Charged Particles Electric Dipole Moment Searches in Storage Rings

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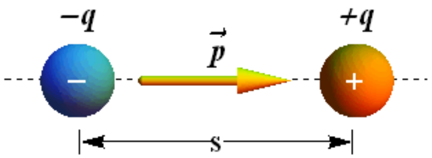
Electric Dipoles

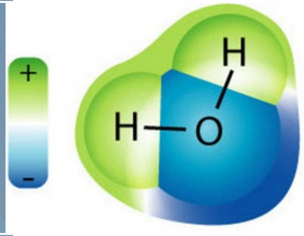
- Definition



$$p = q \cdot s$$

Charge separation creates an electric dipole

- Orders of magnitude



H_2O molecule: permanent EDM (degenerate GS of different Parity)

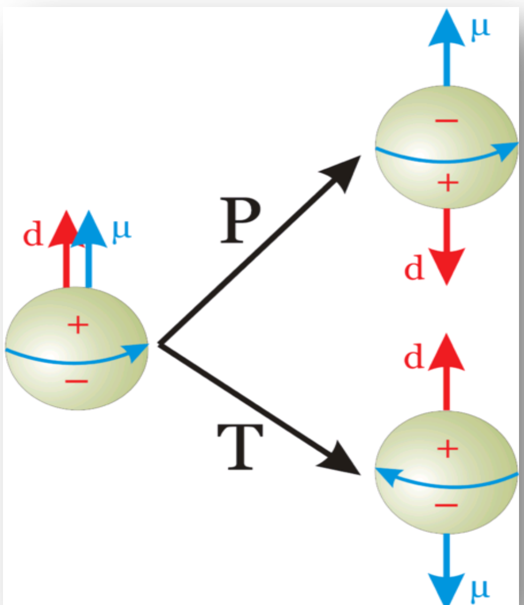
	Atomic physics
Charges	e
$\|r_1-r_2\|$	1 Å = 10^{-8} cm
naive expectation	10^{-8} e cm
observed	water molecule $2 \cdot 10^{-8}$ e cm

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



μ: magnetic dipole moment
d: electric dipole moment

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

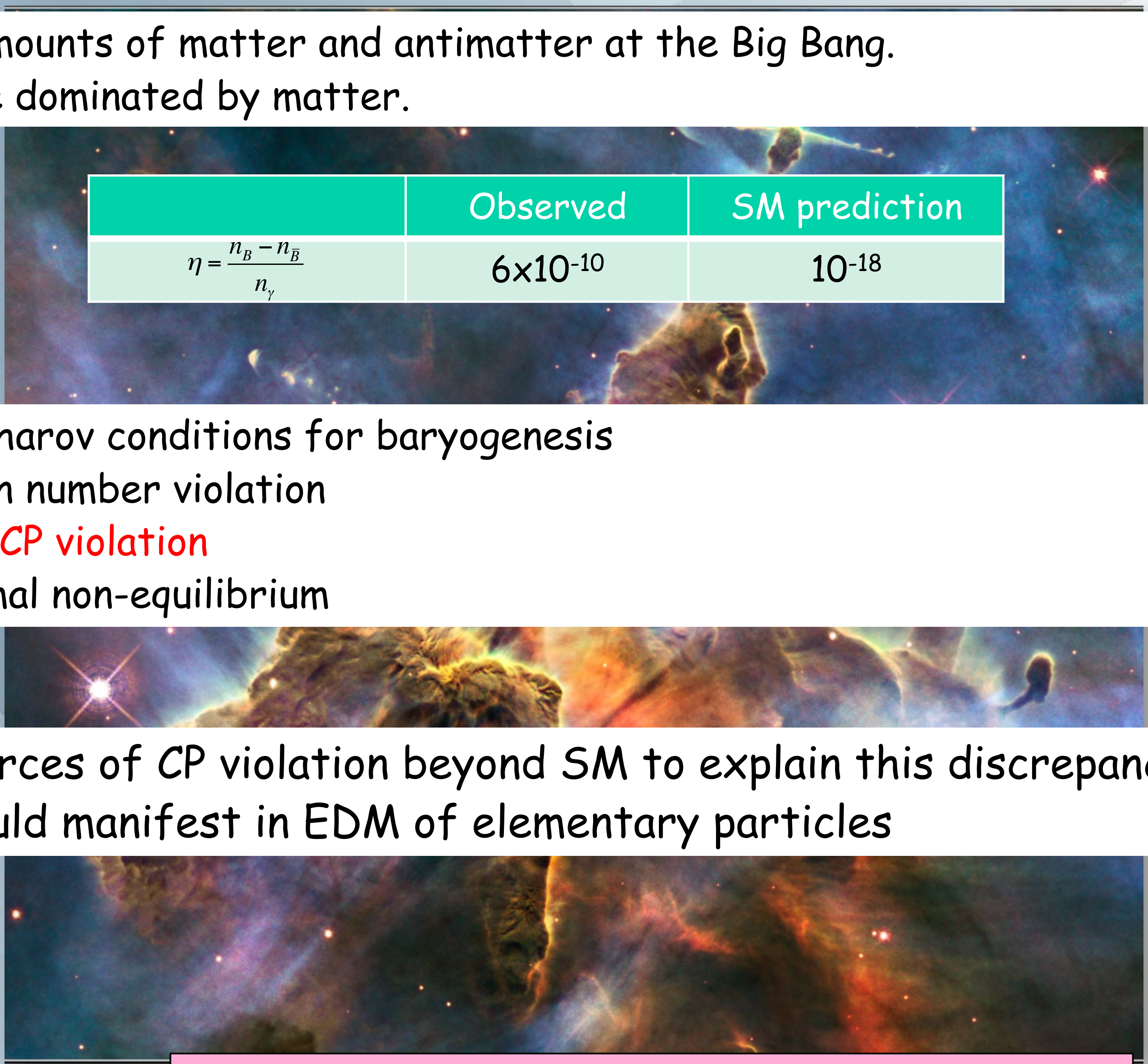
Matter-Antimatter asymmetry

- Equal emounts of matter and antimatter at the Big Bang.
- Universe dominated by matter.

	Observed	SM prediction
$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$	6×10^{-10}	10^{-18}

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

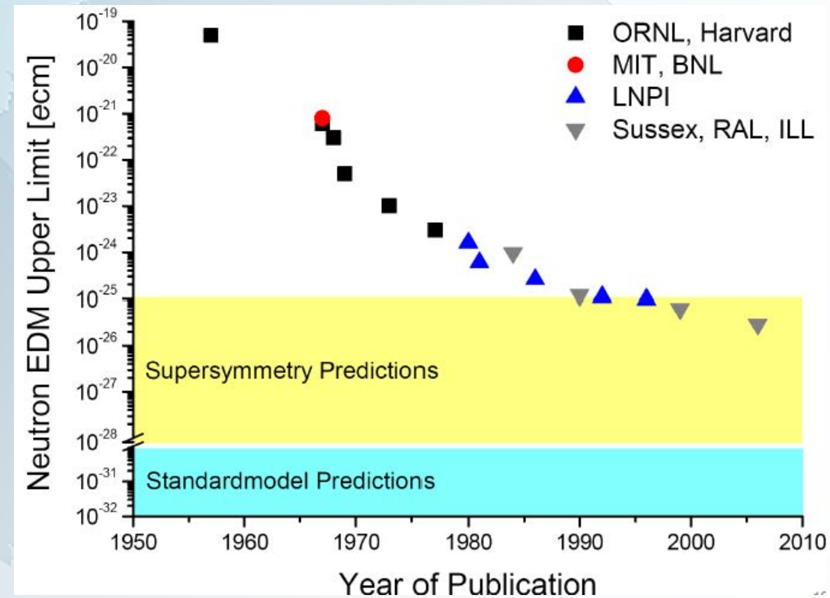
- New sources of CP violation beyond SM to explain this discrepancy
- They could manifest in EDM of elementary particles

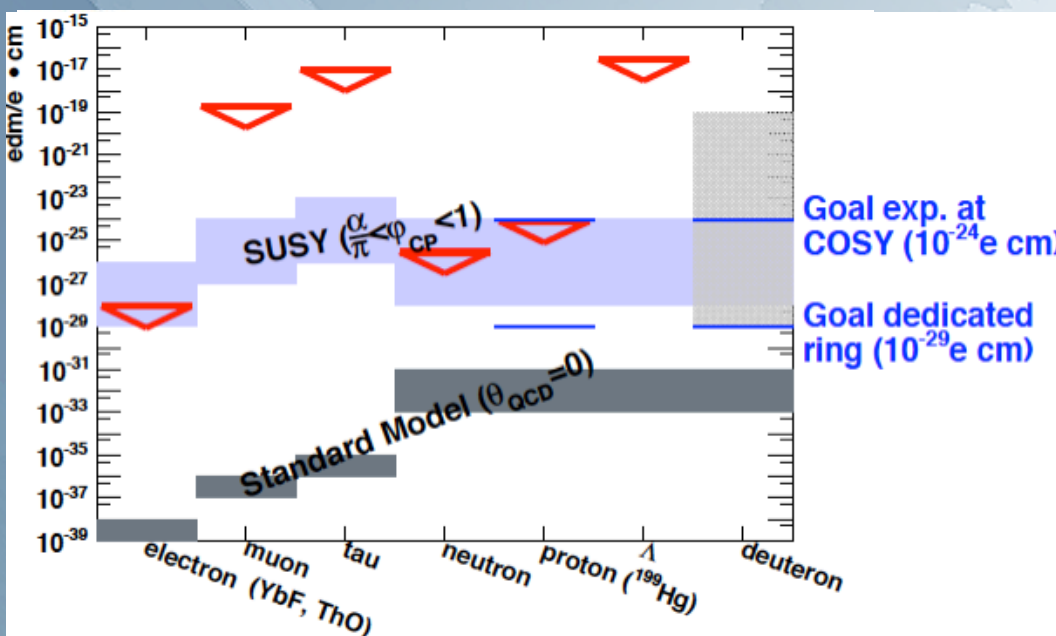


Carina Nebula (Largest-seen star-birth regions in the galaxy)

EDM: hystory and limits

History of neutron EDM





EDM limits

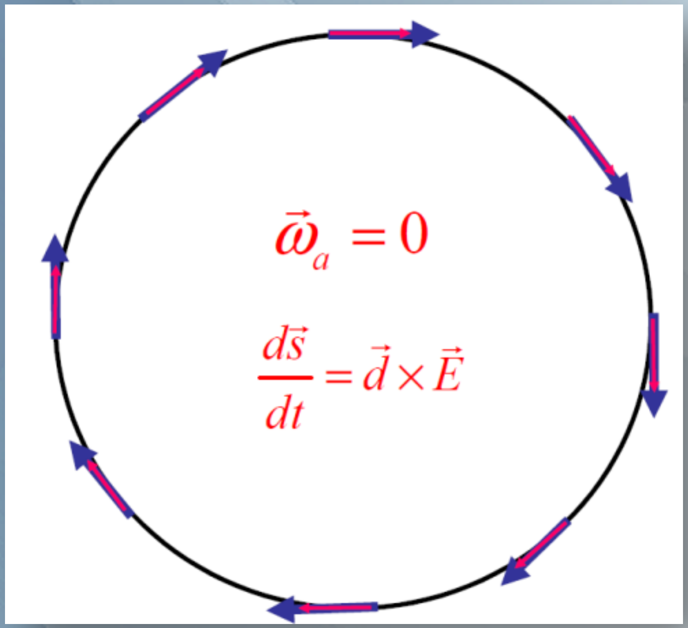
Why charged particles EDMs?

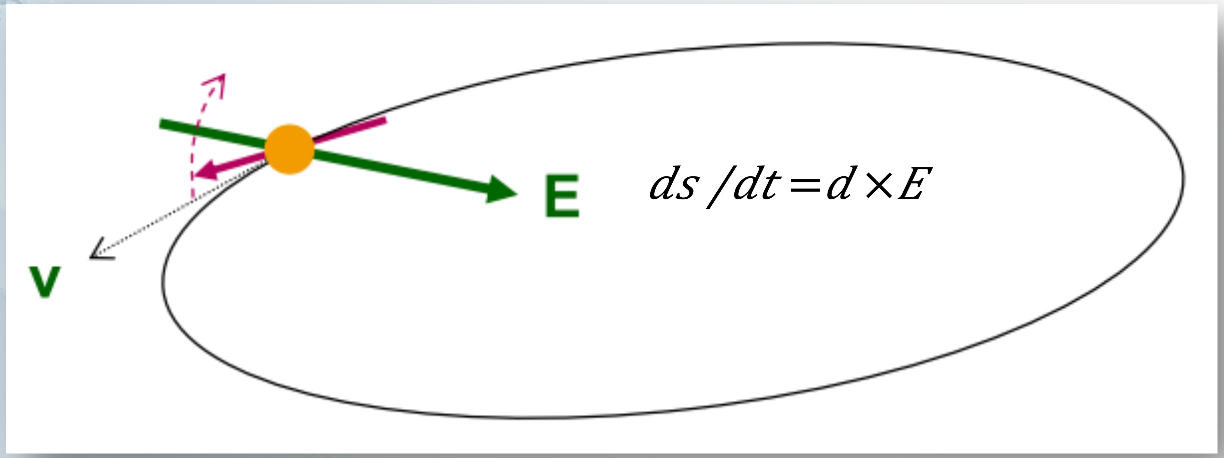
- No direct measurements for charged particles exist;

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





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.

- LARGE ELECTRIC FIELDS (E=10 MV/m).

- SYSTEMATIC ERROR PLAN

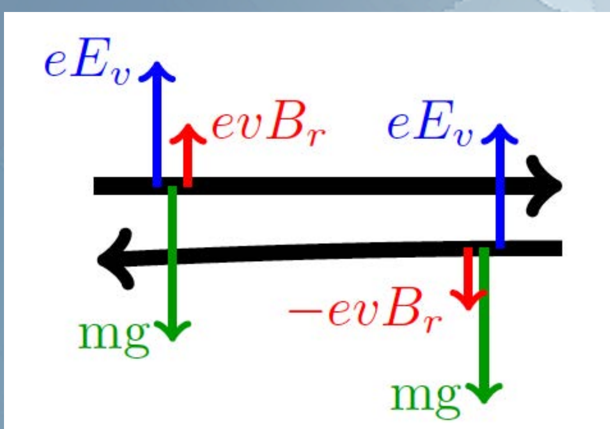
Systematics

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

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

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

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



BPM with relative resolution < 10 nm required
- *use of SQUID magnetomers (fT/√Hz) ? → Study @ FZJ*

Spin precession in a storage ring: Thomas-BMT Equation

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{e}{m}[G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E} + \frac{m}{e\,s} d(\vec{E} + \vec{v} \times \vec{B})] \times \vec{s}$$

Ω: angular precession frequency
γ: Lorentz factor

d: electric dipole moment
G: anomalus magnetic moment

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Dedicated ring:

pure electric field,
freeze horizontal spin motion: $\left(G - \frac{1}{\gamma^2 - 1}\right)=0$
only possible if $G>0$ (proton)

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only possible if *G*>0 (proton)

combined E/B ring
(e.g. deuteron): $G\vec{B} + \left(G - \frac{1}{\gamma^2-1}\right)\vec{v} \times \vec{E}$ =0

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COSY:

pure magnetic ring,
access to EDM d via motional electric field **vxB**
RF - E and B fields to suppress G**B** contribution

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pure magnetic ring,
access to EDM d via motional electric field **vxB**
RF - E and B fields to suppress GB contribution

neglecting EDM term: spin-tune = γG

Summary of different options

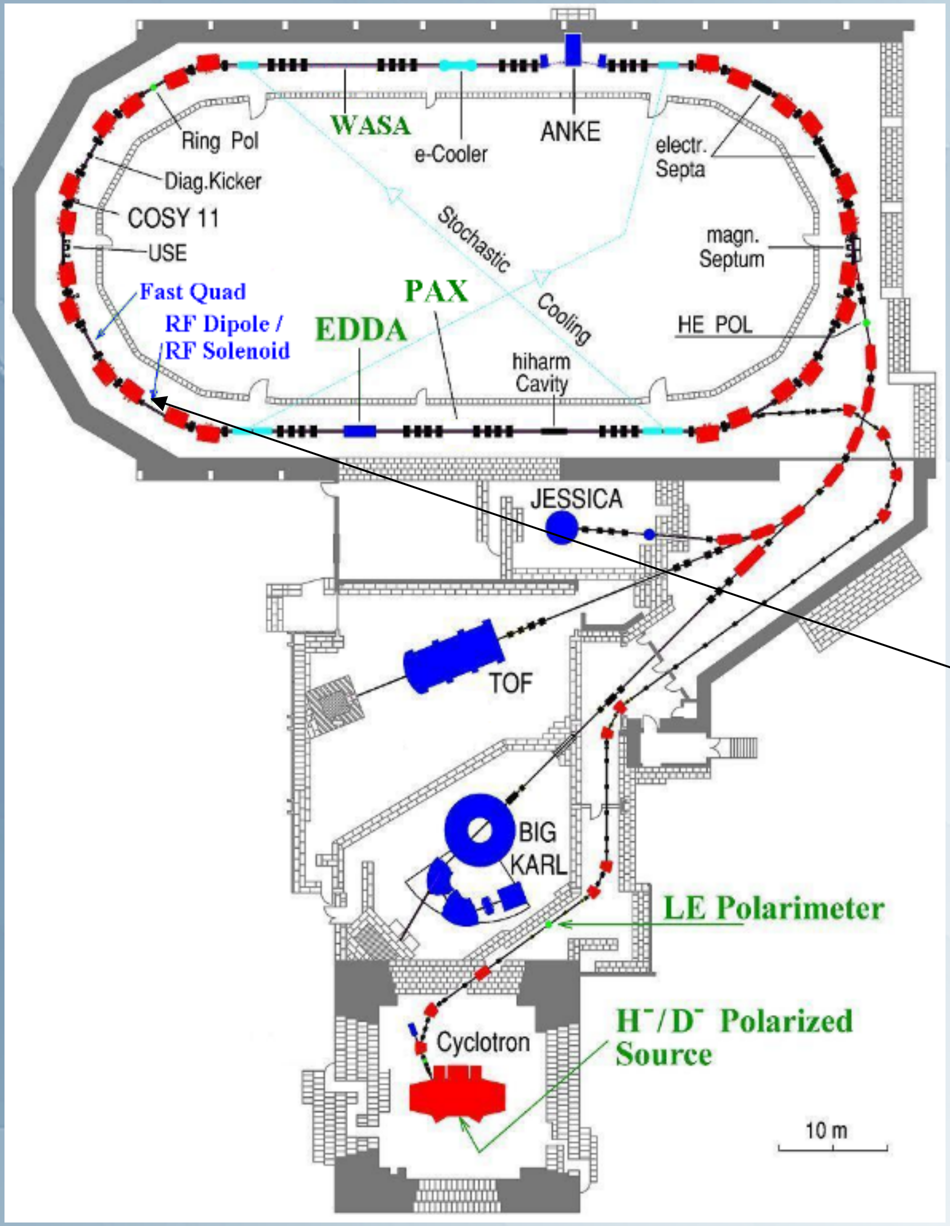
	Advantage	Disadvantage
1. Pure magnetic ring	Existing (COSY upgrade)	Lower sensitivity
2. Pure electric ring	No B field	Only p
3. Combined ring	Works for p, d, ^{3}He	Both E and B required

COoler SYnchrotron (FZ-Jülich, GERMANY)

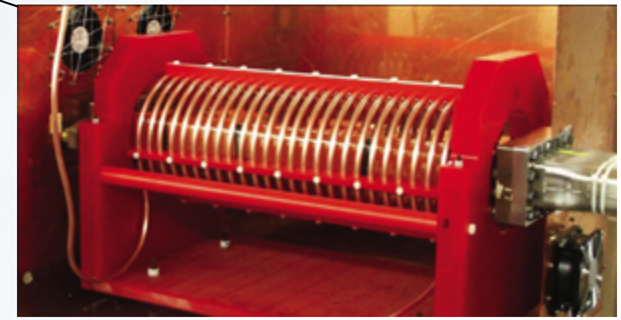
- COSY provides polarized protons and deuterons with p = 0.3–3.7 GeV/c

Ideal starting point for charged particles EDM search

COoler SYnchrotron (FZ-Jülich, GERMANY)

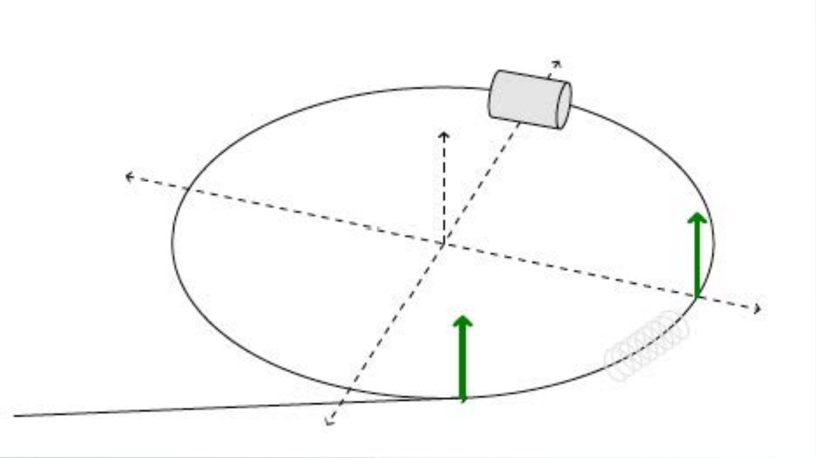


- Momentum: <3.7 GeV/c
- Circumference: 183 m
- **Polarized** proton and **deuteron**
- **Beam polarimeter (EDDA detector)**
- Instrumentation available for **manipulation of polarization** (RF solenoid)



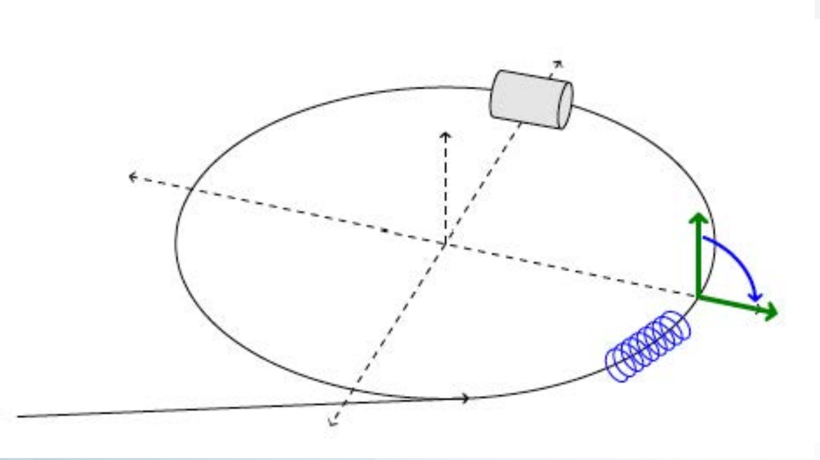
Experimental tests at COSY

- Inject and accelerate polarized deuterons to 1 GeV/c



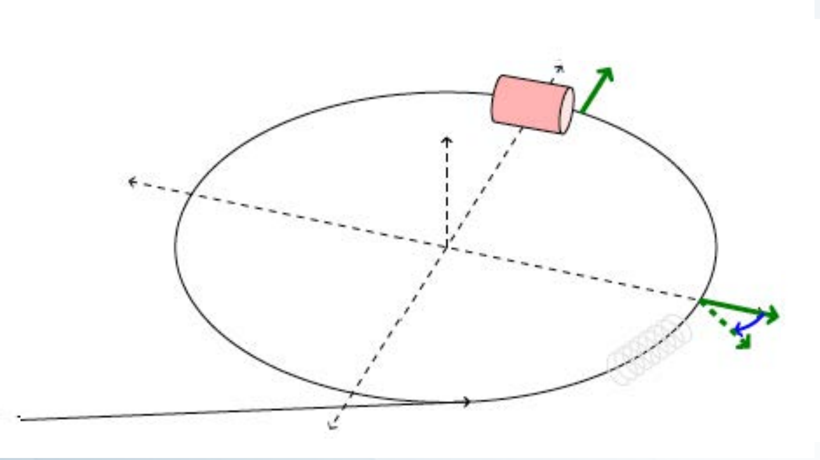
Experimental tests at COSY

- Inject and accelerate polarized deuterons to 1 GeV/c
- Flip spin in the horizontal plane with help of solenoid

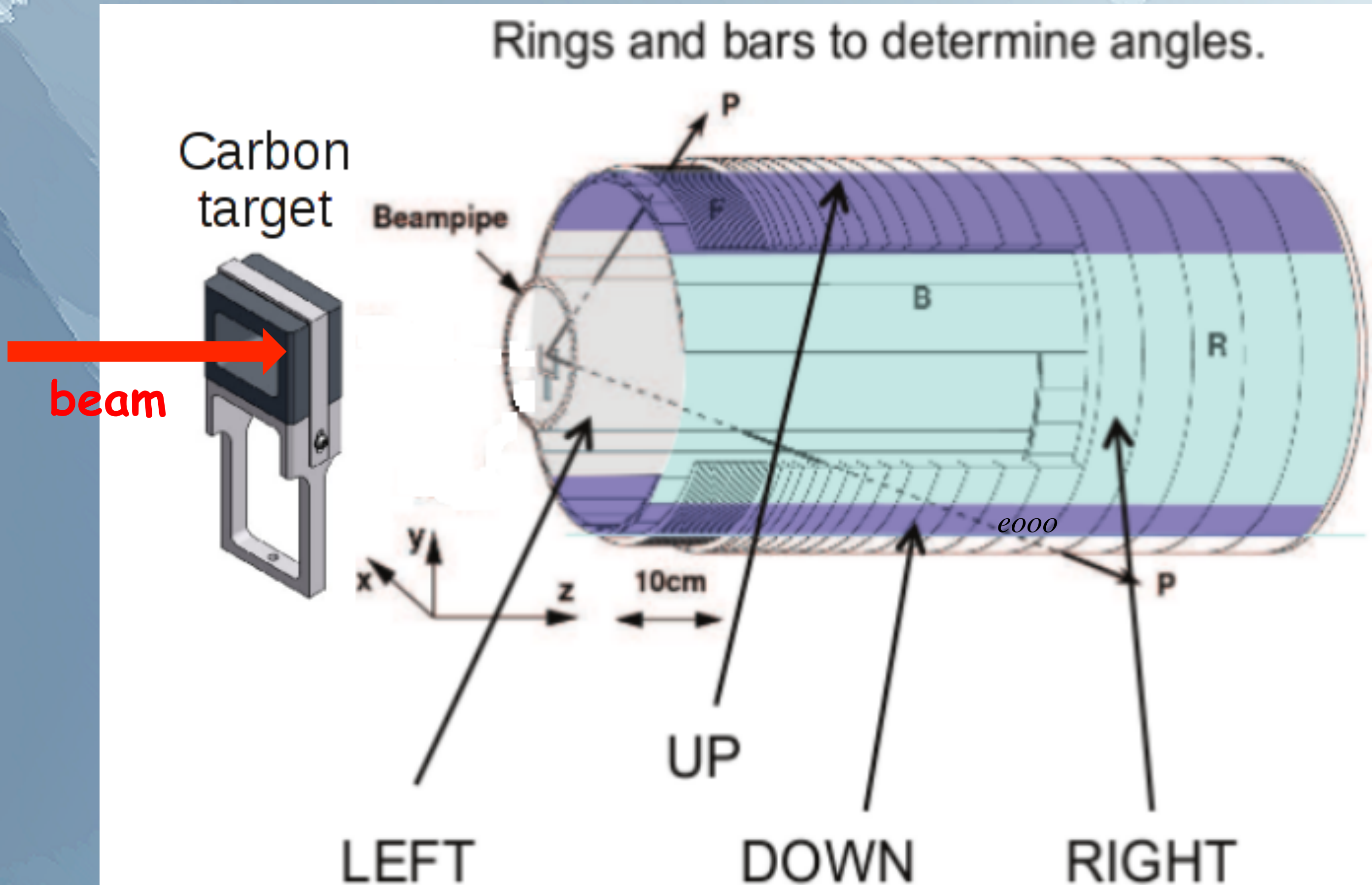


Experimental tests at COSY

- Inject and accelerate polarized deuterons to 1 GeV/c
- Flip spin in the horizontal plane with help of solenoid
- Extract slowly (100 s) beam on target
- Measure asymmetry and determine spin precession



EDDA beam polarimeter



ASYMMETRIES

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

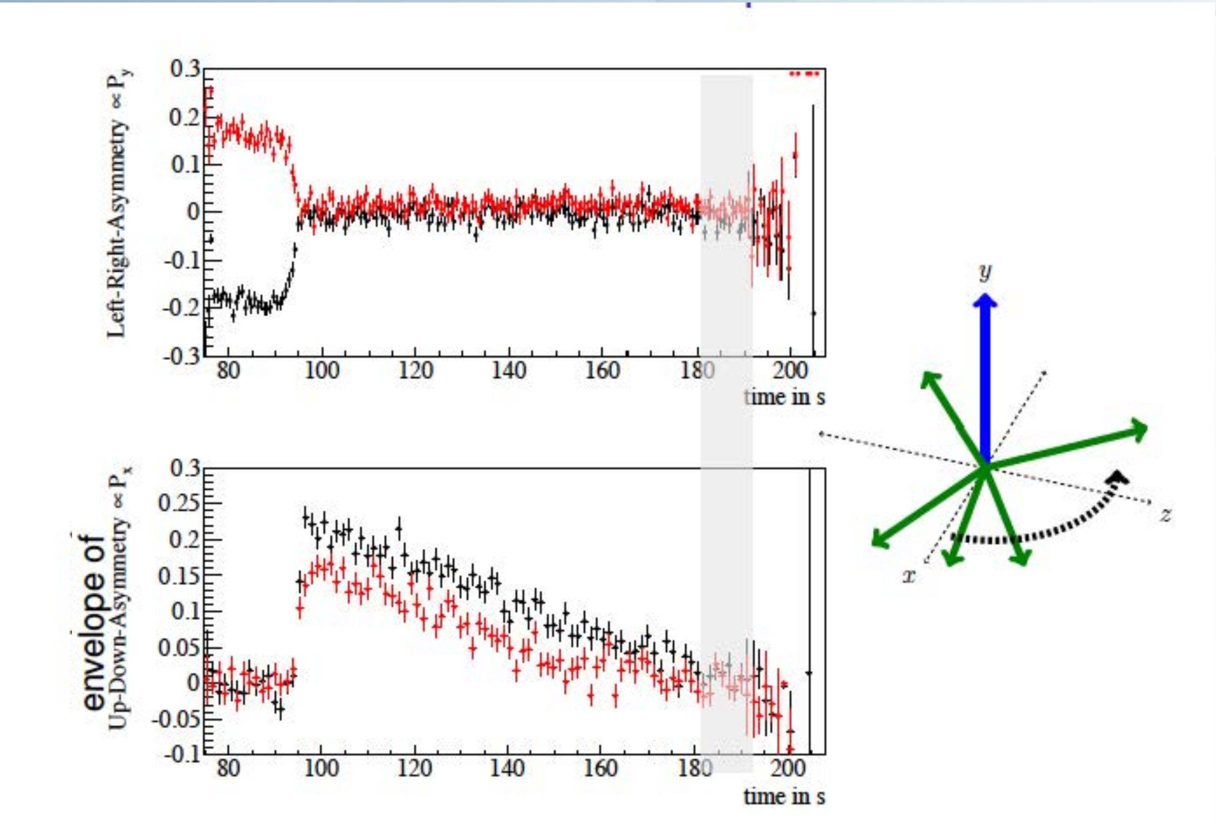
VERTICAL polarization **Analyzing power**

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

HORIZONTAL polarization **Analyzing power**

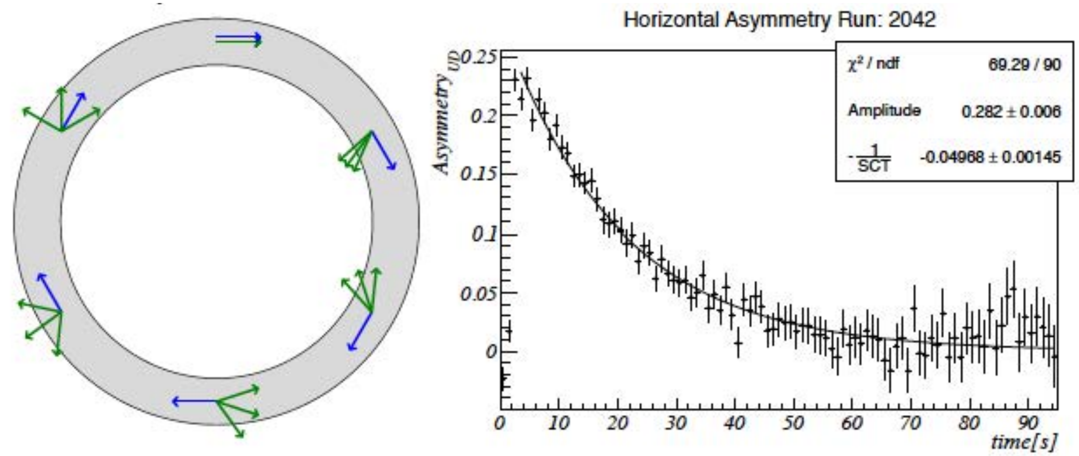
- Beam moves toward thick target $\longrightarrow$ **continuous extraction**
- Elastic scattering (large cross section for d-C)

Spin-precession measurement



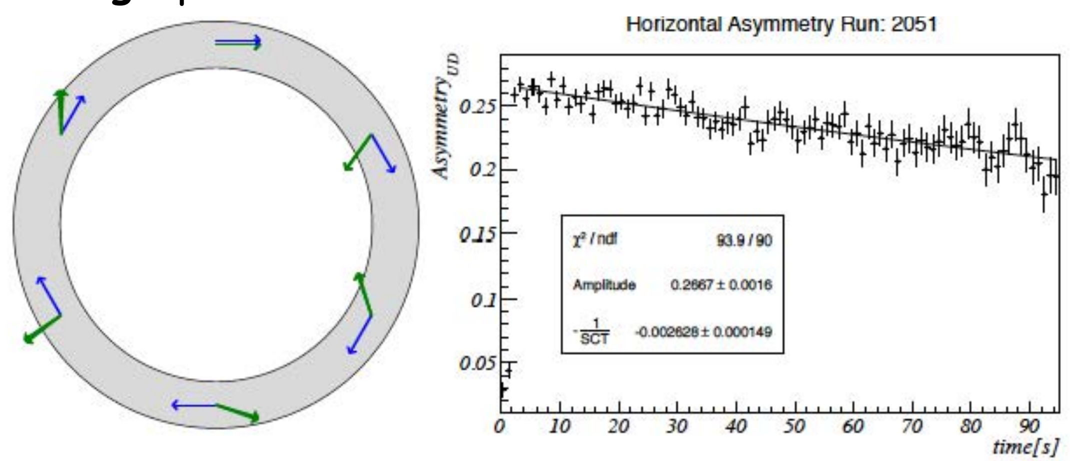
Results: spin coherence time

- **Short** Spin coherence time:



- Unbunched beam:
  - $\Delta p/p=10^{-5}\rightarrow\Delta\gamma/\gamma=2\times10^{-6}$, $T_{rev}=10^{-6}$s
  - Decoherence after < 1s
- Bunching eliminates 1st order effect in $\Delta p/p$:
  - SCT τ = 20 s

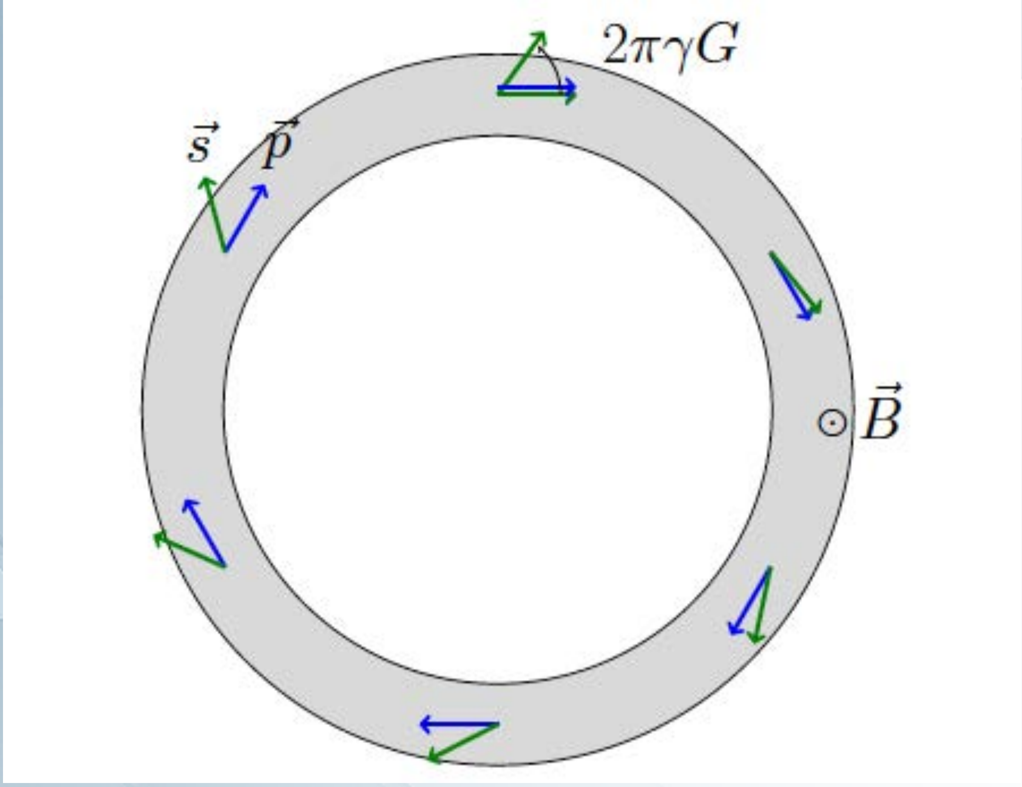
- **Long** Spin coherence time:



- Betatron oscillations cause variation of orbit length
  - Correction wit sextupoles
- SCT τ = 400 s

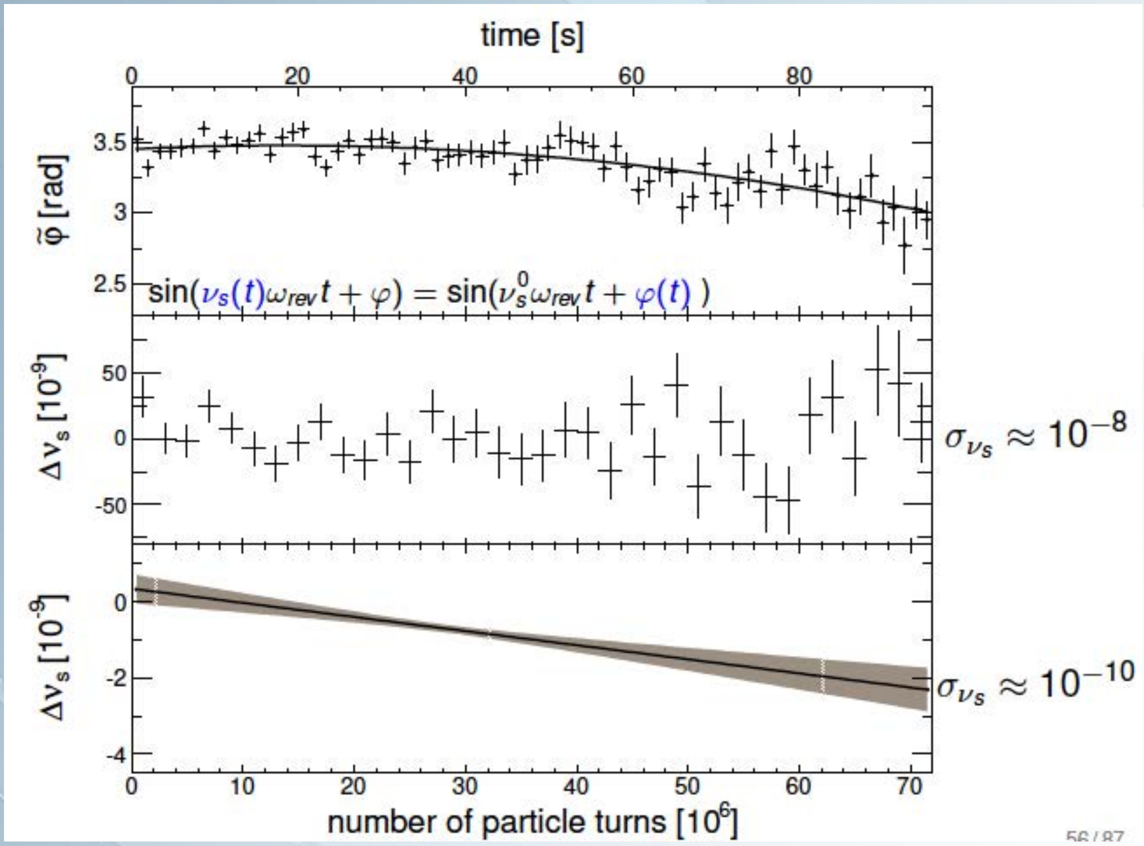
Spin-tune

- Spin tune $\nu_s = \gamma G$ = nb. of spin rotations/nb. of particle revolutions



- Deuterons: p_d= 1 GeV/c (γ=1.13), G = - 0.14256177 (72) -> $\nu_s = \gamma G \approx$ - 0.161

Results: Spin-tune measurement



- Precision: 10^{-10} in one cycle of 100 s (angle precision: $2\pi \times 10^{-10}$ = 0.6 nrad)

- It can be used as a tool to investigate systematic errors
- Feedback system to keep polarization aligned with momentum in a dedicated ring or at with respect to RF Wien filter (-> next slides)

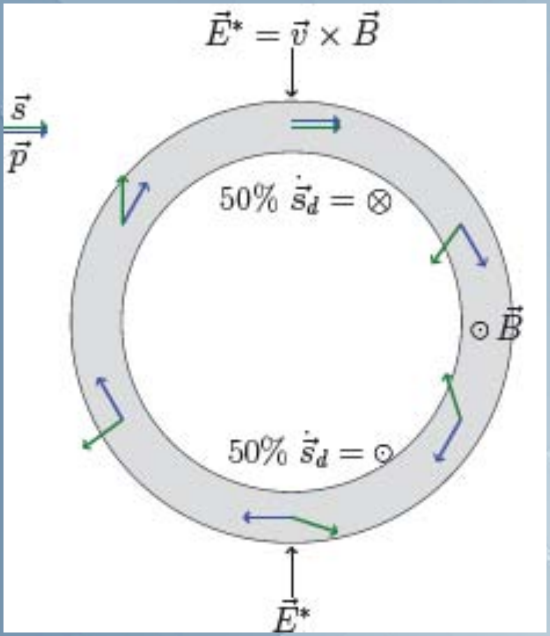
Application: Spin feedback system

- Simulation of an EDM experiment using μ:

The goal: first direct measuerement of deuteron EDM with RF-technique

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

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

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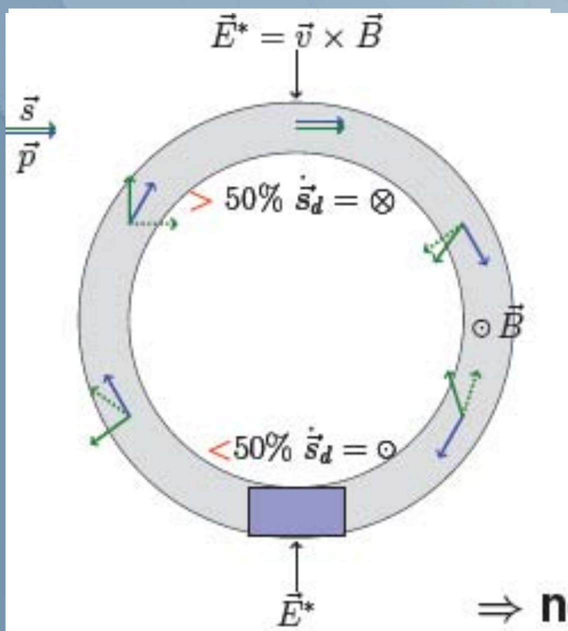


Solution; use of resonant „magic“ Wien-filter in ring (E+vxB=0)

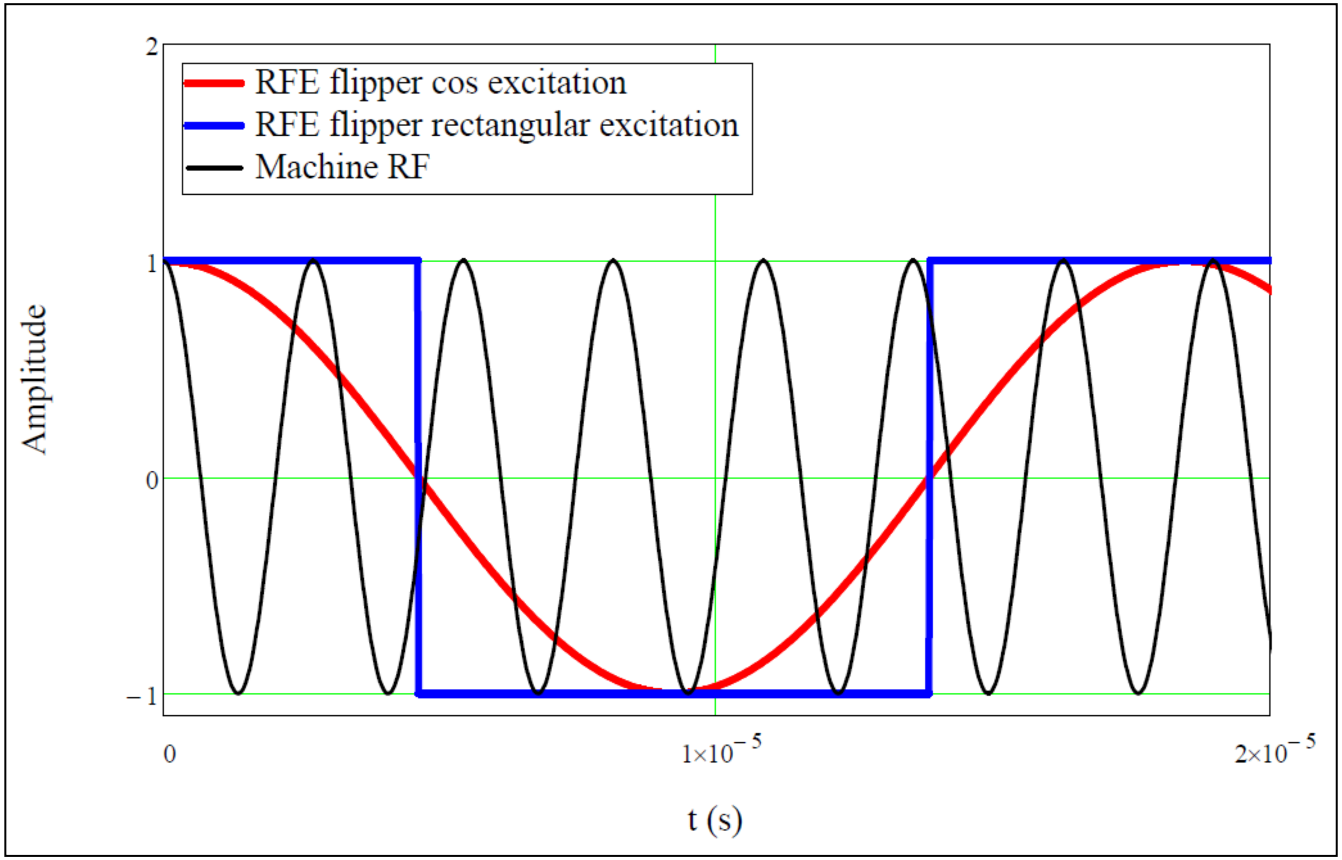
E*=0 → particle trajectory not affected
B*≠0 → magnetic moment is influenced

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

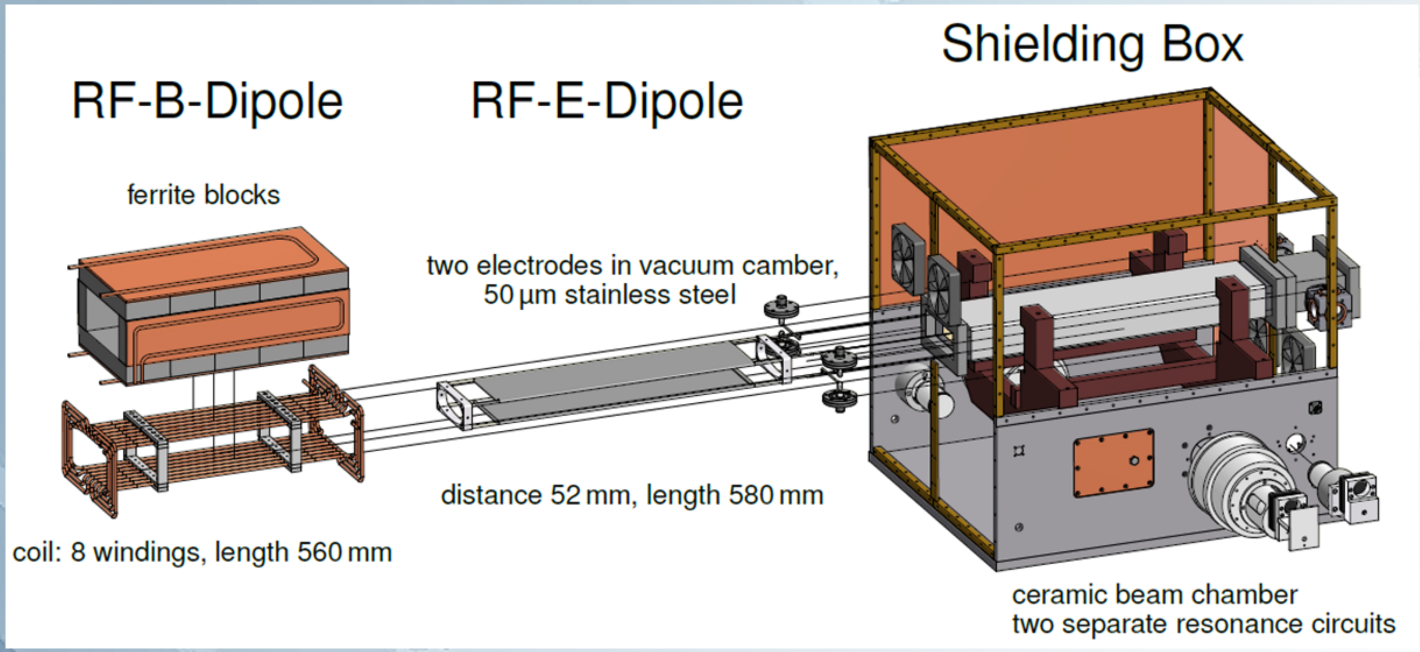
Operation of „magic" RF Wien filter

- Oscillating radial E and B fields.

beam energy
T_d=50 MeV



RF-Wien filter



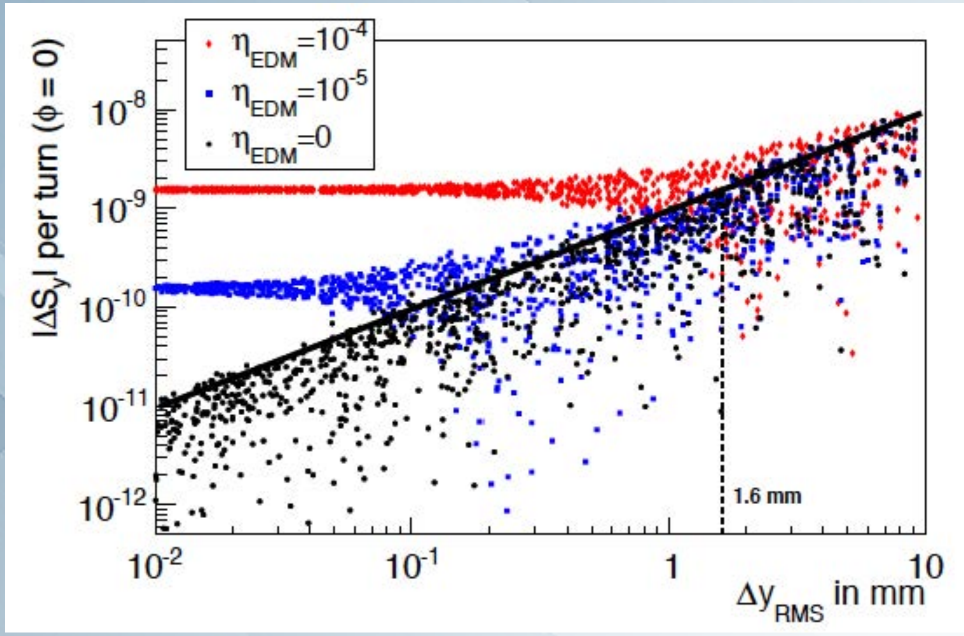
$\Rightarrow E_R = -\gamma \times B_y$ „Magic RF Wien Filter" no Lorentz force

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

- Prototype commissioning in 2015
- New RF stripline Wien filter to be installed at COSY beginning of 2017.

Simulations and Projections

- EDM signal is build-up of vertical polarization
- Radial magnetic field mimic same build-up
  - Eg: misalignments of quadrupoles cause unwanted B_r
- Run simulations to understand systematics effects
- General problem: track 10^9 particles for 10^9 turns!



Simulation by M. Rosenthal

- Orbit RMS Δy_{RMS} is a measure of misalignments
- Random misalignments from 1 μm to 1 mm
- $\eta = 10^{-5}$ corresponds to EDM of 5×10^{-20} e cm

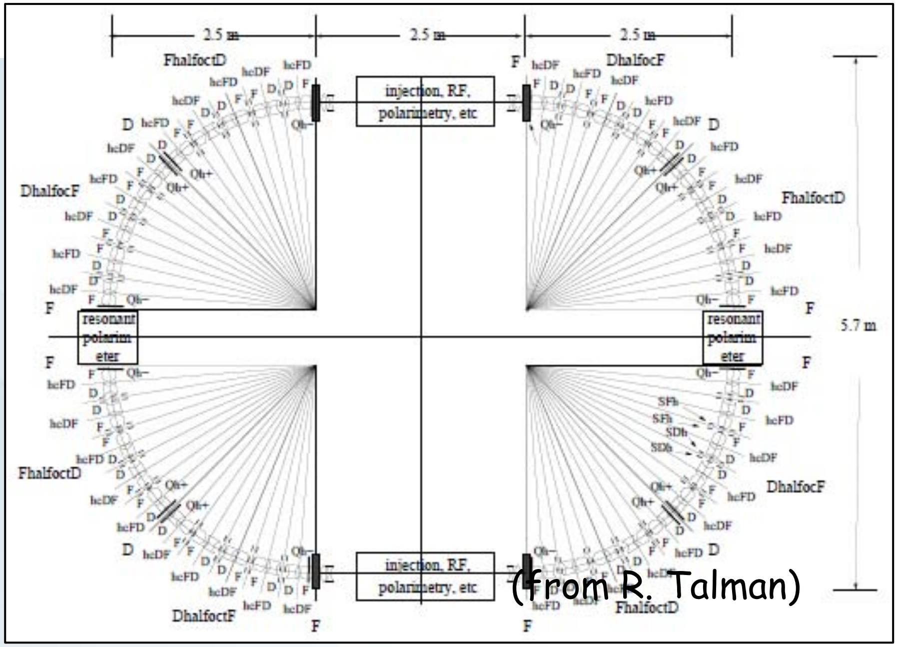
Summary and Outlook

- EDMs high sensitive probes of CP violation.
- Storage ring and polarization technology pave the way to charged particle EDM.
- First promising results at COSY:
  - Spin coherence time: few hundred seconds.
  - Spin tune measurement: 10^{-10} in 100 s.
  - Spin feedback system: allows to control spin.
  - Simulations: to understand systematics.
- Goal: first direct measurement of deuteron EDM in 2018-19
- Technical design report for a dedicated machine.

- 2016 – ERC – AdG "EDM – search in Storage rings"
  - Consortium:
    - FZJ (prof. H. Stroeher)
    - RWTH – Aachen (prof. J. Praetz)
    - University of Ferrara (prof. P. Lenisa)

Electrostatic electron ring

- First ever DIRECT measurement of electron EDM.
- Compact
  - Magic energy for electron: 14.5 MeV (γ=29.4)
  - E = 2-6 MeV/m $\rightarrow$ $2\pi R$ = 50 - 20 m
- Technical challenge, modest investment.
  - ≈ 15 (± 5) M€
  - ≈ 20 FTE
- Mandatory step for larger machines (proton and deuteron $\rightarrow$ $2\pi R$ > 250 m).
- Open issue: polarimetry.



(from R. Talman)