Development of a Caesium magnetometer array for the n2EDM experiment

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on behalf of the nEDM collaboration at PSI

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1. Baryogenisis, CP violation and the neutron EDM

The **Standard Model (SM)** does not account for the baryogenisis (i.e. why the known Universe is made of only matter and not a matter/antimatter mixture).

It has been established that to explain this:

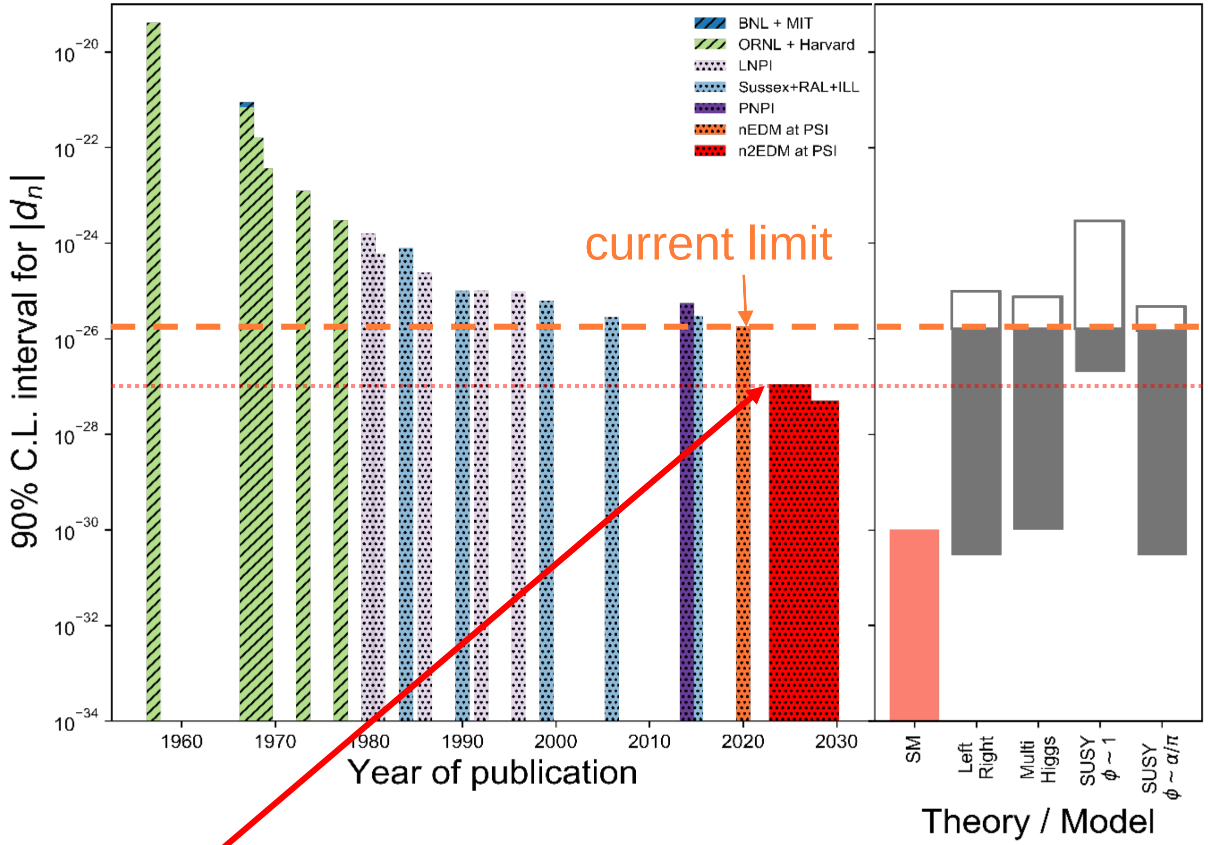
- CP violation processes/observables,

- B number violation and

- Departure from thermodynamic equilibrium are required [Sakharov, JETP Lett.(1967)].

Electric dipole moments of elementary particles and nucleons could provide the sources of CP violation that are required.

The SM prediction for the neutron **electric dipole moment (EDM)** d_n is too small of a CP source, however theories beyond SM predict much higher values.



adapted from Pendlebury & Hinds, NIM-A 440 (2000) 471

C. Abel *et al.*, Phys. Rev. Lett. 124, 081803

GOAL of n2EDM experiment: push down experimental limit of $|d_n| < 1.1 \times 10^{-27} e \cdot \mathrm{cm}$

C. Abel et al. arXiv:1811.02340

1.1 The neutron EDM d_n

If $d_n \neq 0$

The precession frequency of the neutron spin is $\omega_n = \left| \frac{2\vec{\mu}_n \cdot \vec{B}}{\hbar} \pm \frac{2\vec{d}_n \cdot \vec{E}}{\hbar} \right|$

$+$ for $\vec{B} \uparrow\uparrow \vec{E}$ (parallel)

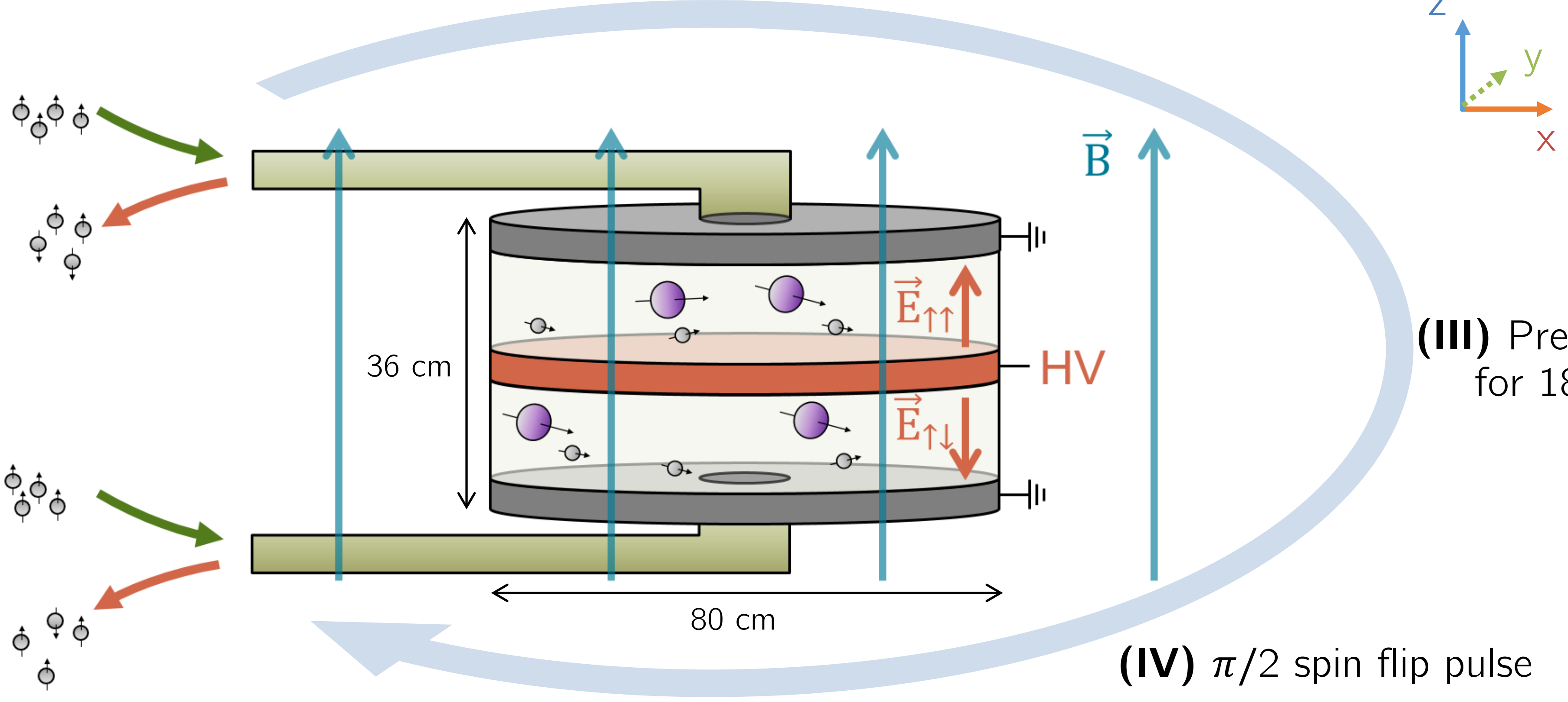
$-$ for $\vec{B} \uparrow\downarrow \vec{E}$ (antiparallel)

Measure $\omega_{\uparrow\uparrow}$ and $\omega_{\uparrow\downarrow}$ such that $\boldsymbol{d_n = \frac{\hbar}{4E}(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow})}$

2. The n2EDM experiment

(I) Polarised **ultra cold neutrons** (UCN) fill in the double chamber.

(II) $\pi/2$ spin flip pulse



(III) Precession for 180 s

(IV) $\pi/2$ spin flip pulse

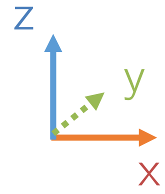
(V) UCN go out

(VI) Get $\omega_{\uparrow\uparrow/\uparrow\downarrow}$ from:

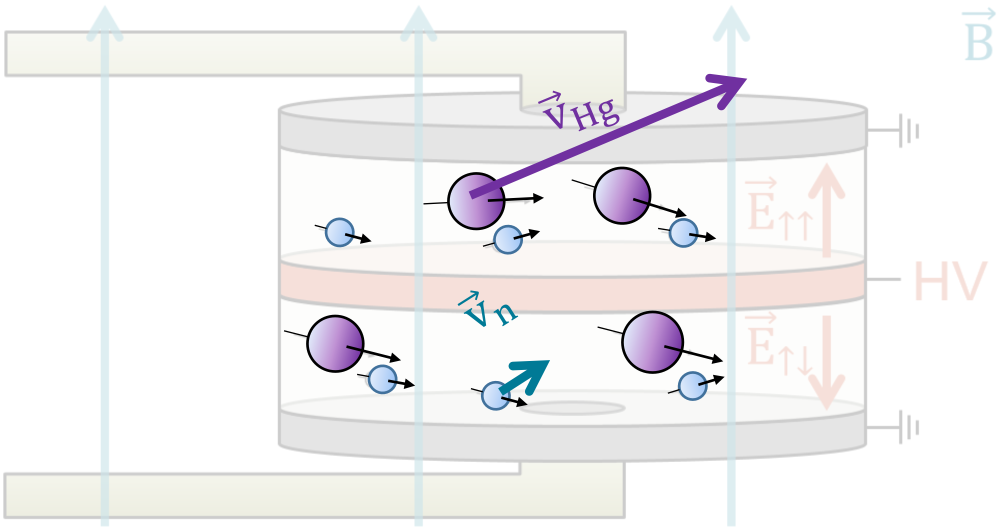
- UCN $_{\uparrow/\downarrow}$ counts
- $\langle|\vec{\mathbf{B}}|\rangle$ (^{199}Hg magnetometer)

2.1 The systematic shift $d_{\mathrm{Hg}\to n}^{\mathrm{false}}$

The neutrons are much slower and precess much faster than the Hg atoms.



$\vec{v}_n \ll \vec{v}_{Hg}$
and
$\gamma_n \approx 4\gamma_{Hg}$



If the $\vec{B}$ field is not perfect

$\langle|\vec{B}|\rangle \neq |\langle\vec{B}\rangle|$

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

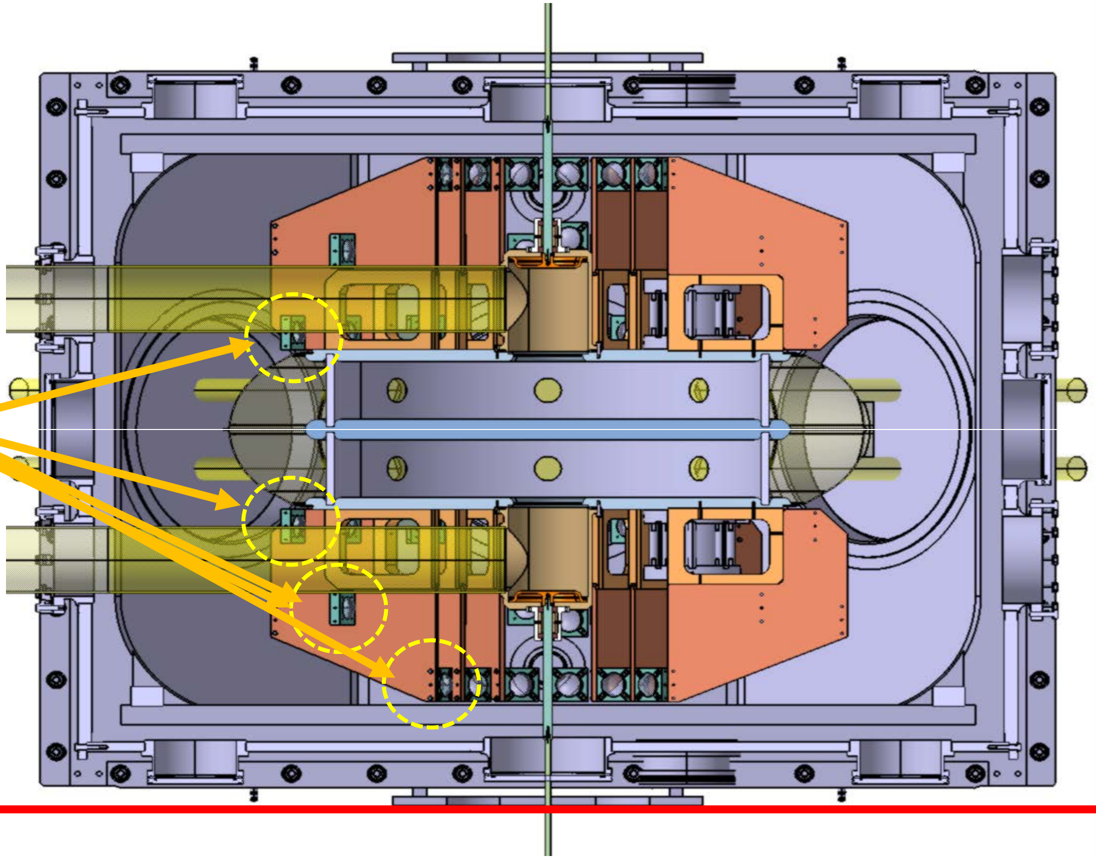
d_n **will be shifted by the amount**

$$d_{\mathrm{Hg}\to n}^{\mathrm{false}} = -\frac{\hbar|\gamma_n\gamma_{Hg}|}{2c^2}\sum_{l,m} G_{l,m}\langle\rho\Pi_{\rho,l,m}\rangle$$

[Abel et al., arXiv:1811.06085 (2018)]

2.2 The caesium magnetometer array subsystem

In the n2EDM experiment $|\vec{B}|$ will be monitored at different positions with an **array of 112 caesium magnetometers (CsM).**

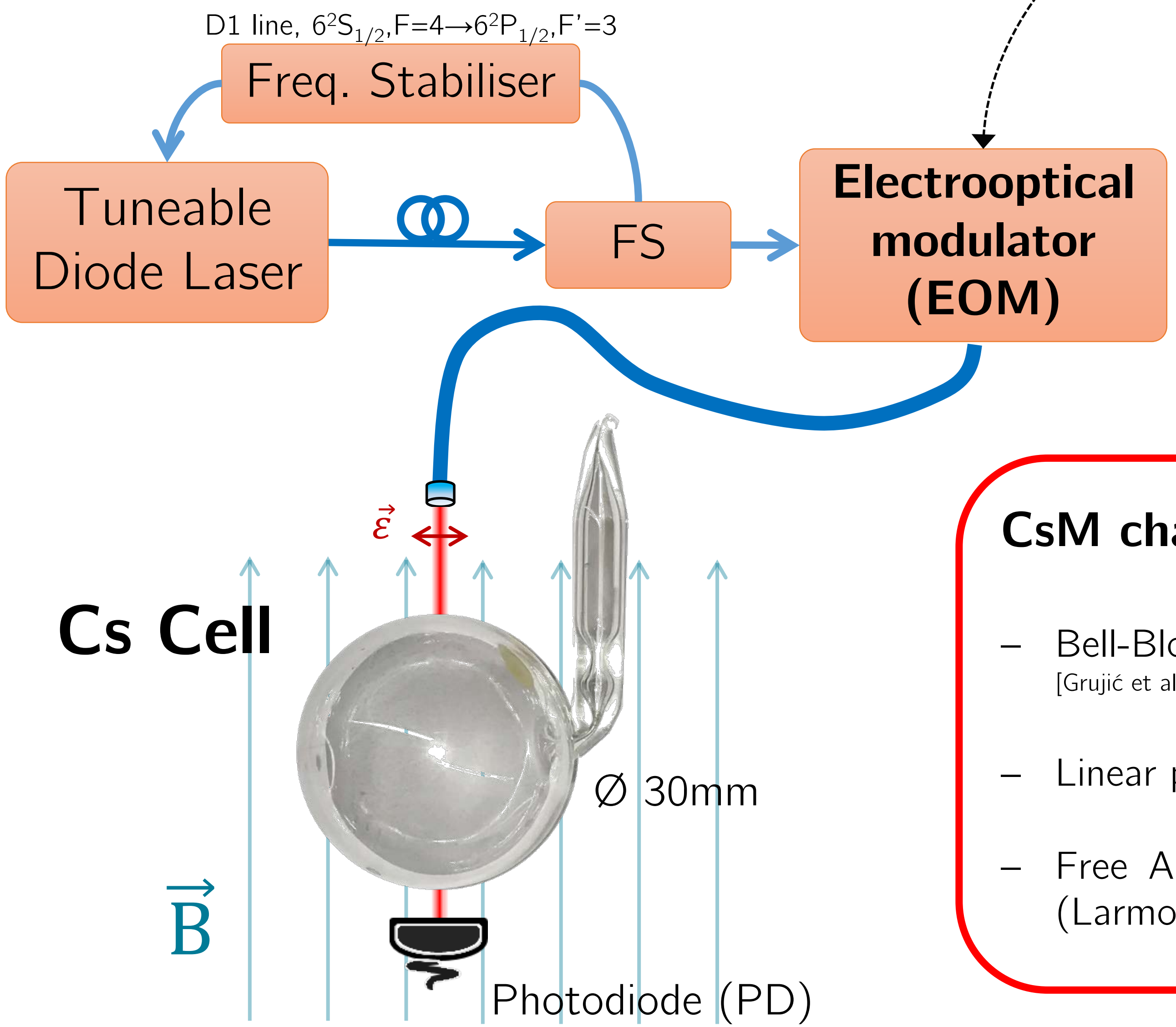


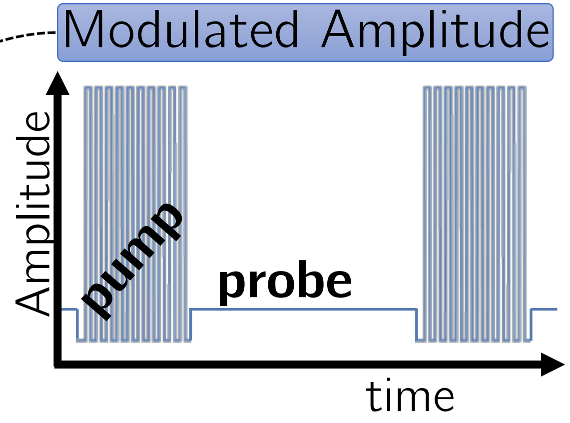
The CsM positions were calculated with a genetic algorithm.

The optimization focused on resilience against imprecision in their positions and magnetic field readings.

$|\vec{B}|$ at CsM xyz → $G_{l,m}$ are calculated → $d^{\text{false}}_{\text{Hg}\to\text{UCN}}$ is characterised (**Goal:** $\Delta d^{\text{false}}_{\text{Hg}\to\text{UCN}} < 4 \times 10^{-28} e \cdot \text{cm}$)

2.3 The caesium magnetometer

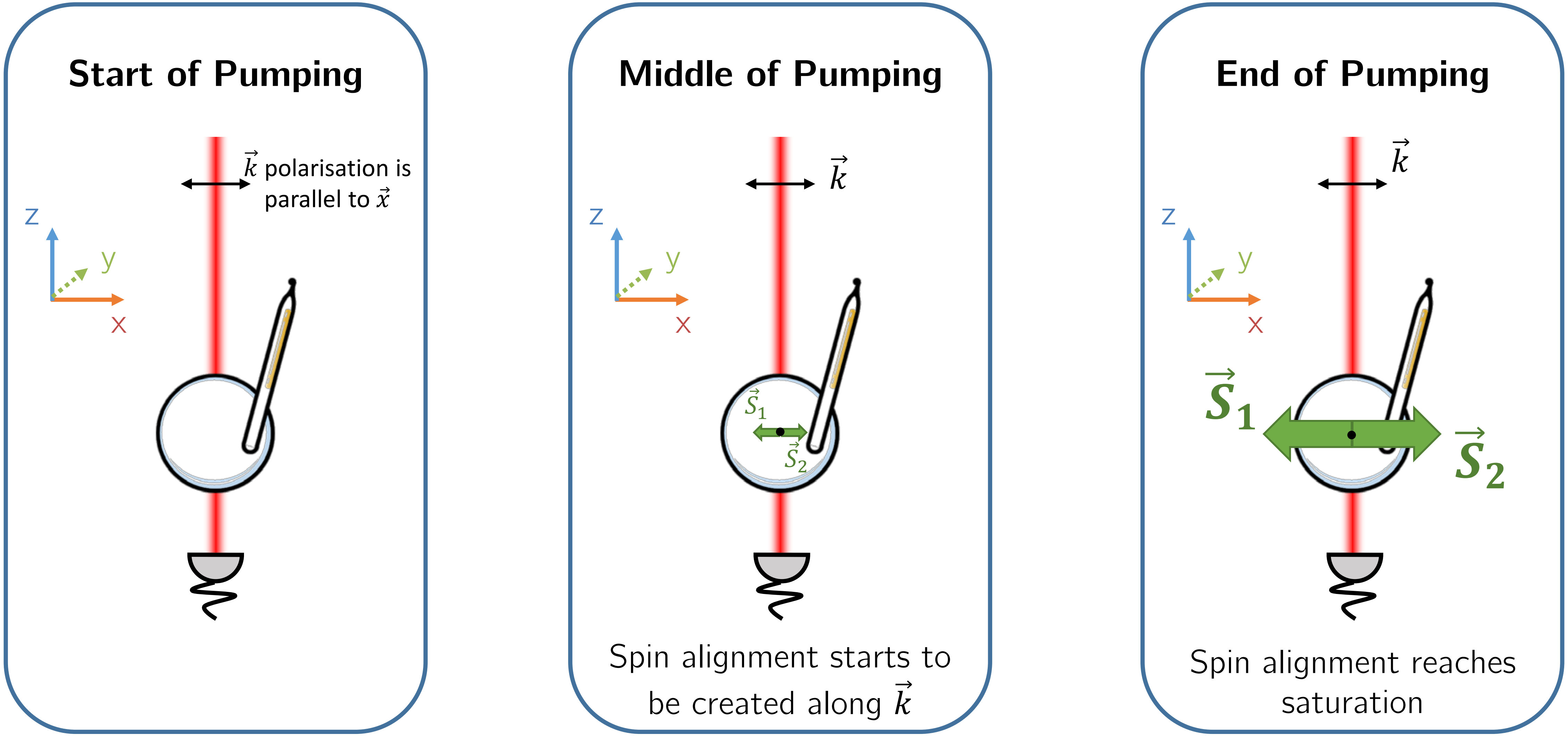




CsM characteristics:

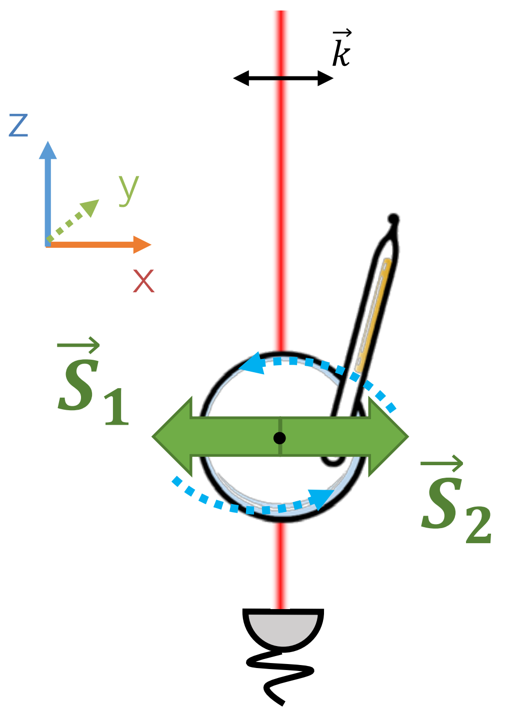
- Bell-Bloom type, with modulated amplitude
  [Grujić et al., EPJ D (2015)]
- Linear polarisation $\vec{\varepsilon} \perp \vec{B}$
- Free Alignment Precession (FAP) at $2\omega_L$ (Larmor frequency)

2.3.1 The caesium magnetometer: pump regime



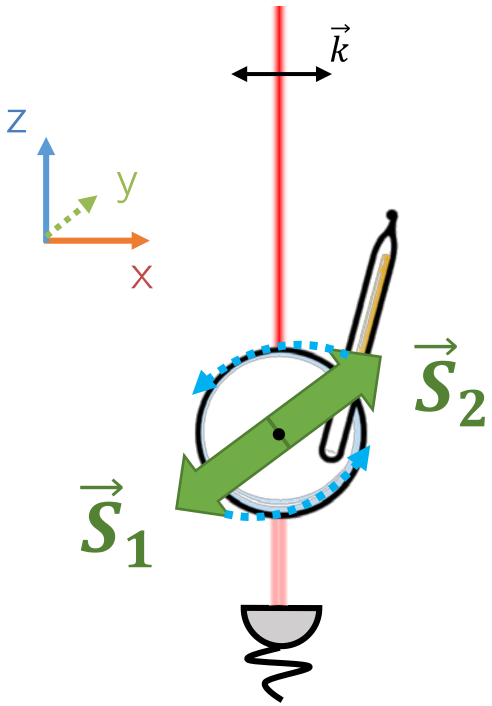
2.3.2 The caesium magnetometer: probe regime

Probing precession



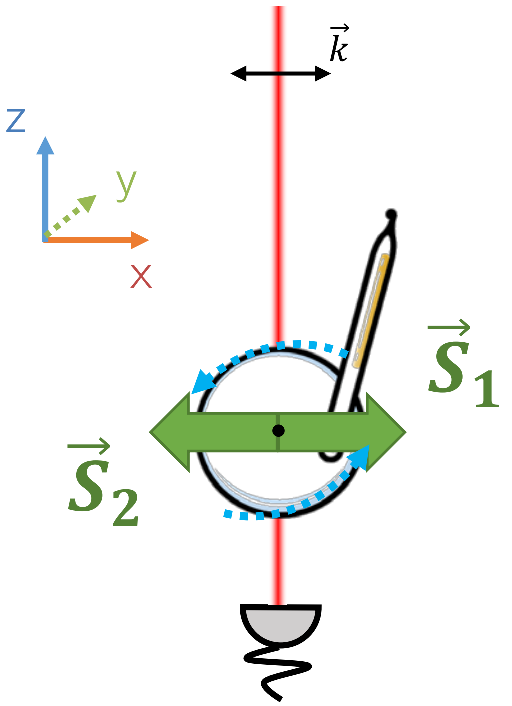
The aligned spins precess freely around $\vec{z}$

Probing precession



Whenever $\vec{S} \perp \vec{k}$, absorption is at its **maximum**

Probing precession

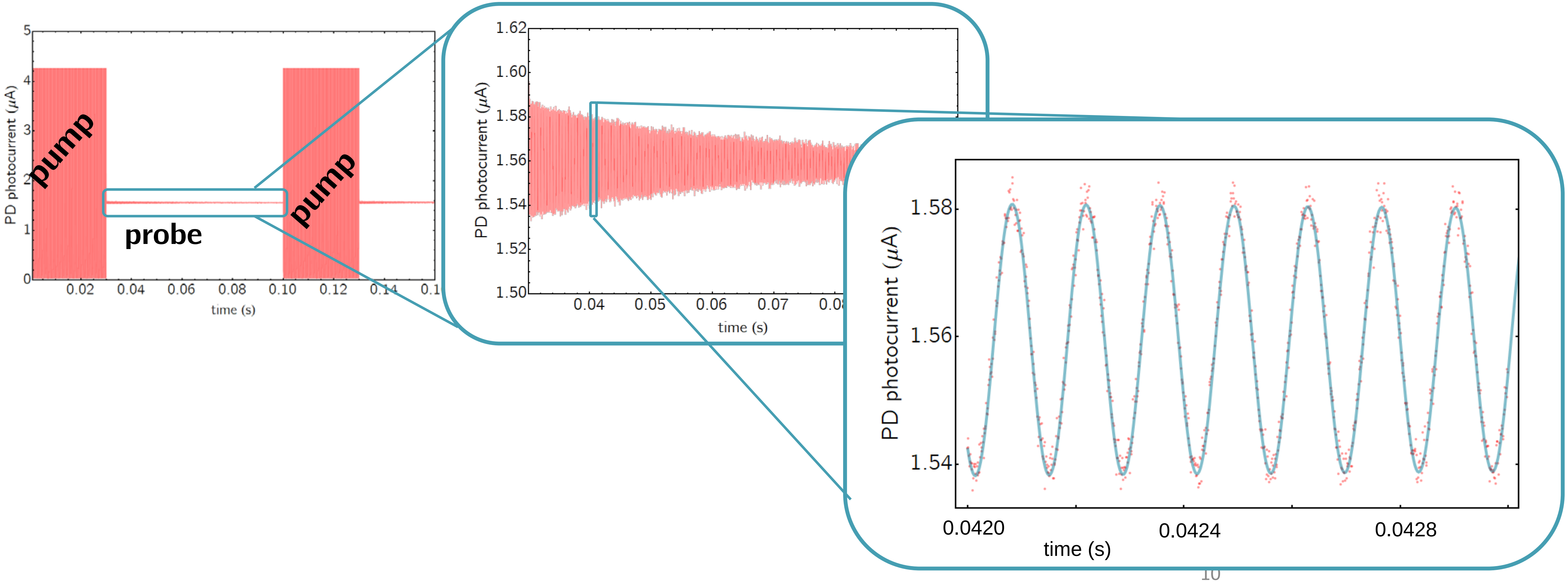


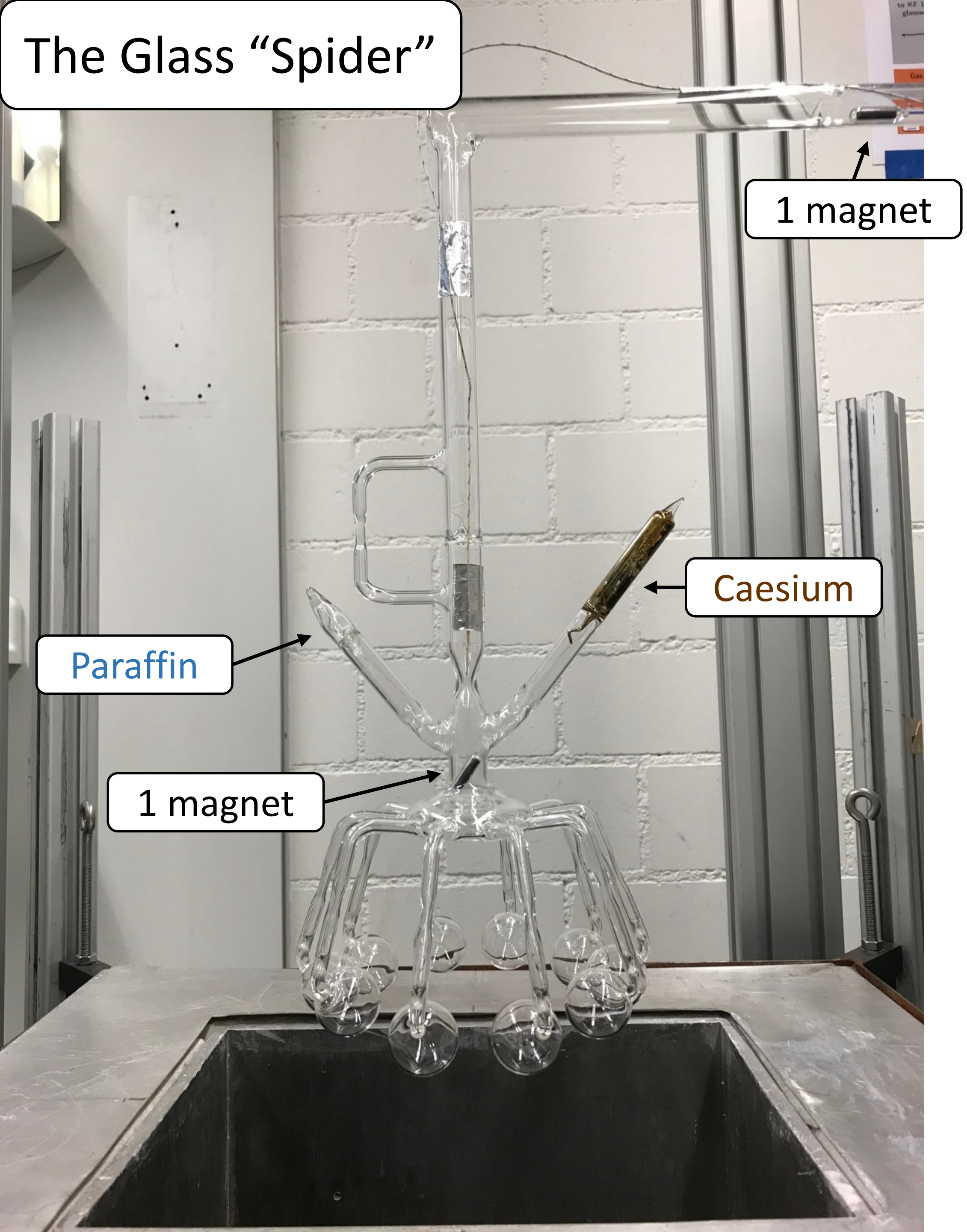
Whenever $\vec{S} \parallel \vec{k}$, absorption is at its **minimum**

2.3.3 The caesium magnetometer: signal

The recorded probe signal is demodulated to obtain ω_L.

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



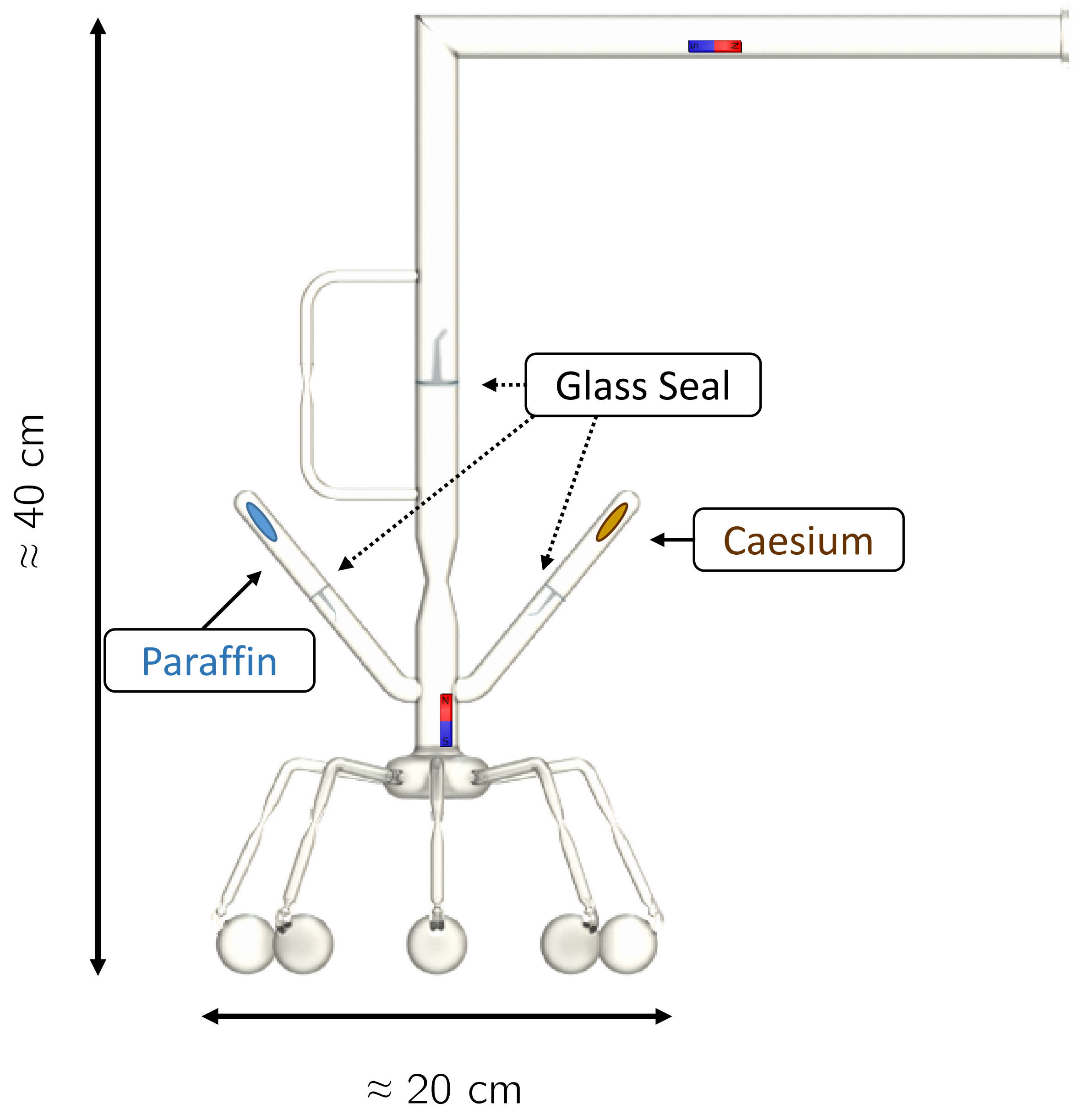


3. Recipe for a caesium magnetometer cell

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

- A glass "spider" (with 10 spherical bulbs)
- Three magnets
- An oven
- A hand torch
- A vacuum system

- A pinch of paraffin
- A pinch of pure caesium



Why Caesium?

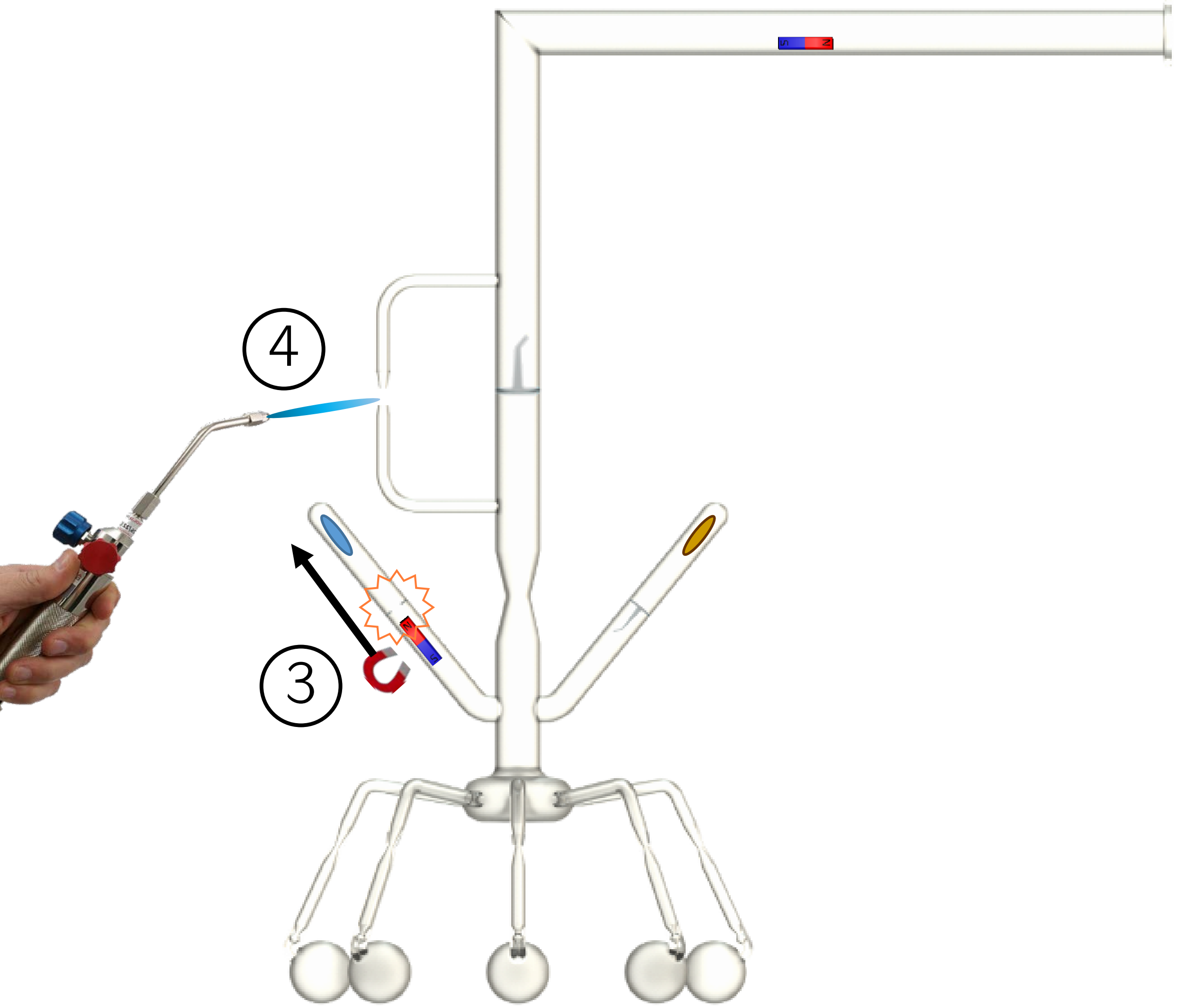
- Good amount of saturated vapour at room temperature.
- Convenient hyperfine spectrum for magnetometry.

Why Paraffin?

- Anti-spin-relaxation coating; it ensures T2 time (i.e. decay of oscillatory signal) is maximised

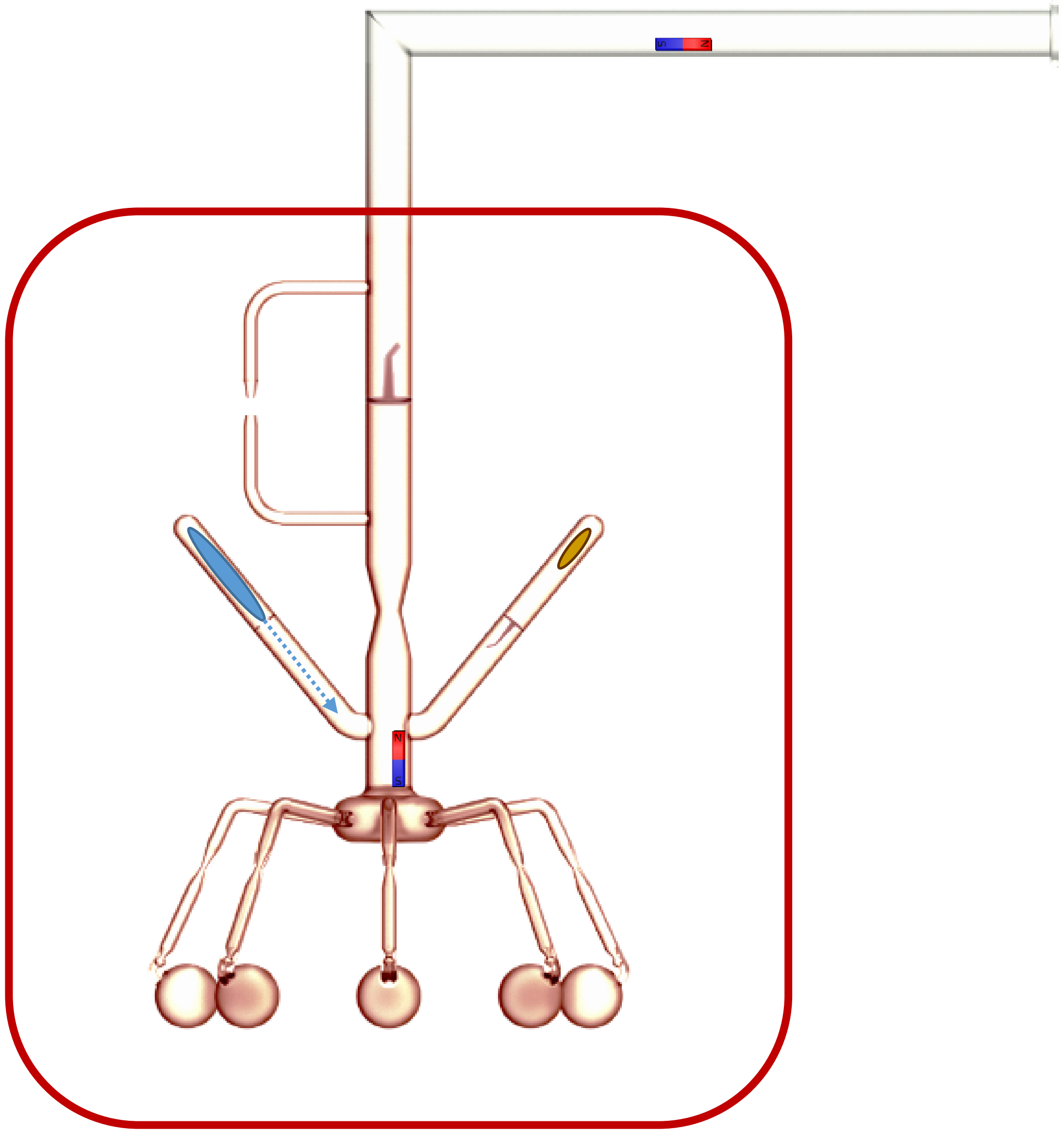
1. Prepare the “spider” with sealed ampoules of paraffin and caesium. Place two magnets inside it in the appropriate positions.

2. Connect the “spider” to the vacuum system and wait until the pressure right before the glass flange stabilises $< 10^{-6}$ mbar.

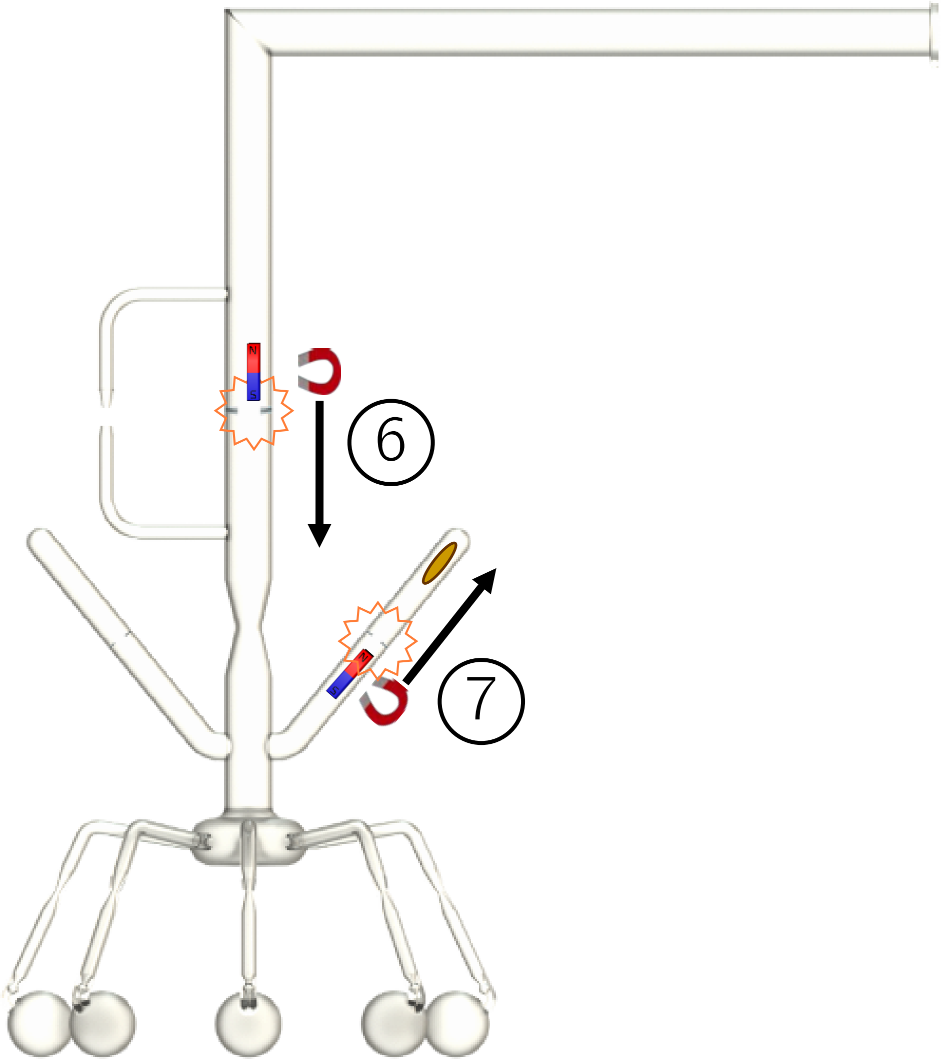


3. Break the paraffin seal.

4. Isolate the “spider” inner volume from the vacuum system with the hand torch.

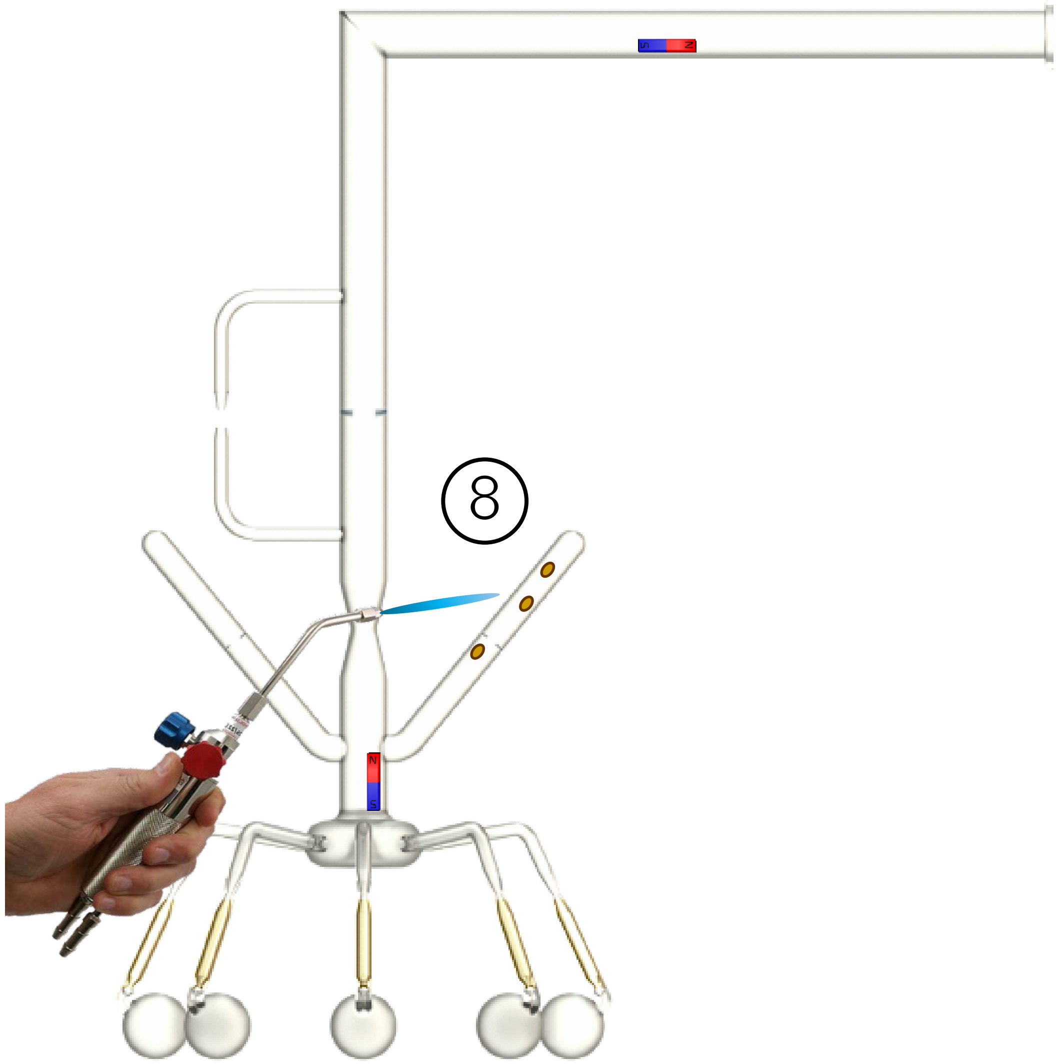


5. Warm up the spider inside the oven at 370°C, such that the paraffin vaporizes and coats the whole inner surface evenly.

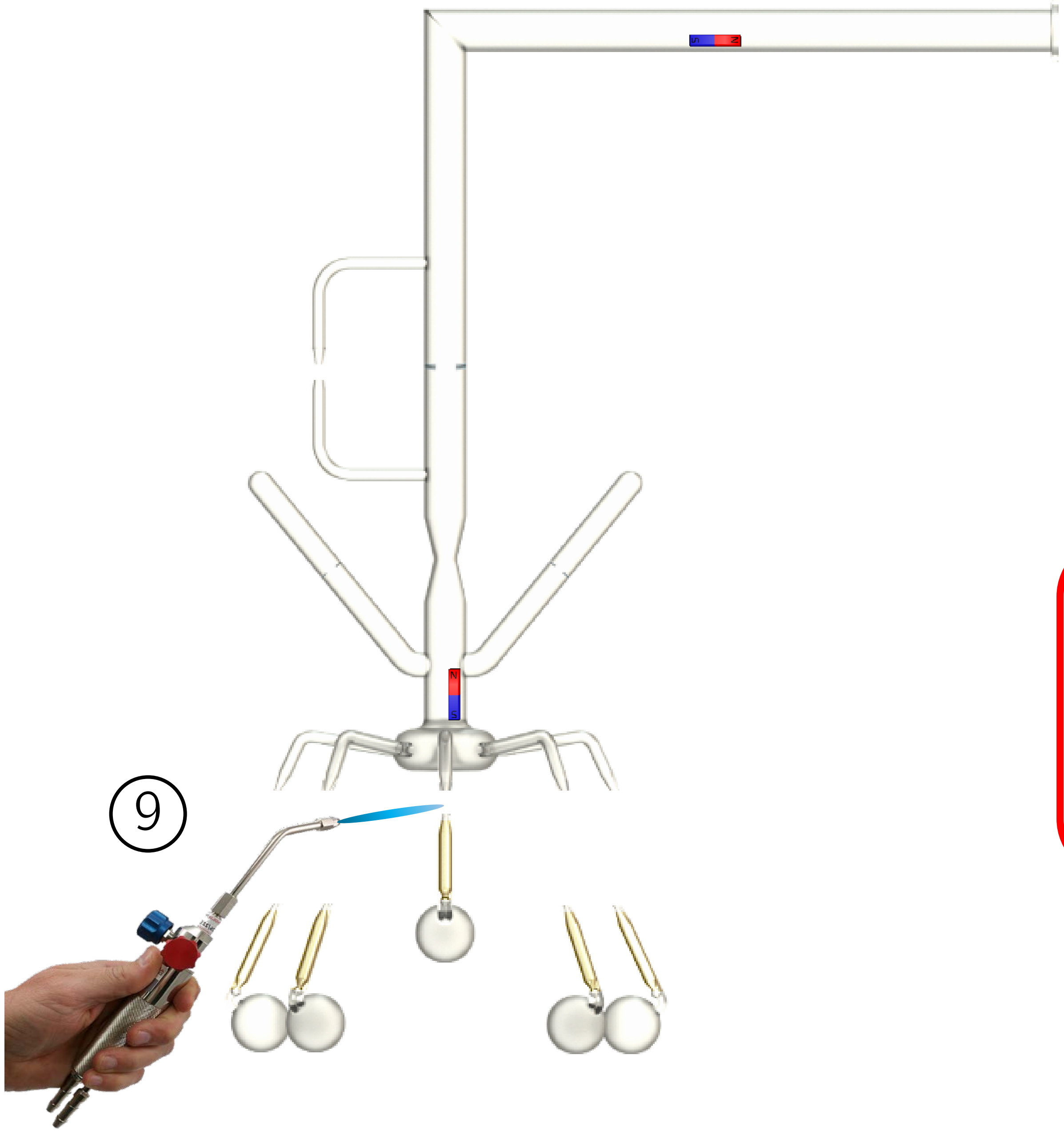


6. Restore the connection of the "spider" volume to the vacuum system.

7. Break the Cs seal



8. Chase the caesium with the hand torch such that it ends up deposited on the appended arm of the spherical bulb.



9. Use the hand torch to remove each cell.

Result: 10 brand new caesium cells, ready to be used in magnetometers!

Final remarks

1. The n2EDM experiment at PSI has the goal of measuring $|\boldsymbol{d_n}| < \mathbf{1.1} \times \mathbf{10^{-27}} \boldsymbol{e} \cdot \mathbf{cm}$ with 90% C.L. This means more insight into beyond SM theories will be gained.

2. In order to characterise the systematic shift $\boldsymbol{d}^{\mathbf{false}}_{\mathbf{Hg}\to\boldsymbol{n}}$, the magnetic field gradients in the experiment need to be properly measured. This will be done with an array of CsM.

3. The fabrication of the caesium cells is ongoing and will most likely be finished before the end of this PhD.

Thank you for your attention.