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High-accuracy Hall-based sensors for high magnetic field applications

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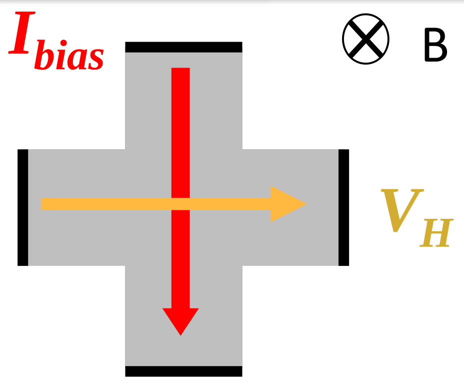
OUTLINE

- **The Hall effect**
- **Parasitic effects in Hall measurements**
- **2D Quantum Well Hall Sensors vs 3D sensors**
- **QWHS for micromagnetometry - Applications and results**
- **The Spinning Current Modulation Technique (SCMT)**
- **Results at high magnetic field (0 to 7 T)**
- **Conclusion**

The Hall effect -1-

Hall effect in a planar device

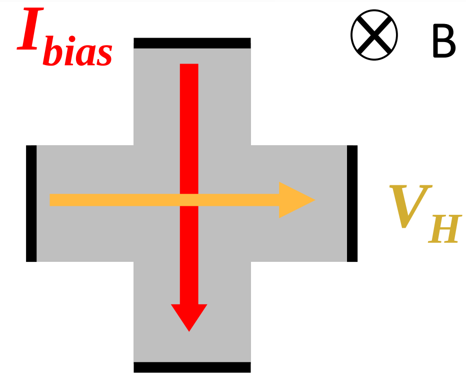
- Lorentz force acting on the moving electrons in the channel:
  - → transverse electric field $\vec{F} = e\vec{v} \times \vec{B}$
- Basic classical Drude-like model:
  - → **Hall voltage** $V_H = K_H I B_\perp = \dfrac{I B_\perp}{e n_S}$



n_S : sheet electron density

The Hall effect -1-

Hall effect in a planar device



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n_S : sheet electron density

Unwanted parasitic effects

cf. R. Popovic's book, "*Hall Effect Devices*"

1. The Hall sensitivity may not be a constant

$$K_H = G_H\left(\mu(T)B\right) \times \frac{r_H(T,B)}{e n_s}$$

Geometric factor G_H :
Can be fixed with adequate probe layout
Under certain conditions $G_H = 1$

Sheet electron density n_S
How to keep it constant?

Hall scattering factor r_H
Microscopic effects: *intrinsic NL*
Depends on material and sensor structure, $r_H = 1$ in degenerate material

2. Additive parasitic terms in the output signal V_{out}

$$V_{out} = K_H I B_\perp + \text{parasitic terms}$$

The Hall effect -2-

Parasitic terms in the output signal V_{out}

- Offset
- Piezoresistance effect
- Non-linearity vs B
- Cross-sensitivity to in-plane $B_{//}$ (PHE = Planar Hall Effect)
- Thermal and temporal drift of offset
- Thermal and temporal drift of sensitivity
- Noise

Their magnitude strongly depends on material and sensor structure

Dynamic cancelation of parasitic terms

- Some of these effects can be canceled out by various techniques, the most powerful is the Spinning Current Modulation Technique (SCMT)

- Again, ***depending on the type of material considered***, SCMT might be more or less powerful in canceling the parasitic effects

Selected material

Quantum Well Hall Sensors (QWHS)

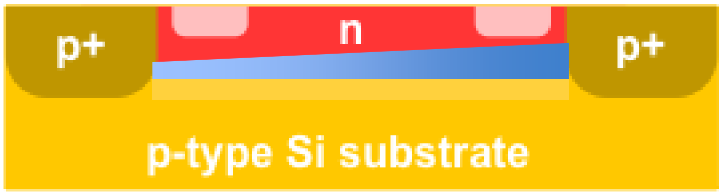
AlGaAs/InGaAs/GaAs

- 2DEG: combines the benefit of
  a degenerate semiconductor
  together with a low electron density n_s
- Available from industrial III-V foundries

Different types of Hall plates -1-

Materials / schematic structure / 2D vs 3D

Silicon based CMOS compatible (Si)



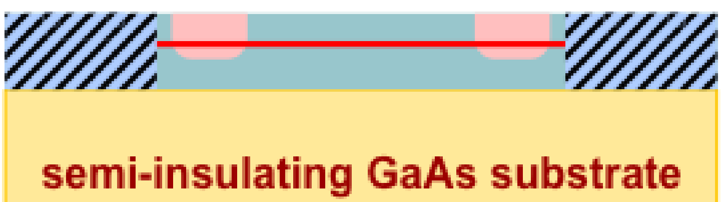
Implanted or epitaxial n-type active layer confined by p-type bulk and p+ implant

High-mobility 3D device *e.g.* InSb-based (III-V)

Epitaxial highly-doped n-InSb layer confined by S.I. substrate

3D active layer thickness: typ. 100 nm to 2 µm or more

Heterostructure based Quantum Well Hall Sensor (III-V)

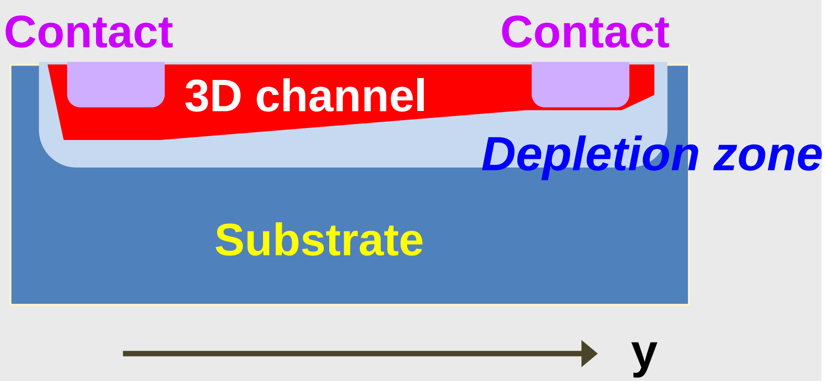


Epitaxial AlGaAs/InGaAs/InAs heterostructure (MBE), laterally defined by isolation implant

2D active layer thickness typ. 8-15 nm

Hall sensor structure: 3D vs. 2D active layer

- **Standard 3D Hall sensor**
  (GaAs, InAs, InGaAs, Si)

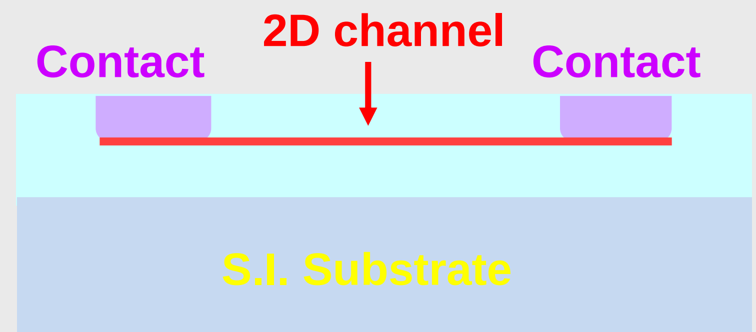


Pinch-off effect (as in MOS transistors)

$n_S\,(y)$ depends on I_{bias} and T

- $K_H = 1/en_s$ @ y=L/2
- **Not homogenous: issue for "spinning current" modulation**
- **Also: larger thermal drift**
- **+ carrier freeze-out at low T in Si**

Quantum Well Hall Sensor
(Heterostructure based on GaAs, InP,...)



No pinch-off:

$n_S\,(y) = n_{S0}$ constant vs I_{bias} and y

- **Very homogenous electron density**
- **Excellent temporal stability**
- **Very weak K_H thermal drift**
  $S_T \approx -100$ ppm/°C

Different types of Hall plates: **features, advantages and drawbacks**

1. **Silicon based Hall sensors**

Active layer = n-type SI on top of bulk p-type Si

- Various galvanomagnetic effects:
  - Magnetoresistance, non-linearity, planar Hall effect (PHE), piezoresistance
- Suited for integration with CMOS electronics

  Behavior of IC at high field ?
- Suited for **monolithic three-axis magnetometers +++**

2. **InSb or InAs based sensors**

Active layer = µm thick highly doped n-type layer

- Degenerate semiconductor
- Actual mobility much lower than for undoped material
- Low sensitivity, need for a large biasing current (10-100 mA)
- Industrial / small batch

3. **Quantum Well Hall Sensors**

Active layer = 10 nm thick QW in a III–V heterostructure, + Remote “delta”-doping

- Std RT mobility 7000 cm²/Vs
- Biasing current 0.2–0.5 mA typ.
- Requires elimination of backgating phenomenon
- Industrial pHEMT technology available from III-V foundry on GaAs substrate

Materials characteristics

Materials	Bandgap (eV)	Mobility (cm²/Vs)
Si	1.12 **	1400 *
InSb	0.17	77000 *
InAs	0.35	40000 *
GaAs	1.42	8600 *
$In_{0.2}Ga_{0.8}As$	1.3	7000

(*) *For undoped material*
(**) Indirect bandgap

QWHS for current sensing and high precision magnetometry

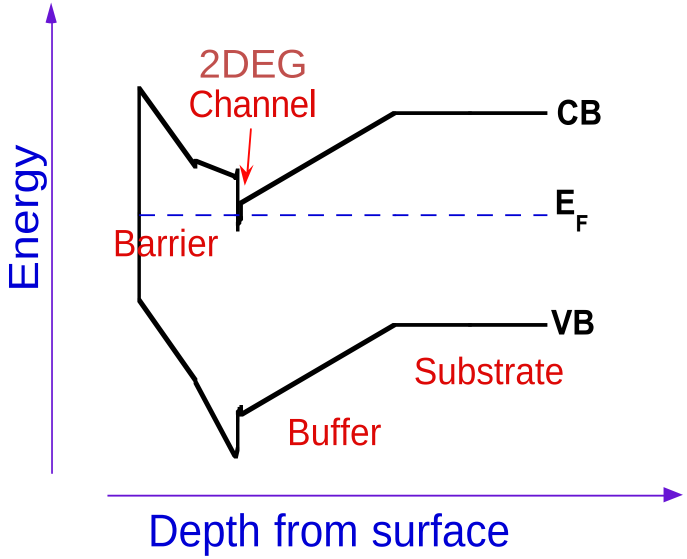
Pseudomorphic heterostructure (AlGaAs/InGaAs/GaAs system)

- **Buried 2DEG (2D Electron Gas)**
- **Designed for precision current sensing - 4th gen. being developed**
- **Batch process: - for production: 150 mm GaAs wafers**
  - for R&D: 3" and 100 mm GaAs wafers

Features:

- **Cross sensitivity** K_H **= 700 Ω /T +/- 5%**
- **Very low thermal drift** S_T **≈ -40/-60 ppm/°C**
- **Magnetic sensitivity 0.1 – 1 V/T typ.**
- **Noise PSD** S_B **a few nT/√ Hz**
- **Low raw offset +/- 3σ ≤ +/1.4 mT**
- **The offset can be dynamically canceled through SCMT down to <100 nT for a magnetometer with 30 mT F.S.**

Band diagram of the heterostructure



- **Temporal stability** validated by >100M Hall plates in ANSI electricity meters since 1999 (class 0.2%)

Comparison high-mobility 3D *versus* QWHS Hall probes

Specs: **3D devices** **QWHS**

Sensor type	AREPOC LHP-Mx series	AREPOC HHP-Vx series	ITRON V50 series		
Magnetic field range	0 - 33	0-5	0-33	0-5	[T]
Temperature range	1.5 - 350	1.5 - 350	0.03 – 420 (450)		[K]
Intrinsic sensitivity K_H	0.25	2.5	700		[Ω/T]
Sheet carrier density n_S	2.5E+15	2.5E+14	9.0E+11		[cm-2]
Nom. biasing current I_N	20	10	0.07 - 0.14	0.28	[mA]
Sensitivity at I_N	> 5	>50	50 - 100	200	[mV/T]
Signal at nominal induction	> 165	> 250	1650	1000	mV
Offset resistance R_{offset} (3s)	0.005	0.020	0.7		[Ω]
Equivalent magnetic offset B_{offset} (3s)	20	8	1		[mT]
Input resistance R_{in} @ 300 K	4	60	3200		[Ω]
Dissipated power @300K, small B $P = R_{in}.I_N^2$	1.6	6	0.015-0.060	0.25	mW

Black: directly taken from specs

Blue: calculated from specs

Effect of offset:

$$V_{out} = V_H + V_{offset}$$

$$= K_H \cdot I_{in} \cdot B + R_{offset} \cdot I_{in}$$

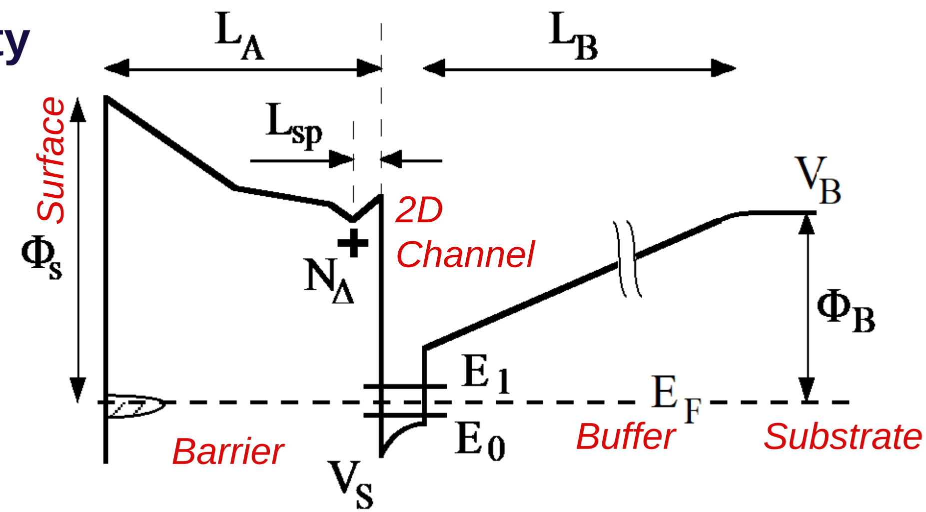
Equivalent magnetic offset

$$B_{offset} = R_{offset} / K_H$$

QWHS STRUCTURE: ANALYSIS OF THERMAL DRIFT

- **Thermal drift of the magnetic sensitivity**

$$\boxed{S_T \equiv \frac{1}{K_H}\times\frac{dK_H}{dT} = -\frac{1}{n_s}\times\frac{dn_s}{dT}}$$



By differentiating the V(z) equation:

$$\frac{dn_S}{dT} \approx \frac{\varepsilon_s}{e\,L_A}\times\left(\frac{d\Phi_s}{dT} - k_B f(n_s,T) + U_0\times\frac{1}{\varepsilon_s}\frac{d\varepsilon_s}{dT}\right) \qquad \text{with } U_0 \approx \Phi_s$$

Thermal drift of the surface barrier energy

Major contributor to S_T (85%)

2D Quantum effects

Permittivity variation with T

Small effects

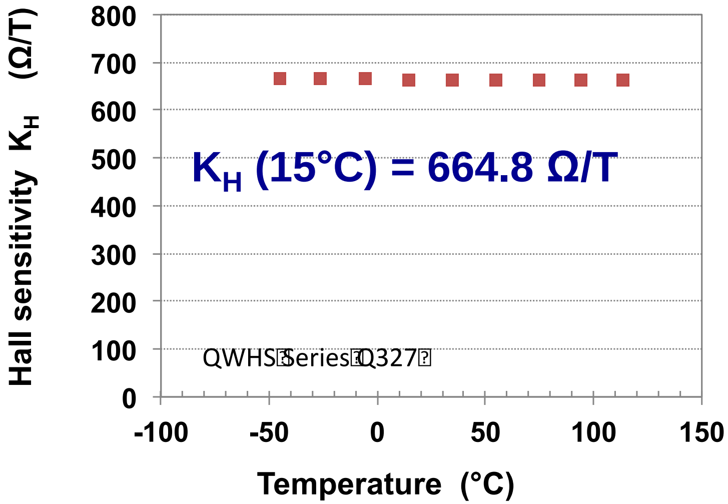
The thermal drift of the sensitivity is mostly controlled by the surface barrier energy

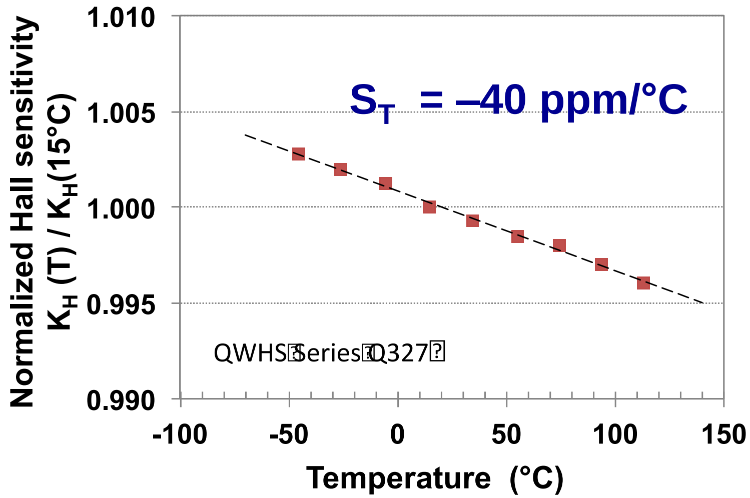
Farah Kobbi's PhD thesis 1996

QWHS Hall probe versus temperature

Hall sensitivity vs temperature

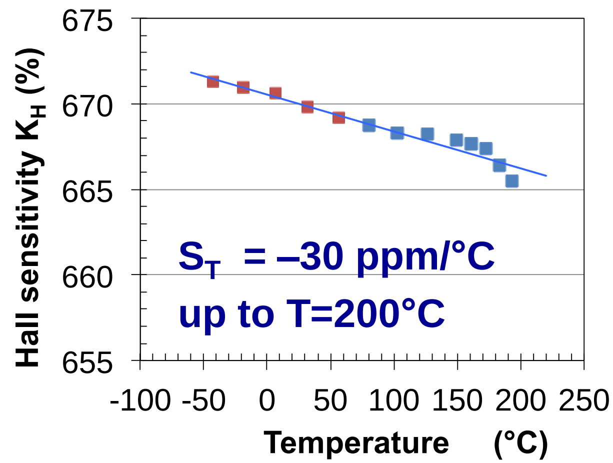
Thermal drift: -40+/-20 ppm/°C in the extended industrial temperature range





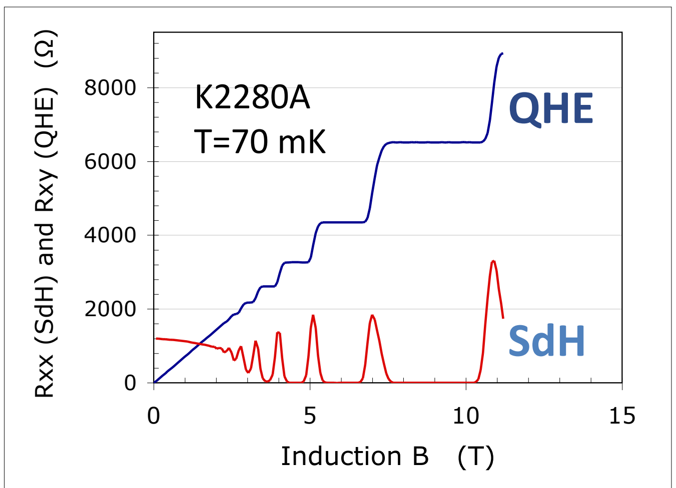
Temperature range

T_{max} at least 200° C when using a Hi-Res



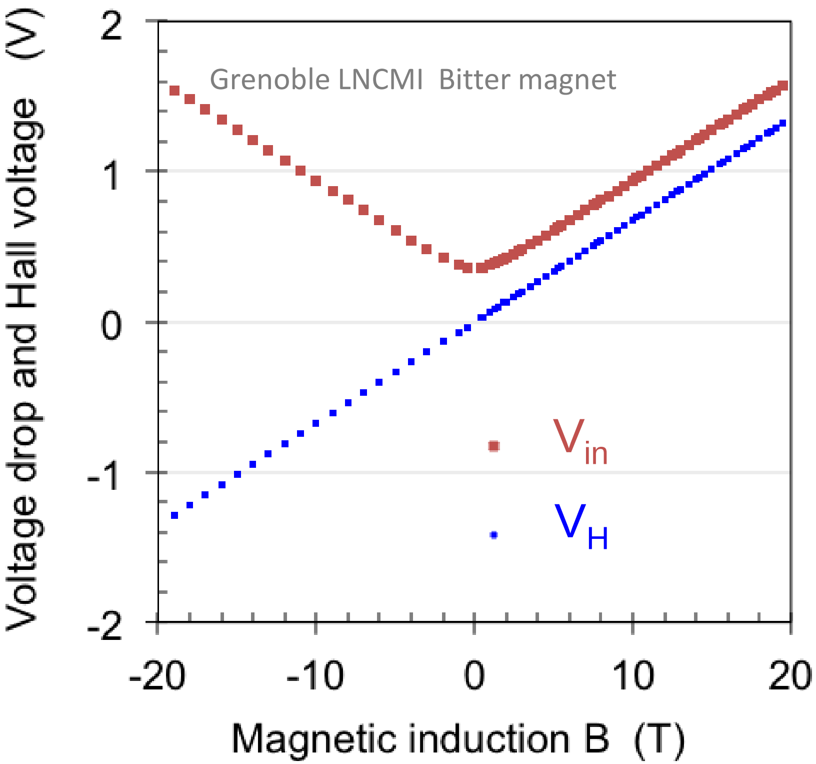
Operation demonstrated at 70 mK

Beware!
QHE at
high field



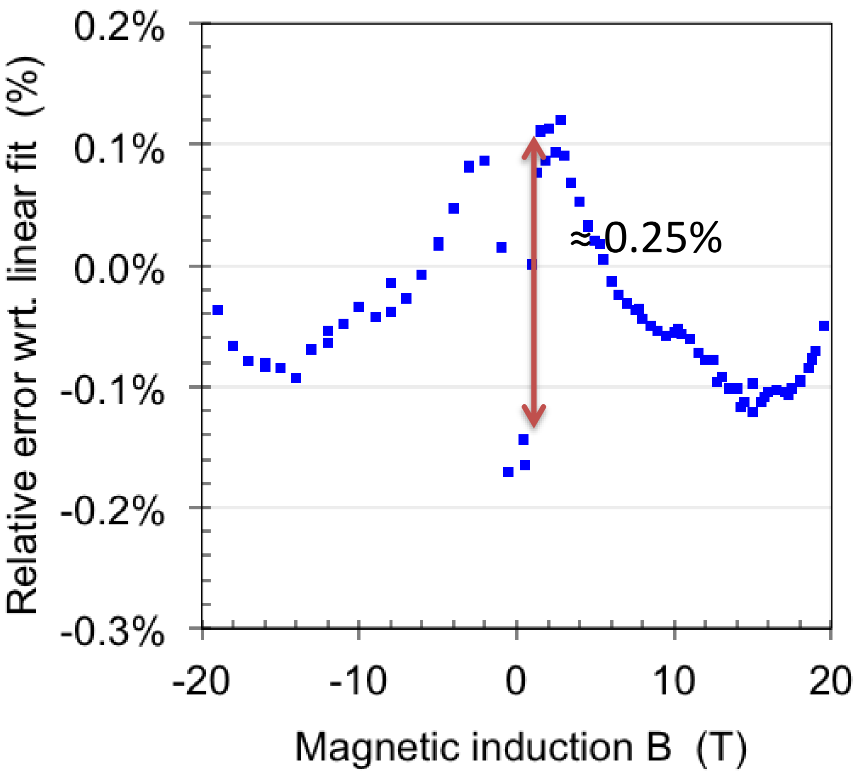
QWHS Hall probe at very high induction

Hall voltage and ohmic voltage drop



Experiment: 22T Bitter magnet, LNCMI Grenoble

Relative error vs. linear fit



I_{in} = 100 µA

Linear fit: K_H = 678.3 Ω/T

R_{offset} = -0.6 Ω

$$e = \frac{V_H^{exp} - V_H^{fit}}{V_H^{fit}}$$

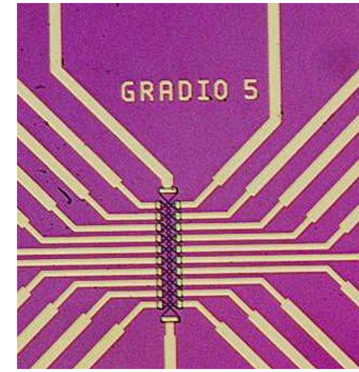
Linearity within ± 0.15% of the magnet calibration

QWHS for micromagnetometry

Hall based sensors: a broad range of device designs

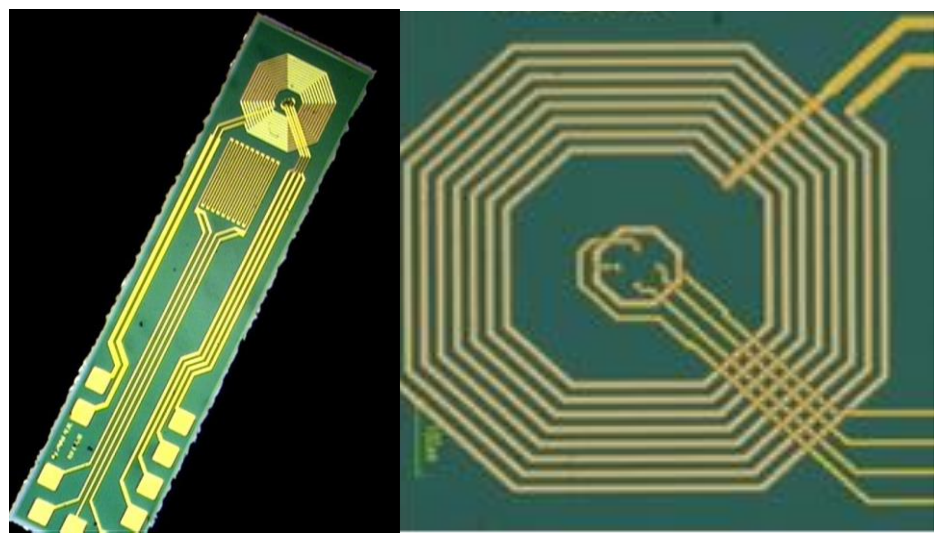
Various QWHS designs developed by ITRON and LSI

- Processed at Thales R&T (S. Xavier/ J. Cholet / Raphaël Aubry)
- Optical lithography – finest structures in the µm range –
  3 metal levels for interconnections
- HTC superconductors, microbead detection, characterization
  of microstructured magnets, Scanning Hall Probe Microscopy, etc …



Hall array
T.Klein et al,
*PRL **105**, 047001 (2010)*

Scanning magnetometer



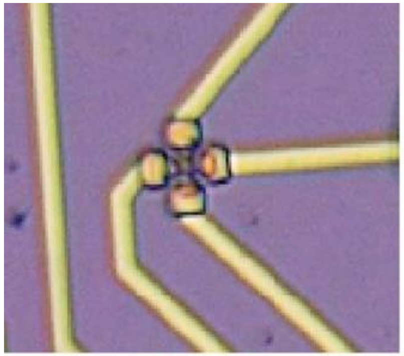
On chip Hall sensor based AC susceptometer
*MI Dolz et al, Phys. Rev. Lett. **115**, 137003 (2015)*

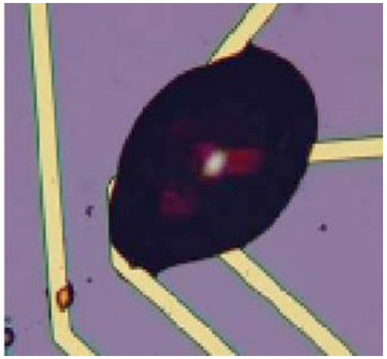
QWHS for micromagnetometry

Hall based sensors: a broad range of device designs

QWHS Hall plate
with 2µm nominal size for
investigating the violation
of the FDT theorem in
ferrofluids

Komatsu et al.,
PRL ***106****, 150603 (2011)*

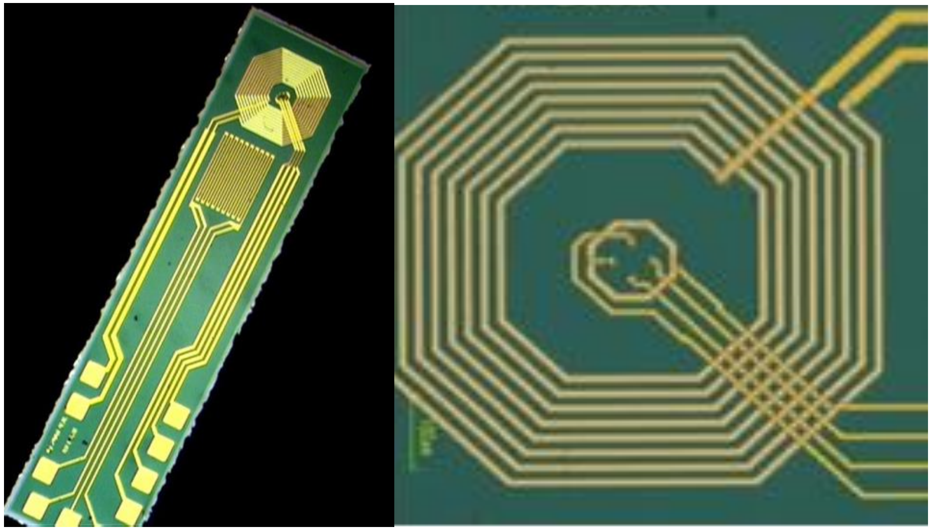




...

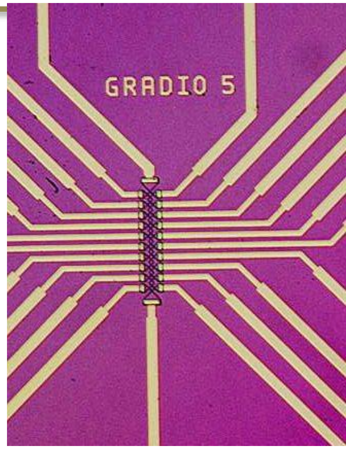
Hall array
T.Klein et al,
PRL ***105****, 047001 (2010)*

Scanning magnetometer



On chip Hall sensor based AC susceptometer
MI Dolz et al, Phys. Rev. Lett. ***115****, 137003 (2015)*

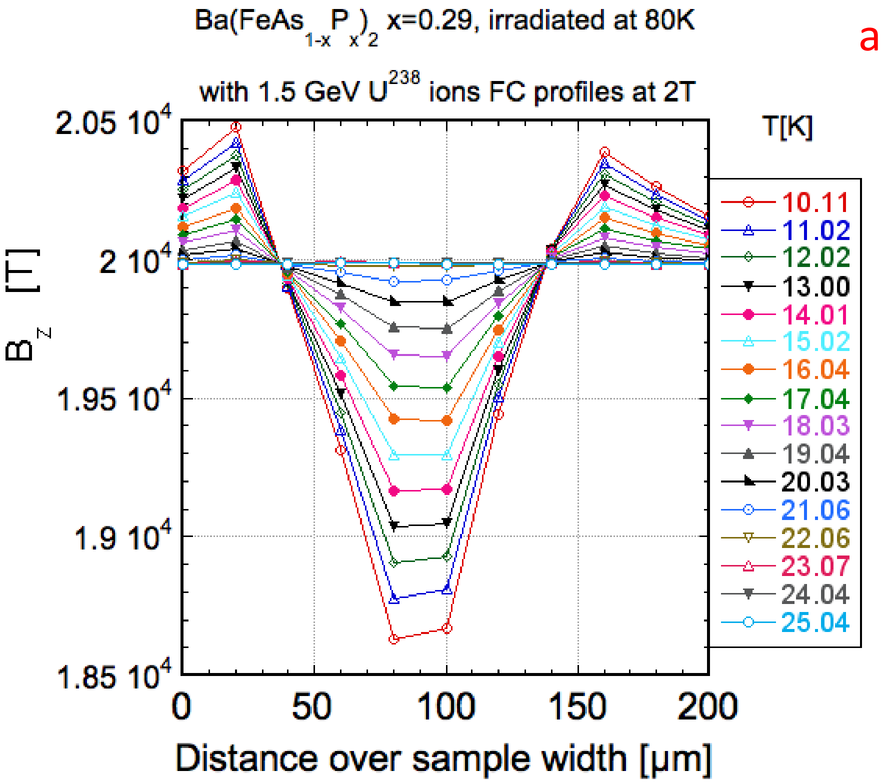
Recent high-field applications of QWHS -1-

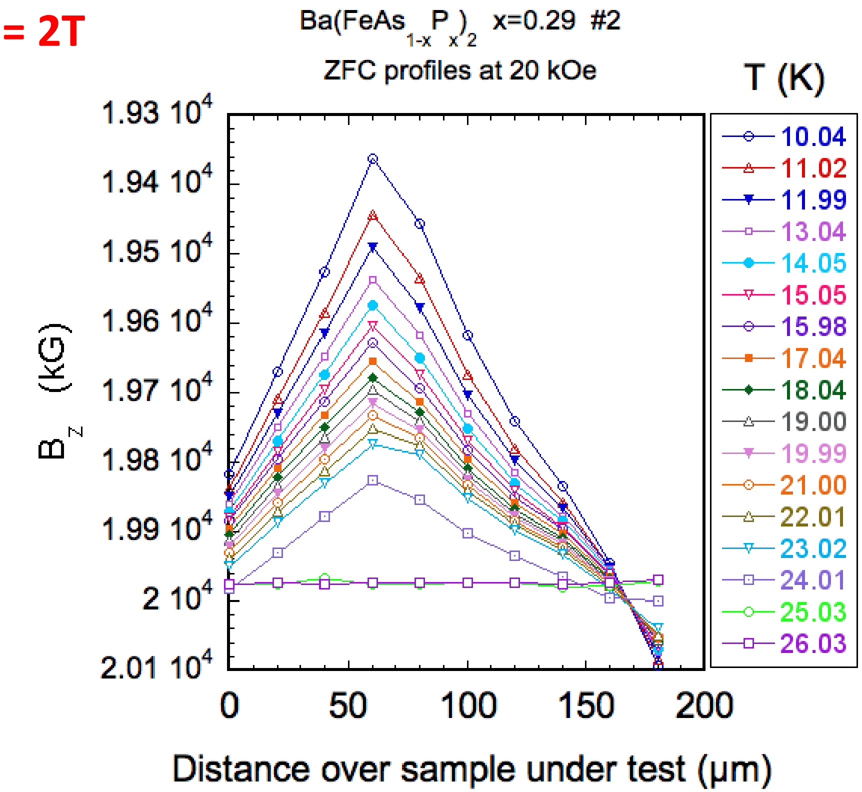


Investigation of topological superconductivity in substituted Iron Pnictides

- BFAP: $Ba(FeAs_{1-x}P_x)_2$ (*Courtesy M. Konczykowski, LSI, Polytechnique*)
- Needs sensitivity matching and stability in 4µm wide Hall array in the 0-2T range

Measurements around **B = 2T**

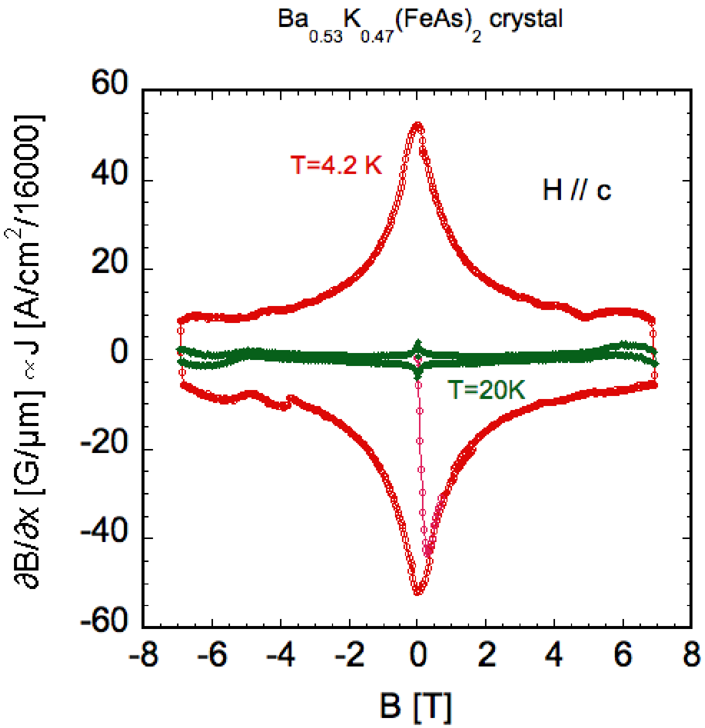


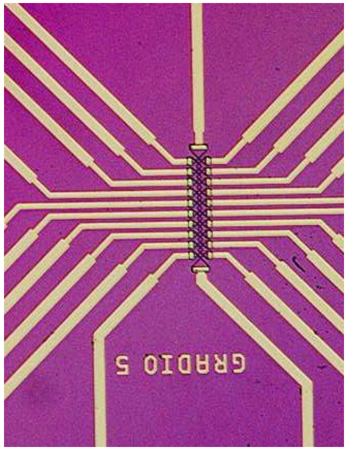


Investigation of topological superconductivity in substituted Iron Pnictides

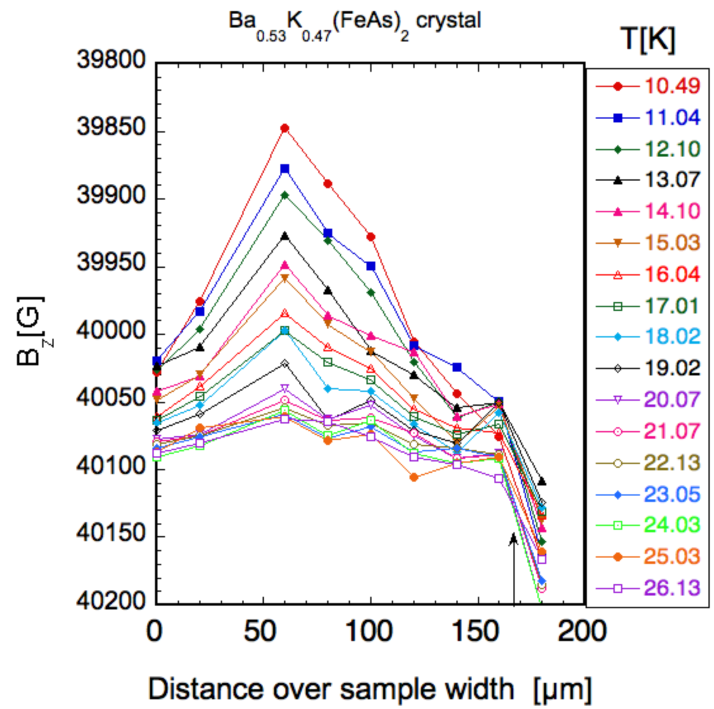
- BKFA: $Ba_xK_{1-x}(FeAs)_2$ (*Courtesy M. Konczykowski, LSI Polytechnique*)
- Needs sensitivity matching and stability in 4µm wide Hall array in the 0-8T range

Magnetic field cycles **-8T – +8T**





Fine measurements around **B = 4T**



Basic quantities involved in the description of Hall plates

Basic quantities

- Sheet electron density (2D device) n_S ***intrinsic 2DEG density***
- Sheet electron density (3D device) $n_S = n_{3D} \times t$ ***3D electron density x thickness***
- Electron mobility $(v_d = \mu_n \cdot F)$ μ_n ***depends on material, doping, temperature, …***

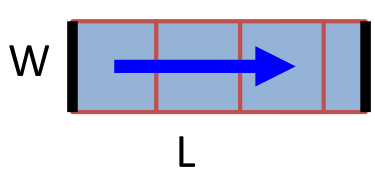
- Intrinsic Hall cross-sensitivity $K_{H0} = 1 / e\, n_S$, unit = Ω / T
- Output sensitivity $V_{H0} / B = K_{H0} \cdot I_{bias}$ unit = V / T

- 2D resistivity / resistance per square $R_{sq} = 1 / (e n_S \cdot \mu_n) = K_H / \mu_n$
- Input or output resistance $R_{in} = G_R \cdot R_{sq}$

(Planar devices)

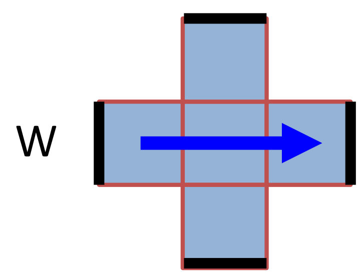
- **Rectangular device:**

G_R = L/W = # of squares N



L/W = 3.5

- **Non rectangular device:** Effective # of squares:



N = L/W = 3 but

G_R =(L/W)* ≈ 2.72 < 3

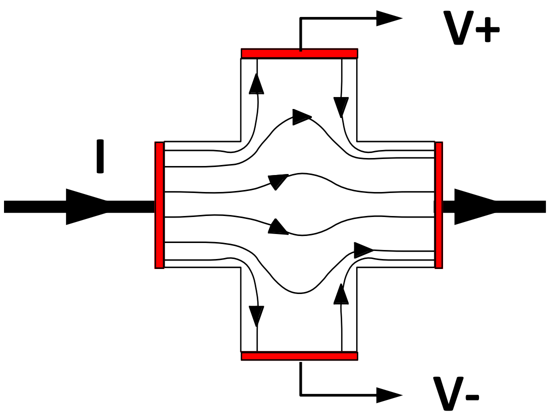
Geometry of Hall plates for high-field measurements

Origin of the geometric factor

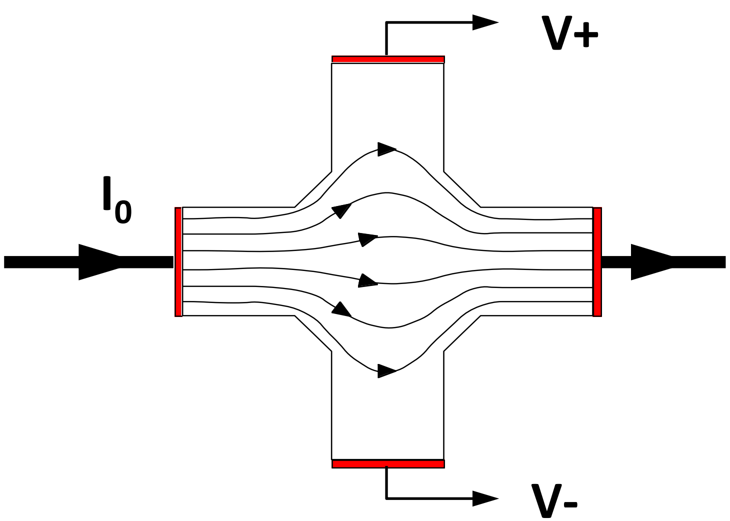
- **Short channel device (L/W = 2.5, $G_R \approx 2.2$):**
  the active zone is shunted
  by the lateral contacts ! $G_H \approx 0.90$

  Side effects

  - Non-linearity when B large
  - Increased noise

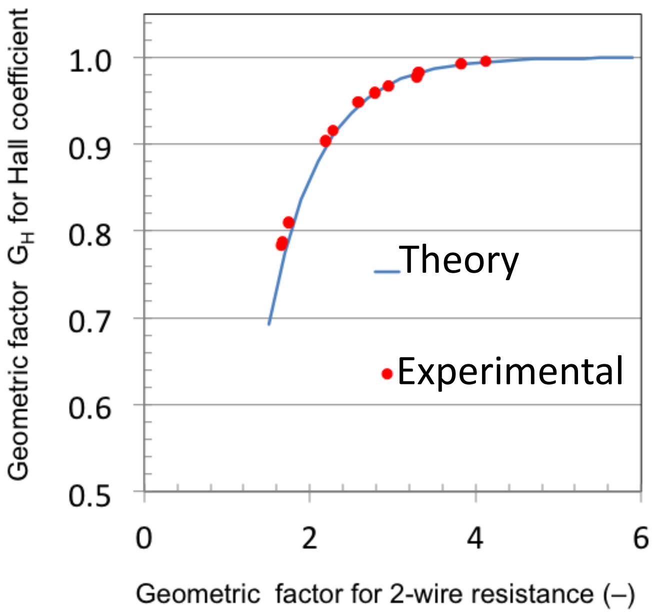


- **Long channel (L/W=4.5, G_R =4)**
  - Geometric factor G_H=0.99
  - Better linearity

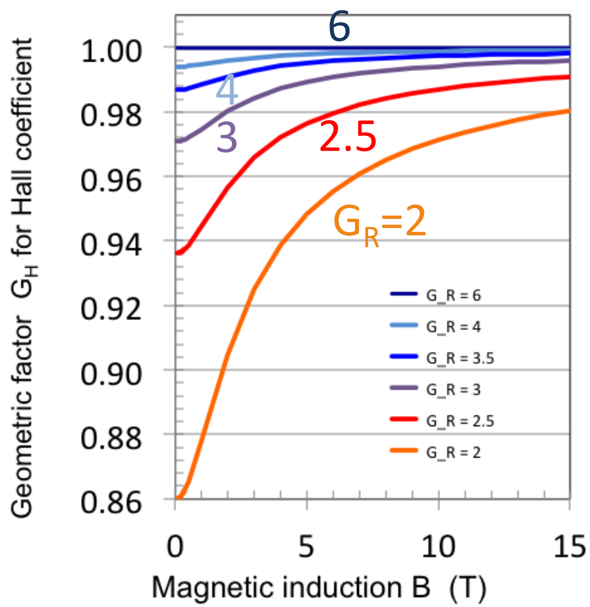


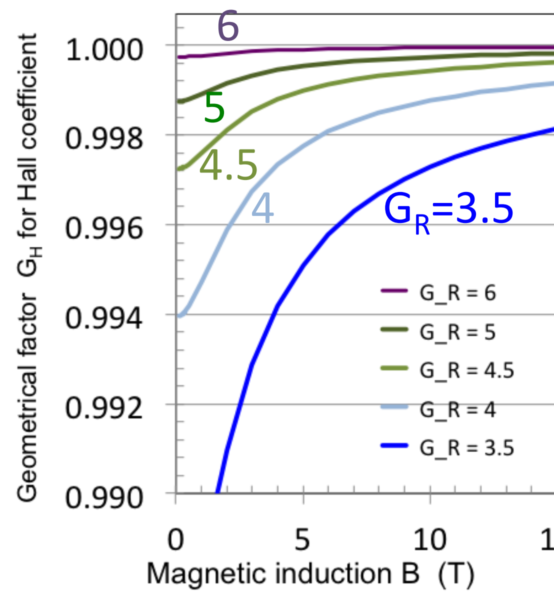
Geometry of Hall plates for high-field measurements

- If the aspect ratio $\mathbf{G_R = R_{in} / R_{sq}}$ of the Hall plate is too low (arms too short), then a geometric factor G_H appears in the Hall factor: $\mathbf{K_H = G_H \cdot K_{H0}} = G_H / e n_{S0}$
- The geometric factor of the resistance (aspect ratio) should be kept large: $G_R \geq 4$, so that G_H remains very close to 1
- Otherwise the geometric factor G_H for the Hall sensitivity would become dependent on B: $\mathbf{K_H = G_H(B) \cdot K_{H0}}$



Geometric factors: G_H *vs* G_R
for devices with 4-fold symmetry





Hall geometric factor G_H (B) for various G_R values

Spinning Current Modulation Technique

Linked to *time-reversal invariance* of electromagnetism → microscopic reversibility

Onsager: symmetry of transport coefficients (*resistivity tensor, piezoresistivity tensor, etc.*)

Macroscopic reversibility in a 4-contact device

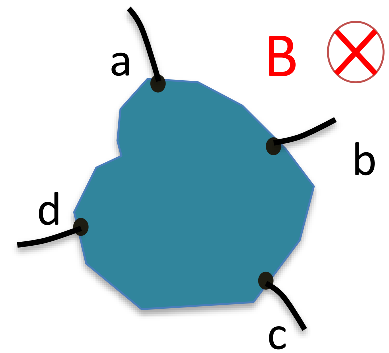
- Permutation of bias and sense:

Assumes that the magnetic field *B* is reversed in the operation (odd vector)

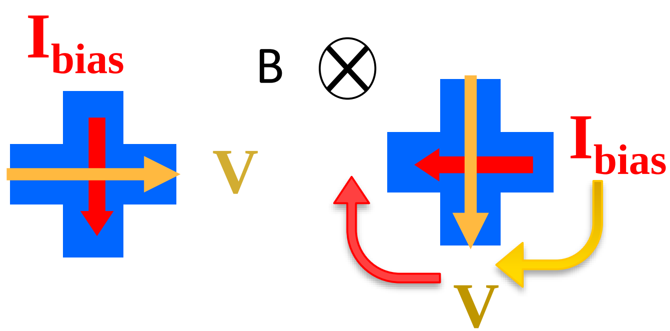
Sample et al., JAP 61, 1079 (1987)

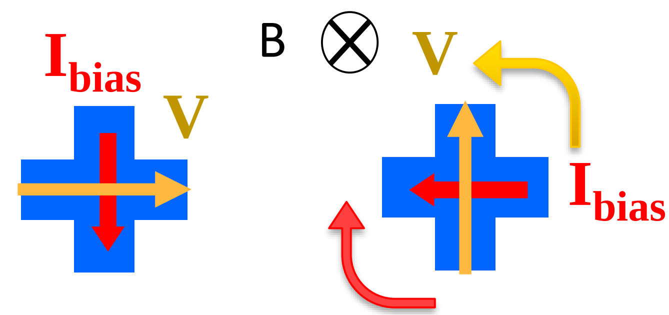
$$R_{ac,\,bd} \propto \frac{V_{bd}}{I_{ac}}$$

$$\boxed{R_{ac,\,bd} = R_{bd,\,ac}}$$



For practical purposes:





- True rotation of biasing and sensing contacts:

$V_{Hall} \rightarrow V_{Hall}$

$V_{offset} \rightarrow -V_{offset}$

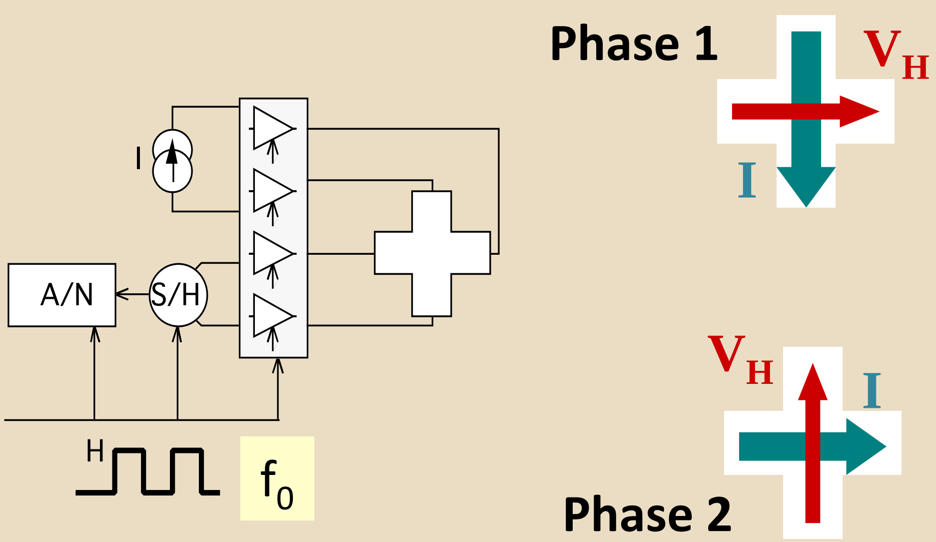
- Antirotation of biasing and sensing contacts

$V_{Hall} \rightarrow -V_{Hall}$

$V_{offset} \rightarrow V_{offset}$

Spinning current method for LF-noise and offset suppression

Basic 2 phase spinning current method



•Offset suppression:

$$V_{out\,1} = K_H I\ B + R_{offset} I$$
$$V_{out\,2} = K_H I\ B - R_{offset} I$$

•LF noise suppression:

$$V_{out\,1} = K_H I\ B + R_{offset} I + r_n\ I + v_n^{th}$$
$$V_{out\,2} = K_H I\ B - R_{offset} I - r_n\ I + v'^{th}_n$$

•Principle of offset suppression in Hall measurements

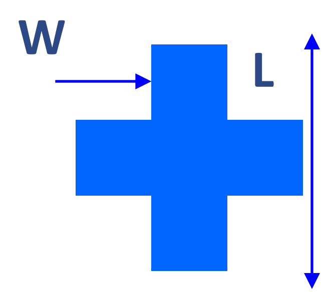
L. Van der Pauw (1958)

•Cancellation of LF noise of Hall sensors

Z. Stoessel and Markus Resch,

Sensors and Actuators **A37-38,** 449 (1993)

• Remained unnoticed for over 10 years



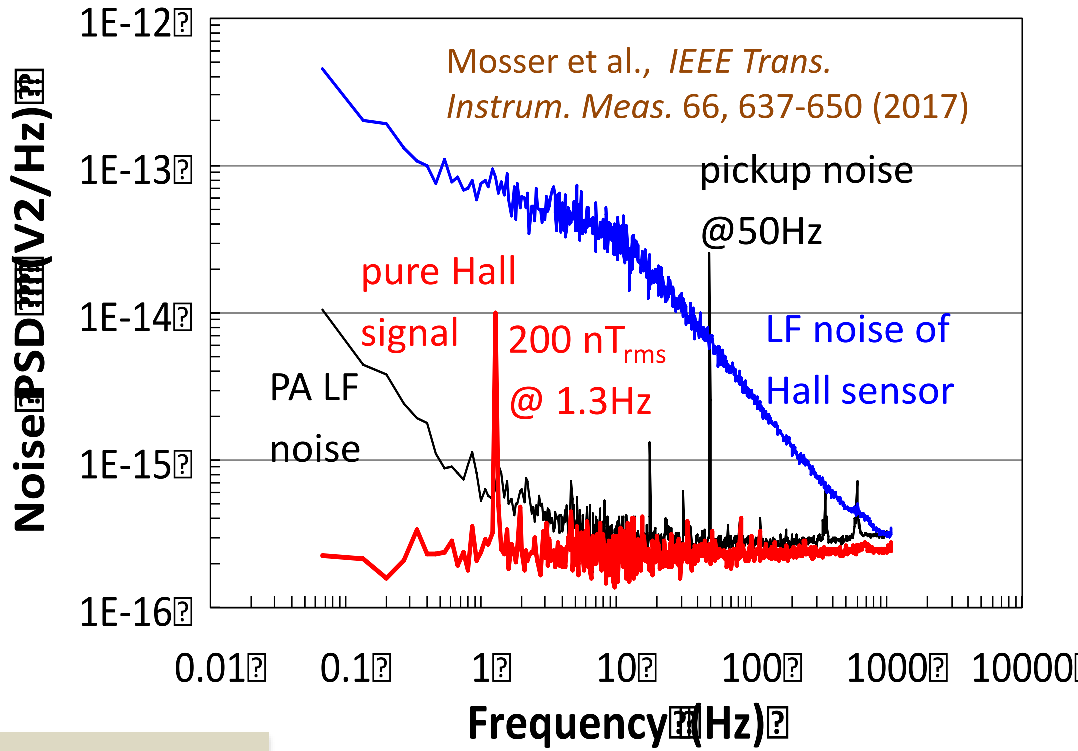
Consequence:

- **Design Hall device with fourfold symmetry (e.g. Greek cross)**

The Spinning Current Modulation Technique (SCMT) -1-

WHAT SCMT DOES

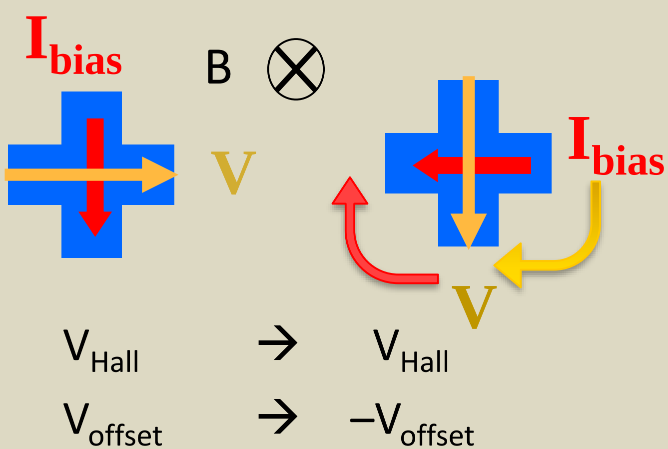
- SCMT effectively cancels the **offset** and **LF noise** of **Hall sensors**
- Also eliminates the **noise and offset of the whole acquisition chain** (amplifier, interconnects)
- Real-time, broadband



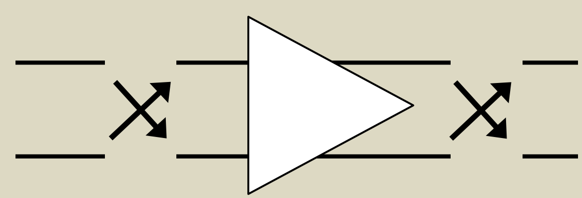
HOW SCMT WORKS

- **A combination of 2 principles:**

1. Reverse Magnetic Field Reversibility (RMFR)



2. Chopped amplifier for offset suppression



The Spinning Current Modulation Technique (SCMT) -2-

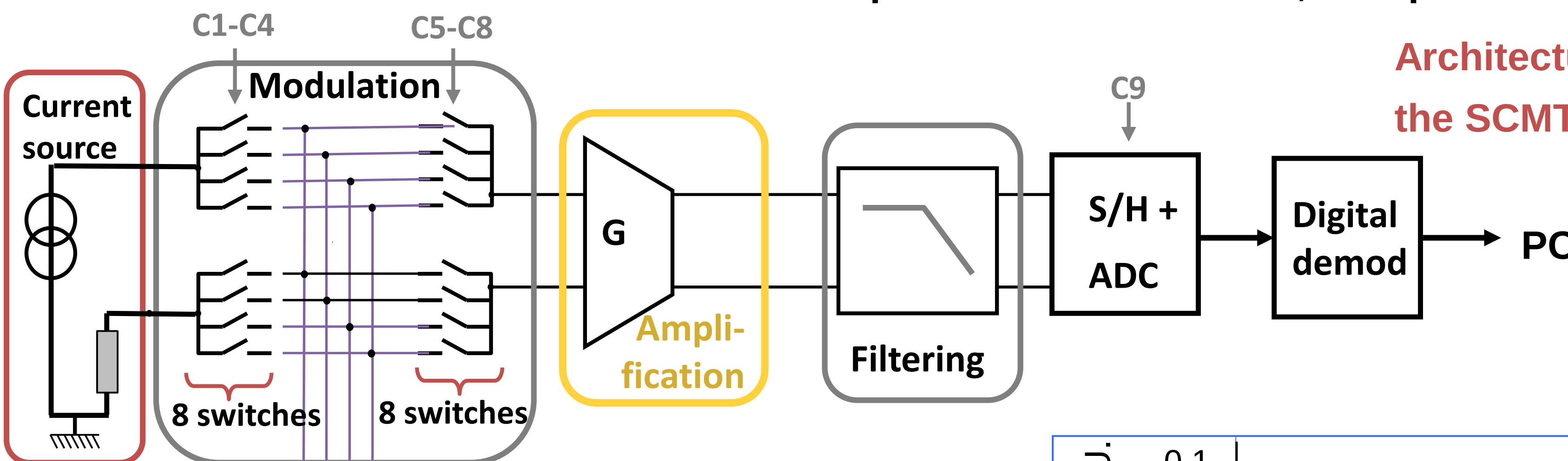
Output signal:

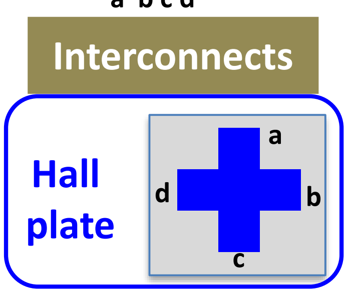
$$V_{out} = G \times \left(V_H + \boxed{V_{offset}^{Hall}} + \boxed{V_{offset}^{PA}} + \boxed{e_{th}} + \boxed{V_{ind}} + \boxed{v_{LF}^{Hall}} + \boxed{v_{LF}^{PA}} + v_{th} \right)$$

HALL PLATE PREAMPLIFIER INTERCONNECTS

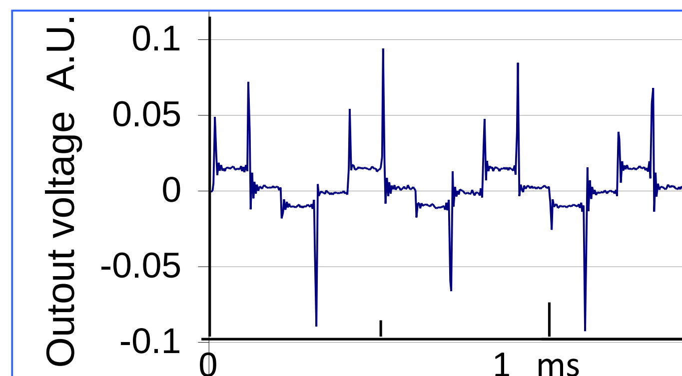
SCMT principle: - By combining 4 successive different configurations, one can suppress all parasitic contributions, excepted thermal noise

Architecture of the SCMT circuit

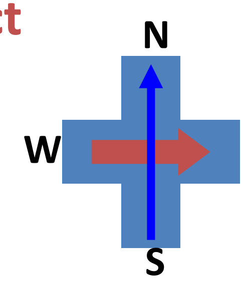




The analog signal before A-to-D conversion



Spinning current circuitry: induced e.m.f. and thermoelectric effect



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$$V_{emf}^{NS} = -\left.\frac{d\Phi}{dt}\right|_{NS}$$

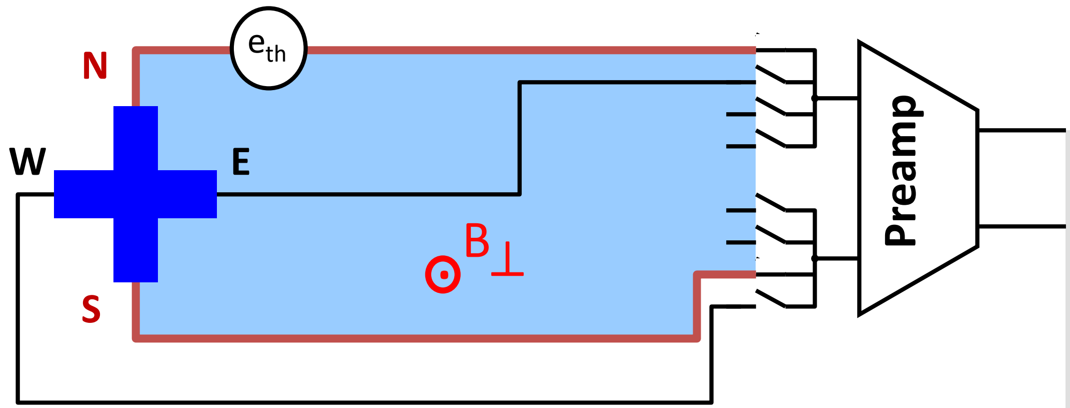
$$= \iint_{area\ NS} \frac{dB}{dt}\, ds$$

Induced e.m.f.

$$V_{emf}^{EW} = -\left.\frac{d\Phi}{dt}\right|_{EW}$$

$$= \iint_{area\ EW} \frac{dB}{dt}\, ds$$

Voltage sense connected to branch NS

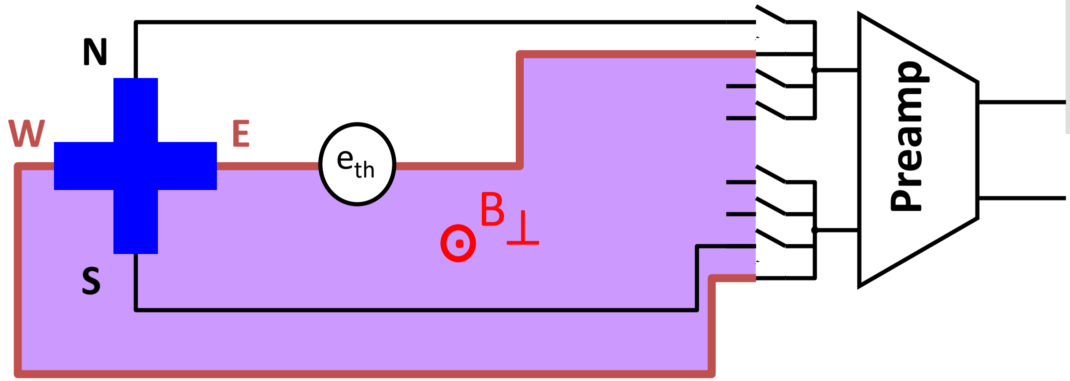


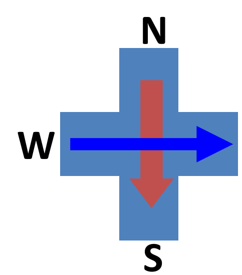
in branch **NS**: e_{th}^{NS}

Thermoelectric effect

in branch **EW**: e_{th}^{EW}

Voltage sense connected to branch EW





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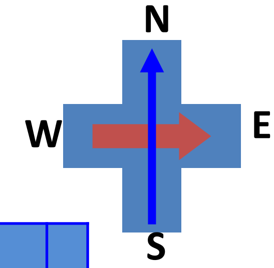
Hall effect measurement: spinning sequence

- **Basic:** canceling **offset** and **LF noise** from **Hall sensor** and **preamp**
- **Advanced:** canceling the **pickup noise** and **thermoelectric effect**



					Hall device		Circuit			
Config #	I+	I-	V+	V-	Hall signal	Hall offset + LFN	Preamp offset + LFN	$\frac{d\Phi}{dt}$	e_{th}	DEM
1	N	S	E	W	+	+	+	$+V_{EW}$	$+e_{EW}$	+1
2	E	W	S	N	+	–	+	$-V_{NS}$	$-e_{NS}$	+1
3	S	N	W	E	+	+	+	$-V_{EW}$	$-e_{EW}$	+1
4	W	E	N	S	+	–	+	$+V_{NS}$	$+e_{NS}$	+1
5	N	S	W	E	–	–	+	$-V_{EW}$	$-e_{EW}$	–1
6	E	W	N	S	–	+	+	$+V_{NS}$	$+e_{NS}$	–1
7	S	N	E	W	–	–	+	$+V_{EW}$	$+e_{EW}$	–1
8	W	E	S	N	–	+	+	$-V_{NS}$	$-e_{NS}$	–1

Suitable sequences

1278
1368
1467
2358
2457
3456

4-phase modulation: choose 2 states among #1-#4 and 2 states among #5-#8

Spinning current modulation

- **Optimized spinning sequence 1278 + demodulation +1/+1/-1/-1**

					After spinning					After demodulation			
Config #	I+	I-	V+	V-	Hall signal	Hall offset + LF noise	PA offset + LF noise	Pickup noise	DEMOD	Hall signal	Hall offset + LF noise	PA offset + LF noise	Pickup noise
1	N	S	E	W	+	+	+	$+V_{EW}$	+1	+	+	+	$+V_{EW}$
2	E	W	S	N	+	–	+	$-V_{NS}$	+1	+	–	+	$-V_{NS}$
7	S	N	E	W	–	–	+	$+V_{EW}$	-1	+	+	–	$-V_{EW}$
8	W	E	S	N	–	+	+	$-V_{NS}$	-1	+	–	–	$+V_{NS}$

Summation for 4 phases: $4\ V_H$ 0 0 0

The offset and LF noise of the Hall sensor,
the offset and LF noise of the preamplifier,
the pickup noise and thermoeffect from the interconnects

are expected to be canceled

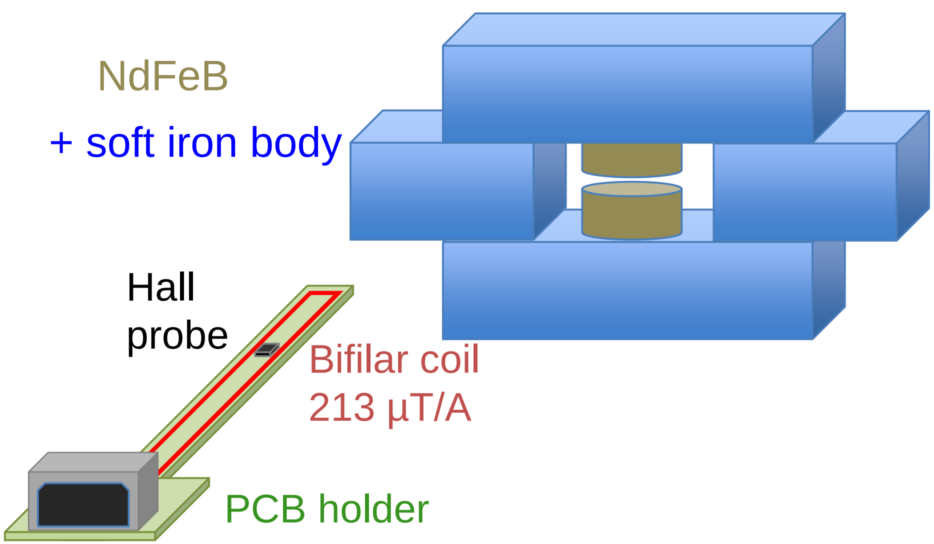
Resolution of Hall microsystem at high field -1-

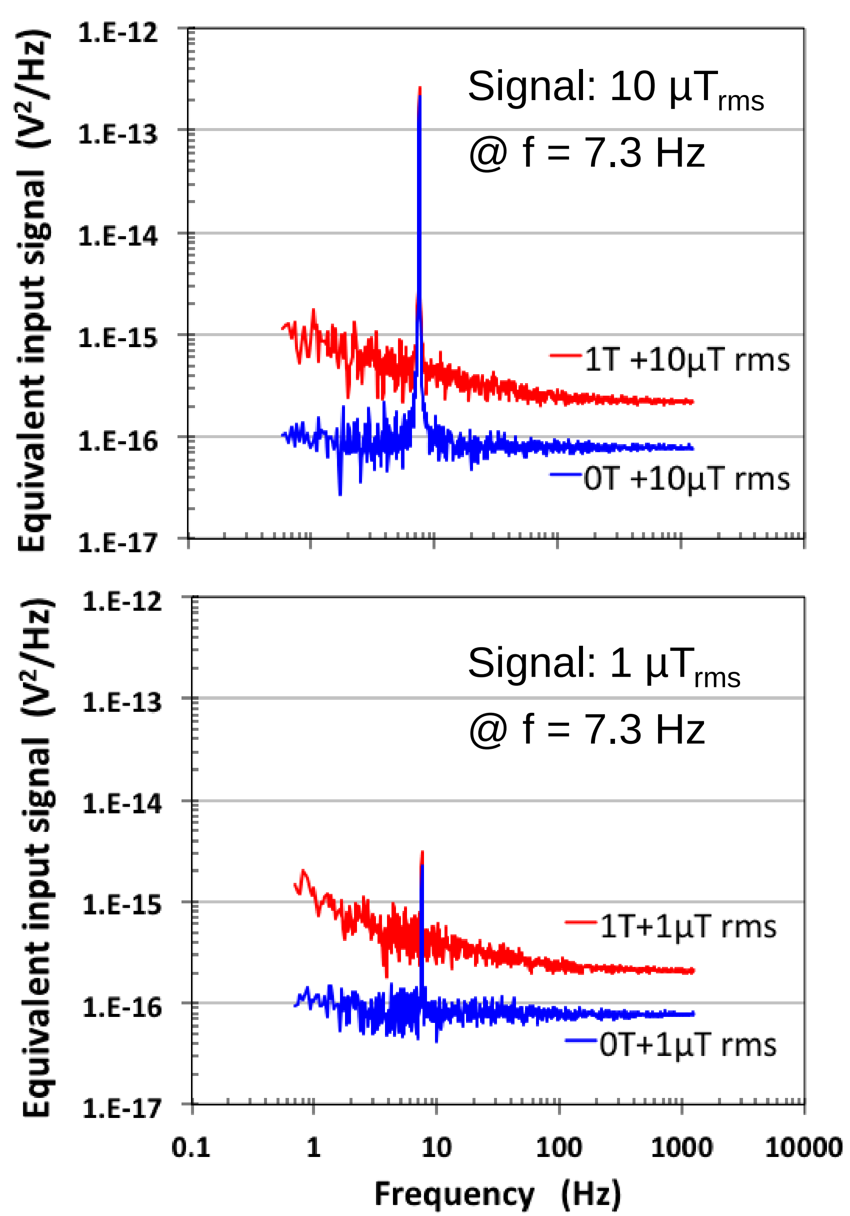
- **Microsystem Hall sensor head + acquisition board including SCMT (spinning current)**

  $K_H.I_{in}$ ≈ 0.095 V/T
  G_{analog} = 10 / G_{dig} = 4
  Full Scale = ±6 T
  Resolution 170 nT @ B_{DC} = 0 T
  500 nT @ B_{DC} = 1 T

- **Magnetic field source:**

  Permanent magnet 1T + bifilar coil





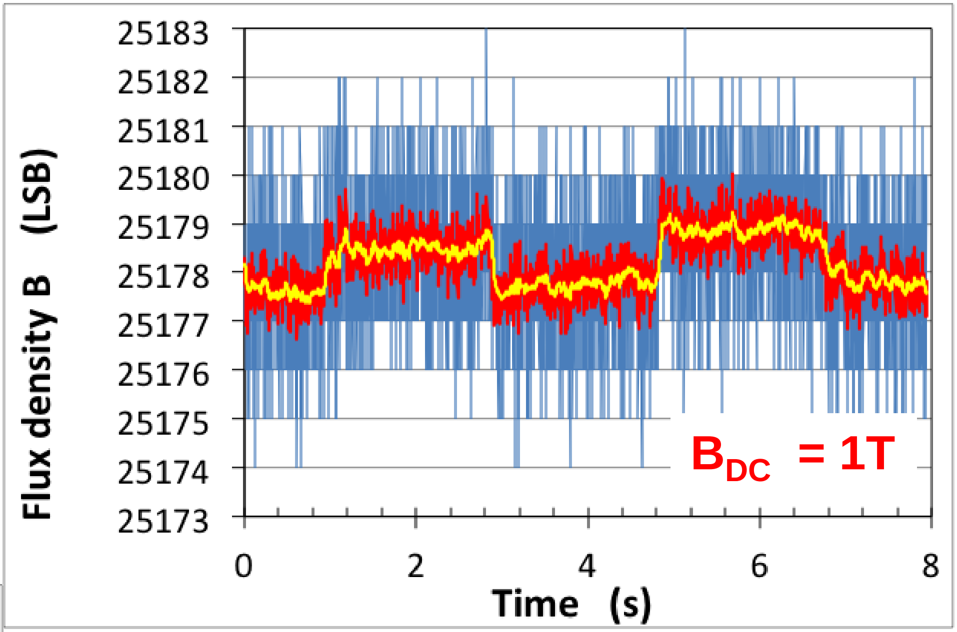
Resolution of Hall microsystem at high field -2-

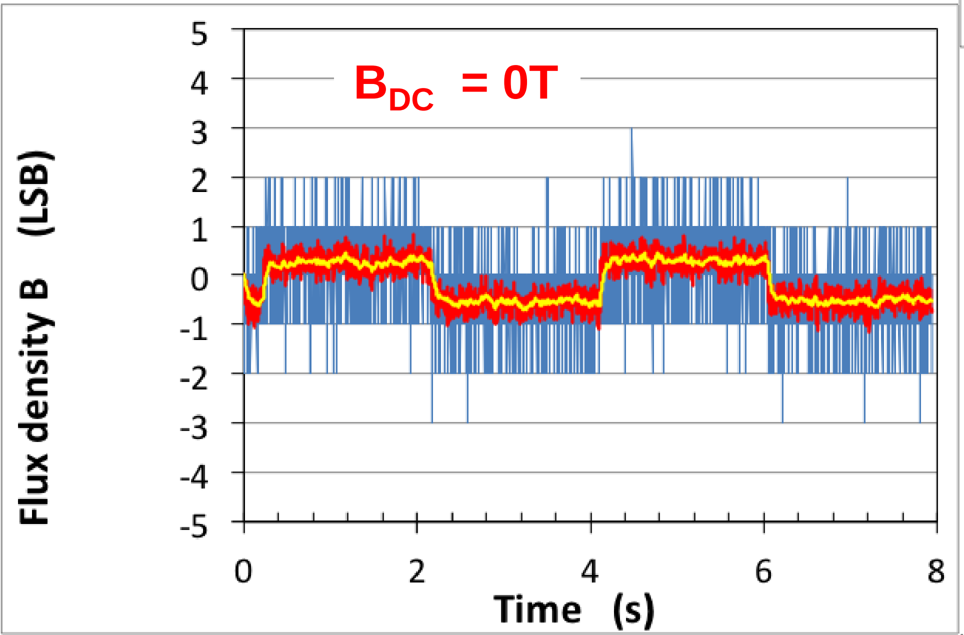
- **In the time domain:**

B_{AC} = square wave 30 µ$T_{p\text{-}p}$

Acquisition 10ks/s+ digital filtering

Blue	raw data	(f_S = 2500 Hz)
Red	t_C = 4 ms	
Yellow	t_C = 40 ms	





System characteristics:

$K_H.I_{in}$ ≈ 0.095 V/T

G_{analog} = 10 / G_{dig} = 4

1 LSB ≈ 35 µT

Full Scale = ±6 T

- **Resolution much better than 1 LSB thanks to the dither effect**
- **More noise at B =1T**

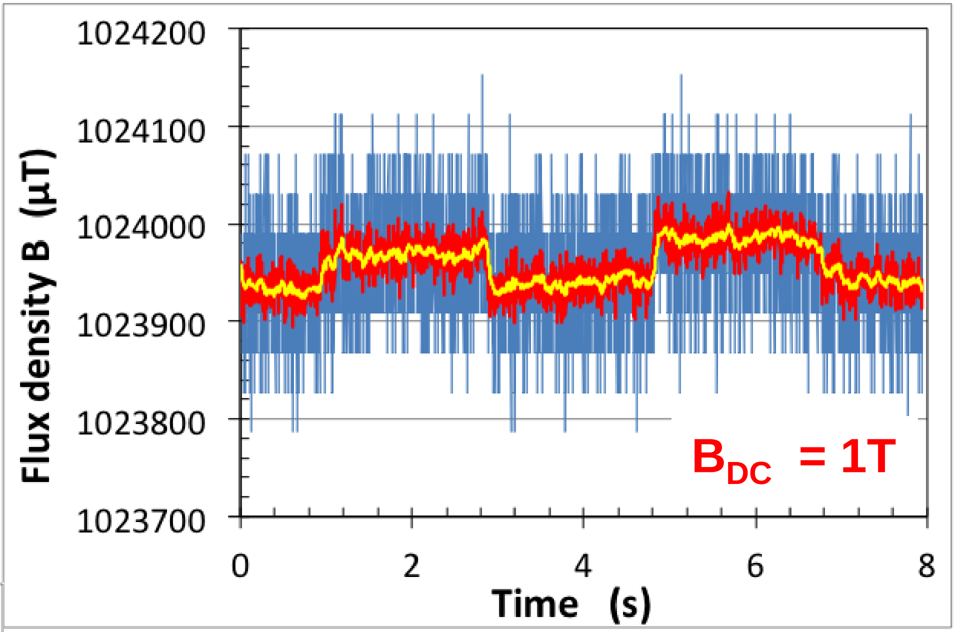
Resolution of Hall microsystem at high field -3-

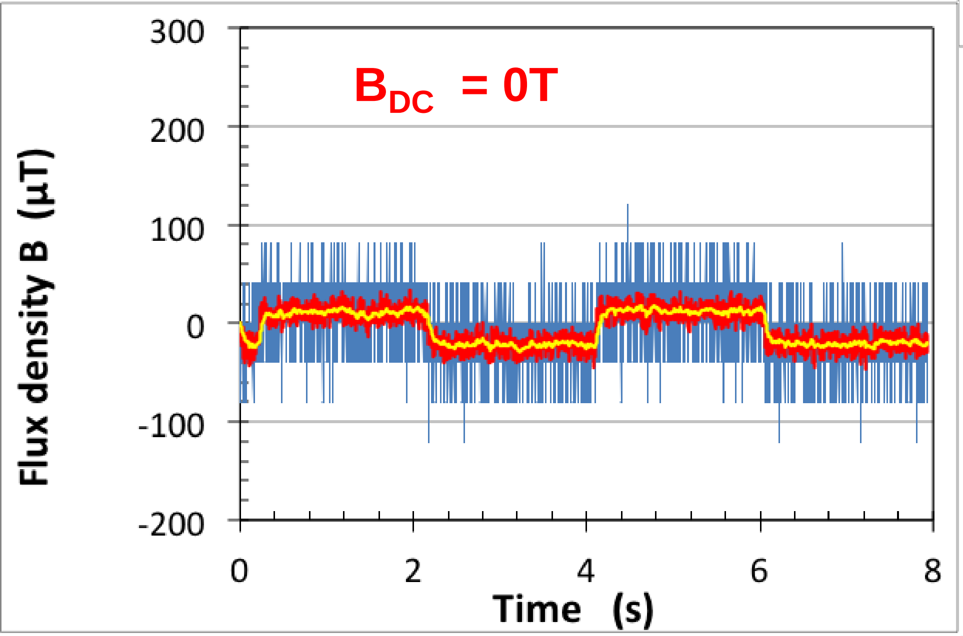
- **In the time domain:**

  B_{AC} = square wave 30 µ$T_{p\text{-}p}$

  Acquisition 10ks/s+ digital filtering

Blue	raw data	(f_S = 2500 Hz)
Red	t_C = 4 ms	
Yellow	t_C = 40 ms	





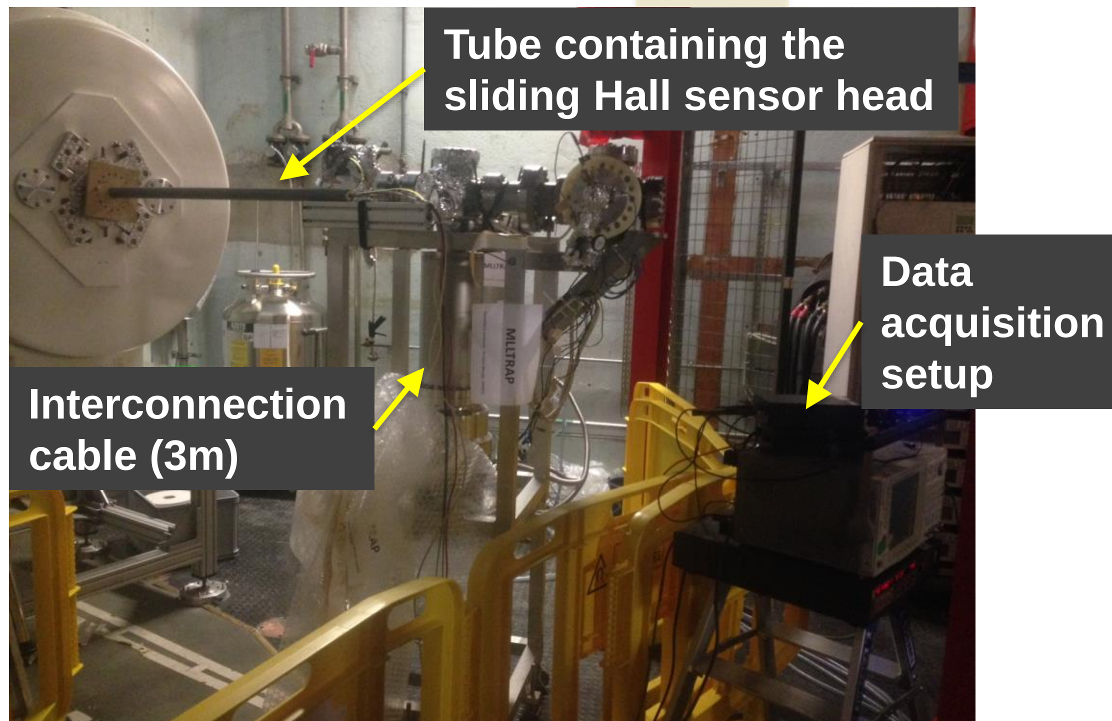
- Full Scale = ±6 T
- The mean signal at B_{DC} = 0 T
  is about -20 µT,
  due to the orthogonal component
  of the earth magnetic field
- Residual offset / Full Scale
  at most in the ppm range

Magnetic field profiling of a 7T Penning trap

Goal:

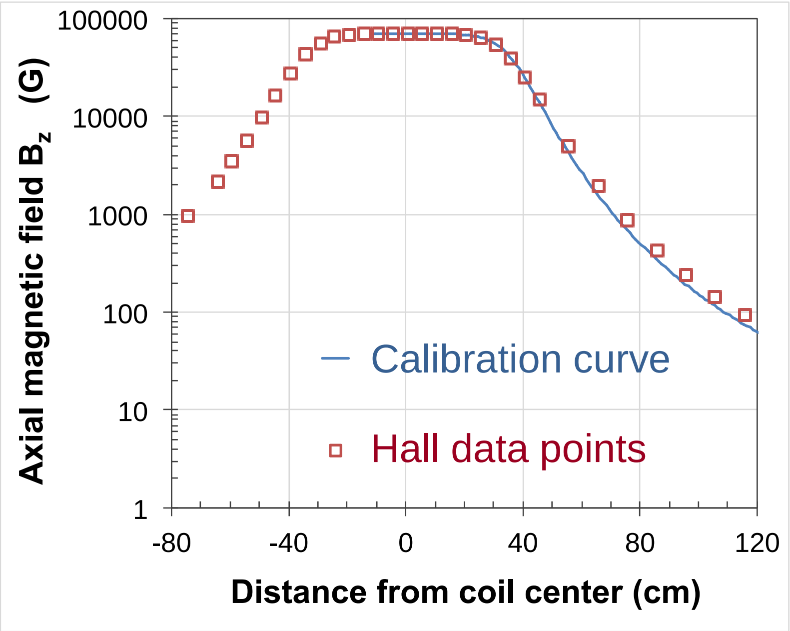
- Profiling the magnetic field along the axis of the MLL-trap superconducting magnet at IPN.
- Penning Trap using a superconducting magnet (Magnex Scientific) in the persistent mode

  Freely accessible cylindrical cavity along the magnet axis (diam. 10 cm)
  - with highly homogenous magnetic field in a 40 cm long region in the magnet center,
  - and decaying magnetic field along the magnet axis

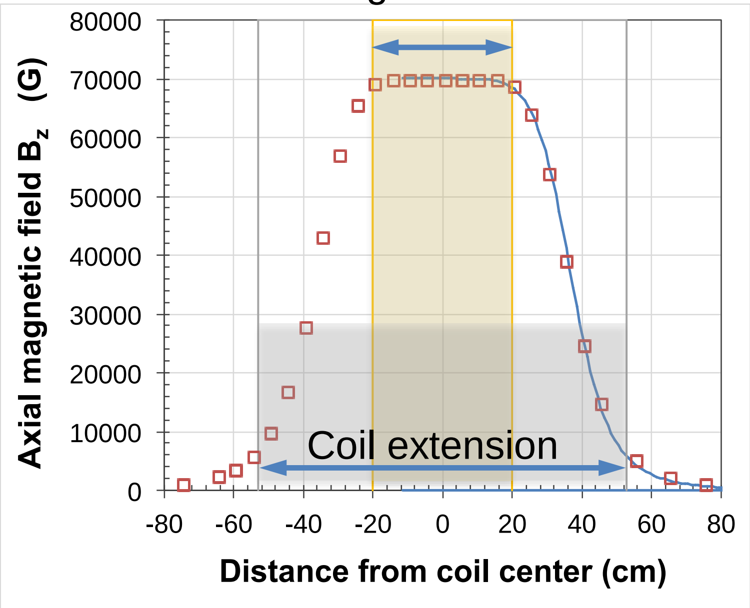


Magnetic field profiling of a 7T Penning trap

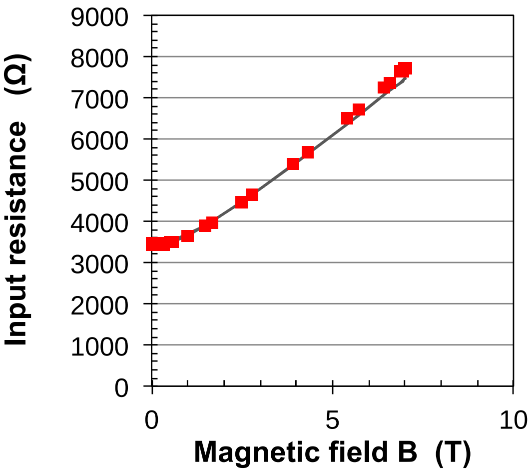
Magnetic field profile along the magnet axis



400 mm highly homogenous zone



- QWHS Hall plate calibrated around 0.5T using a NMR regulated electromagnet
- B found to be 7.006 T in the plateau region, in close agreement with the calibration curve from the provider
- Stray field determined along the magnet axis

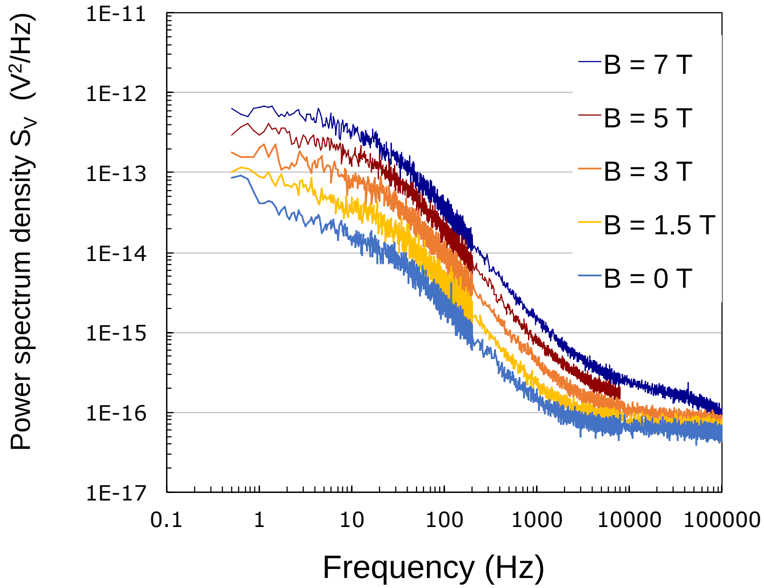


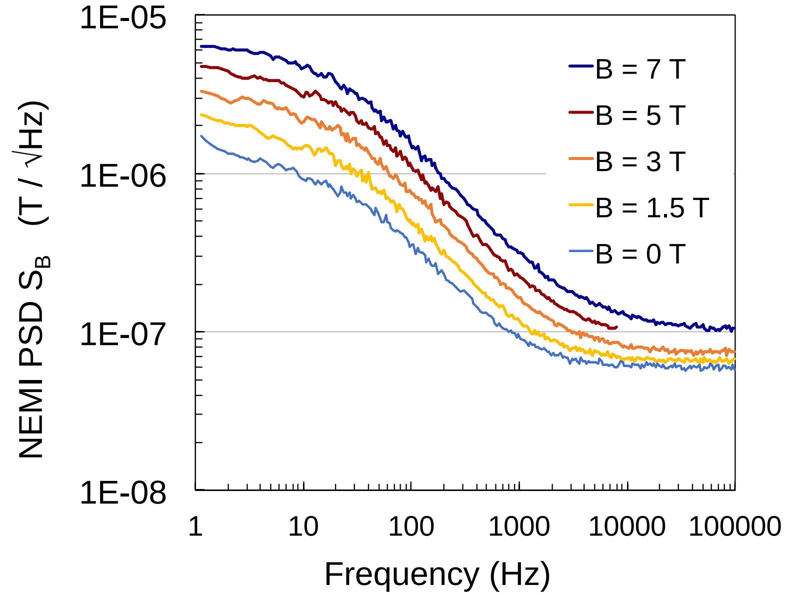
Input resistance vs magnetic induction

Hall sensor noise at high induction

Rationale

Use the noiseless stray magnetic field in order to characterize the sensor noise between 0 and 7T.





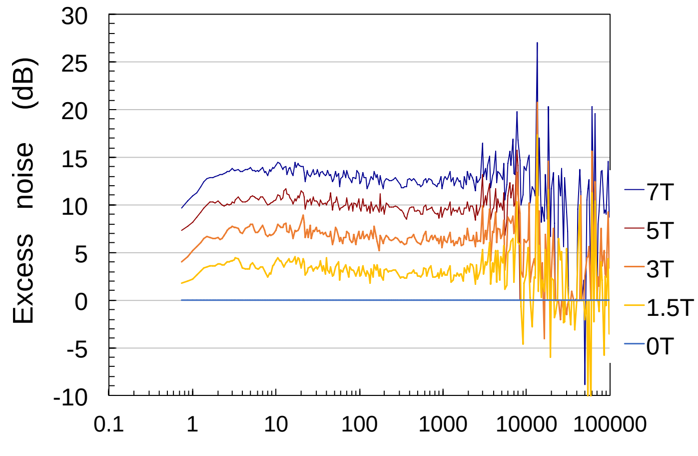
Raw noise spectra
from Fourier transform analyzer

Resulting noise equivalent magnetic induction (NEMI) spectra

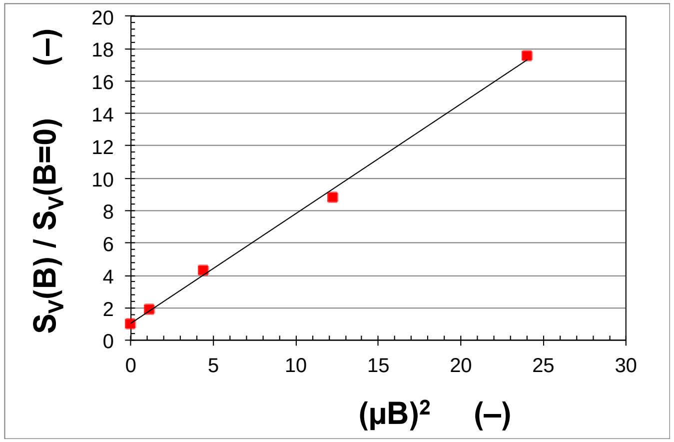
- Eliminate duplicate data
- Data smoothing
- Deembedding of parasitic impedance (C_{cable} = 180 pF)

Hall sensor noise at high induction

Noise PSD vs magnetic induction

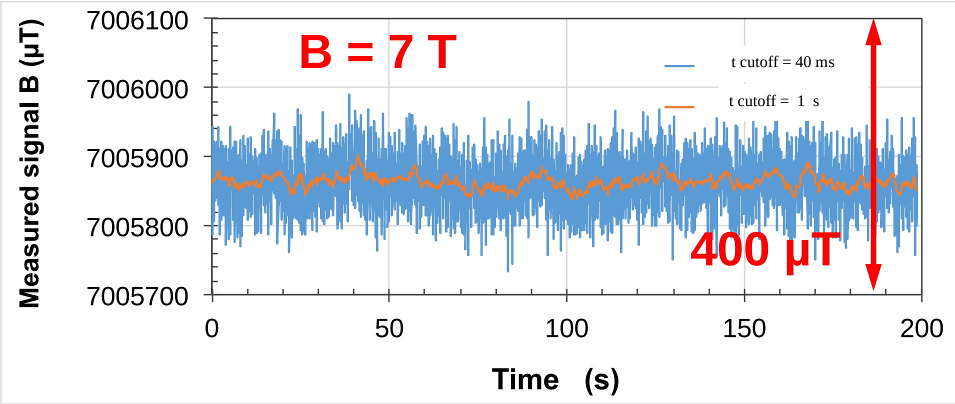


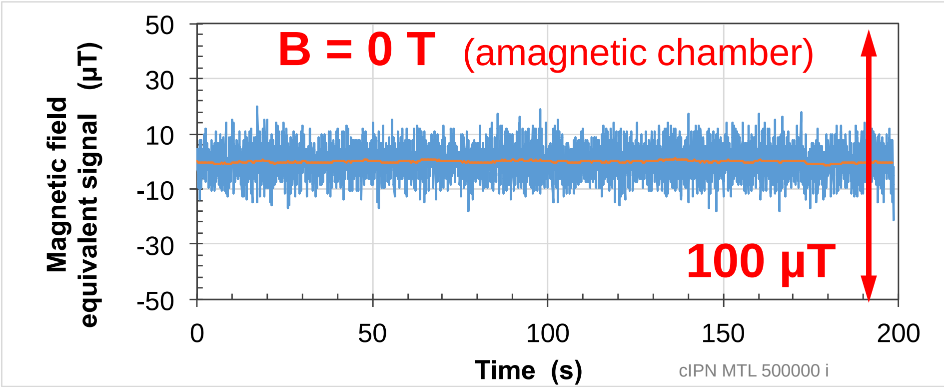
Excess noise vs frequency



Excess noise ~ $1+(\mu B)^2$

In the time domain





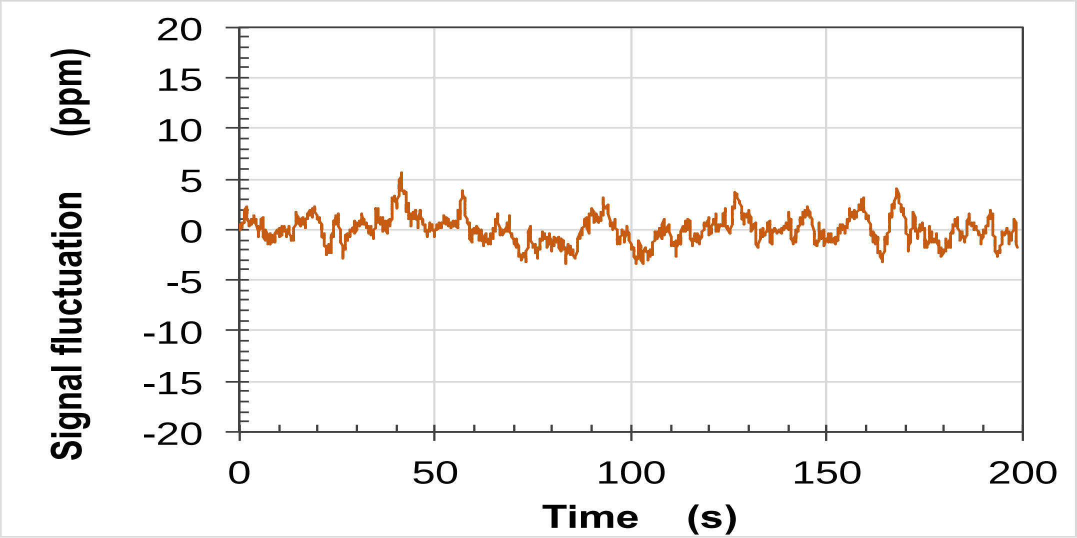
Cutoff frequency:	**Blue**	**f_c = 25 Hz**
	Orange	**f_c = 1 Hz**

Excess noise x 20 from B=0T to B=7T

Hall sensor noise at high induction

Hall signal fluctuation at B = 7 T

- QWHS W = 30 µm, room temperature
- Spinning current SCMT with acquisition frequency 10 kHz



B = 7 T

- **A few ppm signal fluctuation when BW = 1 Hz**
- **Dispersion ±3 σ corresponds to ±10 µT**

CONCLUSION

- **For magnetometry and micromagnetometry applications at high magnetic field, Quantum Well Hall Sensors may be a good choice**

- **We demonstrated the capabilities of QWHS**
  - for magnetic field metrology in the 0-20T range
  - as well for micromagnetometry at the micrometer level in the 0-8T range

- **The temperature range depends on the field strength**
  - 70 mK – 200°C demonstrated at low field (≤ 1 T)
  - Quantum Hall Effect oscillations at higher field and T < a few K

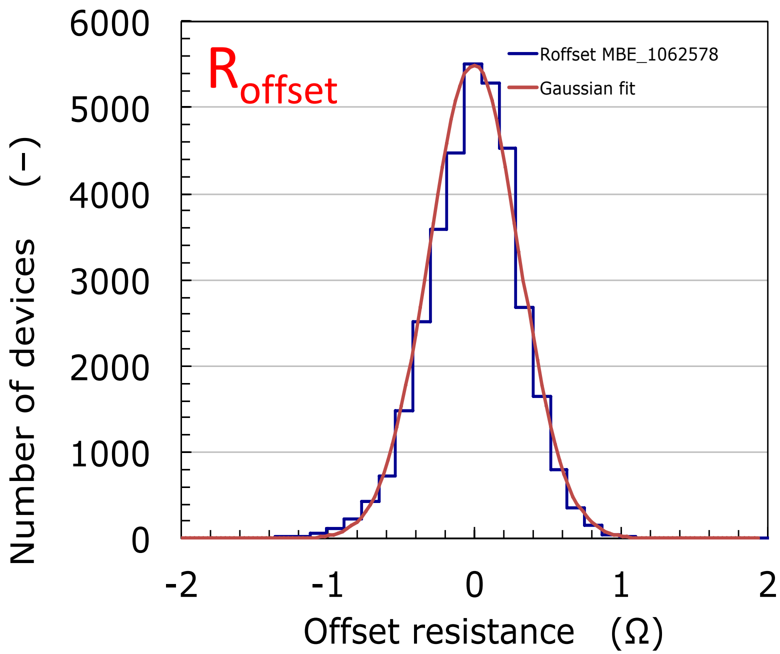
- **Using the Spinning Current Modulation Technique, a QWHS based microsystem with ±6T range shows a resolution better than 1µT, at least @B=1T**

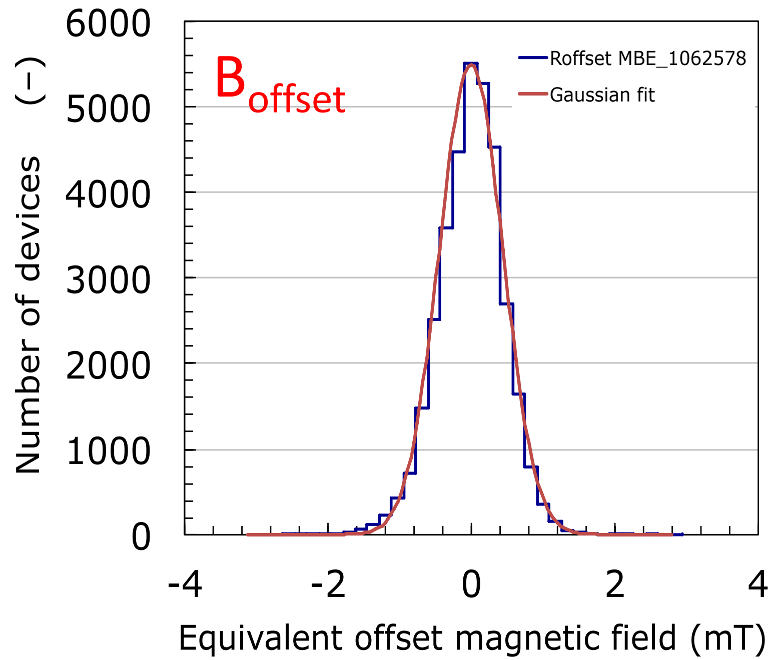
- **A QWHS was characterized between 0 and 7T, using the stray axial field of a Penning trap superconducting electromagnet in persistent mode**

- **Noise increase x 20 from B=0T to B=7T**

Material for discussion

RAW OFFSET OF QWHS SENSORS





R_{offset} : σ = 0.33 Ω
±3 σ = ±1.0 Ω

B_{offset} : σ = 0.43 mT
±3 σ = ±1.3 mT

Equivalent misalignment ΔL_{eff}: σ = 45 nm

Offset distribution over a wafer, 70000 devices (raw data)