EDM @ JEDI:
A Progress Report

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(For the JEDI Collaboration)

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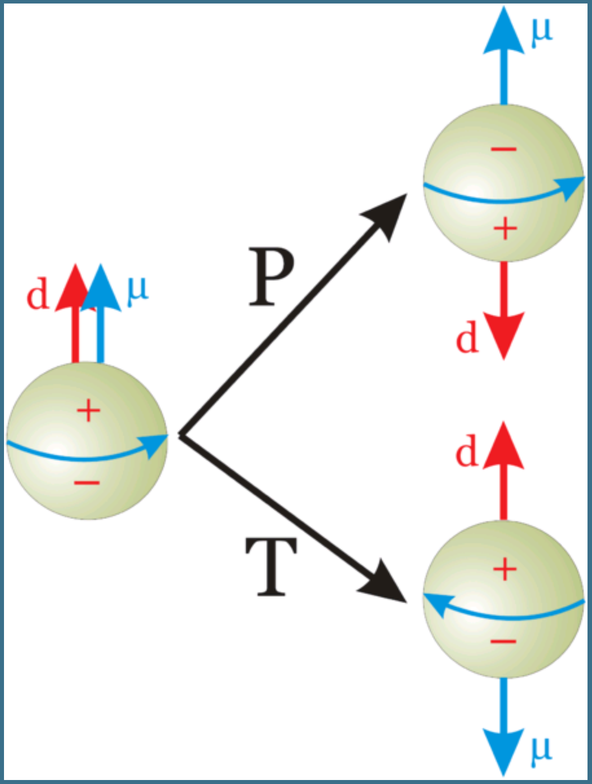
JEDI = Juelich Electron Dipole moment Investigations

- *~ 100 participants*
- *Laboratories and Institutes from China (1), USA (4), Russia (5), Georgia (1), Belarus (1), UK (1) & EC (22)*
- *Strong theoretical support locally and elsewhere*
- *The latest Workshop @ ECT* Trento:* ***EDM Searches at Storage Rings, 1-5 October, 2012*** *http://www.ectstar.eu/node/45*
- *485 W.E. Heraeus Seminar at Bad Honnef:* ***Search for Electric Dipole Moments (EDMs) at Storage Rings,*** *04.07.2011 – 06.07.2011*

Layout

- Why EDM? Baryogenesis after Sakharov
- EDM: High Precision frontier vs. High Energy frontier.
- Frozen spin in pure electric ring and EDM @ BNL
- RF & Static EDM rotators at COSY? ***Highlights:***
- *Part per million polarimetry is feasible*
- Time stamp polarimetry of fast rotating horizontal spin
- *Chromaticity handle on spin coherence time*
- First ever measurement of the spin tune with 8 digits
- *Partial evidence fir spin-decoherence-free energies*
- Steady progress in the theory of spin dynamics at COSY
- **Summary: EDM@COSY is a must do**

Electric Dipole Moments



Electric dipole moment (EDM)

A permanent EDM of a fundamental particle violates both parity (P) and time reversal symmetry (T).

Assuming CPT to hold, the combined symmetry CP is violated as well.

P fell in 1956, CP in 1964

Landau promoted combined CP parity to eliminate a clash of the mirror asymmetry with the isotropy of space

Linear Stark effect in the hydrogen atom:

$U = -dE$ vs polarizability $U = aE^2$

- Amounts to a permanent EDM of n=2 states at the Bohr radius scale!

- No conflict with parity conservation!

- Degeneracy of opposite parity 2S and 2P states in the NR limit

  100% mixing of 2S & 2P in whatever weak external E-field

- Similar parity degeneracy in polar molecules

- No such parity degeneracy for charged particles and light nuclei

A naive scale for EDM:

- CP and P conserving magnetic moment $\sim$ nuclear magneton μ_N

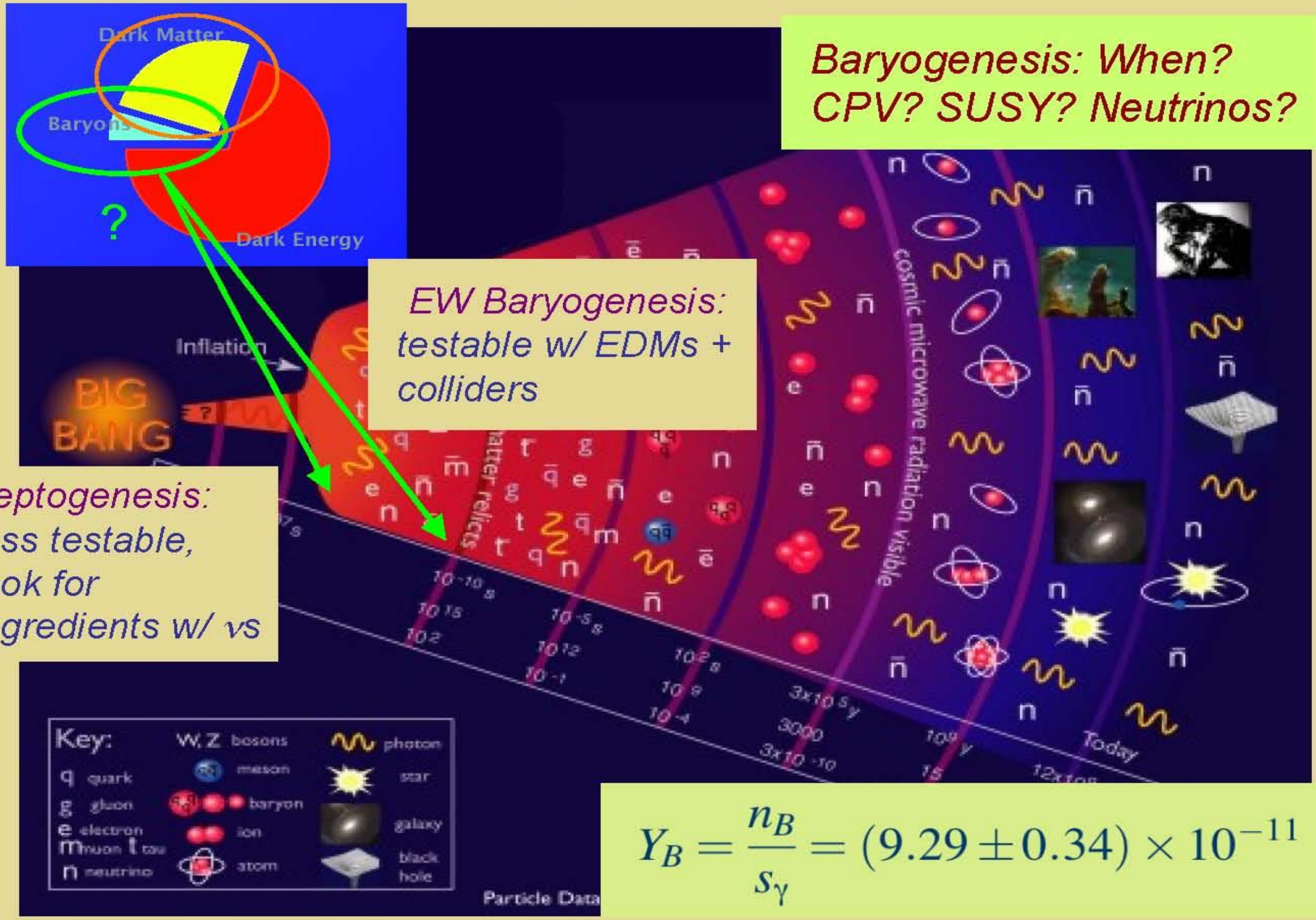
$$\mu_N = \frac{e}{2m_p} = 10^{-14}\mathrm{e}\cdot\mathrm{cm}$$

- EDM demands for parity violation.
  Pay the price $\sim 10^{-7}$
- EDM demands for CP violation.
  Scale for CP violation from K-decays is $\sim 10^{-3}$. Pay this price for EDM.
- Corollary:

$$d_N \sim 10^{-7} \times 10^{-3} \times \mu_N \sim 10^{-24}\mathrm{e}\cdot\mathrm{cm}$$

- NB: Smart parameterizations of CKM matrix siggest CP-violation phase $\sim 10^{-1}$ and stronger CP-violating effects in heavy flavour decays.
- Dynamical models: CP-violation in K-decays might have dynamical smallness $\rightarrow$ larger d_N.
- Isospin dependence remains an open issue

What is the Origin of Matter ?



Baryogenesis: When?
CPV? SUSY? Neutrinos?

EW Baryogenesis:
testable w/ EDMs +
colliders

Leptogenesis:
less testable,
look for
ingredients w/ νs

$$Y_B = \frac{n_B}{s_\gamma} = (9.29 \pm 0.34) \times 10^{-11}$$

EW Baryogenesis: Standard Model

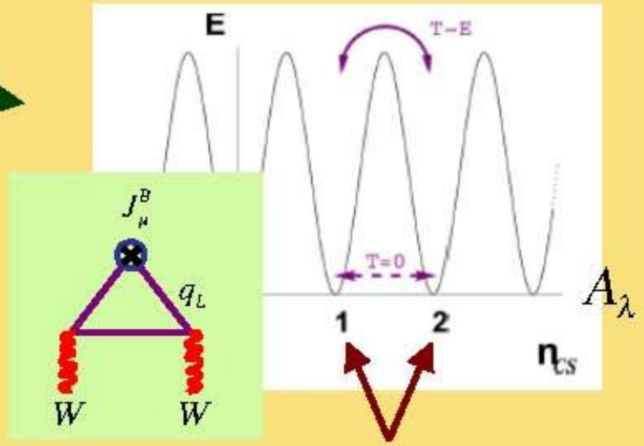
Weak Scale Baryogenesis

- *B violation*
- *C & CP violation*
- *Nonequilibrium dynamics*

Sakharov, 1967

Kuzmin, Rubakov, Shaposhnikov McLerran, …

Anomalous Processes

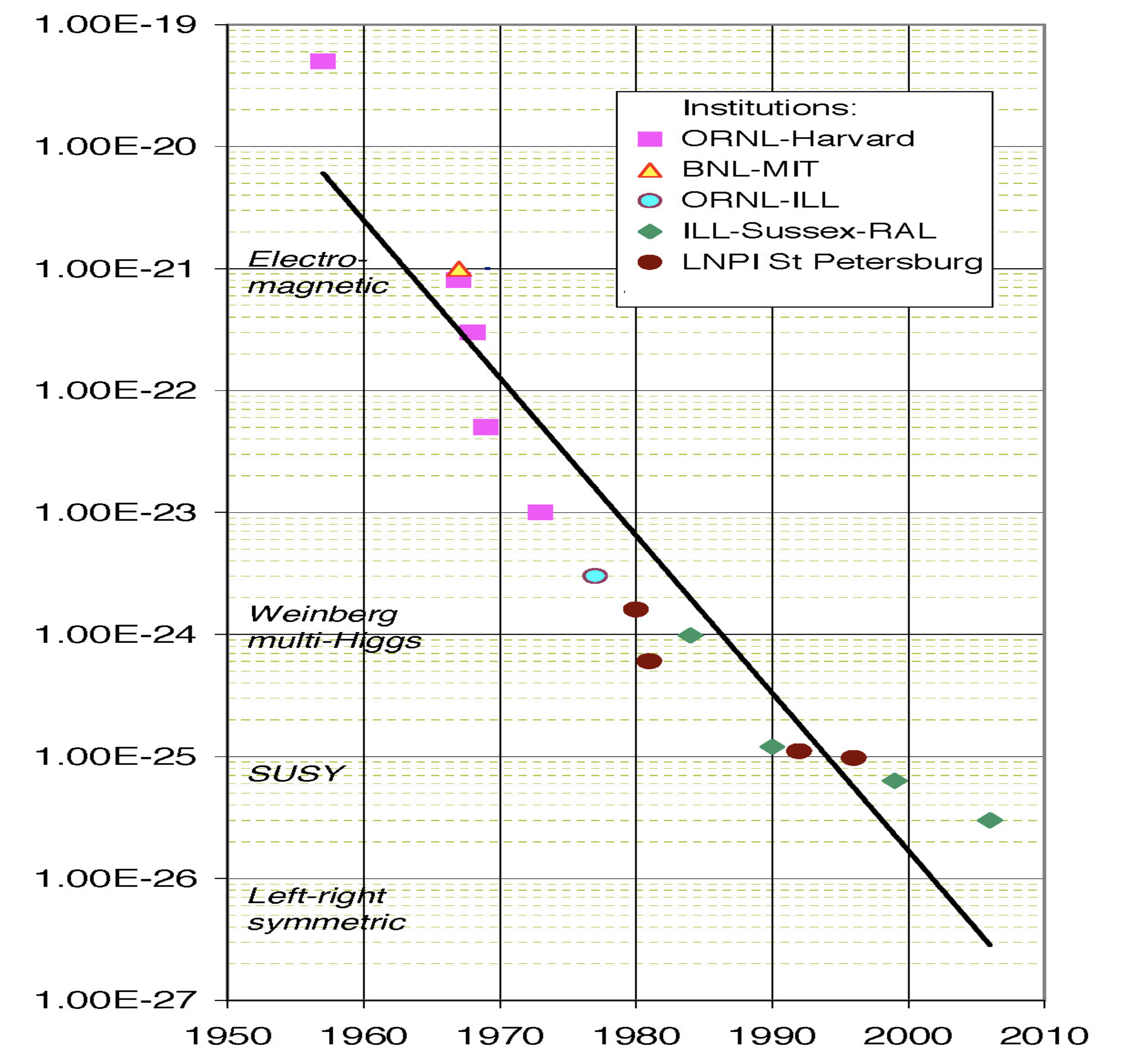


Different vacua: $\Delta(B+L) = \Delta N_{CS}$

Sphaleron Transitions

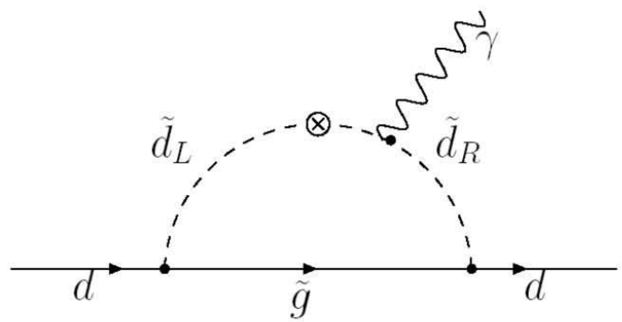
Much too feeble: the SM fails badly !

Upper bounds on the neutron EDM



Supersymmetry / SUSY CP Problem

- MSSM without corrections gives: $\boxed{\text{EDM} = 10^{-23\text{-}25}\ \text{e.cm}}$ ALREADY RULED OUT!!
- SUSY breaking introduces new CPv phases
- EDMs appear at 1-loop level



$$\kappa_i = \frac{m_i}{16\pi^2 M_{\rm SUSY}^2} = 1.3 \times 10^{-25}\text{cm} \times \frac{m_i}{1\text{MeV}} \left(\frac{1\text{TeV}}{M_{\rm SUSY}}\right)^2 ,$$

- SUSY with extensions: $\boxed{\text{EDM} = 10^{-28}\ \text{e.cm}}$ NEARLY WITHIN AIM OF cryoEDM!!

University of Sussex

EDM < 10^{-29} e.cm would kill SUSY approaches to the baryogenesis

Why to go beyond nEDM?

- EM current = isocalar + isovector

- Isospin conserving strong intercations but strongly unequal pMDM and nMDM, nearly pure isovector anomalous pMDM and nMDM

- Large MDM of the isoscalar Λ^{o} hyperon

- pEDM >> nEDM is quite possible even for isoscalar CP-violation (pure gluonic QCD theta-term....)

Limits on Atomic Electric Dipole Moments

only upper limits up to now (in e·cm):

Particle/Atom	Current EDM Limit	Future Goal	~ d_n equivalent
Neutron	$< 3 \times 10^{-26}$	$\sim 10^{-28}$	10^{-28}
^{199}Hg	$< 3.1 \times 10^{-29}$	$\sim 10^{-29}$	10^{-26}
^{129}Xe	$< 6 \times 10^{-27}$	$\sim 10^{-30} - 10^{-33}$	$\sim 10^{-26} - 10^{-29}$
Proton *	$< 7.9 \times 10^{-25}$	$\sim 10^{-29}$	10^{-29}
Deuteron	?	$\sim 10^{-29}$	$3 \times 10^{-29} - 5 \times 10^{-33}$

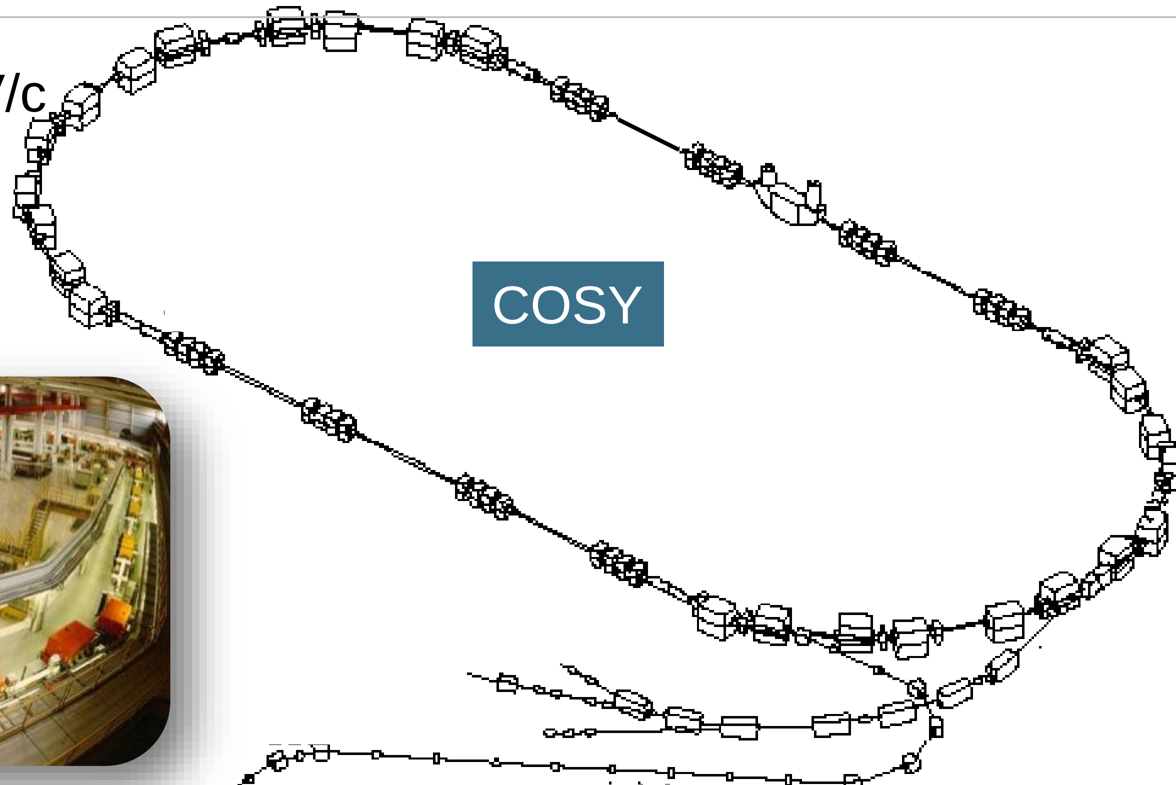
* Extremely model dependent estimate

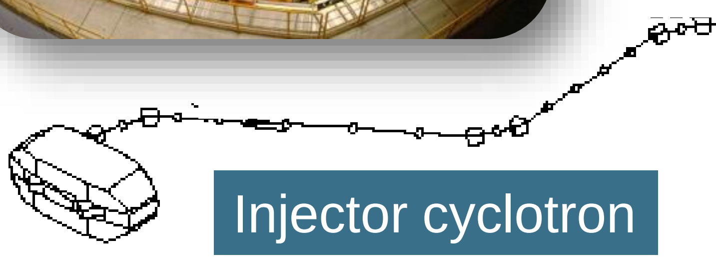
EDM at COSY – COoler SYnchrotron

Cooler and storage ring for (polarized) protons and deuterons

p = 0.3 – 3.7 GeV/c

Phase space cooled internal & extracted beams





… *the* spin-physics machine for hadron physics

BMT equation with EDM (+Frenkel+Thomas)

- Pure radial electric field

$$\vec{E} \perp \vec{B} \perp \vec{\beta}$$

$$(\vec{\beta} \cdot \vec{E}) = (\vec{\beta} \cdot \vec{B}) = 0$$

- EDM,

$$d = \eta \frac{e}{m}$$

- BMT equation (spin w.r.t momentum)

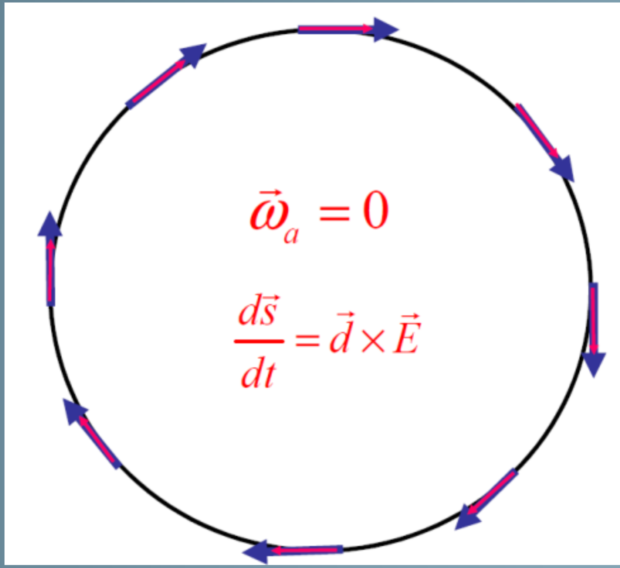
$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S},$$

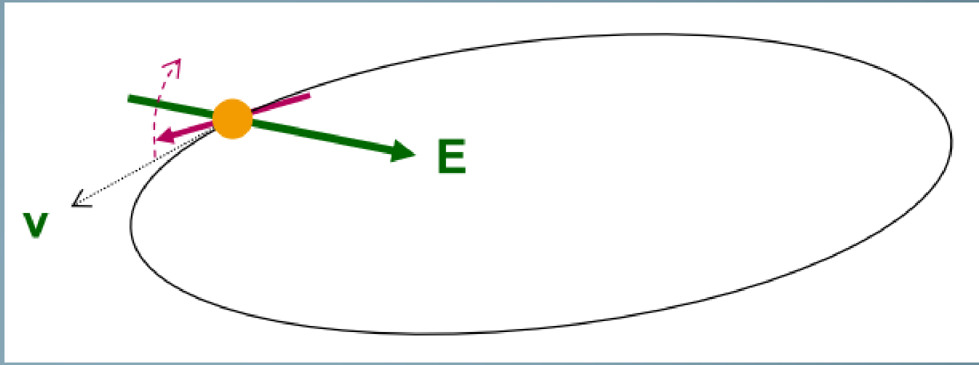
$$\vec{\Omega} = -\frac{e}{m}\left\{\underbrace{G\vec{B} + \left(\frac{1}{\beta^2} - G - 1\right)\vec{\beta} \times \vec{E}}_{\text{MDM}} + \underbrace{\eta\left(\vec{E} + \vec{\beta} \times \vec{B}\right)}_{\text{EDM}}\right\}.$$

- EDM couples to the motional permanent electric field $\propto \vec{\beta} \times \vec{B}$
- Natural scale $\eta \sim 10^{-10}$. Absolutely negligible inwards or outwards tilt of the stable spin axis, still might affect the EDM signal.

Orlov & Semertsidis: EDM search in time evolution of spin in a storage ring :

A *magic* storage ring for protons (electrostatic), deuterons, …





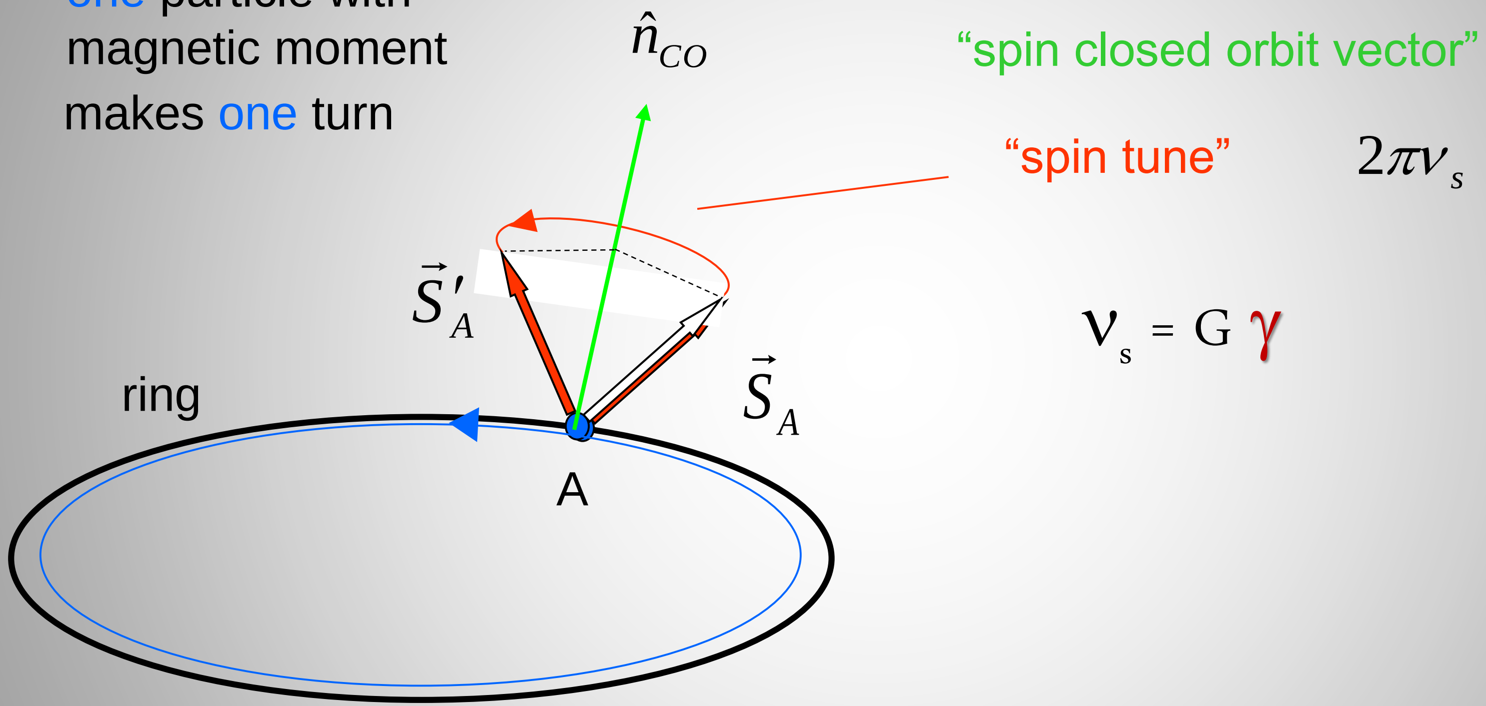
"Freeze" horizontal spin precession; watch for development of a vertical component !

particle	p (GeV/c)	E (MV/m)	B (T)
proton	0.701	16.789	0.000
deuteron	1.000	-3.983	0.160
^{3}He	1.285	17.158	-0.051

One machine with r~30 m

Polarized beam in all magnetic ring

one particle with magnetic moment makes one turn



$\nu_s = G\,\gamma$

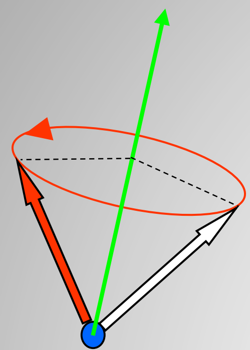
Vertical stable polarization vs. idle precession of the horizontal one with the momentum dependent spin tune

Use EDM coupled to an external T-field to rotate the vertical spin to a horizontal one.

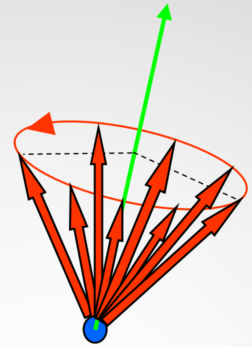
Need to cope with the precession!

Spin coherence

We usually don't worry about coherence of spins along the rotation axis $\hat{n}_{CO}$



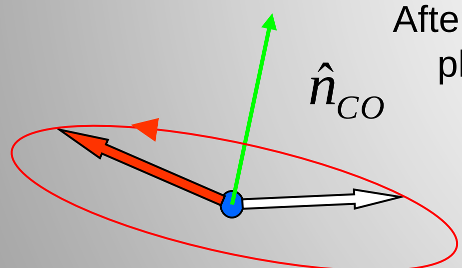
At injection all
spin vectors aligned (coherent)



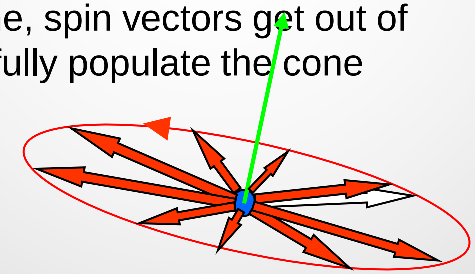
The vertical polarization is not affected!

Situation very different, when you deal with $\vec{S} \perp \hat{n}_{CO}$

After some time, spin vectors get out of phase and fully populate the cone



At injection all spin vectors aligned



After some time, the spin vectors are all out of phase and in the horizontal plane

The horizontal spin-hedgehog: decohered polarization vanishes!

In an EDM machine with frozen spin, decoherence limits the observation time & sensitivity to EDM

Spin coherence time: > 10^3 s for measurement on 10^{-29} e cm level

J. Pretz of JEDI: What JEDI could achieve?

Parameters

$\hbar c$	197.3MeV fm	
c	$3 \cdot 10^8$ m/s	
G	-0.14	deuterons
$\|\vec{S}\|$	1	spin
γ	1.13	deuteron beam with $p = 1\text{GeV}/c$
$E \cdot L$	$1.4 \cdot 10^6$ V	corresponds to $B \cdot L = 10\text{Tmm}$
τ	1000s	spin coherence time
P	0.8	polarization
A	0.6	analyzing power
N	10^9	particles per fill
f	0.005	detection efficiency
U	180m	circumference of COSY

J. Pretz of JEDI: What JEDI could achieve?

$$\sigma_d(1\text{fill}) = 8.3 \cdot 10^{-25} e \cdot \mathrm{cm}\,,$$

for one year (10^4 fills, with 10^3s length)

$$\sigma_d(1\text{year}) = 8.3 \cdot 10^{-27} e \cdot \mathrm{cm}$$

The assumed electric field much to strong? Under study at RWTH

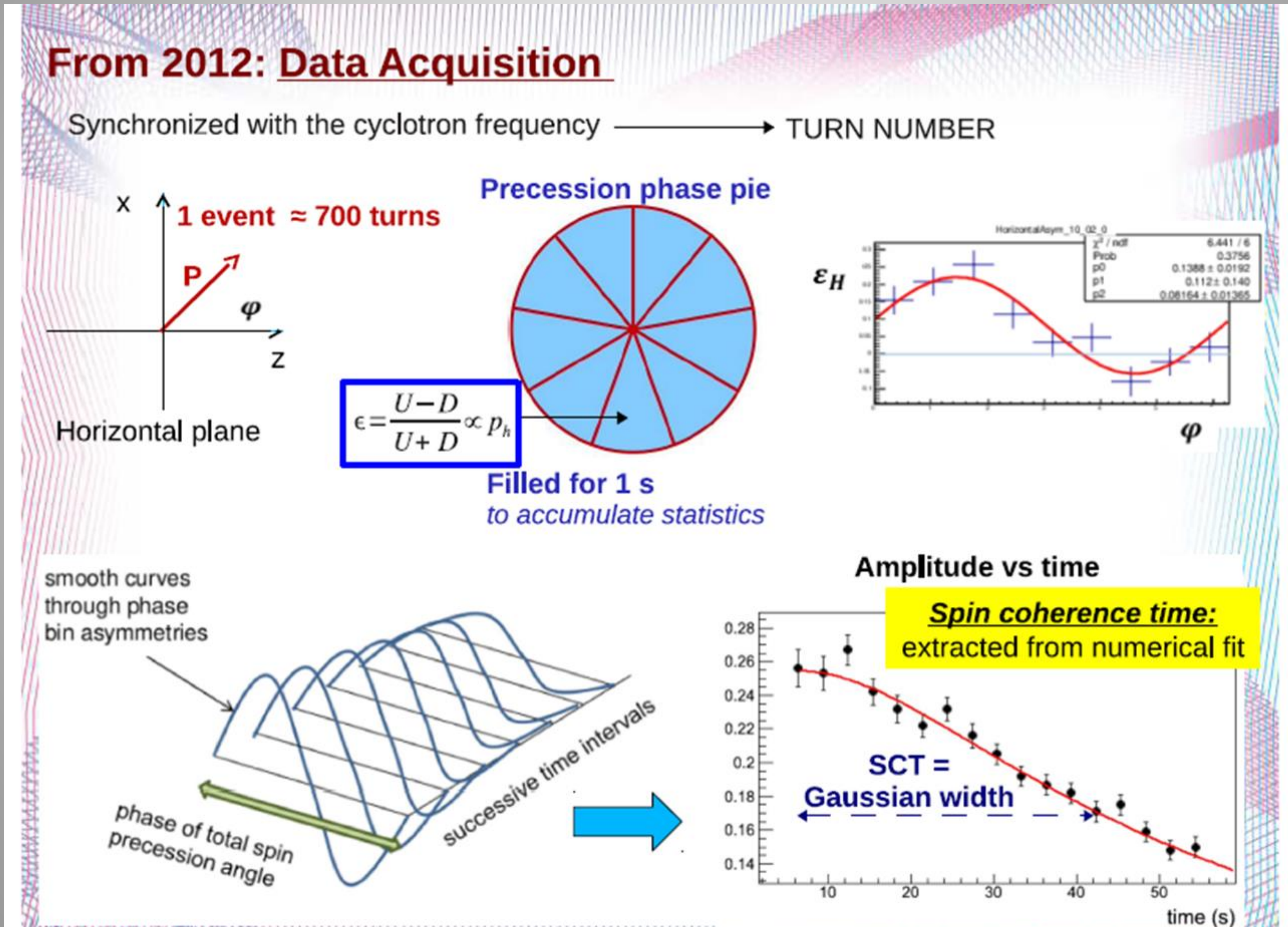
Still tastistics looks fine!

A principal issue: what are limitations from the systematics at COSY ring as is?

RF spin rotator as an imperfection

- Anything in a storage ring which is not a uniform vertical B *is an imperfection*
- **Coupling of the magnetic moment to imperfections masks EDM**
- Under RF resonance spin rotators the spin stable axis does not exist
- But one can ask a well defined question: what is the time dependence of the spin component measured in the polarimeter? Specificallly, the horizontal one is accessible with the novel time stamp technique.
- Why and how the spin decoherence with the RF solenoid on and off could differ?
- ***Stay tuned to the talk by Artem Saleev on Tuesday***

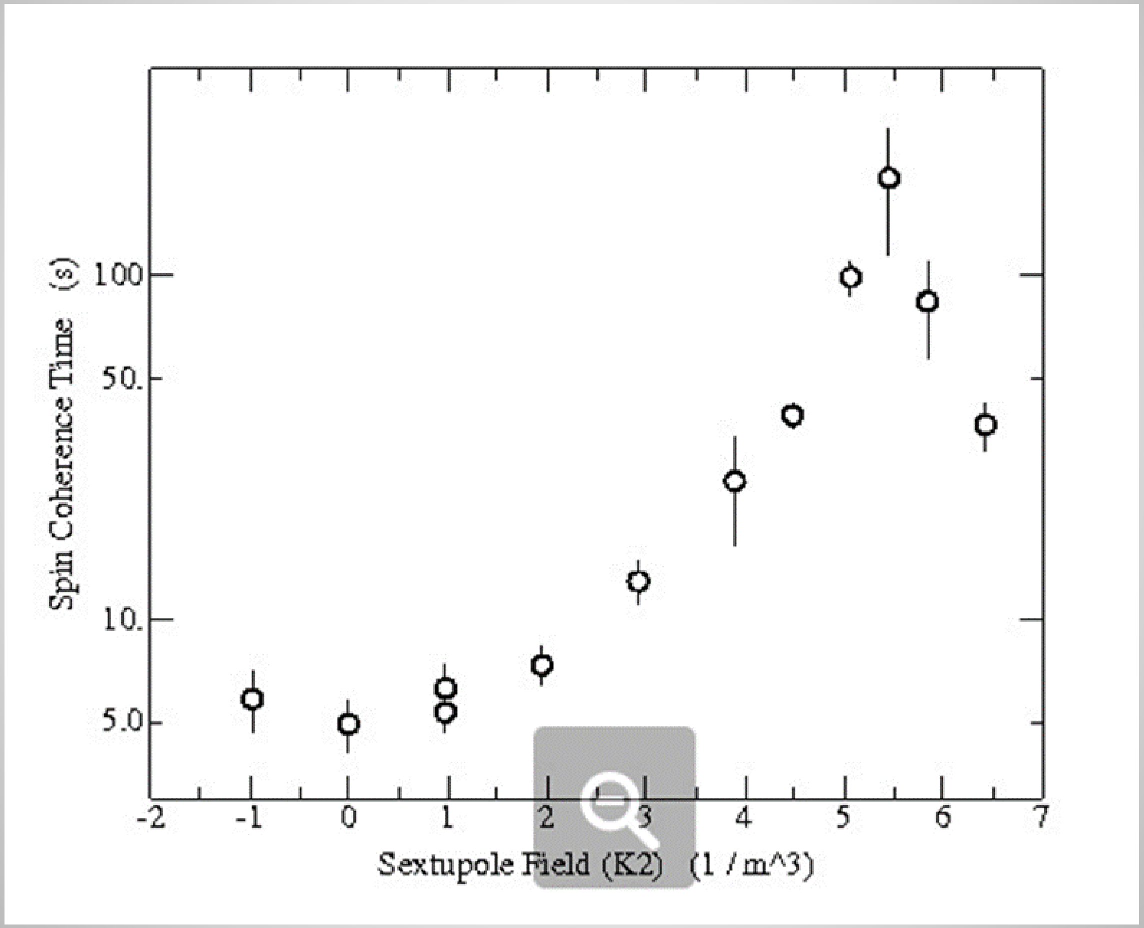
First ever fast time stamp of a precessing spin at a hadronic storage ring COSY



Sextupoles cure spin tune

- *Importance of chromaticity for elimination of path lengthening & emittance effects on the spin tune*
- *The seminal ideas: I.A.Koop and Yu.M.Shatunov "The spin precession tune spread in the storage ring", EPAC1988, Rome --- inspired by the Budker Institute experiment on a comparison of (g-2) of the electrons and positron*
- *Pushing & perfecting the technique at COSY: Ed Stephenson and coworkers*

Courtesy of Ed Stephenson:
Preliminary data from 2012 run at COSY



First ever convincing proof of a control of the spin decoherence in a hadronic storage ring

J. Pretz of JEDI: What JEDI could achieve?

Statistical Error on Spin tune frequency

(see internal note 3/2013 & Dennis presentation)

$$\sigma_\omega^2 = \frac{24}{N(PT)^2}$$

T: time over which N events are evenly distributed
P: measured asymmetry (=polarisation $\times$ analyzing power)

for beam intensity $\approx 5 \times 10^8$ particles per cycle.
number of detected events in the upper and lower detector is ≈ 75000 per cycle in a time window of $T_{\text{cycle}} = 50\text{s}$. With $P = 0.15$ one arrives at an error for the frequency of

$$\sigma_\omega = \frac{1}{0.15 \cdot 30\text{s}} \sqrt{\frac{24}{75000}} = 4 \cdot 10^{-3}$$

with $\omega = 785000/\text{s}$, one arrives at a relative error of

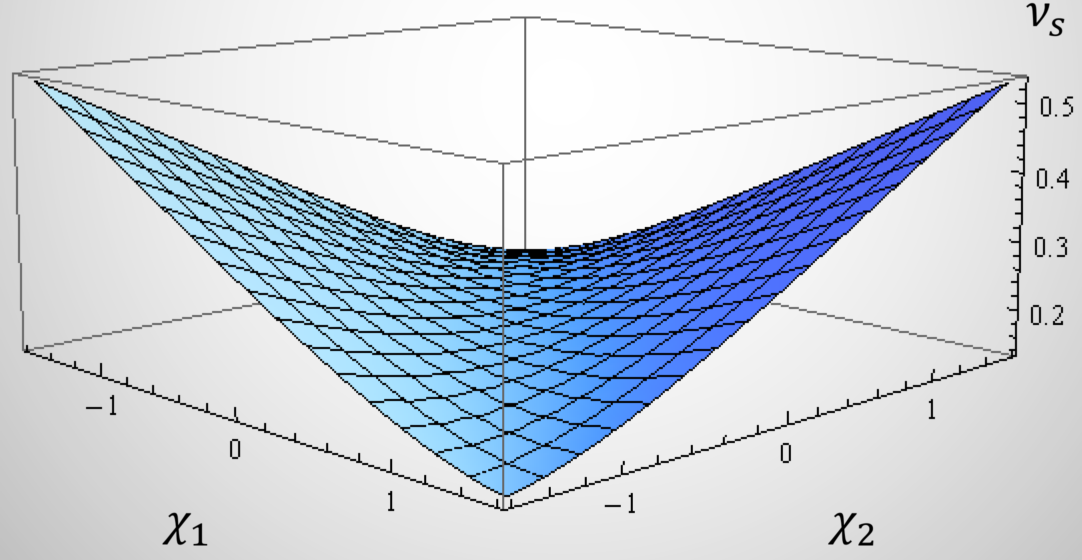
$$\frac{\sigma_\omega}{\omega} = \frac{\sigma_\nu}{\nu} = \frac{4 \cdot 10^{-3}}{785 \cdot 10^3} = 5 \cdot 10^{-9} \quad \text{in single cycle}$$

Preliminary evidence for this accuracy from 2013 JEDI runs at COSY

- *Example: protons at $G\gamma$=2.2*
- *2 corrector solenoids, which do not disturb an orbit, are sufficient at any fixed energy*
- *Spin kicks χ_1 and χ_2, spin tune is given by*

$$\cos \pi\nu_s = \cos[\pi G\gamma] \cos\frac{\chi_1}{2} \cos\frac{\chi_2}{2} - \sin\frac{\chi_1}{2} \sin\frac{\chi_2}{2}$$

- **Correction to a spin tune is quadratic in spin spin kicks**



- To be tested by JEDI

The spin evolution matrix in an RF resonance

- Y-normal to a ring, X-radial, Z-longitudinal, q_s=Gγ
- The MDM solenoid or EDM rotator kick: $S_{\mathrm{y}} \leftarrow\rightarrow S_x$
- $$\begin{pmatrix} S_x(\theta) \\ S_y(\theta) \\ S_z(\theta) \end{pmatrix} = \begin{pmatrix} \cos q_s\theta \cos\chi\theta & -\cos q_s\theta \sin\chi\theta & \sin q_s\theta \\ \sin\chi\theta & \cos\chi\theta & 0 \\ -\sin q_s\theta \cos\chi\theta & \sin q_s\theta \sin\chi\theta & \cos q_s\theta \end{pmatrix} \begin{pmatrix} S_x(0) \\ S_y(0) \\ S_z(0) \end{pmatrix}$$
- The initial state $S_{\mathrm{y}}(0)$=1, $S_x(0)$=$S_z(0)$=0.
- The frequency spectrum of an observable radial $S_x(\theta)$
  $$2\cos q_s\theta \sin\chi\theta = \sin(q_s+\chi)\theta - sin(q_s-\chi)\theta$$
- The splitting of sidebands measures EDM (a similarity to the neutron and atomic EDM expts.)
- **RF spin totator plus frequency locked RF solenoid with tunable phase shift: more reliable separation of the EDM signal**

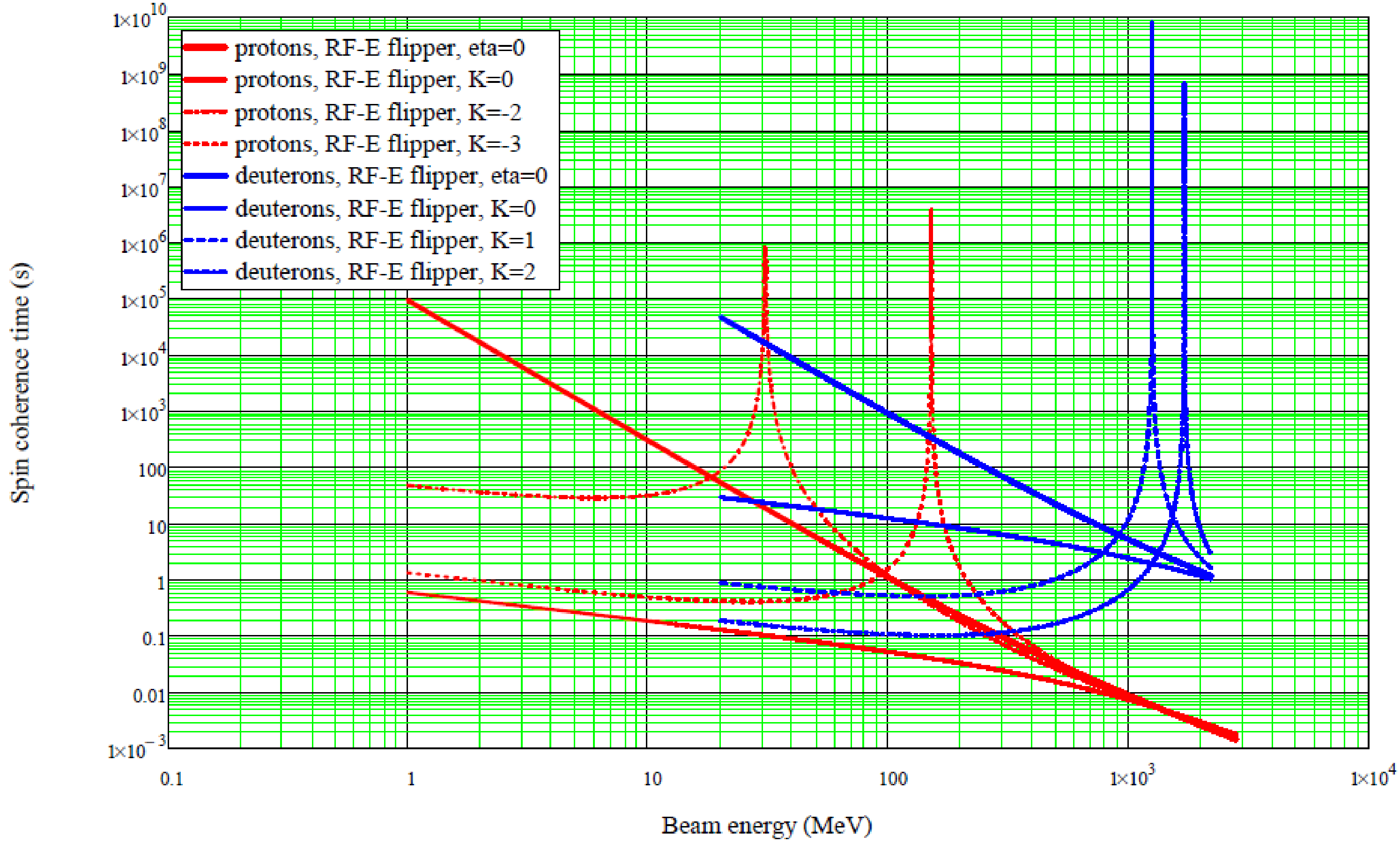
Sensitivity to the EDM

- The frequency shift studies

  $$\mathrm{EDM} < \sigma_{\omega}\, G\, \gamma / \omega \;\; * \; \mathrm{MDM}$$

Spin Coherence Time with RFE Flipper: prediction of a strong dependence on the RF harmonics

Lechrach, Lorenz, Morse, Nikolaev, Rathmann: DSPIN-2011



- Increase the spin coherence time by some orders in magnitude?
- Experiment with polarized COSY beam soon

Vertical-to-horizontal flips with an RF solenoid

- *Synchroton oscillations induce a scattering of the rotator kick*
- *Total spin flip angle*

$$\psi = 2\pi\chi f_R t = 2\pi\chi N_{osc}$$

- ***The flipping spin, with the solenoid on, acquires the oscillating phase slip ~*** ψ
- *The decoherence law:*

$$\langle S_y \rangle = \frac{1}{\sqrt[4]{1 + \frac{9}{16}\psi^2 \boldsymbol{C^2} \Delta_{osc}^4}}$$

- *Checks the LLMNR prediction of properties of*

$$C = 1 - \frac{\eta}{\beta^2}(1 + \frac{K}{G\gamma})$$

- *Preliminary evidence from the recent JEDI runs*

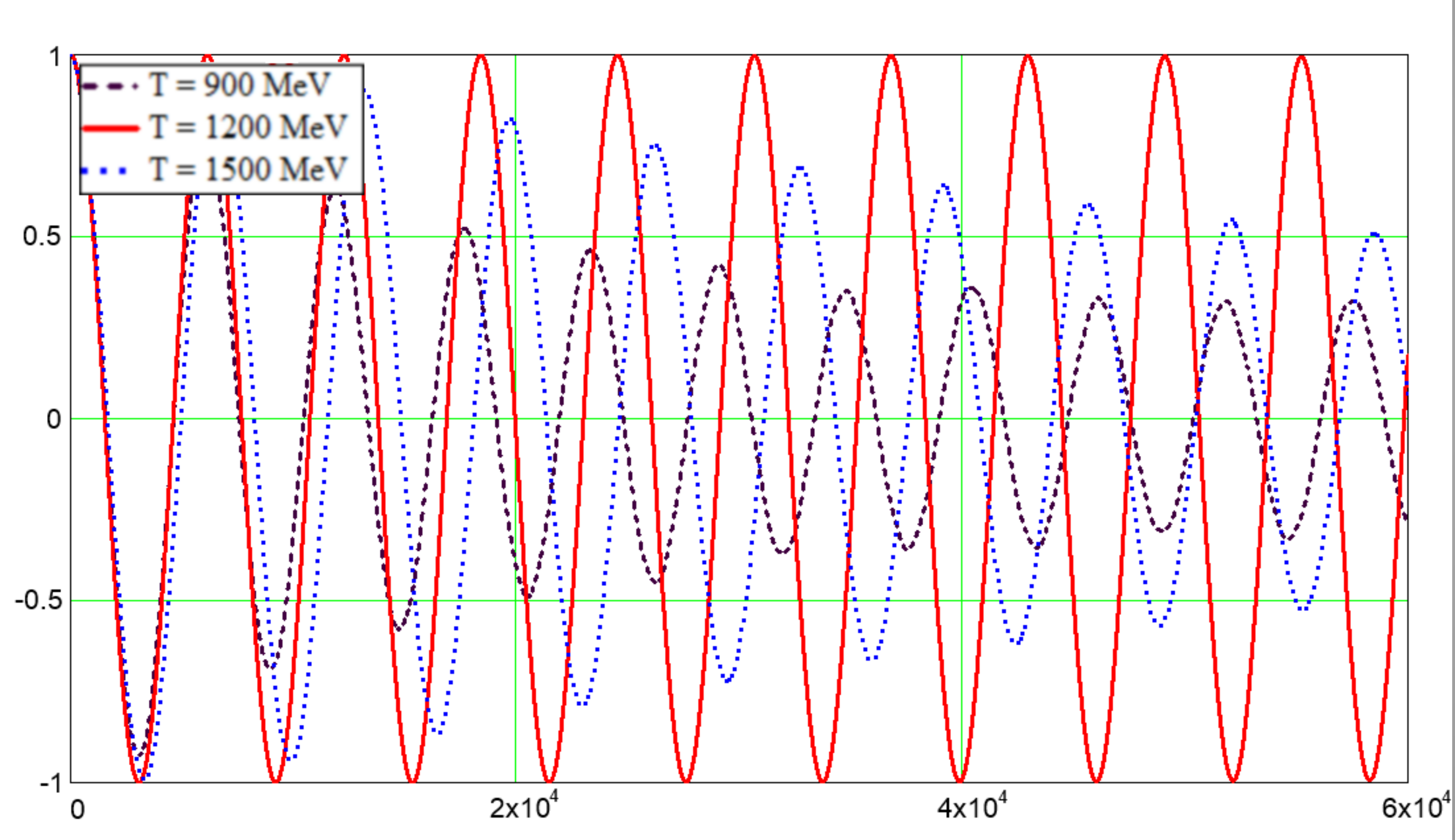
JEDI at COSY as a High Precision Machine: Summary and outlook

- ***Our very existence is the best proof the SM is not the end of the story***
- ***nEDM, pEDM, dEDM, hEDM are must do windows to Beyond the SM physics with tremendous model killer potential***
- ***JEDI is making a tremendous progress***
- ***Successful polarimetry of precessing horizontal spin by fast time stamp***
- ***Long spin decoherence time is possible via controlling the chromaticity by sextupoles***
- ***Magic energies with weak spin decoherence are likely: to be tested in the future experiments***
- ***Lots of preliminary JEDI data are being analyzed, new expts at COSY are in the pipeline***

Vertical polarization of the beam at 3 different energies.

- Spin resonance is driven by RF solenoid on *K* = 0 harmonic of frequency generator.
- At T~1200 MeV spin tune phase slips are compensated by proper phase of RF solenoid field

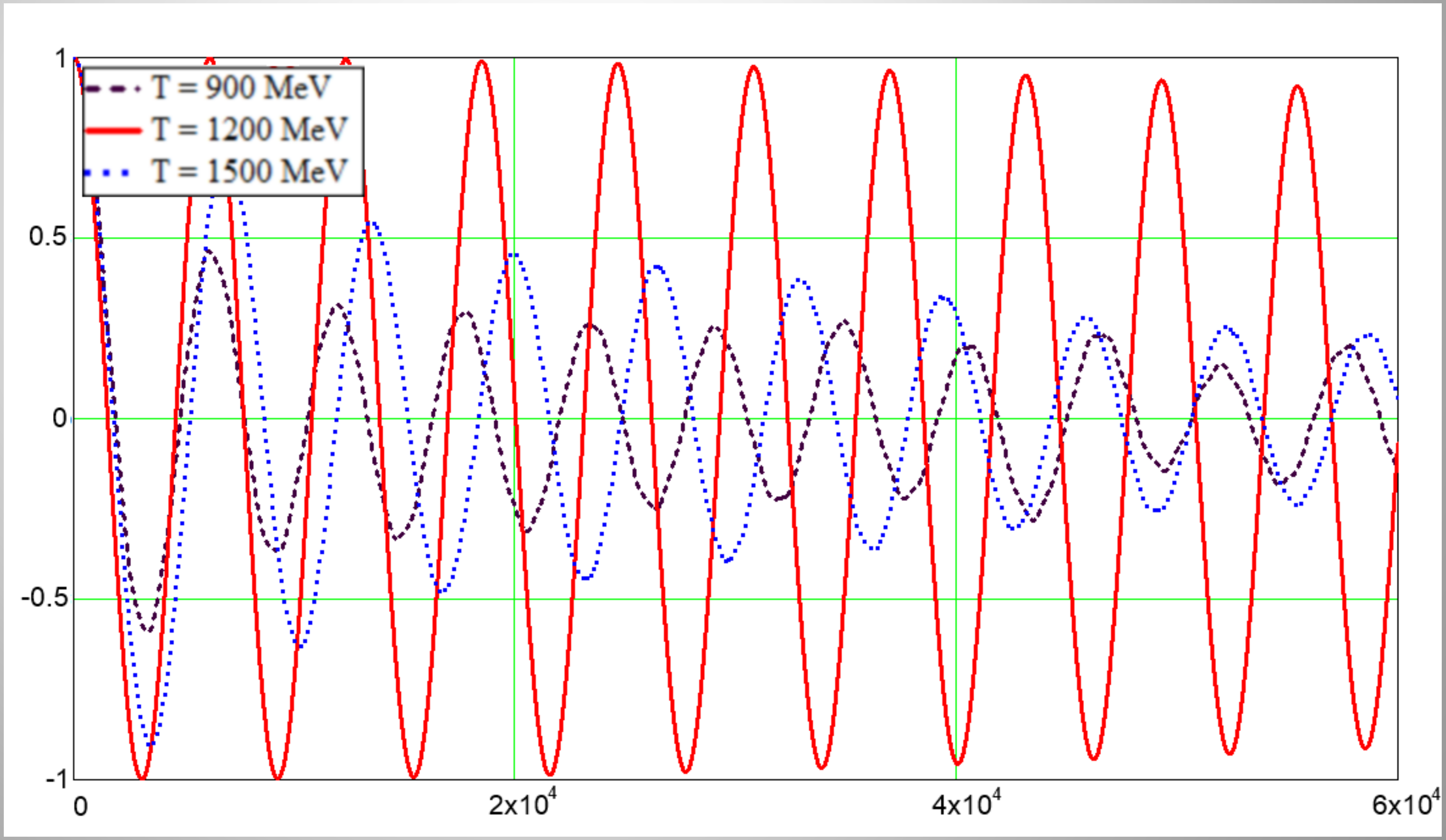
- Ensemble of 500 particles (**deuterons**)
- $\frac{\Delta p}{p} = 0.005$
- Synchrotron tune $Q_s = 0.001$
- Amplitude of spin kick in RF solenoid $\chi = 0.0003$



Vertical polarization of the beam at 3 different energies.

- Spin resonance is driven by RF solenoid on *K* = 1 harmonic of frequency generator.
- At T~1200 MeV spin tune phase slips are compensated by proper phase of RF solenoid field

- Ensemble of 500 particles (deuterons)
- $\frac{\Delta p}{p} = 0.01$
- Synchrotron tune $Q_s = 0.001$
- Amplitude of spin kick in RF solenoid $\chi = 0.0003$



Very preliminary findings from the JEDI 2013 run with RF solenoid at one fixed energy

- *The dependence on the RF harmonics: the theoretical prediction seems to be OK*

- *The theoretical understanding of the decoherence law looks OK*

- *Outlook for a future: a potential suppression of the spin decoherence calls for an exploration of the energy dependence --- calls for a polarimetry in a broad range of energies*

More on RF EDM rotators:

- ***EDM (and momentum) transparent Wien filter:***

(i) does not disturb the orbit

(ii) CP-violating rotation of the spin by an indirect resonfnct coupling of the EDM to the motional electric field in the ring (Morse, Orlov, Semertzides; Silenko; Nikolaev (2012))

(iii) ***a fly in the ointment:*** *simultaneously rotates spin by coupling the MDM to the imperfection magnetic fields*

- ***MDM transparent RFE flipper:***

(i) CP-violating rotation of the spin directly in the flipper field

(ii) is free of a coupling to imperfections

(iii) a fly in the ointment: *excites coherent betatron oscillations: calls for a special beam optics with two counterphase flippers*

- ***New JEDI experiments in preparation***

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- *nEDM, pEDM, dEDM, hEDM are must do windows to Beyond the SM physics with tremendous model killer potential*

- *JEDI is making a tremendous progress*
- *Successful polarimetry of precessing horizontal spin by fast time stamp*
- *Long spin decoherence time is possible via controlling the chromaticity by sextupoles*
- *Magic energies with weak spin decoherence are likely: to be tested in future experiments*
- *Lots of preliminary JEDI data are being analyzed: stay tuned and welcome to the JEDI talks at future spin conferences.*

Thanks to survivors for your attention!

- Backup slides

Status of EDM@BNL: dreams vs grim reality

- > 10 years of theoretical studies
- Proposal submitted to DoE end of 2011
- Will be sent out for refereeing only when the money for funding will be in sight

Ring + RF solenoid at a resonance frequency

- Average spin kick per single pass: $4\pi\chi$

- $\frac{\delta p(t)}{p} = \xi\sqrt{2}\frac{\delta p}{p}\sin(2\pi Q_z f_R t + \sigma)$
- $\omega = 2\pi Q_z f_R t$

- ξ - a Gaussian random number
- $\langle\xi^2\rangle = 1$
- σ is a random phase: $\sigma = [0, 2\pi]$

Ring + RF solenoid at a resonance frequency

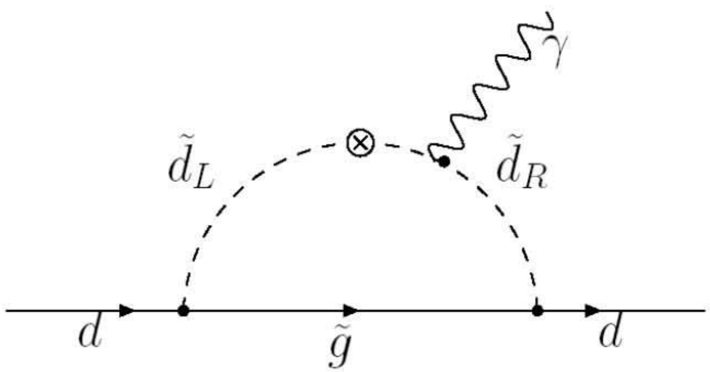
- Average spin kick per single pass: $4\pi\chi$
- The synchrotron oscillation

$$\frac{\delta p(t)}{p} = \xi\sqrt{2}\,\frac{\delta p}{p}\sin(2\pi Q_z f_R t + \sigma)$$

- The synchrotron phase $\omega = 2\pi Q_z f_R t = Q_z\,\theta$
- ξ - a Gaussian random number
- $\langle \xi^2 \rangle = 1$
- σ is a random phase: $\sigma = [0, 2\pi]$

Supersymmetry / SUSY CP Problem

- MSSM without corrections gives: $\boxed{\text{EDM} = 10^{-23\text{-}25}\ \text{e.cm}}$ ALREADY RULED OUT!!
- SUSY breaking introduces new CPv phases
- EDMs appear at 1-loop level

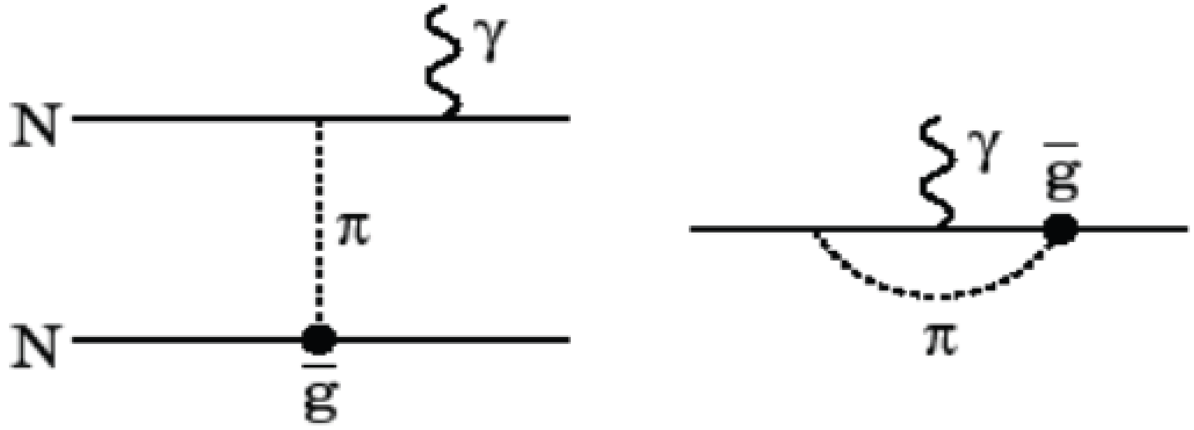


$$\kappa_i = \frac{m_i}{16\pi^2 M_{\text{SUSY}}^2} = 1.3 \times 10^{-25}\text{cm} \times \frac{m_i}{1\text{MeV}} \left(\frac{1\text{TeV}}{M_{\text{SUSY}}}\right)^2,$$

- SUSY with extensions: $\boxed{\text{EDM} = 10^{-28}\ \text{e.cm}}$ NEARLY WITHIN AIM OF cryoEDM!!

University of Sussex

Nuclear EDM:
T,P-odd NN interaction gives 50 times larger contribution than nucleon EDM
Sushkov, Flambaum, Khriplovich 1984



COSY:
Crucial idea from F.Rathmann, refined by Bill Morse:

- EDM in the pure radial E-ring: buildup of the vertical polarization from the horizontal one
- COSY + RF radial electric field & and swap the tole of the vertical and horizontal polarizations

- Need to cope with the precession of the horizonal polarization
- Need very long SCT!

- d < 10^{-24} e.cm for the deuteron EDM is within the reach of COSY (if free of systematics)

Theoretical analysis: ***A.Lehrach, B.Lorentz, W.Morse, N.N.N. & F.Rathmann (2011)***

What decoheres the spin? Idle precession:

- No holding field for horizontal spin
- Spread of spin tune $\theta = \theta_S + 2\pi G\delta\gamma = \theta_S + \delta\theta$,
- The cumulant phase slip $\Delta(k) = \sum_{l=1}^{k} \delta\theta_l$
- The idle precession

$$S_{\|}(t) = S_{\|}(0)\langle\cos\Delta(k)\rangle_{ens} = S_{\|}(0)\left\{1 - \frac{1}{2}\langle\Delta^2(k)\rangle_{ens}\right\} \tag{1}$$

- Synchrotron oscillations: $\Delta(k)$ stays constant, spins don't decohere
  Frequency spectrum with side bands: $f = f_S \pm kf_{synch}$
- Randomization of $\delta\theta_k$

$$\langle\Delta^2(k)\rangle_{ens} = k\Delta_0^2 = f_R t\Delta_0^2\,, \tag{2}$$

- Spin coherence time (SCT)

$$\tau_{SC,I} = \frac{2}{f_R\Delta_0^2} \tag{3}$$

Locking RFE flipper to spin precession

- The horizontal spin precesses: $f_S = \gamma G f_R$. Per single turn, $\theta_S = 2\pi\gamma G$
- Evolution: $S_{||}(k+1) = S_{||}(k) + S_y \alpha \cos\theta(k)$
- Master equation

$$S_{||} = S_y \sum_{l=1}^{k} \alpha \cos(l\theta_S)\,. \tag{1}$$

- Accumulation of $S_{||}$ only if $E = E_0 \cos(l\theta_F) = E_0 \cos(\theta_F f_R t)$, i.e., $\alpha = \alpha_E \cos(\theta_F f_R t)$
- The resonance condition

$$S_{||}(t) = S_y \sum_{l=1}^{k} \alpha_E \cos(l\theta_S)\cos(l\theta_F) = \frac{1}{2}\sum_{l=1}^{k}[\cos(l(\theta_S - \theta_F)) + \cos(l(\theta_S + \theta_F))],$$

$$\theta_F = \pm\theta_S + 2\pi K \qquad f_F = K f_R \pm f_S \tag{2}$$

-

$$S_{||}(t) = \frac{1}{2} S_y \alpha_E f_R t\,, \tag{3}$$

RFE flipper phase slip

- The change of the particle momentum changes the revolution (transit) time τ,

$$\frac{\delta\tau}{\tau} = \eta\frac{\delta p}{p} = \eta\frac{\delta\gamma}{\gamma\beta^2} \,, \tag{1}$$

- The slip-factor

$$\eta = \frac{1}{\gamma_{tr}^2} - \frac{1}{\gamma^2} \tag{2}$$

- Flipper phase slip per pass

$$\delta\theta_F = 2\pi f_F \delta\tau = \frac{f_F}{f_S} \cdot \frac{\eta}{\beta^2}\delta\theta_S \,. \tag{3}$$

- Flipper phase slip is large and enhamced by $1/\beta^2$

The interplay of two phase slips

- Master Equation

$$
\begin{aligned}
S_{||} &= S_y \alpha_E \sum_{l=1}^{k} \cos(l\theta_S + \Delta(l)) \cos(l\theta_F + \frac{f_F}{f_S} \cdot \frac{\eta}{\beta^2} \Delta(l)) = \\
&= \frac{1}{2} S_y \alpha_E \sum_{l=1}^{k} \cos C_{SD} \Delta(l) = \\
&= \frac{1}{2} S_y \alpha_E \sum_{l=1}^{k} \left\{ 1 - \frac{1}{2} C_{SD}^2 \Delta(l)^2 \right\} . \qquad (1)
\end{aligned}
$$

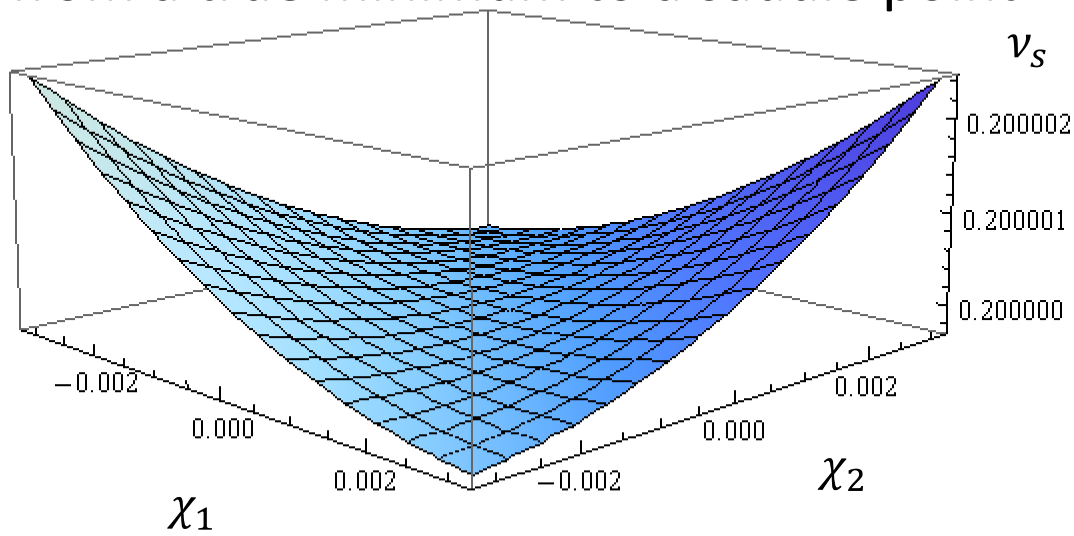
$$
C_{SD} = 1 - \frac{f_F}{f_S} \cdot \frac{\eta}{\beta^2} = 1 - \frac{\eta}{\beta^2} \cdot \left(1 + \frac{K}{G\gamma} \right) . \qquad (2)
$$

- For nonrelativistic particles

$$
\eta \sim -1
$$

Tend to enhance C_{SD}, but....

- At smaller values of χ_1 and $\chi_2 \sim 10^{-3}$ spin tune changes at order of $\sim 10^{-6}$
- Spin tune exhibits a fairly complex pattern of an extremum changing from a true minimum to a saddle point



- Strength of imperfections is minimized at an extremum: see Krish's talk on 96 correctors at AGS

Extreme cases of phase slips:

- Random effects in the momentum spread give finite SCT
- Regular oscillations do not decohere horizontal spin: infinite SCT?
- Runaway decoherence from the path lengthening by betatron oscillations (Ed Stephenson et al. 2012: Successfully learning to tame them at COSY)
- Rectangular (flat-top) exitation of a flipper suppresses dangerous flipper phase effects (A. Lehrach et al. 2011)
- Spin tune and flipper phase slips are of the same origin: cancellations at magic energies, $C_{SD}=0$ at judiciously chosen flipper harmonics, to be tested at COSY (A. Lehrach et al. 2011)
- New development at COSY: fast time stamp in the polarimetry of rapidly precessing horizontal spin

Toy model for SCT

- Entirely unrealistic turn-by-turn randomization of mometnum
- (N.B: One synchrotron oscillations per several thousand turns)
- A positive virtue: offers an analytic formula for SCT

$$\tau_{SC} = \frac{1}{2\pi^2 C_{SD}^2 f_R G^2 \gamma^2 \beta^4} \cdot \left\langle \left(\frac{\delta p}{p}\right)^2 \right\rangle^{-1} . \qquad (1)$$

- Flattop flipper, i.e.,$C_{SD} = 1$, for 100 MeV deuterons with $\delta p/p = 10^{-4}$:

$$\tau_{SC}^{d}(\eta = 0) \sim 10^5\, s$$

- A requested large SCT is within reach at COSY!
- Artificially enhanced randomiziation of momentum: a LOWER limit for SCT
- A Pandora box of other decoherence mechanisms

Why EDM-transparent Wien-Filter?

- The motional E-field in a ring proper rotates EDM but with a constant amplitude
- MDM-transparent RFE filter ➔ Lorentz force & unwanted excitation of coherent betarton oscillations and perhaps a runaway decoherence

- Wien filter eliminates the E-field on EDM
- 2012: Y. Semetrtzides & Yu. Orlov (also NNN and A.Silenko): EDM-transparent Wien-filter in a COSY ring still generates the EDM signal

- The reason: Wien-filter is MDM-nontrasparent and gives rise to a frequency modulation of the spin tune which conspires with the motional E-field in a ring. The EDM signal is the same as for MDM-transparent flipper
- The spin decoherence properties of the two devices are the same

Perfect RF Wien filter (Yannis & Yuri Orlov)

- A definition: vanishing Lorentz force, $\vec{E} + \vec{\beta} \times \vec{B} = 0$
- Is entirely transparent for the EDM of a particle!
- The vertical component of $\vec{\Omega}$ is nonzero:

$$\Omega_{WF} = -\frac{e}{m} \cdot \frac{G+1}{\gamma^2} B = -\frac{e}{m} \cdot \frac{G+1}{\gamma^2 \beta} E(t)$$

- Extra spin precession angle per pass

$$\psi_k = \Omega_{WF} t_F = \psi_E \cos(2\pi f_F t)\,, \qquad \psi_E = -\frac{e}{m} \cdot \frac{G+1}{\gamma^2 \beta} E(t) t_F$$

- Modulates spin tune and breaks $Q_S = G\gamma$

$$\theta(k) = \theta_S f_R t + \underbrace{\sum_0^k \psi_k}_{} \,.$$

Frequency modulation

- Yuri Orlov: it conspires with the EDM rotation in the *permanent* motional radial electric field of the ring

Runaway decoherence

Off tune RFE and spin precession frequences:

- $$\delta P = \langle \delta p \rangle \neq 0$$
- $$\delta f_{FS} = f_F - f_S \neq 0$$
- Runaway phase slip
$$\Delta(k) = 2\pi \delta f_{FS} t$$
- Demands
$$\delta f_{FS} < \frac{2\pi}{\tau_{SC}}$$
- Stringent constraint (for deuterons):
$$\tau_{SC} = 10^5 \mathrm{s} \Longrightarrow \frac{\delta f_{FS}}{f_F} < 10^{-10}$$

Runaway decoherence from betatron oscillations

- Radial & vertical betatron oscillations: a curvilinear trajectory is lengthier than the ideal circular one
- The cyclotron frequency is maintained by the RF cavity: dictates a smaller mean radius of trajectory

- Curvilinear trajectory dictates a finite Δp maintained for a long time
- A momentum shift quadratic in the betatron amplitude

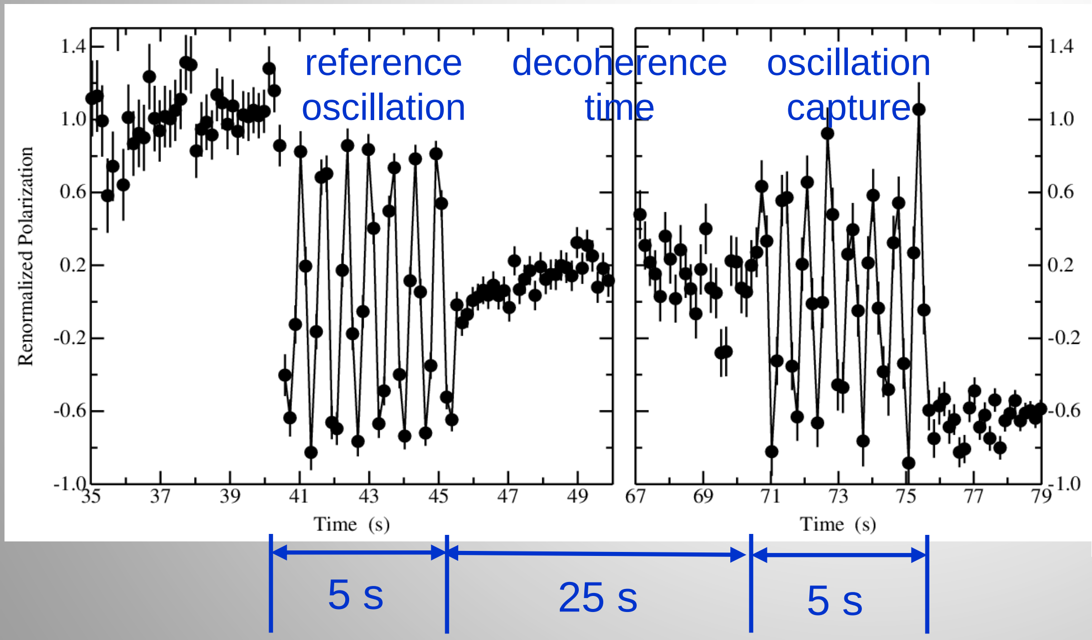
- Koop & Shatunov (Budker Inst. 1987): elimination of the runaway decoherence of electron spins by orbit lengthening fine-tuning the sextupole magnets
- Stephenson at COSY: succesfully testing the idea with deuterons and magnetic RF spin flipper

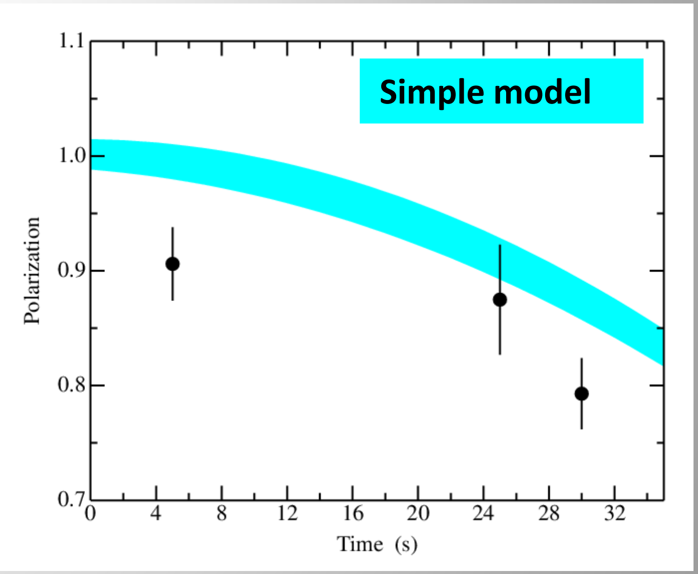
Spin Coherence Measurements at COSY

Longitudinal RF Solenoid:

water-cooled copper coil in a ferrite box

- Length 0.6 m
- Frequency range 0.4 to 1.2 MHz
- Integrated field $\int B_{rms}\, dl \sim 1$ T·mm





RF solenoid: on off on

Spokesperson: E. Stephenson (IUCF)

Summary

- Our very existence is the best proof the SM is not the end of the story
- nEDM, pEDM, dEDM, hEDM are must do windows to Beyond the SM physics with tremendous model killer potential
- Nucleus is not a sum of constituent nucleons!
- COSY is a unique facility for systematic study of EDM related systematics for future dedicated rings
- Much theoretical & experimental progress has already been made towards this goal
- A precursor pEDM and dEDM searches at COSY as is can reach a ballpark of predictions from modern theories of CP violation
- New generation of nEDM and pEDM & dEDM & hEDM at dedicated rings have a potential for constraining the BSM theories much tighter than LHC --- don't miss this opportunity

- Thanks to survivors for your attention!

Perfect RF-E flipper - 1

- Perfect RF-E flipper is MDM-transparent: $\vec{\Omega} \parallel \vec{E}$
- The compensating magnetic field ($\vec{B}^* \neq 0$!)

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

- Nonvanishing Lorentz force and excitation of radial betatron oscillations:

$$\vec{E} + \vec{\beta} \times \vec{B} = \frac{G+1}{G\gamma^2}\vec{E}\,,$$

- Spin tilt per pass

$$\alpha_k = \frac{G+1}{G\gamma^2} \cdot d \cdot t_F E(t)\,, \quad t_F = \frac{L_F}{\beta}$$

- Short (poitlike) flipper: $L_F \ll L_R$

EDM in Wien filter plus ring

- Spin rotation matrix of a Wien filter

$$\hat{R}(0,\psi_k) = \begin{vmatrix} \cos\psi_k & 0 & -\sin\psi_k \\ 0 & 1 & 0 \\ \sin\psi_k & 0 & \cos\psi_k \end{vmatrix}$$

- Wien filter plus ring $\hat{R}(k) = \hat{R}(\alpha_R, \theta_k)\hat{R}(0,\psi_k) =$

$$\begin{vmatrix} \cos(\theta_k+\psi_k) & -\alpha_R(1-\cos\theta_k) & -\sin(\theta_k+\psi_k) \\ \alpha_R\{\cos(\theta_k+\psi_k)-\cos\psi_k\} & 1 & -\alpha_R(\sin(\theta_k+\psi_k)-\sin\psi_k)\} \\ \sin(\theta_k+\psi_k) & \alpha_R\sin(\theta_k) & \cos(\theta_k+\psi_k) \end{vmatrix}$$

- Wien filter effect in spin tune

$$\begin{aligned} \psi(k) &= \sum_0^k \psi_k = \psi_E \sum_0^k \cos\theta_F(k) = \\ &= \psi_E \cdot \frac{1}{2\sin\frac{1}{2}\theta_F}\left(\sin\frac{1}{2}\theta_F + \sin\{\theta_F(k) + \frac{1}{2}\theta_k\}\right) \end{aligned}$$

EDM in Wien filter plus ring - 1

- Rapid precession $Z(k) = Y(k)exp\{-i[\theta(k) + \psi(k)]\}$
- Evolution for an envelope $Y(k)$:

$$Y(k+1) = Y(k) + 2\alpha_R \sin \frac{1}{2}\theta_S S_y(k) e^{i[\theta(k)+\psi(k)+\frac{1}{2}\theta_k]}$$

- Slow rotation: suppress all rapidly oscillating terms

$$e^{+i[\theta(k)+\psi(k)+\frac{1}{2}\theta_k]} = e^{-i(k+\frac{1}{2})\theta_S]}(1 + +i\psi(k))$$
$$\Longrightarrow \psi_E \frac{1}{2\sin\frac{1}{2}\theta_S} \sin(\theta(k) + \frac{1}{2}\theta_S) \sin(\theta_F(k) + \frac{1}{2}\theta_F)$$

- Accumulation of the horizontal spin

$$Y(k+1) = Y(k) + \frac{1}{2}\alpha_R \psi_E S_y(k) \cos\{\theta(k) - \theta_F(k)\}$$

Exact analogy to the Lehrach-Lorenz-Morse-Nikolaev-Rathmann eqn.

Wien Filter is Dual to RF-E flipper

- For both setups a resonance condition is the same: $f_F = f_S + f_R K$
- Average EDM rotation angle per turn:

$$\text{Perfect RF} - \text{E flipper}: \quad \text{pure E} - \text{rotation} \quad \alpha_E = \frac{G+1}{G\gamma^2} \cdot \frac{\eta e}{m} \cdot E_F \tau_F$$

$$\text{Perfect Wien filter}: \quad \text{B} - \text{rotation times E} - \text{rotation} \quad \alpha_R \psi_E \equiv \alpha_E$$

- Identical interplay of the spin precession and flipper phase slips
- Identical conditions for the decoherence-free spin rotation by a flipper
- Educated guess: at a fixed E-filed of the flipper the net EDM signal does not depend on the compensating B-field
- RF Wien filter is superior as it does not excite unwanted betatron oscillations.
- Duality is exact only at a nominal energy. Under- or over-compensated radial electric field $\propto \delta p/p$.
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A central issue:

How come a permanent motional radial electric field in a storage ring generates the resonance EDM signal which grows proportional to an accumulation time?

- Discovery: Yannis Semertzidis. A showcase of *serendipity* times an excellent spin *tracker*.
- Explanation: Yuri Orlov endowed permanent motional electric field with resonance properties
- *Ecclesiastes 1:18: For with much wisdom comes much sorrow:*

  LLMNR have had all the right components but threw out a motional electric field in a ring and motional magnetic field in a flipper much too early.
- A moral conveyed from a story: *a good unbiased tracking is just indispensable*

Perfect RF-E flipper 2

- Harmonic, $\alpha_k = \alpha_E \cos(2\pi f_F t)$, and flattop. $\alpha = \alpha_E \cdot \mathrm{sign}\{\cos(2\pi f_F t)\}$, excitation functions
- Familiar resonance condition $f_F = f_S + K f_R, \quad K = 0, \pm 1, \pm 2, ..$

$$f_S = G\gamma f_R$$

- Pointlike heating of betatron oscillations with an exactly known amplitude.
- Possible remedy: second flipper at betatron phase shift

$$\theta_B = \pm\pi$$

- Second flipper must run with the phase shift

$$\Delta\theta_F = -\frac{G\gamma}{Q_x}\theta_B$$

- Demands special optics and a ring section to tolerate large (?) betatron oscillations.

Perfect RF Wien filter (Yannis & Yuri Orlov)

- A definition: vanishing Lorentz force, $\vec{E} + \vec{\beta} \times \vec{B} = 0$
- Is entirely transparent for the EDM of a particle!
- The vertical component of $\vec{\Omega}$ is nonzero:

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- Modulates spin tune and breaks $Q_S = G\gamma$

$$\theta(k) = \theta_S f_R t + \sum_0^k \psi_k\,.$$

- Yuri Orlov: it conspires with the EDM rotation in the *permanent* motional radial electric field of the ring

EDM in the motional E-field of the ring

- Spin rotation axis with stable $\vec{e}_y$ but rotating $\vec{e}_x$:

$$\vec{\Omega} = -f_R\theta_S(\vec{e}_y - \alpha_R\vec{e}_x)\,, \qquad \theta_S = 2\pi G\gamma, \qquad \alpha_R = \frac{\eta\beta}{G} \ll 1\,.$$

- Principal task is a separation of rapid and slow rotations: $\alpha_R \ll 1$ is a small perturbation parameter
- To the lowest order in α_R

$$Z = S_z + iS_x = Z(0)e^{-i\theta_S f_R t}\,, \qquad S_y = \mathrm{const}$$

- Single pass through a ring to α_R:

$$\begin{aligned}
S_x(k+1) &= S_x(k)\cos\theta_k - S_y(k)\alpha_R(1-\cos\theta_k) - S_z(k)\sin\theta_k\,,\\
S_y(k+1) &= -S_x(k)\alpha_R(1-\cos\theta_k) + S_y(k) - S_z(k)\alpha_R\sin\theta_k\,,\\
S_z(k+1) &= S_x(k)\sin\theta_k + S_y(k+1)\alpha_R\sin\theta_k + S_z(k)\cos\theta_k\,.
\end{aligned}$$

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Exact analogy to the Lehrach-Lorenz-Morse-Nikolaev-Rathmann eqn.

Motional E-field in a ring with perfect RF-E flipper

- Single crossing of a perfect flipper

$$
\begin{aligned}
S_x(1) &= S_x(0) \\
S_y(1) &= S_y(0) - \alpha S_z(0) \\
S_z(1) &= S_z(0) + S_y(0)\alpha
\end{aligned}
$$

- Flipper plus ring rotation matrix $\hat{R}(\alpha_R, \theta_k) =$

$$
\left|
\begin{array}{ccc}
\cos(\theta_k) & -[\alpha_R(1-\cos\theta_k) - \alpha_k \sin\theta_k] & -\sin(\theta_k) \\
-\alpha_R(1-\cos\theta_k) & 1 & -\alpha_R \sin(\theta_k) - \alpha_k \cos\theta_k \\
\sin(\theta_k) & +\alpha_R \sin(\theta_k) + \alpha_k \cos\theta_k & \cos(\theta_k)
\end{array}
\right|
$$

- All motional electric field rotation effects average out: amounts to pure EDM rotation in the flipper times pure MDM rotation in the ring
- LLMNR evolution equations are fully recovered

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