



Miniaturization of the SWARM Isotropic Helium-4 Atomic Scalar Magnetometer Proof-of-principle and Perspectives

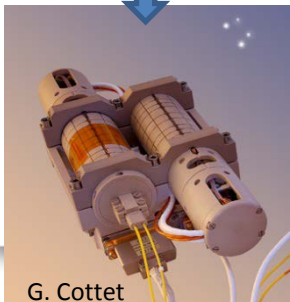
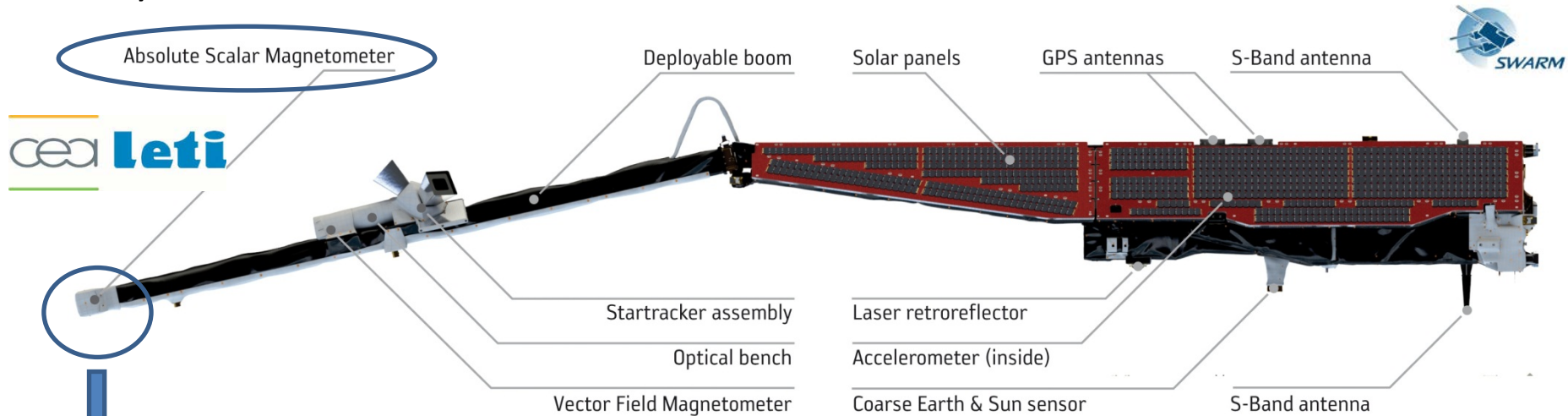
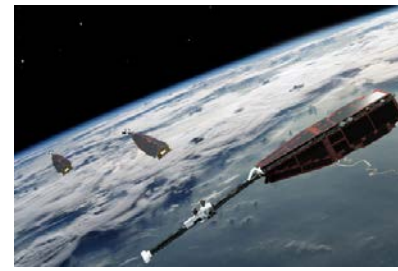
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SWARM space mission

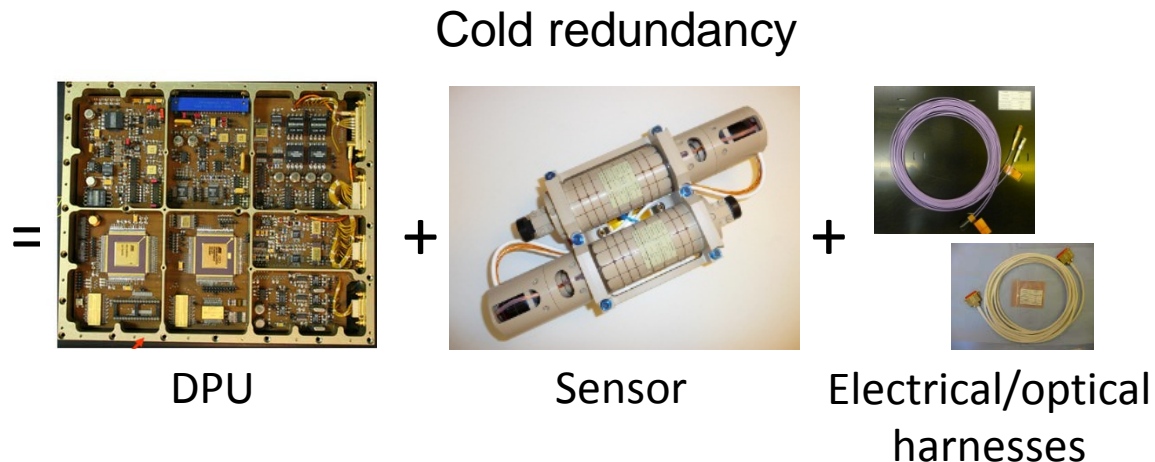
- ESA Earth Explorer Program
- Best ever Earth magnetic field survey → precise measurement of magnetic signals from Earth's core, mantle, crust, oceans & temporal evolution
- Constellation of 3 satellites, launched: 22 November 2013
- Payload:



Observational Requirements (in Orbit)

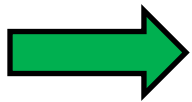
<i>Magnetic Field Magnitude</i>	global – 20 km length scales
<i>Accuracy, stability</i>	0.15 nT (σ); < 0.05nT/3 months
<i>Vector Magnetic Field</i>	global – 2 km length scales
<i>Accuracy, stability</i>	0.5 nT (σ); < 0.5nT/year

SWARM Atomic Scalar Magnetometer



SWARM high performance isotropic Earth's field magnetometer

- Scalar resolution: 1 pT/√Hz
- Vector resolution: 1 nT/√Hz
- Bandwidth: DC – 100 Hz
- Isotropy provided by a nonmagnetic piezoelectric motor: **heading errors < 50 pT**
- Measurement range: [15 - 65] μT
- But... Volume: 460 cm³



Need for a high performance isotropic miniature Scalar Magnetometer

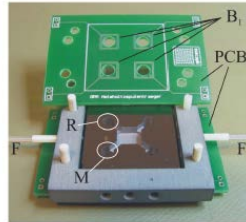
State of the art: Earth's field magnetometers

Miniature Earth's field scalar magnetometers

- **IPHT:**

Sensitivity: **0.5 - 6 pT/vHz**

Gas cell: 50 mm³

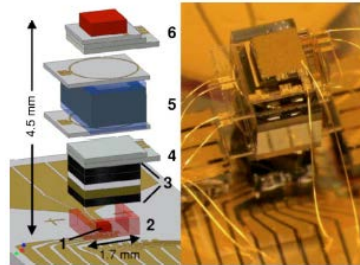


- **NIST:**

Sensitivity: **5 pT/vHz**

Gas cell: 1-2 mm³

Volume: 15 mm³



- **Twinleaf: 10 pT/vHz**

**But... Dead zones
and Heading errors > 2 nT**

Isotropic Earth's field sensors for mobile applications

→ complex architectures

- **3 sensors** (orthogonally mounted)

- **Using multiple resonances**

CPT (Coherent Population Trapping)

TU Graz: 70 pT/ vHz, gas cell 1 cm³

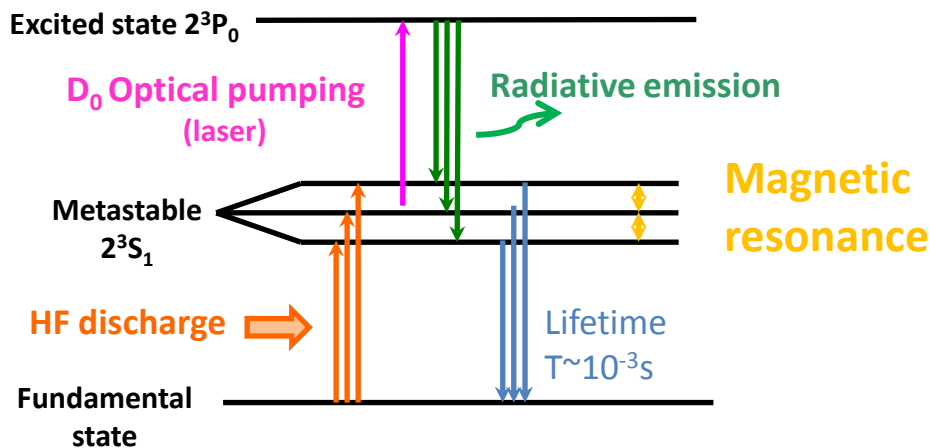
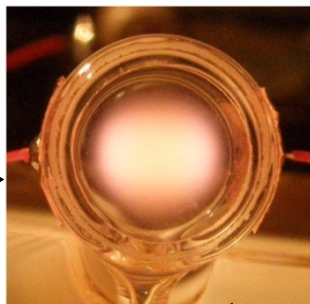
- **SWARM principle**

$(\vec{B}_0; \vec{E}_0) = 90^\circ \rightarrow$ servo-motor

But... Big and expensive

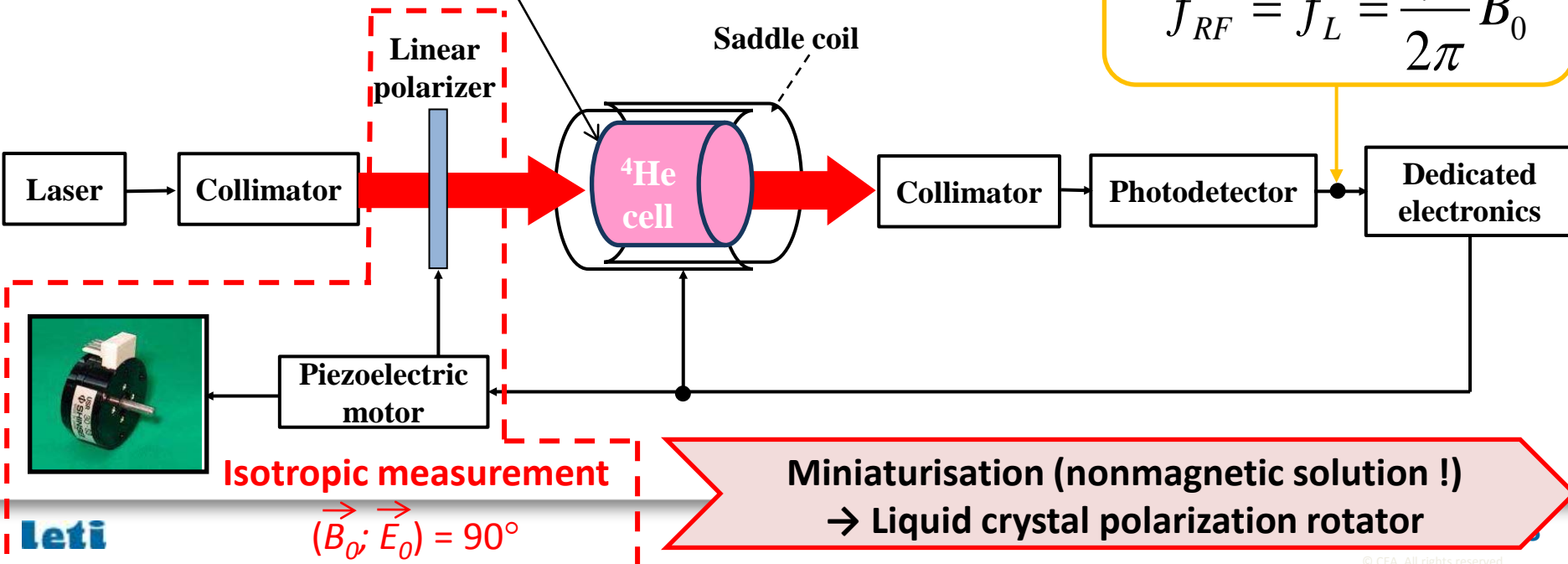
Helium Atomic magnetometers: SWARM

Sensitive element - helium cell



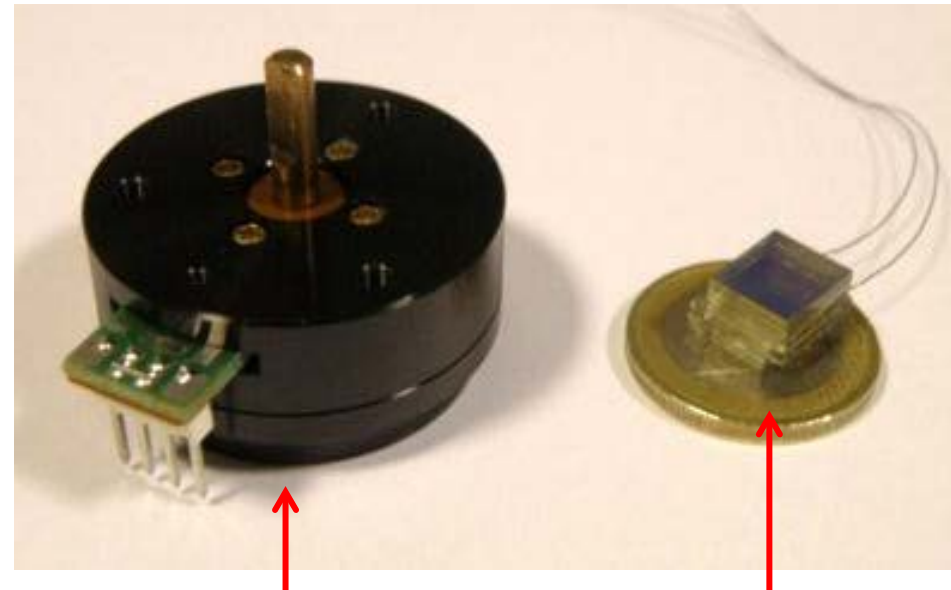
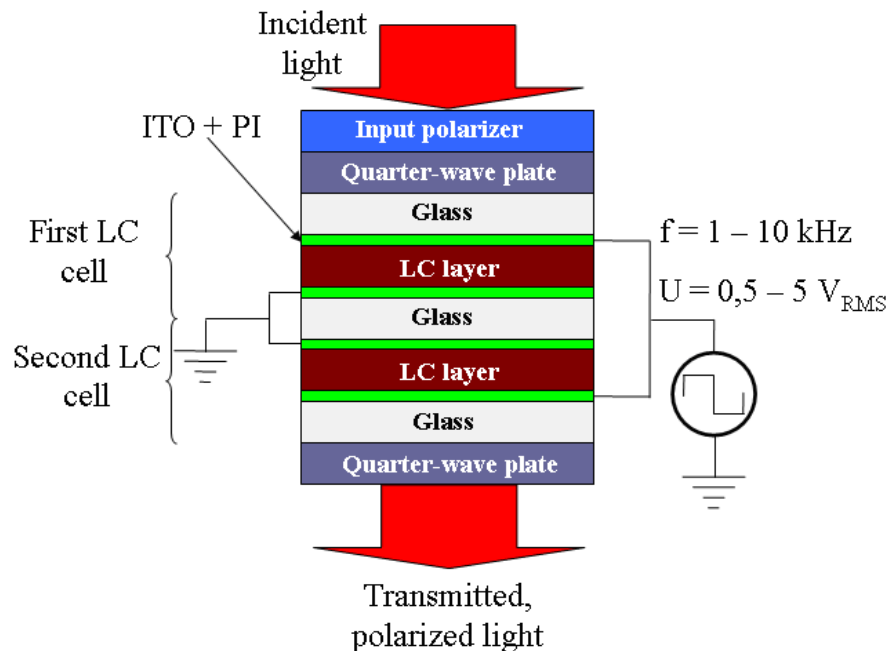
The resonance condition

$$f_{RF} = f_L = \frac{\gamma}{2\pi} B_0$$



Liquid Crystal (LC) Polarization Rotator

- Piezoelectric motor replaced by a LC polarization rotator (*Patented: FR1161946*)
 - Size and power consumption reduction
 - No moving part: no mechanical vibration during operation
 - Nonmagnetic structure → can be placed close to the gas cell
 - Technology issued from the LCD industry (low cost batch processing)



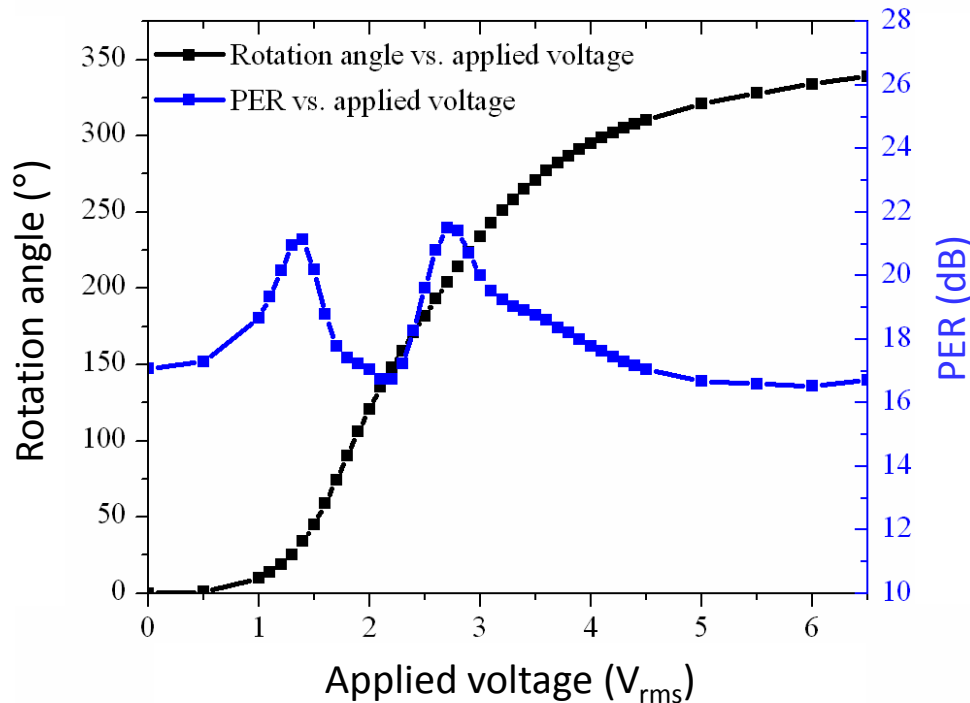
Swarm:
piezoelectric motor

LC rotator

Liquid crystal material: MLC2062
PI alignment layer : SE 7492 diluted with 2M solvent

Liquid crystal rotator performances

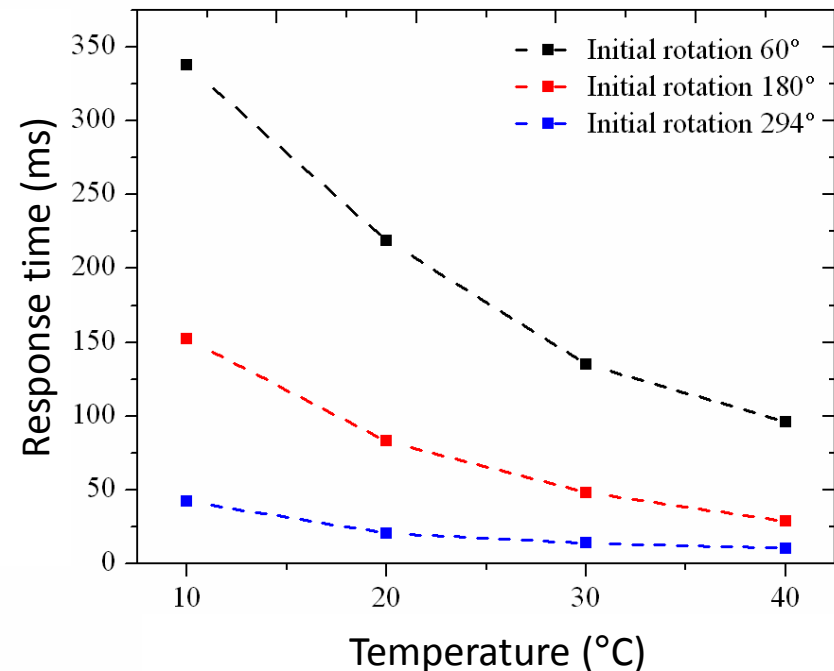
Static characteristics



- ✓ Continuous polarization rotation in the range of **0 to 300 degrees**
- ✓ PER $\sim 18 - 20$ dB

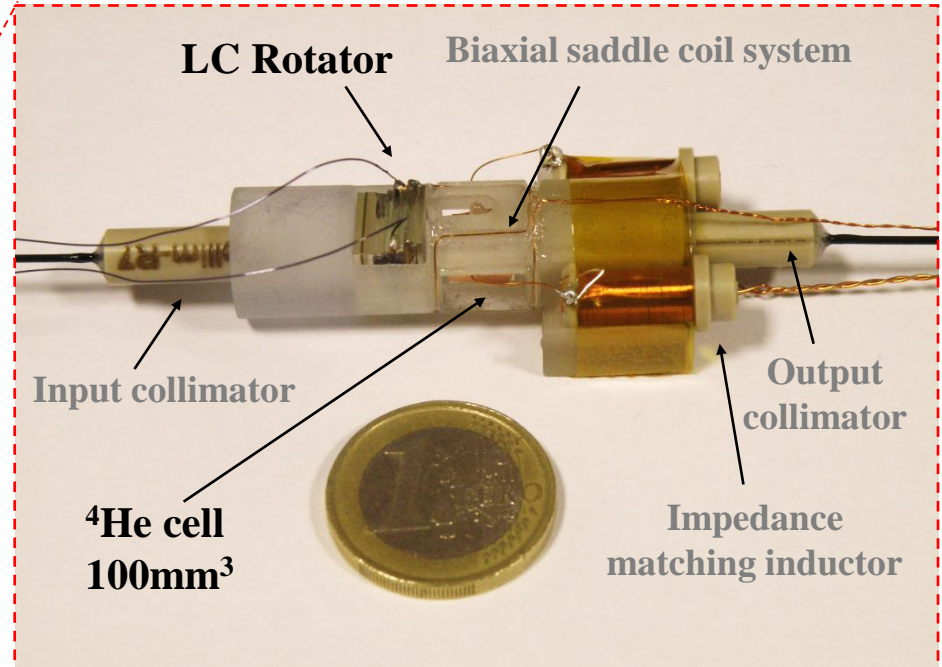
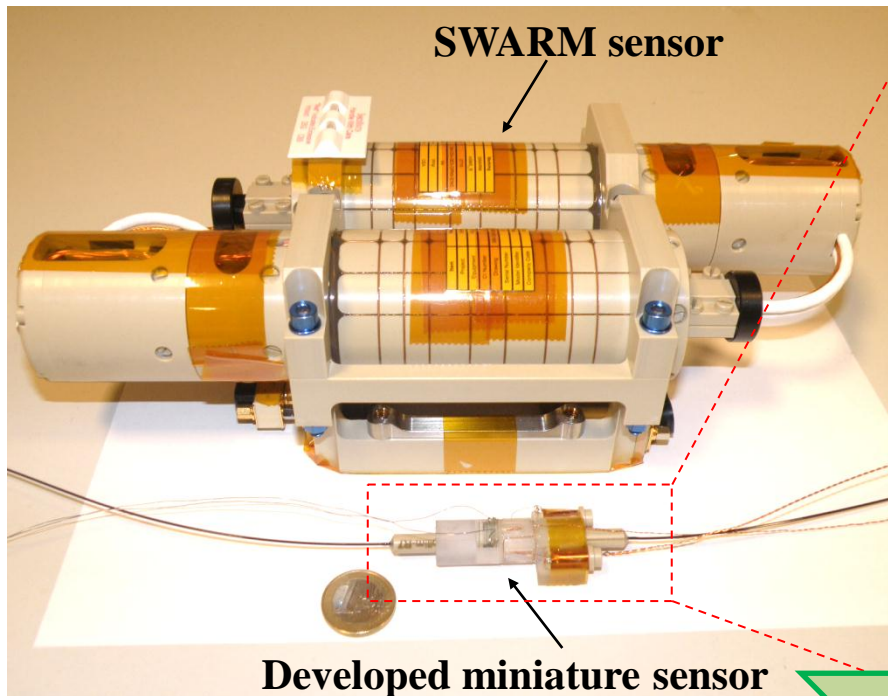
Dynamic characteristics

→ (rotation step of 5°)

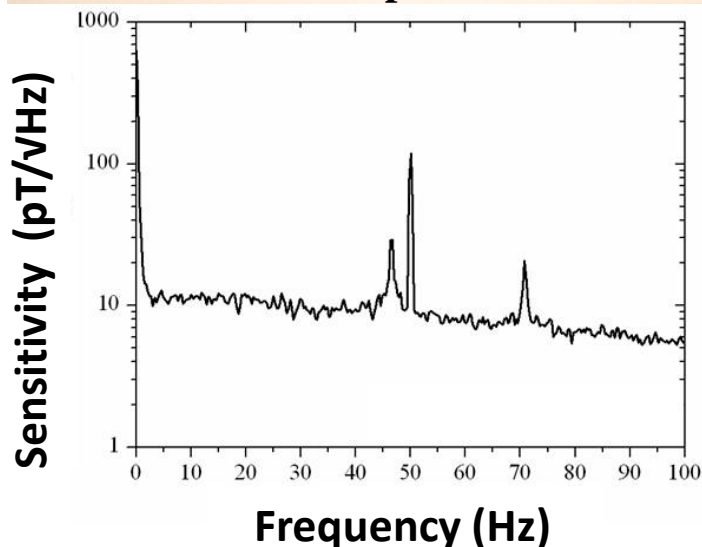


- ✓ Dynamic response in the range of **10-100 ms**, suitable for space applications!

Performances of the first demonstrator



FIRST DEMONSTRATOR OF A MINIATURE ISOTROPIC ATOMIC MAGNETOMETER

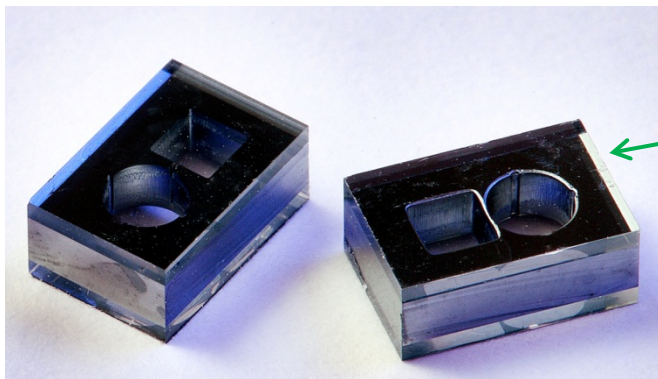
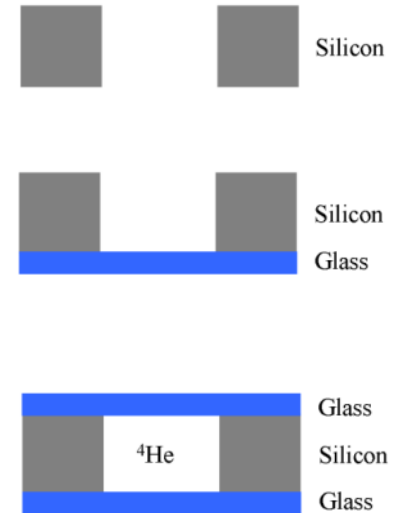


- ✓ Sensitivity: 10 pT/√Hz (*to be optimized...*)
- ✓ Bandwidth: DC – 100 Hz
- ✓ Liquid crystal polarization rotator
- ✓ Volume of the ASM sensor reduced by more than two orders of magnitude
- Accuracy: in progress...

Perspectives: Microfabricated Helium cells

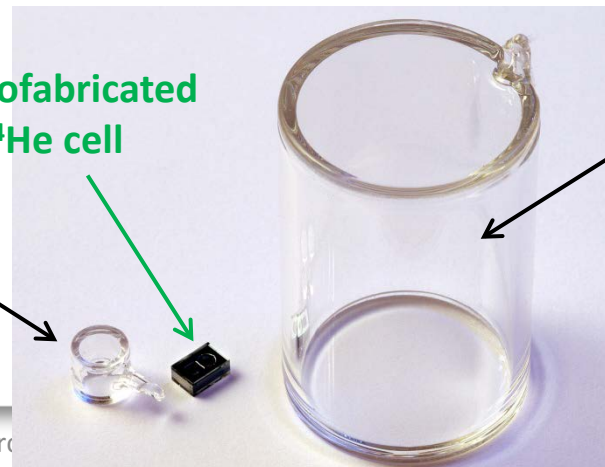
Fabrication steps:

- 1) Through-wafer cavities dry etched in a 1.3 mm thick silicon substrate
- 2) First anodic bonding: Si substrate bonded to a first pyrex wafer (500 μm)
- 3) 2nd anodic bonding in a chamber filled with ^4He gas at the desired pressure.
 - Cell pre-sealed in He gas atmosphere at a voltage lower than the breakdown voltage of the gas in the chamber.
 - Final bonding: the sample is bonded at a higher voltage (900 V) in air.



100 mm³
glassblown
cell

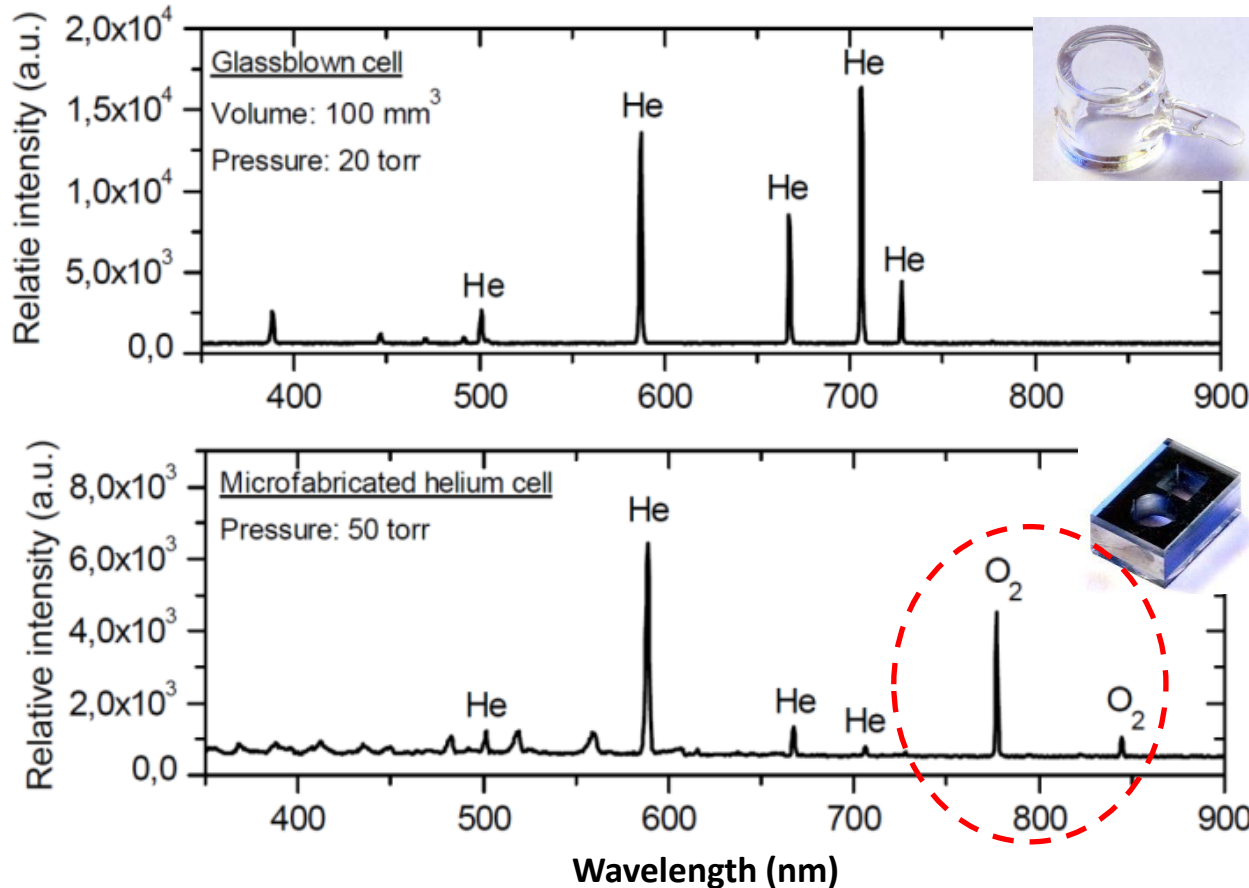
Microfabricated
 ^4He cell



Swarm:
glassblown cell

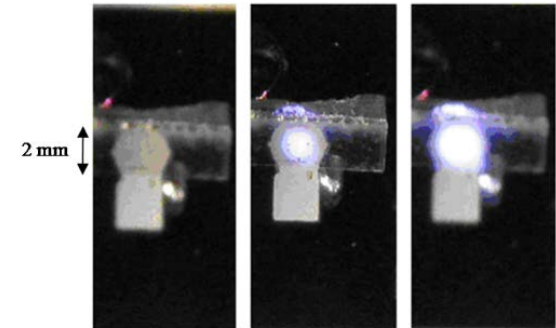
Perspectives: Microfabricated Helium cells

➤ Internal gas purity inspected by optical emission spectroscopy



Miniature glassblown cell

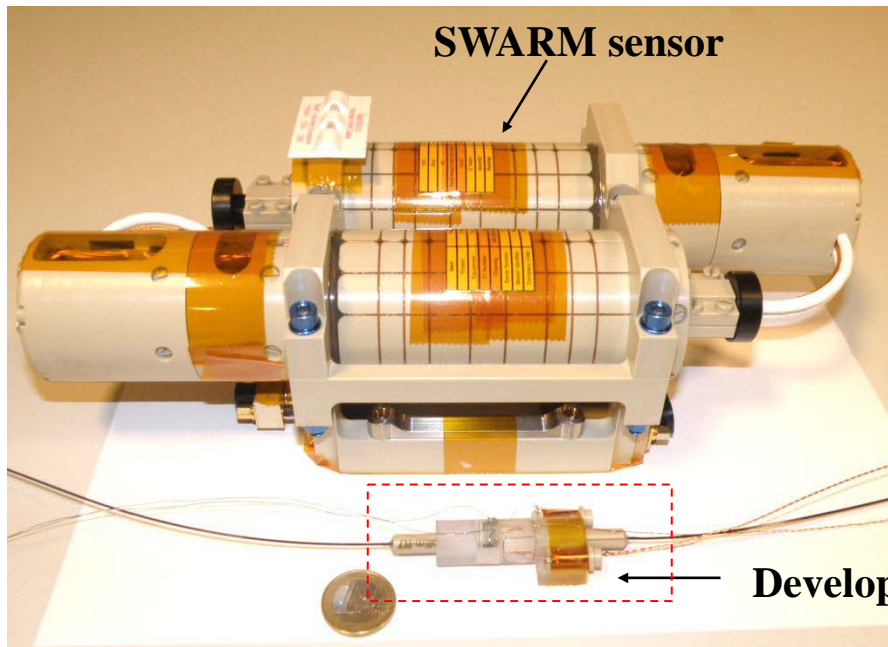
Microfabricated MEMS cells



- High ignition power (3-4 W)
- Unstable discharge
- Problems induced by the presence of O_2

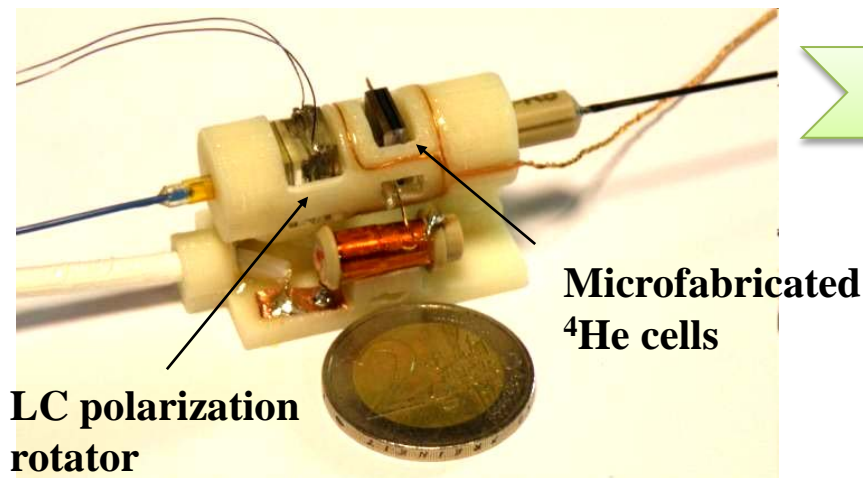
**OPTIMIZATION OF THE GAS PURITY
IN PROGRESS !**

Conclusions & perspectives



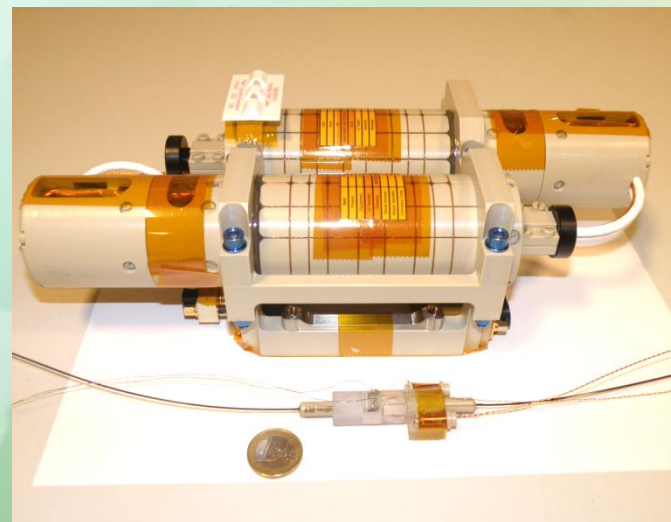
FIRST DEMONSTRATOR OF A MINIATURE ISOTROPIC ATOMIC MAGNETOMETER

- ✓ Sensitivity: 10 pT/√Hz, [DC – 100] Hz
- ✓ Liquid crystal polarization rotator



PERSPECTIVES

- Detailed study of the accuracy
- Development of dedicated electronics
- Optimization of microfabricated gas cells
- Integration of the microfabricated ^4He cells with the polarization rotator.



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Thank you for your attention!