



3-Axis Magnetometer on a Chip

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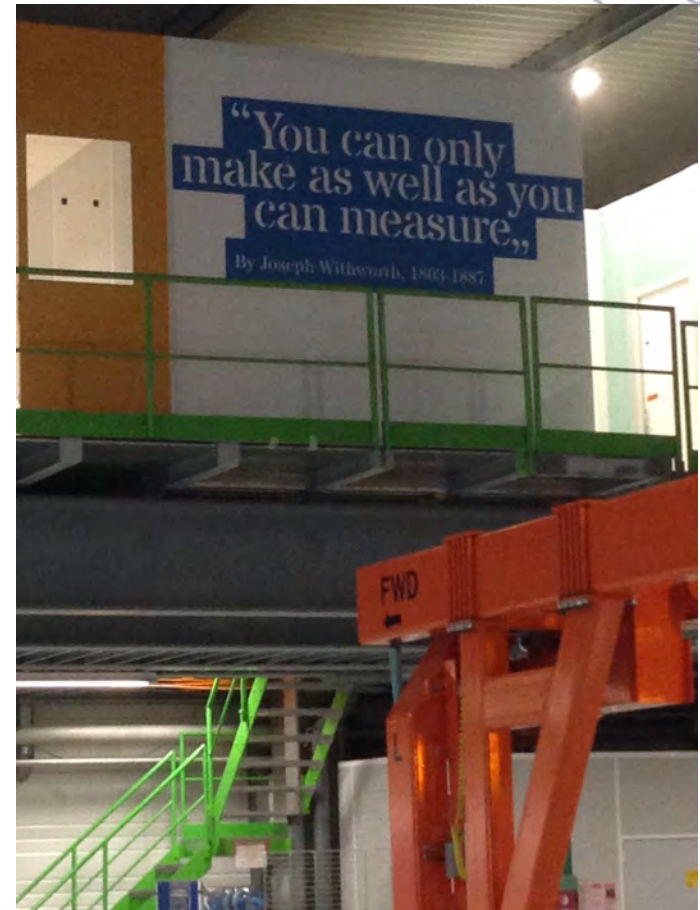
Why magnetometers?

“You can only make as well as you can measure”

Joseph Whitworth
1803-1887
Engineer,
entrepreneur,
inventor,
philanthropist

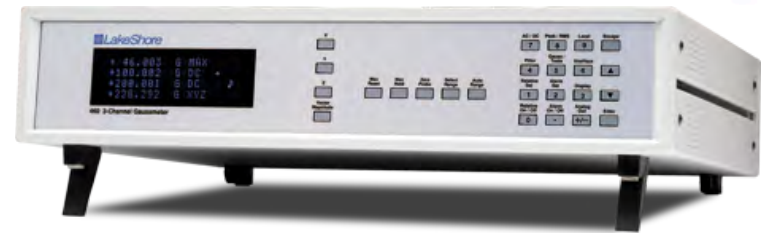


Credit: Grace's Guide to British Industrial History



3-Axis Hall Magnetometers

- Advantages:
 - All vector components
 - Any probe orientation
- Limitations:
 - Orthogonality
 - Sensor separation
 - Planar Hall Effect
 - Cost

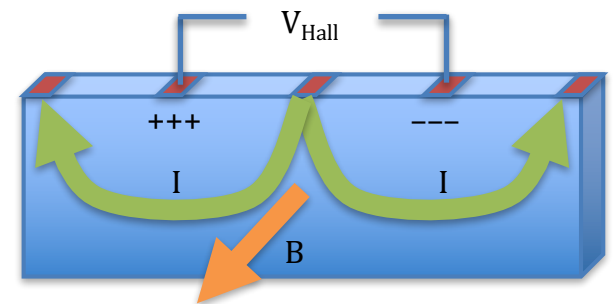
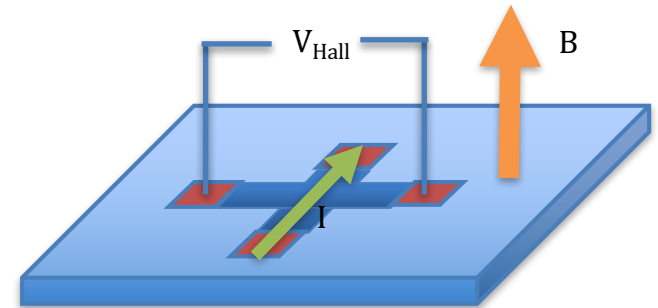


Credits:

- LakeShore Cryotronics (Model 460)
- Magnetic Sciences Inc. (F.W. Bell 8030)
- Metrolab (THM7025)

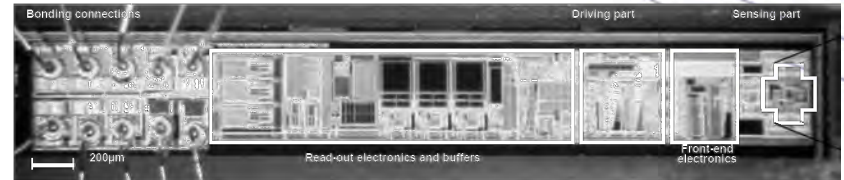
The first revolution

- Vertical Hall sensor
 - Integrated 3-axis sensors
- Advantages:
 - Simplified construction
 - ~100 μm active volume
- Limitations:
 - Si: lower sensitivity, higher noise

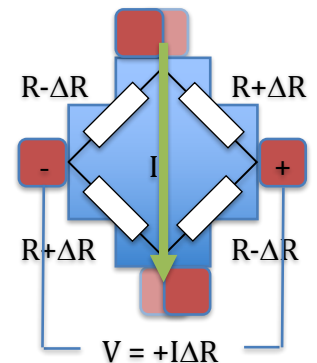
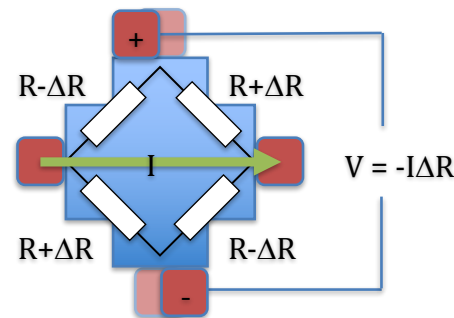
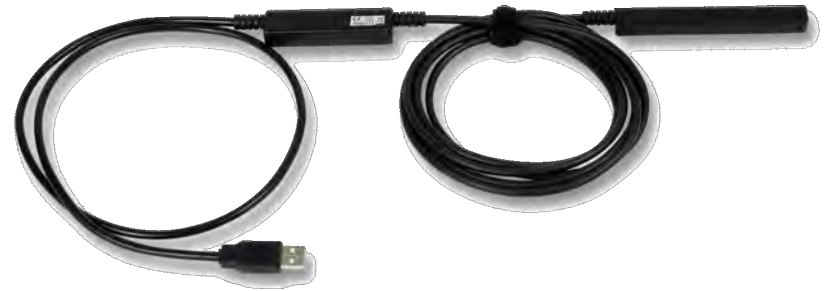


Additional advantages

- Integrated current source and amplifier
- Integrated temperature sensor
- “Spinning current” to minimize offset, Planar Hall Effect, and noise

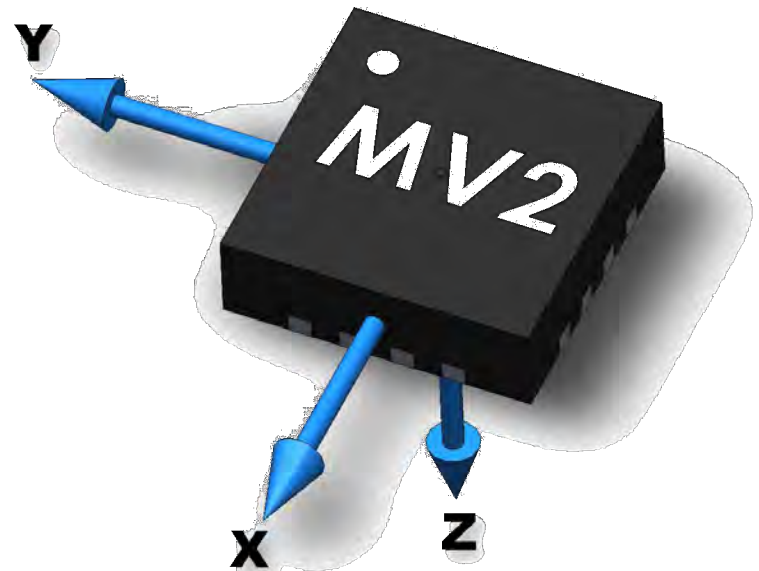


Credit: presentation by D. Popovic (Senis) at IMMW-14

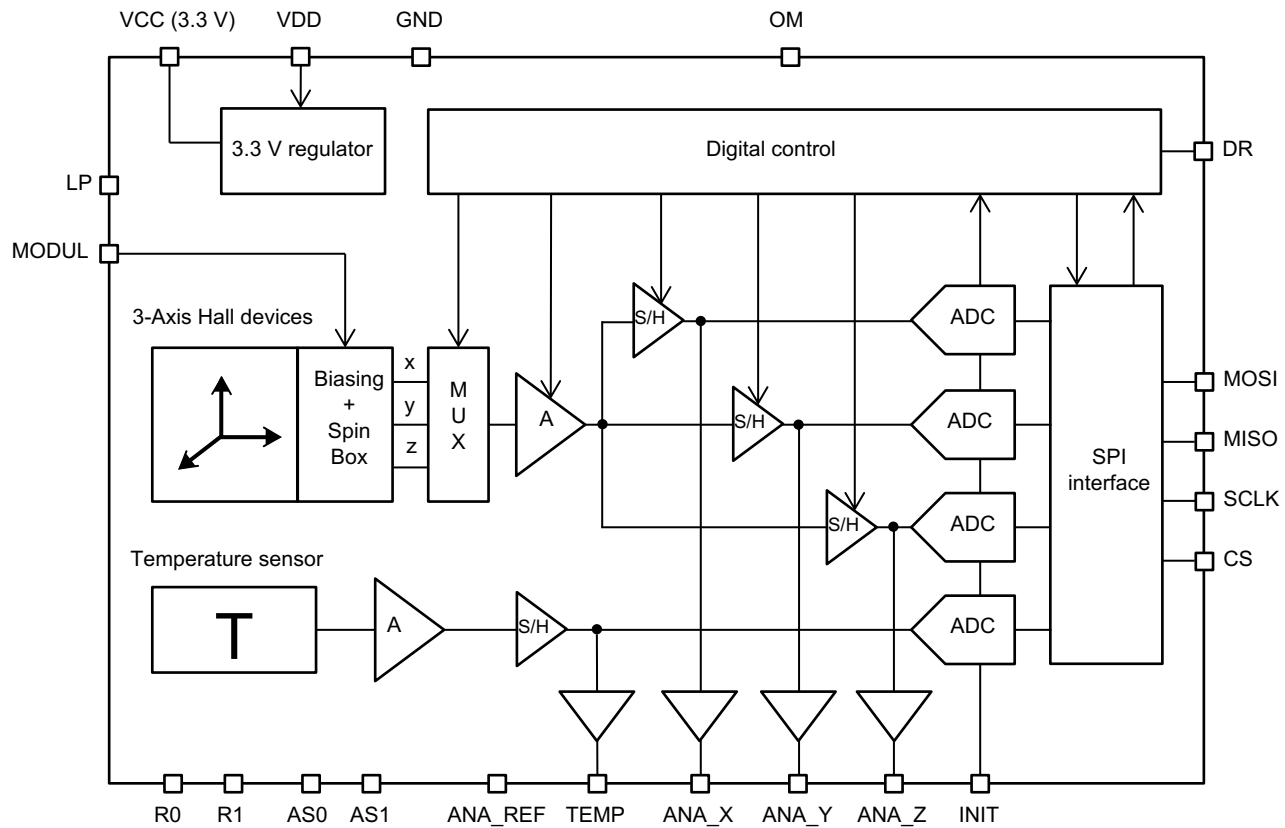


The second revolution

- Integrated ADC
 - Digital interface
- Advantages:
 - Minimize system complexity & cost
 - Minimize errors from inductive voltages
 - Additional controls
 - Sensor arrays feasible
- Disadvantages:
 - ADC performance

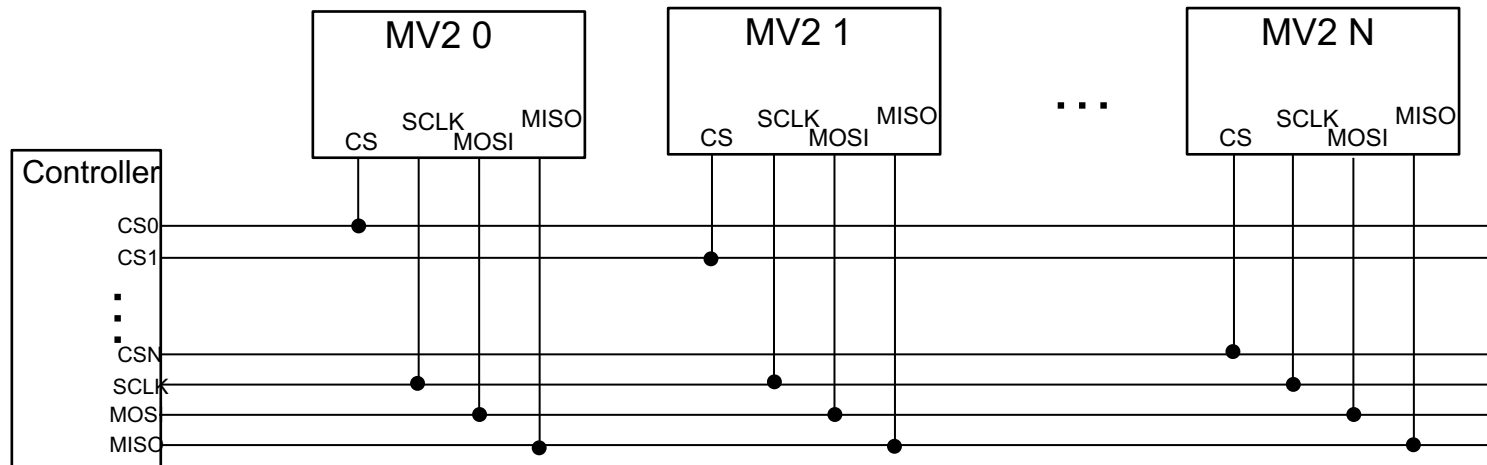


Architecture



Sensor arrays

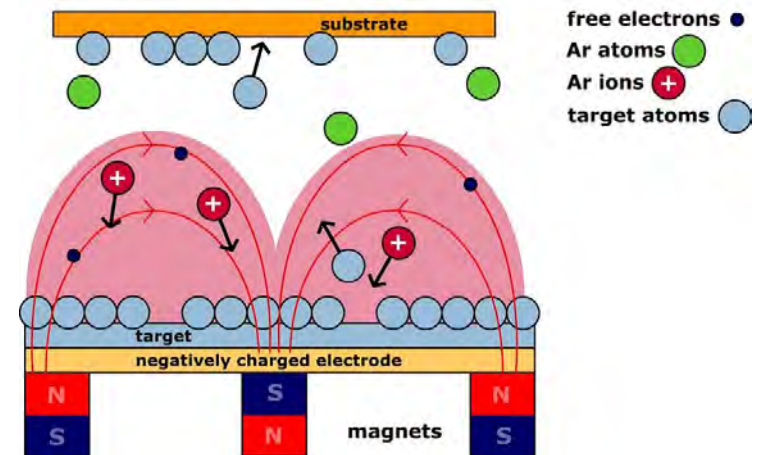
- Communication:
 - SPI bus with individual Chip Select lines



- Synchronization:
 - INIT 1 → 0: reinitialize and start ADC conversion

Example: magnetron sputtering

- Magnets degraded by heat, radiation
- Causes uneven deposition
- Periodic mapping of magnets
- Sensor array:
 - Minimize downtime!
 - Simplify scanning robot

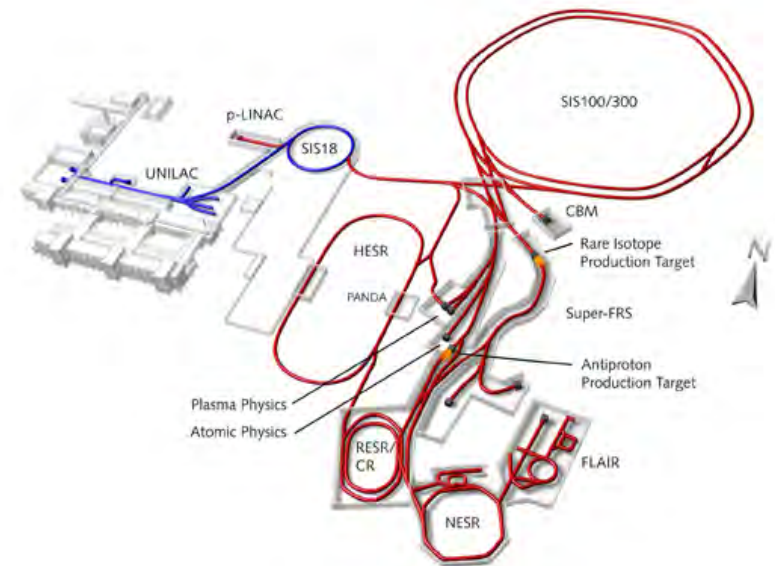


Credits:

- Wikipedia: "Sputter deposition"
- Dep. of Physics of Politecnico di Milano

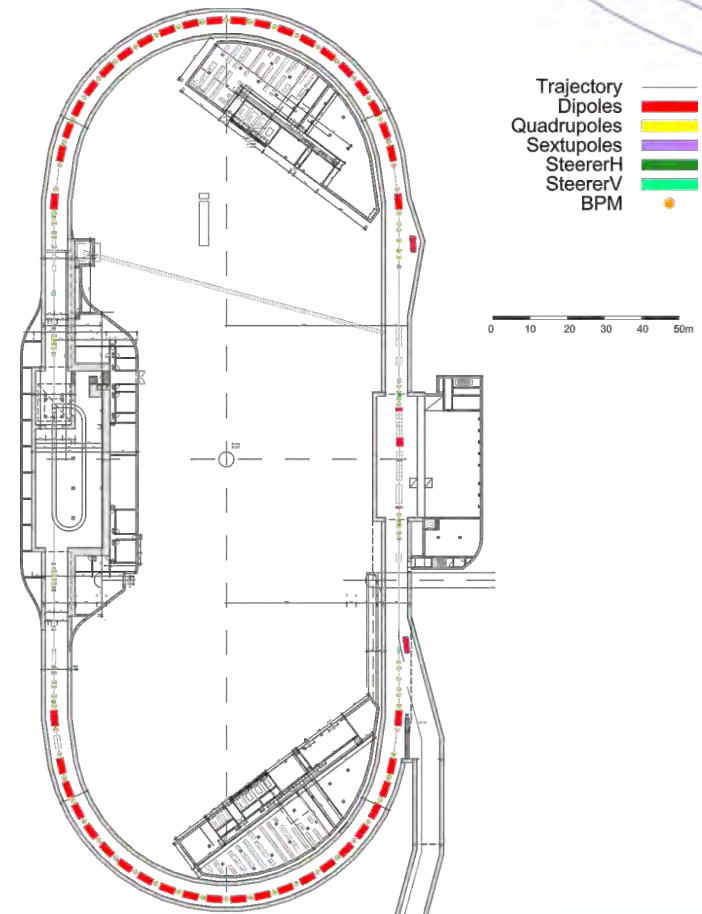
Example: Accelerator magnet mapping

- Facility for Antiproton and Ion Research (FAIR), Darmstadt, DE
- Dipoles of High-Energy Storage Ring (HESR)
- 44 bent dipoles, 4.2 m long, 0.17-1.7 T



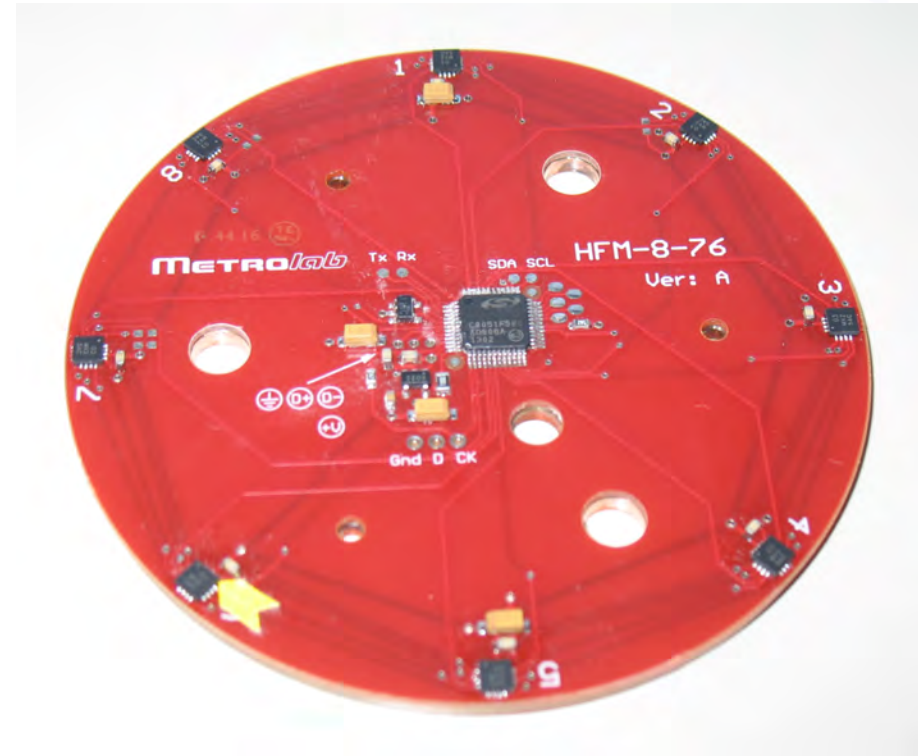
Accelerator magnet mapper

- Angular map along entire magnet length
- 0.17, 0.5, 1.7 T
- 10^{-4} resolution
- 8 sensors
- Rotary motor for additional angles
- Sled for lengthwise motion
- 82 mm free gap



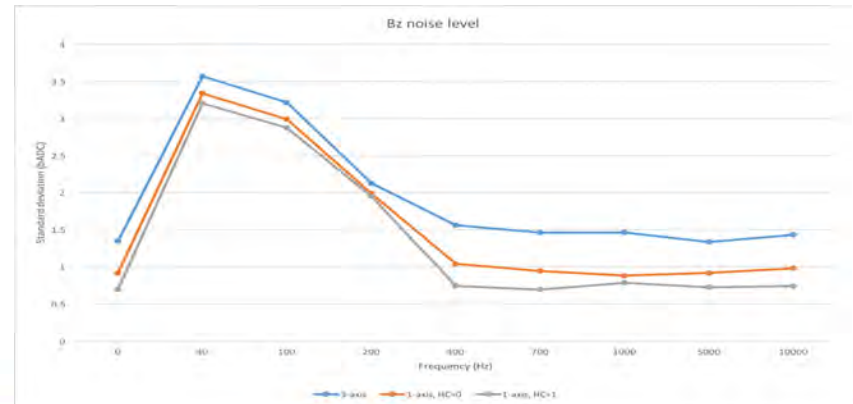
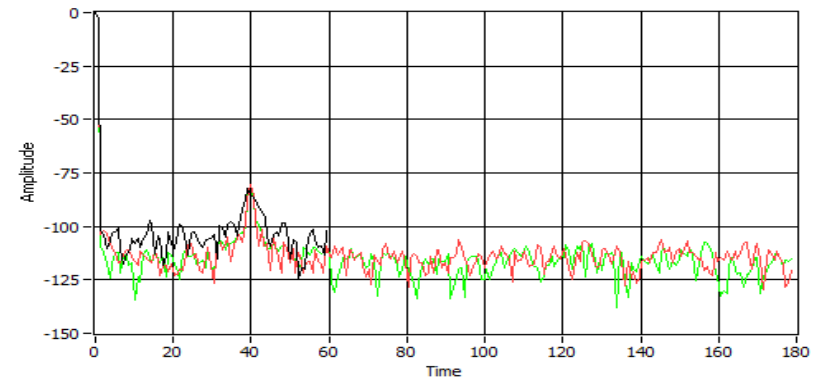
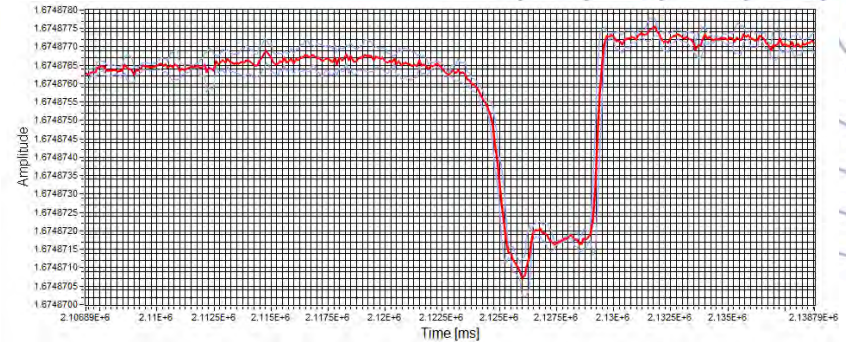
Accelerator magnet mapper

- 8 sensors @ 76 mm diameter
- Radial layout, ± 0.1 mm
- Precision mounting holes
- Temperature stabilization $\sim 0.01\text{C}$:
 - Thermal vias
 - Cu-core PCB
 - Heater
 - Current regulator
 - Insulation
- On-board electronics:
 - μP
 - Temperature sensor
 - Voltage regulator
- USB power & communication
- LabVIEW API



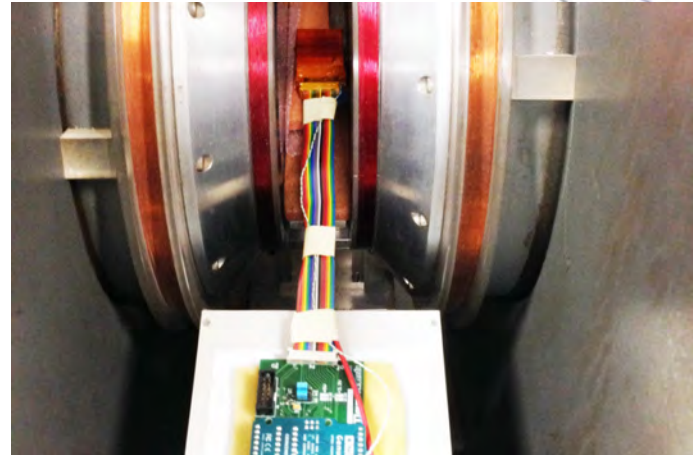
Heater

- Refractory metals:
 - NiCr , FeCrAl, CuNi
 - Mo, W, Ta, Nb, Cr
- 0.5 mm NiCr plate, 1.7 T
 - // : -0.6 μT (0.4 ppm)
 - \perp : -5 μT (3 ppm)
- Field from heater current:
 - ~4 ADC bits
 - Use AC \rightarrow no DC offset
 - Coil inductance \rightarrow roll-off
 - ADC integration \rightarrow negligible $>$ ~400 Hz



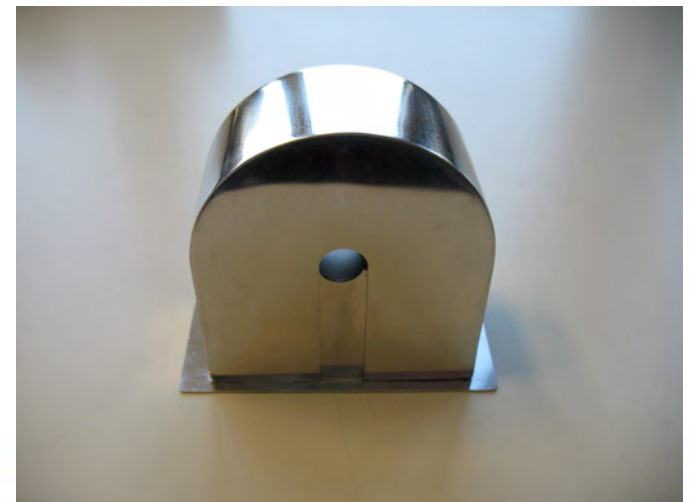
Resolution & stability

- Noise:
 - $\pm 4.7 \mu\text{T}$ (100 mT range)
- Drift:
 - Bx, By: 0.07 bits/hour
 - Bz: 0.4 bits/hour
- Conditions:
 - 4 hour preheat
 - 16 hours measurement
 - $80 \text{ mT} \pm 0.5 \mu\text{T}$
 - $35^\circ \pm 0.01^\circ$
 - 3-axis mode



Zero Gauss Chamber

- Measure initial & final zero-offset; interpolate in time
- Enclose mapper, including drive shaft
- Attenuation goal:
 $\sim 50 \mu\text{T} \rightarrow < 1 \mu\text{T}$
- Measured:
 - $41.754 \mu\text{T} \rightarrow 0.232 \mu\text{T}$
 - Maximum (orientation)
 - $\sim 6 \text{ mm}$ below sensor



Conclusions

- Logical evolution of 3-axis Hall magnetometers
- Size, performance, cost → embedded / custom applications, e.g. mappers
- Calibration, UIF → not a “cheap gaussmeter”
- Unsuitable for special conditions (e.g. high precision, low fields, cryogenic temperatures)

