A new precision measurement of the neutron electric dipole moment (EDM)

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PSI, February 2003

The goal of new nEDM experiment is

1. to reach the accuracy of $2 \cdot 10^{-28}$ e·cm
   (factor of 100 times better than the present best result)

2. to check the prediction of SUSY models with CP-violation
   (nEDM, Baryon asymmetry of Universe,
   SUSY and Standard Model)

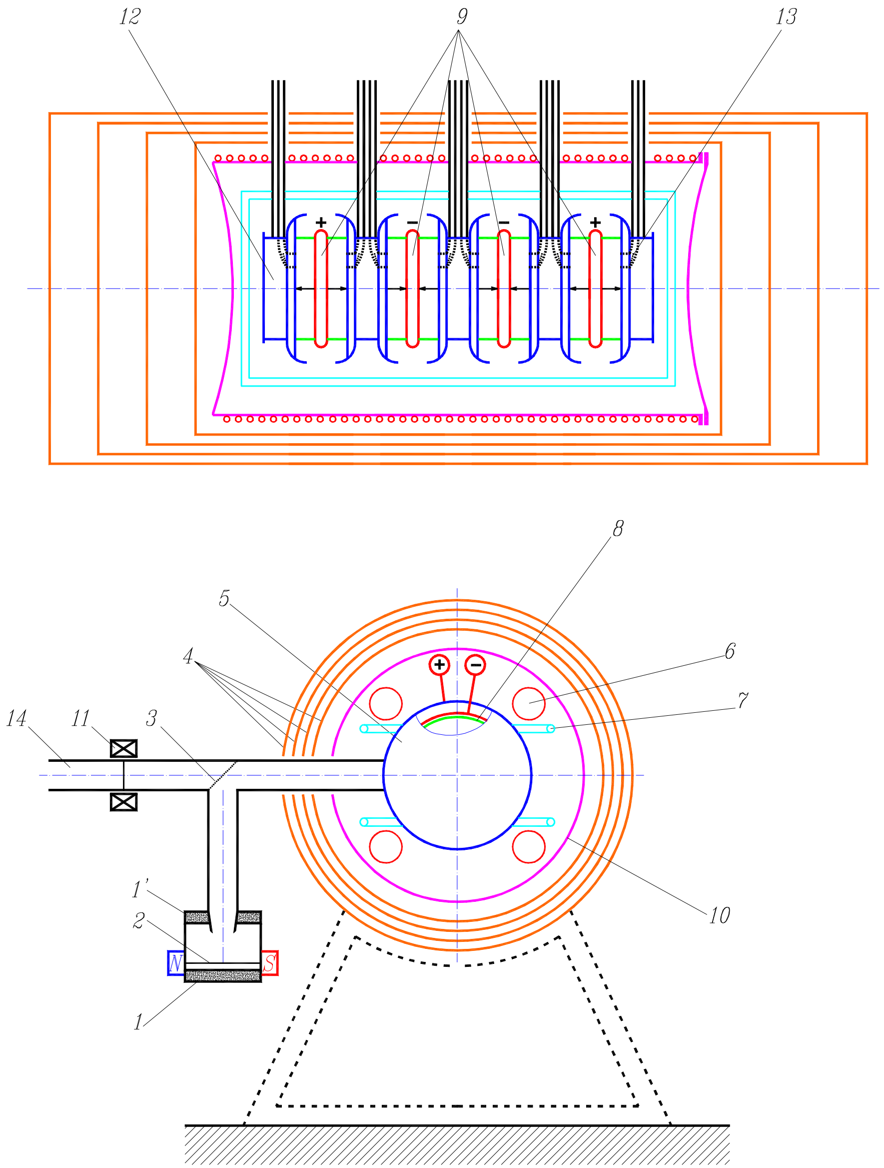
The main results of 2002

1. The detailed proposal of nEDM experiment.
2. The project of mini EDM spectrometer.
3. The test experiment of magnetic field stability with model of magnetic shielding and with Cs-magnetometers.
4. The test experiment for UCN polarizer with superconducting solenoid.
5. The formation of nEDM collaboration.

The detailed proposal of nEDM experiment

1. The estimation of the statistical accuracy of nEDM experiment.
2. The mathematical model of nEDM experiment.
3. Simulation of nEDM measurement by multichamber spectrometer in the conditions of magnetic field fluctuations.
4. Requirements for stability and homogeneity of magnetic field.
5. Test experiments.
6. Systematic effects.
7. High-voltage problems.
8. Design.
9. The plan of the realization of the new nEDM experiment
10. Cost estimate.

The scheme of the multichamber nEDM spectrometer



1. 1' - UCN detectors
2. - polarization analyzer foil
3. - UCN switch
4. - four-layer magnetic shield
5. - electrode with zero potential
6. - channel for Cs magnetometers
7. - oscillating field coils
8. - BeO-coated insulator
9. - HV electrodes
10. - vacuum chamber with magnetic field coil
11. - superconducting polarizer with a membrane to separate the vacuum of the UCN source from the vacuum of the EDM spectrometer
12. - UCN storage chamber (1 out of 13)
13. - UCN shutter
14. - UCN guide

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The estimation of the statistical accuracy of new nEDM experiment at PSI and comparison with nEDM experiments at PNPI and at ILL

	PNPI	ILL	EDM@SUNS
ρ_0	8 UCN/cm^{-3}	40 UCN/cm^{-3}	$3\cdot10^3$ UCN/cm^{-3}
V	$4.8\cdot10^4$ cm^3	$2.0\cdot10^4$ cm^3	$2.0\cdot10^5$ cm^3
N_0	10^4 UCN	$1.2\cdot10^4$ UCN	$2.9\cdot10^7$ UCN
K	0.026	0.016	0.05
E	13 kV/cm	7 kV/cm	15 kV/cm
α	0.7	0.7	0.75
T	100 s	130 s	100 s
$\delta\nu_{stat}$/measurement	$4.5\cdot10^{-5}$ Hz	$3.1\cdot10^{-5}$ Hz	$8\cdot10^{-7}$ Hz
required stability δB/measurement	1.5 pT	1.0 pT	0.026 pT
achieved stability δB/measurement	0.25 pT	0.2 pT	0.010 pT
δd_n/measurement	$3.7\cdot10^{-24}$ e·cm	$5.5\cdot10^{-24}$ e·cm	$5.5\cdot10^{-26}$ e·cm
δd_n/100 days	$1.9\cdot10^{-26}$ e·cm	$2.8\cdot10^{-26}$ e·cm	$2.7\cdot10^{-28}$ e·cm
f	61	90	1

ρ_0: average UCN density at the sources; V: total volume of the storage traps; N_0: number of neutrons registered per measuring cycle with the same polarity of high voltage; K: total UCN loss factor between the source and the detector; α: visibility parameter of the resonance curve; E: electric field; T: time between oscillating field pulses in Ramsey's method; $\delta\nu_{stat}$/measurement: required resonance stability determined from the counting statistics; δd_n/measurement: statistical accuracy per measurement; δd_n/100 days: statistical accuracy for 100 days of data acquisition; f: accuracy of the experiments compared to the design accuracy of the new experiment at the new PSI UCN source

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The comparison of sensitivity of different nEDM spectrometers (multichamber PNPI-PSI spectrometer, PNPI spectrometer, ILL spectrometer)

	PNPI@SUNS	ILL@SUNS	EDM@SUNS
ρ_0	$3\cdot10^3$ UCN/cm^{-3}	$3\cdot10^3$ UCN/cm^{-3}	$3\cdot10^3$ UCN/cm^{-3}
V	$4.8\cdot10^4$ cm^3	$2.0\cdot10^4$ cm^3	$2.0\cdot10^5$ cm^3
N_0	$3.8\cdot10^6$ UCN	$1.0\cdot10^6$ UCN	$2.9\cdot10^7$ UCN
K	0.026	0.016	0.05
E	13 kV/cm	7 kV/cm	15 kV/cm
α	0.7	0.7	0.75
T	100 s	130 s	100 s
$\delta\nu_{stat}$/measurement	$2.3\cdot10^{-6}$ Hz	$3.6\cdot10^{-6}$ Hz	$8\cdot10^{-7}$ Hz
required stability δB/measurement achieved stability δB/measurement	0.08 pT 0.25 pT	0.12 pT 0.2 pT	0.026 pT 0.010 pT
$\delta\nu_{tot}$/measurement	$7.8\cdot10^{-6}$ Hz	$7.0\cdot10^{-6}$ Hz	$8\cdot10^{-7}$ Hz
δd_n/measurement	$6.2\cdot10^{-25}$ e·cm	$1.0\cdot10^{-25}$ e·cm	$5.5\cdot10^{-26}$ e·cm
δd_n/100 days	$3.1\cdot10^{-27}$ e·cm	$5.0\cdot10^{-27}$ e·cm	$2.7\cdot10^{-28}$ e·cm
f	11	18	1

ρ_0: average UCN density at SUNS; V: total volume of the storage traps; N_0: number of neutrons registered per measuring cycle with the same polarity of high voltage; K: total UCN loss factor between the source and the detector; α: visibility parameter of the resonance curve; E: electric field; T: time between oscillating field pulses in Ramsey's method; $\delta\nu_{stat}$/measurement: required resonance stability determined from the counting statistics; $\delta\nu_{tot}$/measurement: required total resonance stability; δd_n/measurement: statistical accuracy per measurement; δd_n/100 days: statistical accuracy for 100 days of data acquisition; f: accuracy of the experiments compared to the design accuracy of the new experiment at the new PSI UCN source

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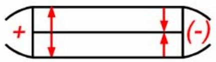
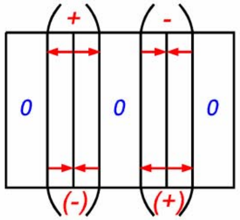
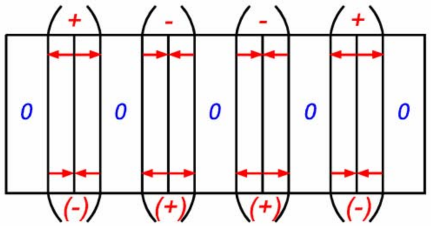
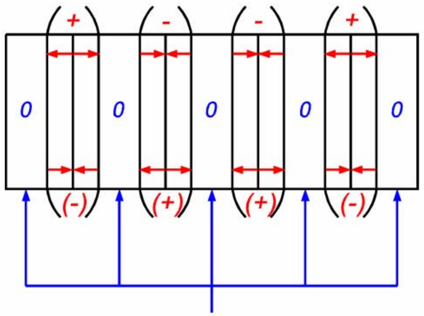
Multichamber nEDM spectrometer and its advantages

1.		Double chamber scheme compensates $\sigma_0(t)$ only
2.		Two double chamber scheme with opposite HV polarity $\left(\begin{smallmatrix}+ & -\\ - & +\end{smallmatrix}\right)$ compensates $\sigma_0(t)+\sum_{z,y,x}\sigma_{1z}(t)\cdot z$
3.		Four double chamber scheme with HV polarity $\left(\begin{smallmatrix}+ & - & - & +\\ - & + & + & -\end{smallmatrix}\right)$ compensates $\sigma_0(t)+\sum_{z,y,x}\sigma_{1z}(t)\cdot z+\sum_{z,y,x}\sigma_{2z}(t)\cdot z^2$
4.	 no electric field	Four double chamber scheme with HV polarity $\left(\begin{smallmatrix}+ & - & - & +\\ - & + & + & -\end{smallmatrix}\right)$ and neutron comagnetometers compensates $\sigma_0(t)+\sum_{z,y,x}\sigma_{1z}(t)\cdot z+\sum_{z,y,x}\sigma_{2z}(t)\cdot z^2+\sum_{z,y,x}\sigma_{3z}(t)\cdot z^3+\ \dots ?$

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Data analysis with a multichamber EDM spectrometer

1.	$\underline{\overline{I}}^{-}=\frac{1}{8}\{[(F_2\text{-}F_3)\text{-}(F_5\text{-}F_6)]\text{-}[(F_8\text{-}F_9)\text{-}(F_{11}\text{-}F_{12})]\}$	$(\Delta\delta F)_L-(\Delta\delta F)_R=D$	neutron EDM indication (from HV-traps only!)
2.	$\underline{\overline{I}}^{+}=\frac{1}{8}\{[(F_2\text{-}F_3)\text{-}(F_5\text{-}F_6)]+[(F_8\text{-}F_9)\text{-}(F_{11}\text{-}F_{12})]\}$	$(\Delta\delta F)_L+(\Delta\delta F)_R$	fluctuations with terms of 2nd, 4th, etc. orders
3.	$\underline{\overline{II}}^{+}=\frac{1}{8}\{[(F_2\text{-}F_3)+(F_5\text{-}F_6)]+[(F_8\text{-}F_9)+(F_{11}\text{-}F_{12})]\}$	δF	fluctuations with terms of 1st, 3rd, etc. orders
4.	$\underline{\overline{III}}^{+}=\frac{1}{8}\{[(F_2+F_3)+(F_5+F_6)]+[(F_8+F_9)+(F_{11}+F_{12})]\}$	F	fluctuations of uniform magnetic field, 2nd, etc. orders
5.	$\underline{\overline{VIII}}^{-}=\frac{1}{8}\{[(B_2\text{-}B_3)\text{-}(B_5\text{-}B_6)]\text{-}[(B_8\text{-}B_9)\text{-}(B_{11}\text{-}B_{12})]\}$	$(\Delta\delta B)_L-(\Delta\delta B)_R$	magnetic field terms of 3rd, 5th, etc. orders
6.	$\underline{\overline{VIII}}^{+}=\frac{1}{8}\{[(B_2\text{-}B_3)\text{-}(B_5\text{-}B_6)]+[(B_8\text{-}B_9)\text{-}(B_{11}\text{-}B_{12})]\}$	$(\Delta\delta B)_L+(\Delta\delta B)_R$	magnetic field terms of 2nd, 4th, etc. orders
7.	$\underline{\overline{VII}}^{+}=\frac{1}{8}\{[(B_2\text{-}B_3)+(B_5\text{-}B_6)]+[(B_8\text{-}B_9)+(B_{11}\text{-}B_{12})]\}$	δB	magnetic field terms of 1st, 3rd, etc. orders
8.	$\underline{\overline{V}}^{+}=\frac{1}{8}\{[(B_2+B_3)+(B_5+B_6)]+[(B_8+B_9)+(B_{11}+B_{12})]\}$	B	average value of the deviation from the resonance

$$EDM(n)=D-D_0$$

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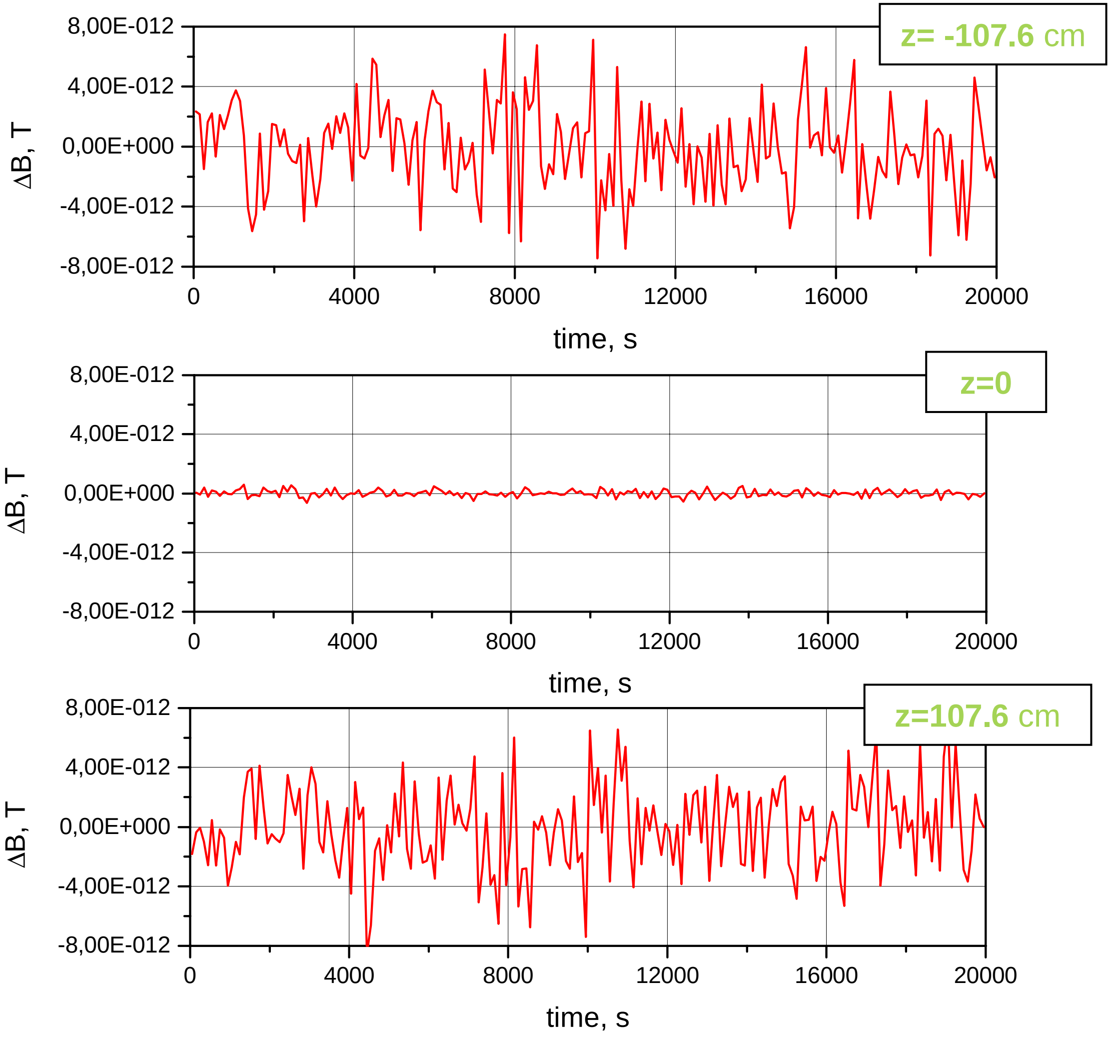
Simulation of magnetic field fluctuations

$$B(x,y,z,t) = B_0 + \sigma_0(t) + \sum_{\substack{z\\y\\x}} \sigma_{1z}(t)\cdot z + \sum_{\substack{z\\y\\x}} \sigma_{2z}(t)\cdot z^2 + \sum_{\substack{z\\y\\x}} \sigma_{3z}(t)\cdot z^3$$



$$\sigma_0 = 0.25 \text{ pT}$$

$$\sigma_{1z} = \sigma_{1x} = \sigma_{1y} = 2.5 \text{ pT/m}$$

$$\sigma_{2z} = \sigma_{2x} = \sigma_{2y} = 0.5 \text{ pT/m}^2$$

$$\sigma_{3z} = \sigma_{3x} = \sigma_{3y} = 0.05 \text{ pT/m}^3$$

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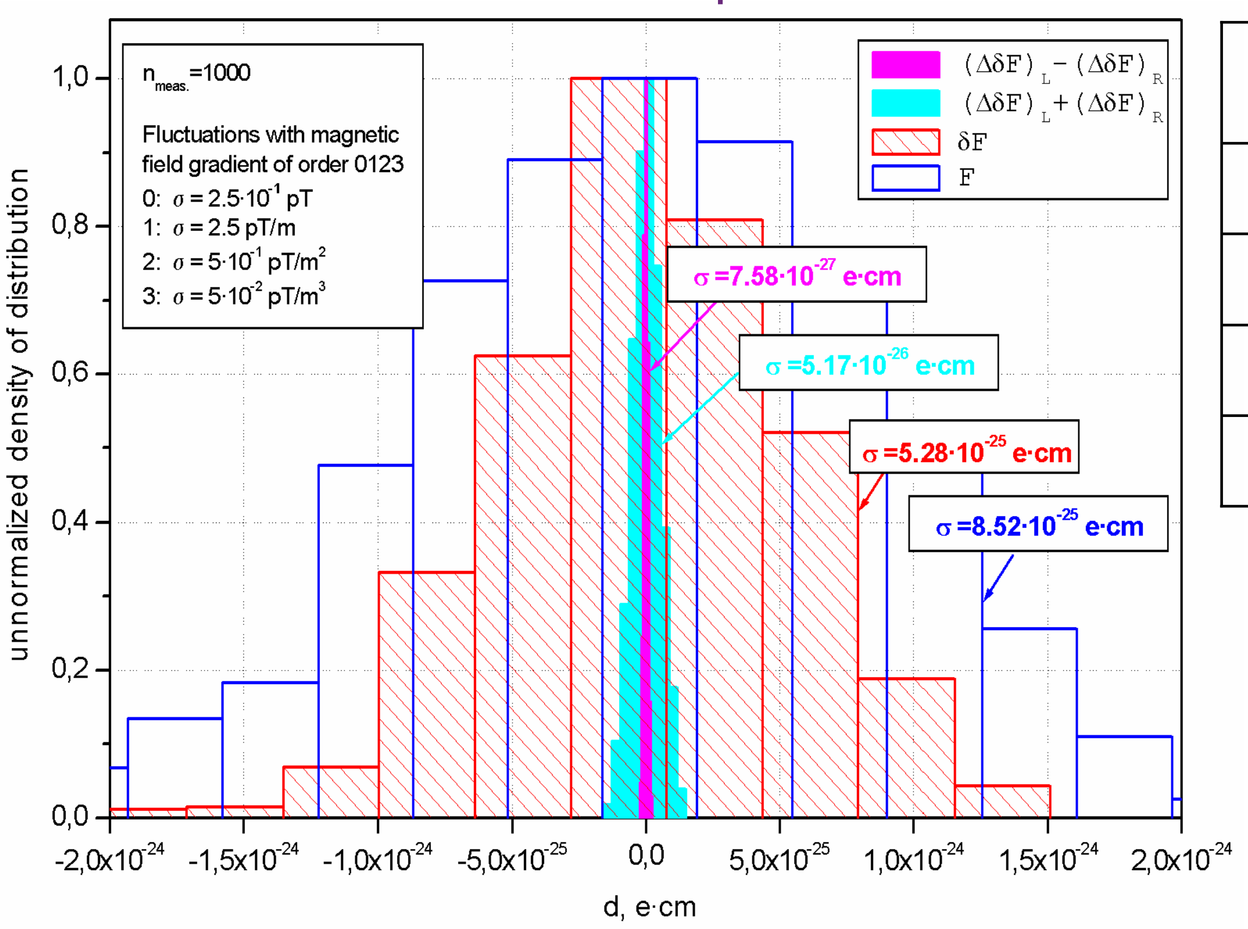
Compensation of magnetic field fluctuations by means of multichamber nEDM spectrometer and requirement for stability of magnetic field

The effect of compensation



The requirement

fluctuation type	Version II final EDM	Version I mini EDM
σ_{0z}	1 pT	3.5 pT
σ_{1z}	10 pT/m	35 pT/m
σ_{2z}	1 pT/m^2	3.5 pT/m^2
σ_{3z}	0.1 pT/m^3	0.35 pT/m^3

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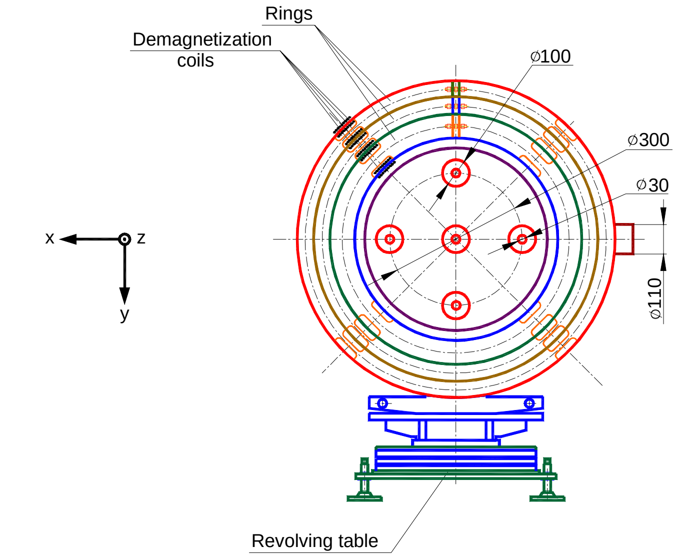
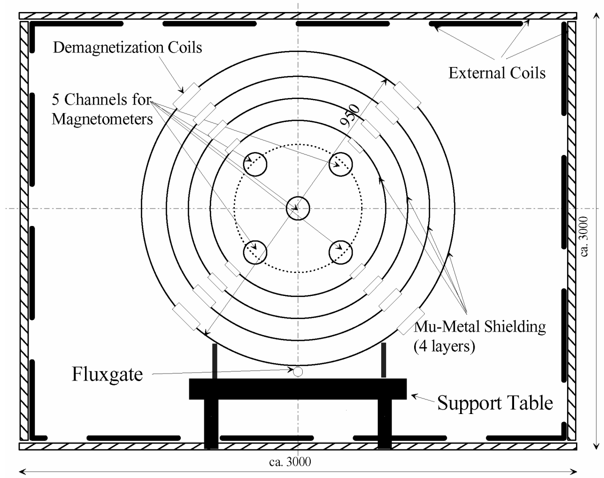
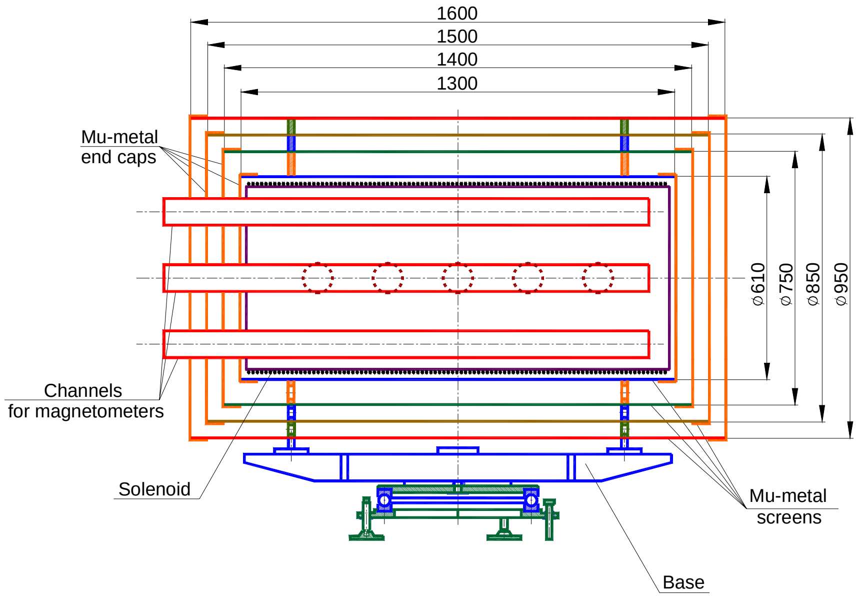
Test experiments for magnetic field stability

(PSI, PNPI, Vavilov Institute, Ioffe Institute, Fribourg)







1. External magnetic field stabilization (factor ~ 20).
2. Magnetic shielding with shaking (factor ~ $5{\cdot}10^3$).
3. Stabilization of resonance conditions with Cs-magnetometers (factor ~ 50).

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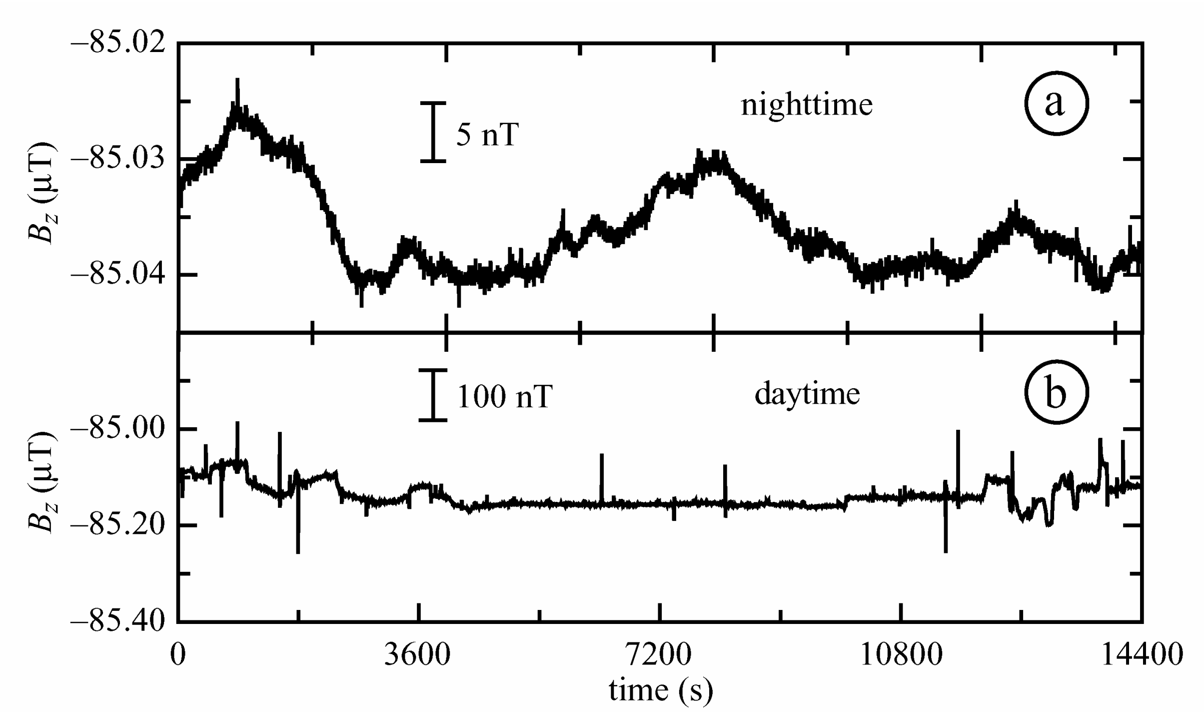
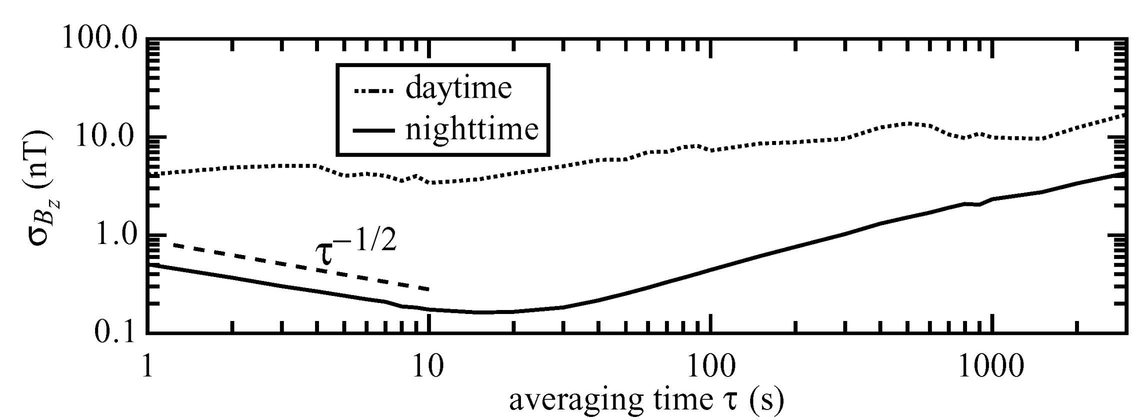
Ambient field at the PSI site of the EDM experiment



$B_z(t)$ at the PSI site during nighttime (a) and daytime (b)



Allan standard deviation of $B_z(t)$ at the PSI site during daytime and nighttime

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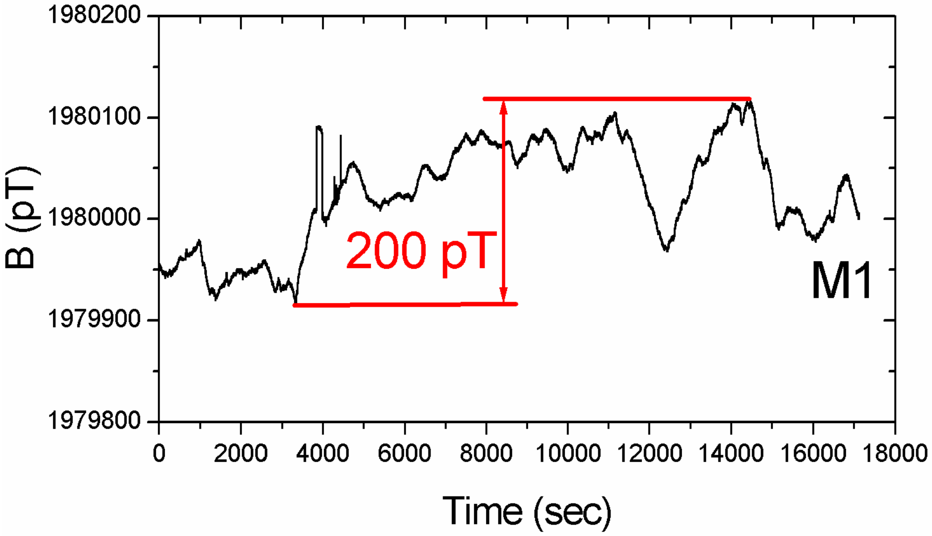
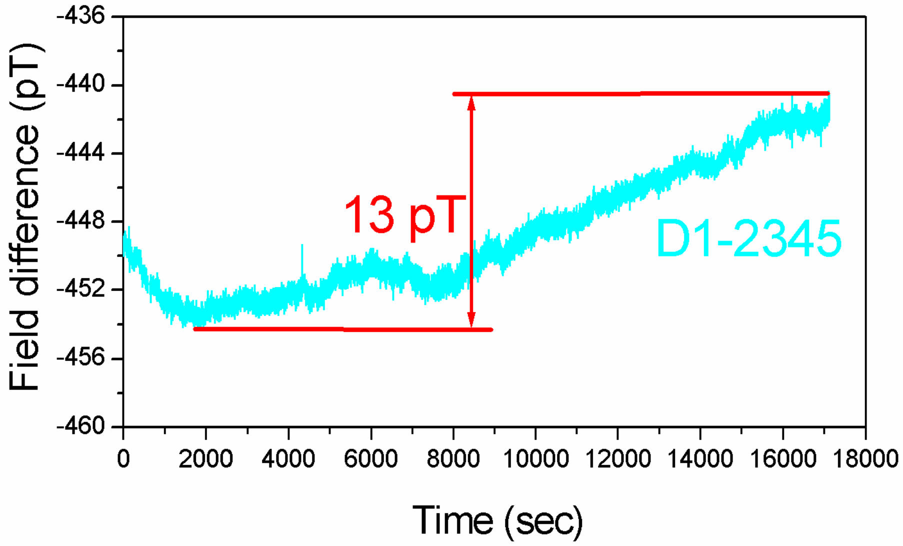
The stability of magnetic field and resonance conditions inside the magnetic shielding



Magnetic field variations in the center of the magnetic shielding (Cs-magnetometer 1)



Stability of resonance conditions (Difference M1-(M2+M3+M4+M5)/4)

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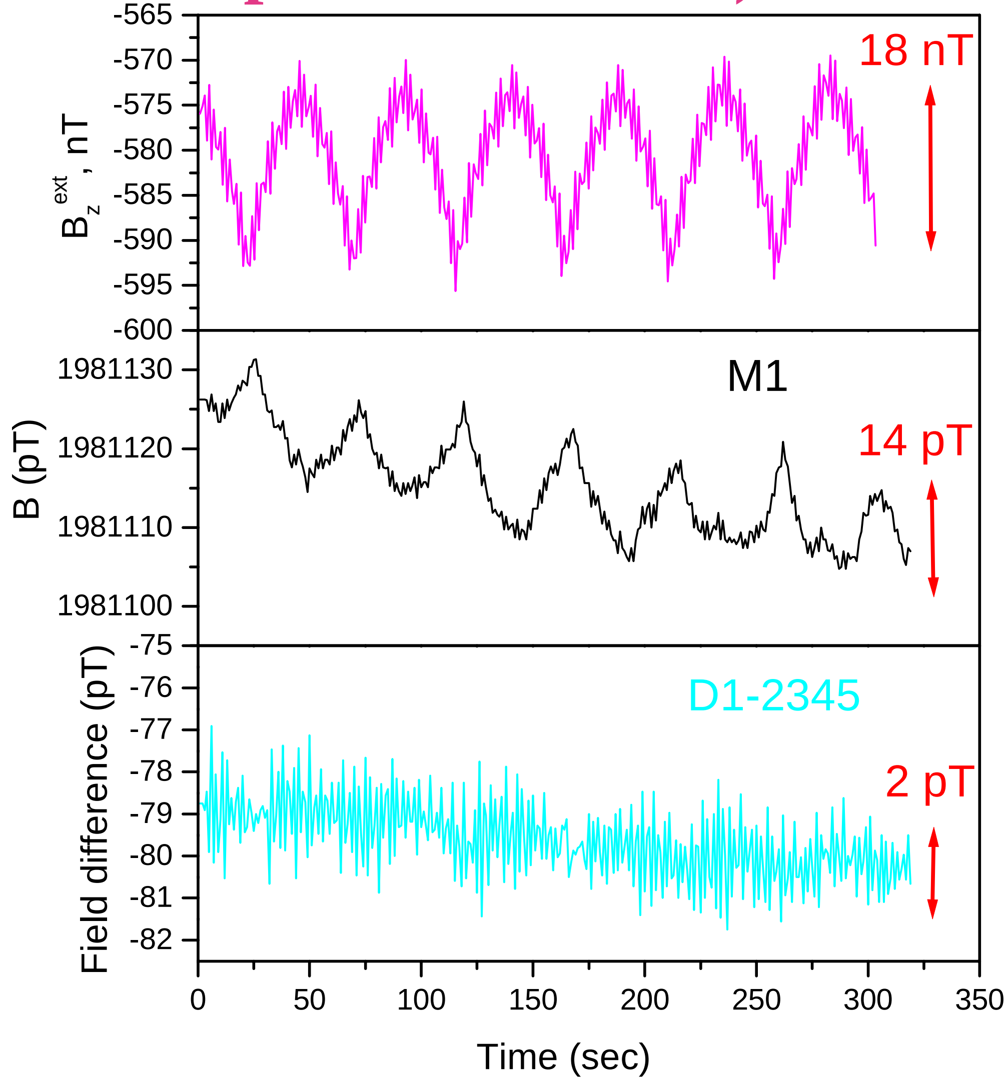
The demonstration of stability of resonance conditions at the big magnetic noise (the operation of the bridge crane in experimental area)



The external magnetic field variation (due to bridge crane motion).

The internal magnetic field variation.

The stability of resonance conditions for EDM experiment.

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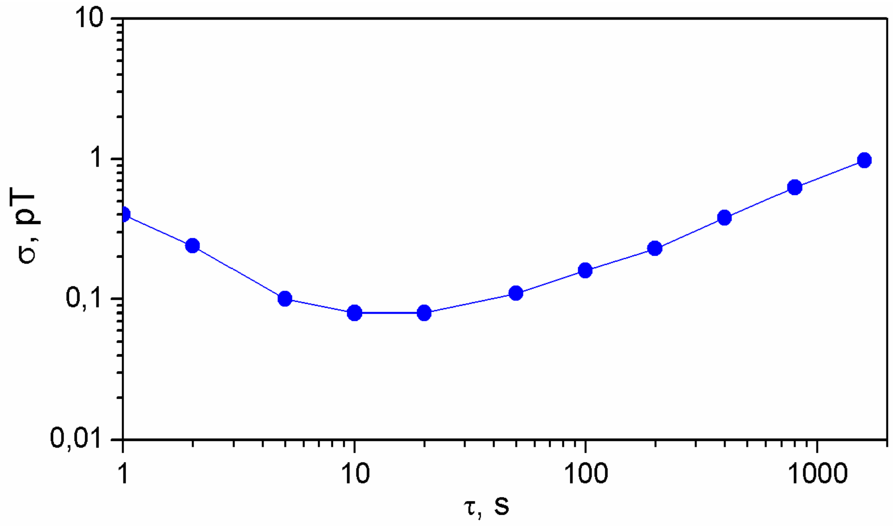
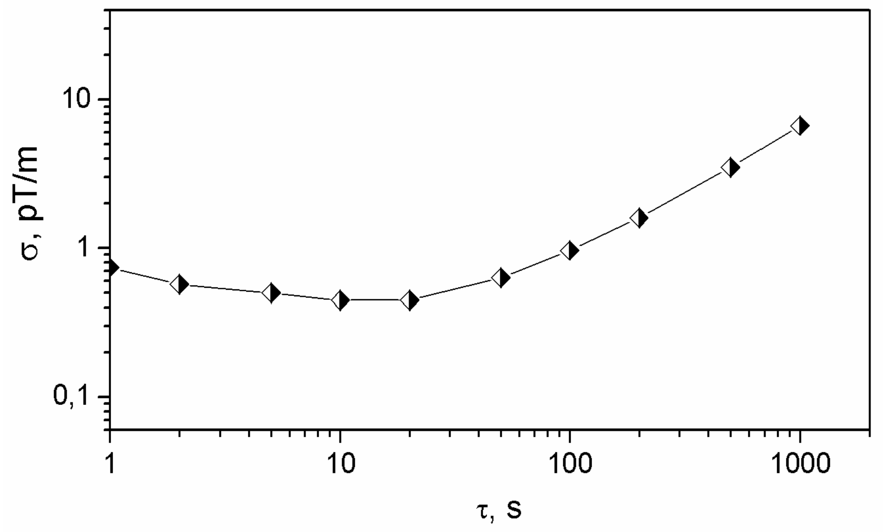
Conclusion from the magnetic test experiment



The stability of resonance conditions is better than 1 pT.



The stability of magnetic field gradient is better than 10 pT/m.

Requirements for mini EDM spectrometer
3.5 pT
35 pT/m

There is no restriction from the side of stability of resonance condition to reach EDM accuracy $5 \cdot 10^{-28}$ e·cm.

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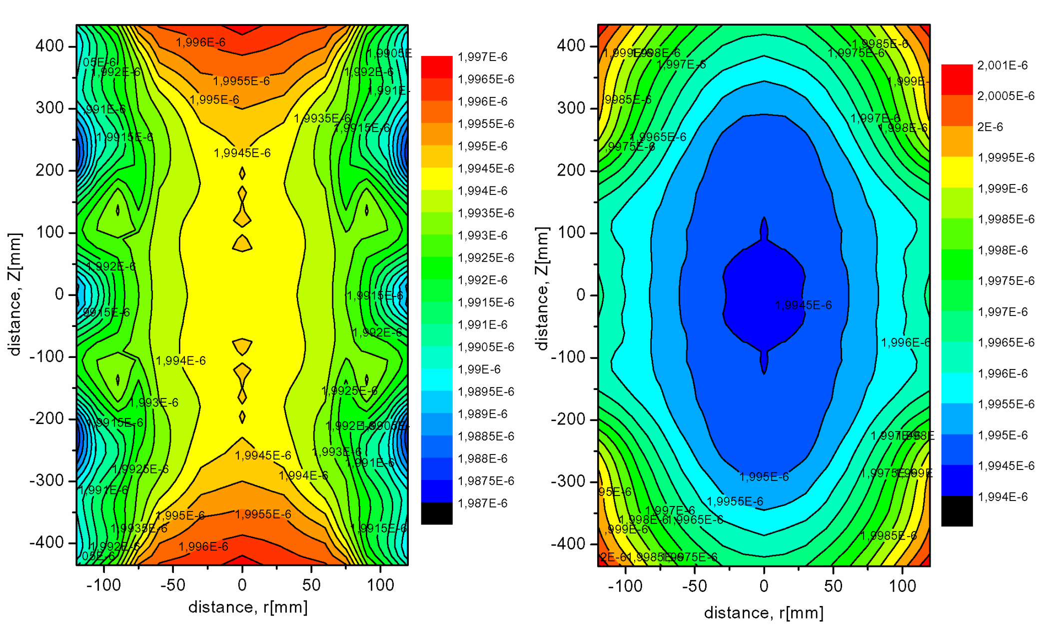
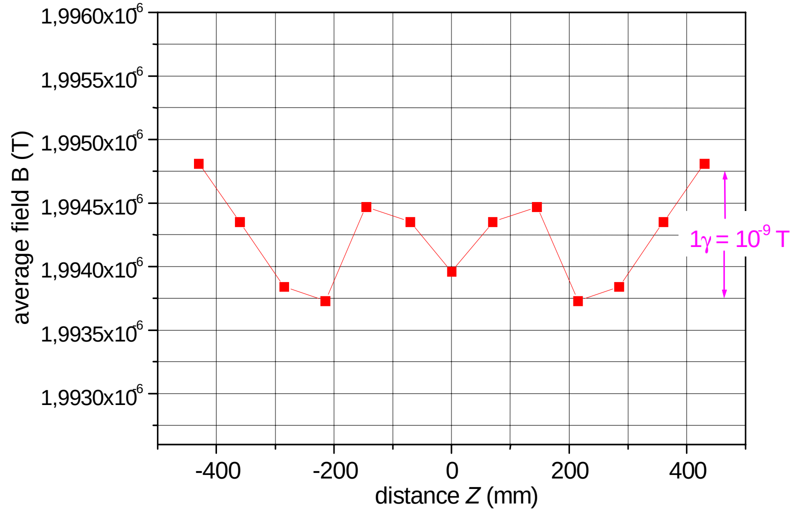
The problem of magnetic field homogeneity in nEDM spectrometer

Calculated magnetic field distributions in the area of storage chamber



Values of the average field in storage chamber



Requirements 0.03÷0.1 nT

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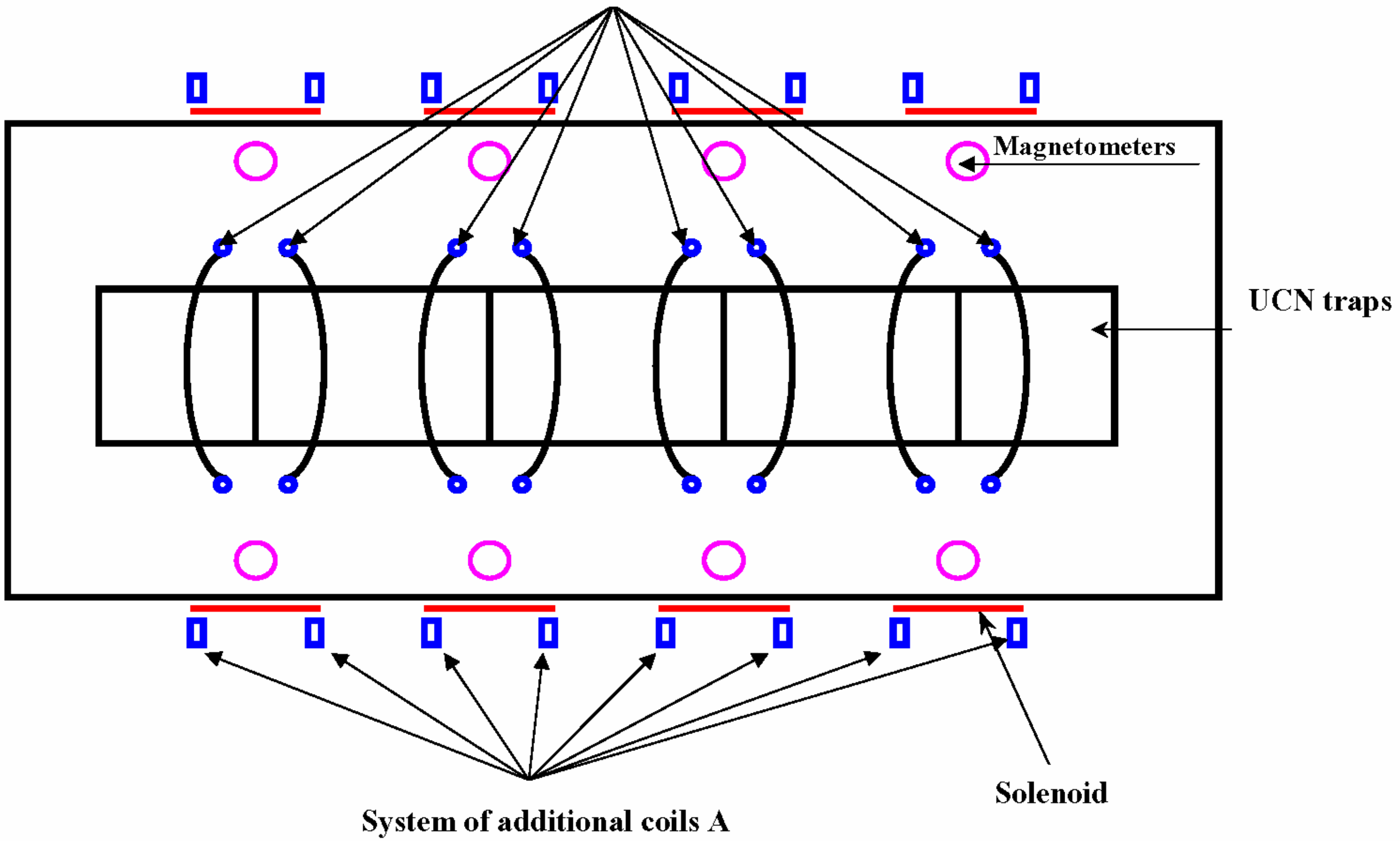
The system of current coils for the fine adjusting of magnetic field homogeneity



Task of experimental test 2003.

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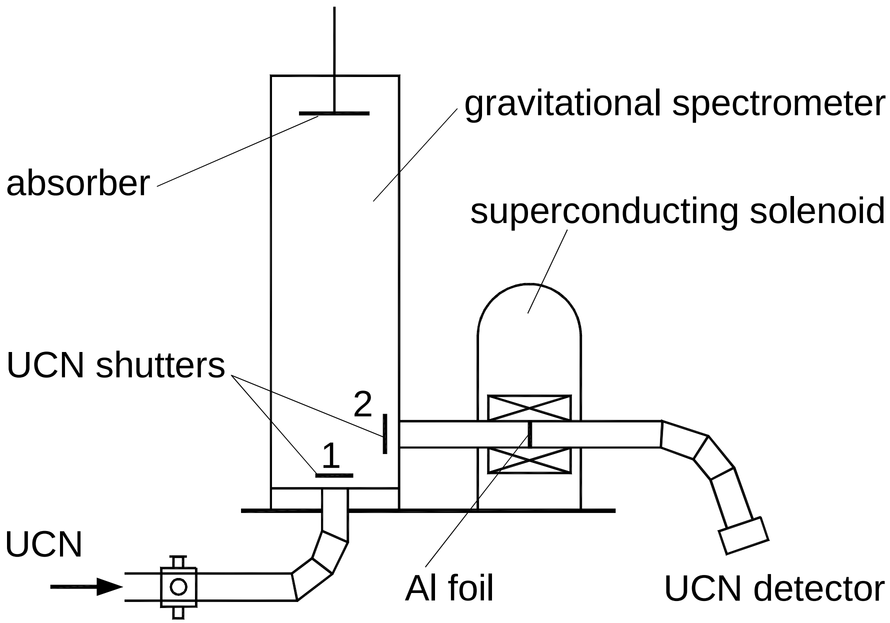
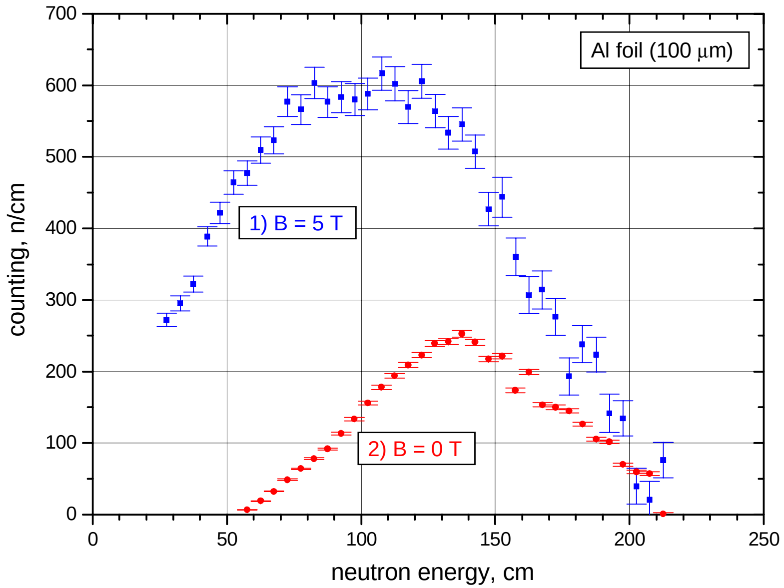
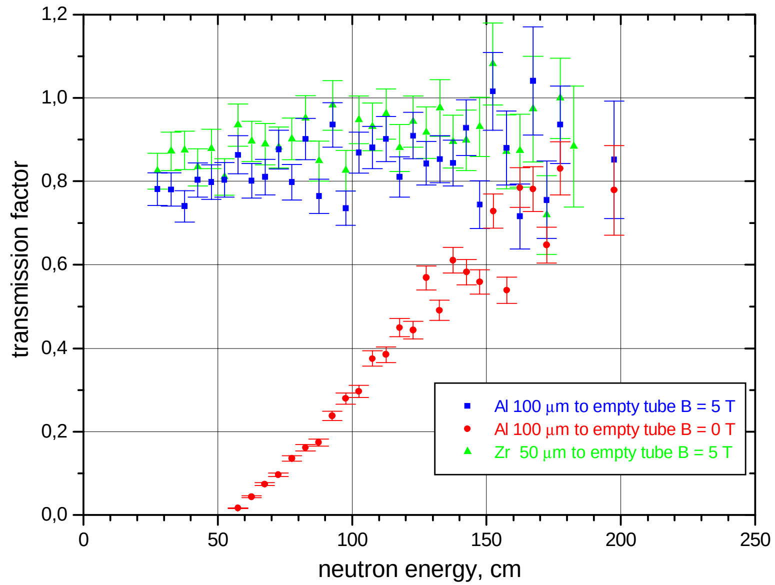
UCN polarization test experiment with superconducting solenoid (PNPI, ILL)







Advantages:

- 100% UCN polarization,
- increasing of useable UCN intensity in the factor of 3.8.

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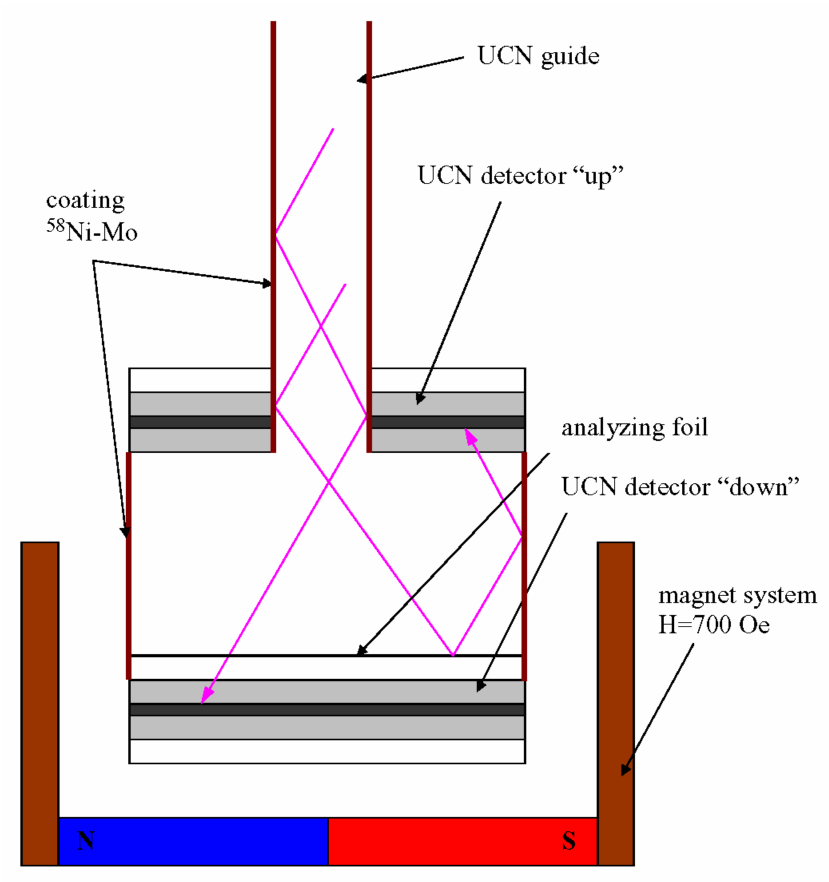
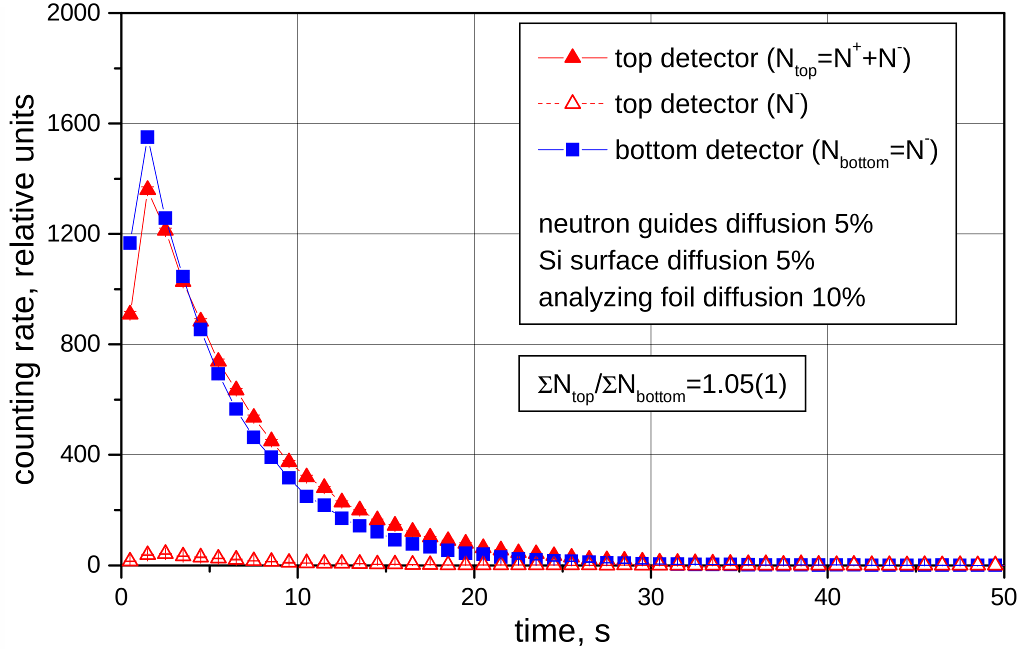
UCN detector for polarization analysis

Test experiment in 2003, preliminary preparations in 2002.
(Caen, Heidelberg, PNPI, PSI)

Scheme of the UCN detector for the polarization analysis



The process of a simultaneous detection of both spin components



Two different type of UCN detectors: semiconductor detector and CASCADE detector will be tested at ILL in 2003.

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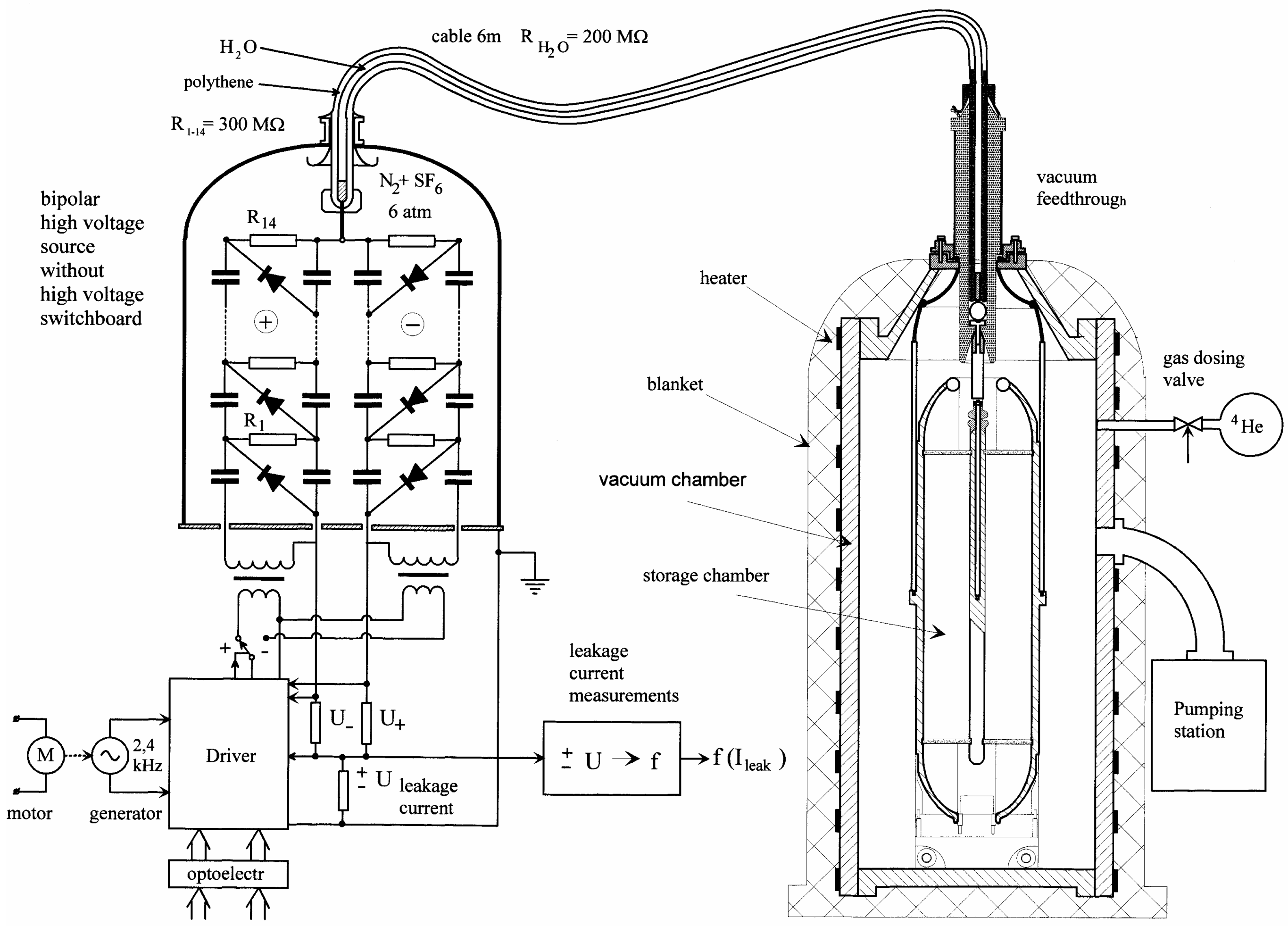
The electric field in the EDM spectrometer

Test experiment in 2003, preliminary preparations in 2002.
(PNPI, PSI …)



Glass-ceramics with $\rho \approx 10^{13}$ Ohm·m

Task: maximum electric field strength ~ 20 kV/cm

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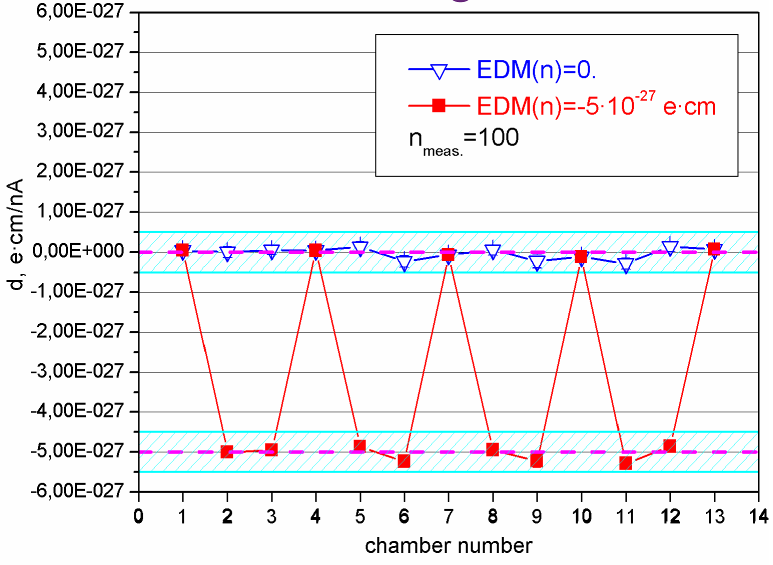
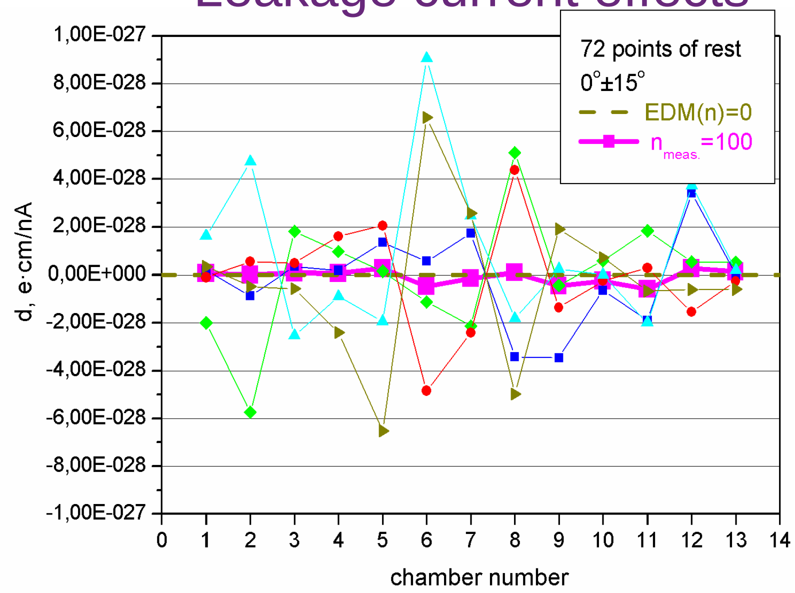
nEDM signature

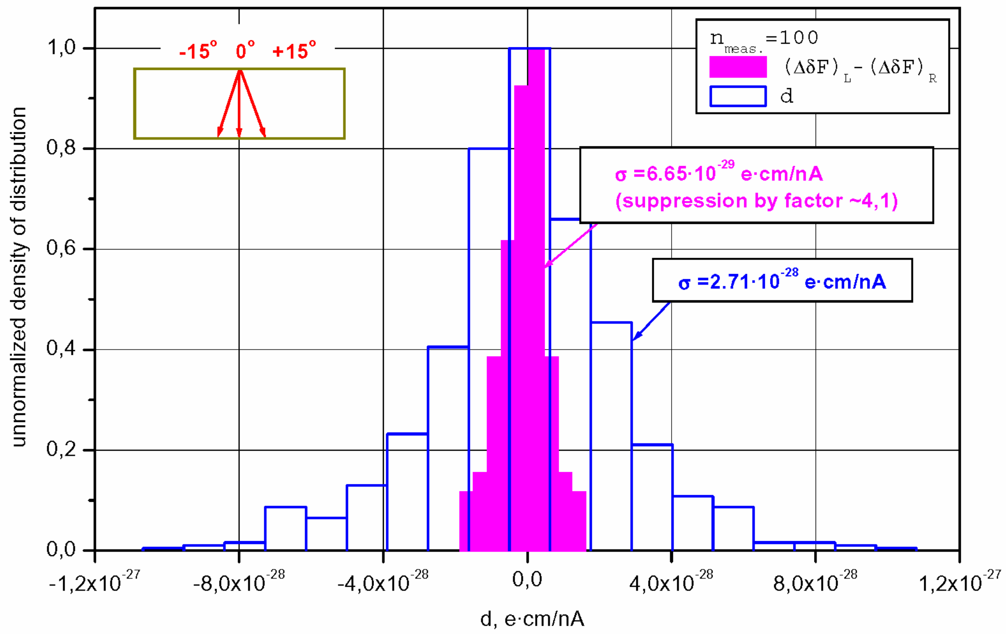


Leakage current effects



The neutron EDM signal and systematic effects due to leakage currents

Suppression of leakage current effect in multichamber spectrometer



The allowed leakage current is 10 nA/chamber.

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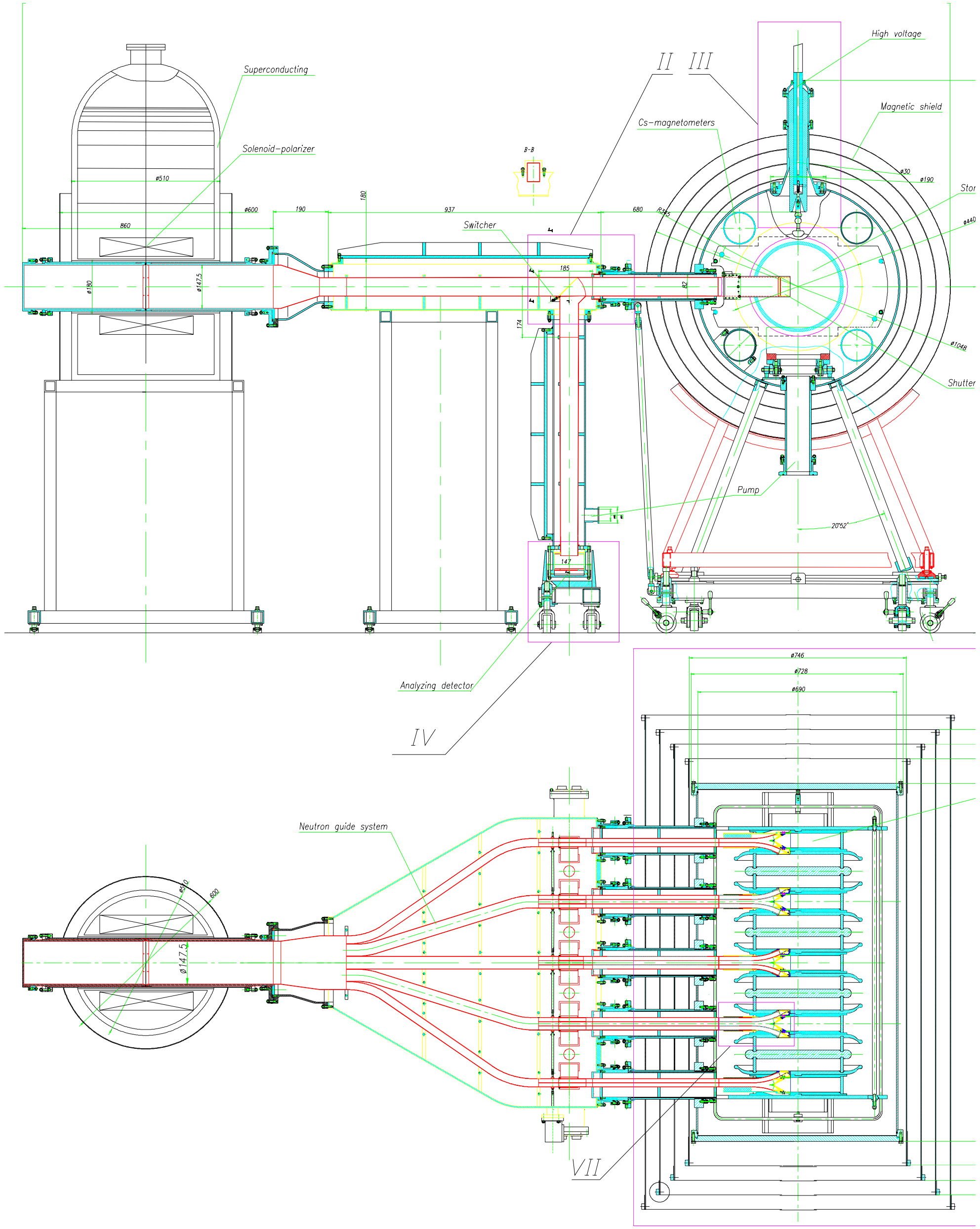
The estimation of systematic effects

1. Quadratic $\vec{v} \times \vec{E}$ effect < $2 \cdot 10^{-28}$ e·cm for one chamber if electric field values for the two polarities differ less than 10%. This effect is cancelled due to double chamber.
2. Non-parallelism of the magnetic and the electric field.
   << $2 \cdot 10^{-28}$ e·cm
3. Ordered motion effect.
   < $2 \cdot 10^{-28}$ e·cm
4. UCN depolarization during spin precession.

nEDM collaboration

Realization of the new EDM experiment

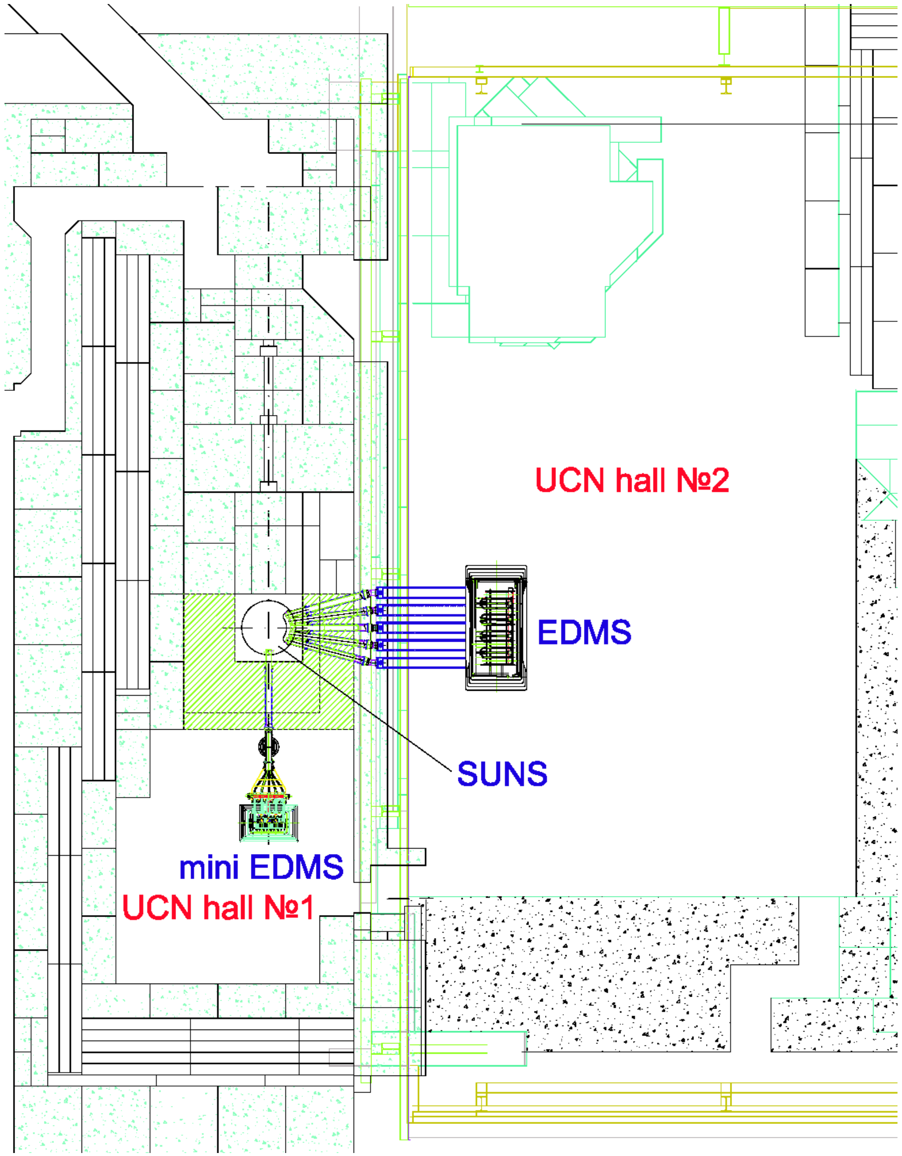


First step: mini EDM spectrometer at ILL

- Construction of the mini EDM spectrometer (2003-2004)
- Test of the spectrometer at ILL with the aim to obtain a new experimental result $\delta d_n \sim 1 \cdot 10^{-26}$ e·cm (2004-2005)

A. Serebrov, PSI Report 2002

Realization of the new EDM experiment



Second step: mini EDM spectrometer at PSI SUNS

- Installation of the mini EDM spectrometer in the small hall of SUNS with the aim to measure d_n with $\delta d_n \sim 1 \cdot 10^{-27}$ e·cm (2006-2007)

Third step: final EDM spectrometer at PSI SUNS

- Manufacturing of the main EDM spectrometer (2007-2008)
- Installation of the main spectrometer in the large hall of SUNS, measuring of d_n with $\delta d_n \sim 2 \cdot 10^{-28}$ e·cm (2008-2010)

A. Serebrov, PSI Report 2002

Cost estimate

The estimated cost of the mini EDM project is 1'810 ksFr.

item	[ksFr]
DAQ system	50
superconducting solenoid	200
vacuum parts	100
vacuum chambers, support	200
UCN traps in EDM (R&D) UCN traps in EDM	125 125
UCN guides	100
HV system	200
Magnetometers	100
Electronics	60
UCN detectors + housing	250
magnetic shielding	100
infrastructure	200
Sum	**1'810**

Contribution of PSI ~ 30%.
Contribution of PNPI ~ 20%.
Contributions of other institutes
~ 10% or less / institute.

A. Serebrov, PSI Report 2002