VERIFICATION OF THE WEAK EQUIVALENCE PRINCIPLE WITH LAUE DIFFRACTING NEUTRONS. CURRENT STATUS OF THE EXPERIMENT

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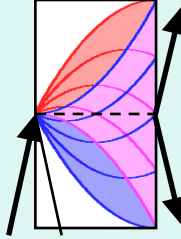
PNPI

ISINN-21

Motivation



- For Laue diffraction with Bragg angles close to the right one there is a significant diffraction enhancement factor of an external force affecting the neutron*:

$$K_d^{Si} \xrightarrow{\theta_B \sim 84 \div 87^0} 10^7 \div 10^8$$

- This factor can be used for observation of small external forces affecting the diffracting neutrons

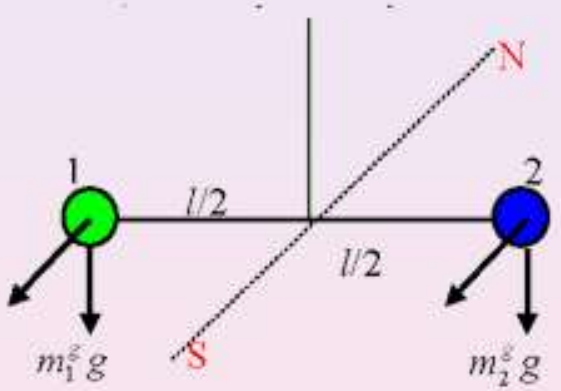
- For example, this enhancement can be used in ***m^i/m^g*** experiment with cold neutron ***(NGrav)***

*V.V. Fedorov et.al. JETP Lett. 85, 82 (2007)

Verification of WEP. Eötvös and novel EP tests

Torsion balance will be in equilibrium if

$$\frac{m_1^i}{m_1^g} = \frac{m_2^i}{m_2^g}$$



L. v. Eötvös (1908) **≤ 5·10^{-9}**

Ann. Physik (Leipzig) 68 11 (1922)

Adelberger, et al. (1990) **≤ 0.8·10^{-12}**

Phys. Rev. D 42 3267 (1990)

Baeßler, et al.(1999) **≤ 5·10^{-13}**

Phys.Rev. Lett 83(18) 3585 (1999)

Earth Orbit (Projects):

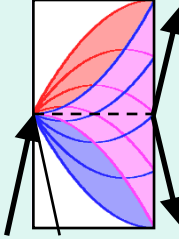
MiniSTEP (202?) **≤ 10^{-16};**

MICROSCOPE (201?) **≤ 10^{-15}**

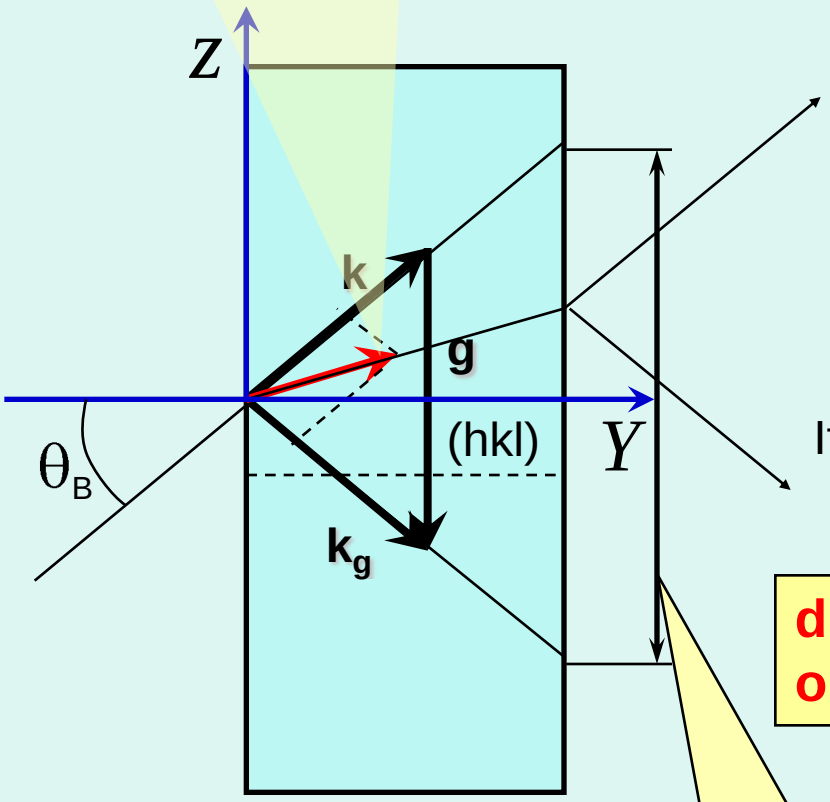
Elementary particles (neutrons): L. Koester (1976) **≤ 2.5 · 10^{-4}**

J. Schmiedmayer *(1989)* **≤ 1.8·10^{-4}; A. Frank, et al. (ongoing) ≤ 2 ·10^{-3}**

Neutron trajectory for Laue diffraction



$$\mathbf{j} = \hbar/m(|a_g(\alpha)|^2\mathbf{k}_g + |a_0(\alpha)|^2\mathbf{k})$$



2tan(θ_B) L
(Borrmann fan)

Amplitudes a_g and a_0 depend on a deviation from exact Bragg condition

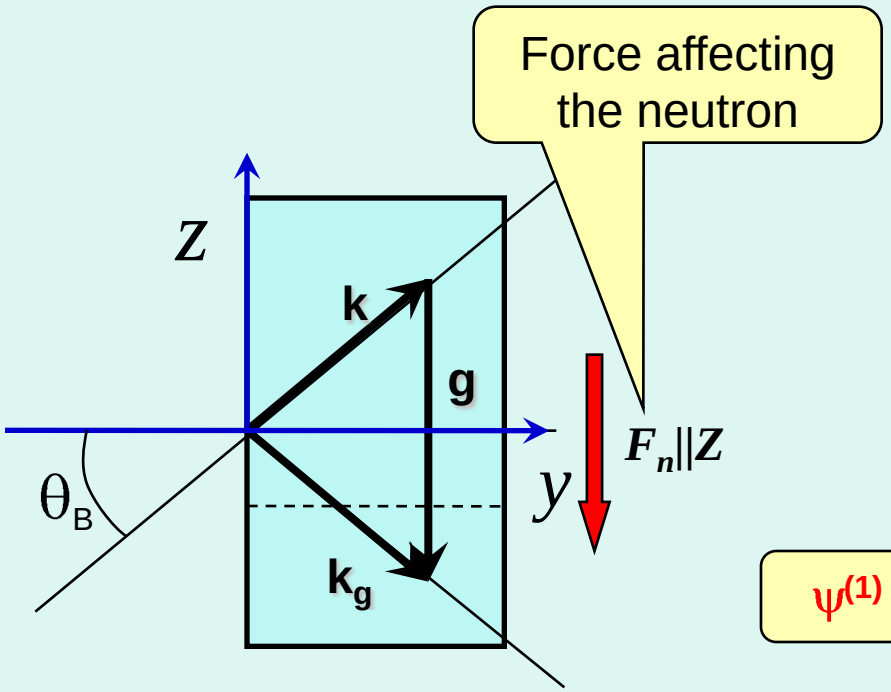
$$\alpha = \frac{2(\Delta\mathbf{k}_0 \cdot \mathbf{g})}{k_0^2}, \quad \Delta\mathbf{k}_0 = \mathbf{k}_0 - \mathbf{g}/2$$

$a_g(\alpha)$ and $a_0(\alpha)$

If α(Y,Z) ⇒ a_g(Y,Z) and a_0(Y,Z)

direction of neutron current depends on spatial coordinates j(Y,Z)

Diffraction enhancement factor



Neutron "Kato trajectory" equation (stands for different Bloch waves):

$$\frac{\partial^2 z}{\partial y^2} = \pm \frac{\tan^2(\theta_B)}{m_0} \frac{\pi}{d} \frac{F_n}{2E_n}$$

Equation for freely flighting neutron:

$$\frac{\partial^2 z}{\partial y^2} = \frac{F_n}{2E_n}$$

$\psi^{(1)}$ or $\psi^{(2)}$

$$K_d = \pm \frac{\tan^2(\theta_B)}{m_0} \frac{\pi}{d}$$

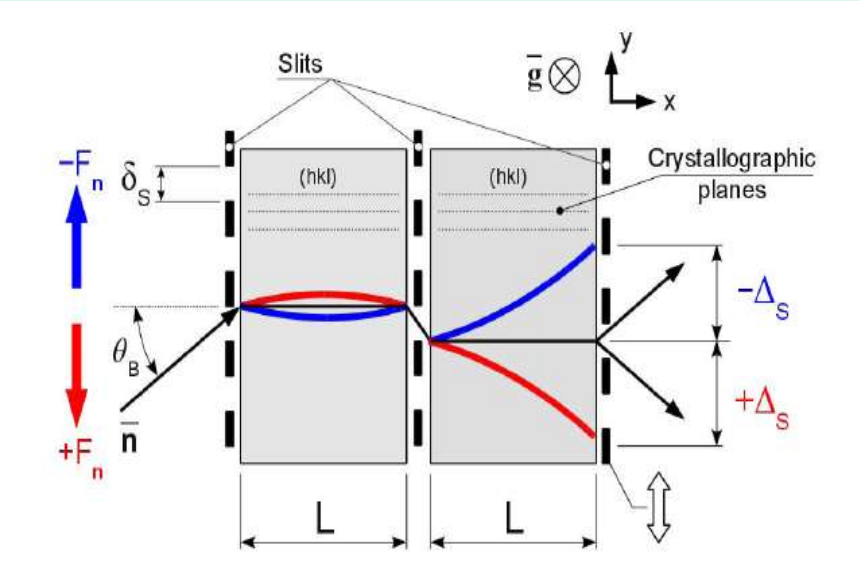
We obtain a gain factor for the diffracting neutron

For silicon (220) planes

$$K_d = \tan^2(\theta_B) \times 2 \cdot 10^5 \xrightarrow{\theta_B (84^0 \div 87^0)} (10^7 \div 10^8)$$

Additional enhancement factor due to neutron delay inside the crystal (Bragg angle close to π/2)

Two-crystal scheme of Laue diffraction



External force shifts the spot of the neutron beam at the exit surface:

$$\Delta_F^1 \quad 1,2 \quad = \pm \frac{\pi \tan^2 \quad \theta_B \quad L^2}{m_0 d E_n} F_n \equiv \pm \Delta_F^1$$

The resolution for this setup is:

$$W_F = \frac{m_0 E_n d}{\pi \tan^2 \quad \theta_B \quad L^2} \delta_S,$$

δ_S – **slit size**

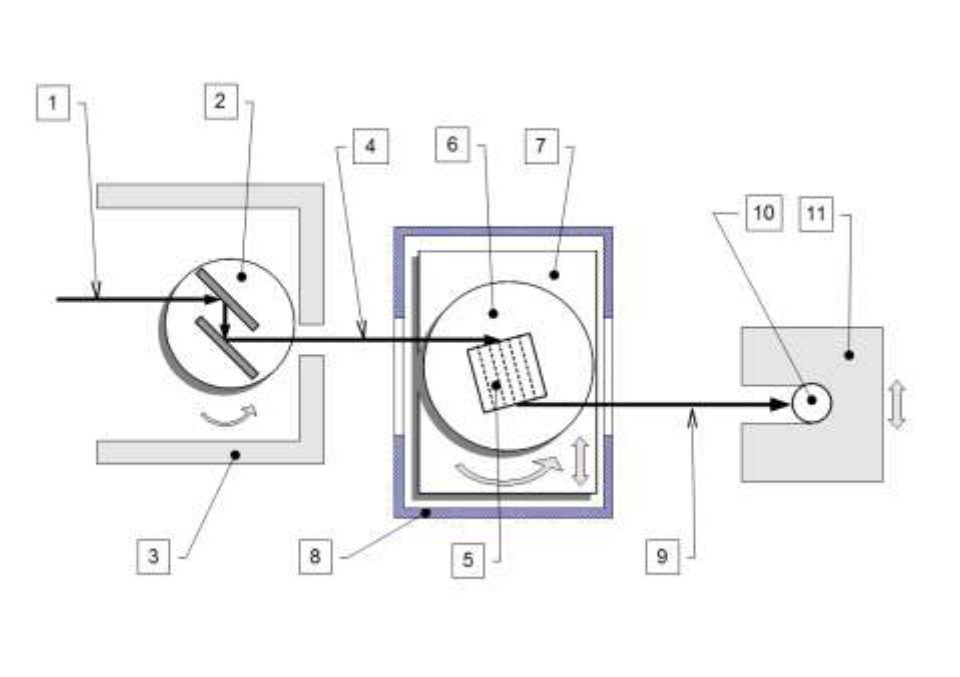
For (220) plane of Silicon:

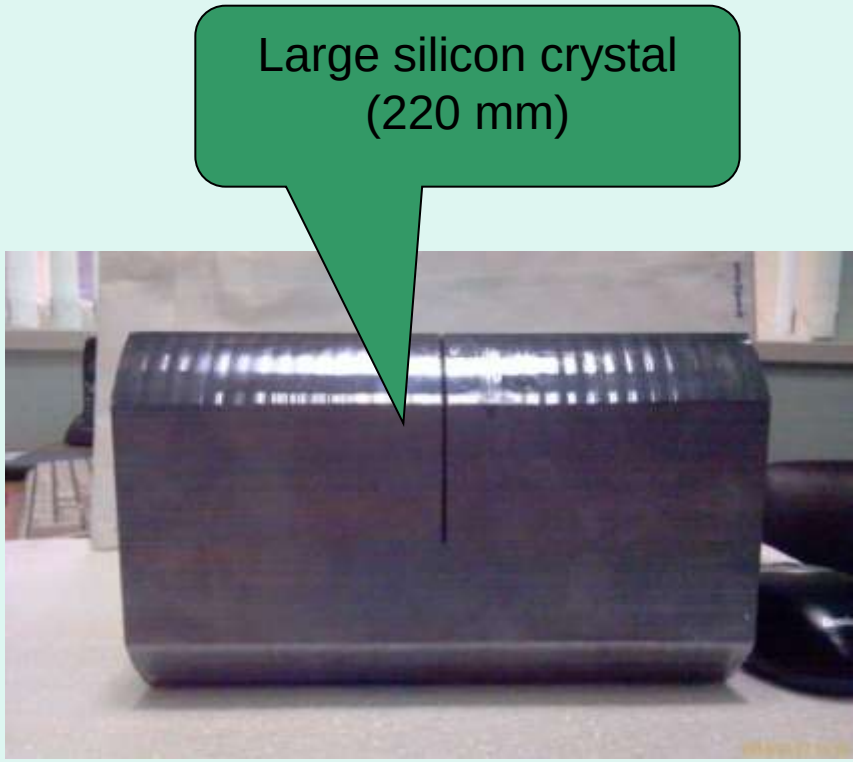
$$L = 10\,cm,\ \delta_S = 1\,mm,\ \theta_B = 86^\circ \Longrightarrow W_F \approx 1,5 \cdot 10^{-13}\,eV/cm \approx 10^{-5} m_n g$$

But, for such initial conditions a neutron should pass effectively through more than 3 meters of silicon (2L/cos(86⁰)).

Is it possible?

Experimental observation of Laue diffraction in the large silicon crystal (L=220 mm)

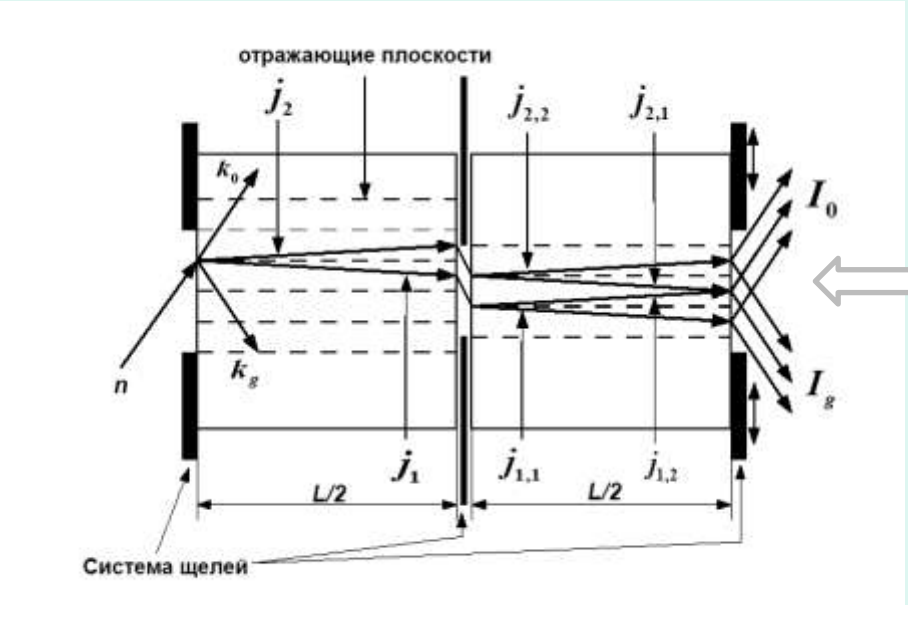


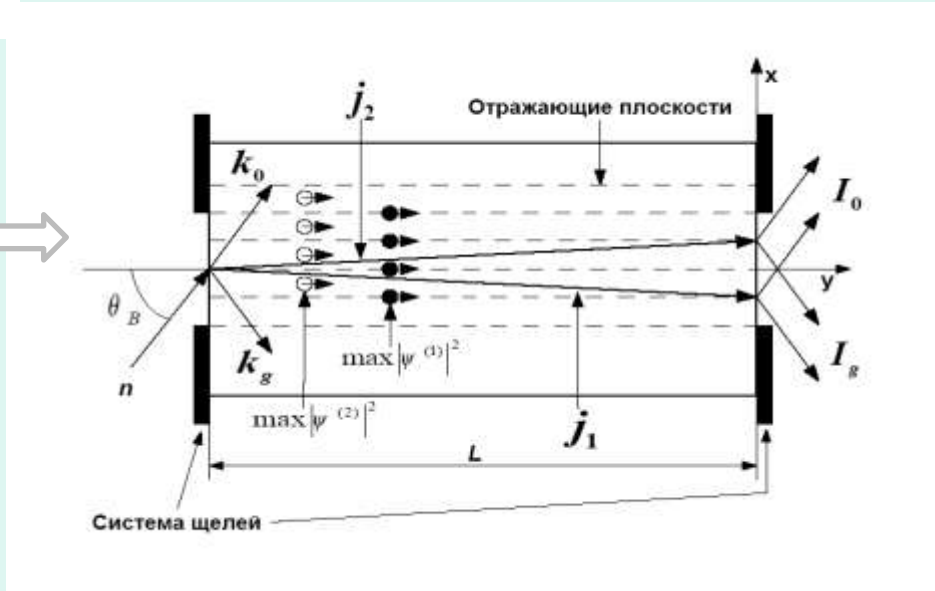


Working crystallographic plane is (220)

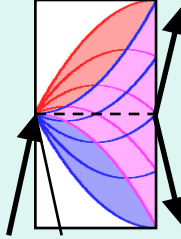
$$d = 1,92 \cdot 10^{-8} cm$$

$$\Delta d / d \sim 10^{-8} cm^{-1}$$


отражающие плоскости
j_2
$j_{2,2}$
$j_{2,1}$
k_0
I_0
k_g
I_g
n
j_1
$j_{1,1}$
$j_{1,2}$
L/2
L/2
Система щелей


x
j_2
Отражающие плоскости
k_0
I_0
y
θ_B
k_g
$\max|\psi^{(1)}|^2$
I_g
n
$\max|\psi^{(2)}|^2$
j_1
L
Система щелей

Experimental observation of Laue diffraction in the large silicon crystal (L=220 mm)



220 silicon plane intensity reflex

$$N_{1,2} \sim \exp\ -L_{eff}\,\mu_{1,2}$$

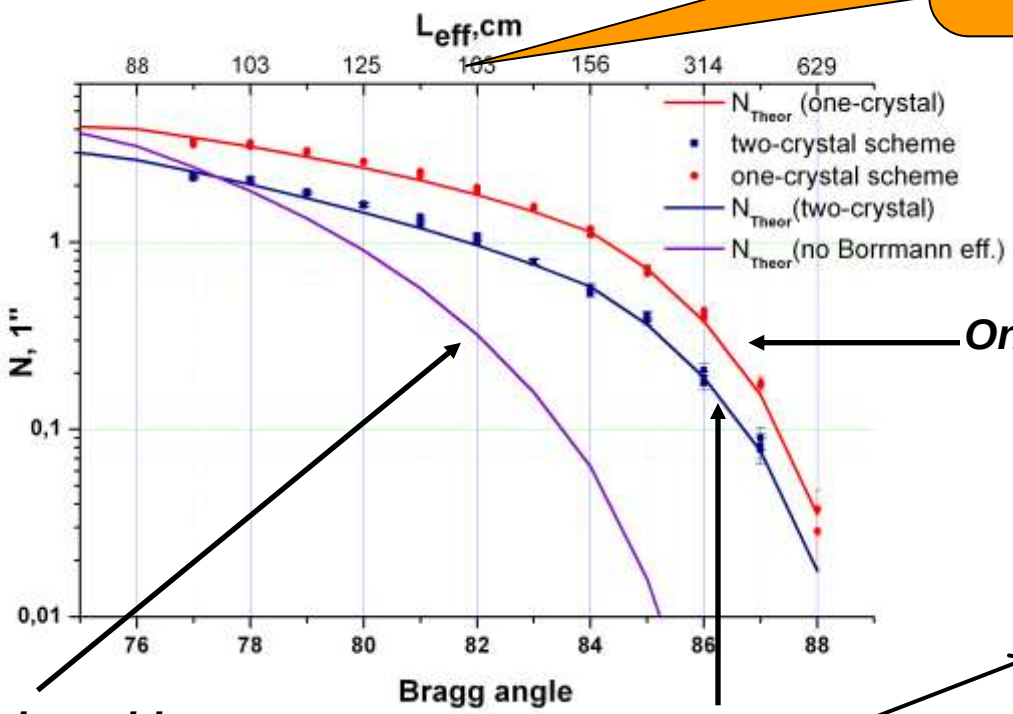
Effective crystal length (L/cos(θ_B)) can reach few meters

$$\mu_{1,2} = \mu_0\ \ 1 \pm \varepsilon_g$$

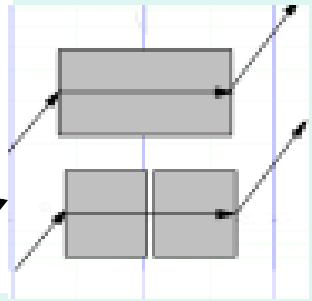
$$\mu_1 = 0,05$$

$$\mu_2 < 0,003$$

$$L_{abs}^{\psi\ 2} \sim 10 L_{abs}$$



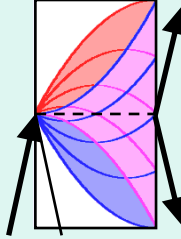
One-crystal scheme



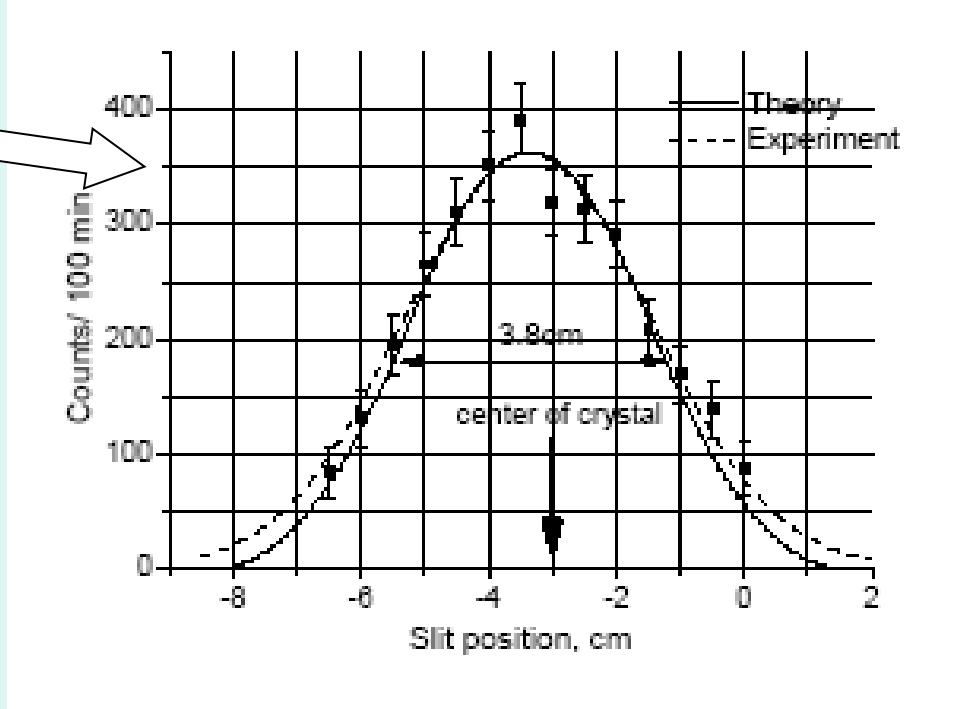
Two-crystal scheme

Theoretical prediction without taking Borrmann effect into account

Experimental test of the two-crystal setup possible resolution



$$\theta_B = 78^\circ$$
$$\delta_S = 15\,mm$$

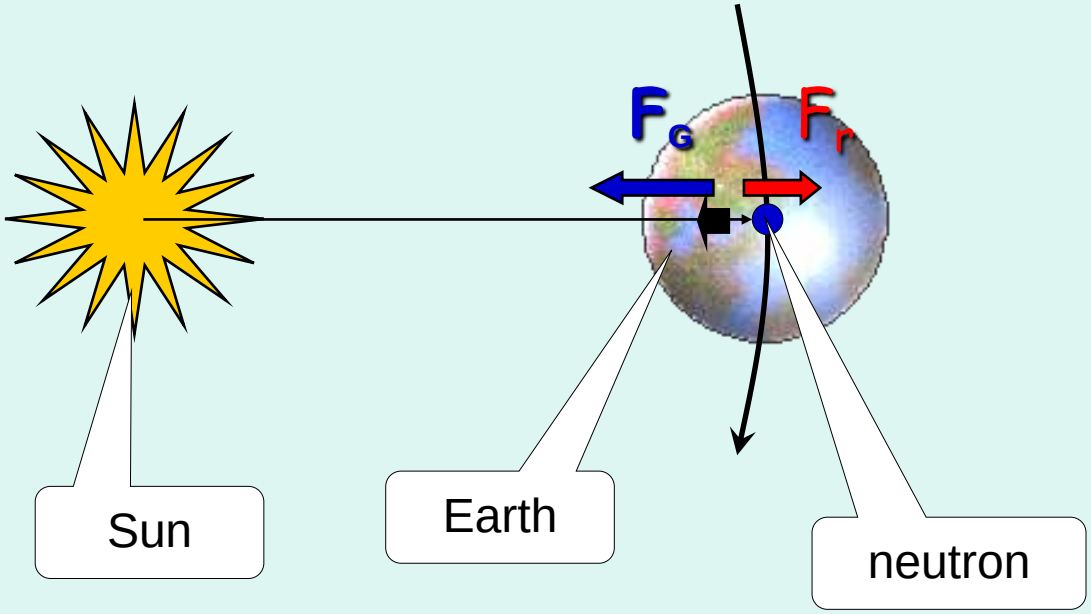


$$W_F^{exp} \approx 4 \cdot 10^{-11}\, eV / cm = 4 \cdot 10^{-2}\, m_n g$$

$$\theta_B = 86^\circ,\ \delta_S = 2\,mm \Rightarrow W_F \approx 5 \cdot 10^{-13}\, eV / cm = 5 \cdot 10^{-4}\, m_n g$$

The possible sensitivity of the setup for 100 days of statistic accumulation (with high flux neutron beam) $\Rightarrow \sigma\ F_{ext} \approx 5 \cdot 10^{-18}\, eV / cm$

Idea of m^i/m^g experiment with neutron (NGrav)



$F_G \sim m^g$; $F_r \sim m^i$

$F_G = F_r$ for the Earth

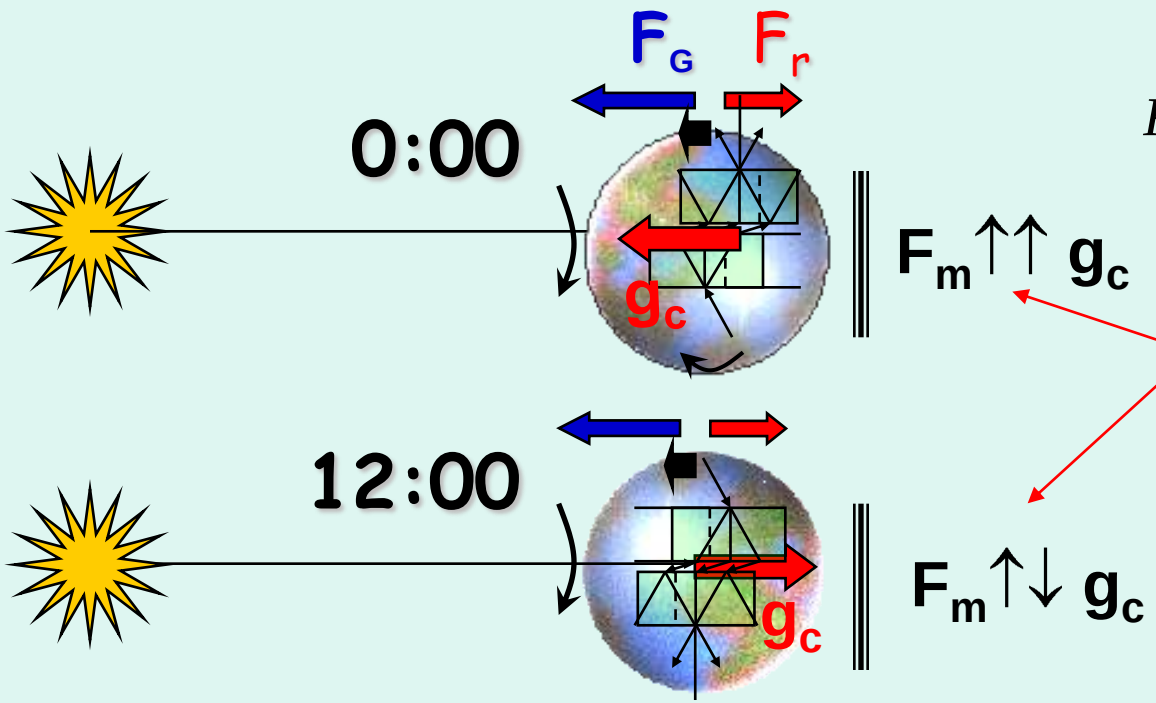
$$? \frac{m_n^i}{m_n^g} \neq \frac{m_\otimes^i}{m_\otimes^g} ?$$

$F_G \neq F_r$ for the neutron

Possible appearance of the non zero force:

$$F_m \equiv F_G - F_r = G \cdot \frac{m_\otimes^g m_n^g}{R^2} \left(1 - \frac{m_n^i / m_n^g}{m_\otimes^i / m_\otimes^g} \right) \Bigg|_{m_\otimes^i / m_\otimes^g \equiv 1} \approx 6 \cdot 10^{-13} \left(1 - \frac{m_n^i}{m_n^g} \right) eV / cm$$

Idea of m^i/m^g experiment with neutron (NGrav)



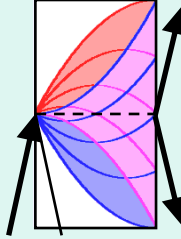
$$F_m \approx 6\cdot 10^{-13}\left(1-\frac{m_n^i}{m_n^g}\right) eV/cm$$

F_m changes its sign in the laboratory coordinate system

Daily oscillations of the *F_m value*

Our setup is sensitive to F_m oscillations

m^i/m^g experiment with cold neutron (NGrav)



Value of the external force in m^i/m^g experiment:

$$F_m \equiv F_G - F_r = G \cdot \frac{m_\otimes m_n^g}{R^2}\left(1 - \frac{m_n^i / m_n^g}{m_\otimes^i / m_\otimes^g}\right)\Bigg|_{m_\otimes^i / m_\otimes^g \equiv 1} \approx 6 \cdot 10^{-13}\left(1 - \frac{m_n^i}{m_n^g}\right) eV / cm$$

The possible sensitivity of the setup:

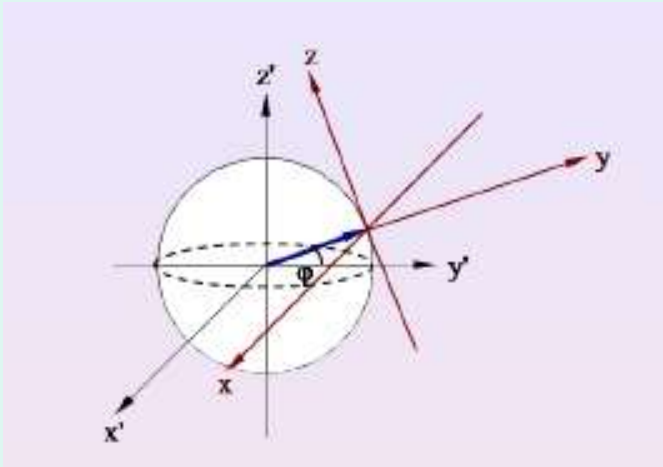
$$\sigma \quad F_{ext} \approx 5 \cdot 10^{-18} eV / cm$$

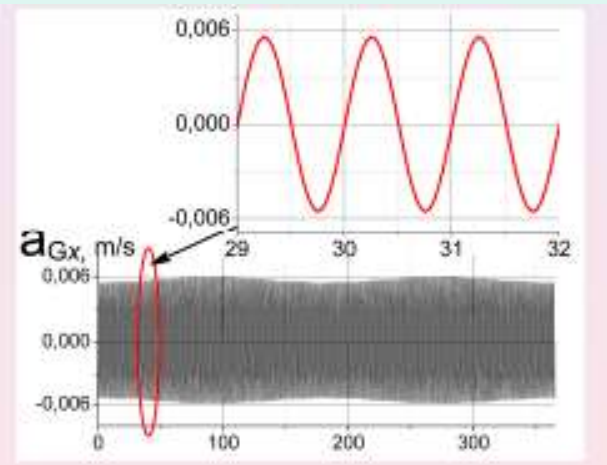
$$\delta_{i/G} \quad (m_G - m_i) / m_G \approx 10^{-5}$$

Present accuracy $1.8 \cdot 10^{-4}$ (Schmiedmayer, 1989)

More than one order better than the present day value

*Influence of noninertial forces**





1. ***Tidal forces:***
   Value ~ 10^{-17} eV/cm
   Period 12 hours

2. ***Coriolis forces for cold neutron:***
   Value ~10^{-12} eV/cm
   Constant

The force we are looking for:
Value~10^{-17}eV/cm
Oscillation period=24 hours

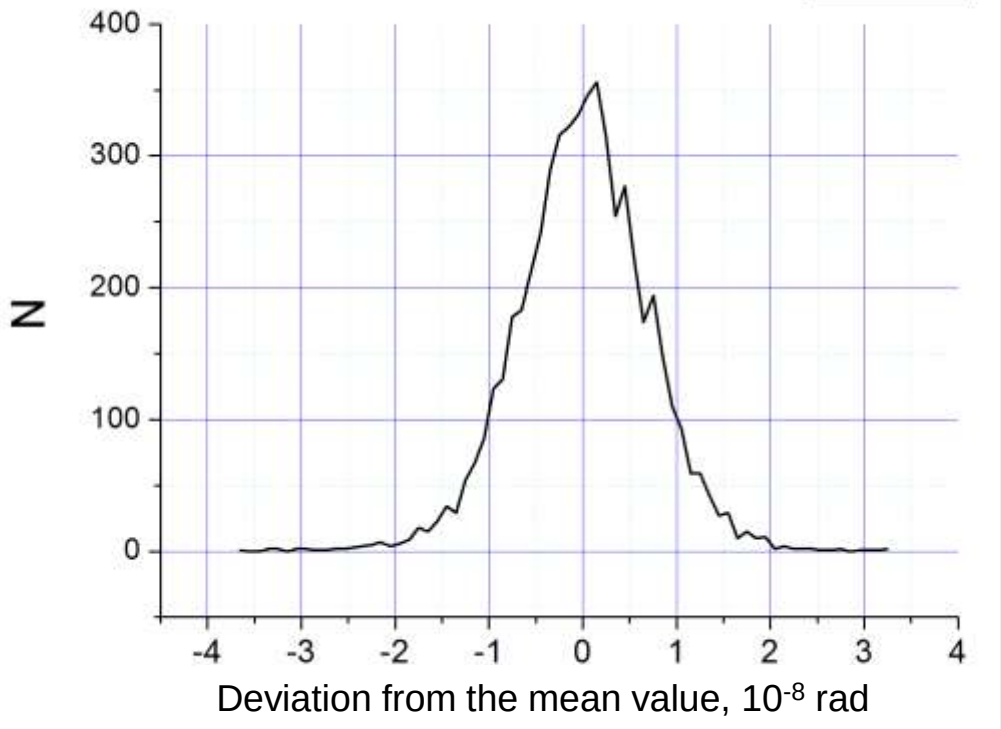
Annual acceleration variations caused by possible EP violation

*estimations are presented in PNPI Preprint-2827 (2009)

Working crystal horizontality control. The inclinometer test

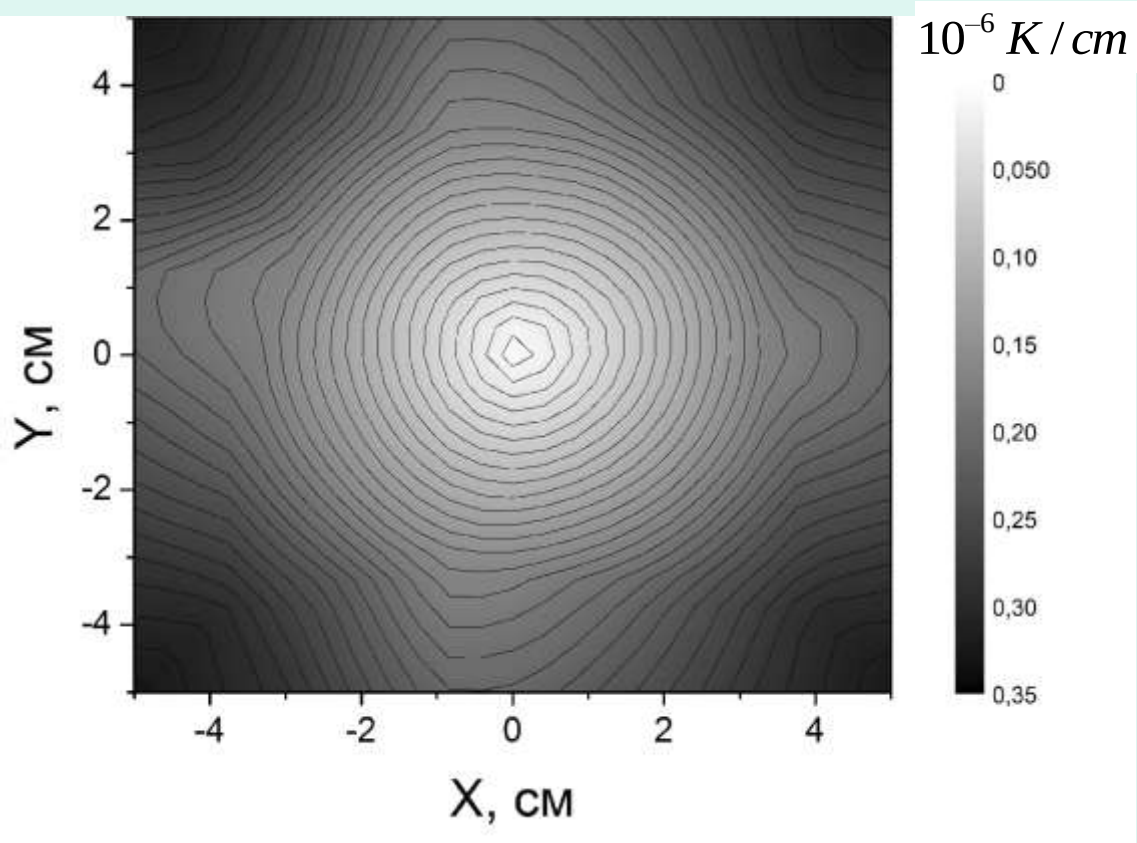
DDYP.02

Reading spread of the DDYP.02 inclinometer (60 seconds)



Reading spread for 60 seconds of measurement $\sim 10^{-8}\ rad$

Temperature uniformity



Simulation of the possible temperature gradients for the linear external thermal changes

$$10 \times 10\, cm^2\ (quartz\ crystal)$$

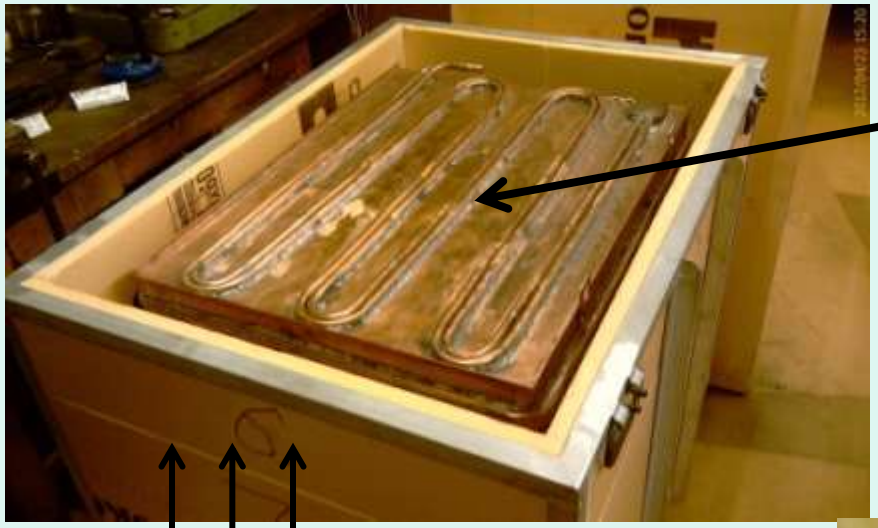
$$Rate\ of\ T^0\ change \approx 10^{-2}\ K/day$$

$$\xi_T \le 10^{-12}\ cm^{-1}$$

$$Influence \sim 10^{-5} m_n g << W_F$$

10^{-7} K/sec (≈0.01 K/day)
for the working crystal

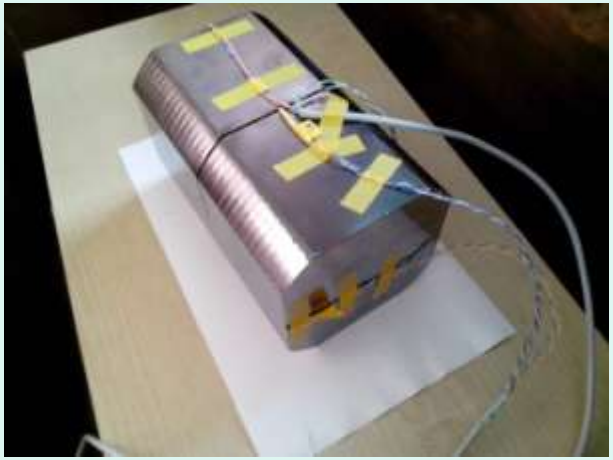
Temperature uniformity. Test of the new thermostat



Active shielding (circulating water)

Temperature control system (JULABO)

Passive shielding (expanded foam)



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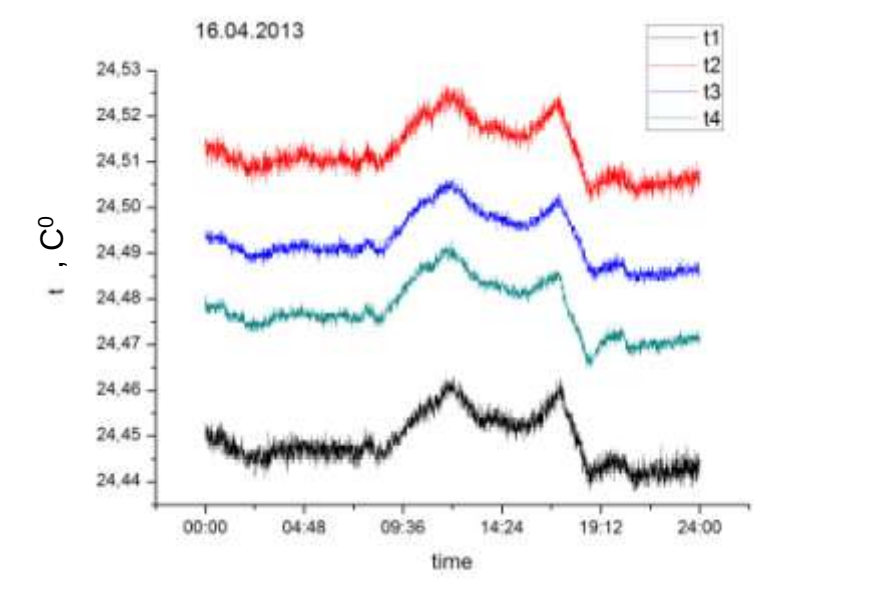
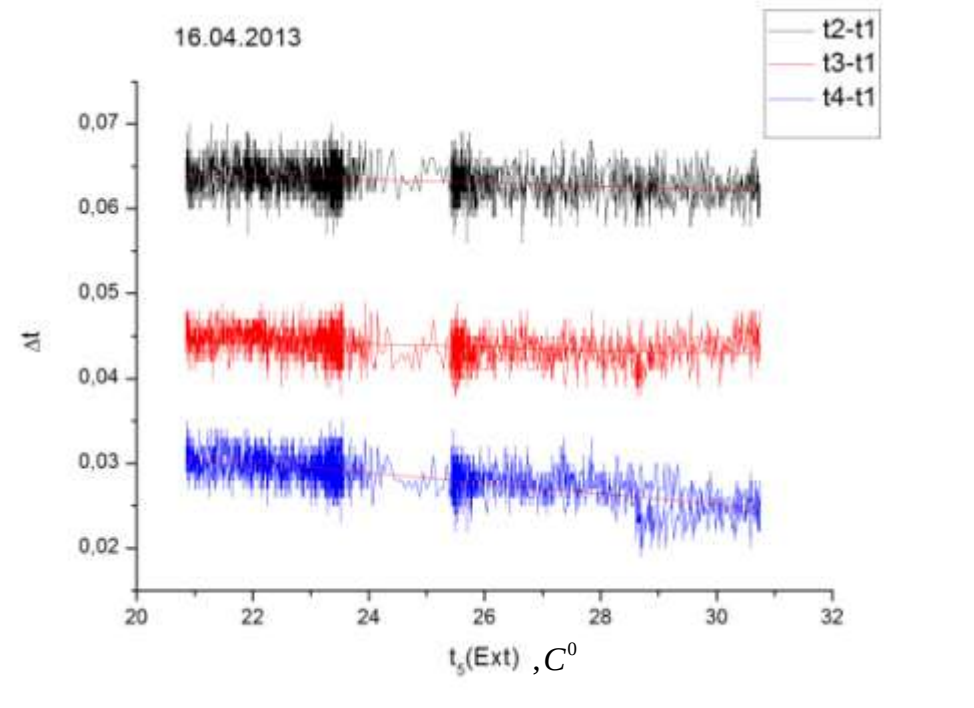


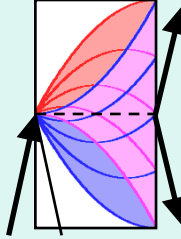
Data from thermal sensors installed on the crystal surface

Dependence of the difference between installed sensors from the external temperature changes.

It is on the level ~10^{-2} K



Summary and future plans



- *Two-crystal scheme of the Laue diffraction with Bragg angles close to the right one is a very sensitive experimental instrument (resolution to the external force reaches 10^{-13}eV/cm)*
- *The uncertainty of measuring inertial to gravitational mass ratio for the neutron (test of WEP) in NGrav experiment can reach magnitude ~10^{-5}*
- *All of the external impacts can be controlled on acceptable level with available technical equipment*
- *Installation of improved NGrav setup on the 2nd beam line of WWR-M - this autumn*
- *After test experiment – installation on a high flux research reactor (ILL, …)*

Thanks for Your attention!