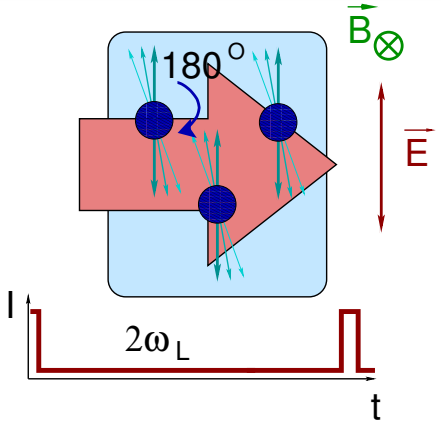

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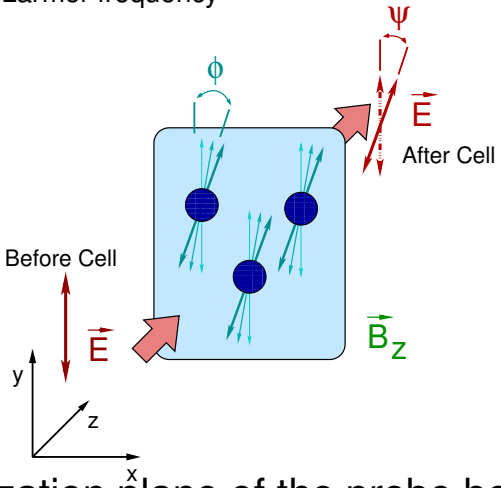
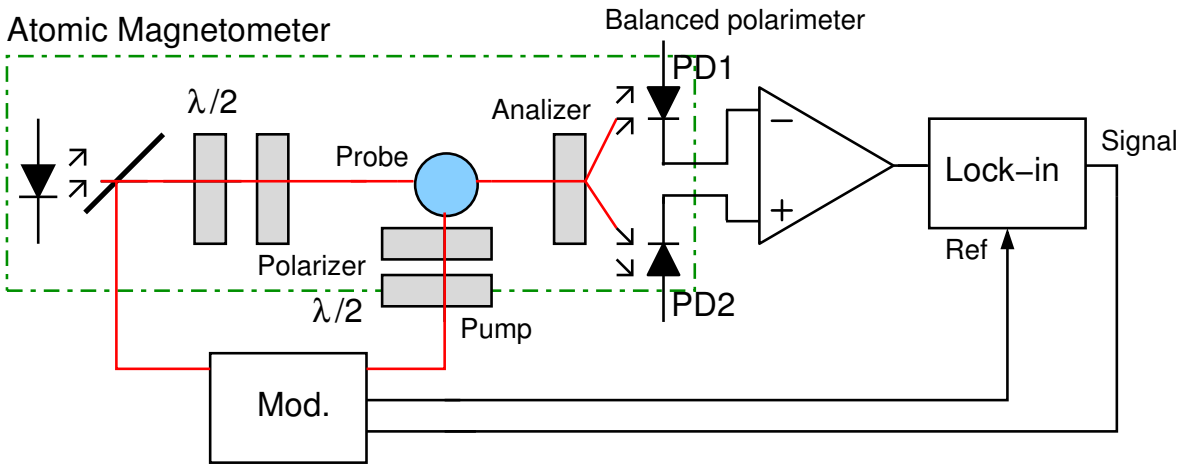


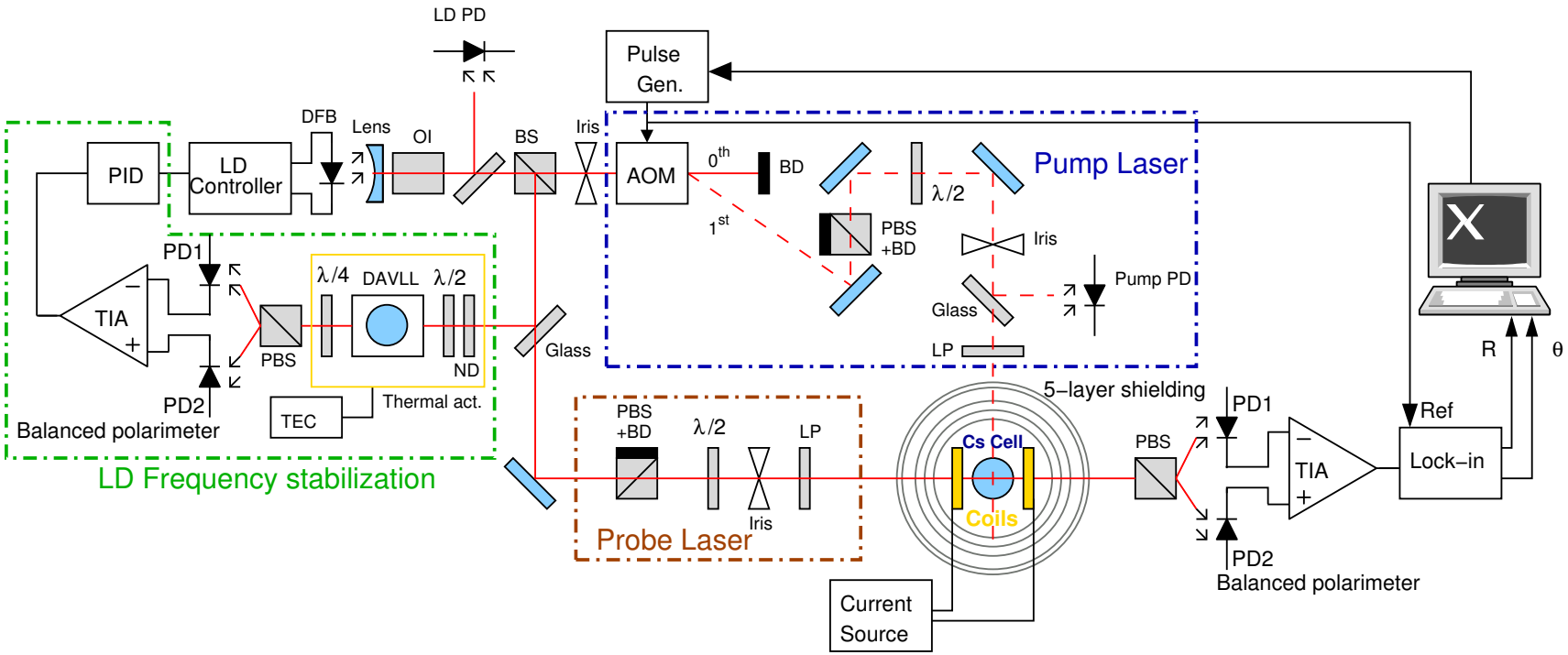
Aligned media rotates the polarization plane of the probe beam (Faraday effect)

Amplitude modulated non-linear magneto optical rotation (AM NMOR)



- Laser is tuned to a magnetically sensitive transition (D_1 or D_2 line)
- Light is linearly polarized before vapor cell
- Optical rotation of the light is measured with a balanced polarimeter
- Signal is demodulated with a reference frequency equal to the Larmor frequency
- ITO heaters are not necessary at the cell
- 2-beams configuration optimize sensitivity

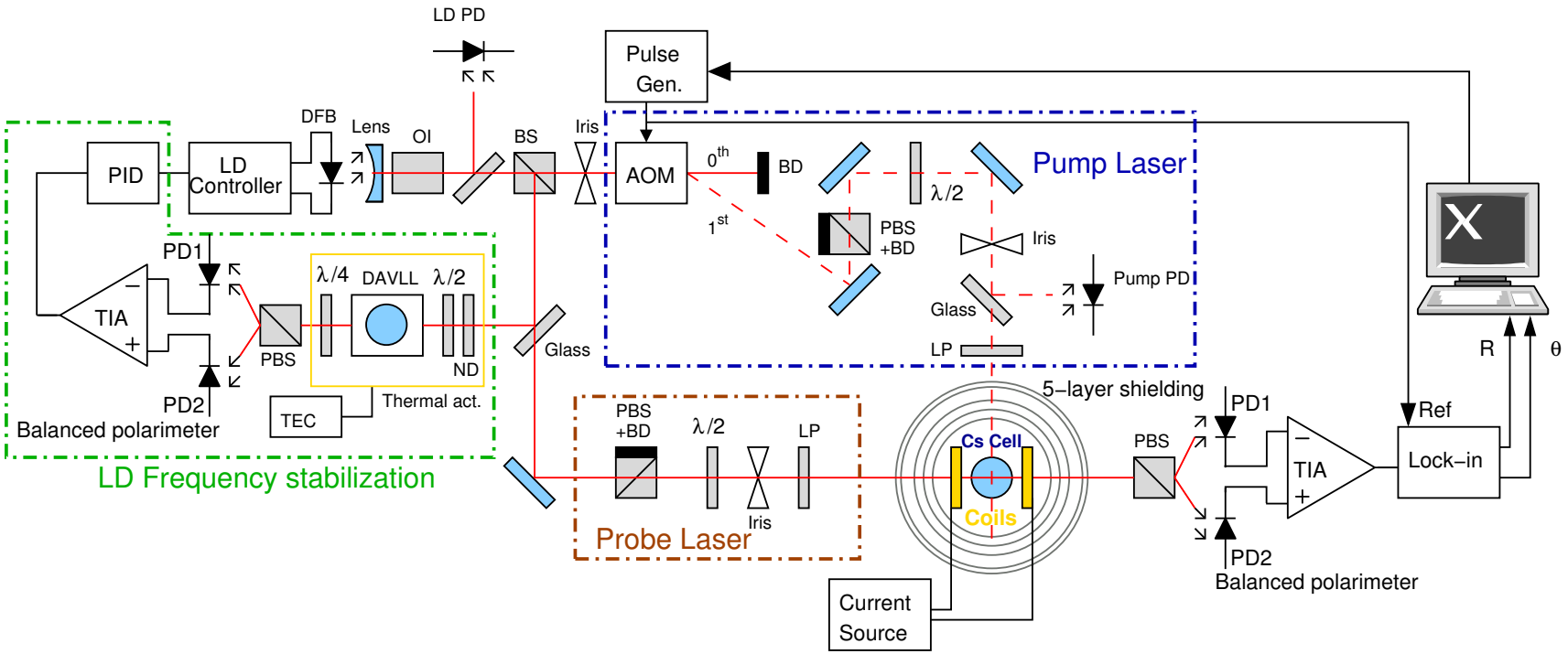
AM NMOR: Block diagram



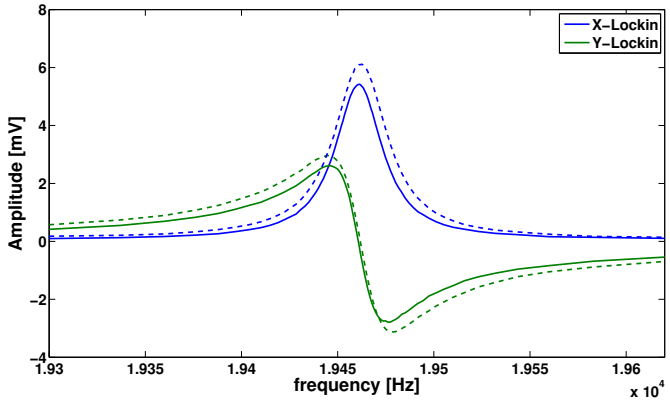
Monitored data

- Output of the lock-in (X-in-phase and Y-out-phase and reference frequency)
- Frequency and power at different points of the laser
- LD current and temperature
- Output of the polarimeters (single and differential)
- Environmental and applied magnetic field (with environmental temperature)

AM NMOR: Block diagram



- Lorentzian distribution is obtained by sweeping around Ω_L
- Signal changes during long measurement
- Zero phase is less sensitive to power fluctuations
- Zero-phase feedback loop to keep acquire Ω_m locked to resonance



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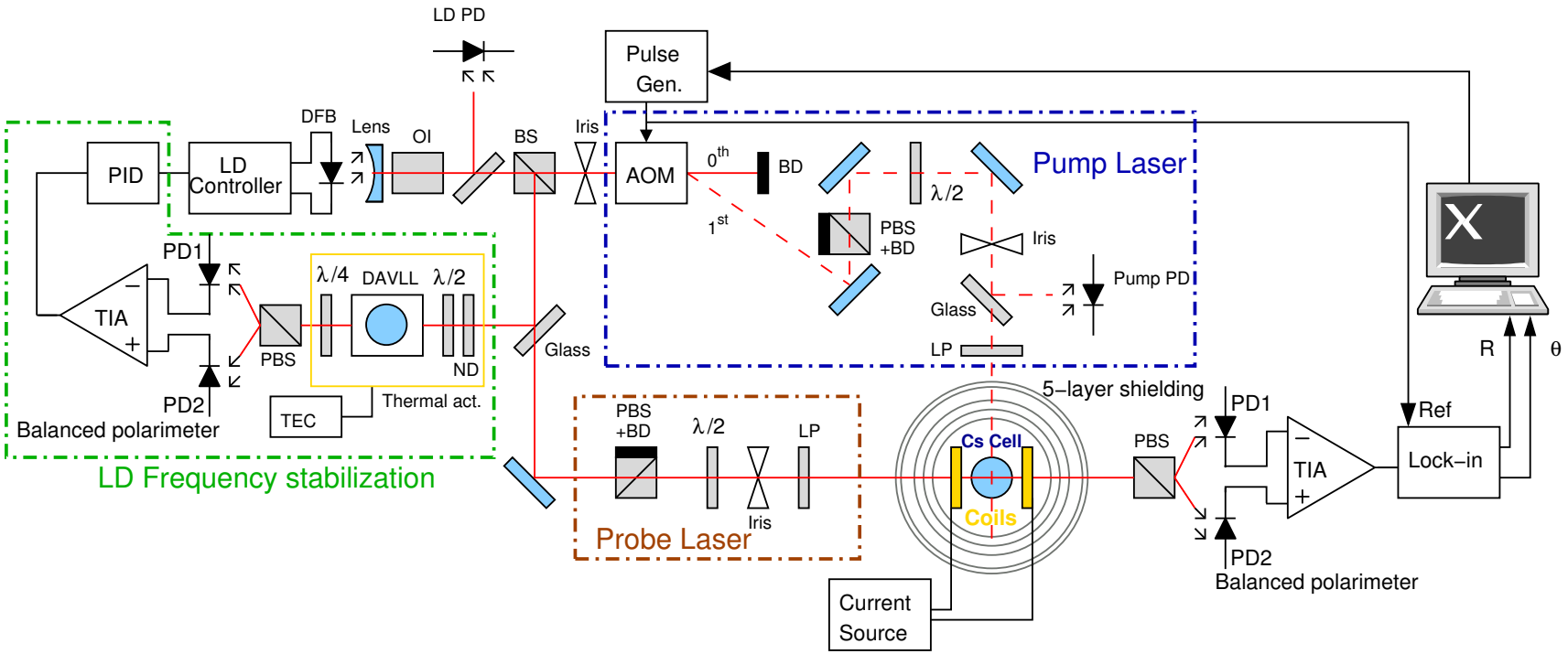

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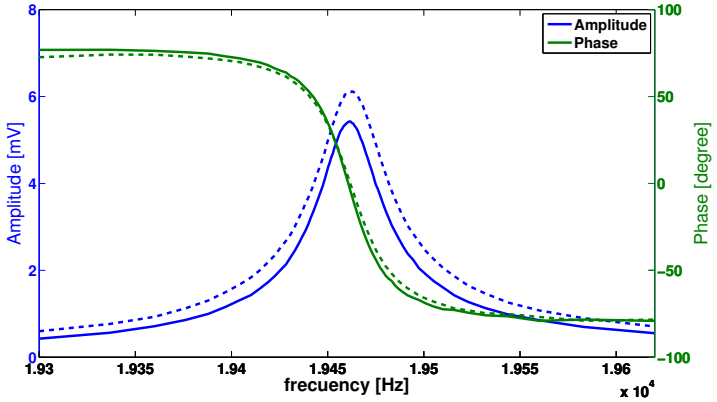

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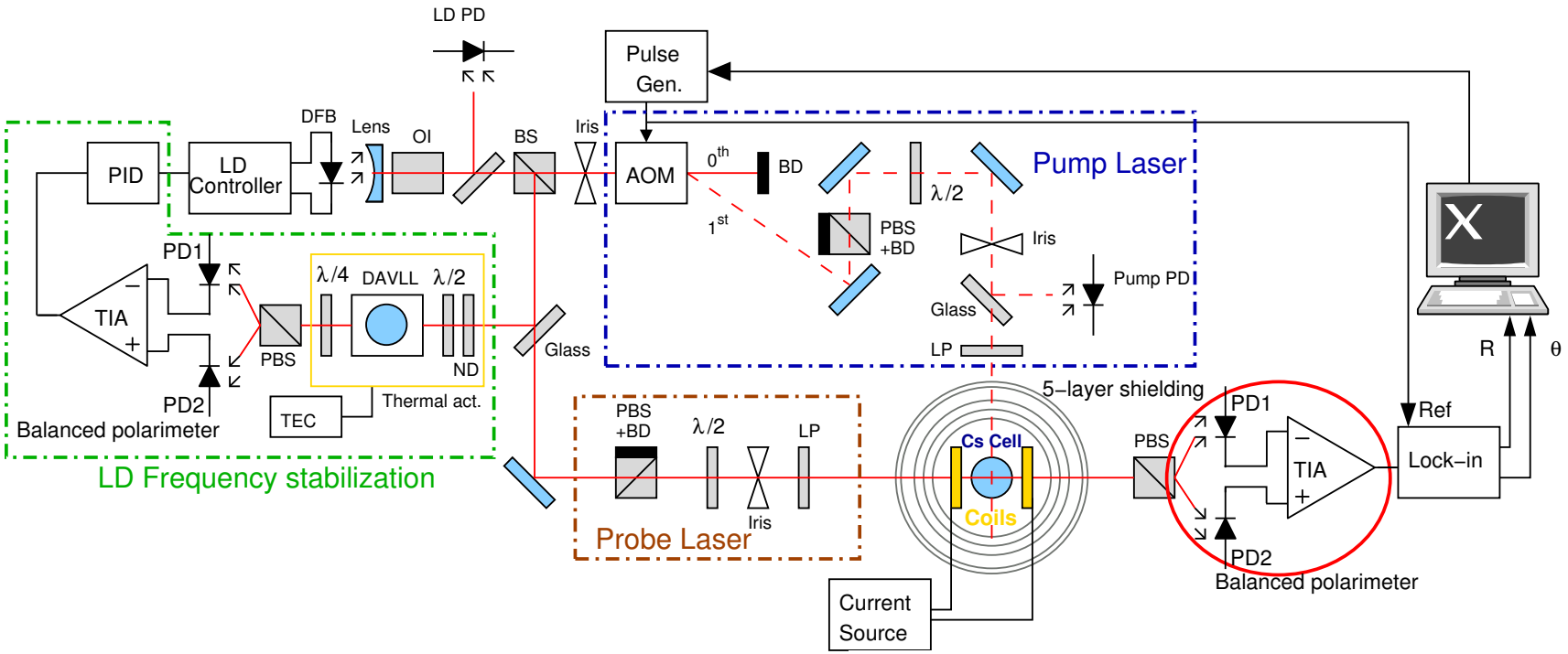
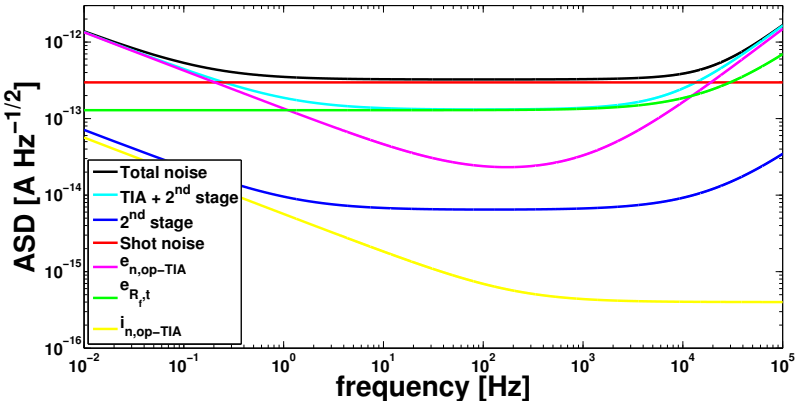


Probe beam polarimeter

- High gain TIA: 11 $\mathrm{mV/nA}$
- Signal is modulated between 1 Hz and hundreds of kHz
- Dominant noise contributions: $e^2_{\mathrm{n,op-TIA}}$, i^2_{SN}, $e^2_{\mathrm{R_f}}$
- High SNR measurements can be made



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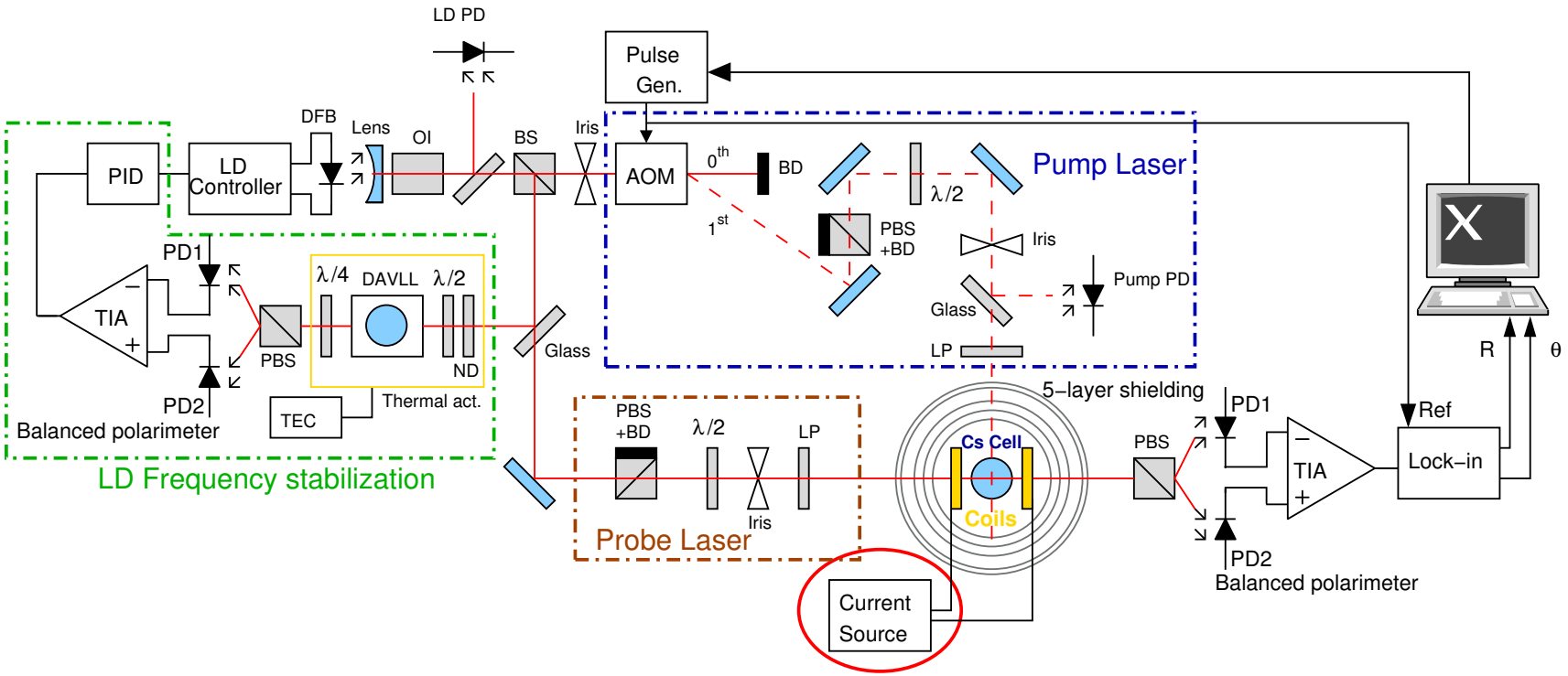
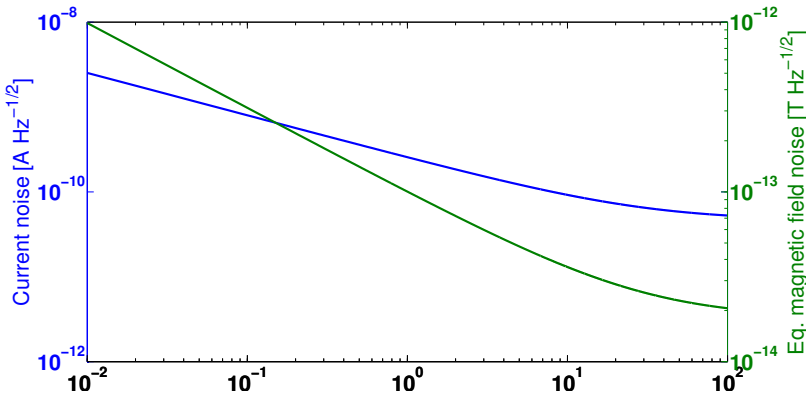
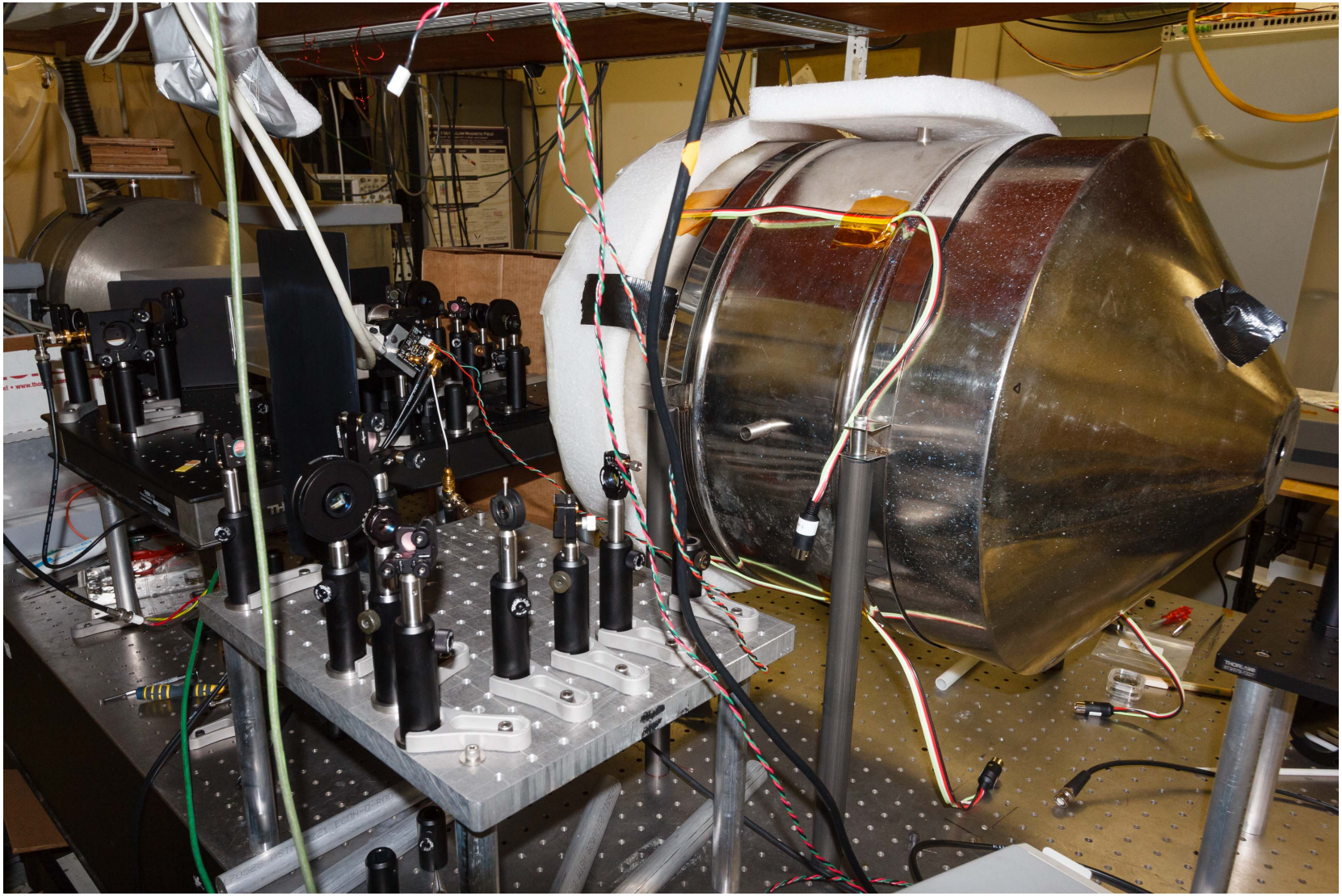


Current source for the applied magnetic field

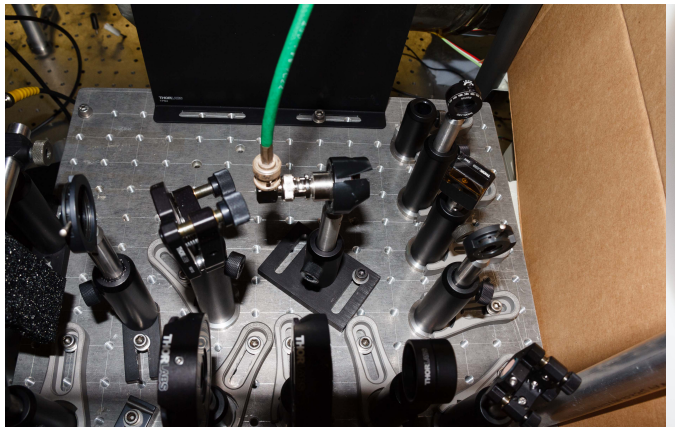
- Main magnetic field to be applied is $\simeq 2.5\ \mu\mathrm{T}$
- $\sim 0.02\ \frac{\mathrm{pT}}{\sqrt{\mathrm{Hz}}}$ @100 Hz and $\sim 10\ \frac{\mathrm{pT}}{\sqrt{\mathrm{Hz}}}$ @0.1 mHz
- Dominant noise contribution is due to the reference voltage
- Thermal contribution appears outside the eLISA BW

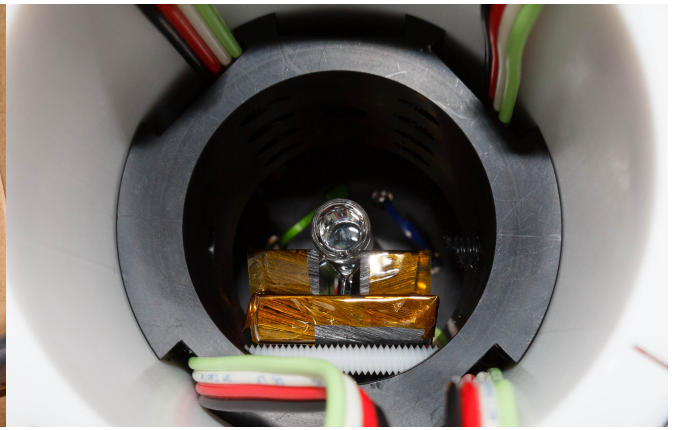


Magnetometer setup: Optical board

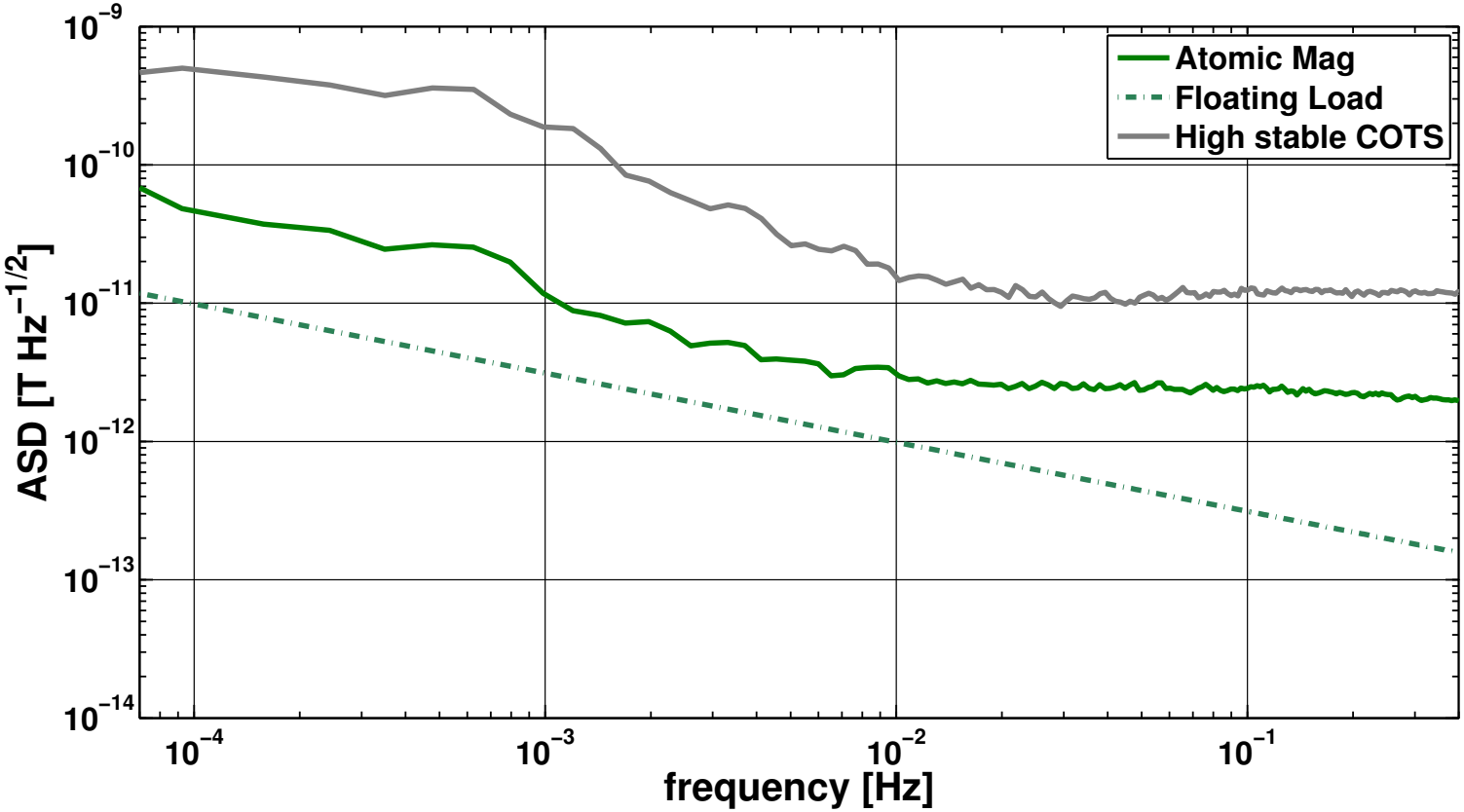


Magnetometer setup: ^{133}Cs Cell, probe and pump board





Equivalent magnetic field noise: $B_{\mathrm{app}} \simeq 2.5\,\mu\mathrm{T}$



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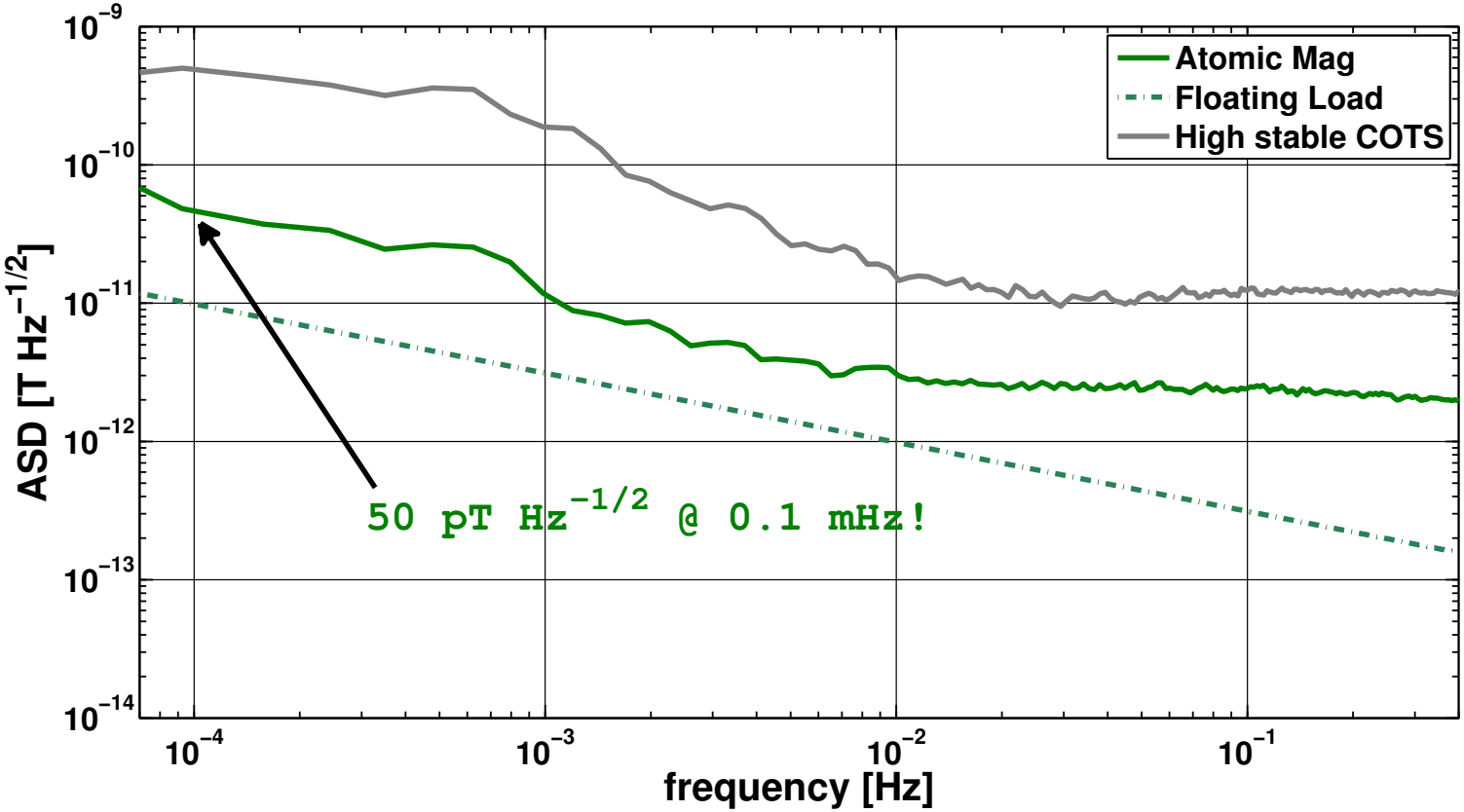
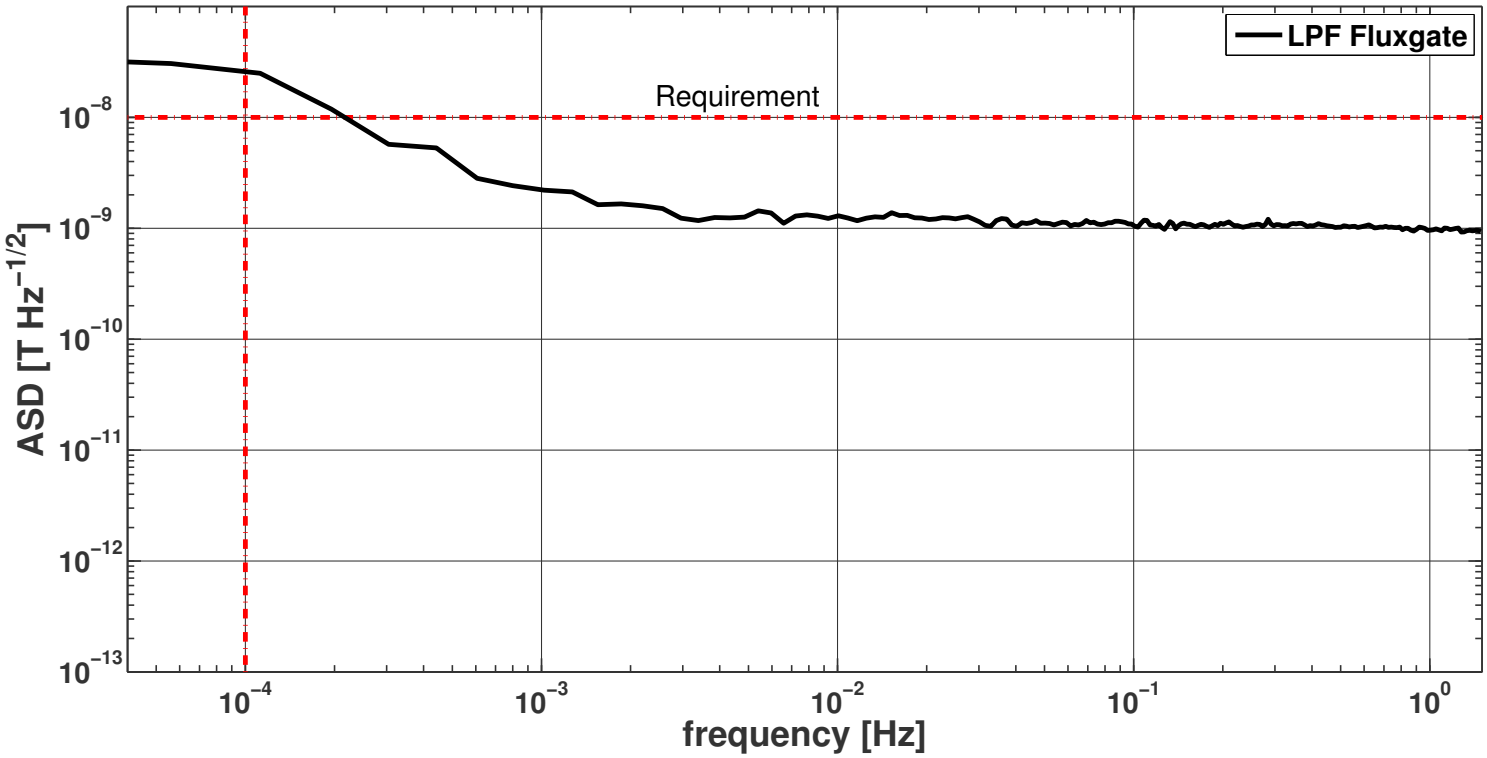


Equivalent magnetic field noise: Fluxgate vs AMR vs atomic magnetometer



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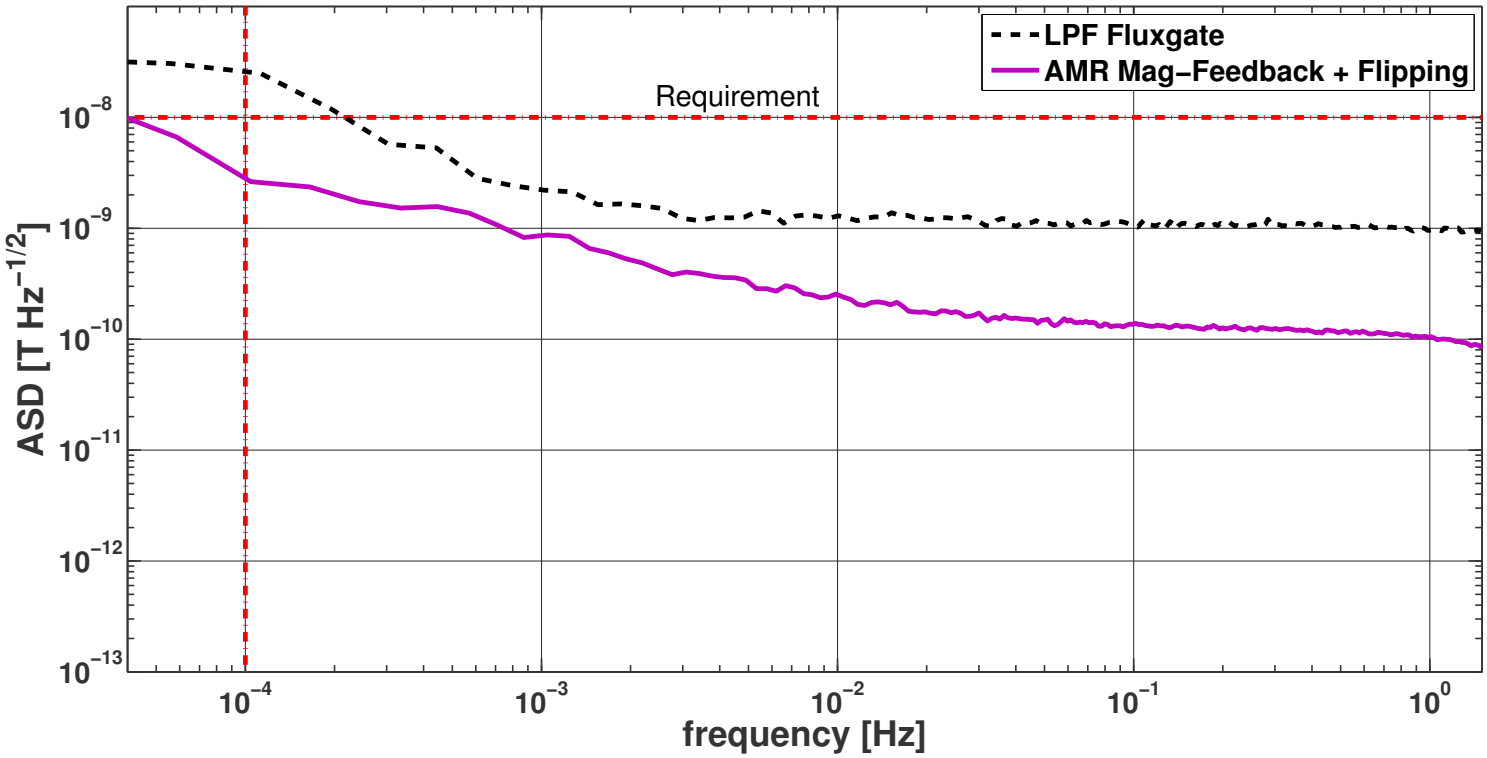

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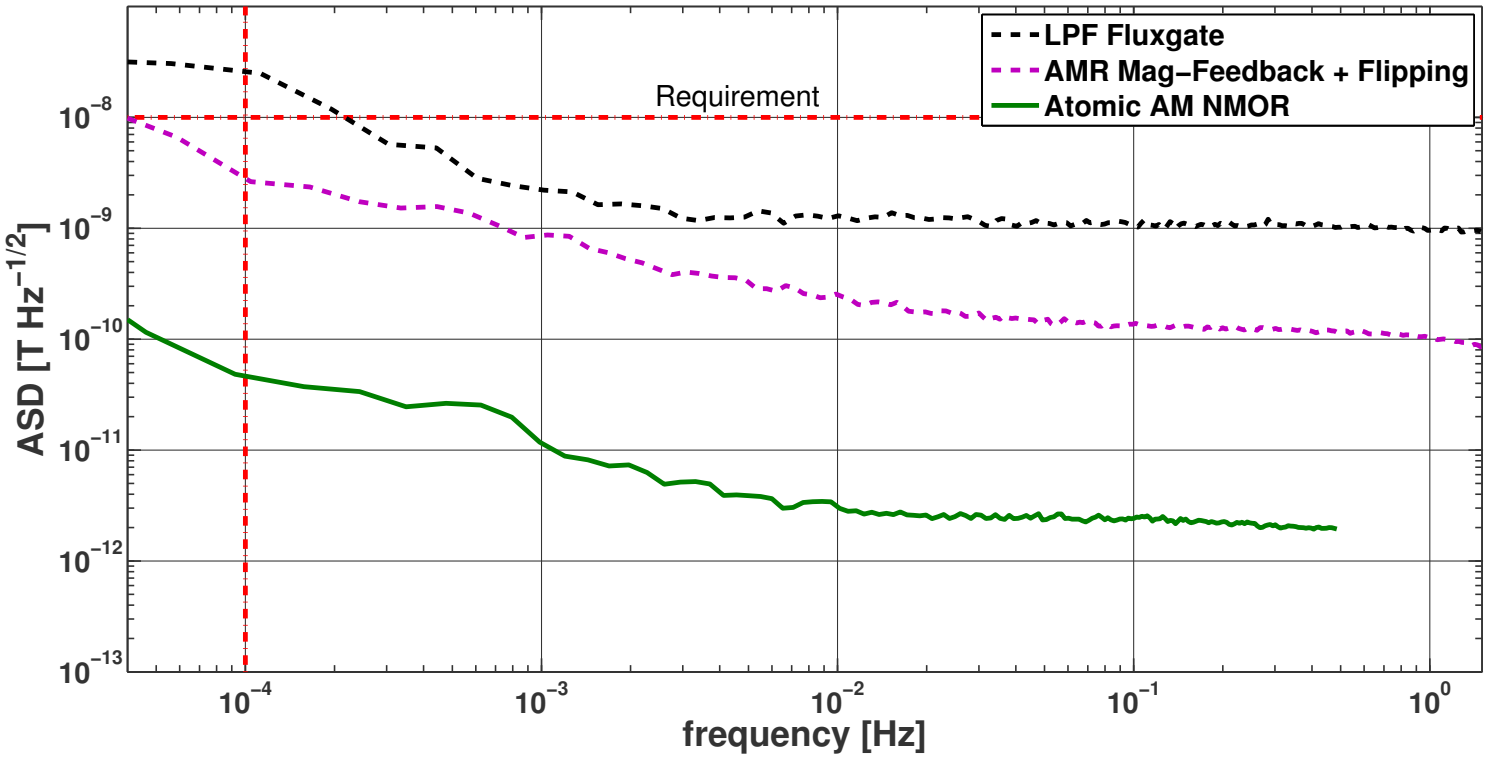

Conclusions

- Multipole expansion with the proposed sensor configuration has produced reliable results to estimate the magnetic field at the positions of the TM.
- Improvement in the accuracy of the magnetic field reconstruction has been achieved due to the small size and low magnetic back action of the AMRs, which enables the possibility to place more sensors and locate them closer to the TMs.
- Based on the experience with LISA *Pathfinder*, the use of AMRs with a dedicated noise reduction technique seems nowadays the most suitable technology for eLISA.
- Atomic magnetometer's noise based on AM NMOR shows promising results at eLISA frequencies $\sim 50\,\mathrm{pT\,Hz^{-1/2}}$. Further work: what happens at chip-scale?

Thank you!