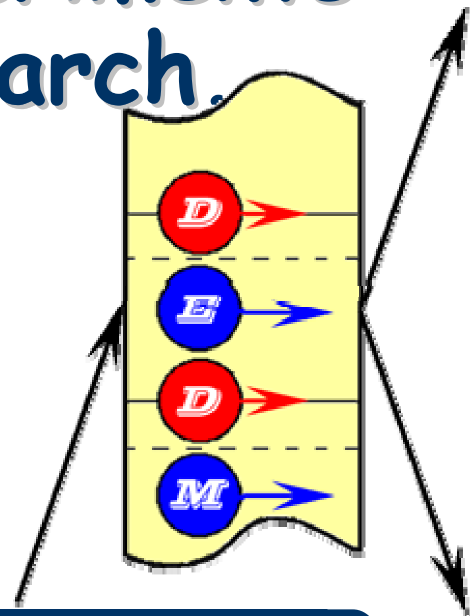
Neutron spin rotation in a non-centrosymmetric crystal. New possibilities for experiments on the neutron EDM search.



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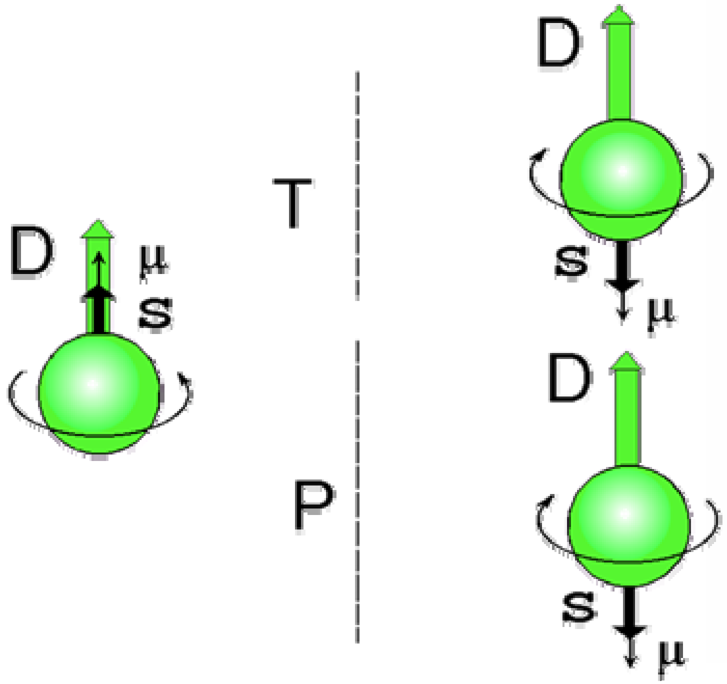
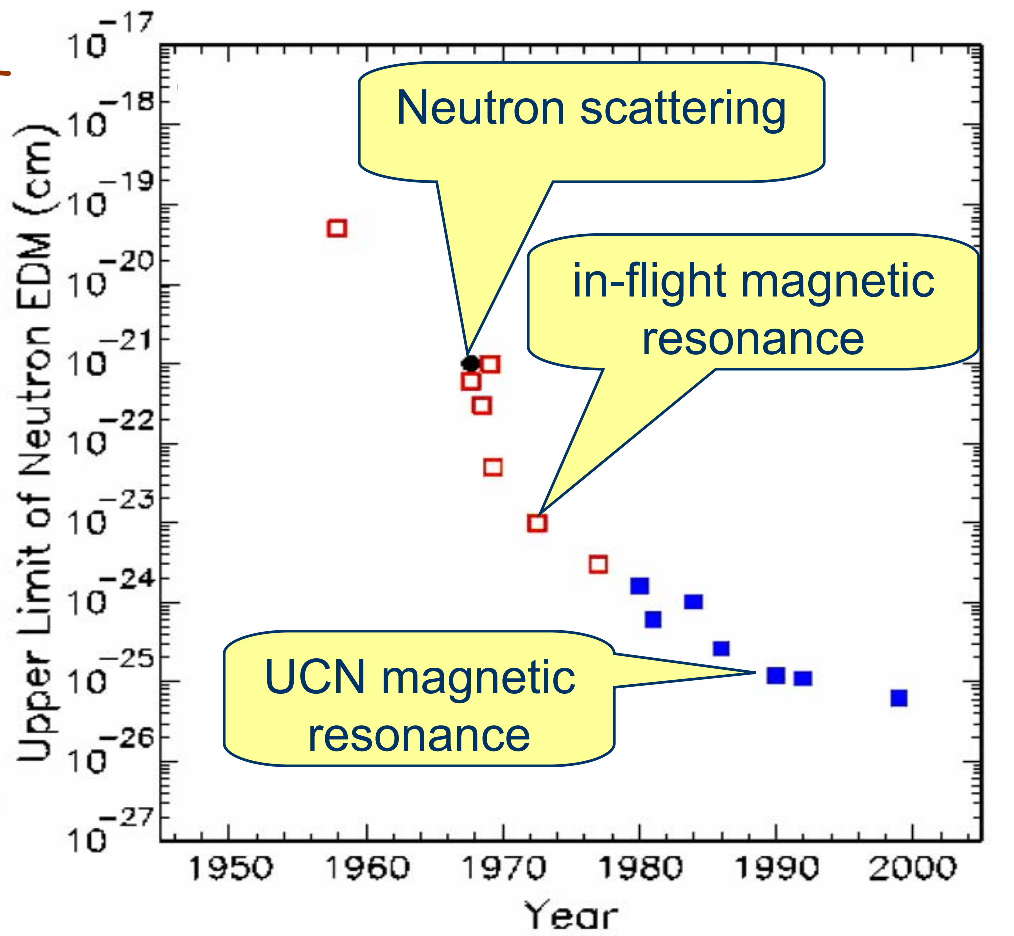
Outline

- Historical review and motivation of new nEDM experiment
- Idea and test of the experimental scheme
- General scheme of the full scale experiment
- Analysis of the statistic sensitivity
- Analysis of systematic
- Conclusion and plan for the future

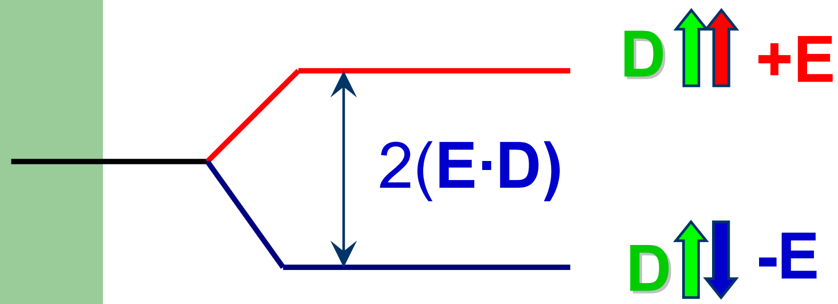
Neutron EDM

Presence of the neutron EDM requires violation of both P and T invariance





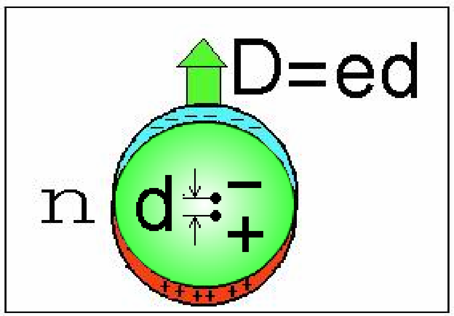
Sensitivity to neutron EDM

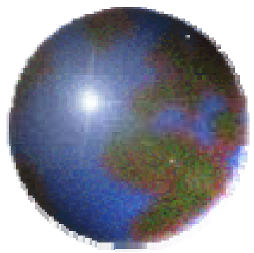


Interaction time with E

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

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





If size of neutron R ~ 10^{-13} cm, then ration d_n/R ~ $6{,}3\cdot 10^{-13}$.
Such a part from Earth radius is **~ 4 μm**.

Sensitivity to neutron EDM (2)

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

UCN method

E ~ 10 kV/cm
τ ~ 1000s (time of neutron life)

Eτ ~ 10^7(V·s)/cm

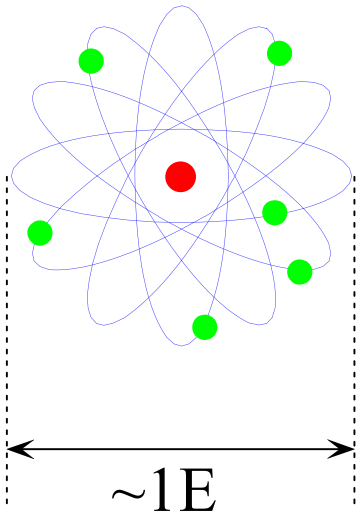
(Current value
Eτ ≈ 10^6 (V·s)/cm)

Crystal-diffraction method

E ~(10^8- 10^9)V/cm

τ_a ~ 0.01 c (absorption)

Energy of an electron-atom interaction ~ a few eV



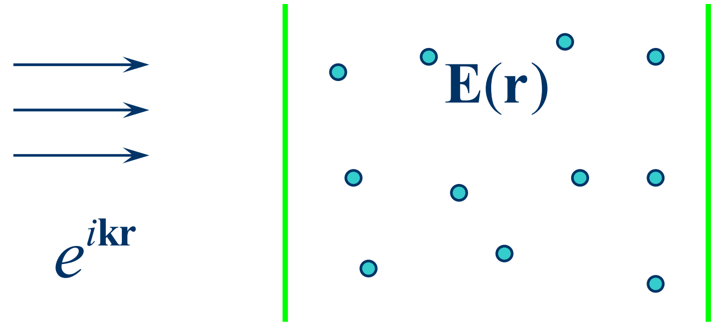
Eτ

10^7 (V·s)/cm

Historical review

1966	**Abov Yu.G., Gulko A.D., Krupchitsky,P.A.** *Polarized Slow Neutrons*; Atomizdat; Moscow, 1966 Interference of the nuclear and spin-orbit amplitudes in a non-centrosymmetric crystal.
1967	**Shull,C.G.; Nathans,R.** Phys. Rev. Lett.1967 **19** 384. Bragg reflection by CdS centrosymmetrical crystal for the EDM search: $d_n<7\ 10^{-22}$e cm
1972	**Golub R., Pendlebury G.M.**, Contemp. Phys. (1972) **13** 519. The idea to use the atomic electric fields for the neutron EDM search. But how?
1983	**Forte M. J.,** Phys. G (1983) **9** 745. Idea to search for neutron EDM by measuring a spin rotation angle for the Bragg diffraction scheme.
1989	**Forte M., Zeyen C.M.E.** Nucl. Instr. and Meth. A (1989) **A284** 147. Experiment on the neutron spin-orbit rotation in the Bragg scheme of the diffraction.
1989	**Fedorov V.V., et al.** Nucl. Instr. and Meth. A (1989) **A284** 181. First measurements of electric field of NCS crystal. $E_g \approx 2\ 10^8$ V/cm for quartz crystal.
1992	**Fedorov V.V., Voronin V.V., Lapin E.G.** J. Phys. G (1992) **18** 1133. Laue diffraction scheme for the neutron EDM search. Spin dependence of pendulum phase.
1995	**Fedorov V.V., Voronin V.V., Lapin E.G., Sumbaev O.I**. Tech.Phys. Lett. (1995) **21** (11) 881; Physica B (1997) **234--236** 8. Depolarization in Laue diffraction scheme and sensitivity to neutron EDM search.
1997-2005	**Fedorov V.V. et al** Series of the test experiments on observation of spin effects in neutron optics and diffraction

Electric field



$$\mathbf{E} = \langle e^{i\mathbf{kr}} \,|\, \mathbf{E}(\mathbf{r}) \,|\, e^{i\mathbf{kr}} \rangle \equiv 0$$

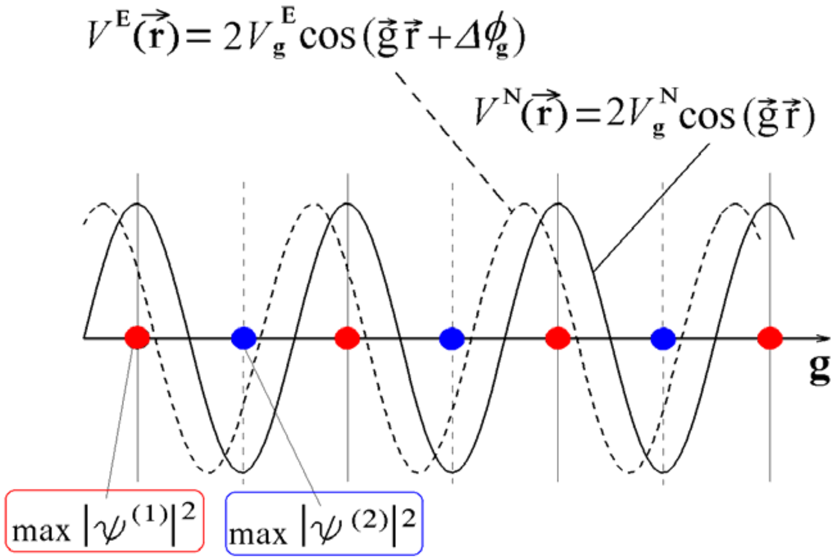
$$\langle \psi(\mathbf{r}) \,|\, \mathbf{E}(\mathbf{r}) \,|\, \psi(\mathbf{r}) \rangle \neq 0 \quad \Longrightarrow \quad \psi(\mathbf{r}) = ???$$

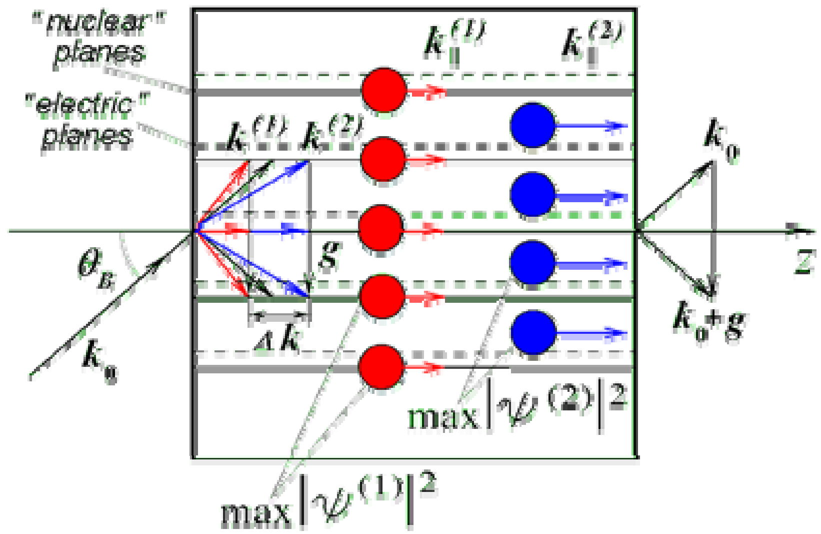
The case of noncentrosymmetric crystal

Bloch theorem – $\psi(\mathbf{r}) \Leftrightarrow \mathrm{V_n}(\mathbf{r})$

$\mathbf{E}(\mathbf{r}) \sim grad(\mathrm{V}_e(\mathbf{r}))$ We should have $\mathrm{V_e}(\mathbf{r}) \Leftrightarrow \mathrm{V_e}(\mathbf{r} + \mathbf{r}_0)$

Laue diffraction





- $\mathbf{E}_g = \langle \psi^{(1)} | \mathbf{E}(\mathbf{r}) | \psi^{(1)} \rangle =$

  $= -\langle \psi^{(2)} | \mathbf{E}(\mathbf{r}) | \psi^{(2)} \rangle = \mathbf{g} V_g^E \sin \Delta\phi_g$

$V_g^E \sim$(1-10)eV, $g \sim 10^8$ 1/cm, so if $\Delta\Phi_g \neq 0$,

E_g can be ~(10^8- 10^9)V/cm

Experimental value for (110) plane of quartz ***$E_g \approx 2 \cdot 10^8$ V/cm***

Bragg diffraction case

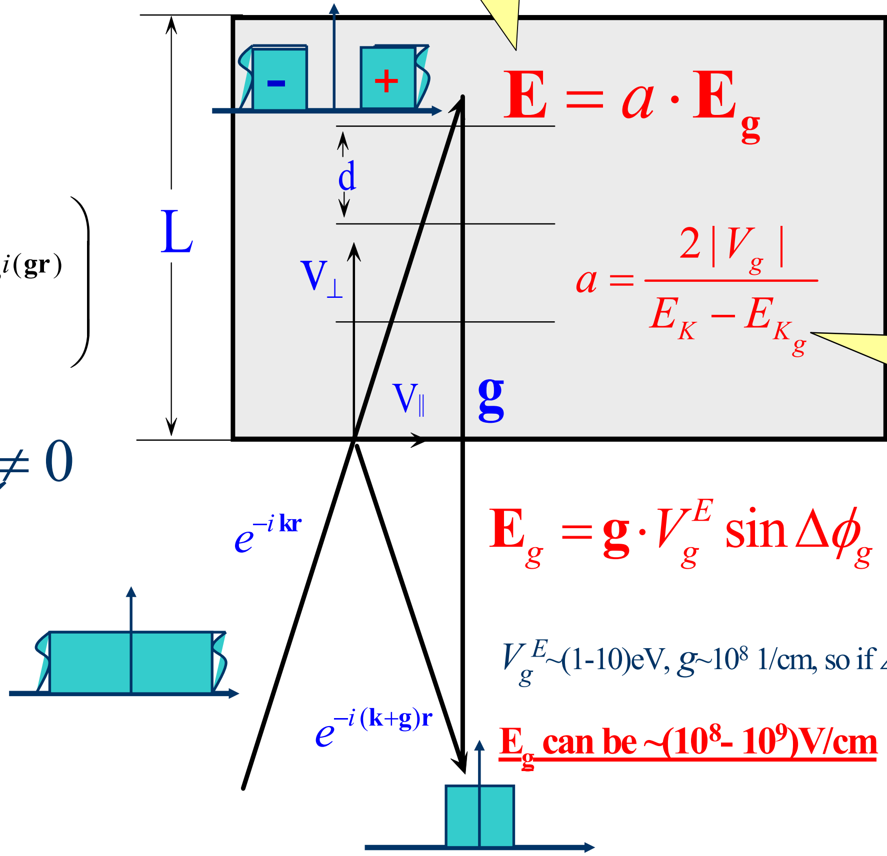
Neutron wave function

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

$$\mathrm{E} = \langle \psi(\mathbf{r}) | \mathbf{E}(\mathbf{r}) | \psi(\mathbf{r}) \rangle \neq 0$$

NCS crystal

Electric field affected the neutron



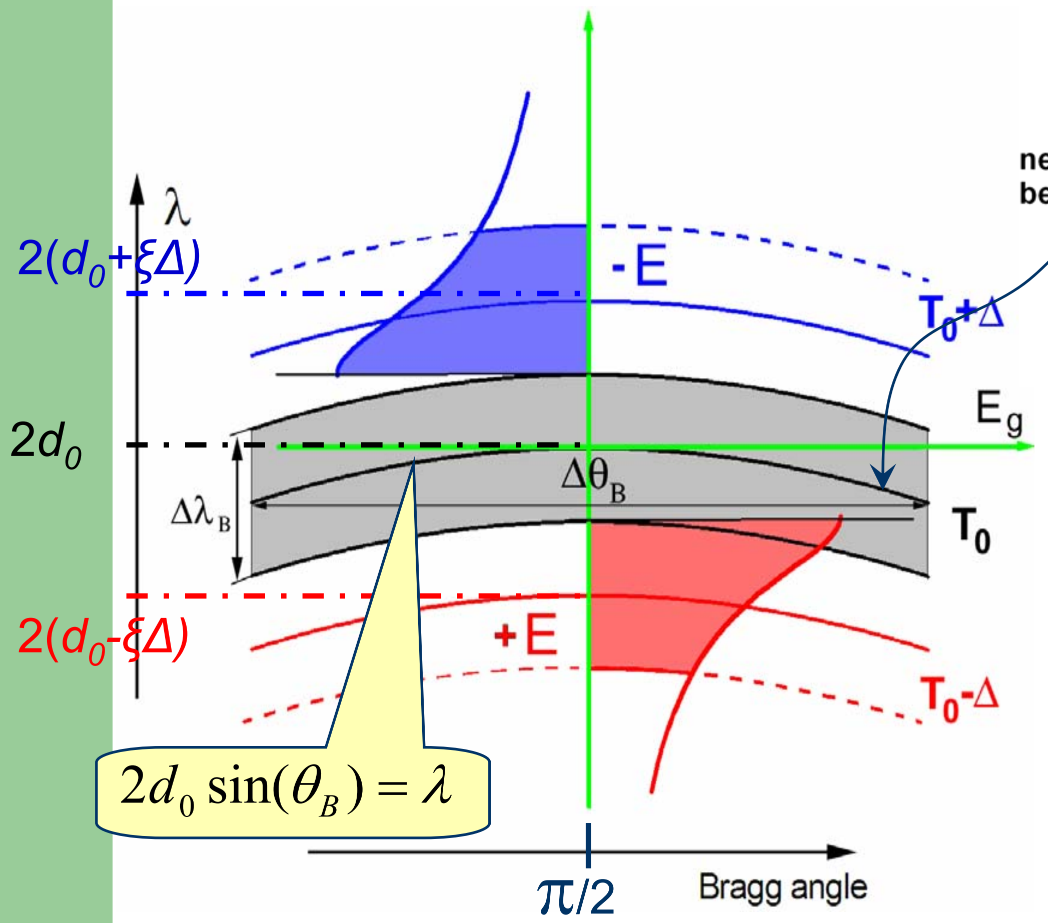
deviation from the exact Bragg condition in an energy units

V_g^E~(1-10)eV, g~10^8 1/cm, so if $\Delta\Phi_g \neq 0$,

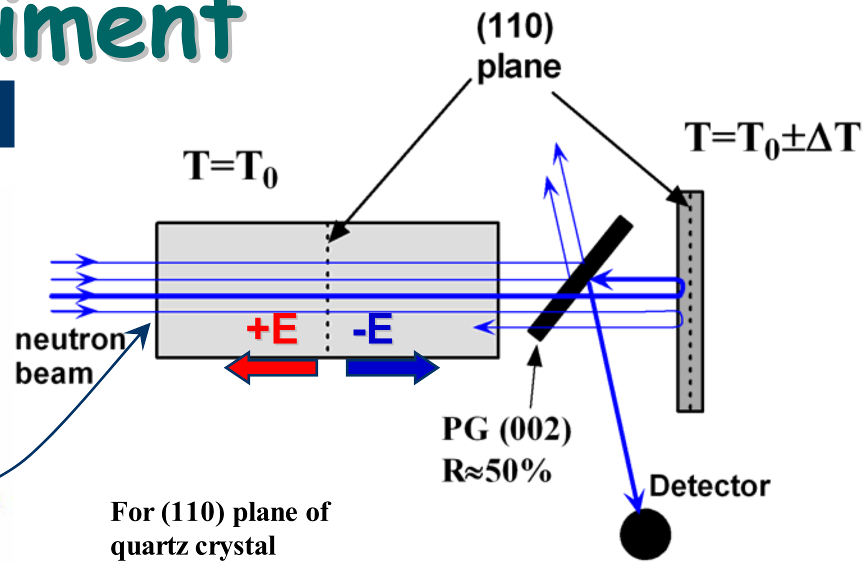
$\mathbf{E_g}$ can be ~(10^8- 10^9)V/cm

Forte M. J., Phys. G (1983) **9** 745.

Idea of the experiment



$2d_0 \sin(\theta_B) = \lambda$



For (110) plane of quartz crystal

$\Delta T = 1^0 C$

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

For π/2 reflection

E || v_n and

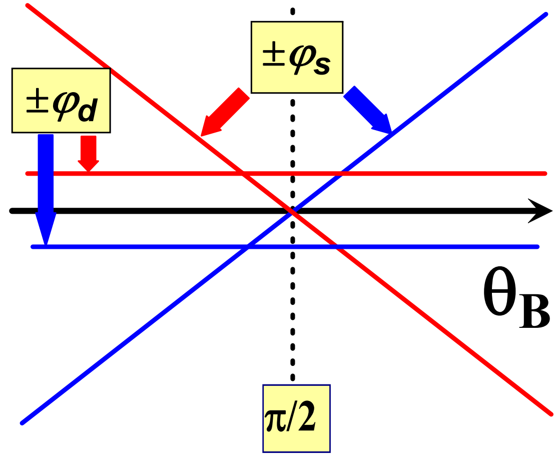
$H_s \sim [E \times v_n] \approx 0$

π/2 reflection → "zero" Schwinger

EDM effect doesn't depend on a Bragg angle

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

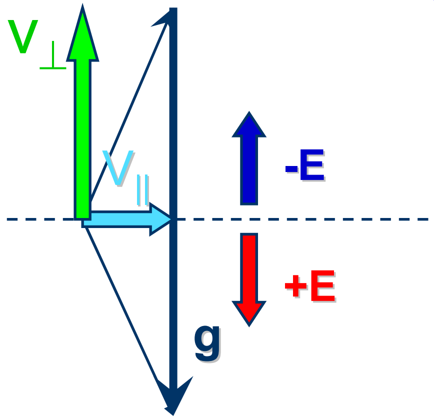
$$v_\perp = \frac{\hbar g}{2m} \equiv const$$



For π/2 reflection

$\mathbf{E} \parallel \mathbf{v}_n$ and

$H_s \sim [\mathbf{E} \times \mathbf{v}_n] \approx 0$

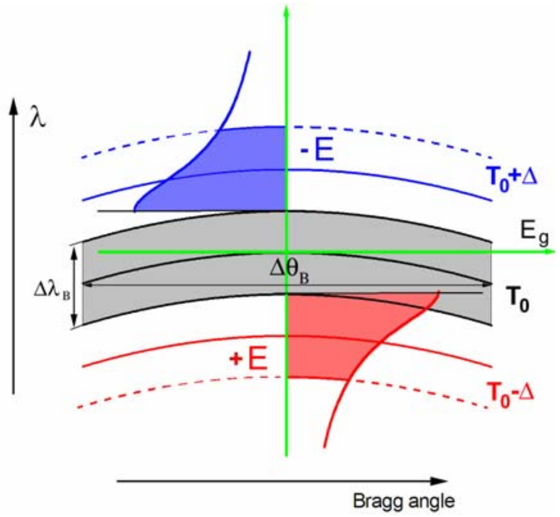


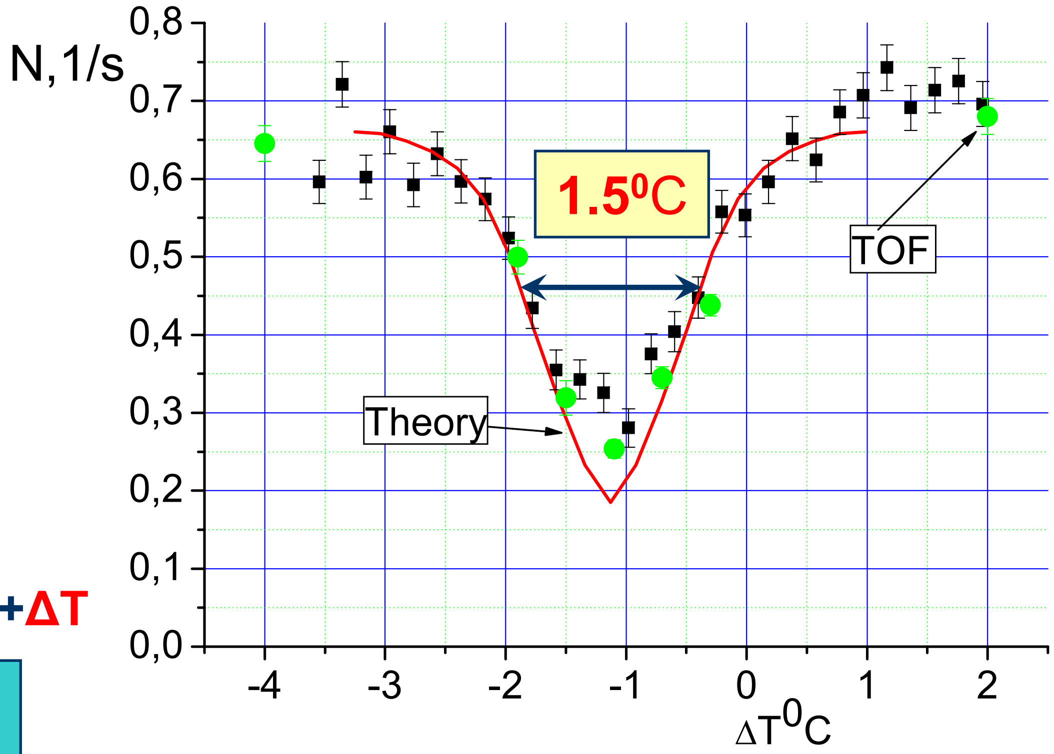
Schwinger effect can be decreased down to zero for the Bragg angle close to π/2

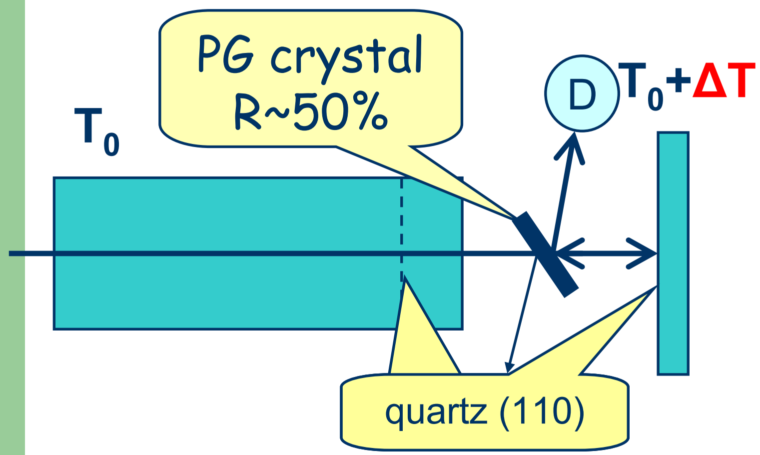
$$\varphi_s = \frac{\mathbf{E} \cdot v_\parallel \cdot \mu \cdot L}{c\hbar v_\perp} = \frac{\mathbf{E} \cdot \mu \cdot L}{c\hbar} ctg(\theta_B) \xrightarrow[\theta_B \to \pi/2]{} 0$$

Experimental test

Two crystal line (ΔT)



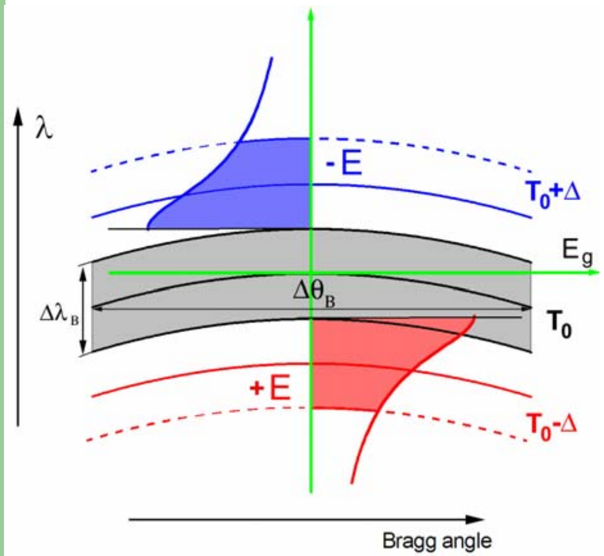


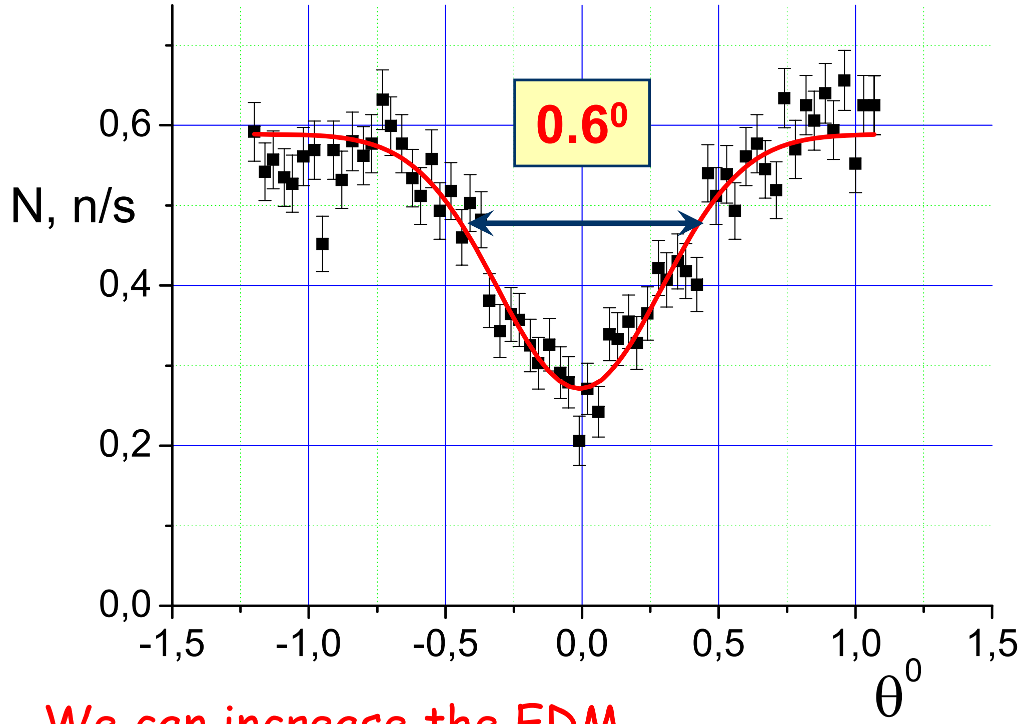


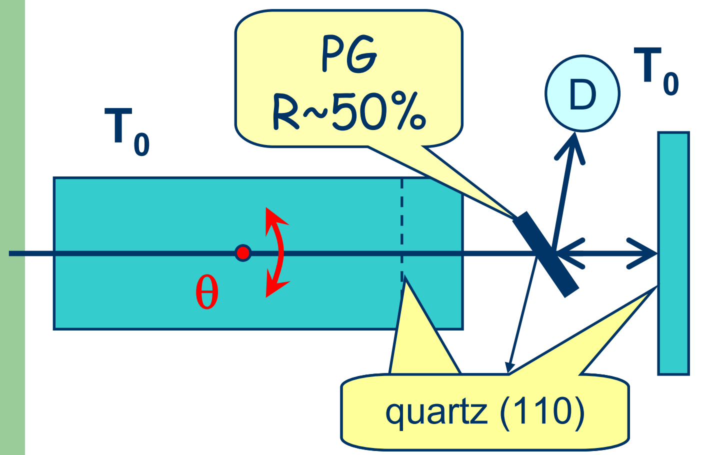
We can control the deviation parameter by the temperature of crystal.

Two crystal line (Angular)

For Bragg angle ~ 45^0 the Bragg width ~ 0.0005^0

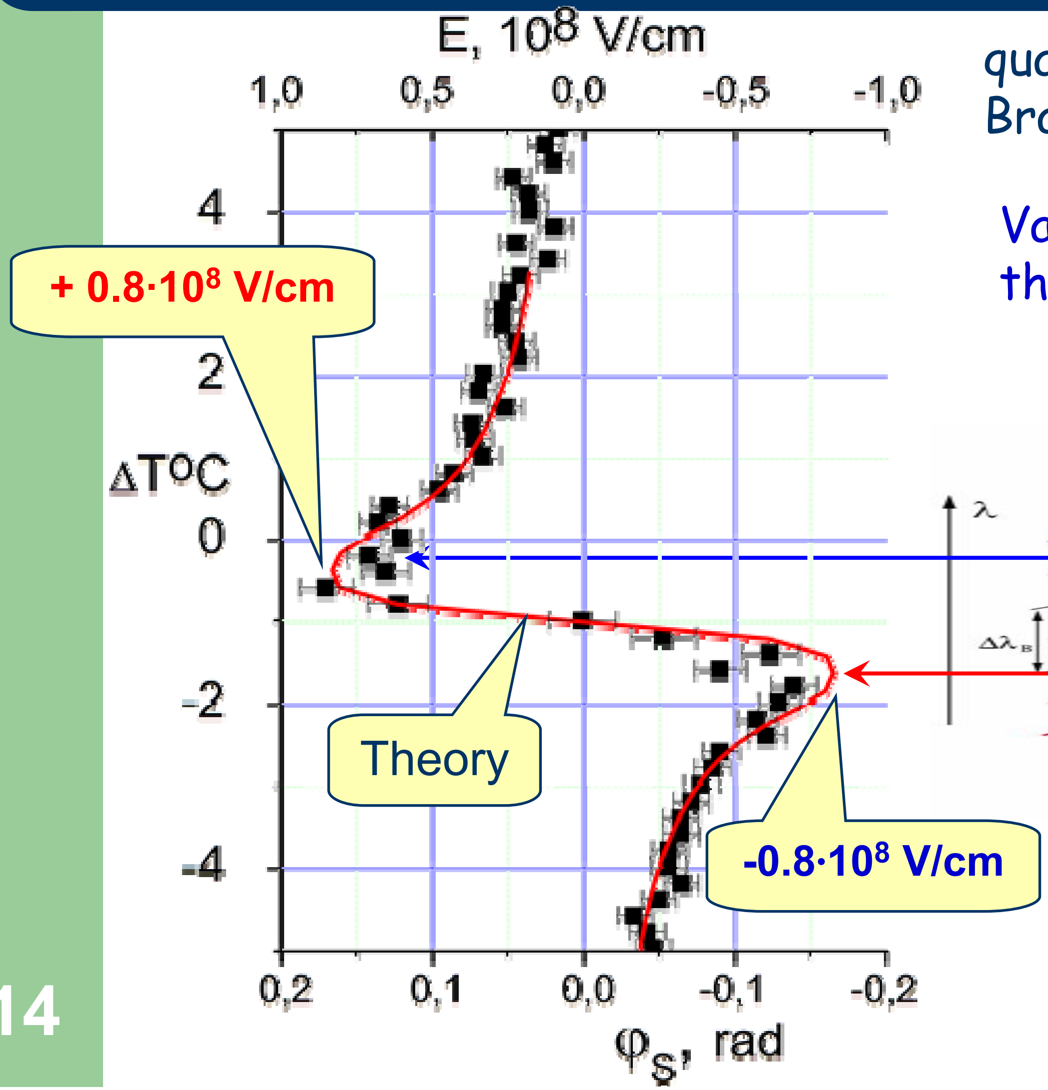






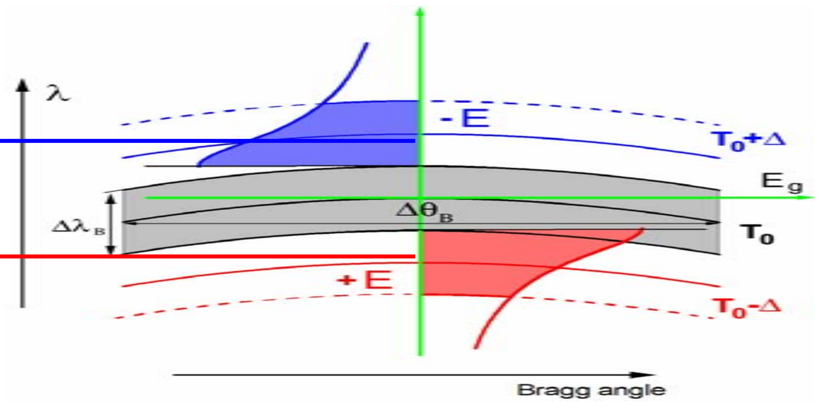
We can increase the EDM effect by using a series of the crystals.

Electric field



quartz (110) plane L_c=14 cm
Bragg angle ≈ 86^0

Variation of the ΔT on ±1^0 ⇒ **E ≈ ± 10^8 V/cm**



DEDM-V project

(search for the neutron EDM by crystal diffraction method)

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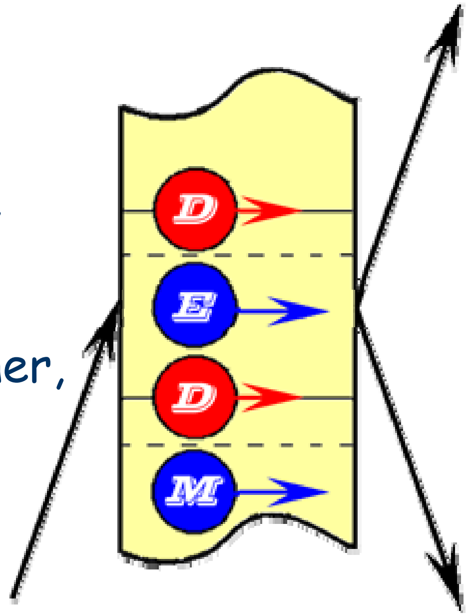
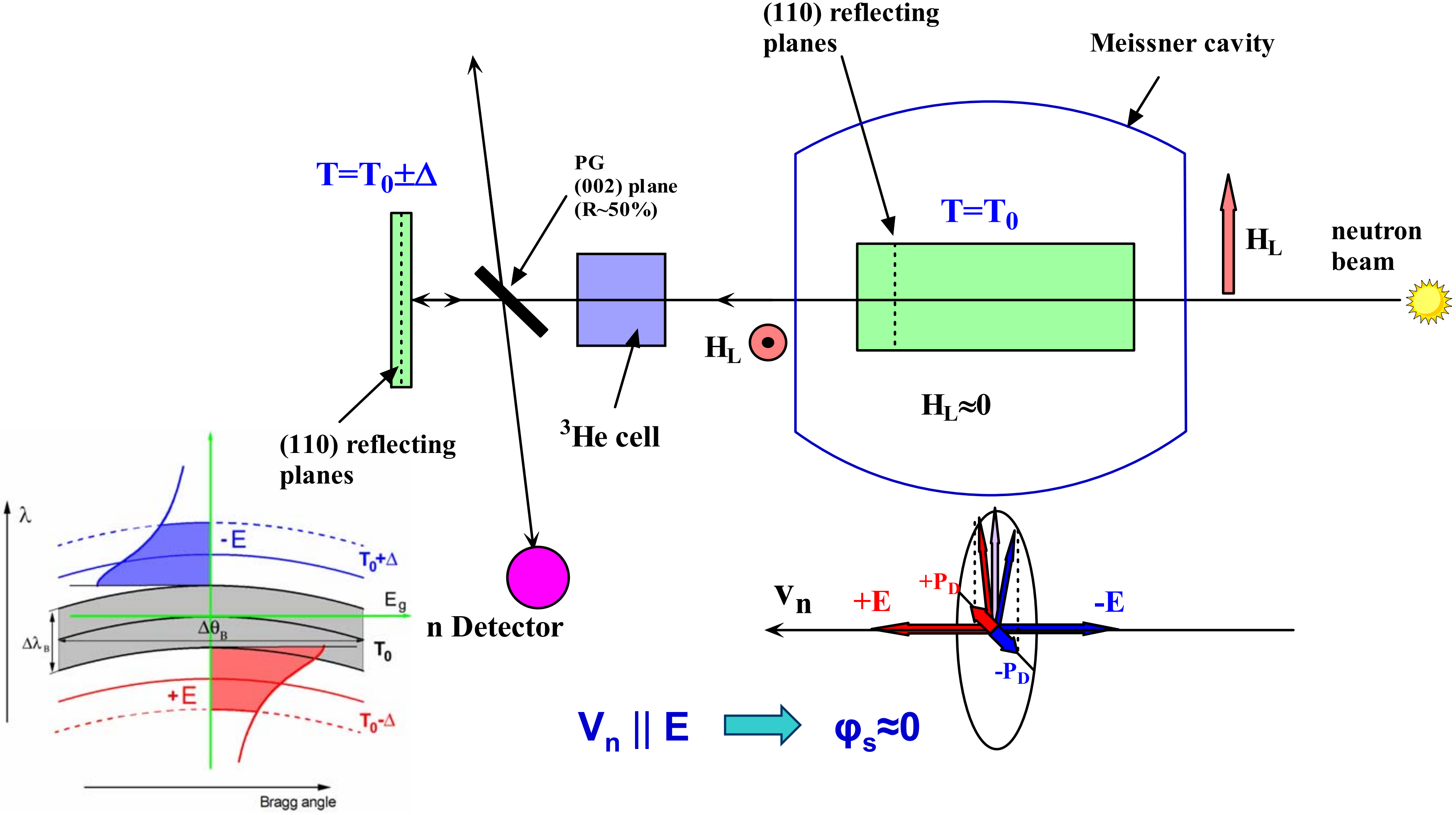
INP, Minsk, Belarus

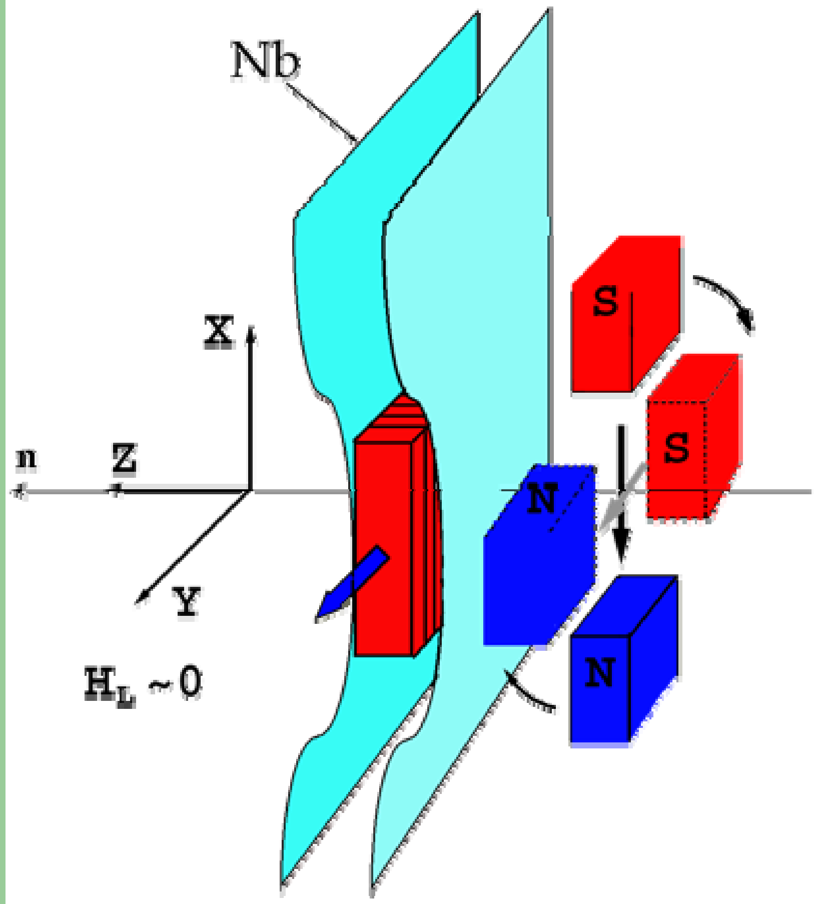


Scheme of the experiment

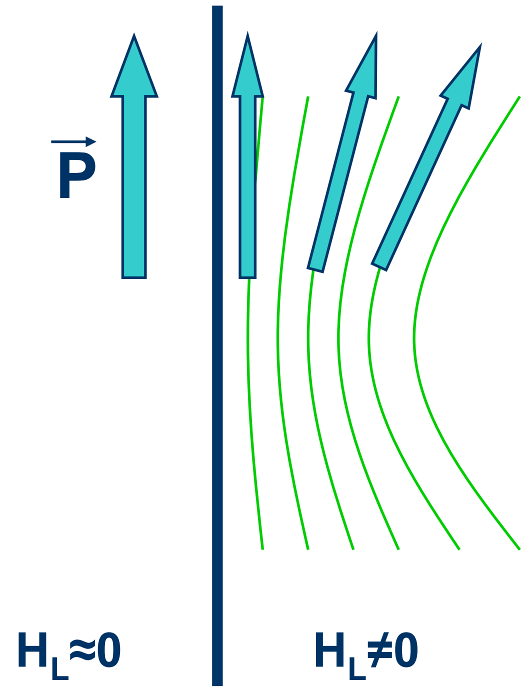


$V_n \parallel E$ ⇨ $\varphi_s \approx 0$

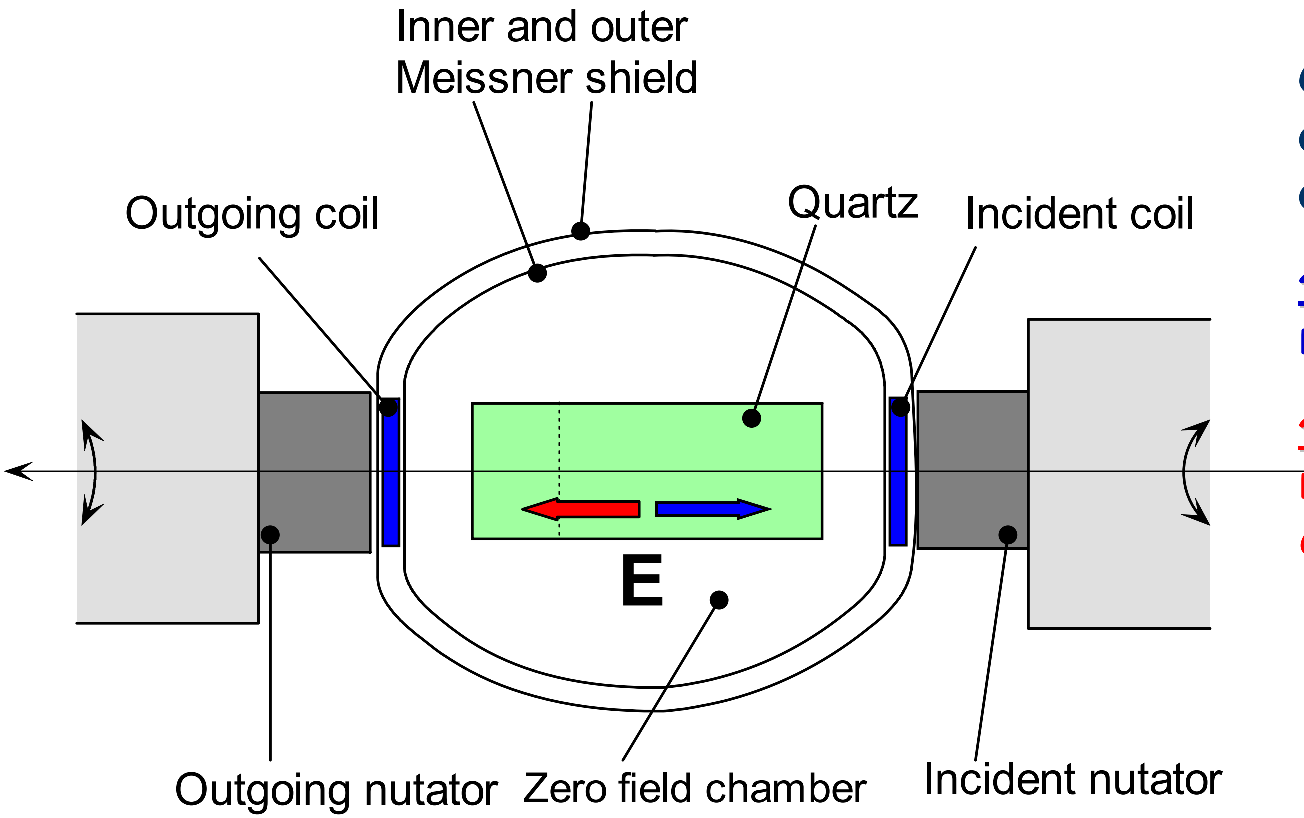
3-D analysis of polarization



Magnetic field || surface of the superconductor.



CRYOPAD



Current accuracy of spin orientation is

~10^{-2} rad for routine experiment

~10^{-3} rad can be reached for special cases

F. Tasset, P.J. Brown, E. Lelie`vre-Berna, T. Roberts, S. Pujol, J. Allibon, E. Bourgeat-Lami, Physica B, **267-268** (1999) 69-74

Photos of Cryopad (1)

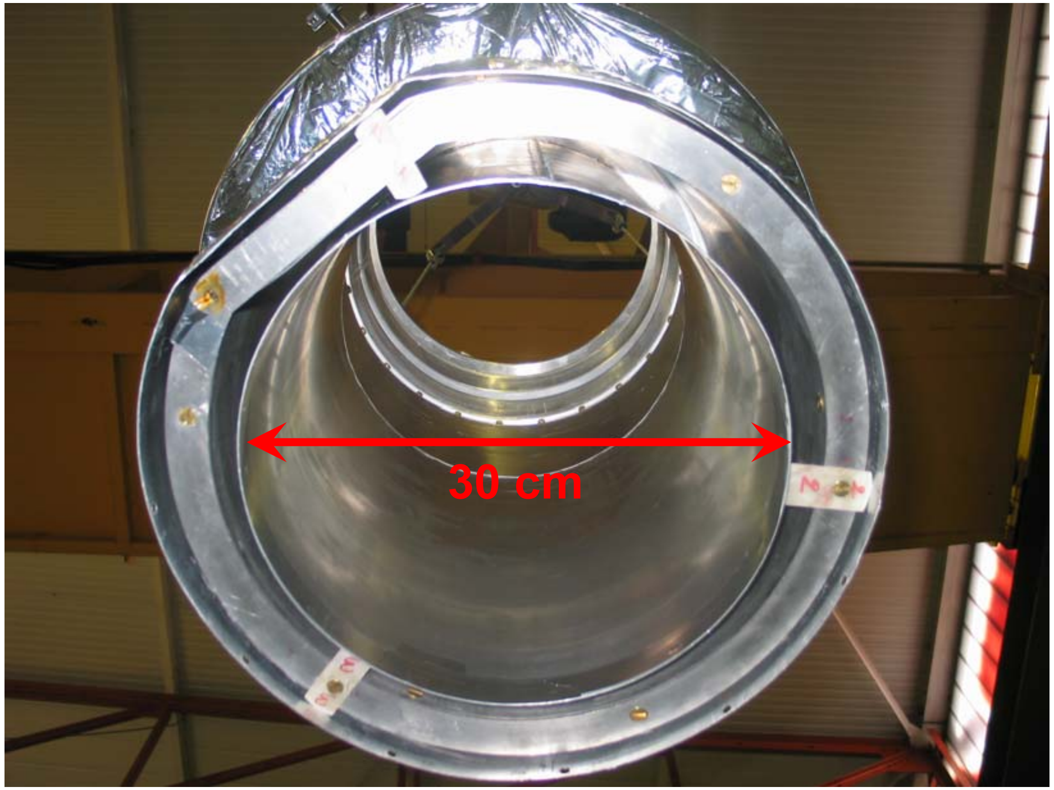
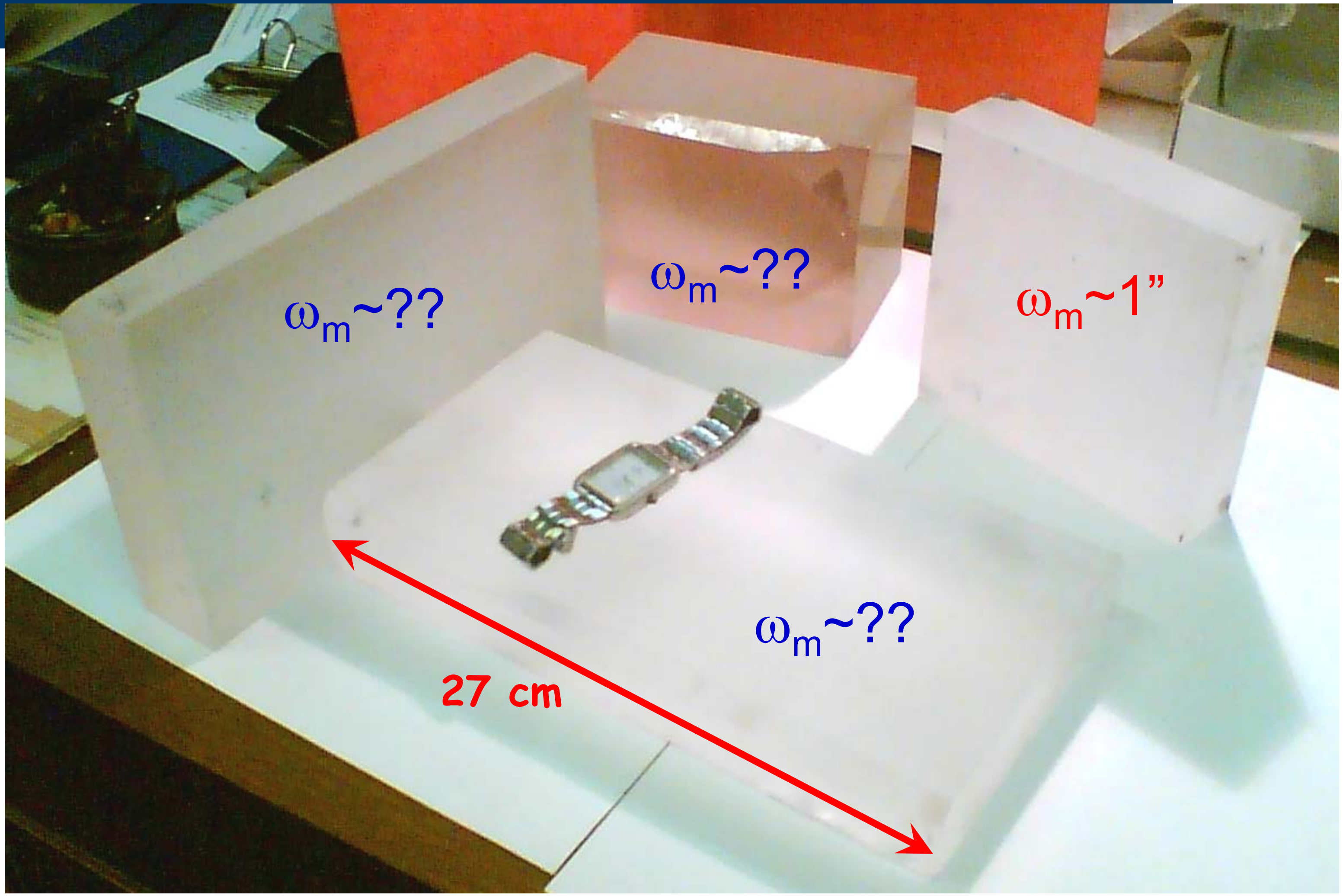


Photo of quartz crystals



Statistical sensitivity (1)

$$\sigma^{-1} \sim E\tau\sqrt{N} = E\frac{L_c}{\mathrm{v}}\sqrt{\Delta\lambda_B e^{-L_c/L_a}\Phi(\lambda)S_b \cdot P \cdot K_{exp}}$$

Bragg width

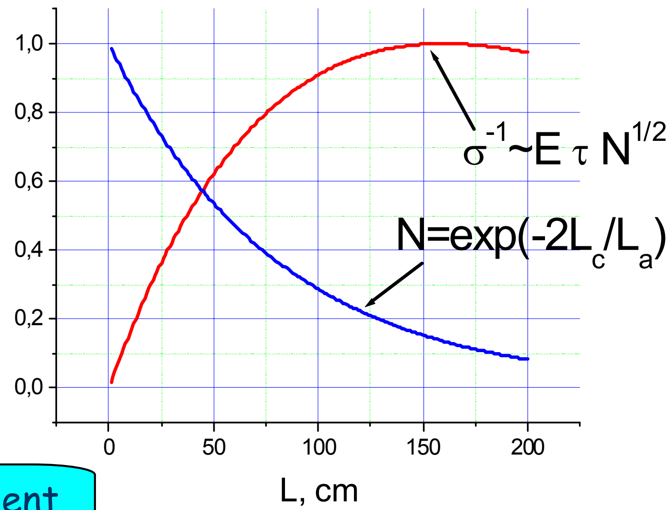
Unpolarized beam flux

Loses for polarization

Absorption

Beam square

Setup coefficient



Optimal length of crystal is the two absorption length.

$$\mathbf{E} \approx 1 \cdot 10^8 \,\mathrm{V/cm}$$

$L_a = 80\mathrm{cm}$ for λ = 4.9 Å

For crystal thickness L_c=50 cm

$$\varphi_d \approx 1.7 \cdot 10^{-5}\,\mathrm{rad}$$

for $d_n = 10^{-25}\, e \cdot cm$

Statistical sensitivity (2)

$\Phi = 10^9$ n/(cm^2 Å s) (λ=5 Å, PF1B of ILL reactor)

S=6x12cm^2, P=1/10, K_{exp}=1/8 **N=2.1 10^4 n/s**

$$\sigma_d = 1.3 \cdot 10^{-25}\ e \cdot cm\ per\ day$$

quartz SiO_2
E_g~ 10^8 V/cm
τ_a~1 ms

Current sensitivity to nEDM in UCN method

~ 6 10^{-25} e·cm/day

$$\sigma_d \sim 10^{-26}\ e\ cm\ per\ day$$

PbO
$Bi_{12}SiO_{20}$
????

$$\sigma_d \sim 10^{-27}\ e\ cm\ per\ day$$

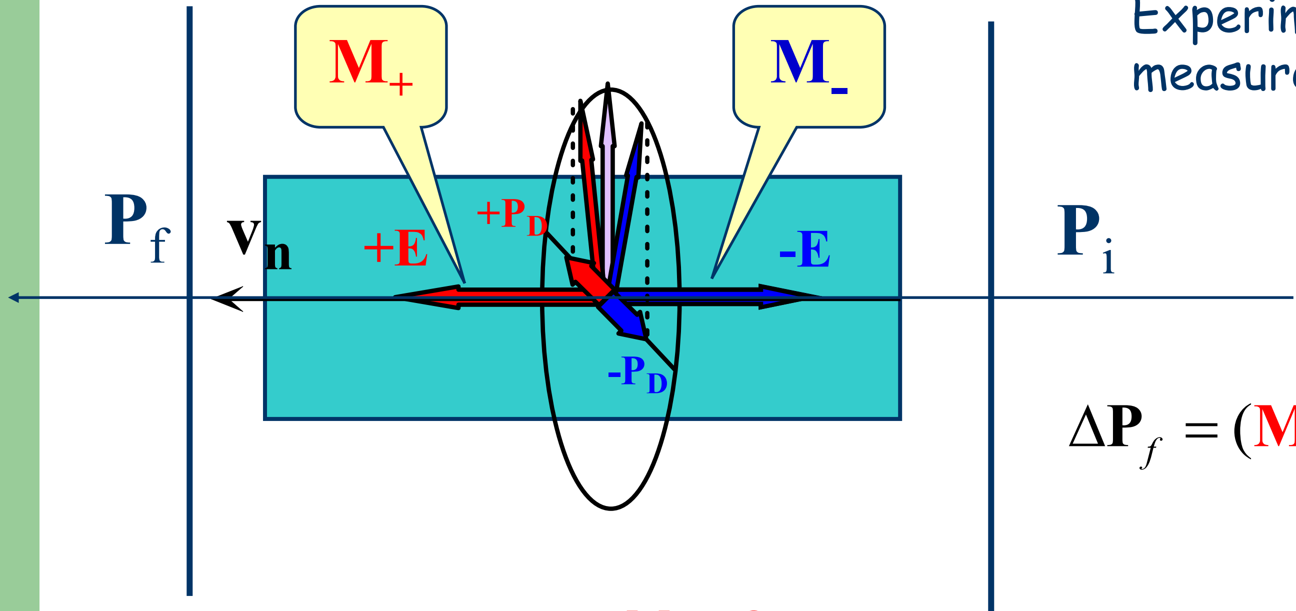
?? Fantasy - ^{208}PbO??
E_g~10^9 V/cm
τ_a~10 ms

Parameters of some NCS crystals

Crystal	Symmetry group	Hkl	d, (Å)	E_g, 10^8V/cm	τ_a, ms	$E_g\ \tau_a$, (kV·s/cm)
α-quartz (SiO_2)	$32(D^6_3)$	111	2.236	**2.3**	**1**	**230**
		110	2.457	**2.0**		**200**
$Bi_{12}SiO_{20}$	I23	433	1.75	4.3	**4**	1720
		312	2.72	2.2		880
$Bi_4Si_3O_{12}$	-43m	242	2.10	4.6	2	920
		132	2.75	3.2		640
PbO	P c a 21	002	2.94	10.4	**1**	**1040**
		004	1.47	10		**1000**
BeO	6mm	011	2.06	5.4	7	3700
		201	1.13	6.5		4500

!!! We should looking for new NCS crystal !!!

Analysis of systematic (1)



Experimentally measured

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

$$\Delta\mathbf{P}_f = (\mathbf{M}_+ - \mathbf{M}_-)\mathbf{P}_i = \Delta\mathbf{M}\cdot\mathbf{P}_i$$

Residual magnetic field $H_r \neq 0$

Schwinger magnetic field $H_s \neq 0$

$\tau_\pm$ ← time of the neutron stay in the crystal for ± **E**

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

Matrix of spin rotation

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

$H_e=(E\, d_n)/\mu_n$

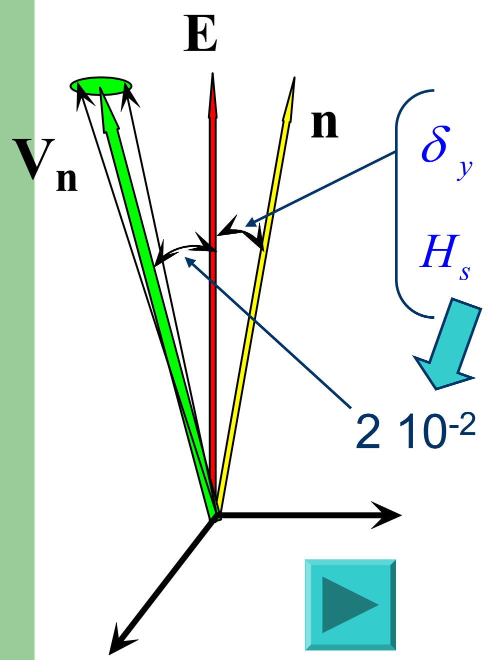
EDM — **Schwinger** — **Residual magnetic field**

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

$H_s \sim [E \times v_n] \perp E || Z$ → EDM and Schwinger effects give an orthogonal matrix elements → 3D spin analysis allows to separate the EDM and Schwinger effect.

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

$H_z = 10^{-4}\,Gs$

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

10^{-7} Gs

$E = 1\cdot 10^8$ V/cm

$D_n = 10^{-26}$ e·cm

$H_e = 1.7\cdot 10^{-7}\,Gs$

$\sigma_d = 6\ 10^{-27}$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	$\sim 0.02^0$
The ΔT^0 control	$\sim 0.01^0$C

$\sigma_d < 6\ 10^{-27}$e cm

Summary of the experimental scheme

- Possibility to reverse 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 ⇨ $\sigma_d \sim 1.3 \cdot 10^{-26}\ e \cdot cm$

Plans

- Full scale test at ILL (Grenoble, France)
  - Time – 2006
  - Sensitivity $\sigma_d \sim (1-2)\cdot 10^{-24}\ e\cdot cm\ per\ day$
- Full scale experiment <u>with the quartz</u>
  - Time – 2008
  - Sensitivity – $\sigma_d \sim 10^{-26}\ e\cdot cm$
- Experiment with another crystal
  - Time – ??
  - Sensitivity – $??\sigma_d \sim 10^{-27}\ e\cdot cm\ ??$