Neutron Electric Dipole Moment

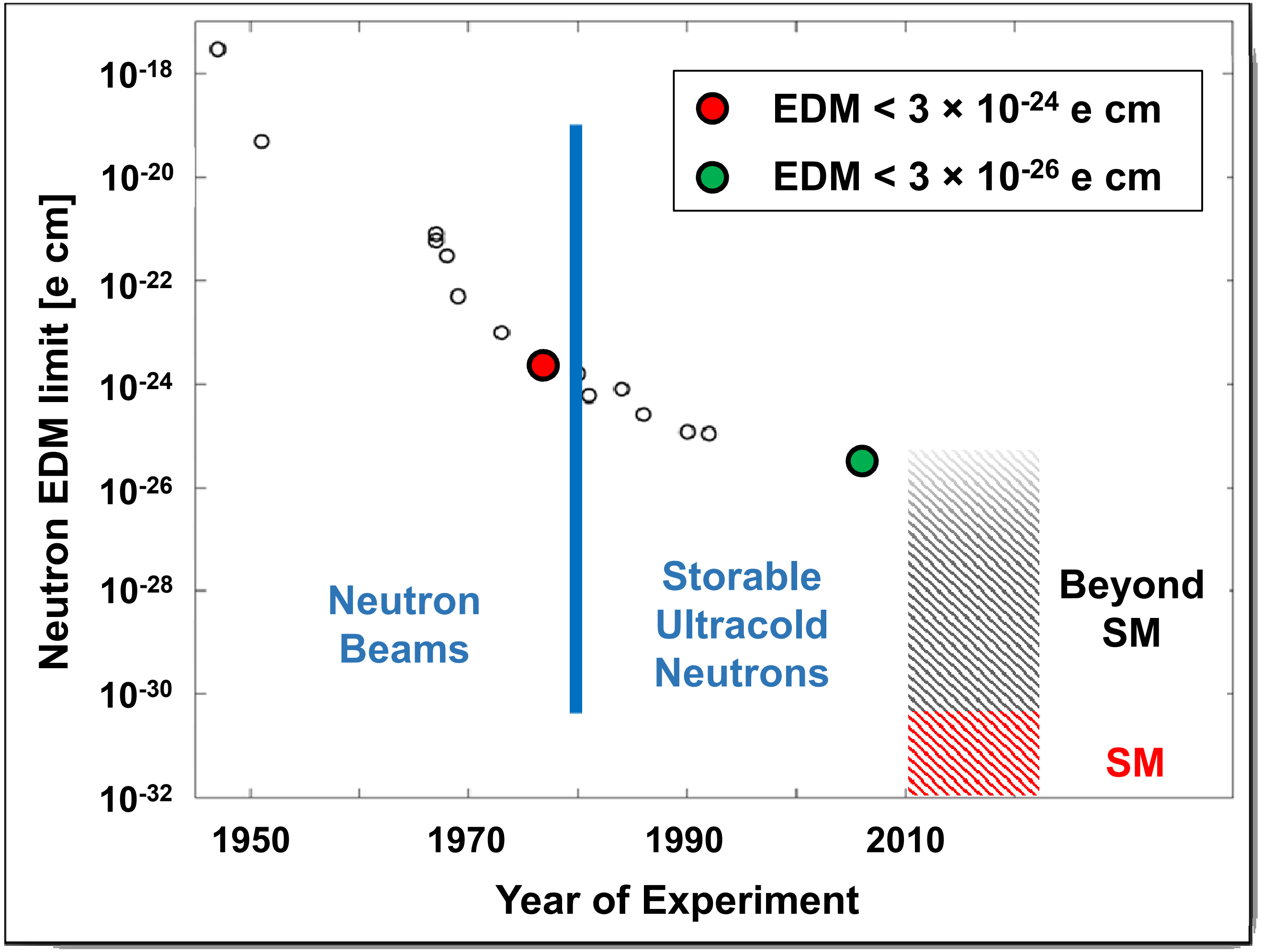
Florian Piegsa

Laboratory for High Energy Physics
Albert Einstein Center for Fundamental Physics
University of Bern

UNIVERSITÄT BERN
AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

erc
European Research Council

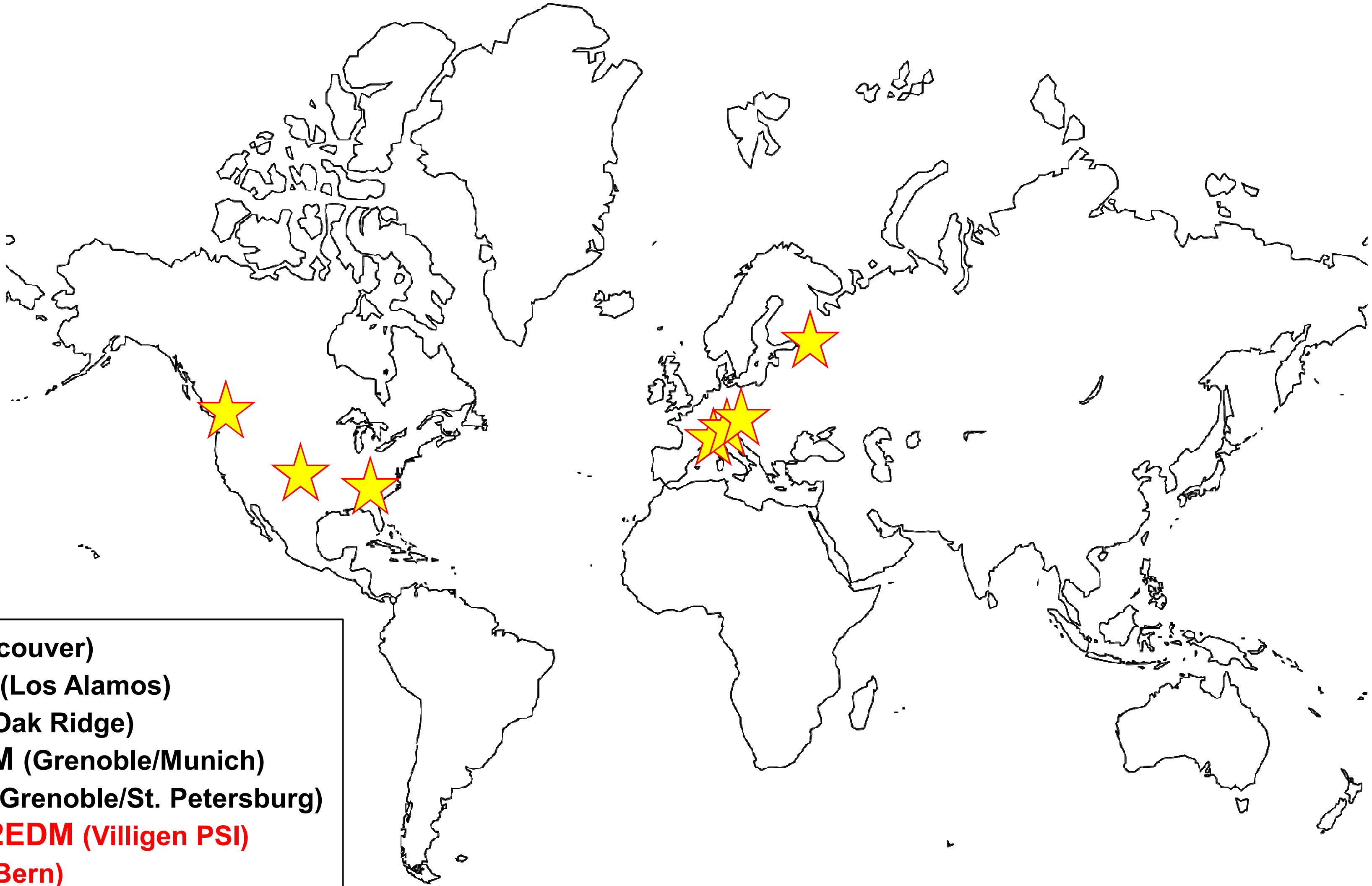


10^{-22} eV

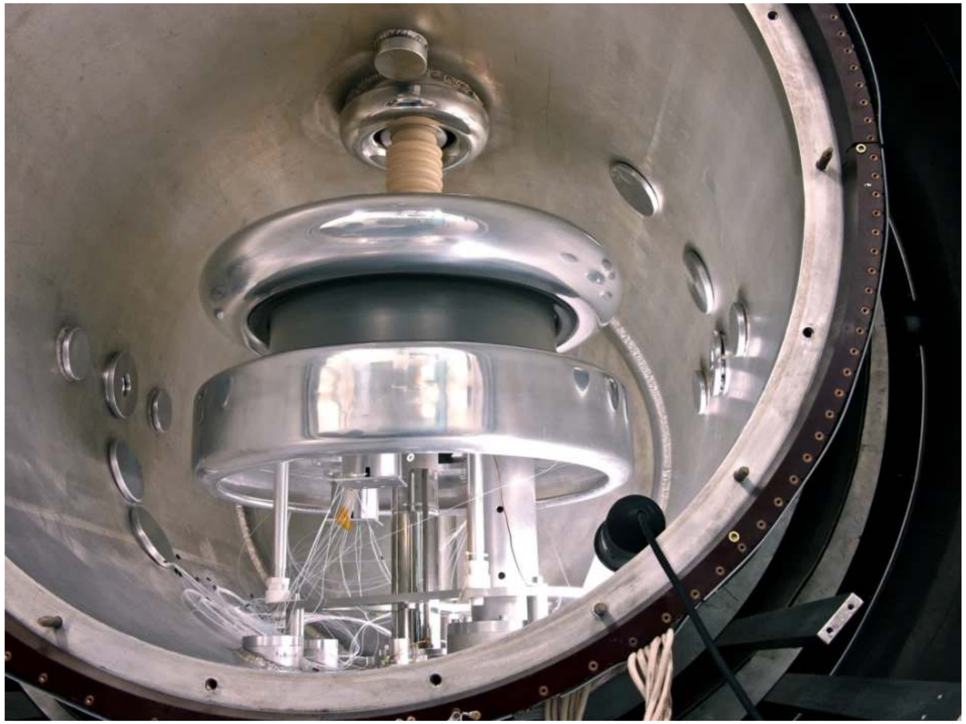
Dress et al., PRD 15, 9 (1977)

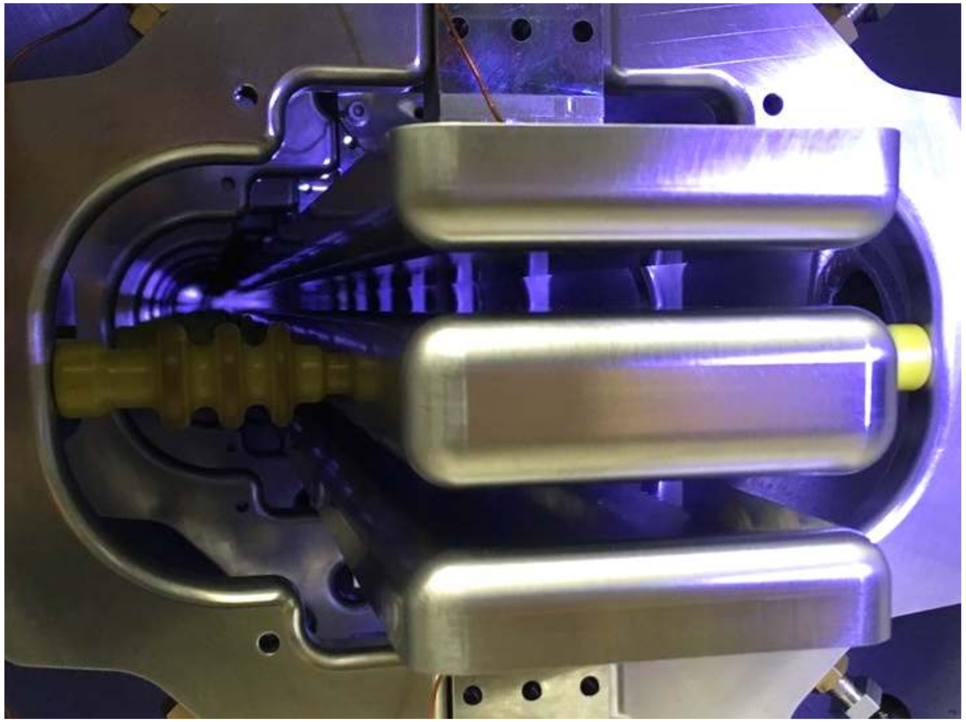
Baker et al., PRL 97, 131801 (2006)
Pendlebury et al., PRD 92, 092004 (2015)

Neutron EDM – a Worldwide Endeavor



TRIUMF (Vancouver)
LANL nEDM (Los Alamos)
SNS nEDM (Oak Ridge)
TUM PanEDM (Grenoble/Munich)
PNPI nEDM (Grenoble/St. Petersburg)
PSI nEDM/n2EDM (Villigen PSI)
Beam EDM (Bern)





Ultracold Neutrons

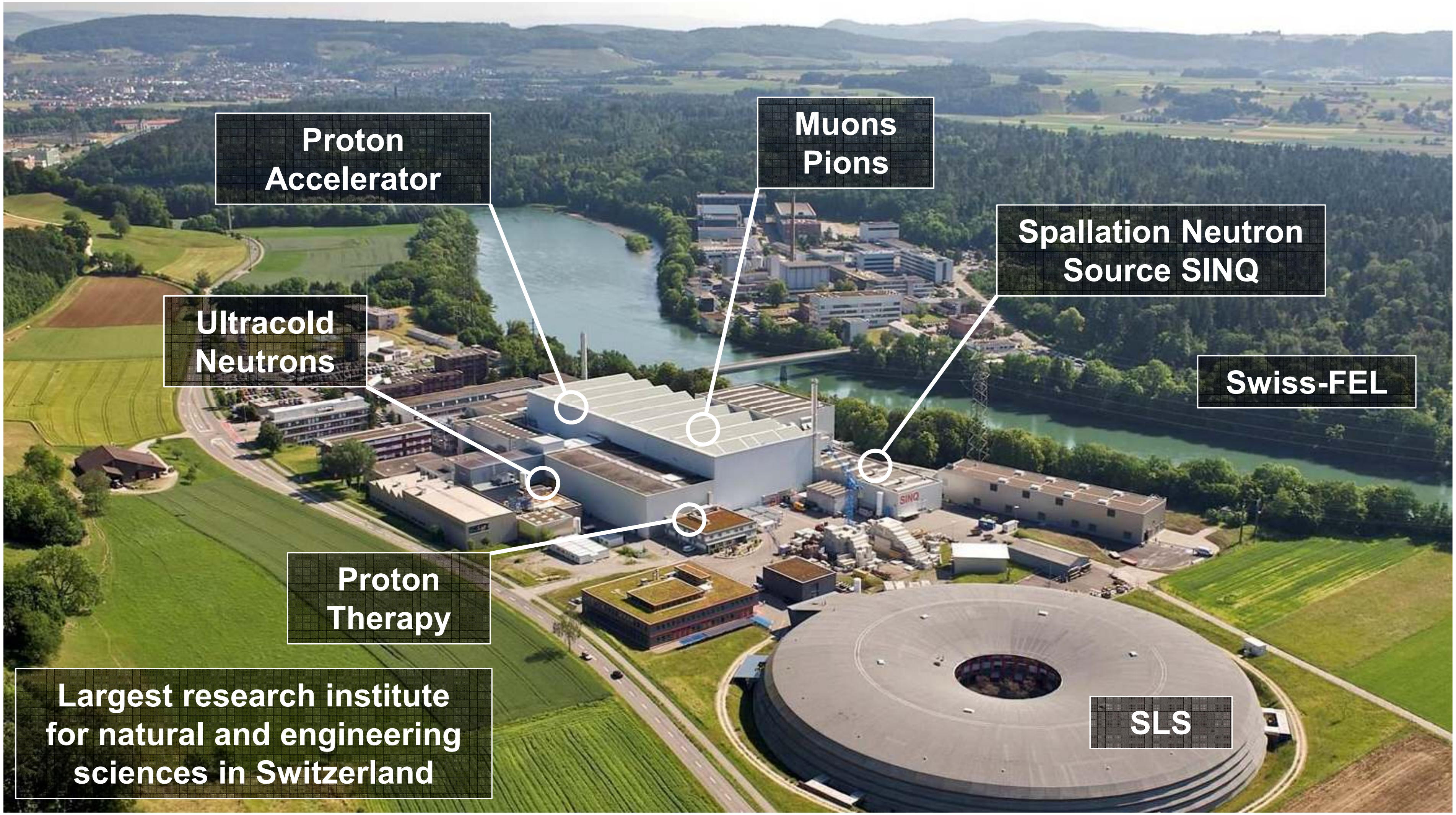
International Collaboration at PSI
***nEDM* and *n2EDM* Experiments**

Pulsed Cold Neutron Beam

Novel complementary approach in Bern
Intended for the European Spallation Source

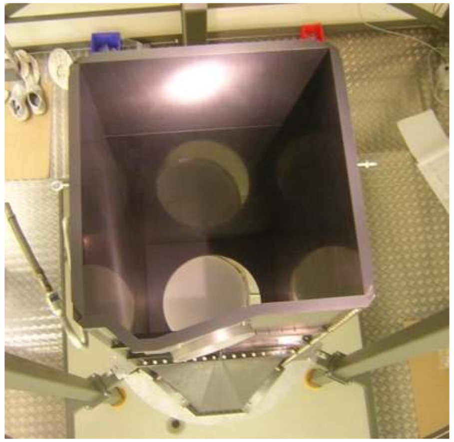
15 institutions
7 countries
50 members
10 PhD students

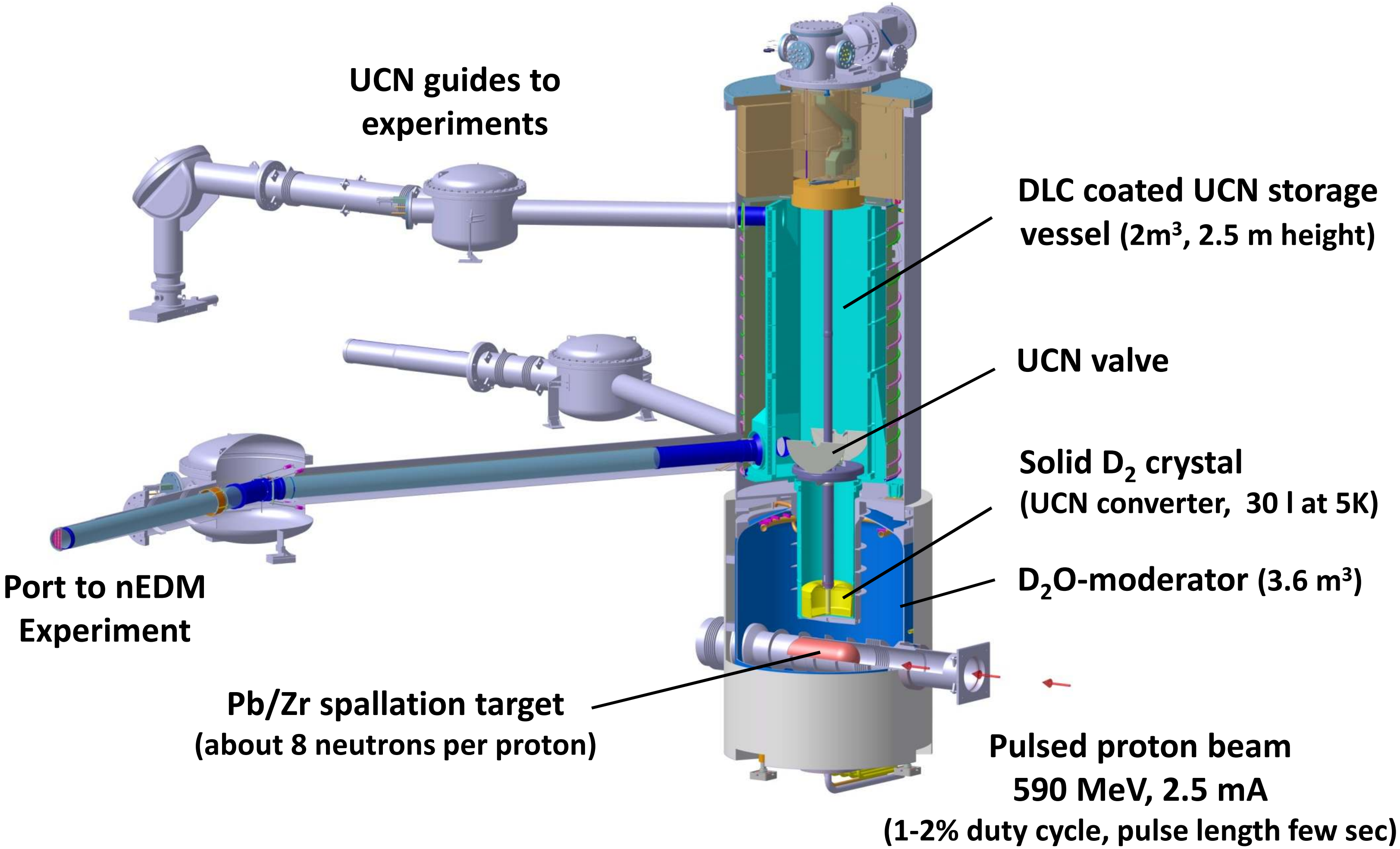
Collaboration Meeting Berlin Nov. 2018


Proton Accelerator
Muons Pions
Spallation Neutron Source SINQ
Ultracold Neutrons
Swiss-FEL
Proton Therapy
SLS
Largest research institute for natural and engineering sciences in Switzerland


Continuous Proton Beam
2.5 mA × 590 MeV = 1.5 MW

UCN Source at PSI



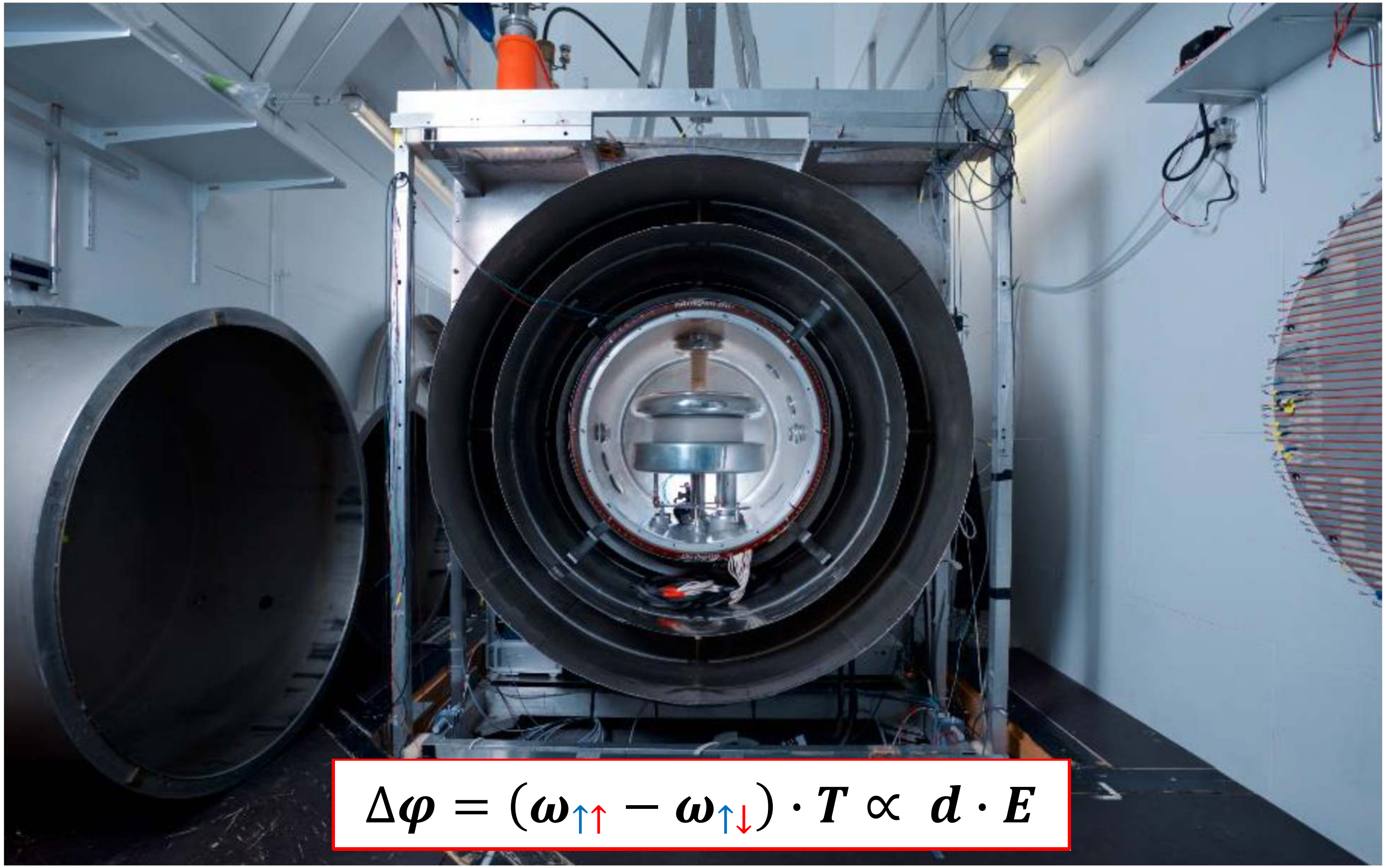


- Four layer mu-metal shield
- Surrounding field compensating coils
- Temperature stabilization

nEDM Experiment

Magnetic Field

1 μT

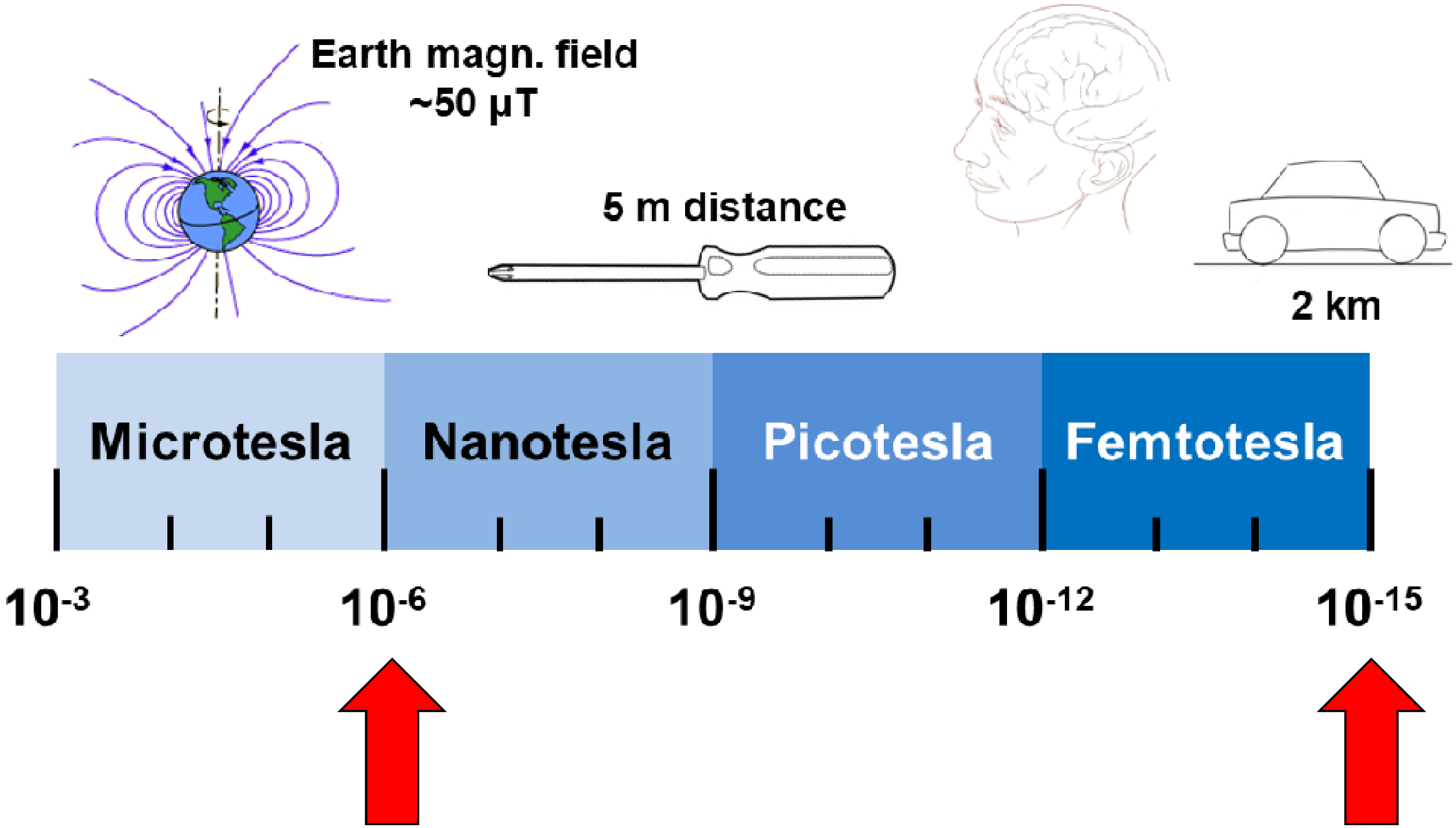


$$\Delta\boldsymbol{\varphi} = (\boldsymbol{\omega}_{\uparrow\uparrow} - \boldsymbol{\omega}_{\uparrow\downarrow}) \cdot \boldsymbol{T} \propto \boldsymbol{d} \cdot \boldsymbol{E}$$

Electr. Field

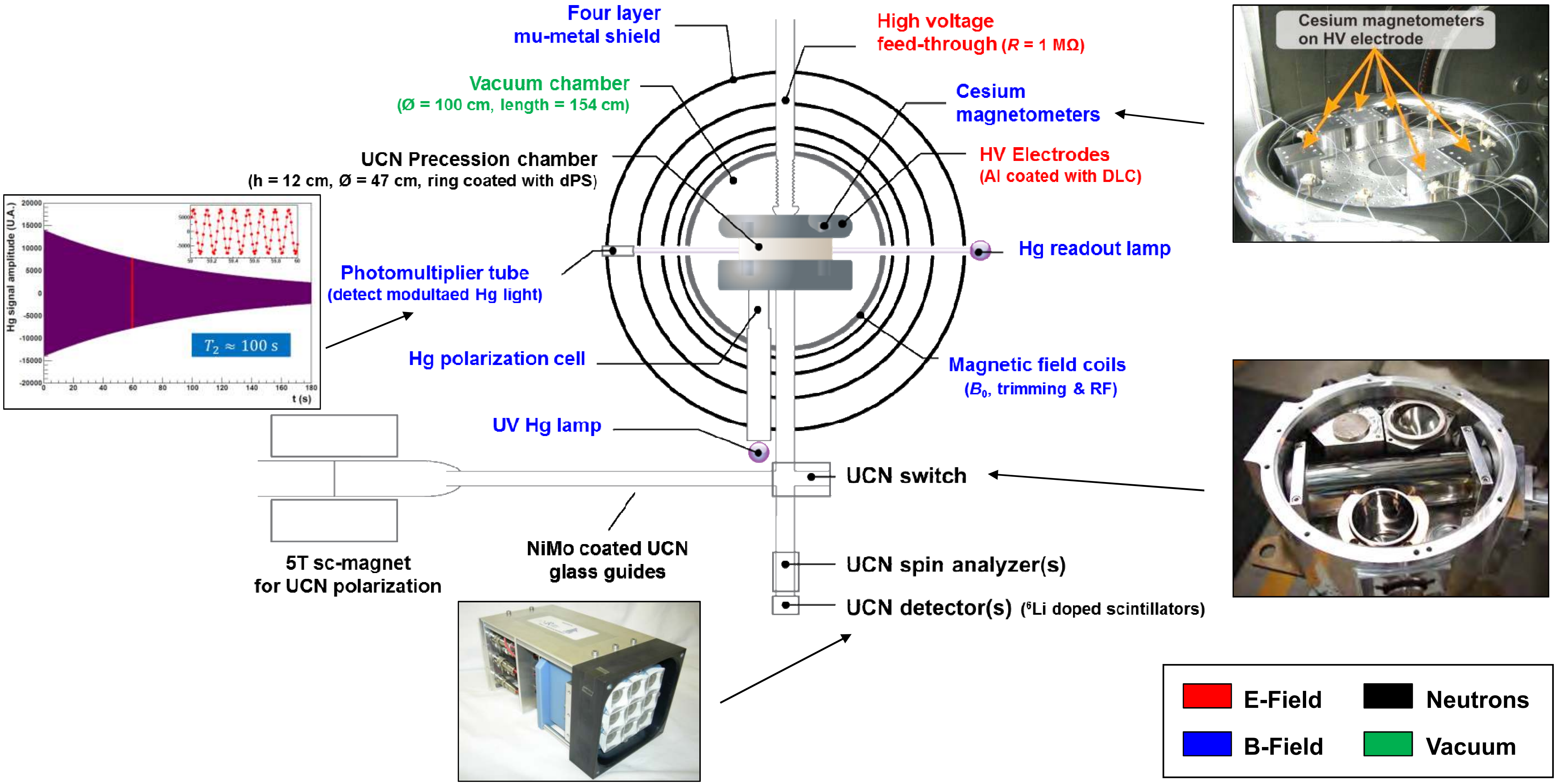
Electr. Field

10 kV/cm

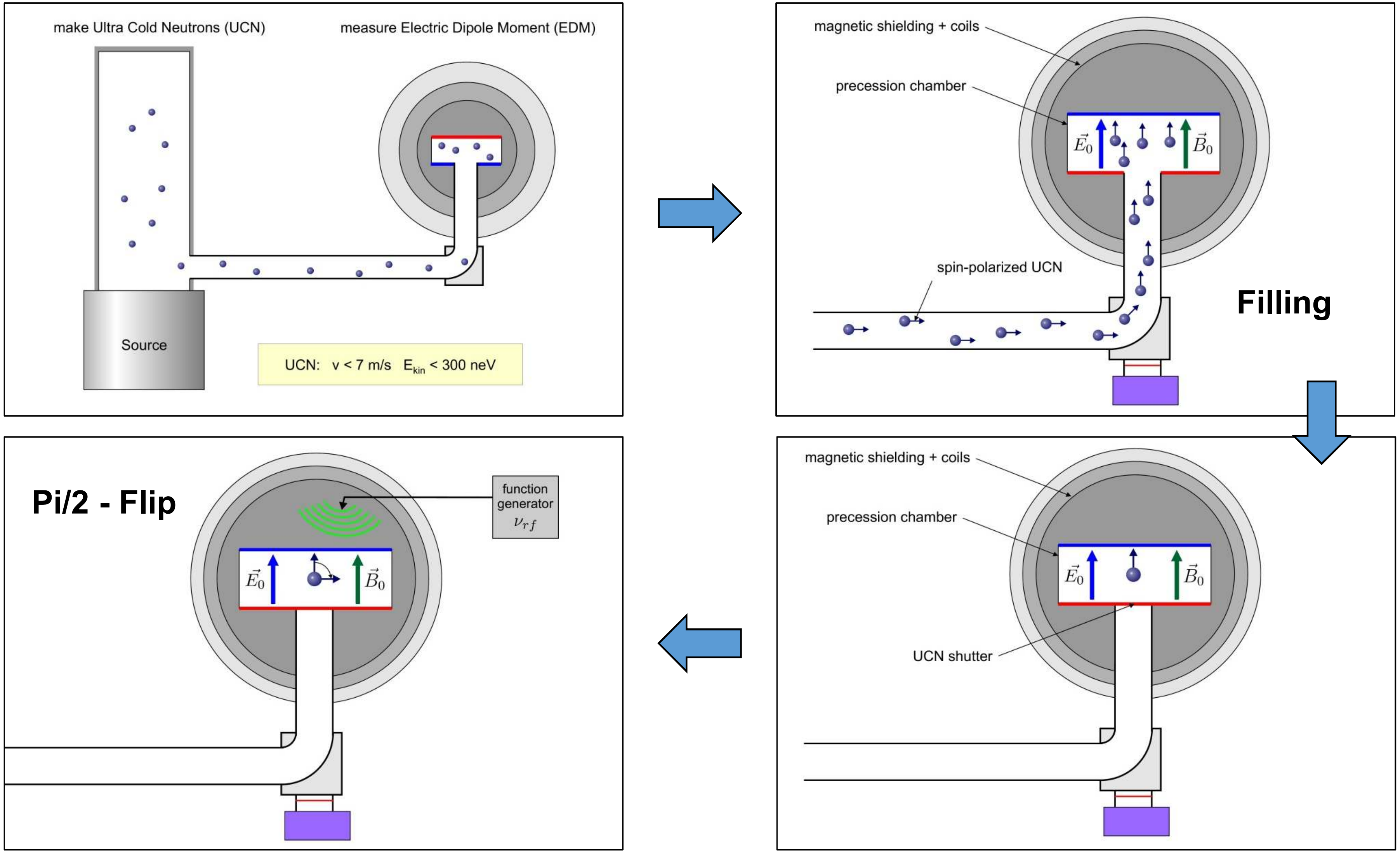


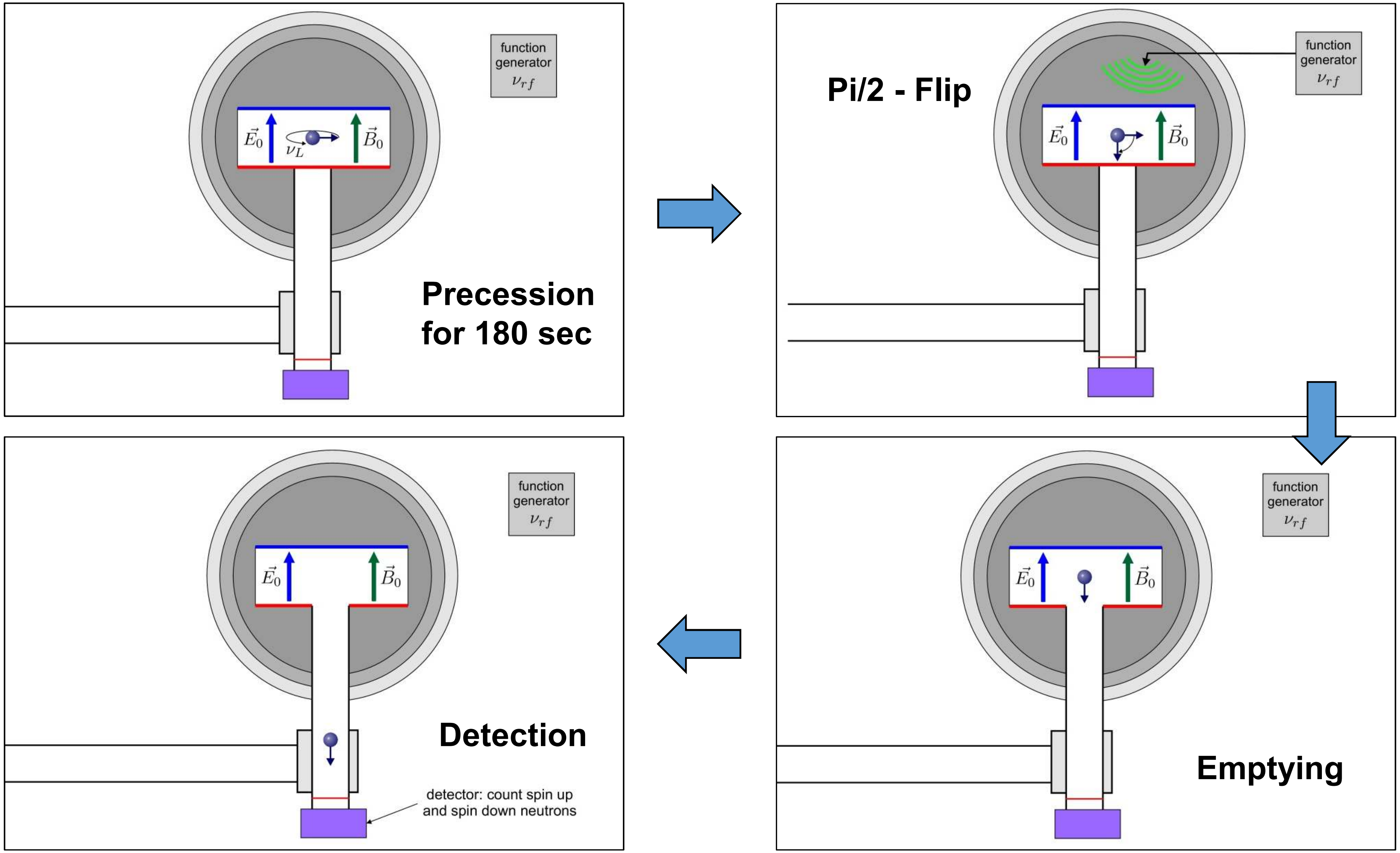
B_0 = 1 µT

10^{-27} ecm at 10 kV/cm

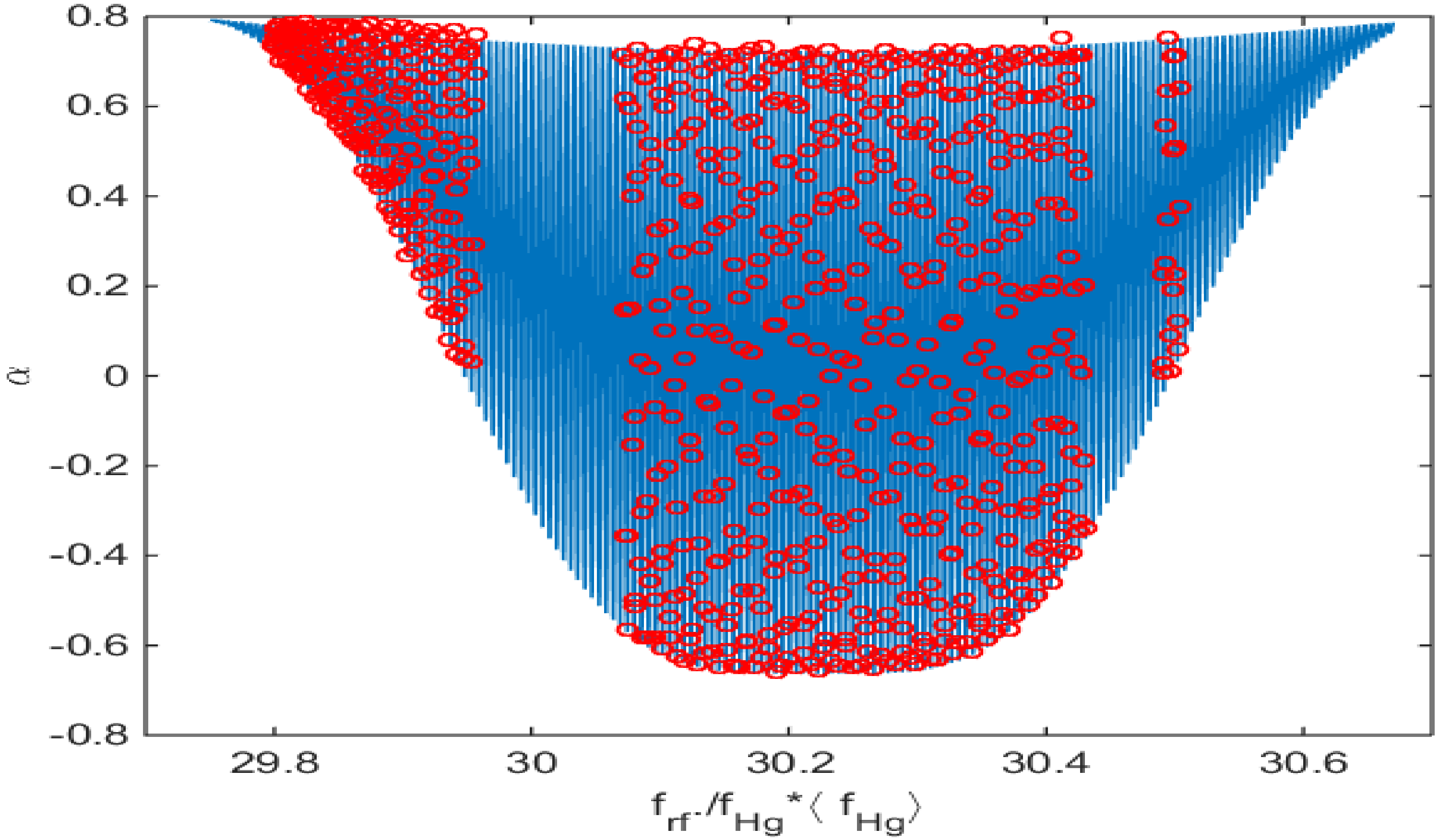

Four layer
mu-metal shield
High voltage
feed-through (R = 1 MΩ)
Vacuum chamber
(Ø = 100 cm, length = 154 cm)
Cesium
magnetometers
Cesium magnetometers
on HV electrode
UCN Precession chamber
(h = 12 cm, Ø = 47 cm, ring coated with dPS)
HV Electrodes
(Al coated with DLC)
Hg readout lamp
Hg signal amplitude (U.A.)
t (s)
T2 ≈ 100 s
Photomultiplier tube
(detect modultaed Hg light)
Hg polarization cell
Magnetic field coils
(B0, trimming & RF)
UV Hg lamp
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
Neutrons
B-Field
Vacuum

Ramsey Cycle





function generator ν_{rf}
$\vec{E}_0$
ν_L
$\vec{B}_0$
Precession for 180 sec
Pi/2 - Flip
function generator ν_{rf}
$\vec{E}_0$
$\vec{B}_0$
function generator ν_{rf}
$\vec{E}_0$
$\vec{B}_0$
Detection
detector: count spin up and spin down neutrons
function generator ν_{rf}
$\vec{E}_0$
$\vec{B}_0$
Emptying

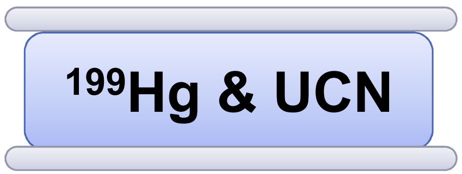


300 sec per data point

„Normal measurement“ only 4 data points

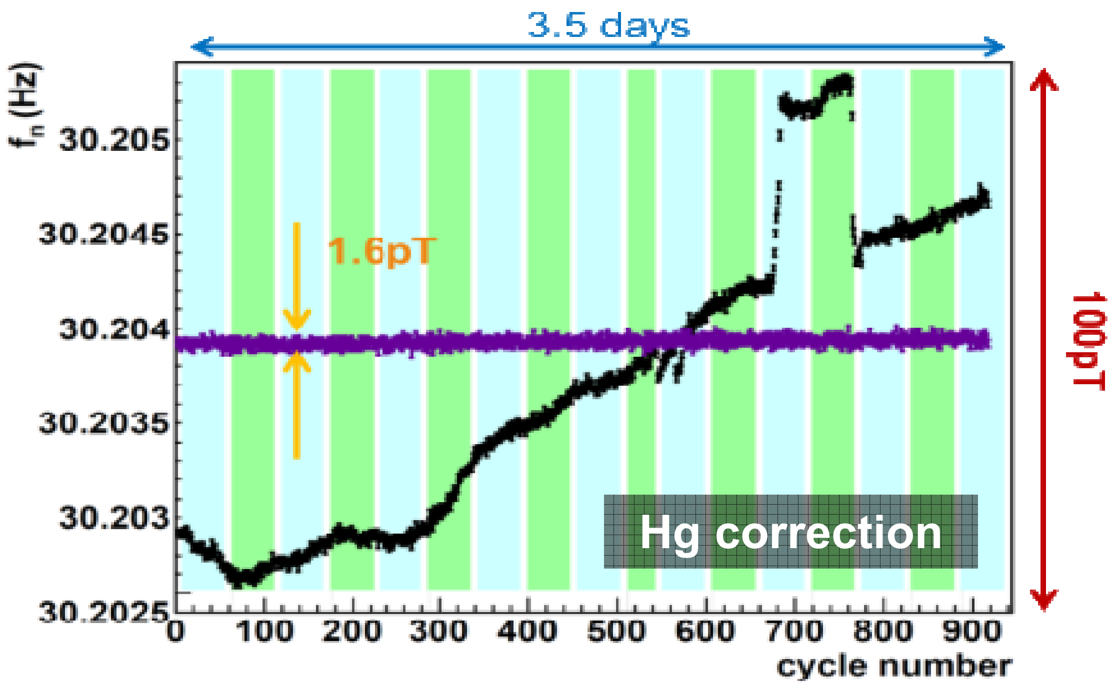
Many details of the measurement: Abel et al., arXiv 1811.04012

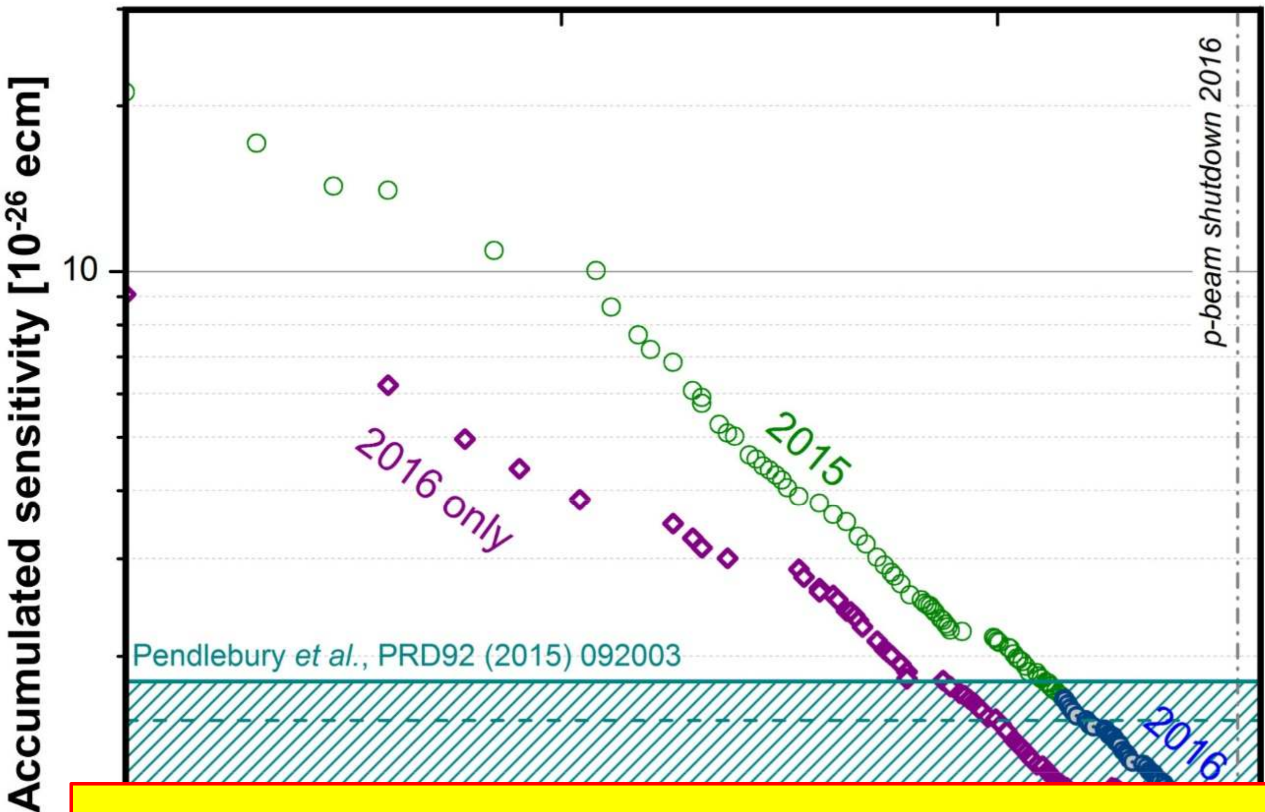
$$R = \frac{\langle f_{\mathrm{UCN}} \rangle}{\langle f_{\mathrm{Hg}} \rangle} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} \left(1 + \delta_{\mathrm{EDM}} \mp \frac{\partial B}{\partial z} \frac{\langle z \rangle}{|B_0|} + \frac{\langle B^2{}_{\perp} \rangle}{|B_0|^2} \mp \delta_{\mathrm{Earth}} + \delta_{\mathrm{Hg-lightshift}} + \cdots \right)$$



$$\frac{\gamma_{\mathrm{n}}}{2\pi} \approx 30\ \mathrm{Hz/\mu T} \qquad \frac{\gamma_{\mathrm{Hg}}}{2\pi} \approx 8\ \mathrm{Hz/\mu T}$$

$$\bar{v}_{UCN} \approx 4\ \mathrm{m/s} \qquad \bar{v}_{\mathrm{Hg}} \approx 160\ \mathrm{m/s}$$



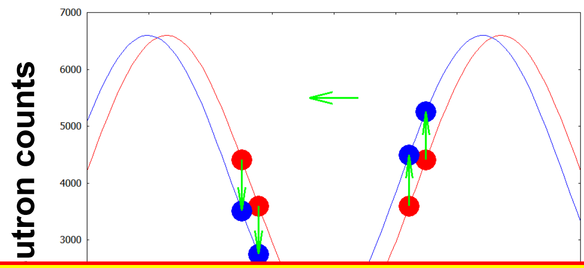


Recorded data sensitivity:

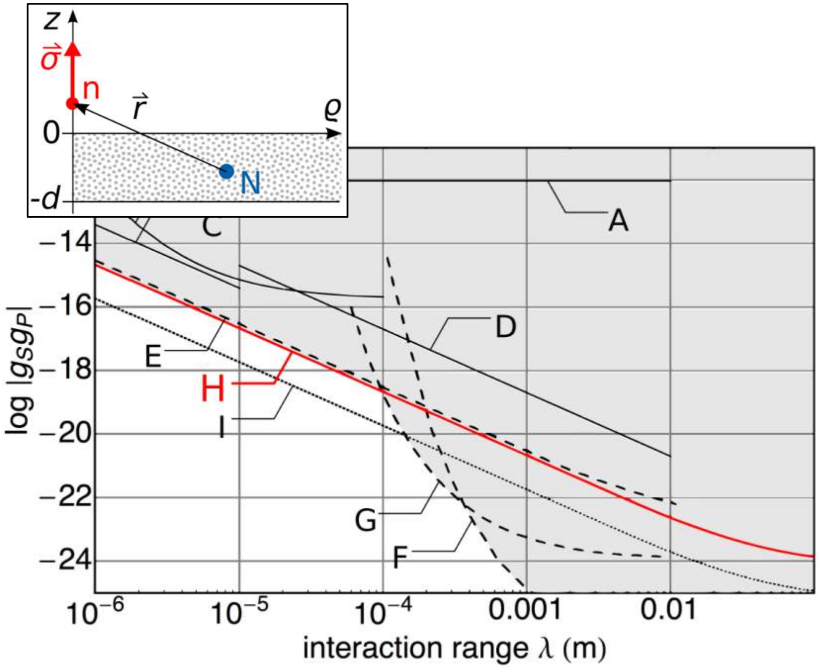
$\sigma = 0.94 \times 10^{-26}$ecm

Analysis ongoing:

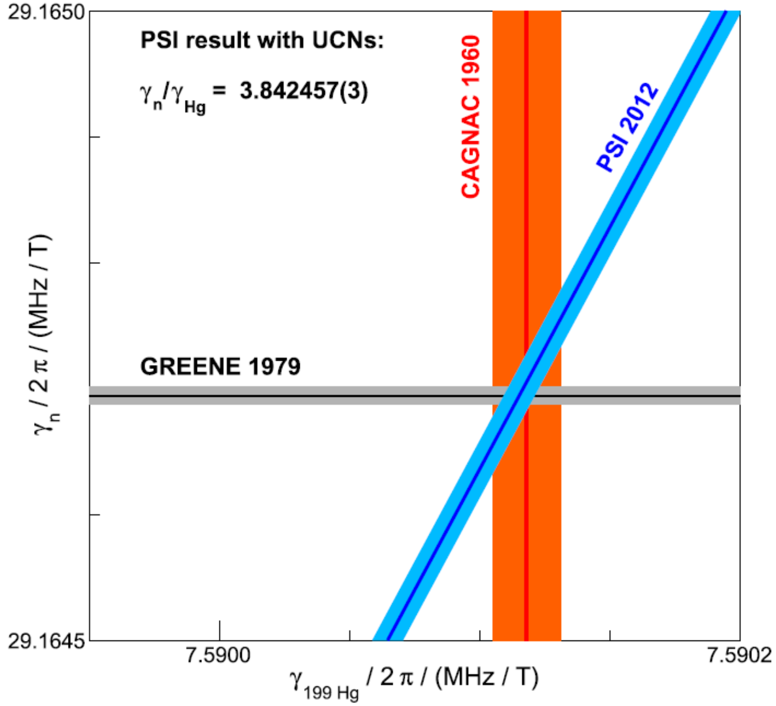
Blinded data in two groups (offset: $\pm 1.5 \times 10^{-25}$ ecm)



NEW EDM RESULT LATER THIS YEAR …

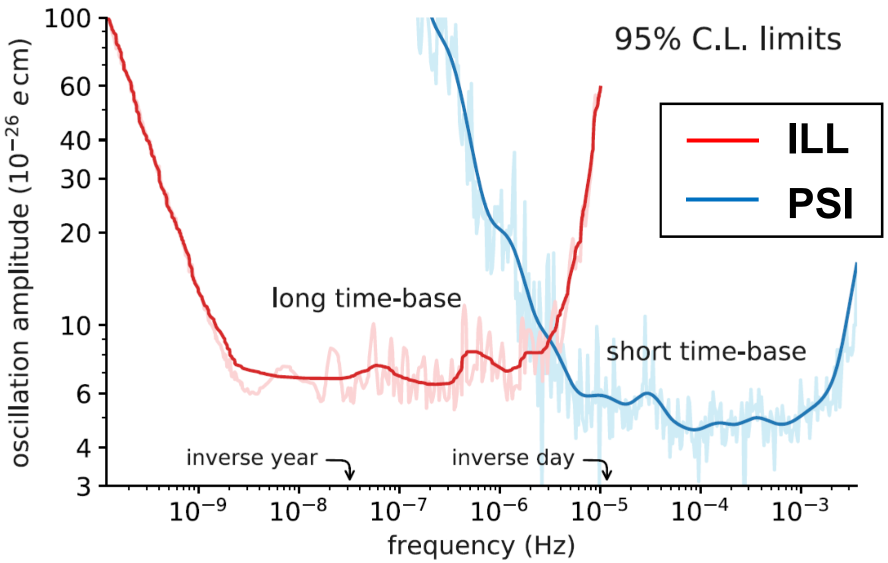


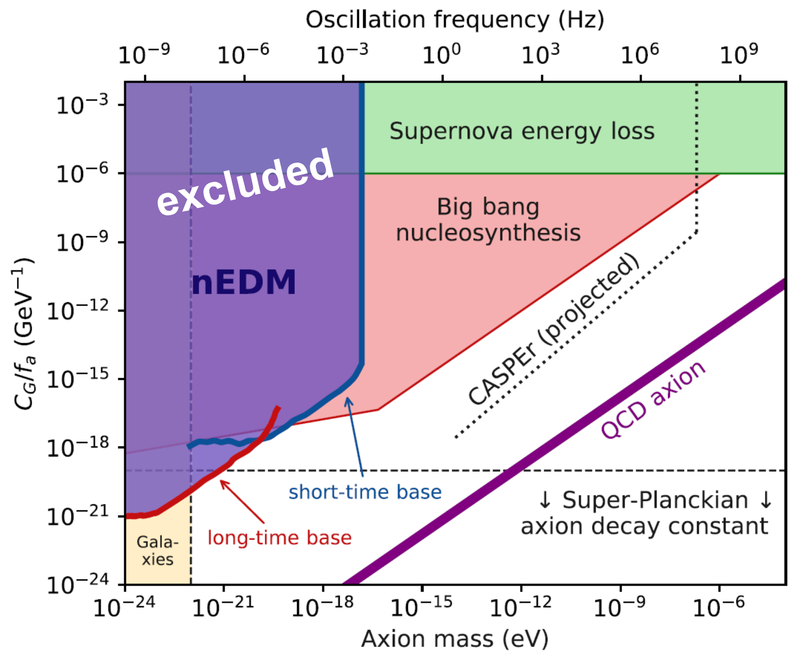
Search for new exotic interactions (Axion-Like-Particles) *



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

* Afach et al., Phys. Lett. B 745, 58 (2015)
** Afach et al., Phys. Lett. B 739, 128 (2014)





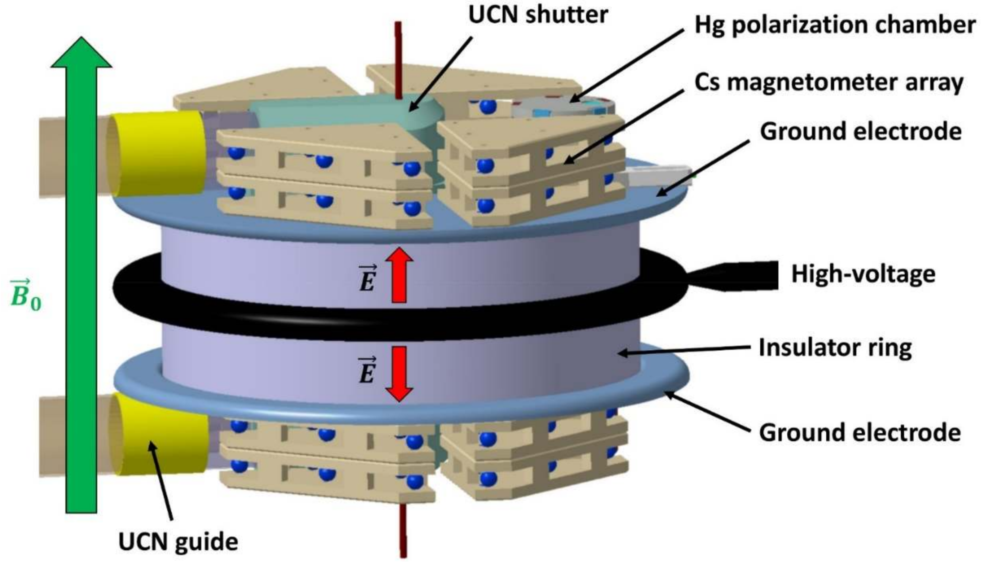
Search for time-oscillating signal in EDM data (ILL 1998-2002 & PSI 2015-2016)
Such a signal could arise from the interaction with ultra-light (dark matter) axions

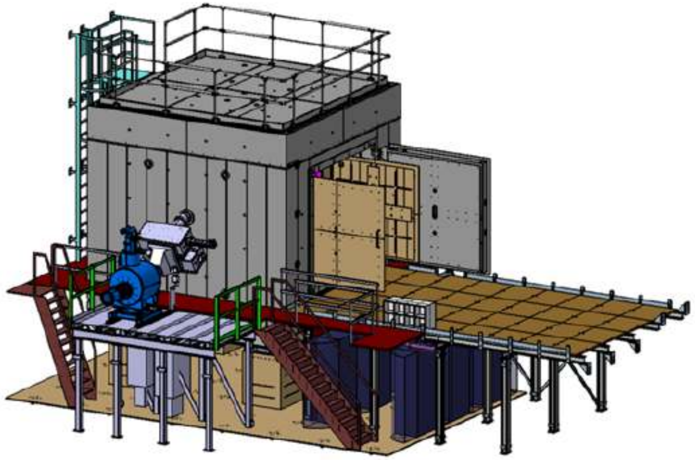
Abel et al., Phys. Rev X 7, 041034 (2017)

	nEDM in 2016	*n2EDM* baseline
Diameter [cm]	47	80
α	0.75	0.8
E [kV/cm]	11	15
T [s]	180	180
N (per cycle)	15000	120000
$\sigma(d_n)$ (per day)	11×10^{-26} ecm	2.6×10^{-26} ecm

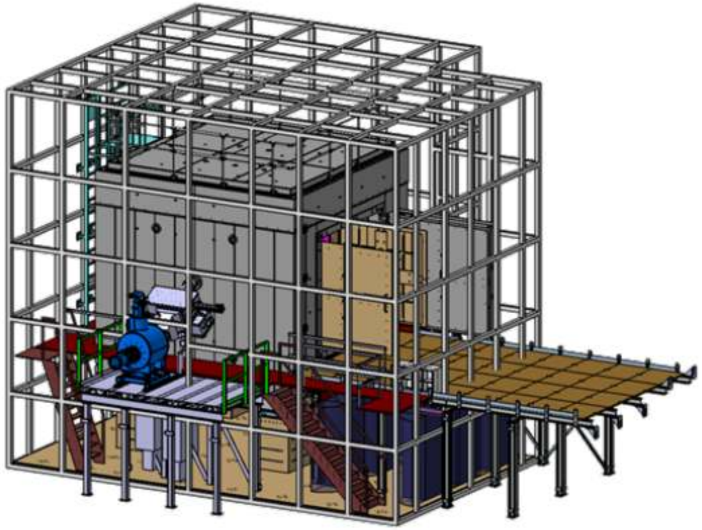
$$\sigma(d_n) \propto \frac{1}{\alpha E T \sqrt{N}}$$

- **Two UCN precession chambers with opposite electric field directions (systematics & *E*-field)**
- **Improved magnetic enviornment (MSR)**
- **Higher neutron statistics mainly due to volume**
- **Improved magnetometry (Hg-laser, Cs-array)**
- **Improved electric field strength (symmetric)**

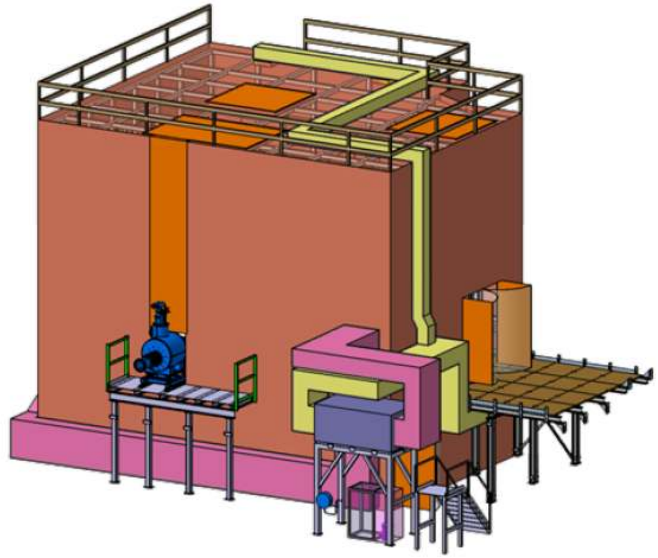




MSR
2+4 layers, 5×5×5 m^3
Expect. shielding > 100‘000

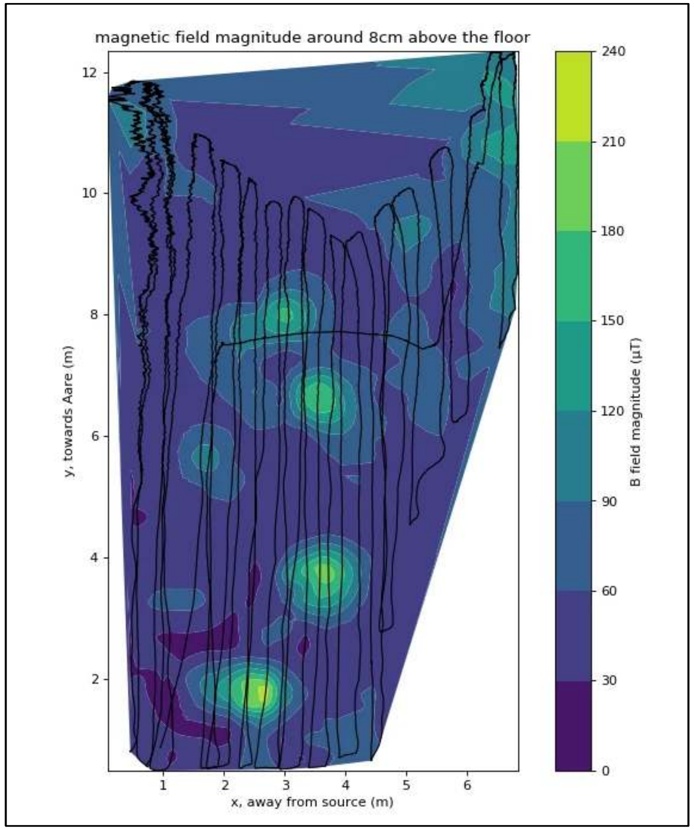


SFC
Magn. field compensation



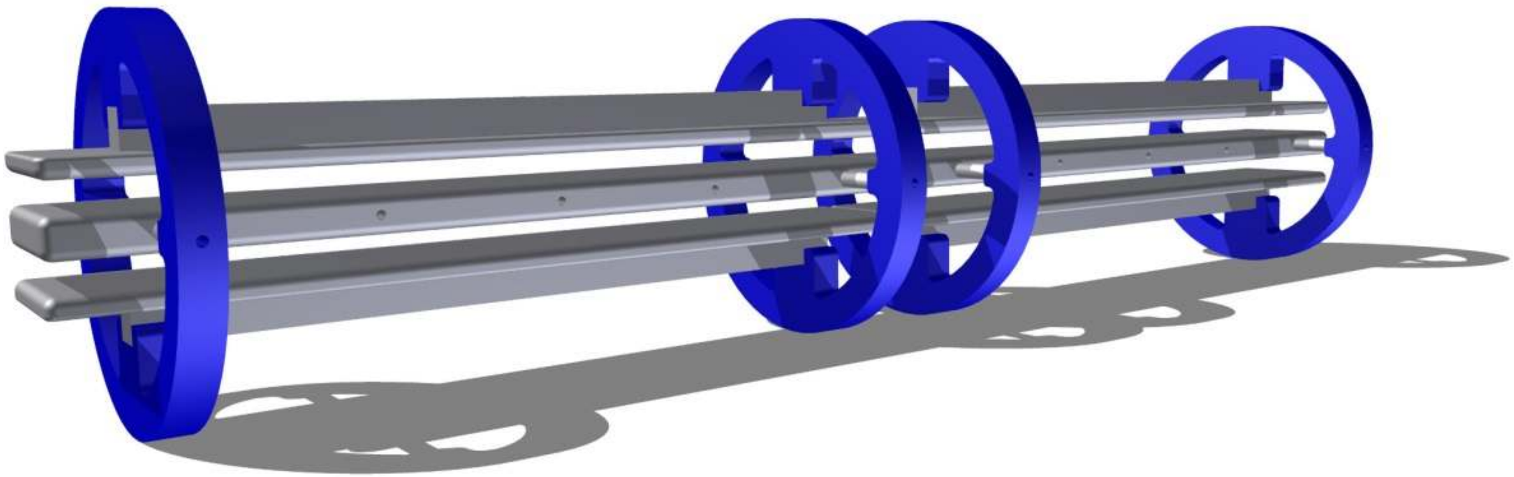
Thermohouse
sub-Kelvin stability


10
11
12
035
039
constructioncam2_2018-01-04_15-55-00.jpg

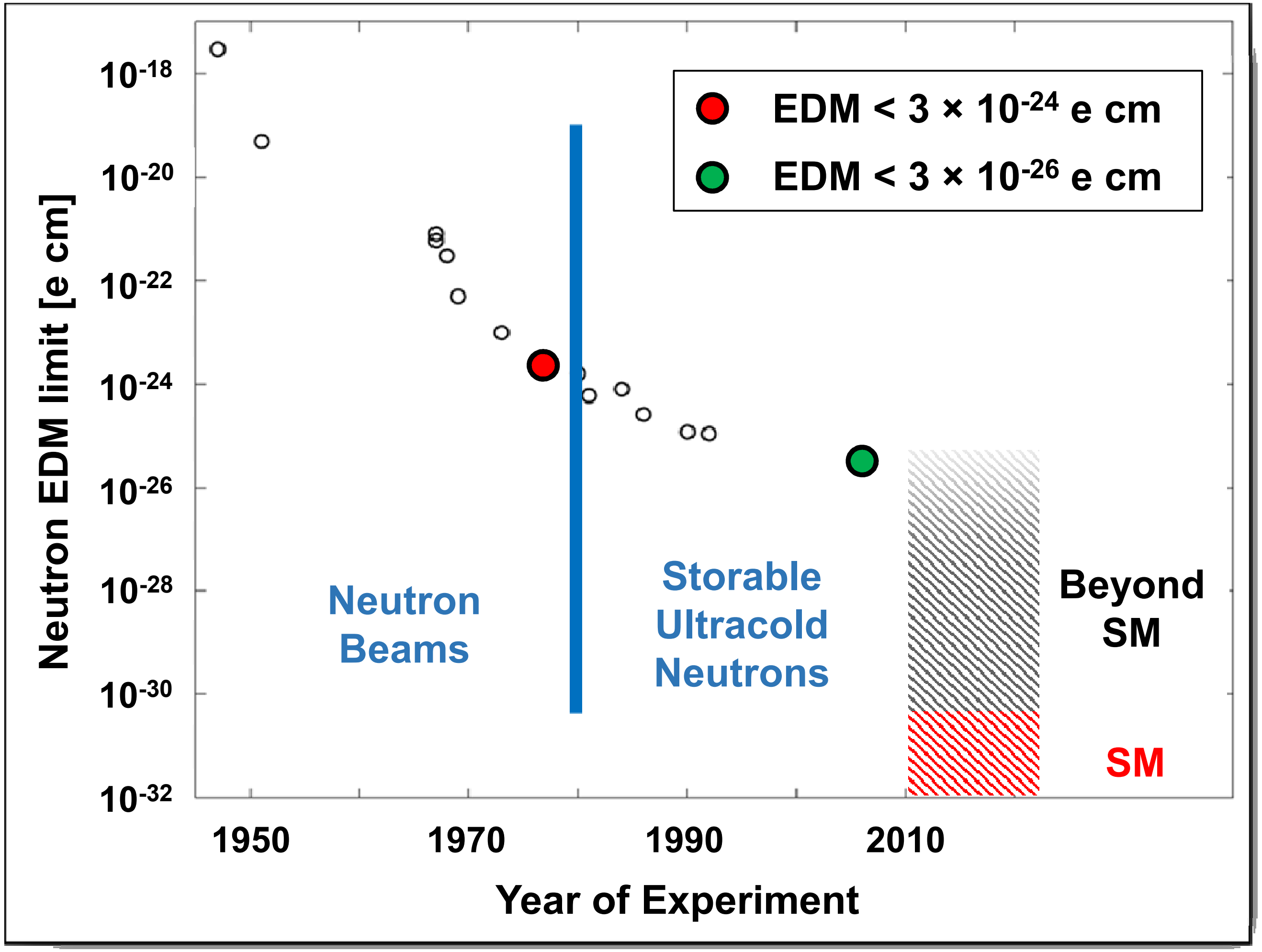

magnetic field magnitude around 8cm above the floor
y, towards Aare (m)
x, away from source (m)
B field magnitude (μT)
0
30
60
90
120
150
180
210
240

Support Construction of MSR 03/2018

Start commissioning of *n2EDM* in 2020 …

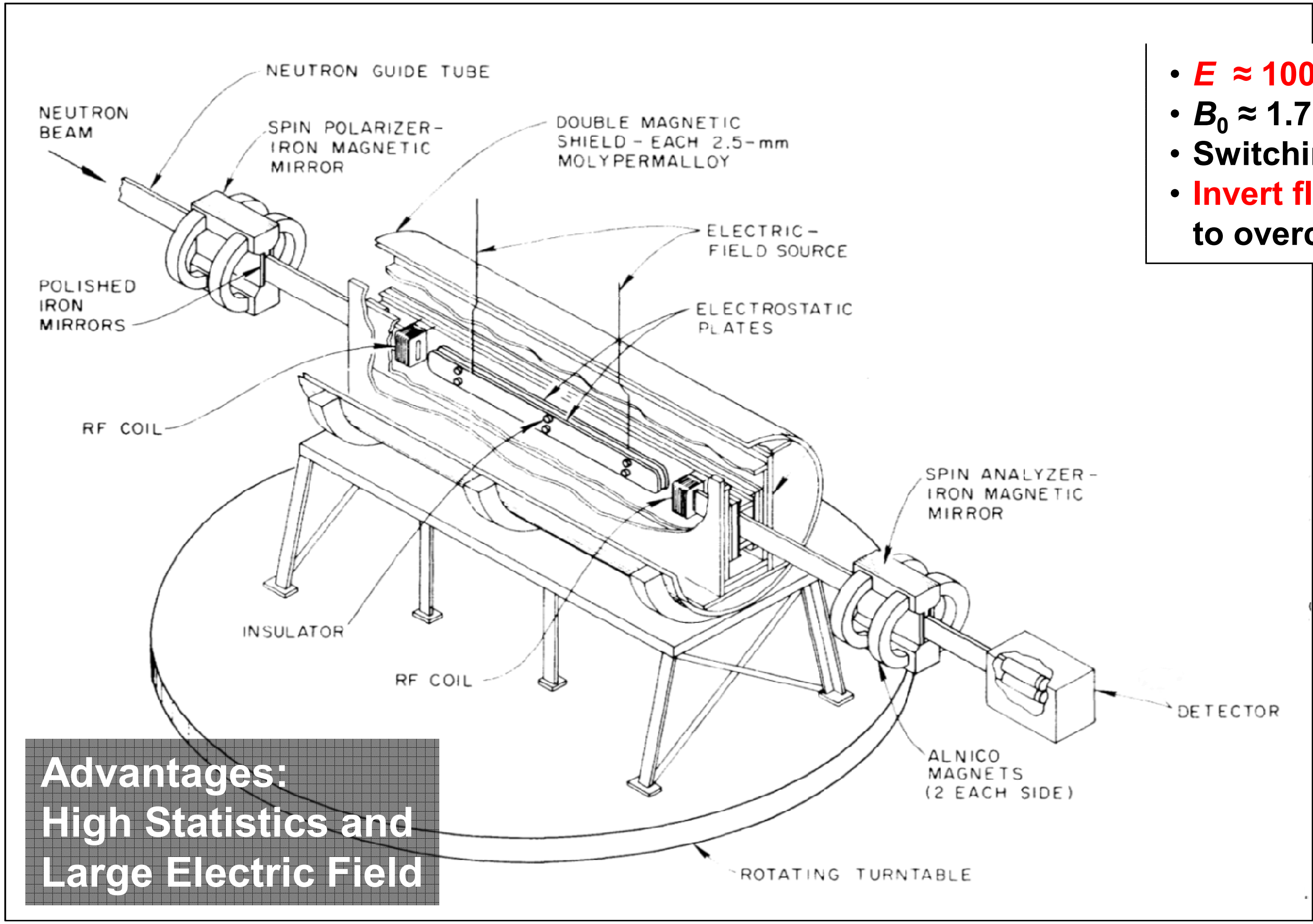


Beam EDM
FNSNF Fonds national suisse Schweizerischer Nationalfonds Fondo nazionale svizzero Swiss National Science Foundation
erc European Research Council



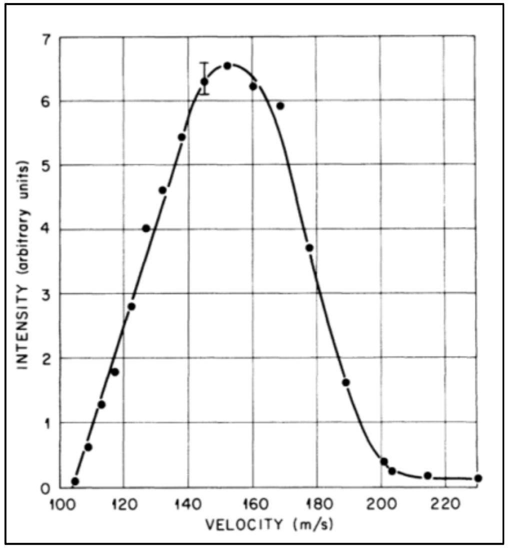
Dress et al., PRD 15, 9 (1977)

Baker et al., PRL 97, 131801 (2006)
Pendlebury et al., PRD 92, 092004 (2015)



Advantages:
High Statistics and Large Electric Field

- E ≈ 100 kV/cm (1.8 m, gap = 1 cm)
- B_0 ≈ 1.7 mT (permanent magnets)
- Switching HV polarity every 200 s
- Invert flight direction every other day to overcome systematic $v \times E$-effect



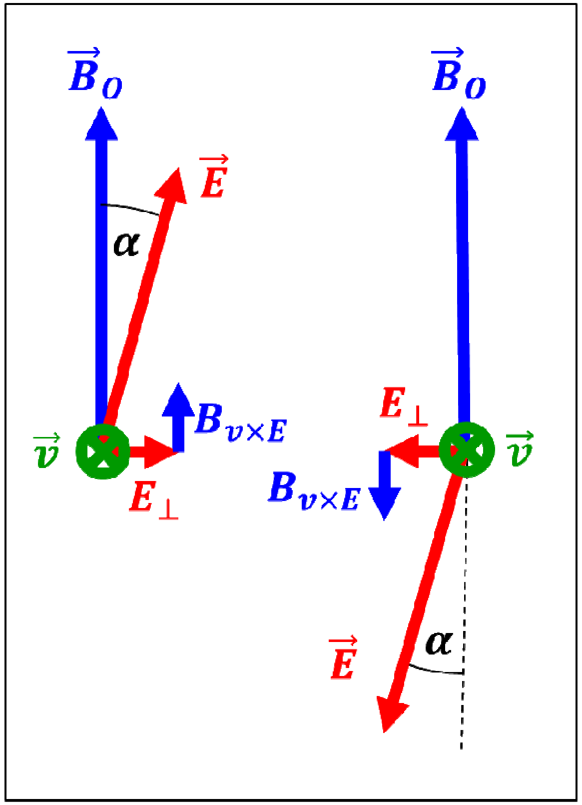
Dress et al., PRD 15, 9 (1977)

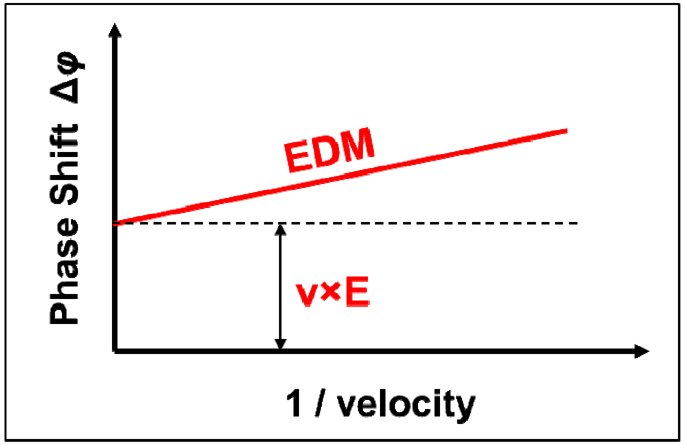
- v×E – effect: $\vec{B}_{v\times E} = -\frac{\vec{v}\times\vec{E}}{c^2}$

- This can cause a **false EDM signal**:

$$d_{\text{false}} \approx 10^{-20}\ \text{e cm}\cdot\sin\alpha \quad \text{for: } v = 100\ \text{m/s}$$

- The false effect is **velocity-dependent**, however, a real EDM signal is not !





Length of experiment

$$\Delta\varphi = \frac{8 d_n E}{\hbar} T + \frac{4\gamma_n E L}{c^2} \sin\alpha$$

slope = EDM   offset = v×E

- **Concept is ideal for pulsed neutron spallation sources e.g. at the European Spallation Source – proposed ANNI beam line**
- **Start with proof-of-principle experiments at Paul Scherrer Institute and Institute Laue-Langevin**

Piegsa, PRC 88, 045502 (2013)

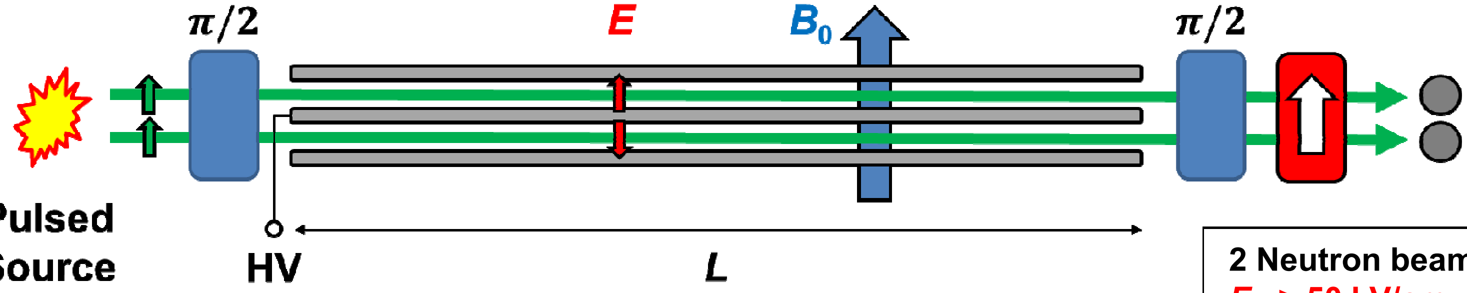
$$\sigma(d_n) \propto \frac{1}{ET\sqrt{N}}$$

BEAM	UCN
E = 100 kV/cm	E = 10 kV/cm
$N \approx$ 100 MHz (ESS)	N = 14'000 / 300 s $\approx$ 50 Hz
$T \approx$ 100 ms (50 m)	T = 130 s (storage)

Baker et al., PRL 97, 131801 (2006)
Pendlebury et al., PRD 92, 092004 (2015)

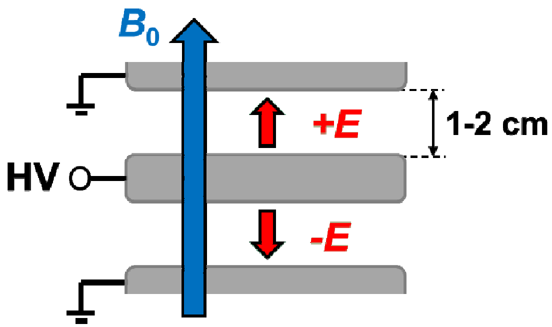
Neutron Beam EDM Experiment

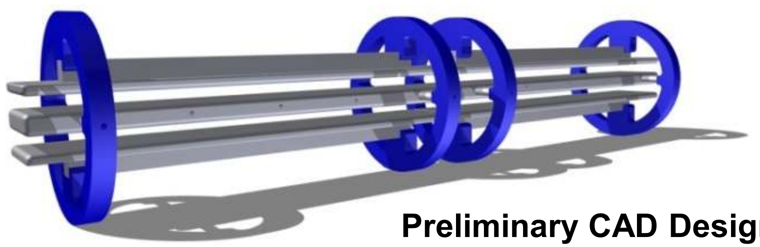
SIDE VIEW



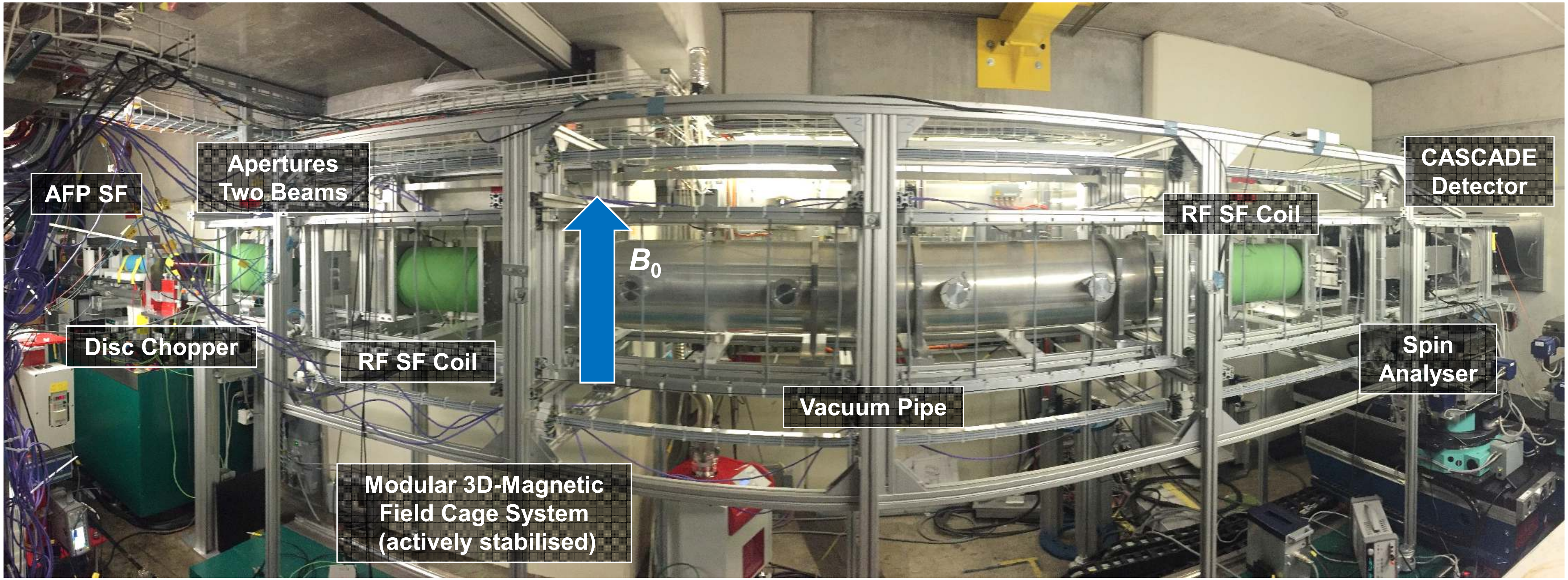
2 Neutron beams
E > 50 kV/cm
B_0 = 100 μT
L = 5 m (proof-of-prin.)
L = 50 m (full-scale)

CROSS SECTION

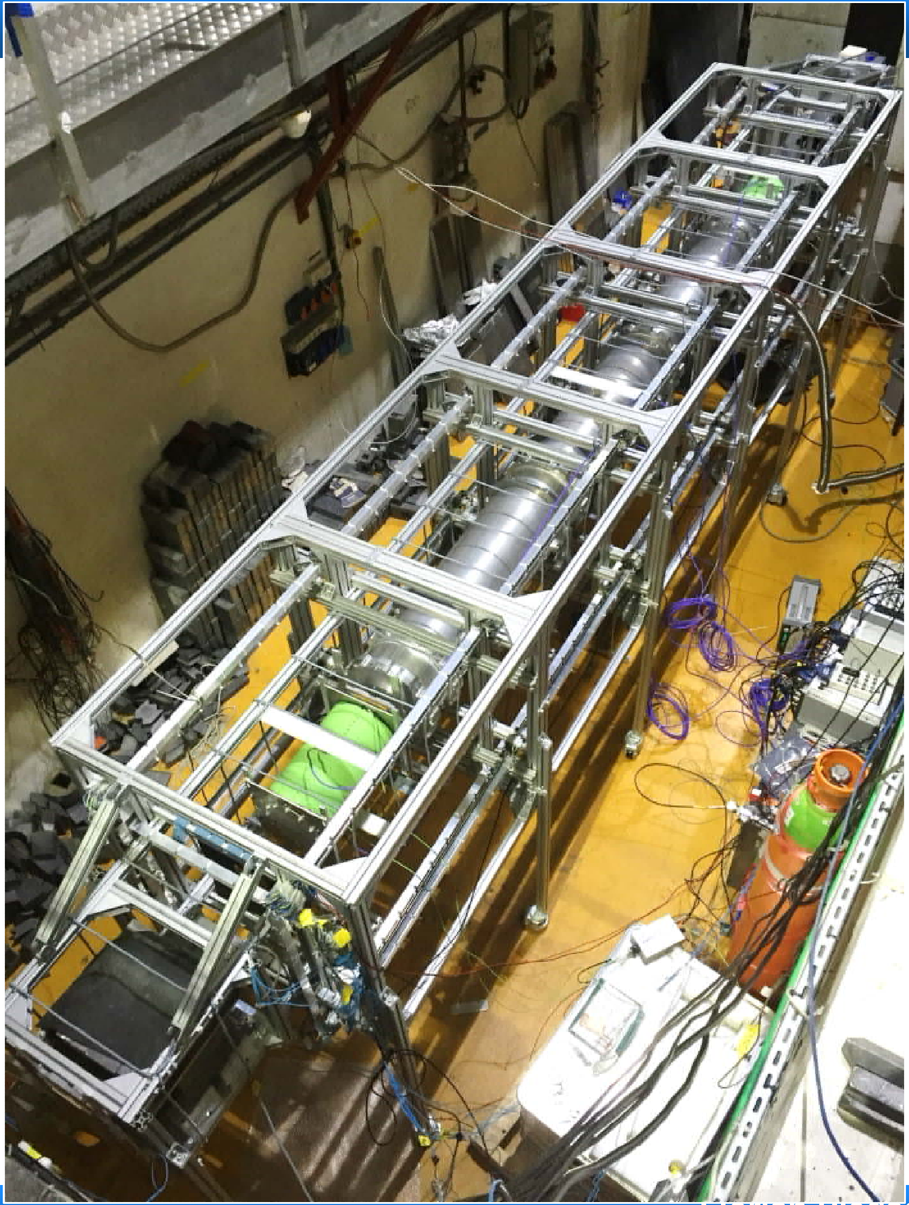




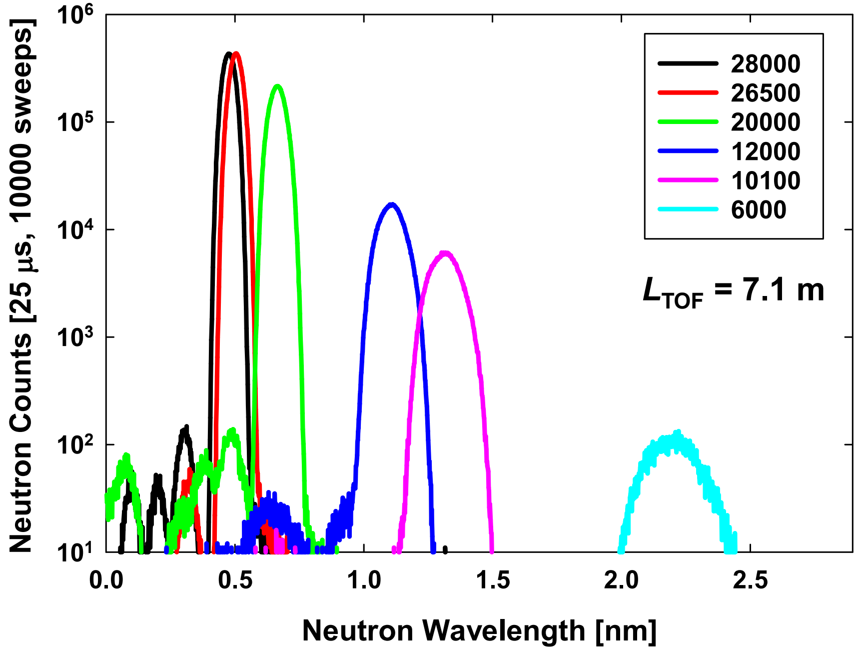
Preliminary CAD Design
(Neutron Guides & Electrodes)

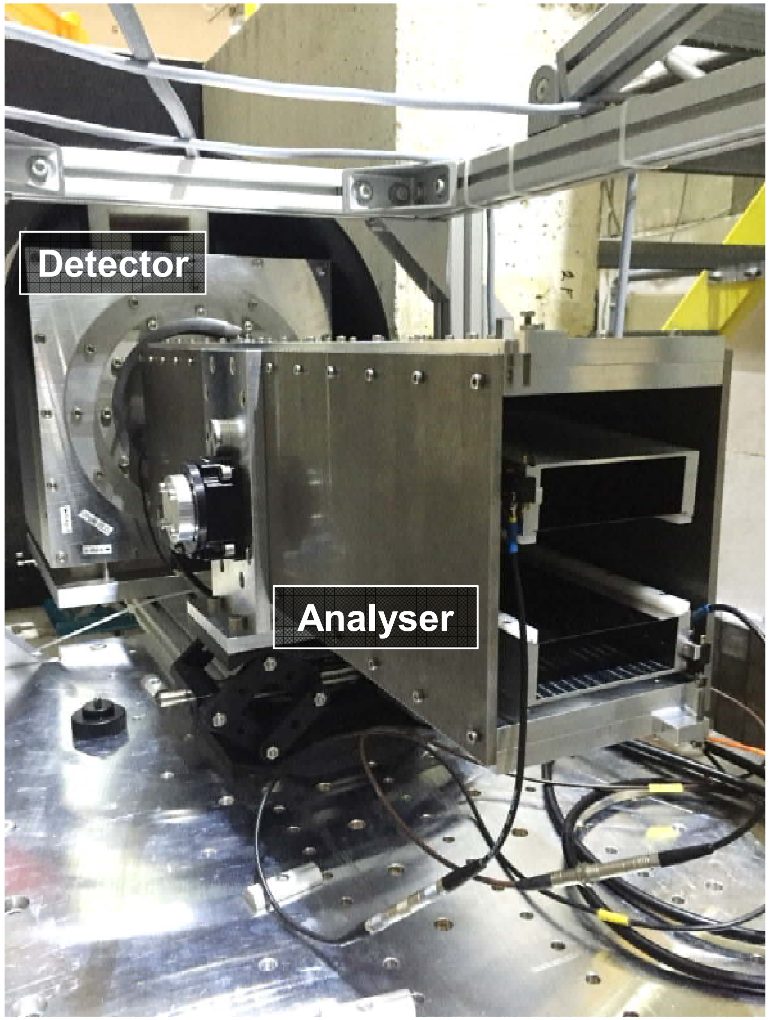


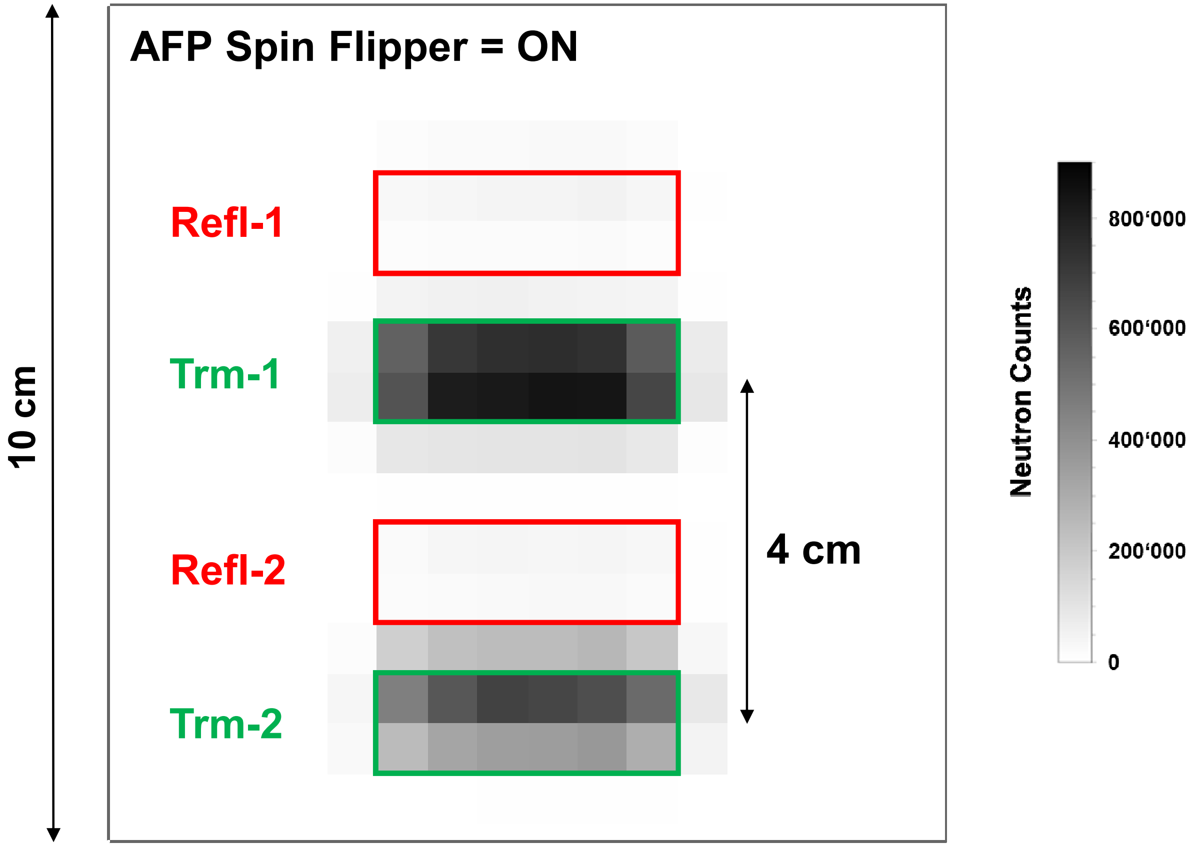
Polarised and White Cold Neutron Beam



Polarised and Monochromatic (Selector) Neutron Beam

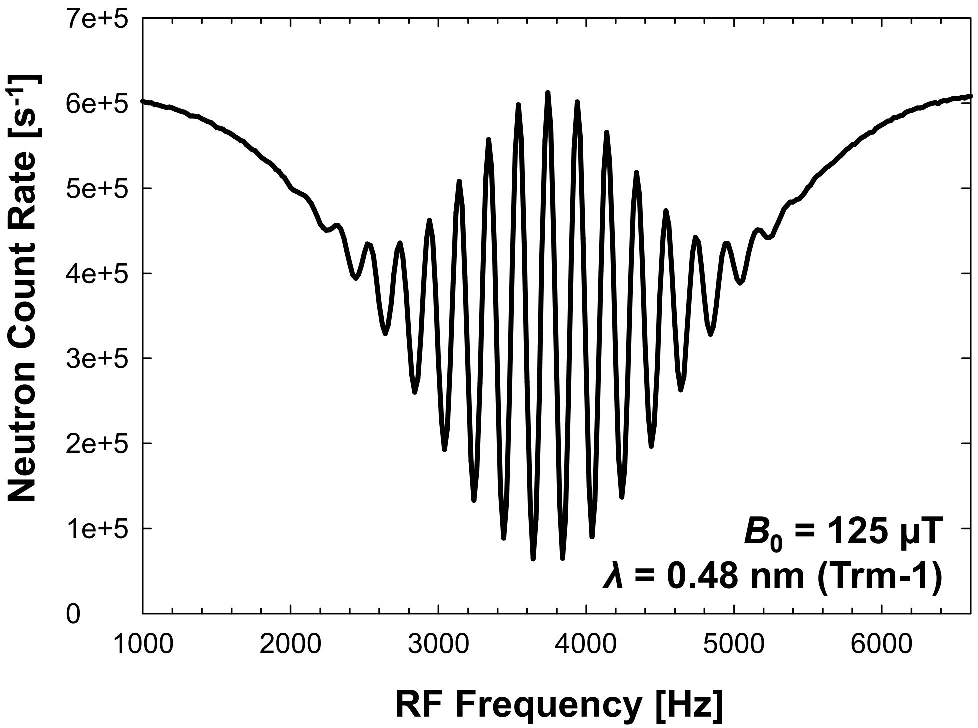




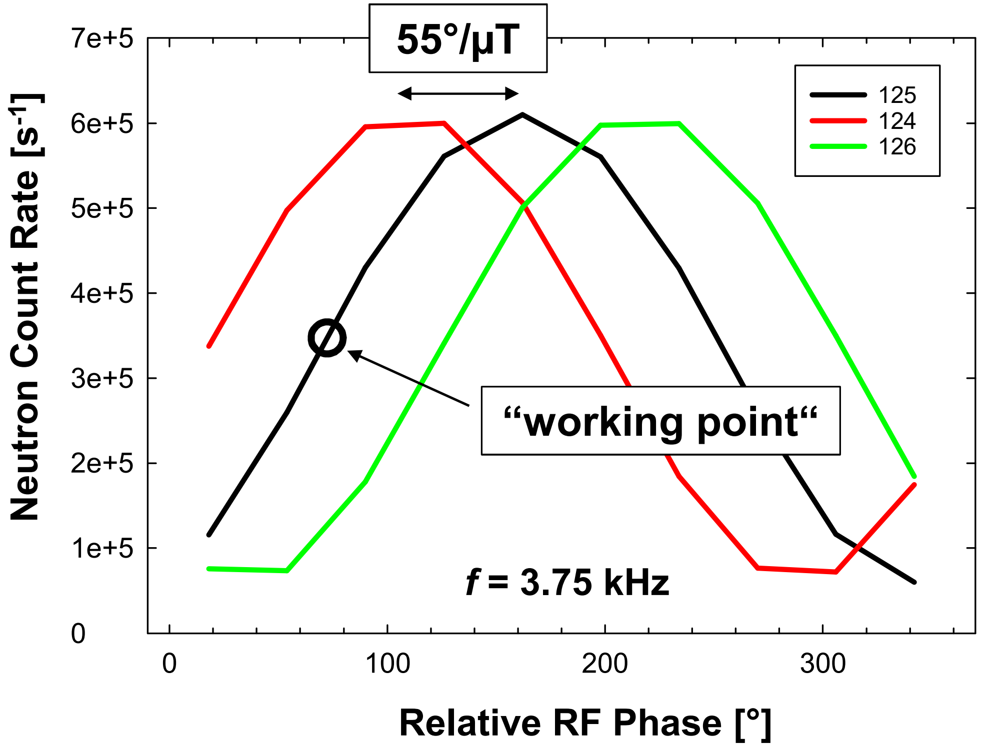


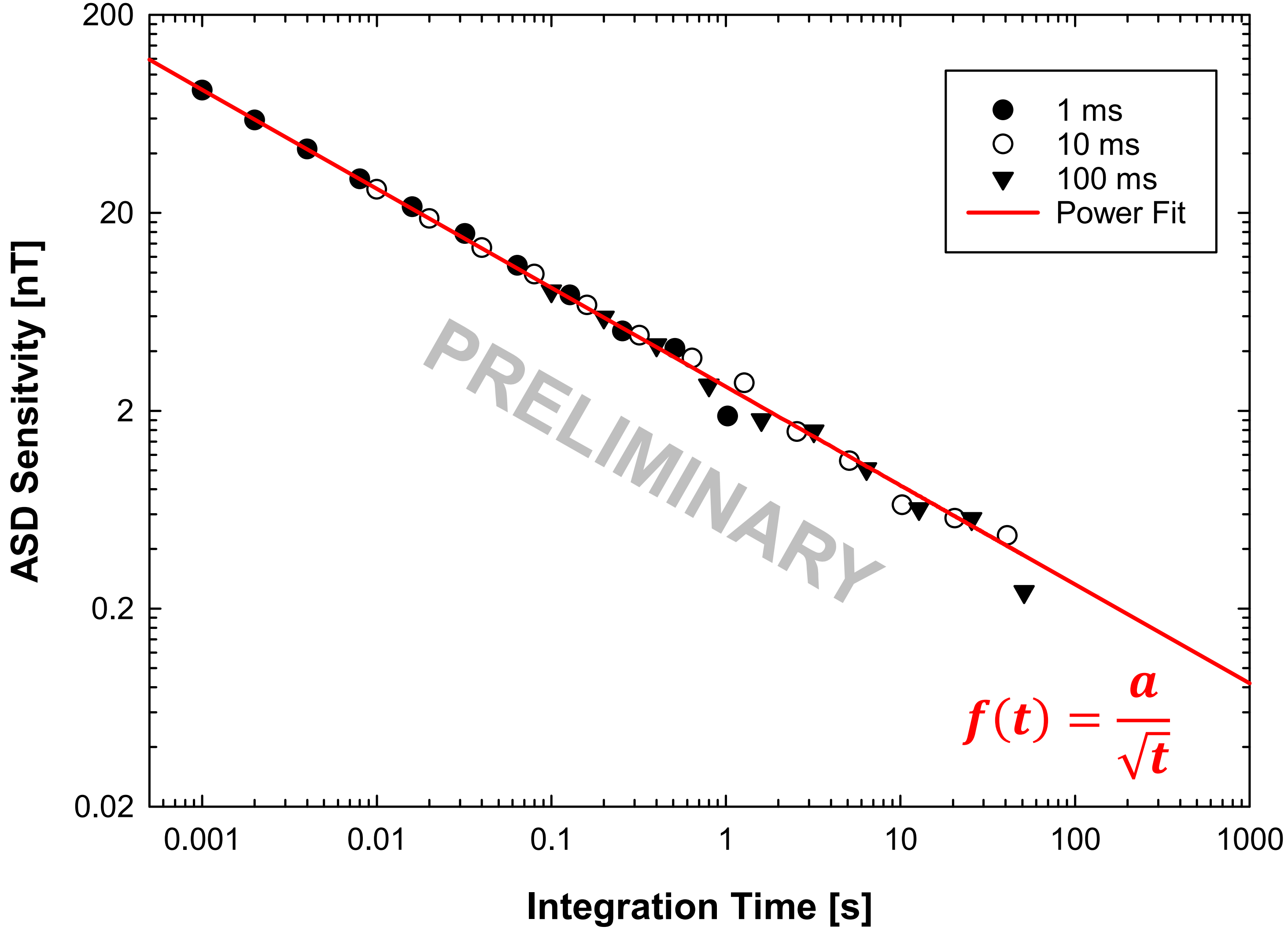
Two beams/Four beam spots each with 3×1 cm^2
16×16 Pixels, Pixel-Size = 6×6 mm^2
Exposure time: 10 sec (at λ = 0.48 nm)
FeSi supermirror m = 5 (*SwissNeutronics*)

“Classic Ramsey“



“Phase Ramsey“

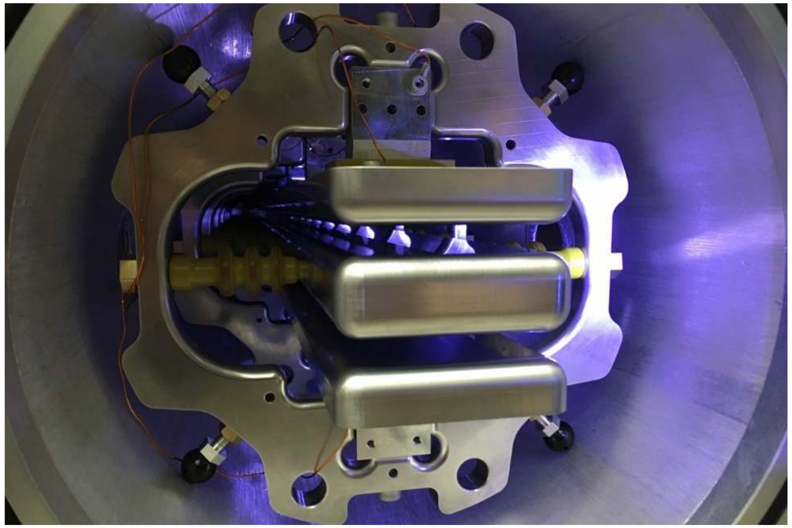


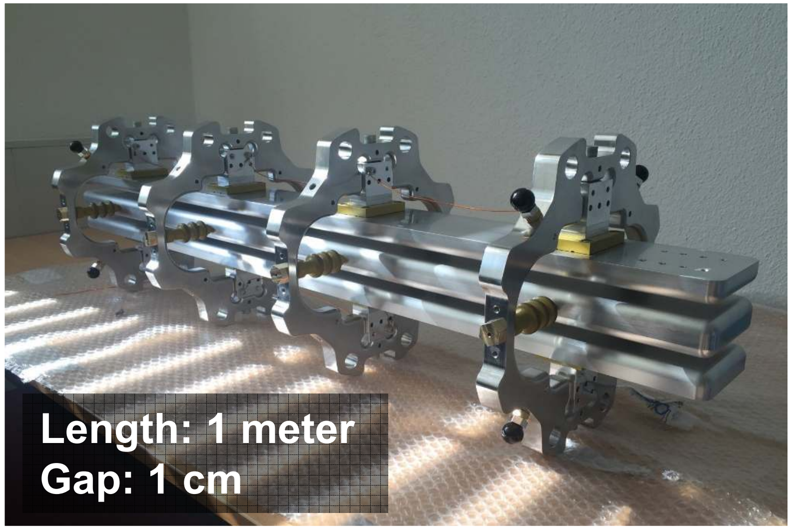


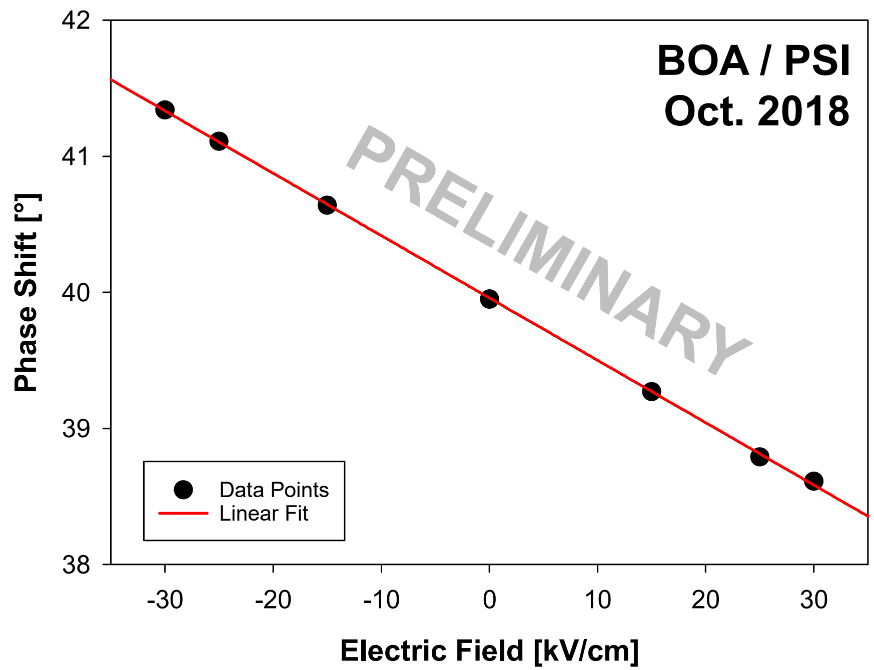
$$a \approx 2\ \mathrm{nT}/\sqrt{\mathrm{Hz}}$$

3×10^{-24} e cm (per day)

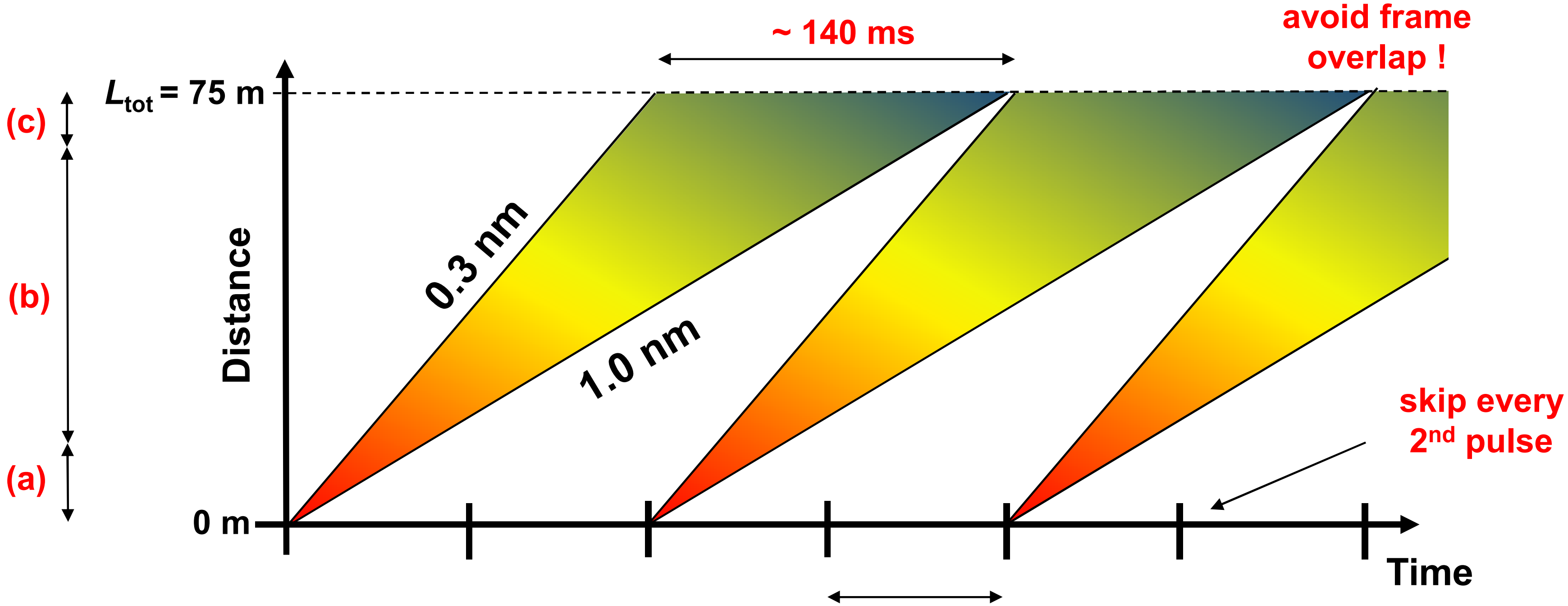
with: L = 3 m, v = 800 m/s,
E = 100 kV/cm



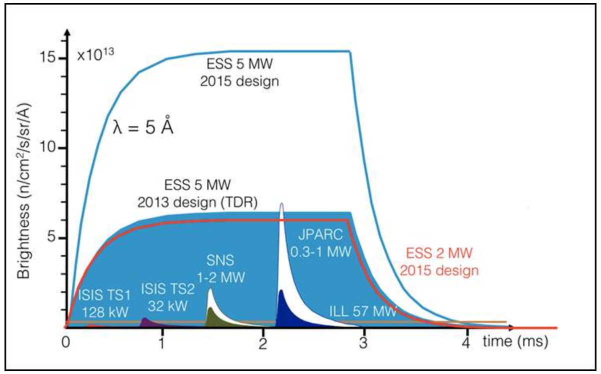




- Direct measurement of *E*-field seen by neutrons
- Maximum v×E-effect (with *B* ⊥ *E*):
  30 kV/cm, 1000 m/s → 30 nT



(a) Beam extraction & preparation
(b) Ramsey precession region (L ~ 50 m)
(c) Spin analysis & detector



- **Statistical sensitivity:**

$$\sigma_{\text{Beam}}(d_{\text{n}}) \approx \frac{2\hbar}{\eta\tau E\sqrt{N}}$$

η = 0.75 , L = 50 m, L_{tot} = 75 m, τ = 90 ms, E = 100 kV/cm

$$N = \underbrace{1.5\times10^{13}\,\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}}_{\text{PF1B part. brightness 0.3 – 1.0 nm (ILL) *}} \times \overbrace{1/3}^{\text{Polarization}} \times \underbrace{1/2}_{\text{Skip every 2}^{\text{nd}}\text{ pulse}} \times \overbrace{1}^{\text{ESS} \approx \text{ILL}} \times \underbrace{(2\times20\,\text{cm}^2)}_{\text{Cross section of two beams}} \times \overbrace{2\times10^{-7}\text{sr}}^{20\,\text{cm}^2/(100\,\text{m})^2} \sim 20\ \text{MHz}$$

$$\sigma(d_{\text{n}}) \approx 1.5\times10^{-25}\ \text{e cm / day}$$

Neutron Absorbing Electrodes

* Abele et al., NIM A 562, 407 (2006)

- **Statistical sensitivity:**

$$\sigma_{\text{Beam}}(d_{\text{n}}) \approx \frac{2\hbar}{\eta \tau E \sqrt{N}}$$

η = 0.75 , L = 50 m, L_{tot} = 75 m, τ = 90 ms, E = 100 kV/cm

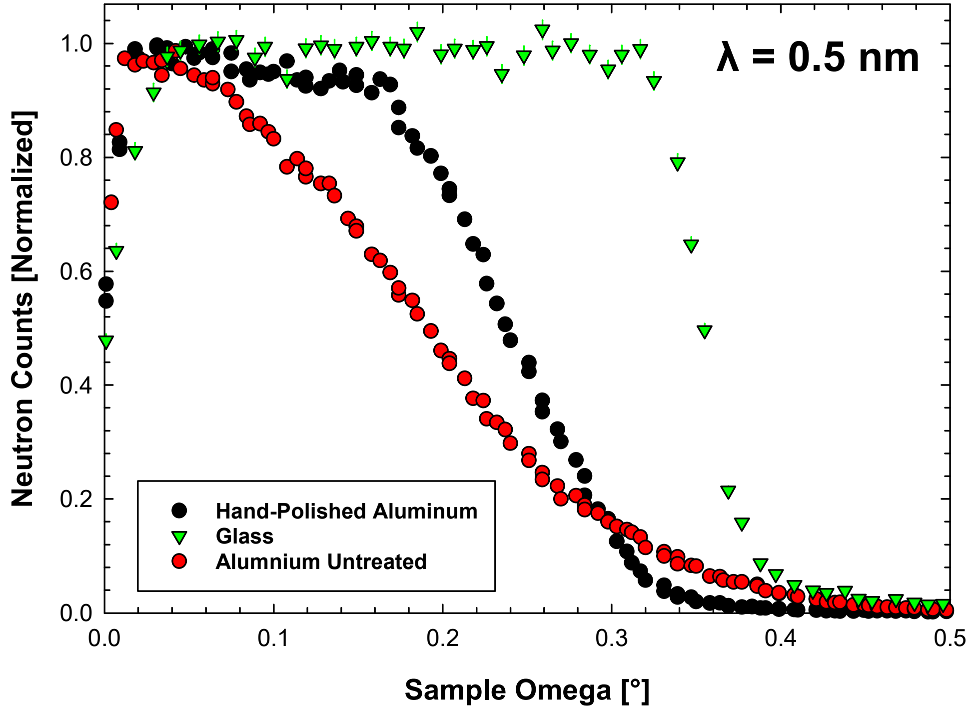
N = 1.5×10^{13} cm^{-2}s^{-1}sr^{-1} × 1/3 × 1/2 × 1 × (2 × 20 cm^2) × 2 × 10^{-7}sr ~ 20 MHz

- 1.5×10^{13} cm^{-2}s^{-1}sr^{-1}: PF1B part. brightness 0.3 – 1.0 nm (ILL) *
- 1/3: Polarization
- 1/2: Skip every 2nd pulse
- 1: ESS ≈ ILL
- (2 × 20 cm^2): Cross section of two beams
- 2 × 10^{-7}sr: 20 cm^2 / (100 m)^2

$$\sigma(d_{\text{n}}) \approx 5 \times 10^{-26} \text{ e cm / day}$$

Guiding Electrodes
Flux Gain ~ 10

* Abele et al., NIM A 562, 407 (2006)



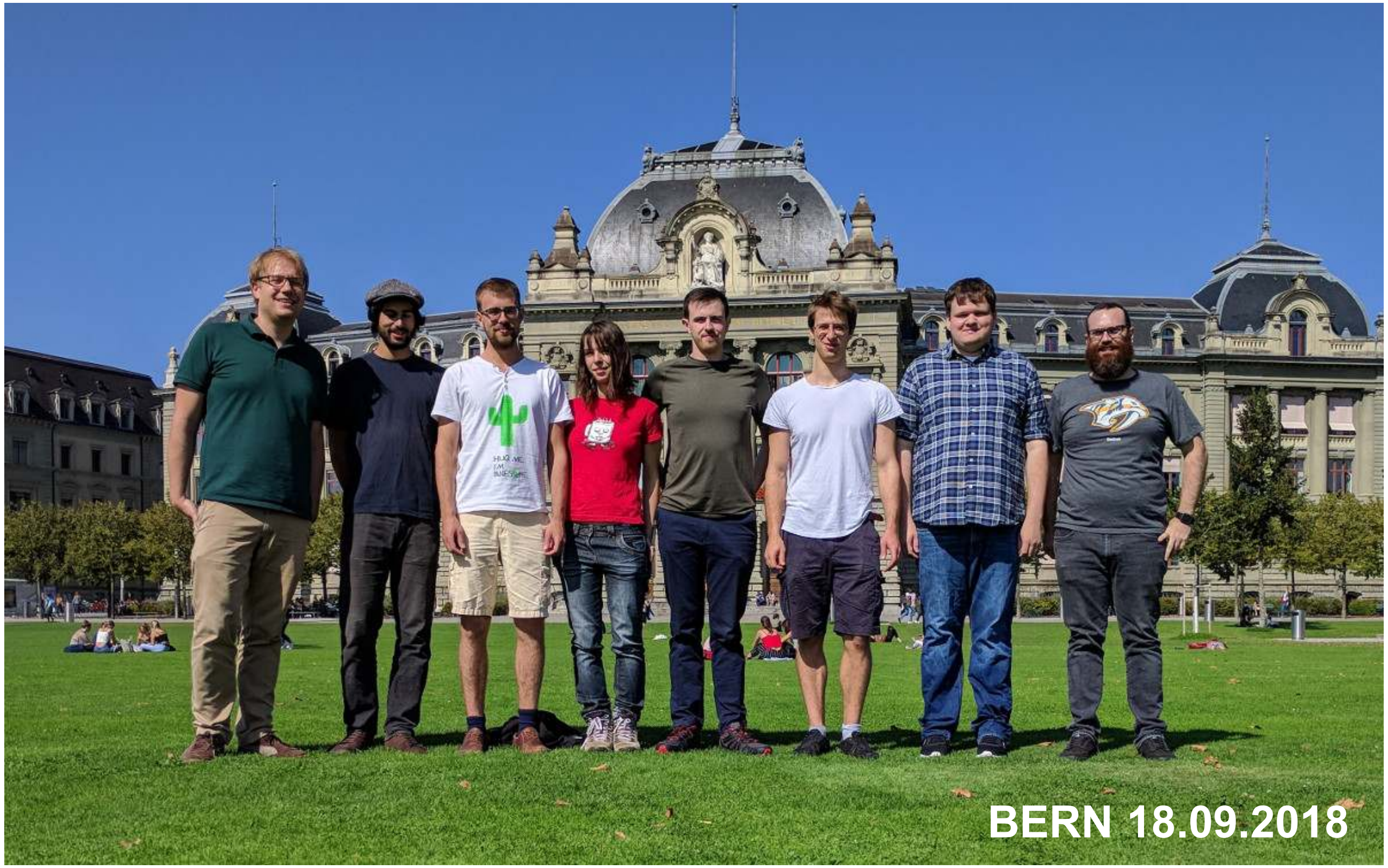
Absorbing Electrodes: 20 mm / 75 m → 0.015° (max. vertical divergence)
Guiding Electrodes: about 0.15° @ 0.5 nm (only polished aluminum)

Factor × 10

- ***nEDM*** **will deliver new best EDM result soon**

- ***n2EDM*** **is currently under construction**

- **Novel approach:**
  - ***Beam EDM*** **experiment in proof-of-principle phase**
  - Future full-scale experiment intended for ESS



Thank you for your attention !