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METHODS AND SYSTEMATIC ERRORS FOR SEARCHING FOR THE ELECTRIC DIPOLE MOMENT OF CHARGED PARTICLE USING A STORAGE RING

Introduction

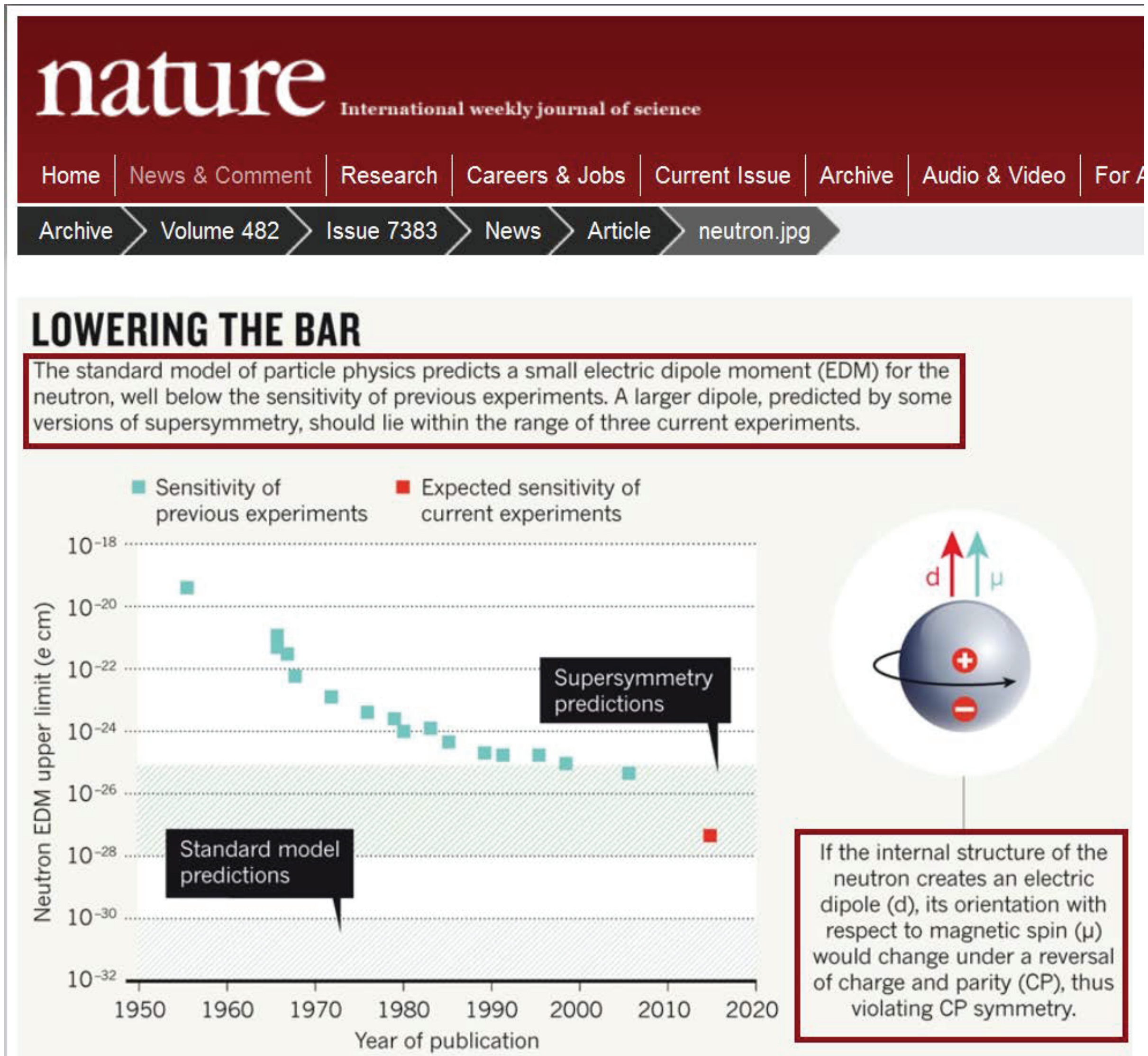
Accelerating complex NICA is the best candidate for searching for dEDM and Axion

The analysis done by the AD Sakharov, showed that this CP-violation is absolutely necessary to explain why on earth and in the visible universe there is a MATTER, but there is practically no ANTIMATTER

First message to search for Electric Dipole Moments(EDM) of fundamental particles: *it came to understand the CP violation*

Second message for Electric Dipole Moments of fundamental particles*: the baryon asymmetry of the Universe that represents the fact of the prevalence of matter over antimatter*

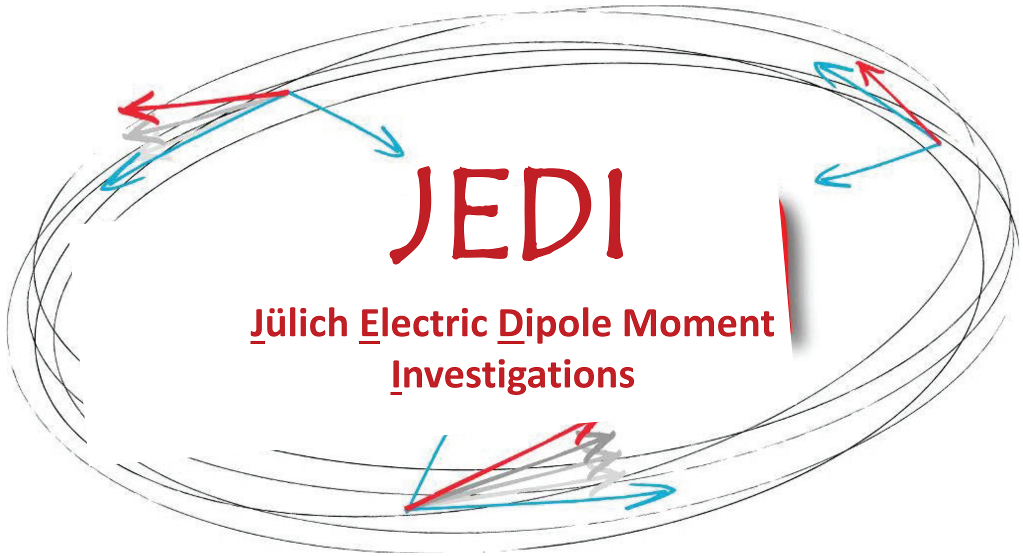
Current results for neutron:



Storage Ring EDM Project

Options:

Electric ring (proton or electron): only **E-field**
Electro-magnetic field ring (deuteron): **E- and B-fields**



JEDI includes Russian institutes: JINR, INR, ITP Landau, St-PbSU, BINP, St-PbNPI

Basic principle of EDM measurement in ring comes from "Tomas-Bargmann, Michel,Telegdi" equation with EDM term

The spin is a quantum value, but in the classical physics representation the "spin" means an expectation value of a quantum mechanical spin operator:

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}$$

$$\vec{\Omega} = -\frac{e}{m}\left\{ G\vec{B} + \left(\frac{1}{\gamma^2 - 1} - G\right)\left(\vec{\beta} \times \vec{E}\right) + \frac{\eta}{2}\left(\vec{E} + \vec{\beta} \times \vec{B}\right) \right\}$$

$G = \dfrac{g-2}{2}$, G is the anomalous magnetic moment, g is the gyromagnetic ratio

EDM

$$d = \eta e\hbar / 4mc$$

$$\eta = \frac{4d \cdot mc^2}{e\hbar c} = \frac{4 \cdot \left[10^{-31} e \cdot m\right] \cdot \left[938.272 MeV\right]}{e \cdot \left[6.582 \cdot 10^{-22} MeV \cdot \sec\right] \cdot \left[2.9979 m/\sec\right]} \approx 2 \cdot 10^{-15}$$

Frozen spin method for purely electrostatic proton ring at “magic” energy

In the **method** the beam is injected in the electrostatic ring with the spin directed along momentum **S**$\|$**p** and **S$\perp$E; S={0,0,S_z} and E={E_x,0,0}**

at “magic” energy : $$\frac{1}{\gamma_{mag}^2 - 1} - G = 0$$

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}$$

$$\vec{\Omega} = -\frac{e}{m}\left\{ \qquad + \frac{\eta}{2}\left(\vec{E} + \qquad \right)\right\}$$

$$G = \frac{g-2}{2},$$

MDM spin frequency

EDM spin frequency

Frozen spin method for deuteron:

Frozen spin lattice for deuteron based on the «B+E» elements:

- the spin of the reference particle is always oriented along the momentum

$$\Omega_{MDM} = G\overrightarrow{B_y} + \left(\frac{1}{\gamma^2 - 1} - G\right)\left(\frac{\overrightarrow{\beta_z}}{c} \times \overrightarrow{E_x}\right) = 0 \quad \Rightarrow \quad E_x \approx G B_y c \beta \gamma^2$$

Most important problems in the ring for EDM search:

1. Frozen (or quasi-frozen) spin lattice
2. Spin decoherence
3. Systematic errors

Two concepts of lattices for deuteron EDM search have been investigated:

1. Frozen Spin (FS) method
2. Quasi-frozen spin (QFS) method

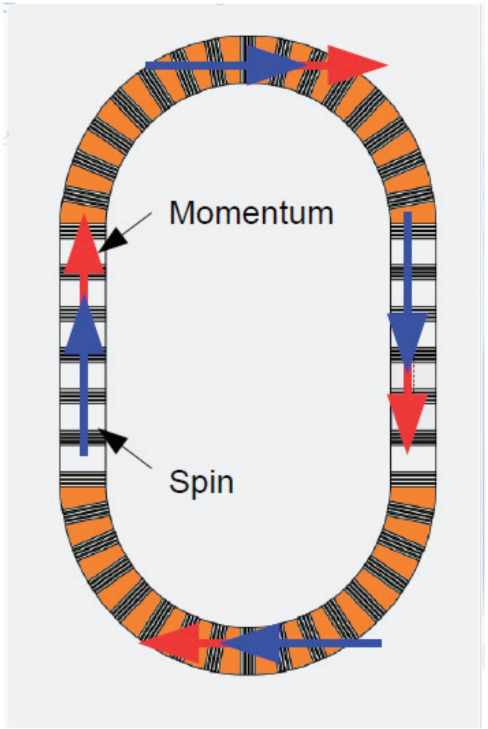
Frozen spin method

$$\left(\frac{1}{\gamma^2-1}-G\right)\left(\frac{\vec{\beta}\times\vec{E}}{c}\right)+G\vec{B}=0$$

- Combined E+B elements:
  radial E field and vertical B field
- The ring radius depends on deuteron G factor and energy
- For 270 MeV deuterons the ring radius and length are:

$$R=\frac{|G|}{(|G|-1)}\cdot\left[\frac{mc^2}{eE}\right]\gamma^3\beta^2\approx 9.2\,\mathrm{m}$$

Length = 145 m



Quasi-frozen spin method

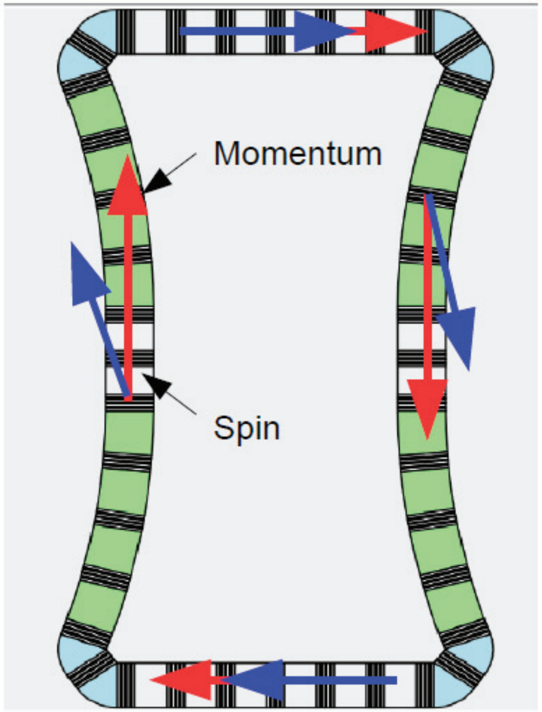
$$\gamma G \Phi_B = \left[\frac{1}{\gamma}(1-G) + \gamma G\right]\Phi_E$$

Φ_E and Φ_B - the angles of the momentum rotation in the electric and the magnetic parts of the ring

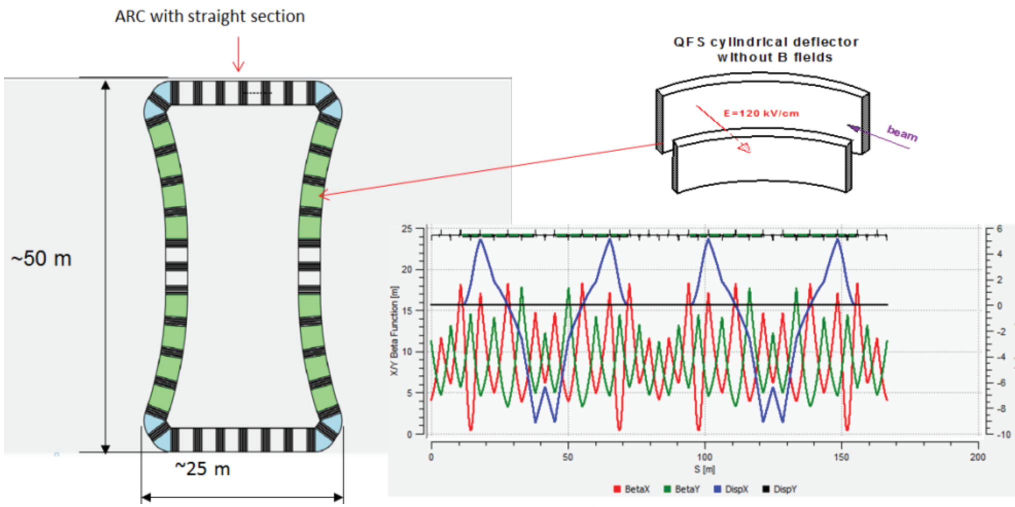
- Electric arcs with negative curvature and magnetic arcs
- The radii should fulfil the condition that keeps the spin vector parallel to the momentum after one revolution

$R_{magnetic} \approx 2.3$ m
$R_{electric} \approx 42.1$ m

Length = 166 m



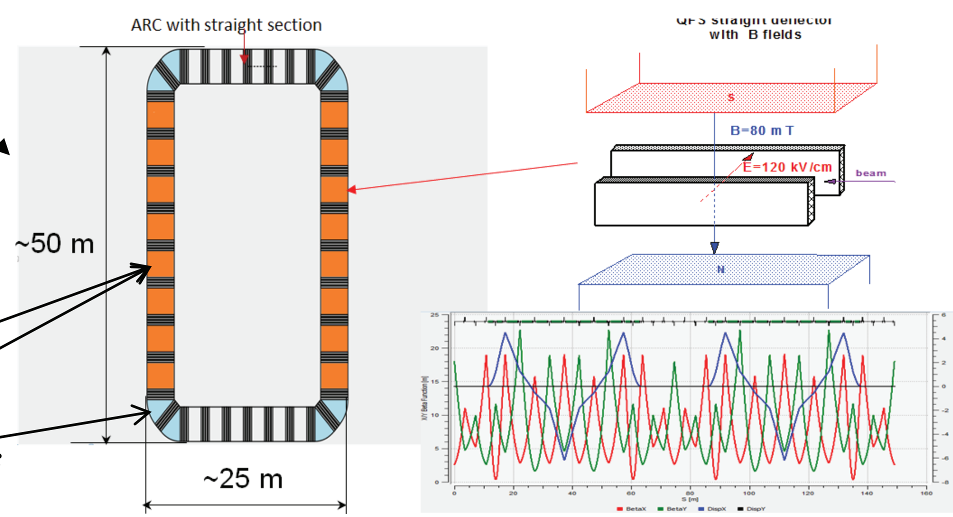
QFS lattice



$$r'' - \frac{1}{r} + \frac{1}{R_{eq}^2} r = 0$$

$$\frac{d^2x}{ds^2} = -\frac{2eU_0}{mv_\vartheta^2 d}$$

$$\frac{d^2y}{ds^2} = 0$$



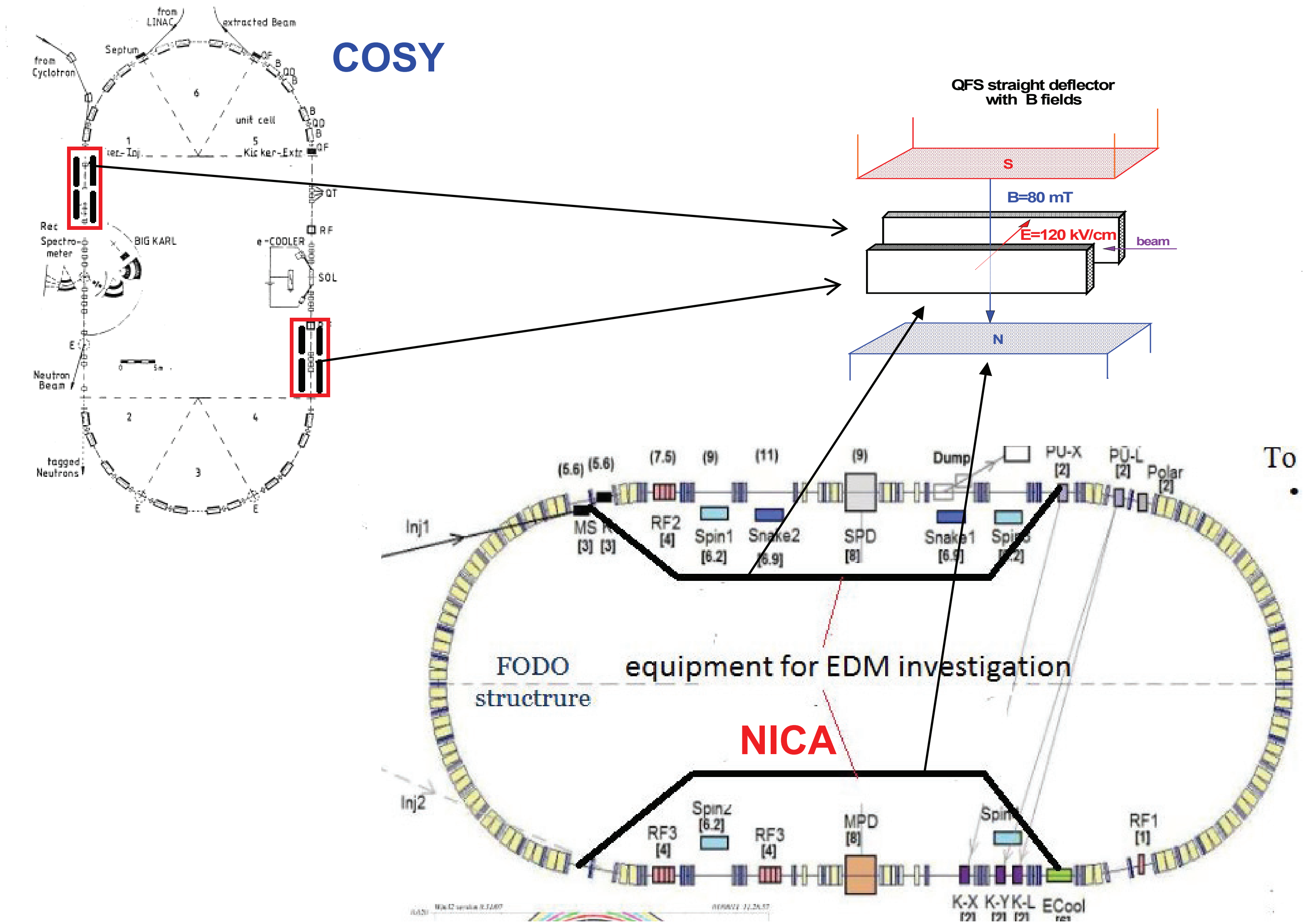
$$\Phi_{spin}^{B_{ss}} - \Phi_{spin}^{E_{ss}} = \Phi_{spin}^{B_{arc}}$$

B~100 mT

Main requirements to the experiment for search for EDM in the ring:

1. **Beam optics** (betatron tunes, sextupoles, DA, RF, straignt sections and so on)
2. **Spin coherence time** maximizing up to t_{coh} **>1000 sec** to provide the possible EDM signal observation
3. **Systematic errors** investigation to exclude "fake EDM signal"
4. Maximum **beam polarization** P~80%
5. **Beam intensity** $\sim 10^{10} \div 10^{11}$ particle per fill
6. Maximum **analyzing power** of polarimeter A~0.6
7. Maximum **efficiency of polarimeter** f> 10^{-3}
8. Total **running time** of accelerator ~5÷7 thousand hours
9. Minimum **radius of machine** with **E~10÷12 MV/m**

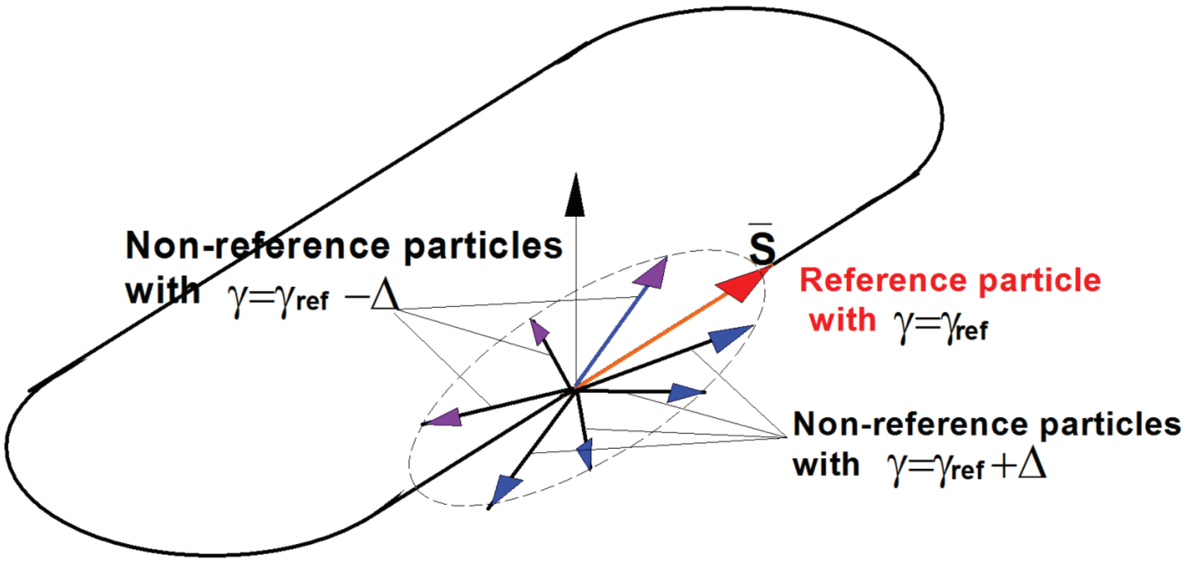
QFS in COSY ring and NICA



Spin tune decoherence

- **In magnetic field** $\longrightarrow$ $\Delta\Omega^{B}_{MDM} = \Delta\gamma \cdot G$
- **In electric field** $\longrightarrow$ $\Delta\Omega^{E}_{MDM} = \Delta\gamma \cdot \left[-G - (1+G)/\gamma_0^2\right] + \Delta\gamma^2 \cdot (1+G)/\gamma_0^3 + ..$

$$\sum_i \vec{S}_i (t = t_{decoh}) \rightarrow 0$$



Spin tune coherence :

RF field as a method for mix particles of energy

RF field

$$\rightarrow \Delta\gamma = \Delta\gamma_m \cdot \cos\left(\Omega_{synch} t + \varphi\right)$$

The longitudinal tune (number of longitudinal oscillations per turn) has to be one-two orders bigger of the spin tune spread without RF field:

$$\nu_z = \frac{1}{\beta_s}\sqrt{\frac{e\hat{V}h\eta}{2\pi E_s}} >> \nu_s = \gamma G \cdot \frac{\Delta\gamma}{\gamma}$$

With RF we increase SCT from 10^{-3} sec up to 10^{2} sec

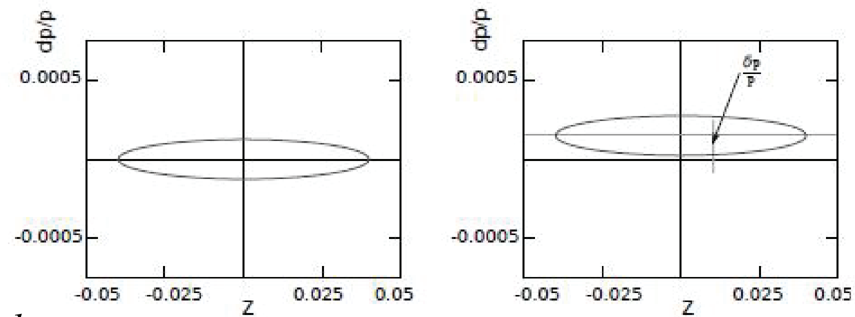
Orbit lengthening effects and effective gamma

- Momentum deviation is described by eq:

$$\frac{d^2\delta}{dt^2}+\frac{eV_{rf}\omega_{rf}}{\beta^2 E}\left(\alpha_0-\frac{1}{\gamma^2}\right)\cdot\delta=\frac{eV_{rf}\omega_{rf}}{\beta^2 E}\cdot\left[-\left(\alpha_1-\frac{\alpha_0}{\gamma^2}+\frac{1}{\gamma^4}\right)\cdot\delta^2-\left(\frac{\Delta L}{L}\right)_\beta\right]$$

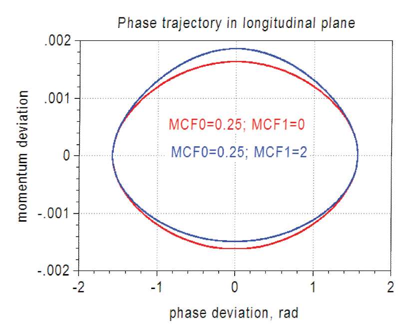
- Thus due to the betatron oscillation, the square term of momentum compaction factor α_1
- and the slip factor η dependent on the equilibrium level energy $\delta = 0$ is shifted
- by the value :

$$\Delta\delta_{eq}=\frac{\gamma_s^2}{\gamma_s^2\alpha_0-1}\left[\frac{\delta_m^2}{2}\left(\alpha_1-\frac{\alpha_0}{\gamma_s^2}+\frac{1}{\gamma_s^4}\right)+\left(\frac{\Delta L}{L}\right)_\beta\right]$$



$$\left(\frac{\Delta L}{L}\right)_\beta=\frac{1}{L}\oint\left(\frac{\rho+x_\beta}{\rho\cos\theta}-1\right)ds=\frac{1}{L}\oint\left(\frac{x_\beta}{\rho}+\frac{x_\beta'^2+y_\beta'^2}{2}\right)ds$$

$$\gamma_{eff}=\gamma_s+\beta_s^2\gamma_s\cdot\Delta\delta_{eq}$$

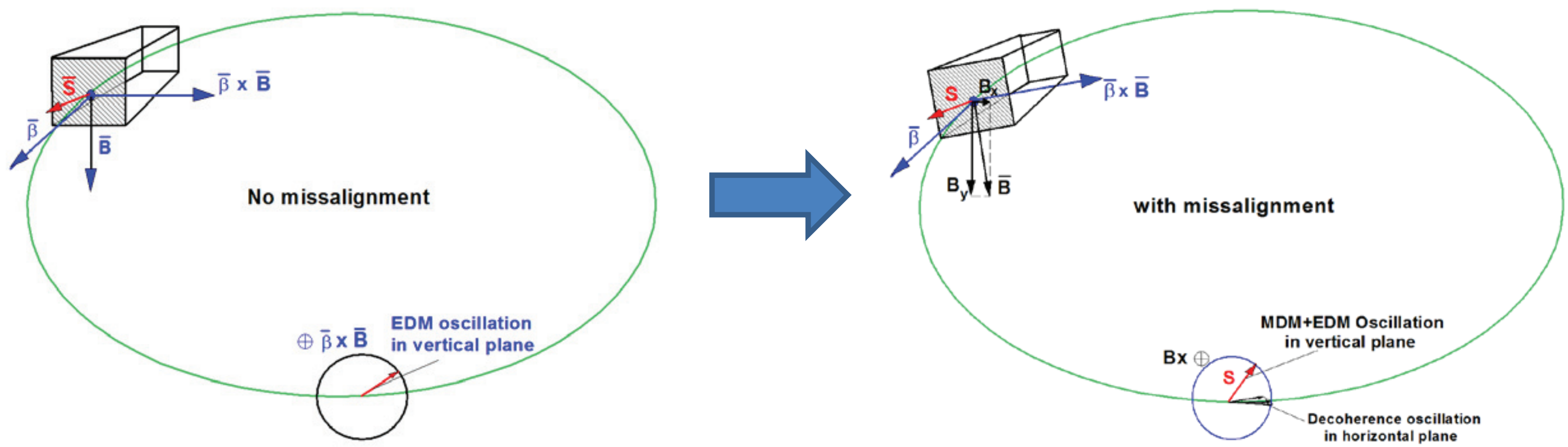


Systematic errors: ring with Imperfections

The difference between rings construction do not play an essential role with respect to the spin-orbital motion, so long as the motion of the reference particle in the perfect ring without imperfections is considered

Radial $\boldsymbol{B_r}$, vertical $\boldsymbol{E_v}$ fields ⟶ fake EDM signal

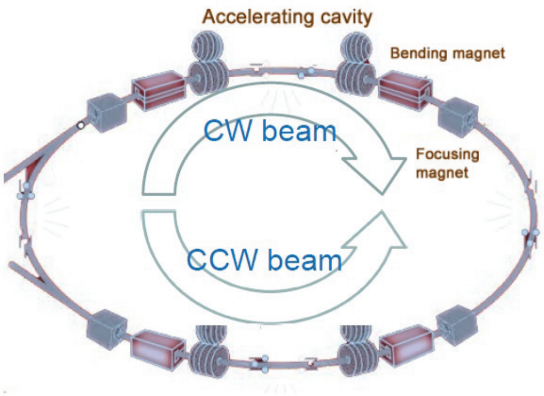
The presence of errors in the installation of the elements (imperfections) of the ring leads to the appearance of vertical and radial components of the electric and magnetic fields, respectively.



They both change the spin components in the vertical plane, in which the EDM signal is expected, and create the systematic errors that initiate <u>the "fake EDM" signal</u>.

CW and CCW procedures

To solve this problem in the case of a proton beam, it was suggested that the procedure of simultaneously injecting two beams in the ring in two opposite directions, clockwise (CW) and counter clockwise (CCW) [BNL], be used.



Adding the CW and CCW results together, the EDM can be separated from a systematic error arising due to MDM.

Currently four methods for measuring EDM are considered as working:

-BNL method

-Koop Wheel method

-Frequency Domain method

The main tasks to be solved by the methods under consideration are:

- what do we measure;
- decoherence suppression mechanism
- implementation of the reverse field at CW and CCW;
- systematic errors.

BNL: what does the method measure?

In the frozen spin regime it measures **the vertical projection of the spin**, that is, the amplitude of the changing part of the signal $\tilde{S}_y$ during a long time ~1000 sec, namely

$$\tilde{S}_y = \sqrt{\left(\frac{\Omega_y \Omega_z}{\Omega^2}\right)^2 + \left(\frac{\Omega_x}{\Omega}\right)^2} \sin(\alpha + \varphi)$$

$$\alpha = \Omega \cdot \mathrm{t}$$

the solution at the initial conditions for zero horizontal, vertical Sx,Sy and for longitudinal components Sz=1 in the general form

$$\Omega_x = \boldsymbol{\Omega_{edm}} + \Omega_{B_r} \qquad \Omega = \sqrt{\left(\boldsymbol{\Omega_{edm}} + \Omega_{B_r}\right)^2 + \Omega_y^2 + \Omega_z^2}$$

where $\Omega_x, \Omega_y, \Omega_z$ are frequencies of spin precession in X,Y and Z planes.

Basic concept of BNL method

- Expecting the EDM value at the level of $\widetilde{S}_y \approx 10^{-6} rad$ after 1000 sec and assuming that **the systematic errors** arise due to imperfection it is necessary to correct all misalignments to such a magnitude $\Omega_{\mathrm{B_r},\mathrm{E_y}} \neq 0$
$$\Omega_y, \Omega_z, \Omega_{\mathrm{B_r}} => 0 \text{ up to } \Omega_y, \Omega_z, \Omega_{\mathrm{B_r}} \leq \Omega_{\mathrm{edm}}$$

- This mode will be called **the 3-D frozen spin** or zero order spin resonance in 3D space, when the direction of the spin is fixed relative to the pulse in all three space directions.

- In that case the contribution will be determined only by the EDM signal, that is the total frequency .
$$\Omega \approx \boldsymbol{\Omega_{\mathrm{edm}}} + o(\Omega_{edm})$$

BNL: requirements to imperfections

- *first,* the accuracy of the installation of magnets should be less than 10^{-9} meters (**super unrealistic !!!);**

- *second*, the amplitude of $\tilde{S}_y$ depends on $\Omega_x, \Omega_y, \Omega_z$

$$\tilde{S}_y = \sqrt{\left(\frac{\Omega_y \Omega_z}{\Omega}\right)^2 + \left(\frac{\Omega_{B_r} + \Omega_{edm}}{\Omega}\right)^2} \sin(\Omega t + \phi)$$

$$\alpha = \Omega \cdot \mathrm{t} \quad \text{where } \Omega^2 = (\Omega_{B_r} + \Omega_{edm})^2 + {\Omega_y}^2 + {\Omega_z}^2$$

At $\Omega t \approx 10^{-6}$ ⇨ $\tilde{S}_y = \sqrt{(\Omega_y \Omega_z)^2 + (\Omega_{B_r} + \Omega_{edm})^2} \cdot t$

and $\Omega_y, \Omega_z, \Omega_{B_r}$ of the same order with Ω_{edm} we do not know the value of $\tilde{S}_y$.

BNL: the geometric phase

the GEOMETRIC PHASE occurs when the invariant spin axis changes direction from element to element, and when the total angle of spin rotation in each of the planes

$$\sum_{i}^{2n} \delta_i = 0$$

is zero, nevertheless after **n**-pairs of elements of one turn we have the non-zero MDM deviation:

$$S_{\mathrm{y}}^{\Sigma} = S_y^0 (1 - n\delta^2)$$

This is an real fact!!!

BNL: criterion for minimizing the contribution of the geometric phase

Obviously, this contribution should be less than the EDM angle rotation per turn

$$S_y^{\Sigma} = S_y^{0}(1 - n\delta^2)$$

that is

$$n\delta^2 < \alpha_{edm} \approx 10^{-6}/10^{9} = 10^{-15}$$

Thus, at n≈100 elements per one turn we must provide:

$$n\delta^2 < \alpha_{edm} \approx 10^{-6}/10^{9} = 10^{-15} \quad \text{or} \quad \delta \approx 10^{-8} \div 10^{-9}$$

- This is again **super unreal**!!!

BNL: how to restore conditions for a polarized beam at passing from CW to CCW

no reasonable ideas

Koop Wheel method: instead CW ⟺ CCW

split average trajectory in vertical plane Δ⟺ -Δ

The idea of measuring EDM by introducing a transverse coil and measuring the spin precession in the vertical plane was proposed in the wheel concept by I. Koop [[I A Koop 2015 Phys. Scr.2015 014034].

Ivan Koop proposes to install a transverse magnetic dipole and changing the polarity of the field in the dipole to use the separation of trajectories to calibrate the magnetic field in solenoid and try to measure the EDM.

Koop Wheel Method: Systematic errors

First, we have modelled Koop's method in a special structure with a large beta function in the vertical plane of ~ 1000 m, and even in this case the trajectories are separated by the distance of 10^{-9} m.

Second, taking into account the systematic errors in the method, we have:

$$\Omega_x(\pm\Delta) = \left(\Omega_{edm} + \Omega_{r,mdm} \pm \Omega_{B_x}\right)\sqrt{1 + (\Omega_y^2+\Omega_z^2)/\left(\Omega_{edm} + \Omega_{r,mdm} \pm \Omega_{B_x}\right)}$$

$$\Omega_x(\Delta) = \Omega_x(-\Delta)$$

$$\Omega_{edm} + \Omega_{r,mdm} + \Omega_{B_{x1}} = \Omega_{edm} + \Omega_{r,mdm} - \Omega_{B_{x2}}$$

$$\frac{\Omega_x(+\Delta)+\Omega_x(-\Delta)}{2} = \Omega_{edm} + \Omega_{r,mdm},$$

Koop Wheel Method: spin decoherence

The decoherence in the horizontal plane becomes almost zero, but simultaneously the spin decoherence arises in the vertical plane, where we are going to measure EDM, and it plays the major role.

$$\langle \Omega_{Bx} \rangle = \frac{e}{m\gamma}(\langle \gamma \rangle G + 1)B_x$$

Frequency Domain Method: what do we measure?

In Frequency Domain method we measure instead amplitude

$$\tilde{S}_y = \sqrt{\left(\frac{\Omega_y \Omega_z}{\Omega^2}\right)^2 + \left(\frac{\Omega_x}{\Omega}\right)^2} \sin[\Omega t + \varphi],$$

the frequency

$$\Omega = \sqrt{\left(\Omega_{edm} + \Omega_{B_r}\right)^2 + \Omega^2_{\mathrm{B_v}, E_r} + \Omega^2_{\mathrm{B_z}}},$$

Ω_x Ω_y Ω_z

Frequency Domain Method: systematic errors

Let us to consider the case when in

$$\Omega = \sqrt{\left(\Omega_{edm} + \Omega_{B_r}\right)^2 + \Omega^2_{\mathrm{B_v},E_r} + \Omega^2_{\mathrm{B_z}}},$$

We can not realize relation $\Omega^2_{\mathrm{B_v},E_r},\ \Omega^2_{\mathrm{B_z}} \ll \Omega^2_{edm}$,

but we can

$$\Omega^2_{\mathrm{B_v},E_r},\ \Omega^2_{\mathrm{B_z}} \ll \left(\Omega_{edm} + \Omega_{B_r}\right)^2$$

we have so called 2D frozen spin option:

$$\left(\Omega_{B_r}\right)^2 \gg \Omega^2_{\mathrm{B_v},E_r},\ \Omega^2_{\mathrm{B_z}}$$

Frequency Domain Method: basic relationships

$$\Omega = \left(\Omega_{edm} + \Omega_{B_r}\right)\left[1 + \frac{1}{2}\frac{\Omega^2_{B_v,E_r} + \Omega^2_{B_z}}{\left(\Omega_{edm} + \Omega_{B_r}\right)^2}\right] \Rightarrow \Omega = \Omega_{B_r} + \Omega_{edm} + \frac{1}{2}\frac{\Omega^2_{B_v,E_r} + \Omega^2_{B_z}}{\Omega_{edm} + \Omega_{B_r}}$$

$$\Omega_{edm} > \frac{1}{2}\frac{\Omega^2_{B_v,E_r} + \Omega^2_{B_z}}{\Omega_{edm} + \Omega_{B_r}} \Rightarrow \Omega_{B_r} > \frac{1}{2}\frac{\Omega^2_{B_v,E_r} + \Omega^2_{B_z}}{\Omega_{edm}}$$

finally

Main idea:

to make the contribution from EDM frequency into the total frequency $\Omega_{edm} + \Omega_{B_r}$ bigger than from MDM additions $\Omega^2_{\mathrm{B_v},E_r}, \Omega^2_{\mathrm{B_z}}$

Frequency Domain Method: 2D frozen spin

- Thus, we do not require 3D frozen spin when all three
- frequencies close to zero:

$$\Omega_y, \Omega_z, \Omega_{B_r} \Rightarrow 0 \text{ up to } \Omega_y, \Omega_z, \Omega_{B_r} \leq \Omega_{\text{edm}}$$

Now we realize 2D frozen spin with simple condition:

$$\Omega_{B_r} (\sim 10^2 \, rad/\sec) >> \Omega_{edm} (\sim 10^{-9} \, rad/\sec)$$

Having the frequency Ω_{B_r} ~50÷100 rad/sec in the vertical plane and making the frequencies Ω_{B_v,E_r} and Ω_{B_z} in other planes much smaller ~10^{-3} rad/sec we realize conditions, when the contribution of other frequencies is less than the contribution of the expected EDM frequency in the vertical frequency.

Frequency Domain Method: geometric phase

Making frequencies Ω_{B_v,E_r} and Ω_{B_z} up to the value of ~ 10^{-3} rad/sec (six orders higher of EDM) it does not mean we need to know them precisely for both CW and CCW.

In Frequency Domain Method there is no problem of the geometric phase, since the spin oscillates around the invariant spin axis under the above condition, and the contribution from frequencies of other planes is less than the EDM frequency.

During a revolution, the invariant axis does not jump, as in the BNL variant, but is oriented all the time along the horizontal direction with a kind of jitter, which on average gives zero contribution.

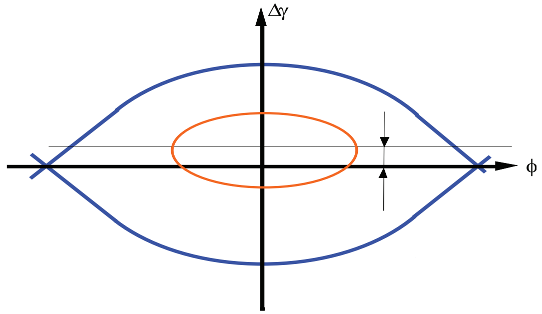
Effective gamma

Equation of Longitudinal motion:

$$\frac{d\phi}{dt} = -\omega_{rf}\left[\left(\alpha_0 - \frac{1}{\gamma^2}\right)\cdot\delta + \left(\alpha_1 - \frac{\alpha_0}{\gamma^2} + \frac{1}{\gamma^4}\right)\cdot\delta^2 + \left(\frac{\Delta L}{L}\right)_\beta\right]$$

$$\frac{d\delta}{dt} = \frac{eV_{rf}\omega_{rf}}{2\pi h\beta^2 E}\phi$$

$$\delta = \frac{\Delta\gamma}{\gamma}$$



$$\Delta\delta_{eq} = \frac{\gamma_s^2}{\gamma_s^2\alpha_0 - 1}\left[\frac{\delta_m^2}{2}\left(\alpha_1 - \frac{\alpha_0}{\gamma_s^2} + \frac{1}{\gamma_s^4}\right) + \left(\frac{\Delta L}{L}\right)_\beta\right]$$

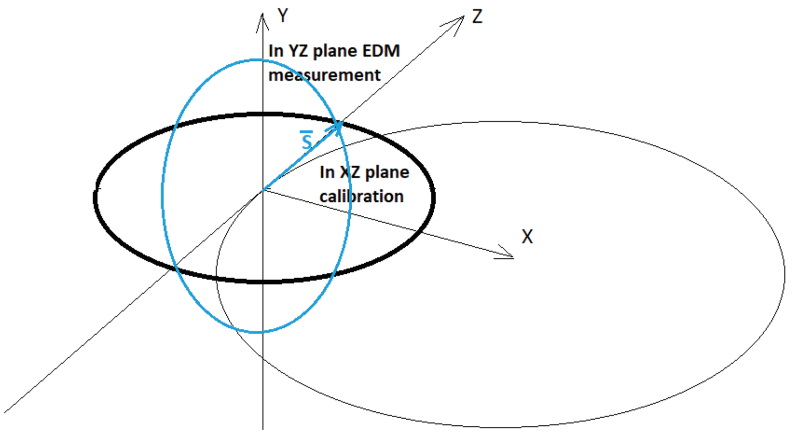
Nonlinear Z motion

Betatron motion

Frequency Domain method:
calibration of effective gamma

The second part of FDM strategy is when we calibrate the effective gamma by measuring the spin precession frequency in the horizontal plane, where there is no EDM, and we have the precession frequency of the spin in the horizontal plane much larger than the frequencies in other planes, that is the invariant spin axis coincides with the vertical axis, and we exclude the influence of frequencies in other planes on the calibration in the horizontal plane

Since the tilt of the spin precession axis is the same for the CW and the CCW beams, $\lim_{\nu_s^{CCW}-\nu_s^{CW}\to 0} \Omega_{r,mdm}^{CCW} - \Omega_{r,mdm}^{CW} \to 0.$



EDM measurement precision

the accuracy of the frequency measurement of determines the precision of the EDM measurement.

For an absolute statistical error of measuring a frequency of the spin oscillation, we can use

$$\sigma_{\Omega} = \delta\varepsilon_A \sqrt{24/N} / T$$

N - the total number of recorded events,

$\delta\varepsilon_A \approx 0.03$ - the relative error in measuring the asymmetry

$T \approx 1000$ sec is the measurement duration.

At 10^{11} particles per fill and a polarimeter efficiency of 0.01 an absolute error of frequency measurement is $\sigma_{\Omega} = 2 \cdot 10^{-7}$.

At an average accelerator beam time of 6,000 hours per year, we can reach $\sigma_{\Omega} \approx 10^{-9}$ rad/sec using one-year statistics,

that is the accuracy of frequency is satisfactory and sufficient for reaching at a parameter of $d_d \approx 10^{-30} e \cdot cm$

Что уже сделано на данный момент?

1. Разработана методика подавления декогеренции спина на COSY кольце за счет секступолей и экспериментально достигнуто время сохранения поляризации порядка 1000 секунд
2. Экспериментально достигнута абсолютная точность измерения прецессии спина на уровне 10^{-7} за один run.
3. Исследовано влияние e-cooling на длительность spin coherence time.
4. Исследован метод измерения EDM с использованием RF flipper
5. Разработан Frequency Domain Method исследования EDM малочувствительный к систематическим ошибкам.
6. Изучена 3D спин-орбитальная динамика пучка

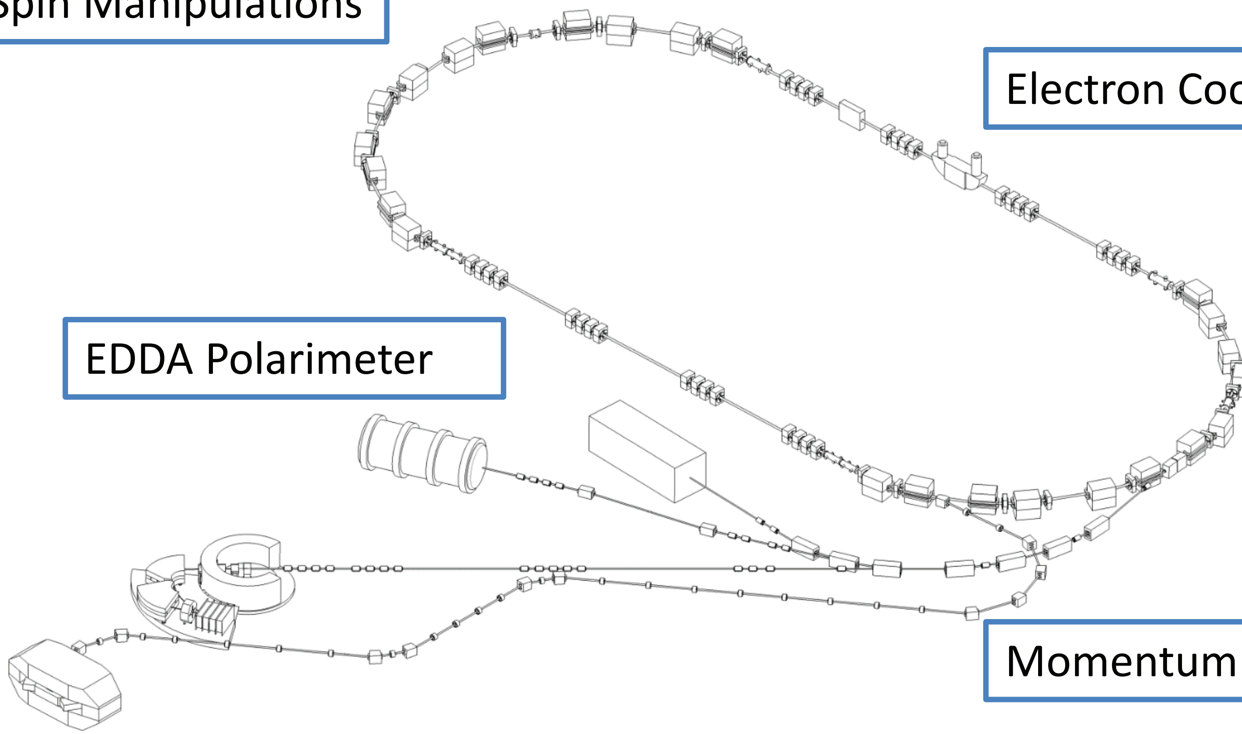
Cooler Synchrotron COSY in Jülich

RF Devices for Spin Manipulations

Sextupole magnets

Electron Cooler

EDDA Polarimeter



Momentum up to 3.5 GeV/c

Polarized Protons / Deuterons

Circumference 184 m

EDDA Polarimeter

- ***Left-Right*** asymmetry

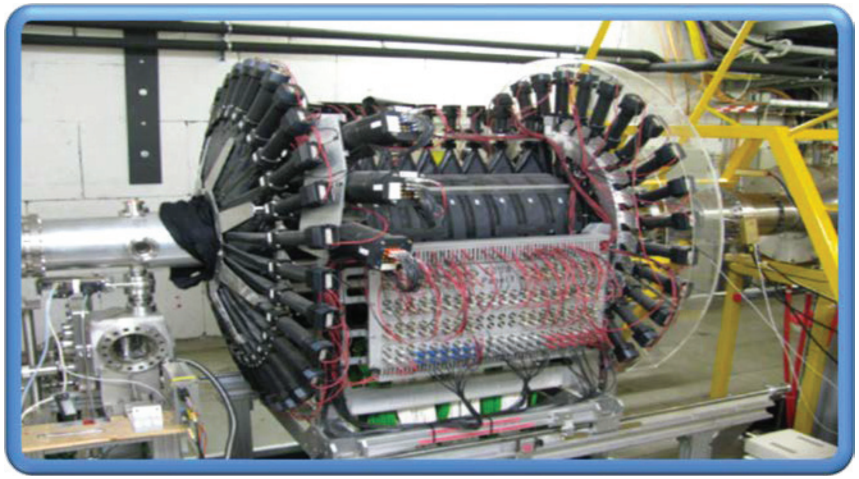
  ⇒ ***vertical*** polarization

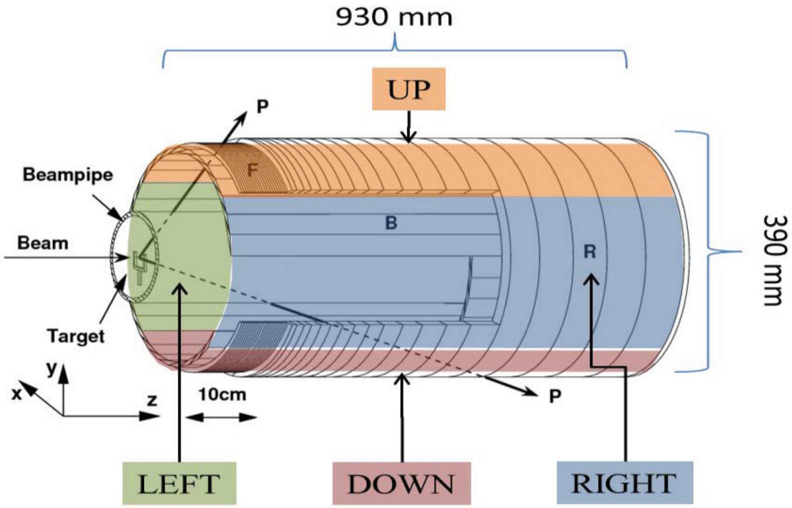
  $$P_V \propto \epsilon_{ver} = \frac{N_l - N_r}{N_l + N_r}$$

- ***Up-Down*** asymmetry

  ⇒ ***horizontal*** polarization

  $$P_H \propto \epsilon_{hor} = \frac{N_{up} - N_{dn}}{N_{up} + N_{dn}}$$





Spin Tune Measurement

Spin vector precesses with $f_{\text{Spin}} = \nu f_{rev}$ in the horizontal plane

Asymmetry given by:

$$\epsilon_V(t) = \frac{N_{up} - N_{dn}}{N_{up} + N_{dn}} \approx AP(t)\sin(2\pi\nu f_{rev} t + \phi)$$

What do we expect? (Deuterons, $p = 0.97\ \text{GeV/c}$)

$$\nu \approx 0.16, \qquad f_{rev} = 750\ \text{kHz}$$

Spin precession frequency: $\nu \cdot f_{rev} \approx 125\ \text{kHz}$

Detector rates: $5\ \text{kHz}$

Only every 25$^{\text{th}}$ spin revolution is detected

⇒ No direct fit is possible

Measurement of polarization asymmetry

$$\epsilon(\varphi_s) = \frac{N_D^-(\varphi_s) - N_U^-(\varphi_s)}{N_D^+(\varphi_s) + N_U^+(\varphi_s)}$$

An rf solenoid-induced spin resonance was employed to rotate the spin by 90° from the initial vertical direction into the transverse horizontal direction. Subsequently, the beam was slowly extracted onto an internal carbon target using a white noise electric field applied to a stripline unit. Scattered deuterons were detected in scintillation detectors, consisting of rings and bars around the beam pipe[, and their energy deposit was measured by stopping them in the outer scintillator rings. The event arrival times, with respect to the beginning of each cycle and the frequency of the COSY rf cavity, were recorded in one long-range time-to digital converter; i.e.,the same reference clock was used for all signals.

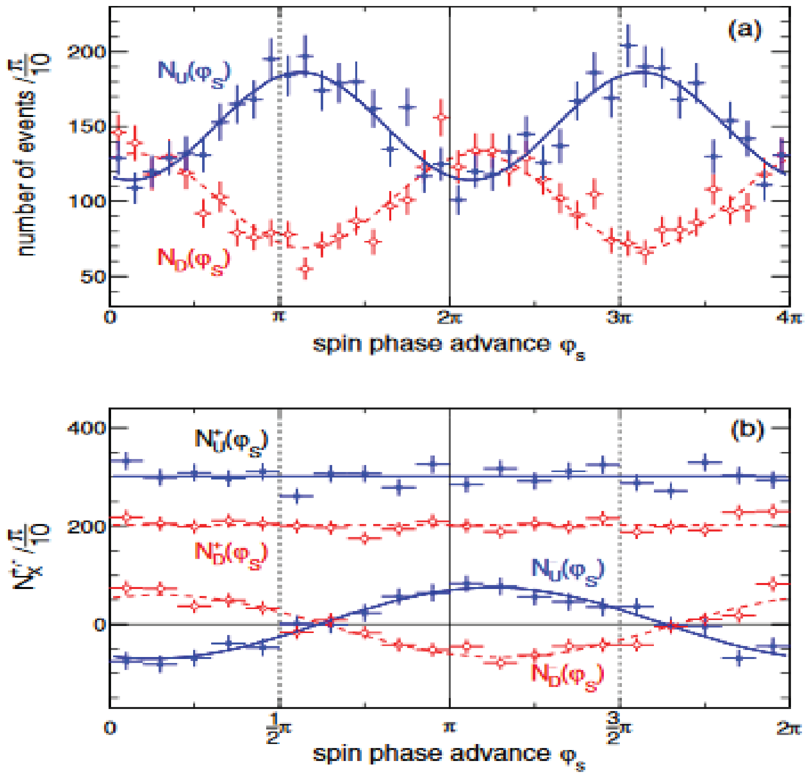
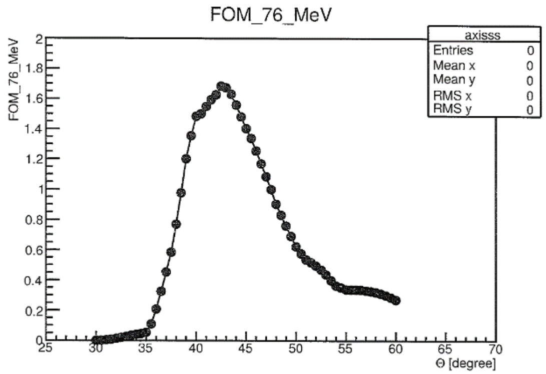


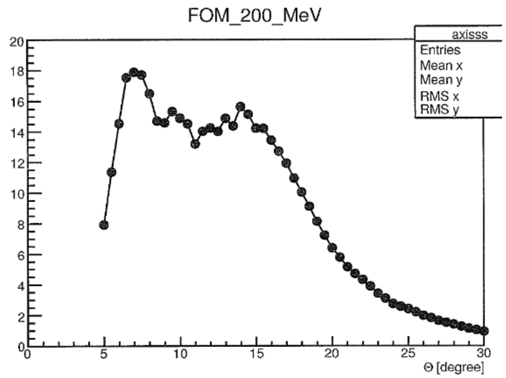
FIG. (a) Counts N_U and N_D after mapping the events recorded during a turn interval of $\Delta n = 10^6$ turns into a spin phase advance interval of 4π. (b) Count sums $N^+_{U,D}(\varphi_s)$ and differences $N^-_{U,D}(\varphi_s)$ of Eq. (6) with $\varphi_s \in [0, 2\pi)$ using the counts $N_U(\varphi_s)$ and $N_D(\varphi_s)$, shown in panel (a). The vertical error bars show the statistical uncertainties, the horizontal bars indicate the bin width.

Figure Of Merit vs Energy: choice of energy

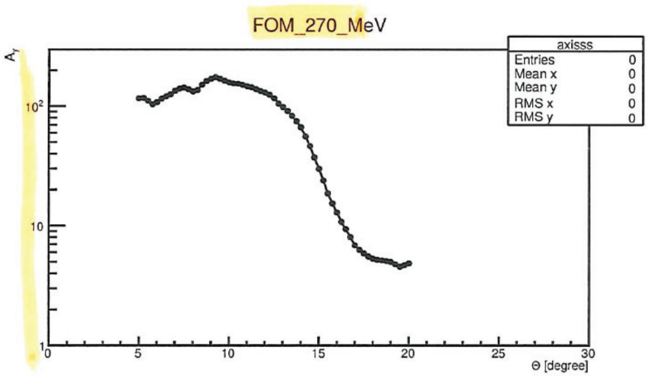
- 76 MeV



200 MeV



270 Mev



Search for AXION dark matter at NICA (K.Nikolaev ITP Landau)

- Peccei-Quinn (pseudogoldstone) axions solve the strong-CP problem
- Relic very light axions as a credible candidate for dark matter
- Extensive serch for axions in dozen expts worlwide
- Galactic axion field generates oscillating EDM and pseudomagnetic oscillating solenoidal field in the storage ring (Silenko 2021)
- Axion oscillation frequency $\omega_a = m_a c^2$
- Scan spin precession frequency ramping magnetic field in the ring until hitting the axion frequency (with good luck!): the axion signal is a sudden resonance (Froissart-Stora) rotation of vertical polarization towards horizontal one
- Detect the buildup of precessing horizontal polarization at SPD by the JEDI time stamp technique via azimuthal asymmetry of elastic scattering in the internal carbon target in SPD
- The beam halo is brought into interaction with the target heating the beam
- Detuned quasi-frozen spin regime gives access to very small axion masses
- No demand for any extra equipment beyond the internal target in SPD and heating the beam: just keep ramping the beam energy as much as possible


Thank you!