Spin Coherence Time

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Sensitivity

General expression for the uncertainty of an EDM experiment

$$\sigma_d \propto \frac{1}{P E \sqrt{N} \tau A}$$

N : total number of detected particles

P : initial polarization of sample

A : analyzing power of polarimeter

E : electric field strength in particle rest frame

τ : characteristic time of single measurement

$$= \frac{1}{P E \sqrt{n T_{tot}} \tau A}$$

n : number of detected particles per fill

T_{tot} : total time to run the experiment

τ : determined by storage time and <u>spin coherence time</u>

A few words on spin dynamics

Highly simplified spin-EoM

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

For frozen spin $\Omega_{MDM} \approx 0$, $\Omega_{MDM} » \Omega_{MDM}$

Longitudinal : $S_z = S_z^{(\cdot)} \cos \Omega_{MDM} t \simeq S_z^{(\cdot)}$

Radial : $S_x = S_z^{(\cdot)} \sin \Omega_{MDM} t \simeq 0$

Vertical : $S_y = \int_0^t S_z \Omega_{EDM} dt \simeq S_z^{(0)} \Omega_{EDM} t$

Ex. 1: depolarization from spin tune spread

A particle moves through E & B fields

→ <u>magnitude</u> Ω_{MDM} varies with $\delta\Omega$

$$P(t) \stackrel{\text{def}}{=} \langle S_z \rangle (t) \quad = S_z^{(0)} \langle \cos \delta\Omega t \rangle \cdot \cos \langle \Omega \rangle t$$

$$\simeq S_z^{(0)} \left(1 - \frac{1}{2} \langle \delta\Omega^2 \rangle t^2 + \cdots \right)$$

Beam depolarizes with characteristic time $T_2 = 1/\delta\Omega$

→ Reduced sensitivity for EDM

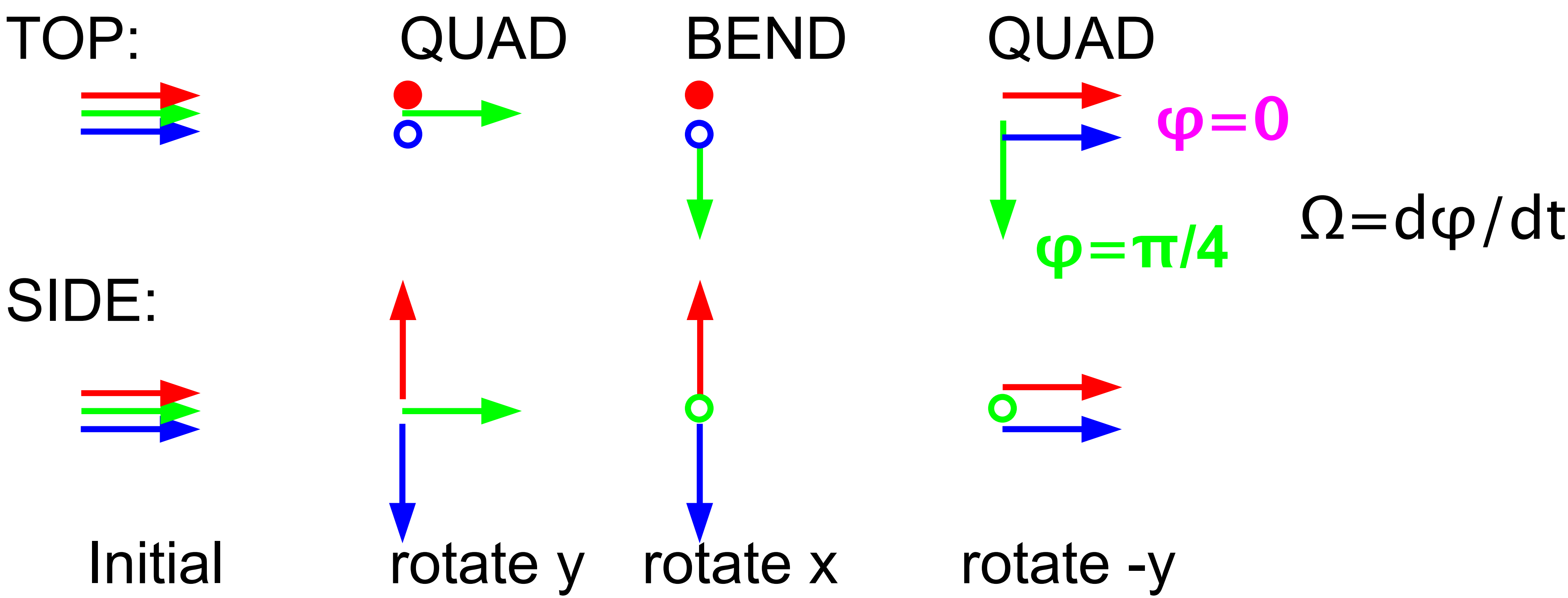
$$\langle S_y \rangle = \langle \int_0^t S_z(t)\, \Omega_{EDM}\, dt \rangle = \Omega_{EDM} \int_0^t P(t)\, dt$$

Ex. 2: Depolarization from 3D-rotations

A particle moves through E & B fields

→ <u>orientation</u> of Ω_{MDM} varies

Rotations in 3D do not commute



SCT in practice

Aim: spin coherence time 1000 s

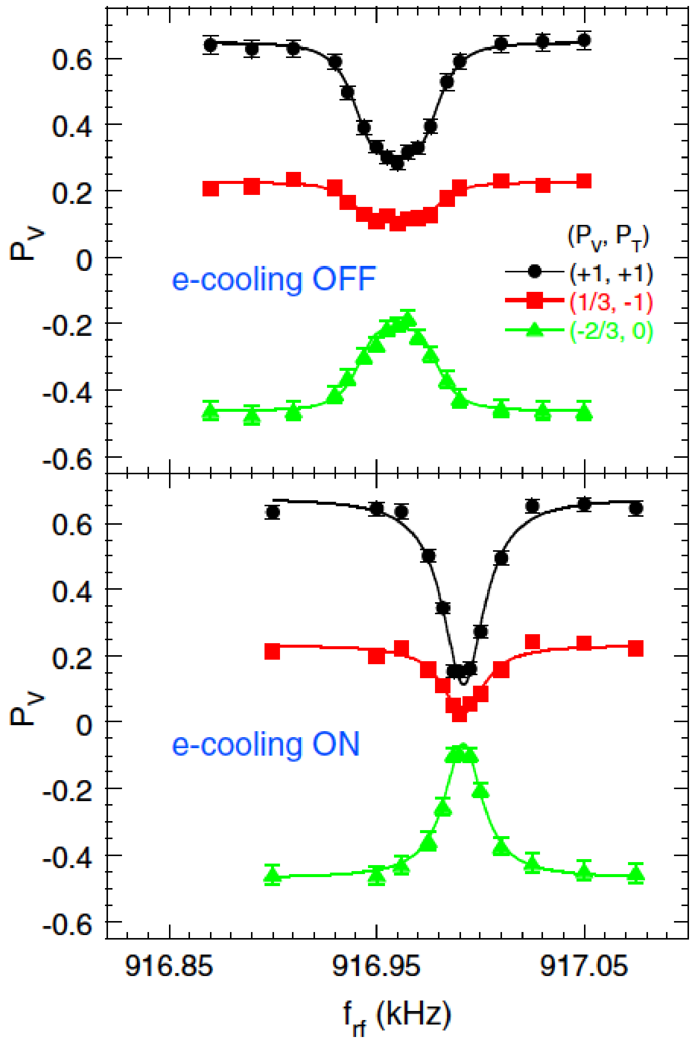
Perspective

- this is about 10^8-10^9 particle revolutions
- this corresponds to $\delta\Omega$ = 1mHz

- observed in E821 ($\mu^\pm$)	: $\tau > 10^5$ turns
- observed @ COSY-Jülich (D)	: $\tau \sim 1 \text{x} 10^3$ turns (coasting)
	: $\tau \sim 5 \text{x} 10^3$ turns (cooled)
	: $\tau \sim 2 \text{x} 10^4$ turns (bunched)
- observed @ VEPP ($e^\pm$)	: $\tau \sim 10^7$ turns

Spin@COSY Results (^2H)

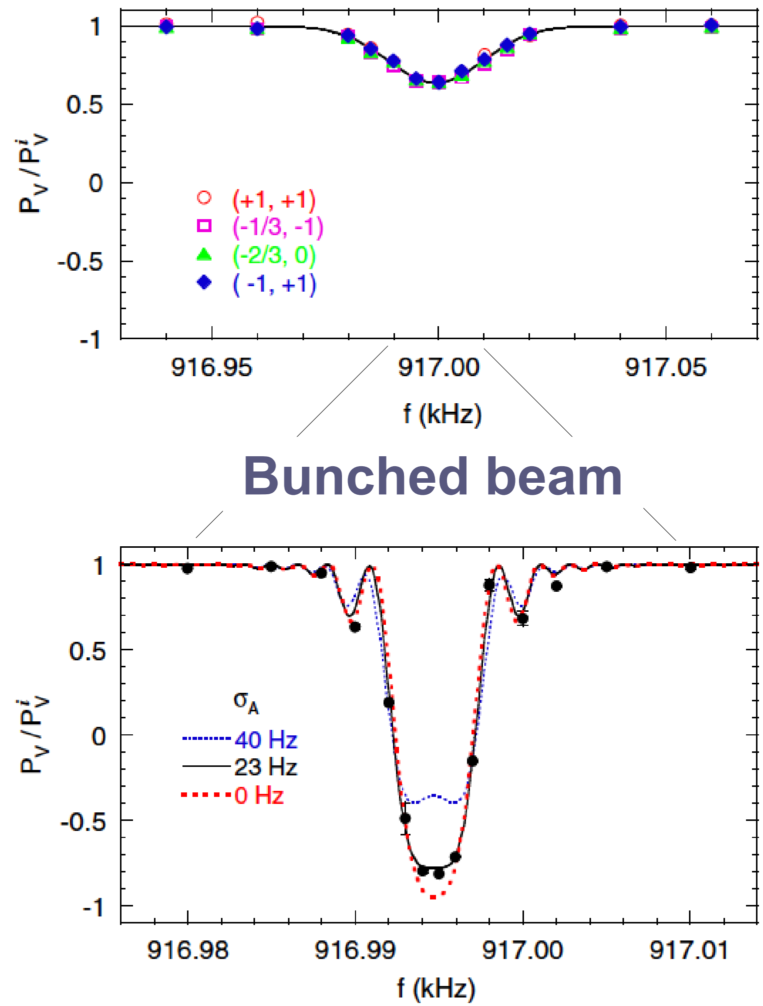
Effect of emittance



Phys. Rev. ST Accel. Beams 10, 071001

Unbunched beam

Bunched beam



PRL 103, 144801 (2009)

SCT vs. beam dynamics

Spin coherence depends on

- Particle properties (J, G, p, m, ...)
- Storage ring lattice (layout, $\nu_{x,y,s}$, RF, acceptance, ...)
- Beam dynamics (emittances, ...)
- Interactions within beam (space charge, ...)
- Interactions with environment (stray fields, power, ...)
- ....

All may have to be considered to reach SCT of 1000s

MODEL SIMULATION & EXPERIMENTAL VERIFICATION

Simulation Plan

- **Choose modeling tools**

  Need well-understood simulation tool
  that approximates relevant physical phenomena
  with sufficient precision.

- **Identify causes & cures for depolarization**

  Identify all relevant causes for spin decoherence.
  Apply this knowledge to develop a strategy
  that guides preparation of ring lattice
  with the longest possible spin coherence time

- **Experimentally verify results**

  Demonstrate robustness of strategy
  despite limited knowledge of imperfections.
  Development tools to expose these imperfections.

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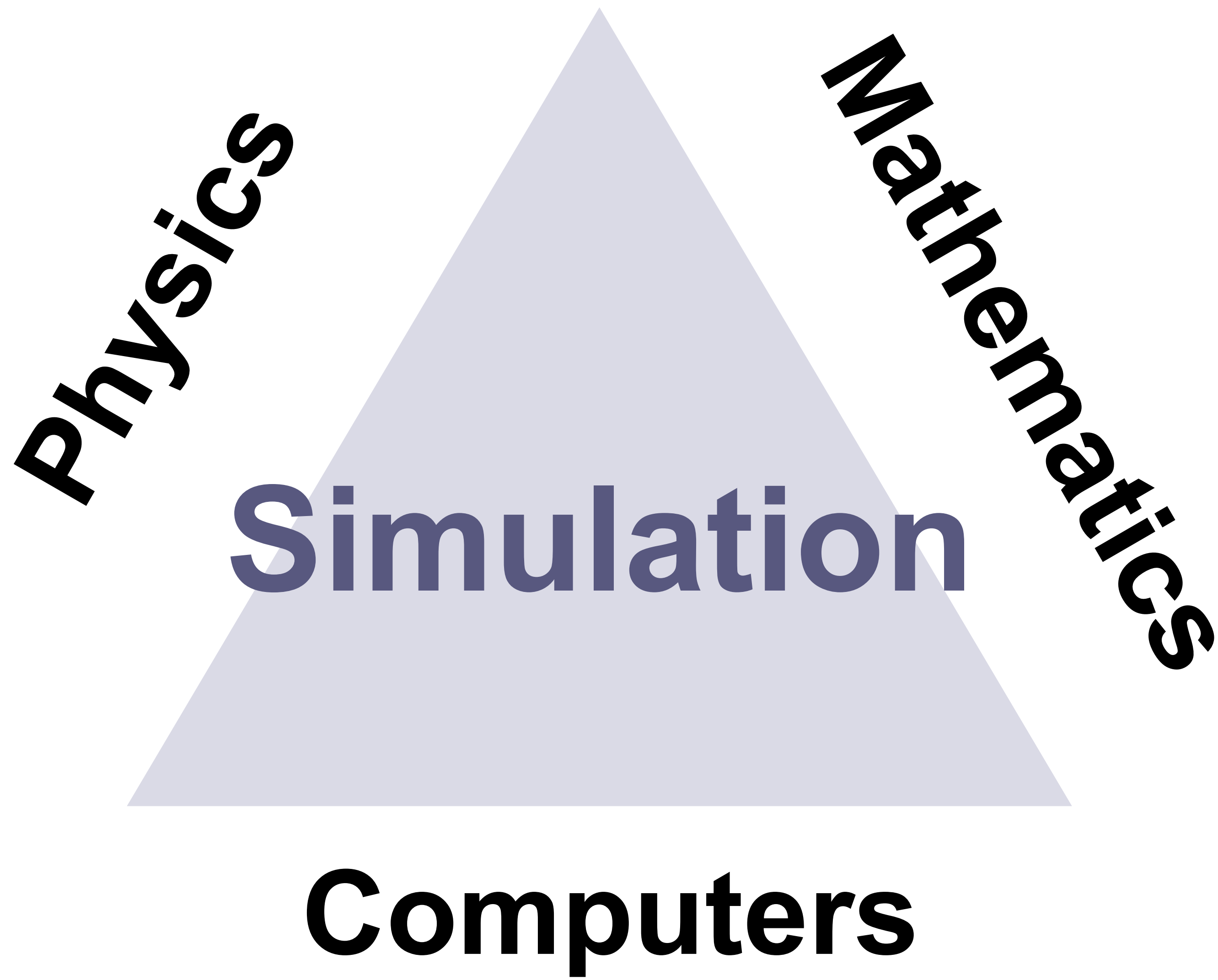
Simulation Ingredients



Physics Principles

Models should incorporate underlying physics

EM Fields
Maxwell's Equations
thin lens
hard edge
fringe fields: $\nabla \times B=0$
RF : $\nabla \times H=\partial D/\partial t$?
Images?

Spin
Thomas-BMT Equation
reference frame
completeness

Phase space
Liouville's Theorem
Conservation laws

Dynamics
Lorentz Force
Stern-Gerlach?
Inter/intra beam?
Gravity?
Rest gas interaction?

Particles
Properties
CODATA

Quantum
Fundamental
Visible?

Mathematical Principles

Techniques should be appropriate

MC Integration
Convergent for dt $\rightarrow 0$

Practical stepsize>0

Euler : poor

Runge-Kutta : strong(er)

Predictor-Corrector : strong

Differential Algebra
Iteratively solve DEs

Powerful, but unfamiliar to most

Taylor Expansion
Expansion around fixed point

Practical order « ∞

Symbolic Manipulation
For analytic solution

Applicable to simpler problems

Fourier Expansion
Expansion around fixed point

Practical order « ∞

Numerical Accuracy

Limits predictive power

Real Number Representation

Radix + Exponent

Float $1{:}10^7$

Double $1{:}10^{15}$

Spin

Rotation matrix

Orthogonal

Constants

"Exact"

$\pi = 4\ \mathrm{atan}(1)$

Beam dynamics

Symplectic

Avoid "explosive" solution

Status-I

- **Monte Carlo ray-tracing**

  Flexible, arbitrarily complicated field configurations
  Can only trace particles, i.e. cannot map
  <u>Far too slow</u> for detailed studies
  Abandoned for detailed studies

- **Mad-X+Spink**

  Limited collection of field configurations
  Solves beam dynamics for limited order
  Relies on thin lenses for tracking
  Spin dynamics is done "after the fact"
  Abandoned for detailed studies

Status-II

- **Unified Accelerator Libraries (UAL)**

  Very flexible & complete suite of tools
  Modular set up
  Spink partially incorporated / ThinSpin being developed
  Proven in HEP environment
  Further developed for detailed studies

- ***COSY-Infinity***

  Uses differential algebra to solve EoM to arbitrary order
  Solves beam & spin dynamics simultaneously
  Complex field configurations possible
  Facilitates "knobs" for parametric studies
  Fast tracking in ROOT
  Widely used in LE/nuclear environment
  Ready for use in detailed studies

EDM isn't in yet
Can be added easily

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Questions asked

1. *What are the sources of spin decoherence at second and higher order?*
2. *What is the magnitude of each of these sources?*
3. *Does electric or magnetic focusing give the smallest spin decoherence?*
4. *To what level can sextupoles and higher multipoles reduce decoherence?*
5. *What is the effect of fringe fields?*
6. *How can two counter propagating beams be accommodated?*
7. *What is the effect of beam heating (necessary for polarimetry)?*
8. *What are the (quantitative) effects of lattice errors?*
9. *…*
10. *Many, many more ....*

Complex & diverse list → needs a structured approach!

Identify, Quantify, Cure

Some first ideas

ideal ↓ real

Inherent → beam dynamics
→ multipole expansion of E/B fields
→ fringe fields

Imperfections → alignment
→ strength
→ stability
→ additional multipoles

(**Stray** → earth magnetic field
→ accelerator environment
→ beam-beam interaction
→ wake fields & images)

Bottom-Up Approach

Start with simple lattice
consisting of identical unit cells
with high degree of symmetry (mirror)
that can store particles

Analyze analytically
qualitative insight in sources of SCT

Targeted & systematic mapping of dependencies
Ceteris Paribus condition (change one thing at a time)
quantitative insight → prioritize, confirm earlier solution

Cure Decoherence
a) Eliminate decoherence
b) Reduce decoherence to an acceptable level
c) Discard lattice for unacceptable results

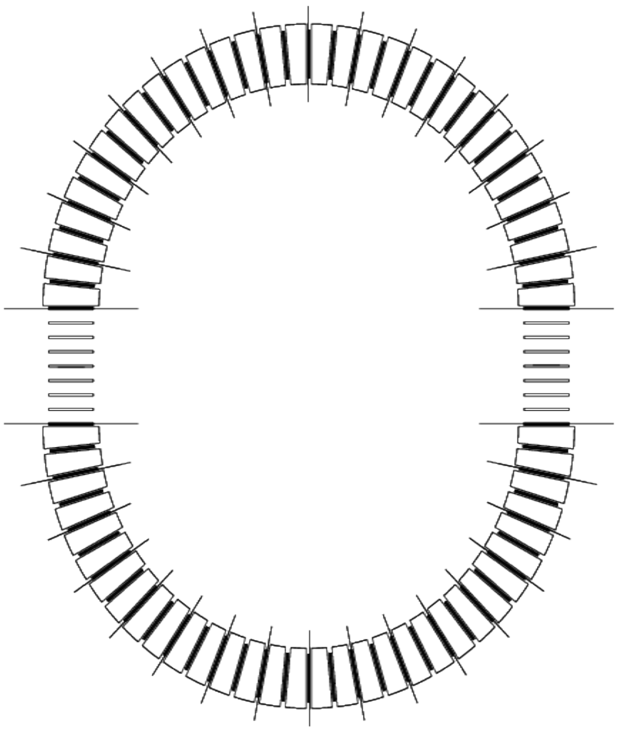
Evolve to more realistic configurations
Incorporate solutions
Quantify tolerances (e.g. for PS, BPMs)
Meet boundary conditions (e.g. for acceptance, polarimeter, injection)

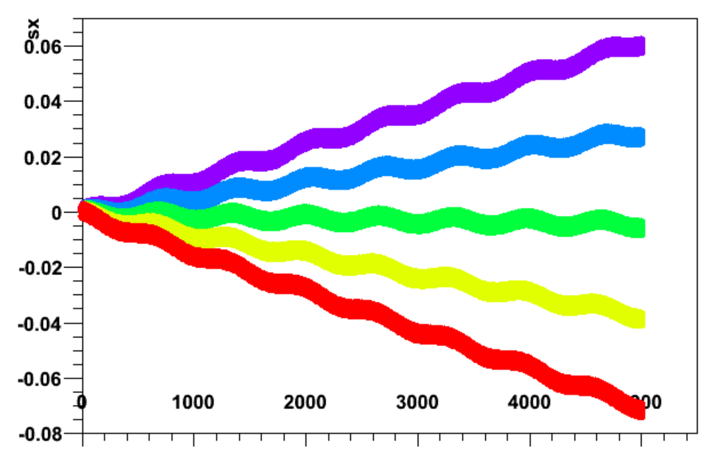
Status

Analytic work underway
- Confirms expected sources
- SCT of 1000s expected to be doable
- Ideas for solutions & diagnostics

Simulations started
- Lattice defined
- Using both COSY & UAL
- <u>Preliminary</u> results match theory
- <u>Preliminary</u> studies show effect of sextupoles on spin precession

In need of dedicated manpower!





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Experimental Test

WITH POLARIMETER TEAM

- **Real-life test is indispensable**
  - *In many respects COSY approaches EDM ring*
  - *Describe existing lattice*
  - *Reproduce existing results (spin & beam), e.g. Spin@COSY*
  - *Proposal accepted at COSY*

- **Demonstrate ability to expose perturbing effects**
  - *Create known perturbations*
  - *Via "contrast" measurements, i.e. with/without/exaggerated*
  - *Verify effect on coherence quantitatively*
  - *Identify & quantify other perturbations (for next step)*

- **Demonstrate ability to create long coherence**
  - *Apply SCT prolongation strategy to create long coherence*
  - *Predict & study sensitivities*
  - *Pragmatically optimize*

COSY @ Jülich

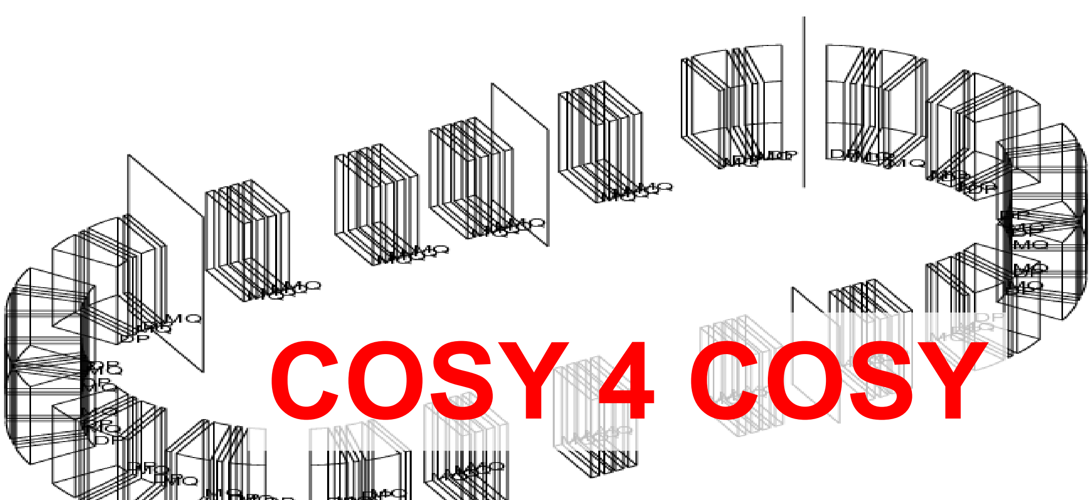

TABLE I. COSY parameters for the December 2003 polarized deuteron experiment.

Parameter	Value
Circumference	183.4 m
Beam type	Polarized deuterons
Flattop momentum (p)	1.850 GeV/c
Flattop energy (γ)	1.4046
Circulation frequency (f_c)	1.147 430 MHz
Spin tune (ν_s)	−0.200 84
Momentum spread $(dp/p)_{\mathrm{rms}}$	5×10^{-4}
Horizontal emittance (ϵ_h)	7 mm mrad
Vertical emittance (ϵ_v)	<5 mm mrad
Max. beta-functions (H, V)	30 m in both planes
Max. dispersion function (H)	15 m
Horizontal betatron tune (ν_h)	3.62
Vertical betatron tune (ν_v)	3.60
H. chromaticity $\frac{(d\nu/\nu)_{h,v}}{(dp/p)}$	−2.6
V. chromaticity	0.2
Synchrotron tune (ν_{syn})	None: rf off on flattop
Transition energy (γ_{tr})	2.2
Transverse coupling	No skew-quads or solenoids
Cooling	Off
Orbit flatness ($\Delta y_{\max}$)	±5 mm
Mag. Align. error ($\Delta\theta_{\max}$)	<0.1 mrad
Injection momentum (p_i)	0.538 GeV/c
Acceleration rate (dp/dt)	1.15 (GeV/c) s^{-1}

Team

Fanglei Lin	Mad/Spink/UAL	BNL (now NSLS)
Alfredo Luccio	Spink	BNL
Bill Morse	analytic	BNL
Nikolay Malitsky	UAL	BNL
Gerco Onderwater	COSY-Infinity	KVI
Yuri Orlov	analytic	Cornell
Vadim Ptitsyn	UAL	BNL
Yannis Semertzidis	analytic	BNL
Richard Talman	analytic	Cornell

Need dedicated/fulltime manpower!

Cost Estimate

Item	Amount requested [k$]	Comments
Postdoc	300	
Graduate student	135	
Stationing	105	
Travel to BNL	45	6 person-trips per year
Travel to COSY	25	3 expt's / 2wks / 3 people
Conference visits	15	2 people-conf. / year
Computing & DAQ facilities	35	Computer + electronics
Sub-total	705	
Miscellaneous (30%)	210	Overheads, unforseen
Total	**916**	

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