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Spin Tracking For Polarized Beam Experiments At The JüLich Cooler Synchrotron COSY
(Juelich Electric Dipole Moment Invesigations JEDI)

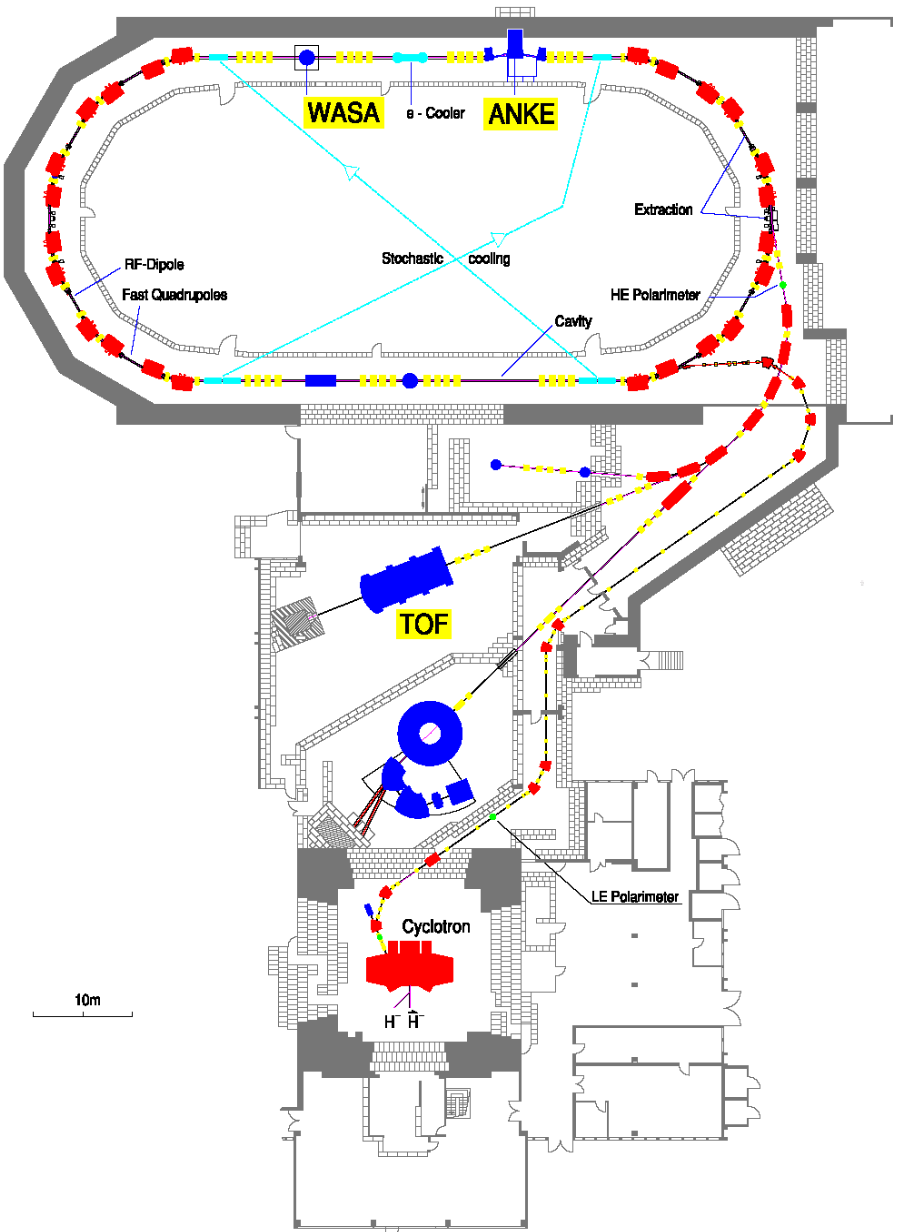
December 17, 2011

Bernd Lorentz
(for the JEDI collaboration, Forschungszentrum Juelich)
Taylor Model Methods VII,
Key West, USA

Topics

- Polarized beams at COSY
- Future Project srEDM
  - *Motivation for EDM measurement*
  - *Concept of Storage Ring EDM measurements*
- The Juelich EDM Investigation (JEDI)
  - *SC studies (ongoing)*
  - *Precursor experiments (next two years)*
  - *JEDI magnetic/electrostatic storage ring (longterm)*
- Summary

The Accelerator Facility



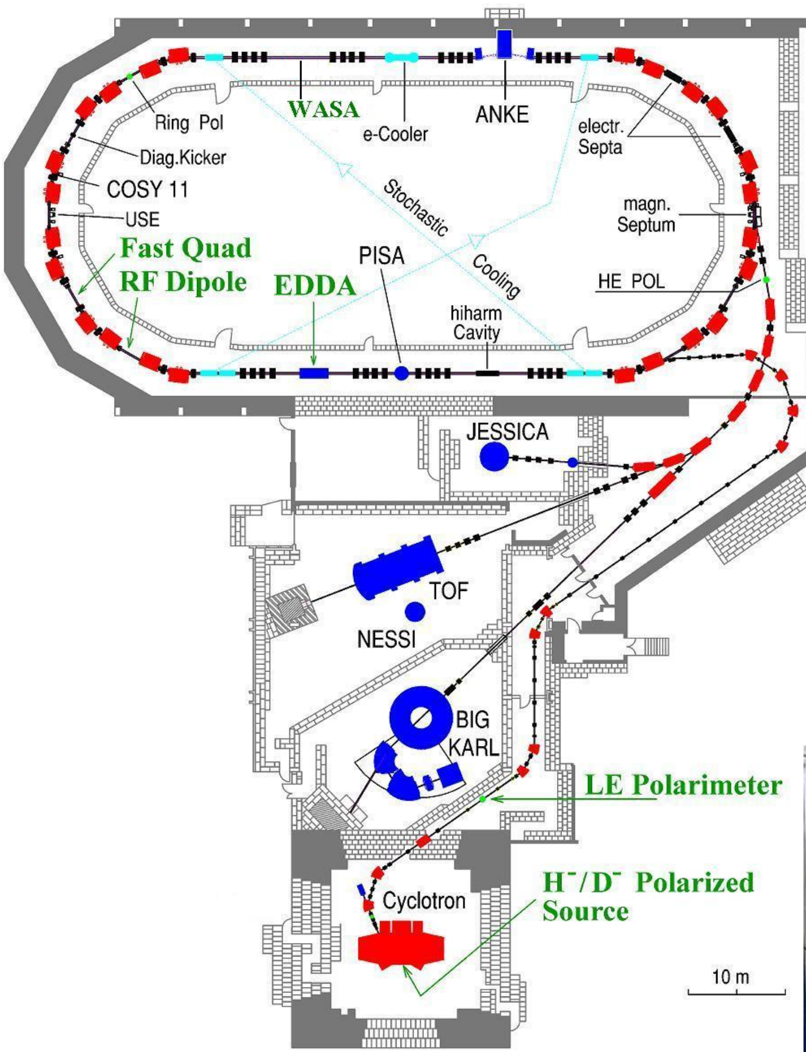
COoler **SY**nchrotron
COSY accelerates (polarized) protons/ deuterons between 300/600 and 3700 MeV/c

4 internal and 3 external experimental areas

Electron cooling at low momenta

Stochastic cooling at high momenta

Why is COSY interesting for EDM



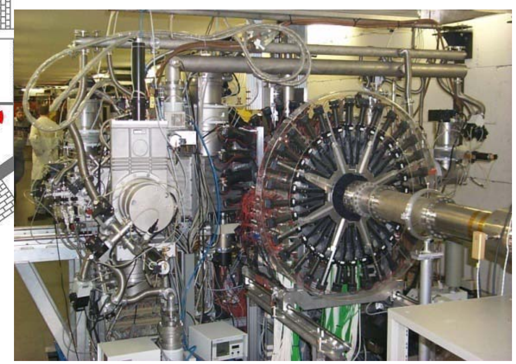
Ions: (pol. & unpol.): p and d

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

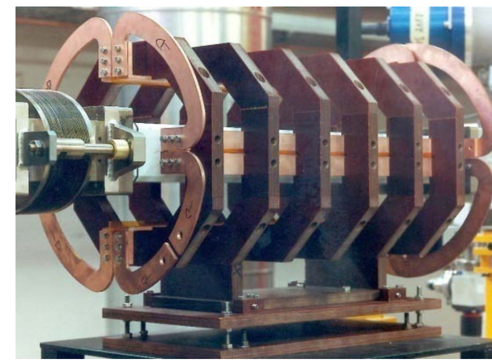
Electron Cooling at injection

Stochastic Cooling above 1.5 GeV/c

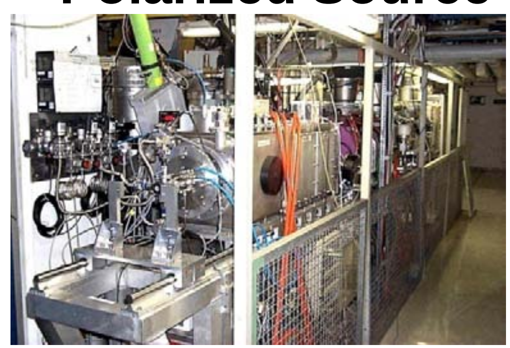
EDDA



Jump Quadrupole



Polarized Source



RF Solenoid

Spin Motion

Thomas-BMT equation (Thomas [1927], Bargmann, Michel, Telegdi [1959]):

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m}\,\vec{S}\ x\ [(1+\gamma G)\vec{B}_\perp + (1+G)\vec{B}_\parallel]$$

Precession Equation in Laboratory Frame

Number of spin rotation per turn: $\nu_p = \gamma G$

$$G = \frac{g-2}{2},\ G_p = 1.7928473,\ G_{\bar{p}} = 1.800,\ G_d = -0.142987$$

Imperfection resonance:

$$\gamma G = k$$

k: integer

Field and positioning errors of magnets

Resonance strength ~ y_{rms}

→ vertical orbit correction
→ adiabatic spin flip (partial snake)

Intrinsic resonance:

$$\gamma G = (kP \pm Q_y)$$

P: super-periodicity
Q_y: vertical tune

Vertical focusing fields

Resonance strength ~$\sqrt{\varepsilon_y}$

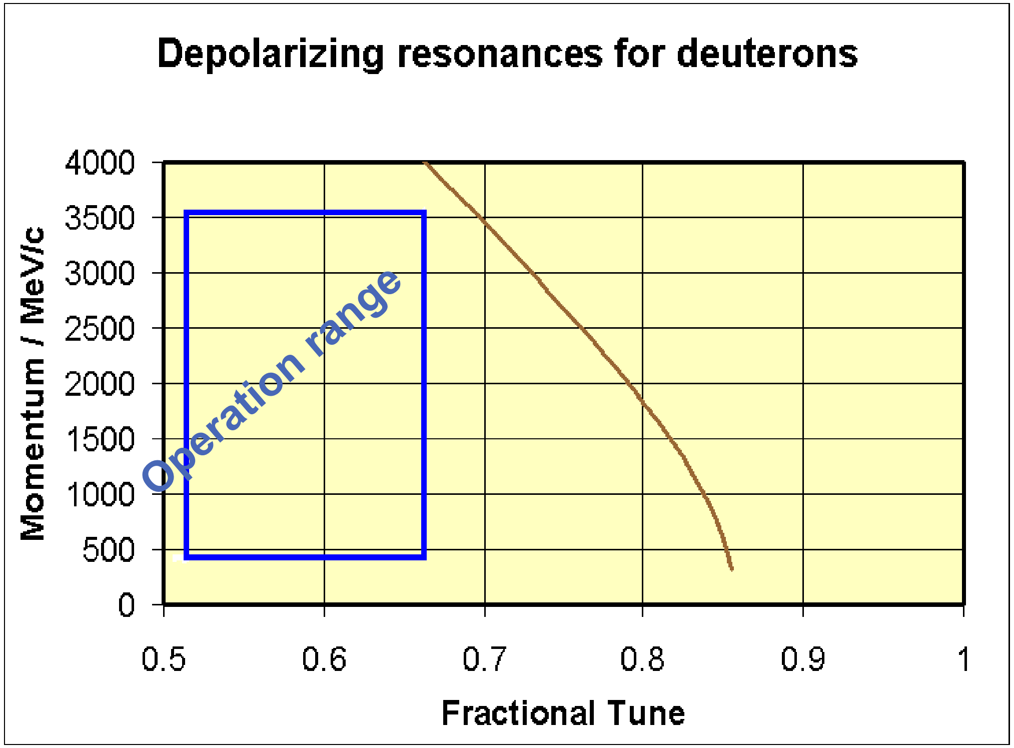
→ vertical tune jumps
→ vertical coherent betatron oscillations

Spin Resonances

Protons

Momentum GeV/c	Kinetic energy GeV	Imperfection resonance $\gamma \cdot G = \dots$	Intrinsic resonance $\gamma \cdot G = \dots \pm Q_y$
0.464	0.108	2	
0.835	0.318		6-
0.986	0.422		-1+
1.259	0.632	3	
1.512	0.841		7-
1.634	0.946		0+
1.871	1.155	4	
2.103	1.364		8-
2.217	1.469		1+
2.443	1.678	5	
2.666	1.888		9-
2.776	1.992		2+
2.997	2.202	6	
3.215	2.411		10-
3.324	2.516		3+

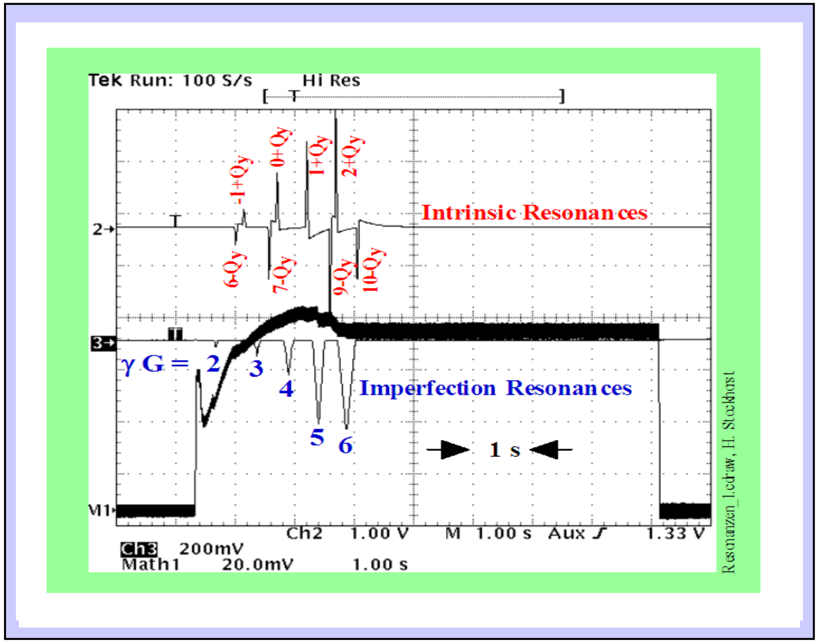
Deuterons



$Q_y = 3.60$

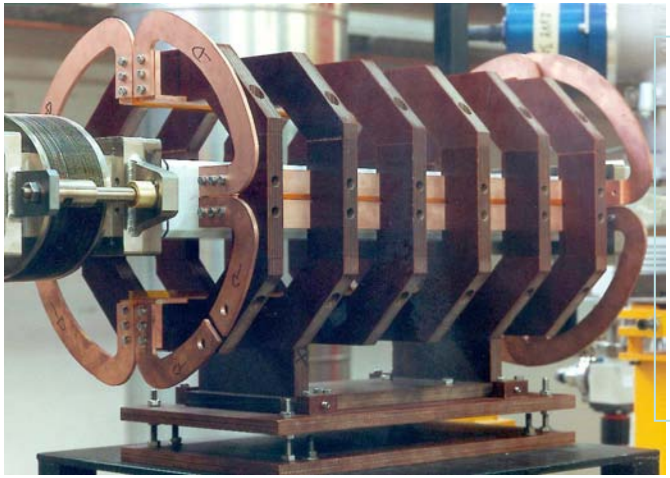
Polarized Proton Beam

Methods to preserve polarization



→ **tune jumps**

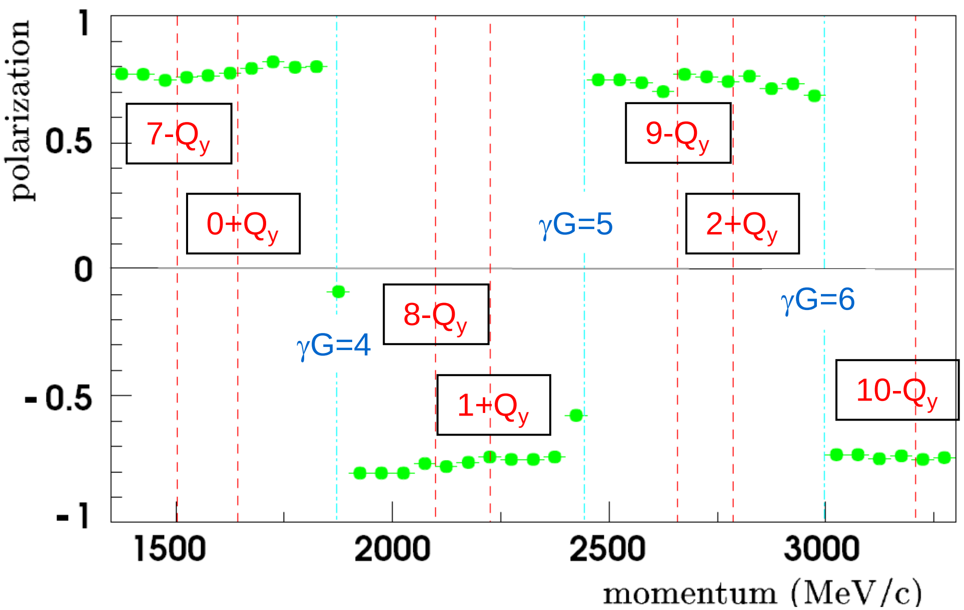
→ **vertical orbit excitation**



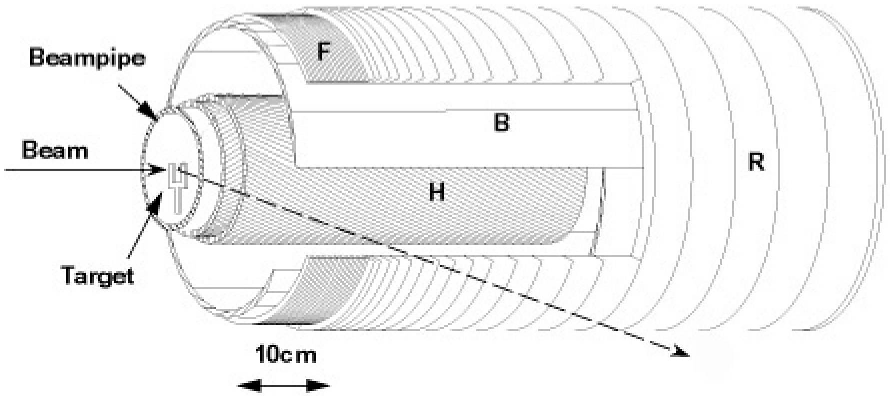
Tune-Jump Quadrupole

- Copper coil air core
- Length 0.6 m
- Max. current 3100 A
- Max gradient 0.45 T/m
- Rise time 10 μs,
- Fall time 10 to 40 ms

Polarization during acceleration



EDDA Polarimeter



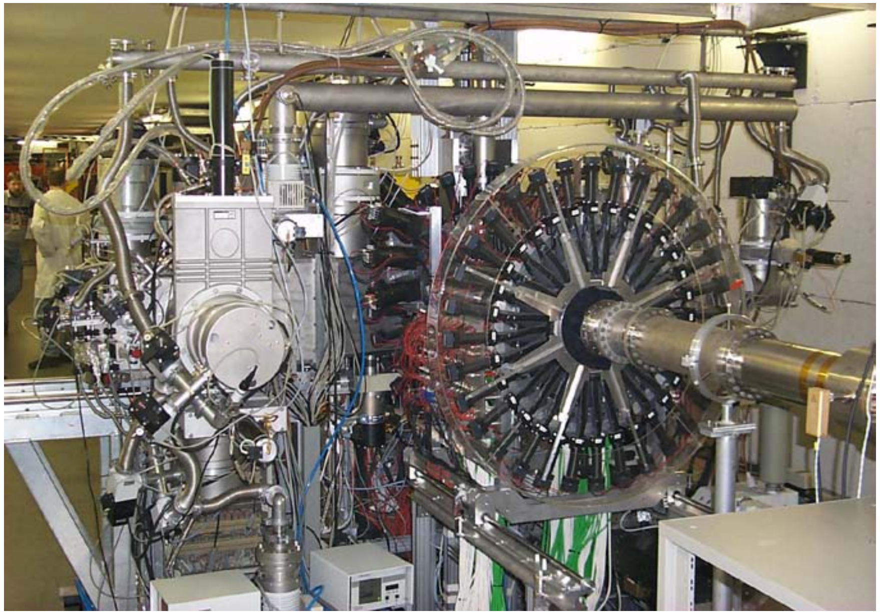
- two-layered cylindrical scintillator structure
  - Outer Layer ($\rightarrow$ trigger!)

    D: 32 overlapping slabs of triangular cross-section ($\Delta\phi = 11.25^o$)

    F,R: 2x29 semirings ($\Delta\theta_{\mathrm{lab}} = 2.5^o$)

    left semirings $\phi \in [-90^o, 90^o]$

    right semirings $\phi \in [90^o, 270^o]$



Proton Polarimetry: Kinematic and Coplanar Coincidences (pp elastic). Left-Right Asymetries by selection on Halfrings => P_V.
Deuteron Polarimetry for dEDM:
Coincidence Halfrings and groups of bars:
Left/Right/Top/Bottom Asymetries =>P_V, P_T

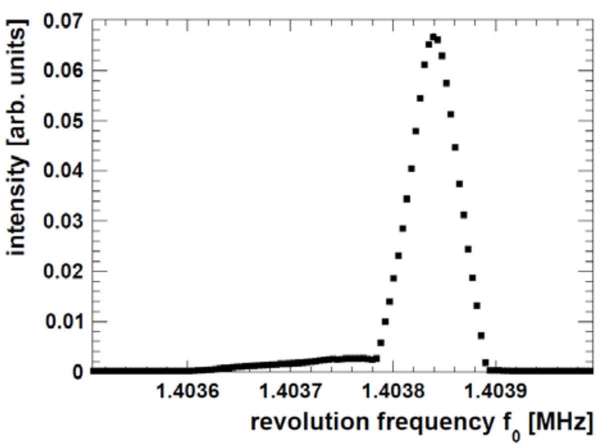
Highlight from recent polarized beam experiments

P.Goslawski et al.,High precision beam momentum determination
in a synchrotronusing a spin-resonance method
Physical Review Special Topics - Accelerators and Beams (Vol.13, No.2) Feb. 2010

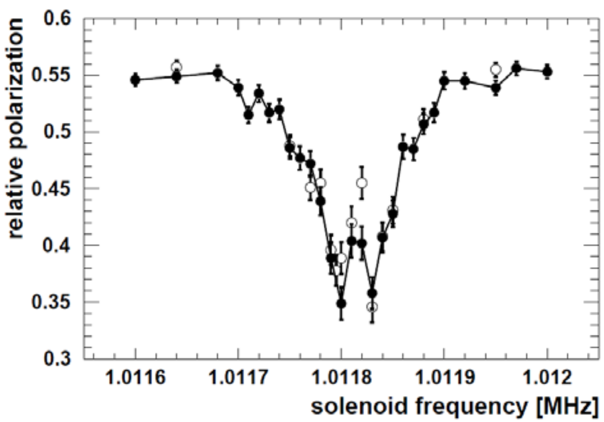
η-mass determination in d p -> ^{3}He η at Anke
Use depolarizing resonance for accurate determination of beam momentum

$$f_{res} = (1+\gamma G)\, f_0$$

f_0 from Schottky Spectra



f_{res} from depolarization (measured with EDDA)



Result: $\Delta p/p < 6\ 10^{-5}$ at 13 momenta between 3100 and 3200 MeV/c

Conclusion from COSY experience

Polarized Proton and Deuteron Operation well under control (no spin tracking needed for this so far)

All tools needed for detailed experimental studies of polarized beam behaviour are available at COSY-Juelich

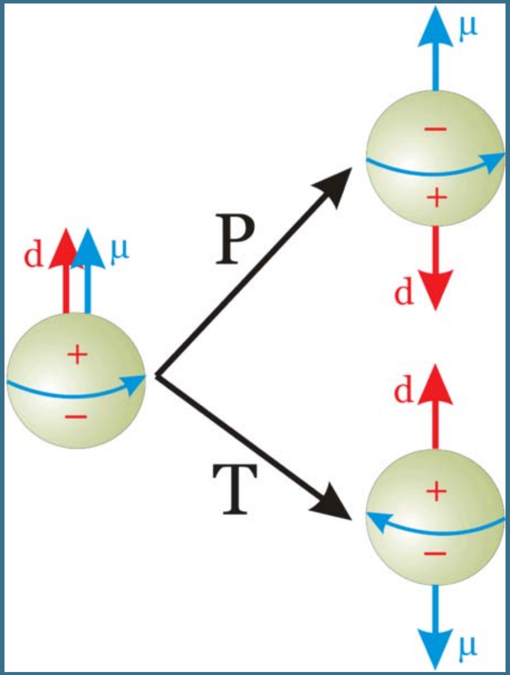
➡ ***THE* spin-physics machine for hadron physics**

➡ ***THE* ideal test facility for the future srEDM measurements**

The polarimetry group of the BNL srEDM collaboration is running tests at COSY in close collaboration with COSY staff since 2008 (LOI 2004) (E.Stevenson)

Recently, at COSY the potential for a dedicated srEDM Experiment is pursued by the just forming JEDI collaboration

Electric Dipole Moments (EDMs)



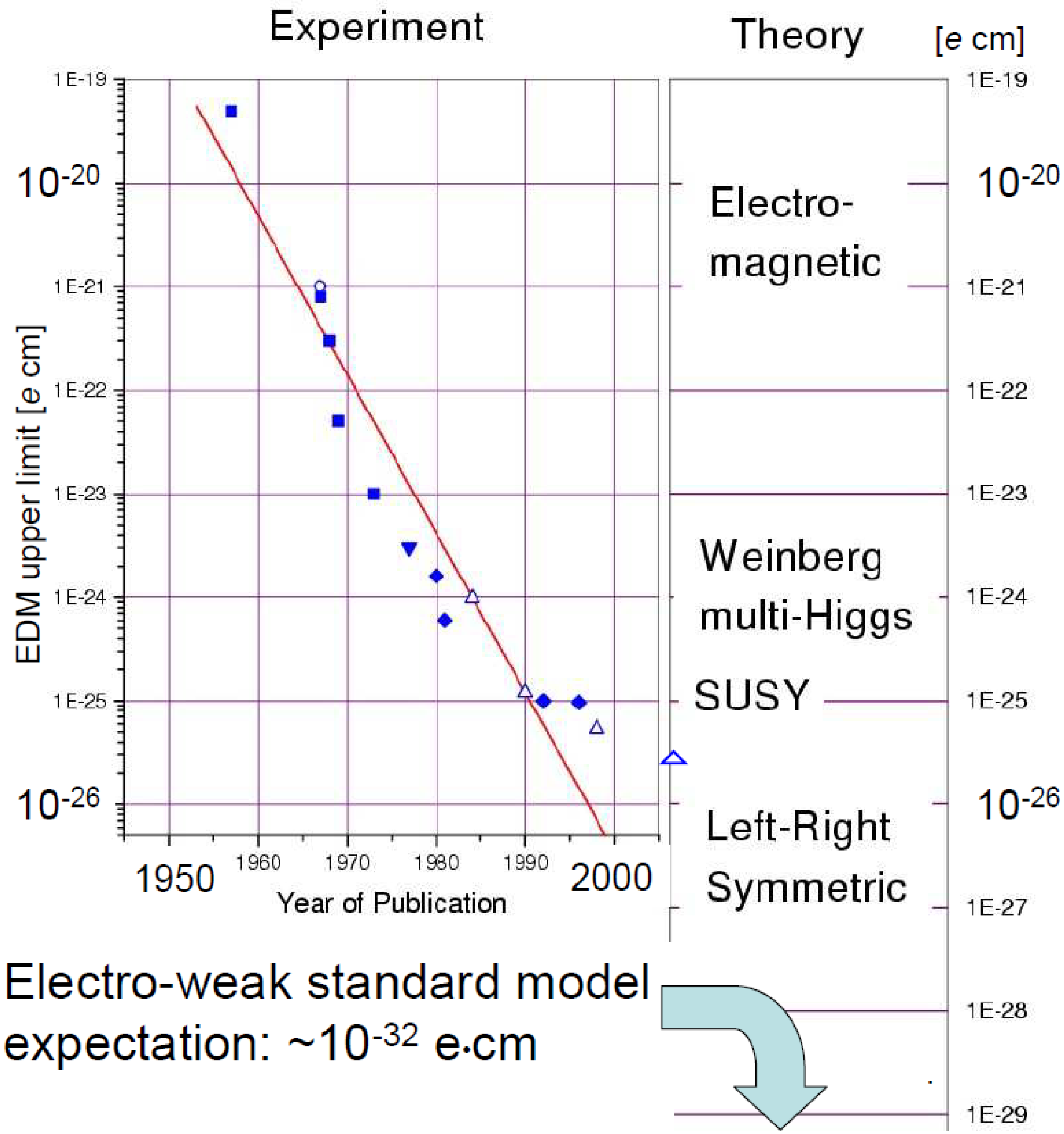
Permanent EDMs violate parity **P** and time reversal symmetry **T**

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

EDMs are candidates to solve mystery of matter-antimatter asymmetry
→ may explain why we are here!

History of neutron EDM limits

- **Smith, Purcell, Ramsey**
  PR 108, 120 (1957)
- **RAL-Sussex-ILL**
  ($d_n < 2.9 \times 10^{-26}$ e·cm)
  PRL 97,131801 (2006)



Adopted from K. Kirch

Limits for Electric Dipole Moments

EDM searches - 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	?	$\sim 10^{-29}$	$3 \times 10^{-29} - 5 \times 10^{-33}$

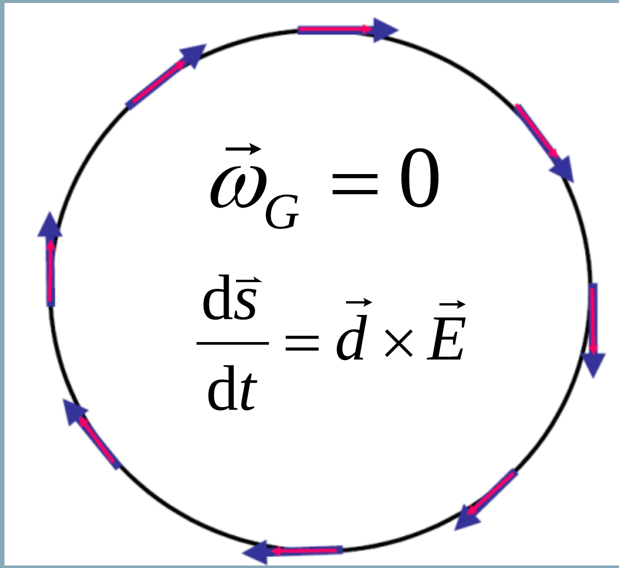
Huge efforts underway to improve limits / find EDMs

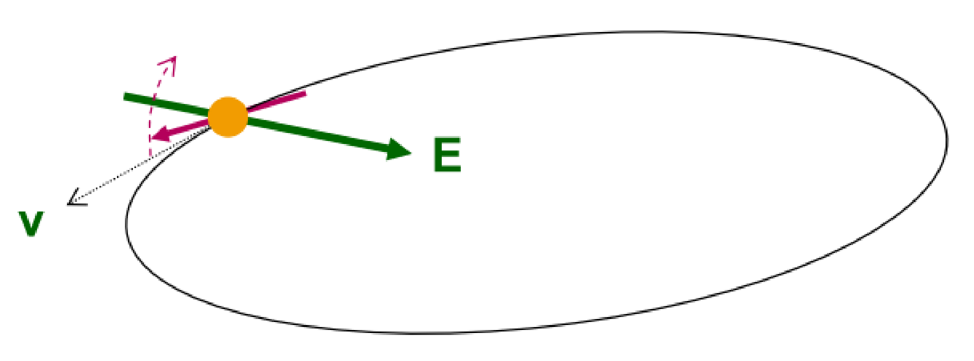
Sensitivity to **NEW PHYSICS** beyond the Standard Model

485. WE-Heraeus-Seminar (July 04–06, 2011)
Search for Electric Dipole Moments (EDMs) at Storage Rings
http://www2.fz-juelich.de/ikp/edm/en/

Search for Electric Dipole Moments

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





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

The frozen spin Method

For transverse electric and magnetic fields in a ring ($\vec{\beta}\cdot\vec{B}=\vec{\beta}\cdot\vec{E}=0$), anomalous spin precession is described by

$$\vec{\omega}_G = -\frac{q}{m}\left\{\cancel{G\vec{B}} + \left[G-\left(\frac{m}{p}\right)^2\right]\frac{\vec{\beta}\times\vec{E}}{c}\right\} \qquad \left(G=\frac{g-2}{2}\right)$$

Magic condition: Spin along momentum vector

1. For any sign of G, in a combined electric and magnetic machine

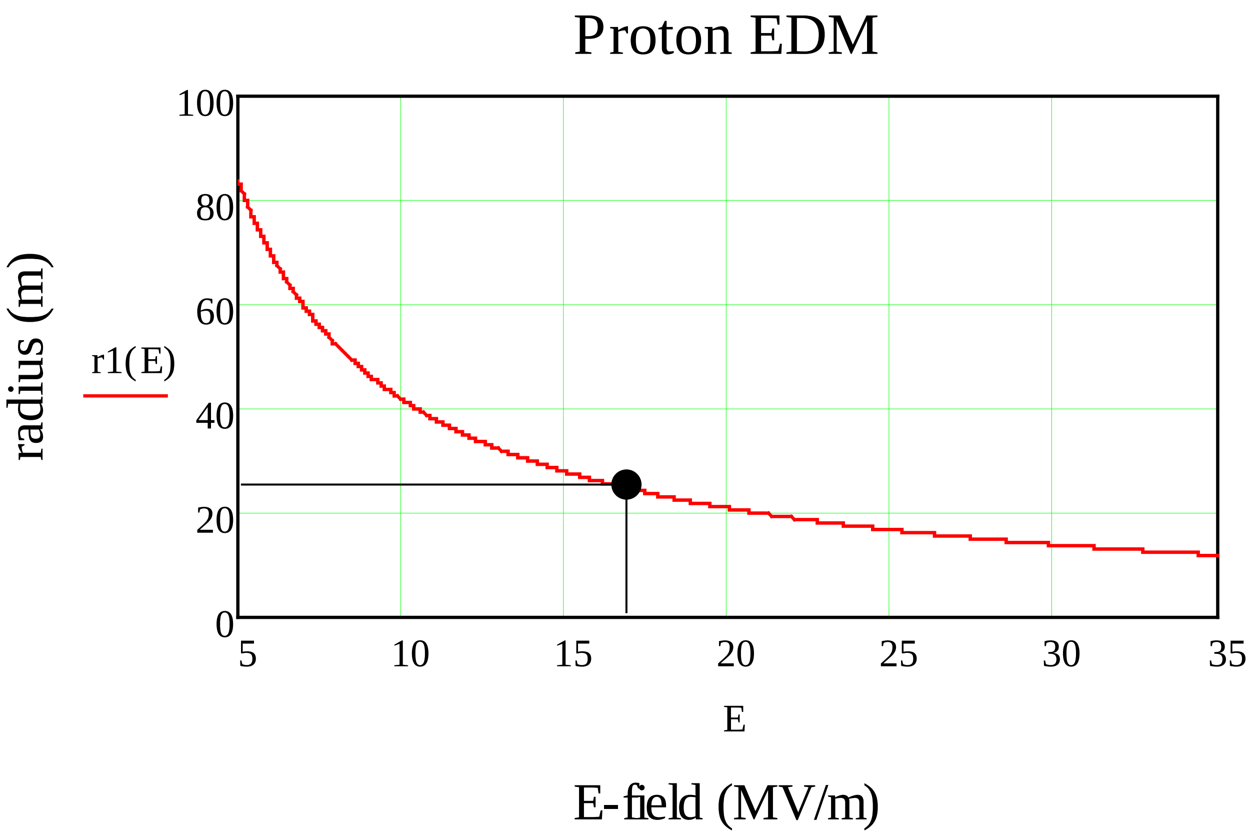
$$E = \frac{GBc\beta\gamma^2}{1-G\beta^2\gamma^2} \approx GBc\beta\gamma^2$$

2. For G>0 (protons) in an all electric ring

$$G-\left(\frac{m}{p}\right)^2 = 0 \rightarrow p = \frac{m}{\sqrt{G}} = 700.74\,\frac{\mathrm{MeV}}{\mathrm{c}} \qquad \text{(magic)}$$

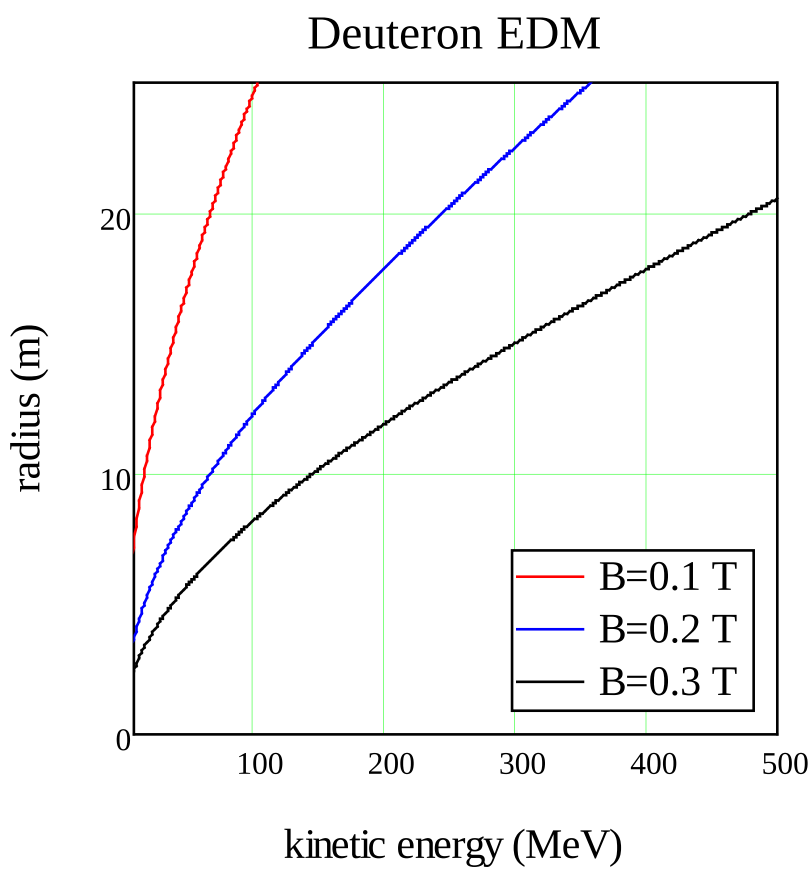
Magic condition: Protons

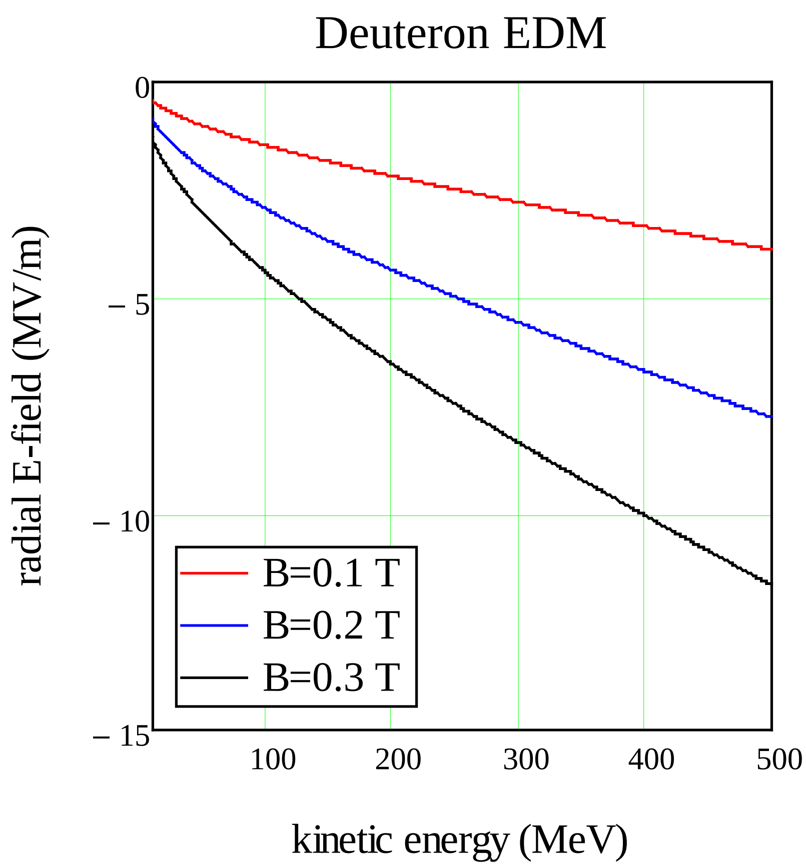
E-field only



Magic condition: Deuterons

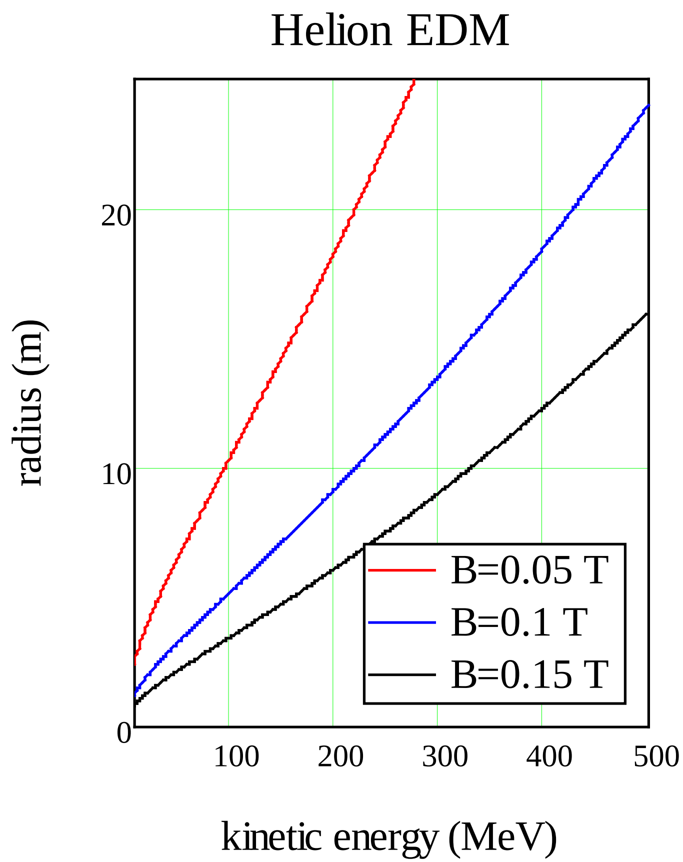
E and B fields

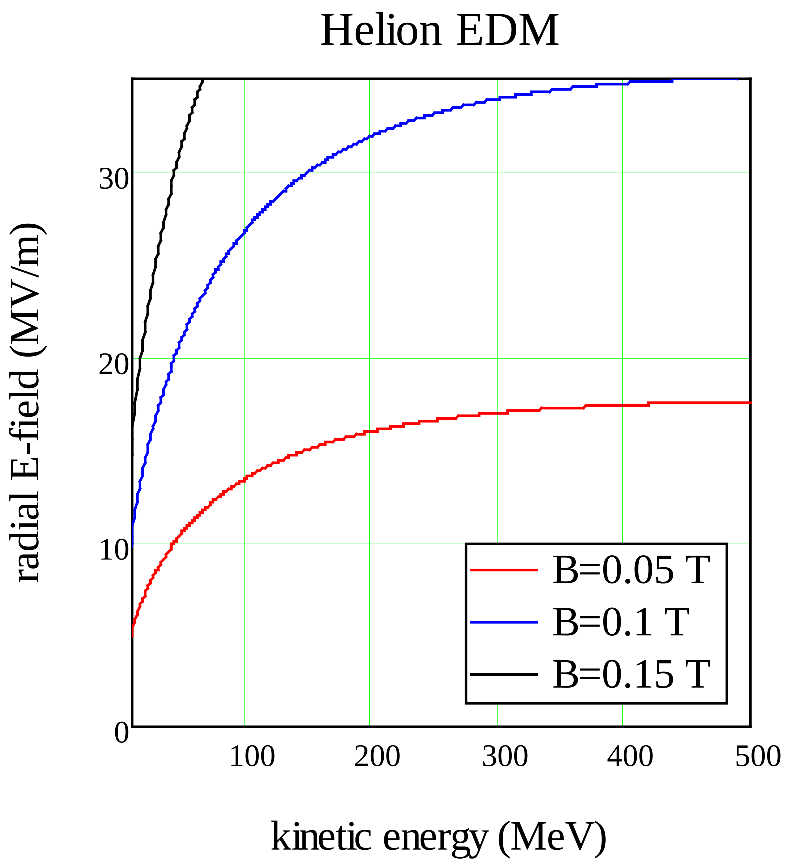




Magic condition: Helions

E and B fields





Search for Electric Dipole Moments

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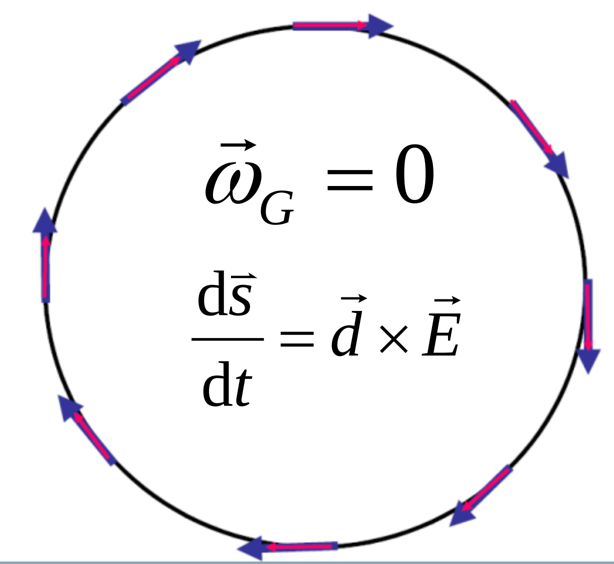
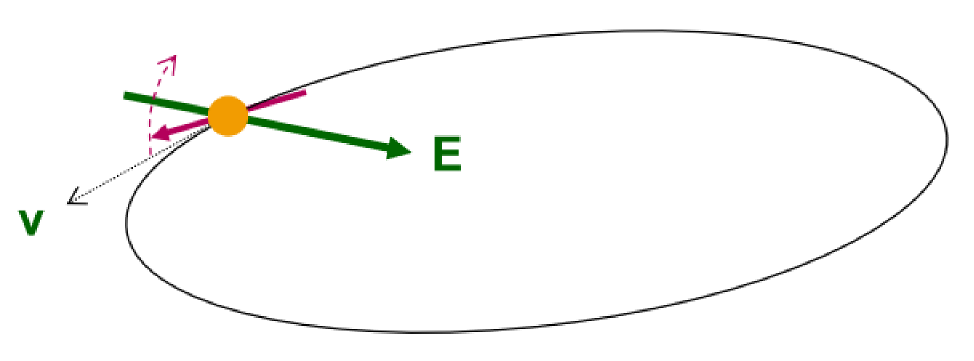


$$\vec{\omega}_G = 0$$

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



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

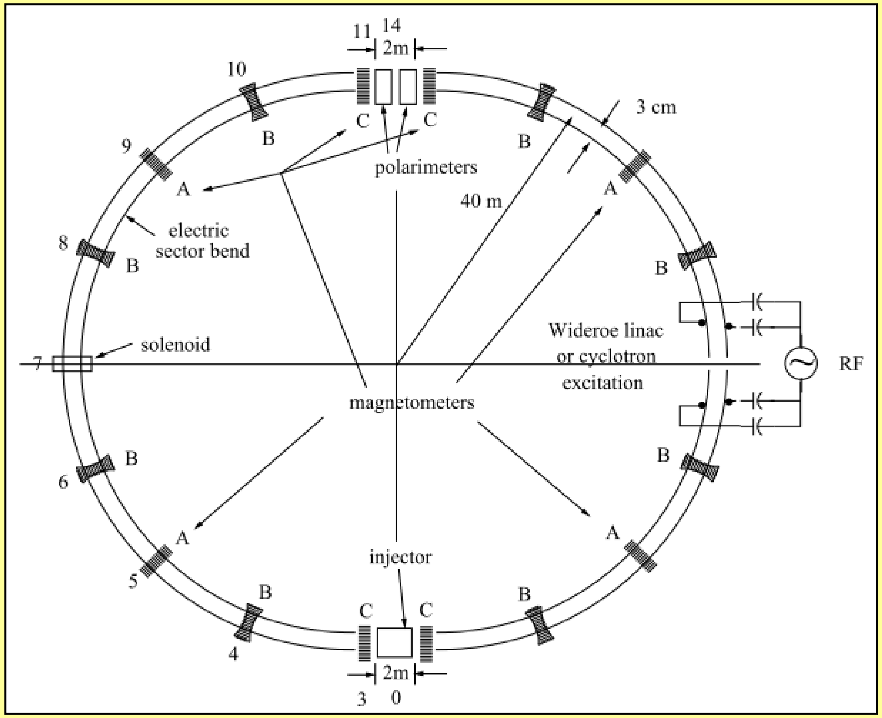
A *magic* storage ring for protons (electrostatic), deuterons, …

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

Two storage ring projects being pursued

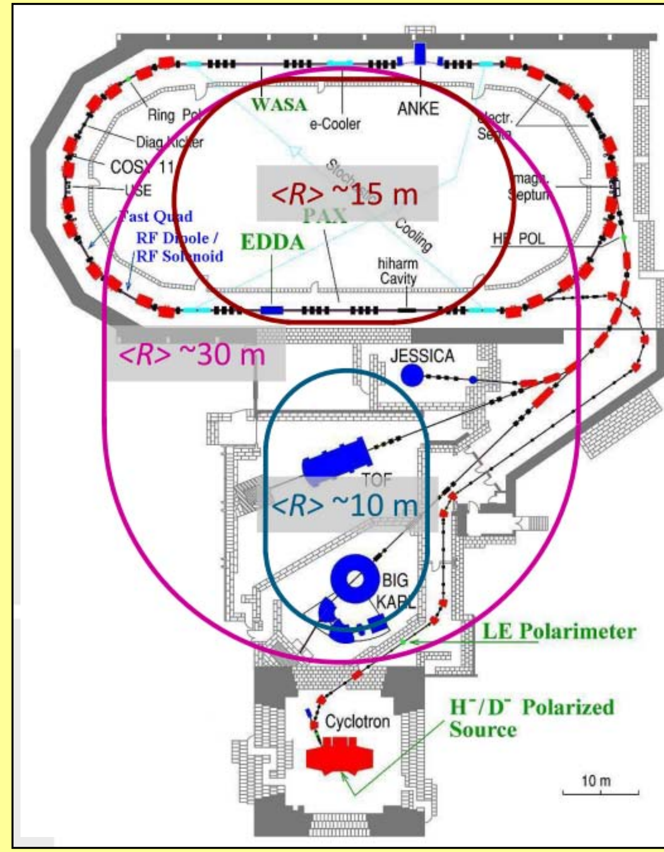
BNL for protons all electric machine



CW and CCW propagating beams

(from R. Talman)

Jülich, focus on deuterons,
or a combined machine



(from A. Lehrach)

srEDM cooperations

International srEDM Network

Institutional (MoU) and Personal (Spokespersons …) Cooperation, Coordination

srEDM Collaboration (BNL)	srEDM Collaboration (FZJ)

Common R&D

RHIC	**EDM-at-COSY**
Beam Position Monitors	Polarimetry
(…)	Spin Coherence Time
	Cooling
	(…)

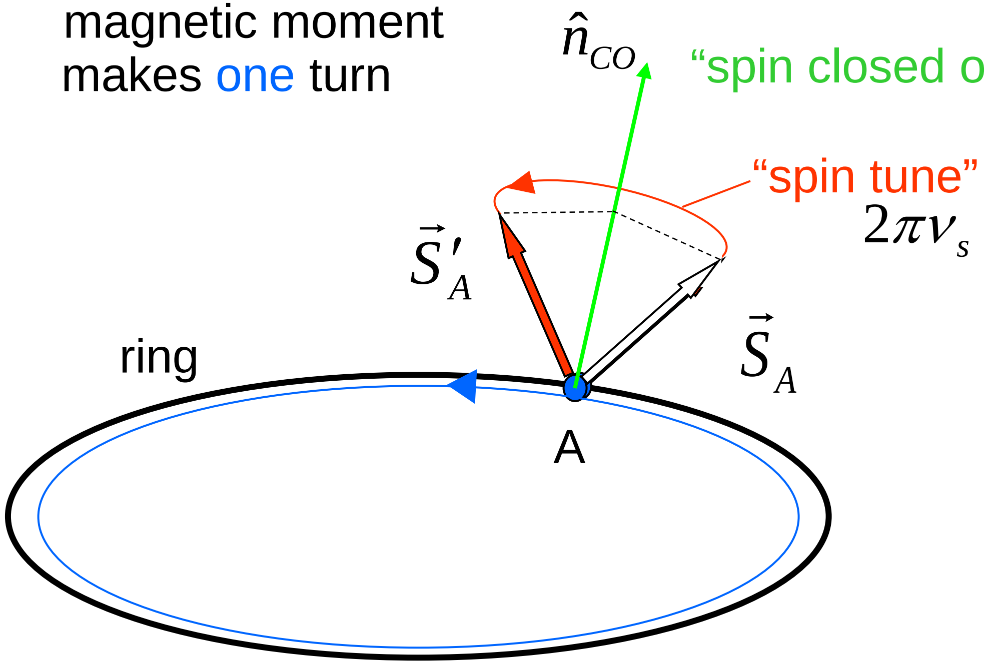
Spin Tracking

	Study Group
DOE-Proposal	Precursor; Ring Design
CD0, 1, …	HGF Application(s)
pEDM Ring at BNL	**JEDI**

Why do we need longterm spintracking calculations, now

Spin closed orbit

one particle with magnetic moment makes one turn



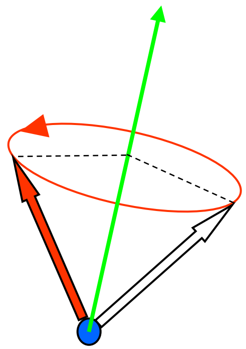
stable polarization
if $\vec{S} \parallel \hat{n}_{CO}$

And that's all we needed to run the hadron physics experiments of interest

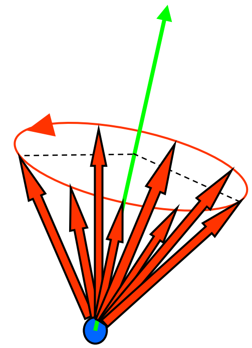
Adopted from H.O. Meyer

Spin coherence

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



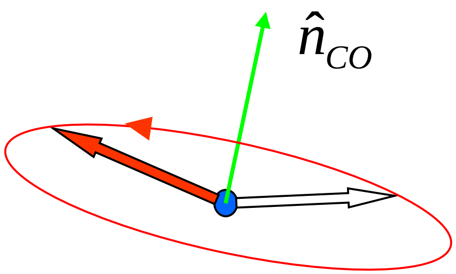
At injection all
spin vectors aligned (coherent)



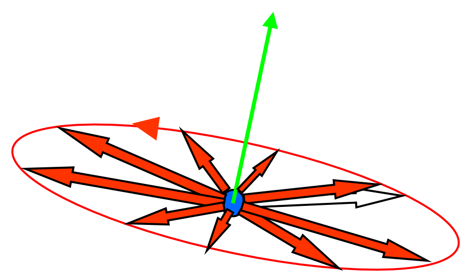
After some time, spin vectors get out of
phase and fully populate the cone

Polarization not affected!

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



At injection all spin vectors aligned



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

Longitudinal polarization vanishes!

In an Edm machine with frozen spin, observation time is limited.

Estimate of spin coherence times (Kolya Nikolaev)

One source of spin coherence are random variations of the spin tune due to the momentum spread in the beam

$\delta\theta = G\delta\gamma$ and $\delta\gamma$ is randomized by e.g., electron cooling

$$\cos(\omega t) \Rightarrow \cos(\omega t + \delta\theta)$$

$$\tau_{sc} \approx \frac{1}{f_{rev} G^2 \langle \delta\gamma^2 \rangle} \approx \frac{1}{f_{rev} G^2 \gamma^2 v^4} \left\langle \left(\frac{\delta p}{p} \right)^2 \right\rangle^{-1}$$

Estimate: $T_{kin} = 100\ \mathrm{MeV}$ $f_{rev} = 0.5\ \mathrm{MHz}$

$G_p = 1.79$ $G_d = -0.14$

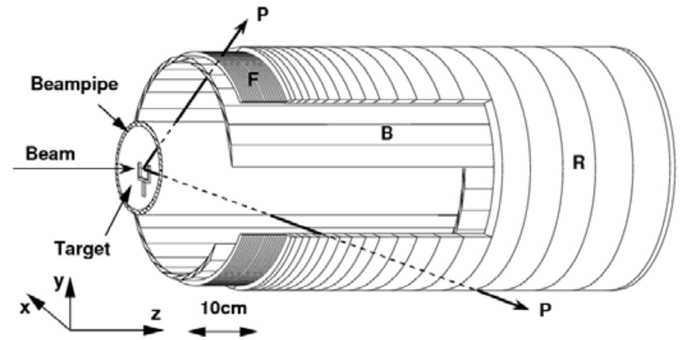
$\tau_{sc}(p) \approx 3 \times 10^3\ \mathrm{s}$ $\tau_{sc}(d) \approx 5 \times 10^5\ \mathrm{s}$

Spin coherence time for deuterons may be ~100 larger than for protons

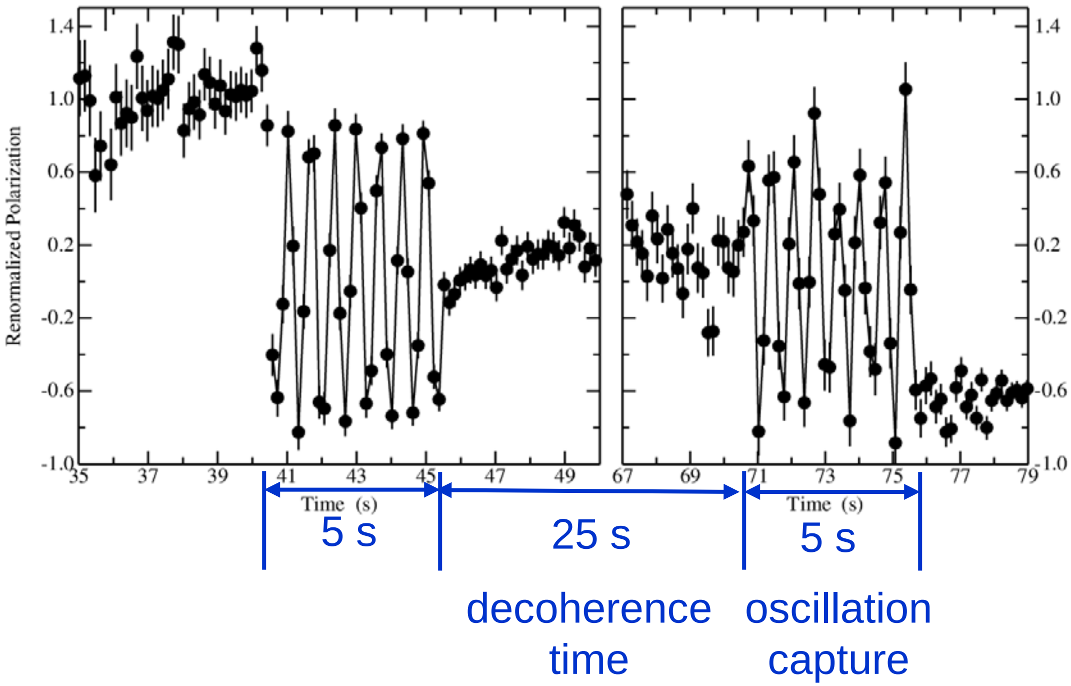
First measurement of spin coherence time

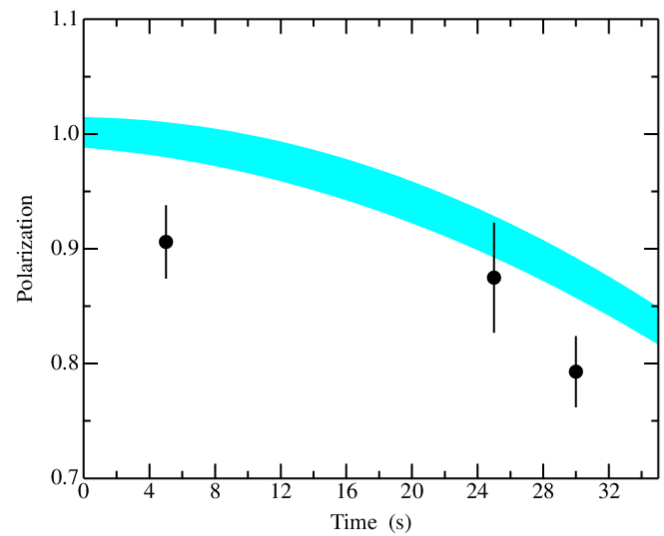
Test measurements at COSY

Polarimetry:



Spin coherence time:





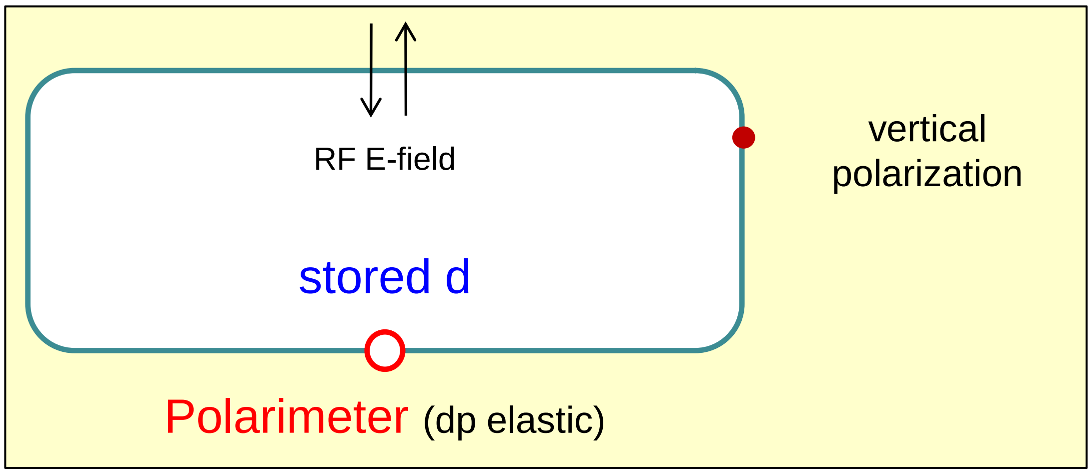
from E. Stephenson
(BNL polarimetry group)

Precursor Experiment in COSY:
Resonance Method with RF E-fields

spin precession governed by: $$\frac{d\vec{S}}{dt^*} = \vec{d} \times \vec{E}^* + \vec{\mu} \times \vec{B}^*$$ (* rest frame)

Two situations:

1. $B^*=0 \Rightarrow B_y = \beta \times E_R$ (= 70 G for E_R=30 kV/cm) EDM effect
2. $E^*=0 \Rightarrow E_R = -\beta \times B_y$ no EDM effect



P_y *drops*

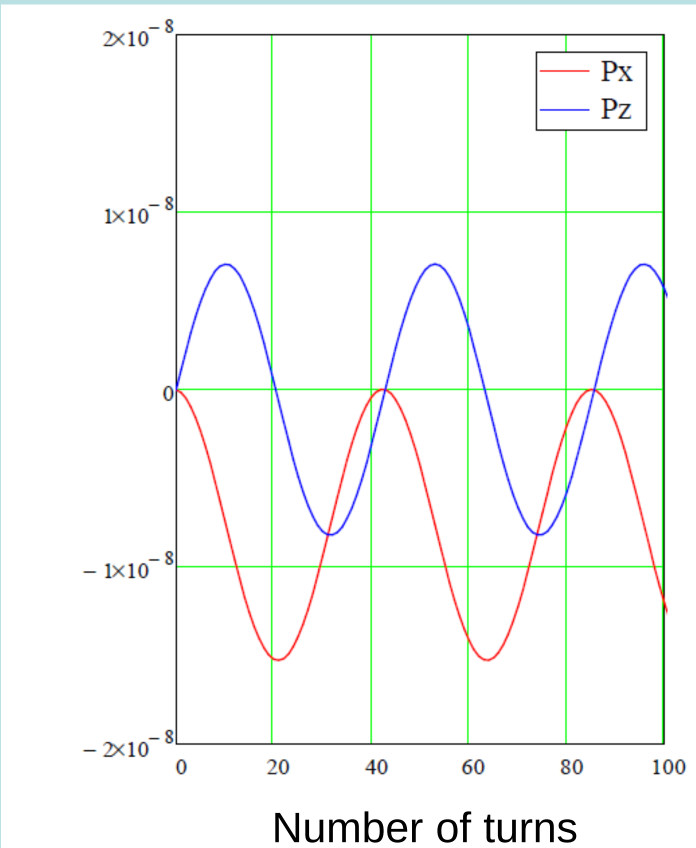
$\sqrt{P_x^2 + P_z^2}$ *grows*

This way, the Edm signal gets **accumulated** during the cycle. .
Brings us in the 10^{-24} e·cm range for d_d

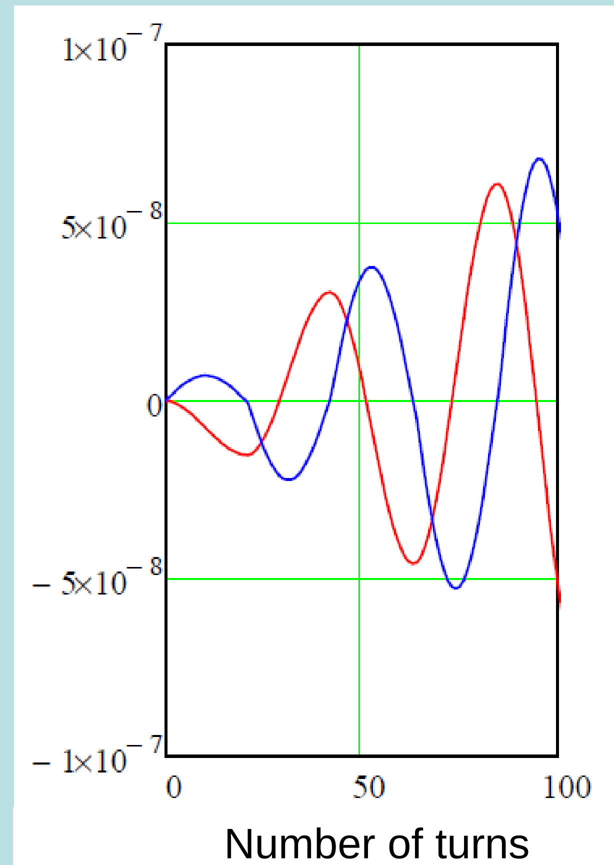
PE 2: Simulation of resonance Method with RF E-fields and deuterons at COSY

Parameters:	beam energy	T_d=50 MeV
	assumed EDM	$d_d=10^{-20}$ e·cm
	E-field	10 kV/cm

Constant E-field



E-field reversed every $-\pi/(G\cdot\gamma) \sim 21$ turns



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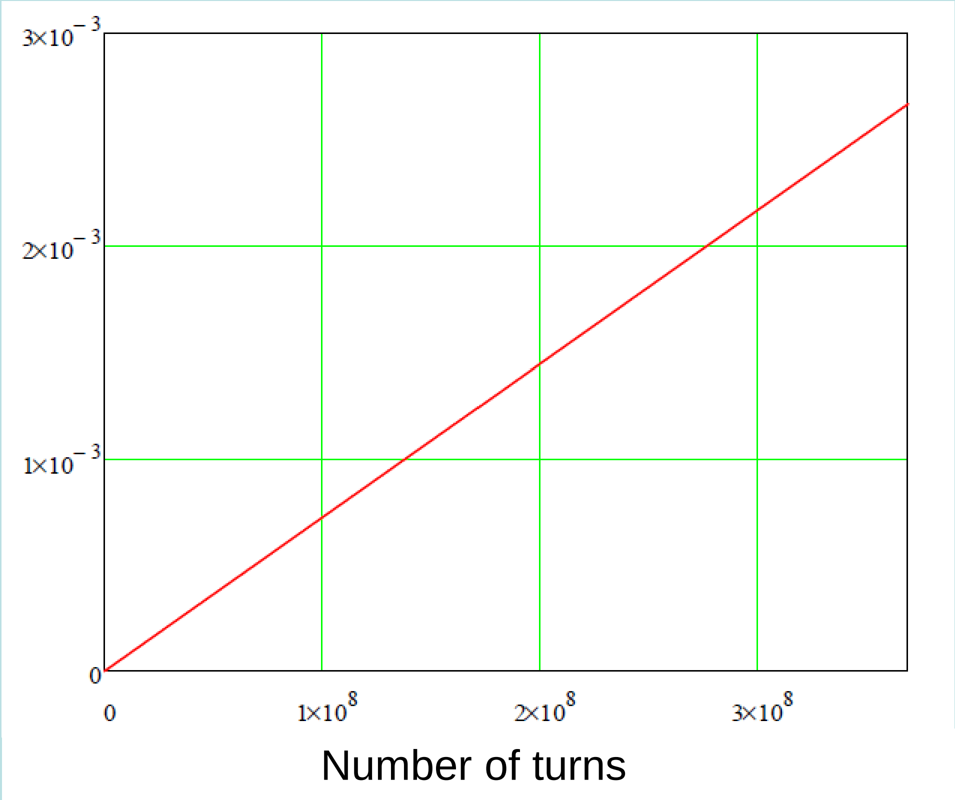
Parameters:	beam energy	T_d=50 MeV
	assumed EDM	d_d=10^{-20} e·cm
	E-field	10 kV/cm

Linear extrapolation of $P = \sqrt{P_x^2 + P_z^2}$ for a time period of τ_{sc}=1000 s (=$3.7\cdot10^8$ turns)



EDM effect accumulates

Polarimeter determines P_x, P_y and P_z

Status of the Spin Tracking Calculations

The shown results for explanation of measured data and for predictions for the precursor experiments use a so-called ‚no lattice' model, i.e. only the precession of the spin in the bending fields is considered. (no betatron oscillation, no higher order fields, no fringe fields…)

This obviously is not sufficient for a high precision experiment as envisioned, a long term tracking code with polarization is urgently needed, COSY-INFINITY was identified as good candidate

⬇

We started to use COSY-INFINITY earlier this year, but we are at the very beginning

People working on this

PD Dr. A.Lehrach, Dr. B.Lorentz, A.Peece

- Modelling of Polarization in COSY
- Comparison of Model and Experiment
- Modelling Precursor Experiments

Prof. Dr. Yuri Senichev, D.Zyuzin,

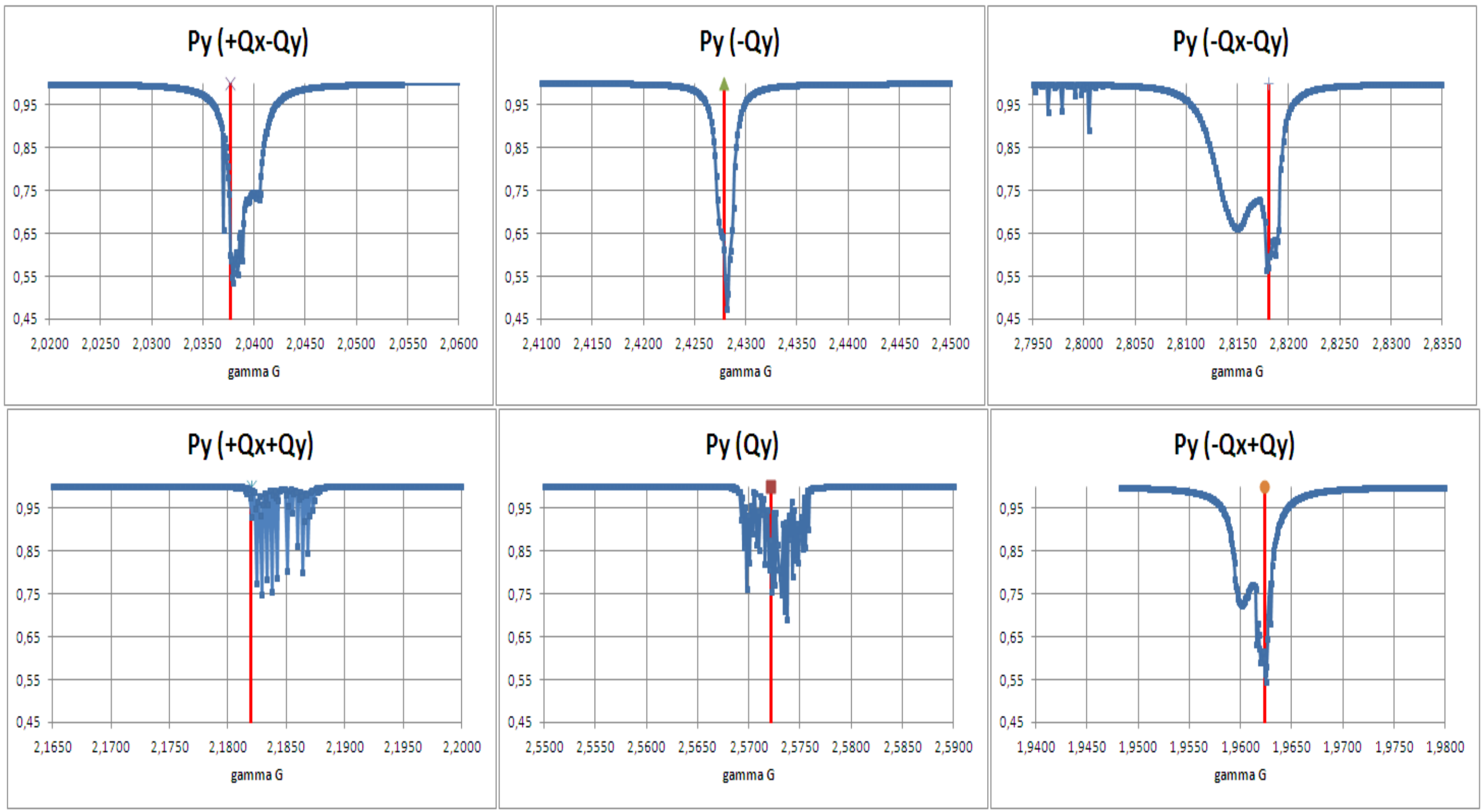
- Multi Processor Installation of the code in Juelich >Talk D. Zyuzin
- Design of a pure electrostatic lattice (p-EDM)
- Fringe field effects in electrostatic ring (Cooperation with Prof. S.Andrianoz, A. Ivanov of St. Petersburg SU)

We need to work in close cooperation with M.Berz

Spin Tracking through the COSY lattice

Qualitative Check of Intrinsic Resonances

19 rays, with horizontal, vertical and momentum offsets

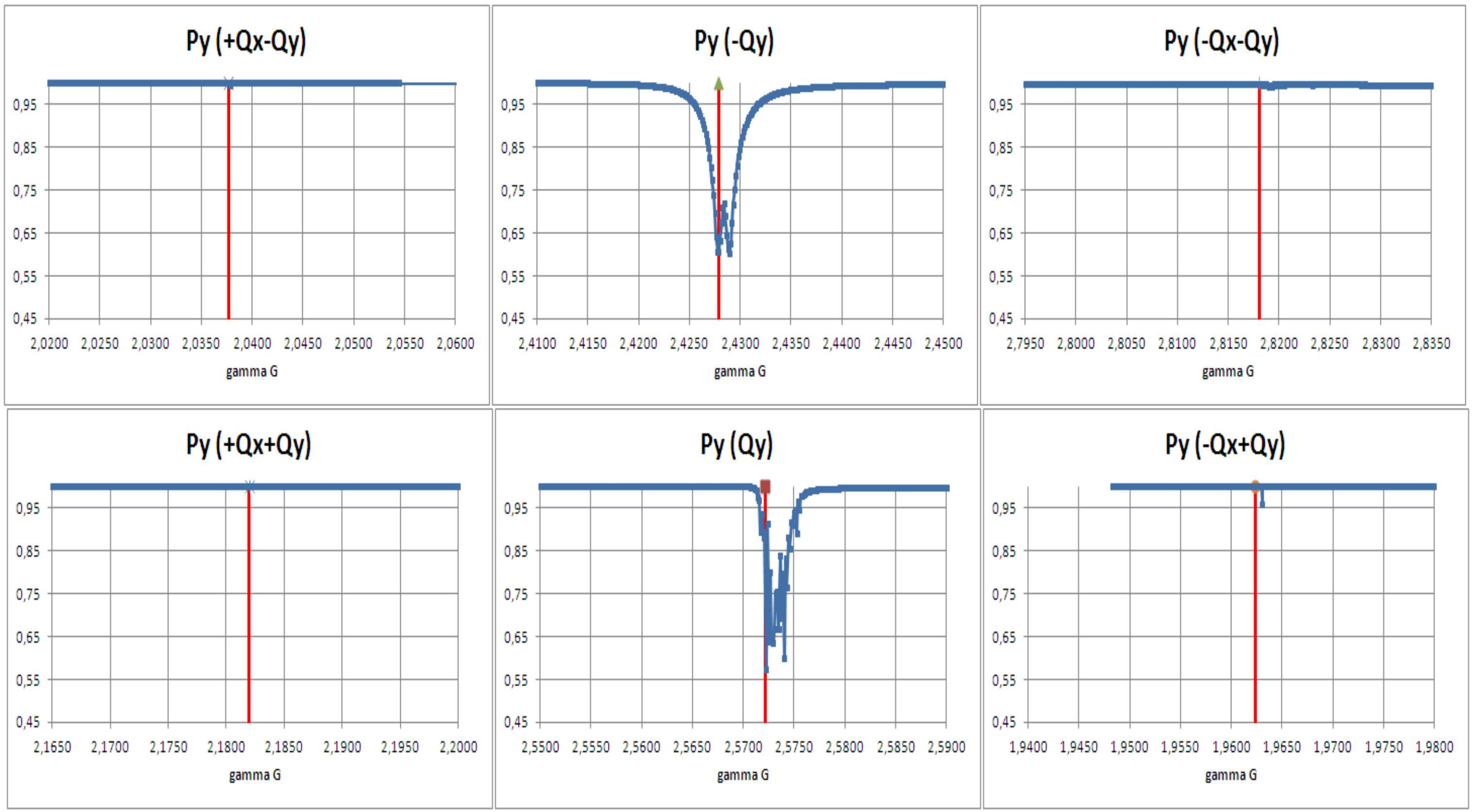


Py = average vertical polarization over all turns and rays

Spin Tracking through the COSY lattice

Qualitative Check of Intrinsic Resonances

9 rays, with vertical and momentum offsets

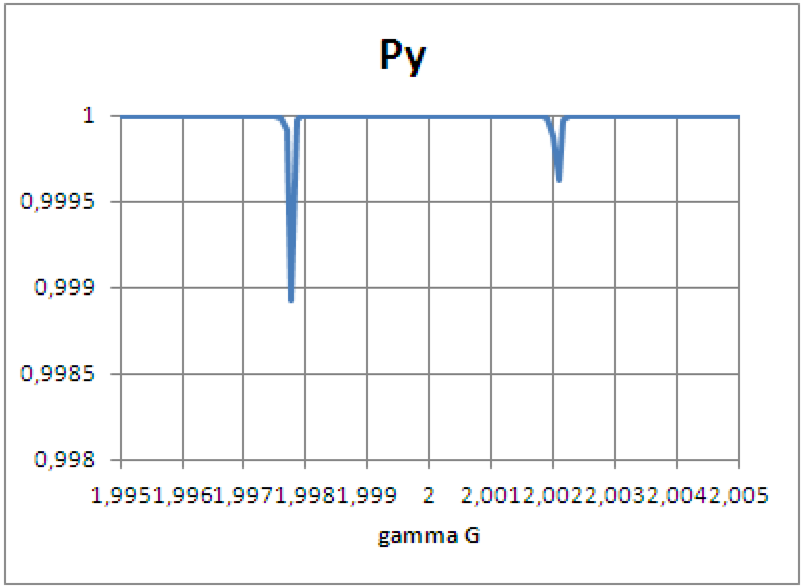


Py = average vertical polarization over all turns and rays

Spin Tracking through the COSY lattice

Qualitative Check of Imperfection Resonances

momentum offsets

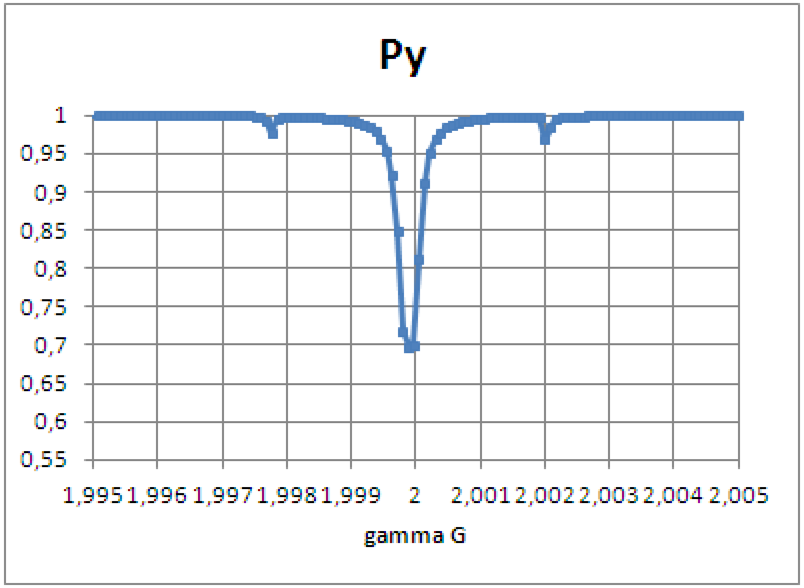


Py = average vertical polarization over all turns and rays

Spin Tracking through the COSY lattice

Qualitative Check of Imperfection Resonances

horizontal offsets



Py = average vertical polarization over all turns and rays

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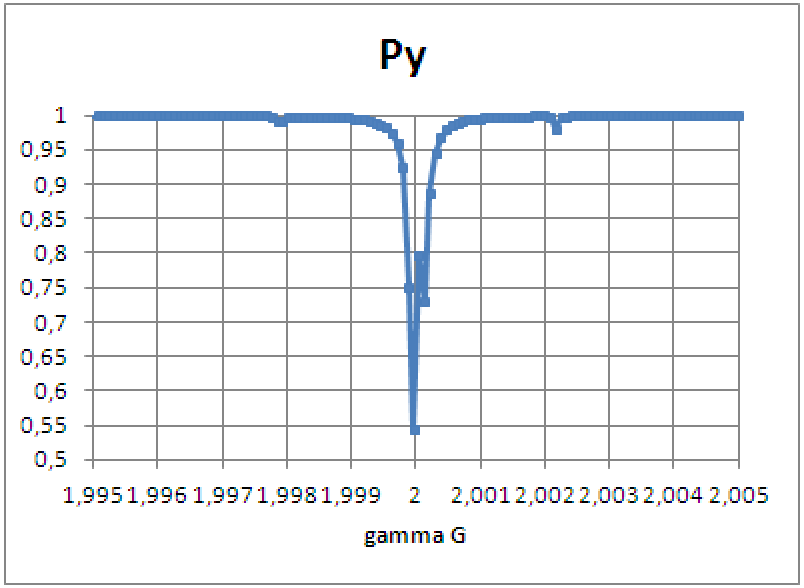
vertical offsets



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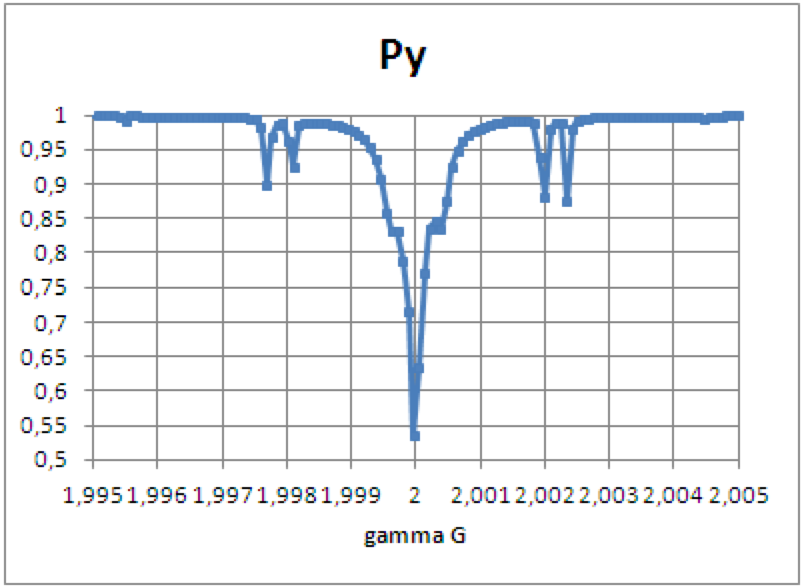
Qualitative Check of Imperfection Resonances

vertical and horizontal offsets



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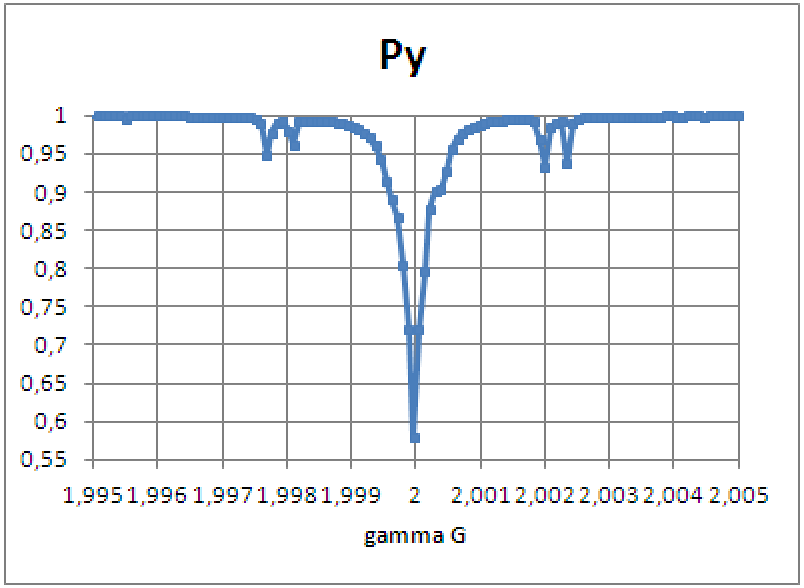
Spin Tracking through the COSY lattice

Qualitative Check of Imperfection Resonances

vertical, horizontal and momentum offsets



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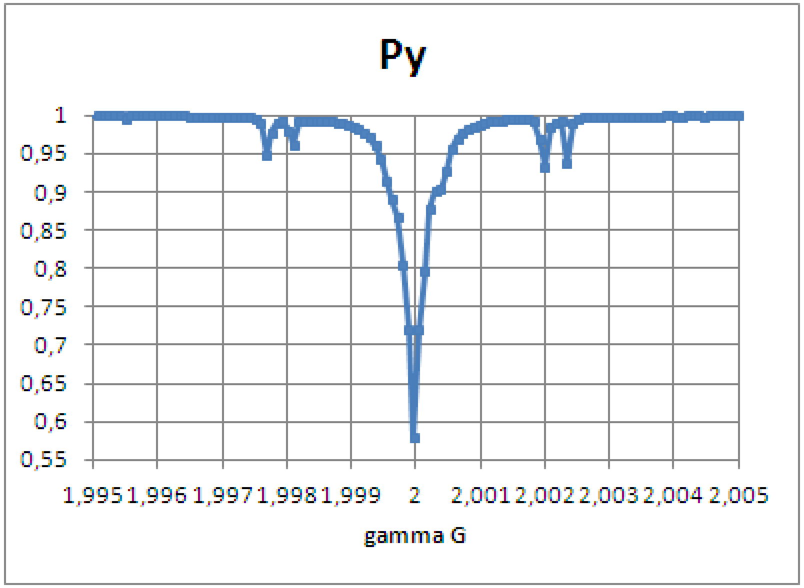
Spin Tracking through the COSY lattice

Qualitative Check of Imperfection Resonances

vertical, horizontal and momentum offsets



All that was shown is only qualitative, to learn how to use COSY Infinity with Juelich COSY lattice, I think I know what I am doing

Quanitative investigations need to follow (we could even think to compare to measurements)

Spin Tracking through the COSY lattice

Next steps:

We could (and probably will) go in a more quantitative investigation of the started spin tracking calculations.

But more important:
introduce „spin flipper“ element in COSY-Infinity Tracking

- spin coherence time measurements (ongoing) use rf solenoid magnet
- precursor experiment will use rf electrostatic element

Both of these elements are run as „spin flipper“ on the frequency of the spin precession, not on the revolution frequency

$f_{flipper}=f_{rev}*(k+\gamma G)$

Therefore the OTM tracking method of COSY-Infinity needs to be extended (discussion with M. Berz are ongoing)

srEDM cooperations

International srEDM Network

Institutional (MoU) and Personal (Spokespersons …) Cooperation, Coordination

srEDM Collaboration (BNL)	srEDM Collaboration (FZJ)

Common R&D

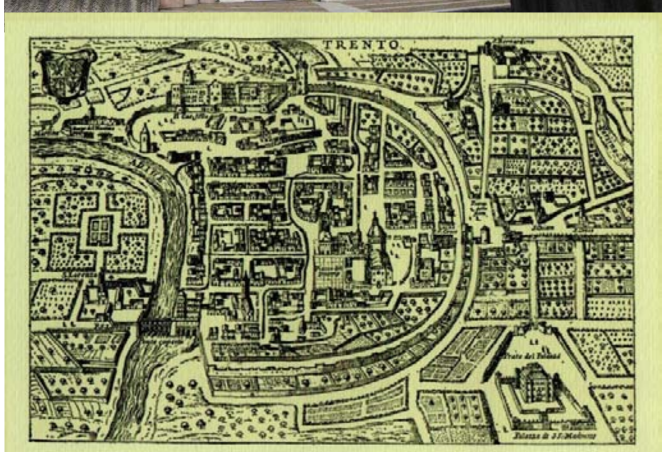
RHIC	EDM-at-COSY
Beam Position Monitors	Polarimetry
(…)	Spin Coherence Time
	Cooling
	(…)

Spin Tracking

BNL	FZJ
	Study Group
DOE-Proposal	Precursor; Ring Design
CD0, 1, …	HGF Application(s)
pEDM Ring at BNL	**JEDI**

EDM Workshop at ECT* (Trento)

October 1-5, 2012



Organizing committee

- **Jülich**
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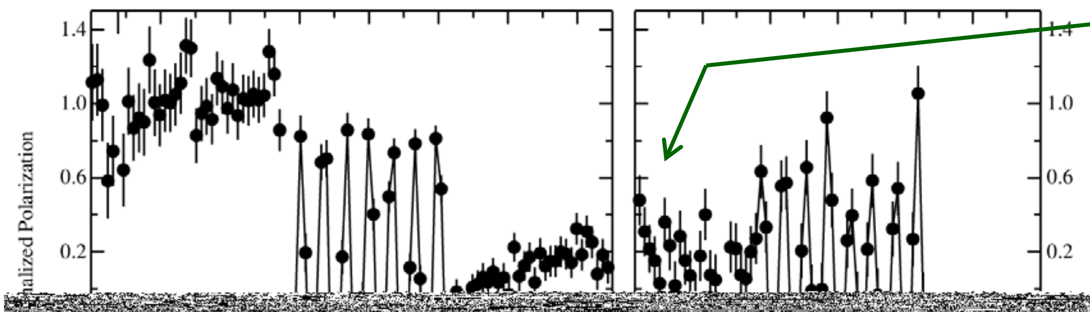
Summary

- Measurement of EDMs extremely difficult,
  but the **physics is fantastic!**
- **COSY** is a perfect test facility,
  spin coherence time measurements and comparison to model expectations will come soon
- Systematic error estimates for all precursor experiment require reliable spin tracking tools, e.g. COSY-INFINITY.
  Top priority to make them available ASAP!
- New collaboration „JEDI“ being formed

Lower limit on electron-cooled SCT from January run

RF-solenoid produces small polarization kicks about longitudinal direction.
(Kicks vary as cosine with maximum < 4 μrad.)
On (1–Gγ) resonance, this produces continuously reversing vertical P_Y.

Set process to turn RF-solenoid ON, OFF, then ON again.



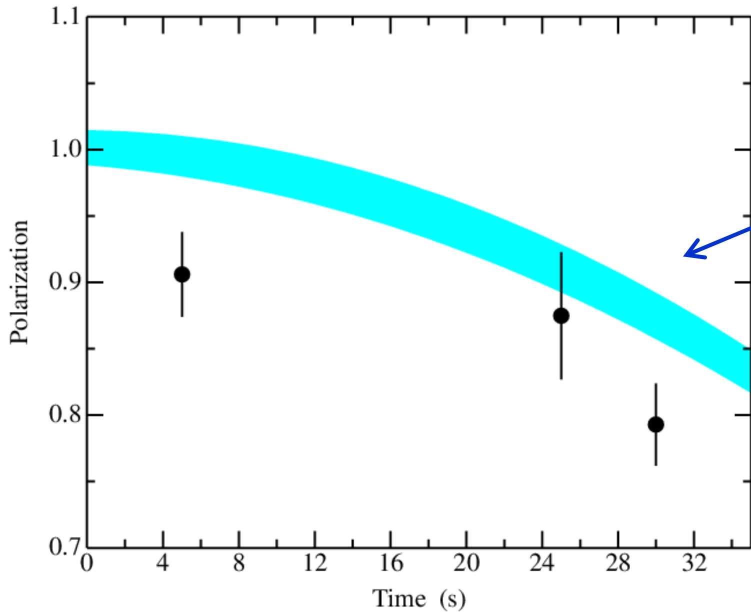
During this time the polarization is in the ring plane and free to decohere.

If oscillation returns, (1) beam is still polarized, and (2) the RF-solenoid was still in phase (thus this is a lower limit).

Lines added to guide the eye.

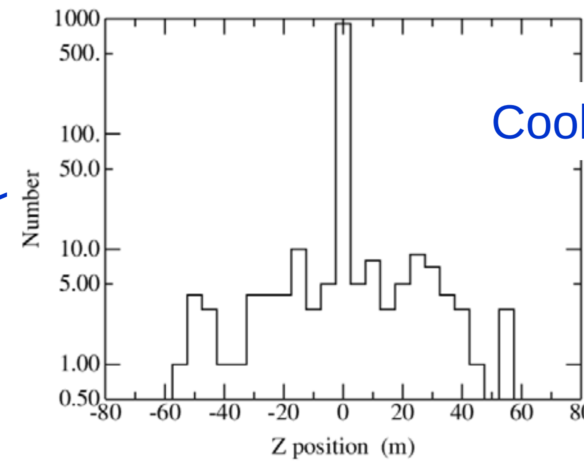
5 s	25 s	5 s
reference oscillation	decoherence time	oscillation capture

3 ON-OFF-ON runs had usable data.



Distribution of synchrotron amplitudes

Cooled



Uncooled