
# Worldwide Search for a Neutron Electric Dipole Moment

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ETH Zürich – Institute for Particle Physics

**INT Workshop – QCD for New Physics at the Precision Frontier**

# SLIDES KINDLY PROVIDED BY:

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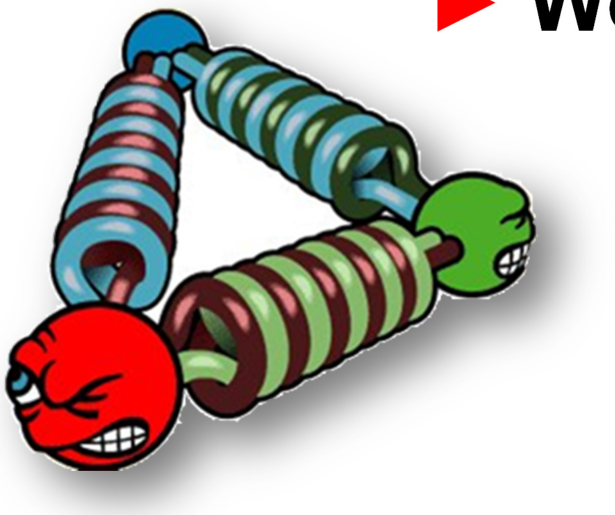
- **Rüdiger Picker (TRIUMF)**
- **Anatolii Serebrov (PNPI)**
- **Maurits van der Grinten (RAL) – CryoEDM**
- **Takeyasu Ito (Los Alamos)**
- **Peter Fierlinger (TUM / FRM2)**
- **Clark Griffith (Sussex) – Hg EDM**

# A Worldwide Endeavor

**TRIUMF** (Vancouver) – **LANL** (Los Alamos) – **SNS** (Oak Ridge) – **RAL** (Oxford) – **ILL** (Grenoble) – **PSI** (Villigen) – **FRM2/TUM** (Munich) – **PNPI/PIK** (St. Petersburg) – **RCNP** (Osaka) – …

- Introduction & Motivation
- Ultracold Neutrons
- Ramsey's Method & nEDM
- nEDM Experiment at PSI
- Worldwide Neutron EDM Searches

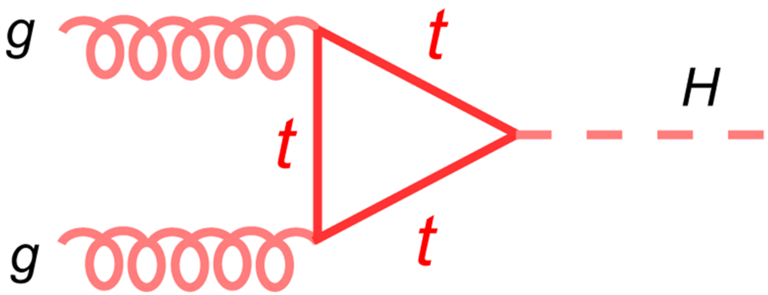


# ► Introduction & Motivation

# Search for New Physics

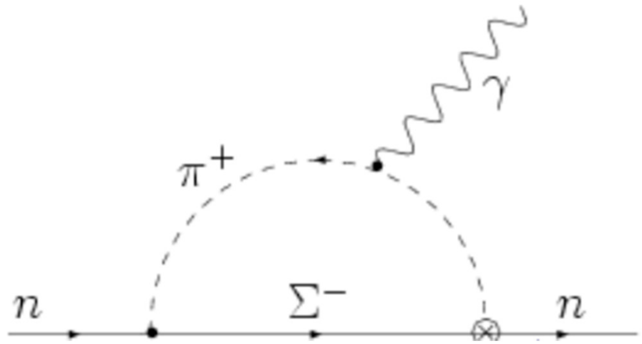
## High Energy Frontier

### Direct production of new particles




## High Intensity/Precision Frontier

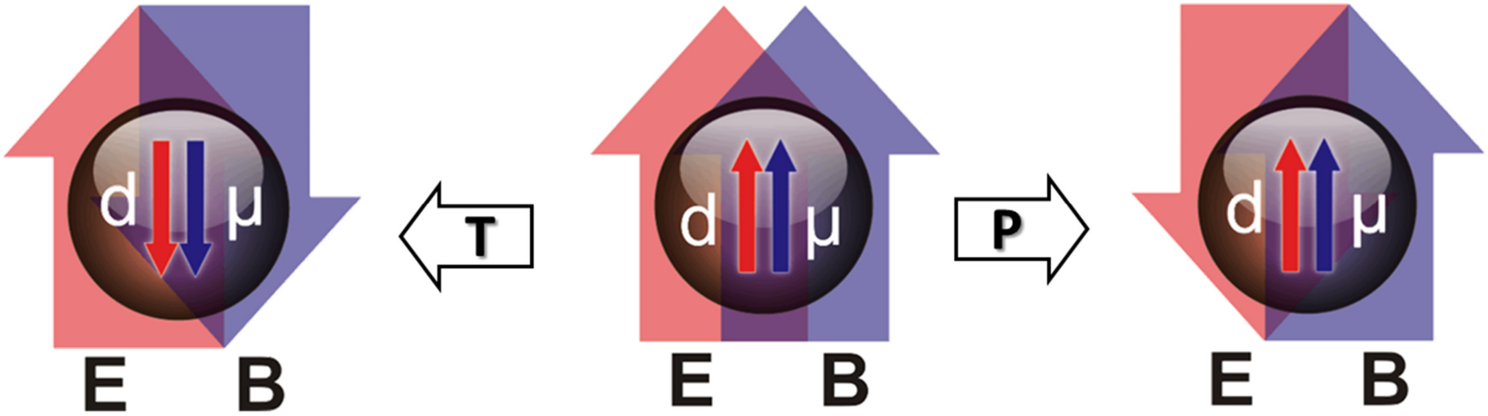
### Search for a (neutron) EDM




**EDM searches describe a promising route for discovering new physics beyond the SM.**

$$\mathcal{H} = -\mu \cdot \frac{\vec{S}}{|\vec{S}|} \cdot \vec{B} - d \cdot \frac{\vec{S}}{|\vec{S}|} \cdot \vec{E}$$

(non-relativistic interaction Hamiltonian)




- A non-zero EDM of a fundamental particle violates parity (P) and time-reversal symmetry (T).
- With CPT conservation*, it follows CP violation.

* Lüders, Ann. Phys. 2, 1 (1957)

**Electroweak SM expectation:**

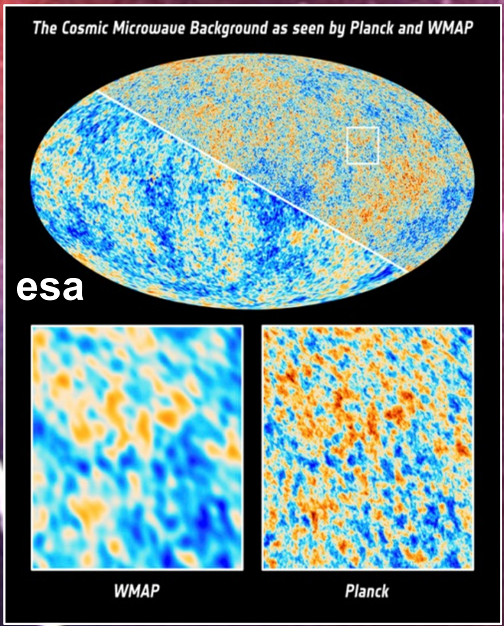
$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-18}$$

**vs.**

**Observed*:**

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10}$$

**Connection between Cosmology and SM of Particle Physics !**




**Sakharov criteria for Baryogenesis in the early universe:**

1. *Baryon number violation*
2. *C and CP violation*
3. *Thermal non-equilibrium*

JETP Lett. 5, 24 (1967)

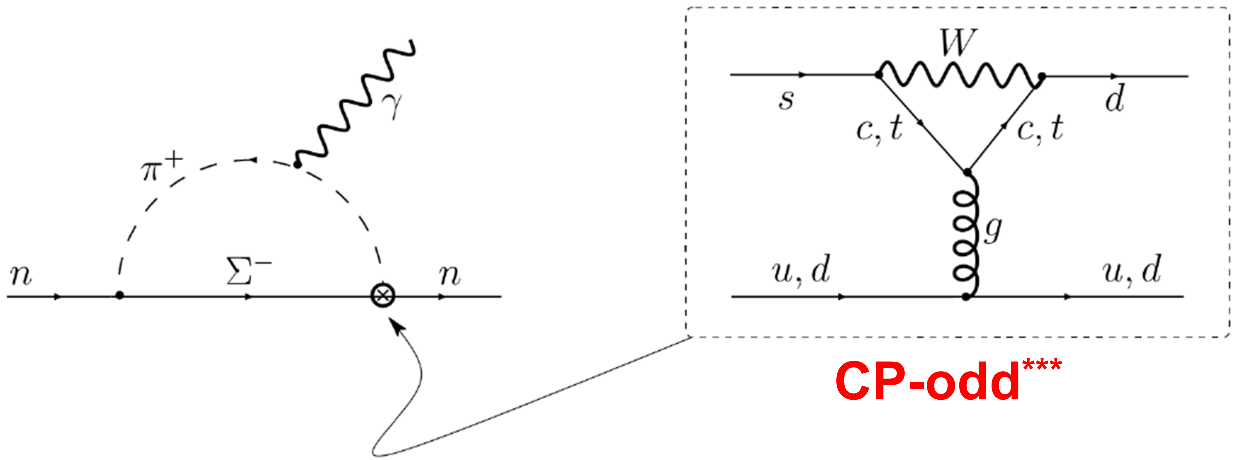

* e.g. WMAP, COBE, Planck

## ► Electroweak SM:

**CP violation is included in the SM via the phase in the CKM matrix.**

**However, the SM CP violation is very small and accounts for a neutron EDM of only $10^{-31\pm1}$ e cm *,**,***.**

$$\text{CKM} = \begin{bmatrix} c_1 & -s_1 c_3 & -s_1 s_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta} \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & c_1 s_2 s_3 - c_2 c_3 e^{i\delta} \end{bmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$




* Mannel, Uraltsev, Phys. Rev. D 85, 096002 (2012)
** He, McKellar, Pakvasa, Int. J. Mod. Phys. A4, 5011 (1989)
*** Khriplovich, Zhitinitsky, Phys. Lett. B 109, 490 (1982)

## ► QCD – Strong CP-Problem:

QCD includes a CP violating term. The strength of the CP violation is characterized by the angle $\theta_{QCD}$, which is expected to be of order one.

CP-odd '$\theta$-term'

$$\mathcal{L}_{QCD} = \mathcal{L}_{QCD}^{\theta_{QCD}=0} + \frac{g^2}{32\pi^2}\theta_{QCD} G\tilde{G}$$

Lattice QCD*:

$$d_n^{QCD} = (-2.9 \pm 0.9) \cdot 10^{-16}\,\theta_{QCD} \text{ e cm}$$

$$d_p^{QCD} = (+1.1 \pm 1.1) \cdot 10^{-16}\,\theta_{QCD} \text{ e cm}$$


With current nEDM limit**: $\theta_{QCD} \lesssim 10^{-10}$

**Why is $\theta_{QCD}$ so small ?**

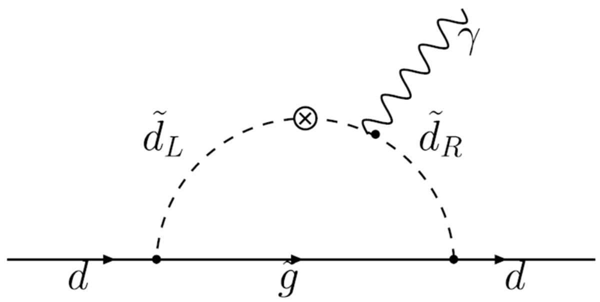
Axion's as a possible way out*** ?!?!

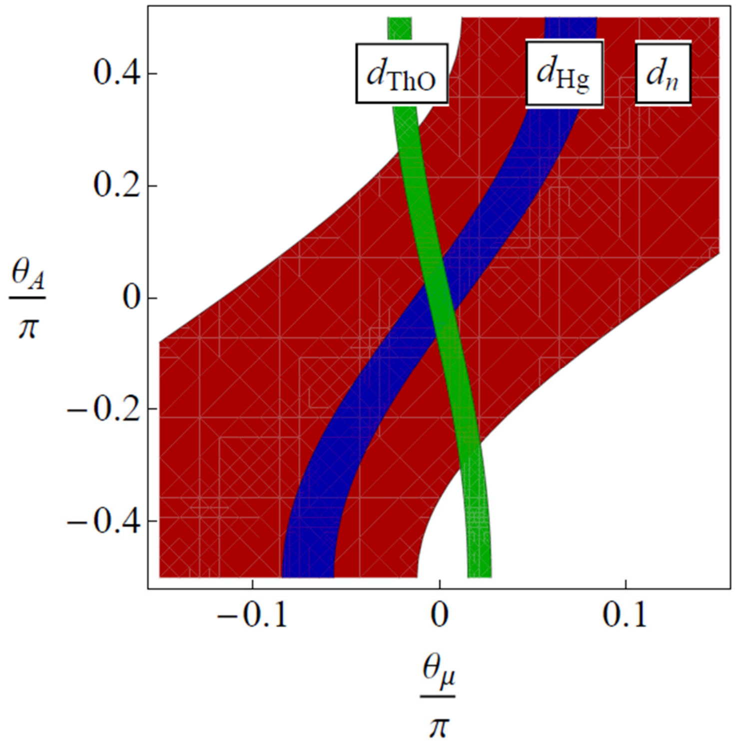
* Guo, Meissner, JHEP 12, 097 (2012)
** Baker et al., PRL 97, 131801 (2006)
*** Peccei & Quinn, PRL 38, 1440 (1977)

# ► SUSY CP-Problem:

$$d_n \approx 10^{-24}\ e\ cm \left(\frac{1\ TeV/c^2}{M_{SUSY}}\right)^2 \sin\phi_{SUSY}$$

Probing for new physics at very high energies, even beyond the reach of large accelerators/colliders !




with: $M_{SUSY}$ = 2 TeV, tan β = 3

Combination of EDM constrains (e, n & Hg) to a constrain on CP violating SUSY phases

**Why is $\phi_{SUSY}$ so small or $M_{SUSY}$ so large ?**

Pospelov, Ritz, Ann. Phys. 318, 119 (2005)
updated: Ritz, Lepton Moments (2014)

| System | Upper Limit [e cm] | Ref. | Comment |
|---|---|---|---|
| | | | |
| Neutron | $3.0 \times 10^{-26}$ (90%CL) | [1] | direct limit |
| Muon | $1.9 \times 10^{-19}$ (95% CL) | [2] | direct limit |
| $^{199}$Hg | $3.1 \times 10^{-29}$ (95% CL) | [3] | best dir. limit of any EDM & indir. limit for proton: $d_p < 7.9 \times 10^{-25}$ e cm (also provides indir. limits for n & e) |
| $^{205}$Tl | $9 \times 10^{-25}$ (90% CL) | [4] | used to set a limit for the electron: $d_e < 1.6 \times 10^{-27}$ ecm |
| YbF | $1.1 \times 10^{-22}$ (90% CL) | [5] | $d_e < 1.05 \times 10^{-27}$ ecm |
| ThO | | [6] | $d_e < 8.7 \times 10^{-29}$ ecm |
| Xe, Ra, Rn, … p, d, … Molecules, … | | | |

[1] Baker et al., PRL 97, 131801 (2006), Pendlebury et al., arXiv:1509.04411
[2] Bennett et al., PRD 80, 052008 (2009)
[3] Griffith et al., PRL 102, 101601 (2009)
[4] Regan et al., PRL 88, 071805 (2002)
[5] Hudson et al., Nature 473, 493 (2011)
[6] ACME Collaboration, Science 343, 269 (2014)

Diamagnetic atom

Paramagnetic atom

Paramagnetic/Polar molecule

# Neutron EDM – Situation & Perspective

- **First Ramsey measurement**

  Smith, Purcell & Ramsey, Phys. Rev. 108, 120 (1957)

- **Current limit:**

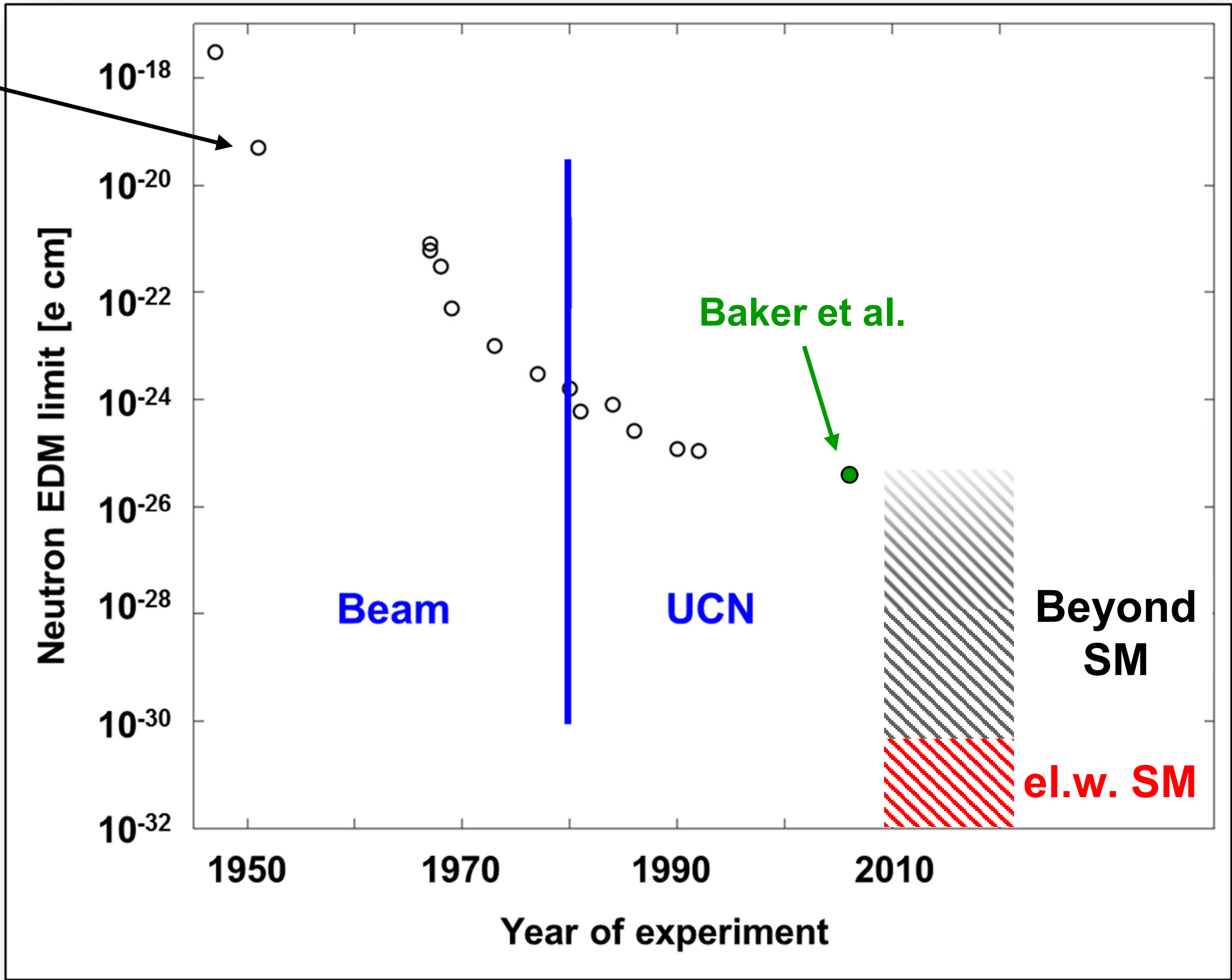
$$|d_n| < 2.9 \times 10^{-26} \text{ e cm}$$

(90% CL)

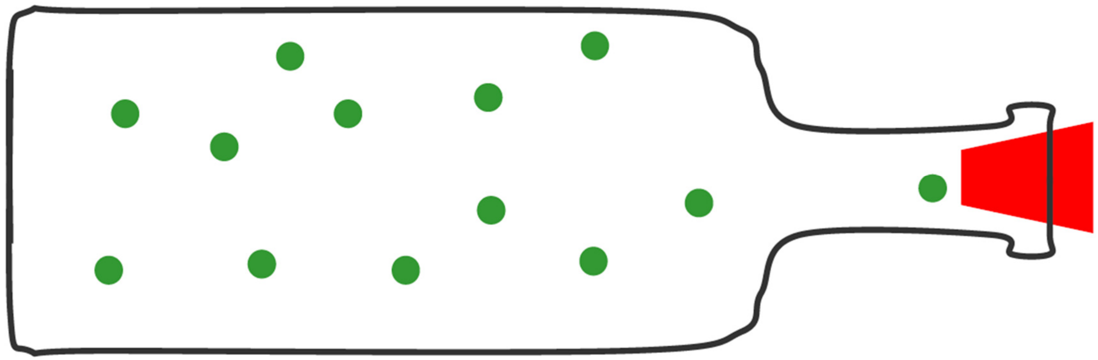
Baker et al., PRL 97, 131801 (2006)

- **Sensitivity:**

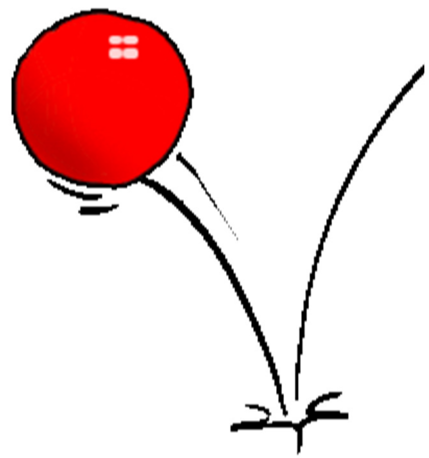
$$\sigma(d_\mathrm{n}) \propto \frac{1}{E\,T\,\sqrt{N}}$$



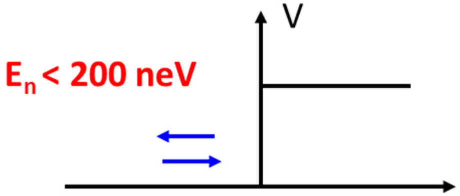
## ► Neutrons in a Bottle (UCN)

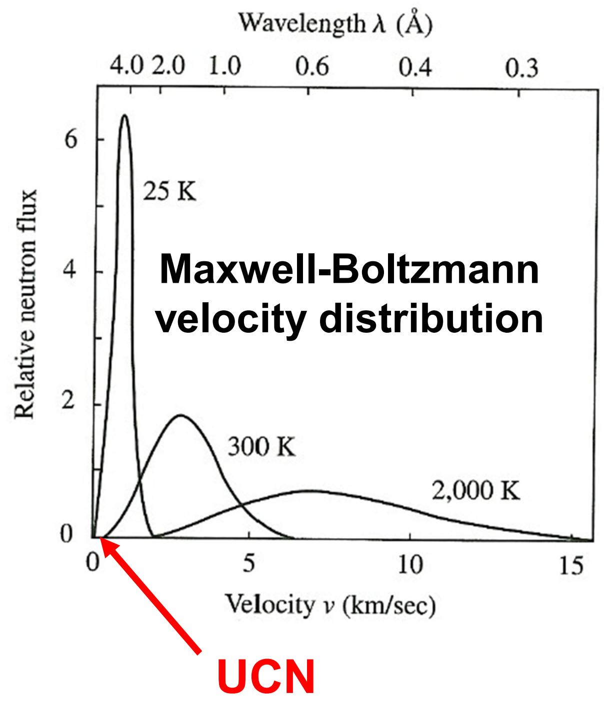


- Ultracold Neutrons (UCN) behave similar to an ideal gas with temperatures in the mK range
- Velocities ≈ a few m/s
- Storable in material traps/bottles

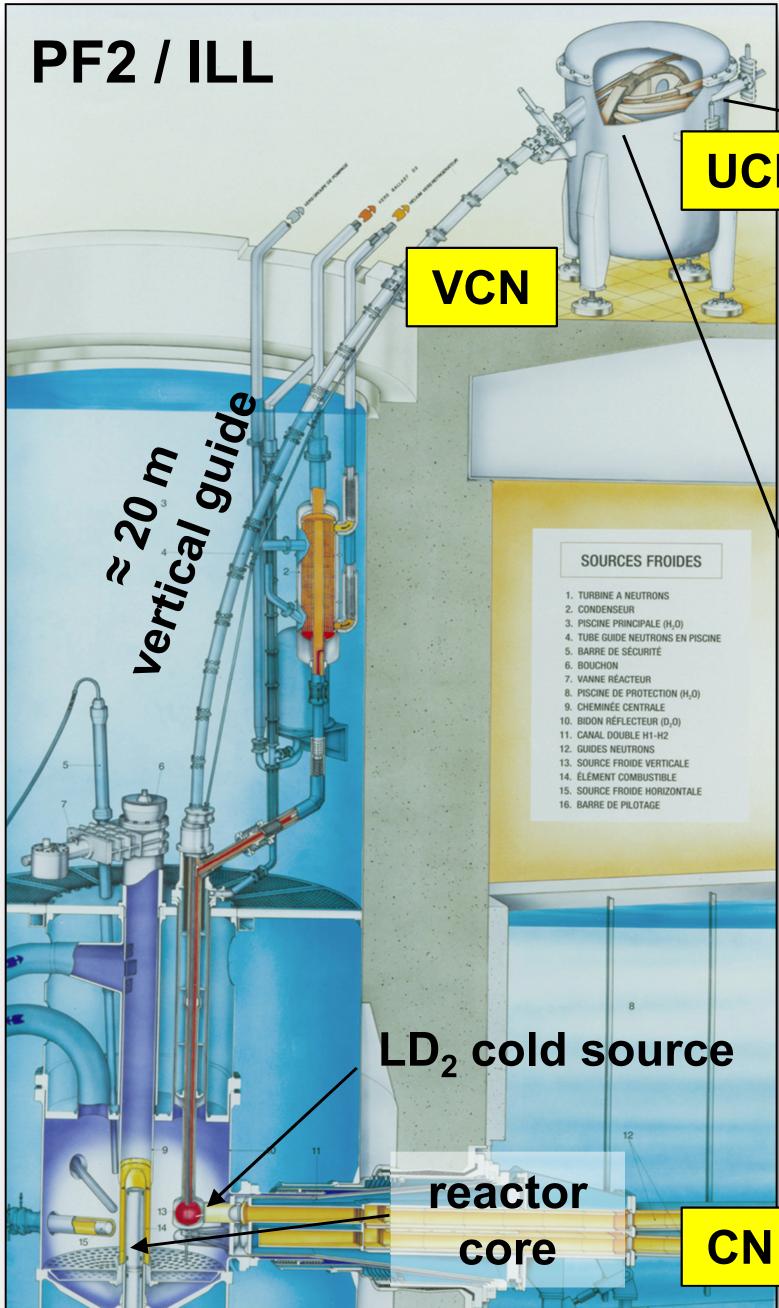


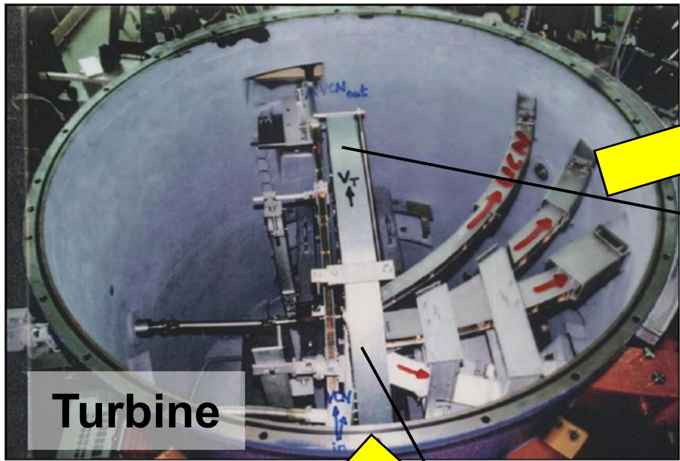
| strong | magnetic | gravitation |
|---|---|---|
| Fermi potential $V_F$ | $V_m = -\mu B$ | $V_g = m_n g h$ |
| ↓ | ↓ | ↓ |
| 200 neV | 60 neV $T^{-1}$ | 100 neV $m^{-1}$ |
| | ↓ | ↓ |
| | 3.3 T field → 200 neV | 2 m → 200 neV |



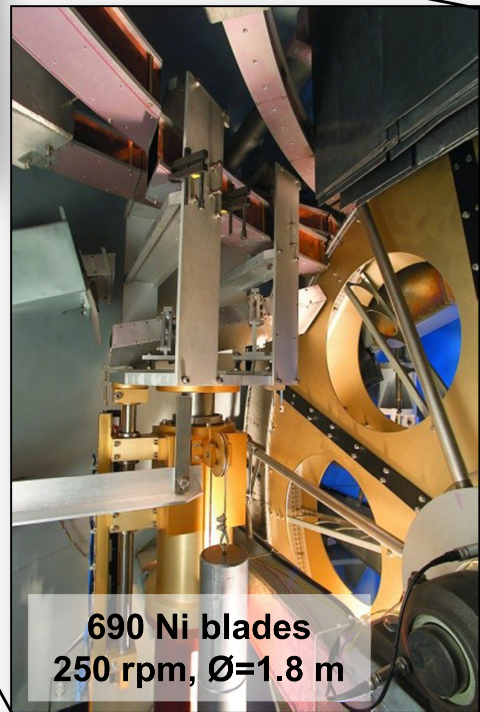
## About 30 years of UCN production at PF2



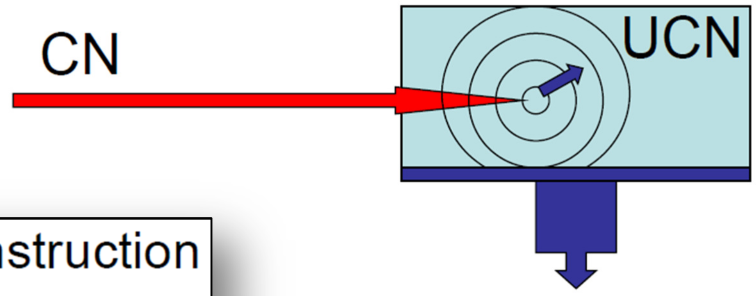

UCN to experiments 10-50 cm$^{-3}$

VCN from vertical guide



## ► Superthermal UCN Production

$$\rho_{UCN} = \phi_{CN} R \tau_{UCN}$$




- Operating:
  - ILL PF-2 (turbine)
  - LANL (sD2)
  - PSI (sD2)
  - TRIGA Mainz (sD2)
  - RCNP (SF-He)
  - ILL SUN (SF-He)
  - [ILL: GRANIT, cryoEDM]
  - [NIST: lifetime]
- R&D and construction
  - ILL SuperSUN
  - TRIUMF/RCNP
  - PNPI WWR-M
  - NCSU PULSTAR
  - FRM-2
  - SNS-EDM
- Possible projects
  - J-PARC
  - PIK
  - ESS

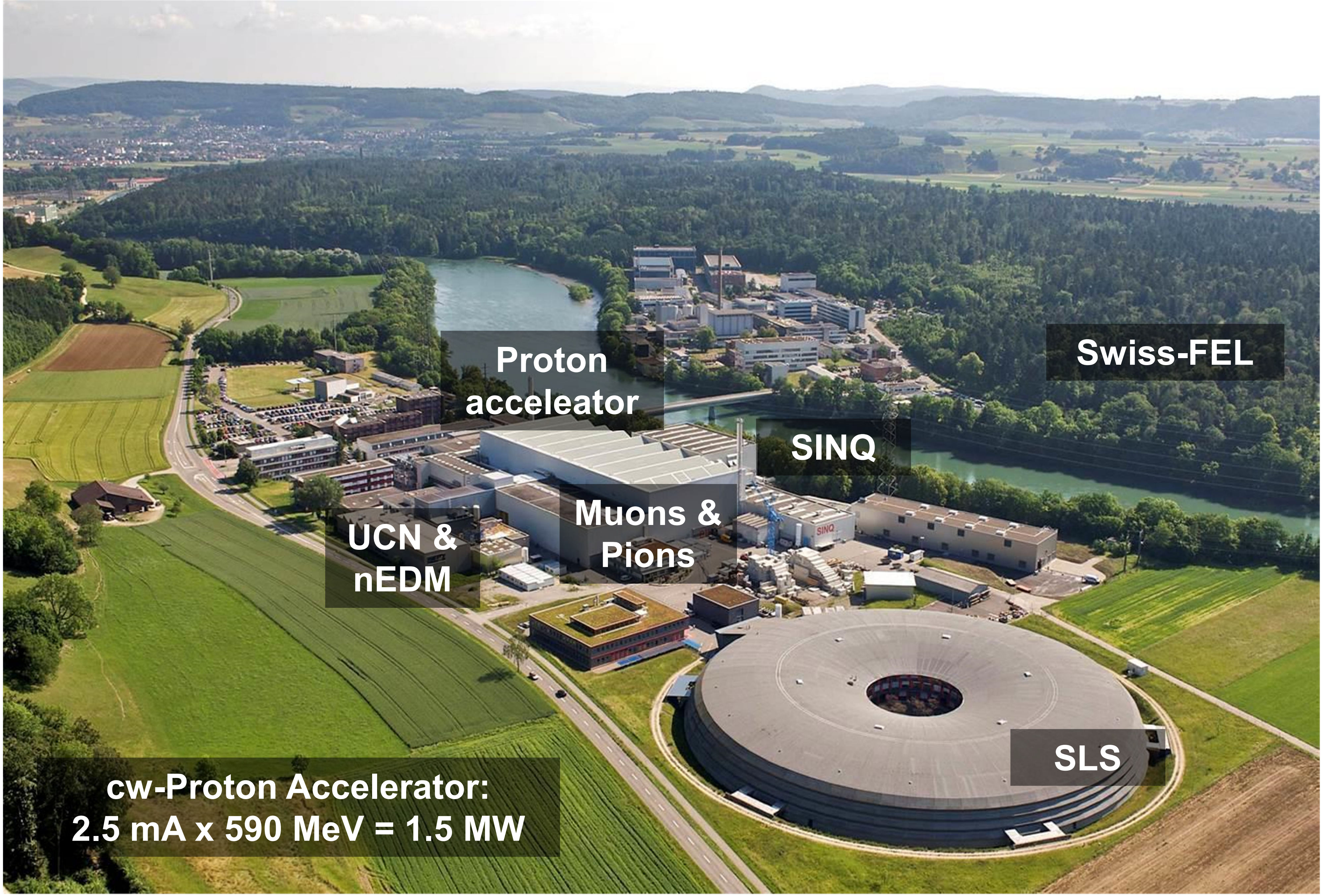
From: Roger Pynn

SF He: Golub & Pendlebury, PL 62A, 337 (1977)

$SD_2$: Golub & Böning, ZPB 51, 95 (1983)
Yu, Malik & Golub, ZPB 62, 137 (1986)

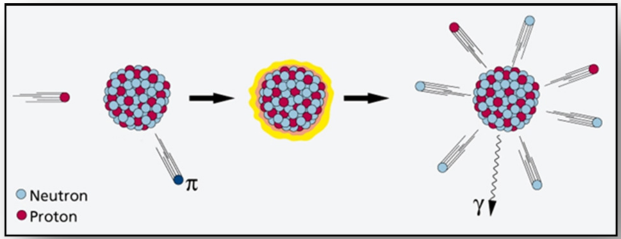
**SF He: small $R$, long $\tau$**
**$SD_2$: large $R$, short $\tau$**

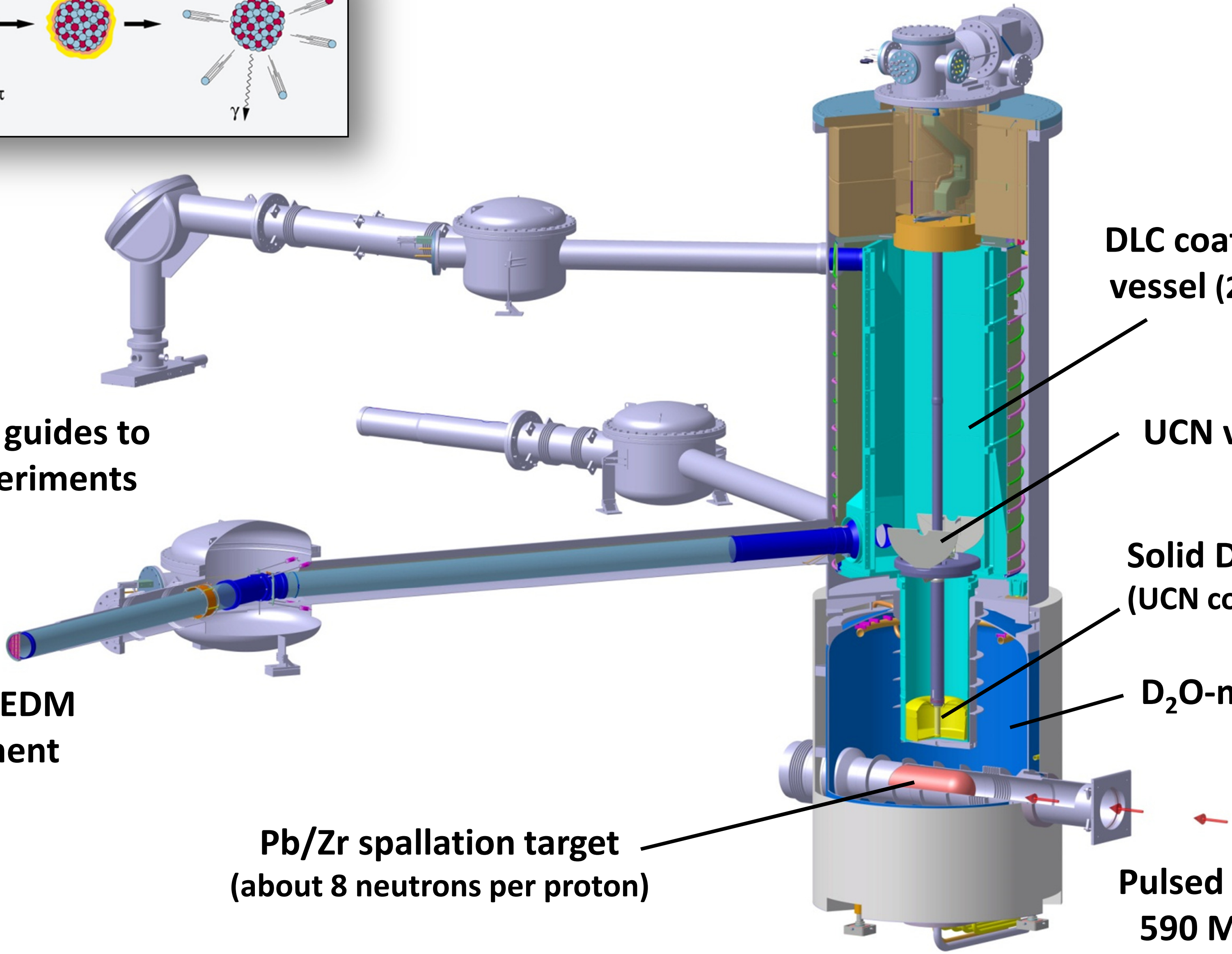
# Paul Scherrer Institute



Ultra Cold Neutron Source

# Solid Deuterium UCN source at PSI



DLC coated UCN storage vessel ($2 m^3$, 2.5 m height)

UCN valve

Solid D2
(UCN converter, 30 l at 5K)

$D_2O$-moderator ($3.6\ m^3$)

UCN guides to experiments

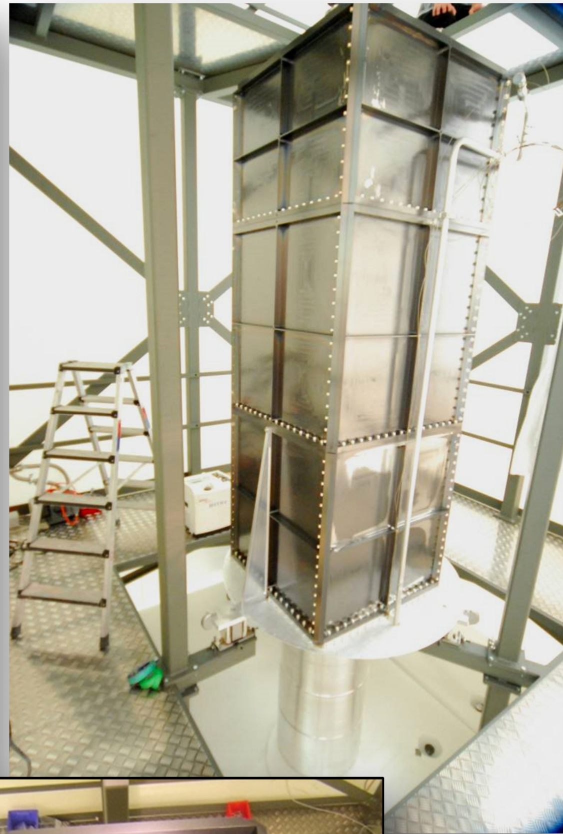
Port to nEDM Experiment

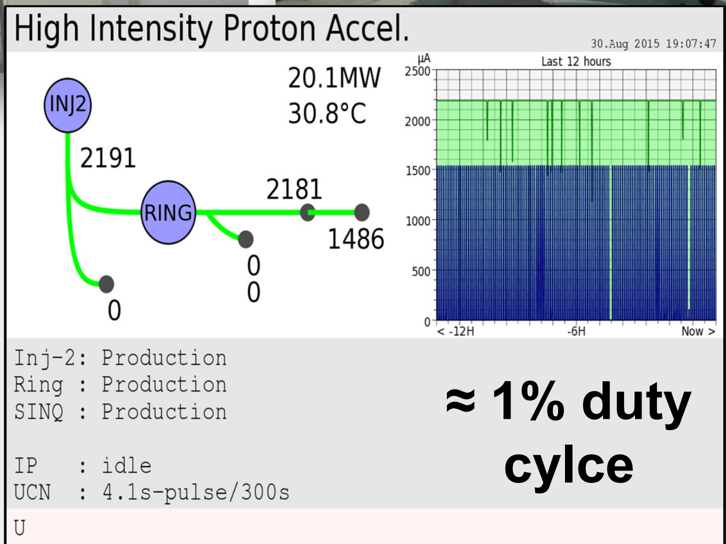
Pb/Zr spallation target
(about 8 neutrons per proton)

Pulsed proton beam
590 MeV, 2.5 mA
(1% duty cycle, pulse length ≈ sec)

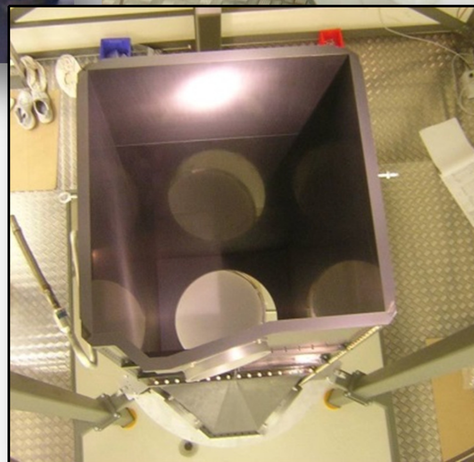
Currently about 30 UCN $cm^{-3}$ - ctd. improvement
UCN to nEDM experiment since 2012

# Solid Deuterium UCN source at PSI

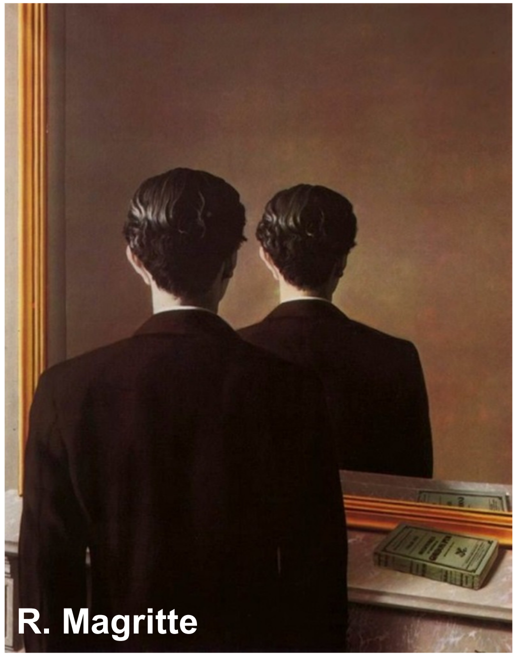




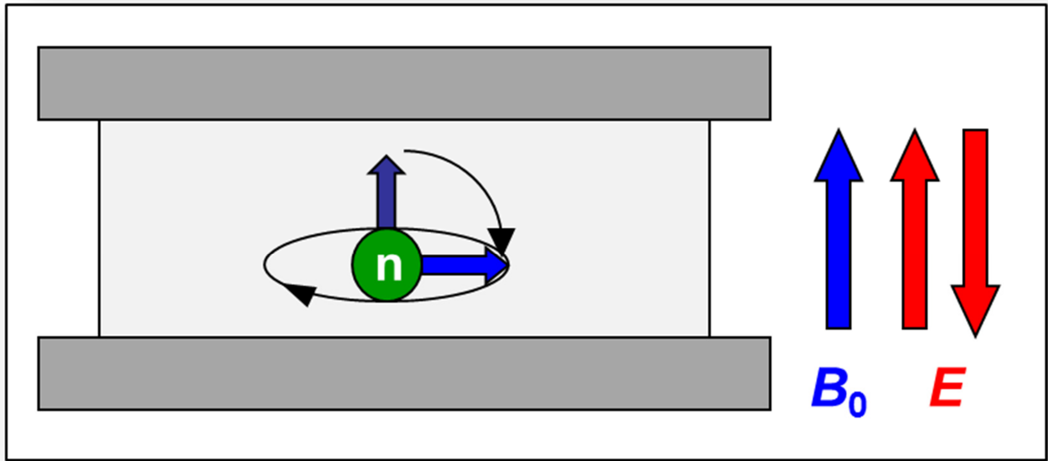

**≈ 1% duty cylce**



# ► Ramsey's Method & nEDM



- Determine Larmor precession frequency of UCN in E//B fields:




$$\hbar\omega_{\uparrow\uparrow} = -2\mu_n B_0 - 2d_n E$$

$$\hbar\omega_{\uparrow\downarrow} = -2\mu_n B_0 + 2d_n E$$

$$\Rightarrow \hbar\Delta\omega = 4d_n E$$

for $B_0$ = const.

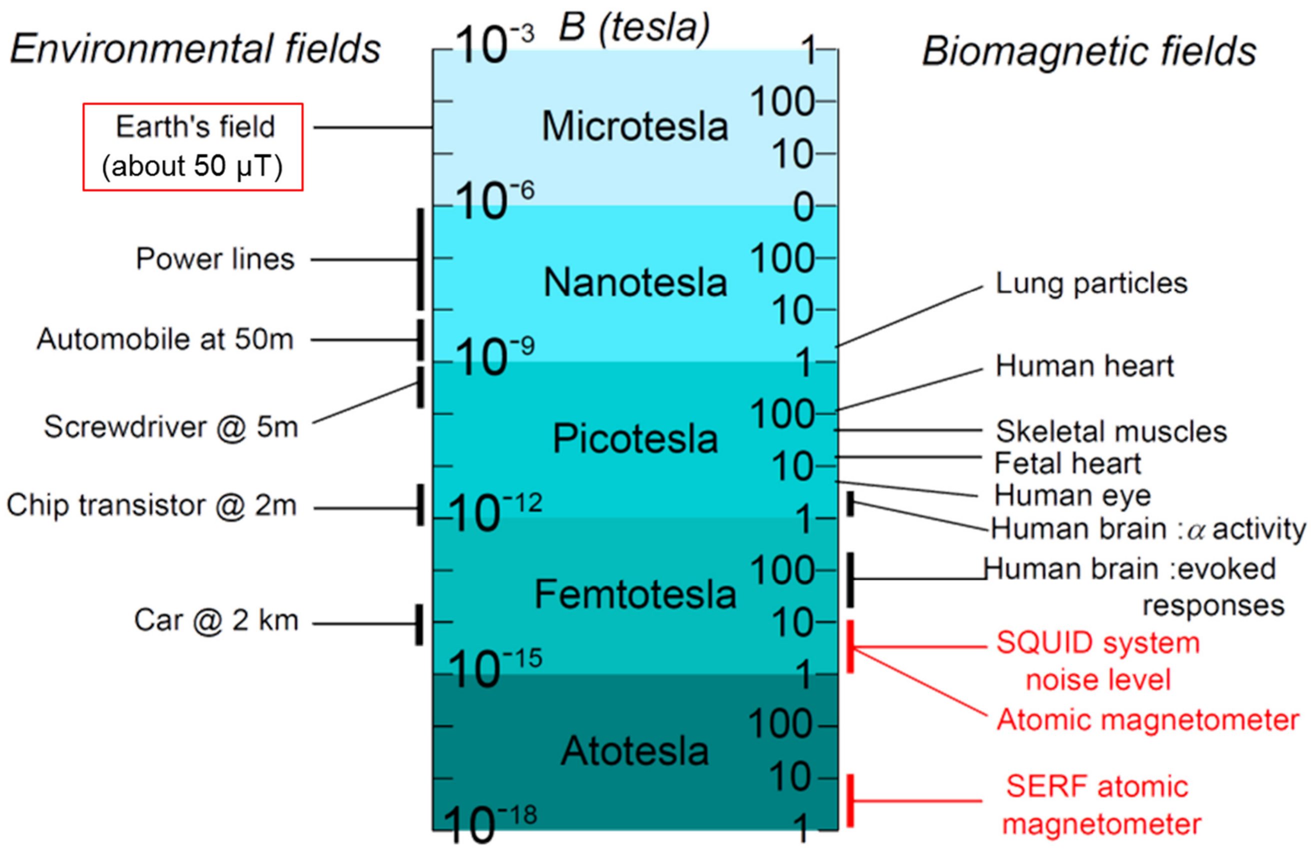
- Ideal technique:
  Ramsey's method of separated oscillating fields


Norman Ramsey

$$d_{n,false} = \frac{\hbar \gamma_n}{4E} \cdot \Delta B$$

$$d_{n,false} = 3 \times 10^{-27} \text{e cm}$$

with: $\Delta B$ = 1 fT, $E$ = 10 kV/cm



$$d_{n,false} = \frac{\hbar \gamma_n}{4E} \cdot \Delta B$$

$$d_{n,false} = 3 \times 10^{-27} \text{e cm}$$

with: $\Delta B$ = 1 fT, $E$ = 10 kV/cm

- Is it necessary to stabalize the field on the below fT level ?

**YES**

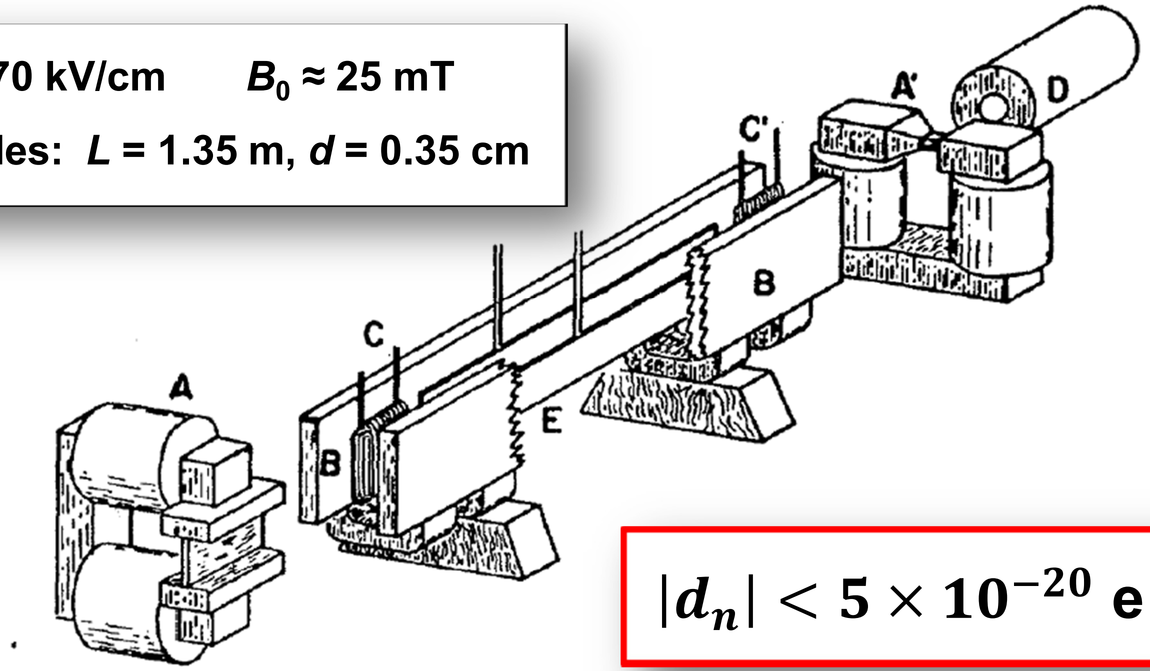
for effects correlated with *E*-field direction, e.g. leakage currents, magnetisation due to charging of electrodes (gradients), geom. phases etc.

**NO**

for random noise effects, which will average out over time.

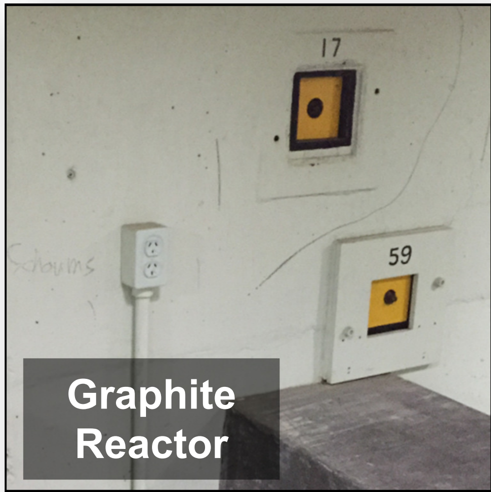
$E \approx 70$ kV/cm  $B_0 \approx 25$ mT

Electrodes: $L = 1.35$ m, $d = 0.35$ cm




$$|d_n| < 5 \times 10^{-20} \text{ e cm}$$

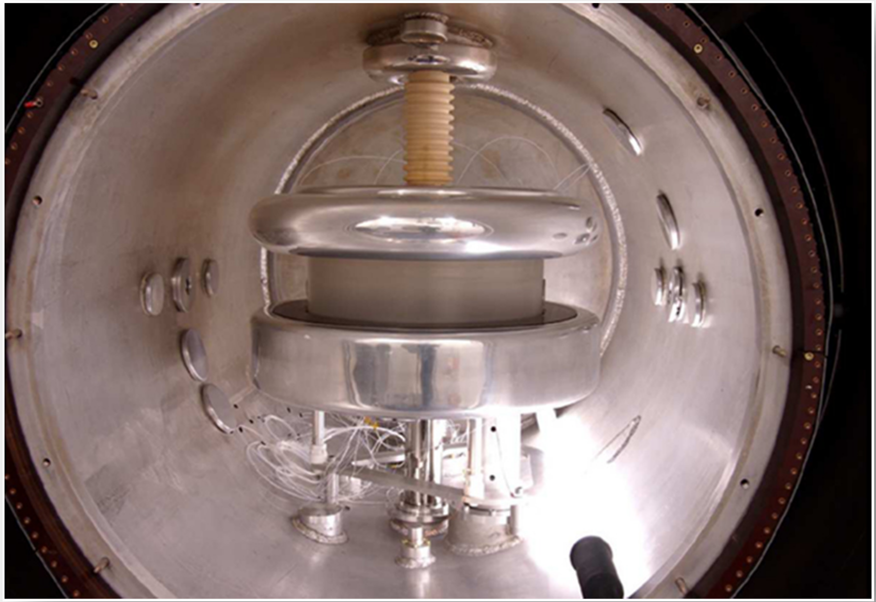
FIG. 1. Schematic diagram of the apparatus. $A$, the magnetized iron mirror polarizer. $A'$, the magnetized iron transmission analyzer. $B$, the pole faces of the homogeneous field magnet. Note the horseshoe-like magnets bolted along the bottom. $C$, $C'$, the coils for the radio-frequency magnetic field. $D$, the $BF_3$ neutron counter. The magnetic fields in the polarizing magnet and the homogeneous field magnet are at right angles, and two twisted iron strips were used between them to rotate the neutron spins adiabatically.




Graphite Reactor

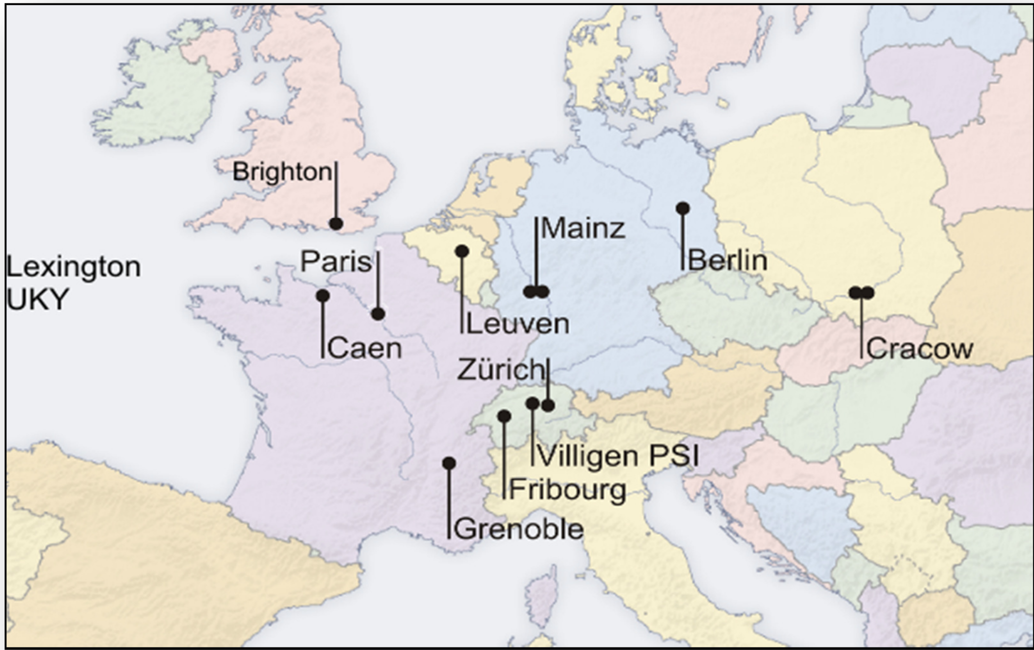
Smith, Purcell, Ramsey, Phys. Rev. 108, 120 (1957)

# ►nEDM Experiment at PSI



- **About 50 members from 8 countries and 14 institutions.**
- **Experiment is performed at the new UCN source at the Paul Scherrer Institute in Villigen (Switzerland).**

➡ **nedm.web.psi.ch**



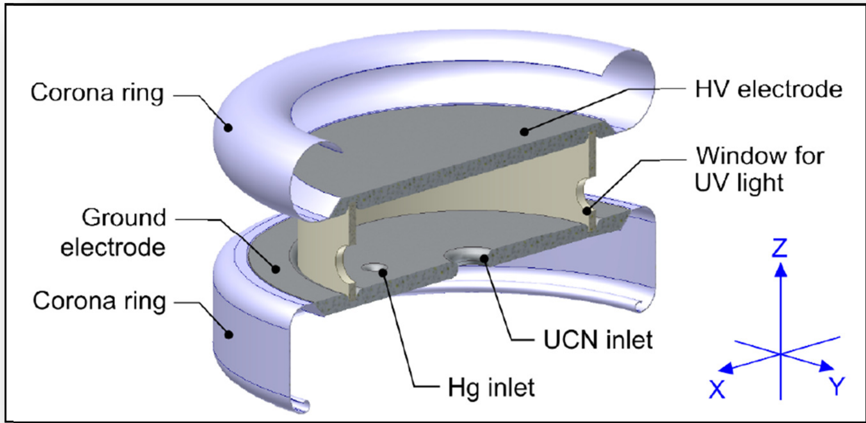

Collaboration Meeting 2014

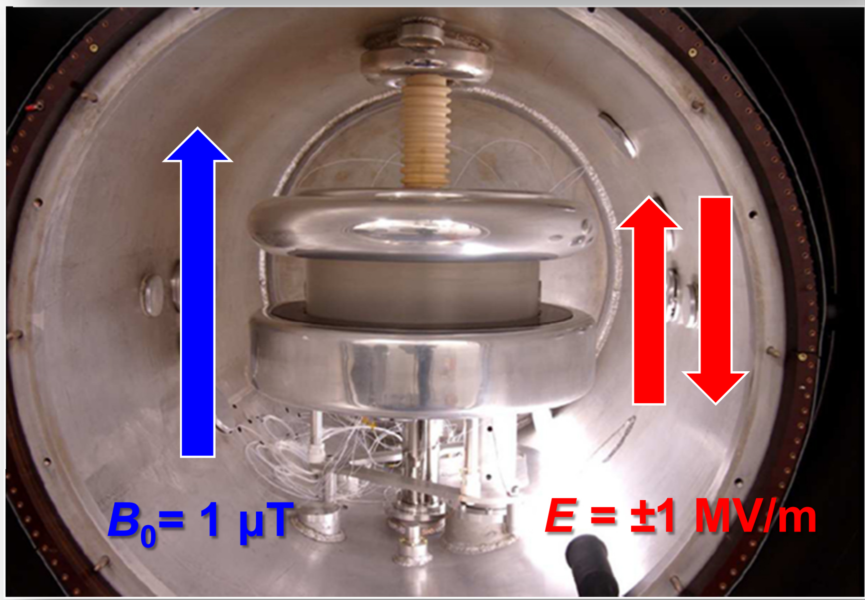
# nEDM Experiment at PSI

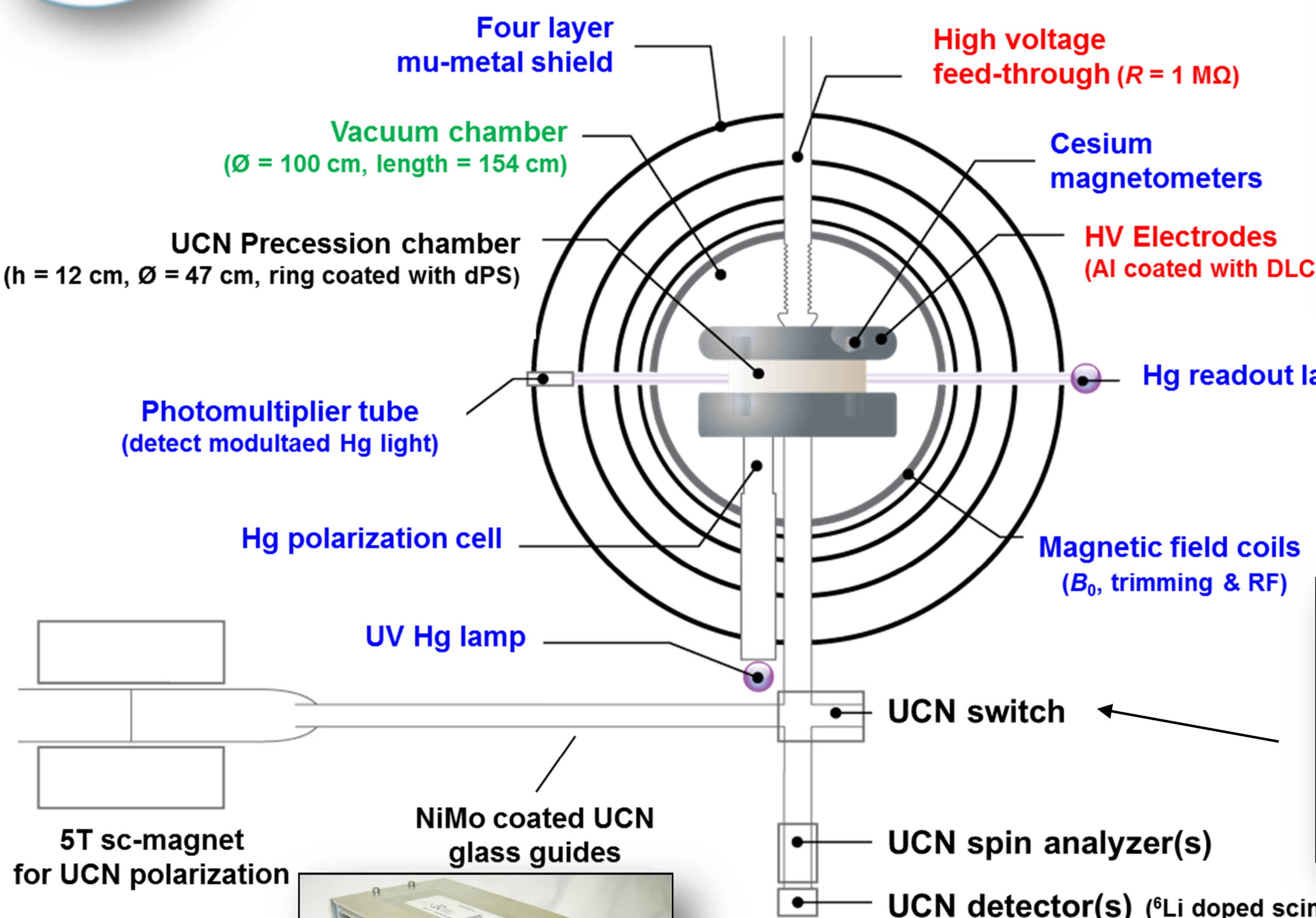
Thermal Insolation & Stabilization

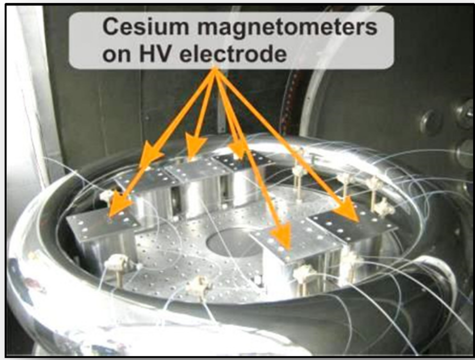
Active Magnetic Shielding Coils (3D)

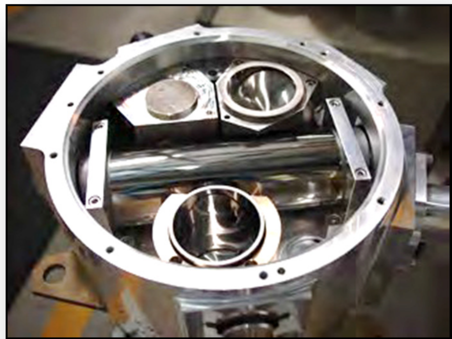
## Improved apparatus of the RAL/Sussex/ILL experiment

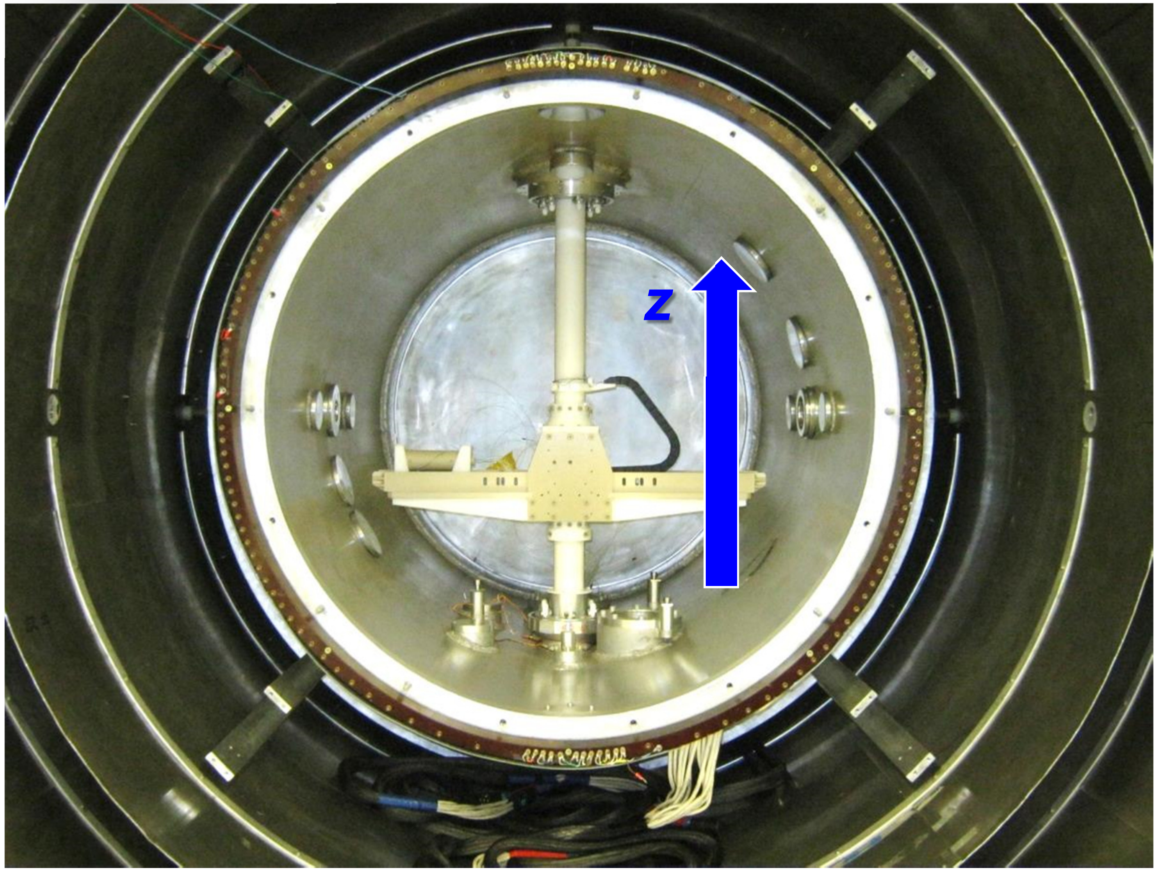


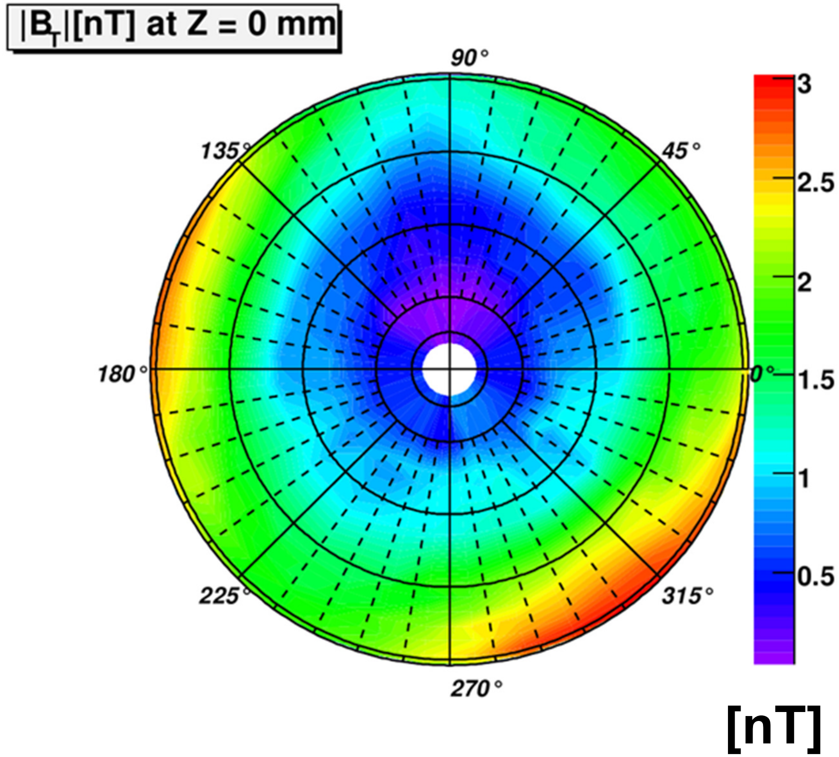




Four layer
mu-metal shield
Vacuum chamber
(Ø = 100 cm, length = 154 cm)
UCN Precession chamber
(h = 12 cm, Ø = 47 cm, ring coated with dPS)
Photomultiplier tube
(detect modultaed Hg light)
Hg polarization cell
UV Hg lamp
High voltage
feed-through (R = 1 MΩ)
Cesium
magnetometers
HV Electrodes
(Al coated with DLC)
Hg readout lamp
Magnetic field coils
(B0, trimming & RF)
UCN switch
5T sc-magnet
for UCN polarization
NiMo coated UCN
glass guides
UCN spin analyzer(s)
UCN detector(s) (6Li doped scintillators)
E-Field
B-Field
Neutrons
Vacuum

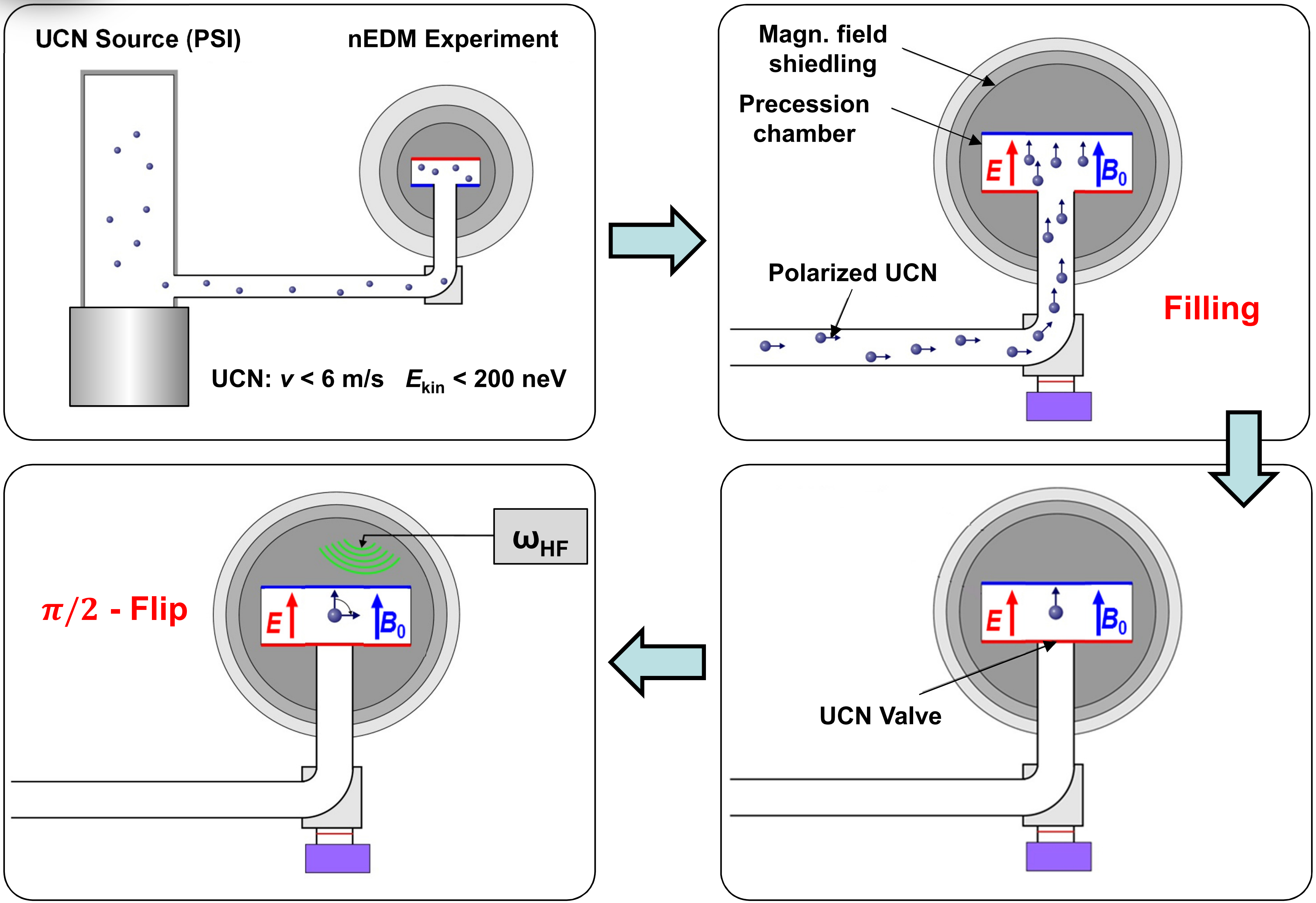

Cesium magnetometers
on HV electrode

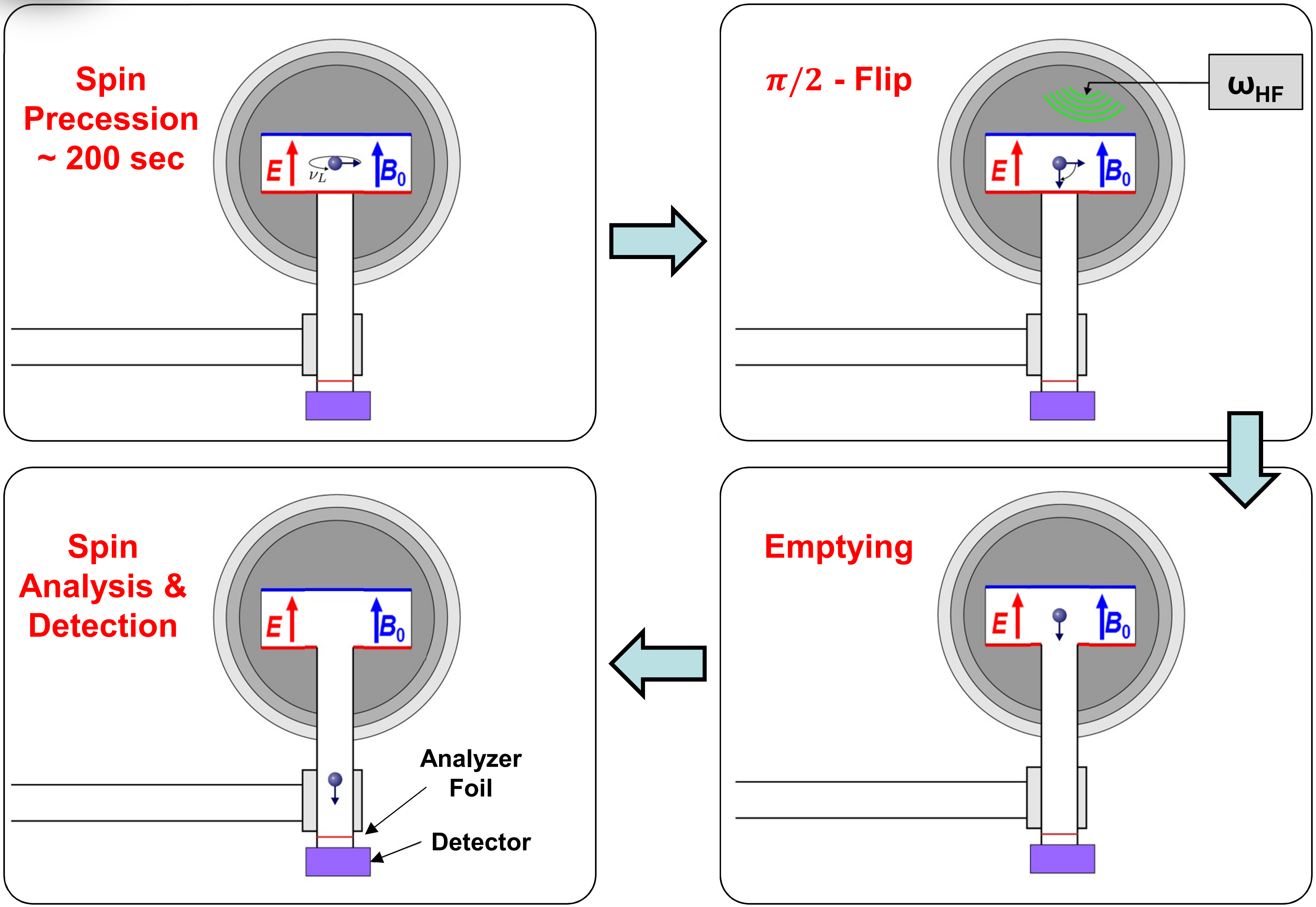


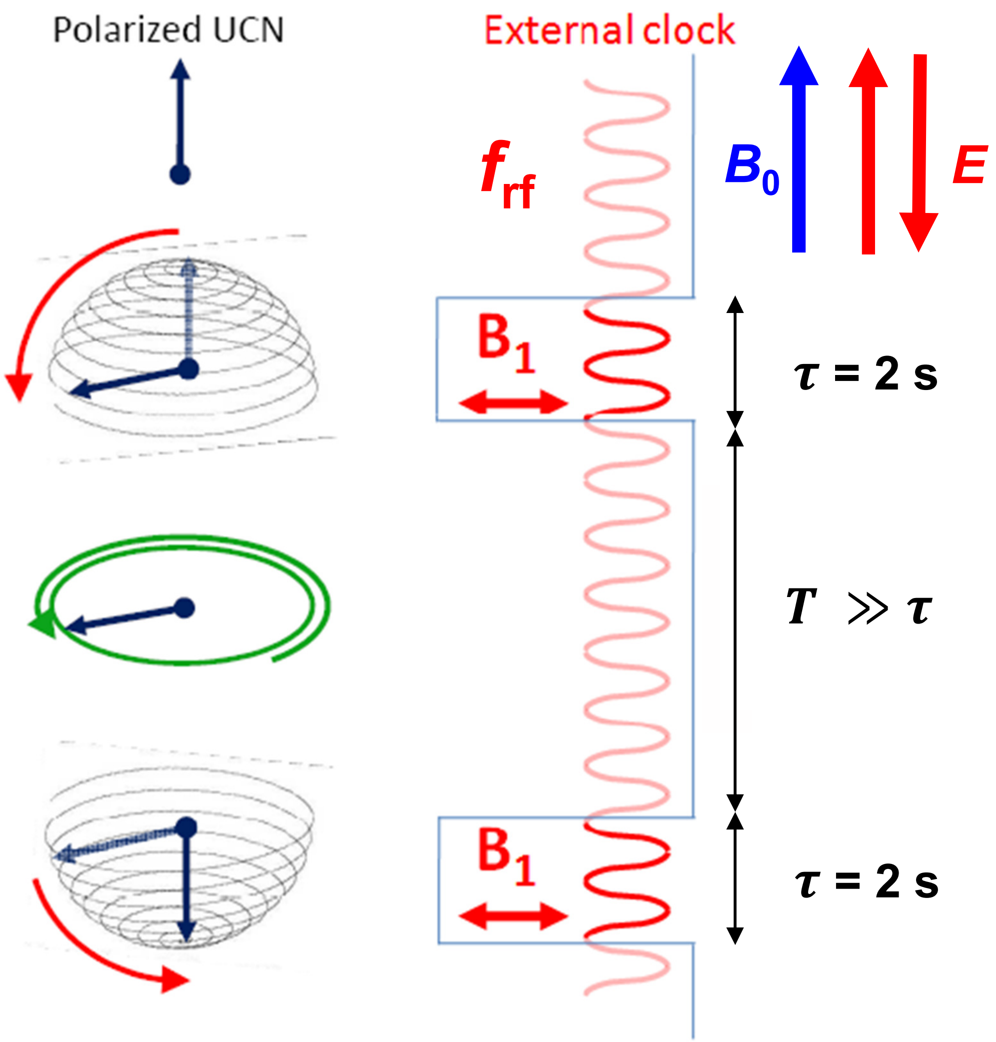


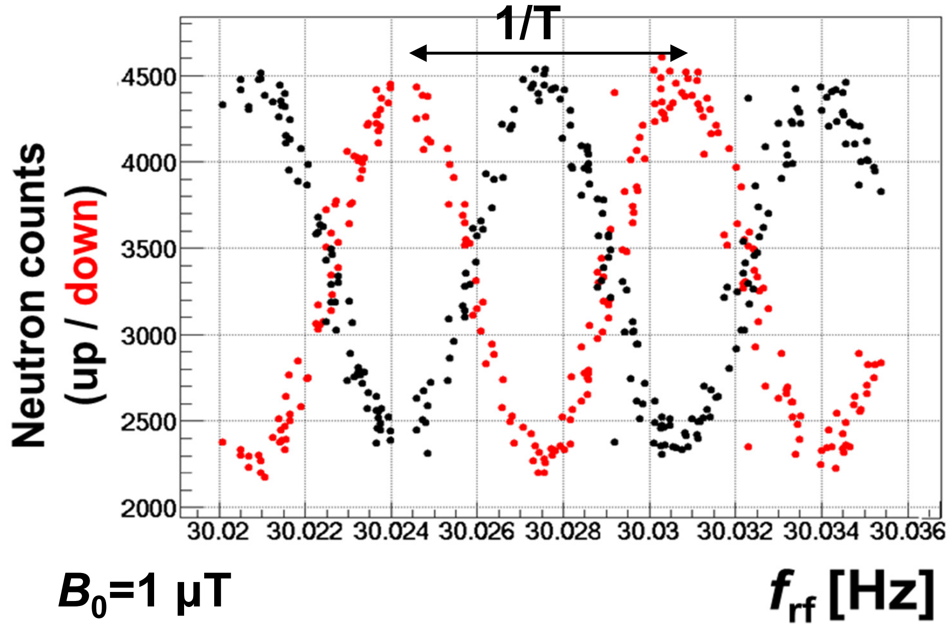




- **Automated field mapping using a 3-axis precision fluxgate**
- **Robot-arm made from non-magnetic materials**
- **Perform regular offset-calibration runs to compensate for drifts**


UCN Source (PSI)
nEDM Experiment
UCN: $v$ < 6 m/s $E_{kin}$ < 200 neV
Magn. field shiedling
Precession chamber
Polarized UCN
Filling
$E$
$B_0$
UCN Valve
$\omega_{HF}$
$\pi/2$ - Flip


Spin Precession ~ 200 sec
$\nu_L$
E
$B_0$
$\pi/2$ - Flip
$\omega_{HF}$
Emptying
Spin Analysis & Detection
Analyzer Foil
Detector




## Sensitivity

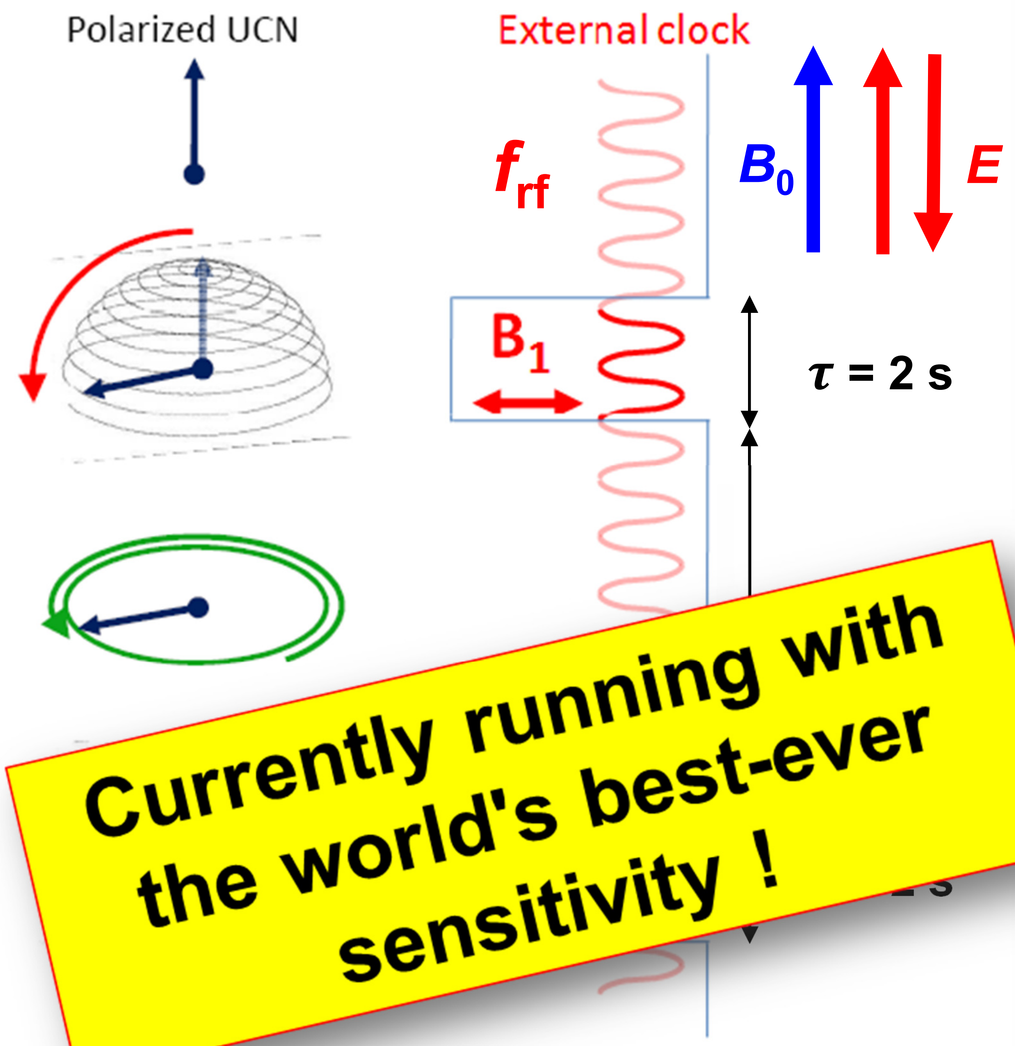
$$\sigma(d_n) \propto \frac{1}{\alpha T E \sqrt{N}}$$

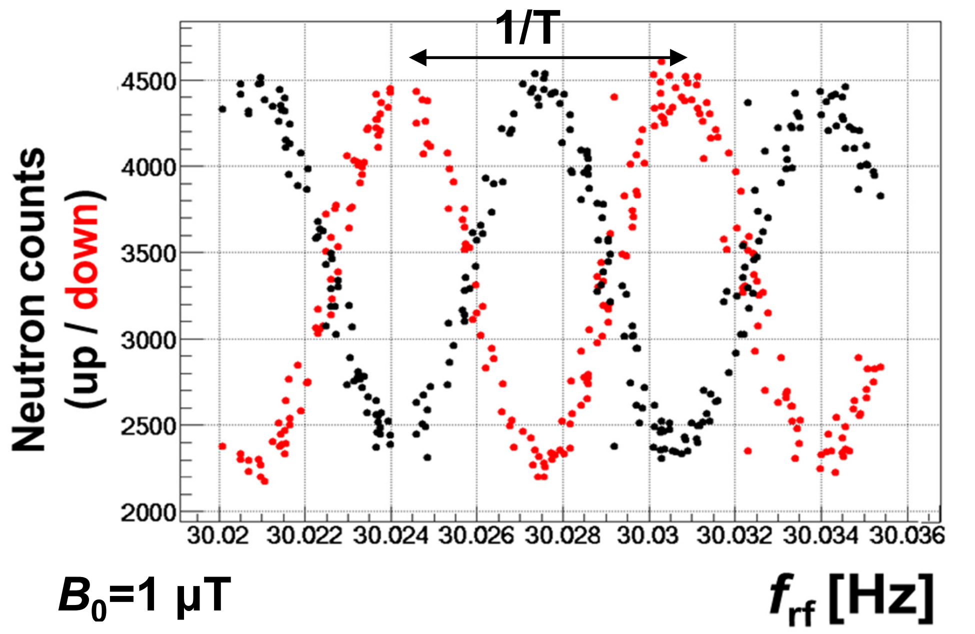
- $\alpha$: signal visibility (≈ 0.75)
- $T$: free precession time (about 200 s)
- $E$: electric field strength (≈ 10 kV/cm)
- $N$: number of neutrons (≈ 8000/cycle)

Currently (2015): $\sigma \approx 2 \times 10^{-25}$ ecm/day

Accum. sensit. (by 2015): $2 \times 10^{-26}$ ecm

# Ramsey Method with UCN




**Currently running with the world's best-ever sensitivity !**

## Sensitivity

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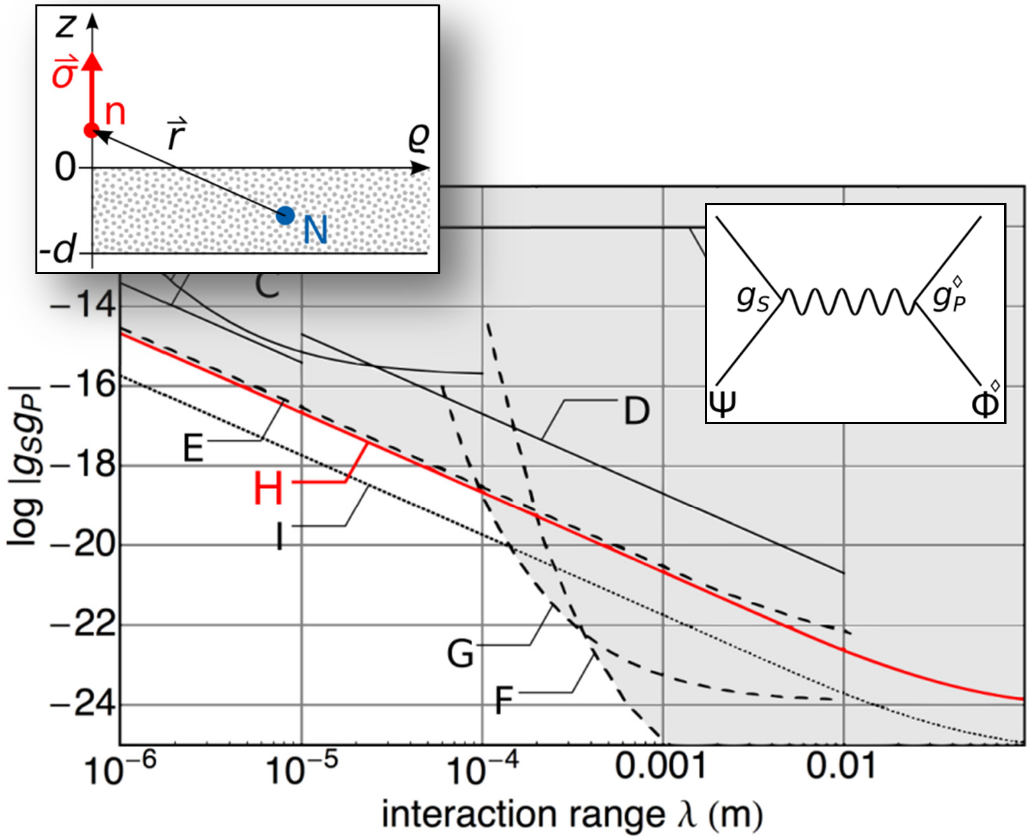
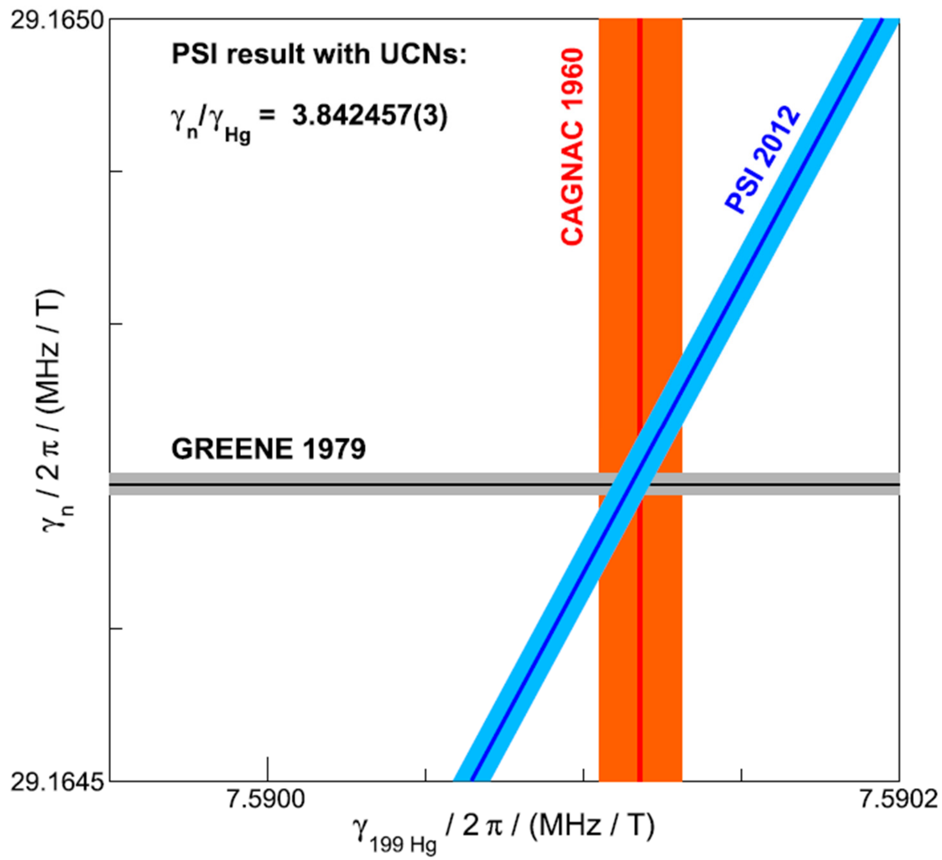
Accum. sensit. (by 2015): $2 \times 10^{-26}$ ecm

# Two recent Higlights beyond the nEDM

► **Physics results obtained with the same Ramsey apparatus:**




**Search for new exotic interactions (Axion-Like-Particles) ***

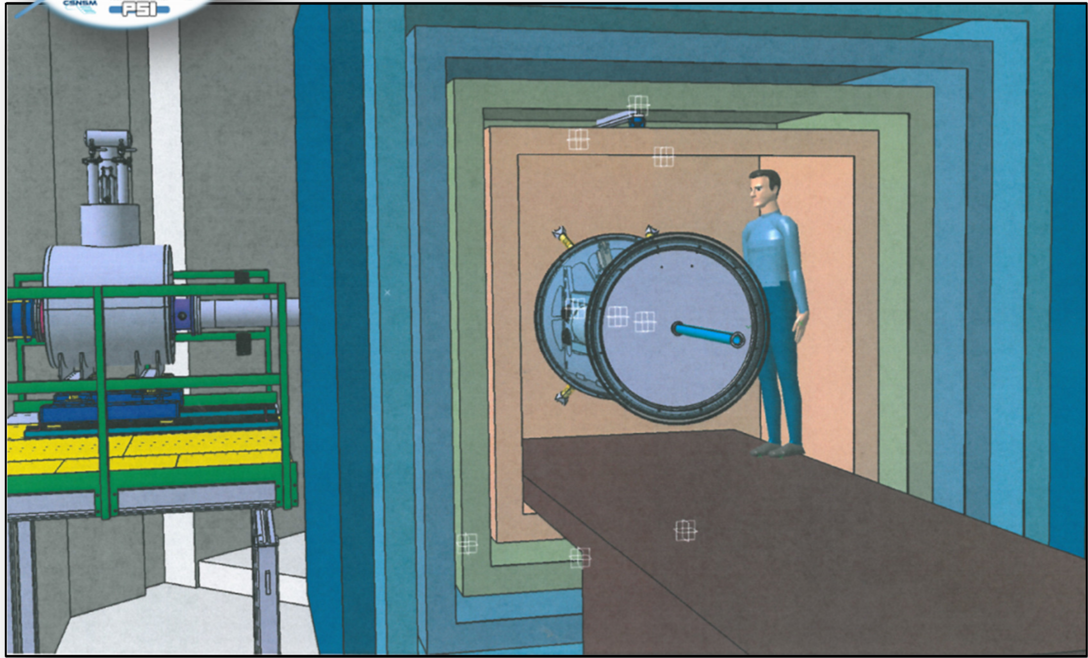


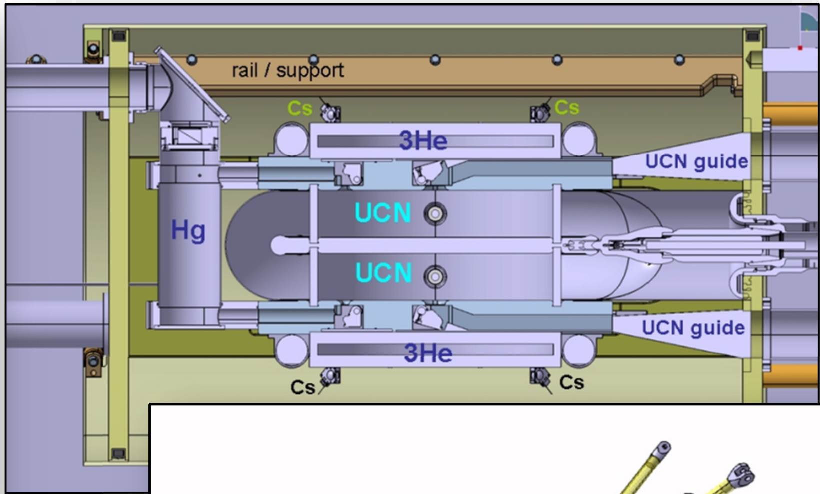

**n/$^{199}$Hg - magnetic moment ratio ****

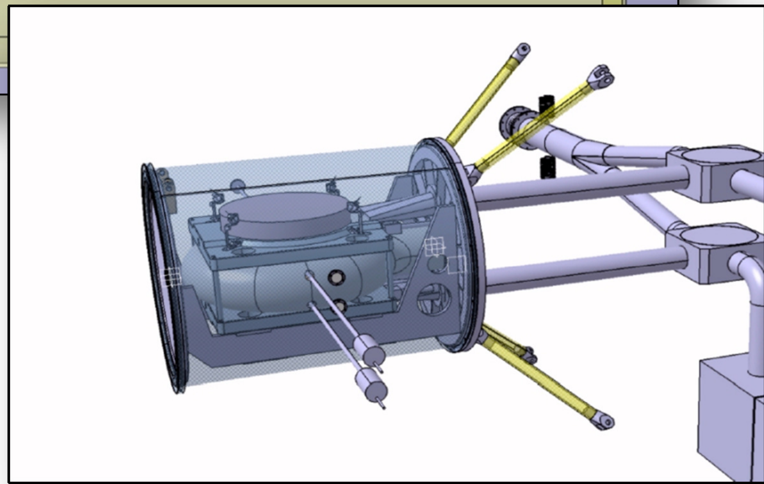
* Afach et al., Phys. Lett. B 745, 58 (2015)

** Afach et al., Phys. Lett. B 739, 128 (2014)

# Planned n2EDM Experiment at PSI





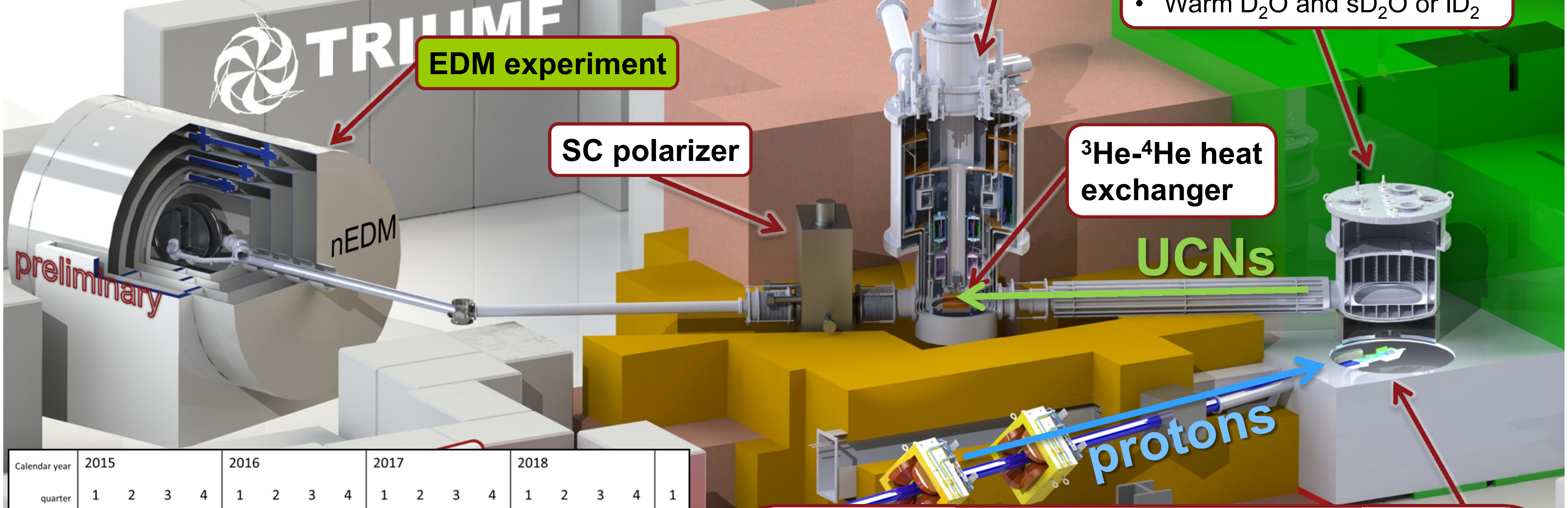
## ► New features/improvements:

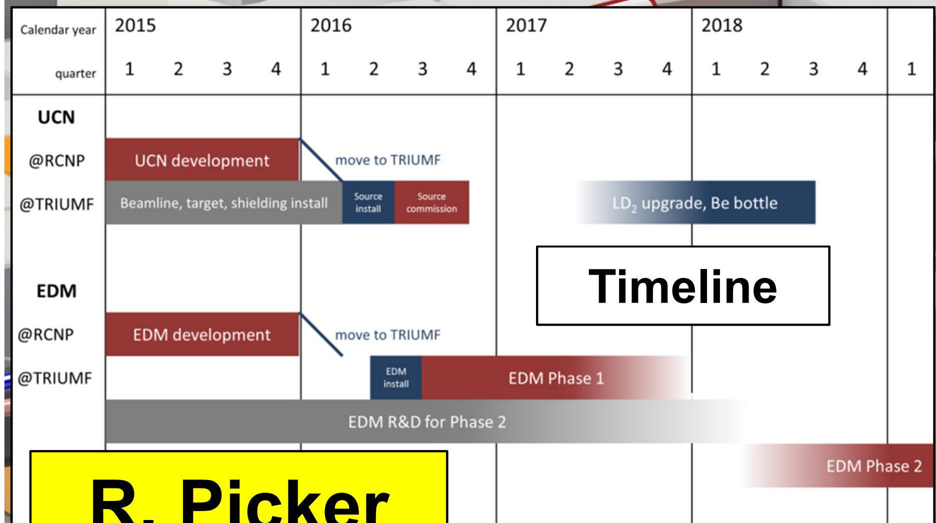
- **Two UCN precession chambers with opposite electric field directions (surpress *B*-field drift susceptibility, *E*-field correlated gradients remain important)**
- **Improved magnetic enviornment due to better shielding & compensation**
- **Higher neutron statistics due to better adaption to PSI UCN source**
- **Improved magnetometry (Hg, Vector-Cs, $^{3}$He)**

## ► Worldwide Neutron EDM Searches

# BL1U downstream

1. 500 meV protons on tungsten create spallation neutrons
2. lead, graphite, heavy water, deuterium moderate fast neutrons to cold neutrons
3. $^4$He at 0.7 K converts them to UCN
4. Extraction to experiments via material guides

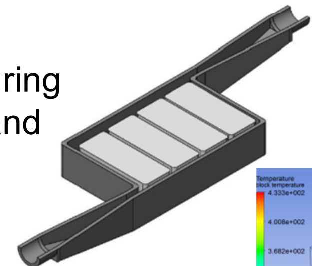


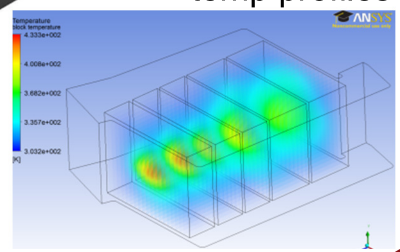

**R. Picker**

## Spallation target

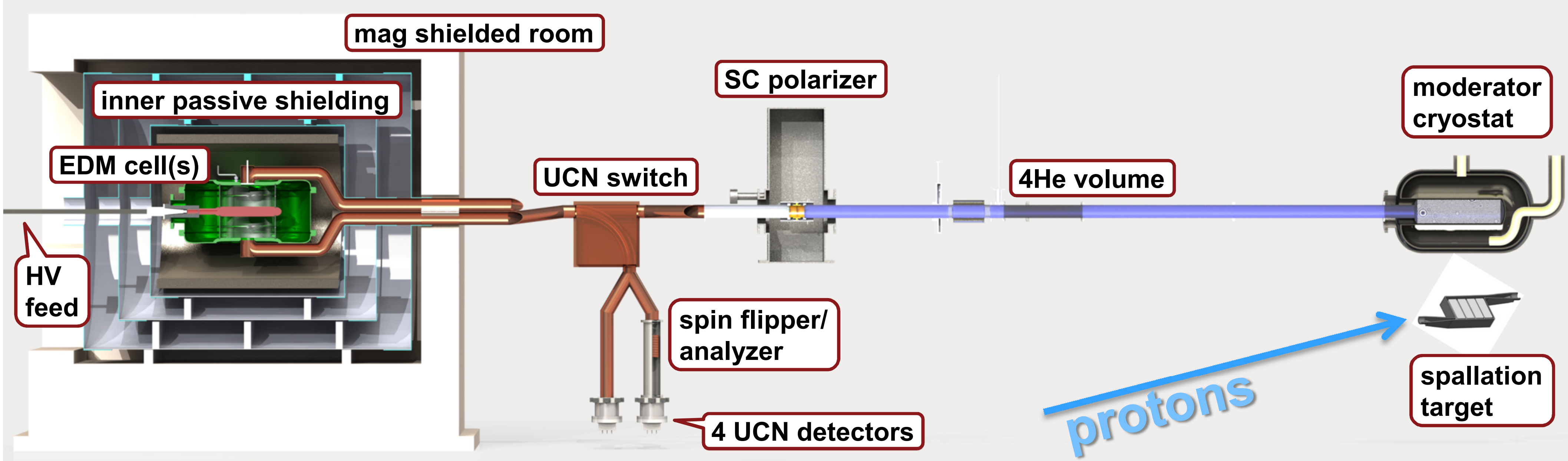
- beam power: 20 kW (during 1 min beam on target) and 5 kW (average)
- **tungsten (Ta cladded)**
- water cooled
- **cladded target blocks have been fabricated in Japan**



temp profiles

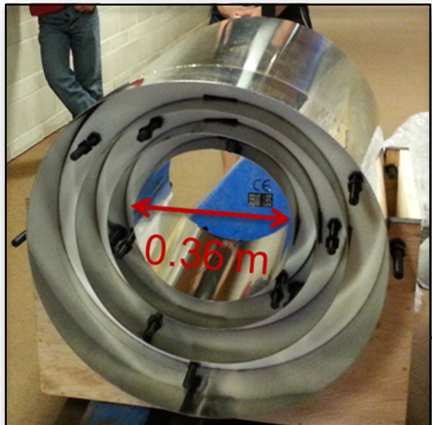


# Layout draft – Phase 2

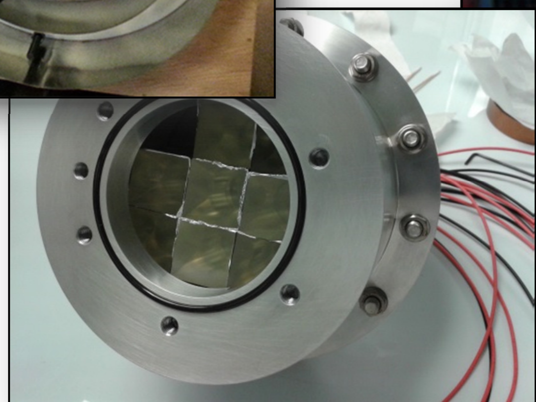


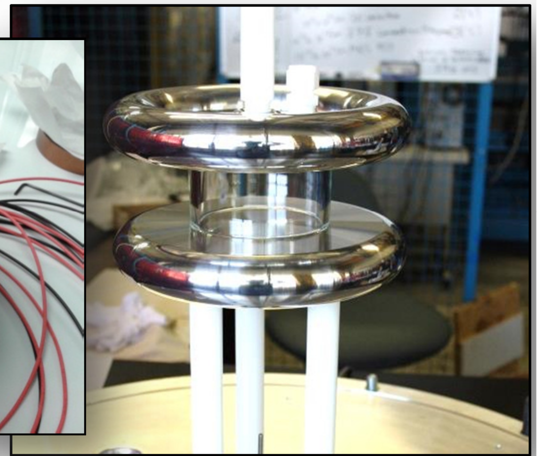

**Conceptual design guidelines**

- high count rate UCN detector
- two larger EDM cells, central HV electrode
  - increase in total UCN number
  - simultaneous measurement of both E field directions
  - additional symmetry
- higher Fermi potential
  - DLC, NiMo + dPS, dPE, larger phase space
- dual co-magnetometer
  - cross check
  - gradient determination
- simultaneous counting of both spin states
  - gain in sensitivity
- improved magnetic environment
  - magnetically shielded room for mag development and longer lasting flexibility



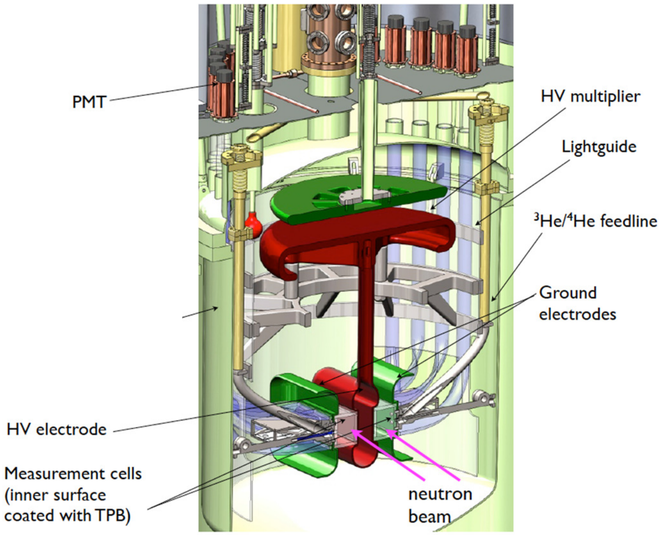

Many R&D items and simulations ongoing

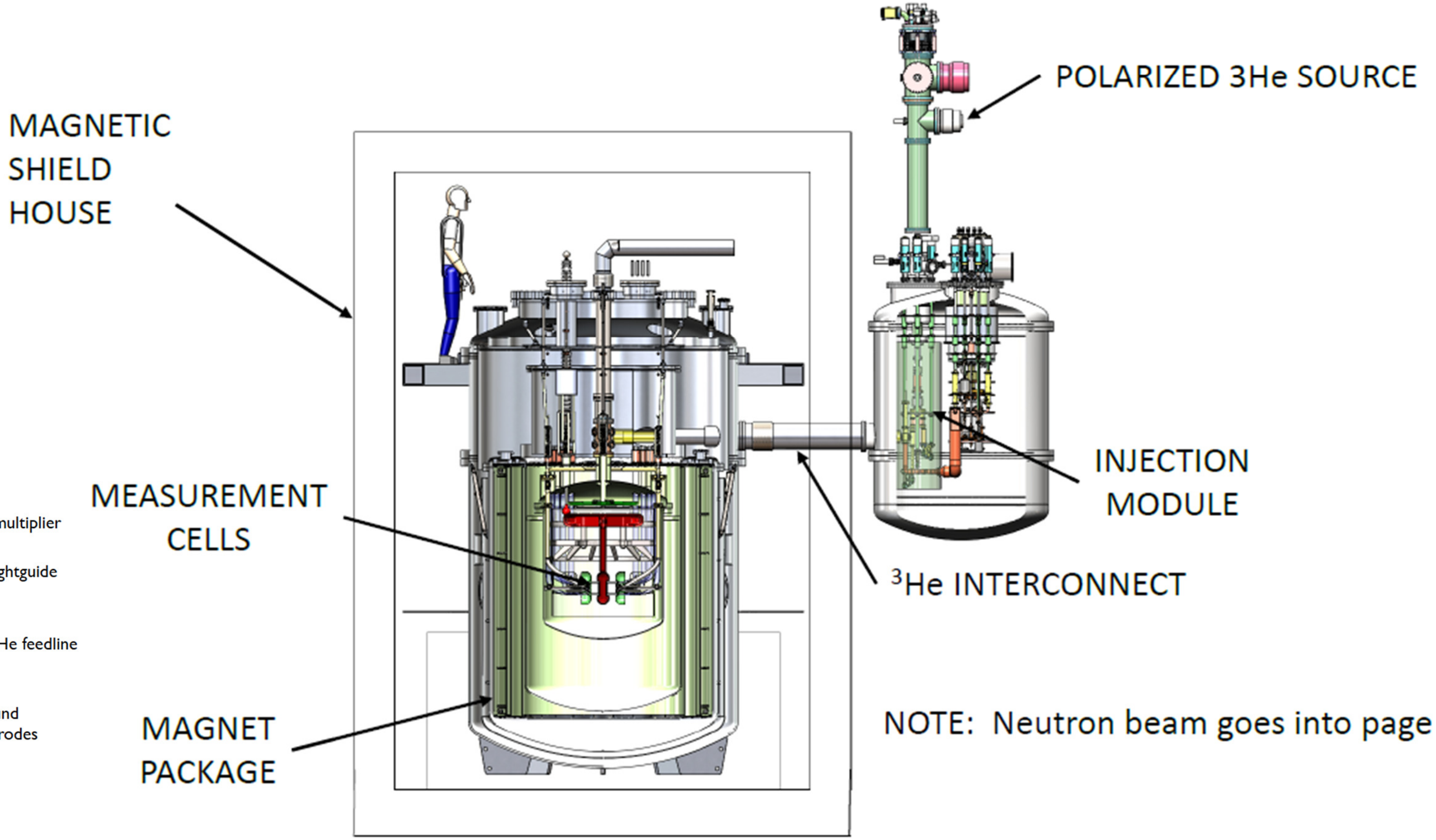




**R. Picker**

**A cryogenic experiment**




| | |
|---|---|
| **2014-2017** | **Critical Component Demonstration is underway** |
| **2018-2020** | **Large Scale Integration etc.** |
| **2021** | **Begin Commissioning & Data-taking** |

**B. Filippone**

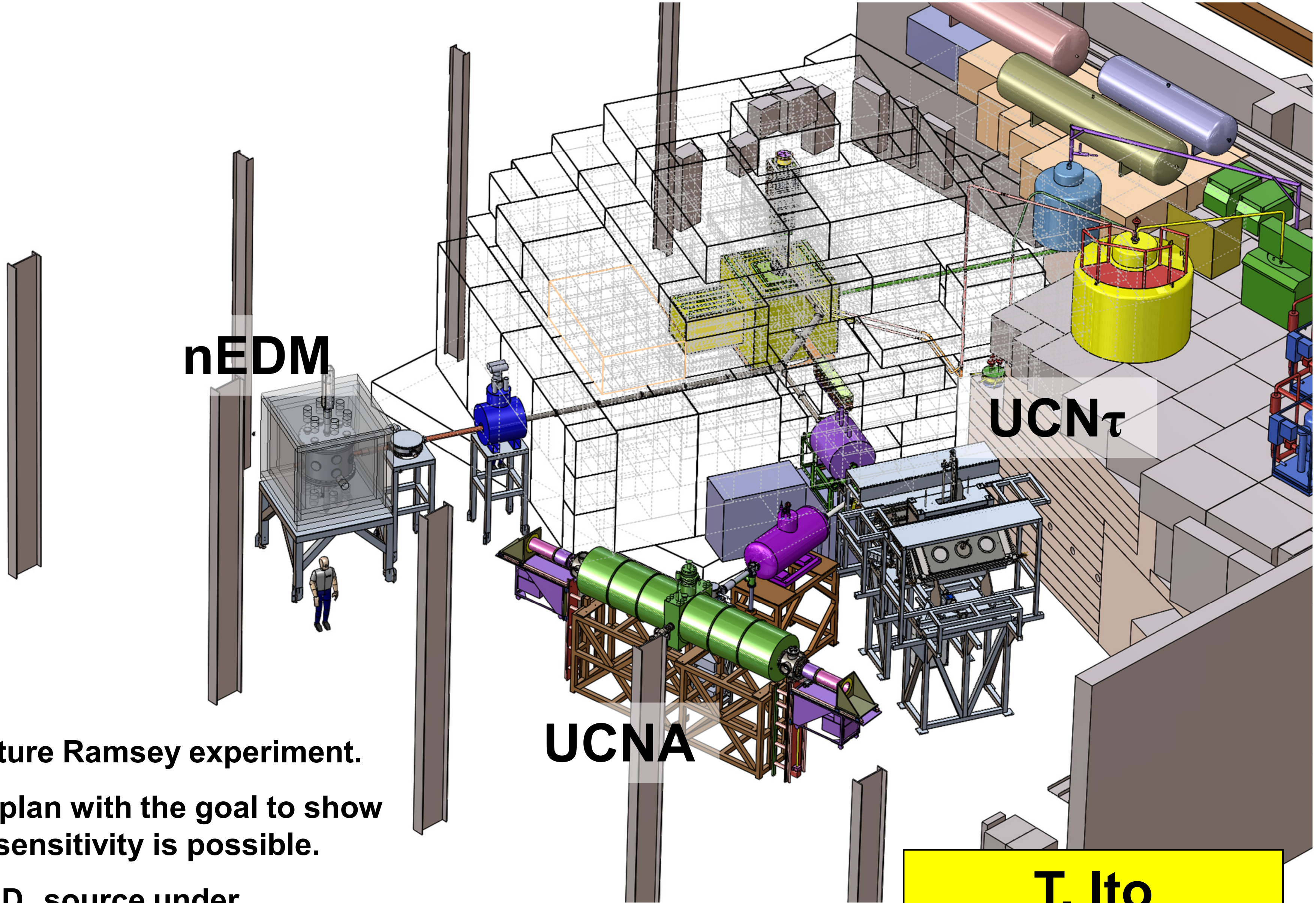
# Key Features of nEDM@SNS

- Sensitivity: ~2x$10^{-28}$ e-cm, 100 times better than existing limit
- In-situ Production of UCN in superfluid helium (no UCN transport)
- **Polarized $^3$He co-magnetometer**
  - Also functions as neutron spin precession monitor via spin-dependent n-$^3$He capture cross section using wavelength-shifted scintillation light in the LHe
  - Ability to vary influence of external B-fields via "dressed spins"
    - Extra RF field allows synching of n & $^3$He relative precession frequency
- Superconducting Magnetic Shield
- Two cells with opposite E-field
- Control of central-volume temperature
  - Can vary $^3$He diffusion (mfp)- big change in geometric phase effect on $^3$He

**Arguably the most ambitious of all neutron EDM experiments**

**B. Filippone**

# Schematic of Area B with the proposed nEDM experiment at **LANL**



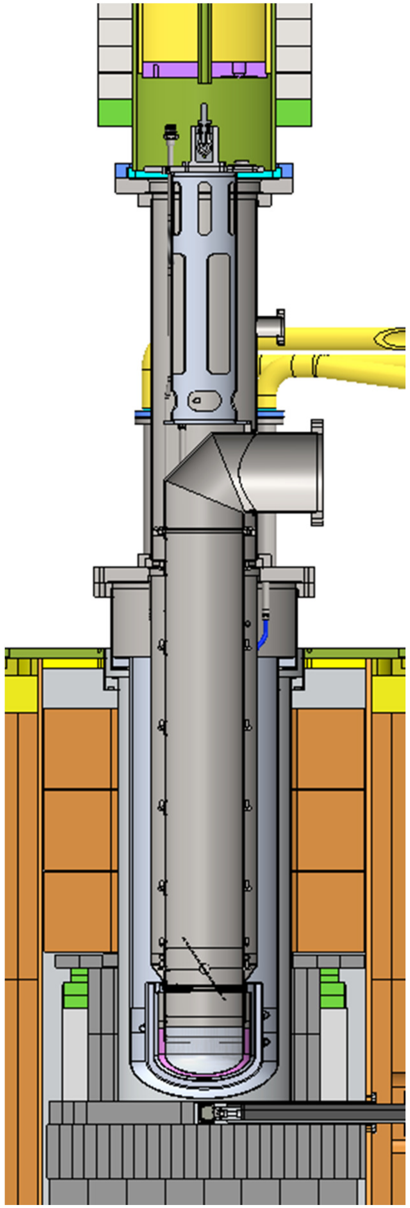

**A room temperature Ramsey experiment.**

**A 3 year project plan with the goal to show that a $10^{-27}$ ecm sensitivity is possible.**

**New upgraded $SD_2$ source under construction.**

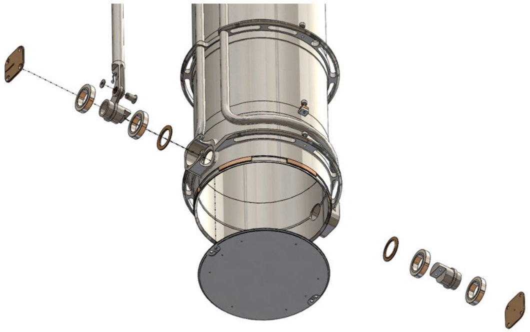
**T. Ito**

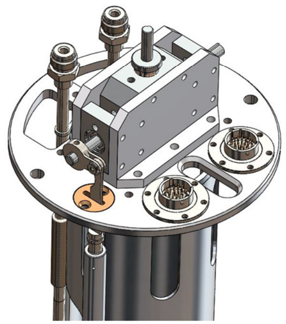
# Engineering design of the new $SD_2$ source @ **LANL**



## Near term schedule

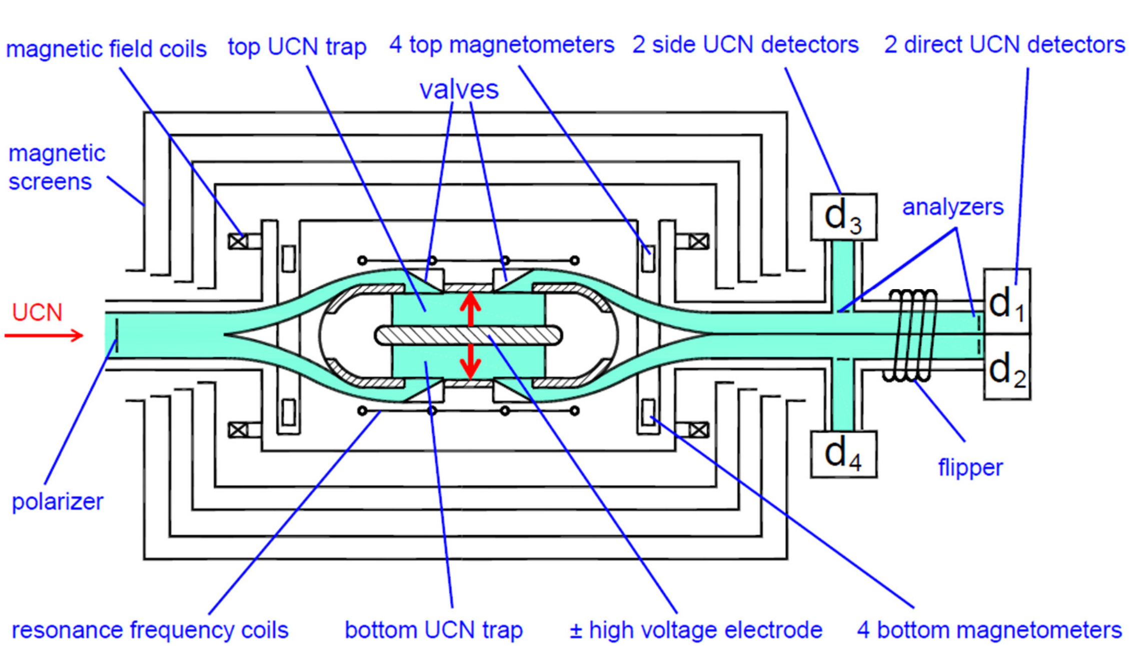
- Present – Dec 2015
  - Fabrication of source and guide components
  - Fabrication of a prototype nEDM cell, cell valve, and UCN switcher
- Oct 2015 – Feb 2016
  - Test source and guide components with UCN
  - Test of the prototype nEDM cell, cell valve, and UCN switcher
- March – August 2016
  - Installation of the new source and guides
- Sep – Dec 2016
  - Test of the new UCN source

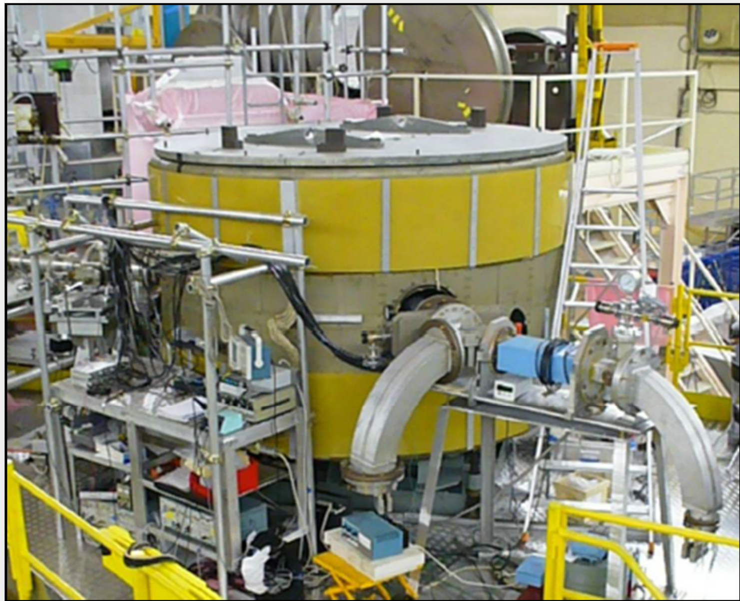




**T. Ito**

*Scheme of EDM spectrometer*



**A. Serebrov**

**Recent measurement: 5.5 x $10^{-26}$ ecm (90% CL)**

**Serebrov et al., JETP Lett. 99 (2014) 4**

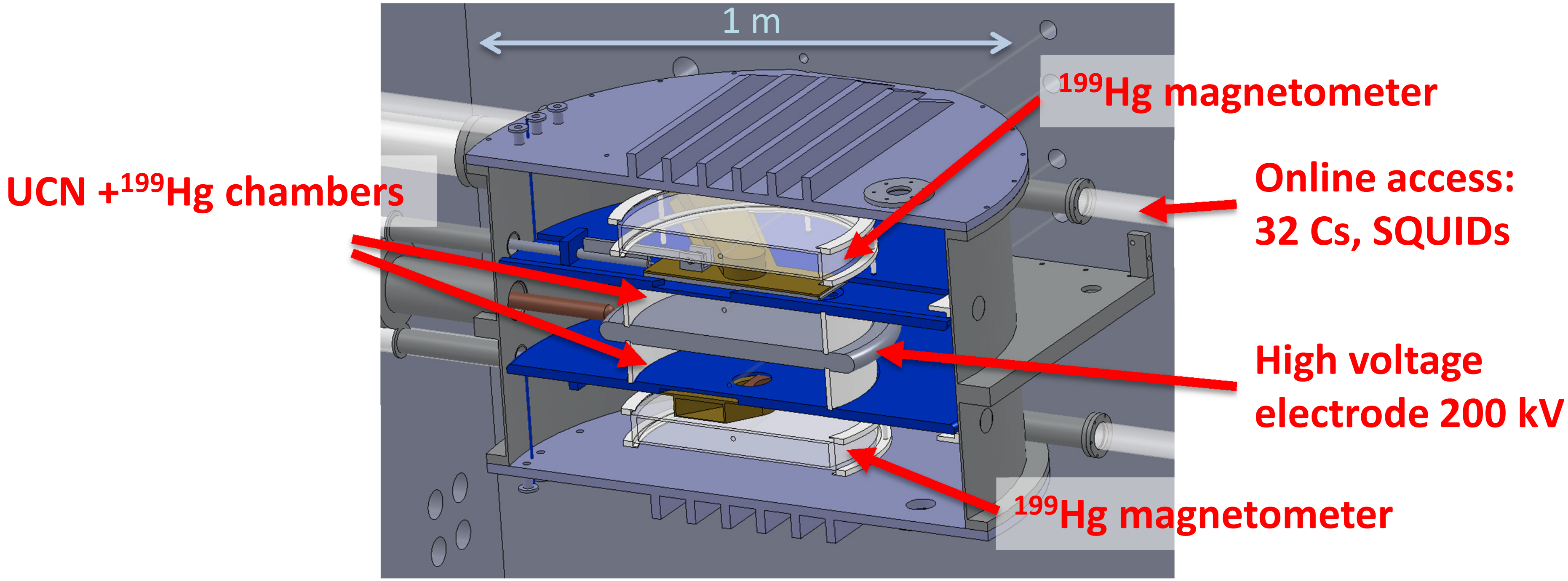
**Already using a double chamber setup.**

**Prospects for an improved experiment at a better source at ILL and later with a new apparatus at the PIK reactor (SF He, in St. Petersburg).**

# EDM apparatus

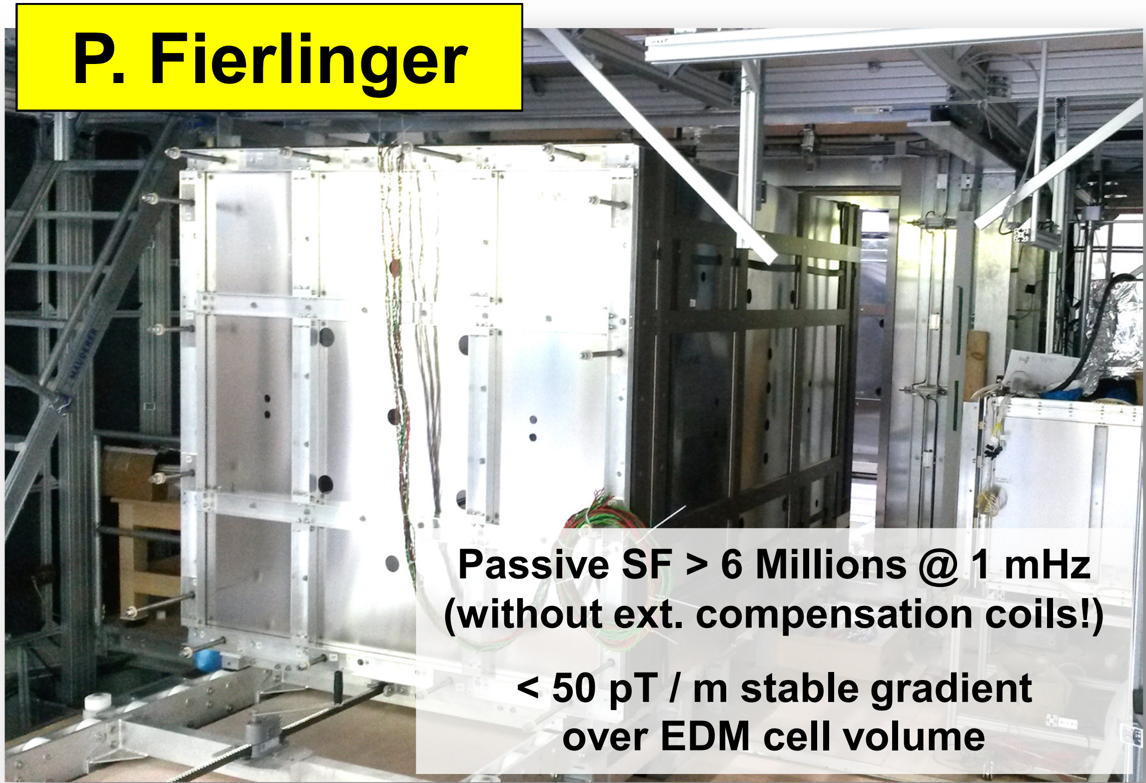
**P. Fierlinger**

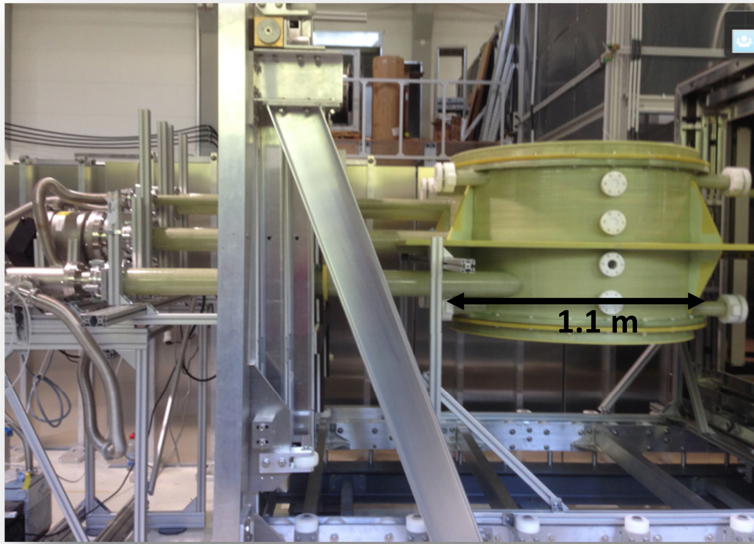
- Initially a ‚conventional' Ramsey experiment
- UCN trapped at **room temperature**, **ultimately cryogenic trap**
- **Double chamber** with co-magnetometer option
- $^{199}$**Hg, Cs,** $^{129}$**Xe,** $^{3}$**He, SQUID magnetometers**
- **Portable setup**, including magnetically shielded room
- Extremely modular design

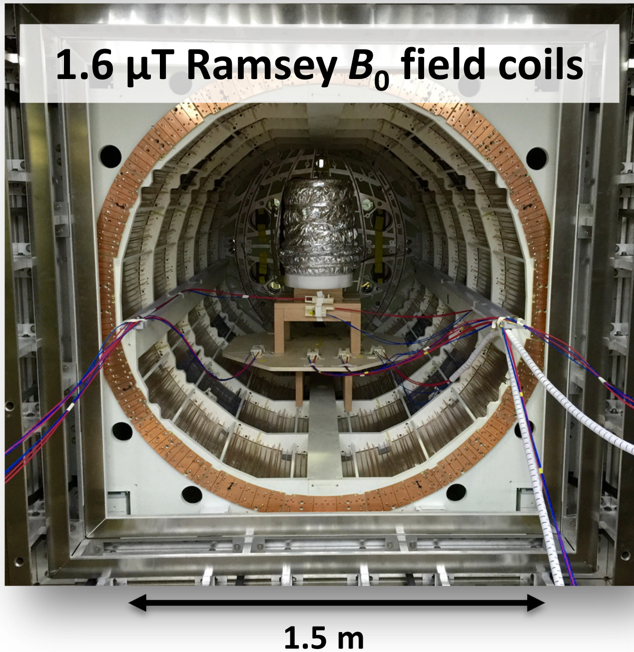



**I. Altarev et al., Il Nuovo Cimento 35 C 122 (2012)**

# The magnetic shields / fields




**UCN Tests at ILL:**

- Adiabatic spin transport, spin-flipping, simultaneous spin detection tests
- Polarizer foils, guides, bends, shutters, plates, dummy electrodes …

I. Altarev et al., arXiv:1501.07408
I. Altarev et al., arXiv:1501.07861

# An (optimistic but possible ) plan towards a physics result

**P. Fierlinger**

**Move Inner Shield to ILL: (2015)**
UCN components, Cs magnetometers
Siting, connecting guides

Magnetic environment tests (2015)
Ramsey measurements at SUN-2 / PF2 (2016)
First EDM runs at SUN-2 / PF2 (2016+)
Best possible results ~ $8.10^{-27}$ ecm (stat, 1 σ)

EDM at Super-SUN w/o magnet (2017+)
EDM runs at Super-SUN w/ magnet
Best possible result ~ $1.10^{-27}$ ecm (stat, 1 σ)

**Work with Outer Shield:**
Outer magnetic shield
External field compensation
HV R&D and assembly

Magnetometry development
Magnetometer comparisons
$^{129}$Xe (gas) EDM runs
Component optimization and testing

**Development of cryogenic chambers**

**Best possible result:**
(i) Cryogenic chambers with Outer and Inner Shield (after (i) and (ii) )
... Best possible result ~ $2.10^{-28}$ ecm (stat+syst, 1 σ)

# Cryogenic nEDM

$$\sigma(d_n) = \frac{\hbar}{2ETP^2\sqrt{N}}$$

**M. van der Grinten**

Super-thermal UCN source ($N$)

higher electric fields in *l*He ($E$)


**CryoEDM developed a range of technologies for a future cryogenic nEDM measurement**

- UCN transport and storage in *l*He
- In-situ UCN detection in a cryogenic environment
- High precision low temperature SQUID magnetometry
- Large scale cryogenic operations
- Electric and magnetic field in a cryogenic environment

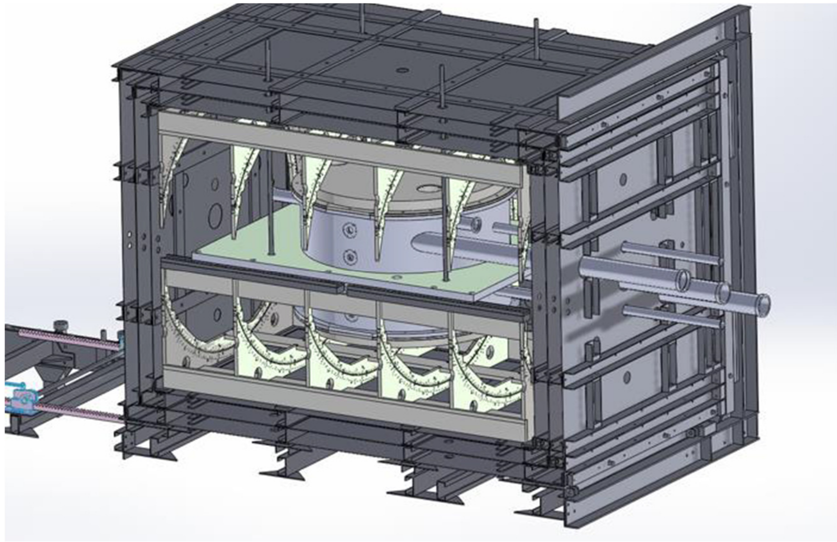
**Two-stage follow up**

- Super-thermal source (SuperSUN) coupled to room temperature experiment
- Super-thermal UCN (SuperSUN) coupled to a cryogenic experiment

# Cryogenic nEDM

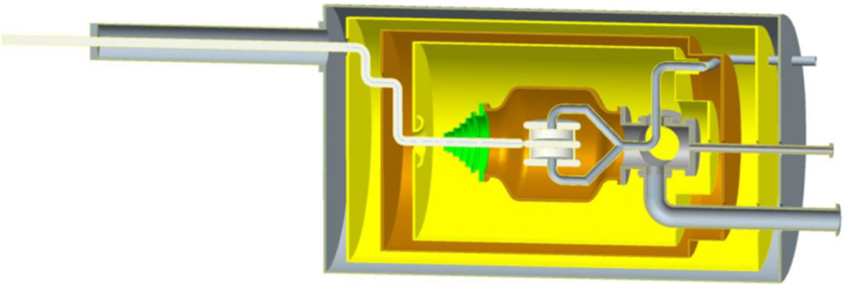
M. van der Grinten

**Super-thermal source (SuperSUN) coupled to room temperature experiment at ILL**



- Magnetic environment will be established prior to new 9A beam construction
- New source will be constructed in parallel
- Room temperature experiment will be coupled to super-thermal source

**Super-thermal UCN (SuperSUN) coupled to a cryogenic experiment**



- Cryogenic environment of experiment designed in parallel to room temperature data-taking
- Fully cryogenic experiment running after room temperature data taking completed

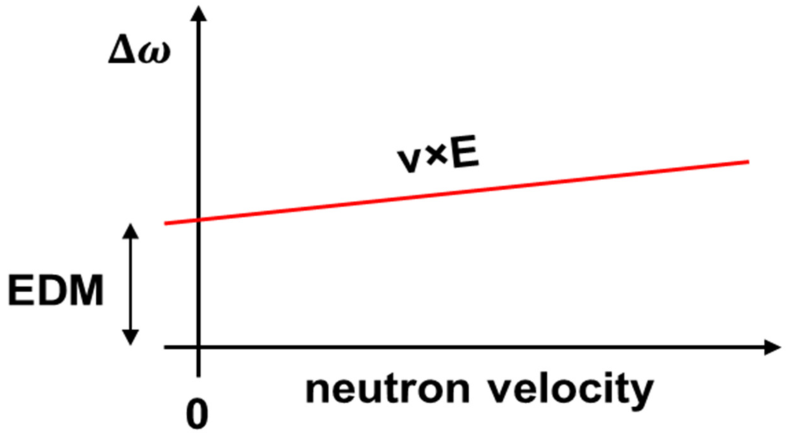
**Possible move to different beam**

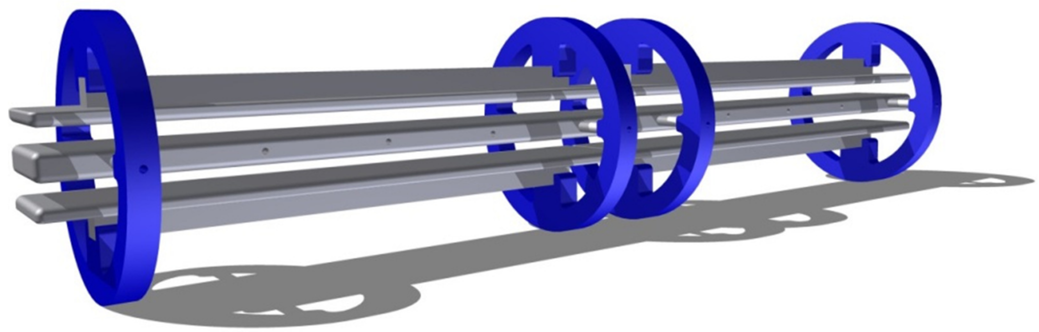
- Letter of Intent for new super-thermal UCN source operating at ESS

- Main systematic in nEDM beam experiment caused by ***v×E* - effect**:

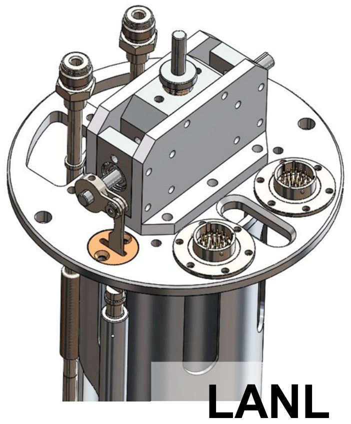
$$\hbar\Delta\omega = 4d_{\mathrm{n}}E + 4\mu_{\mathrm{n}}\frac{vE}{c^2}\sin\alpha$$

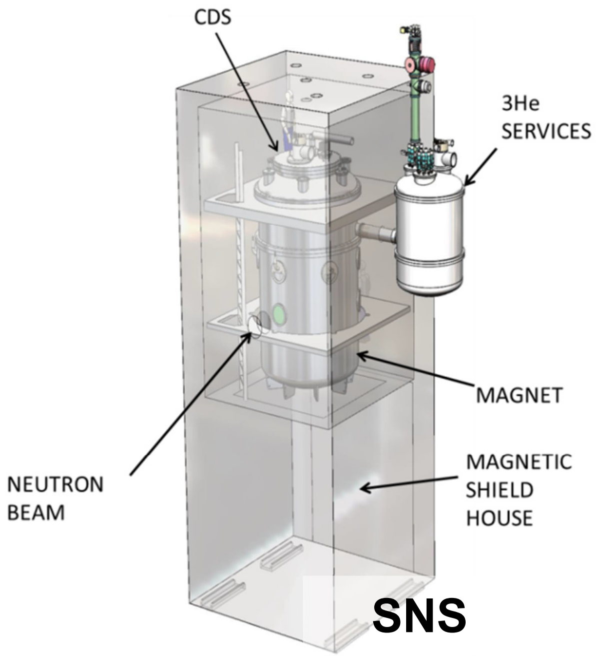
- **Idea:** Measure change in Larmor frequency as a function of the neutron velocity at a **pulsed spallation source**:

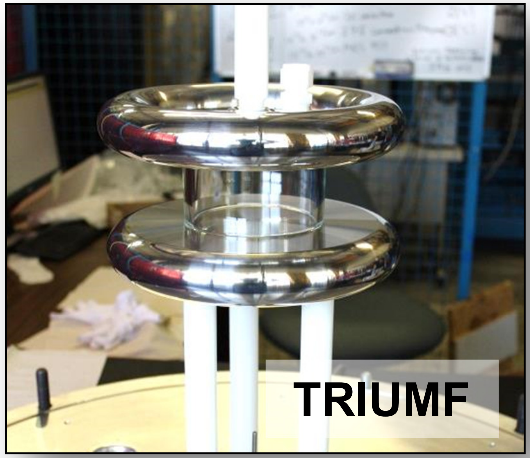


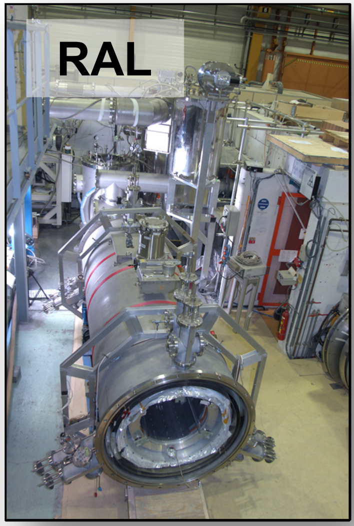



Piegsa, PRC 88, 045502 (2013)

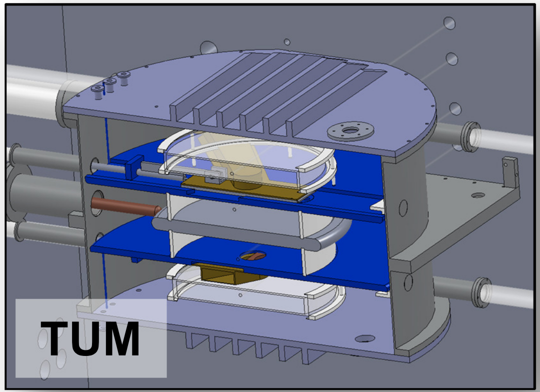


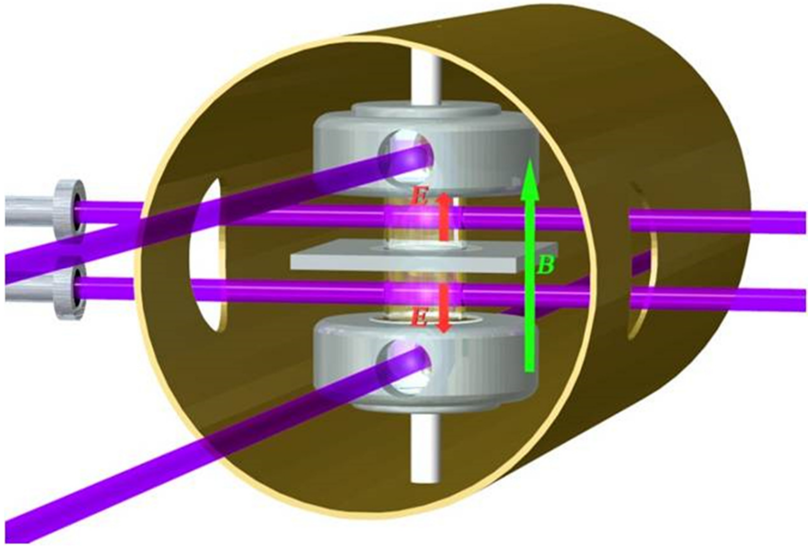



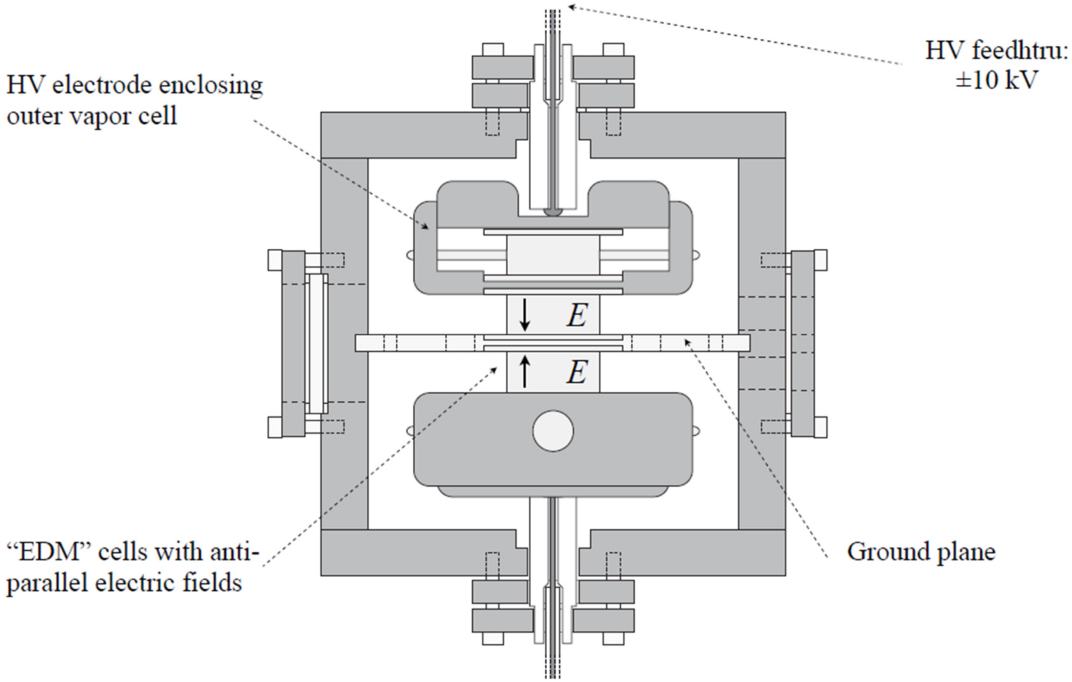






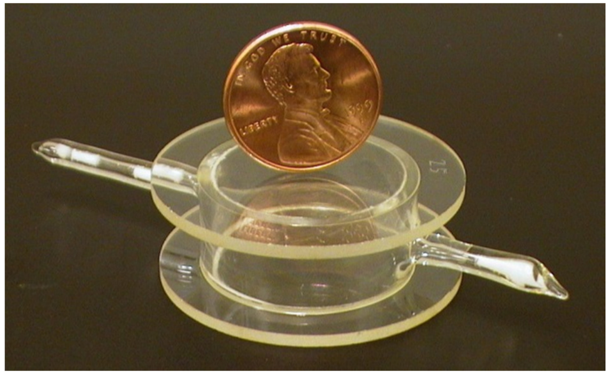
**We have exciting times ahead of us !**



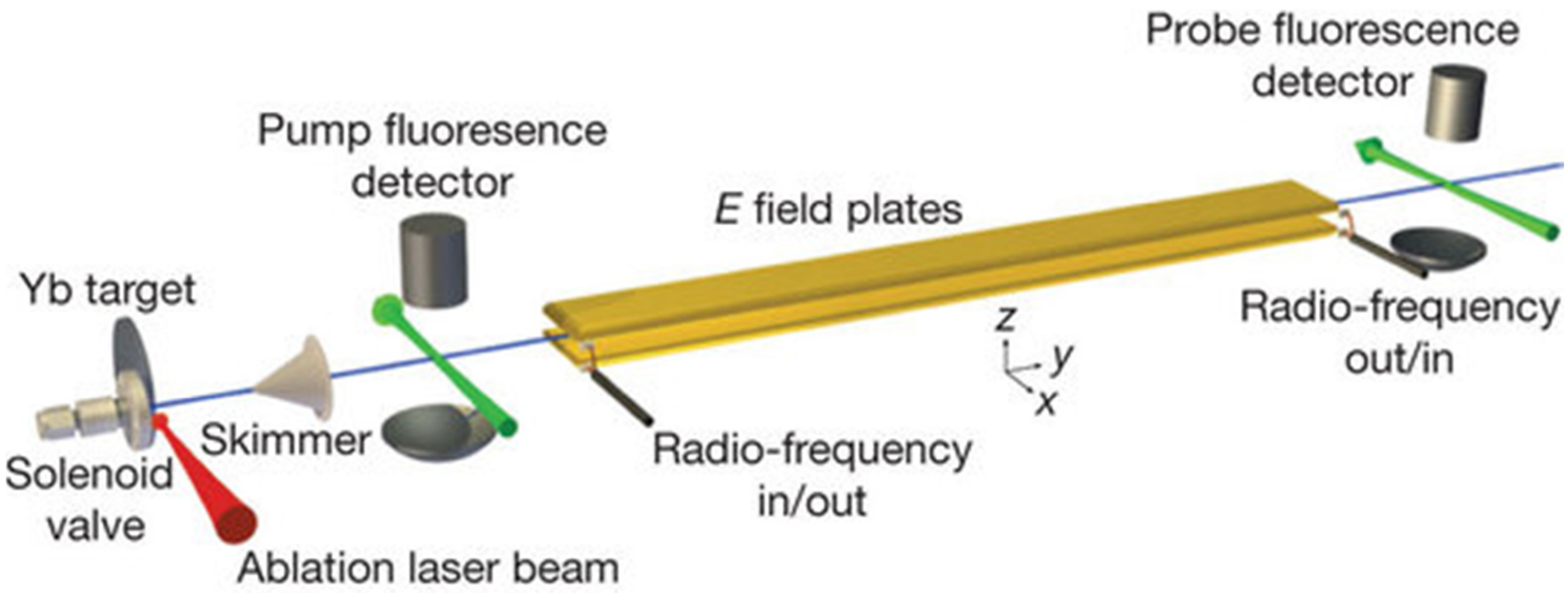




**$d_{Hg}$ < 3.1 x $10^{-29}$ ecm (95% CL)**

**$d_p$ < 7.9 x $10^{-25}$ ecm (95% CL)**

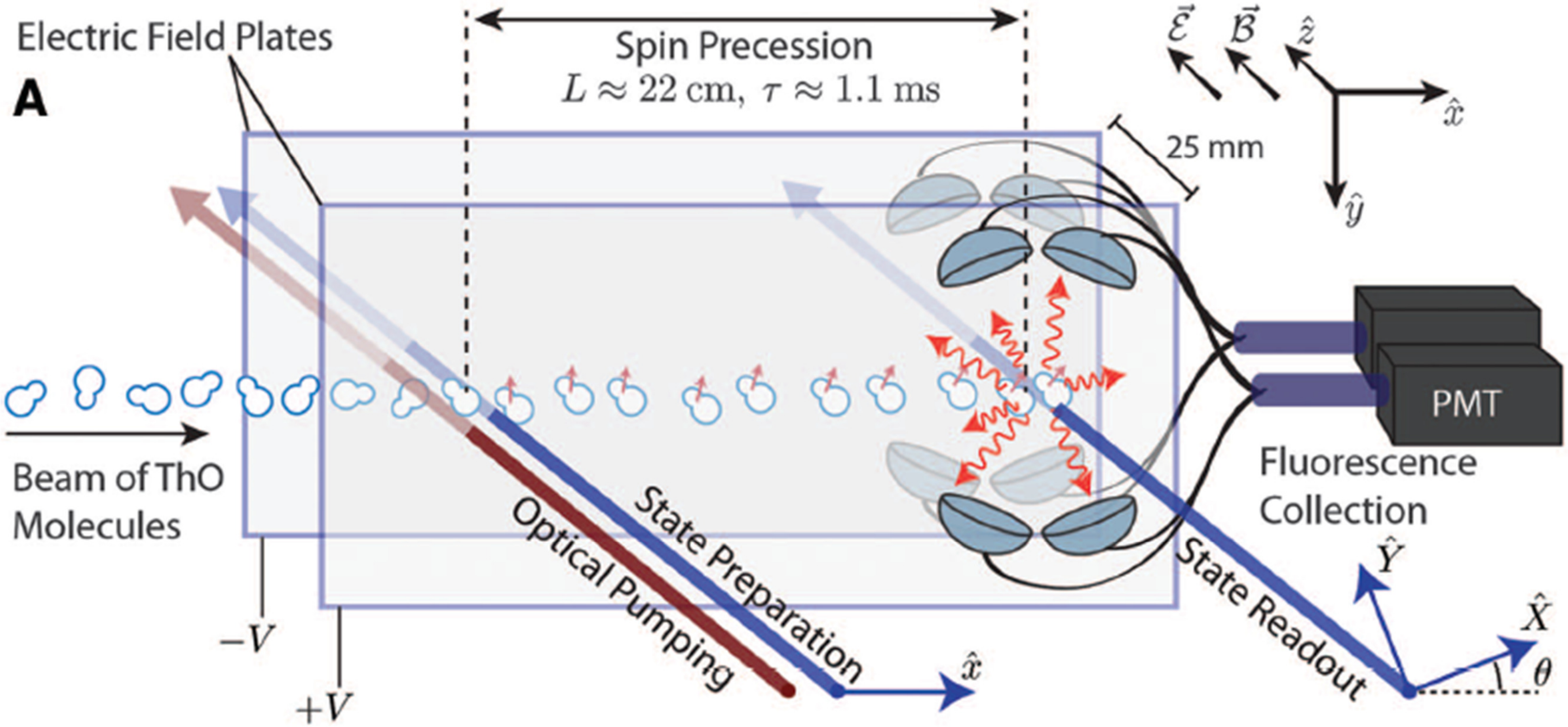


**Griffith et al. PRL 102, 101601 (2009)**




- no motional magnetic field effect, as in Tl-atom experiment
- Electric field enhancement by a factor $10^6$ (10 kV/cm → 13 GV/cm)
- $d_e < 1.05 \times 10^{-27}$ e cm (90% CL)

Hudson et al., Nature 473, 493 (2011)




- Electric field enhancement by a factor $10^9$ (140 V/cm → 84 GV/cm)
- Small magnetic moment reduces sensitivity to spurious magn. Fields
- $d_e < 8.7 \times 10^{-29}$ e cm (90% CL)

ACME Collaboration, Science 343, 269 (2014)