The caesium magnetometer array for the n2EDM experiment

Duarte Pais
on behalf of the nEDM collaboration at PSI

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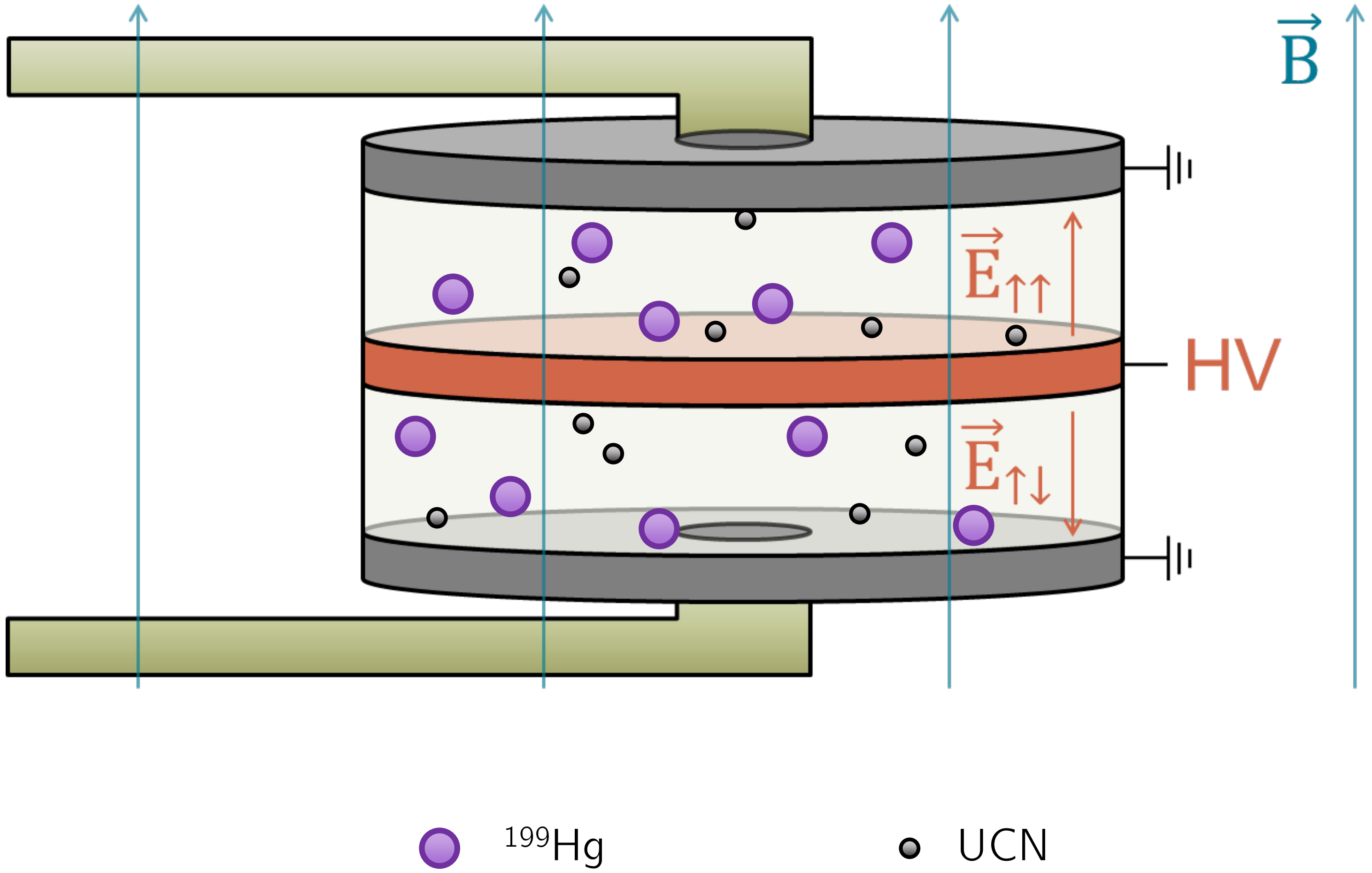
1. The n2EDM experiment: double chamber



The double chamber allows the simultaneous measurement of:

$\omega_{n,\uparrow\uparrow}$ for $\vec{B} \uparrow\uparrow \vec{E}$ (parallel)

$\omega_{n,\uparrow\downarrow}$ for $\vec{B} \uparrow\downarrow \vec{E}$ (anti-parallel)

The $|\langle\vec{B}\rangle|$ for both chambers is monitored with a ^{199}Hg co-magnetometer (HgM).

A $\vec{B}$ drift correction is possible, which can be (simply) thought of correcting ω_{RF} with the term $\frac{\gamma_n}{\gamma_{Hg}}\omega_{Hg}$

1. The n2EDM experiment: d^{false}

Both UCN and 199 Hg experience a $\boldsymbol{d^{false}}$ effect, which arises from their motion in $\vec{E}$.

	^{199}Hg	Neutron
RMS velocity	≈ 200 m.s^{-1}	few m.s^{-1}
Precession frequency	$\omega_{\mathrm{Hg},L} = \gamma_{\mathrm{Hg}}\,\lvert\vec{B}\rvert$	$\omega_{n,L} \approx 3.8\ \omega_{\mathrm{Hg},L}$
Magnetic field sampled after T	$\lvert\langle\vec{B}\rangle\rvert$	$\langle\lvert\vec{B}\rvert\rangle$

However, due to their different sampling regimes

e.g. $$\boldsymbol{d_{Hg}^{false}} \approx 20\left|d_n^{false}\right| = 3.3\times10^{-27}e.\mathrm{cm},$$

assuming a vertical gradient of $1\ \mathrm{pT/cm}$, the current chamber dimensions and an offset $\vec{B} = (0,0,1)\ \mu\mathrm{T}$.

Individual d^{false} expressions given in Abel, C. et al. Phys.Rev.A 99, 4 (2019)

1. The n2EDM experiment: d^{false}

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For more on this topic, see Thomas Bouillaud's talk

So the HgM correction $\frac{\gamma_n}{\gamma_{\text{Hg}}}\omega_{\text{Hg}}$ introduces a systematic shift to d_n.

The $\boldsymbol{d^{false}}$ induced by the HgM reading on the neutrons is

$$d^{false}_{\text{Hg}\to n} = \left|\frac{\gamma_n}{\gamma_{\text{Hg}}}\right| d^{false}_{\text{Hg}} \approx 3.8\, d^{false}_{\text{Hg}}.$$

Considering the previous gradient example,

$$d^{false}_{\text{Hg}\to n} \approx 1.3 \times 10^{-26} e.\text{cm}$$

(10x n2EDM goal experimental sensitivity)
[arXiv:2101.08730]

1. Tackling the systematic $d^{false}_{\mathrm{Hg}\to n}$

A convenient representation of $\vec{B}$ in spherical harmonics [Abel, C. et al. Phys.Rev.A 99, 4 (2019)] allows the representation of $d^{false}_{\mathrm{Hg}\to n}$ in terms of the gradients $G_{l,0}$ (k_l are simple coefficients)

$$d^{false}_{\mathrm{Hg}\to n} = -\frac{\hbar|\gamma_{\mathrm{n}}\gamma_{\mathrm{Hg}}|}{2c^2}\sum_{l,m} \mathbf{G_{l,m}} \langle \rho \Pi_{\rho,l,m} \rangle = k_1 G_{TB} + k_3 G_{3,0} + k_5 G_{5,0} + \cdots$$

$\mathbf{G_{l,m}}$ are the magnetic field gradients

HgM

(online)

see Selim Touati's talk

Field mapper

(offline) see Kseniia Svirina's talk

Caesium magnetometer array

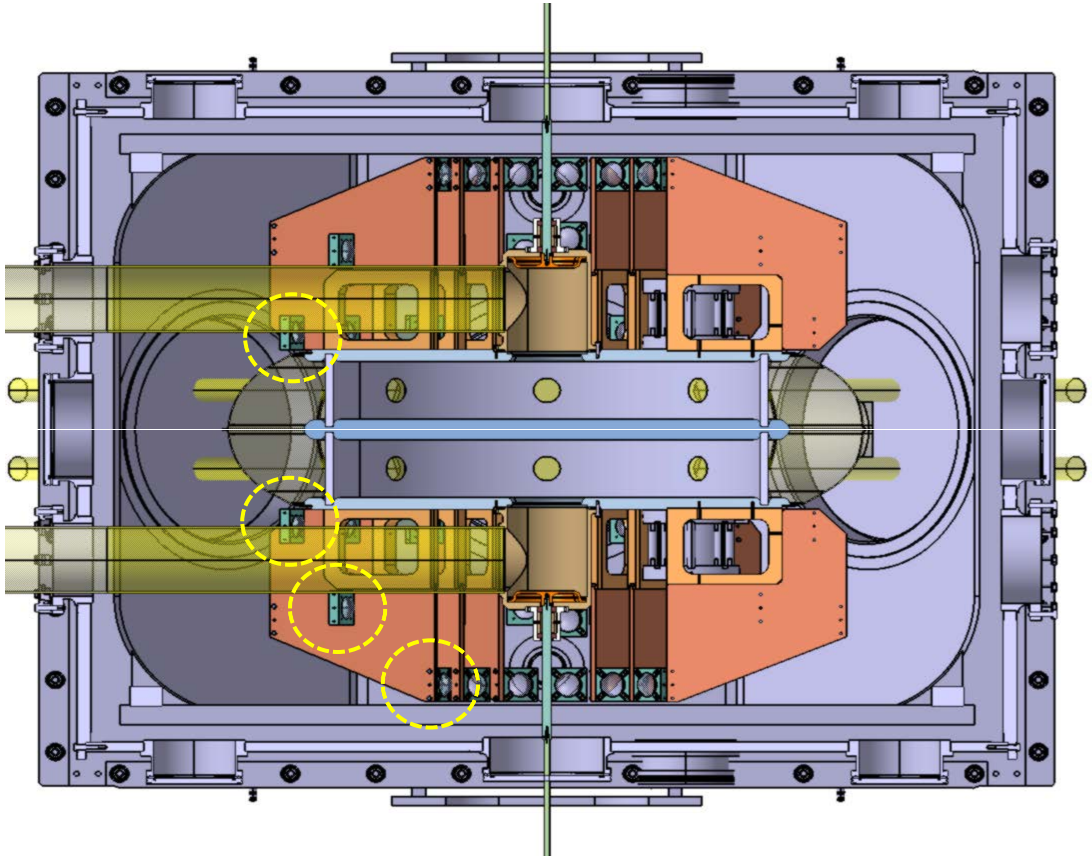
(online)

2. The caesium magnetometer array subsystem

Characterisation Goal:
$\Delta(k_3 G_{3,0}) \leq 3 \times 10^{-28}\ e.\mathrm{cm}$

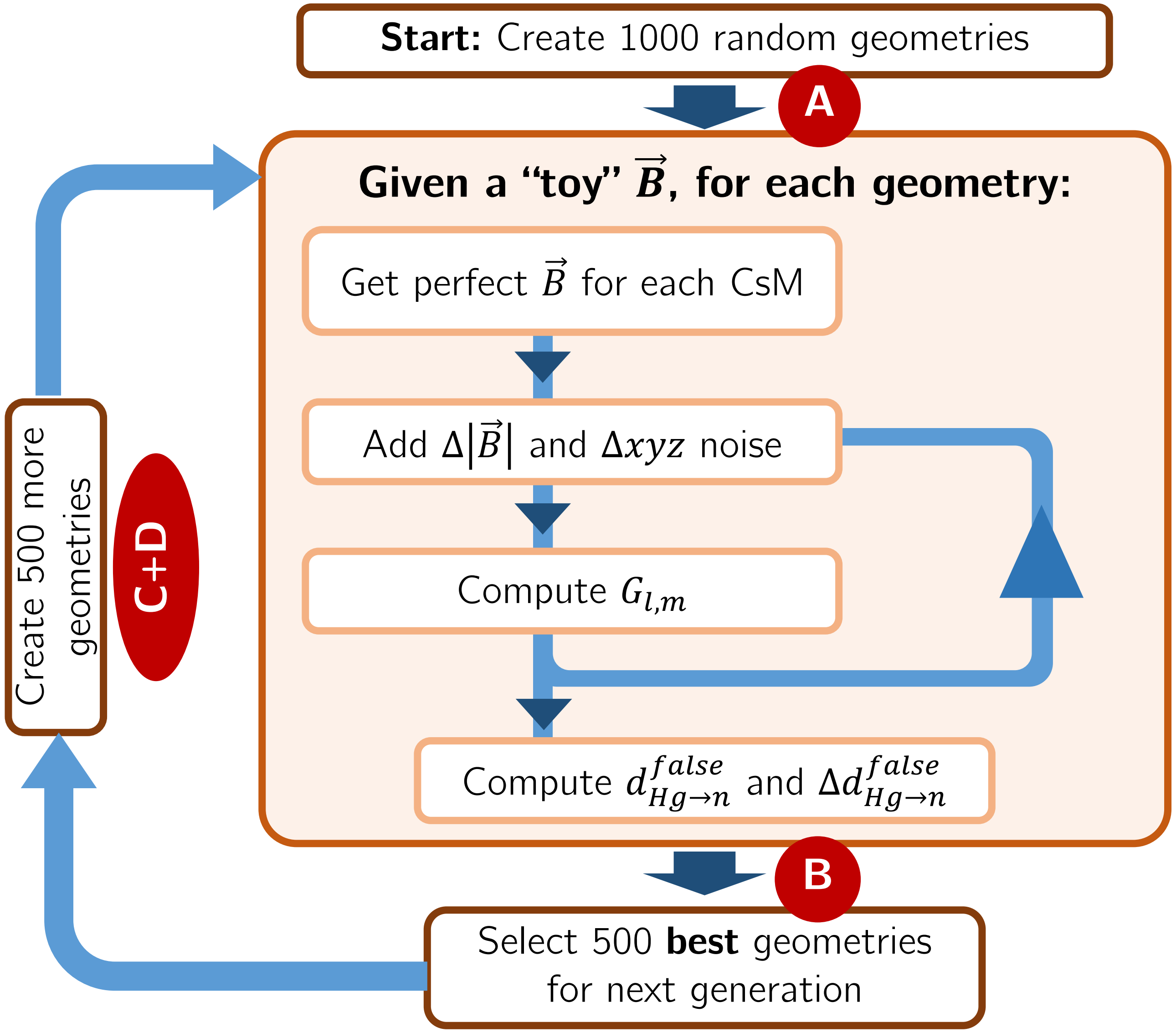
This is possible with an **array of caesium magnetometers (CsM).**

$|\vec{B}|$ at CsM xyz → $G_{l,m}$ are calculated → $d^{\text{false}}_{\text{Hg}\rightarrow\text{UCN}}$ is characterised



To ensure this performance, the geometry of the array has been optimised with a genetic algorithm.

2. The CsM array: genetic algorithm



A Gene pool

The genes of one individual are the (x_i, y_i, z_i) coordinates of its sensors

B Selection

Fittest individuals survive

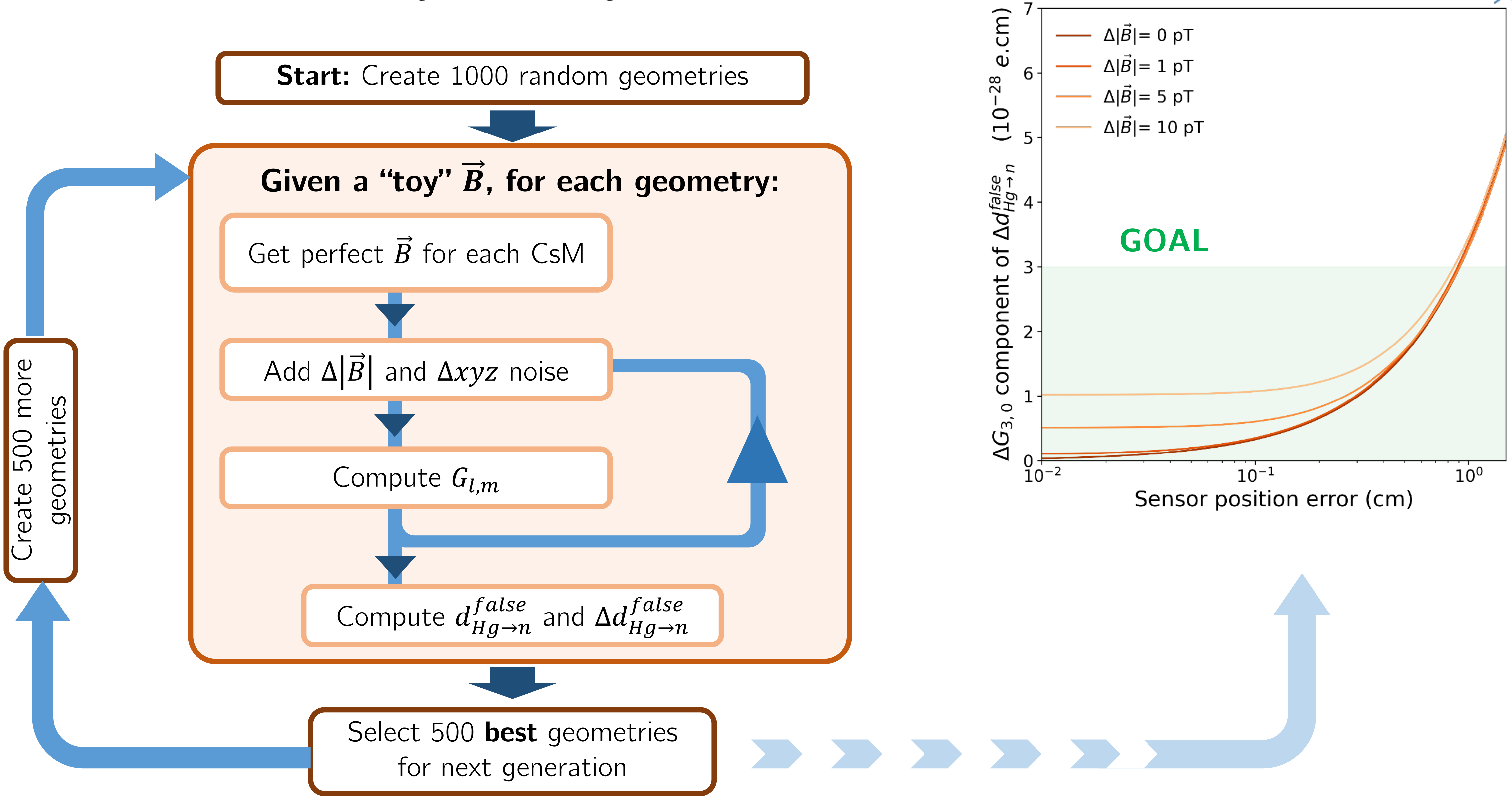
C Crossover

The genes of the fittest individuals are mixed to generate new ones

D Mutation

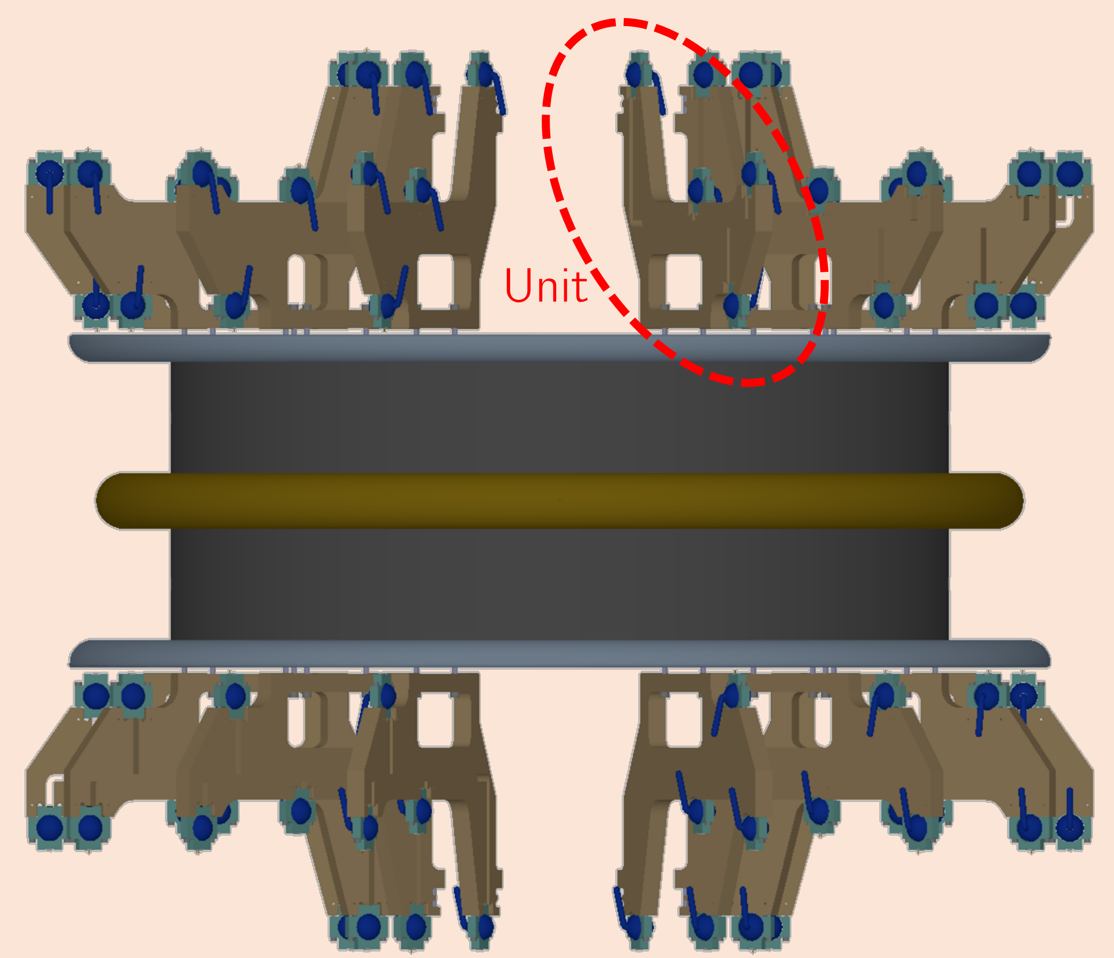
The genes of random individuals are changed.

2. The CsM array: genetic algorithm

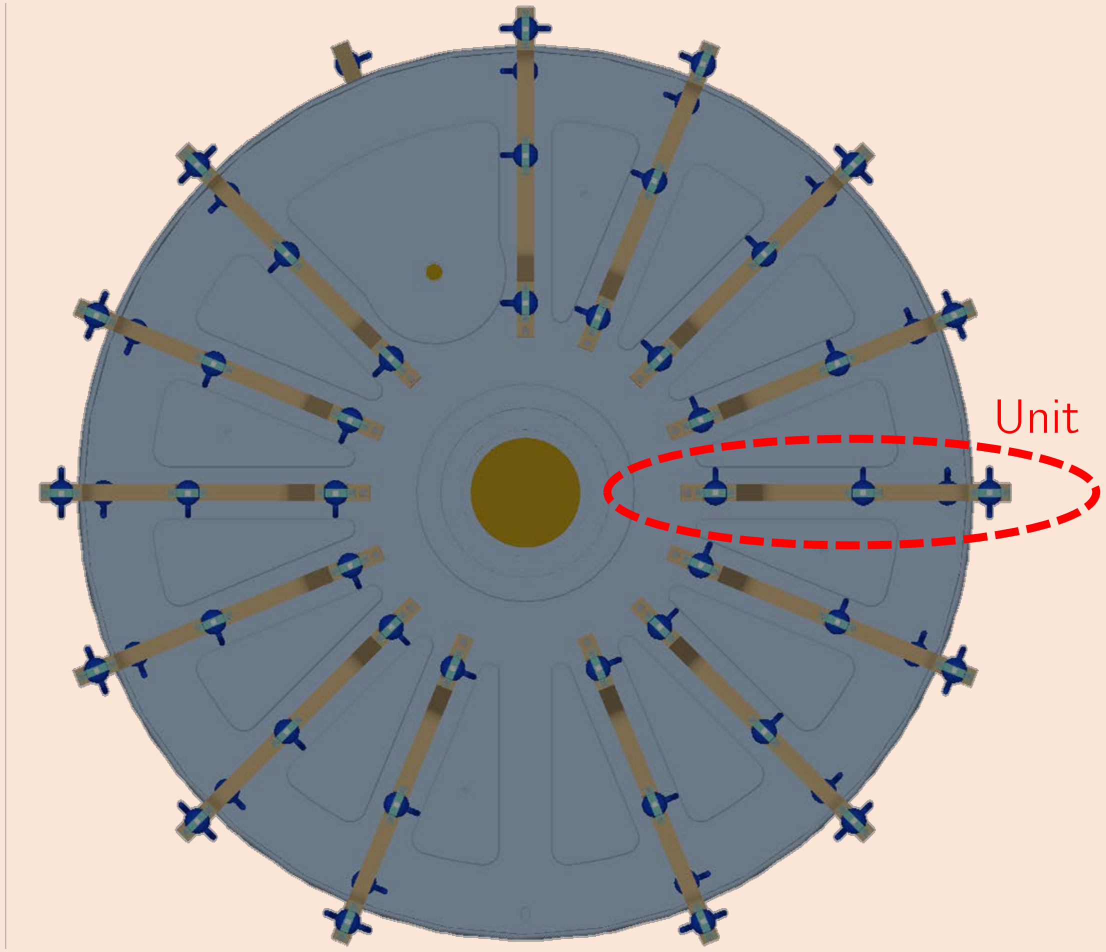


2. The CsM array: current geometry

Side view

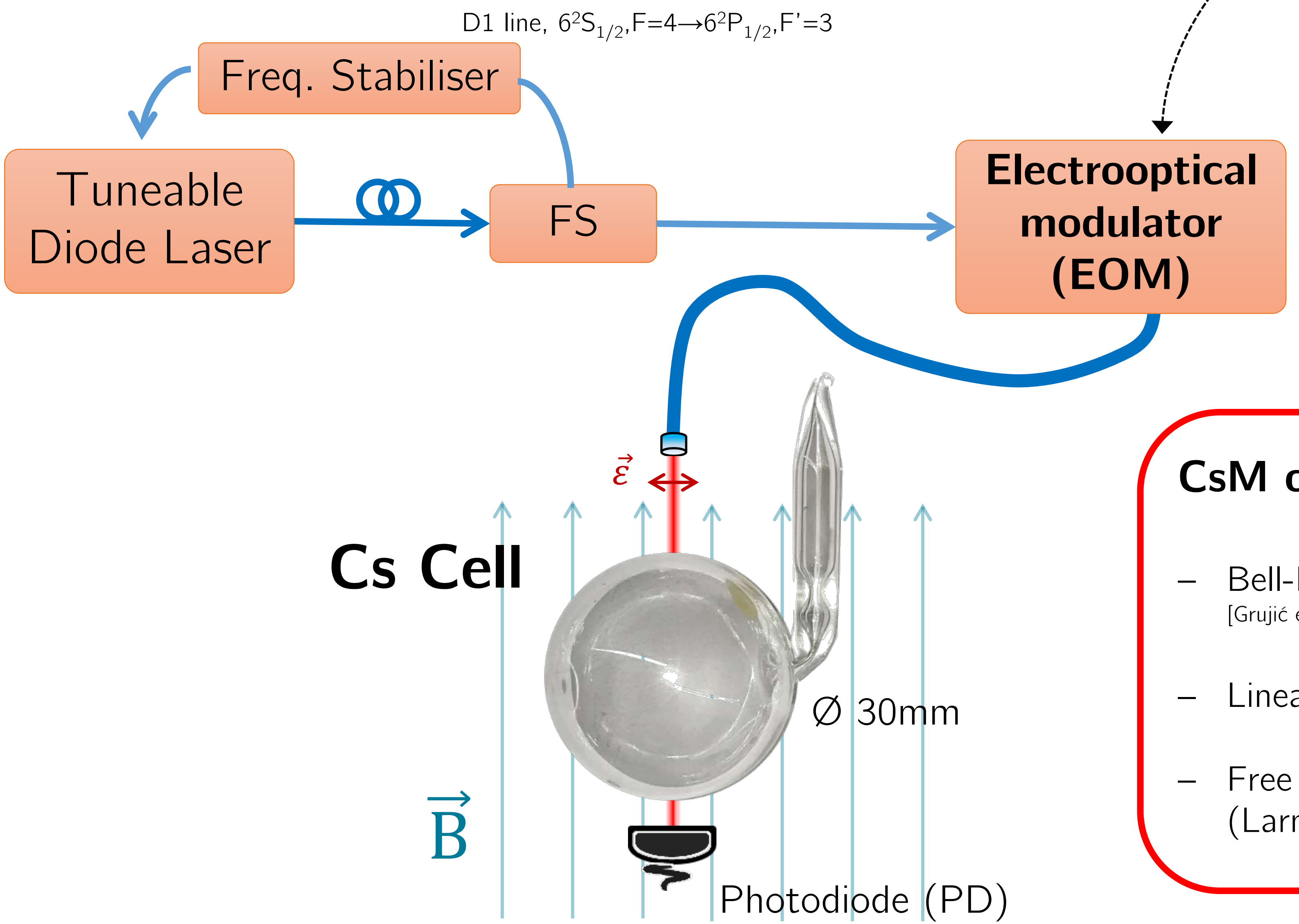


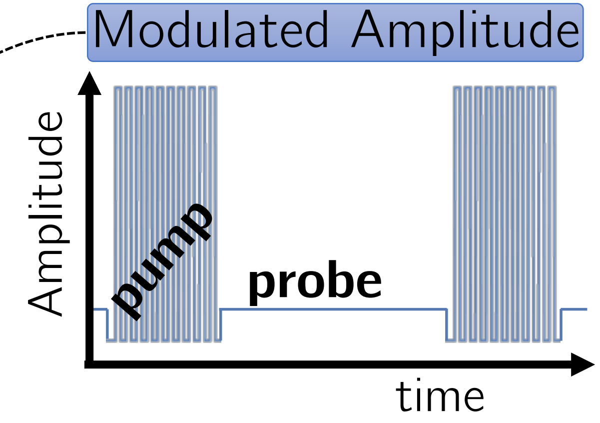
Top view



4 CsM per unit ⇒ 14 units at the top + 14 units at the bottom ⇒ 112 CsM in total

3. The caesium magnetometer





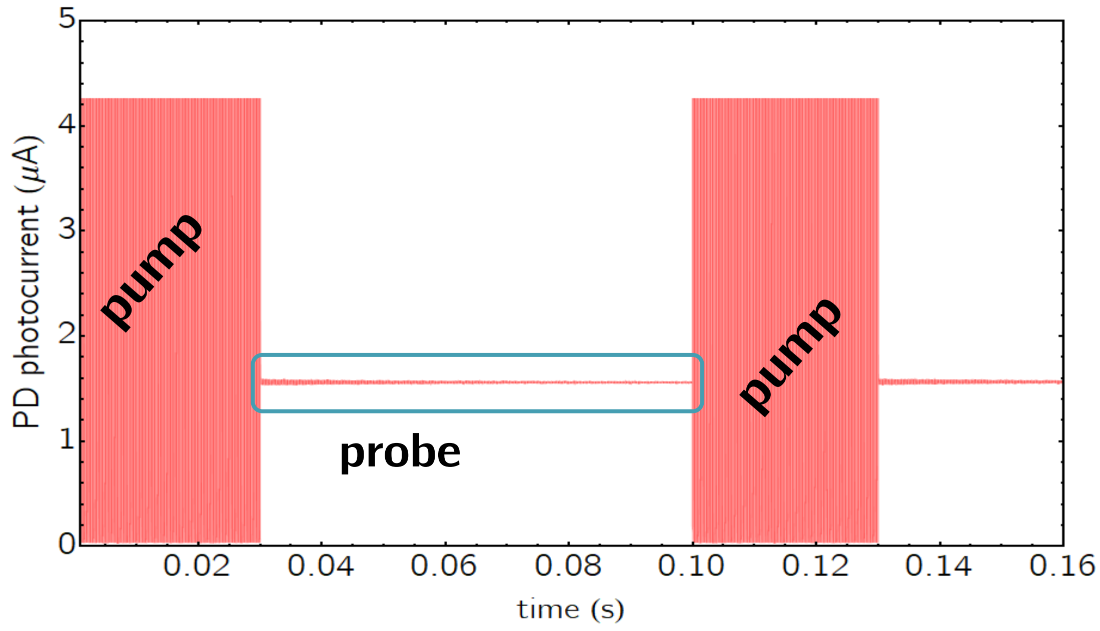
CsM characteristics:

- Bell-Bloom type, with modulated amplitude [Grujić et al., EPJ D (2015)]
- Linear polarisation $\vec{\varepsilon} \perp \vec{B}$
- Free Alignment Precession (FAP) at $2\omega_L$ (Larmor frequency)

3. CsM: the signal

The recorded probe signal is demodulated to obtain ω_L.

Each CsM provides a $|\vec{\mathrm{B}}| = \frac{\omega_L}{\gamma_{\mathrm{Cs}}}$ measurement at a rate of 10 Hz.



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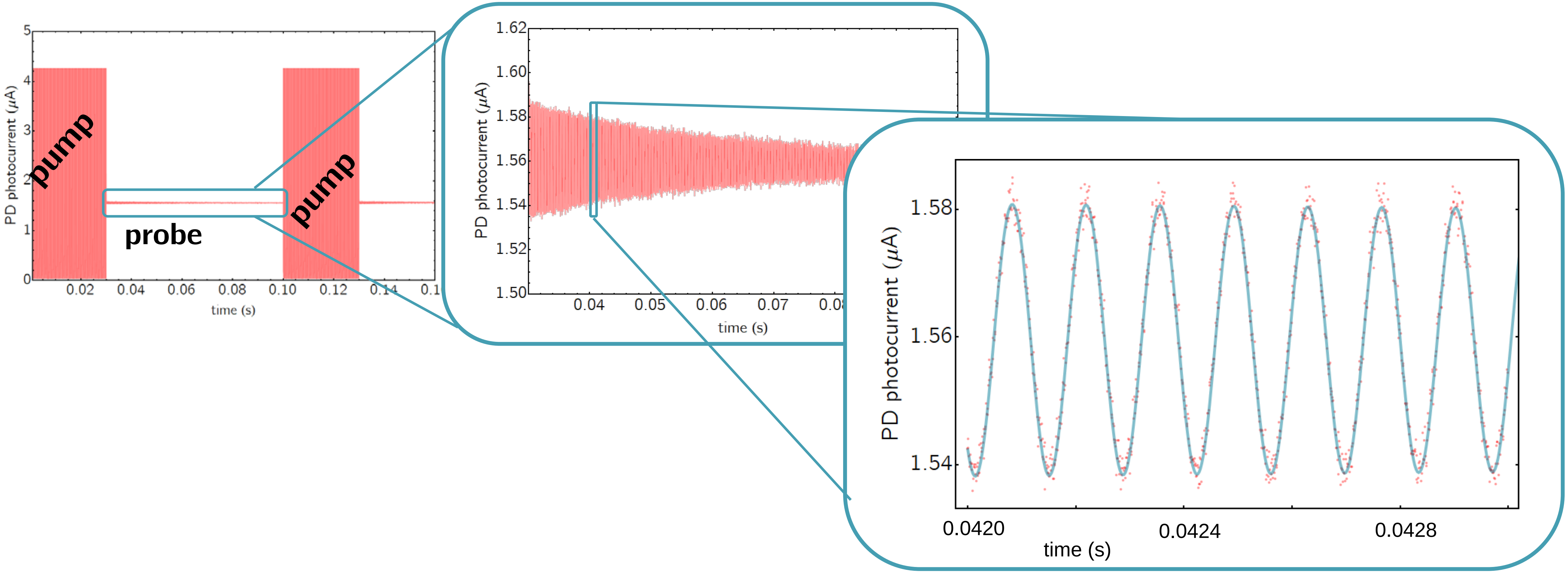


3. CsM: the cell

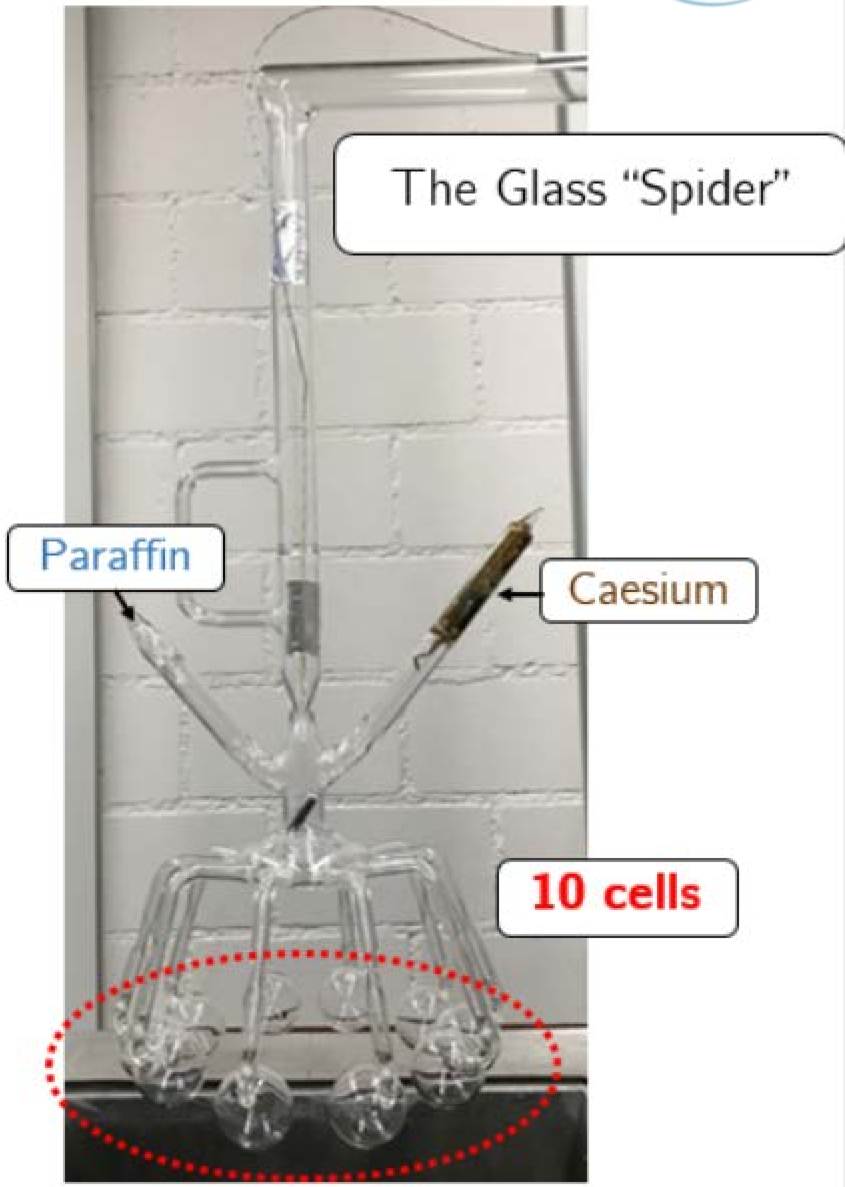
Adapted from procedure developed in the University of Fribourg arXiv:0812.4425

The cell is the only element of the CsM which is not available off-the-shelf. It contains:

- **saturated Cs vapour** – convenient hyperfine spectrum and vapour pressure at room temperature
- **paraffin** – anti-relaxation coating to maximise the T2 time of the signal

A 5-day long procedure, using 1 spider, allows the production of 10 cells. This is done by:

1. Evacuating the spider
2. Filling with paraffin
3. Filling Cs
4. Detaching all cells



79 / 112 ready to be used in CsM

4. Conclusion

1. The strategy to characterise $d_{\mathrm{Hg}\rightarrow n}^{false}$ has been devised; CsM array is essential to the monitor cubic gradient term (dependent on $G_{3,0}$).

2. The design of the optimised array is expected to achieve characterisation goal

3. Cs cells are currently under production. Once they are assembled in sensor modules, these need to be calibrated with respect to:
   - its measuring position (x,y,z)
   - its $|\vec{B}|$ measurement value

   A dedicated apparatus is currently being characterised to start these calibrations.

Thank you for your time