Search for Electric Dipole Moments with Polarized Beams in Storage Rings

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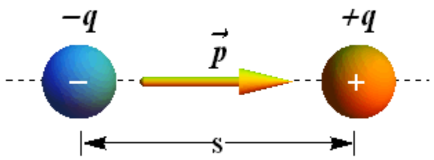
LNS. November 20 th 2013

Electric Dipoles

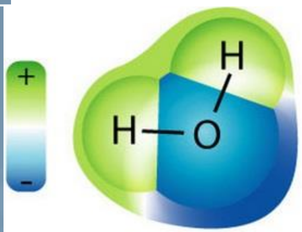
- Definition



$$\vec{p} = q \cdot \vec{s}$$

Charge separation creates an electric dipole

- Orders of magnitude



H_2O molecule: permanent EDM

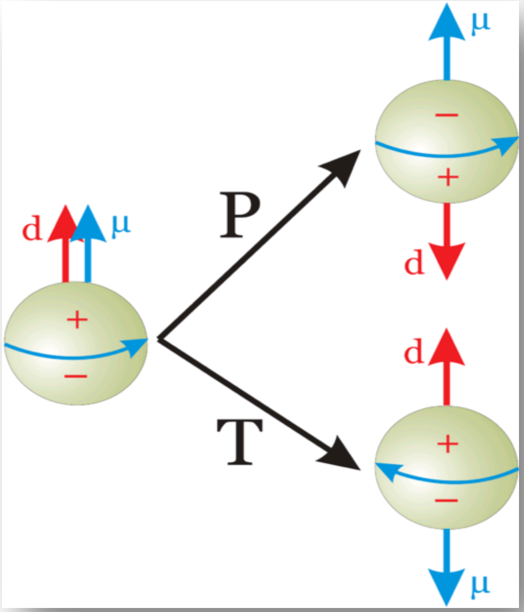
	Atomic physics
Charges	e
$\|r_1-r_2\|$	10^{-8} cm
EDM (naive) exp.	10^{-8} e cm
observed	H_2O molecule $2\cdot10^{-9}$ e cm

EDM of fundamental particles

Molecules have large EDM because of degenerated ground states with different parity

Elementary particles (including hadrons) have a definite partiy and cannot have EDM

Unless P and T reversal are violated



$\vec{\mu}$: magnetic dipole moment
$\vec{d}$: electric dipole moment
(both aligned with spin)

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

Permanent EDMs violate P and T
Assuming CPT to hold, CP violated also

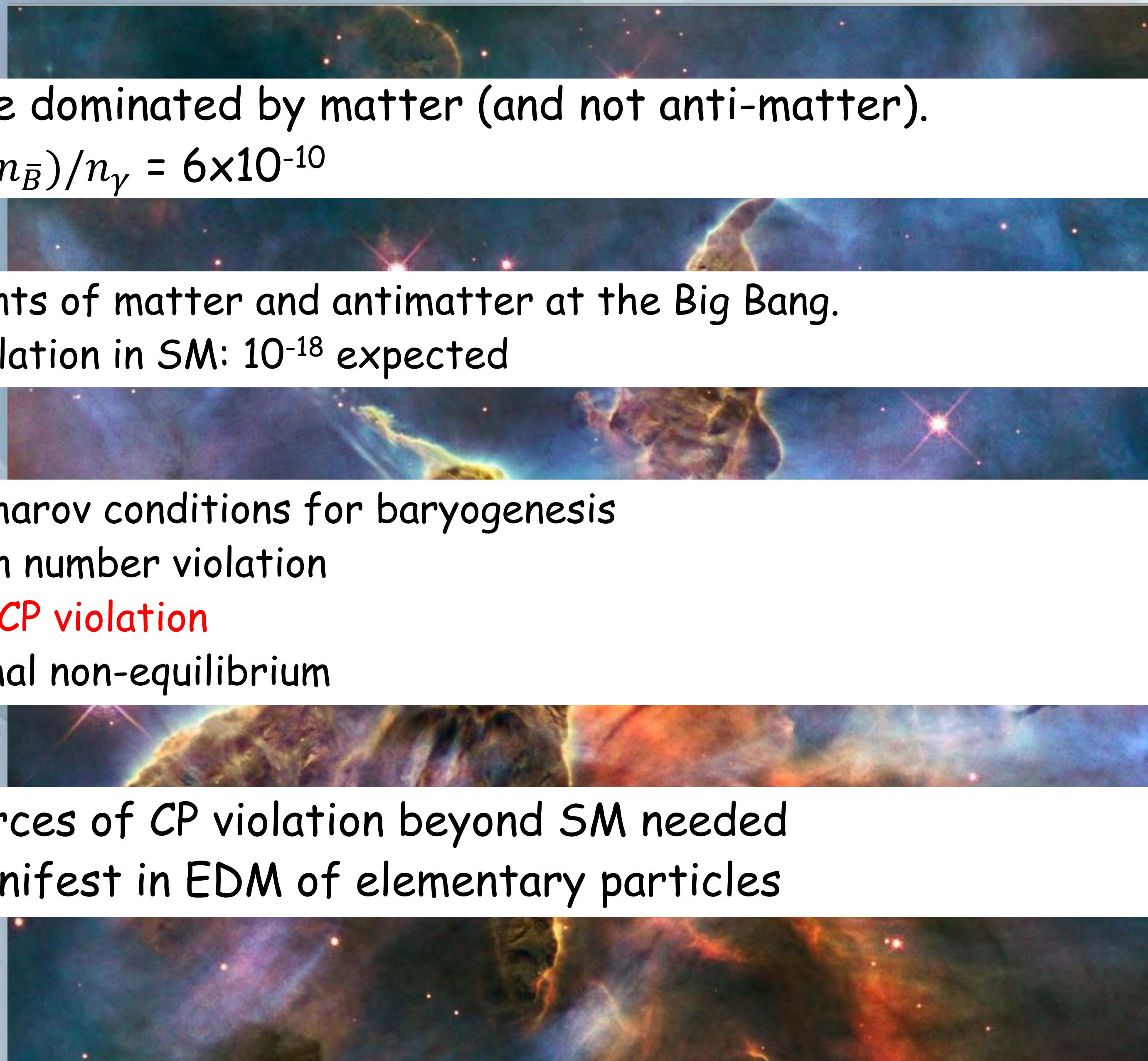
CP violation

- .Universe dominated by matter (and not anti-matter).
  - $(n_B - n_{\bar{B}})/n_\gamma$ = 6×10^{-10}

- Equal emounts of matter and antimatter at the Big Bang.
  - CP violation in SM: 10^{-18} expected

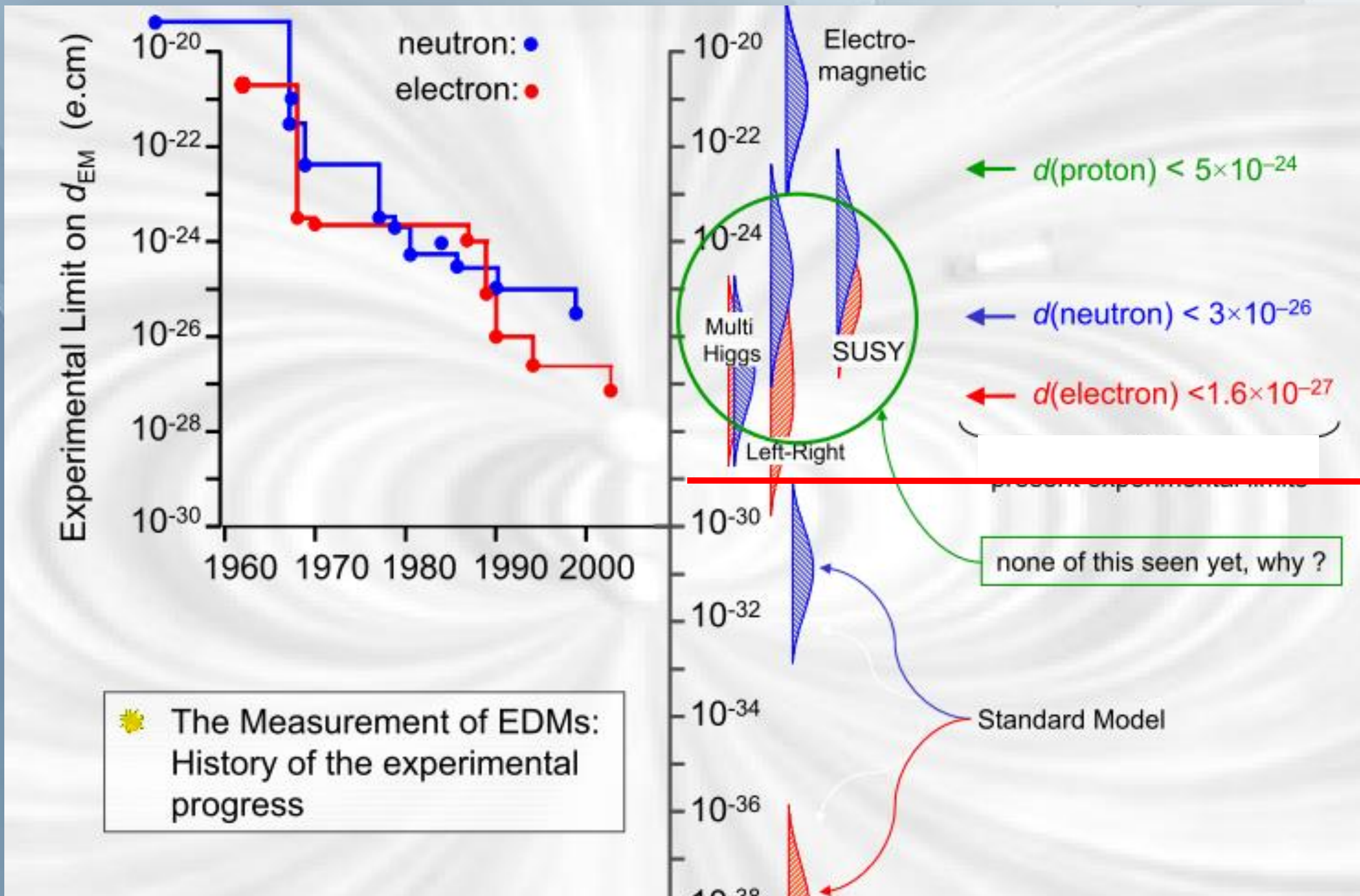
- 1967: 3 Sacharov conditions for baryogenesis
  - Baryon number violation
  - C and CP violation
  - Thermal non-equilibrium

- New sources of CP violation beyond SM needed
- Could manifest in EDM of elementary particles



Carina Nebula (Largest-seen star-birth regions in the galaxy)

Theoretical predictions



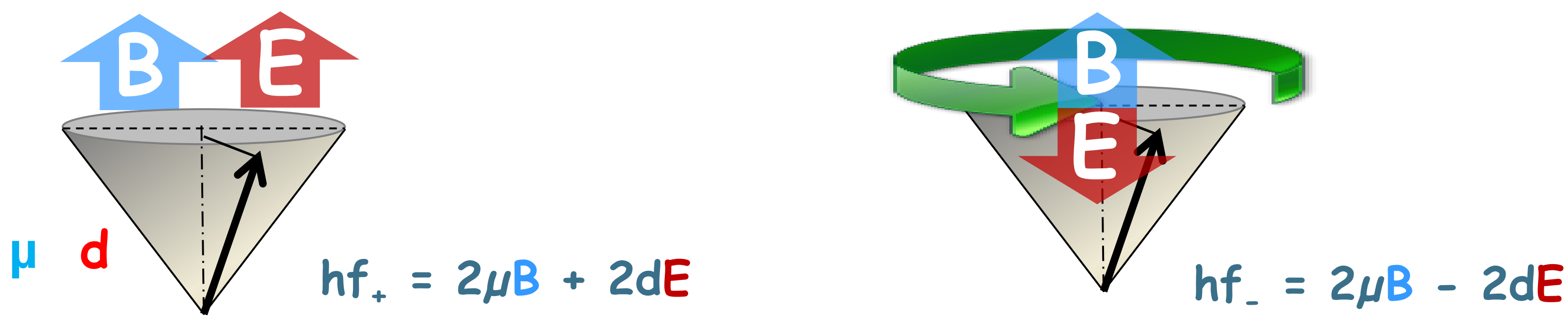
No Standard Model Background!

J.M. Pendlebury: „nEDM has killed more theories than any other single expt.“

EDM searches: state of the art

- EDM searches: only upper limits yet
- E-fields accelerate charged part. → search limited to neutral systems

- „Traditional" approach: precession frequency measurement in B and E fields



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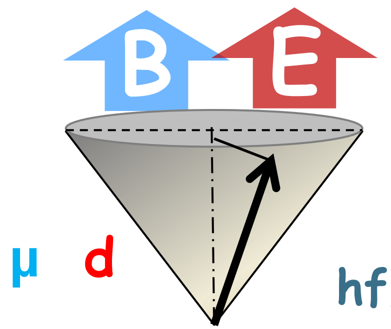
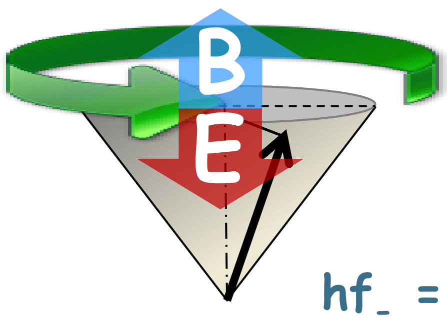


$hf_+ = 2\mu B + 2dE$



$hf_- = 2\mu B - 2dE$

(Till now) two kinds of experiments to measure EDMs:
- Neutrons
- Neutral atoms (paramagnetic/diamagnetic)

No direct measurement of electron or proton EDM yet

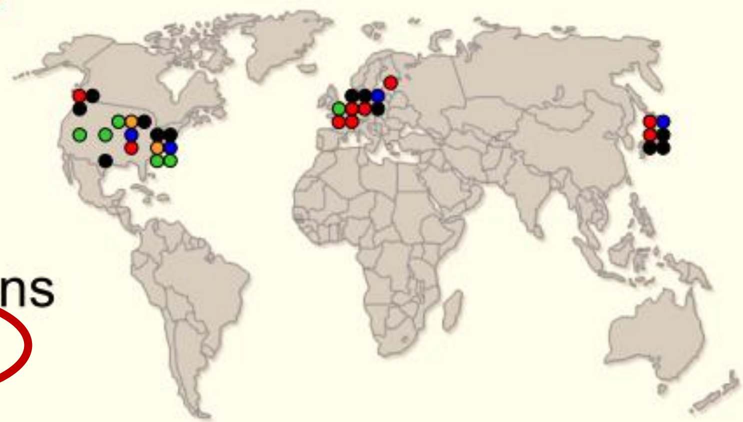
Ongoing/planned Searches

Rough estimate of numbers of researchers, in total ~500 (with some overlap)

- Neutrons ~200
  - @ILL
  - @ILL,@PNPI
  - @PSI
  - @FRM-2
  - @RCNP,@TRIUMF
  - @SNS
  - @J-PARC

- Molecules ~50
  - YbF@Imperial
  - PbO@Yale
  - ThO@Harvard
  - HfF+@JILA
  - WC@UMich
  - PbF@Oklahoma

- Atoms ~100
  - Hg@UWash
  - Xe@Princeton
  - Xe@TokyoTech
  - Xe@TUM
  - Xe@Mainz
  - Cs@Penn
  - Cs@Texas
  - Fr@RCNP/CYRIC
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto



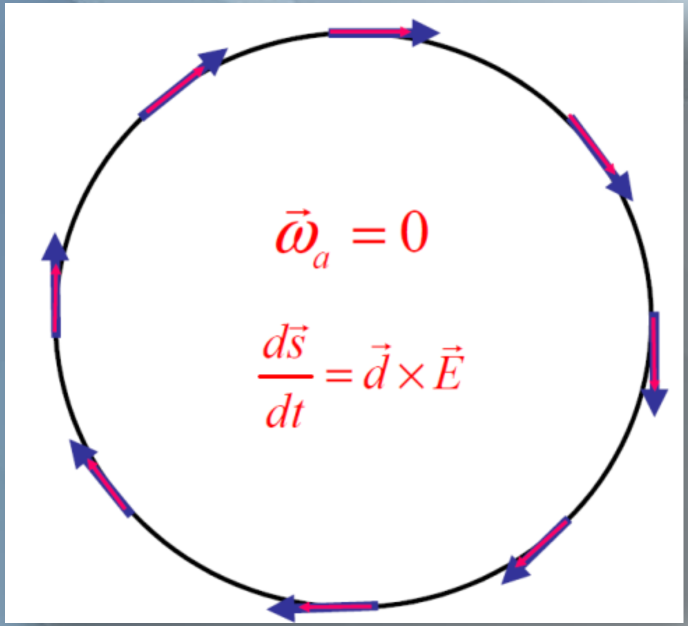
- Ions Muons ~200
  - new @BNL
  - @FZJ
  - @FNAL
  - @JPARC

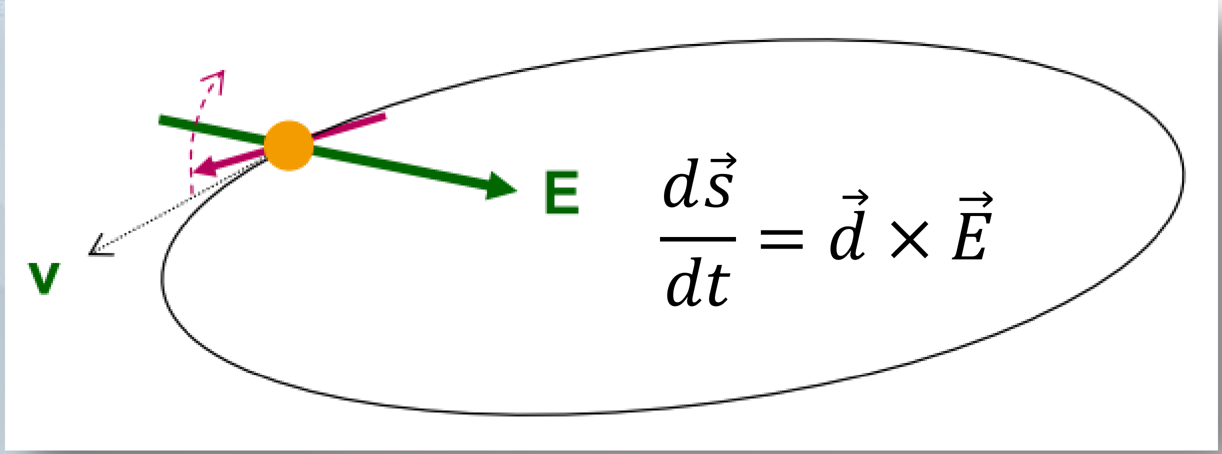
- Solids ~10
  - GGG@Indiana
  - ferroelectrics@Yale

EDM of charged particles: use of storage rings

PROCEDURE

- Place particles in a storage ring
- Align spin along momentum (→freeze horizontal spin precession)
- Search for time development of vertical polarization





Frozen spin method

Spin motion is governed by Thomas-BMT equation:

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

$$\vec{\Omega} = \frac{e\hbar}{mc}[G\vec{B} + \left(G - \frac{1}{\gamma^2-1}\right)\vec{v} \times \vec{E} + \frac{1}{2}\eta(\vec{E} + \vec{v} \times \vec{B})]$$

$$\vec{d} = \eta\frac{e\hbar}{2mc}\vec{S}, \quad \vec{\mu} = 2(G+1)\frac{e\hbar}{2m}\vec{S}, \quad G = \frac{g-2}{2}$$

d: electric dipole moment μ: magnetic dipole moment

Two options to get rid of terms $\propto$ G (magic condition):

1. Pure E ring (works only for G>0, e.g proton):

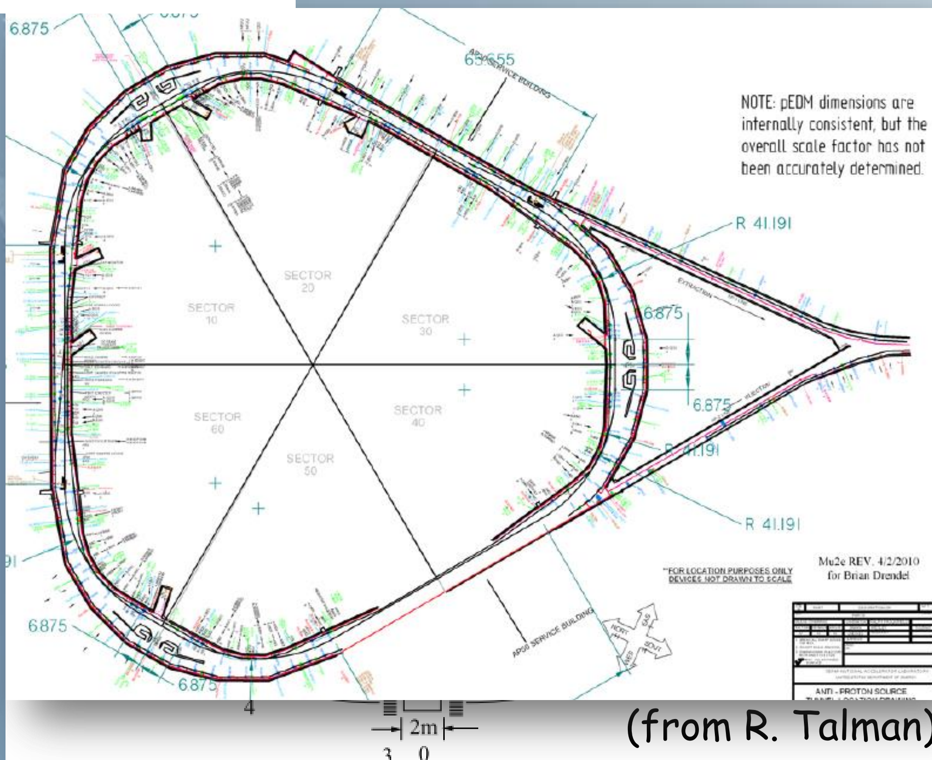
$$\left(G - \frac{1}{\gamma^2 - 1}\right) = 0$$

2. Combined E.B ring (works also for G<0, e.g deuteron)

$$-G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E} = 0$$

Storage ring projects

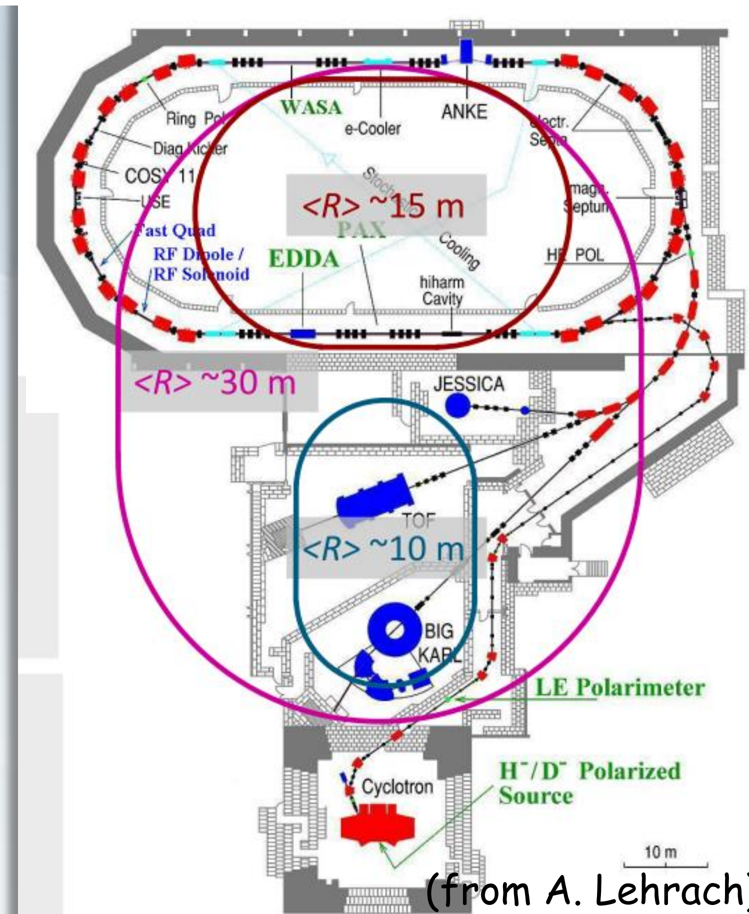
pEDM in all electric ring at BNL
or at FNAL



(from R. Talman)

CW and CCW propagating beams

Jülich, focus on deuterons,
or a combined machine

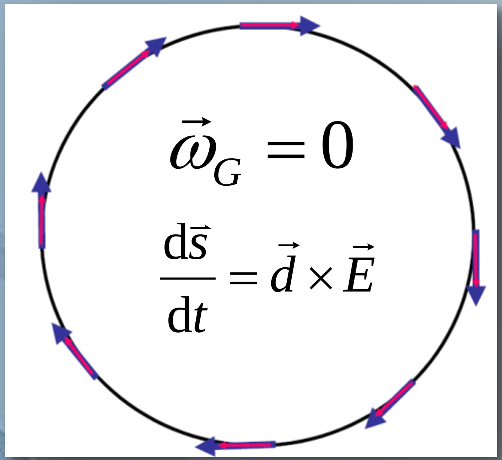


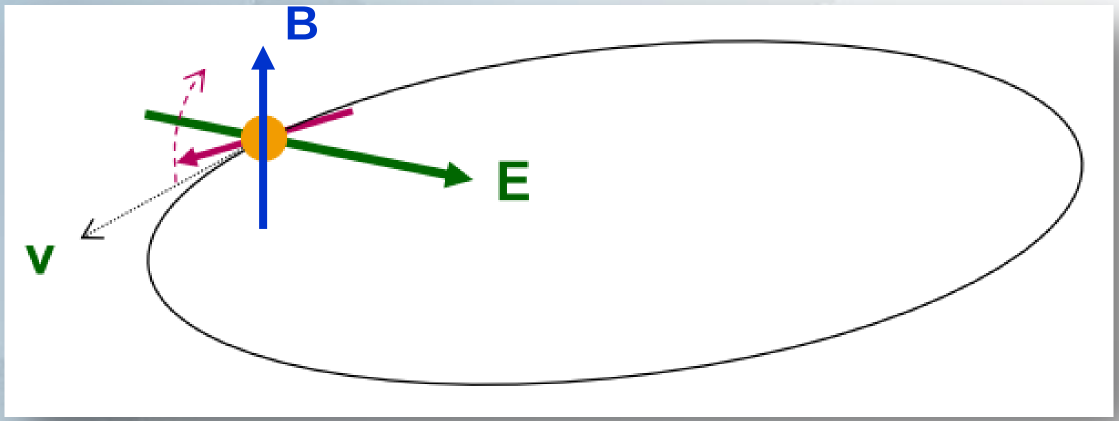
(from A. Lehrach)

Two projects: **US** (BNL or FNAL) and **Europe** (FZJ)

Magic Storage rings

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





Particle	p(GeV/c)	E(MV/m)	B(T)	R(m)
Proton	0.701	16.789	0.000	~ 25

Possible to measure p, d, $^3\mathrm{He}$ using **ONE** machine with $r \sim 30$ m

Statistical sensitivity

$$\sigma \approx \frac{\hbar}{\sqrt{N f T \tau_P P E A}}$$

E	Electric field	10 MV/m
P	Beam polarization	0.8
A	Analyzing power	0.6
N	Particles/cycle	4×10^{7}
F	Detection efficiency	0.005
τ_P	Spin-coherence time	1000 s
T	Running time per year	10^{7} s

- **Sensitivity:** $\sigma = 10^{-29}$ e-cm/year ($\rightarrow 10^{-27}$ e-cm/week)
- **Expected signal:** $3\mathrm{x}10^{-9}$ rad/s for d= 10^{-29} e-cm

Technological challenges

- SYSTEMATIC ERROR PLAN

- PROTON BEAM POSITION MONITORS (<10 nm)

Systematics

- One major source:
  - Radial B_r field mimics EDM effect
  - Example: d = 10^{-29} e cm with E = 10 MV/m
  - If $\mu B_r \approx dE_r$ this corresponds to a magnetic field:

$$B_r = \frac{dE_r}{\mu_N} = \frac{10^{-22}\mathrm{eV}}{3.1 \cdot 10^{-8}\mathrm{eV/T}} \approx 3 \cdot 10^{-17}\mathrm{T}$$

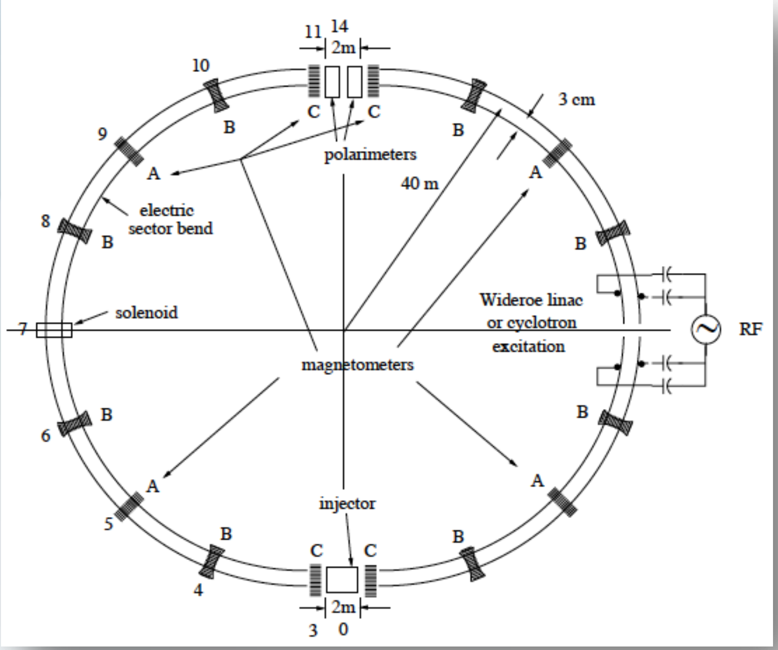
  - (Earth magnetic field = $5 \cdot 10^{-5}$ T)

BNL Proposal: counterpropagating beams

2 beams simultaneously rotating in an all electric ring (cw, ccw)

CW & CCW beams cancels systematic effects

	CW		CCW	
Polarization (P_z)	+	−	+	−
EDM ($\vec{d} \times \vec{E}$)	−	+	+	−
Sokolov-Ternov	−	−	+	+
Gravitation	−	+	−	+



BPM with relative resolution < 10 nm required

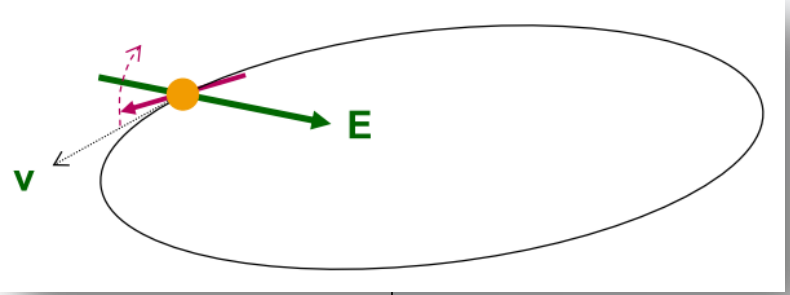
- *use of SQUID magnetomers (fT/√Hz) ? → Study started at FZJ*

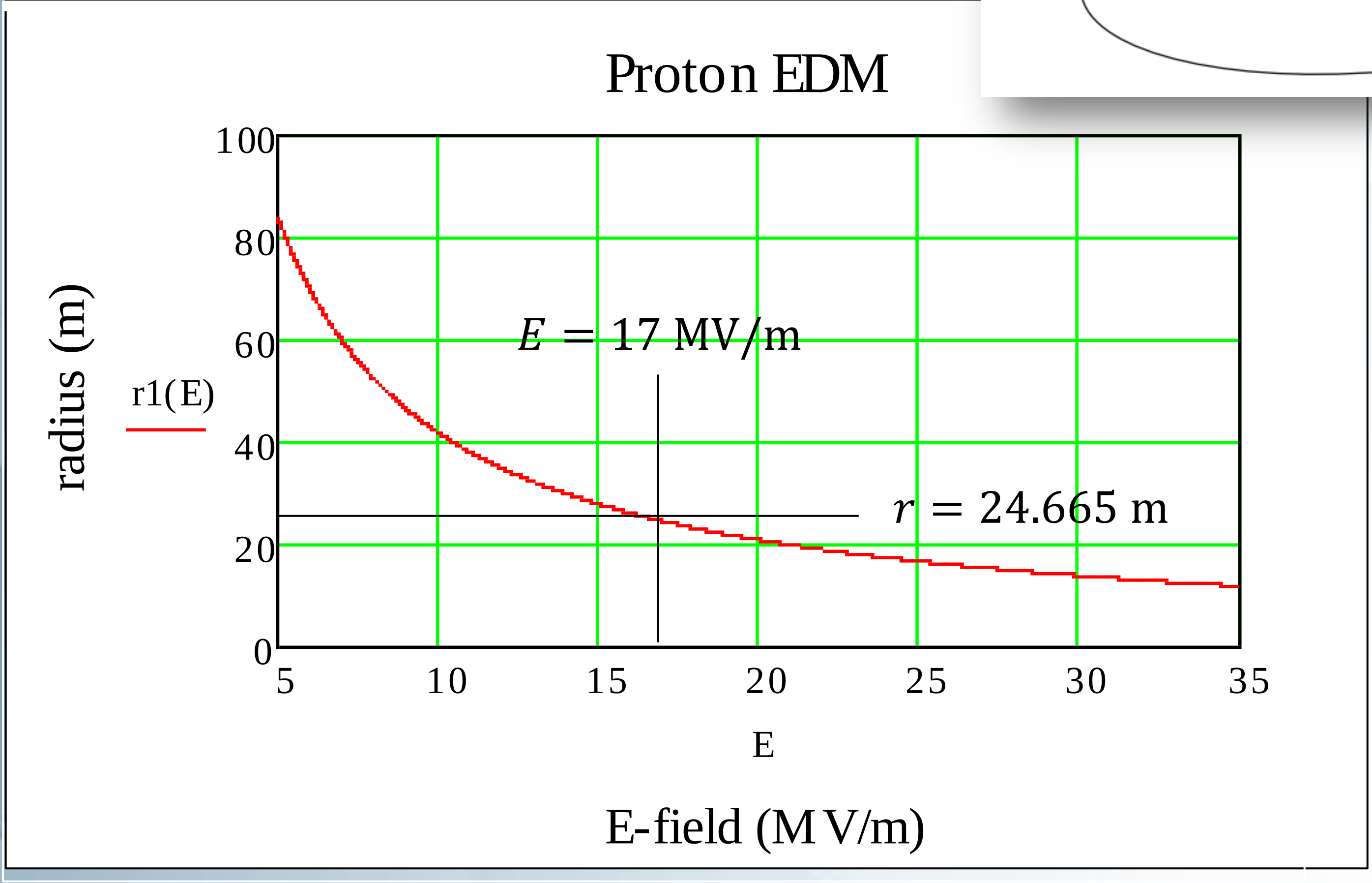
Technological challenges

- SYSTEMATIC ERROR PLAN
- PROTON BEAM POSITION MONITORS (<10 nm)
- ELECTRIC FIELD, as large as practical (no sparks).

Electric field for magic rings

Radial E field only





Challenge to produce large electric fields

Tevatron electrostatic separators

- avoids unwanted $\bar{p}p$ interactions
- electrodes made from Titanium

Routine operation at 1 spark/Year at 6 MV/m (180 kV at 3 cm)

Winter 2013-14: Transfer of separator unit plus equipment from FNAL to Jülich

Development of new electrode materials and surfaces treatment

Technological challenges

- SYSTEMATIC ERROR PLAN

- PROTON BEAM POSITION MONITORS (<10 nm)

- ELECTRIC FIELD, as large as practical (no sparks).

- POLARIMETER
  - The sensitivity to polarization must by large (0.5).
  - The efficiency of using the beam must be high (> 1%).
  - Systematic errors must be managed (< 10^{-6}).

N.P.M. Brantjes et al. NIMA 664, 49 (2012)

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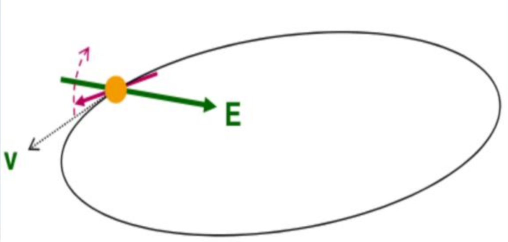
- POLARIZED BEAM
  - Polarization must last a long time (> 1000 s).
  - Polarization must remain parallel to velocity.

EDM buildup time

- Minimal detectable precession $\vartheta \approx 10^{-6}$ rad



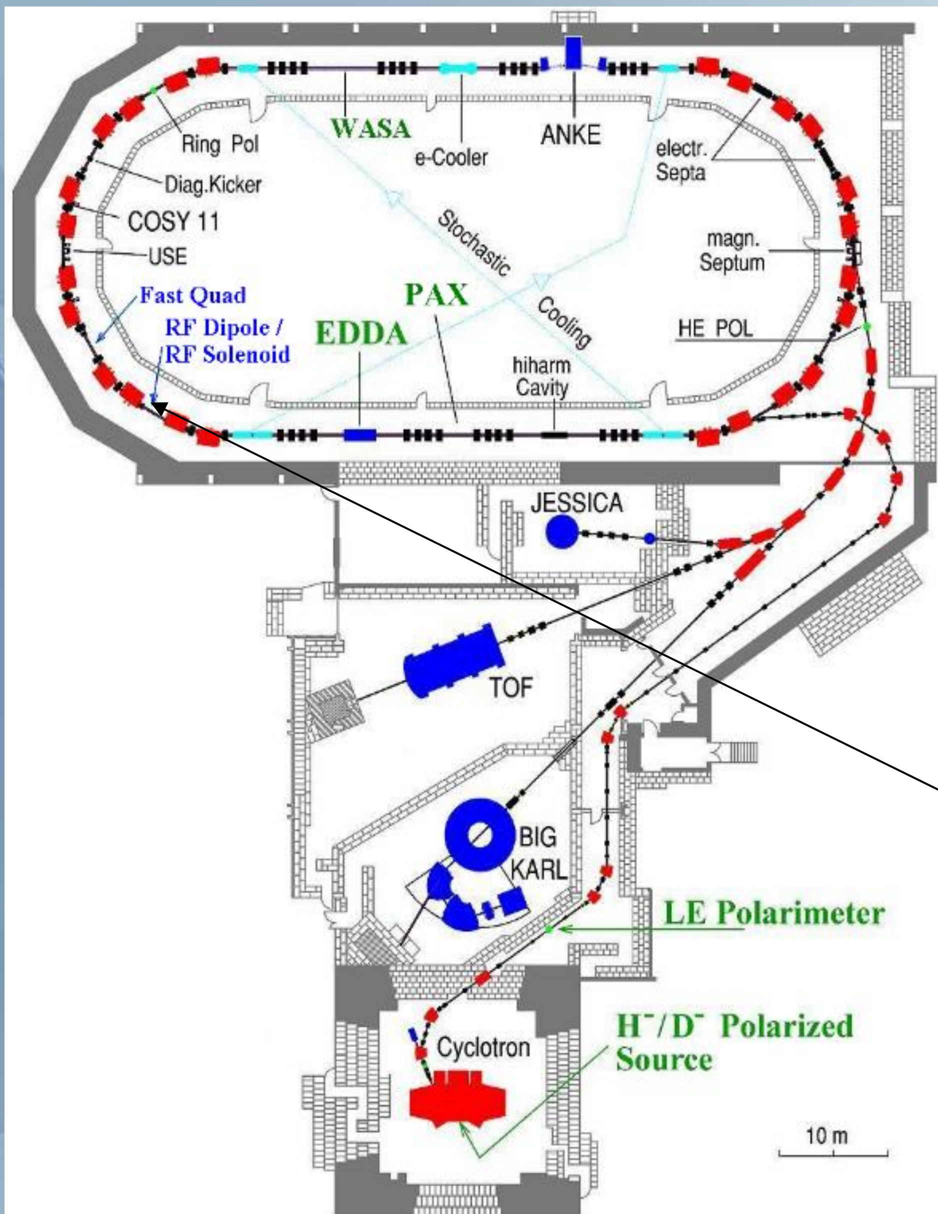
- Assuming $d \approx 10^{-29} e \cdot cm \qquad E = 17 MV/m$

$$\left.\begin{array}{l} \vartheta_{EDM} = \dfrac{2dE}{\hbar} \sim 5 \left(10^{-9}\, {rad}/{s}\right) t \\[2em] 1\ turn \sim 10^{-6}\ s \end{array}\right\} \quad \vartheta_{EDM} \sim \frac{10^{-15} rad}{turn}$$

- 10^9 turns needed to detect EDM signal
- Spin aligned with velocity for t>1000 s (→ *Spin Coherence Time* next slides)

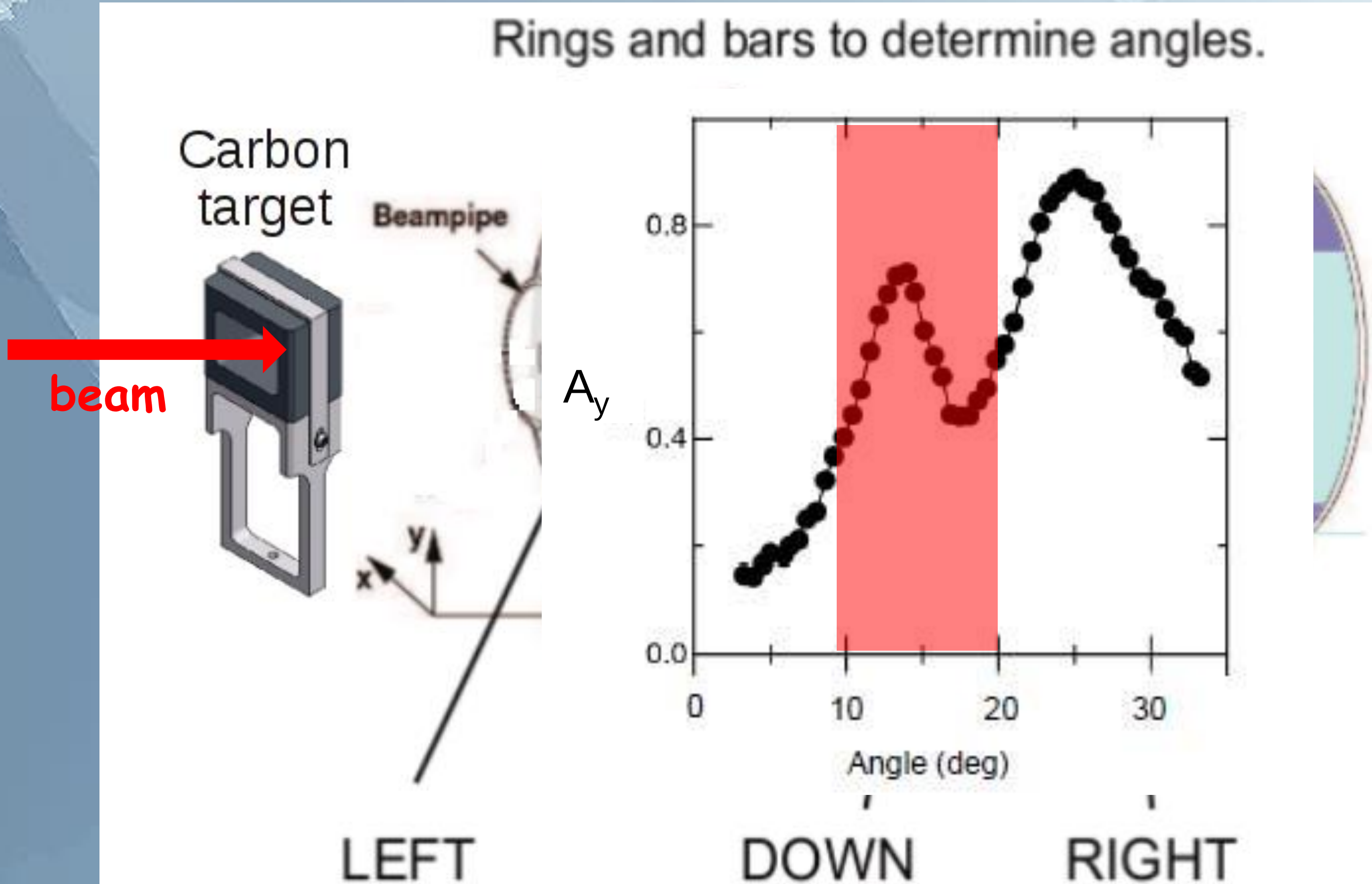
Feasibility studies @ COSY

COoler SYnchrotron (FZ-Jülich, GERMANY)



- Momentum: <3.7 GeV/c
- Circumference: 183 m
- **Polarized** proton and **deuteron**
- **Beam polarimeter (EDDA detector)**
- Instrumentation available for **manipulation** of
  - **beam size** (electron/stochastic cooling, white noise)
  - **polarization** (RF solenoid)

EDDA beam polarimeter



ASYMMETRIES

$$\varepsilon_V = \frac{L-R}{L+R} \propto p_V A_y$$

VERTICAL polarization **Analyzing power**

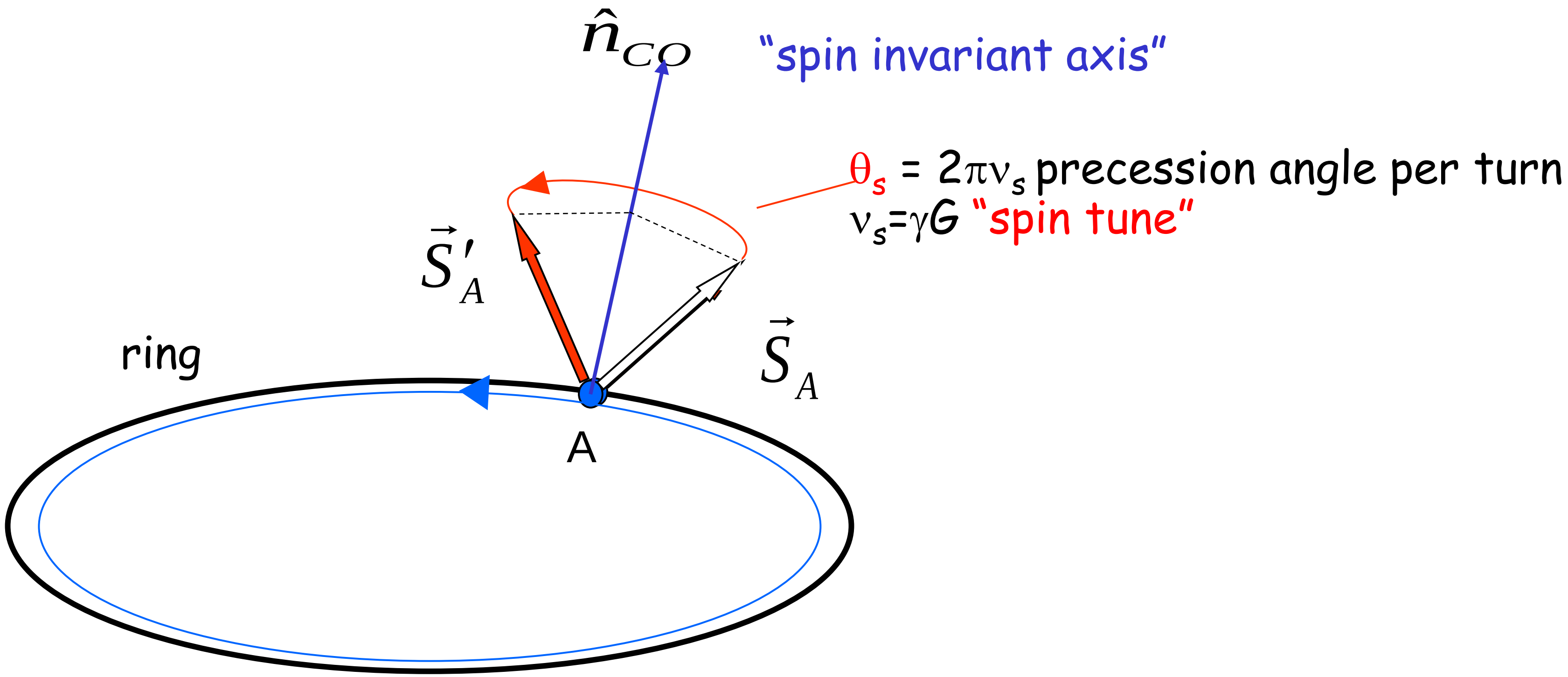
$$\varepsilon_H = \frac{U-D}{U+D} \propto p_H A_x$$

HORIZONTAL polarization **Analyzing power**

- Beam moves toward thick target ⟶ **continuous extraction**
- Elastic scattering (large cross section for d-C)

Spin invariant axis

- one particle with magnetic moment makes one turn

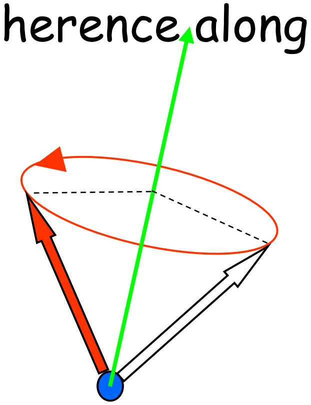


Stable polarization if **S**||**n**$_{co}$

Spin coherence time

- Ensemble of particles circulating in the ring

- Spin coherence along $\hat{n}_{co}$ is not an issue



At injection all
spin vectors aligned (coherent)

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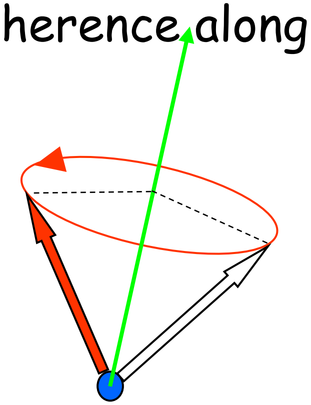

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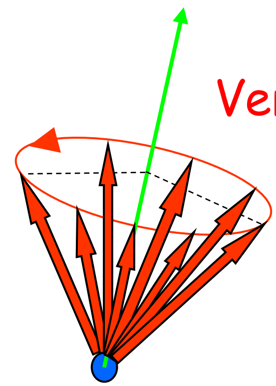
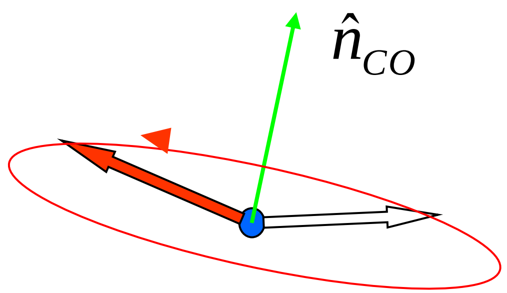


Vertical polarization not affected

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

- For $\vec{S} \perp \hat{n}_{co}$ (machines with frozen spin) the situation is different



At injection all spin vectors aligned

In EDM machine observation time is limited by SCT.

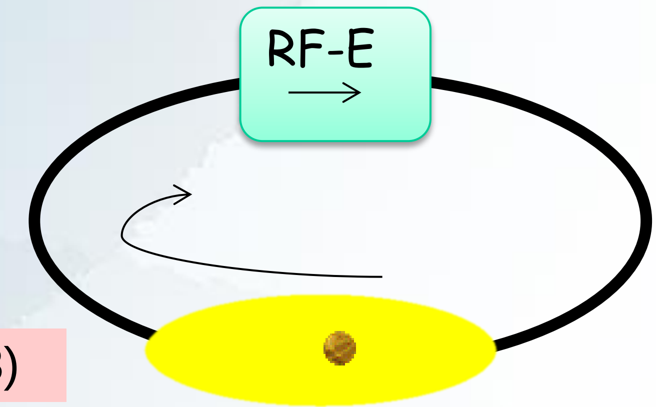
Decoherence: where does it arise?

LONGITUDINAL PHASE SPACE
Problem: beam momentum spread ($\Delta p/p \neq 0 \rightarrow \Delta \nu_s/\nu_s \neq 0$)

- *E.g.* $\Delta p/p = 1 \cdot 10^{-4} \rightarrow \Delta \nu_s/\nu_s = 2.1 \times 10^{-5} \rightarrow \tau_{pol} = 63$ *ms*

Solution: use of bunched beam ($\langle \Delta p/p \rangle = 0$)

P. Benati et al. Phys. Rev. ST, 049901 (2013)



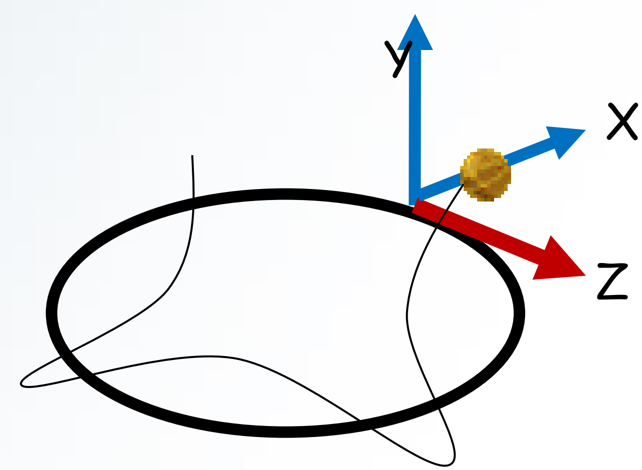
TRANSVERSE PHASE SPACE
Problem: beam emittance $\neq 0 \rightarrow$ betatron oscillations

Δx (Δy) from reference orbit

$\rightarrow$ Longer path: $$\frac{\Delta L}{L_0} = \frac{\vartheta_x^2 + \vartheta_y^2}{4}$$

$\rightarrow$ Higher particle speed $\rightarrow \Delta \nu_s$

- *E.g.* $\theta = 1 \cdot$ *mrad* $\rightarrow \tau_{pol} = 9.9$ *s*



Possible solution to this problem investigated at COSY

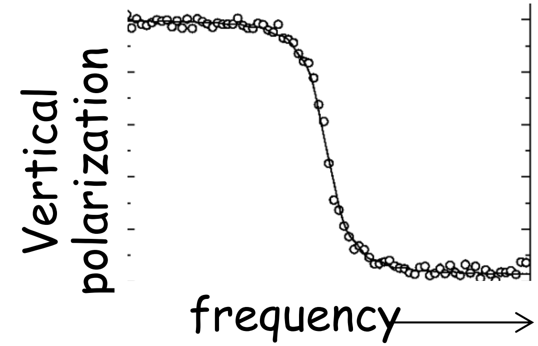
Preparing a longitudinal polarized beam with RF-solenoid

1) Froissart-Stora scan

Identification spin resonance frequency

$$f_{RES} = (1 - G\gamma) f_{CYC} \simeq 871434 \text{ Hz}$$

$\Delta f = 400$ linear ramping in 40 s

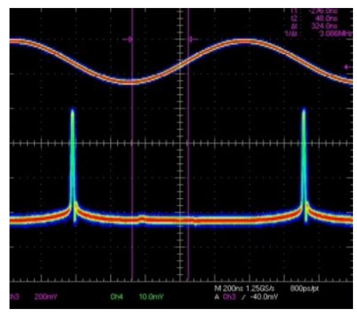


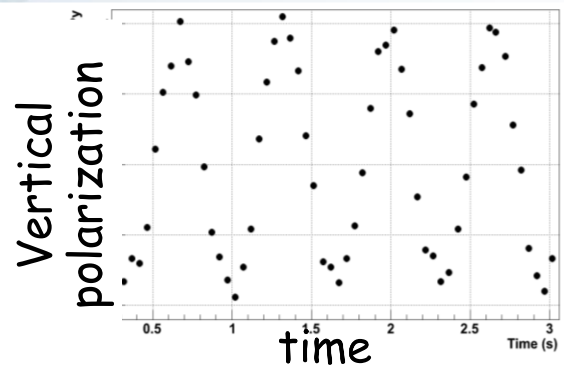
(L-R asymmetry)

2) Fixed frequency measurements

On resonance

COOLED BEAM



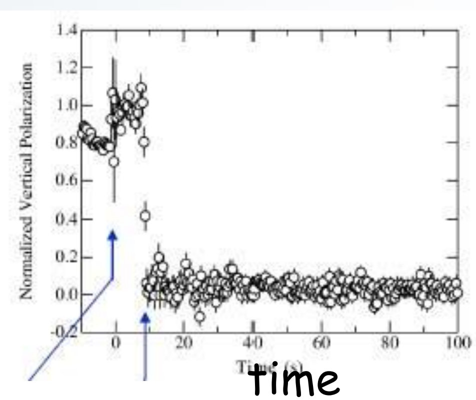


(L-R asymmetry)

3) Solenoid on for half-cycle

Vertical polarization = 0

Polarization is horizontal

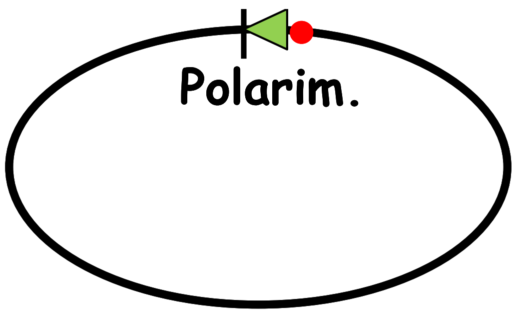


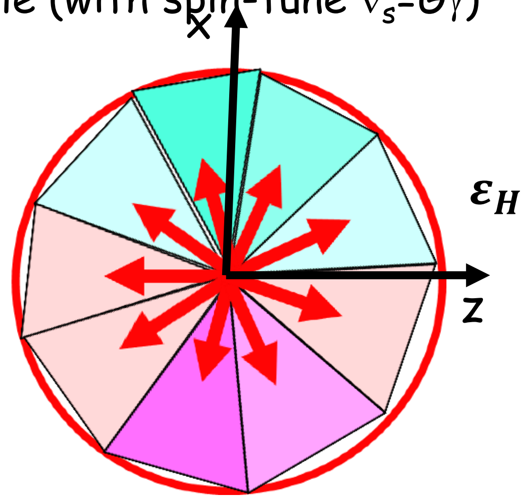
(L-R asymmetry)

Polarimetry of precessing horizontal polarization

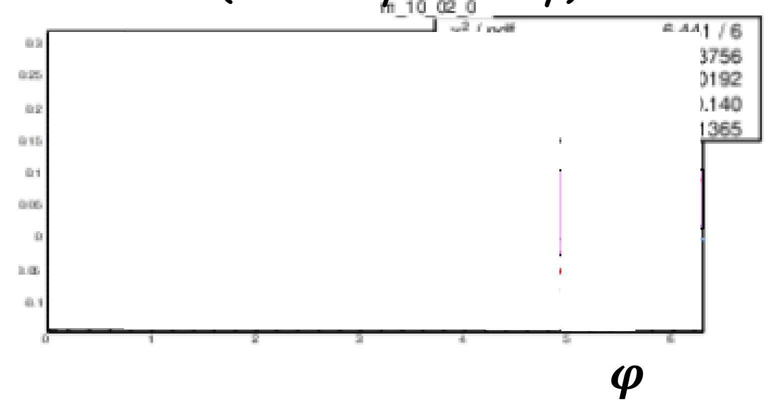
No frozen spin: polarization rotates in the horizonthal plane at 120 kHz

- DAQ synchronized with cyclotrhon freqyency -> count turn number N
- Compute total spin-precession angle (with spin-tune ν_s=$G\gamma$)
- Bin by phase around the circle
- Compute asymmetry in each bin

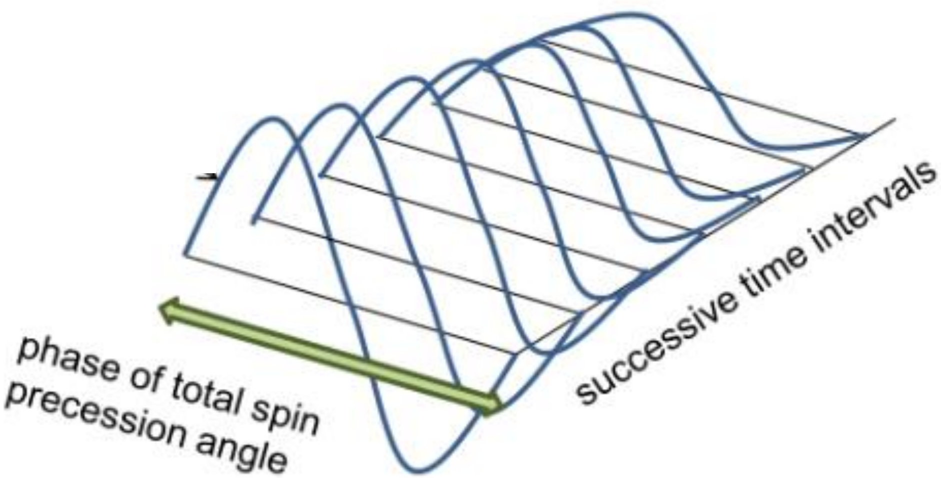




(U-D asymmetry)



- Derivation of horizontal spin coherence time

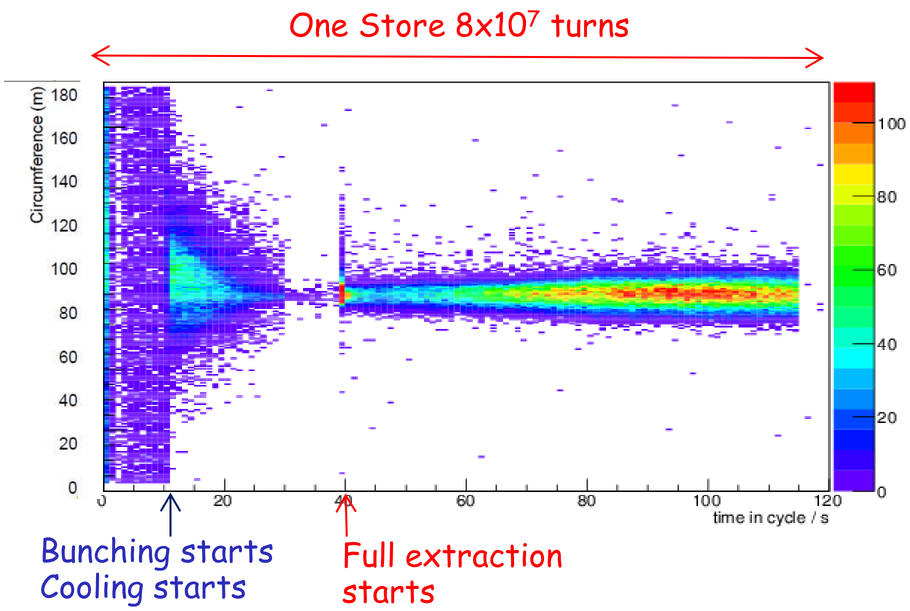


Spin coherence time extracted from numerical fit

Performance

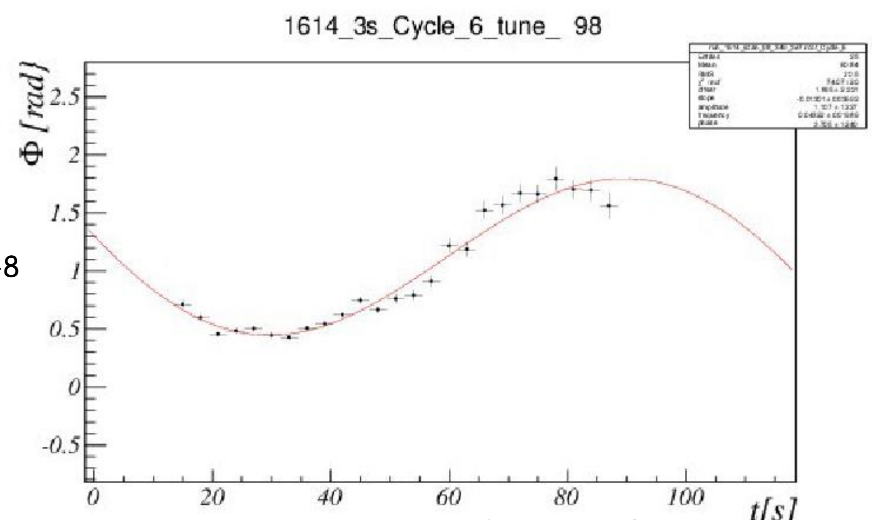
Time stamp system

COSY orbit = 183 m



Spin-tune and machine stability

- Phase over time can be tracked with precision ~ 10^{-8}
- Stability of the ring magnets < 2×10^{-7}



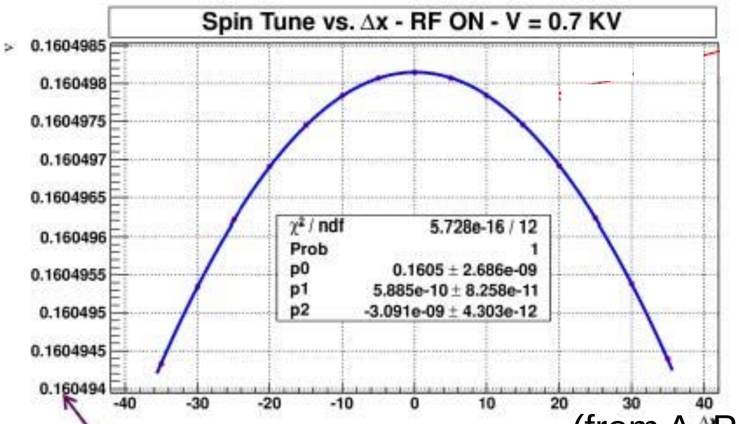
from Dennis Eversmann

Beam emittance studies

Beam preparation

- Pol. Bunched deuteron beam at p=0.97 GeV/c
- Preparation of beam by electron cooling.
- Selective increase of horizontal emittance
    - Heating through white noise

Quadratic dependence of spin tune on size of horizonthal betatron oscillation



(from A. Pesce)

Simulations (COSY Infinity)

Beam emittance affects spin-coherence time

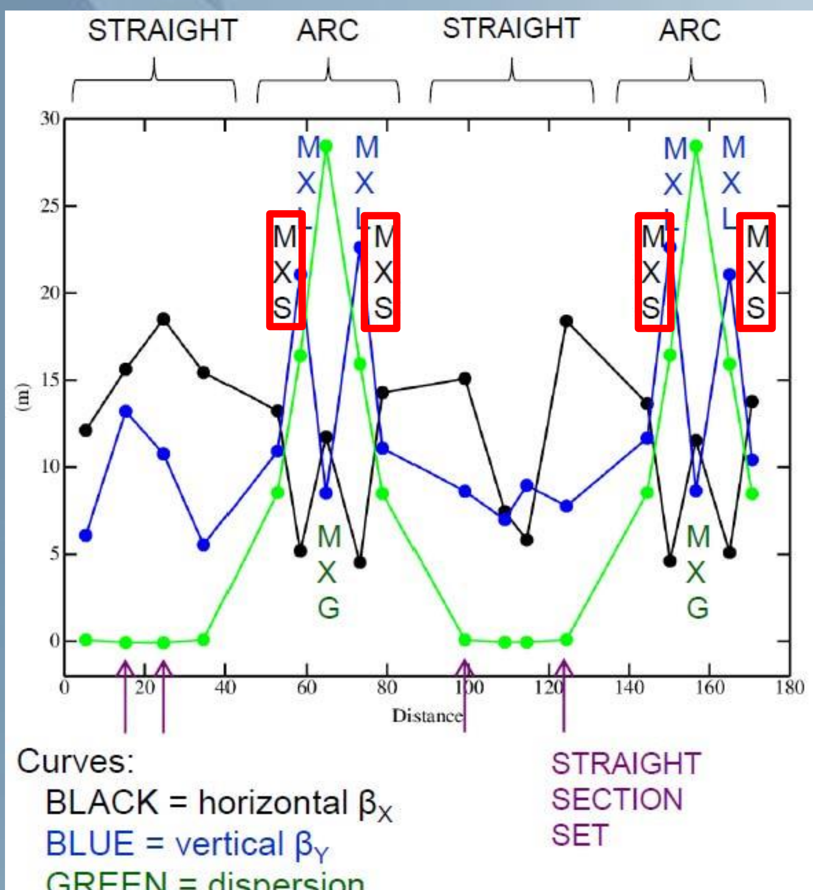
Lengthening the SCT by COSY sextupoles

6-pole field: $B = kx^2$ ⟶ Particle orbit correction ⟶ Spin tune spread correction

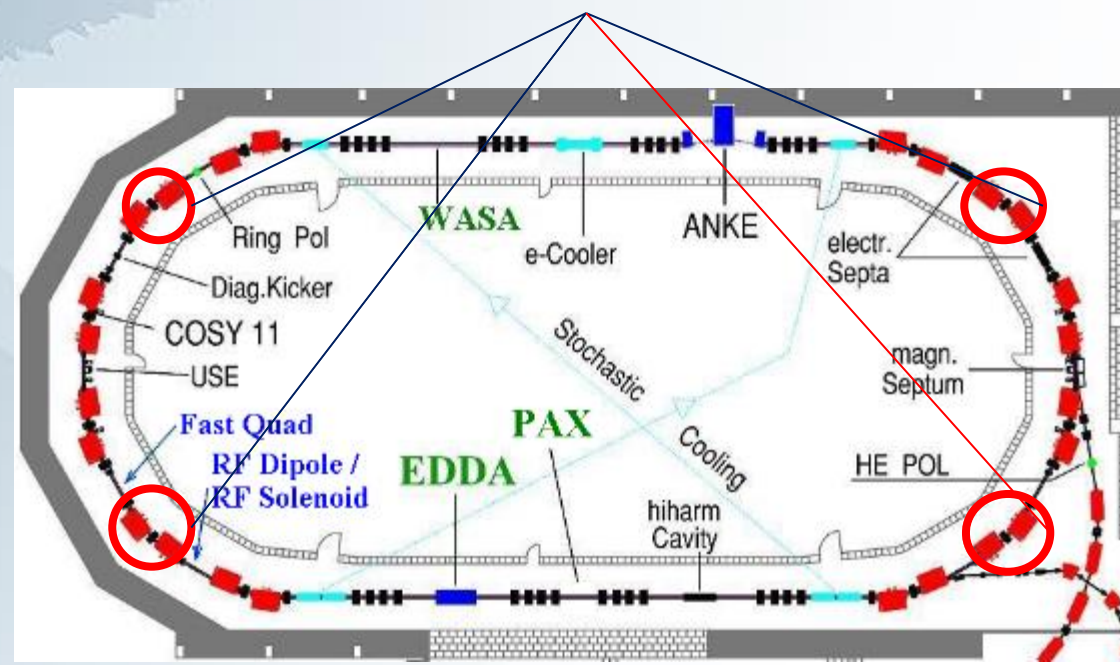
$$\frac{\Delta L}{L_0} = \frac{\vartheta_x^2 + \vartheta_y^2}{4}$$

$$\Delta\nu_s = G\Delta\gamma$$

Use of 6-poles where β_x function is maximal



Sextupoles at β_x max



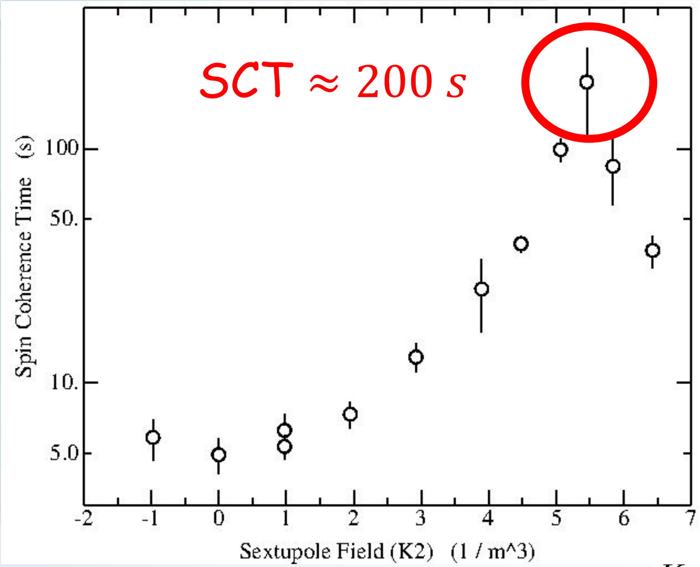
Results

Compensation by means of 6-pole fields:

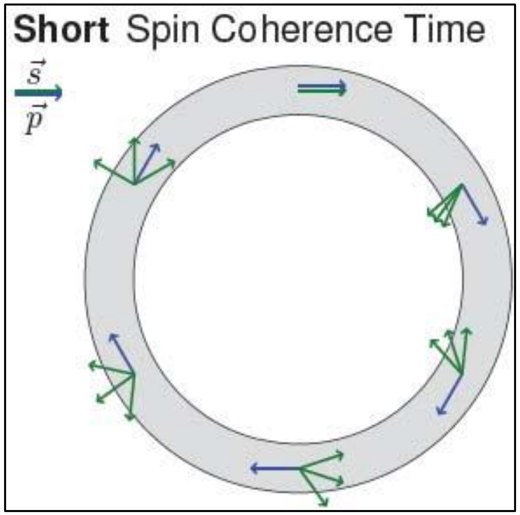
$1/\tau_{SCT} = A\langle\theta^2_x\rangle + a\langle\theta^2_x\rangle$

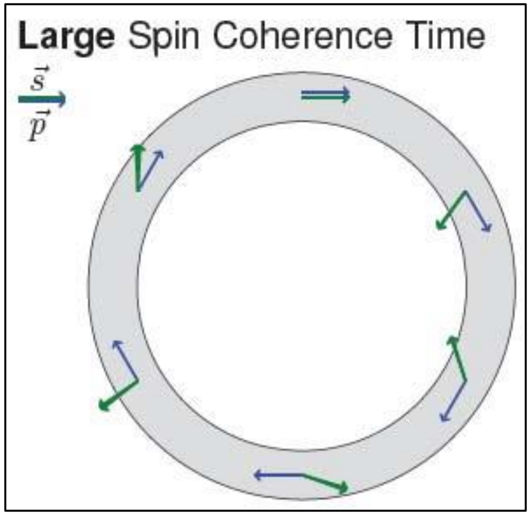
A = original effect
a = sextupole effect

Choose a= -A



$$K_2 = \frac{1}{B\rho}\frac{\partial^2 B}{\partial x^2}$$





- 10^9 particles synchronously precessing for > 2×10^8 revolutions!
- Previous best 10^7 @ Novosibirsk

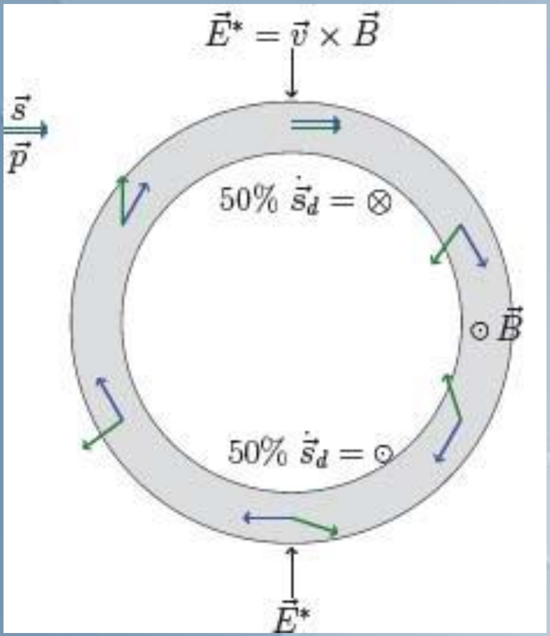
MILESTONE FOR THE FIELD!

Sextupole fields can be used to increase τ_{SCT}!

APPENDIX: Precursor experiments RF methods

$$\vec{\Omega} = \frac{e\hbar}{mc}\left(G\vec{B} + \frac{1}{2}\eta\vec{v}\times\vec{B}\right)$$

Pure magnetic ring (existing machines)



Problem: precession caused by magnetic moment:.
- 50 % of time longitudinal polarization || to momentum
- 50 % of time is anti-||

E* in particle rest frame tilts spin (due to EDM) up and down

→ No net EDM effect

APPENDIX: Precursor experiments RF methods

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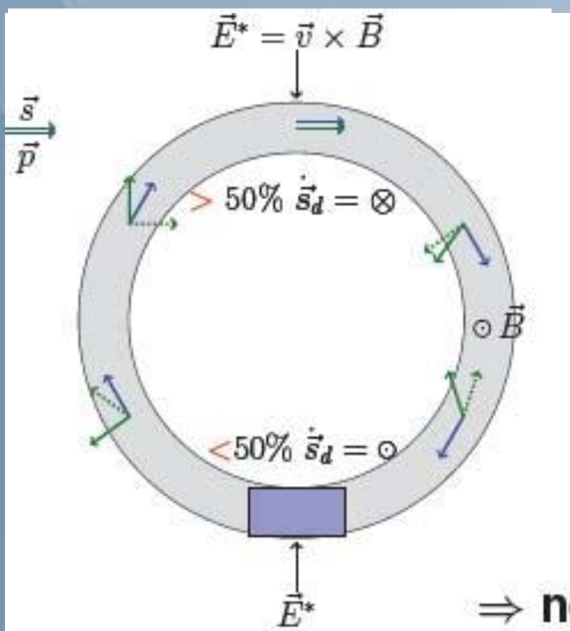
Pure magnetic ring (existing machines)



Solution; use of resonant „magic" Wien-filter in ring (E+vxB=0)

E*=0 → particle trajectory not affected
B*≠0 → magnetic moment is influenced

→ net EDM effect can be observed!
→ No net EDM effect

Principle: make spin prec. in machine resonant with orbit motion

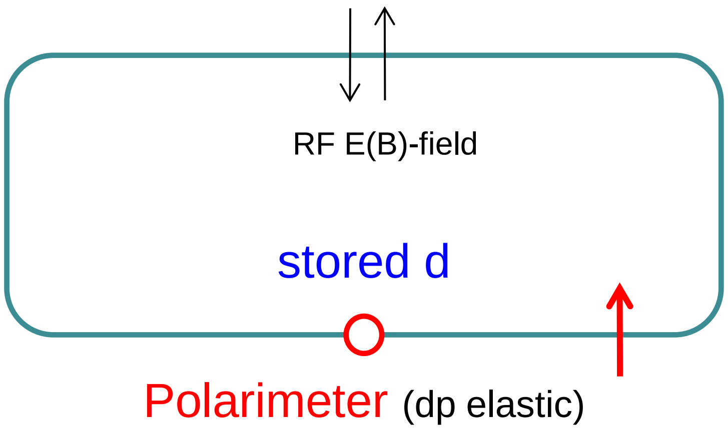
Two ways:

1. Use of RF device operating at some harmonics of the spin prec. frequency
2. Ring operation on an imperfection resonance

Resonance Method with „magic" RF Wien filter

- Avoids coherent betatron oscillations of beam. .
- First direct measurement at COSY.

$\boldsymbol{E}^* = \mathbf{0} \Rightarrow \boldsymbol{E}_{\boldsymbol{R}} = -\beta \times \boldsymbol{B}_{\boldsymbol{y}}$ „Magic RF Wien Filter" no Lorentz force



- In plane polarization
- P_y buildup during spin coherence time

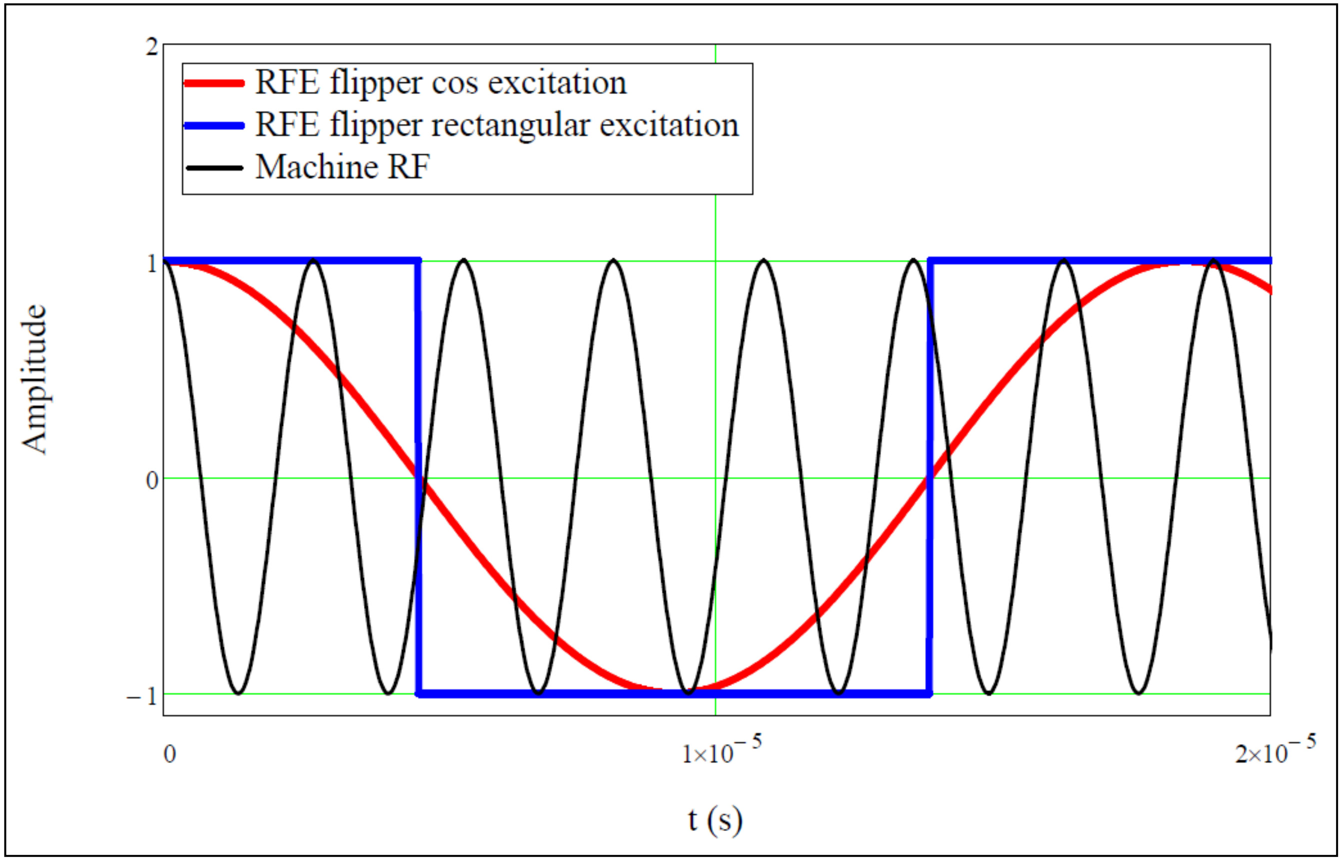
Statistical sensitivity for d_d in 10^{-23} to 10^{-24} $e{\cdot}cm$ range possible.

- Alignment and field stability of ring magnets
- Imperfection of RF-E(B) flipper

Operation of „magic" RF Wien filter

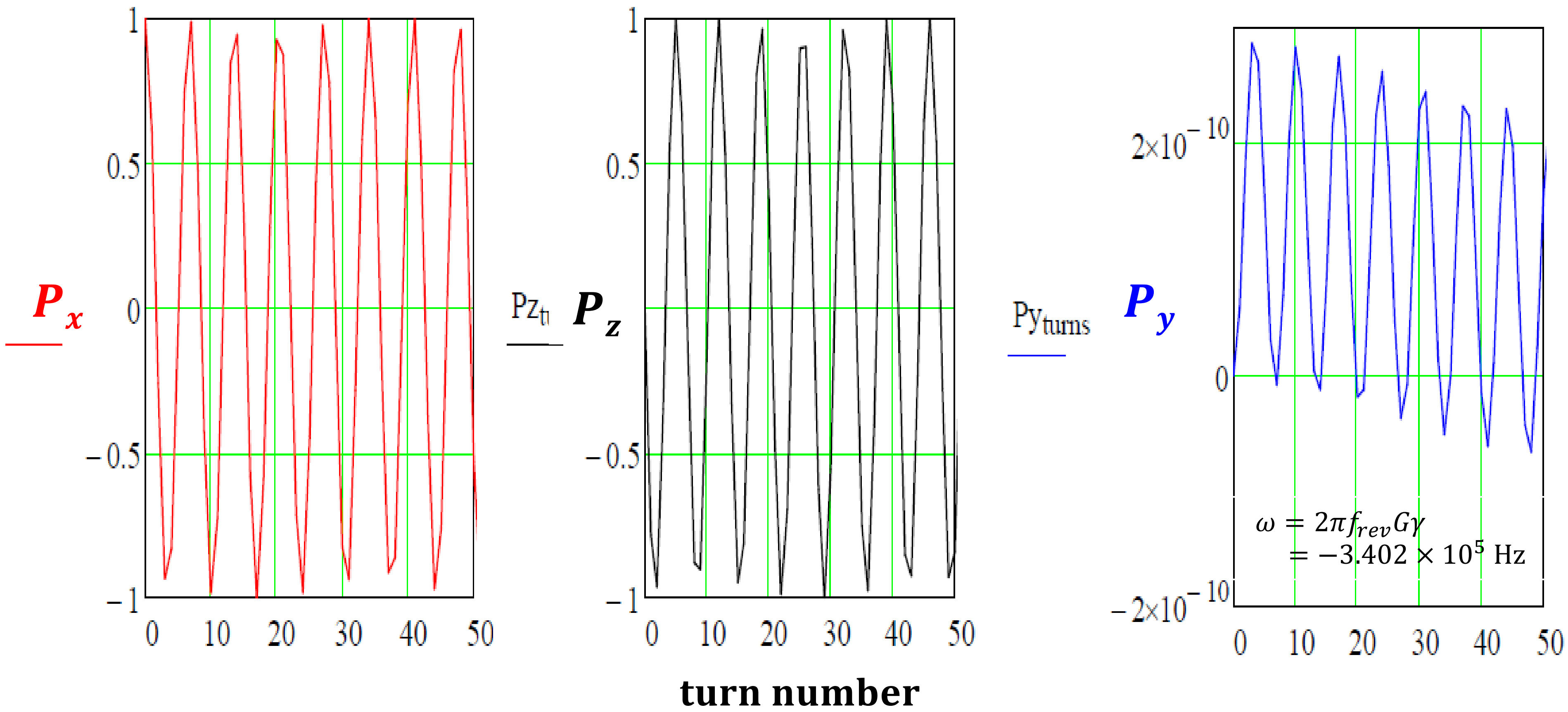
Radial E and vertical B fields oscillate, e.g., with
$f_{HV} = (K + G\gamma) \cdot f_{\mathrm{rev}} = -54.151 \times 10^3\ \mathrm{Hz}$ (here $K = 0$).

beam energy
$T_d = 50\ \mathrm{MeV}$



Resonance Method for deuterons at COSY

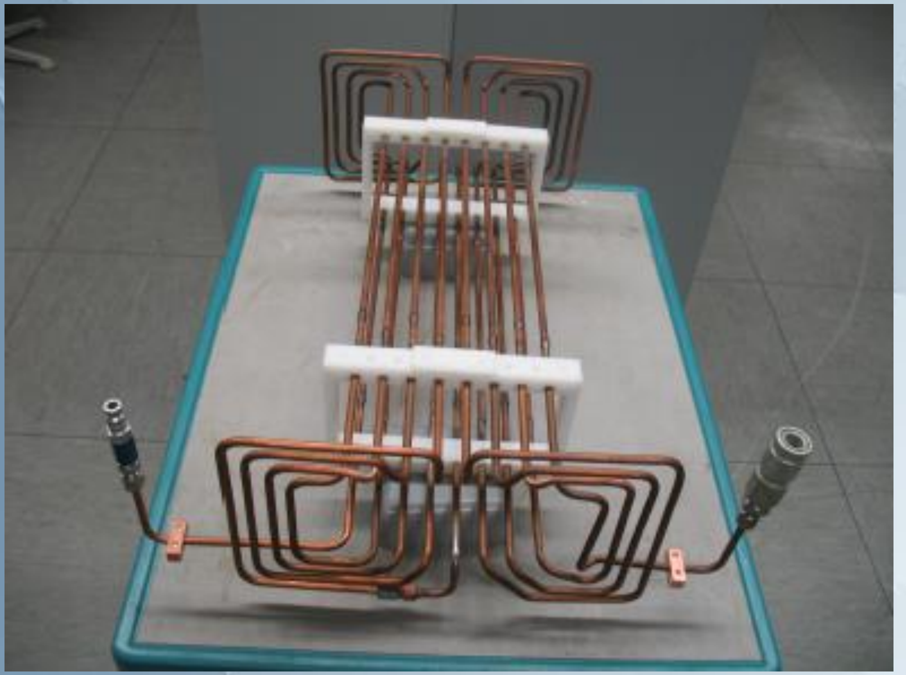
Parameters:	beam energy	$T_d = 50\ MeV$	$L_{RF} = 1\ m$
	assumed EDM	$d_d = 10^{-24}\ e{\cdot}cm$	
	E-field	$30\ kV/cm$	



EDM effect accumulates in P_y

Development: RF E/B-Flipper (RF Wien Filter)

1. Upgrade test flipper with electrostatic field plates (end of year).
2. Build lower power version using a stripline system
3. Build high-power version of stripline system ($E > 100\ \mathbf{kV/m}$)



Work by S. Mey, R. Gebel (Jülich)
J. Slim, D. Hölscher (IHF RWTH Aachen)

Conclusions

- Non-zero EDM within the actual experimental limits clear probe of new physics
- Pol. beam in S. R. might pave the way to direct measurement of EDM of ch. particles.
- Challenges willl stimulate development in Storage Ring technology.

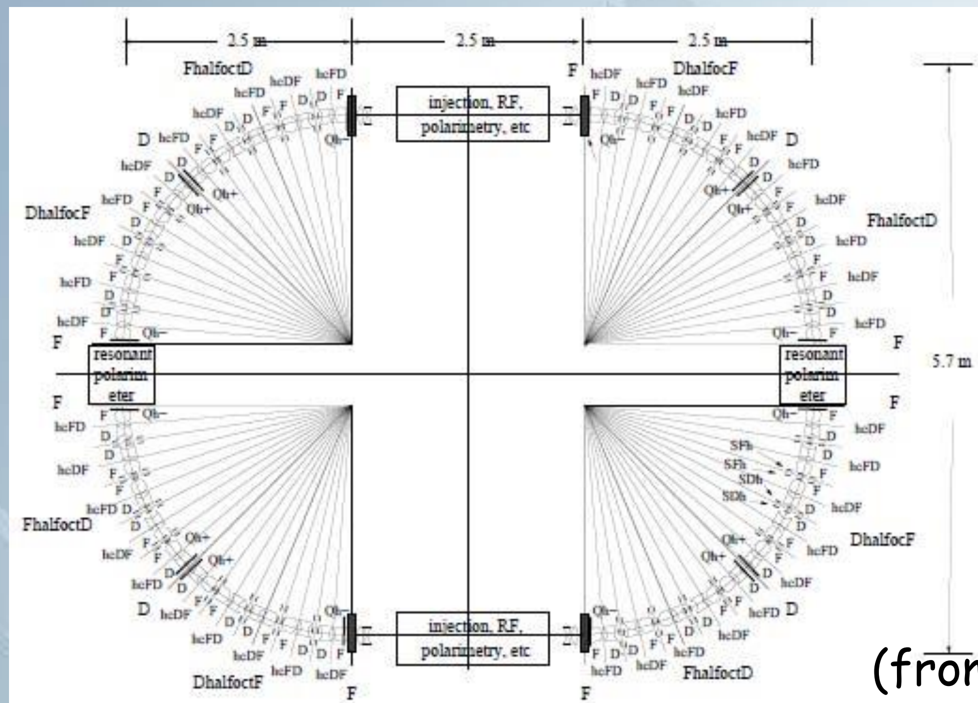
- At the COSY ring dedicated feasibility tests are underway.
- SCT studies on a real machine
  - Emittance affects SCT of the stored beam.
  - Sextupole field can be effectively used to increase SCT.
  - Next step:
    - Compensation of $(\langle \Delta P/P \rangle)^2$ with the same principle

- The way to a Storage Ring EDM:
  - Precursor experiment
  - (Prototype electron ring?)
  - Proton/deutern storage ring

- *P.S. A srEDM experiment is realatively cheap….*

All electric electron-EDM storage ring

- Magic energy for electron: 14.5 MeV (γ=29.4)
- E = 6 MeV/m $\rightarrow$ R = 2.5 m



(from R. Talman)

Note:

- Electron $\rightarrow \mu_e$ = 5.788 x 10^{-5} eV/T G_e=0.001159 $\rightarrow \frac{G_e \mu_e}{\hbar}$ =1.020 x$10^8 s^{-1}$/T
- Proton $\rightarrow \mu_p$ = 3.152 x 10^{-8} eV/T G_p=1.792 $\rightarrow \frac{G_p \mu_p}{\hbar}$ =0.859 x$10^8 s^{-1}$/T

Almost same precession frequency in magnetic field

Issue: polarimetry?

Georg Christoph Lichtenberg (1742-1799)

"Man muß etwas Neues machen, um etwas Neues zu sehen."

"Devi creare qualcosa di nuovo se vuoi vedere qualcosa di nuovo"

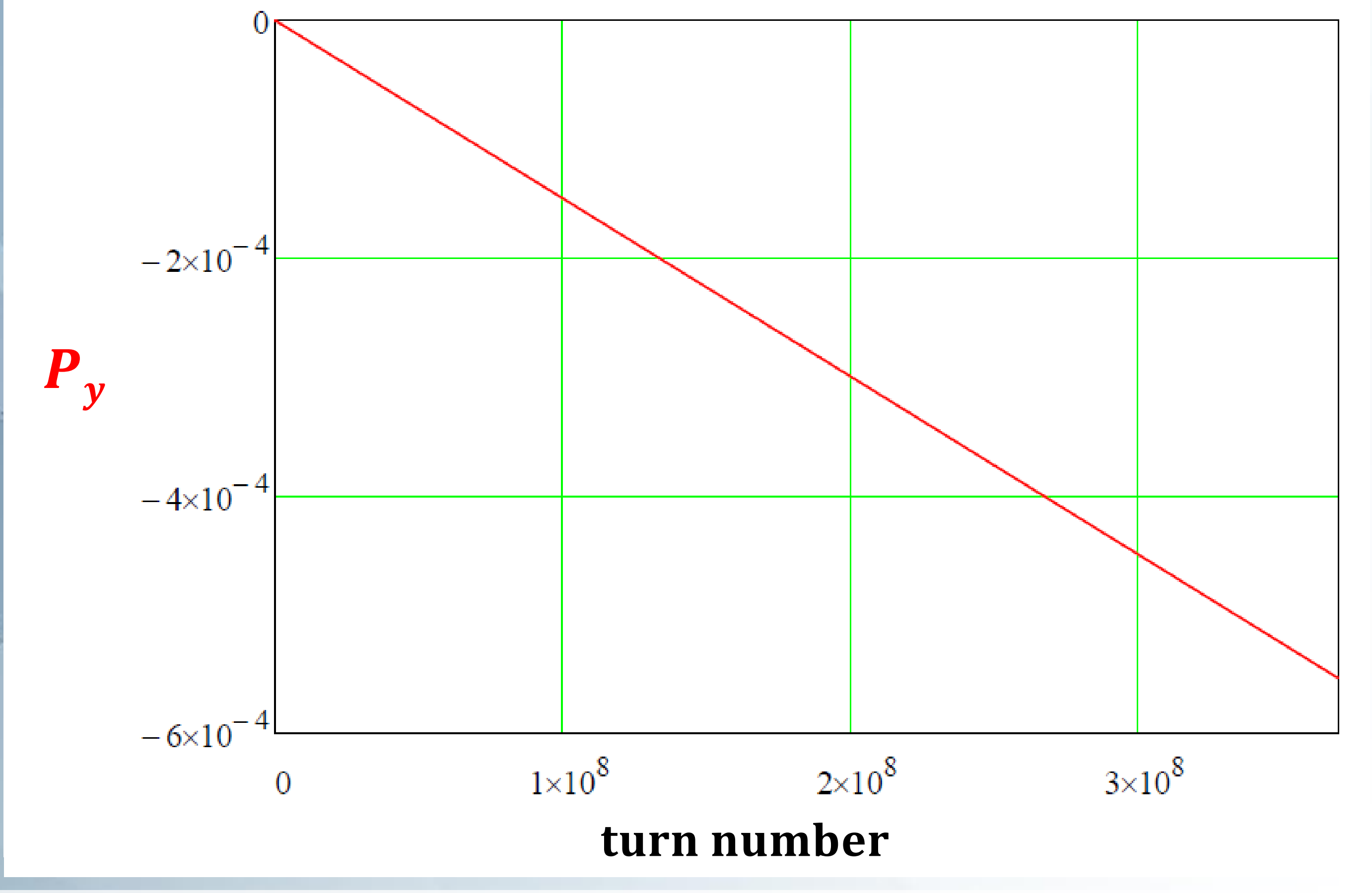
Spin coherence time collaboration

Z. Bagdasarian[1], P. Benati[2], S. Bertelli[2], D. Chiladze[1,3], J. Dietrich[3], S. Dimov[3,4], D. Eversmann[5], G. Fanourakis[6], M. Gaisser[3], R. Gabel[3], B. Gou[3], G. Guidoboni[2], V. Hejny[3], A. Kacharava[3], V. Kamerdzhiev[3], P. Kulessa[7], A. Lehrach[3], P. Lenisa[2], Be. Lorentz[3], L. Magallanes[8], R. Maier[3], D. Michedlishvili[1,3], W. M. Morse[9], A. Nass[3], D. Öllers[2,3], A. Pesce[2], A. Polyanskiy[3,10], D. Prasun[3], J. Pretz[5], F. Rathmnann[3], Y. K. Semertzidis[9], V. Schmakova[3,4], E. J. Stephenson[11], H. Stockhorst[3], H. Ströher[3], R. Talman[12], Yu. Valdau[3,13], Ch. Weideman[2,3], P. Wüstner[14].

[1]*Tbilisi State University, **Georgia***
[2]*University and/or INFN of Ferrara, **Italy***
[3]*IKP Forschungszentrum Jülich, **Germany***
[4]*JINR, Dubna, **Russia***
[5]*III. Physikalisches Institut RWTH Aachen, **Germany***
[6]*Institute of Nuclear Physics NCSR Democritos, Athens, **Greece***
[7]*Jagiellonian University, Krakow, **Poland***
[8]*Bonn University, **Germany***
[9]*Brookhaven National Laboratory, New York, **USA***
[10]*Institute of Theoretical and Experimental Physics, Moscow, **Russia***
[11]*Center for Exploration of Energy and Matter, Indiana University, Bloomington, **USA***
[12]*Cornell University, New York, **USA***
[13]*Petersburg Nuclear Physics Institute, Gatchina, **Russia***
[14]*ZEL Forschungszentrum Jülich, **Germany***

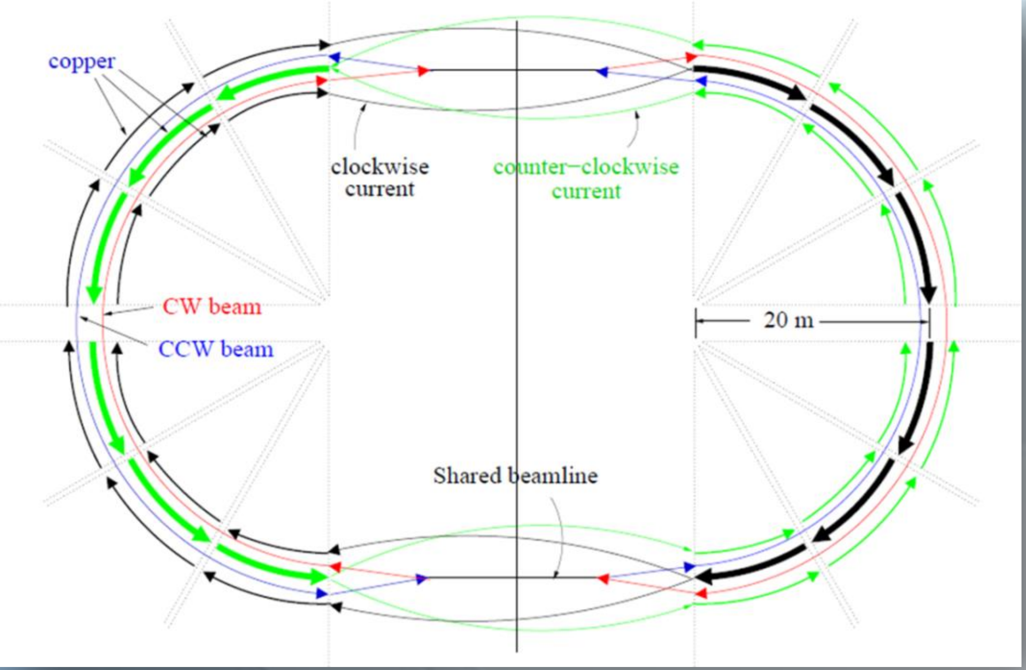
Precursor experiments:
1. Resonance Method for deuterons at COSY

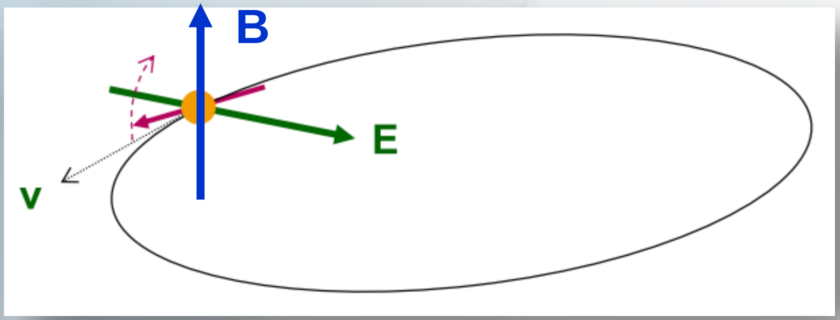
Parameters: beam energy $T_d = 50$ MeV $L_{RF} = 1$ m
assumed EDM $d_d = 10^{-24}$ e·cm
E-field 30 kV/cm



Linear extrapolation of P_y for a time period of $\tau_{sc} = 1000$ s $(= 3.7\cdot10^{8}$ turns) yields a sizeable $P_y \sim 10^{-3}$.

All-in-one machine (R. Talmans concept)





Maximum achievable field of copper magnets ~ 0.15 T.

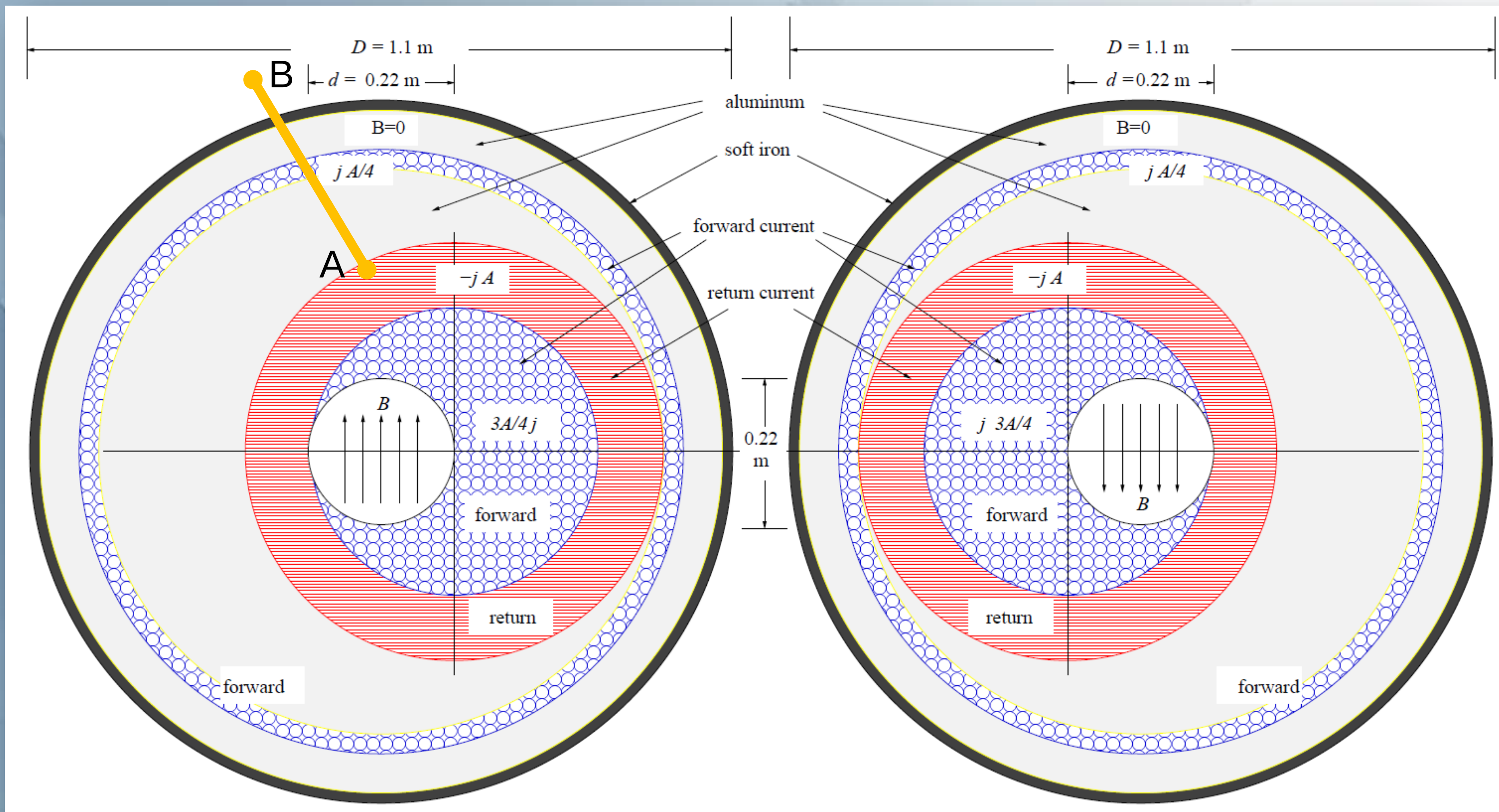
$r = 10$ m

Particle	p(GeV/c)	T(GeV)	E(MV/m)	B(T)
Proton	855.3	331.3	6.8	-0.005
Deuteron	381.0	38.3	-1.3	-0.015
^{3}He	739.8	95.8	13.240	-0.050

Very compact machines seem possible for srEDM searches

CCW & CCW with magnetic field: Concept for a Jülich all-in-one machine

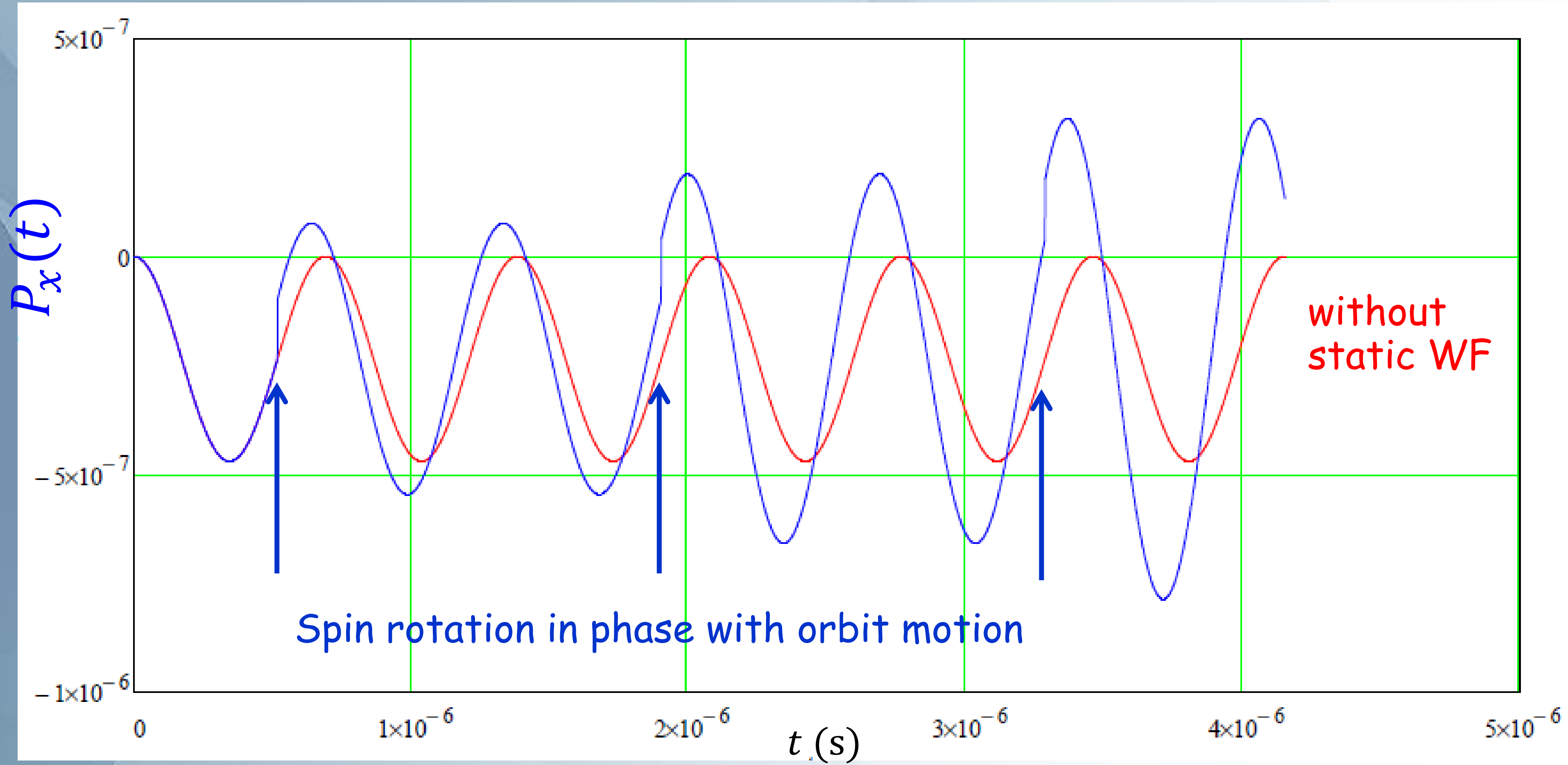
Iron-free, current-only, magnetic bending, eliminates hysteresis



A Configuration generates close-to-perfect vertical **B** fields B

2. Resonant EDM measurement with static Wien Filter

Machine operated on imperfection spin resonance at $\gamma G = 2$

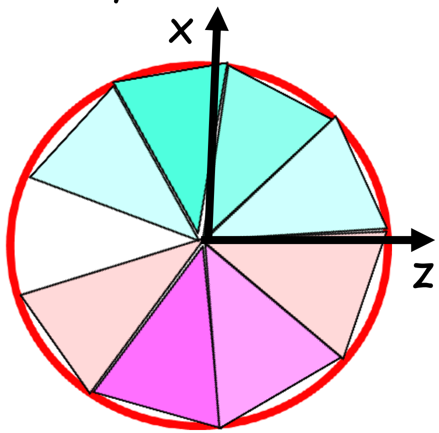


Similar accumulation of EDM signal, systematics more difficult, strength of imperfection resonance must be suppressed by closed-orbit corrections.

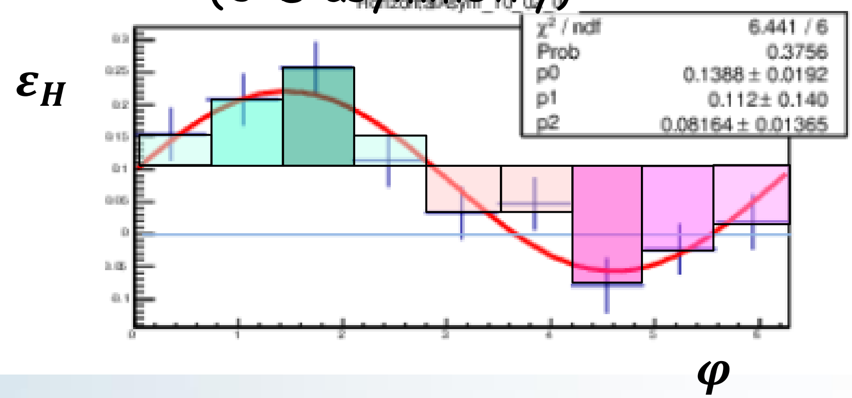
Measurement of the horizonthal SCT

No frozen spin: polarization rotates in the horizonthal plane at 120 kHz

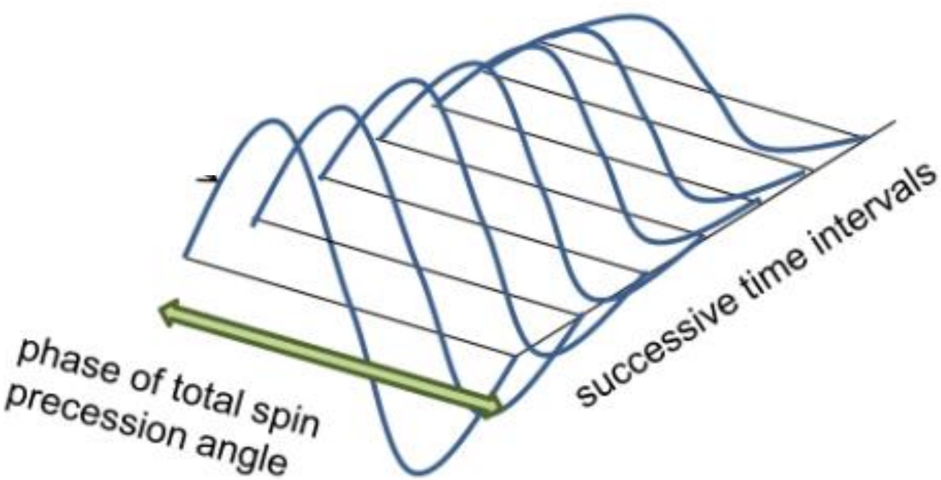
- DAQ synchronized with cyclotrhon freqyency -> count turn number N
- Compute total spin-precession angle (with spin-tune $\nu_s = G\gamma$)
- Bin by phase around the circle
- Compute asymmetry in each bin



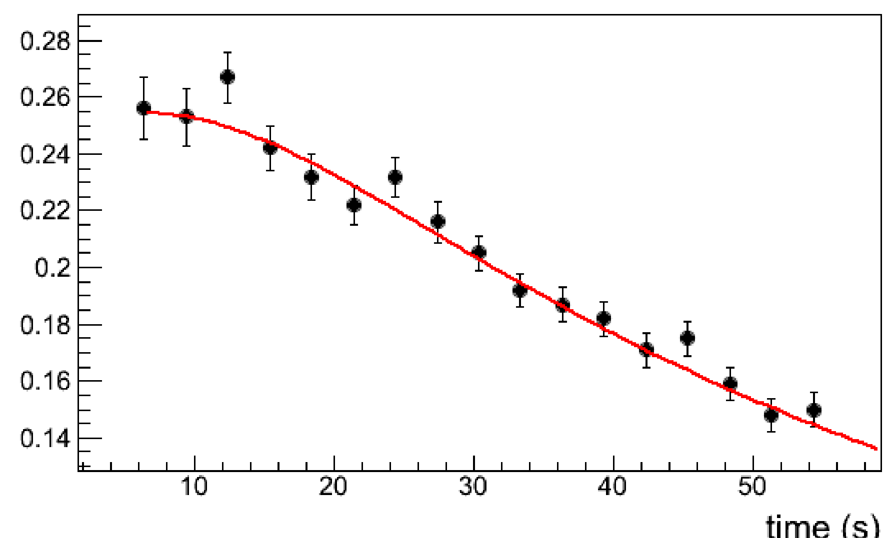
(U-D asymmetry)



Derivation of horizontal spin coherence time



Amplitude vs time



Spin coherence time extracted from numerical fit