Search for Electric Dipole Moments with Polarized Beams in Storage Rings

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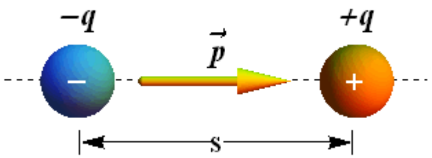
Electric Dipoles

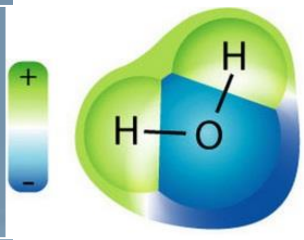
- Definition



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

Charge separation creates an electric dipole

- Orders of magnitude



H_2O molecule: permanent EDM (degenerate GS w/ different Parity)

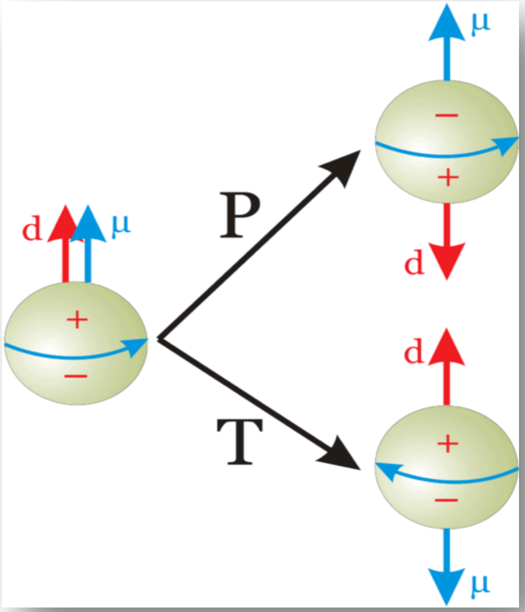
	Atomic physics
Charges	e
$\lvert r_1-r_2 \rvert$	10^{-8} cm
EDM (naive) exp.	10^{-8} e cm
observed	H_2O molecule $4{\cdot}10^{-9}$ e cm

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)

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

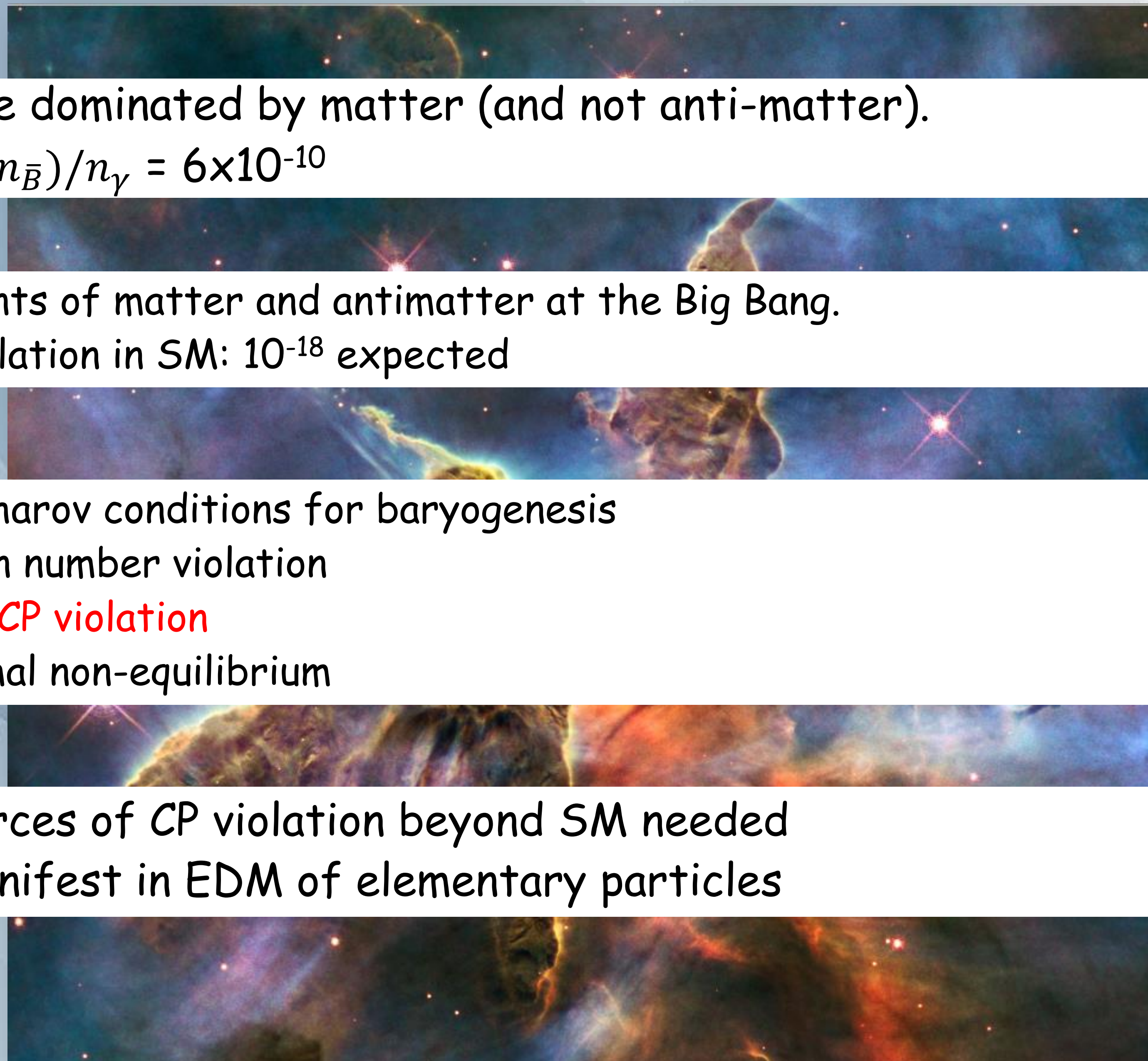
CP violation

- .Universe dominated by matter (and not anti-matter).
  - $(n_B - n_{\bar{B}})/n_\gamma$ = 6x10^{-10}

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

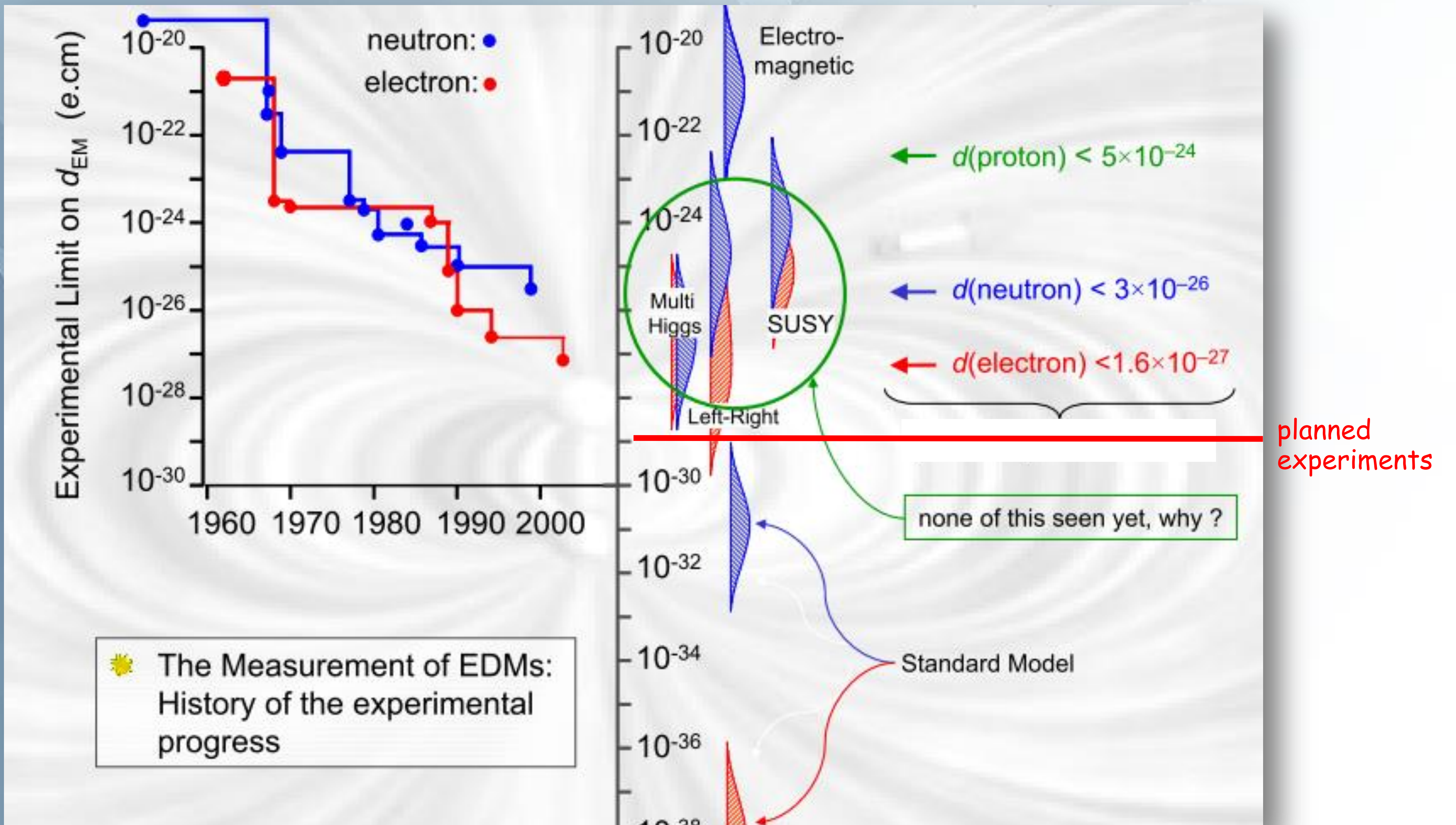
- 1967: 3 Sacharov conditions for baryogenesis
  - Baryon number violation
  - C and CP violation
  - Thermal non-equilibrium

- 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

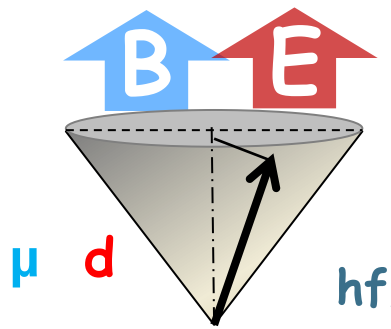


No Standard Model Background!

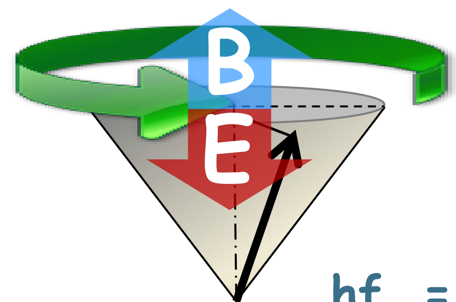
Experimental limits

- EDM searches: only upper limits yet (in $e\cdot\text{cm}$)
- E-fields accelerate charged part. $\rightarrow$ search limited to neutral systems

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



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



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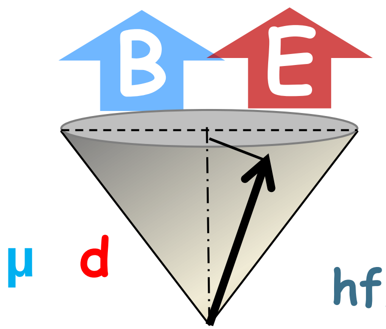

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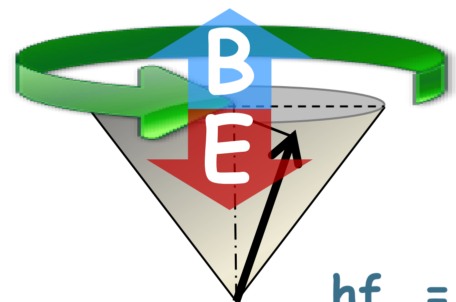


$hf_- = 2\mu B - 2dE$

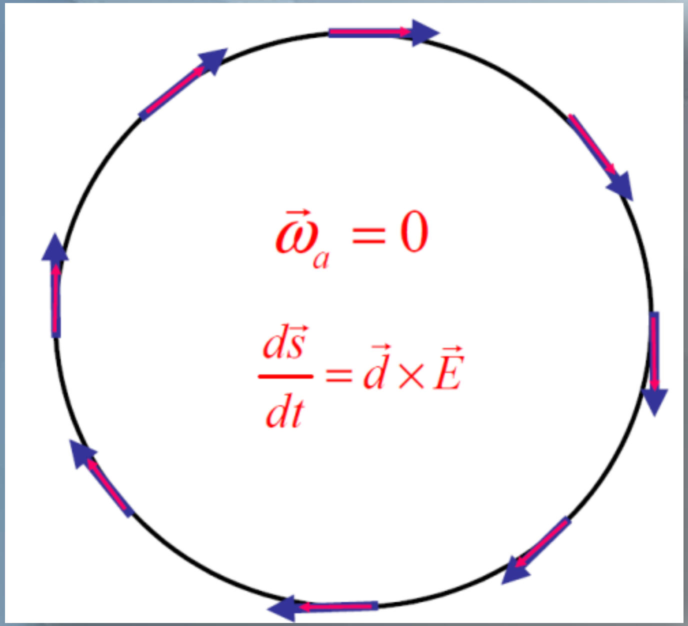
(Till now) two kinds of experiments to measure EDMs:
- Neutrons
- Neutral atoms (paramagnetic/diamagnetic)

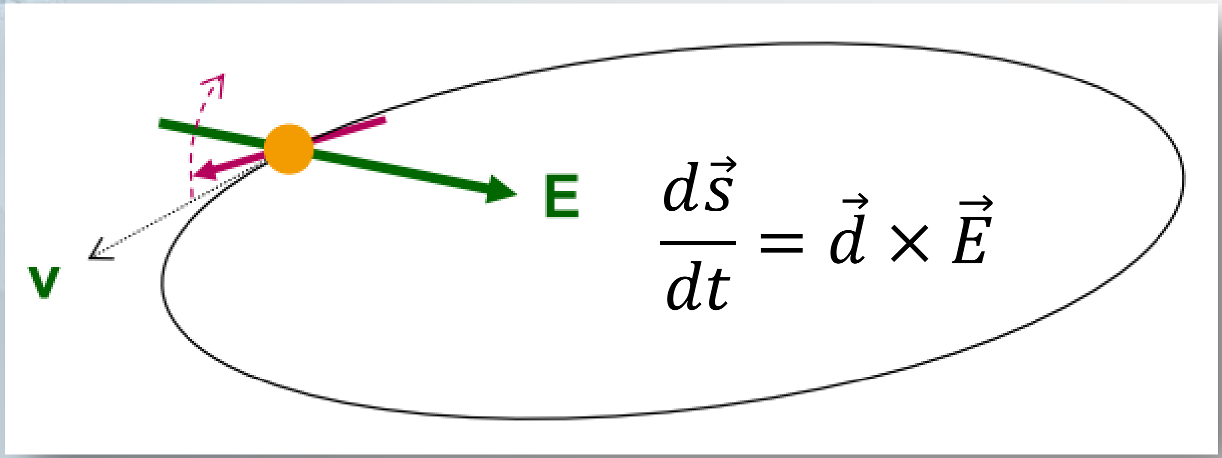
No direct measurement of electron or proton EDM yet

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):

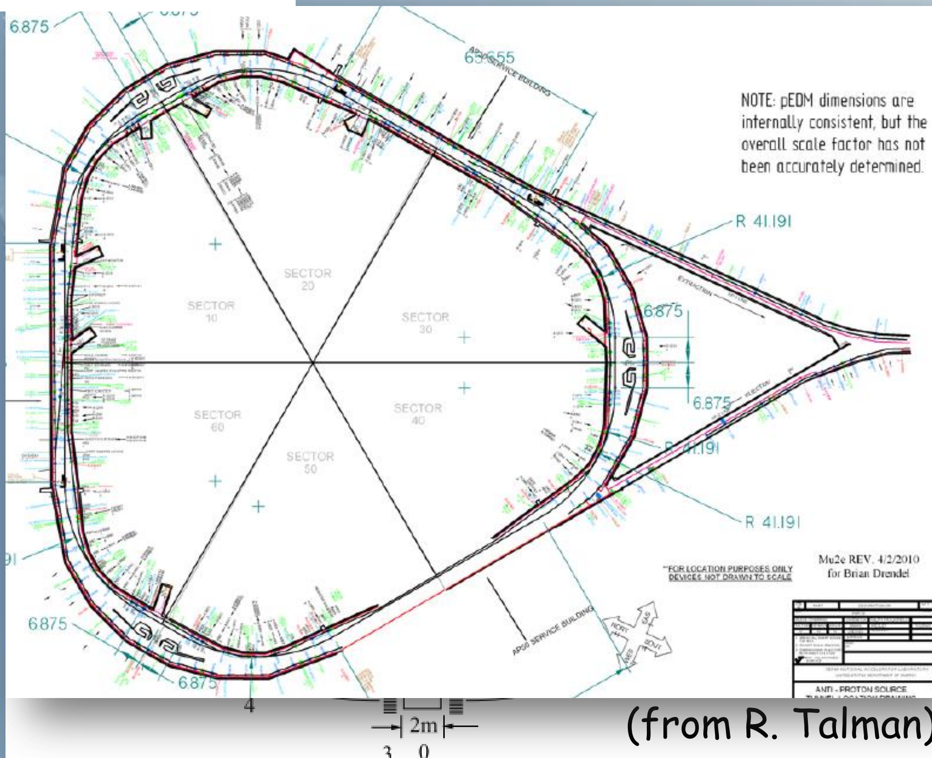
$$\left(G - \frac{1}{\gamma^2 - 1}\right) = 0$$

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

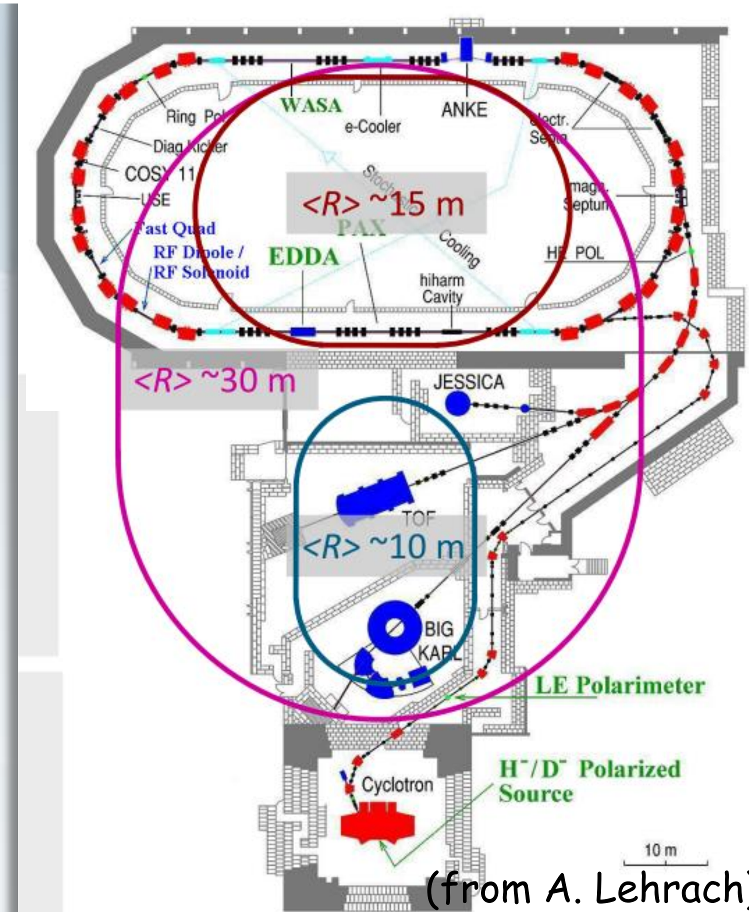
pEDM in all electric ring at BNL
or at FNAL



(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)

Feasibility requirements

- 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)

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

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

- PROTON BEAM POSITION MONITORS (<10 nm)

- SYSTEMATIC ERROR PLAN

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:

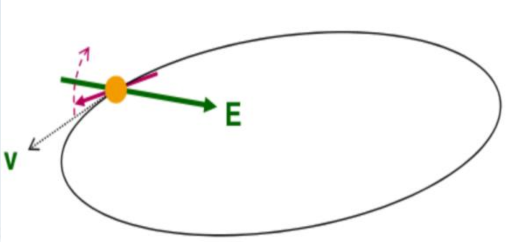
$$B_r = \frac{dE_r}{\mu_N} = \frac{10^{-22}\mathrm{eV}}{3.1 \cdot 10^{-8}\mathrm{eV/T}} \approx 3 \cdot 10^{-17}\mathrm{T}$$

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

Solution

- Use two beam running clockwise and counterclockwise.
- Separation of two beams sensitive to B

EDM buildup time



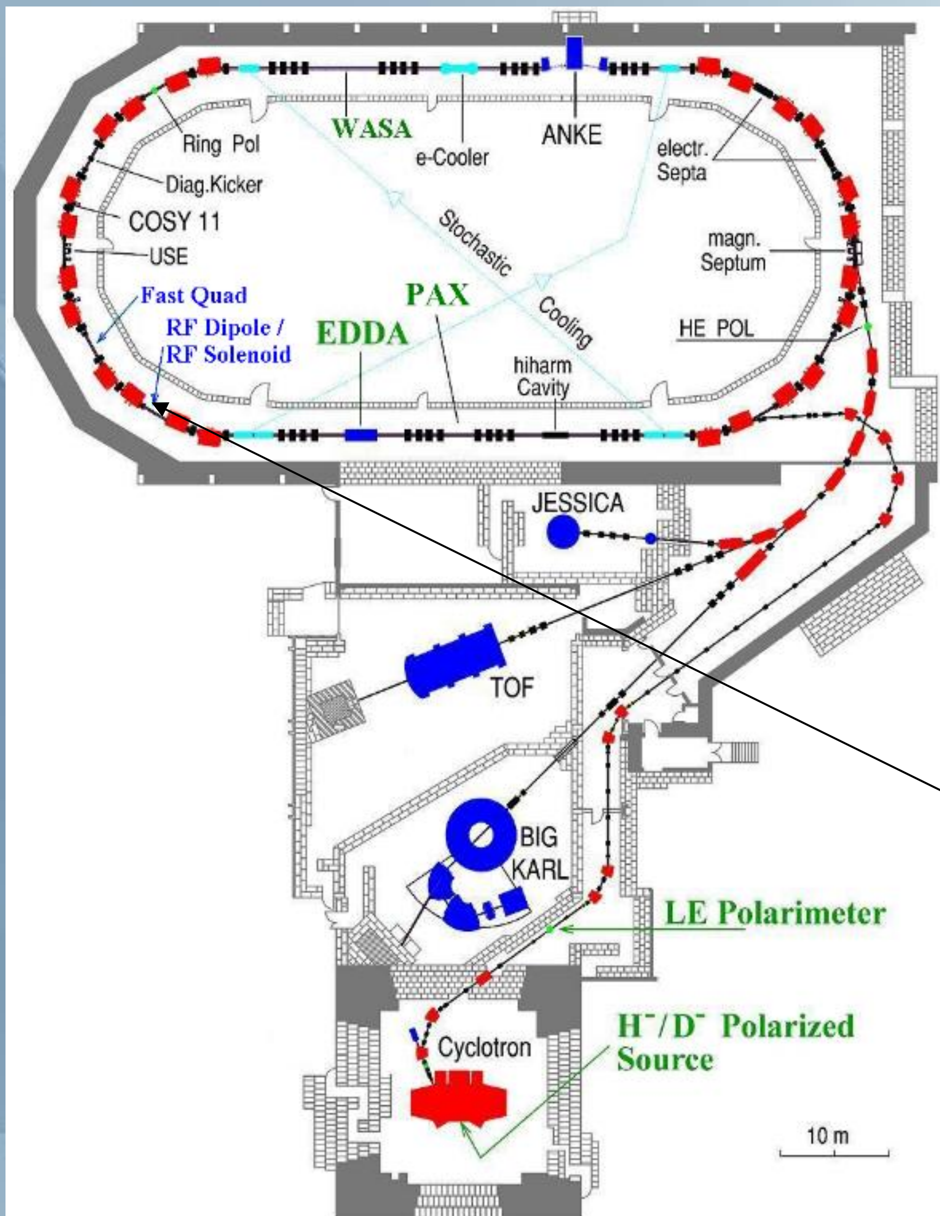
- Minimal detectable precession $\vartheta \approx 10^{-6}$ rad

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

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

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

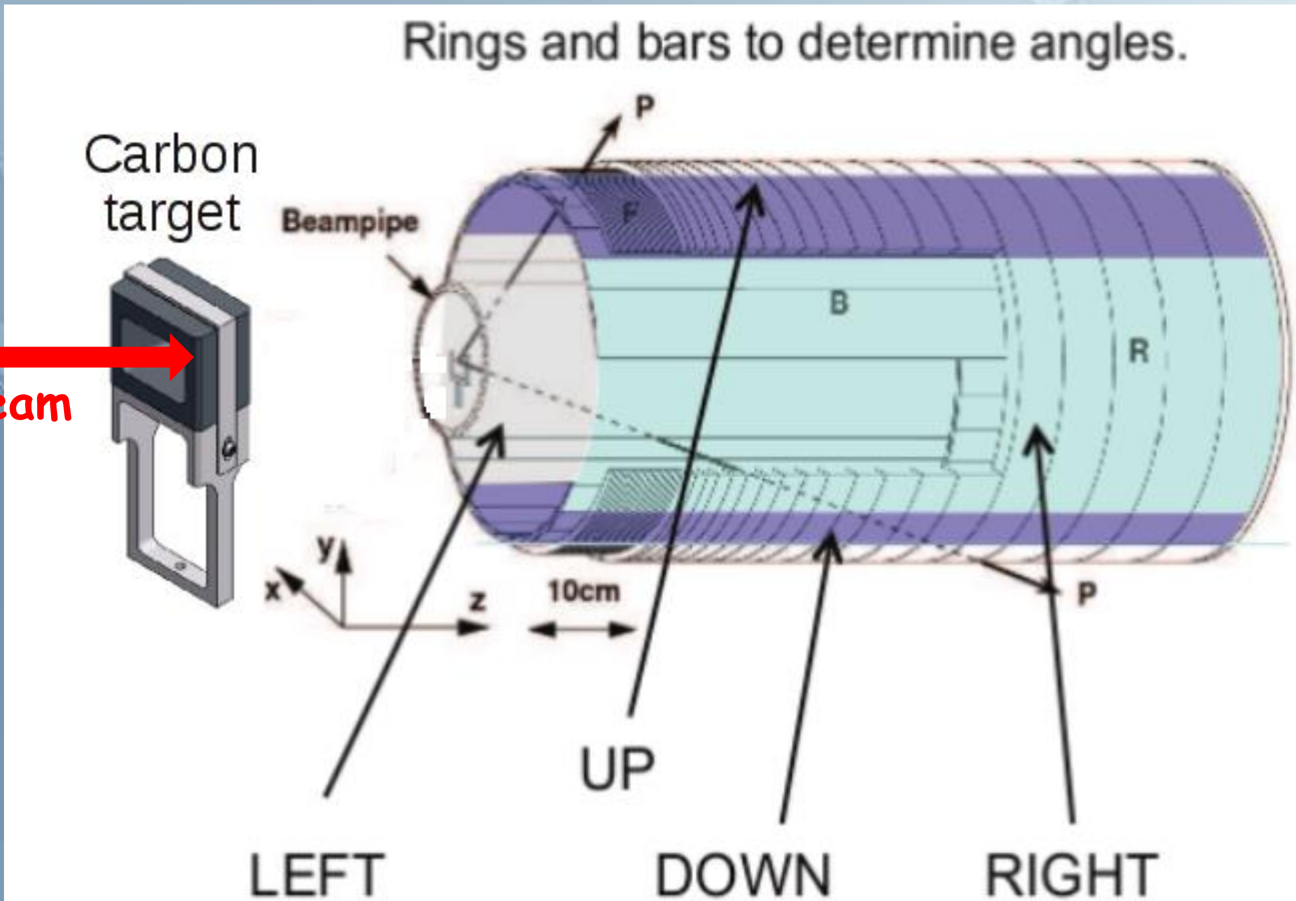
COoler SYnchrotron (FZ-Jülich, GERMANY)



- 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**

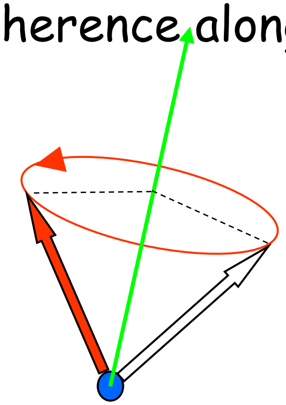
$$\varepsilon_H = \frac{U-D}{U+D} \propto p_H A_x$$

HORIZONTAL polarization **Analyzing power**

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

Spin coherence time

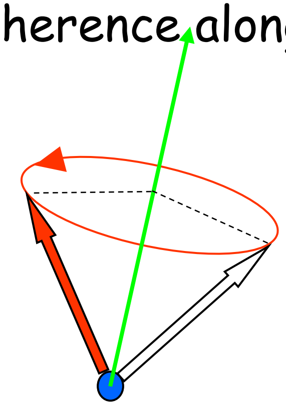
- Spin coherence along $\hat{n}_{co}$ is not an issue



At injection all
spin vectors aligned (coherent)

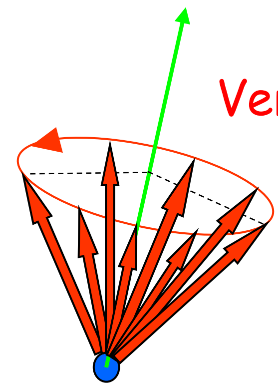
Spin coherence time

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



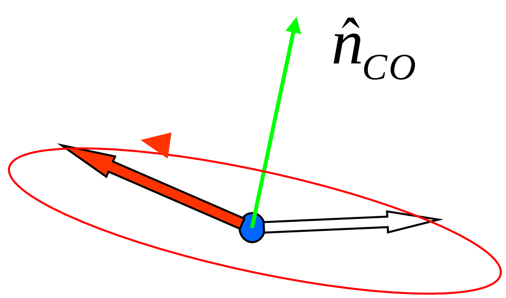
At injection all
spin vectors aligned (coherent)

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?

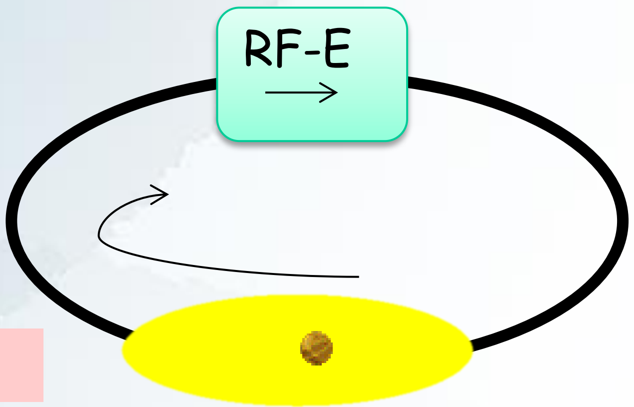
LONGITUDINAL PHASE SPACE

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

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

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

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



TRANSVERSE PHASE SPACE

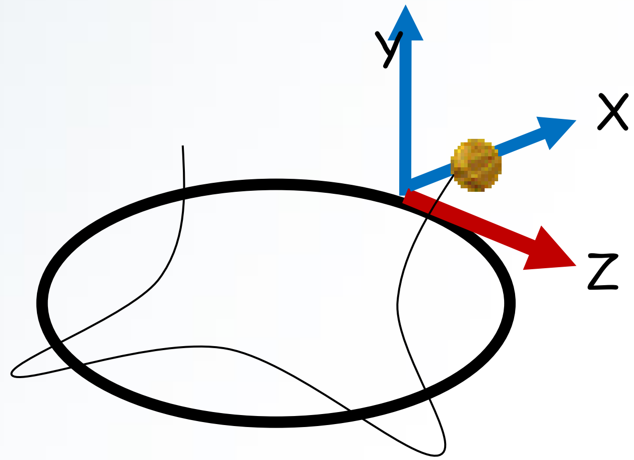
Problem: beam emittance $\neq 0 \rightarrow$ betatron oscillations

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

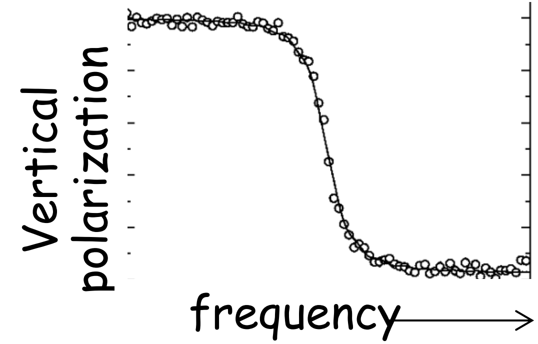
Preparing a longitudinal polarized beam with RF-solenoid

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

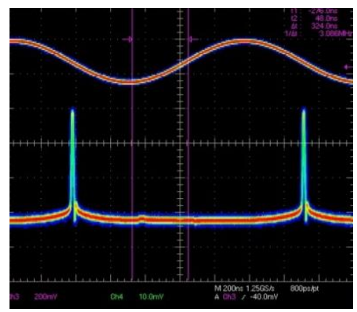


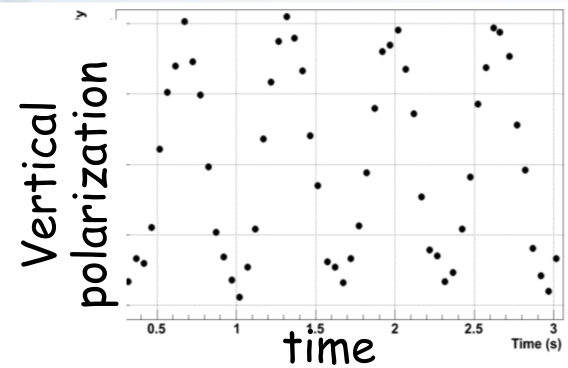
(L-R asymmetry)

2) Fixed frequency measurements

On resonance

COOLED BEAM



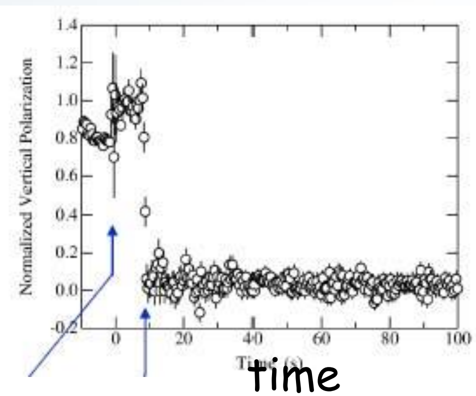


(L-R asymmetry)

3) Solenoid on for half-cycle

Vertical polarization = 0

Polarization is horizontal

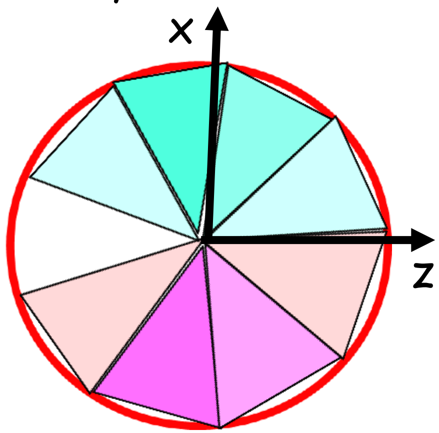


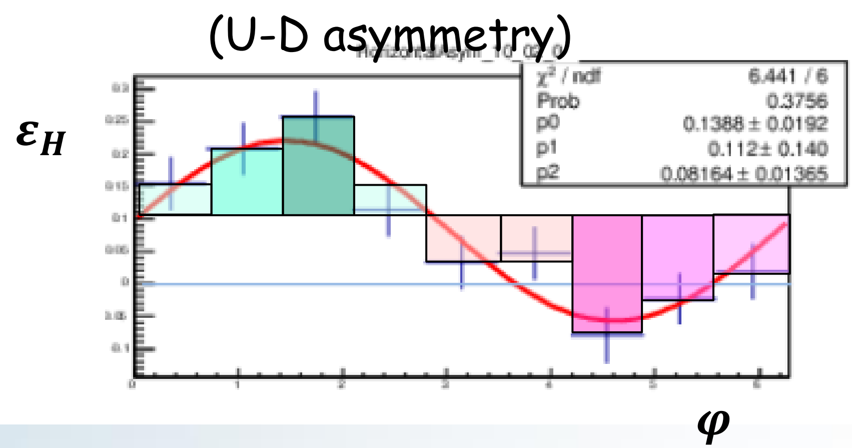
(L-R asymmetry)

Measurement of the horizonthal SCT

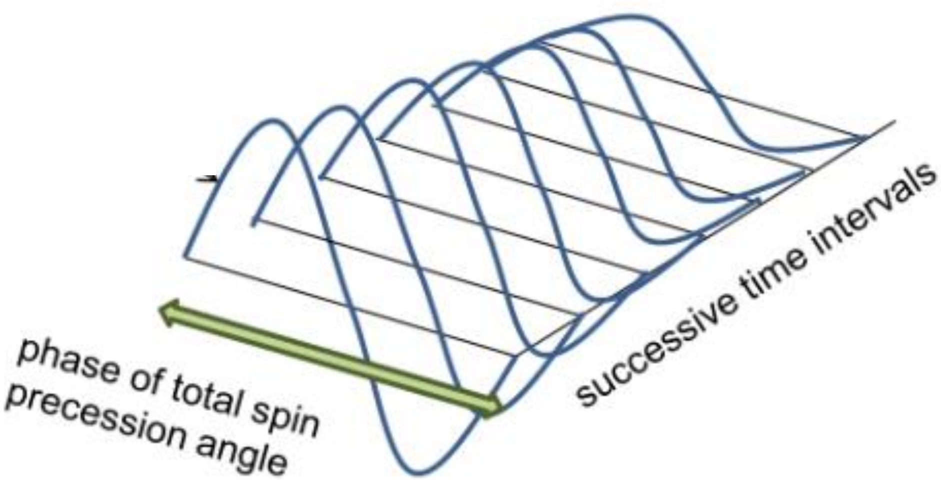
No frozen spin: polarization rotates in the horizonthal plane at 120 kHz

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

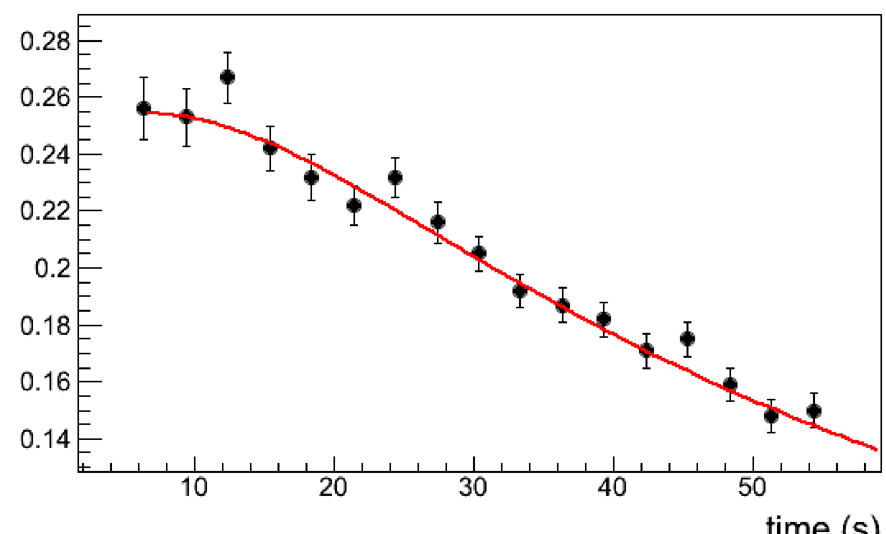




Derivation of horizontal spin coherence time



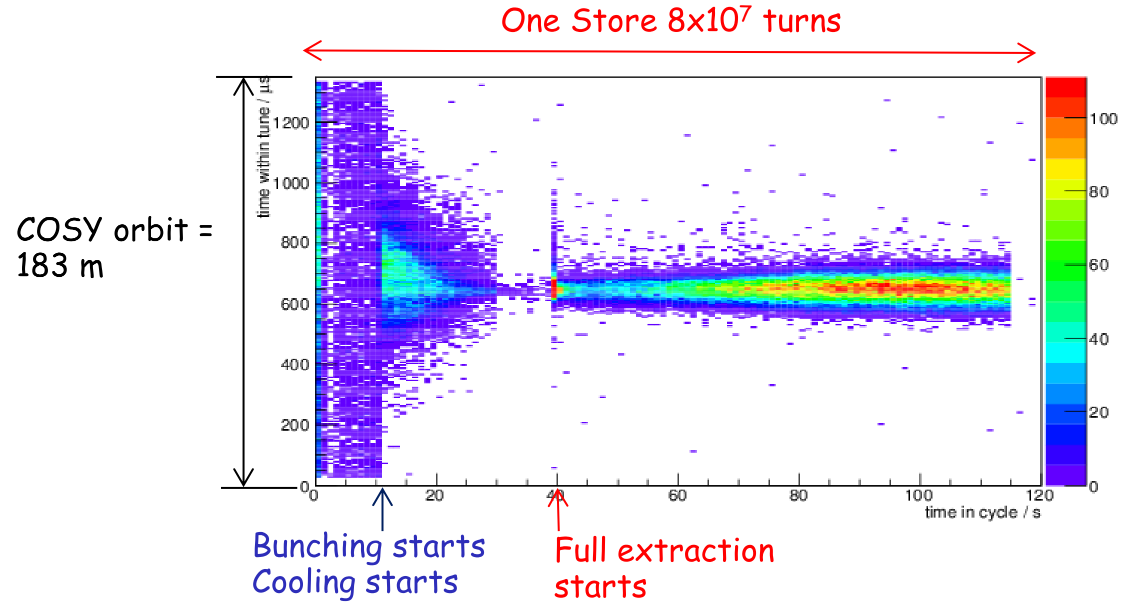
Amplitude vs time



Spin coherence time extracted from numerical fit

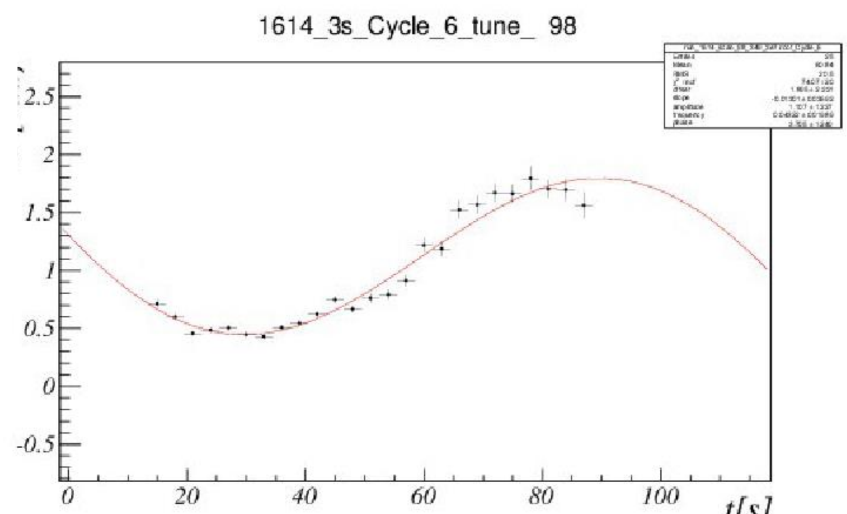
Performance

Time stamp system



Spin-tune and machine stability

- Phase over time can be tracked with precision ~ 10^{-8}
- Stability of the ring magnets < $2x10^{-7}$



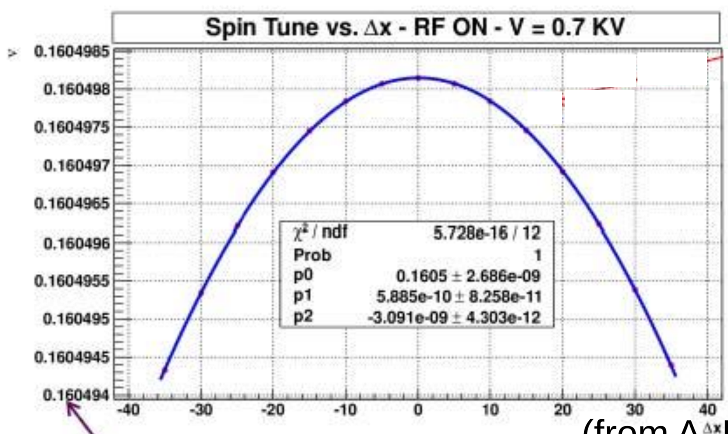
from Dennis Eversmann

Beam emittance studies

Beam preparation

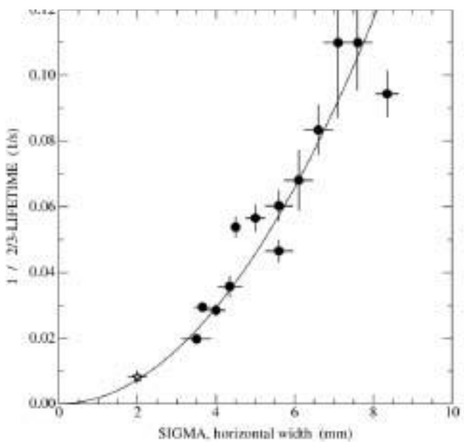
- Pol. Bunched deuteron beam at p=0.97 GeV/c
- Preparation of beam by electron cooling.
- Selective increase of horizontal emittance
    - Heating through white noise

Quadratic dependence of spin tune on size of horizonthal betatron oscillation



(from A. Pesce)

Simulations (COSY Infinity)



Measurement at COSY

Beam emittance affects spin-coherence time

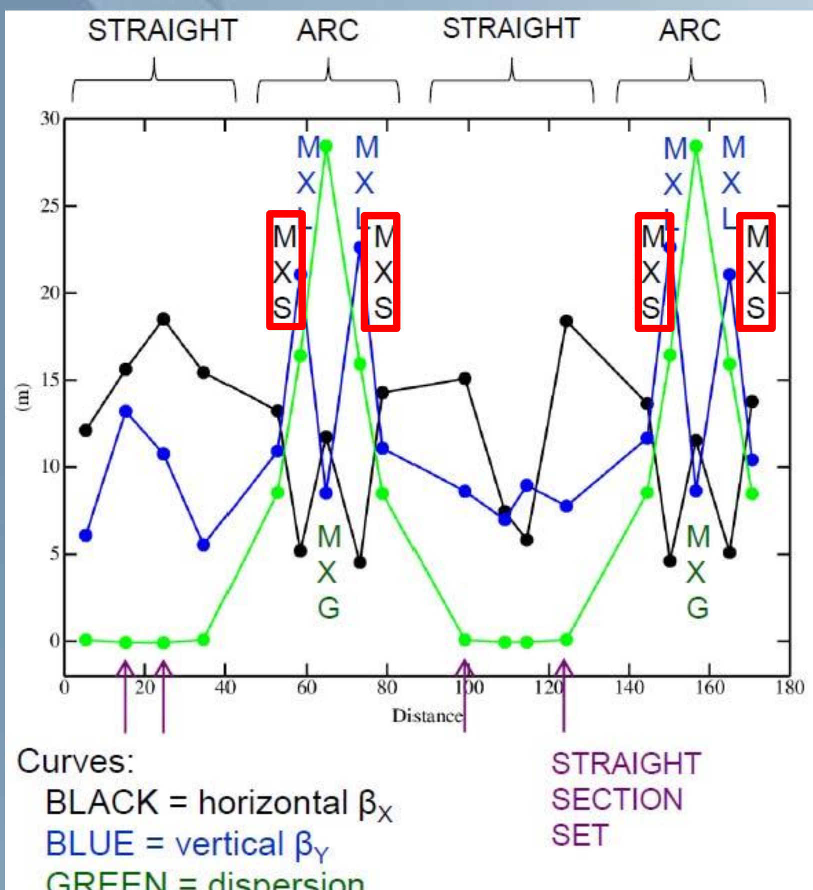
Lengthening the SCT by COSY sextupoles

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

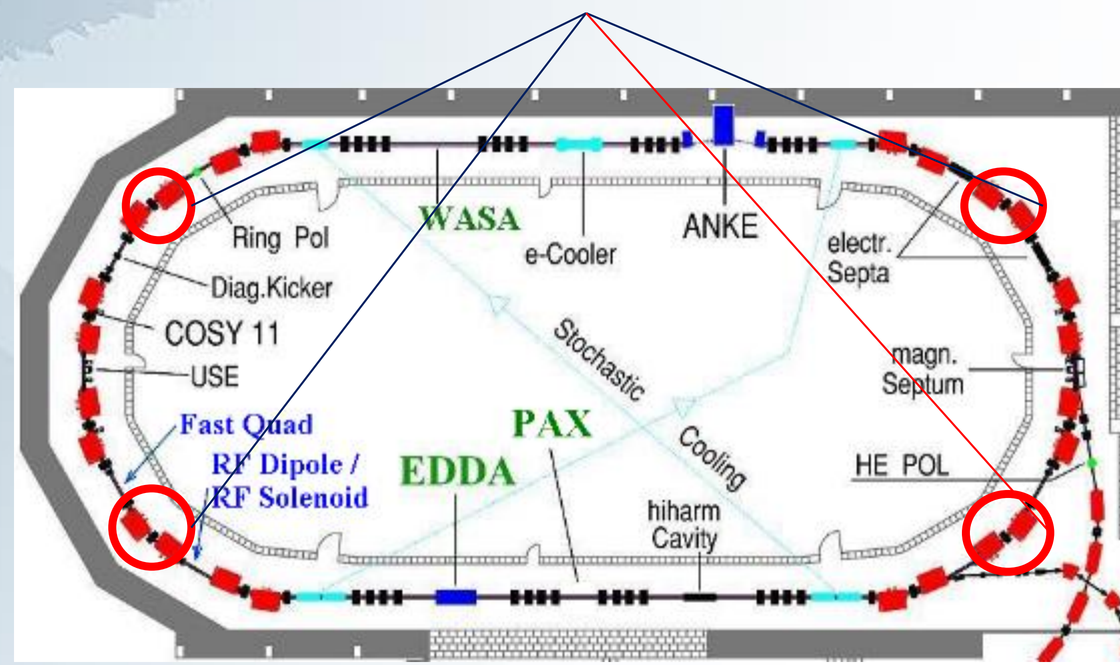
$$\frac{\Delta L}{L_0} = \frac{\vartheta_x^2 + \vartheta_y^2}{4}$$

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

Use of 6-poles where β_x function is maximal



Sextupoles at β_x **max**



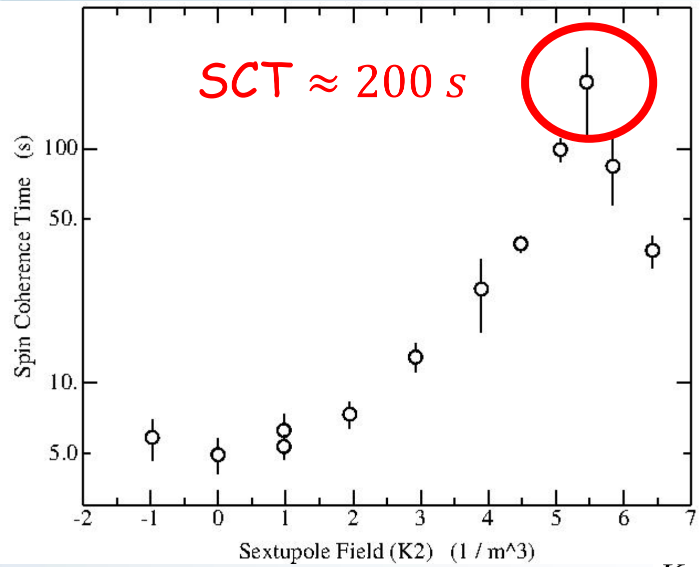
Results

Compensation by means of 6-pole fields:

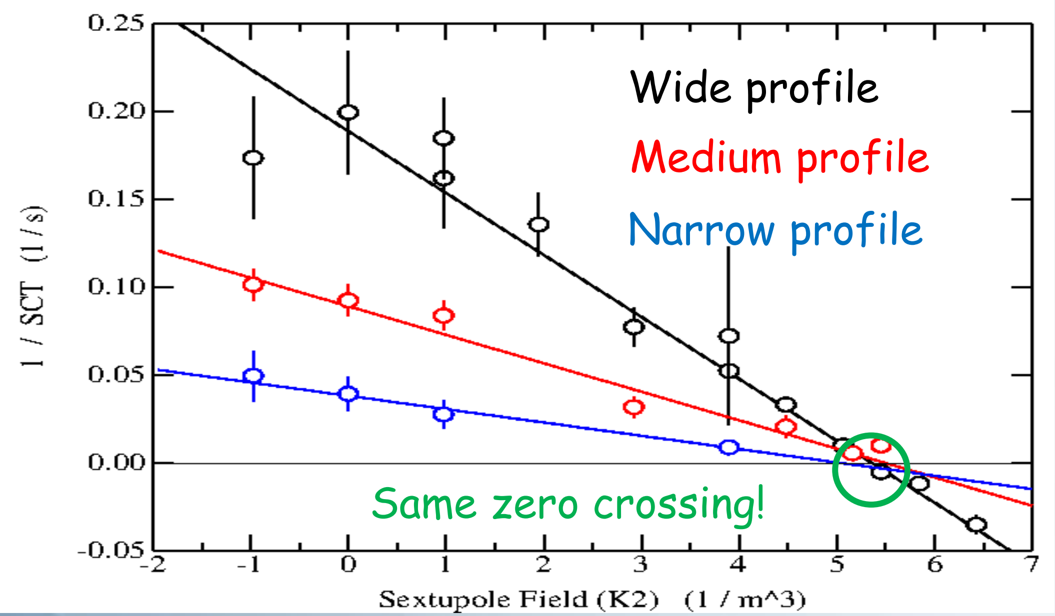
$1/\tau_{SCT} = A\langle\theta^2_x\rangle + a\langle\theta^2_x\rangle$

A = original effect
a = sextupole effect

Choose a= -A



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



Different **horizontal** profile widths

- Different slopes
- Zero crossing indep. of width

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

Conclusions

- Non-zero EDM within the actual experimental limits clear probe of new physics
- Polarized beam in Storage Rings might pave the way to first direct measurement of EDM of charged particles.
- Technical challenges for the EDM experiment in Storage Ring.
    - Long Spin Coherence Time.

- 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.

- .Further developments:
    - Measurement repetition in y – axis inhibithed by vertical machine acceptance
    - Compensation of $(\langle\Delta P/P\rangle)^2$ with the same principle
    - Test of spin-tracking codes on the real measurement

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].

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