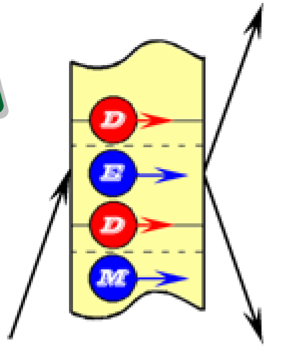
Status of the crystal-diffraction neutron EDM experiment



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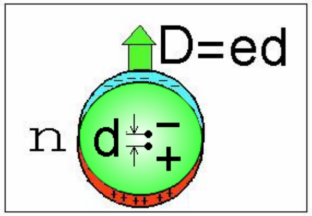
Outlook

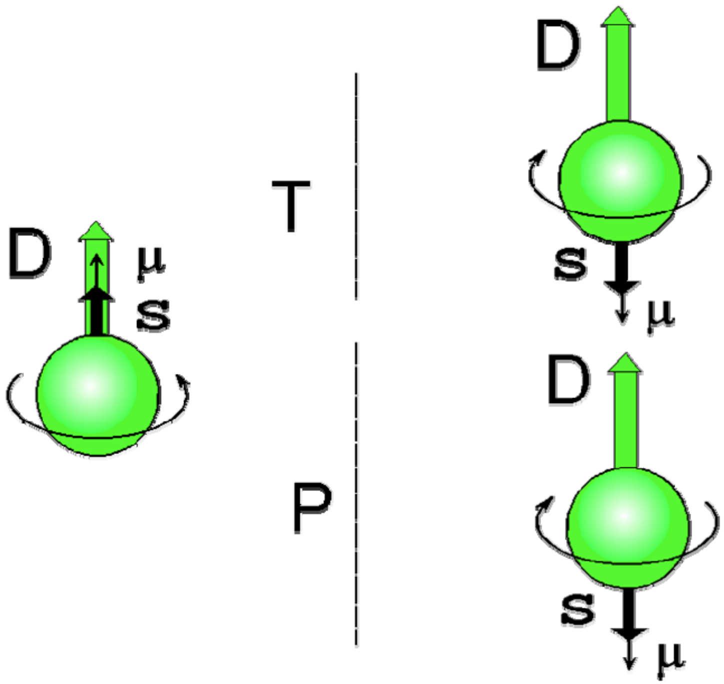
1. Introduction
2. Test experiment (ILL-3-07-196)
3. Full scale experiment
4. Conclusion

Neutron EDM



Non zero EDM means the P and T violation

P – spatial inversion
C – particle – antiparticle inversion
T – time inversion



CPT theorem
(Lüders (1954); Pauli(1955))
(Our world is CPT invariant)

Non zero nEDM means CP violation

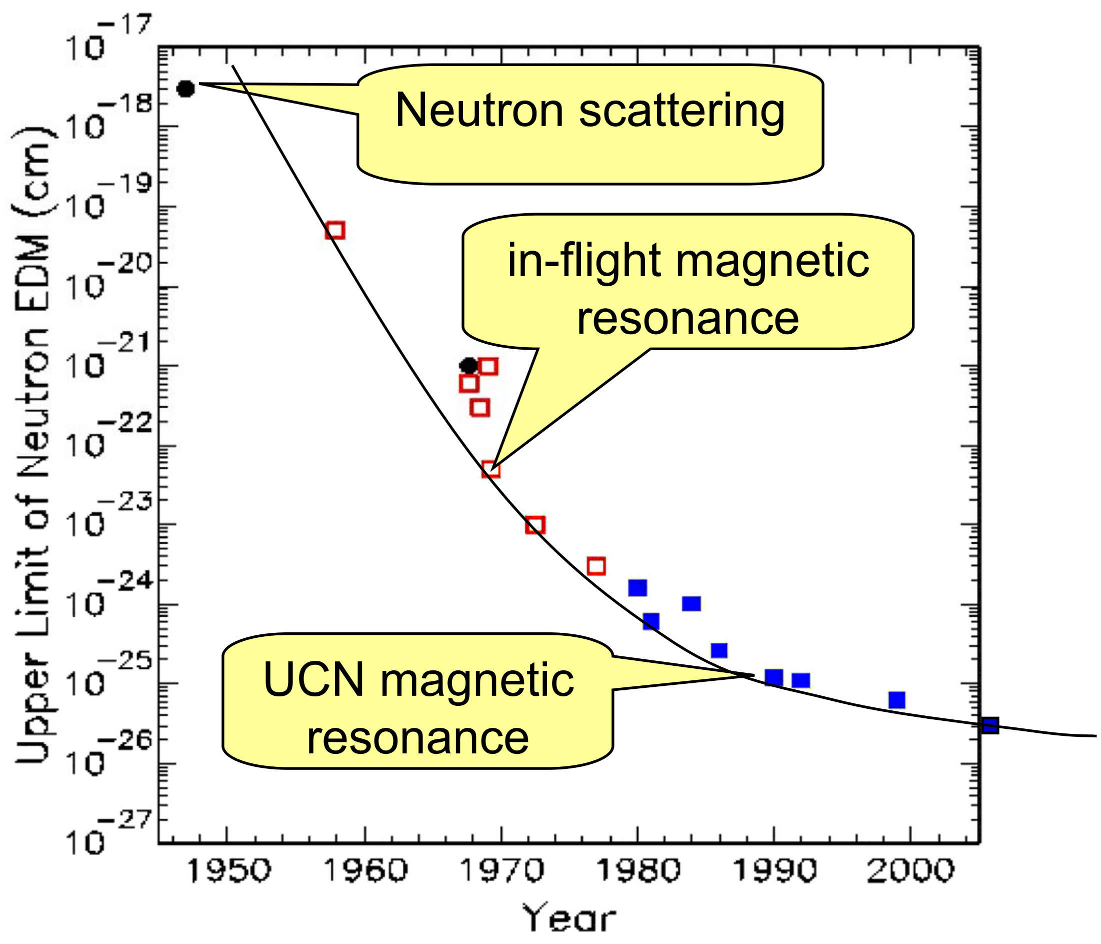
History of nEDM experiment

Standard model

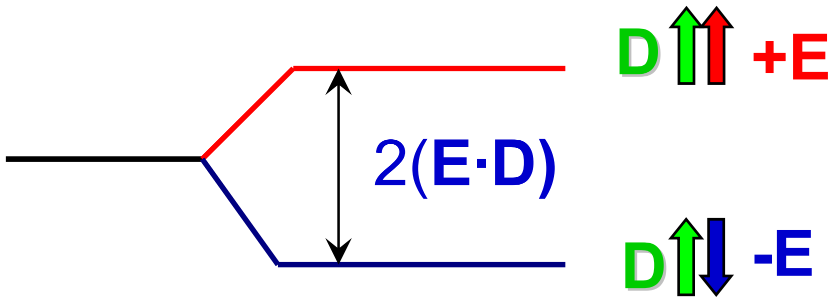
$d_n \sim (10^{-31} - 10^{-33})$ e cm

New physics to explain the baryon asymmetry (experiment - $n_b/n_\gamma \sim 10^{-11}$ SM - $n_b/n_\gamma \sim 10^{-21}$)

$d_n \sim (10^{-25} - 10^{-30})$ e cm



Idea nEDM experiment

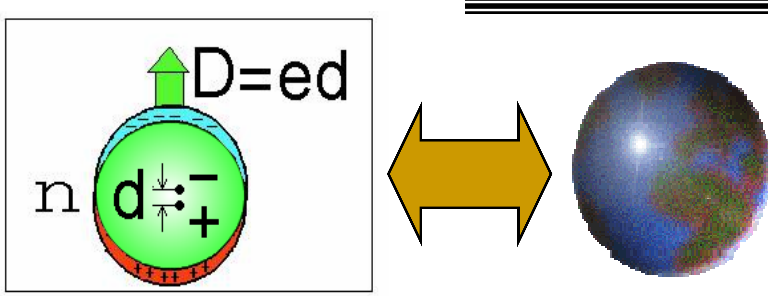


Interaction time with **E**

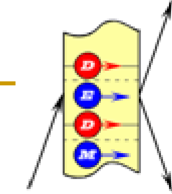
$$\varphi_D = 2(\mathbf{E}\cdot\mathbf{D})\tau / \hbar$$

Sensitivity to nEDM ⇒ $\sigma^{-1} \sim E\tau\sqrt{N}$

Current accuracy to d_n



Neutron size $R_n \sim 10^{-13}$ cm,
$d_n/R_n \sim 3\cdot 10^{-13}$.
Corresponding size from Earth is
~ 2 μm



Sensitivity to neutron EDM

$$\sigma^{-1} \sim E\tau\sqrt{N}$$

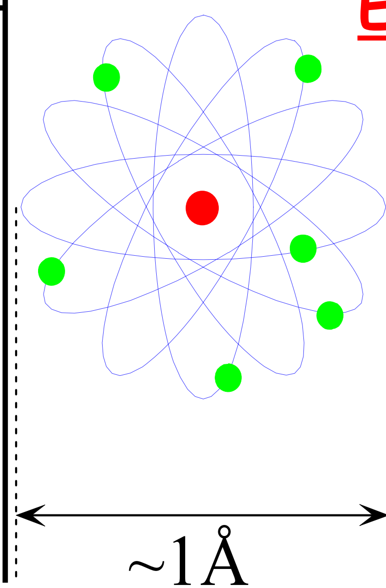
UCN method

E ~ 10 kV/cm
τ ~ 1000s (time of life)
$E\tau \sim 10^7 (V \cdot s)/cm$
Now
$E\tau \approx 10^6$ (V·s)/cm

Crystal-diffraction method

Electron separation energy ~ a few eV

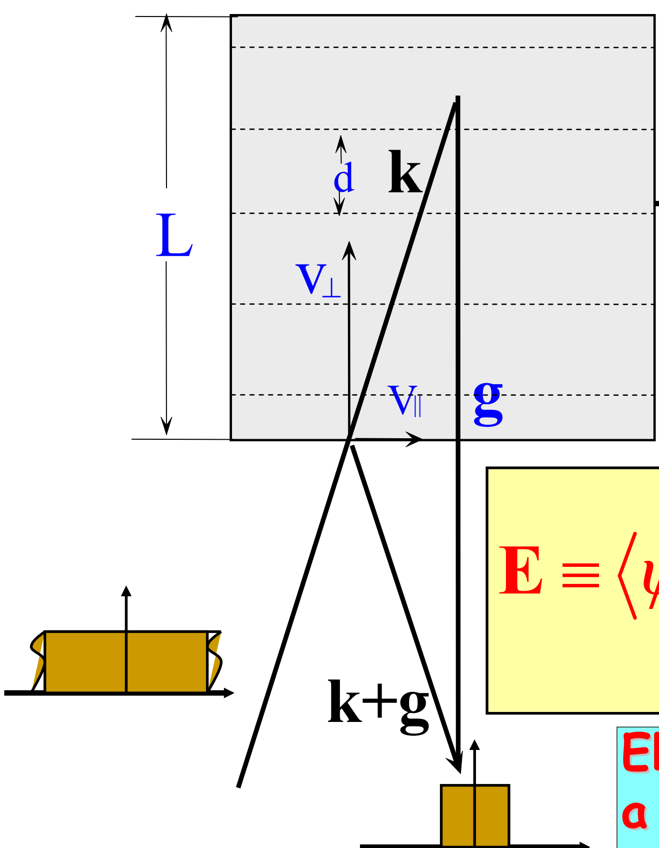
E~ grad V_e ~(0.1-1)GV/cm

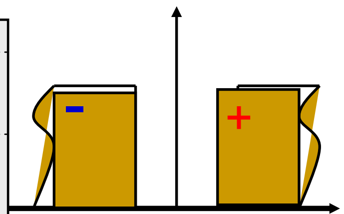


τ_a ~ 0.01 c
(absorption)

$E\tau$
↓
$10^7 (V \cdot s)/cm$

Neutron optic of NCS crystal





Wave function

$$\psi(\mathbf{r}) = e^{i(\mathbf{kr})}\left(1 + \frac{V_g}{E_K - E_{K_g}} e^{i(\mathbf{gr})}\right)$$

Deviation from Bragg condition

Electric field

$$\mathbf{E} \equiv \langle \psi(\mathbf{r}) | E(\mathbf{r}) | \psi(\mathbf{r}) \rangle = \frac{2|V_g|}{E_K - E_{K_g}} \cdot \mathbf{E_g}$$

Electric field depends on a deviation from Bragg condition

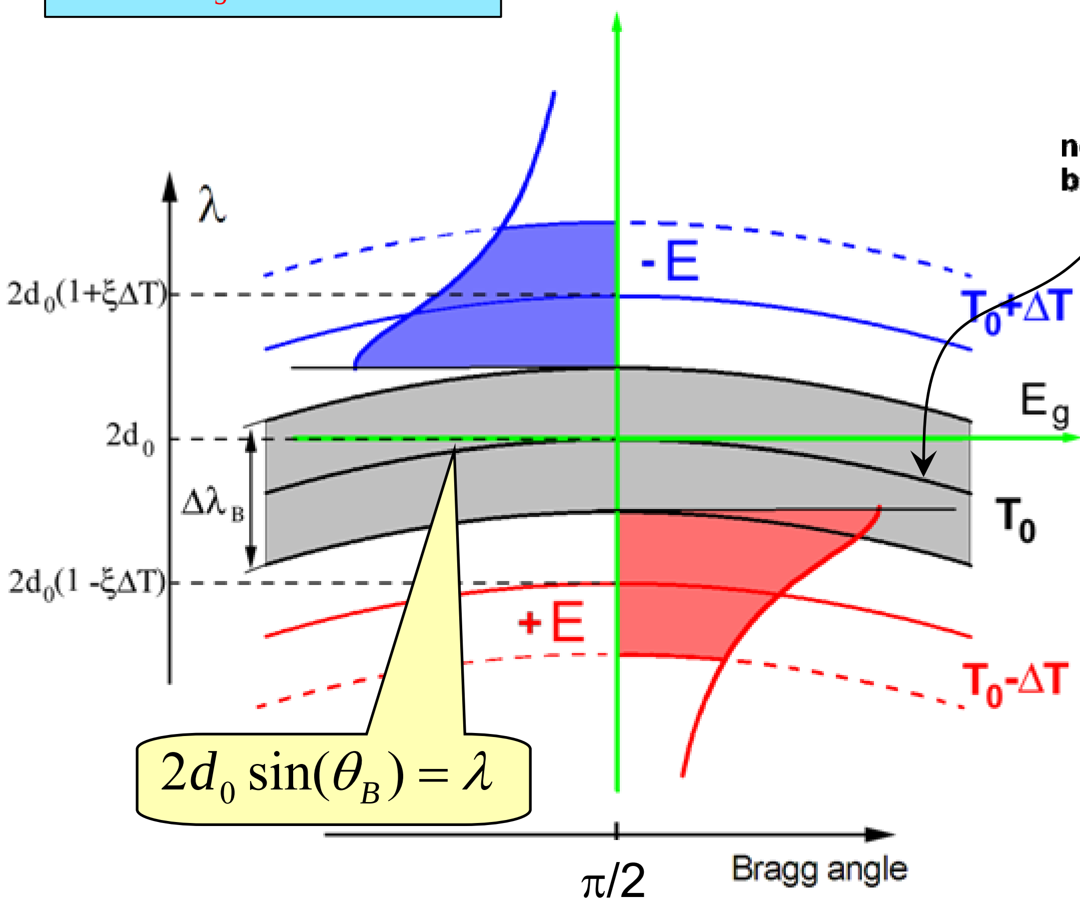
E(Neutron energy)

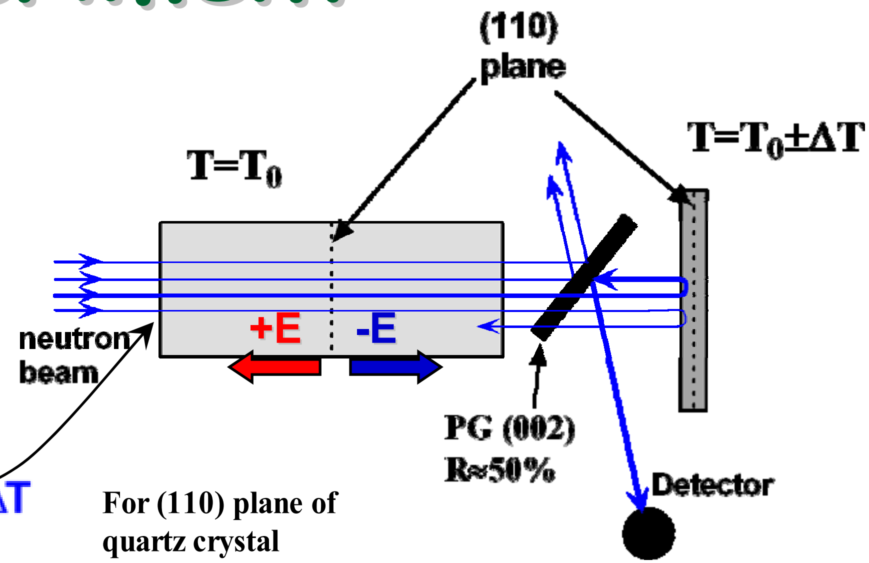
M. Forte, J. Phys. G: Nucl. Phys. (1983) 745-754.

- V. G. Baryshevskii and S. V. Cherepitsa, Phys. Stat. Sol. B128 (1985) 379-387.
- V. V. Fedorov, Proc. of XXVI Winter LNPI School, vol. 1, Leningrad (1991) 65.

Idea of the experiment

$$\frac{2v_g^N}{E_K - E_{K_g}} \sim (0.5 \div 0.3)$$





For (110) plane of quartz crystal

$\Delta T = 1^0 K$

$\Delta\lambda/\lambda \approx 10^{-5} = \Delta\lambda_B/\lambda$

For $\pi/2$ reflection

$E \parallel v_n$ and

$H_s \sim [E \times v_n] \approx 0$

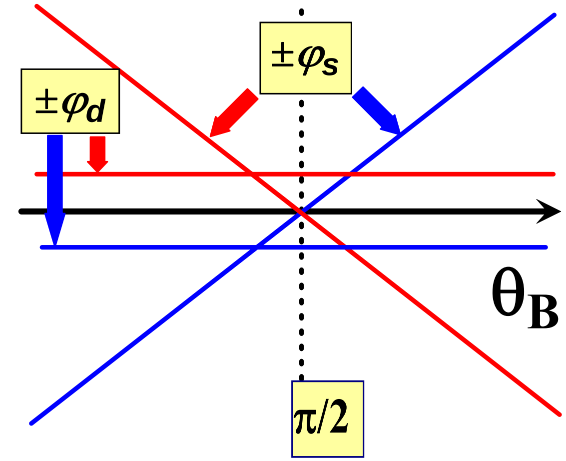
PNPI

π/2 reflection → "zero" Schwinger

EDM effect doesn't depend on a Bragg angle

$$\varphi_d = \frac{\mathbf{E}\cdot d_n \cdot L}{\hbar v_\perp}$$

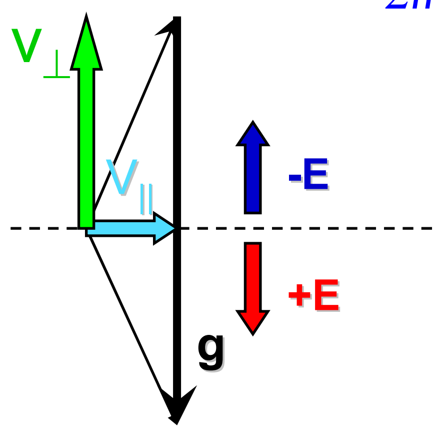
$$v_\perp = \frac{\hbar g}{2m} \equiv const$$



For π/2 reflection

E || v_n and

H_s~[E x v_n]≈0



Schwinger effect can be decreased down to zero for the Bragg angle close to π/2

$$\varphi_s = \frac{\mathbf{E}\cdot v_{\parallel}\cdot \mu \cdot L}{c\hbar v_\perp} = \frac{\mathbf{E}\cdot \mu \cdot L}{c\hbar} ctg(\theta_B) \xrightarrow[\theta_B \to \pi/2]{} 0$$

Summary of the DEDM project (ILL seminar 30 Jan. 2006)

- Possibility to control value and sign of the electric field.
- "Zero" Schwinger effect.
- Possibility to control and suppress the systematic.
- Low influence of crystal quality. (For $\omega_m \gg \Delta\theta$ the effects ~ $\Delta\theta / \omega_m$. Intensity ~ ω_m). ⇨ New kinds of NSC crystals
- One can increase the effect by using a series of crystals

For quartz crystal, 100 day ⇨

$$\sigma_d \sim 1.3 \cdot 10^{-26}\ e \cdot cm$$

Test experiment (ILL-3-07-196) (2006)

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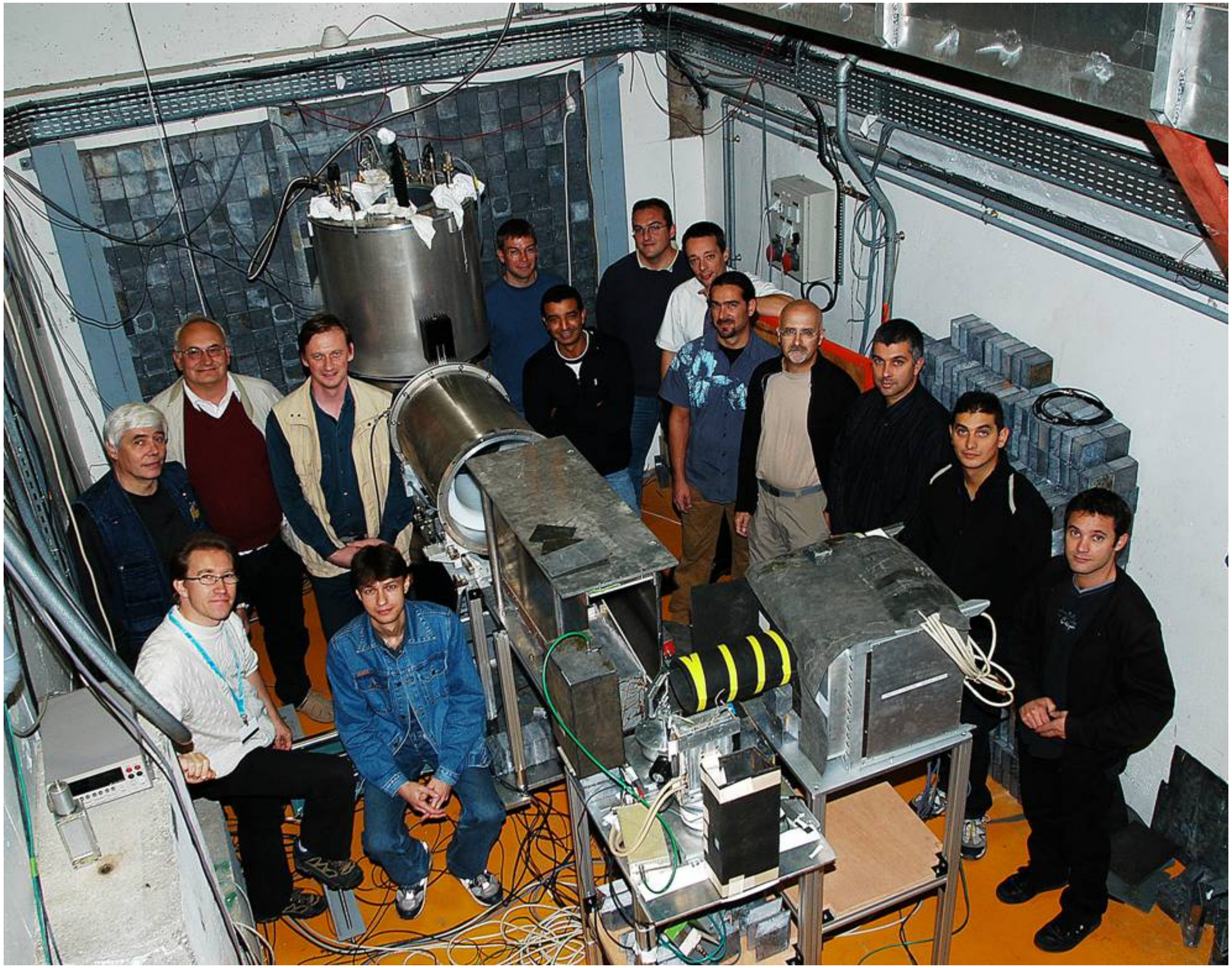
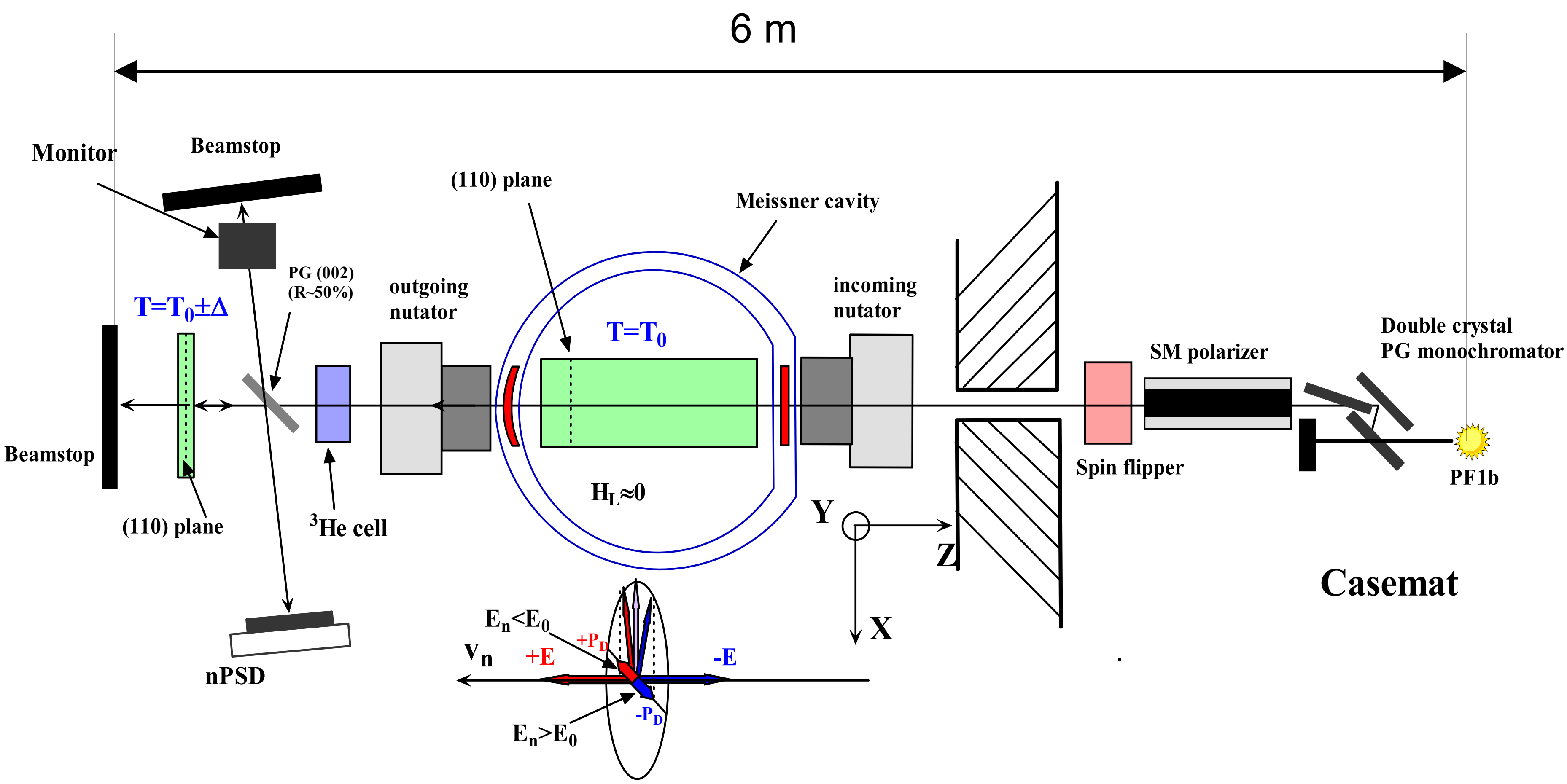
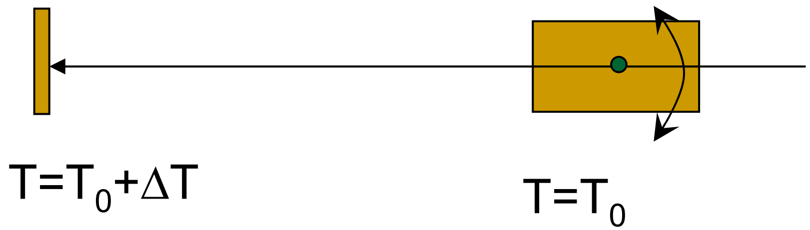
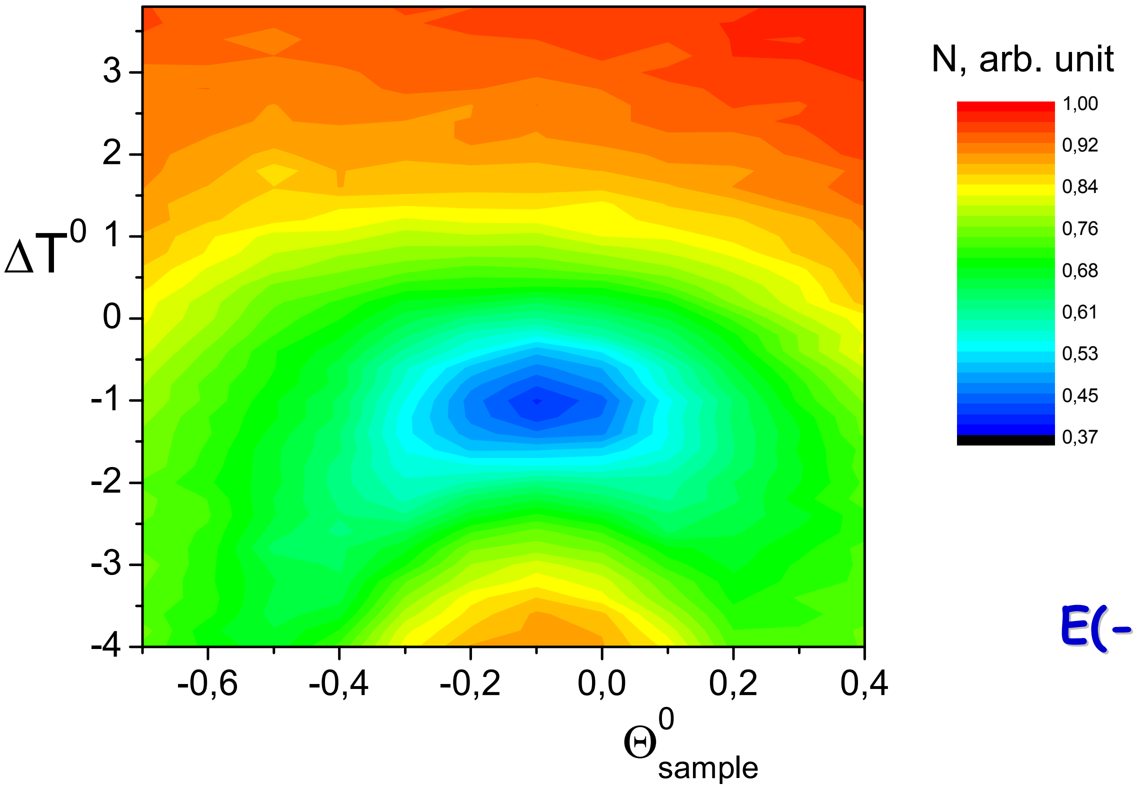


Layout of the experiment

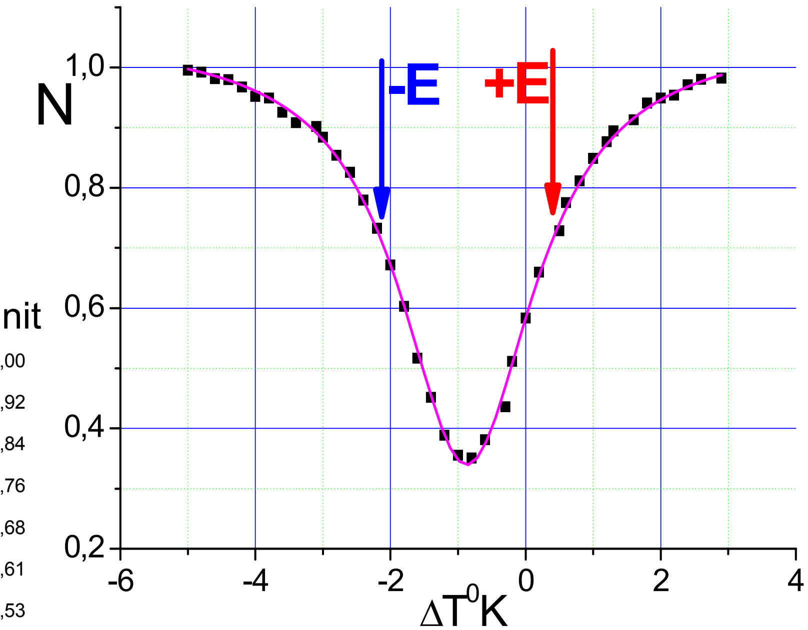


Two crystal line





$X_c = (-0.87 \pm 0.01)^0K$
$W = (2.42 \pm 0.03)\ ^0K$

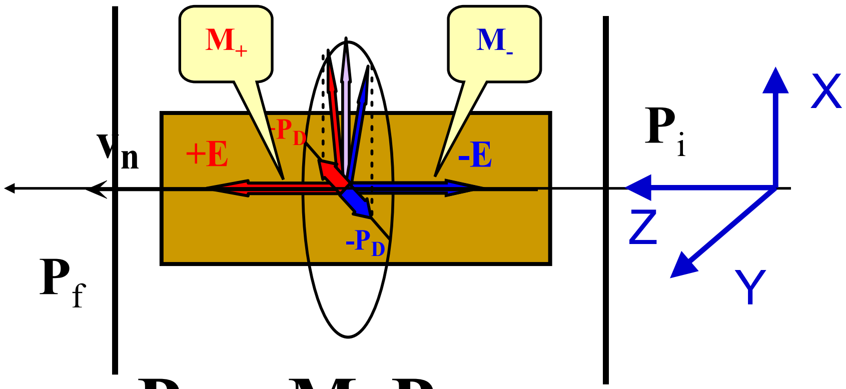


$\Delta T_- = -2.0^0K$ $\Delta T_+ = +0.4^0K$

$E(-) = -0.7\cdot10^8$ V/cm

$E(+) = +0.7\cdot10^8$ V/cm

3-D spin analysis



$\tau_{\pm}$ ⇐ time of the neutron stay in the crystal for ± E

$$\Delta\tau = (\tau_{+} - \tau_{-})/2 \qquad \tau_0 = (\tau_{+} + \tau_{-})/2$$

$$\mathbf{P}_f = \mathbf{M}_{\pm}\mathbf{P}_i$$

$$\mathbf{M}_{+} - \mathbf{M}_{-} \equiv \Delta\mathbf{M} = g_n\tau_0 \left[\begin{pmatrix} 0 & -H_d & 0 \\ H_d & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & H_{sy} \\ 0 & 0 & -H_{sx} \\ -H_{sy} & H_{sx} & 0 \end{pmatrix} + \Delta\tau/\tau_0 \begin{pmatrix} 0 & -H_z & H_y \\ H_z & 0 & -H_x \\ -H_y & H_x & 0 \end{pmatrix} \right]$$

EDM | **Schwinger** | **Residual magnetic field**

$$g_n = 1.8\cdot 10^4 \ \ [1/Gs/s]$$

$H_d = (E\, d_n)/\mu_n \approx$

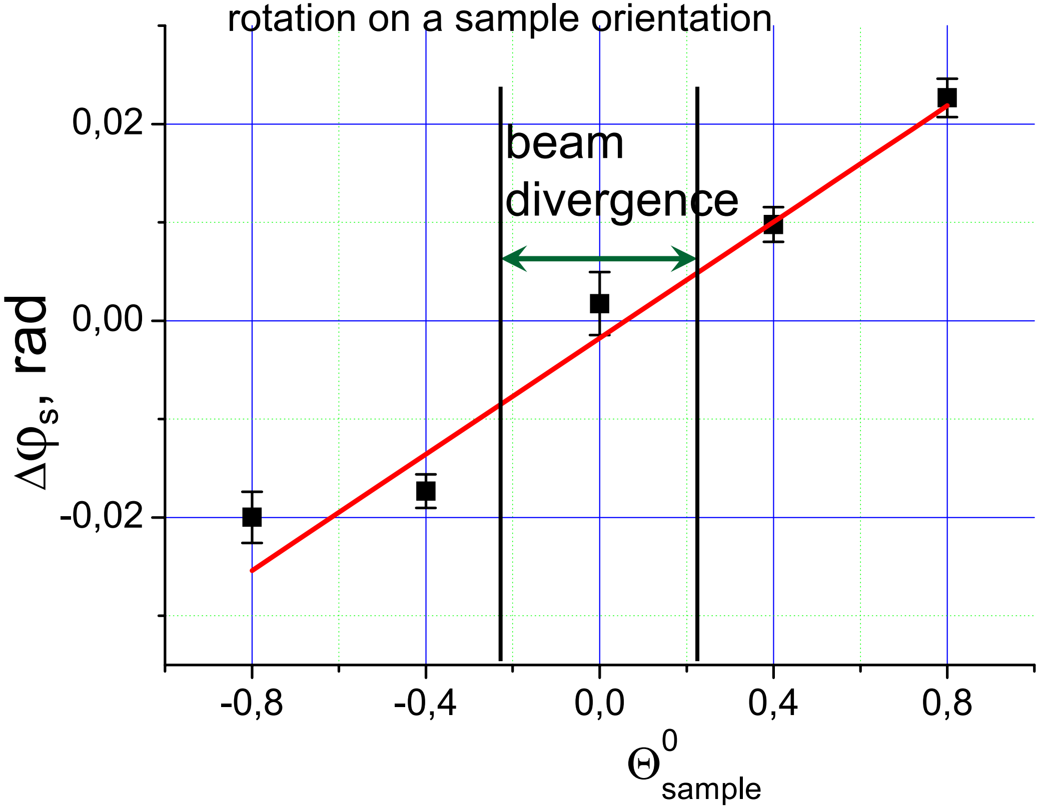
$\approx 1.6\ 10^{19}\ E\ d_n [e\cdot cm]$

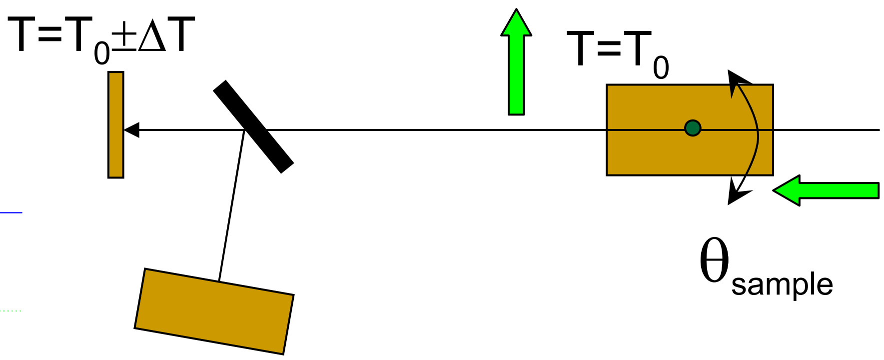
$H_s = 0.9\ E\ \tilde{\theta}$

$E\ [10^8\ V/cm]$

Measurement of Schwinger effect

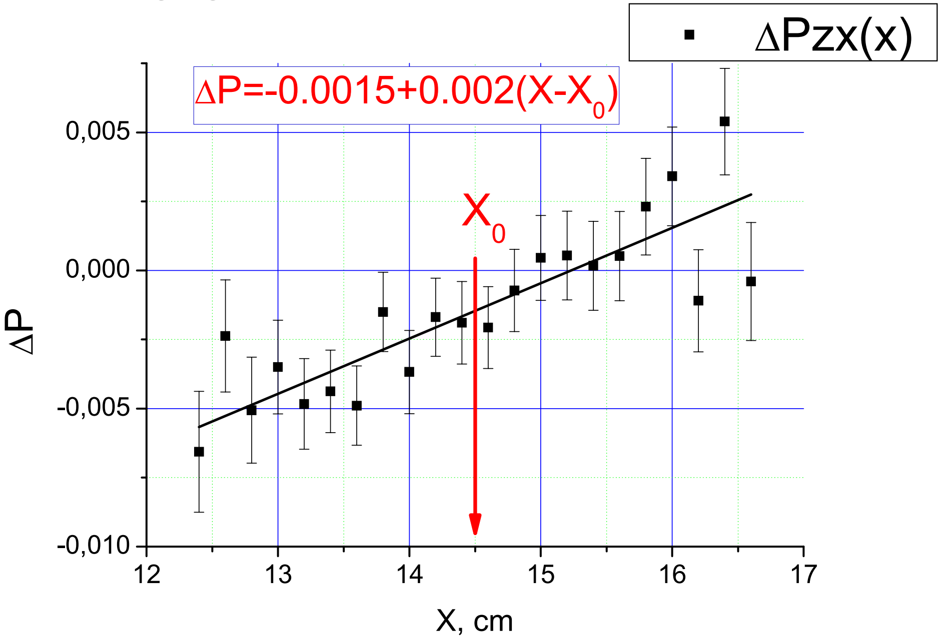
The dependence of angular of neutron spin rotation on a sample orientation

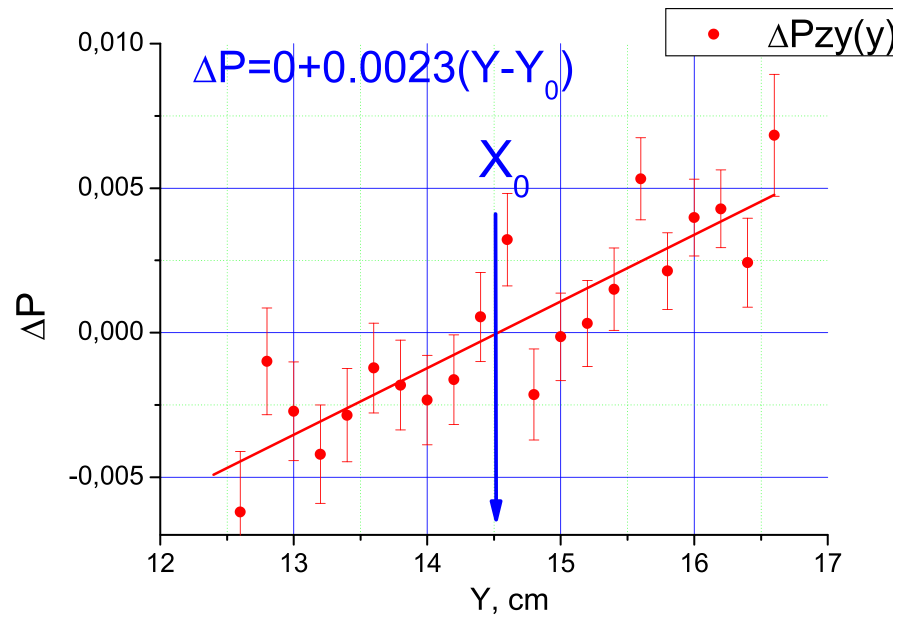


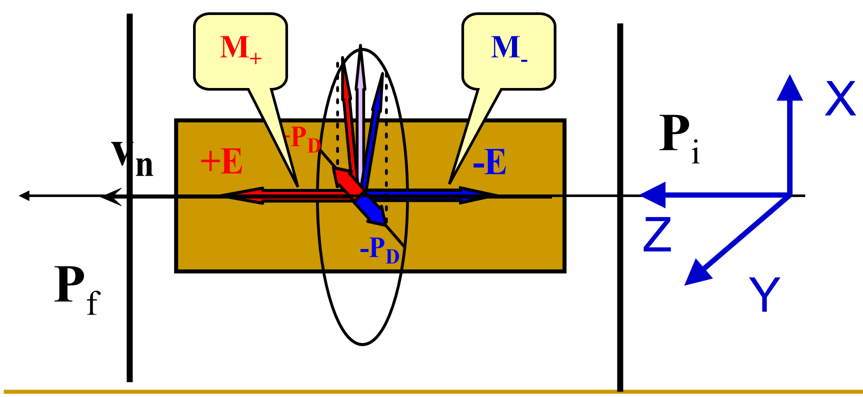


1. **Schwinger effect is zero for $\theta_B=90^0$**
2. **E~ (0.7±0.1) 10^8 V/cm**

Spatial distribution of Schwinger effect



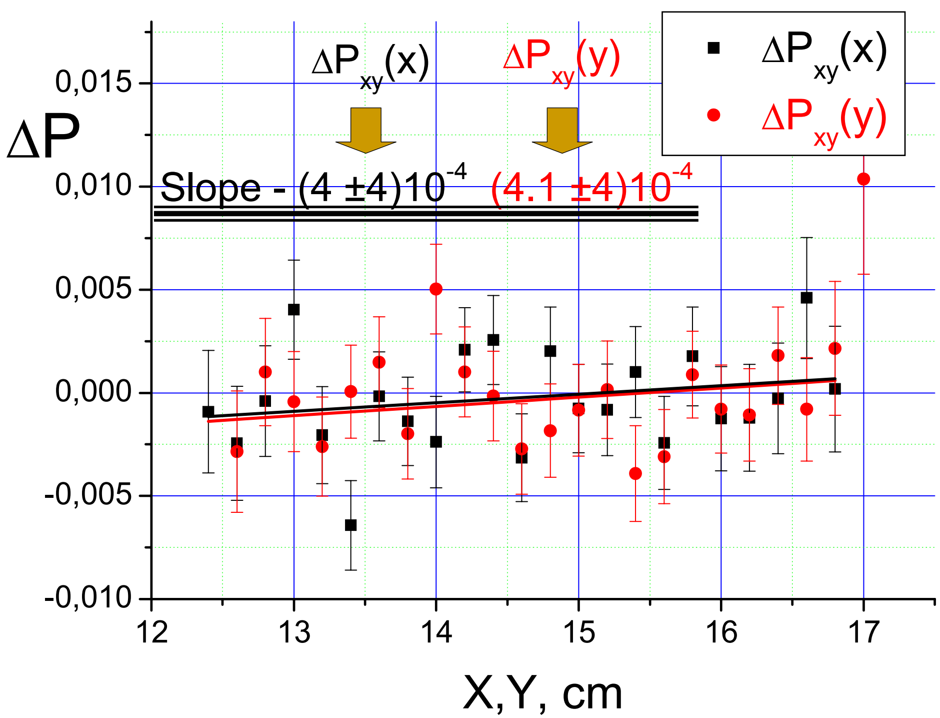


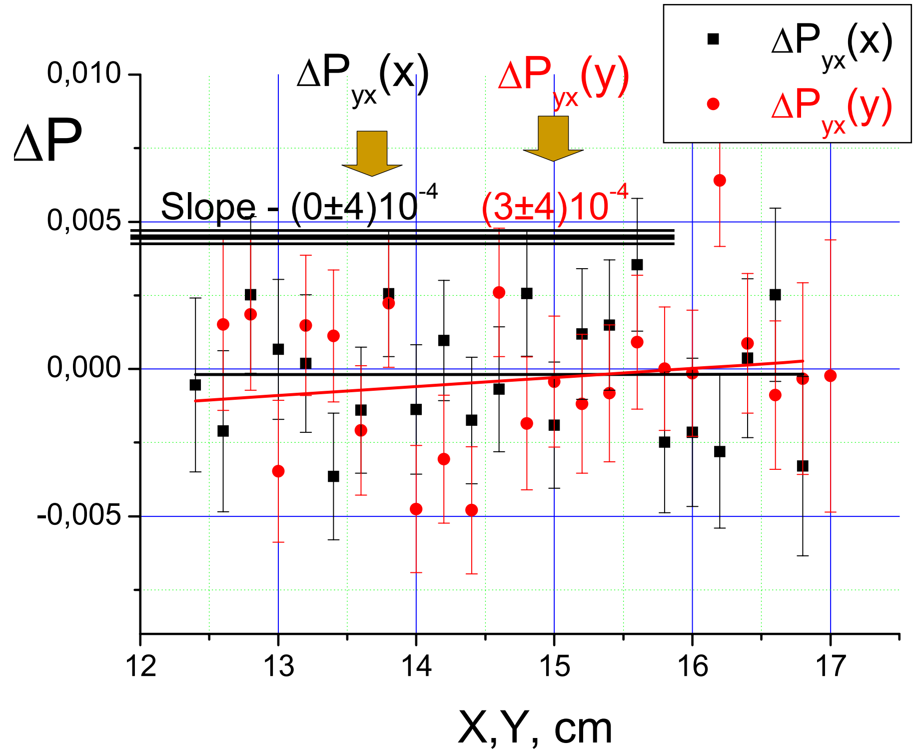


$$\Delta P = P(\Delta T_{+}) - P(\Delta T_{-})$$

We should observe the same dependence for Pxy and Pyx components responsible for nEDM

nEDM effect spatial distribution





Schwinger $\Delta P_s < 1.1\ 10^{-4}$
stat. accuracy is
$\Delta P \sim 1.5\ 10^{-4}$

We don't see the spatial dependence of Pxy and Pyx components responsible for nEDM.

Residual magnetic field

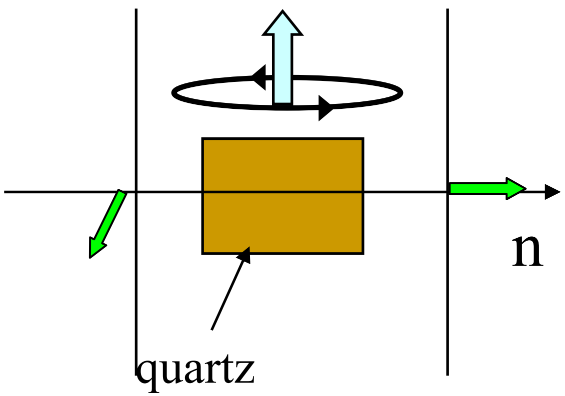
$H_r \sim (1\text{-}2)\ 10^{-3} G$

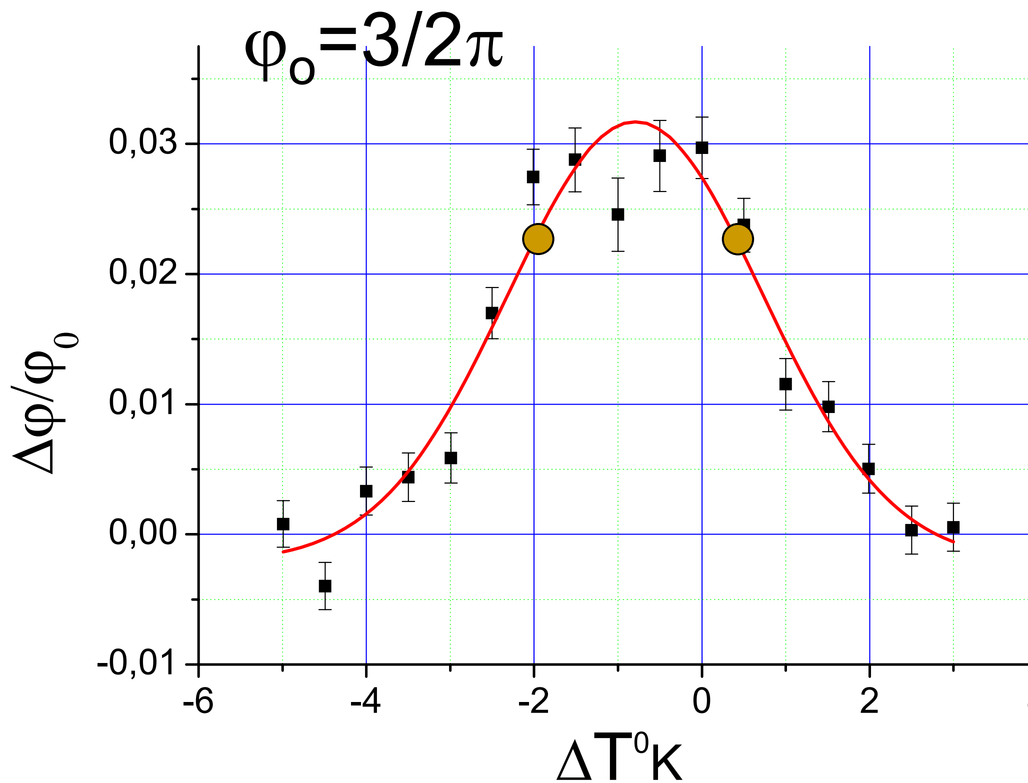
$\Delta\tau/\tau_0 = \Delta\varphi/\varphi_0 < 10^{-3}$ – difference of time of neutron stay

$\tau = 3.8\ 10^{-4}$, $\Delta\tau < 4\ 10^{-7}$ sec.

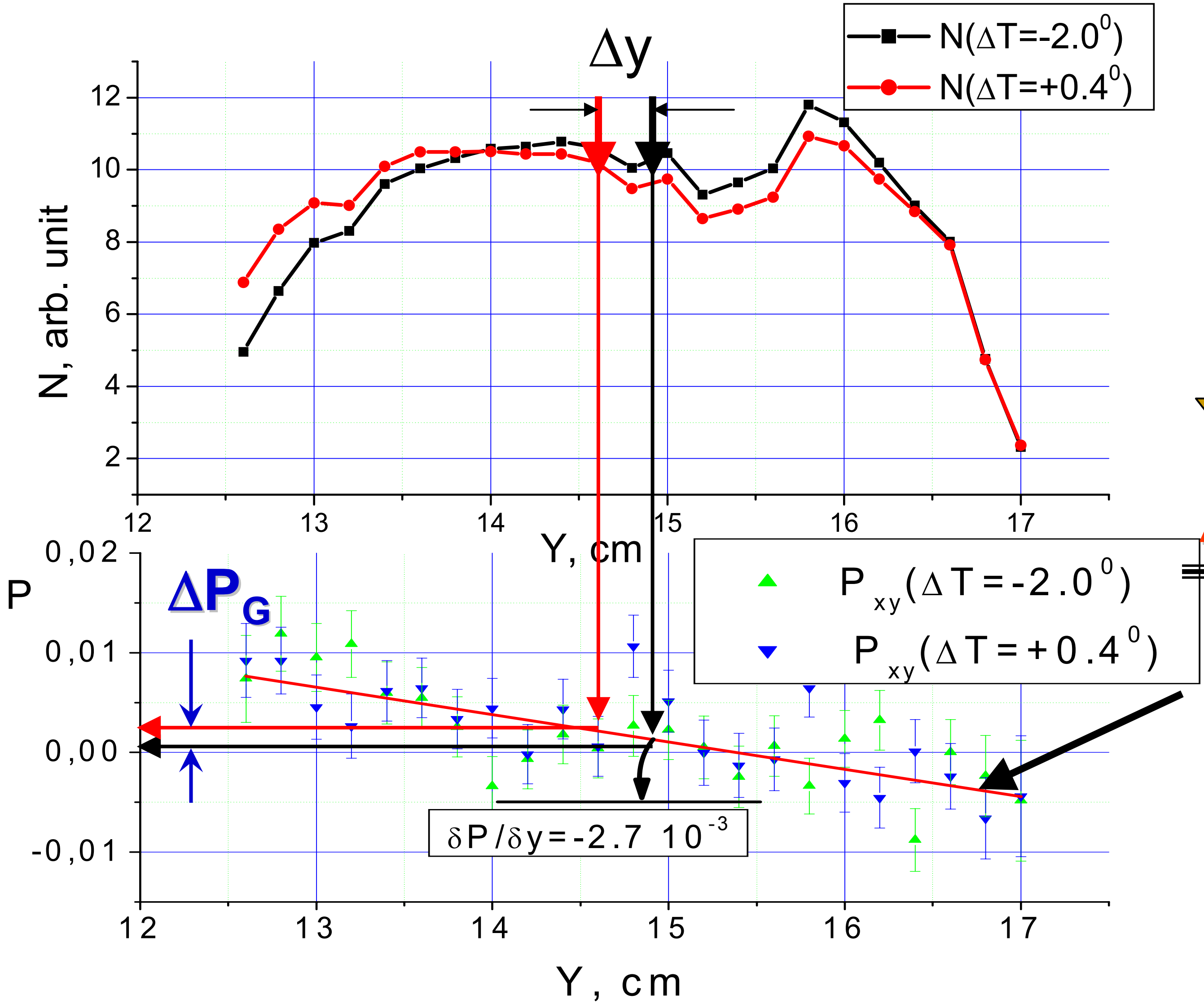
The contribution to EDM effect –

$\varphi_H = H_r \Delta\tau g_n < 1.5\ 10^{-5}$





Effect of spatial beam distribution



False effect
$\Delta P \cong \Delta y\ \delta P/\delta y$

$\Delta y \sim 0.03$ cm

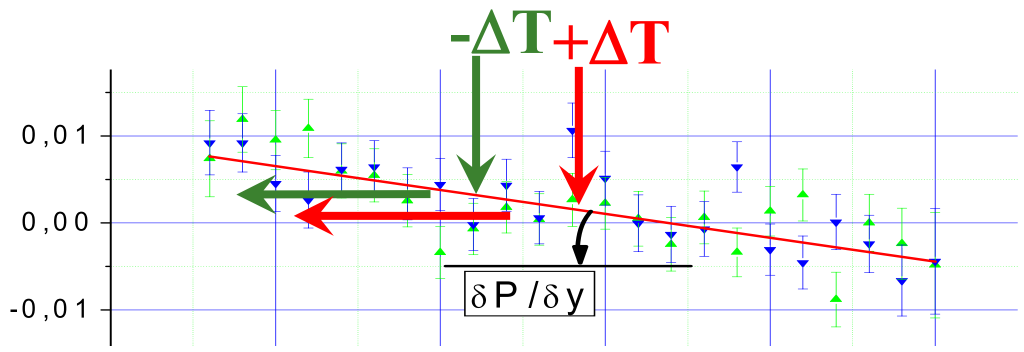
$\delta P/\delta y = -2.7\ 10^{-3}$/cm

$\Delta P_G = 0.8\ 10^{-4}$

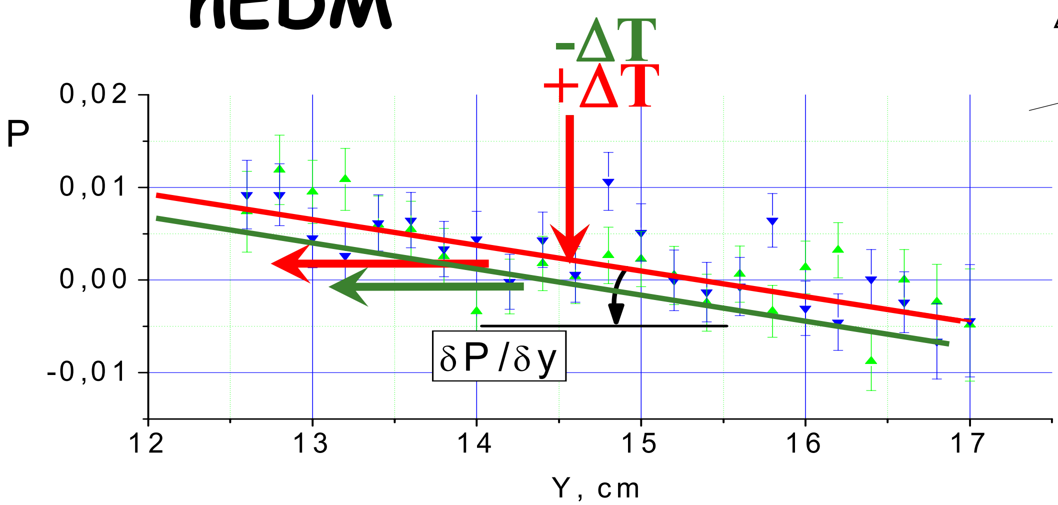
Cylinder output window of CRYOPAD?

Possible solution

Systematic



nEDM



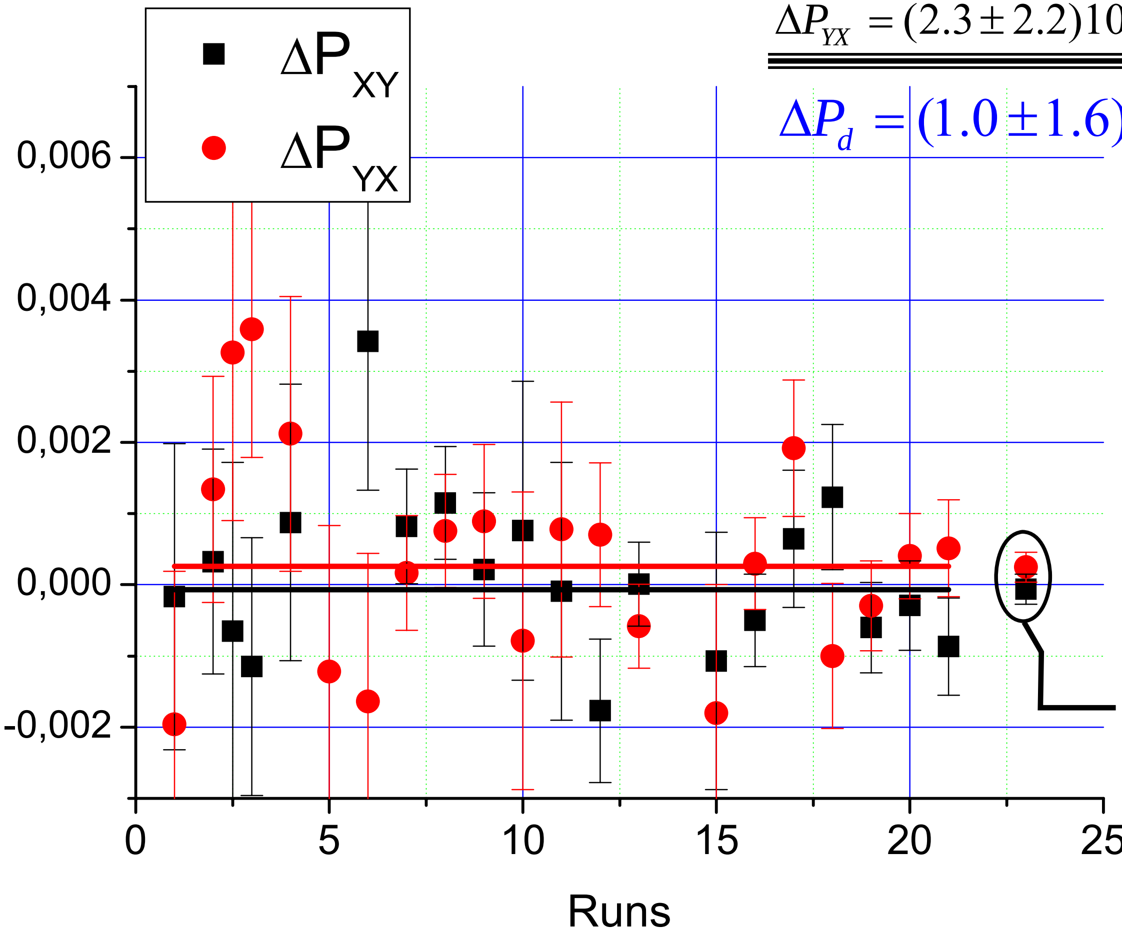
We should use right data processing

$$\Delta P_{old} = \frac{1}{2}\left(\int_{S_{beam}} P(+)ds - \int_{S_{beam}} P(-)ds \right)$$

$$\Delta P_{new} = \frac{1}{2}\left(\int_{S_{beam}} (P(+) - P(-))ds \right)$$

nEDM measurement

Old processing	New processing
$\Delta P_{XY} = (0.2 \pm 2.3)10^{-4}$	$\Delta P_{XY} = (0.6 \pm 2.3)10^{-4}$
$\Delta P_{YX} = (2.3 \pm 2.2)10^{-4}$	$\Delta P_{YX} = (1.9 \pm 2.2)10^{-4}$
$\Delta P_d = (1.0 \pm 1.6)10^{-4}$	$\Delta P_d = (0.6 \pm 1.6)10^{-4}$



$P_0=0.82$

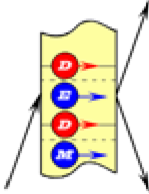
$K_{BG}= 0.85$

$K_r=0.7$

$$\Delta\varphi_d = (0.9 \pm 2.3)10^{-4}$$

$d_n=(2.4\pm6.5)10^{-24}$ e cm

Summary of the test experiment



- **Main idea of the experiment works**
- 3D spin analysis and positional sensitive detector allow to control the systematic on-line with the main measurements
- Current nEDM sensitivity 1.6 10^{-23} e cm per day **($d_n=(2.5 \pm 6.5)10^{-24}$ e cm.)**

Improvement the sensitivity for current geometry of experiment

	Test setup	Full scale setup	K_{imp}
Crystal length, cm	**14**	**50**	3.6
Beam size, cm	∅27 S=**5.7**	6x12 S=**72** K_L=280 (Vitess simulation gives K_L=275)	3.6
Beam collimation, sr	$(4/700)^2$= **3.2 ·10^{-5}**	$(12/450)^2$ **=7.1 ·10^{-4}**	4.7
Reducing the background	**0.85**	**1**	1.17
Absorption in quartz	**0.84**	**0.54**	0.8

d_n, e cm per day

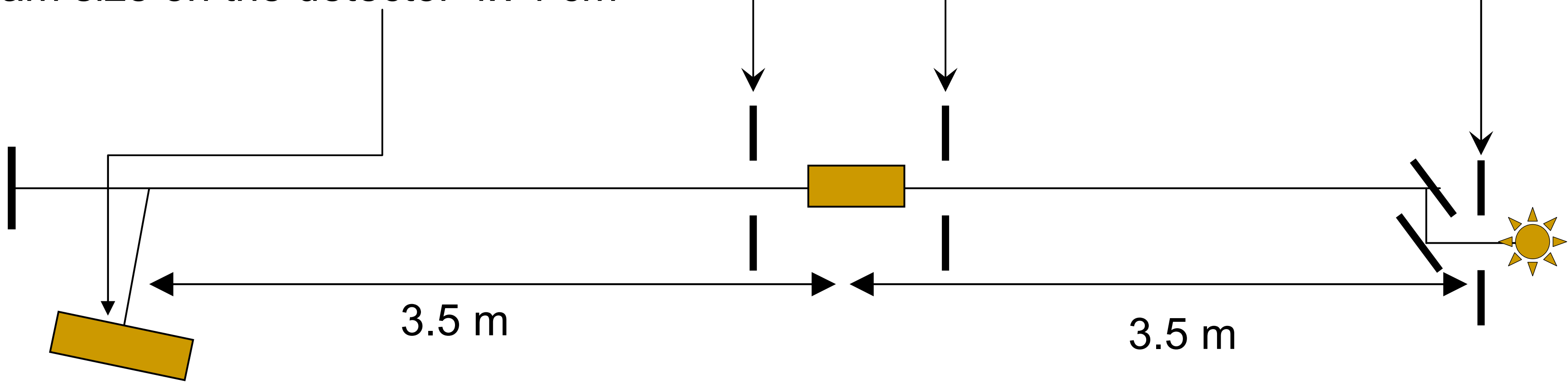
1.6 10^{-23}

K_s=57

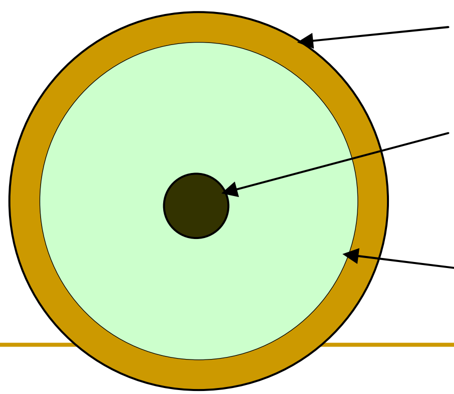
2.8 10^{-25}

Beam collimation

Slit on the double PG monochromator 3x4 cm^2
Slits of nutators ~ 2.7 cm
Beam size on the detector 4x 4 cm^2



After 7 meters



Beam size after 7 meter is Ø 24 cm

Collimation for test setup

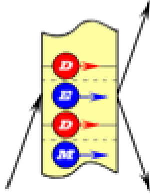
Collimation for full scale setup

Coefficient of intensity loses for test setup

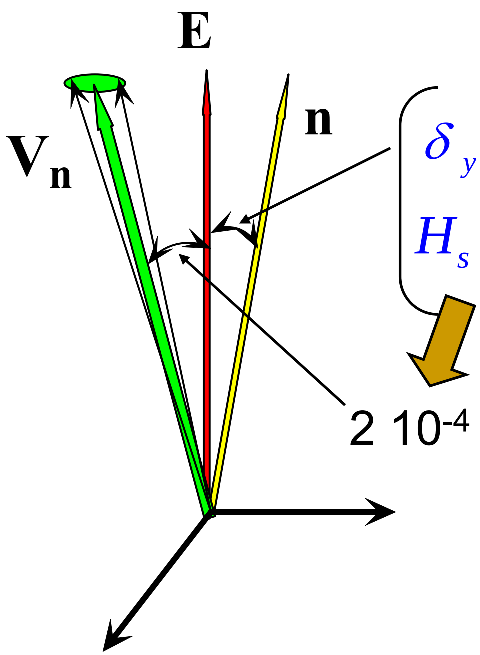
$K_{div} = (4/24)^2 = 0.027$

$K_{div} \approx 0.6$

What we need to reach $\sigma_d < 10^{-26}$ e cm?



Schwinger effect ⇒ $\tilde{H}_s = H_s \times \delta_y$



$\delta_y \approx 10^{-3}$

$H_s \approx 10^{-4} Gs$

10^{-7} Gs

Residual magnetic field $\tilde{H}_z = H_z \dfrac{\Delta\tau}{\tau_0}$

$H_z = 10^{-4} Gs$

$$\frac{\Delta\tau}{\tau_0} = 1 \cdot 10^{-3} (\delta T \approx 0.01^0 K)$$

10^{-7} Gs

$E = 0.7 \cdot 10^8$ V/cm

$d_n = 10^{-26}$ e·cm

$H_e = 1.1 \cdot 10^{-7} Gs$

$\sigma_d = 10^{-26}$ e cm

Summary of the systematic

Residual magnetic field	
Value	$\mathbf{H}_r \sim 10^{-4}\,Gs$
Time stability	$\Delta\mathbf{H}_r \sim 10^{-5}\,Gs/hour$
3D analysis of polarization	$\delta_y \sim 10^{-3}\,rad$
The crystals alignment	**~0.01 arc degree**
The ΔT^0 control	$\sim 0.01^0$K
Flat windows of CRYOPAD	$\delta_f \sim 10^{-4}\,rad$

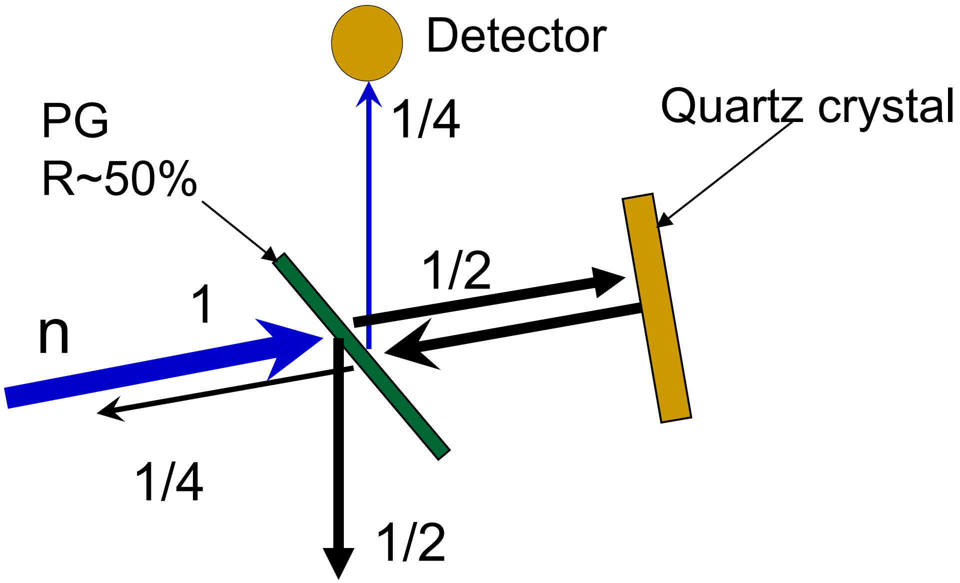
$d_n < 10^{-26}$ e cm

P odd rotation is $\Delta\varphi_P = \varphi_P \dfrac{\Delta\tau}{\tau_0} < 10^{-4} \cdot 10^{-3} = 10^{-7}$

$d_n \sim 10^{-27}$ e cm

Possible setup upgrade

$\sigma_n \sim$ ~~E~~ ~~τ~~ $N^{1/2}$

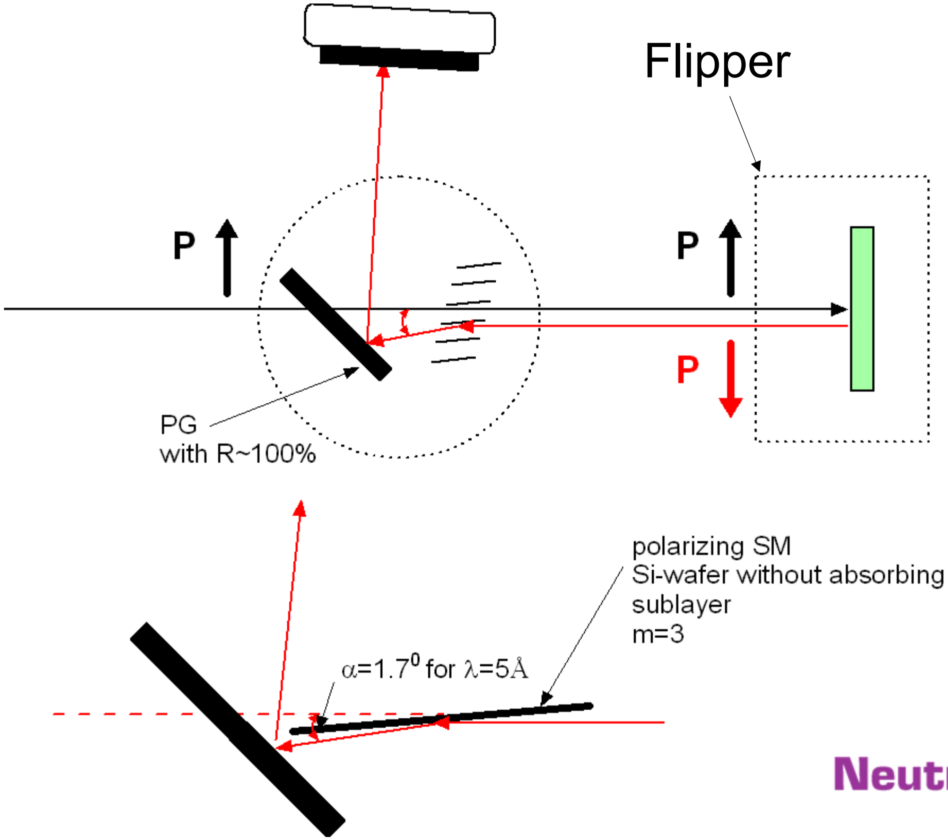


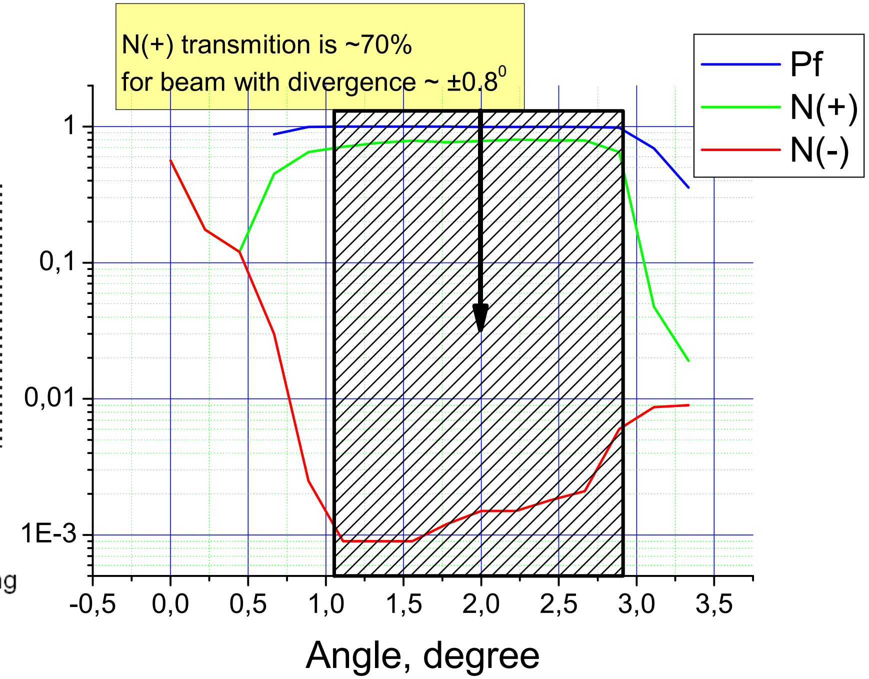
Only 25% of useful neutrons come to the detector

$N_f = N_0 * K_T(0.7) * K_{mono}(0.7) * K_P(0.5*0.6) * K_q(0.54) * K_{PG}(0.25) * K_A(0.5*0.6) * K_{div}(0.6) =$

$= N_0 * 0.09 * 0.15 * 0.25$

Fe/SiNx mirrors





Transition coefficient is ~ 0.7 instead of 0.25 gain factor **~3**

$\sigma_d \sim 1.6\ 10^{-25}$ e cm

Neutron polarising Fe/SiN$_x$ mirrors

P. Høghøj, I. Anderson, K. Ben-Saidane, W. Graf (ILL).

Accurate characterisation of periodic Fe/Si multilayers helps to understand the growth process and the structural and magnetic properties of these layers. We find that diffusion of Si into Fe makes the Si layers thinner than expected and creates an interface region of non-magnetic Fe, a so-called magnetically dead layer. This information enables us to grow multilayers with precise layer thickness by using reactive sputtering of Si with N_2 to reduce the interdiffusion. Use of these techniques gives us the capability to produce polarising Fe/SiN$_x$ supermirrors with high neutron spin-up reflectivity, and neutron polarisation above 95 % in reflection and above 90 % in transmission geometry. This method was successfully used for the new IN15 polariser.

Conclusion

For the full scale setup

- Crystal quartz (110) plane with the size $100 \times 120 \times 500 mm^3$
- Beam size $80 \times 120\ mm^2$
- Count rate ~ 10^4 n/s
- nPSD resolution – (2-5) mm for two coordinate
- CRYOPAD ~ ∅ 60 cm with flat windows

The accuracy can be

- Statistical ~ **$(2.5\text{-}3.0) \cdot 10^{-25}$ e·cm per day**
- Systematic ~ **10^{-26} e·cm**

The statistical accuracy can be improved at ~ 2 times by using Fe/SiNx mirror.

Other crystals with the higher electric field (BSO) with the same size can improve the sensitivity on ~ 3 times, so it can be ~$6 \cdot 10^{-26}$ e·cm per day