JÜLICH FORSCHUNGSZENTRUM

Yury Senichev

Search for charged particle Electric Dipole Moments in storage rings

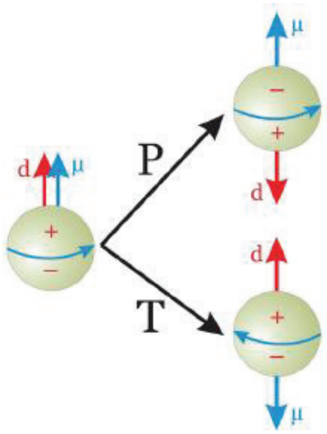
on behalf of Collaboration "JülichElectricDipole moment Investigation"

18. November 2016

Electric Dipole Moment and Standard Model

Within the framework of the Standard Model,
the reasons for the violation of the **CP symmetry**
is still not understood .

But CP violation is the only known mechanism
(A.D. Sakharov) that could explain
the matter-antimatter asymmetry found in Universe.



The electric dipole moments (EDM) of fundamental particles are excellent probes of physics beyond the standard model (SM), e.g. SUSY,
since they allow for values within experimental reach whereas
the SM predictions are several orders below them.

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

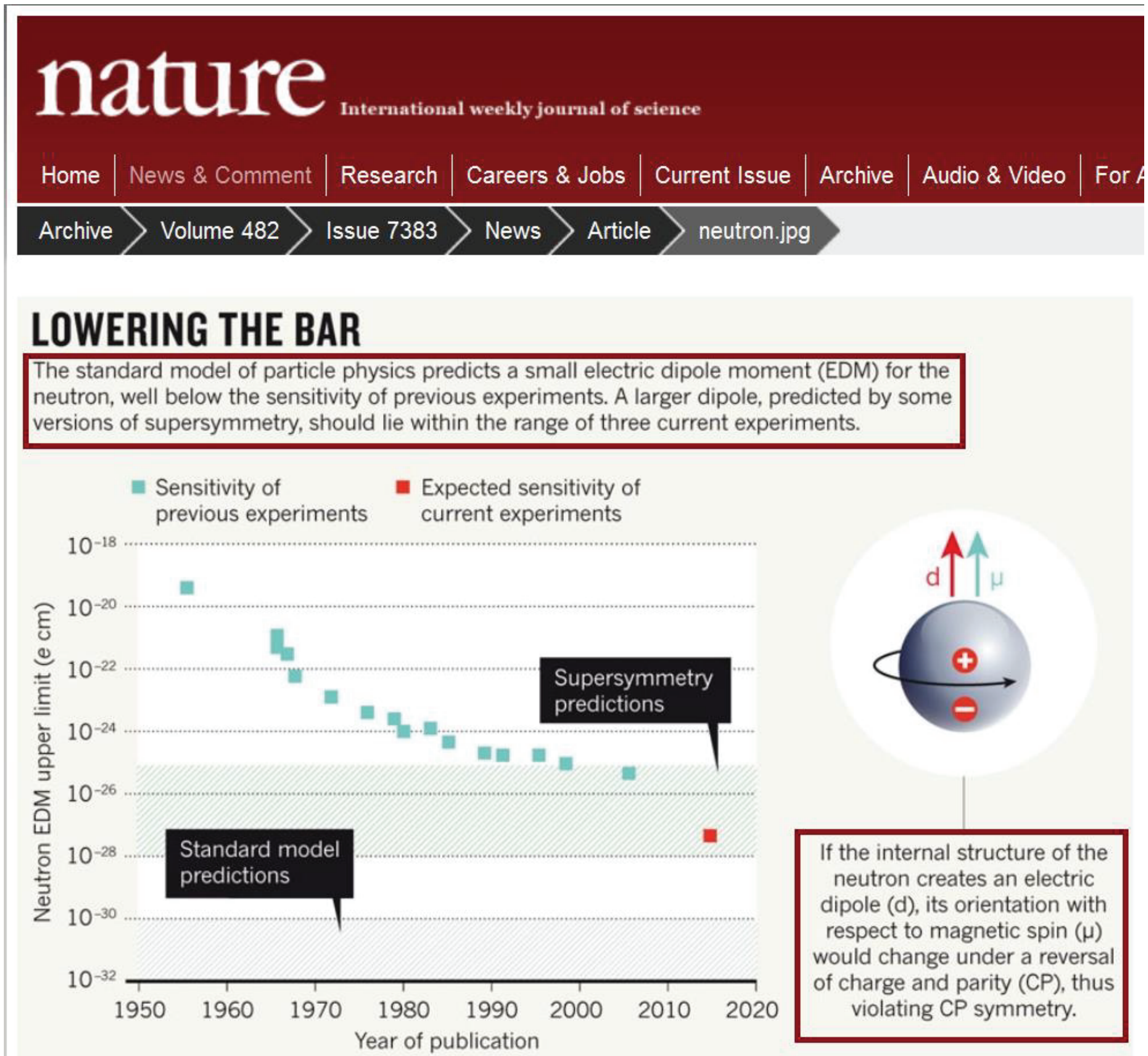
Second message for Electric Dipole Moments of fundamental particles: *the baryon asymmetry of the Universe that represents the fact of the prevalence of matter over antimatter*

In 1967 A.Sakharov has shown three necessary conditions for baryogenesis (initial creation of baryons)

- • Baryon number violation;
- • C-symmetry and CP-symmetry violation;
- • Interactions out of thermal equilibrium

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**.

Current results for neutron:



Current achievements in EDM measurement for fundamental particles:

The **S**tandart **M**odel predicts tiny non-vanishing values for EDMs of elementary particles for:

neutron EDM $d_n \sim 10^{-31} \div 10^{-32}$ e·cm,

electron EDM $d_e \sim 10^{-40}$ e·cm,

muon EDM $d_n \sim 10^{-38}$ e·cm.

but

Theories beyond the Standard Model provides EDMs that are several orders of magnitude higher such as SUSY models where neutron EDM is of the order of $d_n \sim 10^{-26} \div 10^{-30}$ e·cm.

at present

Despite of the efforts being made, an EDM of any elementary particle has not been found yet, and we have the limit estimation

neutron EDM $d_n < 2.9 \cdot 10^{-26}$ e·cm (with certainty 90%),

electron EDM $d_e < 10^{-29}$ e·cm, (with certainty 90%)

muon EDM $d_\mu < 1.8 \cdot 10^{-19}$ e·cm, (with certainty 95%)

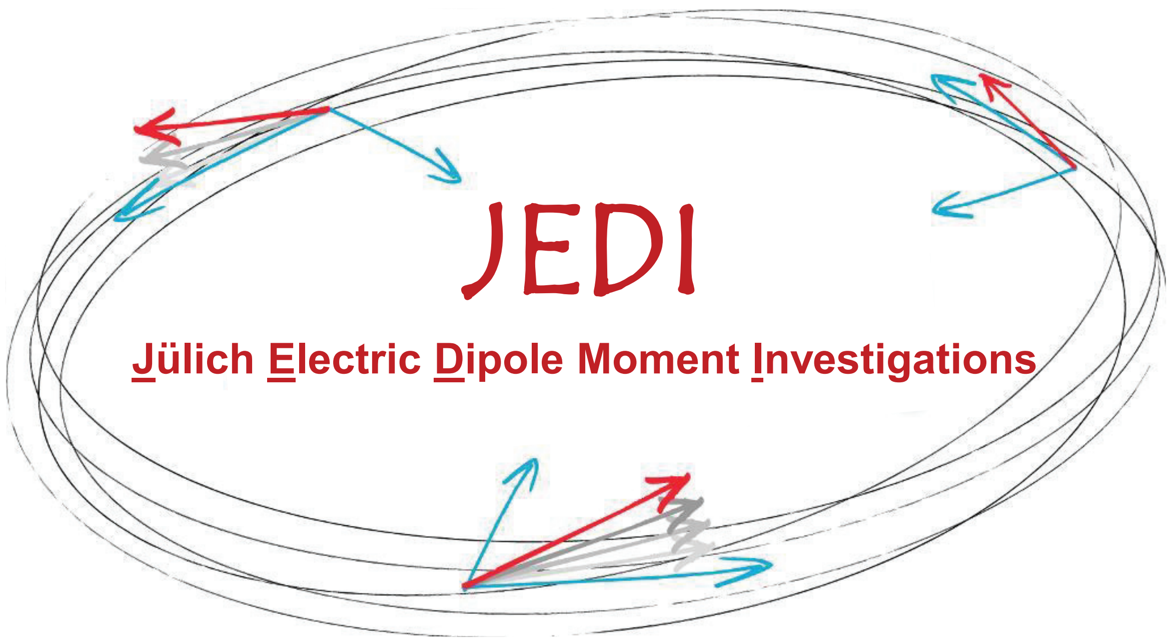
proton EDM $d_p < 5.4 \cdot 10^{-24}$ e·cm (without statistic estimation)

EDM opens the door to the "New Physics" and sheds light on the mystery of our Universe creation.

Storage Ring EDM Project

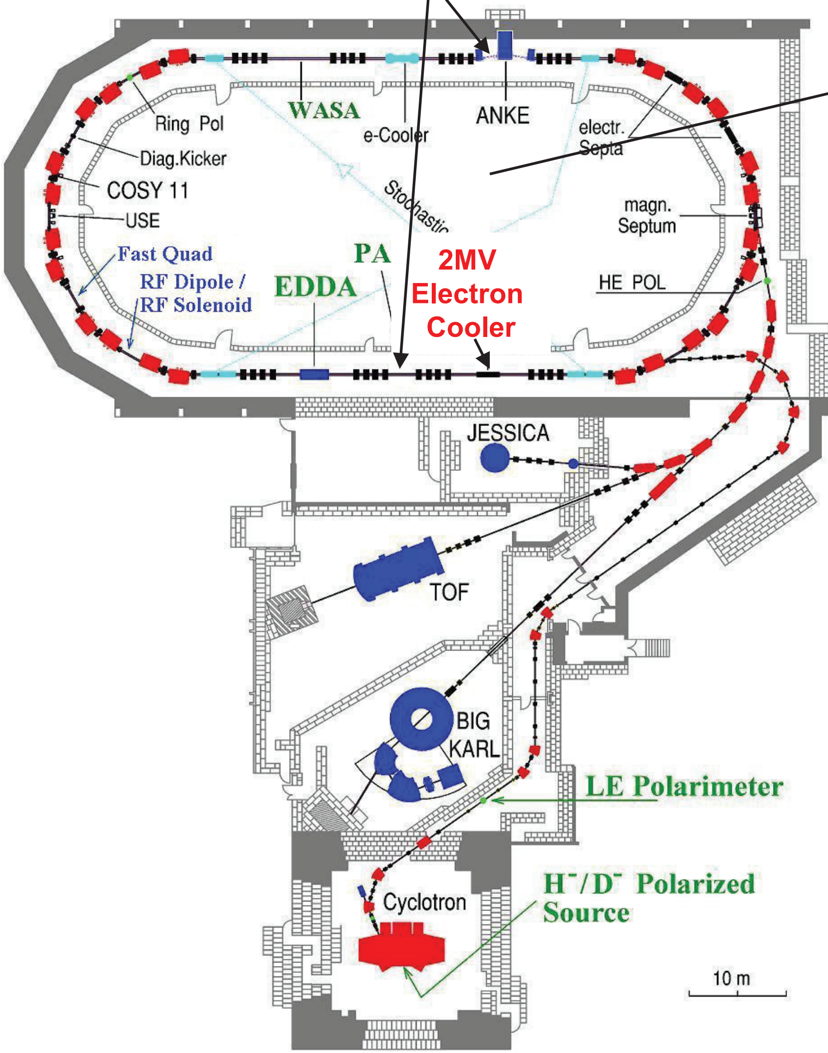
Options:

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



JEDI-Collaboration

Cooler Synchrotron COSY



Ions: (pol. & unpol.) p and d

Momentum: 300/600 to 3700 MeV/c for p/d, respectively

Circumference of the ring: 184 m

Electron Cooling up to 550 MeV/c

Stochastic Cooling above 1.5 GeV/c

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Basic principle of EDM measurement in ring comes from "Thomas-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:

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

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

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

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

EDM

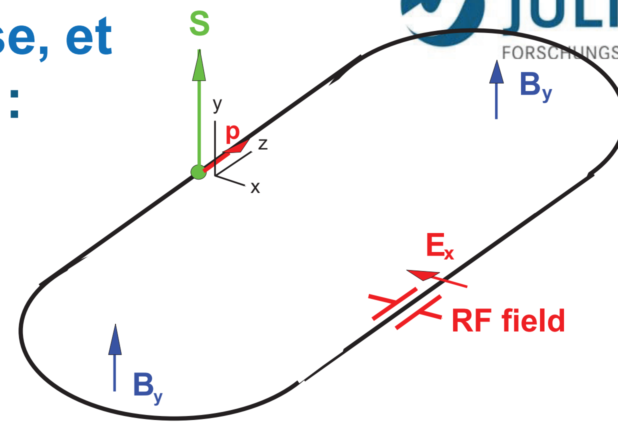
$$\eta = \frac{4d \cdot mc^2}{e\hbar c} = \frac{4 \cdot \left[10^{-31} e \cdot m\right] \cdot \left[938.272 MeV\right]}{e \cdot \left[6.582 \cdot 10^{-22} MeV \cdot \sec\right] \cdot \left[2.9979 m/\sec\right]} \approx 2 \cdot 10^{-15}$$

Two conceptions of ring for proton and deuteron EDM search:

1. Resonant method based on RF flipper
2. Frozen spin method

In resonant method* for p and d (W.Morse, et al.,) the spin frequency is parameterized :

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

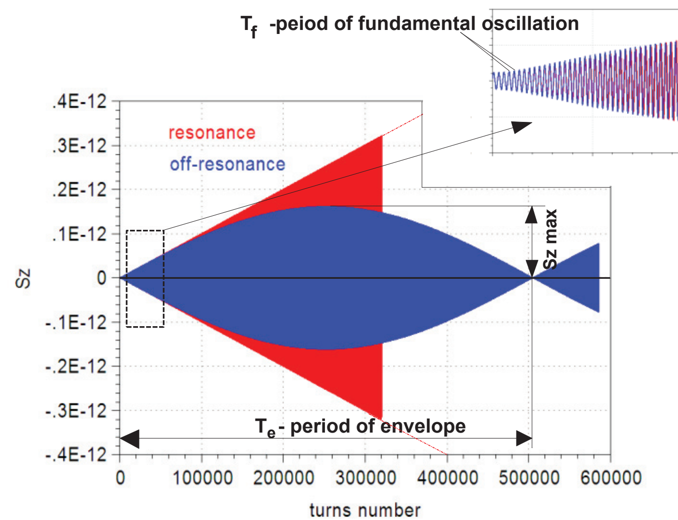


using RF field $\quad E \sim e^{i(f_{rf} \pm k f_{rev})t}$.

In case of parametric resonance when $\frac{f_{rf}}{f_{rev}} \pm k = \gamma G;\; k = 0,1,2,\ldots$ **we shall observe the resonant build up:**

$$S_z(n) = \frac{(2\nu_e \nu_s + h\nu_s)\cdot \sin 2\pi\nu_s n}{2\nu_s^2} - h\pi n \cdot \cos 2\pi\nu_s n$$

$$h = \frac{\eta}{2}\cdot\gamma\cdot\frac{E_{rf} l_{rf}}{B_y L_{cir}} \sim \text{EDM signal} \qquad \nu_s = \gamma G$$



Advantage: the method can be realized in COSY ring

Disadvantage: the high requirement to stability of f_{rf} and slow process

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

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

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

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

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

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

MDM spin frequency

EDM spin frequency

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

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

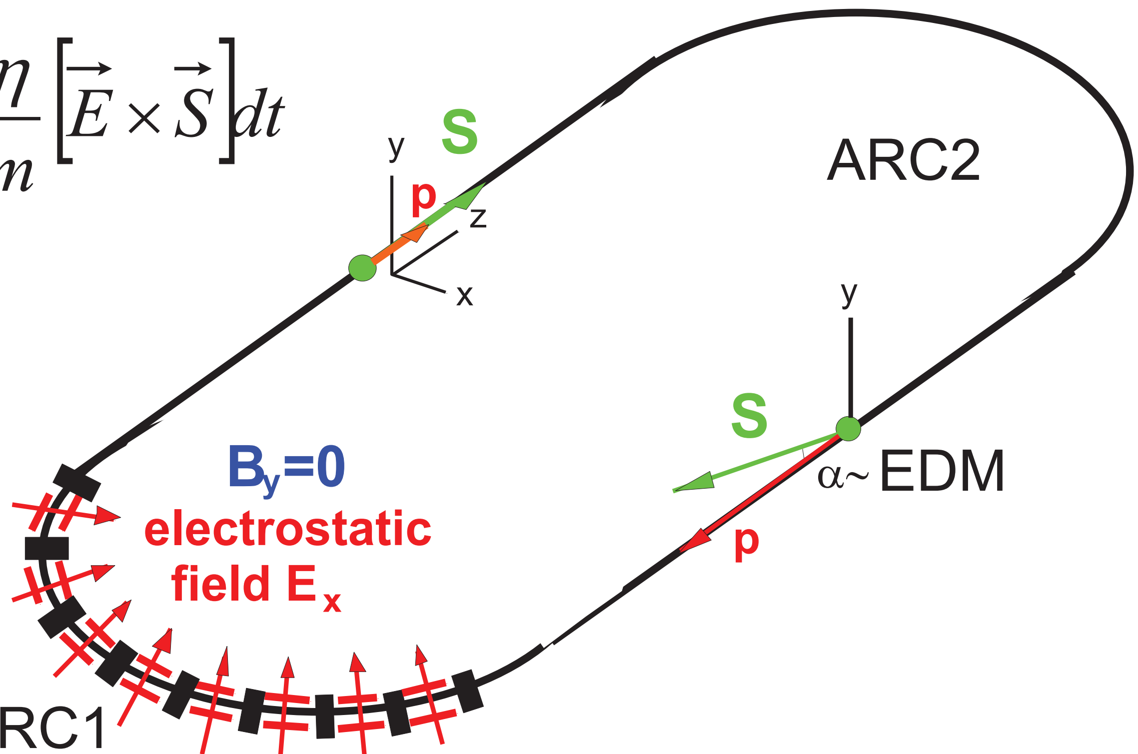
MDM spin frequency

EDM spin frequency

Frozen spin method for purely electrostatic proton ring at "magic" energy

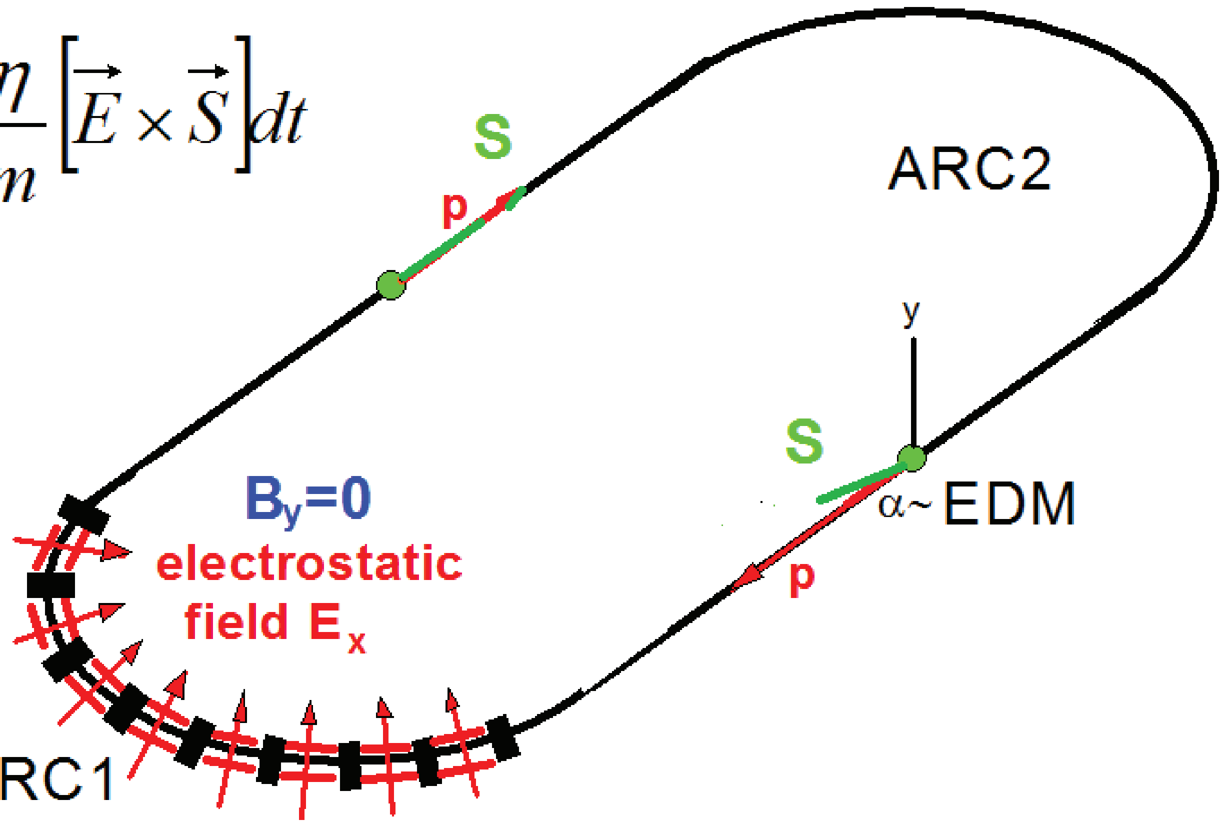
In purely electrostatic ring the spin of particle with "magic energy" rotates with the same angular frequency as the momentum and it tilts up in the YZ plane due to the EDM with angular rate

$$d\vec{S} = -\frac{e\eta}{2m}\left[\vec{E}\times\vec{S}\right]dt$$



EDM growth in FS concept

$$d\vec{S} = -\frac{e\eta}{2m}\left[\vec{E}\times\vec{S}\right]dt$$



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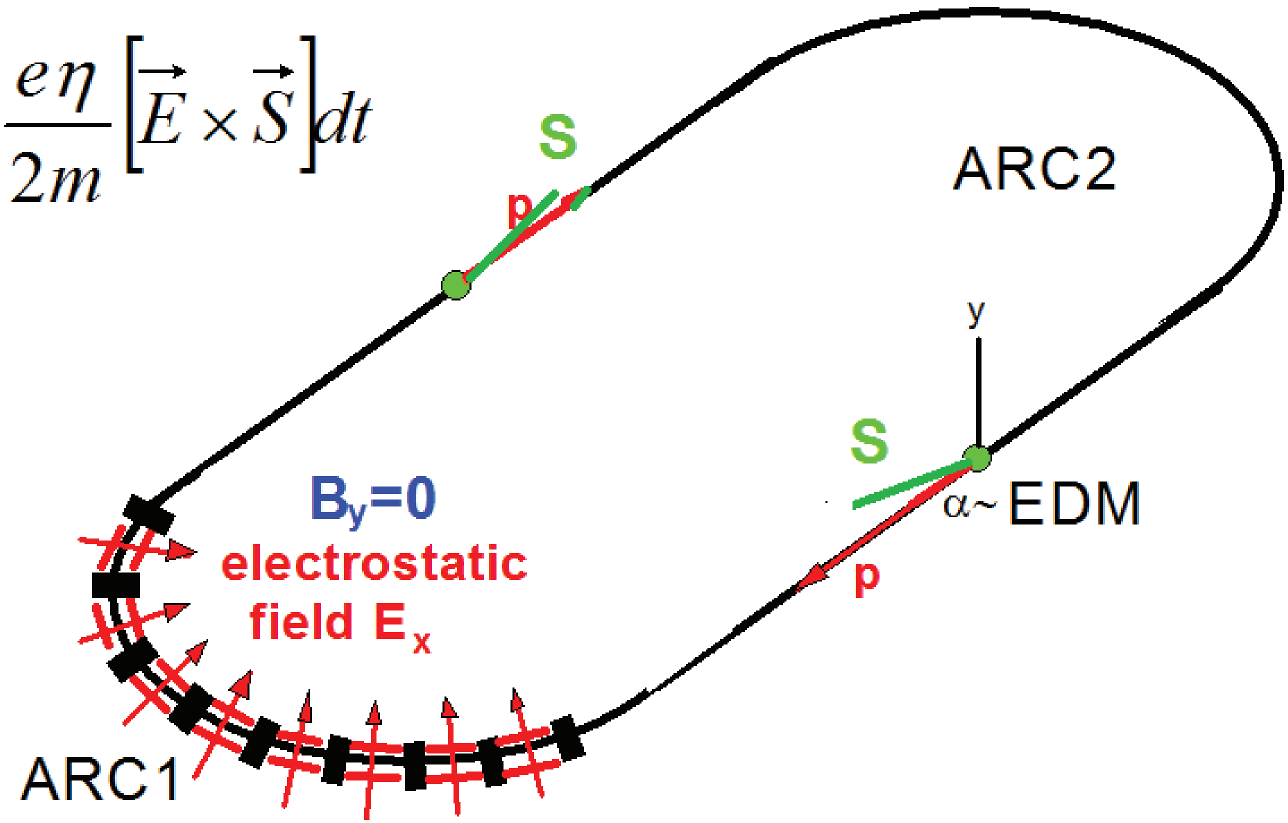

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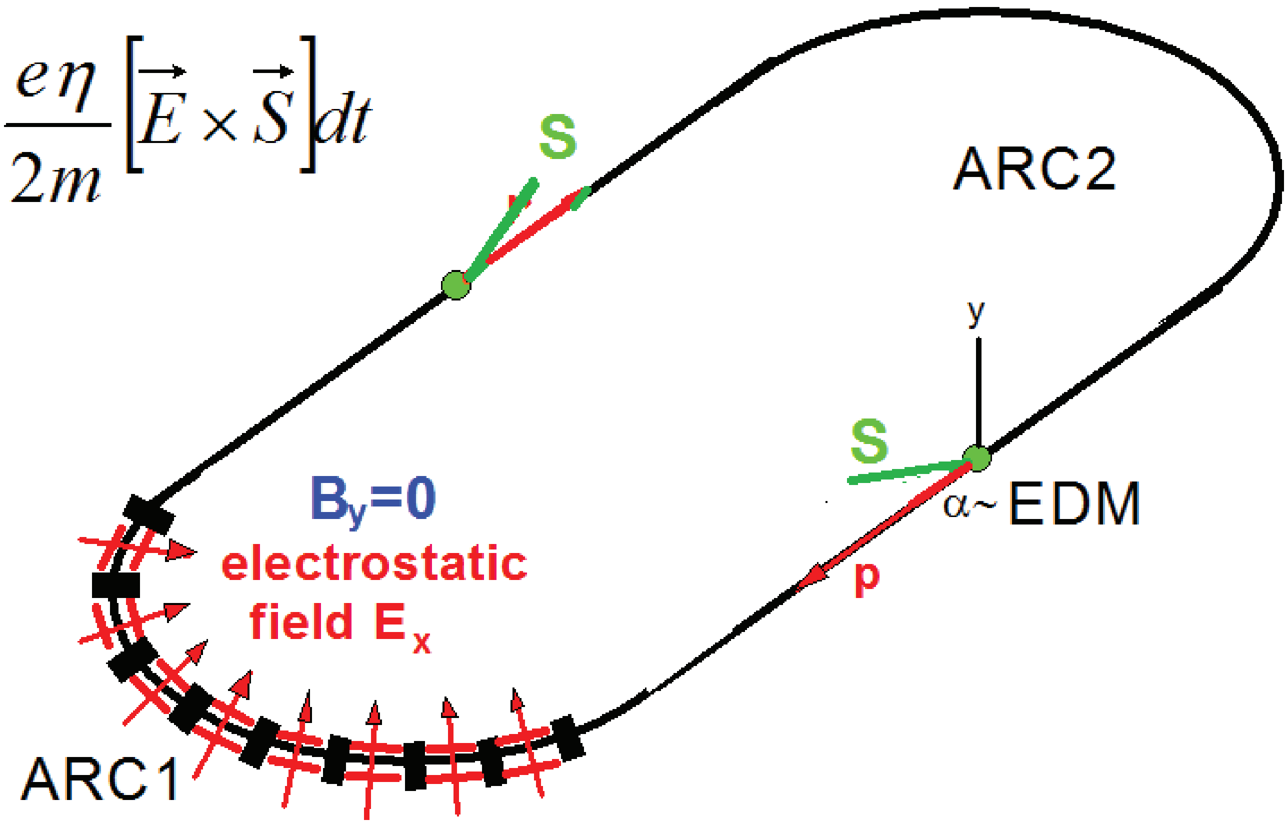


Frozen spin method for deuteron:

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

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

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

Sensitivity of EDM experiment

$$\sigma_{d_p} \approx \frac{3\hbar}{PAE_R\sqrt{N_{Beam} f T_{Tot} \tau_{Spin}}}$$

$P = 0.8$	Beam polarization
$A = 0.6$	Analyzing power of polarimeter
$E_R = 12$ MV/m	Radial electric field strength
$N_{Beam} = 2 \cdot 10^{10}$ p/fill	Total number of stored particles per fill
$f = 0.55\%$	Useful event rate fraction (polarimeter efficiency)
$T_{Tot} = 10^7$ s	Total running time per year
$\tau_{Spin} = 10^3$ s	Polarization lifetime (Spin Coherence Time)

$$\sigma_{d_p} \approx 3 \cdot 10^{-29} \mathrm{e} \cdot \mathrm{cm}$$ for one year measurement

To design the new EDM ring we should solve the next problems

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**

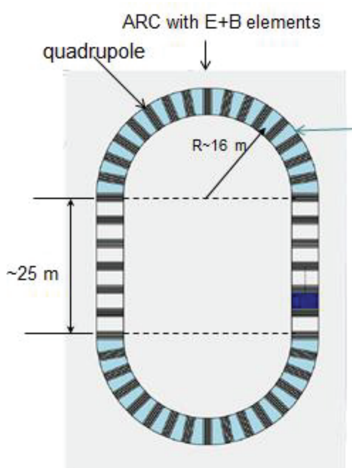
Frozen Spin lattice for deuteron

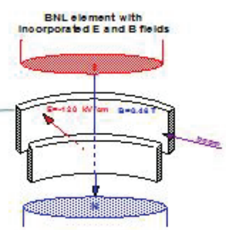
The condition of the zero MDM spin precession frequency in FS lattice [1,2]

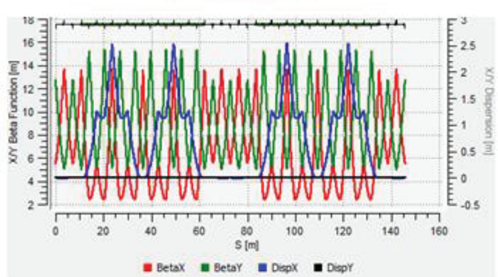
$$\Omega_{MDM} = G\vec{B_y} + \left(\frac{1}{\gamma^2 - 1} - G\right)\left(\frac{\vec{\beta_z}}{c} \times \vec{E_x}\right) = 0$$

creates the relation between E and B fields in incorporated bending elements:

$$E_r \approx GBc\beta\gamma^2$$







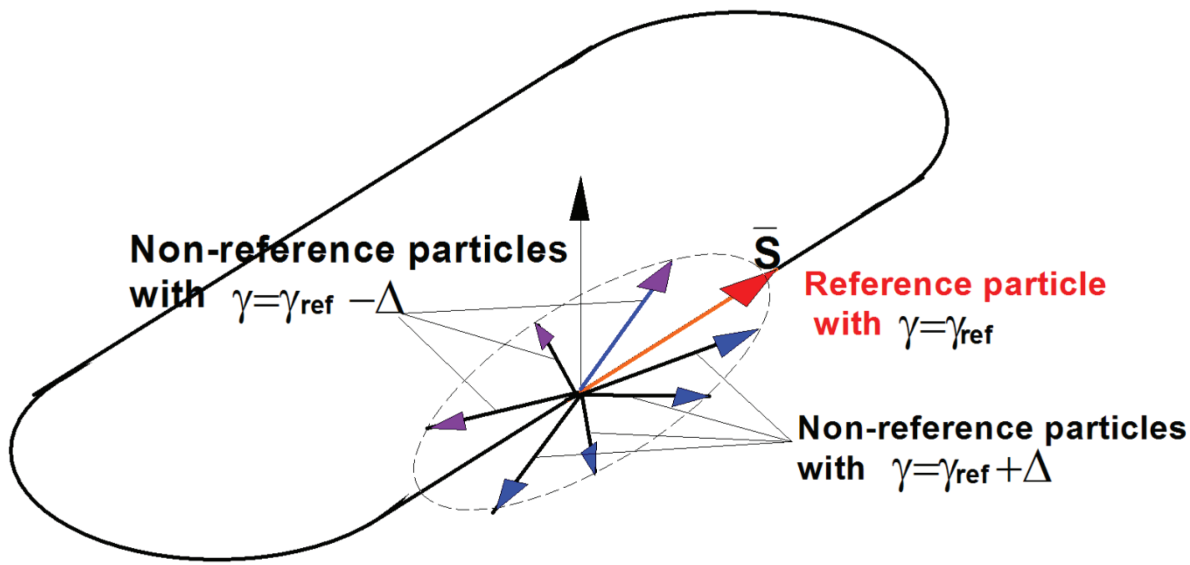
Frozen Spin lattice based on B+E elements and TWISS functions

Spin tune coherence

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

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

Spin tune coherence: 3D dependence

Equation of Longitudinal motion:

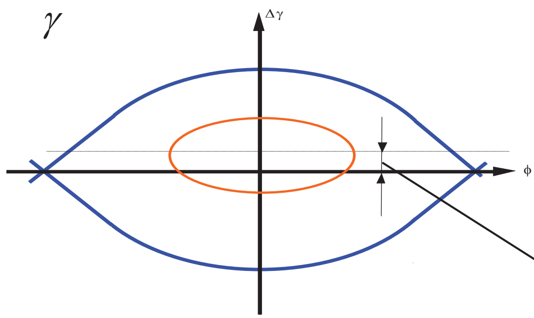
$$\frac{d\varphi}{dt} = -\omega_{rf}\left[\left(\alpha_0 - \frac{1}{\gamma^2}\right)\cdot\delta + \left(\alpha_1 - \frac{\alpha_0}{\gamma^2} + \frac{1}{\gamma^4}\right)\cdot\delta^2 + \left(\frac{\Delta L}{L}\right)_\beta\right]$$

x and y orbit lengthening

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

nonlinear term of energy oscillation

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



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

Nonlinear Z motion

Betatron motion

Spin tune coherence: sextupole correction

We know the second order momentum compaction α_1 depends on sextupole strength:

$$\Delta\alpha_{1,sext} = -\frac{S_{sext} \cdot D_0^3}{L} \quad \Rightarrow \quad \alpha_1 + \Delta\alpha_{1,sext} - \frac{\alpha_0}{\gamma_s^2} + \frac{1}{\gamma_s^4} \Rightarrow 0$$

and simultaneously the sextupole affects on the orbit lengthening directly:

$$\left(\frac{\Delta L}{L}\right)_{sext} = \mp \frac{S_{sext} D_0 \beta_{x,y} \varepsilon_{x,y}}{L}$$

Spin tune coherence: COSY ring experiment

In COSY ring in regime of “non-frozen spin “ we experimentally have proved that

-SCT~1000 sec can be reached;

-spin tune measurement with relative errors 10^{-10} is possible, which will allow calibrating the particle energy using the clock-wise and counter clock-wise procedure.

D. Eversmann et al., (JEDI Collaboration)

New method for a continuous determination of the spin tune in storage rings and implications for precision experiments,

Phys. Rev. Lett. 115, 094801 (2015)

G. Guidoboni et al. (JEDI Collaboration)

How to Reach a Thousand-Second in-Plane Polarization Lifetime with 0.97−GeV/*c* Deuterons in a Storage Ring

Phys. Rev. Lett. 117, 054801, (2016)

Quasi-Frozen Spin (QFS) method for deuteron

From T-BMT equations follows that the growth of the EDM signal is directly dependent on the angle between the spin and momentum direction.

Exact fulfillment of the frozen spin condition is not required. We need an equal deviation of spin in magnetic and electric fields totally on the ring

To realize the quasi-frozen spin concept, we have to fulfil the condition:

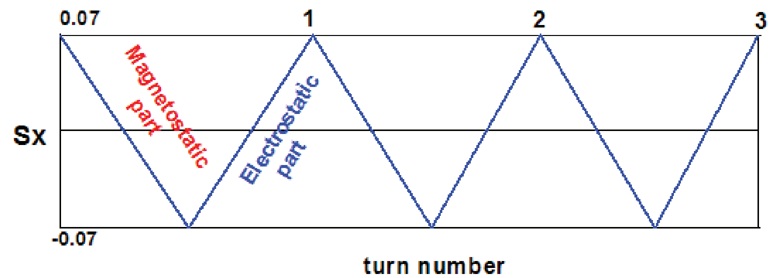
$$\Phi_{spin}^{B_{ss}} - \Phi_{spin}^{E_{ss}} = \Phi_{spin}^{B_{arc}}$$

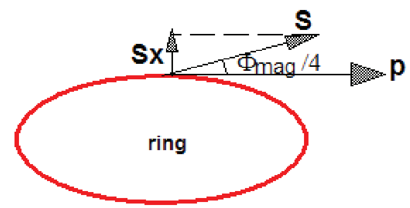
$$\boxed{(\gamma G+1)\cdot\Phi_{p}^{B_{ss}}} - \boxed{\left(\gamma G+\frac{\gamma}{\gamma+1}\right)\beta^{2}\cdot\Phi_{p}^{E_{ss}}} = \boxed{\gamma G\cdot\Phi_{p}^{B_{arc}}}$$

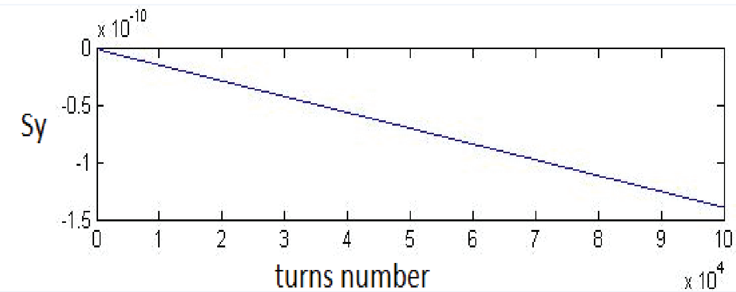
The basic relations are:

$$L_{\Sigma}E_{ss} = \frac{G}{G+1}\cdot\frac{mc^{2}}{e}\cdot\pi\beta^{2}\gamma^{3} \qquad B_{ss} = -\frac{E_{ss}}{c\beta}$$

dEDM growth: 3D spin orbital simulation by MODE and COSY Infinity codes





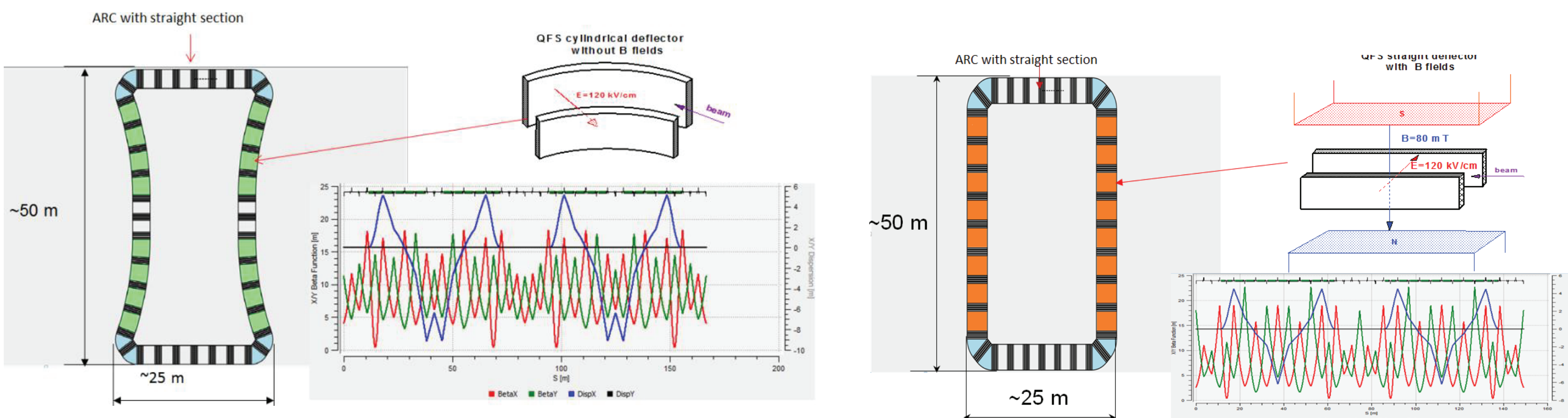


Results of 3D spin-orbital simulation:

- Due to Sx oscillation (QFS) the EDM signal decreases by 1%
- In each magnet EDM signal grows by $-2.14133779995135 \cdot 10^{-16}$ and in each deflector by $3.20268895179507 \cdot 10^{-17}$
- Total EDM signal grows by $-1.39074513140842 \cdot 10^{-15}$ per turn
- In order to get total EDM signal $\sim 10^{-6}$ we have to keep the beam in ring during $N_{turn} \sim 10^{9}$ or **~800 sec**

QFS lattice

In QFS lattice we introduced a magnetic field of small value ~80 mT, compensating the Lorentz force of the electric field in electrostatic deflector located on the straight sections.



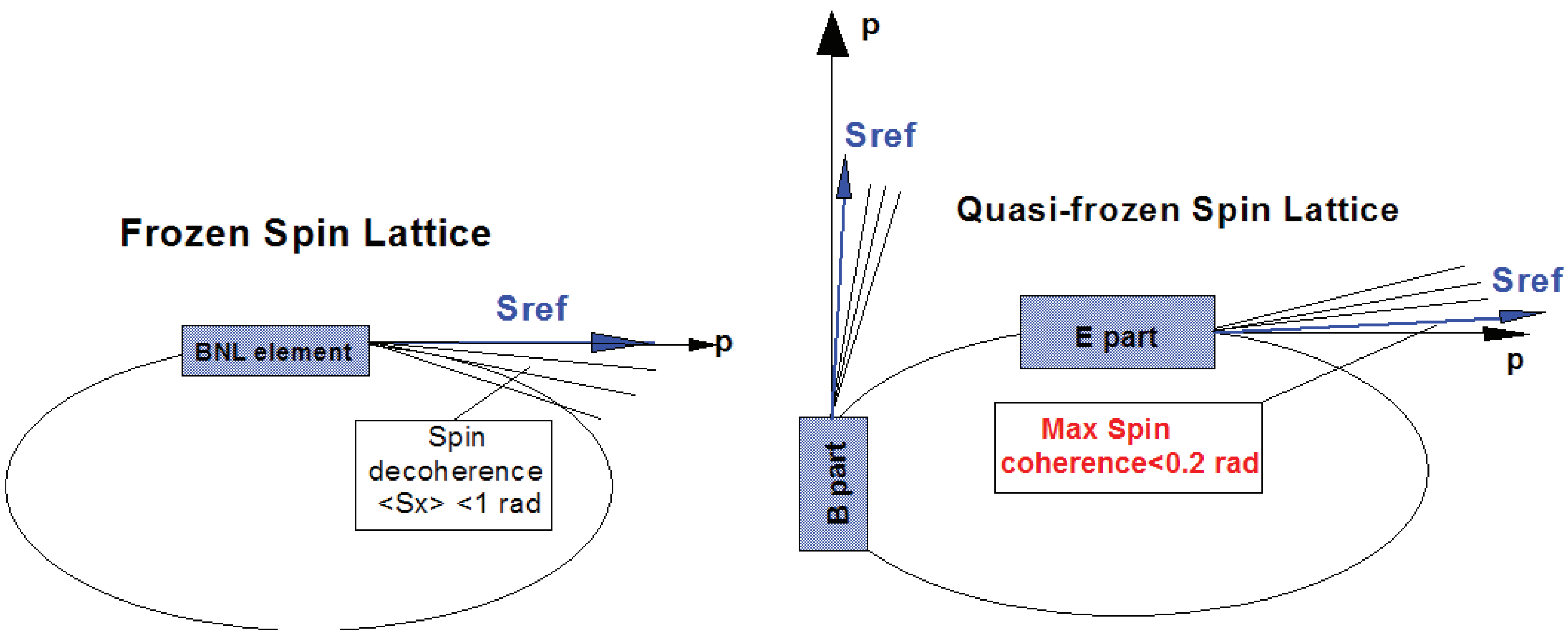
Ring lattice based on QFS concept: ring view with main elements and TWISS functions

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

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

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

Spin decoherence in FS and QFS



QFS in COSY ring

In precursor experiment we do not need a large statistics and we can start working on energy 75 MeV. This allows to use only 4 “E+B” straight elements, which is four times less than at 270 MeV. The total length is 2x7 m. Further, E+B elements can be used for a full scale experiment at 270 MeV. In result, it will provide Quasi Frozen Spin at energy of 75 MeV. Due to small B field value the E+B elements on the straight sections may be made using ordinary electrical coils with field 120-100 mT. The condition for spin recovery is fulfilled using E field (working regime <120 kV/cm).

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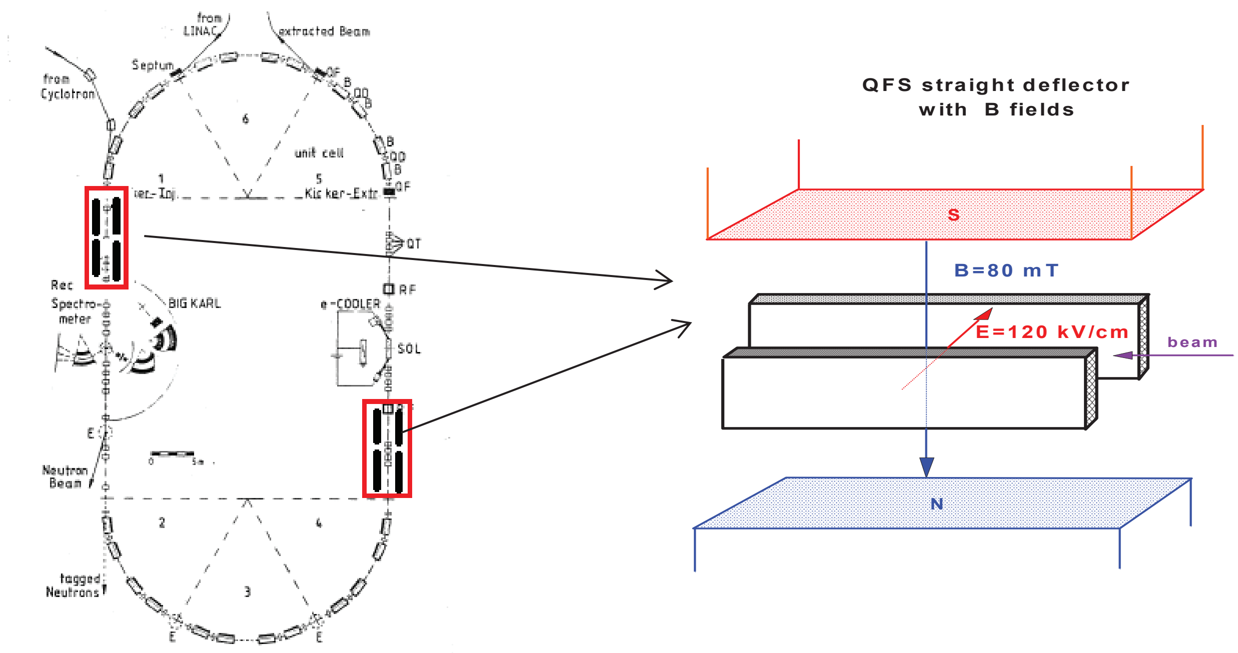
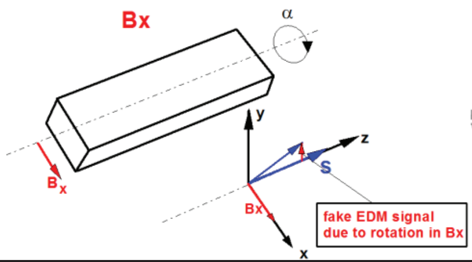
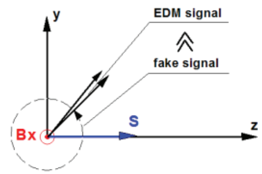


Systematic errors due to magnet rotation around the longitudinal axis ($B_x \neq 0 \Longrightarrow \Omega_{Bx} \neq 0$, $\Omega_y = \langle \Omega_{decoh} \rangle$)





Misalignment, Bx≠0:
Due to magnet rotation relative to the longitudinal axis the horizontal component of the magnetic field arises and causes the spin rotation $\Omega_x = \Omega_{Bx}$. In COSY simulation we took the magnets misalignment 10 µm, which corresponds to the rotation angle of magnet around the axis about $\alpha_{max} = \pm 10^{-5}$ rad and causes MDM spin rotation Ω_{Bx}=3 rad/sec in vertical plane

+

Ω_{Bx} rotation is in the same plane where we expect the EDM signal with Ω_{EDM}, and **initially we considered this fact as main factor limiting EDM measurement.** At presumable **EDM value of 10^{-29} e·cm**, the EDM rotation should be **Ω_{EDM}= 10^{-9} rad /sec** and **Ω_{EDM} / Ω_{Bx}** ~ **10^{-9}**

+

Spin tune decoherence in horizontal plane is supposed to be as usual **$\langle \delta\Omega_{decoh} \rangle$=$10^{-3}$ rad/sec**

$$\frac{d\vec{S}}{dt} = \vec{S} \times \left(\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}\right)$$

For initial condition
$S_x = 0,\ S_y = 0,\ S_z = 1, \Omega_z = 0$
from T-BMT equations:

$$S_x(t) = \frac{\Omega_y \cdot \sin(\sqrt{\Omega_x^2 + \Omega_y^2} \cdot t)}{\sqrt{\Omega_x^2 + \Omega_y^2}};$$

$$S_y(t) = -\frac{\Omega_x \cdot \sin(\sqrt{\Omega_x^2 + \Omega_y^2} \cdot t)}{\sqrt{\Omega_x^2 + \Omega_y^2}};$$

$$\Omega_x = \Omega_{EDM} + \Omega_{Bx}$$
$$\Omega_y = 0 + \langle \delta\Omega_{decoh} \rangle$$

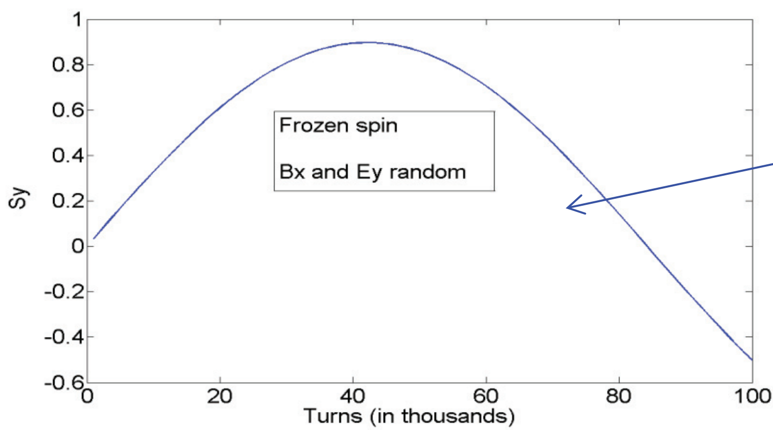
$$< S_x(t) > = \frac{\langle \delta\Omega_{decoh} \rangle}{\Omega_{Bx}} \cdot \sin\Omega_{Bx} \cdot t;$$
$$S_y(t) \approx -\sin(\Omega_{Bx} + \Omega_{EDM}) \cdot t$$

1. $\Omega_{Bx} = \frac{e}{m\gamma} \cdot \gamma G B_x >> \Omega_{EDM}$

1. Spin tune decoherence in horizontal plane is not growing and stabilized on the level **$\langle \delta\Omega_{decoh} \rangle$/ Ω_{Bx} ~10^{-3}** and
2. Spin decoherence is transferred in vertical plane
3. MDM rotation in vertical plane is greater by factor of 10^9 faster EDM

COSY Inf+MODE simulation of systematic errors due to magnet rotation around the longitudinal axis

Coherent component



$$S_y(t) \approx -\sin(\Omega_{Bx} + \Omega_{EDM}) \cdot t$$

$$< S_x(t) >= \frac{\langle \delta\Omega_{decoh} \rangle}{\Omega_{Bx}} \cdot \sin\Omega_{Bx} \cdot t$$

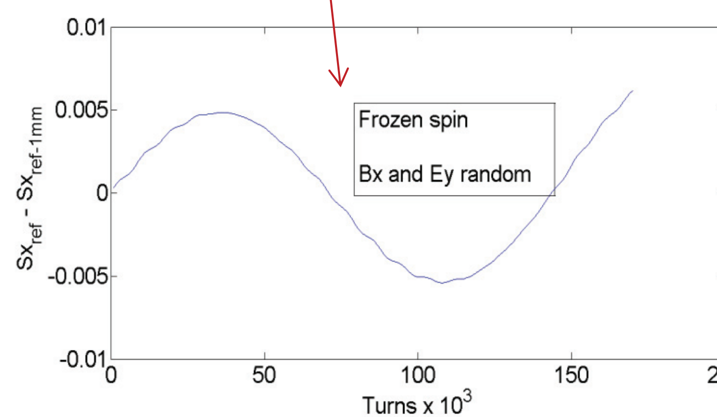
Decoherent component

$$\sigma_\Omega = 2\sqrt{6/N}/(\tilde{\varepsilon}T)$$

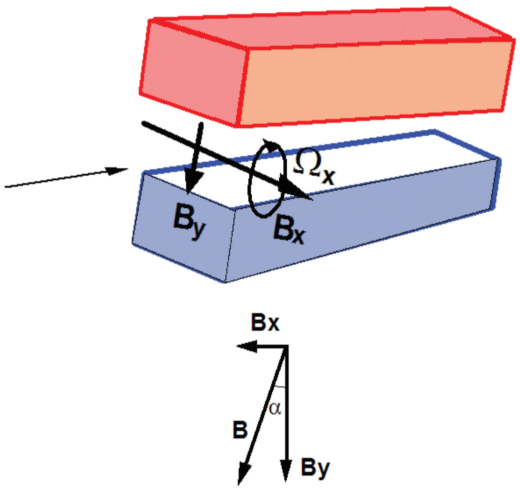
N is the total number of useful events,
$\tilde{\varepsilon} \approx 0.27$ is the oscillation amplitude of measured asymmetry of polarization,
T is the measurement duration.
detector rate of 5000 s^{-1}

For 6000 hours (one year) statistic error is $\sigma_\Omega \approx 5 \cdot 10^{-8}$
It means EDM value could be defined on the level $10^{-27} \div 10^{-28}$ e· cm

Parameters of decoherent component



The best way to get rid of the enemy - make him a friend, or how to use systematic errors to measure EDM in CW+CCW procedure



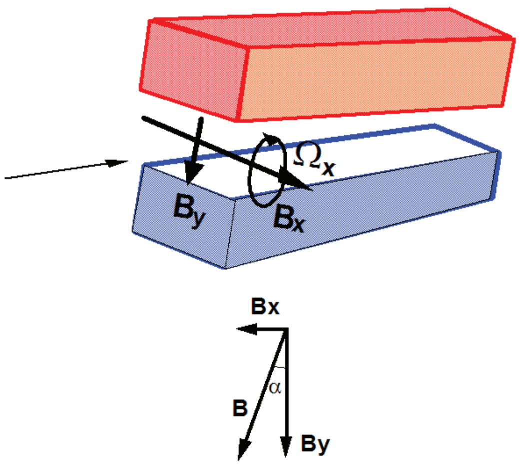
To split out the EDM signal from the sum signal we use **CW+CCW procedure:**

1. Calibration of **Bx** throught **By**
2. Measurement of the total spin frequency in the experiment with a counter clock-wise (**CW**) direction of the beam $\Omega_{CW} = \Omega_{Bx}^{CW} + \Omega_{EDM}$
3. Installation of B field after the polarity change using calibration
4. Measurement of the total spin frequency in the experiment with a counter clock-wise (**CCW**) direction of the beam $\Omega_{CCW} = -\Omega_{Bx}^{CCW} + \Omega_{EDM}$
5. Compare **CCW** with clock-wise (**CW**) measurements

$$\Omega_{EDM} = (\Omega_{CW} + \Omega_{CCW})/2 + (\Omega_{Bx}^{CCW} - \Omega_{Bx}^{CW})/2$$

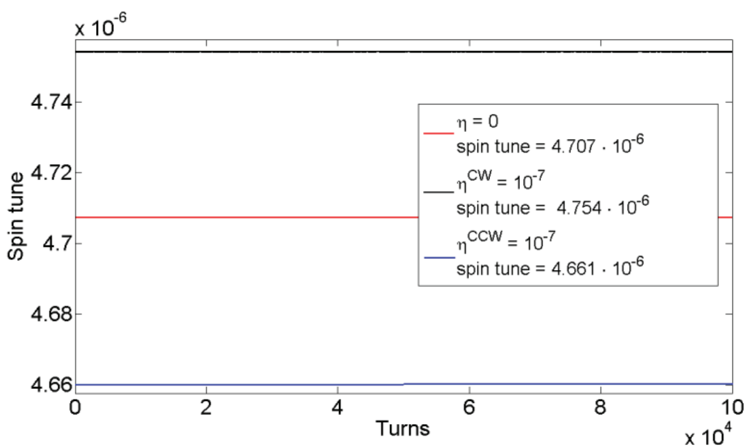
6. The difference $\Delta\Omega_{Bx} = \Omega_{Bx}^{CCW} - \Omega_{Bx}^{CW}$ determines the accuracy of the EDM measurement. Calibrating **Bx** we can minimize $\Delta\Omega_{Bx}$ up to value of calibration accuracy.

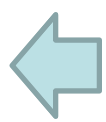
Bx and By calibration procedure



First, we suggest calibrating the field of the magnets using the relation between the beam energy and the spin precession frequency in the horizontal plane, that is, determined by the vertical component By. Since the magnet orientation remains unchanged, and the magnets are fed from one power supply, the calibration of By will restore the component Bx with the same accuracy 10^(-10), that is the difference $\Omega_{Bx}^{CCW} - \Omega_{Bx}^{CW}$ as well. Such procedure does not involve EDM signal.

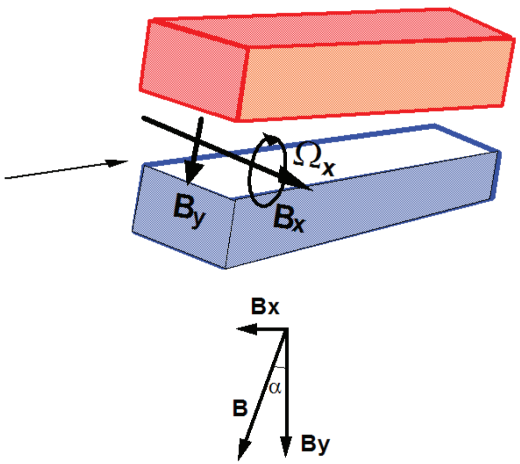
If we assume that we can measure the spin frequencies $\Omega_{CW}, \Omega_{CCW}$ with an accuracy of 10^(-10) already experimentally demonstrated in COSY and reach the calibration accuracy of **Bx** up to 10^(-10) we will be able to determine the EDM frequency up to 10^(-10) rad/sec, which corresponds to the EDM measurement on the level of **10^(-29)÷10^(-30) e·cm**





the results of a numerical simulation of the EDM measurement procedure, we took the EDM 10^(-21), that is $\Omega_{EDM} = 0.1 rad/\sec$

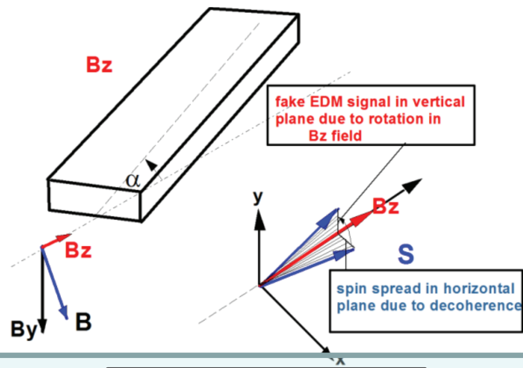
Bx coil



Nevertheless, the fundamental question of how to calibrate the field By using the spin tune measurement in a horizontal plane, if due to misalignments the spin rotates in the vertical plane with relatively high frequency ~10 rad/sec, remains. To solve this problem, we plan for the calibration time only to introduce the inhibitory vertical field, for example by means of a horizontal coil. Having inhibited rotation in the vertical plane to the reasonable value of ~0.1 rad/sec and calibrated, then we turn off the coil. In this case we do not need to know the value of the field in the coil

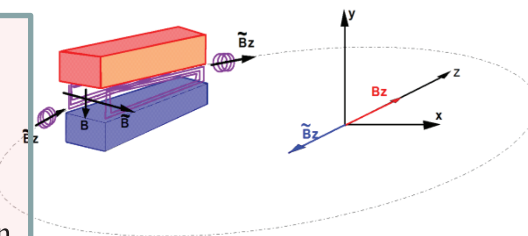
Nevertheless introducing the coil we can modify the integral value of the guiding magnetic field By. Let us estimate this value. We know that due to misalignment of magnets with an accuracy of 10 micrometer, we have in Bx/By = 10 ^(-)6. Obviously the coil can be installed with the same accuracy and By(coil)/Bx(coil)=10^(-6). Thus, the coil introduces in By of ring 10^(-12)

Systematic errors due to magnet rotation around the transverse axis ($B_z \neq 0 \Longrightarrow \Omega_z \neq 0$, $\Omega_y = \langle \Omega_{decoh} \rangle$)



The longitudinal component of field is most undesirable as it transforms the spin decoherence from the horizontal plane into the vertical plane where we expect a signal of EDM. The fake signal depends on the ratio between $<\Omega_{decoh}>$ and Ω_{Bz}

Because of the oscillations around the longitudinal axis the EDM signal periodically changes the sign of growth. Therefore, the only way is to minimize the longitudinal component of the magnetic field with $\Omega_{Bz} \sim 10^{-9}$ rad/turn



$$\frac{d\vec{S}}{dt} = \vec{S} \times \left(\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}\right)$$

For initial condition $S_x = 0, S_y = 0, S_z = 1$ from T-BMT equations:

$$S_x(t) = \frac{\Omega_y \cdot \sin(\sqrt{\Omega_z^2 + \Omega_y^2} \cdot t)}{\sqrt{\Omega_z^2 + \Omega_y^2}};$$

$$S_y(t) = \frac{\Omega_y \Omega_z}{\Omega_z^2 + \Omega_y^2}\left[1 - \cos(\sqrt{\Omega_z^2 + \Omega_y^2} \cdot t)\right];$$

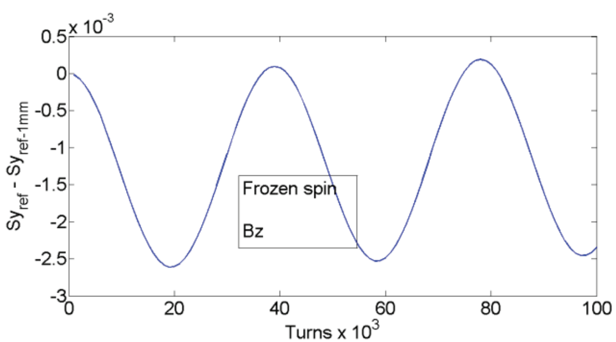
$$\Omega_z = \Omega_{Bz}$$
$$\Omega_y = 0 + \langle \delta\Omega_{decoh} \rangle$$

$$\Omega_{Bz} \ll \langle \delta\Omega_{decoh} \rangle$$

$$< S_x(t) > = \sin(\langle \Omega_{decoh} \rangle \cdot t);$$
$$< S_y(t) > = \frac{\Omega_{Bz}}{\langle \Omega_{decoh} \rangle}\left[1 - \cos(\langle \Omega_{decoh} \rangle \cdot t)\right];$$

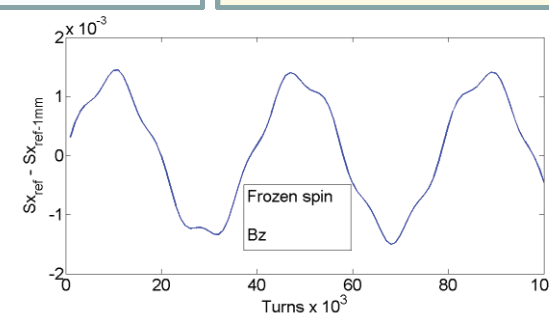
$$\Omega_{Bz} \gg \langle \delta\Omega_{decoh} \rangle$$

$$< S_x(t) > = \frac{\langle \Omega_{decoh} \rangle}{\Omega_{Bz}} \sin(\Omega_{Bz} \cdot t);$$
$$< S_y(t) > = \frac{\langle \Omega_{decoh} \rangle}{\Omega_{Bz}}\left[1 - \cos(\Omega_{Bz} \cdot t)\right];$$

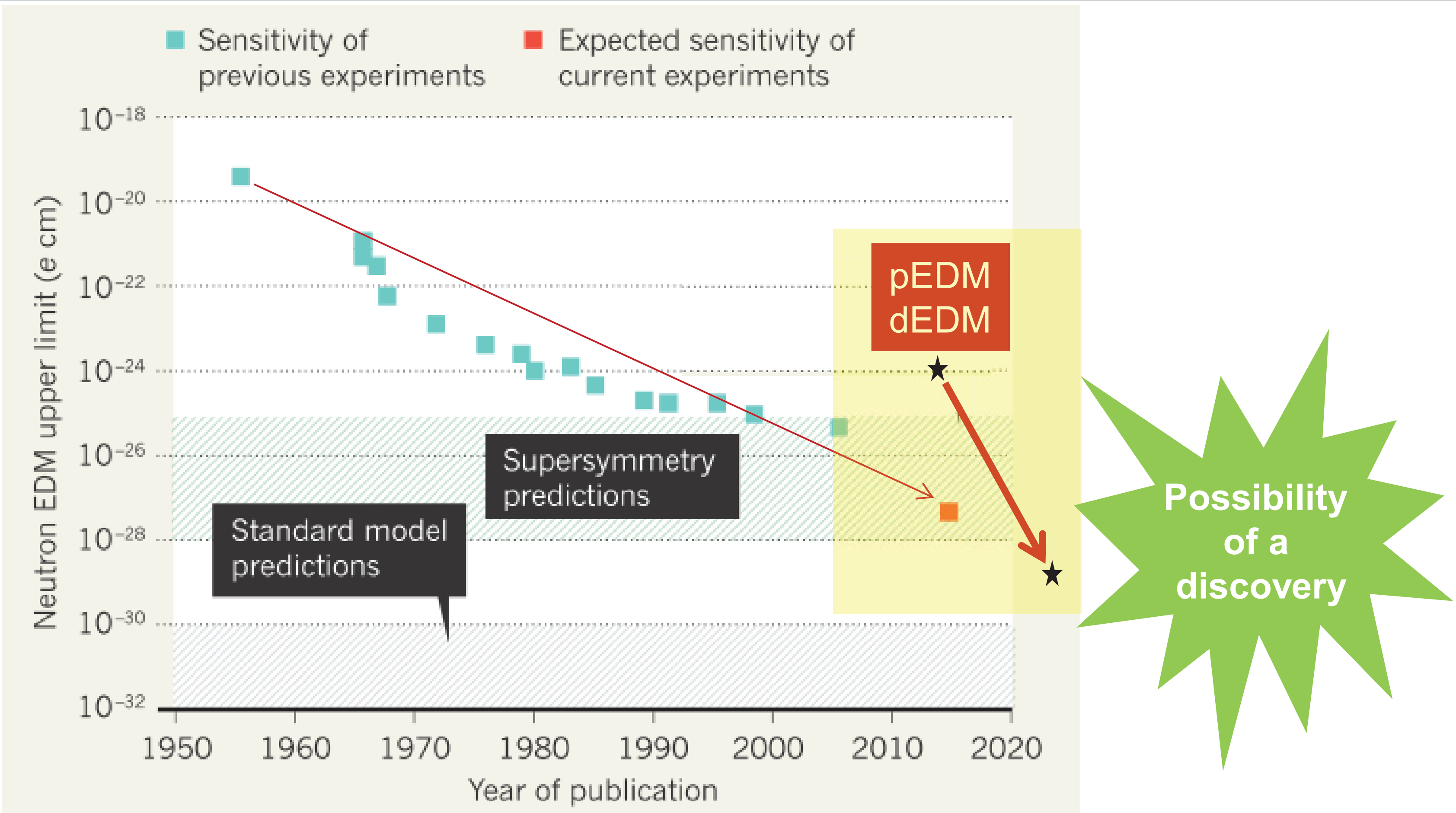


MODE 3D simulation

In the experiment, E. S. the vertical component increases with rate $\sim 10^{-4}$ rad/s



Storage Ring EDM Project



Highest sensitivity

COSY Infinity and MODE codes

Spin-orbit dynamics of polarized beam investigated using:

- the code COSY Infinity
(M. Berz,Michigan State University, USA)

- the code MODE
(S. Andrianov and A. Ivanov St.Petersburg University).

St. Petersburg
State University

The algorithm of the MODE is based on an original idea of S. Andrianov and A. Ivanov

Conclusion

- We have formulated the basic requirements for the accelerator, in which it is possible measuring EDM at 10^{-29}
- We have developed and tested experimentally the method of how to achieve a long spin coherence time using sextupoles
- We learned how to measure the spin frequency with an relative accuracy of 10^{-9}
- We have developed the concept of quasi-frozen spin lattice and learned how to adapt the concept of QFS to COSY ring
- We figured out how to take into account systematic errors
- We designed and produced a high-frequency flipper, which will be installed in the near future onto COSY


Thank you!