Magnetic polarisation effects of temperature sensors and heaters (NTC's) in LISA PathFinder

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Introduction

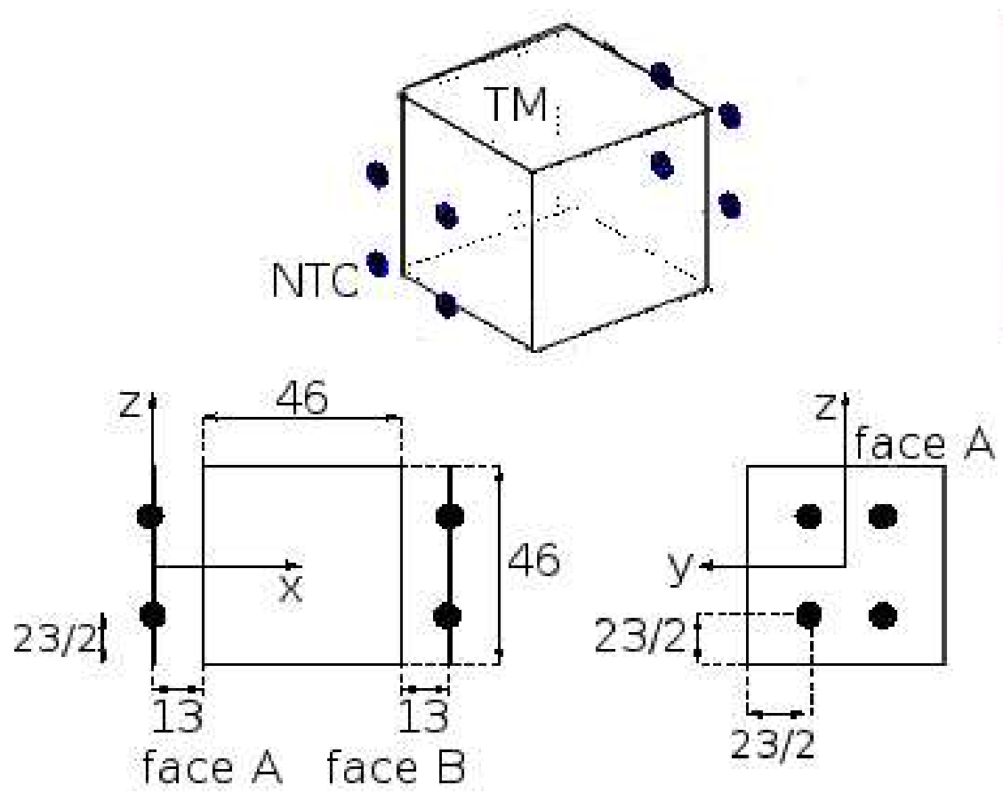
LISA PathFinder goal:

$$S^{1/2}_{\Delta a,\,\mathrm{LPF}}(\omega) \leq 3\times 10^{-14}\left[1+\left(\frac{\omega/2\pi}{3\,\mathrm{mHz}}\right)^2\right]\,\mathrm{m\,s^{-2}\,Hz^{-1/2}}$$

This requirement implies stringent limitations on *internal* environment fluctuations, specifically, thermal and **magnetic** fluctuations in the LTP must be very low.

The temperature diagnostic subsystem onboard the LTP includes 8 thermistors surrounding each of the TM's. The inherent *magnetic* nature of the thermistors make them potentially dangerous as they are placed quite near the TM's. The potential problem arises from:

1. NTC's are manufactured mixing and synthesising oxides doped with ferromagnetic materials
2. 8 NTC devices are attached to the outer faces of the Electrode Housing surrounding the TM's: 4 as temperature sensors and 4 as heaters
3. NTC's are very close to the TM's: 13 mm
4. Magnetic field and magnetic field gradient induce parasitic acceleration in the TM's




NTC (r=3 mm)

Dimensions in mm.

The noise acceleration budget assigned to magnetic effects in the TM is

$$S^{1/2}_{\Delta a,\,\mathrm{magnetic}}(\omega) \leq 12\times 10^{-15}\,\mathrm{m\,s^{-2}\,Hz^{-1/2}}$$

The steps performed in order to quantify the effect of the presence of the NTC's around the TM in the LTP performance are basically:

1. Measurement of the magnetic properties of the NTC's
2. Calculation of the magnetic field and magnetic field gradient in the TM's due to the presence of the 8 NTC's surrounding the TM's
3. Evaluation of the impact on the TM acceleration

Force fluctuations in the TM due to Magnetic Fields

The force fluctuation in the TM due to magnetic effects is:

$$S_{\delta F_x}(\omega) = V^2|\langle\mathbf{M}\rangle|^2 S_{\nabla B_x}(\omega) + \left(\frac{\chi V}{\mu_0}\right)^2 |\langle\boldsymbol{\nabla} B_x\rangle|^2 S_{\mathbf{B}}(\omega) + \\ + \left(\frac{\chi V}{\mu_0}\right)^2 |\langle\mathbf{B}\rangle|^2 S_{\nabla B_x}(\omega)$$

The nominal properties and background conditions are:

- TM magnetic properties: $|\chi| = 10^{-5}$ and $\mathbf{M}$=10^{-4} A m^{-1}
- Bg. *dc* values: $|\mathbf{B}_{\mathrm{bg}}| \leq$ 10 μT and $|\boldsymbol{\nabla} B_{\mathrm{bg},\,x}| \leq 5\sqrt{3}\,\mu$T m^{-1}
- Fluctuation values: $S^{1/2}_{\mathbf{B}}(\omega) \leq$650 nT Hz$^{-1/2}$ and $S^{1/2}_{\nabla B_x}(\omega) \leq 250\sqrt{3}$ nT m^{-1} Hz$^{-1/2}$

Noise acceleration due to magnetic effects is:

Term	$S_{\Delta a_x}$ [fm s^{-2} Hz$^{-1/2}$]
$V\|\langle\mathbf{M}\rangle\|S^{1/2}_{\boldsymbol{\nabla}B_x}(\omega)$	2.15
$(\chi V/\mu_0)\|\langle\boldsymbol{\nabla}B_x\rangle\|S^{1/2}_{\mathbf{B}}(\omega)$	2.22
$(\chi V/\mu_0)\|\langle\mathbf{B}\rangle\|S^{1/2}_{\nabla B_x}(\omega)$	1.70
$S^{1/2}_{\mathrm{total\ mag}}(\omega)$	4.46

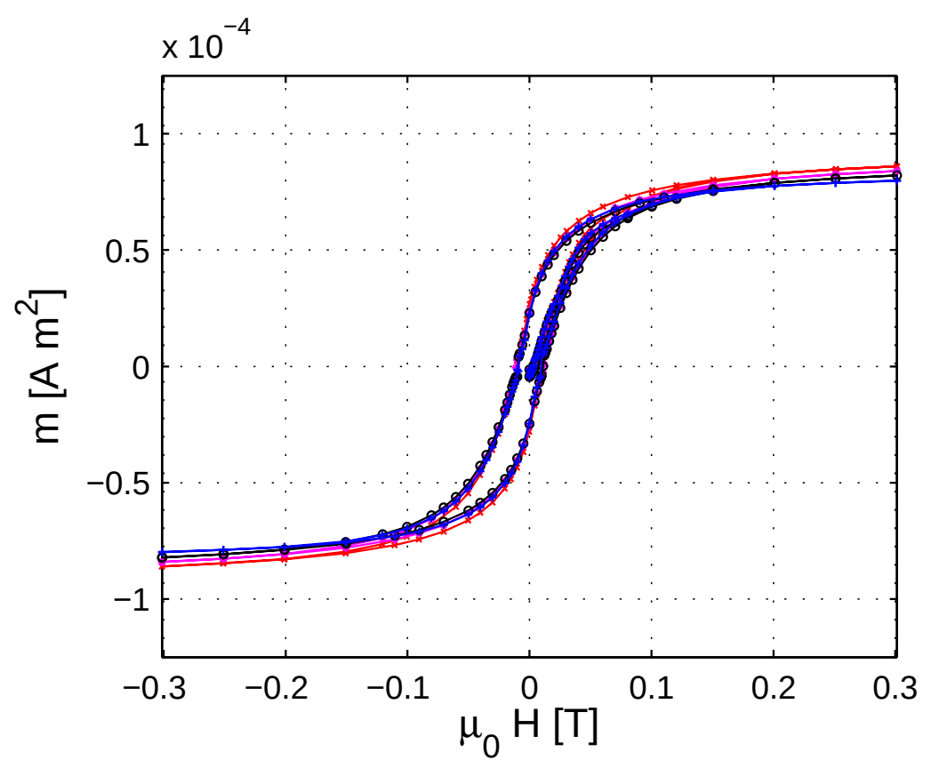
When the NTC's are present the magnetic field is:

$$\mathbf{B} = \mathbf{B}_{\mathrm{background}} + \mathbf{B}_{\mathrm{NTC}}$$

The effect of $\mathbf{B}_{\mathrm{NTC}}$ in the TM acceleration has to be quantified.

NTC's magnetic characterisation: the Hysteresis curve

Measurement of the magnetic moment, $\mathbf{m}$, of the NTC's when subjected to an external magnetic field, $\mathbf{H}$ (Quantum Design MPMS XL Squid — UB).



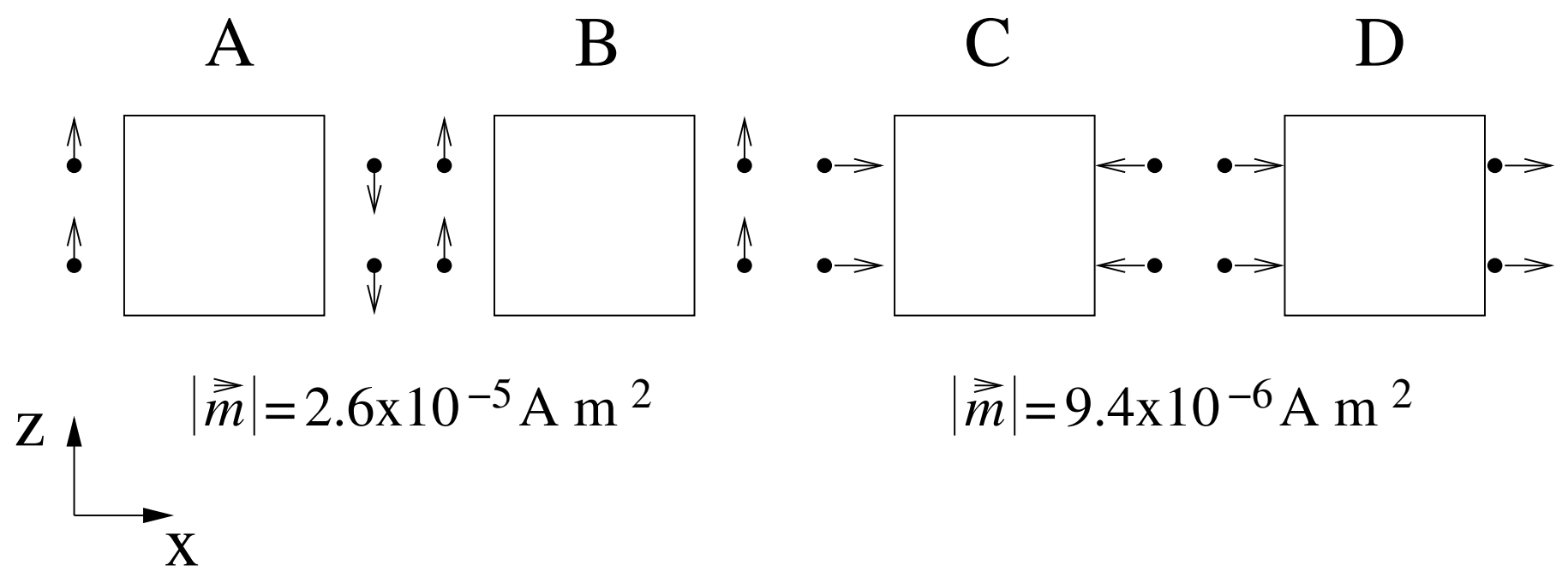
$\|\mathbf{m}_{\mathrm{r}}\|$	$\|\mathbf{m}_{\mathrm{sat.}}\|$	$\mu_0\|\mathbf{H}_{\mathrm{coer.}}\|$
24±2 μA m^2	83±2.5 μA m^2	10 mT

- $|\mathbf{m}_{\mathrm{r}}|$: remanent magnetic moment after saturation and at zero magnetic field
- $|\mathbf{m}_{\mathrm{sat.}}|$: magnetic moment at the saturating magnetic field
- $\mu_0|\mathbf{H}_{\mathrm{coer.}}|$: coercitive field

Numerical calculations

- NTC's assumed to behave like magnetic dipoles
- 8 NTC's surrounding the TM considered
- A Finite Element Model used for the calculations
- Different magnetic moment orientations analysed
- Remanent magnetic moment after NTC saturation used ($\mathbf{m}_{\mathrm{r}}$ — worst possible scenario)

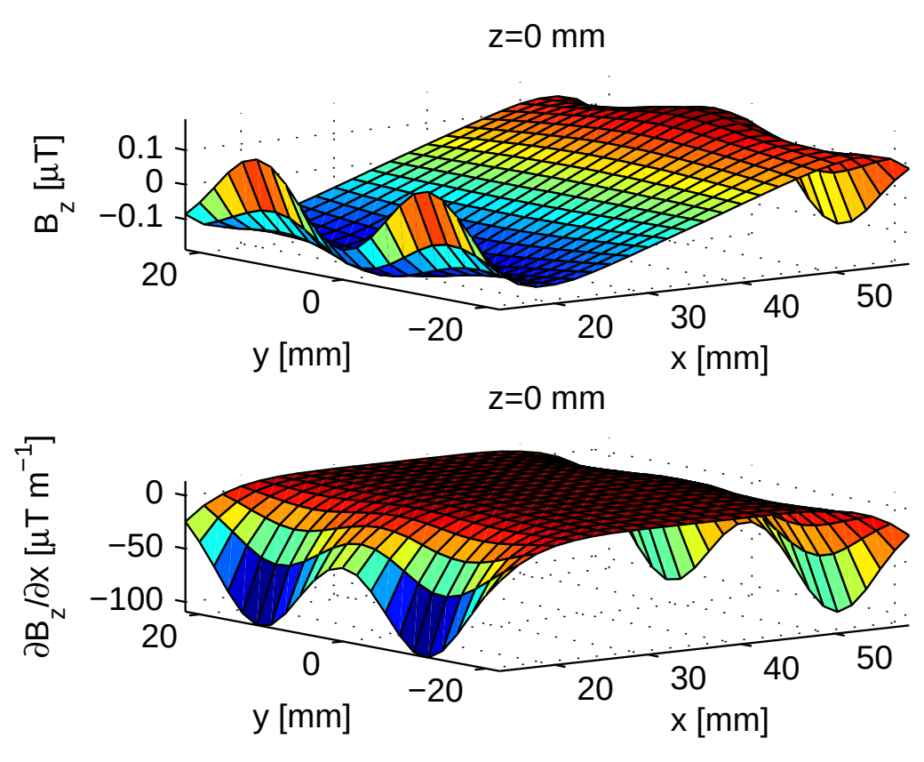
Calculations considering different orientations of the 8 magnetic moments of the NTC's allow us to know the worst possible combinations. A simple scheme of the magnetic moment orientations (arrows in the figure) surrounding the TM and the numerical values obtained are shown.



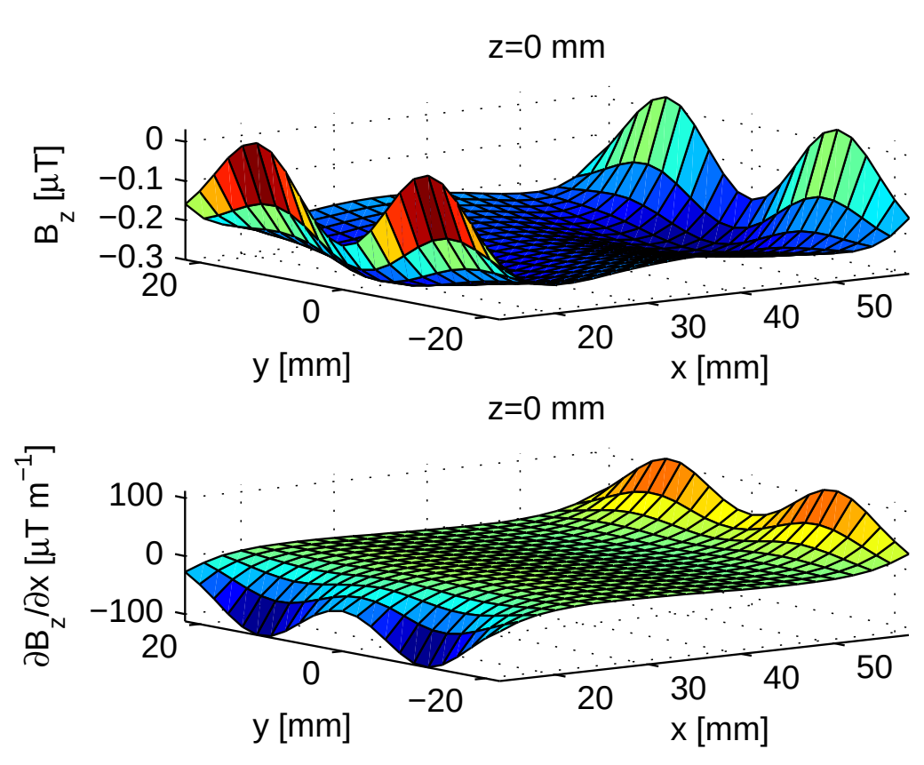
Conf.	$\|\langle\mathbf{B}\rangle\|$ [μT]	$\|\langle\boldsymbol{\nabla}B_x\rangle\|$ [μT m^{-1}]
A	0	15.5
B	0.25	0
C	0	11.3
D	0.18	0

Graphical representation for configurations A and B:

Top: z-component of the magnetic field in the equatorial plane of the TM.
Bottom: Partial derivative of the z-component of the magnetic field with respect to x.



CONFIGURATION A

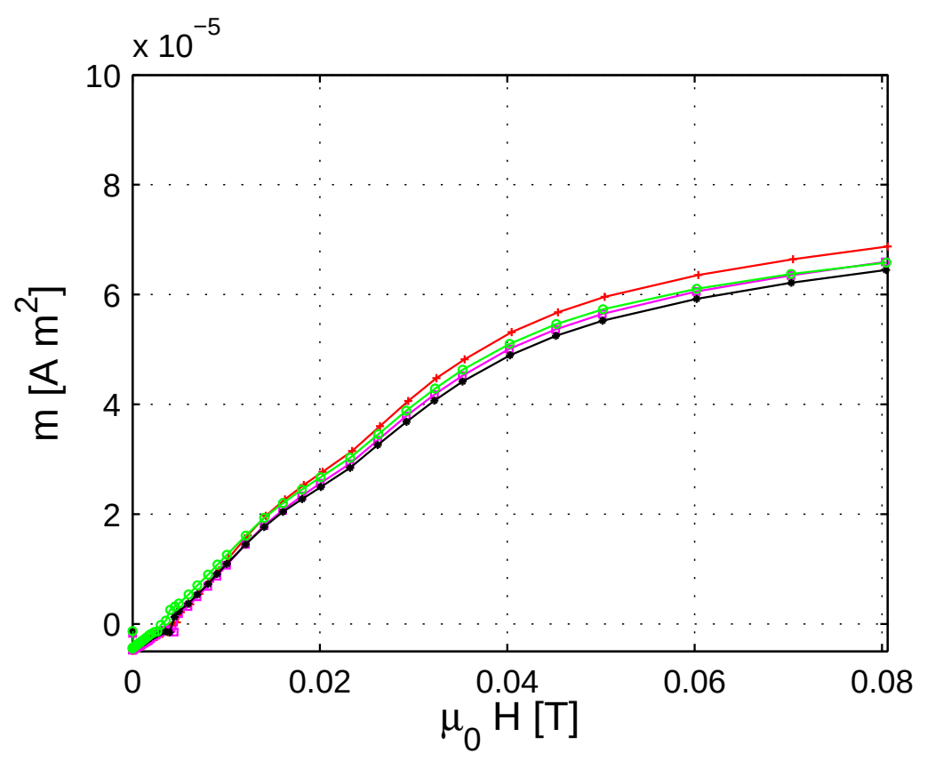


CONFIGURATION B

NTC's First Magnetisation Curve (FMC)

The FMC was measured due to the following reasons:

- LTP magnetic environments are orders of magnitude below the NTC saturation field
- Remanent magnetic moment after NTC saturation is a very unrealistic scenario
- First Magnetisation Curve measurement:
  1. De-magnetisation
  2. Magnetic field excitation



The remanent magnetic moment after de-magnetisation is:

$|\mathbf{m}_{\mathrm{demag}}|$=1.4±0.2 [$\mu$A m^2]

The FMC for the BetaTherm NTC's can be linearised near the full demagnetisation zone as:

$$|\mathbf{m}_{\mathrm{FMC,\,BetaTherm}}| \simeq 1.45\times 10^{-3}\,\mu_0\,|\mathbf{H}_{\mathrm{FMC}}|$$

Excess TM noise calculations

Acceleration noise for three different scenarios is compared:

- Absence of thermistors
- Presence of thermistors with the maximum possible remanent magnetic moment, i.e., after saturation, $|\mathbf{m}_{\mathrm{r}}|$
- Presence of thermistors after de-magnetisation, $|\mathbf{m}_{\mathrm{demag}}|$

Term	No NTC's	$\|\mathbf{m}_{\mathrm{r}}\|$= 24 μA m^2	$\|\mathbf{m}_{\mathrm{demag}}\|$= 1.4 μA m^2
$V\|\langle\mathbf{M}\rangle\|S^{1/2}_{\boldsymbol{\nabla}B_x}(\omega)$	2.1	2.1	2.1
$(\chi V/\mu_0)\|\langle\boldsymbol{\nabla}B_x\rangle\|S^{1/2}_{\mathbf{B}}(\omega)$	2.22	6.12	2.44
$(\chi V/\mu_0)\|\langle\mathbf{B}\rangle\|S^{1/2}_{\nabla B_x}(\omega)$	1.70	1.70	1.70
$S^{1/2}_{\mathrm{total\ mag.}}(\omega)$	4.45	7.29	4.54
Δ	—	64%	2%

Units: fm s^{-2} Hz$^{-1/2}$
Δ: increase wrt to "NO NTC's" noise

If $\Delta < 10$% is required:

1. **NTC's must be de-magnetised**
2. **NTC's should not be exposed to magnetic fields higher than 5 mT**

Conclusions

- NTC's shown ferromagnetic behaviour
- The magnetic properties of the NTC's can degrade the performance of the LTP, increasing the magnetic noise by $\sim$65 % relative to the background in the very worst possible situation. Even in such extreme conditions the budgeted magnetic noise (12 fm s$^{-2}/\sqrt{\mathrm{Hz}}$) is not reached
- De-magnetisation of the NTC's produces very good results: the magnetic noise they induce can be reduced by about an order of magnitude, which makes it mostly negligible