Project No: CZ.02.2.69/0.0/0.0/18_070/0010457
Mezinárodní mobility výzkumných pracovníků MSCA-IF II na ČVUT v Praze
Multi-scale Modelling of Elastocaloric Materials for Integrated Cooling

Využití piezomagnetického a elastokalorického jevu pro chlazení v pevné fázi

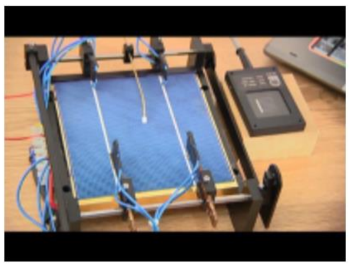
Jan Zemen

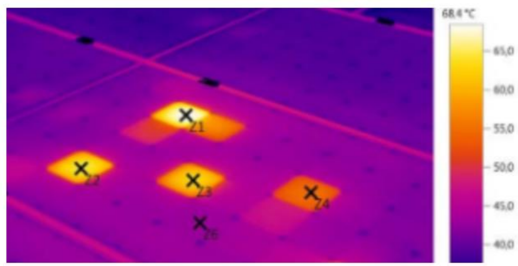
Konference COMSOL Multiphysics 2021
Vinařství U Kapličky, Zaječí
28.5.2021

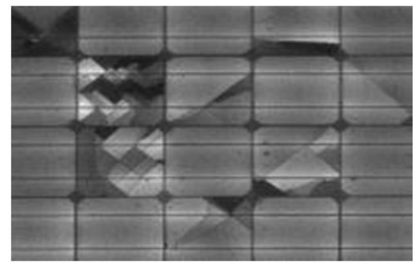
Katedra elektrotechnologie, ČVUT, FEL

Photovoltaic systems

- Diagnostics of PV cells (cell parameters, LBIV, LBIC,...)
- Thermographic measurement
- Flash test (PASAN)
- PV modules I-V characteristic measurement
- Temperature measurement of PV modules
- Sun irradiation measurement
- Electroluminescence measurement

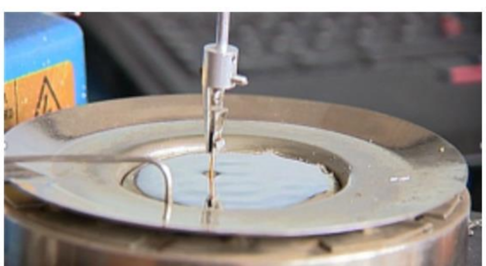


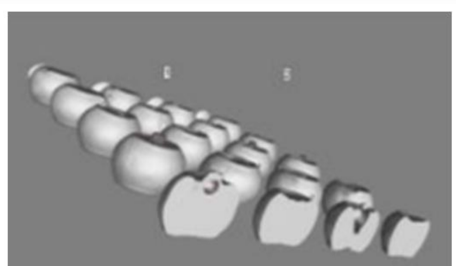


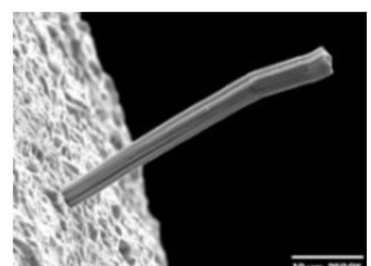


Conductive joining – soldering or electrically conductive adhesives (ECAs)

- Printed circuit board diagnostics
- Diagnostics of voids in soldered joints, intermetallic layers, whisker and dendritic growth
- Soldering on uncommon substrates: glass, ceramics, silicon, etc.





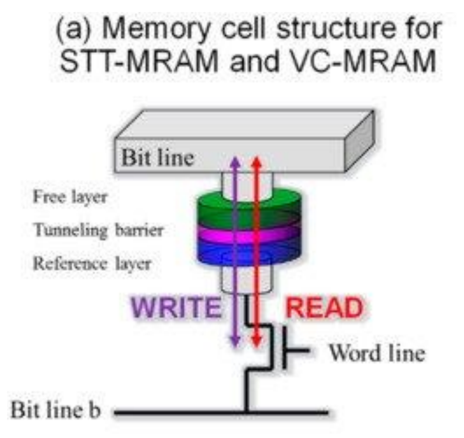


Outline

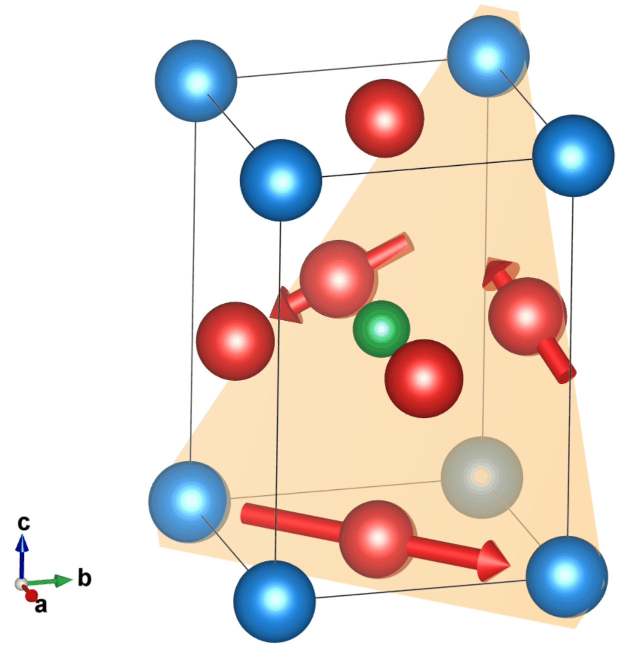
- Piezomagnetický jev
  - mikroskopický původ jevu – linearní závislost magnetizace na strainu
  - FEM model – využití výstupů mikroskopického modelu (SDFT)
- Elastokalorický jev
  - mikroskopický původ jevu – uvolňování latentního tepla
  - FEM model a nutné aproximace
- Shrnutí

Canted triangular antiferromagnetic structure of Mn_3XN

Motivation



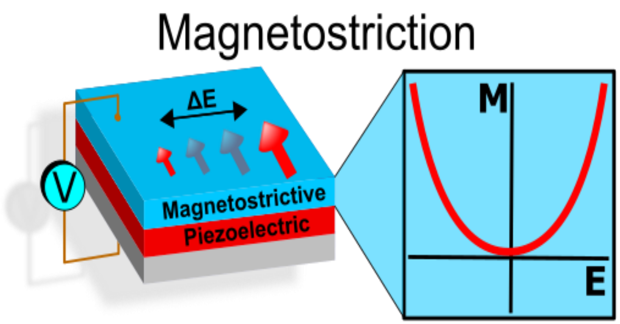
Endoh, Tetsuo; Honjo, Hiroaki. 2018. *J. Low Power Electron. Appl.* 8, no. 4: 44. https://doi.org/10.3390/jlpea8040044

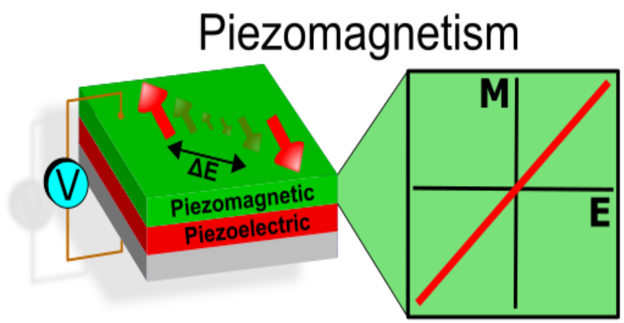


Ni, Pt, Ir, Ga, In, Sn

Mn

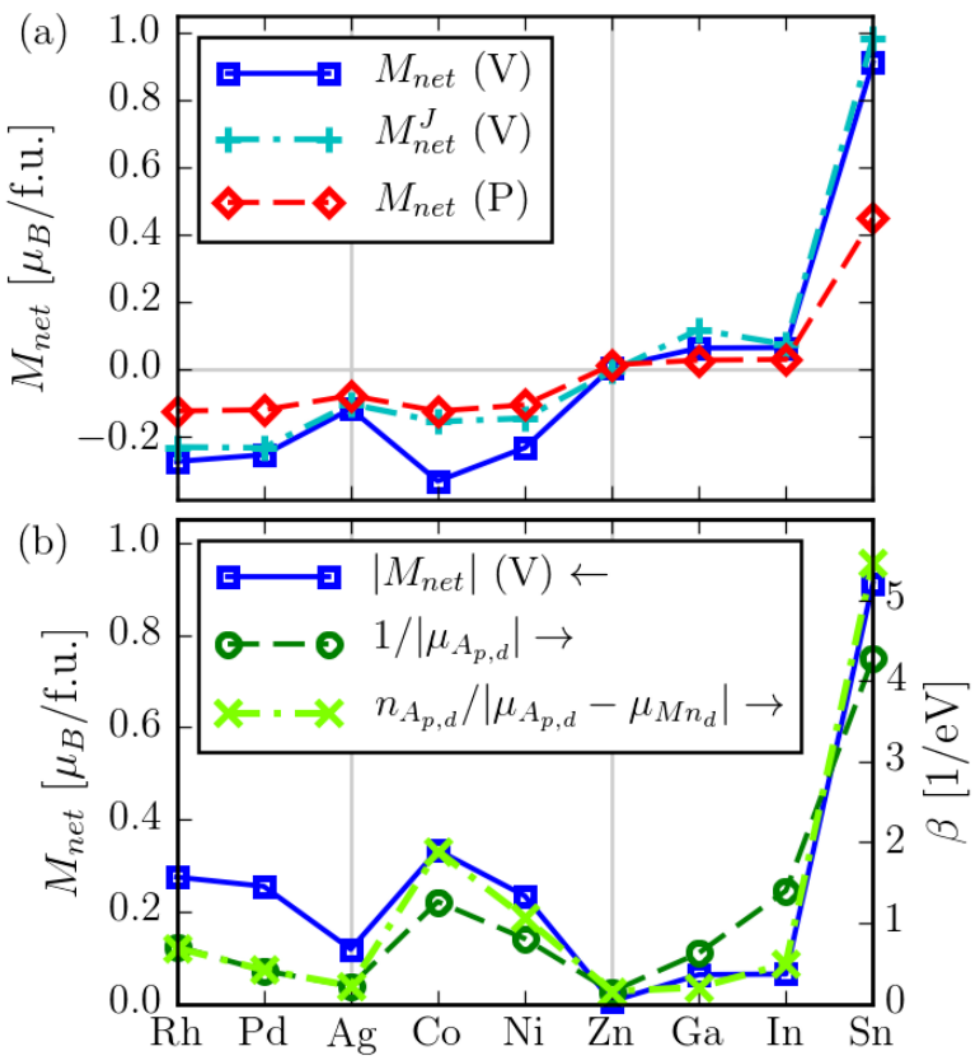
N

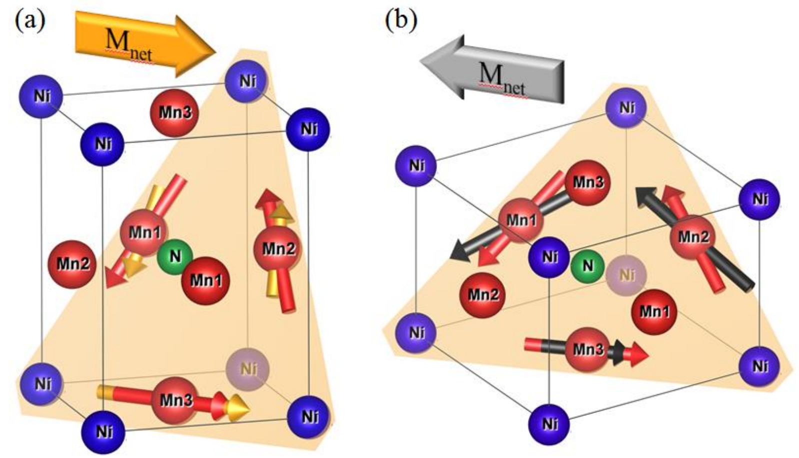




Piezomagnetic effect in Mn_3GaN - P. Lukashev et al., PRB (2008)

Modeling of piezomagnetism from first principles (SDFT)

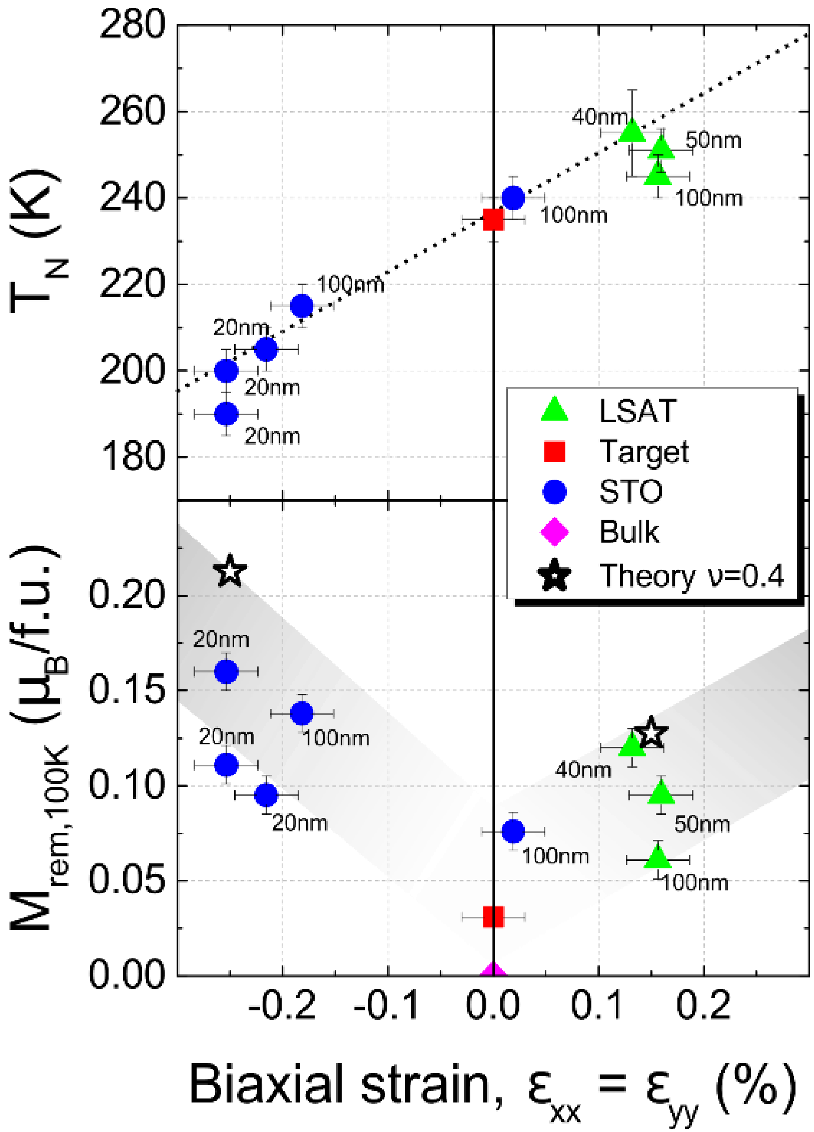


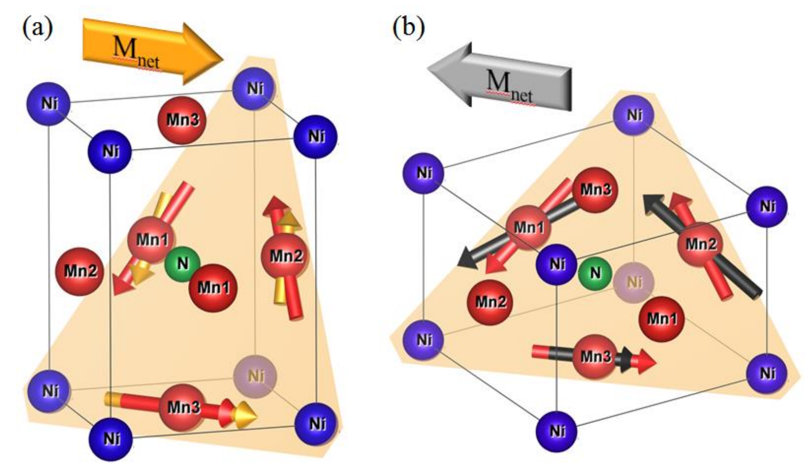


J. Zemen, Phys. Rev. B (2017)

Comsol model input:
Biaxial strain ~ 1% results in
Net magnetic field ~ 1 mT

Piezomagnetic effect in Mn_3NiN on different substrates





Giant Piezomagnetism in Mn_3NiN

David Boldrin, Andrei P. Mihai, Bin Zou, Jan Zemen, Ryan Thompson, Ecaterina Ware, Bogdan V. Neamtu, Luis Ghivelder, Bryan Esser, David W. McComb, Peter Petrov, and Lesley F. Cohen

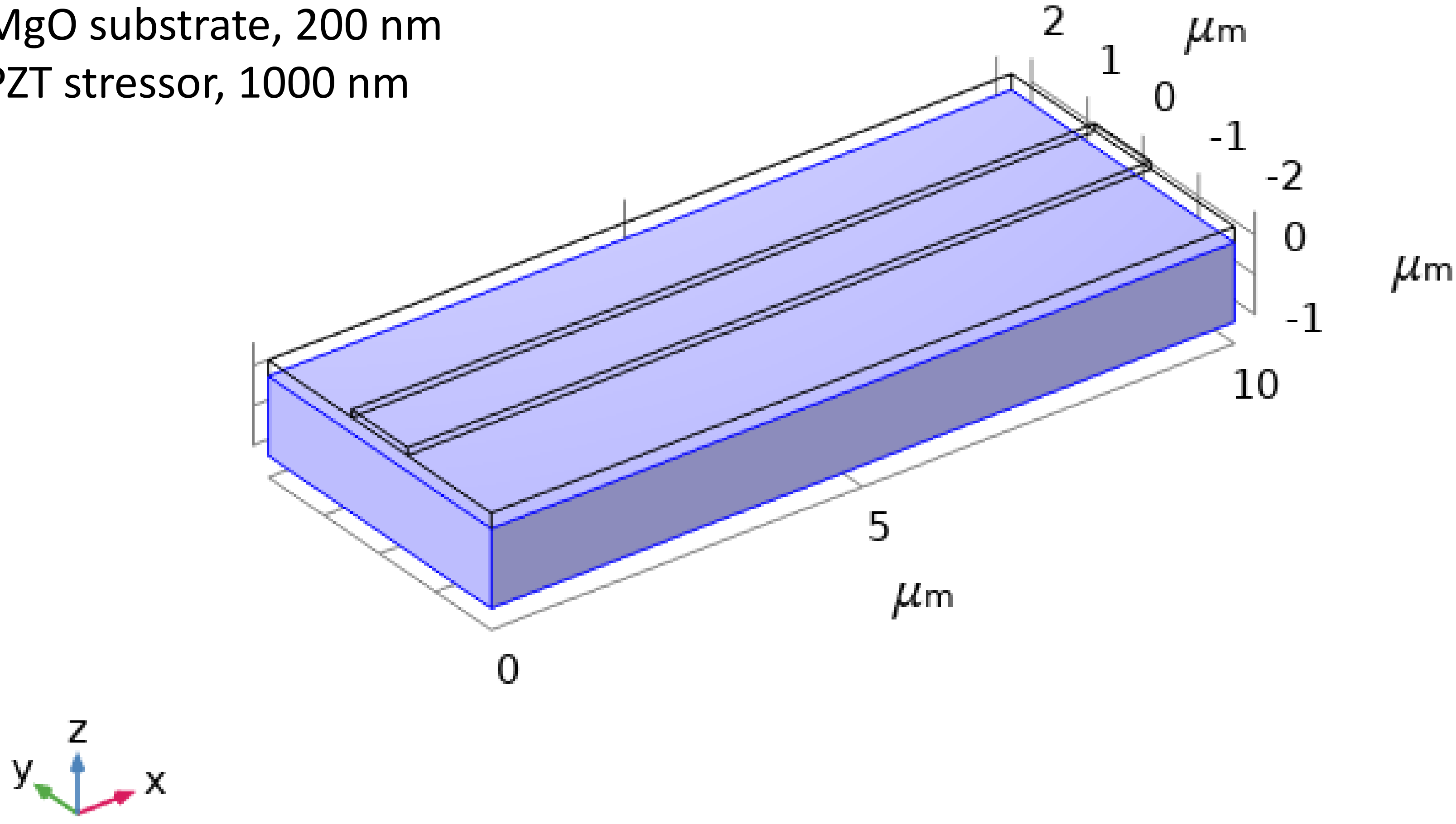
ACS Applied Materials & Interfaces **2018**

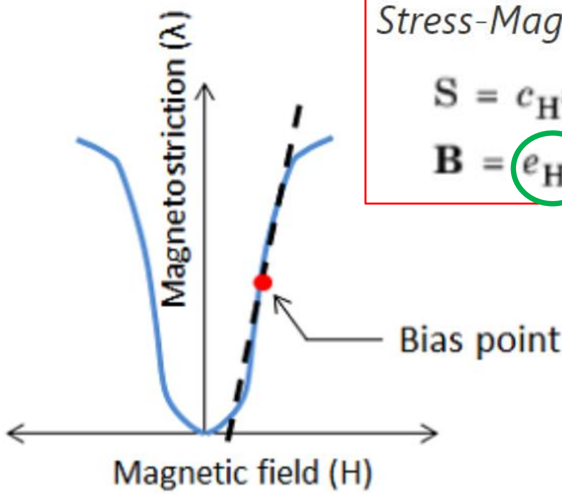
10 (22), 18863-18868

DOI: 10.1021/acsami.8b03112

Device simulated in Comsol

Mn_3NiN bar, 100 nm
MgO substrate, 200 nm
PZT stressor, 1000 nm

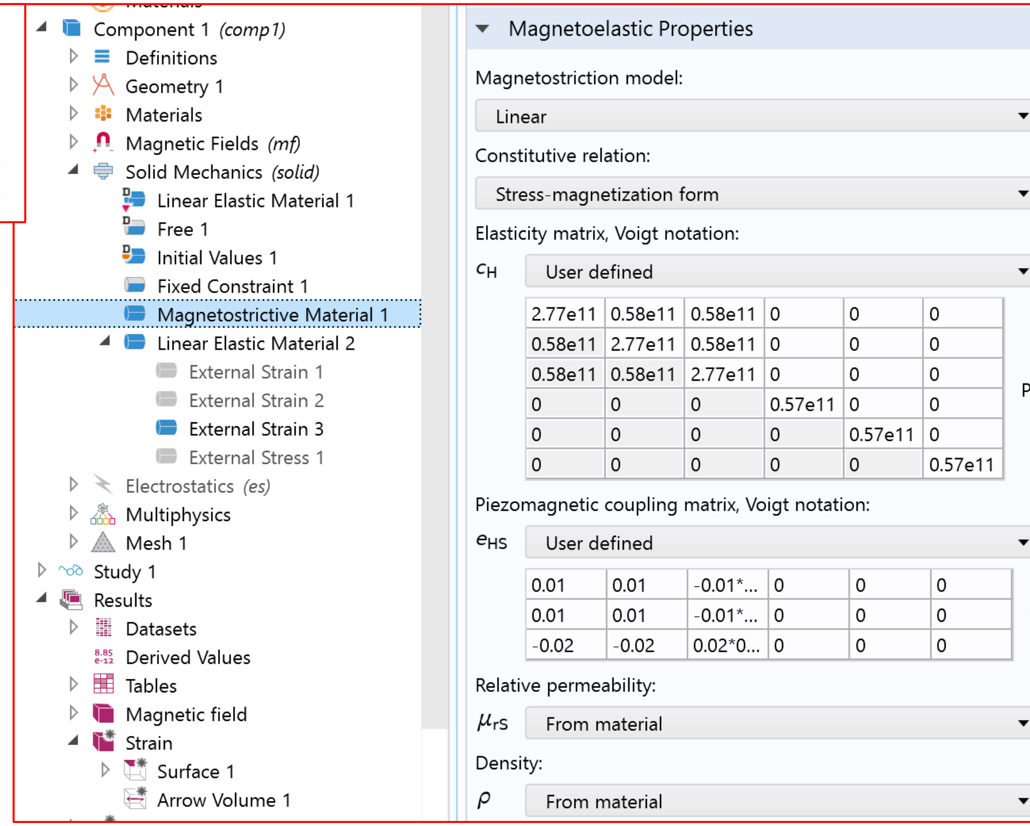




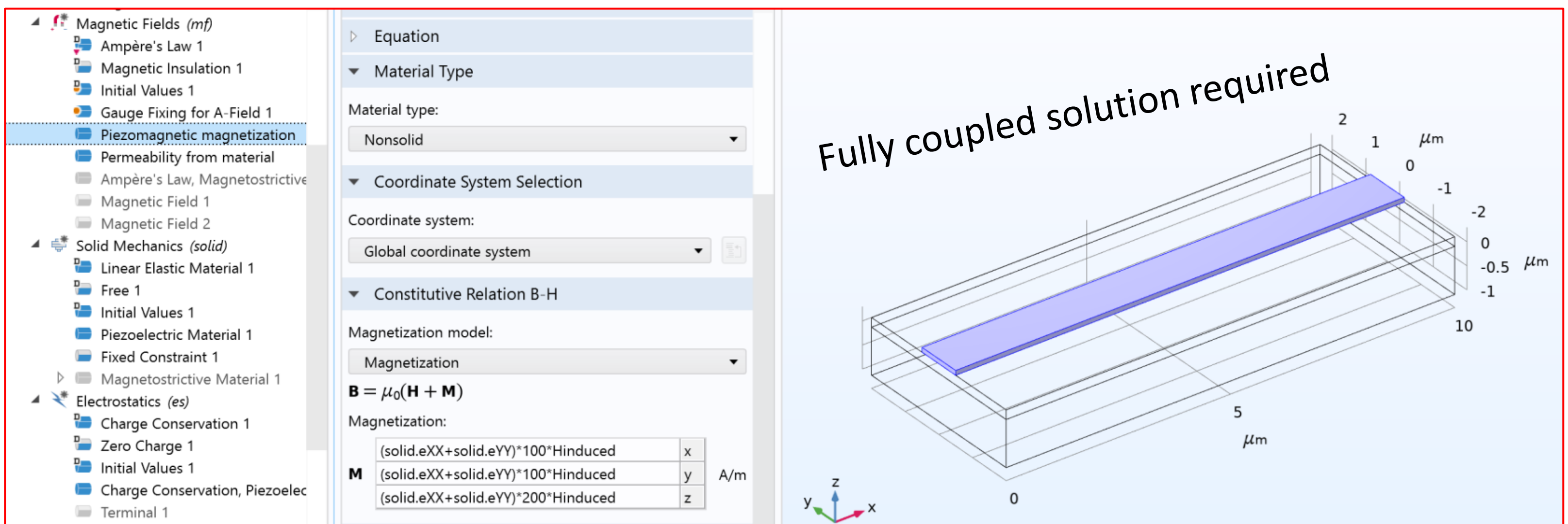
Stress-Magnetization

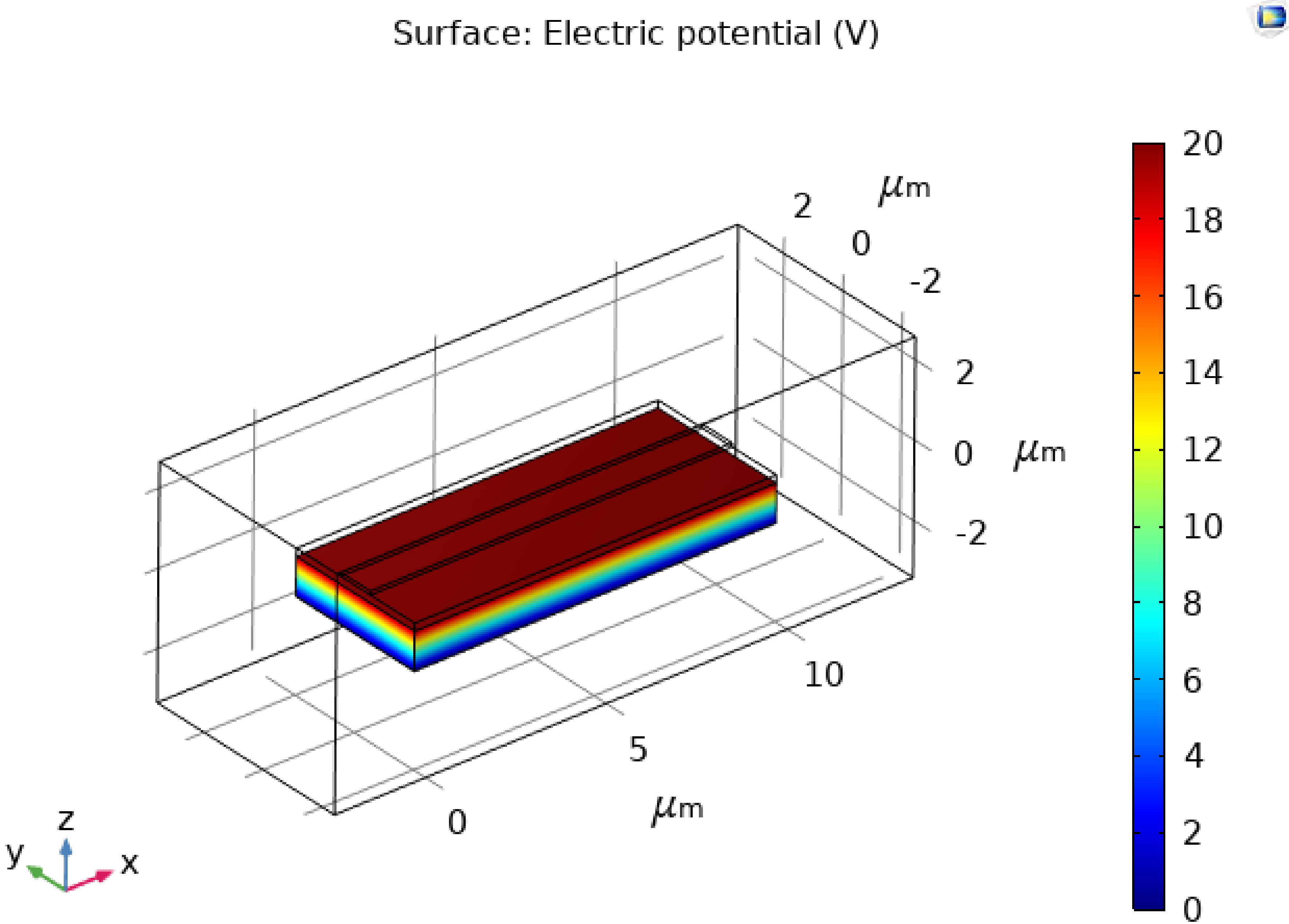
$$\mathbf{S} = c_H \varepsilon - e_{HS}^{T} \mathbf{H}$$

$$\mathbf{B} = e_{HS} \varepsilon_{el} + \mu_0 \mu_{rS} \mathbf{H}$$



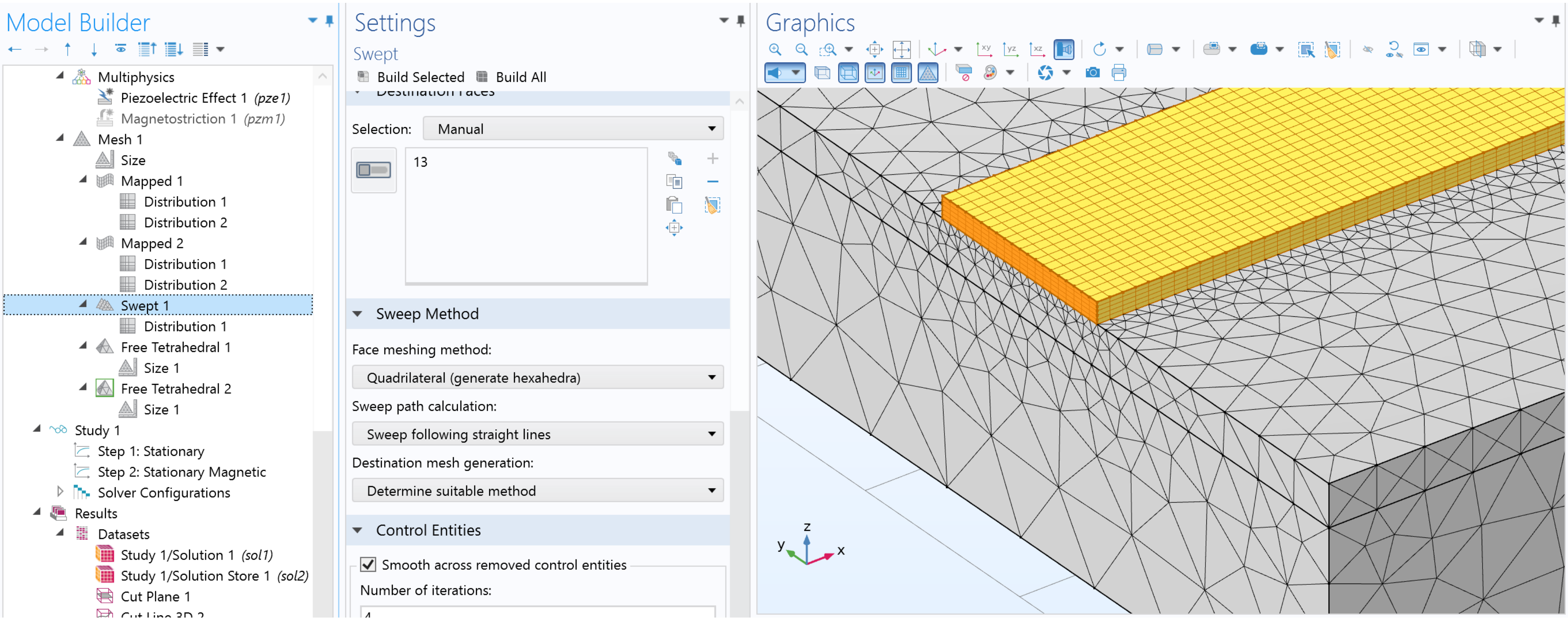
Linearized magnetostriction
or
Ampère's law with strain dependent magnetization





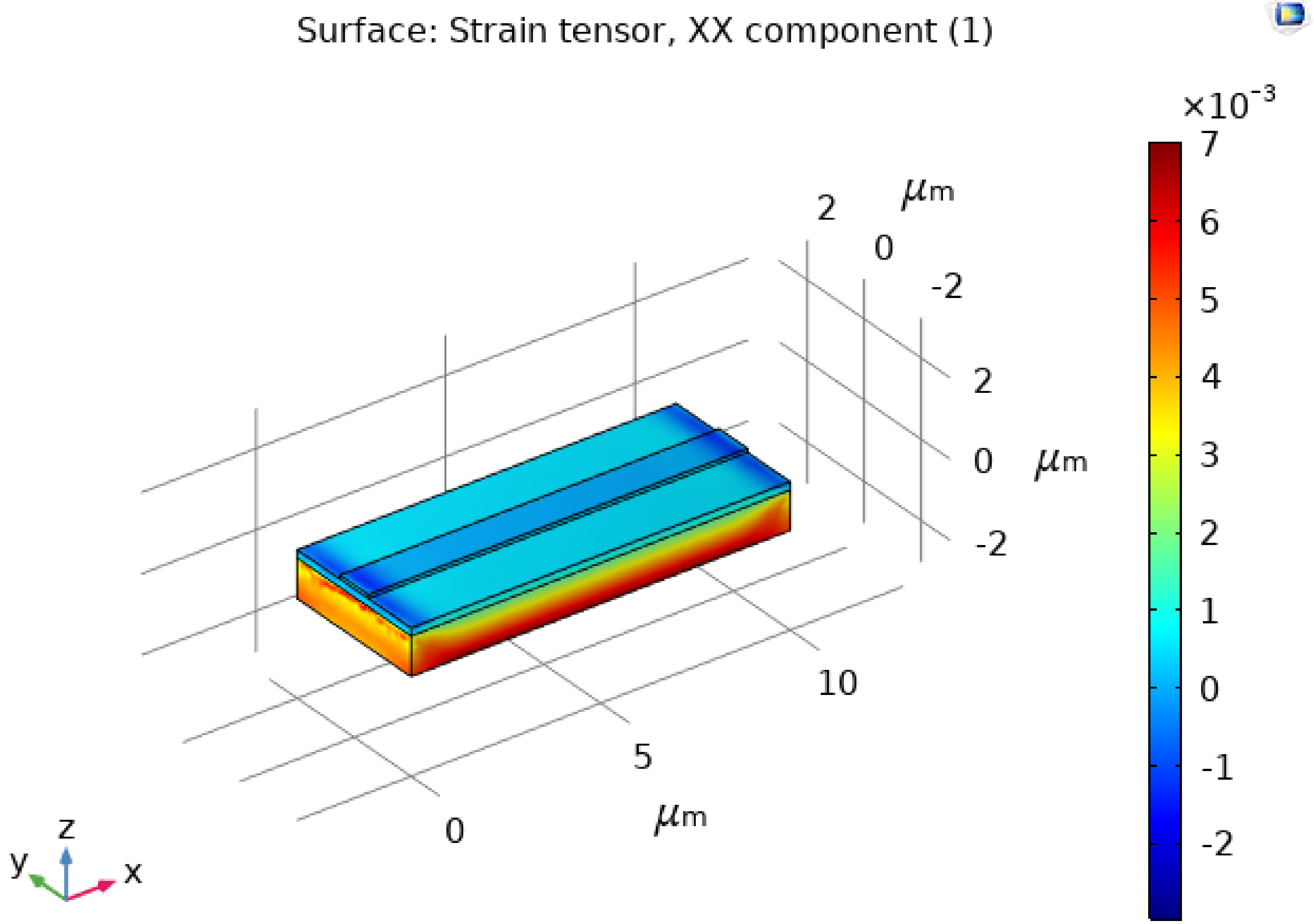
Surface: Electric potential (V)
20
18
16
14
12
10
8
6
4
2
0
μm
2
0
-2
2
0
-2
μm
10
5
0
μm
z
y
x

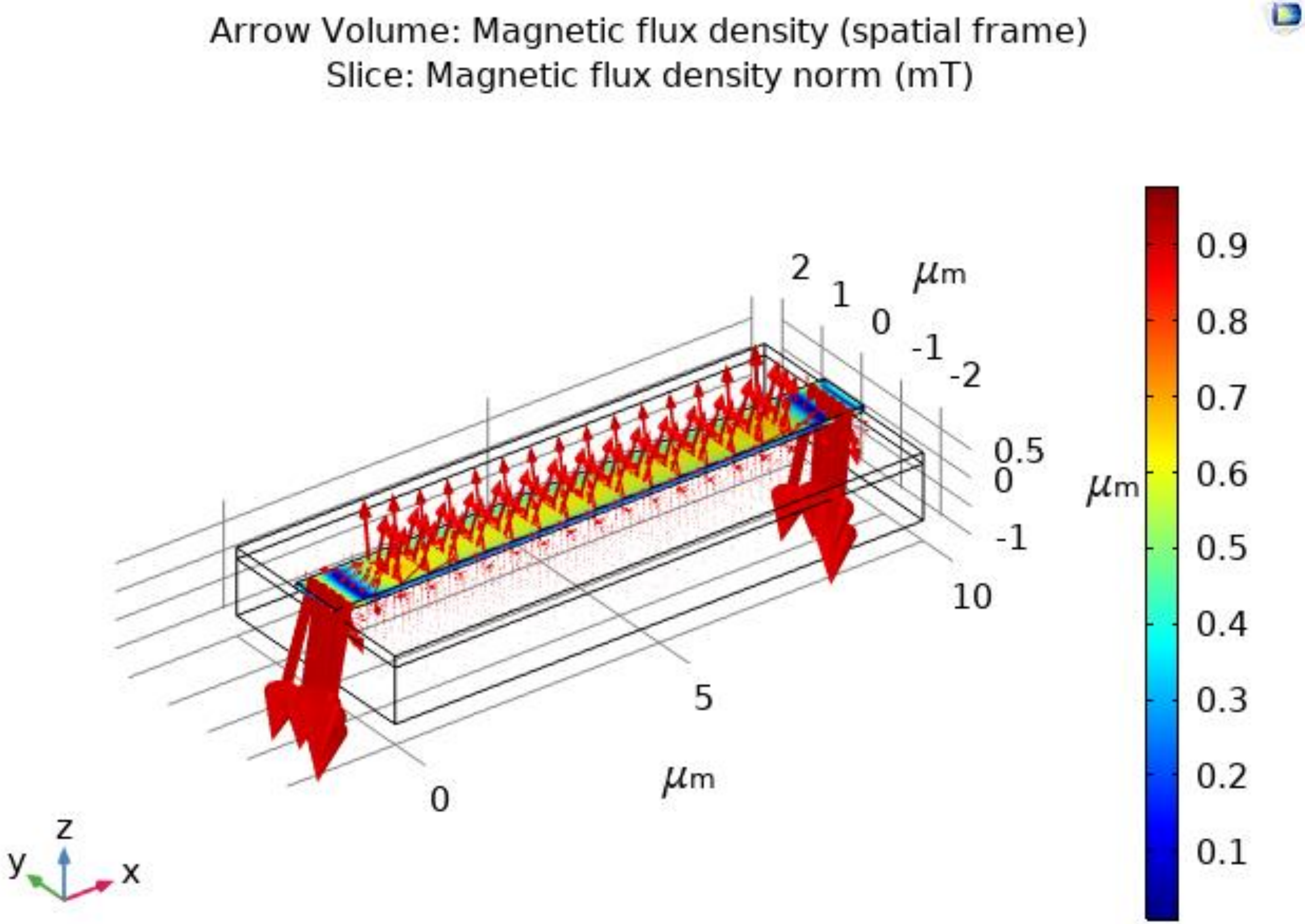
Meshing



Domain element statistics

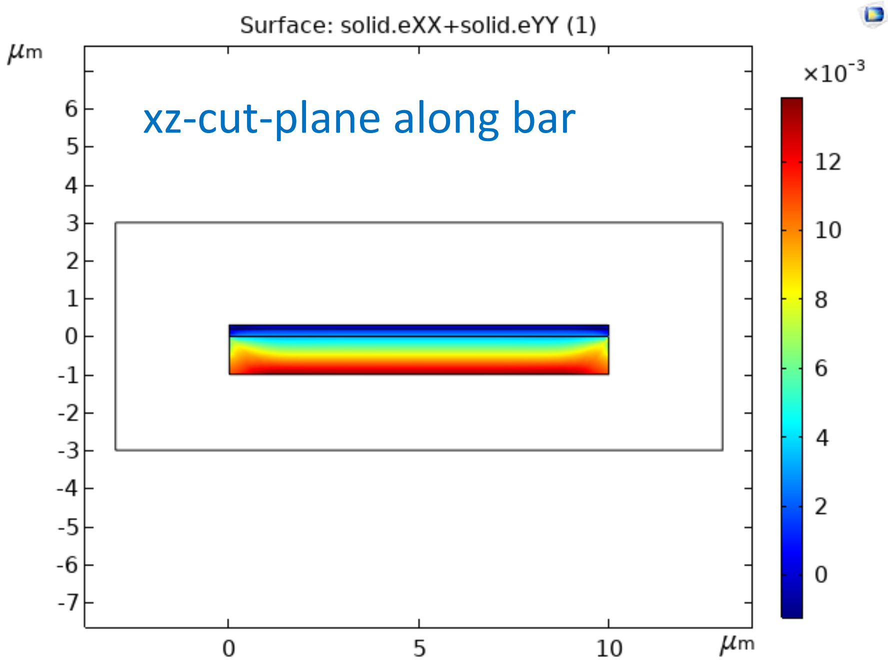
Number of elements:	213444
Minimum element quality:	0.1512
Average element quality:	0.6638
Element volume ratio:	9.665E-7
Mesh volume:	576 μm^3

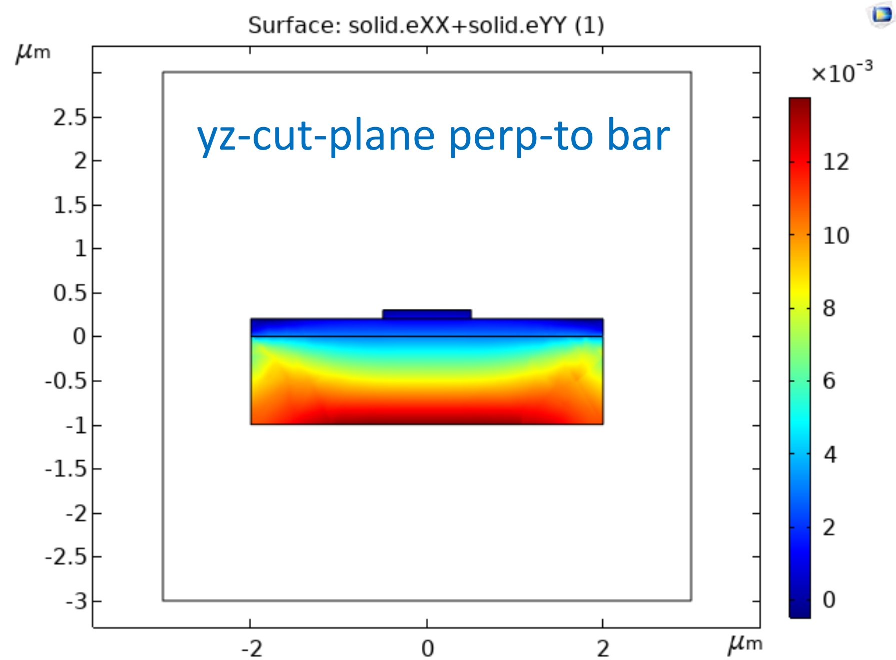

Surface: Strain tensor, XX component (1)
×10^-3
7
6
5
4
3
2
1
0
-1
-2
μm
2
0
-2
2
0
-2
μm
10
5
0
μm
z
y
x

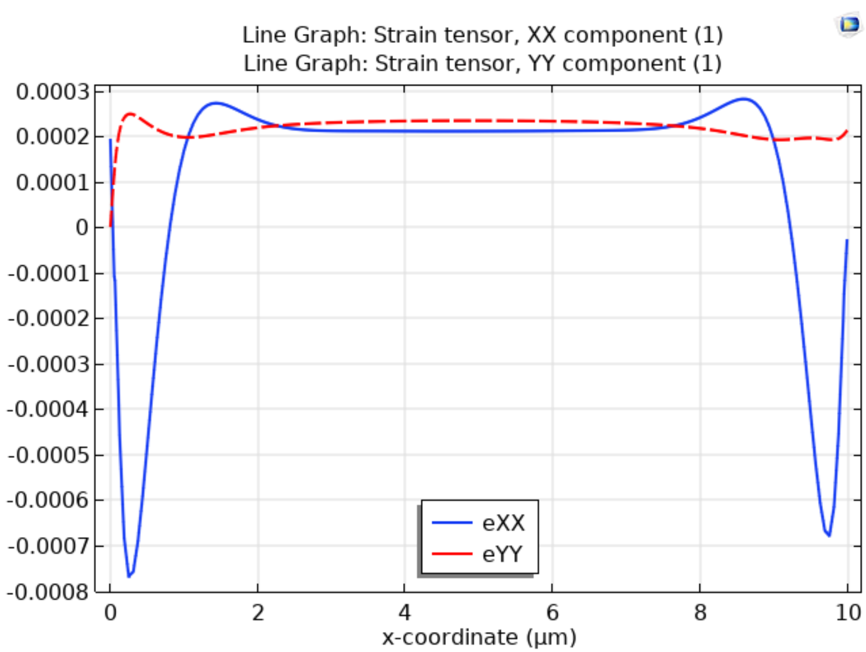


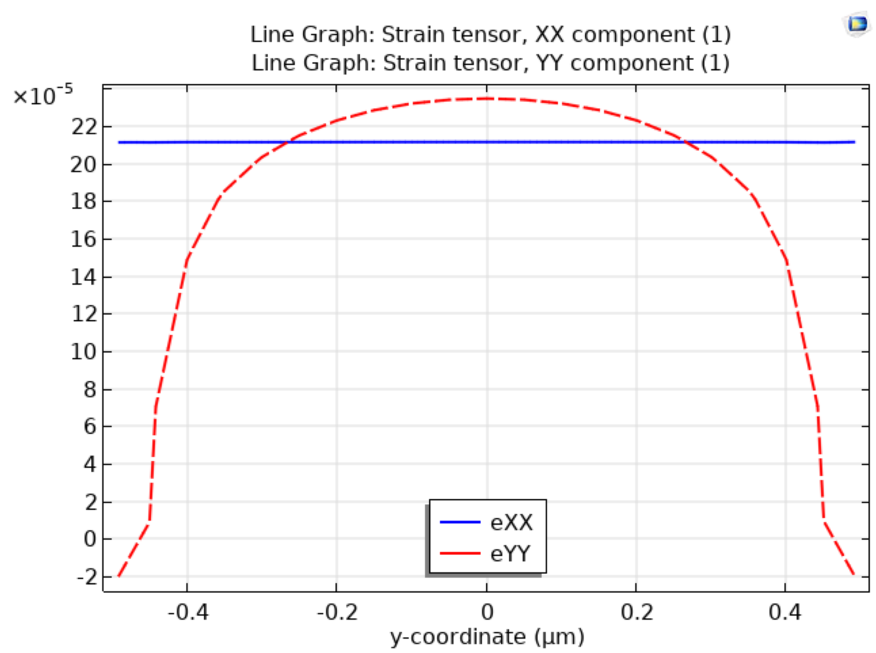
Arrow Volume: Magnetic flux density (spatial frame)
Slice: Magnetic flux density norm (mT)
2
1
0
-1
-2
μm
0.5
0
-1
μm
10
5
0
μm
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
z
y
x

Strain profile









More realistic design with time dependence

External Strain

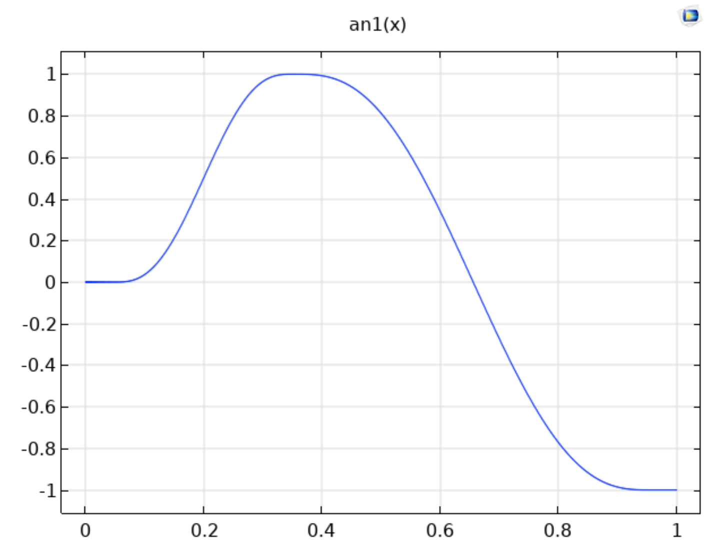
Strain input:

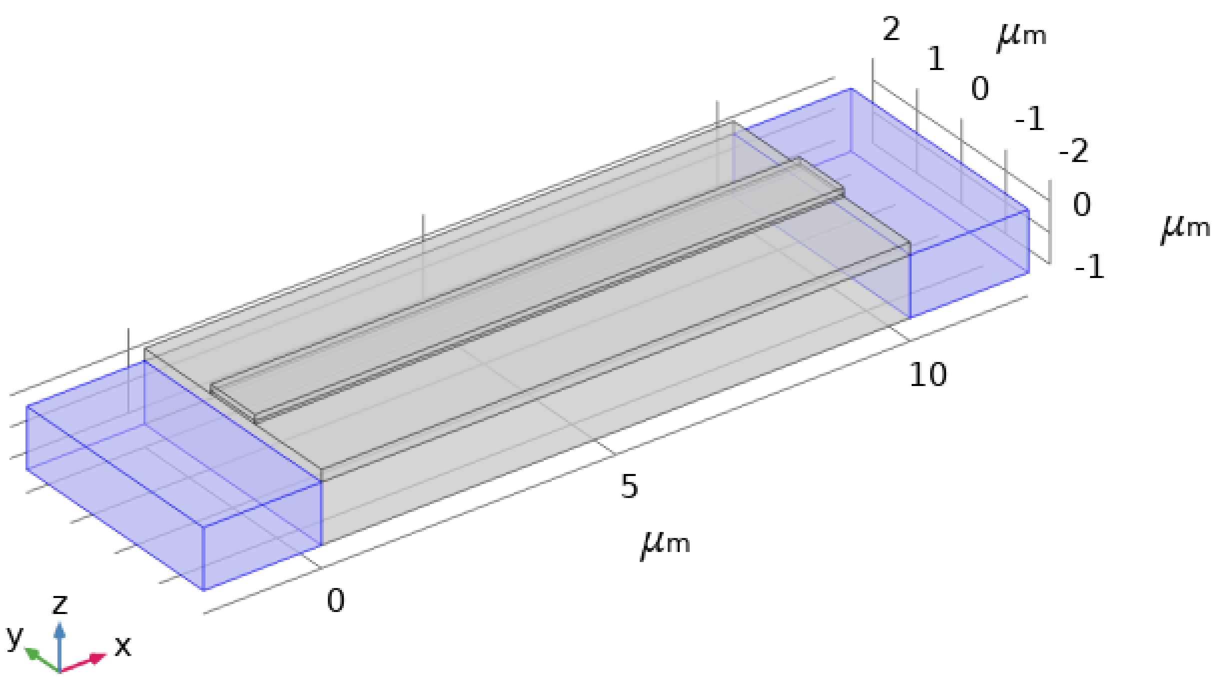
Strain tensor

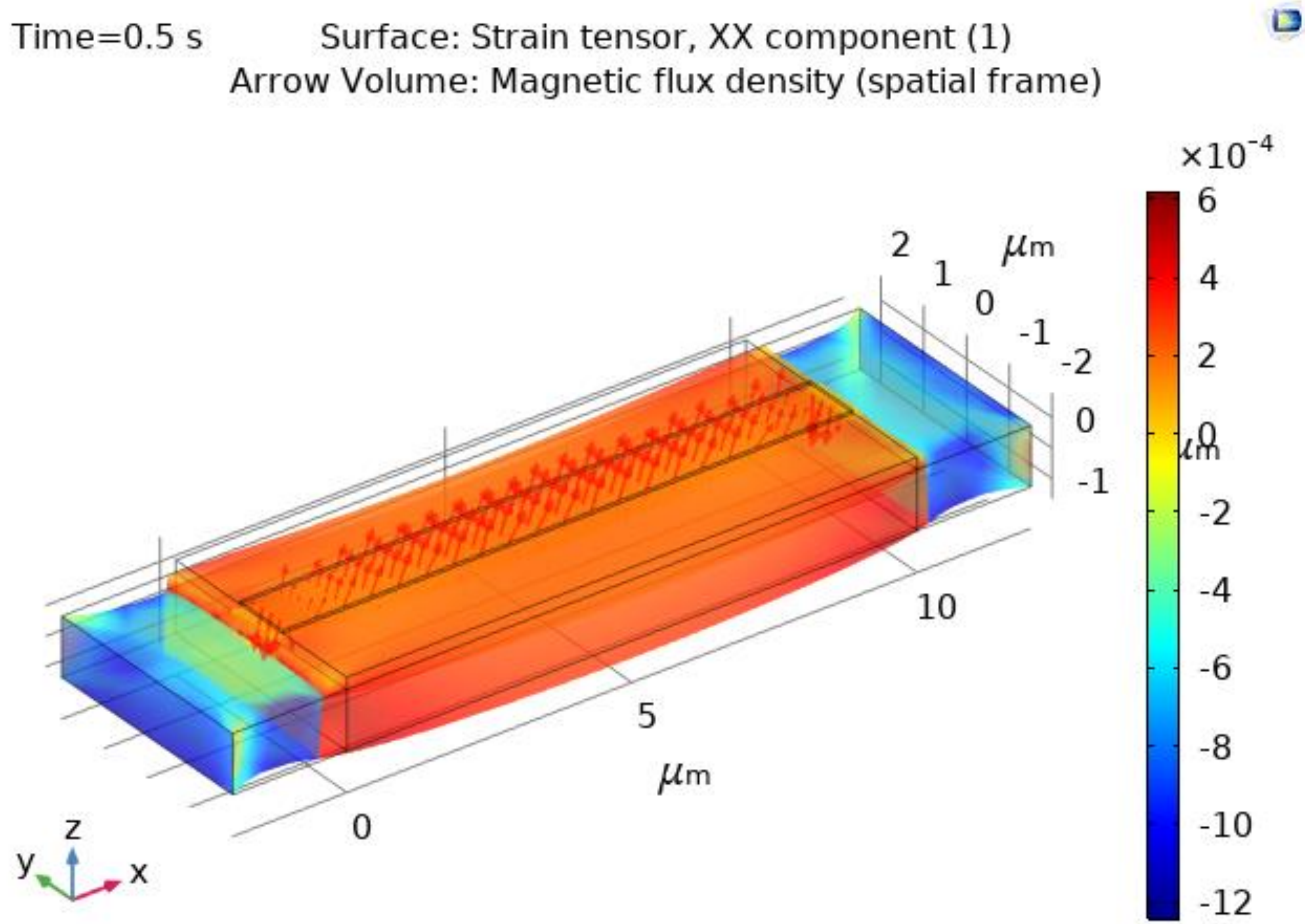
Strain tensor:

ϵ_{ext} User defined

-0.001*an1(t[1/s])	0	0	
0	-0.001*an1(t[1/s])	0	1
0	0	0	







Time=0.5 s
Surface: Strain tensor, XX component (1)
Arrow Volume: Magnetic flux density (spatial frame)
×10^-4
6
4
2
0
-2
-4
-6
-8
-10
-12
μm
2
1
0
-1
-2
0
-1
μm
10
5
μm
0
z
y
x

Outline

- Piezomagnetický jev
  - mikroskopický původ jevu – linearní závislost magnetizace na strainu
  - FEM model – využití výstupů mikroskopického modelu (SDFT)
- Elastokalorický jev
  - mikroskopický původ jevu – uvolňování latentního tepla
  - FEM model a nutné aproximace
- Shrnutí

Solid state cooling

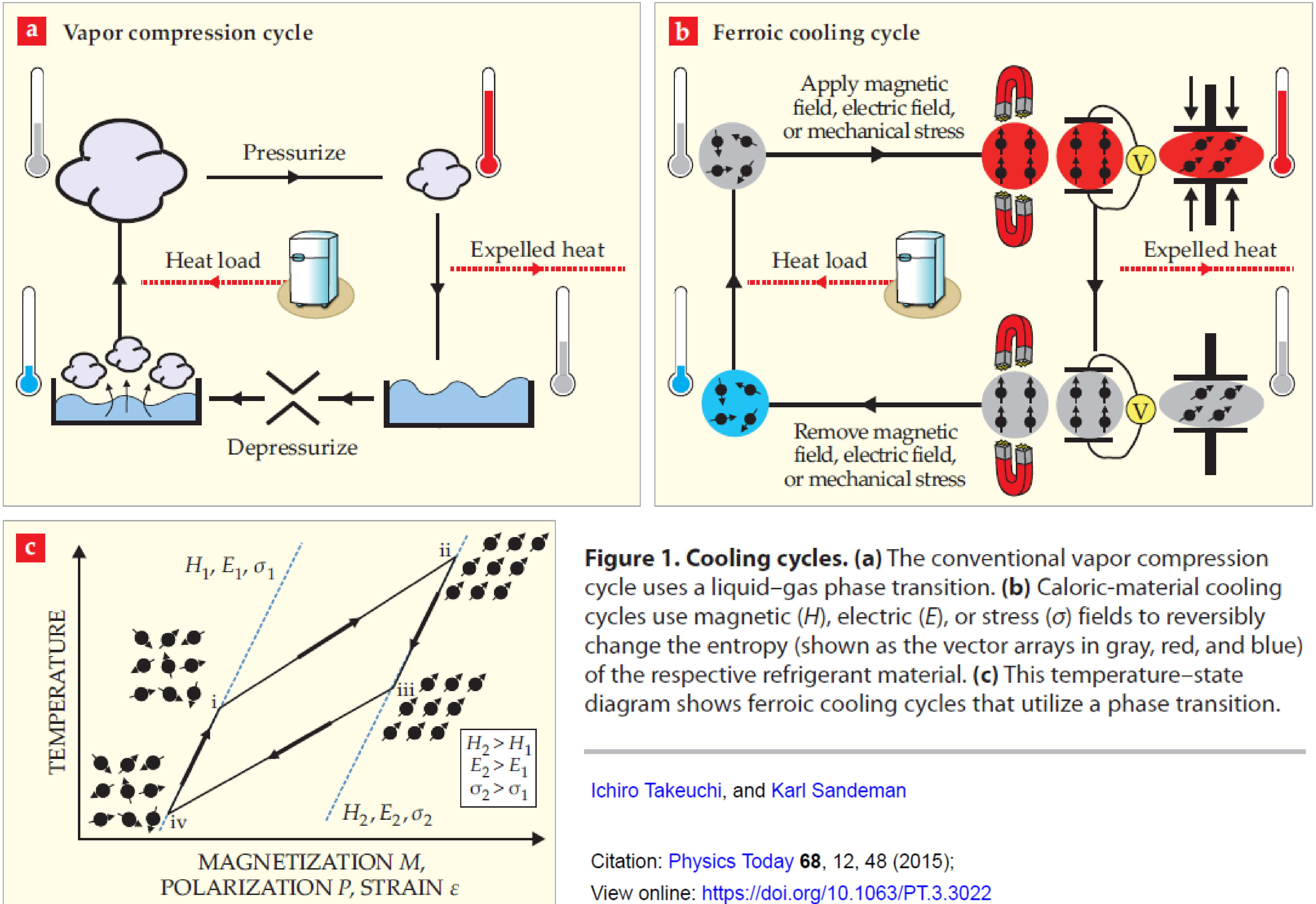
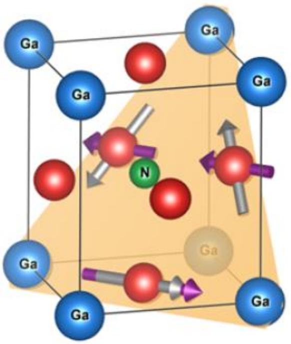


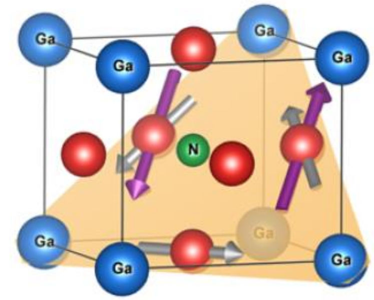
Figure 1. Cooling cycles. (a) The conventional vapor compression cycle uses a liquid–gas phase transition. **(b)** Caloric-material cooling cycles use magnetic (*H*), electric (*E*), or stress (*σ*) fields to reversibly change the entropy (shown as the vector arrays in gray, red, and blue) of the respective refrigerant material. **(c)** This temperature–state diagram shows ferroic cooling cycles that utilize a phase transition.

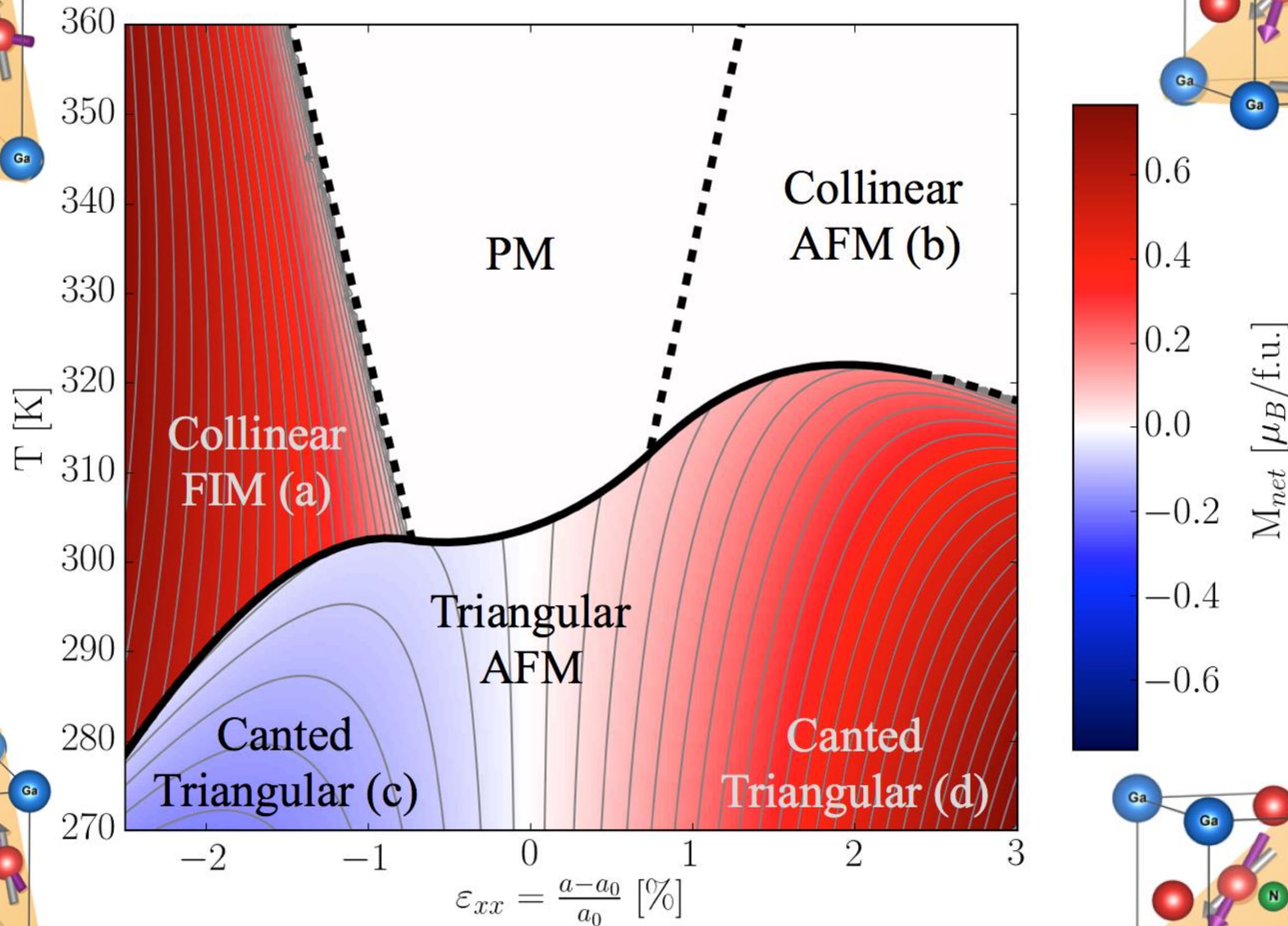
Ichiro Takeuchi, and Karl Sandeman

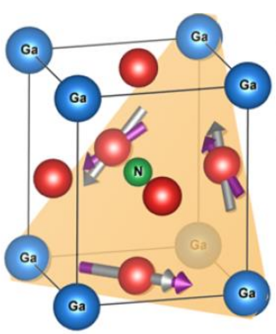
Citation: Physics Today **68**, 12, 48 (2015);
View online: https://doi.org/10.1063/PT.3.3022

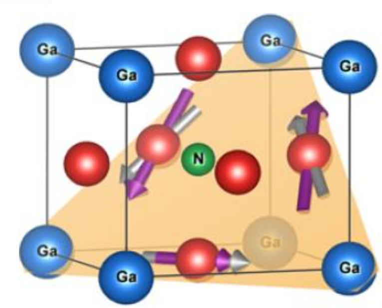
Temperature-strain phase diagram





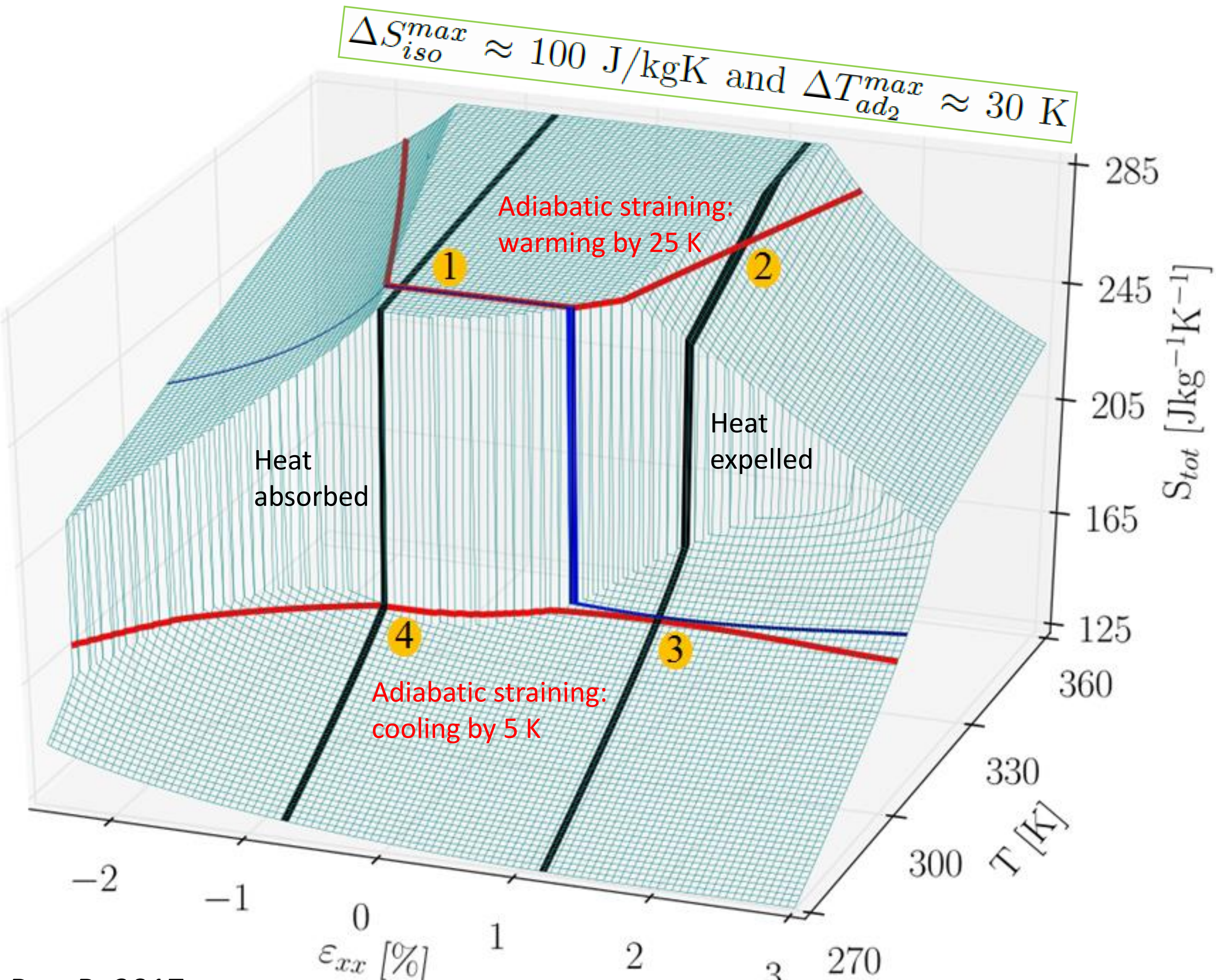






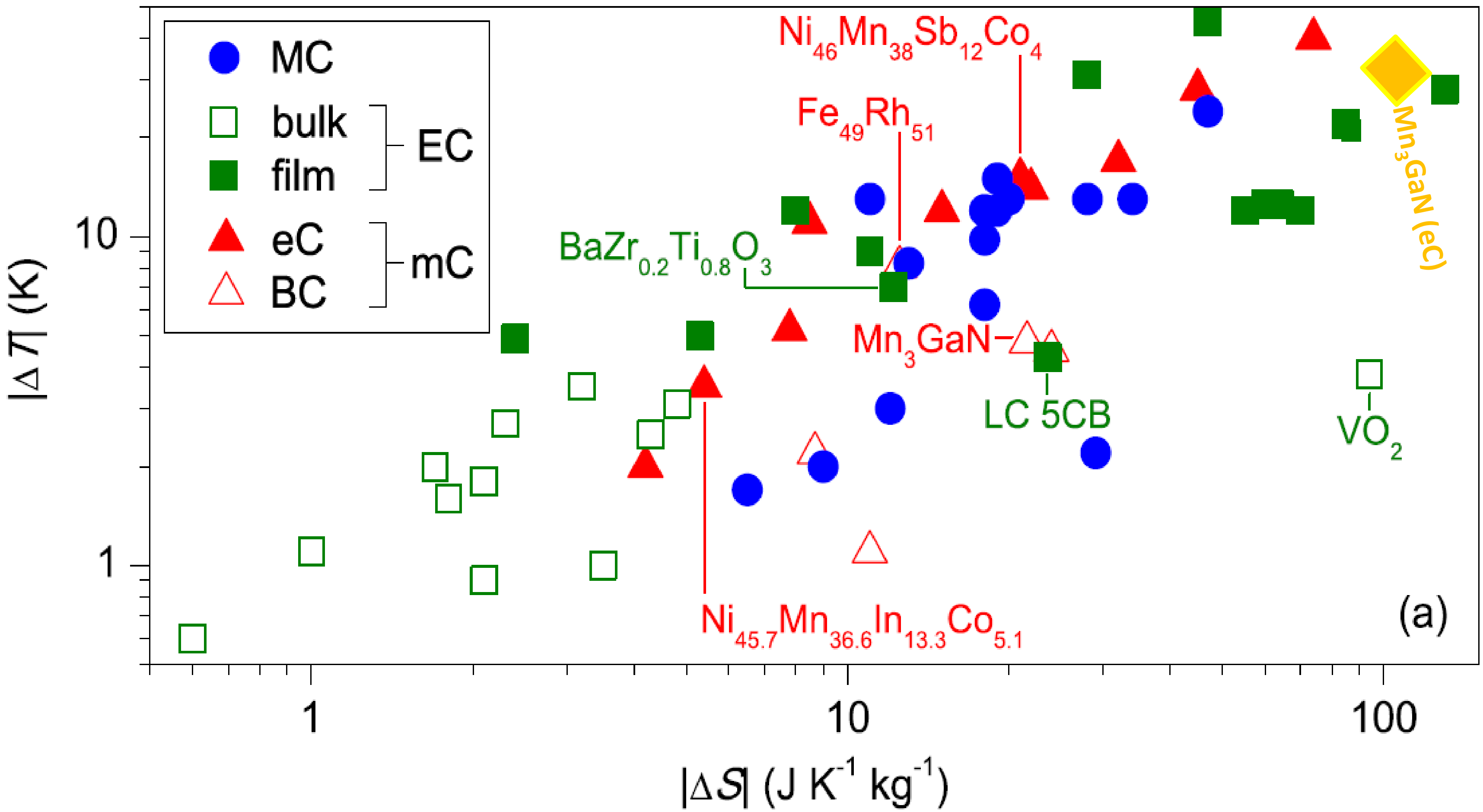
J.Zemen, Phys. Rev. B, 2017

Elastocaloric cooling cycle – an alternative to magnetocaloric cooling
(Rare earth free, driven by a piezo-stressor)



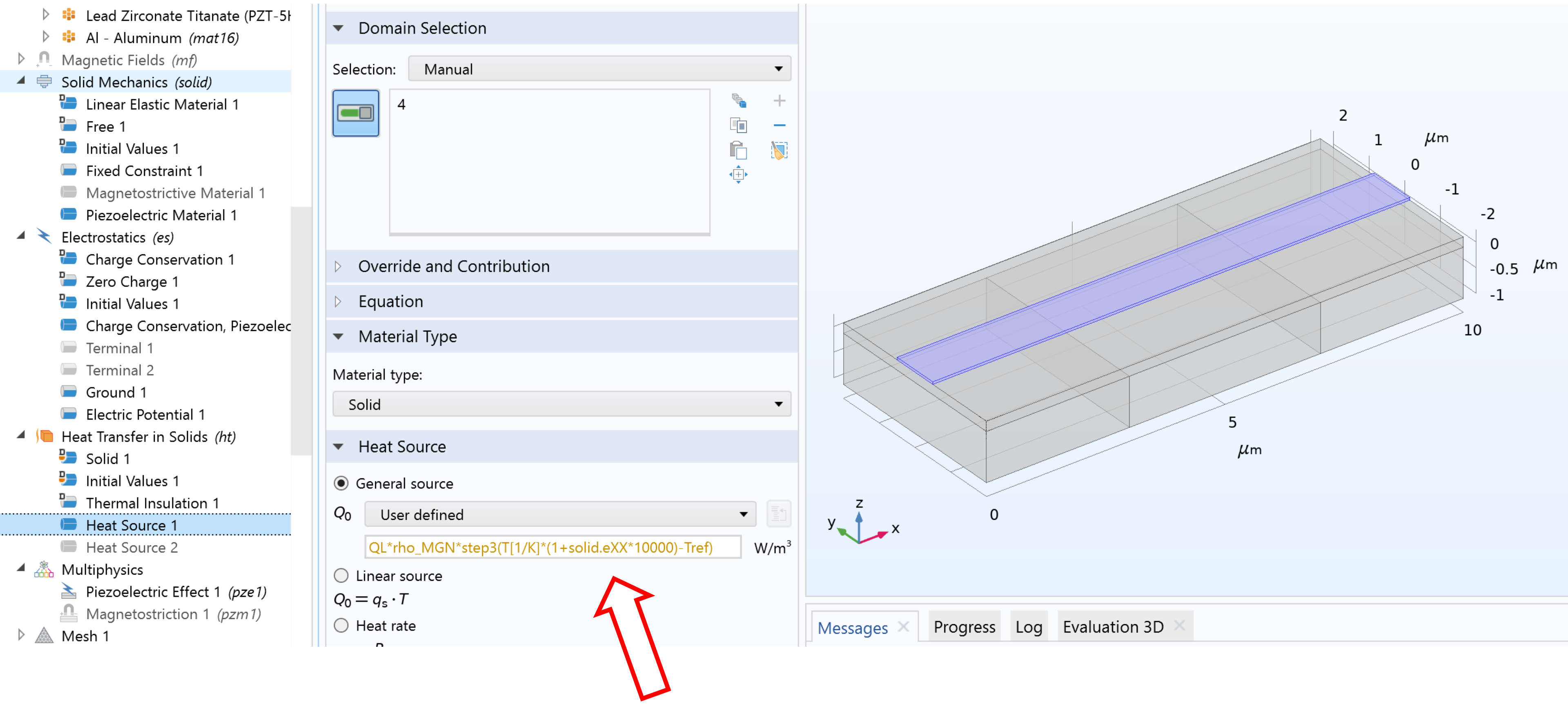
J.Zemen, Phys. Rev. B, 2017

Comparison to other solid-state cooling mechanisms
(MagnetoCaloric, ElectroCaloric, mechanoCaloric)

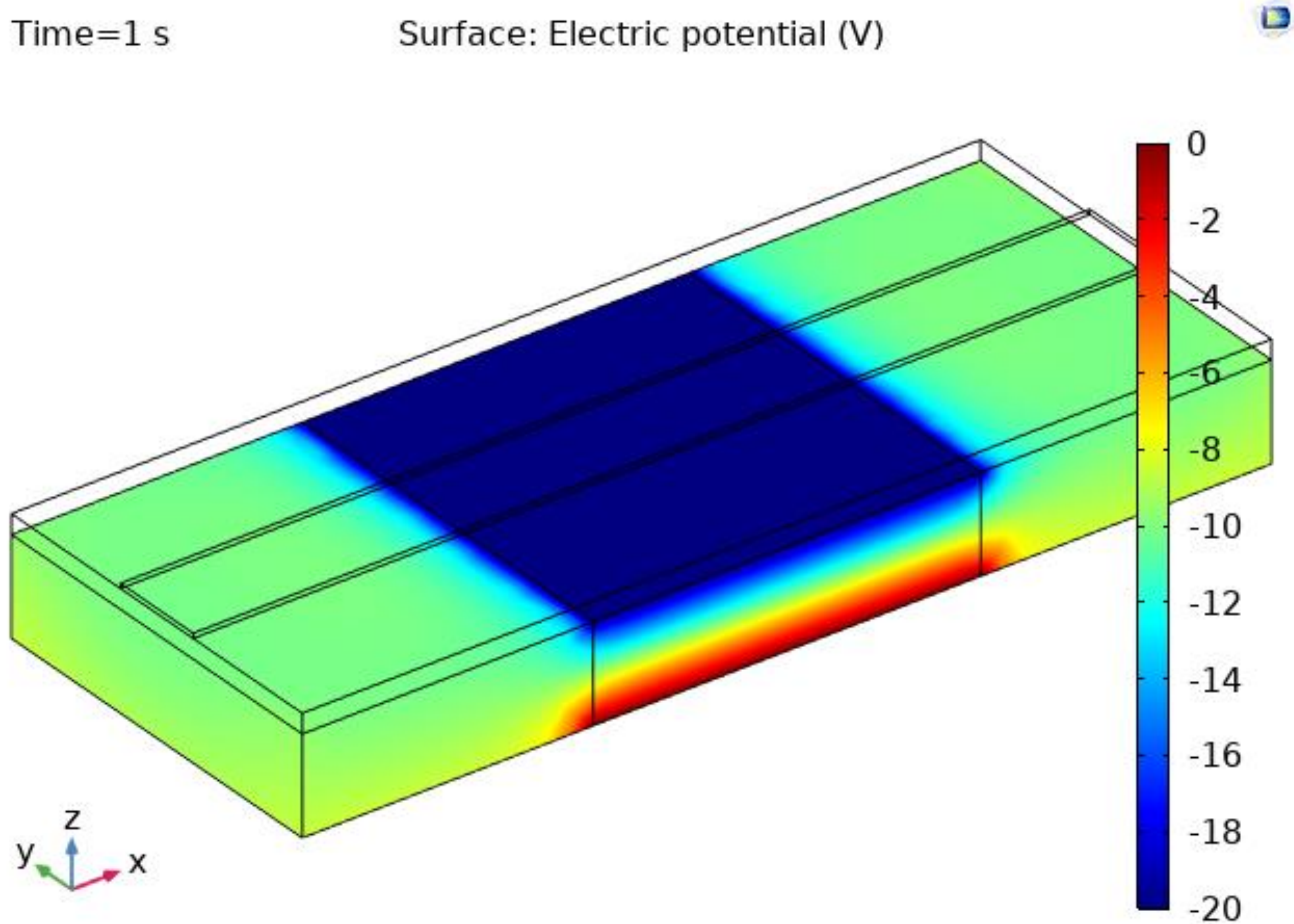


S. Crossley, N. D. Mathur, and X. Moya, AIP Advances **5**, 067153 (2015)

Heat source releasing the latent heat
(instead of temperature dependent heat capacity)

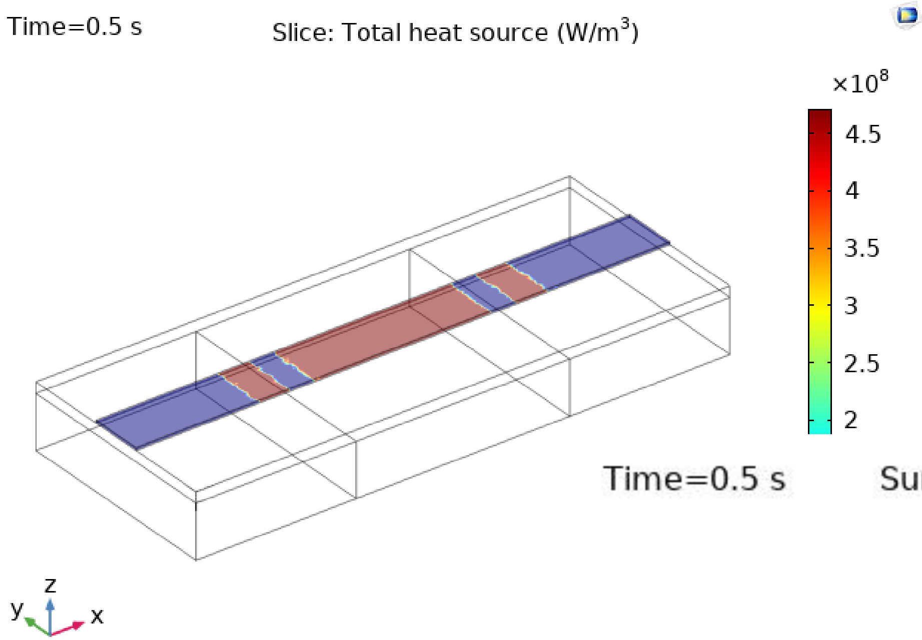


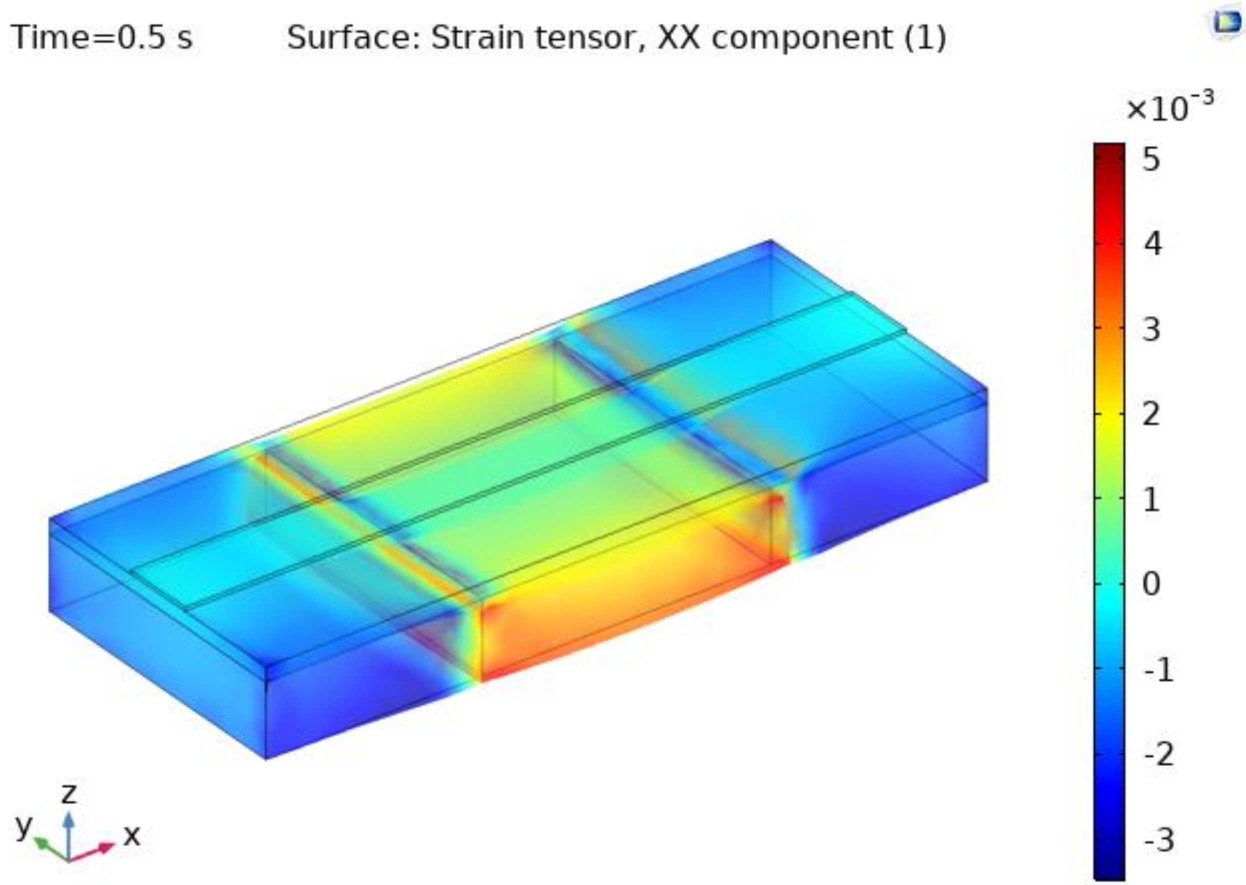
QL ~ latent heat released or absorbed at phase transition

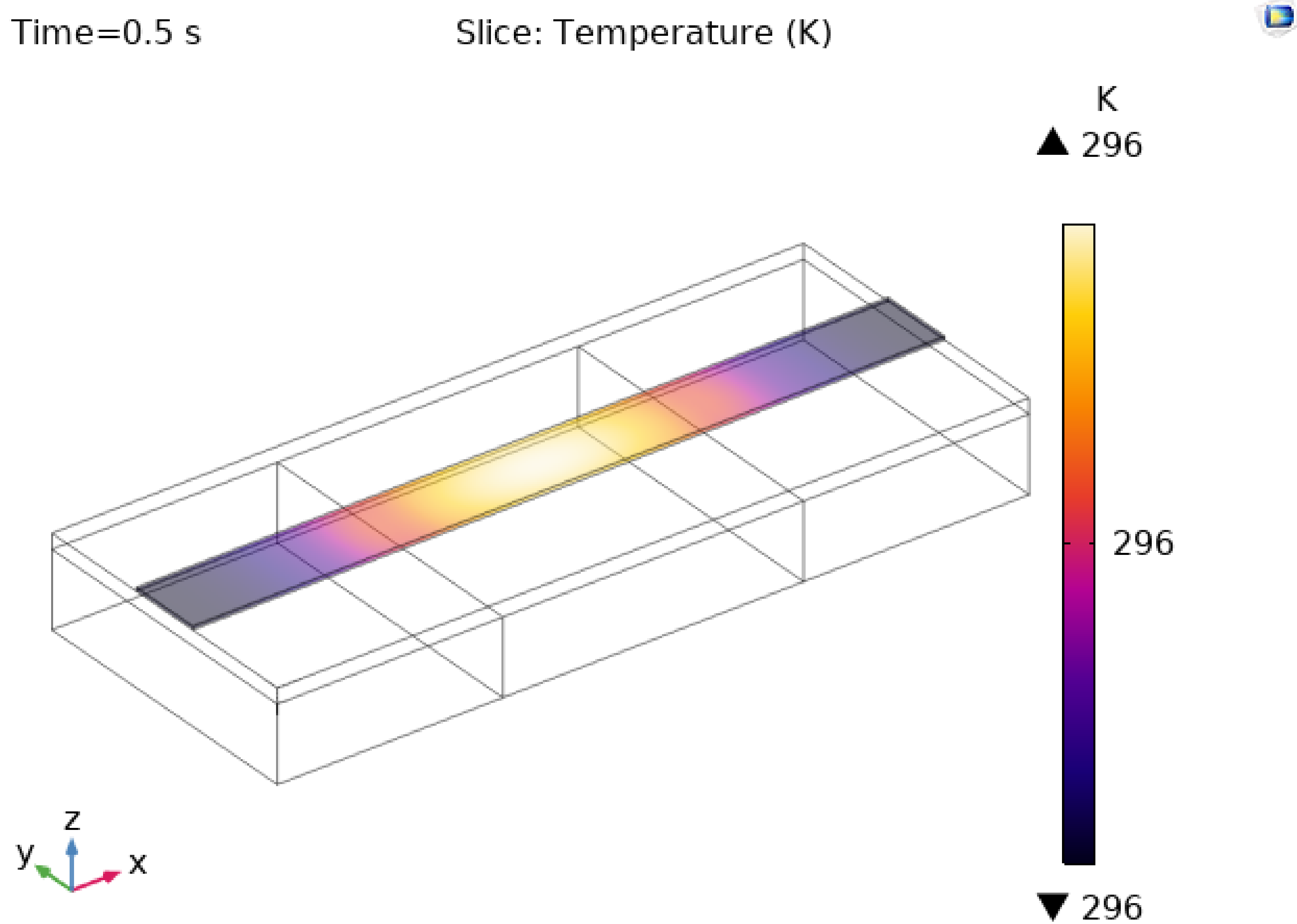


Stressor is activated locally (not along the whole bar as in previous case)

Heat source locally activated by strain



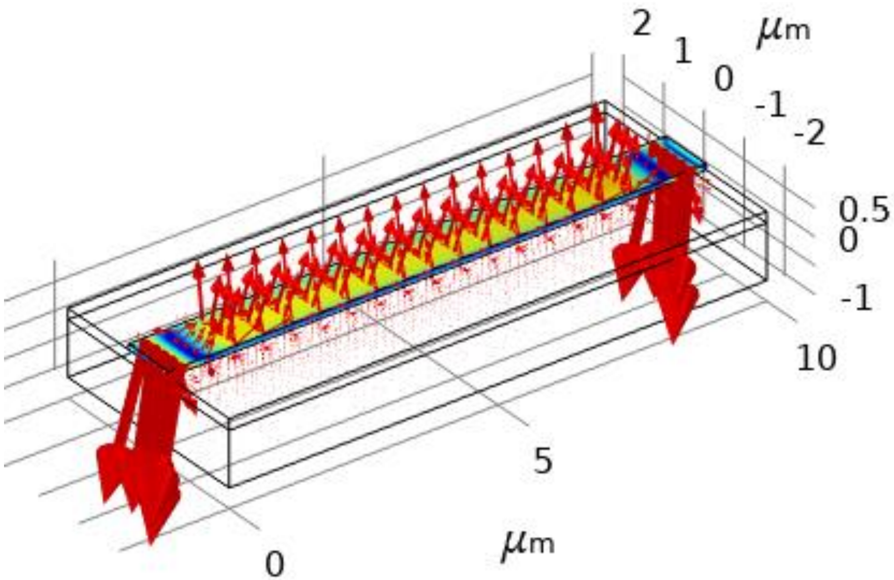




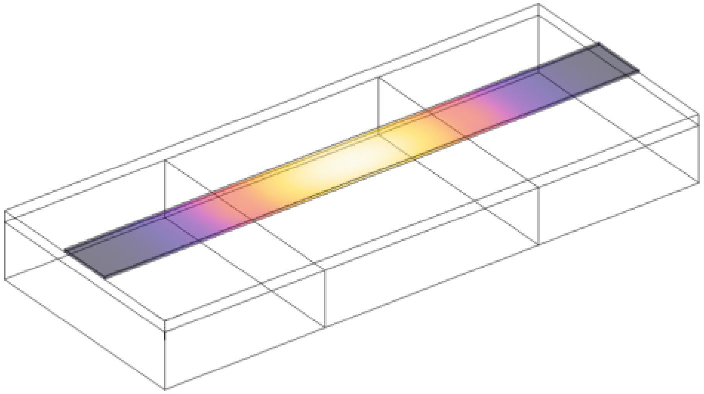
Time=0.5 s
Slice: Temperature (K)
K
▲ 296
296
▼ 296
z
y
x

Summary

- Piezomagnetický jev
  - Magnetization control
  - MRAM



- Elastokalorický jev
  - Phase transition control
  - Solid state cooling



Díky za pozornost

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
Development and Education

MINISTRY OF EDUCATION,
YOUTH AND SPORTS