Methods and Instrumentation for Expulsion Efficiency Measurements

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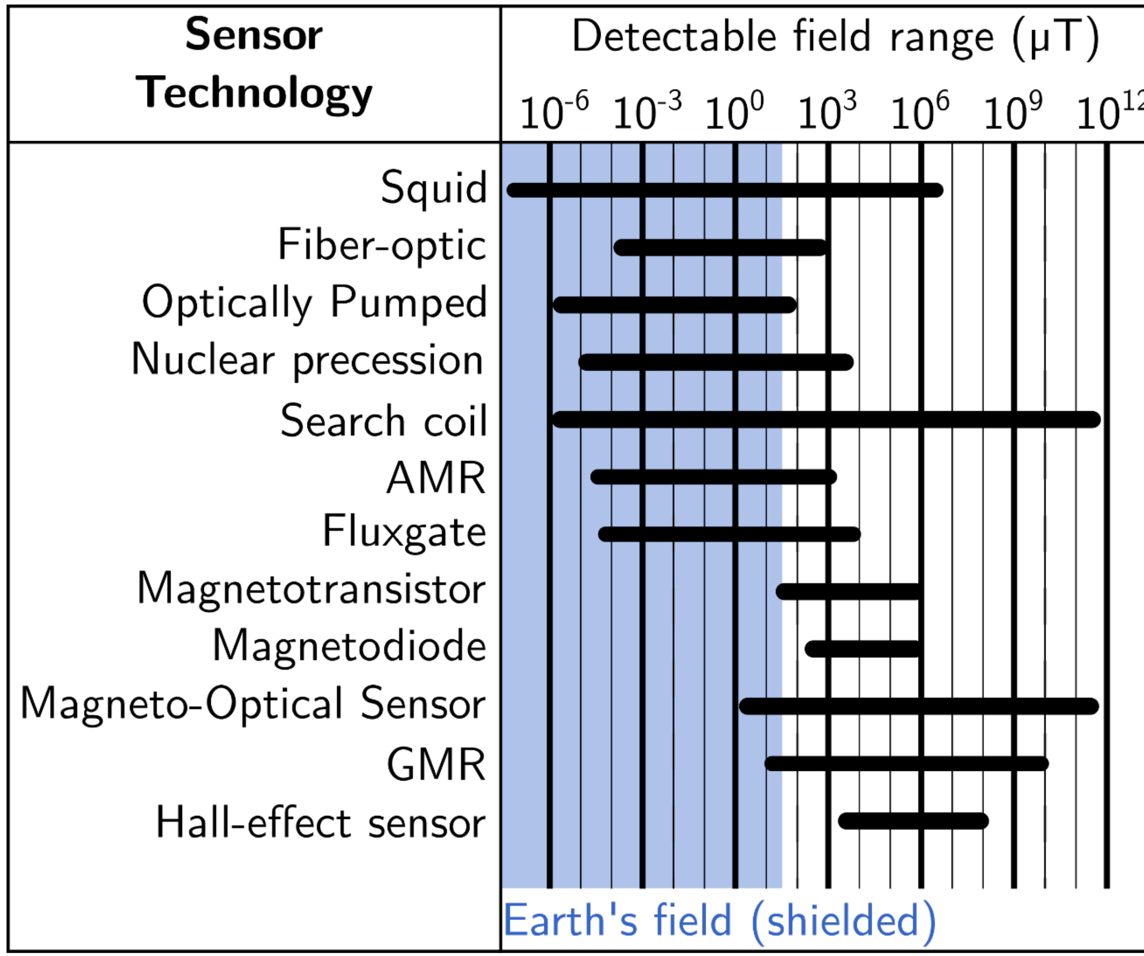
TTC/ARIES topical workshop on flux trapping and magnetic shielding

08.11. 2018

Magnetic field measurement techniques *(incomplete!)*

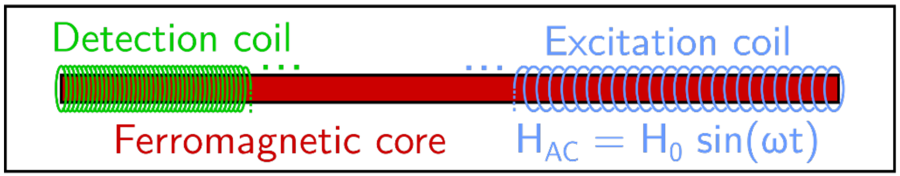
Measurement
of Expulsion
=
Measurement
of Magnetic Field

- Material (microscopic level)
- Geometry (macroscopic level)
- Dynamics of system

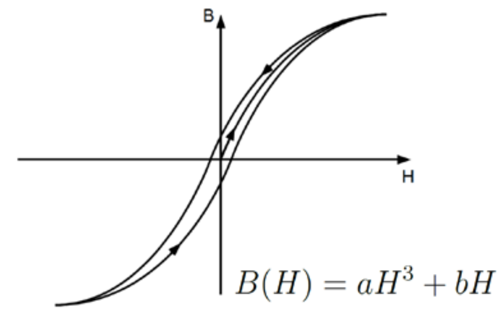


M. Caruso and C. Smith, "A new perspective on magnetic field sensing," Sensors, vol. 15(12), pp. 34–46, 1998

Where we started: Fluxgates as established sensor



Ferromagnetic core



Magnetic field in the core $$H = H_{AC} + H_{ext}$$

Voltage induced in detection coil $$V_{ind} = nA\frac{dB}{dt}$$

$$\begin{aligned} V_{ind} &= nA\frac{d}{dt}\left[a\left(H_{ext} + H_0\sin(\omega t)\right)^3 + b\left(H_{ext} + H_0\sin(\omega t)\right)\right] \\ &= nA\omega\left[\left(3aH_{ext}^2H_0 + bH_0 + \frac{3}{4}aH_0^3\right)\cdot\cos(\omega t)\right. \\ &\quad + \left(3aH_0^2H_{ext}\right)\cdot\sin(2\omega t) \\ &\quad \left. + \left(\frac{3}{4}aH_0^3\right)\cdot\cos(3\omega t)\right] \end{aligned}$$

Example numbers:

Bartington Mag-01H (F)
Cryogenic axial probe
- 0.1 nT resolution
- Precise
- Stable over time and temperature range

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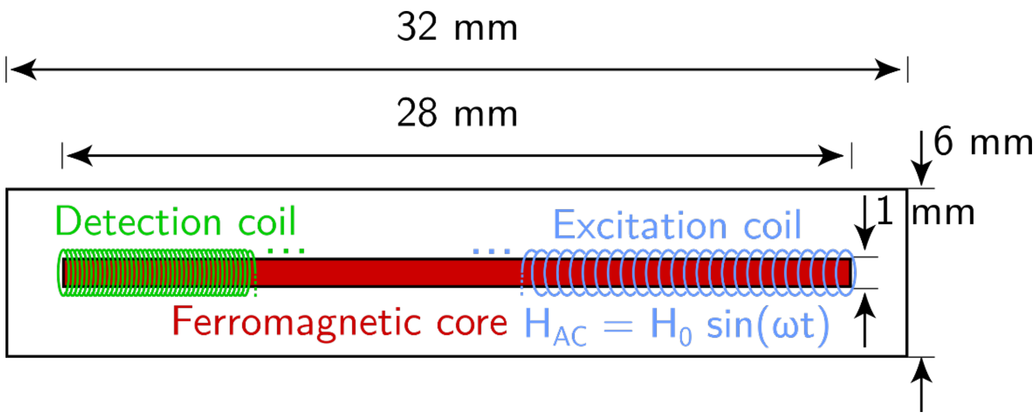
Where we started: Fluxgates as established sensor



Example numbers:

Bartington Mag-01H (F)
Cryogenic axial probe

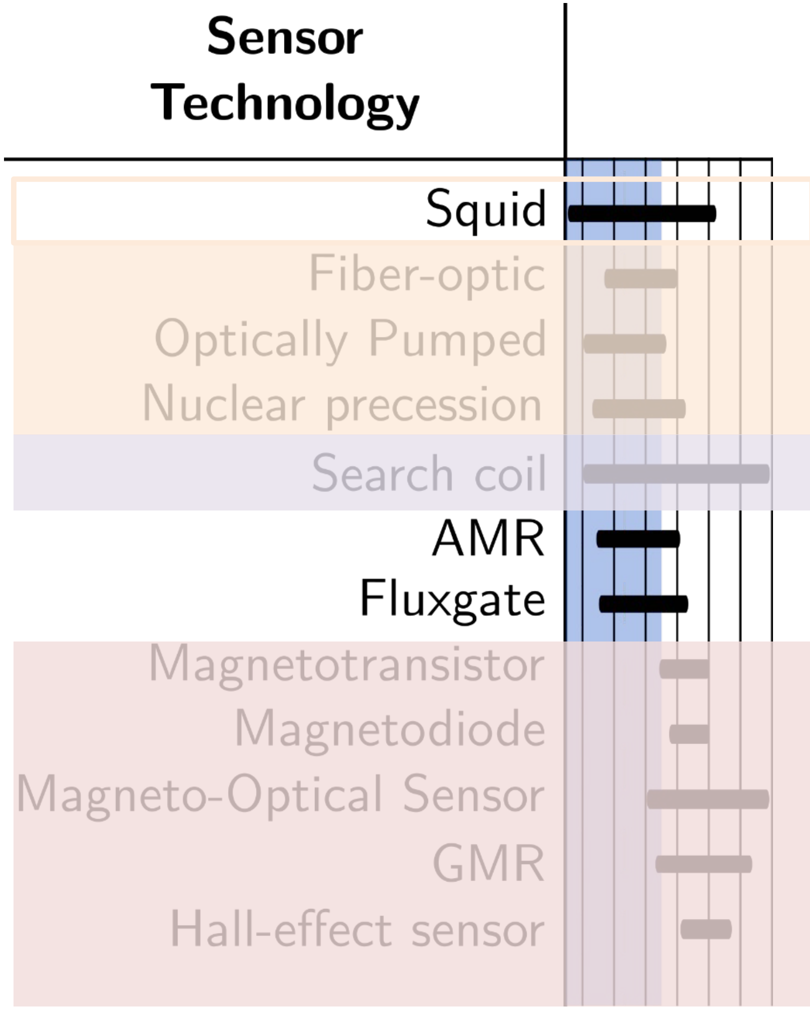
- 0.1 nT resolution
- Precise
- Stable over time and temperature range

Drawback

- Size
- Price

-> local resolution?
-> field distribution?

What are the questions?
What are the criteria?



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Criteria in addition to range:

- Resolution (field, space)
- Sensitivity
- Bandwidth
- Scalar/vector/projection
- Stability and drift
- Gradient tolerance
- Size
- Temperature dependence
- Sample rate
- Errors and noise
- Cost and complexity

Magneto-optical imaging

Based on

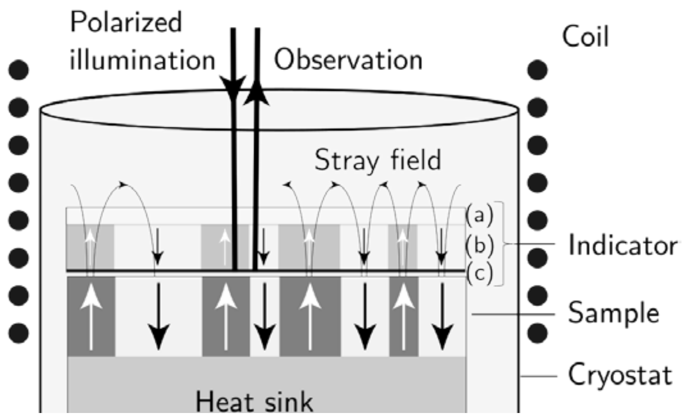
- Kerr effect

  magnetic circular birefringence:
  different refractive indices of circularly polarized components of light,
  rotation of plane of polarization of linearly polarized light during transmission through a medium

- Faraday effect

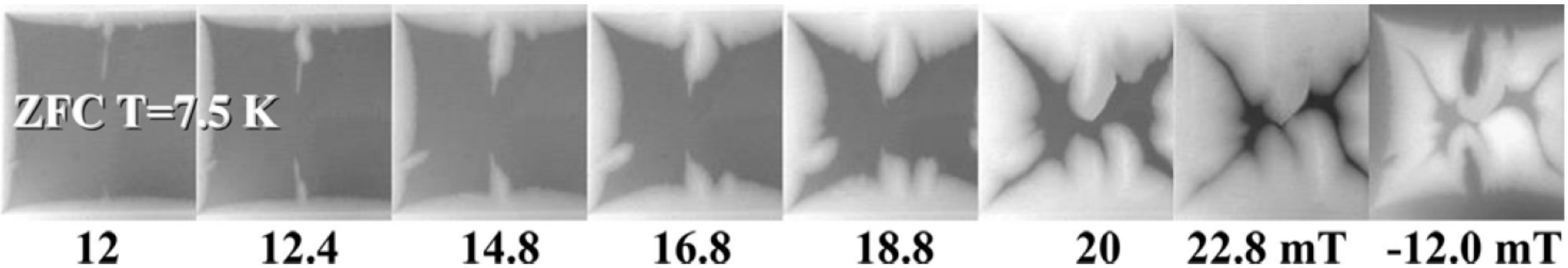
  magnetic dichroism:
  difference in absorption coefficients of left- and right-handed circular polarized light in a medium,
  plane of polarization of the light is rotated during reflection from a magnetized and reflective sample

Niobium exhibits neither. Hence indicator:

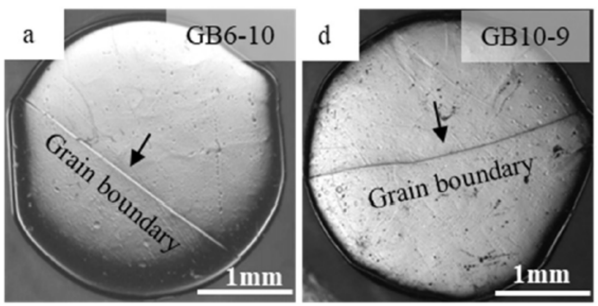


Magneto-optical imaging: Flux penetration

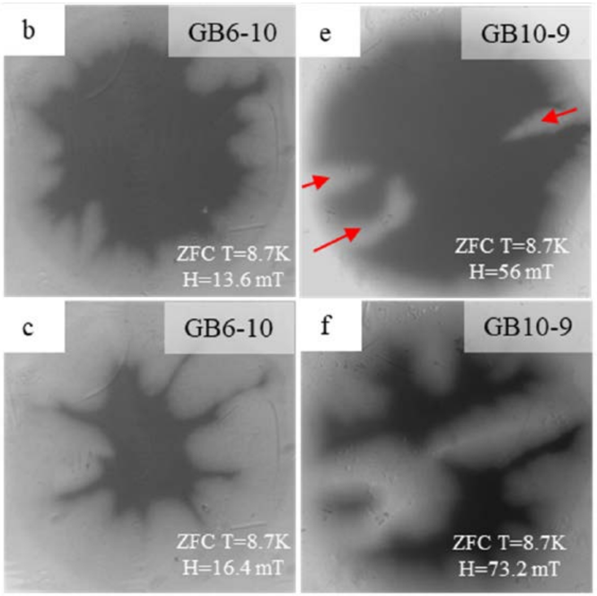
sample size: 5x5mm²



P. Lee et. al., "Grain boundary flux penetration and resistivity in large grain niobium sheet" Proceedings SRF2005, pp. 372–374, 2005

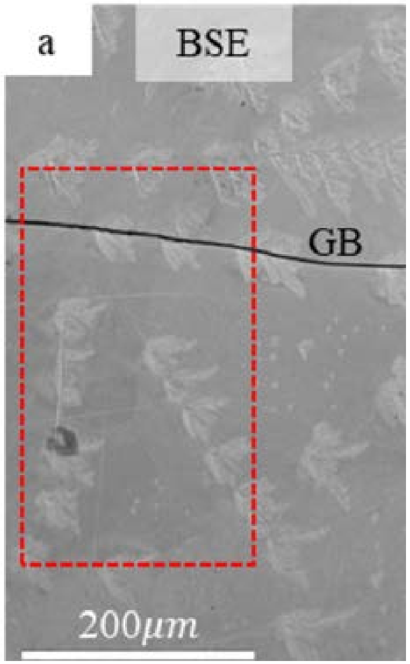


M. Wang et. al., "Investigation of the effect of strategically selected grain boundaries on superconducting properties of SRF cavity niobium" Proceedings SRF2017, pp. 787–791, 2017



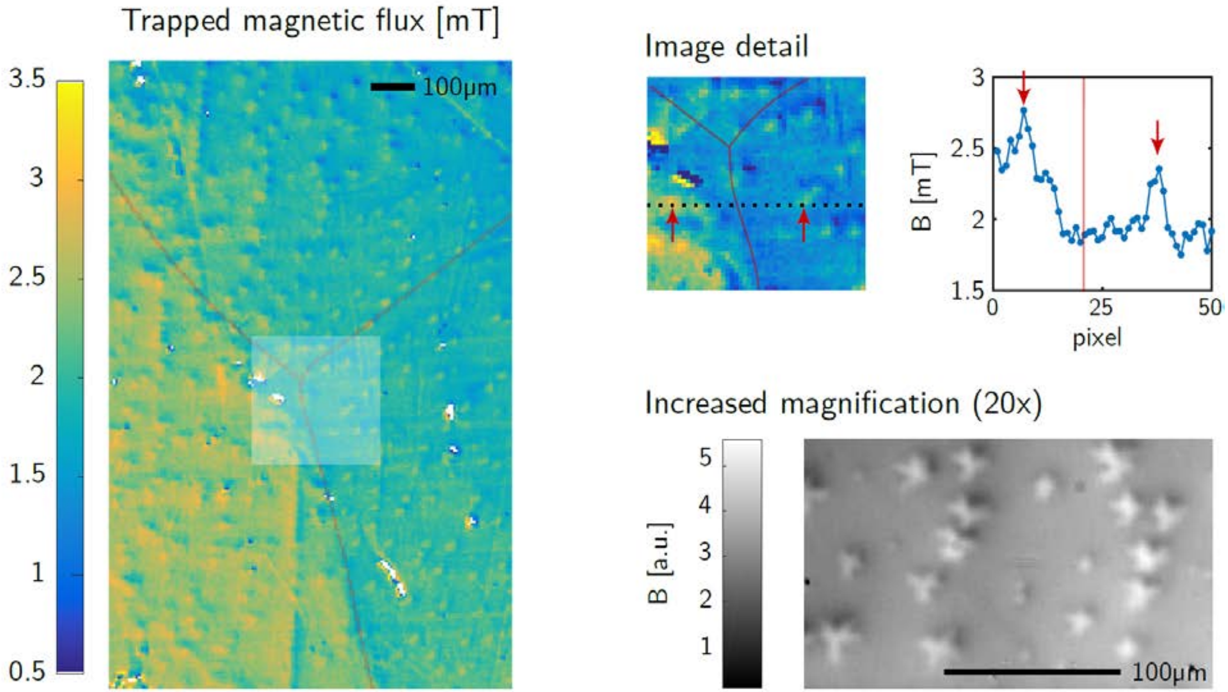
Magneto-optical imaging: Trapped flux

Maps from EBSD analysis of the sample surface after MOI

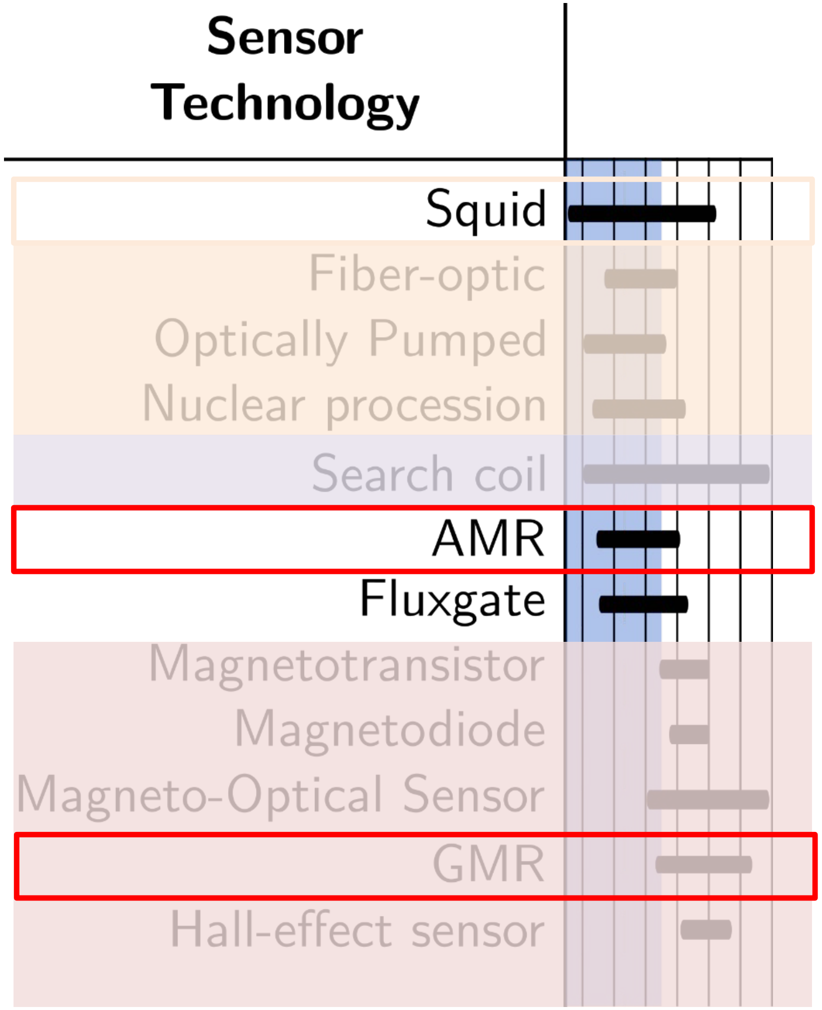


M. Wang et. al., Proceedings SRF2017, pp. 787–791, 2017

MOI of trapped flux



J. Köszegi et. al., "Towards the perfect Meissner state: A magneto-optical study on competing pinning centers in Niobium" Proceedings SRF2017, pp. 766–770, 2017



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Magnetoresistive (MR) sensors: staple goods for industry

High demand in automotive, communication etc. industries leads to improvements in sensor properties as well as reliability and reduction in costs.

"Magnetoresistive" effects:

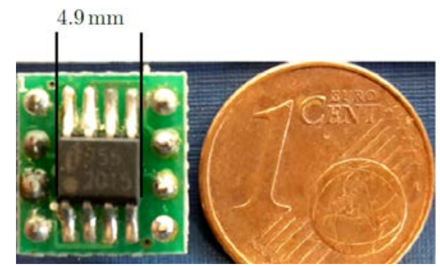
- AMR - anisotropic magnetoresistance
- GMR - giant magnetoresistance
- TMR - tunnel magnetoresistance
- CMR - colossal magnetoresistance

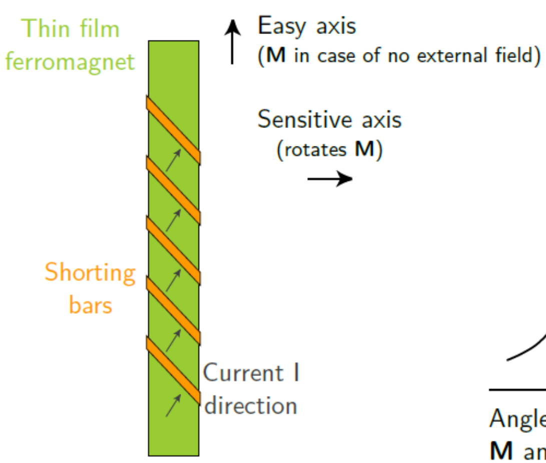
L. Jogschies et.al., "Review: Recent Developments of Magnetoresistive Sensors for Industrial Applications," Sensors, vol. 15(11), pp. 28665-28689, 2015

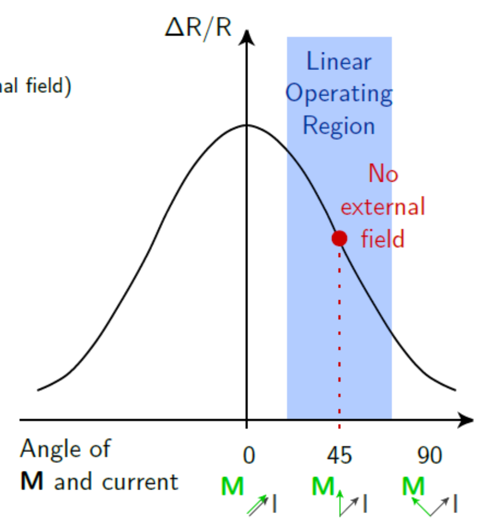
Magnetoresistive (MR) sensors: staple goods for industry

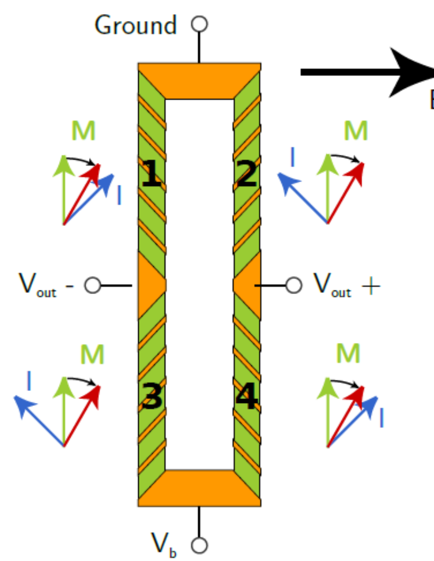
AMR: anisotropic magnetoresistance

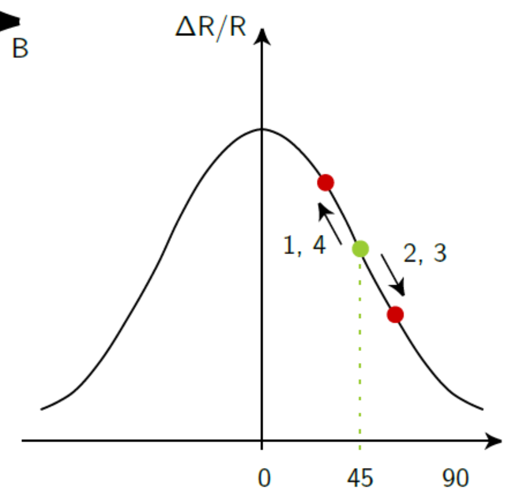
Resistance varies in ferromagnetic material with angle between current and magnetization (spin-orbit coupling)











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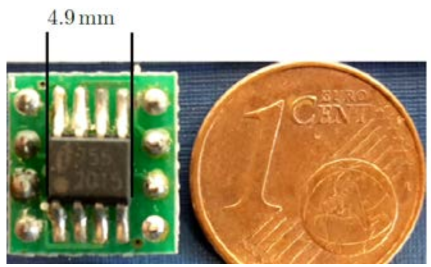
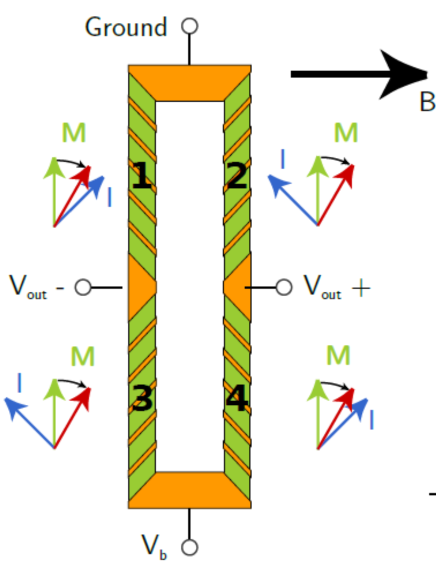
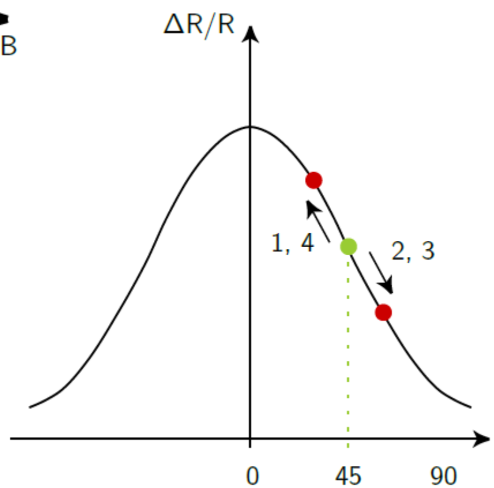
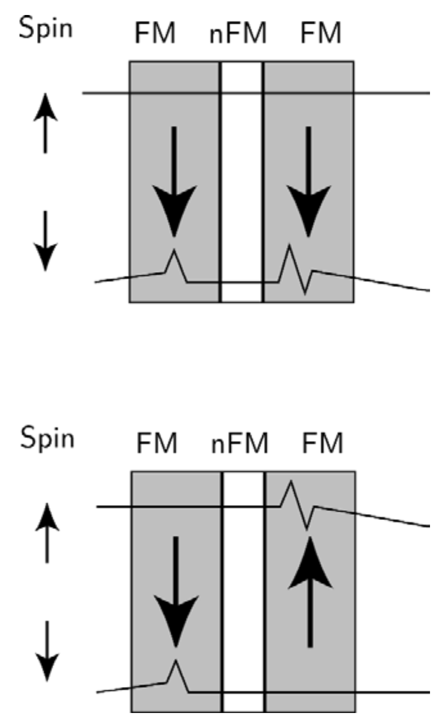






GMR: giant magnetoresistance

Resistance varies in multilayer structures (FM, nFM) depending on parallel or anti-parallel orientation (spin-dependent transport)



Sketch of a "spin valve"

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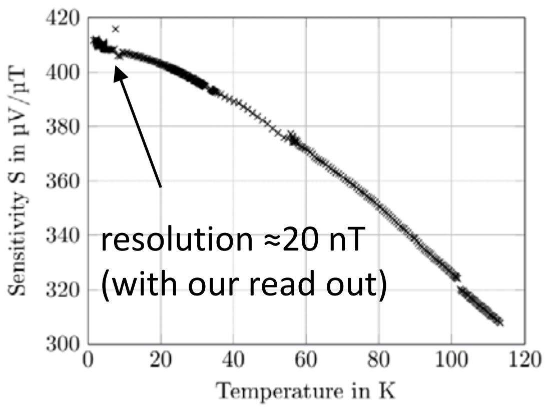
AMR and GMR: Temperature dependence

Sensitivity increases at cryogenic temperatures

AMR: AFF755 (Sensitec)

GMR: GF708 (Sensitec)

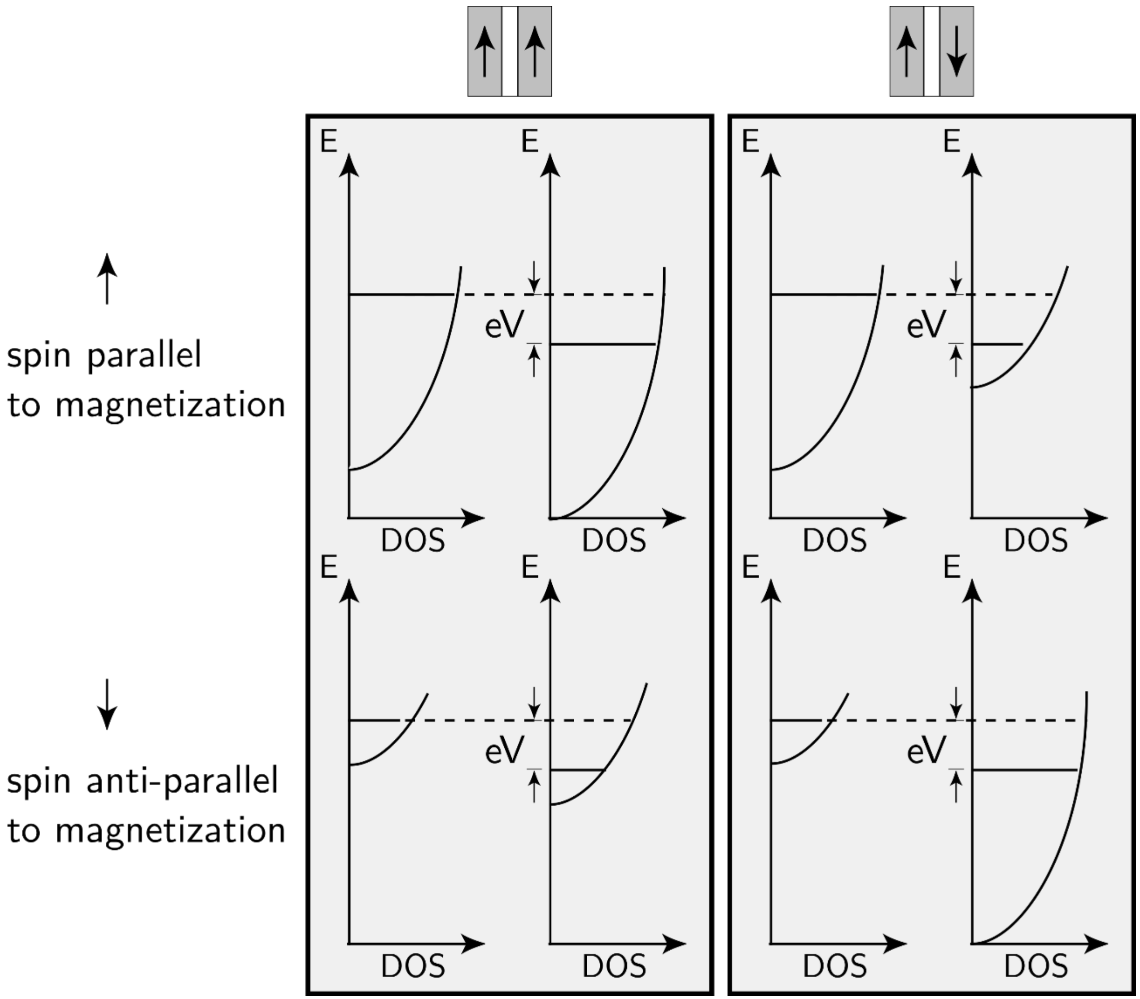


With 180mV/V /mT at RT and about 2mV/µT in cold

F. Nording et. al., "Temperature dependence of AMR and GMR Sensor Properties" Proceedings of the 14th Symposium on Magnetoresistive Sensors and Magnetic Systems, pp. 85–92, 2017

TMR Sensors: Spin dependent tunneling in magnetic tunneling junctions

- *Cryo compatible (discovered at 4.2 K)*
- *Sensitivity increases at lower temperatures*
- *Commercially available but still in development*



Low resistance state

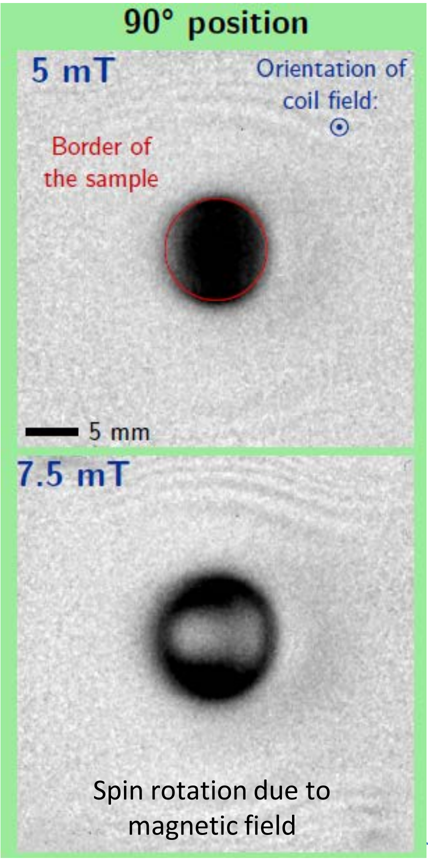
High resistance state

Perspectives for SRF

- Utilize comparatively cheap AMR technology for applications with many sensors
- Characterize small GMR/TMR sensors at cryo temperatures for increased spatial resolution. BUT: layer technology more expensive than simpler AMRs
- “The sensitivity of the TMR sensor is 10 times that of the AMR sensor and 3 times that of the GMR sensor.” *C. Duret and U. Ueno. "TMR: A new frontier for magnetic sensing." NTN technical review 80, 64-71,2012*
- Flexible substrates

M.Melzer et. al., “Ultra-Flexible, Stretchable and Printed GMR Sensors” Proceedings of the 14th Symposium on Magnetoresistive Sensors and Magnetic Systems, pp. 159–166, 2017

- And beyond: For example bulk magnetization by neutrons



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THANK YOU FOR YOUR ATTENTION!