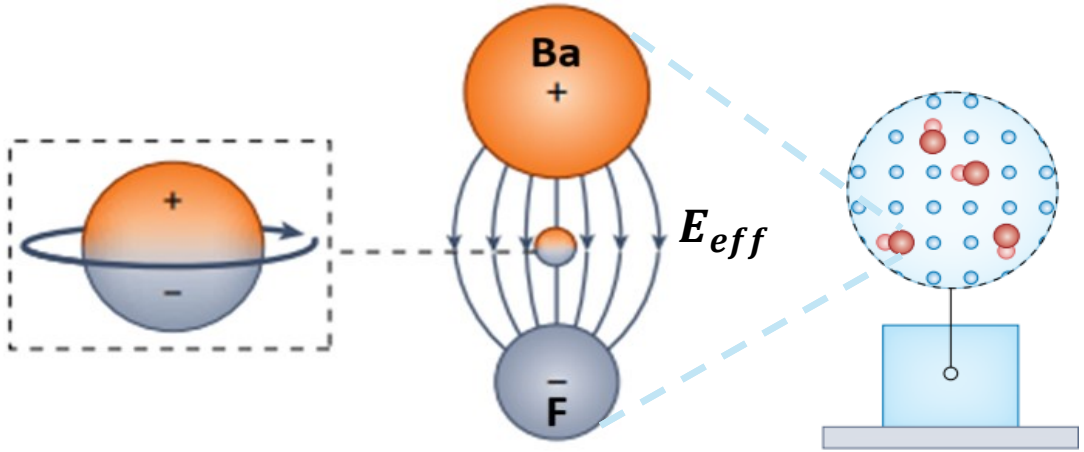
PNRR MUR project PE0000023-NQSTI

Measuring the electric dipole moment of the electron using polar molecules in a parahydrogen matrix



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on behalf of the PHYDES Collaboration

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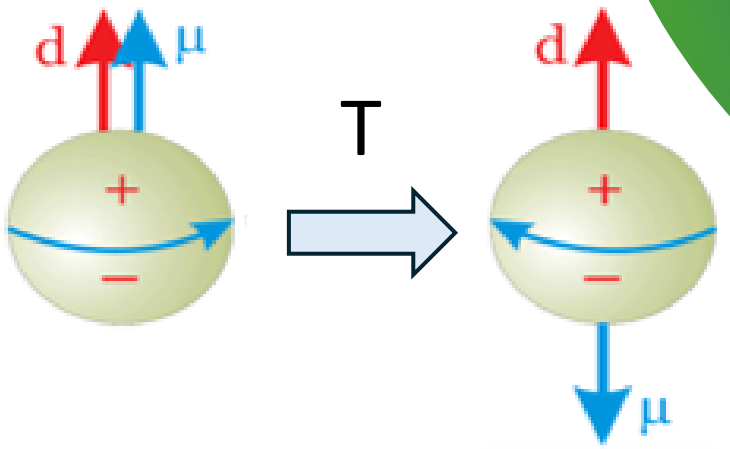
CSN gruppo V

Outline

- Motivation for an eEDM measurement
- Phydes proposal
- pH_2 production and characterization
- BaF molecular source
- Conclusions and future work

BSM physics with eEDM

A nonzero eEDM implies an aspherical charge distribution along the electron's spin axis
→ violation of T-symmetry
→ violation of CP.

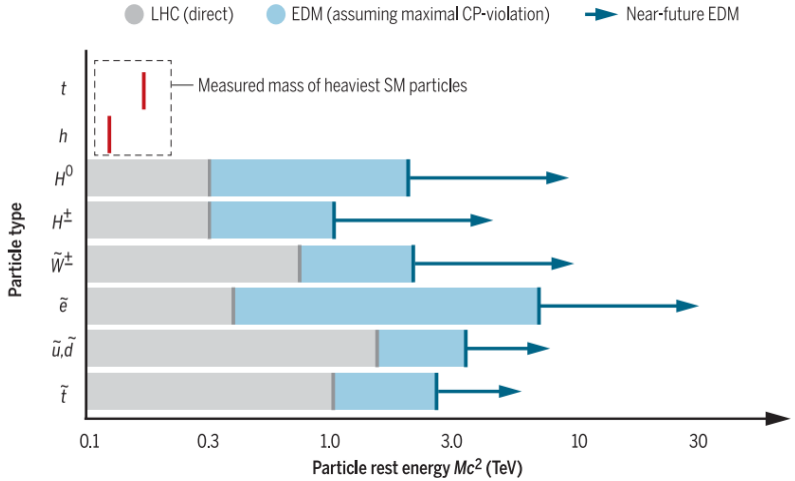


STANDARD MODEL PREDICTION

$$d_e^{SM} \leq 10^{-38} e\ cm$$

TOO SMALL

SM extensions allow a much larger eEDM that is within reach of near-term experiments.



[DeMille et al., *Science* **357**, 990–994 (2017)]

CURRENT EXPERIMENTAL LIMIT

$$d_e < 4.1 \times 10^{-30} e\ cm$$

@ 90% confidence level

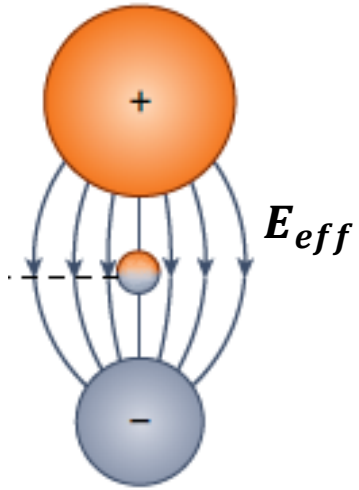
[T. S. Roussy *et al., Science* **381**,46-50 (2023)]

(obtained with trapped HfF+)

Powerful window on energy scales much larger than those probed directly at LHC!

Ingredients for an eEDM measurement

Diatomic polar molecules (BaF, YbF, ThO) have a single valance electron exposed to a huge effective molecular electric field ($E_{eff} \sim 10$ GV/cm)



Measure electron spin precession frequency in a magnetic and electric field and detect changes in precession rate when the electric field direction is reversed.

FIGURE OF MERIT

$$\delta d_e = \frac{\hbar}{2\, E_{eff} \sqrt{N}\, t_P}$$

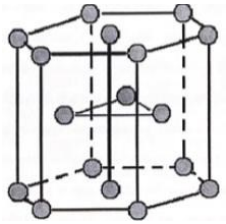
E_{eff} = effective electric field inside the molecule ($> \sim 10$ GV/cm)
t_P = spin precession measurement time $\leq T_{coherence}$
N = integrated n° of electrons whose precession is detected

Assuming:
N ≈ 10^{16} number of molecules (electrons) interrogated
$t_P \approx$ 3 ms

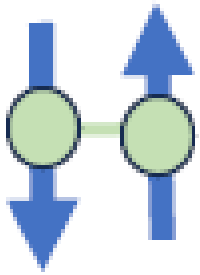
$$\delta d_e = \sim 10^{-31} e\ cm$$

Matrix isolation technique

pH_2 : anti-parallel nuclear spins, lower-energy state of molecular H_2

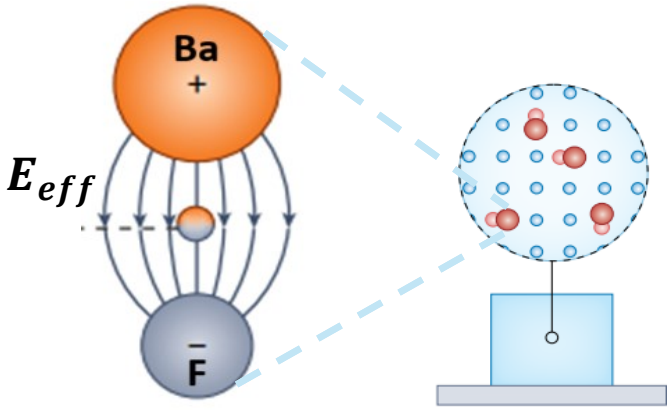


Stable hexagonal closed packed (hcp) structure.
Lattice parameter ≈ 3.78 Å
ρ = 0.086 g / cm^3
optically transparent media



Guest molecules in a matrix of pH_2 gas solidified at cryogenic temperature

- Big intermolecular distance → no significant deformations of the crystalline structure due to doping
- Minimal interactions → long coherence time



modified from:
[DeMille, et al., *Nat. Phys.* **20**, 741–749 (2024)]

$T_{coherence}$ measured in alkali atoms in pH_2 ≈ hundreds of ms
[J. Weinstein et al., PRL 125, 043601(2020)]

Pros: high number number of molecules within the measurement volume (BaF is very reactive!)

Cons: solid environment, need to control systematics to preserve coherence times

PHYDES

(Parahydrogen and diatomic molecules for EDM studies)

R&D project (CSN5 INFN) to study the production of BaF-doped pH2 crystal matrices (n ≈ 10^{15} BaF molecules / cm3, approx. 0.1 ppm)

Detection methods under study:

- **Optical detection** with Laser Induced Fluorescence spectroscopy:

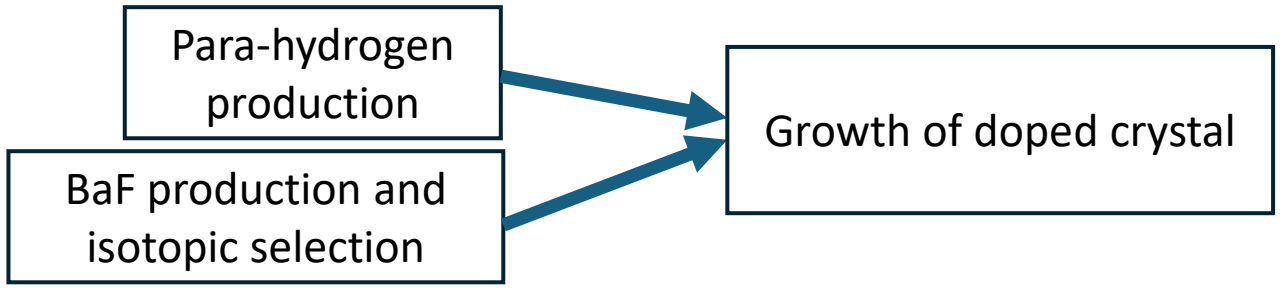
Measure the population of a prepared coherent superposition state and detect any change in population (precession angle) when E is reversed.

- **Electron Paramagnetic Resonance (EPR)** detection:

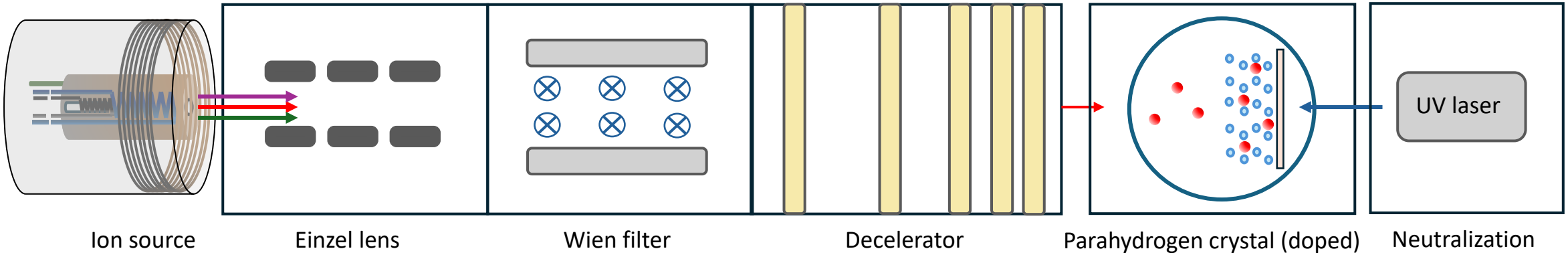
Microwave induced precession frequency shift in a high external field.

BaF-doped crystal production

2 different sub-systems

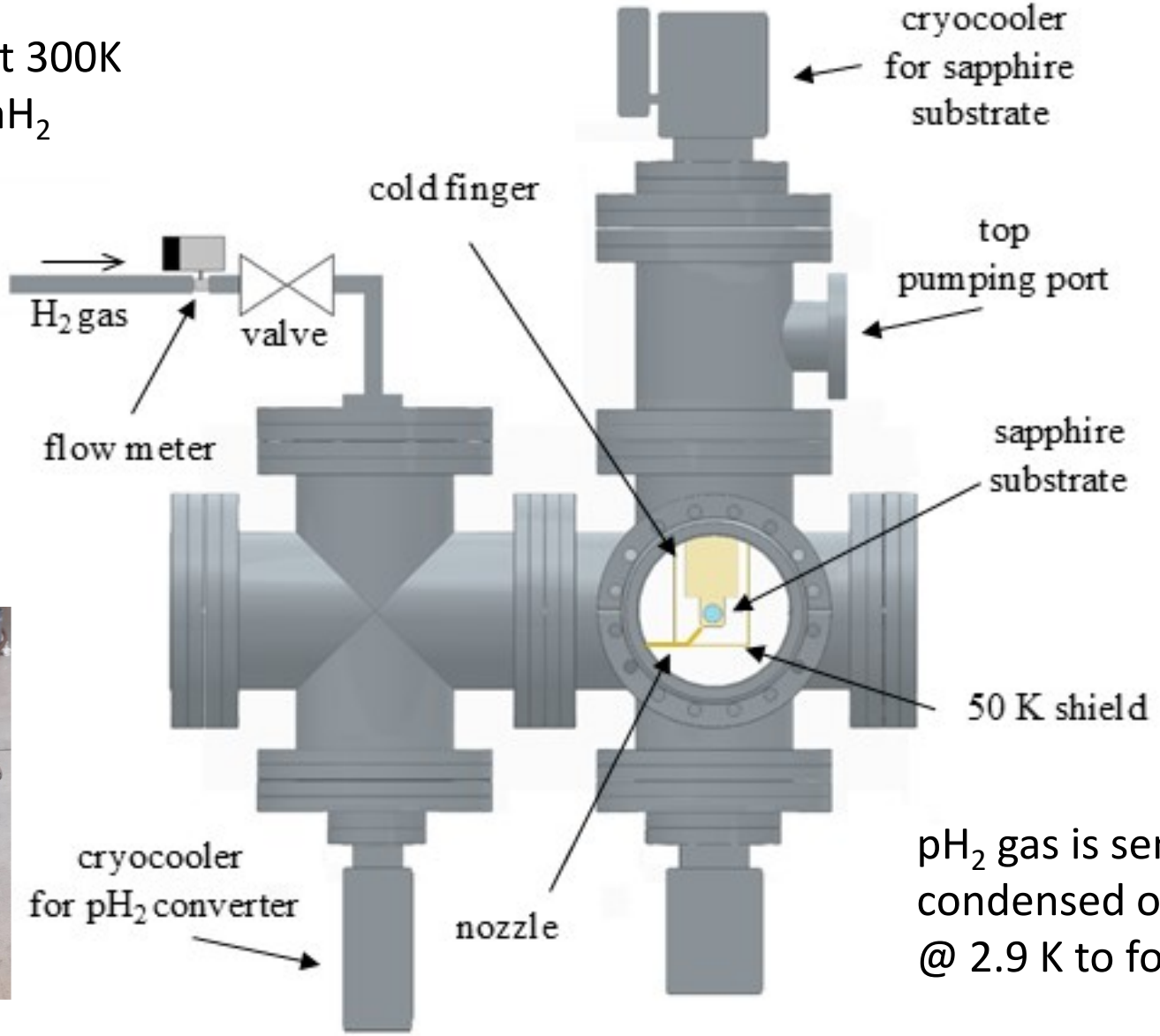


- BaF+ is produced in a glow discharge chamber from BaF_2 powder
- molecules are accelerated to 1 keV
- isotopically selected with a Wien velocity filter ($\vec{E} \times \vec{B}$)
- decelerated to ≈ 5 eV and mixed with a pH_2 gas flow on a sapphire substrate
- neutralized with photo-extracted electrons from a gold layer on the substrate



Parahydrogen production and crystal growth

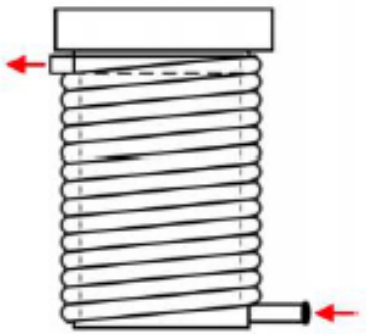
High purity hydrogen gas at 300K
75% orthoH_2, 25% paraH_2



Sapphire substrate
ϕ = 1''
$T_{sapphire}$ = 2.9 K

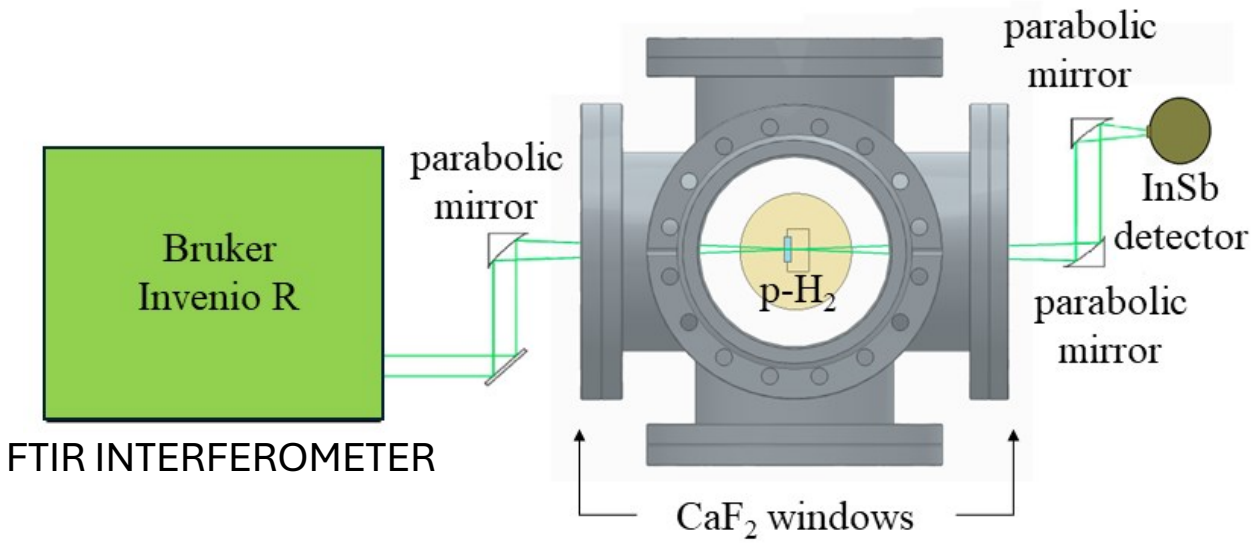
CONVERTER

Copper line filled with
hydrous ferric oxide catalyst
$T_{converter} \approx 20$ K

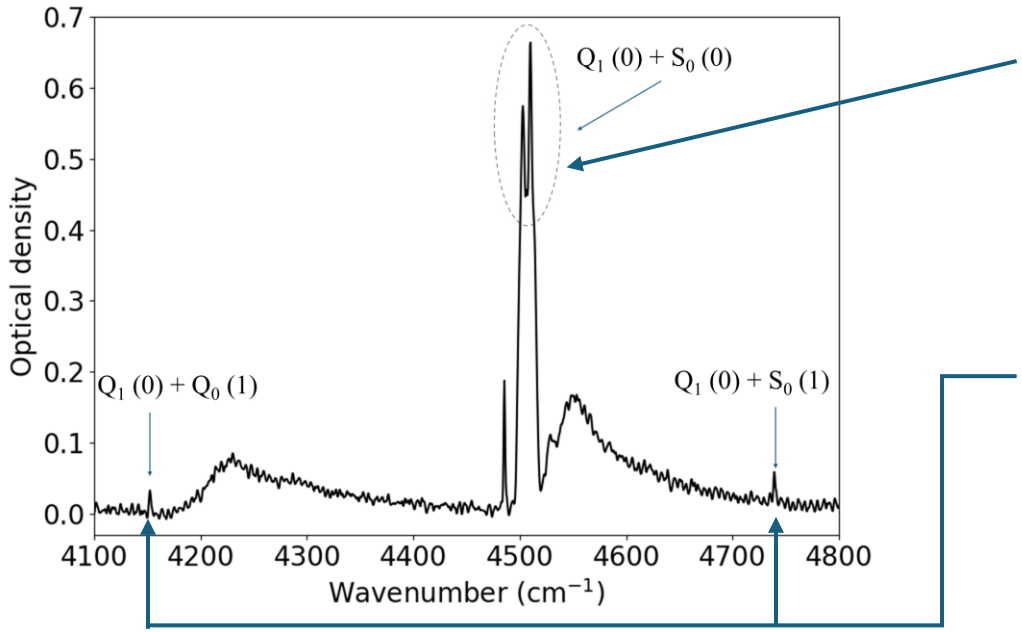


pH_2 gas is sent through a nozzle and condensed on a sapphire substrate @ 2.9 K to form a solid crystal

Characterization of the cryogenic matrix (I)



A Fourier transform interferometer (FTIR) with a near-infrared light source is used to measure the absorption spectrum of the pH_2 matrix.



Thickness of deposited layer

$$h(mm) = 0.048 \int_{4485\ cm^{-1}}^{4520\ cm^{-1}} OD(\nu)\, d\nu$$

Ortho/para-H_2 ratio

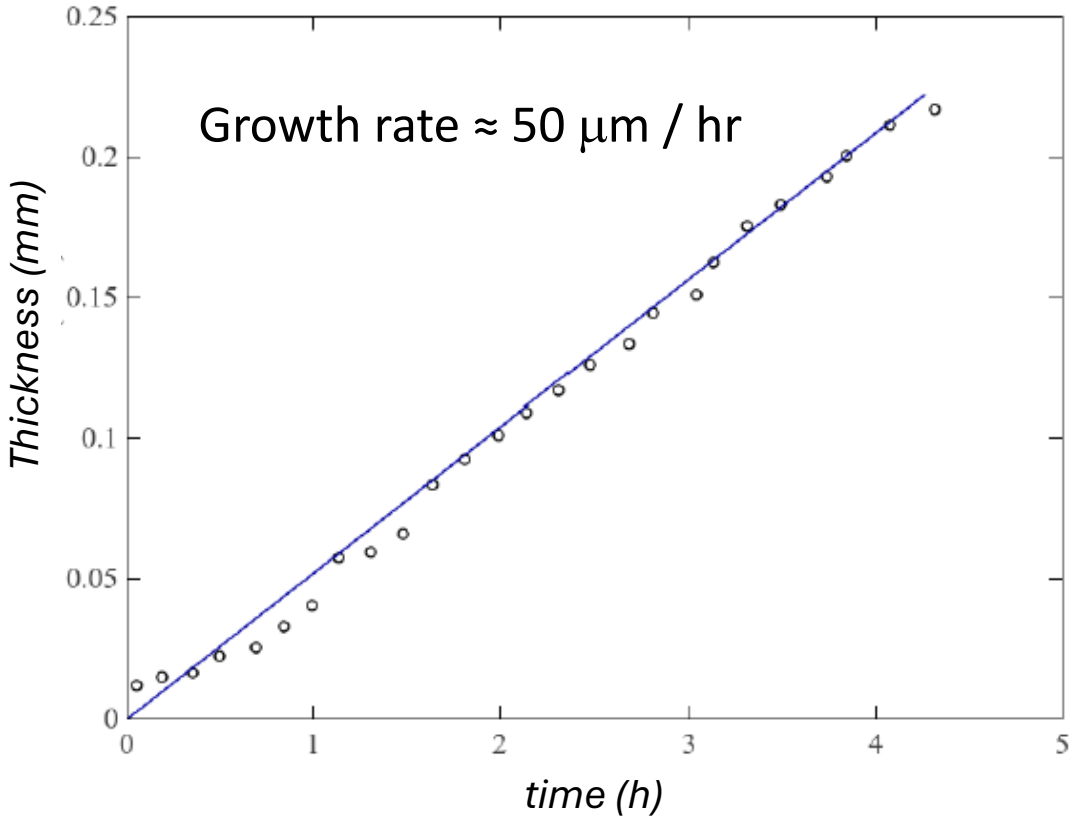
$$f_{ortho} = \frac{0.124\ mm}{h(mm)} \int_{4151\ cm^{-1}}^{4154\ cm^{-1}} OD(\nu)\, d\nu$$

$$f_{ortho} = \frac{0.0787\ mm}{h(mm)} \int_{4732\ cm^{-1}}^{4742\ cm^{-1}} OD(\nu)\, d\nu$$

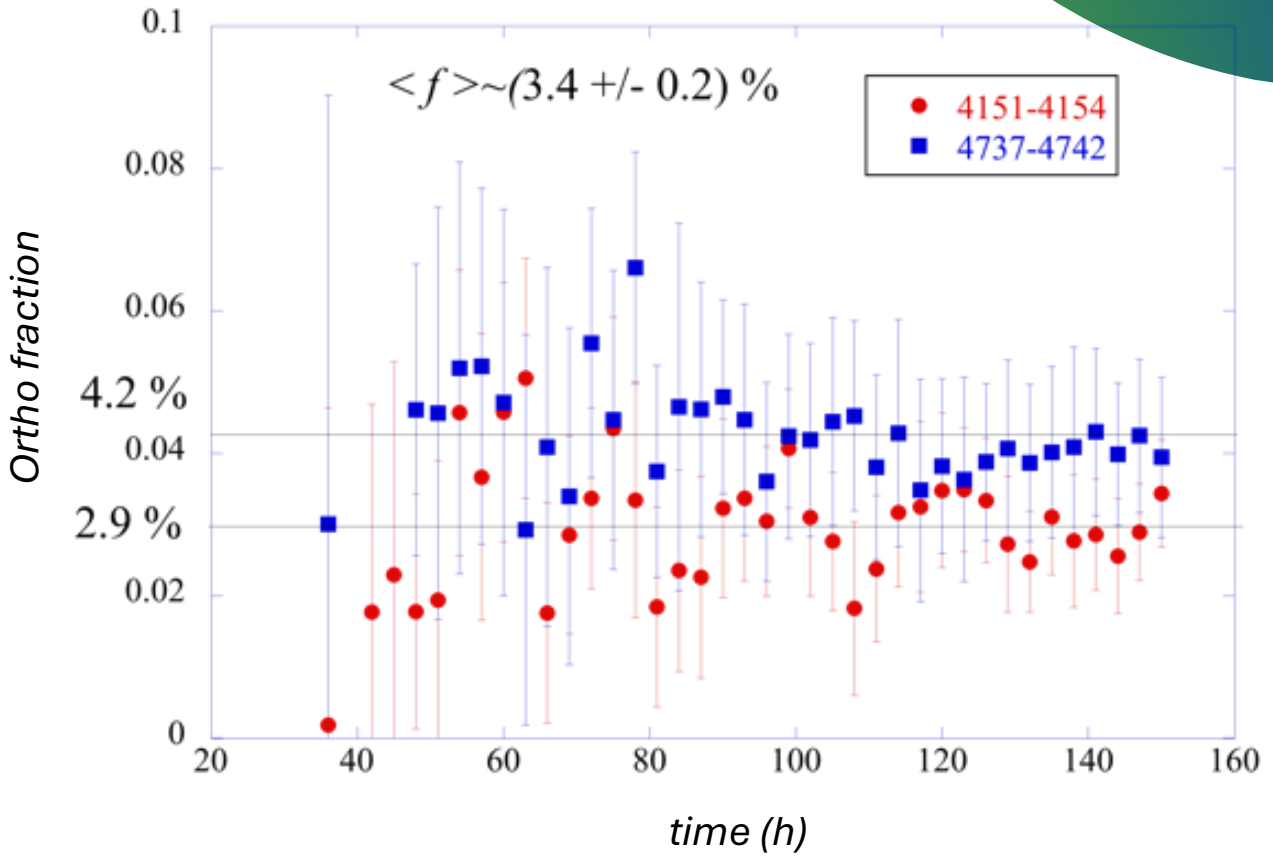
[Fajardo, Applied Spectroscopy 73.12, 1403–1408 (2019)]

Characterization of the cryogenic matrix (II)

Parahydrogen Thickness

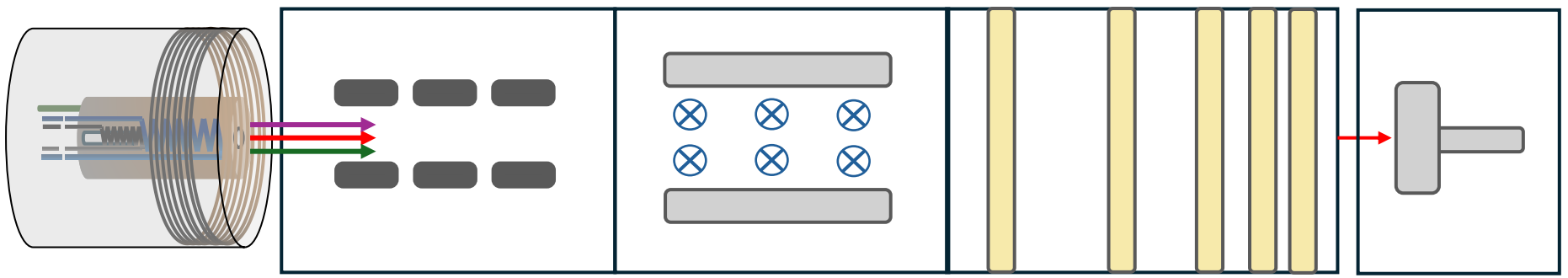


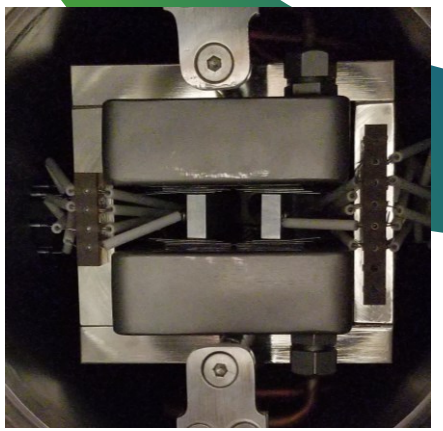
o-H_2 @ 3.5% level

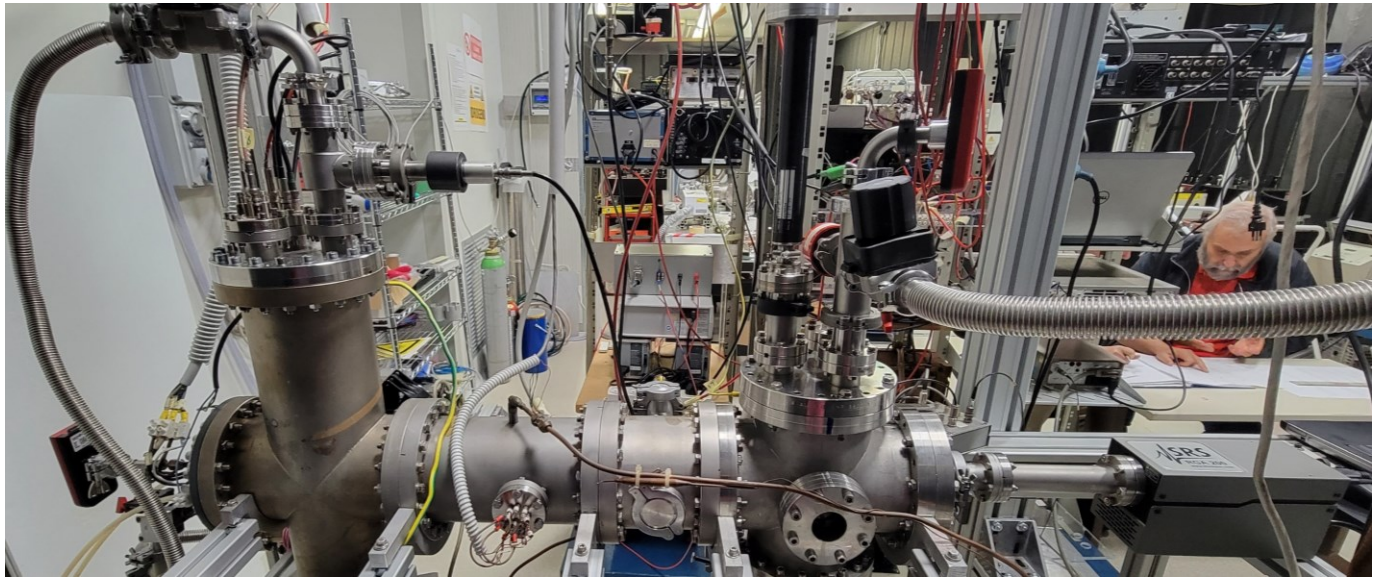


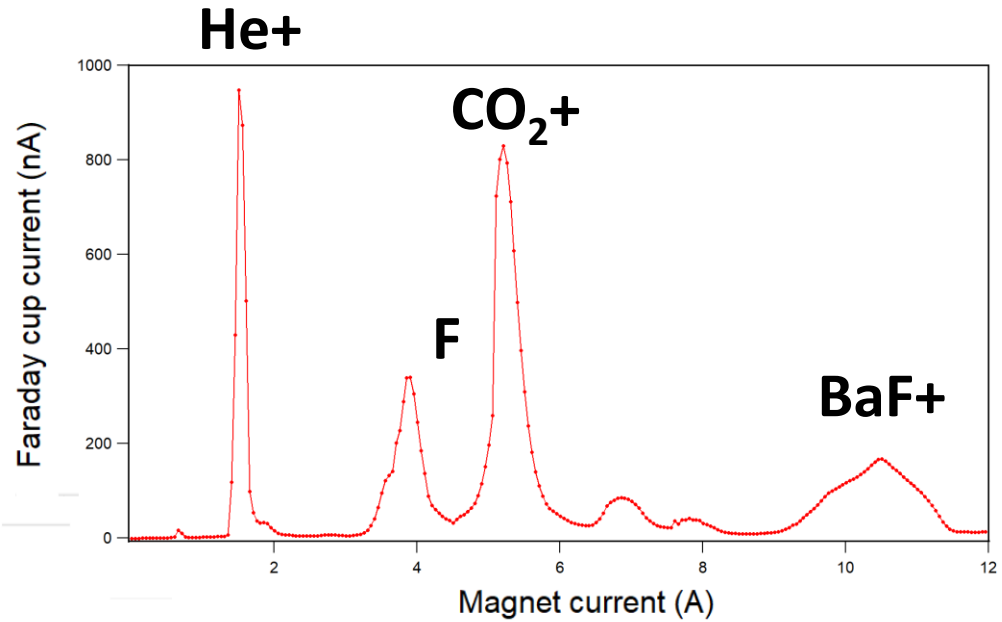
can be reduced to 100 ppm level
if $T_{converter}$ is lowered to 15 K

BaF production: molecular source









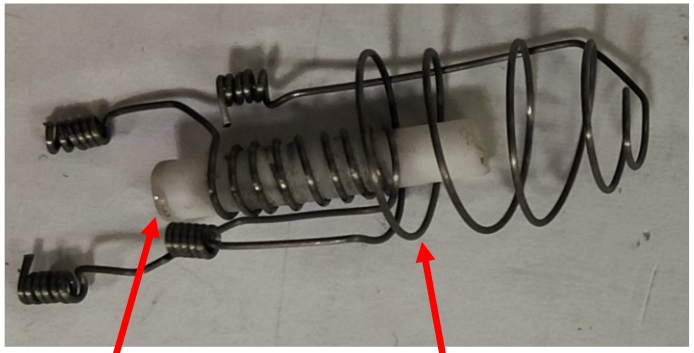
Current status:

- extracted a BaF+ beam @ 1 KeV with few μA
- after decelerator 20nA @ 5eV, 10 cm from output (10^{14} molecules / hr)

NOT STABLE OVER TIME!

BaF molecular source

50 eV beam



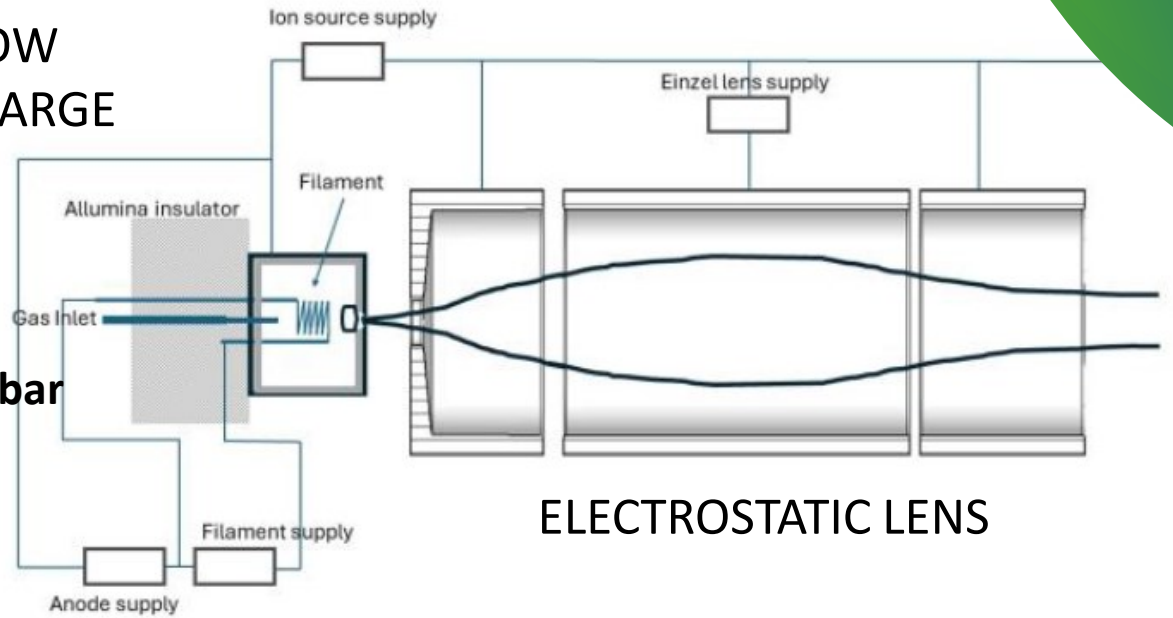
BaF_2 oven

e^- filament

GLOW DISCHARGE

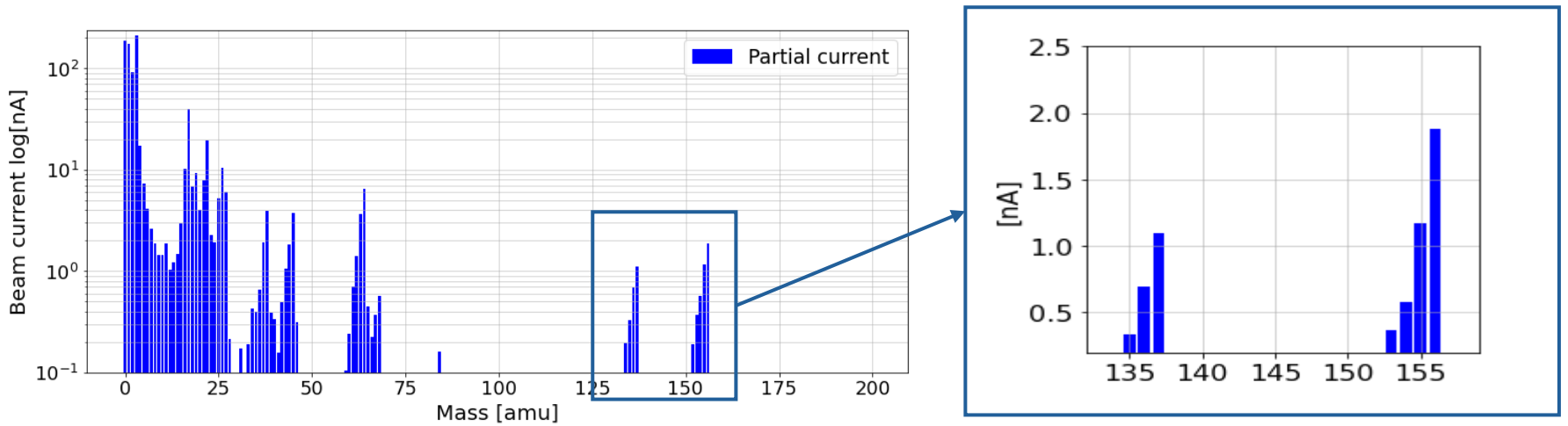
He

$p_{He}=5x10^{-3}$ mbar



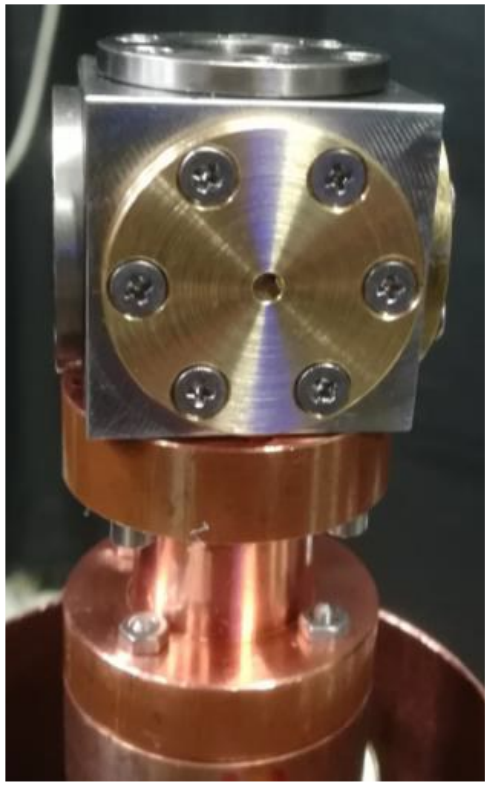
ELECTROSTATIC LENS

Ba and BaF isotopes beam current (with RGA)



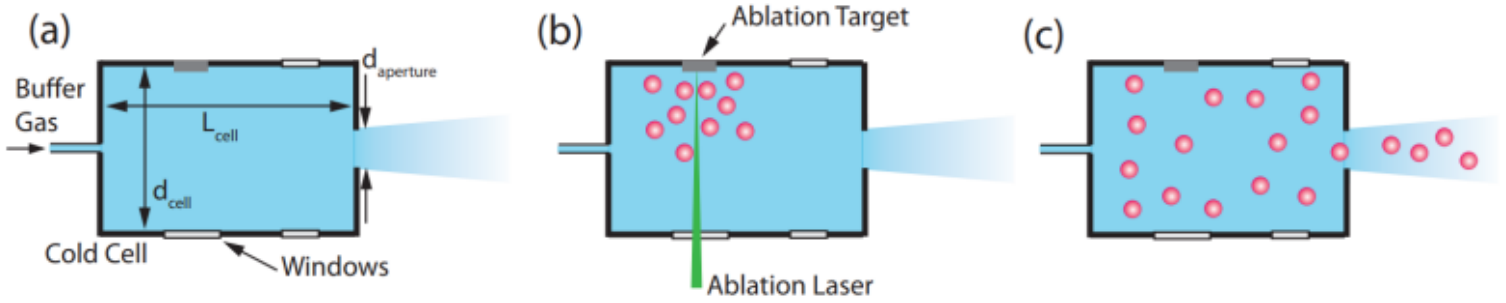
BaF production: laser ablation

Producing BaF molecules with laser ablation and pH_2 as a buffer gas



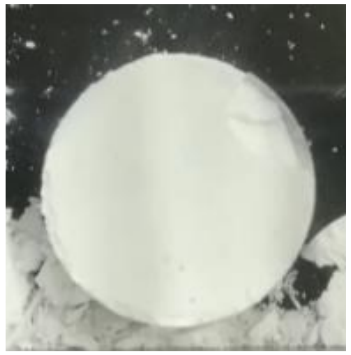
Cell: 25x25x20mm
Output aperture
ϕ = 2mm

Attached to pH_2 converter



[The NL-eEDM collaboration., **Eur. Phys. J. D** 72, 197 (2018)]

Laser for ablation: Q-switch @ 1064nm, mJ energy pulses



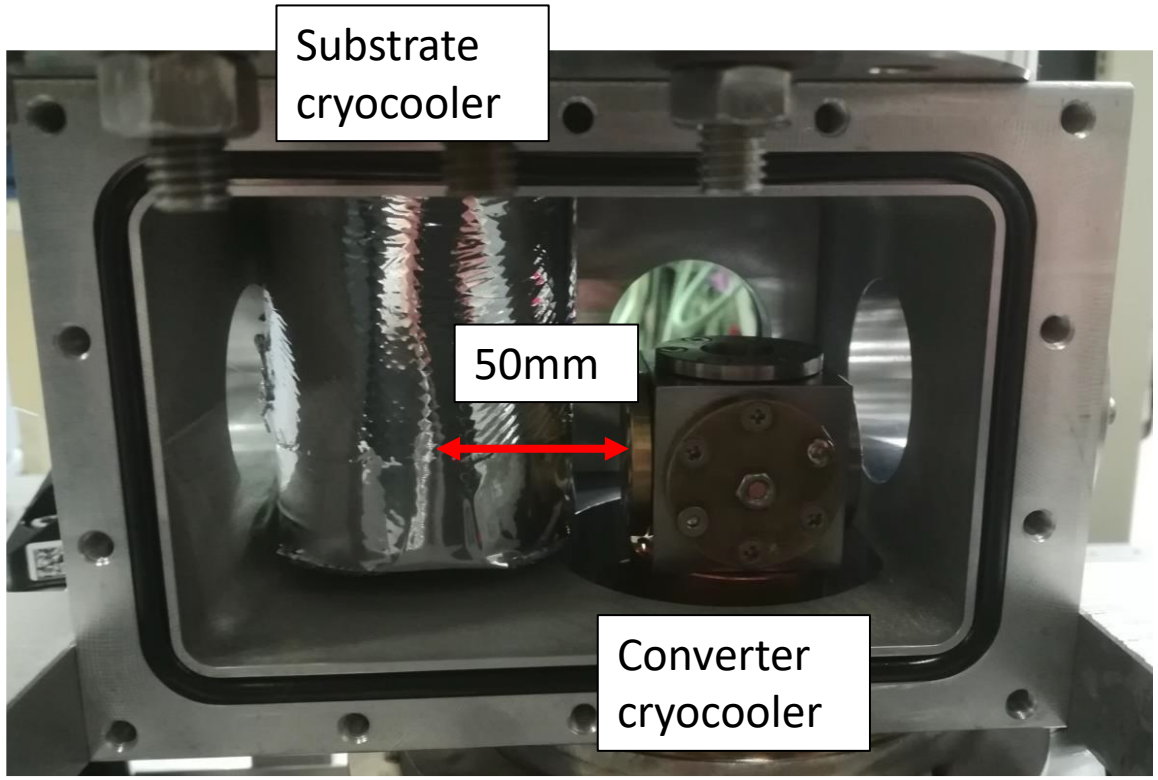
BaF_2 powder pad

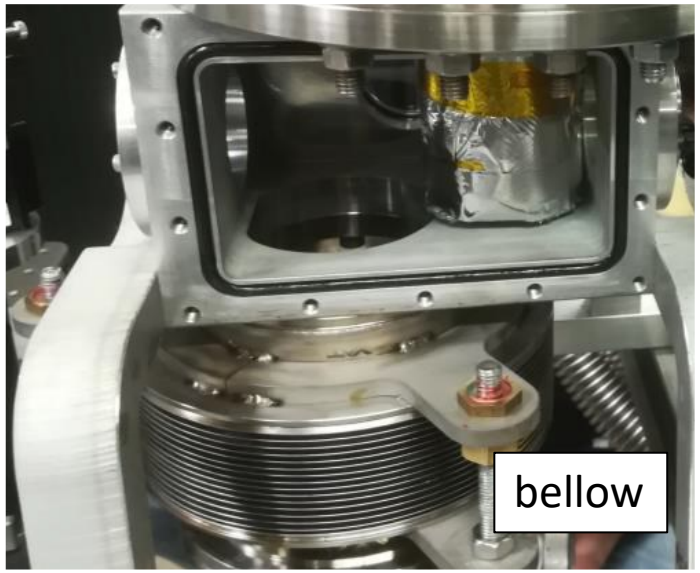
optical windows on 2 sides:

- Ablation
- BaF absorption probe

(laser light tuned to
$X^2\Sigma^+ \rightarrow A^2\Pi^{1/2}$ λ = 859.8 nm)

BaF-doped pH2 crystal





Distance cell to sapphire substrate (pH2): 50mm

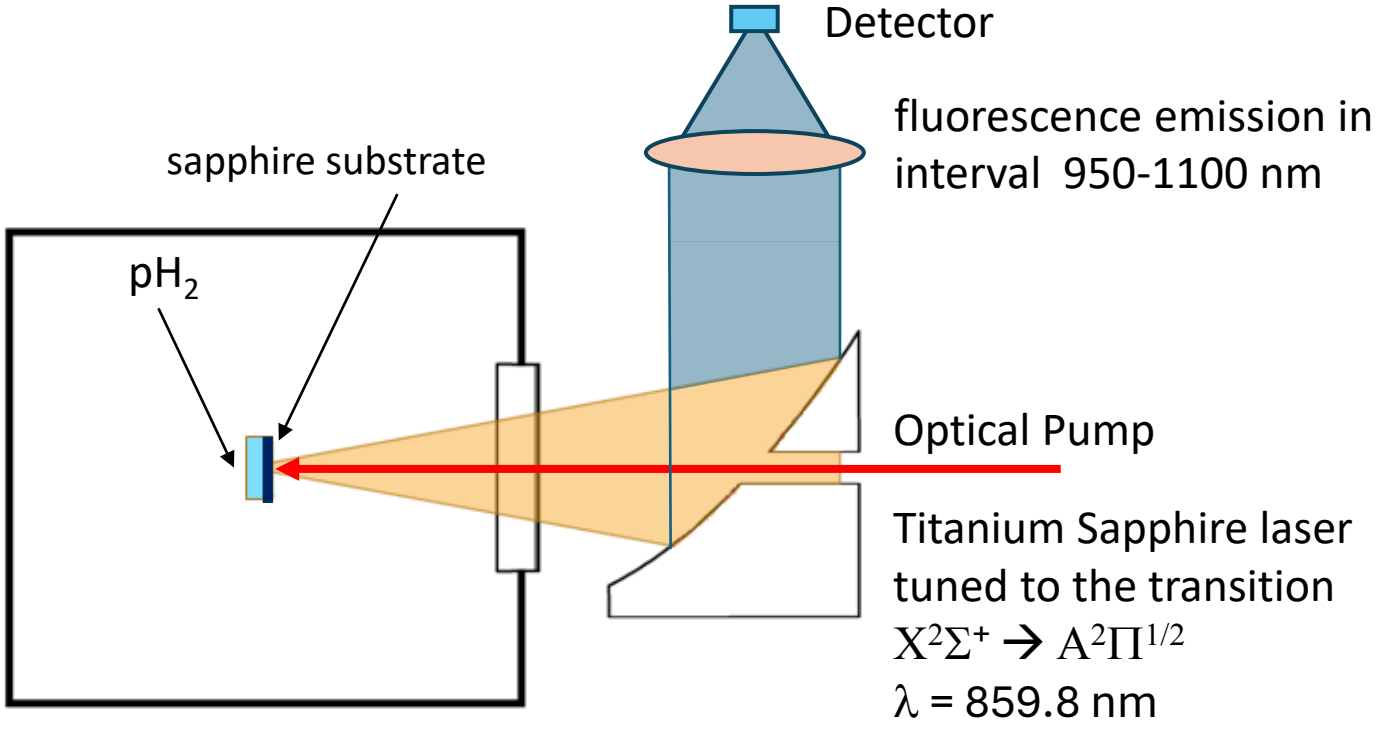
Grew a doped crystal, but…

Bad optical quality → strong absorption in all NIR range

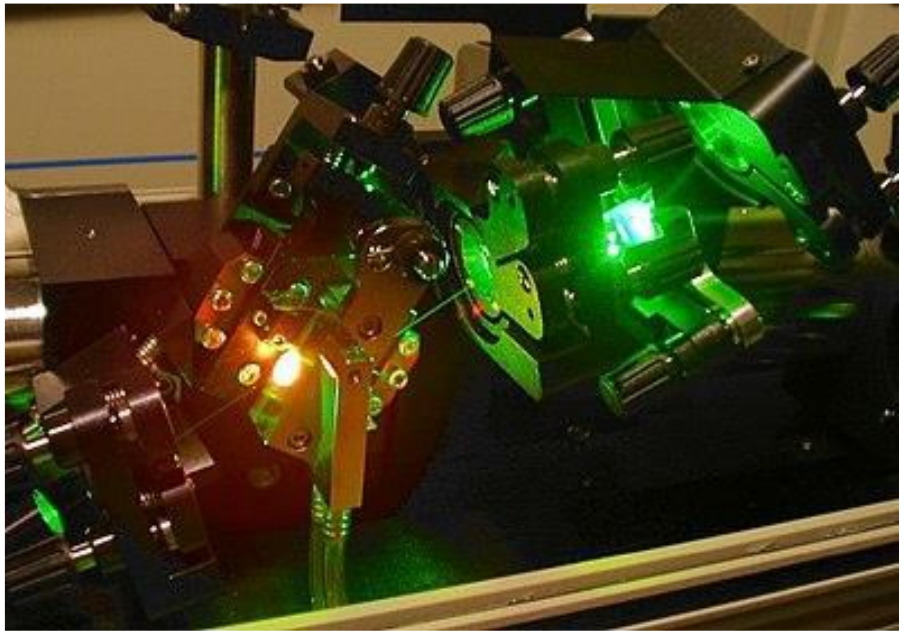
Cell can be moved out of the optical axis with a bellow for spectroscopy and absorption measurements.

Laser Induced Fluorescence (LIF) spectroscopy

- Measure shifts and broadening of lines in solid from gas phase
- Infer quality of BaF doping procedure and quantity of molecules.

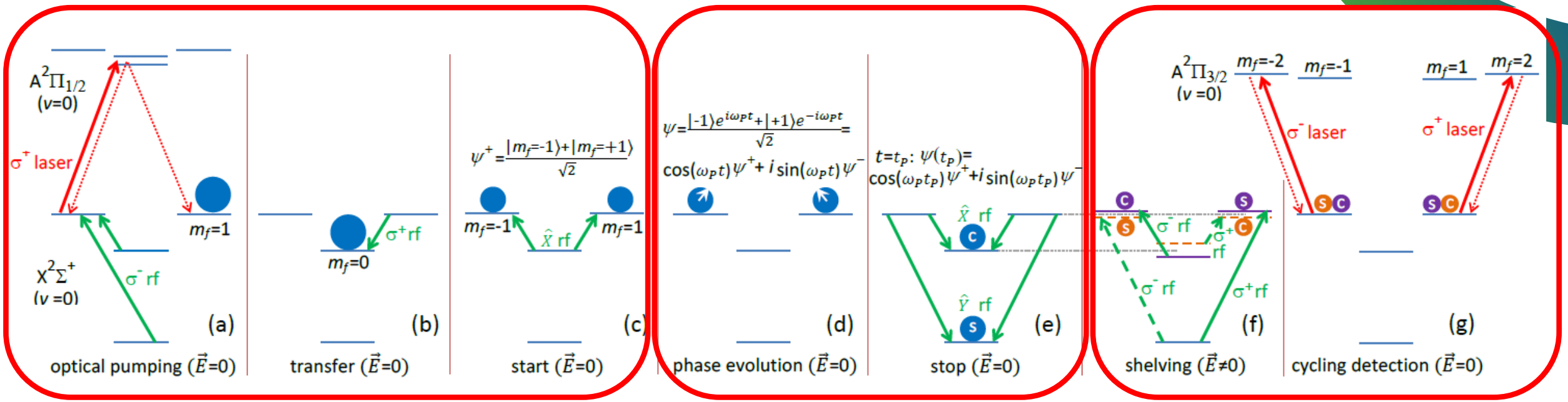


Ti:S laser (720-850 nm, linewidth 10kHz)



Optical detection scheme

[A. Vutha et al., PRA 98, 032513 (2018)]



STATE PREPARATION EVOLUTION MEASUREMENT

EDM measurement using laser-induced fluorescence spectroscopy

The ratio of the fluorescence for the σ^- and σ^+ determines:

$$\omega_P = (g\mu_B B_Z \pm d_e \mathcal{E}_{\text{eff}})/\hbar$$

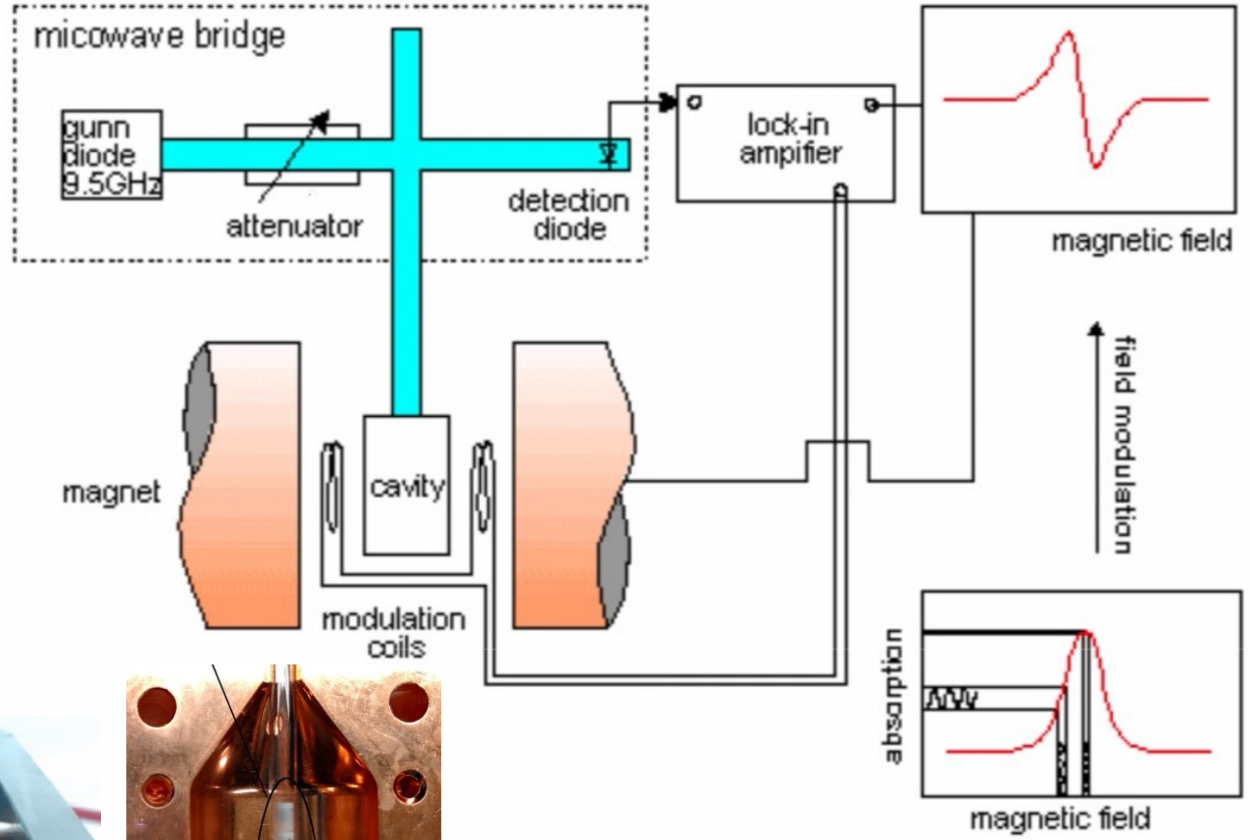
EPR detection scheme

$$H = -\mu_B \frac{\mathbf{S}}{\mathrm{S}} \cdot \mathbf{B_0} - \mathrm{d_e} \frac{\mathbf{S}}{\mathrm{S}} \cdot \mathbf{E_0}$$

$$\omega_S = \gamma_e B_0 + \frac{\mathrm{d_e}}{\hbar} \mathrm{E}_0 = \omega_L + \omega_d$$

$$\Delta\omega_{1/2} = 2\pi \left(\frac{g\mu_B}{h} \right) \Delta H_{1/2} = \gamma \Delta H_{1/2} = \frac{2}{T_2},$$

Electron Gyro-Magnetic Ratio 28 GHz/T

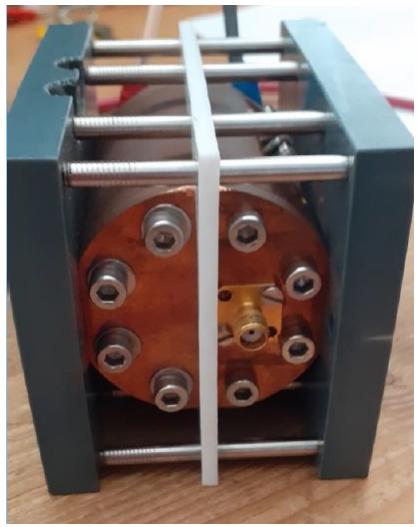


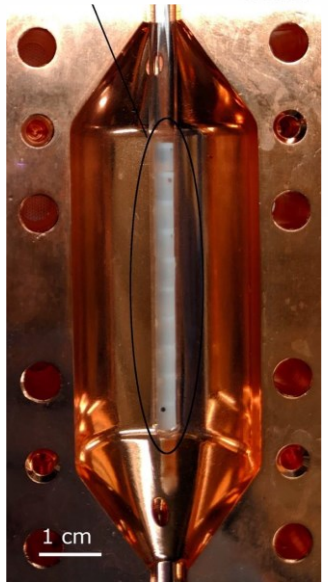
Biasing a microwave cavity with a high DC Electric Field

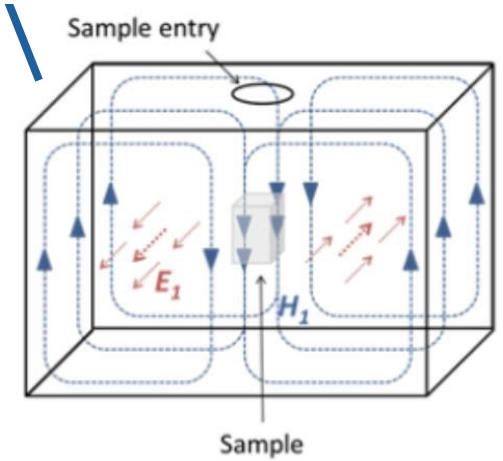
$\nu \approx 10$ GHz

$E \approx 10^6$ V/m

$\nu_{mod} \approx 100$ kHz







Conclusions and future work

1) We have demonstrated:

- Ability to grow pH_2 cryogenic crystal with t ≈ 500 mm and characterize them with IR spectroscopy
- a BaF molecular source producing 20nA @ 5eV (10^{14} molecules / hr) with isotopic selection

2) We started integrating in pH_2 BaF molecules from a laser ablation source

FUTURE WORK:

- New laser ablation cell in setup to grow doped crystals
- Laser Induced Fluorescence spectroscopy studies
- BaF molecular source: improve stability and output current to ≈ 100 nA
- Increase purity of pH_2 crystals f_{ortho} to 100 ppm with $T_{converter}$ ≈ 15 K
- EPR setup and measurements of paramagnetic samples