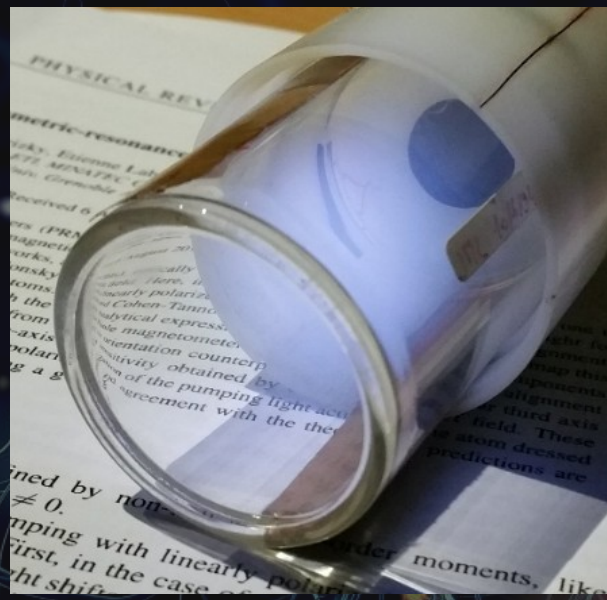
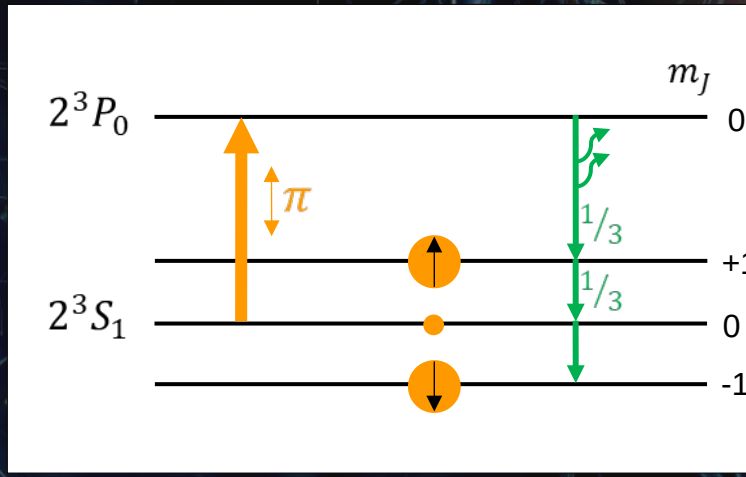
MAG ^{4}He alth



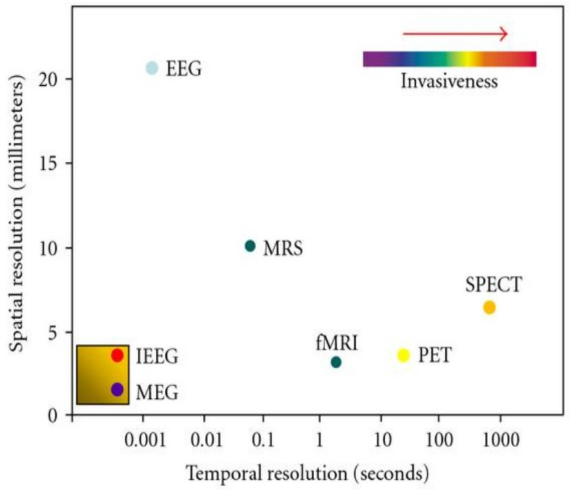
HELIUM-4 OPM FOR BRAIN FUNCTIONAL IMAGING



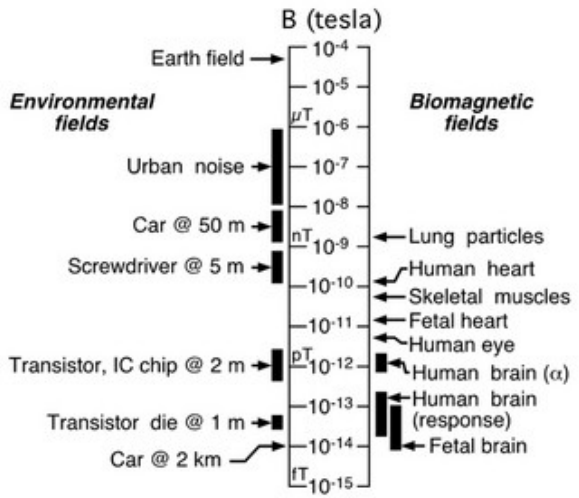
Agustín Palacios-Laloy
Mag^{4}Health
Grenoble, France

Tiny biomagnetic signals were only visible with cryogenic MEGs...

- Magnetic fields bring a picture of brain activity with the best spatial & temporal resolution



- But they are tiny...



- Until recently, only SQUID sensors operating near zero Kelvin were able to measure such tiny fields...

~300 SQUIDs
+ flux transformers

Heavy magnetic shielding

The hope of democratizing MEG...

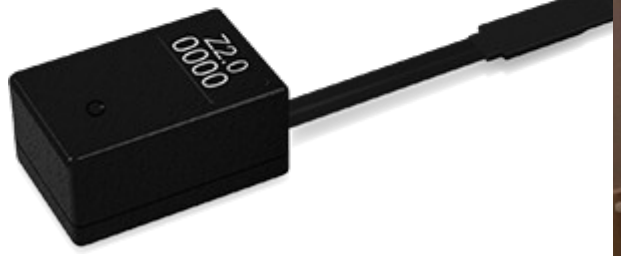
Room temperature sensor technology : ***the*** key asset

- Cheaper and maintenance-free
- Examination compatible with movement
- Sensor closer to scalp : richer spatial information
- Adaptable helmet for anybody : Kids, adults, primates...

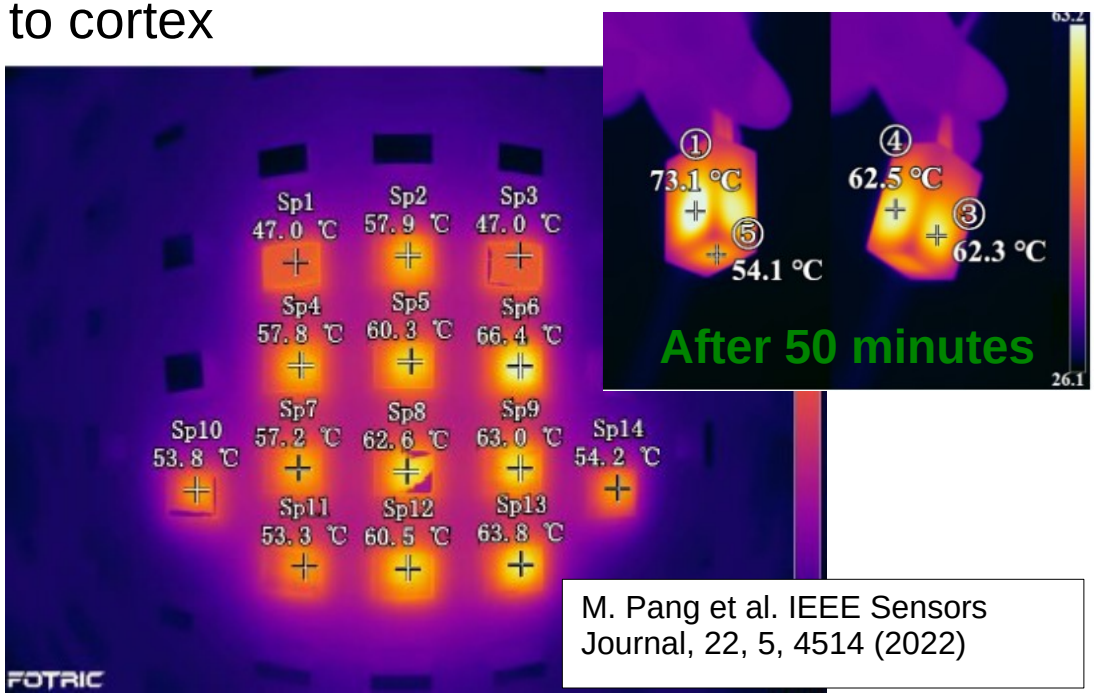
Integrated alkali OPM

- Based on Rb in the SERF regime (heated at ~150 ºC)
- Good sensitivity :
  - 10 fT/sqHz on single axis or 15 fT/sqHz dual axis
- From 2018 multichannel OPM systems have allowed numerous fruitful MEG works
  - Mutichannel recordings of « natural » activities
  - More information than SQUID due to closer proximity to cortex
- Still challenges
  - Limited dynamic range (2-5 nT) requires field-nulling coils
    - From Cerca Magnetics or custom
    - Otherwise: cross-axis effects also problematic
  - Bandwidth : 135 Hz
  - Thermal load (500 mW/sensor)
    - Sensor surface: nominally 41ºC

QUSPIN
AN ATOMIC DEVICES COMPANY

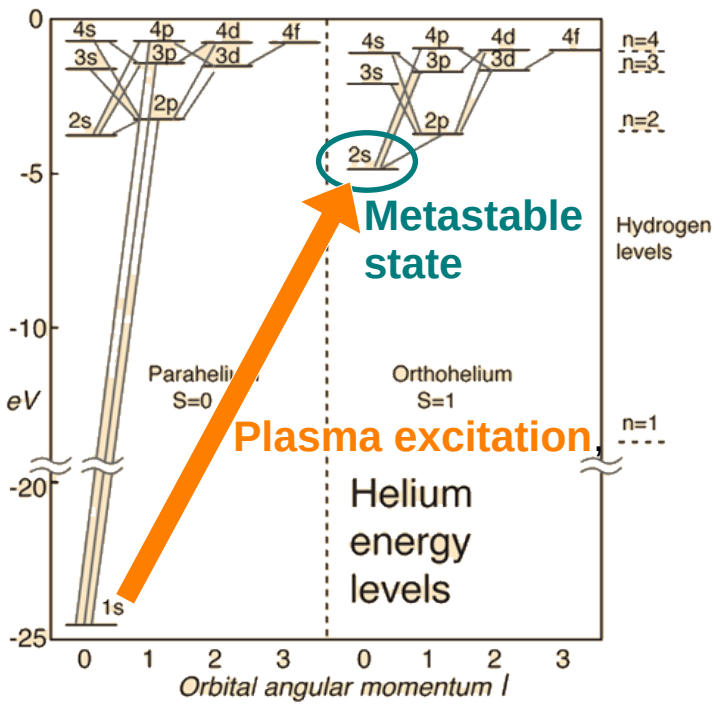


Boto et al. Nature (2018)



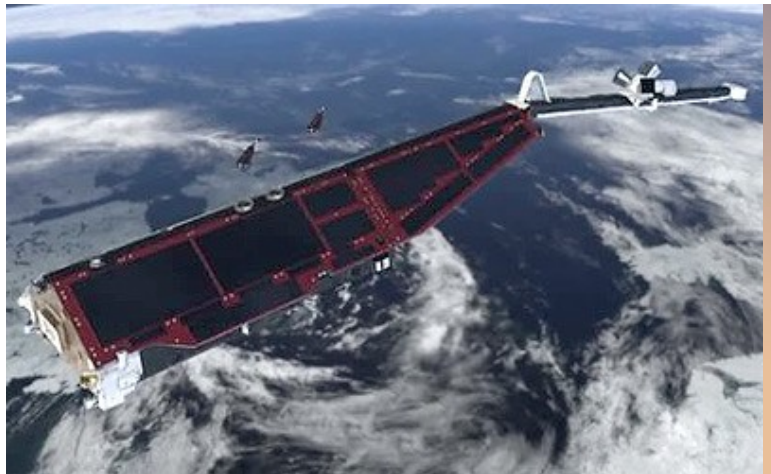
M. Pang et al. IEEE Sensors Journal, 22, 5, 4514 (2022)

An alternative sensitive element: metastable helium-4



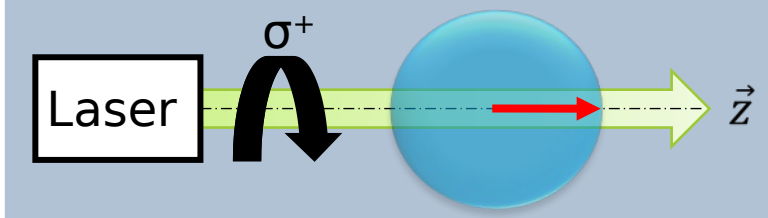
- Helium-4 needs to be brought to an excited level for measuring
  - Requires **plasma excitation**, dissipating ~10 mW.
  - Working at any temperature, no noticeble heating
  - Requires specific electronics and know-how

- Mag^{4}**He**alth inherits this know-how from Space exploration
  - Magnetometers of CEA Leti for ESA Swarm mission
  - Fiability : still measuring after >8 years of continous operation

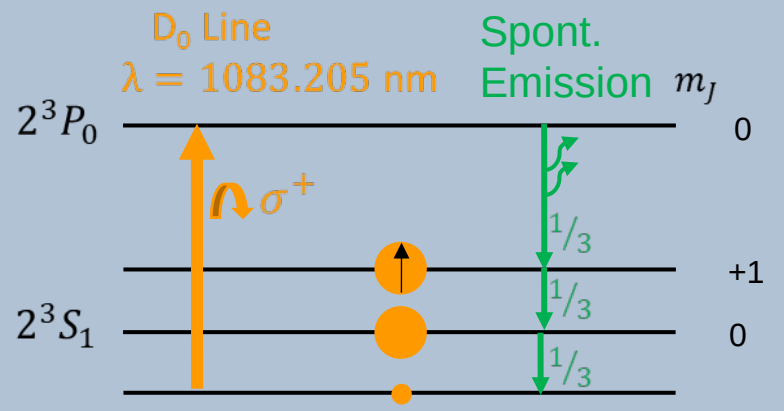


A useful yet mysterious atomic polarisation: alignment

Circularly-polarized light:
Orientation

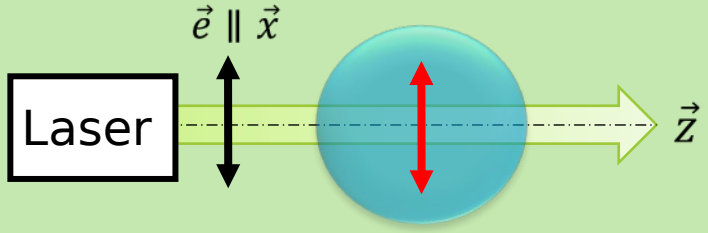


$$\langle \hat{S}_z \rangle \neq 0, \langle \hat{S}_x \rangle = 0, \langle \hat{S}_y \rangle = 0$$



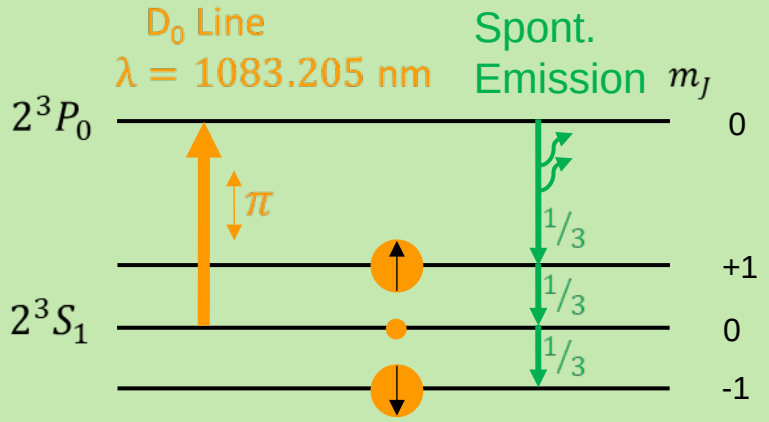
Magnetic dipole moment → **Vector**

Linearly-polarized light:
Alignment



$$\langle \hat{S}_x \rangle = 0, \langle \hat{S}_y \rangle = 0, \langle \hat{S}_z \rangle = 0$$

$$\langle 3\hat{S}_x^2 - \hat{S}^2 \rangle \neq 0$$

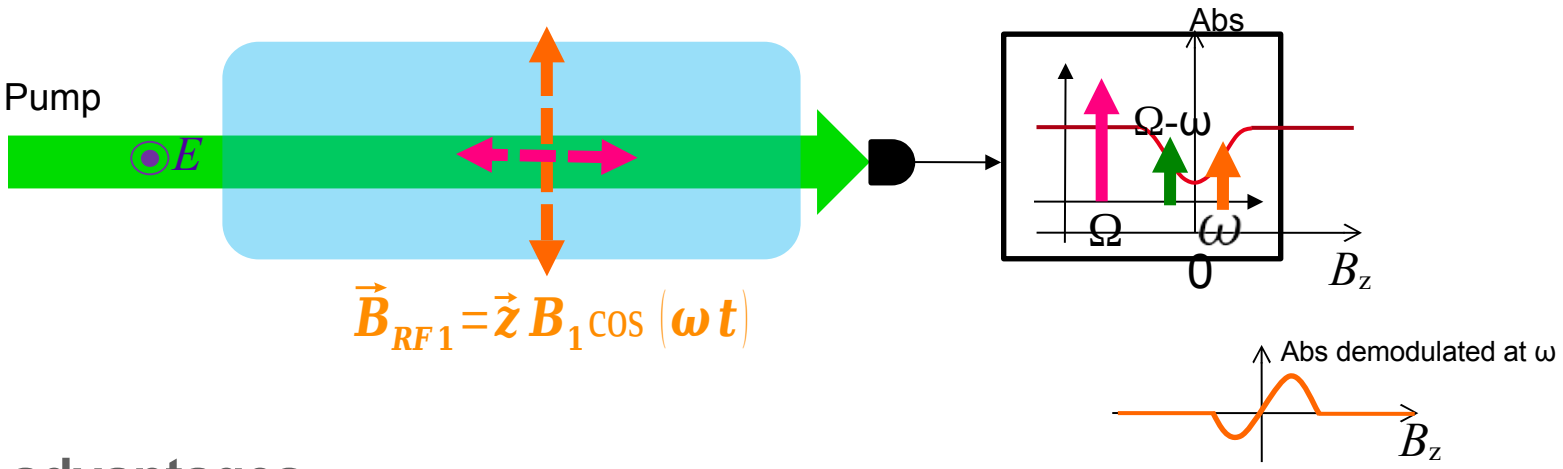


Magnetic quadrupole moment → **Tensor**

Parametric resonance allows obtaining the 3 components of B

- Handling several optical beams in a magnetometer array → not easy
- Adding RF fields allows getting the same information with 1 single beam

J. Dupont-Roc, *Journal de Physique* (1971)

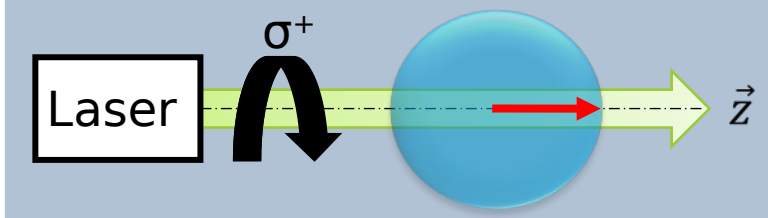


- Important advantages
  - Vector sensitivity to the component parallel to the RF field
  - Linear dependence around zero-field
  - Allows working out of zero-frequency → our of highest laser noise
  - Two RF → three components of the field can be measured
    - **The one parallel to the polarization with worse sensitivity**
    - Calculation not so easy → dressed-atom formalism

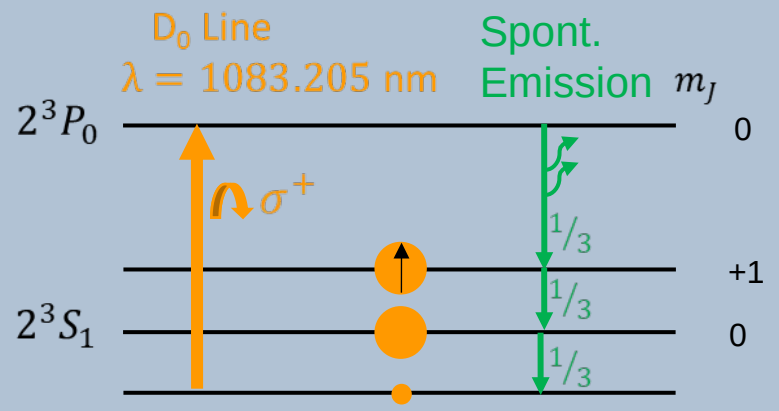
F. Beato et al., *Physical Review A* (2018)

A useful yet mysterious atomic polarisation: alignment

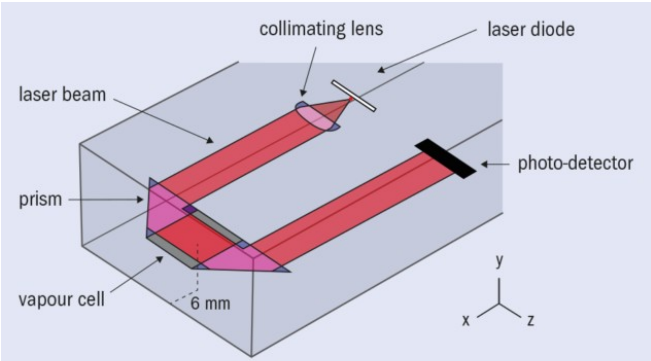
Circularly-polarized light: **Orientation**



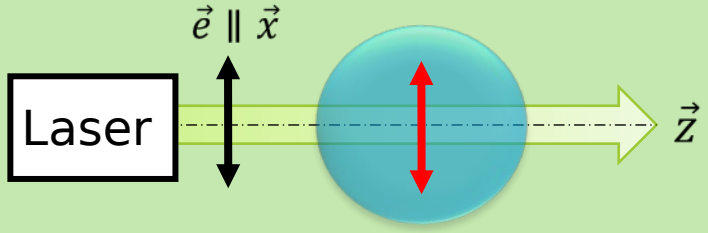
$$\langle \hat{S}_z \rangle \neq 0, \langle \hat{S}_x \rangle = 0, \langle \hat{S}_y \rangle = 0$$



Magnetic dipole moment → **Vector**

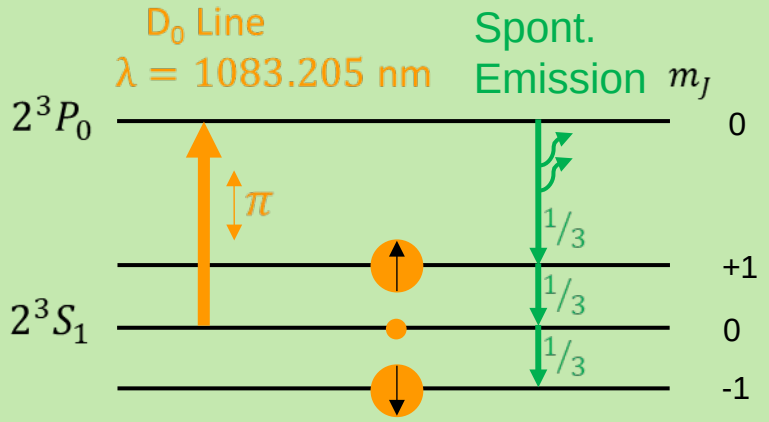


Linearly-polarized light: **Alignment**

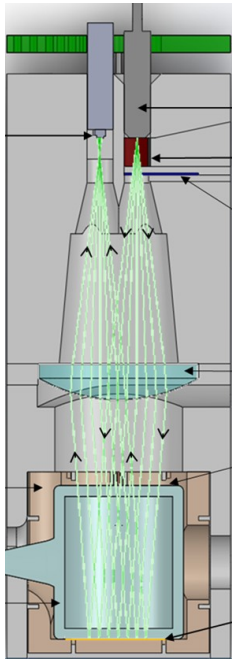


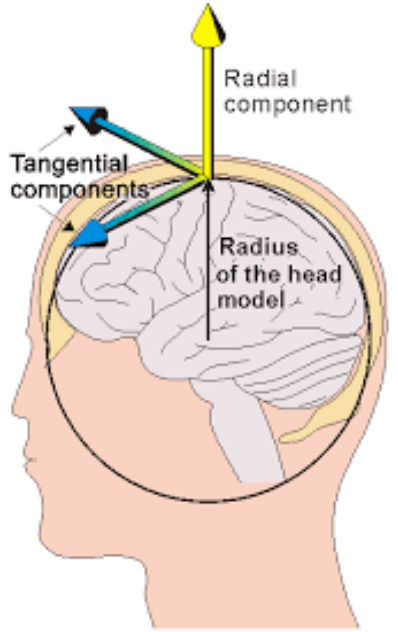
$$\langle \hat{S}_x \rangle = 0, \langle \hat{S}_y \rangle = 0, \langle \hat{S}_z \rangle = 0$$

$$\langle 3\hat{S}_x^2 - \hat{S}^2 \rangle \neq 0$$



Magnetic quadrupole moment → **Tensor**

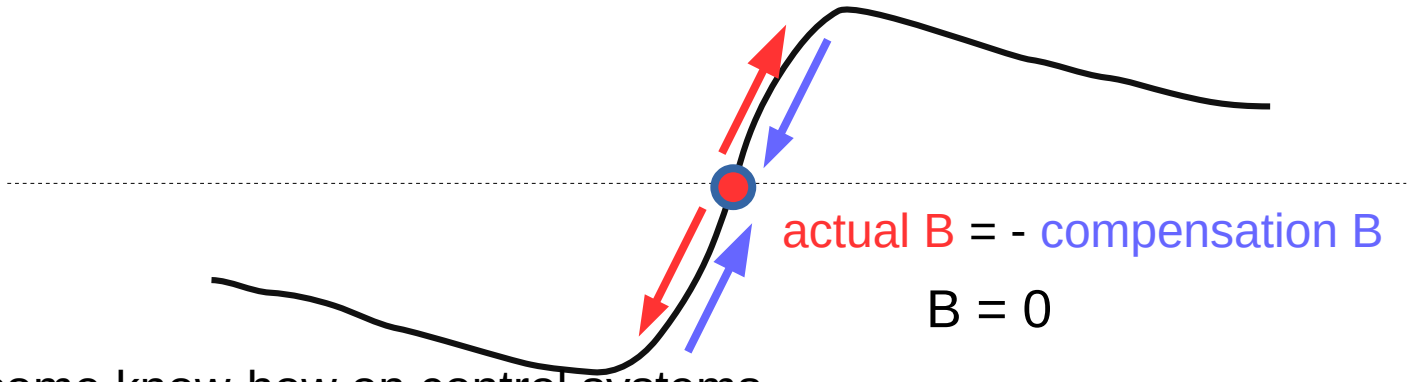




In addition : **no systematic errors due to light-shifts !**

Closed-loop zero-field measurements

- Consists in making the sensor operate at zero-field all the time
  - Apply fields to cancel those measured, in real-time

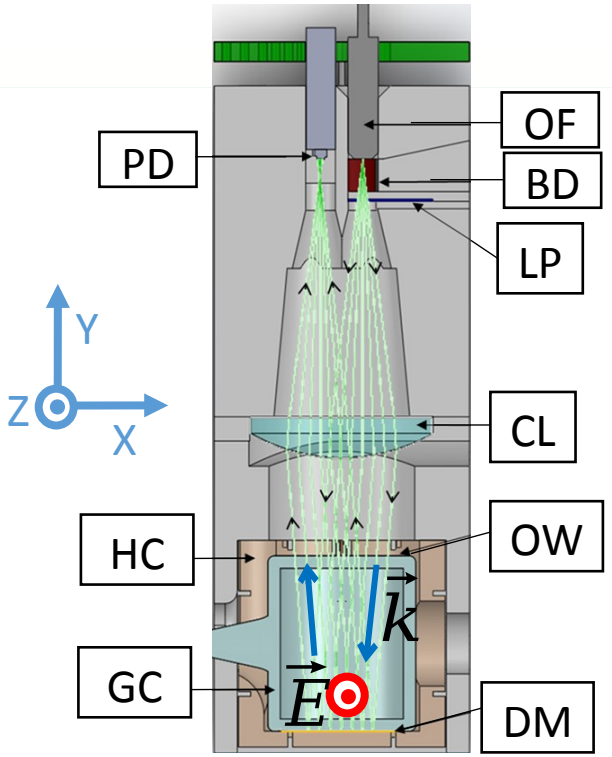


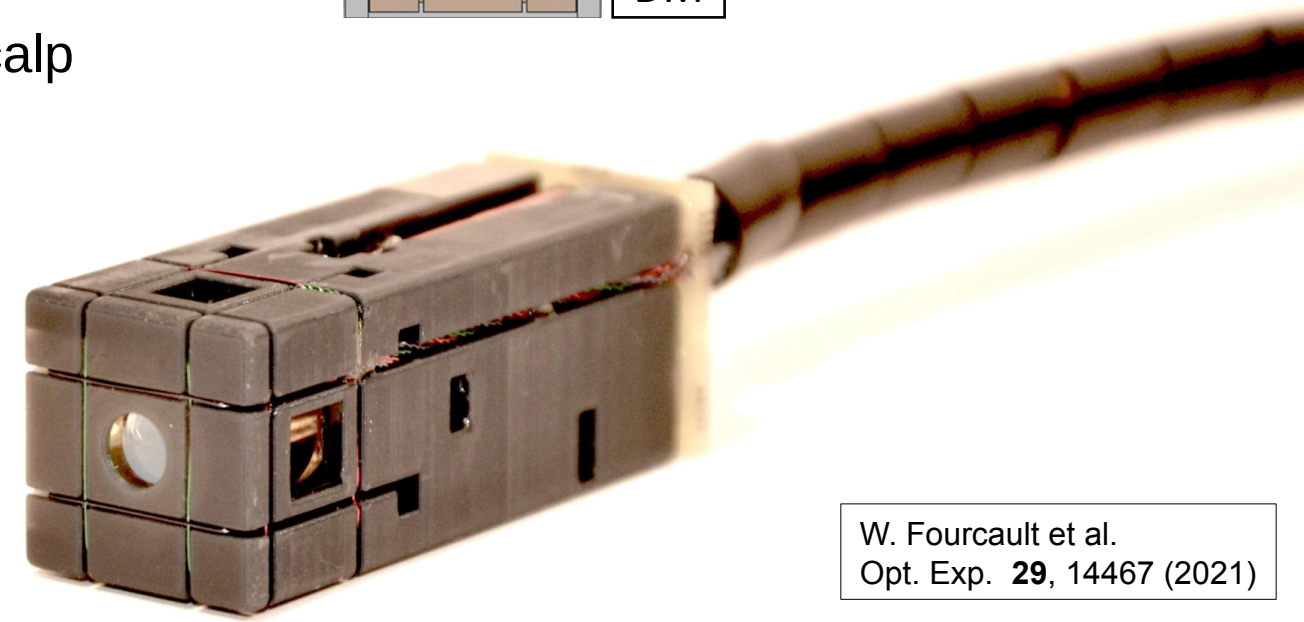
  - Requires some know-how on control systems
- Extremely useful
  - Dynamic range can become as large as wanted → Earth field for our CEA Leti colleageS !
  - But more importantly cancels most systematic errors → **accuracy**
    - Cross-axis effects
    - Fluctuation of laser power
    - ...
  - Self-alibrated : measurement relies on no calibration except for the compensation coils

F. Bertrand et al., Review of Scientific Instruments 92, 105005 (2021).

Mag⁴Health sensor for MEG

- Large cell in direct contact with scalp
  - Possible thanks to absence of heating
  - Pumping with linearly polarized light avoids optical beam bending
- Sensitivity
  - <30 fT/sqHz in dual-axis mode
  - Not the ultimate limit : work still in progress
  - Signal larger due to the direct contact with scalp
- Bandwidth of >2 kHz
- Dynamic range of 250 nT
- Closed-loop on the 3 axes

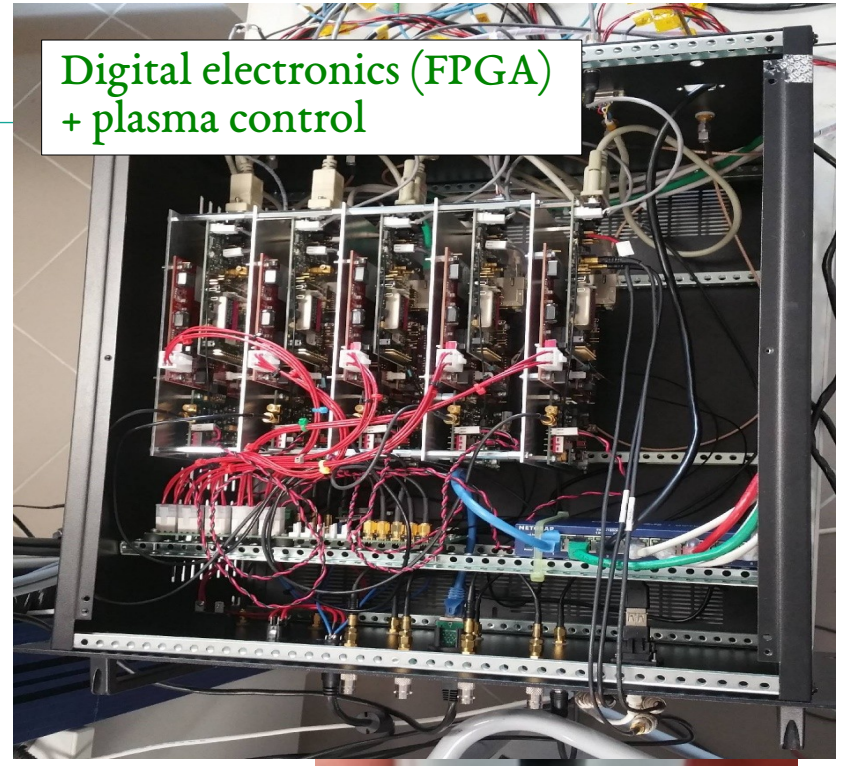




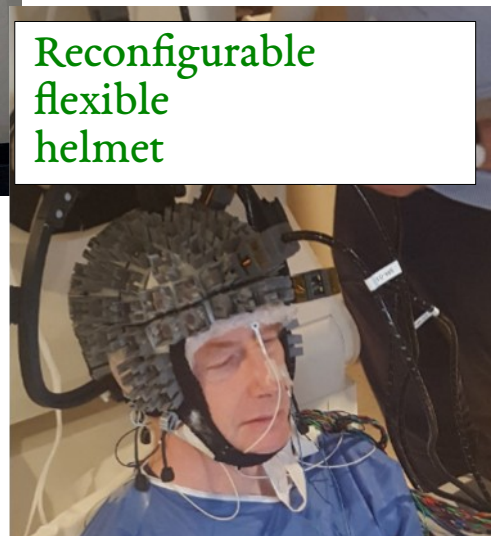
W. Fourcault et al.
Opt. Exp. **29**, 14467 (2021)

A few shots of the first prototype system...

Control interface running on a laptop



Digital electronics (FPGA) + plasma control



Reconfigurable flexible helmet

Five sensors

- Current test system of 5 sensors
- **Etienne Labyt will speak about 1st recordings at 13:40**

Crosstalks: closed-loop is not a problem but a useful ressource...

Closed-loop operation → each sensor creates its own field

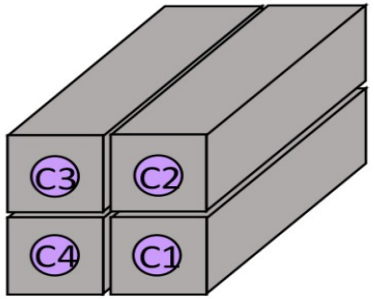
W. Fourcault et al. Opt. Exp. **29**, 14467 (2021)

$$\begin{pmatrix} B_1 \\ B_2 \\ \vdots \\ B_N \end{pmatrix} - \begin{bmatrix} \frac{\partial B_1}{\partial I_1} & \frac{\partial B_1}{\partial I_2} & \cdots & \frac{\partial B_1}{\partial I_N} \\ \frac{\partial B_2}{\partial I_1} & \frac{\partial B_2}{\partial I_2} & \cdots & \frac{\partial B_2}{\partial I_N} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial B_N}{\partial I_1} & \frac{\partial B_N}{\partial I_2} & \cdots & \frac{\partial B_N}{\partial I_N} \end{bmatrix} \begin{pmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

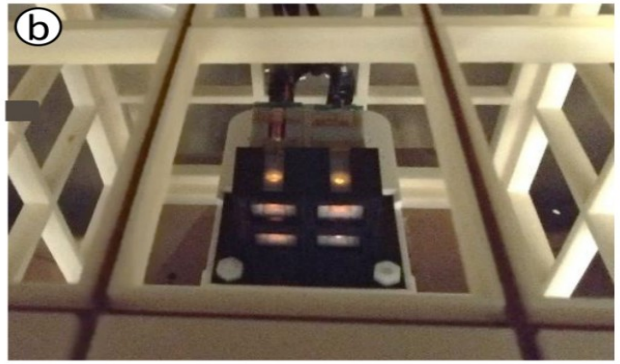
actual field components

intra/inter-sensors cross-talks

(a)



(b)



(c)

		C1			C2			C3			C4		
		x	y	z	x	y	z	x	y	z	x	y	z
C1	x	100,0%	0,0%	-0,3%	0,0%	0,0%	3,1%	0,6%	-0,1%	1,7%	0,2%	-0,2%	-6,3%
	y	0,0%	100,0%	0,0%	-0,4%	-2,8%	-0,1%	-0,1%	-1,1%	-0,1%	0,0%	-3,0%	0,3%
	z	0,0%	0,0%	100,0%	6,1%	-0,3%	0,0%	1,8%	-0,1%	0,6%	-3,4%	0,0%	-0,2%
C2	x	0,1%	-0,5%	6,3%	100,0%	0,0%	-0,1%	0,0%	-0,1%	-3,2%	0,6%	-0,1%	1,9%
	y	0,0%	-2,9%	-0,6%	0,0%	100,0%	0,0%	-0,1%	-3,0%	0,0%	0,0%	-1,1%	-0,1%
	z	3,3%	0,0%	0,0%	0,0%	0,0%	100,0%	-6,2%	0,0%	0,1%	1,8%	-0,1%	0,7%
C3	x	0,6%	-0,1%	1,8%	-0,1%	-0,1%	-6,2%	100,0%	0,0%	-2,1%	0,0%	-0,1%	3,5%
	y	-0,1%	-1,1%	-0,1%	-0,1%	-2,9%	0,3%	0,0%	100,0%	0,1%	-0,2%	-3,1%	0,0%
	z	1,8%	-0,1%	0,6%	-3,3%	0,1%	0,2%	0,1%	0,0%	100,0%	6,5%	-0,3%	0,0%
C4	x	-0,1%	0,0%	-3,4%	0,6%	-0,1%	1,7%	0,0%	-0,2%	6,2%	100,0%	0,0%	-0,1%
	y	-0,3%	-3,0%	0,1%	-0,1%	-1,1%	-0,1%	0,0%	-3,0%	-0,3%	0,0%	100,0%	0,0%
	z	-6,3%	0,3%	0,1%	1,8%	0,0%	0,6%	3,3%	0,0%	-0,2%	0,0%	0,0%	100,0%

preparing 24 & 64-OPM systems for delivery in June 2023

Thanks for your attention !

The team:

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S. Mitryukovskiy
R. Romain
A. Palacios-Laloy
E. Labyt
M. Le Prado

http://www.mag4health.com/