Beam and Spin Dynamics for Charged Particle EDM Searches in Storage Rings

September 11, 2015 | Andreas Lehrach

RWTH Aachen University & Forschungszentrum Jülich

on behalf of the JEDI collaboration

(Jülich Electric Dipole Moment Investigations)

Outline

Introduction

Motivation for EDM measurements

Principle and methods

Beam and Spin Dynamics

Measurements:

- spin tune
- spin coherence time

Simulations:

- precursor experiment
- final ring

Achievements & Goals

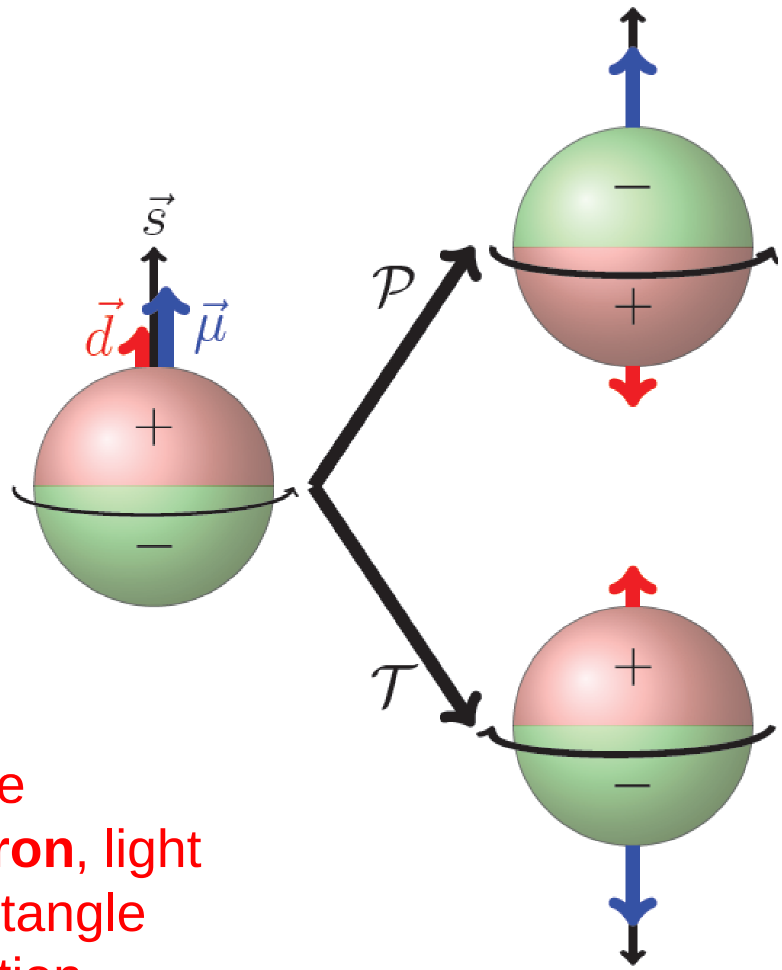
Electric Dipole Moments

$\vec{d}$: EDM

$\vec{\mu}$: magnetic moment

both || to spin

$$\begin{aligned} & H &=& -\mu\vec{\sigma}\cdot\vec{B}-d\vec{\sigma}\cdot\vec{E} \\ \mathcal{T}: & H &=& -\mu\vec{\sigma}\cdot\vec{B}+d\vec{\sigma}\cdot\vec{E} \\ \mathcal{P}: & H &=& -\mu\vec{\sigma}\cdot\vec{B}+d\vec{\sigma}\cdot\vec{E} \end{aligned}$$



It is important to measure neutron **and proton and deuteron**, light nuclei EDMs in order to disentangle various sources of CP violation.

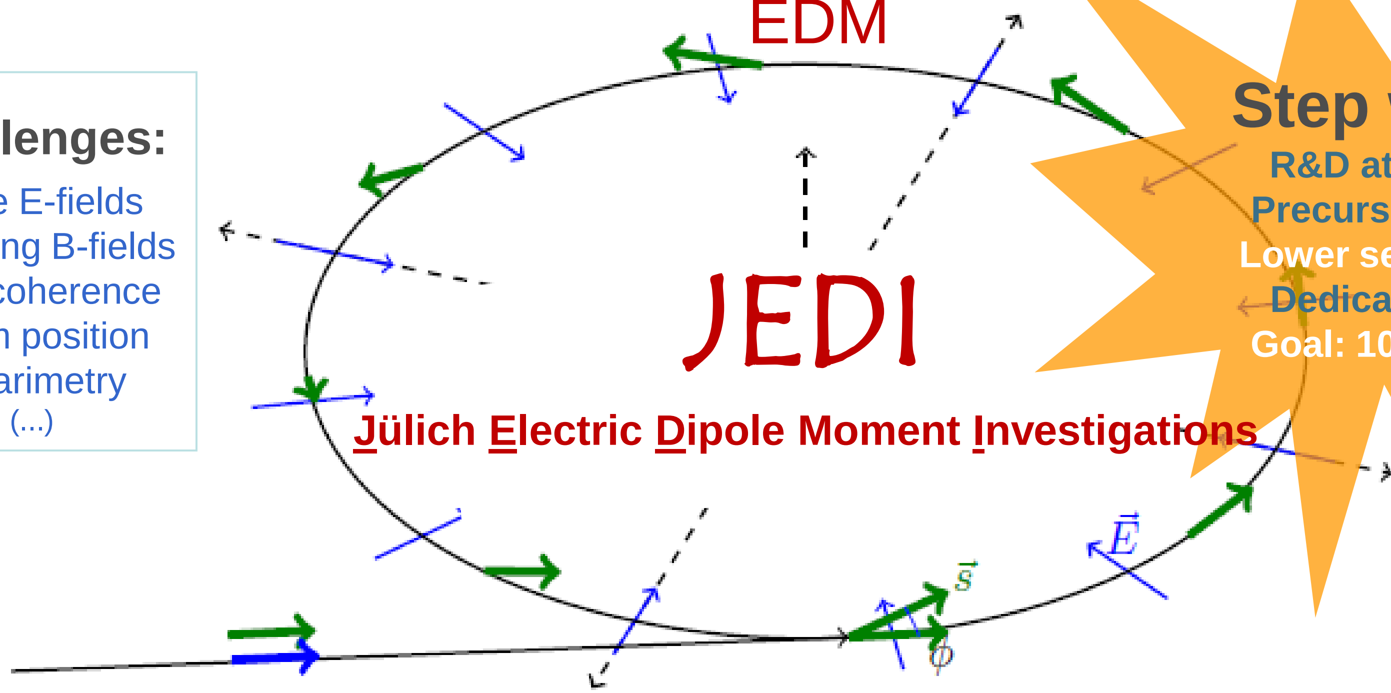
EDMs are candidates to solve mystery of matter-antimatter asymmetry

Storage Ring EDM Project

… measure for development of vertical polarization

⇔

EDM



Challenges:

Huge E-fields
Shielding B-fields
Spin coherence
Beam position
Polarimetry
(…)

Step wise:

R&D at COSY
Precursor Expt.
Lower sensitivity
Dedicated SR
Goal: 10^{-29} e·cm

~ 110 members
(11 countries and 33 institutes)
12 PhD students from JARA-FAME (**F**orces **a**nd **M**atter **E**xperiments)
http://collaborations.fz-juelich.de/ikp/jedi/

Spin Precession with EDM

Equation for spin motion of relativistic particles in storage rings

for $\vec{\beta}\cdot\vec{B} = \vec{\beta}\cdot\vec{E} = 0$.

The spin precession relative to the momentum direction is given by:

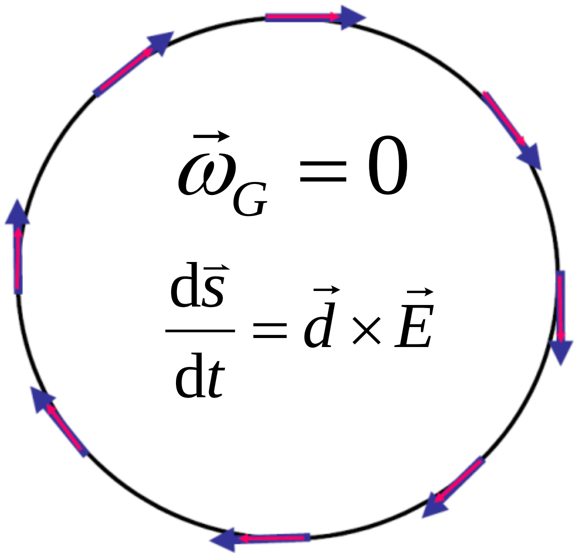
$$\frac{d\vec{S}}{dt} = \vec{\Omega}\times\vec{S}$$

$$\vec{\Omega} = \frac{q}{m}\left\{\underbrace{G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\left(\vec{v}\times\vec{E}\right)}_{\text{Magnetic Dipole Moment}} + \underbrace{\frac{\eta}{2}\left(\vec{E} + \vec{v}\times\vec{B}\right)}_{\text{Electric Dipole Moment}}\right\}.$$

$$G = \frac{g-2}{2},\ \vec{\mu} = 2(G+1)\frac{q}{2m}\vec{S},\ \text{and}\ \vec{d} = \eta\frac{q}{2m}\vec{S}.$$

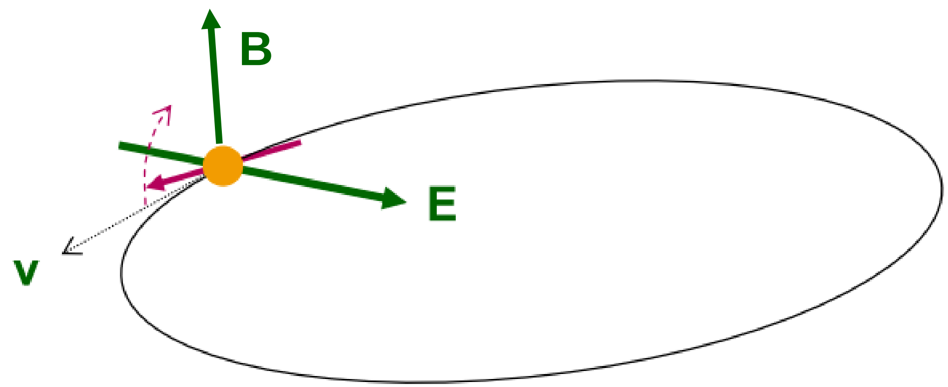
Search for Electric Dipole Moments

Approach: EDM search in time development of spin in a storage ring:



$$\vec{\omega}_G = 0$$

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{d} \times \vec{E}$$



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

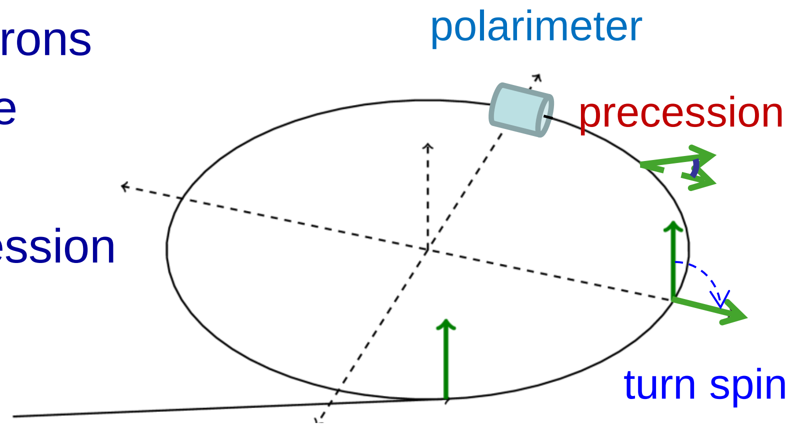
A *magic* storage ring for protons (electrostatic), deuterons, and helium-3

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

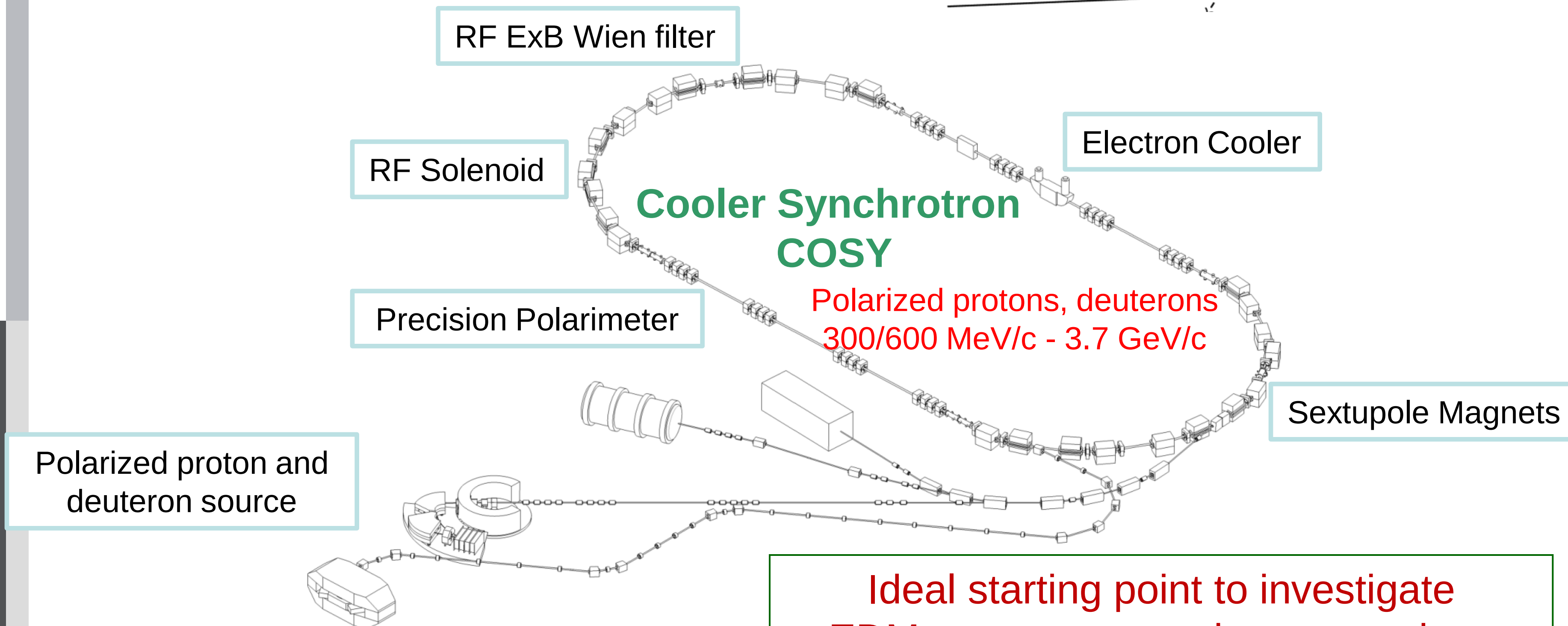
One machine with r ~ 30 m

Experimental Setup at COSY

- Inject and accelerate vertically polarized deuterons
- Spin rotated with RF fields into horizontal plane
- Move beam slowly (in 100 s) on internal target
- Measure asymmetry and determine spin precession



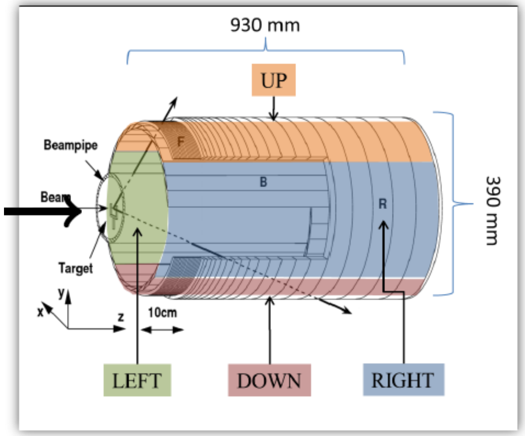
At 970 MeV/c deuterons: $\gamma G \cdot f_{rev} \approx 120$ kHz

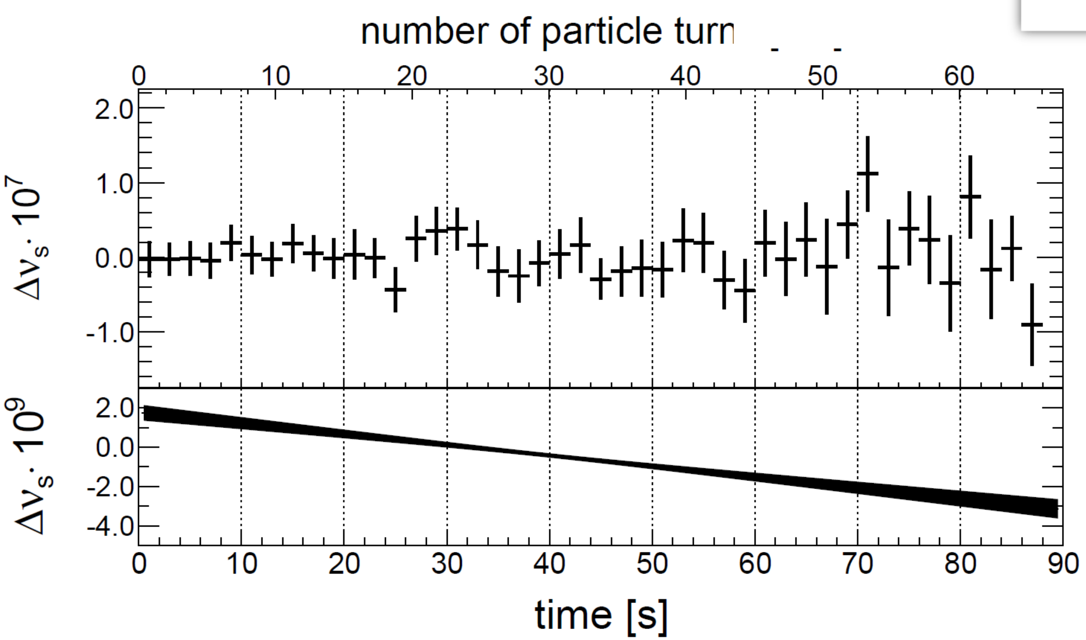


Ideal starting point to investigate
EDM measurements in storage rings

Spin Tune Measurement at COSY

- EDDA Detector to measure asymmetries
- Sophisticated read-out system, which can time stamp individual event arrival times with respect to turn number: Phys. Rev. STAB 17 (2014)
- Map events into first spin oscillation period
- Analyse the spin phase advance throughout the cycle





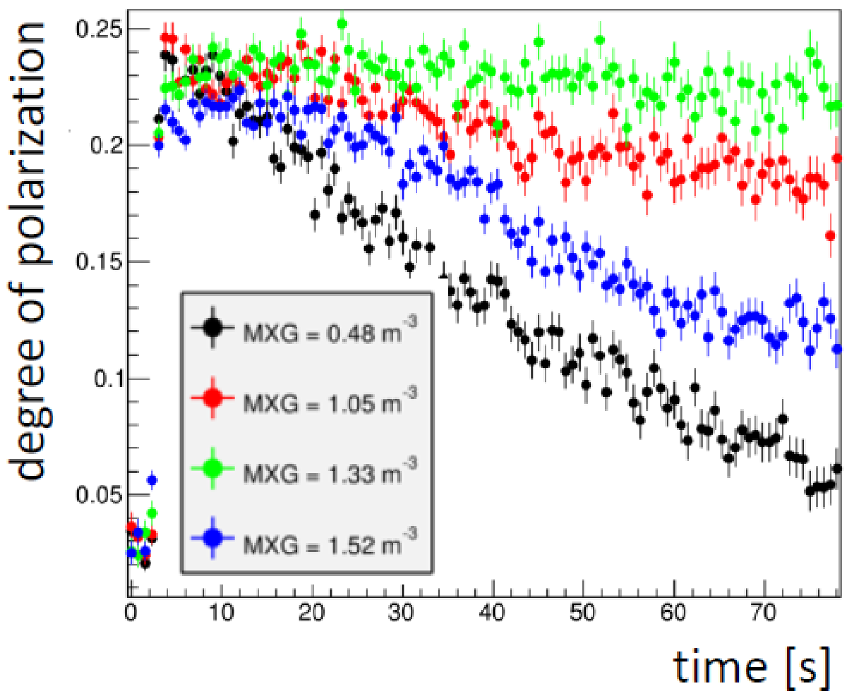
Spin tune ν_s determined to $\approx 10^{-7}$ in 2 s.

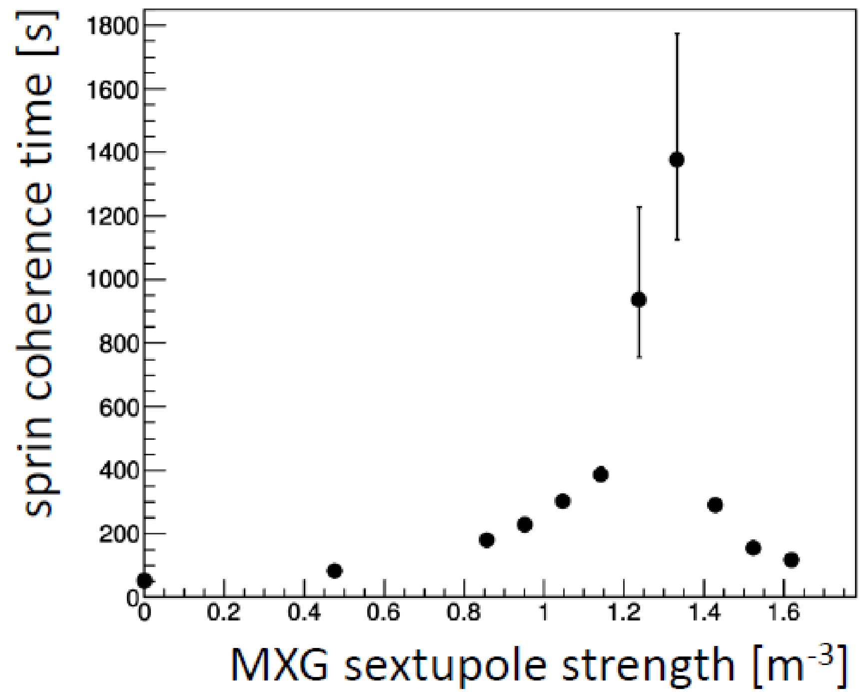
$\bar{\nu}_s$ in cycle at $t \approx 40$ s is determined to $\approx 10^{-10}$. Phys. Rev. Lett. 115 (2015)

Spin coherence time at COSY

10^9 polarized deuterons at 970 MeV/c, bunched and electron cooled

adjust three arc sextupoles to increase spin coherence time



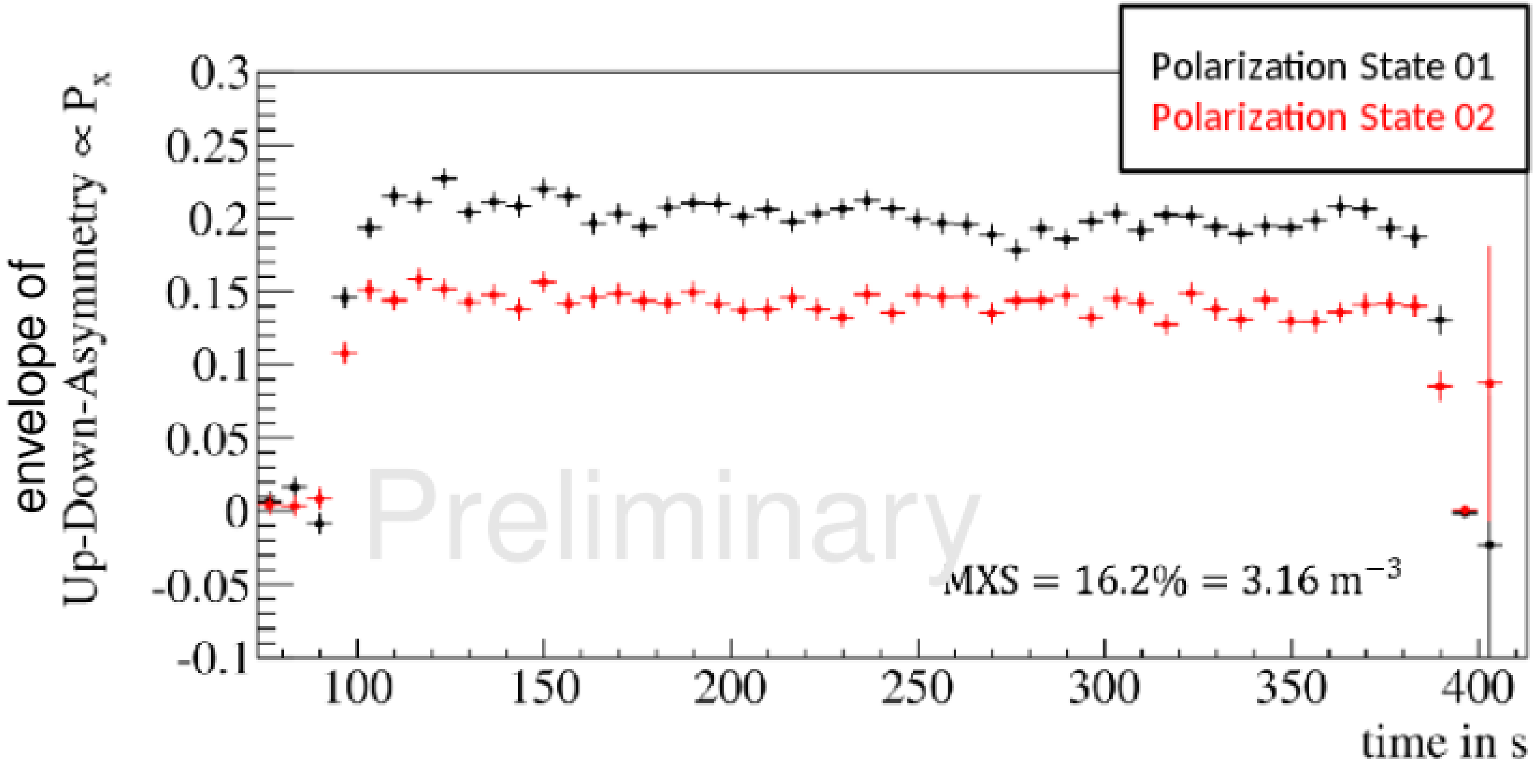


→ Long SCT for adjusted transverse beam chromaticities

Poster by Greta *Guidoboni* (UNIFE, Ferrara) at IPAC 2015: THPF146
Spin Coherence Time Lengthening of a Polarized Deuteron Beam with Sextupole Fields

Spin coherence time at COSY

Recent result from last beam time



Longer cycles: spin coherence time of a few 1000 s

Utilized Simulation Programs at Jülich

COSY INFINITY by M. Berz and K. Makino (MSU),

MODE by S. Andrianov, A. Ivanov (StPSU):

- based on map generation using differential algebra and the subsequent calculation of the spin-orbital motion for an arbitrary particle
- including higher-order nonlinearities, normal form analysis, and symplectic tracking
- an MPI version of COSY Infinity is running on the Jülich supercomputer

- bench marking with “analog computer” Cooler Synchrotron COSY and other simulation codes

Spin Simulations with COSY INFINITY

COSY Toolbox

COSY Lattice → COSY Toolbox

COSY INFINITY ↔ COSY Toolbox

Armadillo ↔ COSY Toolbox

COSY Toolbox → ROOT

COSY INFINITY

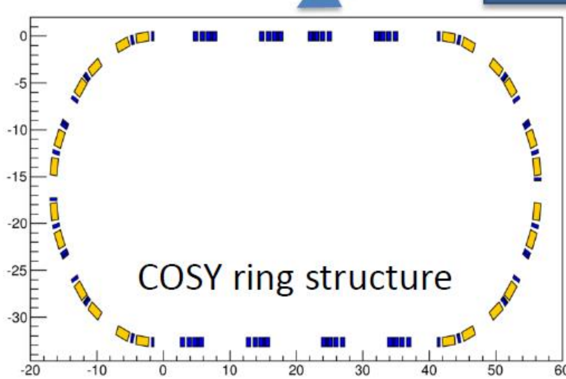
- Calculator:
  - Optical functions
  - Closed orbit
  - Spin tune …
- Tracker:
  - Static maps
  - RF maps (*)

Armadillo

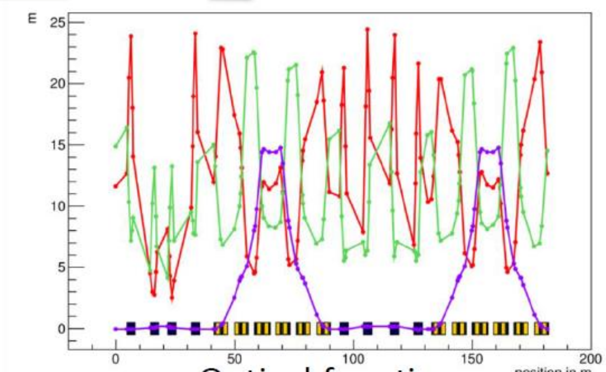
- linear algebra operations
- SVD, pseudo-inverse

ROOT

- plotting
- storage (ROOT files/trees)



COSY ring structure

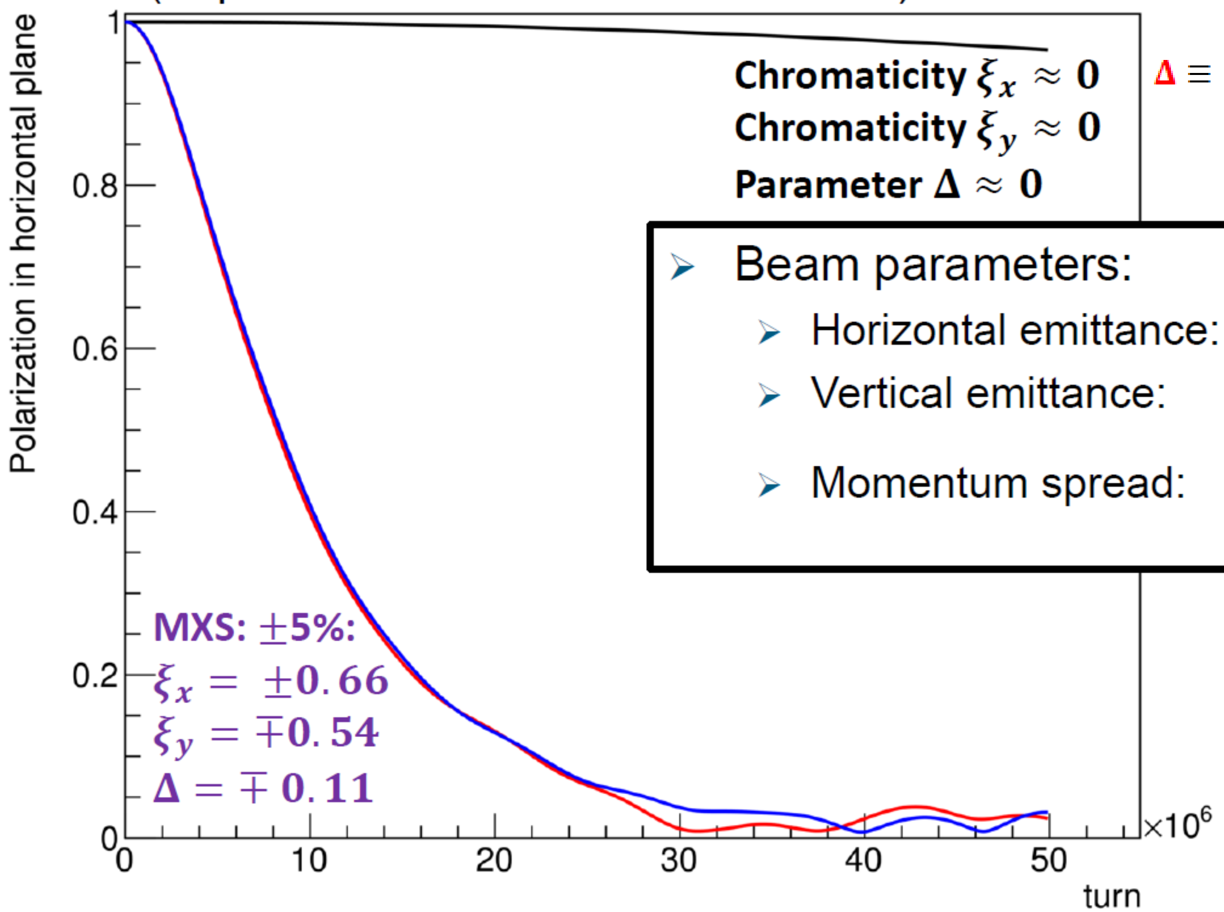


Optical functions

Simulations of SCT (COSY INFINITY)

- Deuterons, $p = 970\ MeV/c$, initially radial polarized (→ precession around vertical axis)

$$\Delta \equiv \left[\alpha_1 + \frac{3}{2\gamma_0^2}\left(\beta_0^2 - \left(\alpha_0 - \frac{1}{\gamma_0^2}\right)\right)\right] = 0$$



- Beam parameters:
  - Horizontal emittance: $\epsilon_x = 5\ \mathbf{mm\ mrad}$
  - Vertical emittance: $\epsilon_y = 5\ \mathbf{mm\ mrad}$
  - Momentum spread: $\left(\frac{\Delta p}{p}\right)_{rms} = 5 \cdot 10^{-4}$

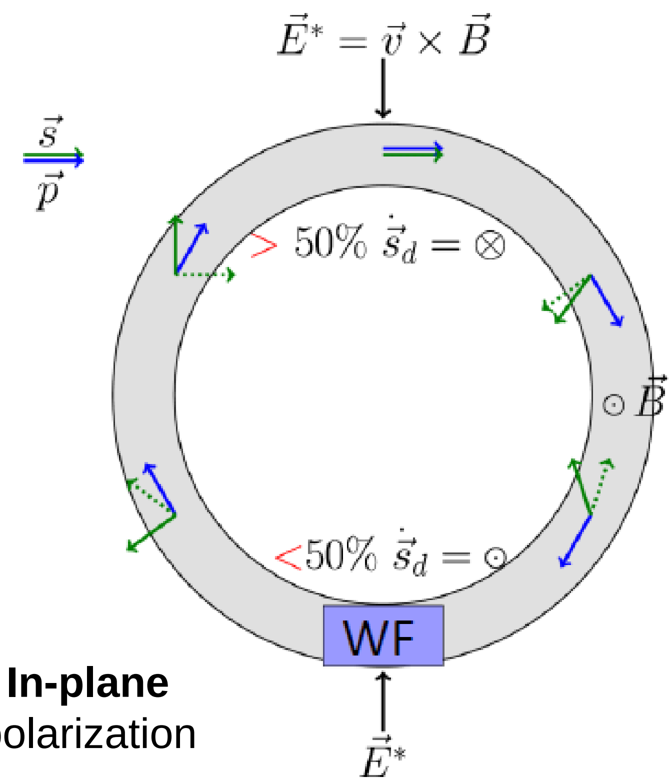
No nearby spin resonances!

Courtesy: Marcel *Rosenthal* (FZJ)

Resonance Method in Magnetic Rings

RF *ExB* dipole in “Wien filter” mode
→ Avoids coherent betatron oscillations

$\boldsymbol{E}^* = \boldsymbol{0} \Rightarrow \boldsymbol{E_R} = -\beta \times \boldsymbol{B_y}$ „Magic RF Wien Filter“ no Lorentz force
→ **Indirect** EDM effect



In-plane polarization

- Modulation of horizontal spin precession in the RF Wien filter
- EDM’s interaction with the motional electric field in the rest of the ring

→ continuous buildup of vertical polarization in a horizontally polarized beam.

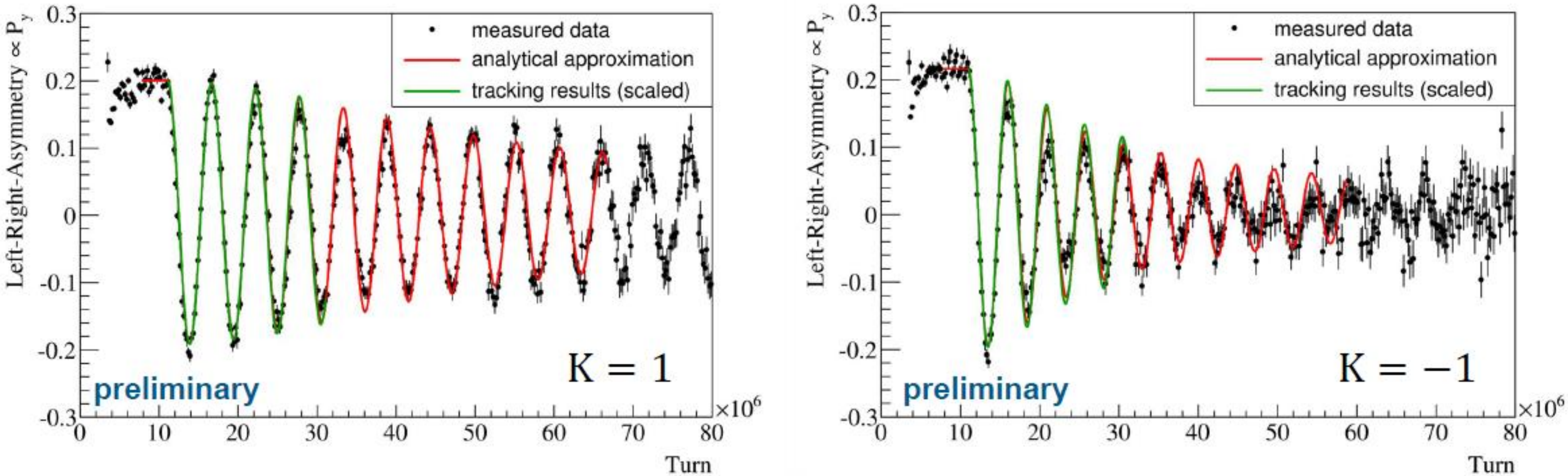
→ **net effect due to EDM**

→ Investigation of sensitivity and systematic limitations

Benchmarking (COSY INFINITY)

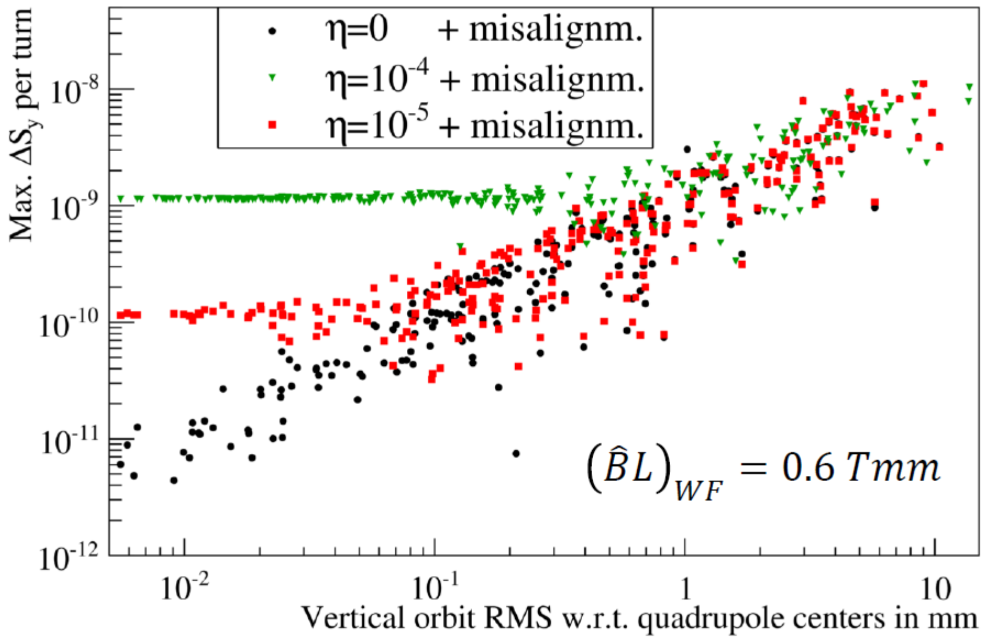
RF spin manipulation elements implemented.
Benchmarking experiment at COSY using driven oscillations induced by the RF solenoid

RF field: $B_{sol} = B_0 \cdot cos\ (2\pi \cdot \nu_{sol} \cdot n + \Phi_{sol})$, *resonance condition* $\nu_{sol} = \gamma G \pm k$



Poster by Marcel *Rosenthal* (FZJ, Jülich; RWTH, Aachen) at IPAC 2015: THPF032
Spin Tracking Simulations towards Electric Dipole Moment Measurements at COSY

Simulation of Resonance Method (COSY Infinity)

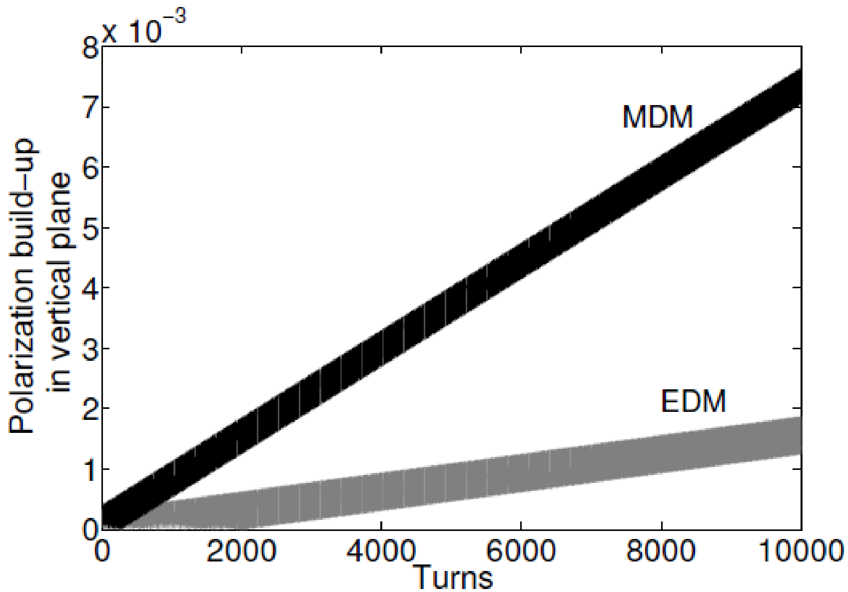


Uncorrected Gaussian distributed misalignments of the COSY lattice quadrupoles with a standard deviation of 0.1 mm generate a similar buildup as an EDM of $d = 5{\cdot}10^{-19}$ e cm

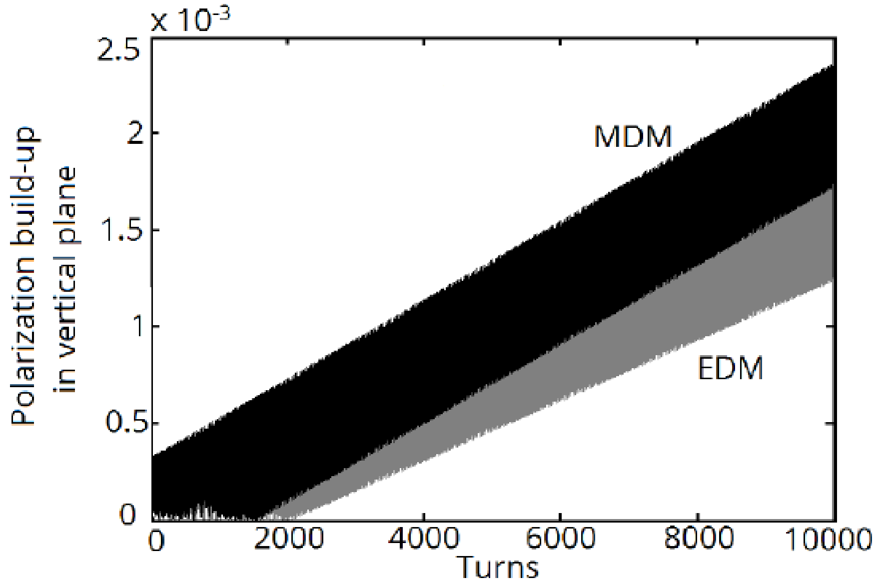
Systematic EDM limit at COSY is in the order of $d = 10^{-19}$ e·cm for a remaining orbit excitations below the millimeter level,

Courtesy: M. Rosenthal (FZJ)

Simulation of Resonance Method (MODE)



Black: Misalignments of magnets by 0.1 mm (mrad)
Grey: EDM of $2.6 \cdot 10^{-19}$ e cm



Black: rotation RF Wien filter by of 10^{-4} rad
Grey: EDM of $2.6 \cdot 10^{-19}$ e cm

Error sources:

Magnet misalignments

Wien filter:

- rotation of 10^{-4} rad with respect to invariant spin axis
- relative mismatch between RF Wien filter frequency and the spin resonance frequency of 10^{-5}

→ EDM in the order of $d = 10^{-19}$ e·cm

Courtesy: Stas *Chekmenev* (FZJ)

Simulation Program Development

Aim

- Robust and advanced numerical tracking codes for exploring various systematic effects.
- Sophisticated lattice design tools for EDM storage rings with all electrostatic as well as combined magnetic and electric elements.

Capabilities

- Accurate description of all ring elements including fringe fields.
- Allowing various error inputs for systematics investigation.
- Accurate implementation of RF spin manipulation elements.
- Calculation of orbital and spin motion with a high accuracy for over 10^9 orbital revolutions.
- User friendly graphic interfaces for extracting physical information from tracking data.

  (e.g., orbit, betatron tune, and spin tune from tracking data)

IPAC15 satellite meeting
on Spin Tracking for Precision Measurements
https://indico.cern.ch/event/368912/program

Presentation of Codes

15mins presentations from COSY-infinity, E-Teapot, Tspink, PTC, zgoubi, BMAD, etc on its strength and limitations for EDM spin tracking:

- D. Sagan (Cornell): BMAD
- R. Talman (Cornell): E-Teapot
- D. Abell (Tech-X): Tspink
- F. Meot (BNL): zgoubi
- M. Gaisser (CAPP/IBS at KAIST), Fast integration algorithm for spin tracking
- M. Berz (MSU): COSY-infinity
- K. Makino (MSU): Fringe field treatment in COSY-infinity

Summary of IPAC15 Satellite Meeting: List of Spin Tracking Codes

Table 1: Spin Tracking Codes

Code	Tracking algorithm	Electrostatic element	EXB hybrid bender	Fringe field	Time varying field	RF cavity incl. Off-axis B field	Machine error imple. algorithm	Longterm symplec-ticicity	Longterm tracking accuracy	Tracking speed
Seluck	RK	Yes with hardedge idea model				N		N		
Martin	RK	Yes with hardedge idea model				N		N		
BMad	RK, PTC, etc	Yes with field map		Field map		N	Yes	Y, except RK		
COSY-Infinity	DA map	Yes with field map		Field map	Y, verify simplec-ticity	N		Y		
ETeapot	DkD	Y				N				
TSpink	DKD	N				N				
zgoubi	RK	Yes with field map		Field map	Yes	N		N		
PTC	TPSA map					N				

Next meeting during IPAC16 in South Korea

RK: Runge-Kutta integration

DA: Taylor map generation using differential algebra

DKD: Bend-kick-bend code

TPSA: Truncated power series algebra by Taylor expansion

PTC: Polymorphic tracking code, kick code plus TPSA

Deuteron EDM Proposal (srEDM)

Deuteron momentum: p = 1 GeV/c,

Ring parameter: R_B = 8.4 m, $<R>$ ~ 10 m, C = 85m

Deflectors: E_R = -12 MV/m (radial), B_V = 0.48 T (vertical)

- 2004 BNL proposal: single ring

  CW and CCW consecutive beam injections

  Limiting error: time-dependent part of the average vertical electric field over the entire ring

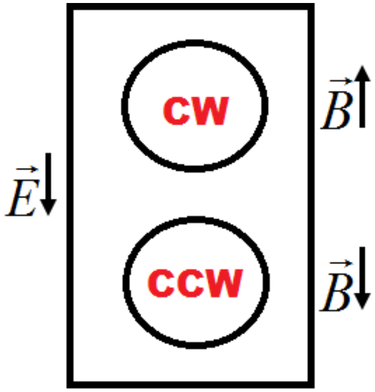
  → sensitivity ~ 10^{-27} e · cm for one year measurement

- 2008 BNL proposal: double ring

  CW and CCW simultaneously

  2-in-1 magnet design with common E-field plates

  → sensitivity ~ 10^{-29} e · cm for one year measurement



See http://www.bnl.gov/edm

EDM with E- and B-Fields for different Particles

„all-in-one“ storage ring

Protons: p_p = 0.701 GeV/c
E_R = 16.8 MV/m, B_V = 0 T

Deuterons: p_d = 1.0 GeV/c
E_R = -4.0 MV/m, B_V = 0.16 T

Helium-3: $p_{^3He}$ = 1.285 GeV/c
E_R = 17.0 MV/m, B_V = -0.05 T

„all-in-one“ storage ring

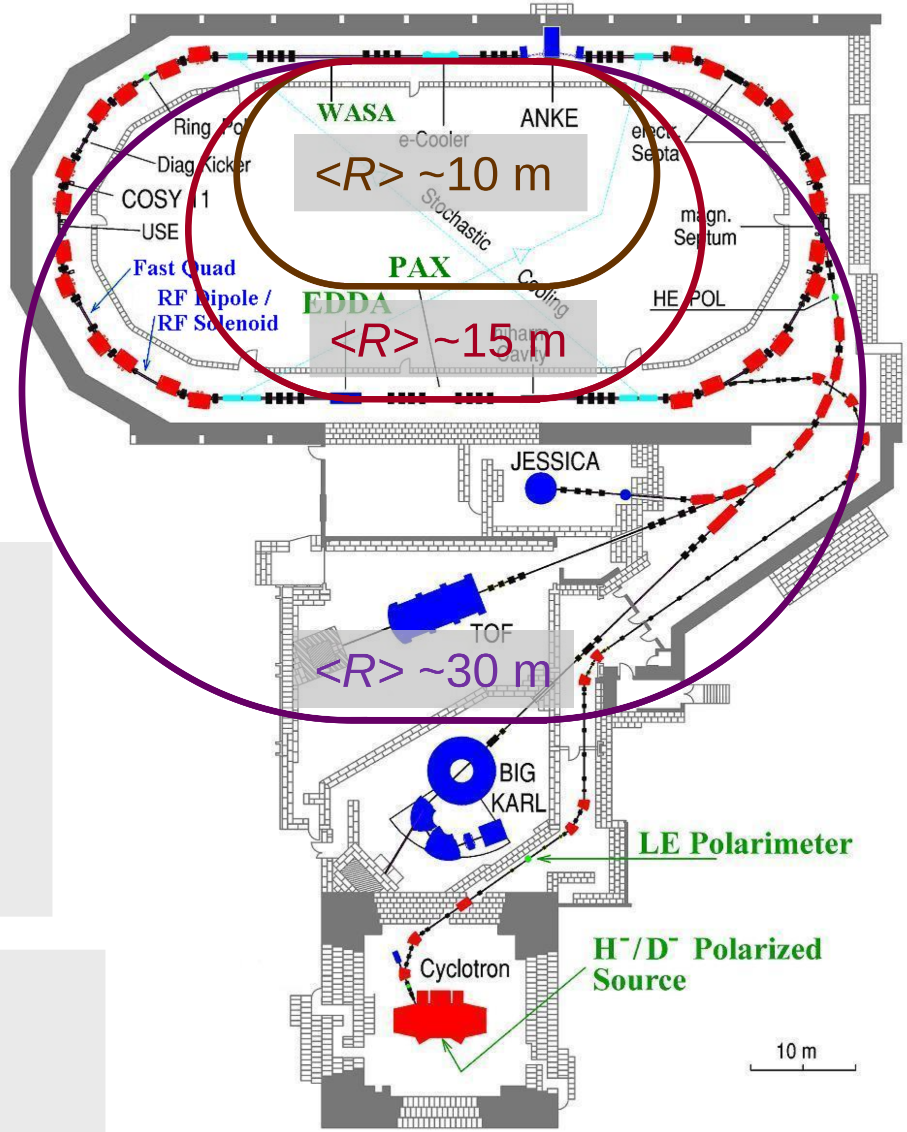
Protons: p_d = 0.527 GeV/c
E_R = 16.8 MV/m, B_V = 0.02 T

Deuterons: p_d = 1.0 GeV/c

Helium-3: $p_{^3He}$ = 0.946 GeV/c

Dedicated deuteron storage ring

Deuterons: p_d = 1.0 GeV/c
E_R = -12.0 MV/m, B_V = 0.48 T



Optics Requirement and Control

CW/CCW procedure with consecutive beam injections will not perfectly cancel systematic errors:

1. CW/CCW runs are taken at different times (separated by 10^3s)

   → Field stability, ground motion, temperature stability

2. Spatial extent of the beam will be different for CW/CCW

3. Systematic change in E_V when magnetic field is reversed

4. Magnetic field does not reverse perfectly for CW/CCW

Measures:

→ Measure the E-plate alignment and B-fields as a function of time
→ Install active feedback system
→ Measure beam position and profile

Lattice Options

Total Length: C= 351.15 m

“ExB“ element:

E= -4 MV/m

B= 0.153342595

Length L= 1.81m

Number per arc N= 48

Bending radius: R_{ExB}= 27.62 m

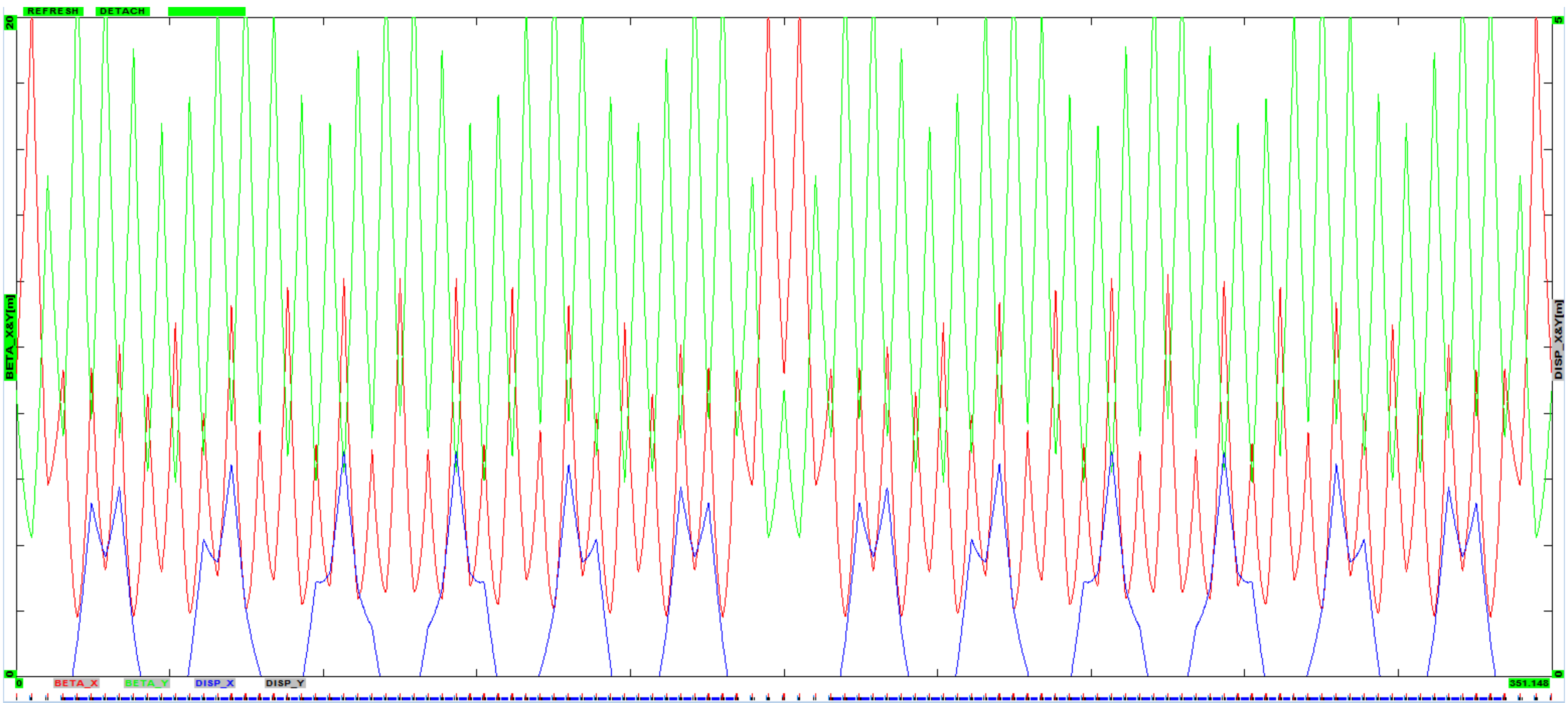
OptiM - Computer code for linear and non-linear optics calculations

Tunes: Q_x= 12.23, Q_y= 5.24

Momentum compaction: α= 0.0055

Chromaticity: ξ_x= -12.68, ξ_y = -11.05

Energy: E_{kin}= 270 MeV



Lattice Options

Total Length: C= 145.85 m

"E+B" element:

E= -12 MV/m

B= 0.460027785

Length L= 1.81m

Number per arc N= 16

Bending radius: R_{ExB}= 9.21 m

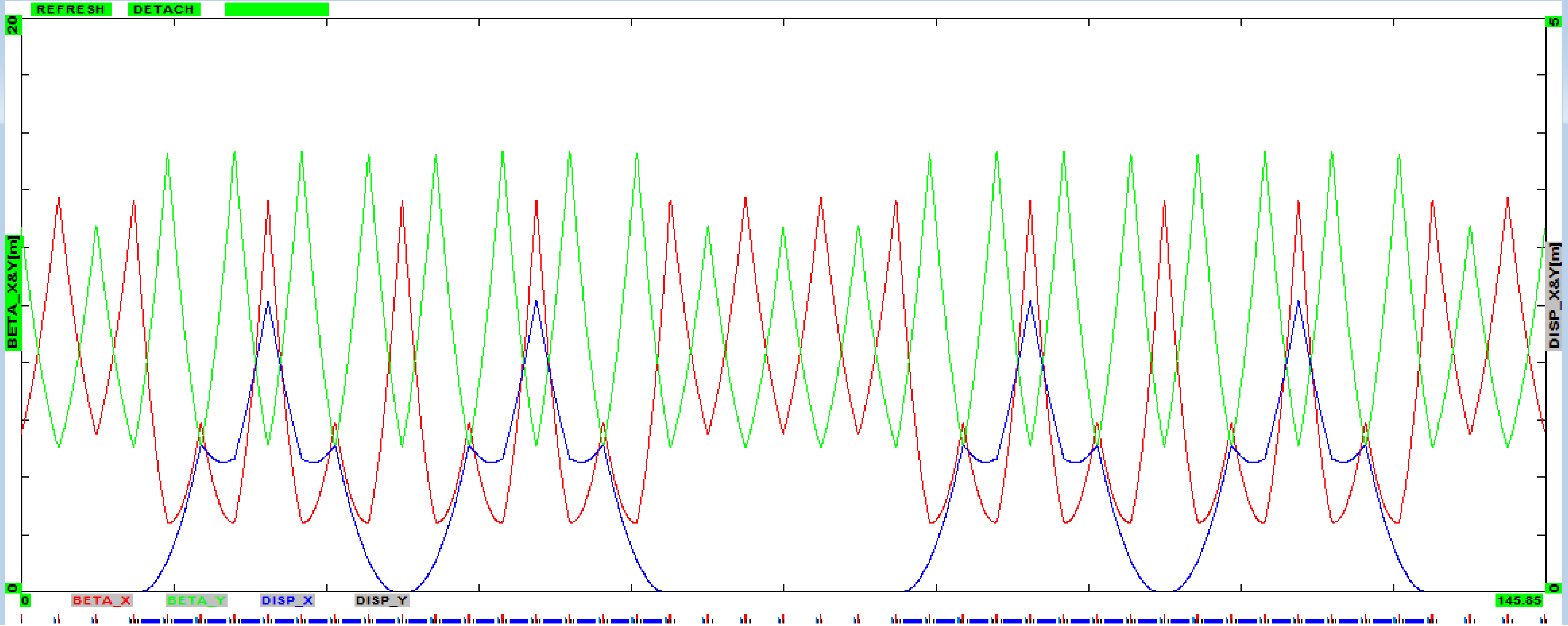
OptiM - Computer code for linear and non-linear optics calculations

Tunes: Q_x= 4.82, Q_y= 2.80

Momentum compaction: α= 0.0033

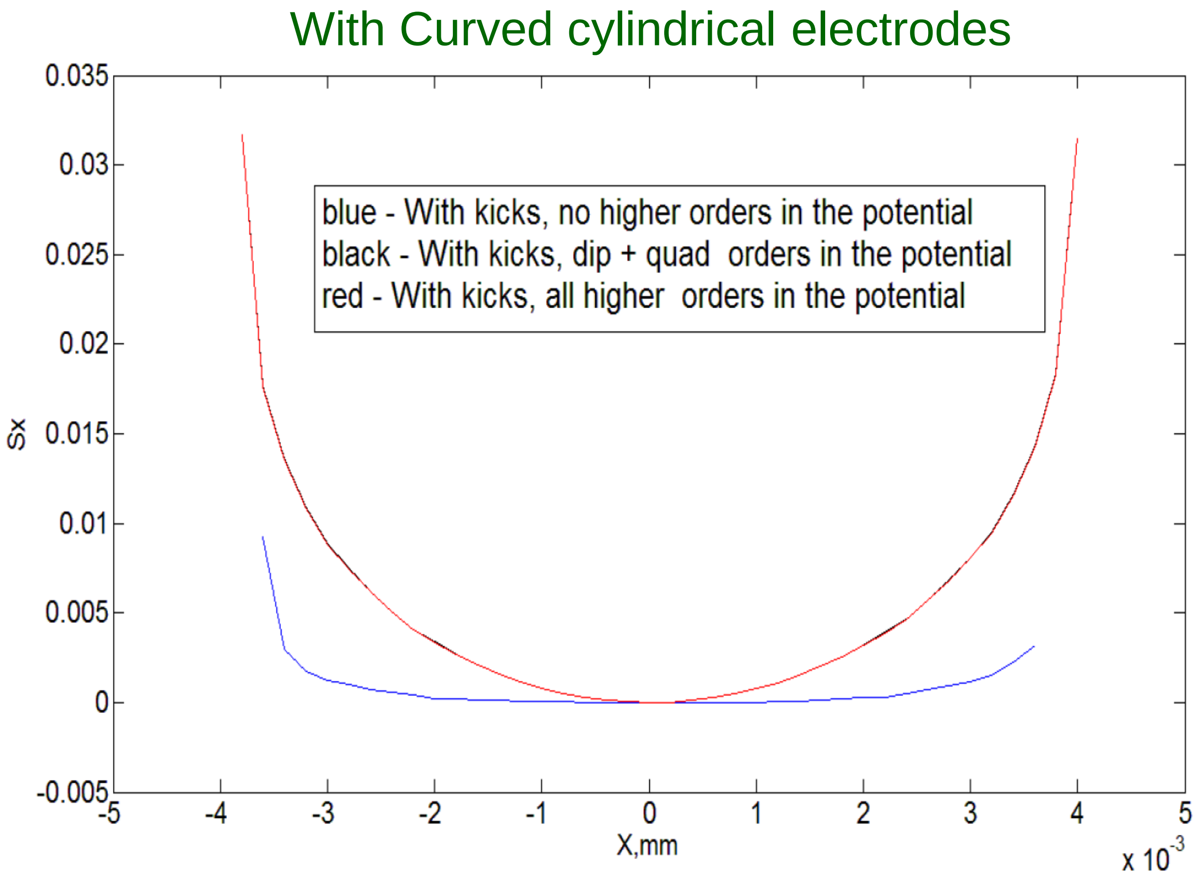
Chromaticity: ξ_x= -4.86, ξ_y = -4.11

Energy: E_{kin}= 270 MeV



Courtesy Y. Senichev

Spin Precession in Electrostatic Potential



In the x-plane the off-center particle sees an electric field in x
Quadrupole component of the field is important
The beam and spin motion in the y plane is not effected

Courtesy: Stas *Chekmenev* (RWTH)

Conclusion

Achievements:

- Spin tune measurement with precision of 10^{-10} in a single cycle
- Long spin coherence time of more than 1000s
- Several spin tracking codes developed and benchmarked
- Investigation of systematic limit for resonance methods

Goals:

- Beam and spin dynamics studies at COSY
- First direct EDM measurement at COSY
- R&D work and design study for dedicated EDM storage ring