Search for Electric Dipole Moments with Polarized Beams in Storage Rings

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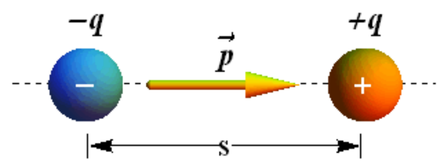
Motivation

Electric Dipoles

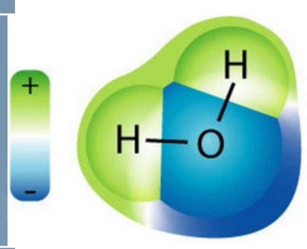
- Definition



$$p = q \cdot s$$

Charge separation creates an electric dipole

- Orders of magnitude

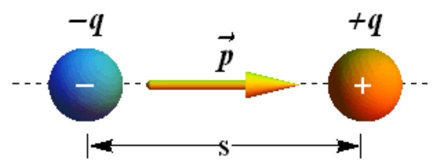


H_2O molecule: permanent EDM

	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

Electric Dipoles

- Definition



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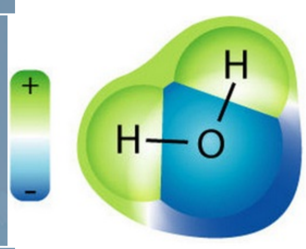
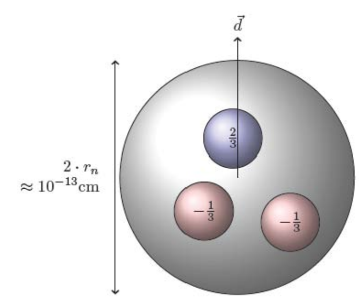


H_2O molecule:
permanent EDM

	Atomic physics	Hadron physics
Charges	e	e
$\lvert r_1 - r_2 \rvert$	10^{-8} cm	10^{-13} cm
EDM (naive) exp.	10^{-8} e cm	10^{-13} e cm
observed	H_2O molecule $2 \cdot 10^{-9}$ e cm	Neutron $< 3 \cdot 10^{-26}$ e cm



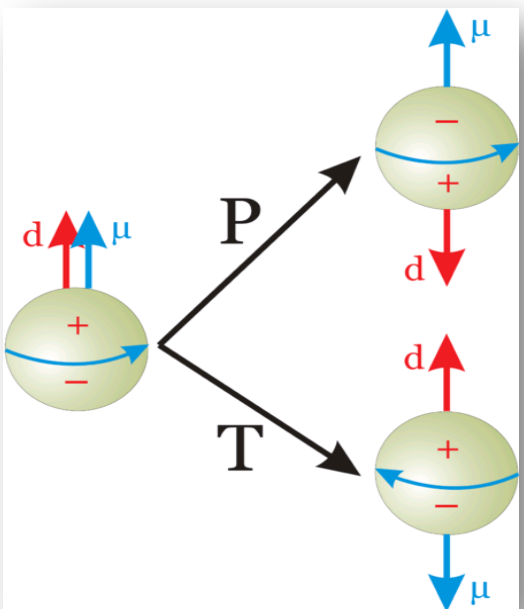
EDM $3 \cdot 10^{-26}$ e cm → charge separation < $5 \cdot 10^{-26}$ cm between u and d quarks

EDM of fundamental particles

Molecules have large EDM because of degenerate 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
(both aligned with spin)

$$H = -\mu\vec{\sigma}\cdot\vec{B} - d\vec{\sigma}\cdot\vec{E}$$

$$\mathcal{T}: \quad H = -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}$$

$$\mathcal{P}: \quad H = -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}$$

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

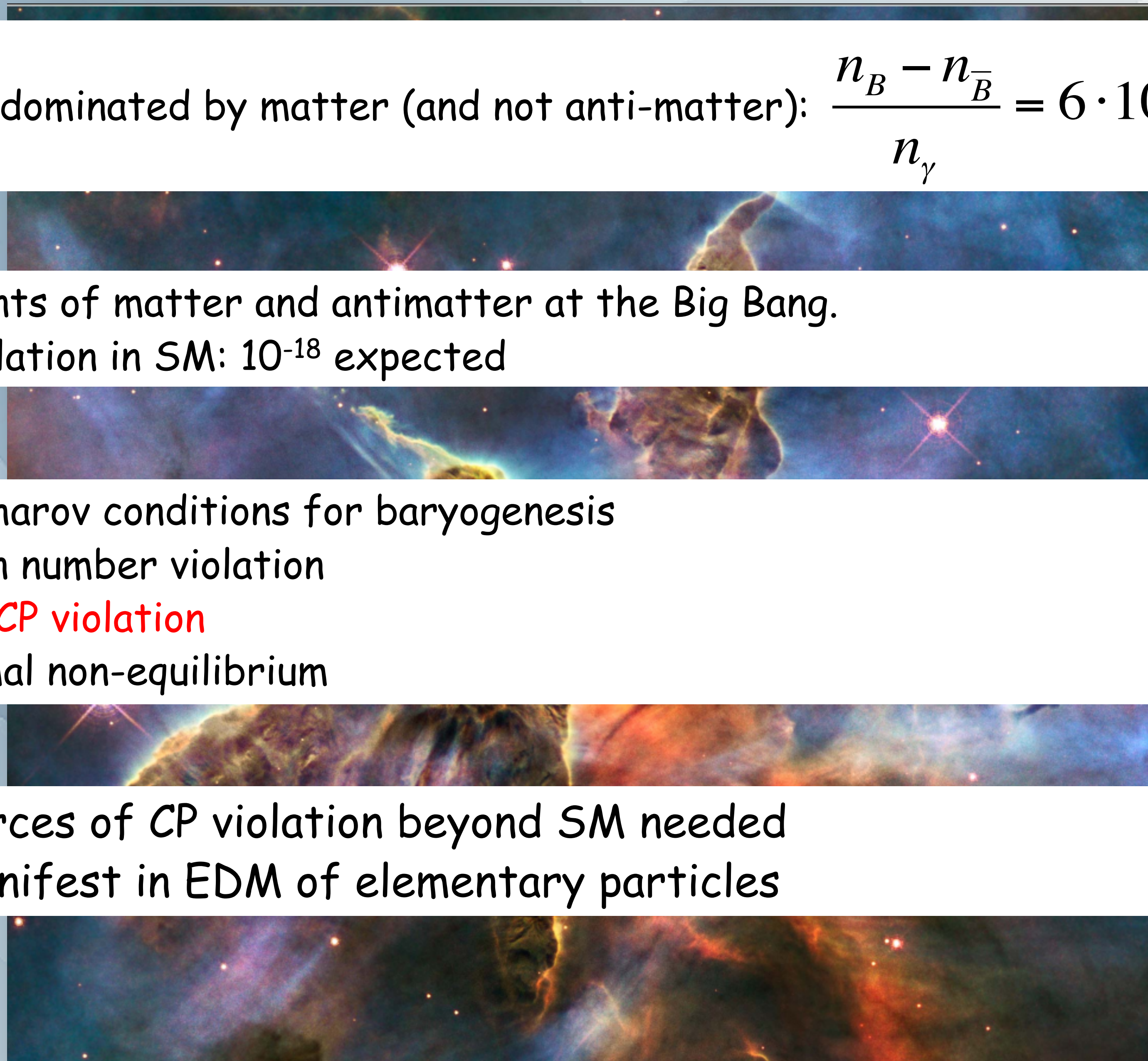
CP violation

- Universe dominated by matter (and not anti-matter): $\dfrac{n_B - n_{\bar{B}}}{n_\gamma} = 6 \cdot 10^{-10}$

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

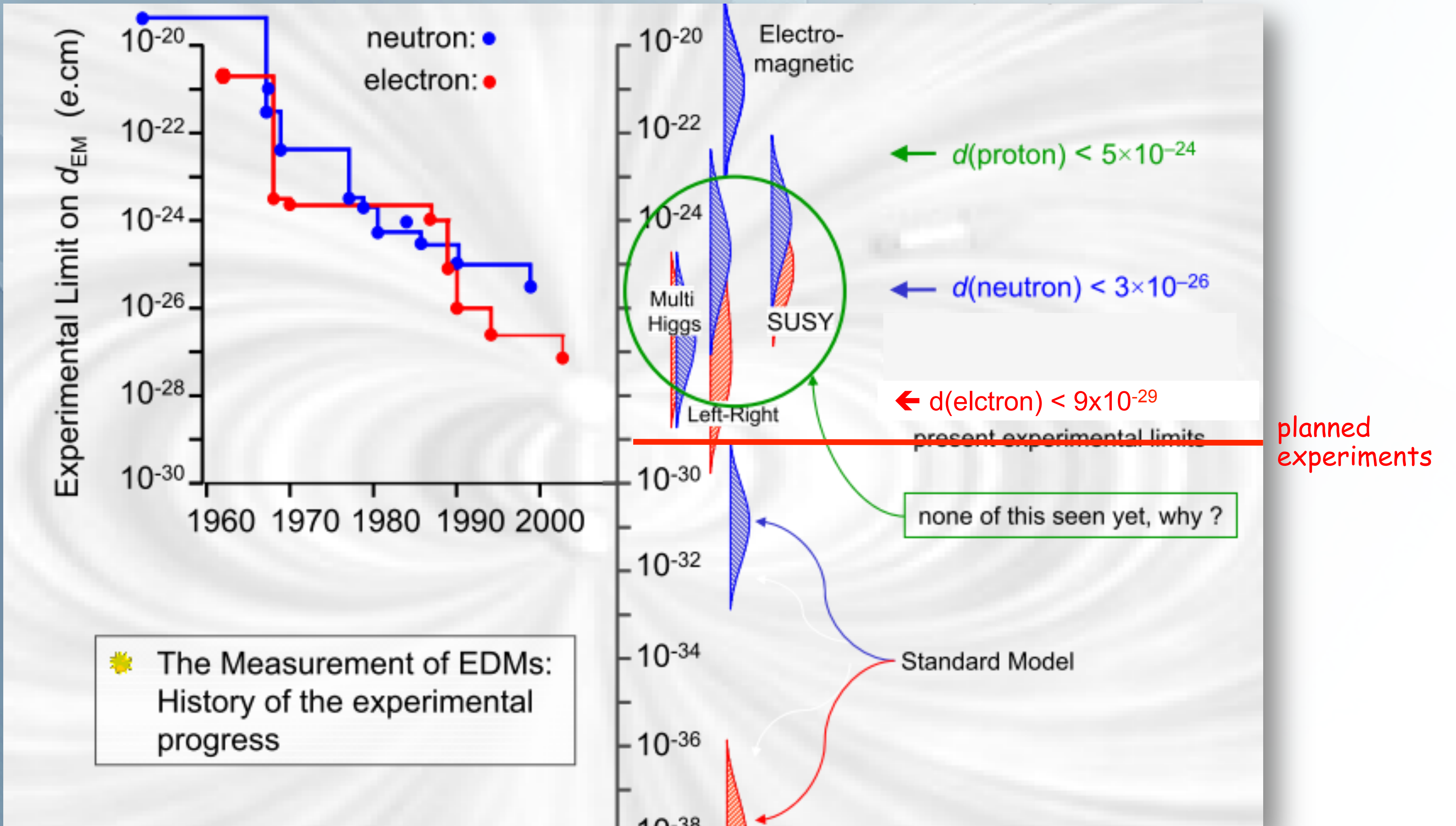
- 1967: 3 Sacharov conditions for baryogenesis
  - Baryon number violation
  - C and CP violation
  - Thermal non-equilibrium

- 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)

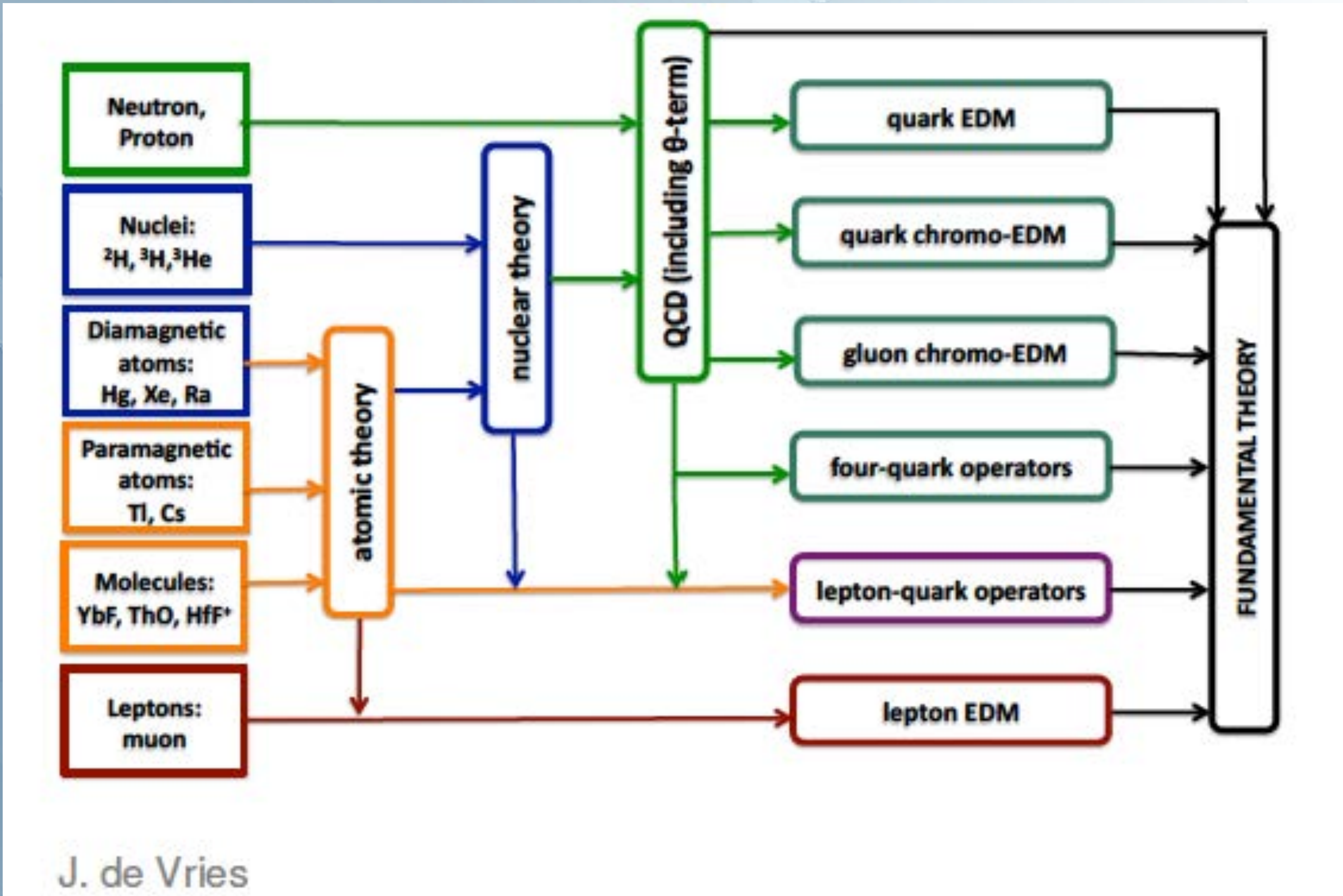
Theoretical predictions



No Standard Model Background!

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

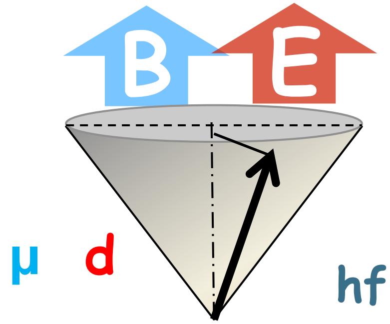
Sources of CP violation



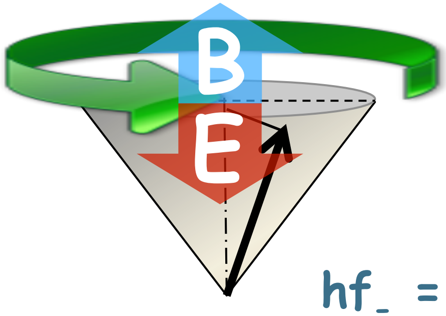
EDM searches: state of the art

- 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



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



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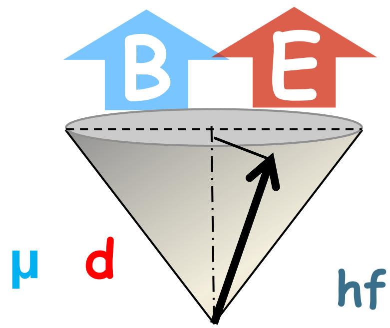

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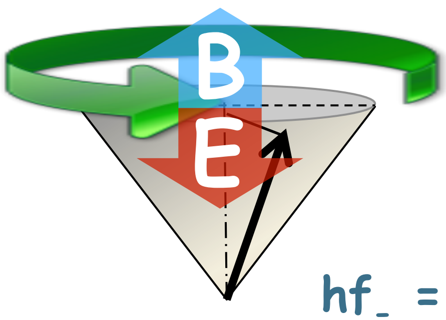

$hf_- = 2\mu B - 2dE$

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

No direct measurement of electron or proton EDM yet

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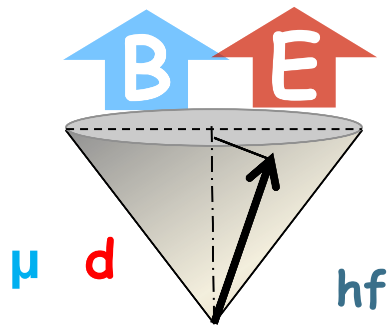

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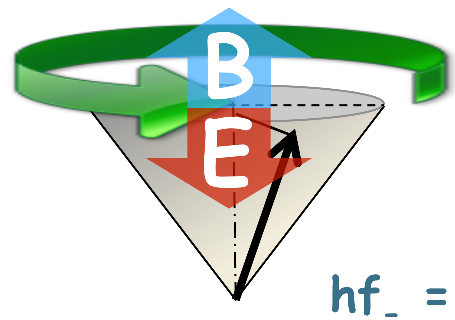


$hf_{-} = 2\mu B - 2dE$

Particle/Atom	Current EDM Limit	Future Goal	$\sim d_n$ equivalent
Electron	$< 8.9 \times 10^{-29}$		
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	?	$\sim 10^{-29}$	3×10^{-29}- 5×10^{-51}

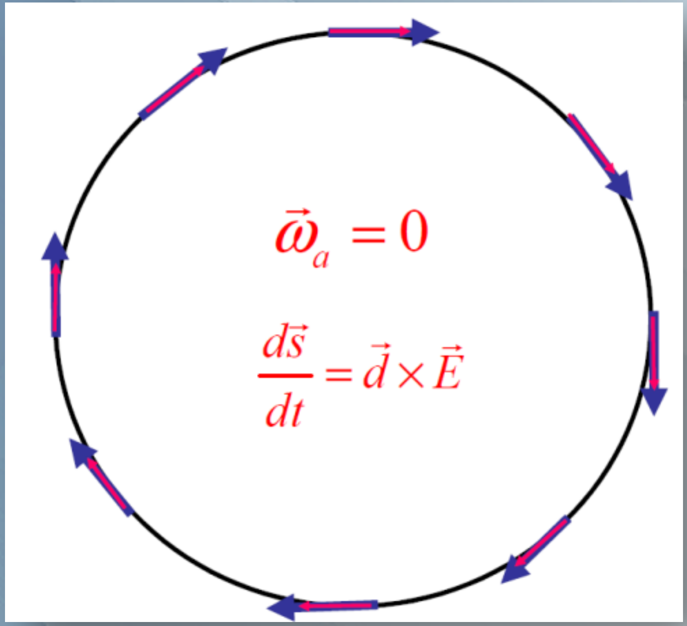
No direct measurement of electron or proton EDM yet

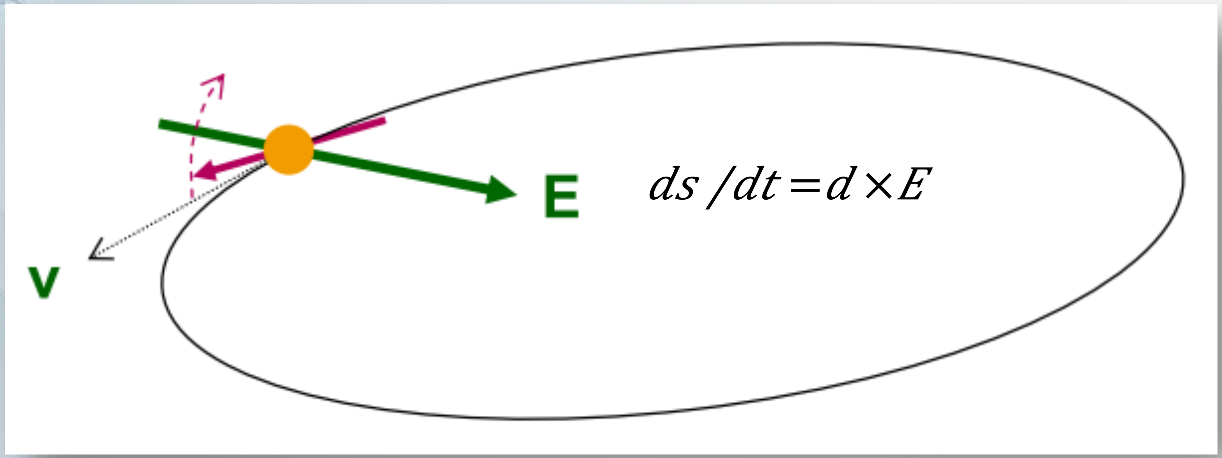
Measurement of charged particles EDM

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):

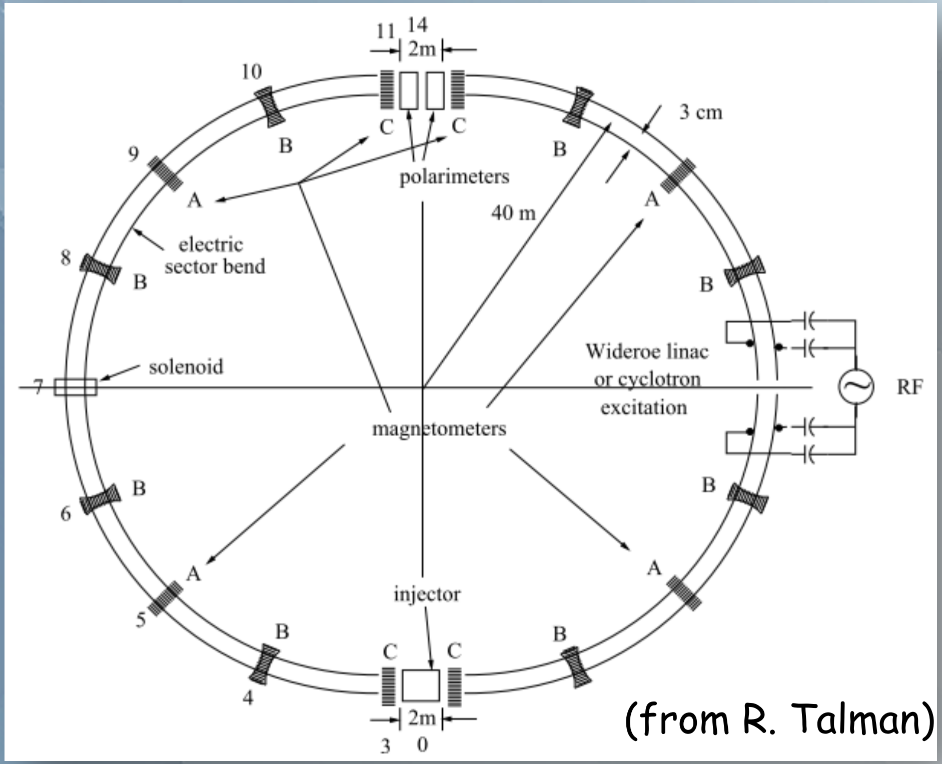
$$\left(G - \frac{1}{\gamma^2 - 1}\right) = 0$$

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

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

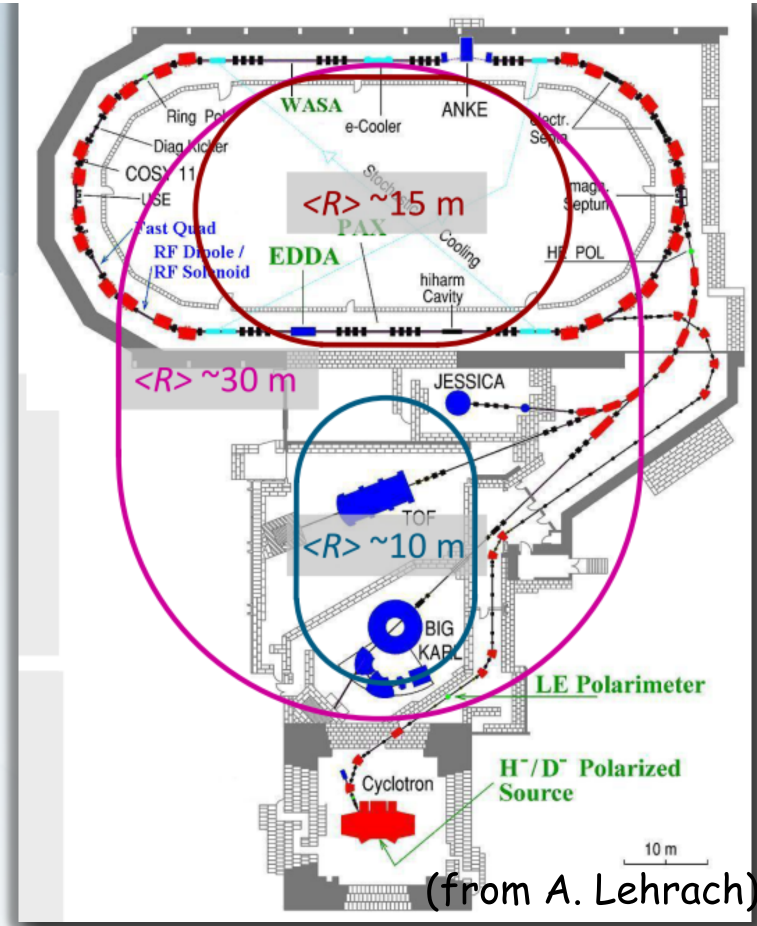
Storage ring projects

pEDM in all electric ring at BNL



CW and CCW propagating beams

Jülich, focus on deuterons, or a combined machine



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

Statistical sensitivity

$$\sigma_{stat} = \frac{h}{\sqrt{NF\tau_p PAE}}$$

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

- **Sensitivity:** $\sigma_{stat} = 10^{-29}$ e-cm/year ($\rightarrow 10^{-27}$ e-cm/week)
- **Challenge:** bring σ_{syst} at the same level

Technological challenges

- SYSTEMATIC ERROR PLAN
- PROTON BEAM POSITION MONITORS (<10 nm)

Systematics

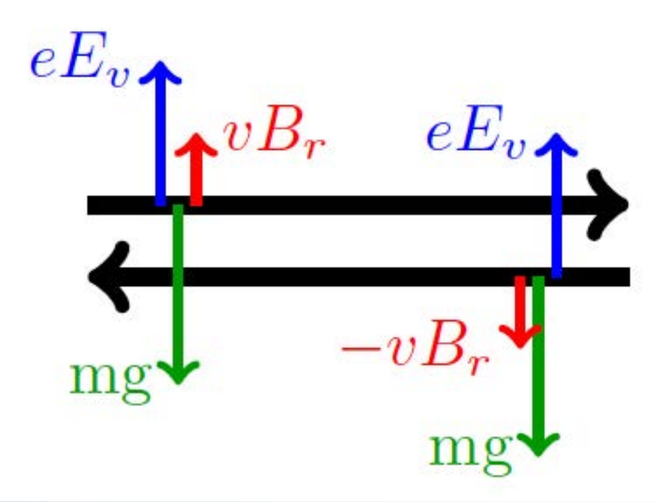
- One major source:
  - Radial B_r field mimics EDM effect
  - Example: d = 10^{-29} e cm with E = 10 MV/m
  - If $\mu B_r \approx dE_r$ this corresponds to a magnetic field:

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

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

Use of two counterpropagating beams

- Solution:
  - Use two beams running clockwise and counterclockwise
    - Separation of the two beams proportional to B_r



BPM with relative resolution < 10 nm required

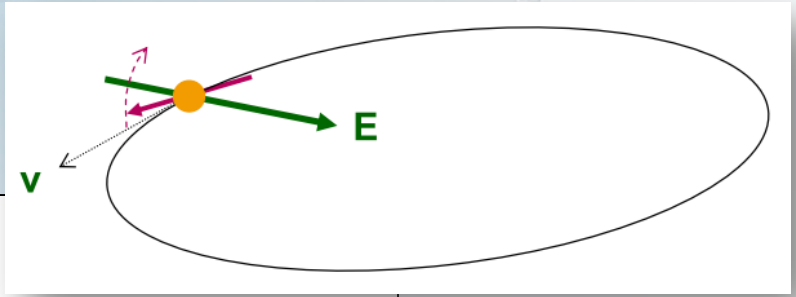
- *use of SQUID magnetomers (fT/√Hz) ? → Study started at FZJ*

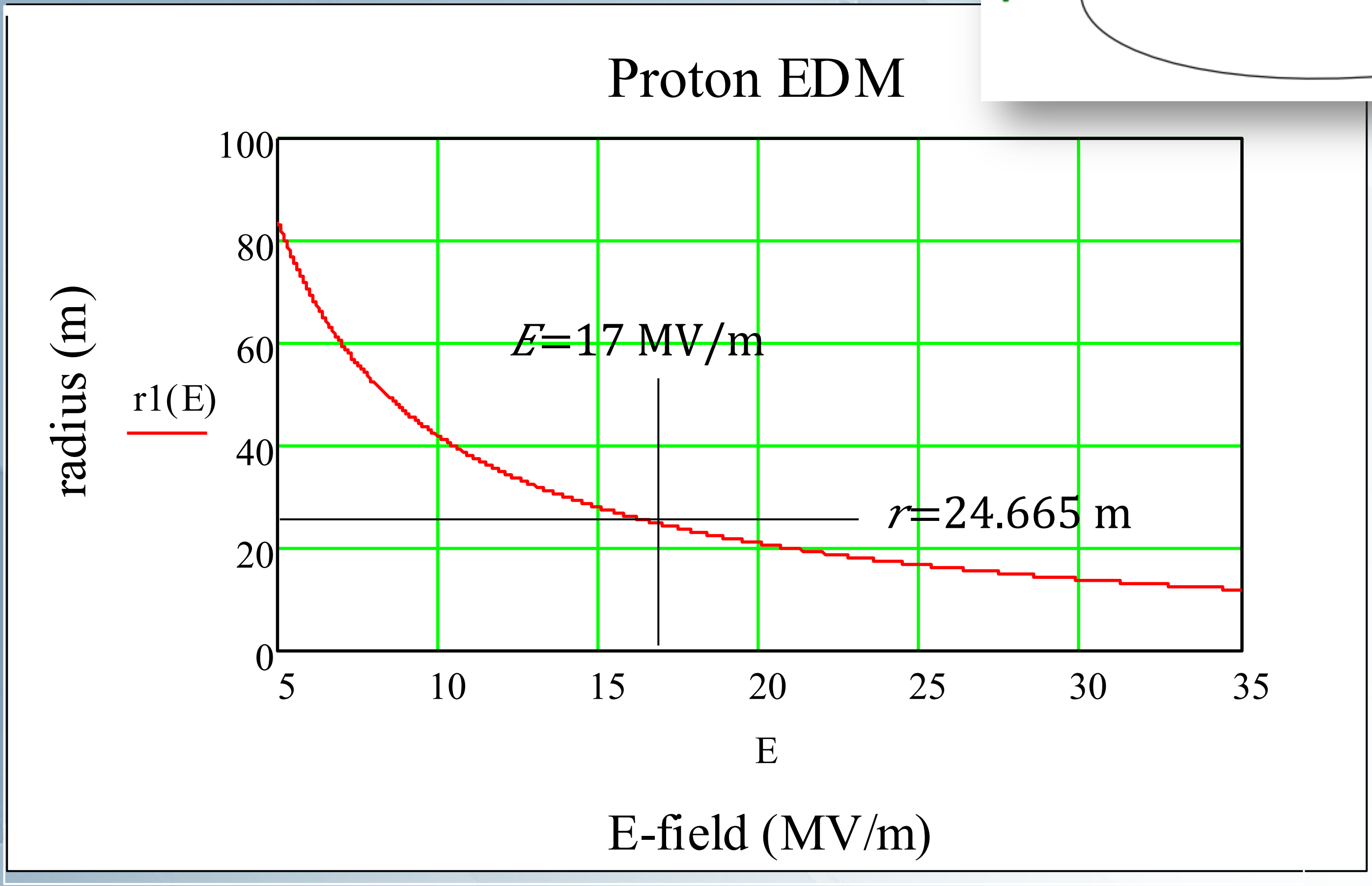
Technological challenges

- 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 $p\,p$ interactions
- electrodes made from Titanium

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

Summer 2014: Separator unit plus equipment transferred 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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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.

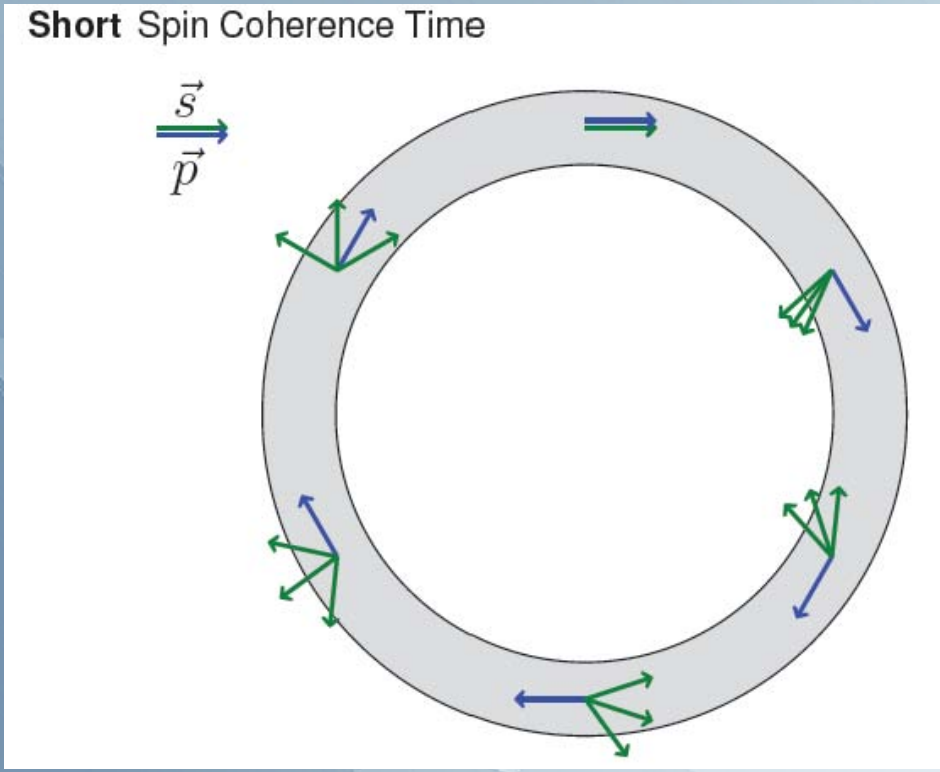
Results of first test measurements

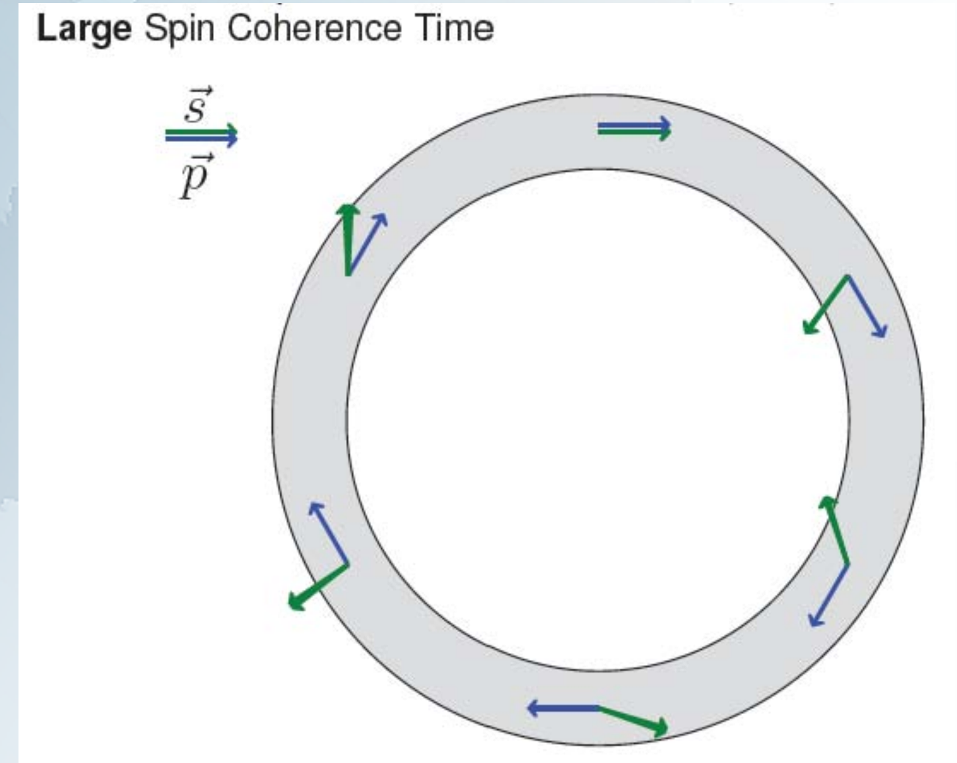
COoler SYnchrotron (FZ-Jülich, GERMANY)

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

Ideal starting point for charged particles EDM search

Spin coherence time τ_{sc}





Request for EDM experiment: τ_{sc} > 1000 s

Decoherence: where does it arise?

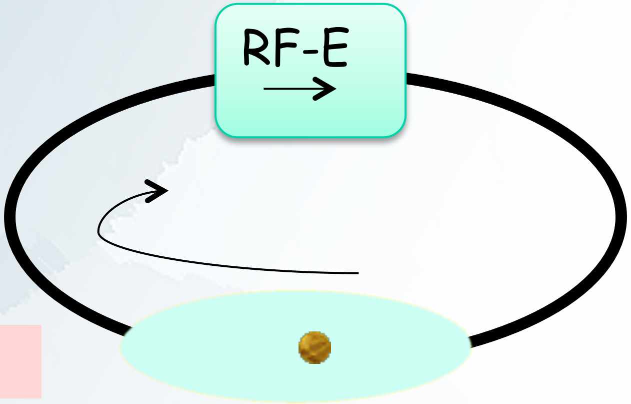
LONGITUDINAL PHASE SPACE

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

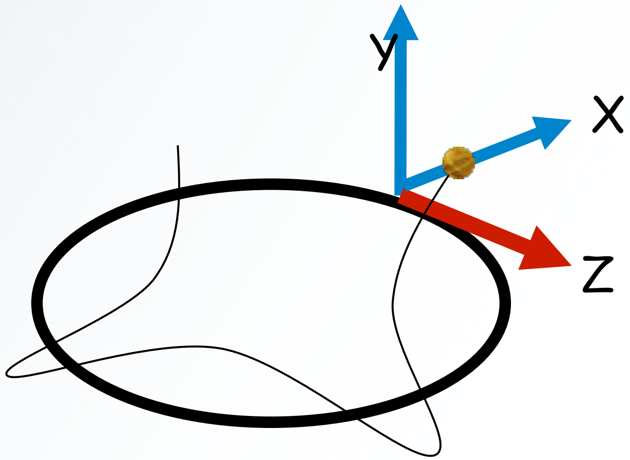
Problem: beam emittance ≠ 0 → betatron oscillations

Δx (Δy) from reference orbit

→ Longer path: $$\frac{\Delta L}{L} = \frac{\theta_x^2 + \theta_y^2}{4}$$

→ Higher particle speed → $\Delta\nu_s$

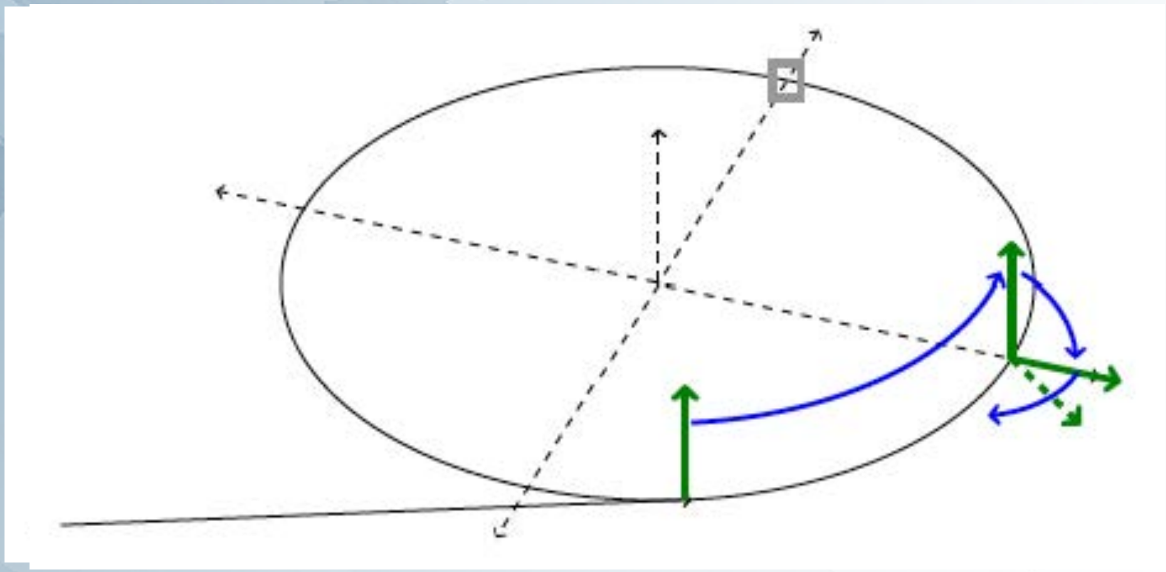
- *E.g.* $\theta = 1\cdot$ *mrad* $\rightarrow \tau_{pol} = 9.9$ *s*



Possible solution to this problem investigated at COSY

Experimental setup

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

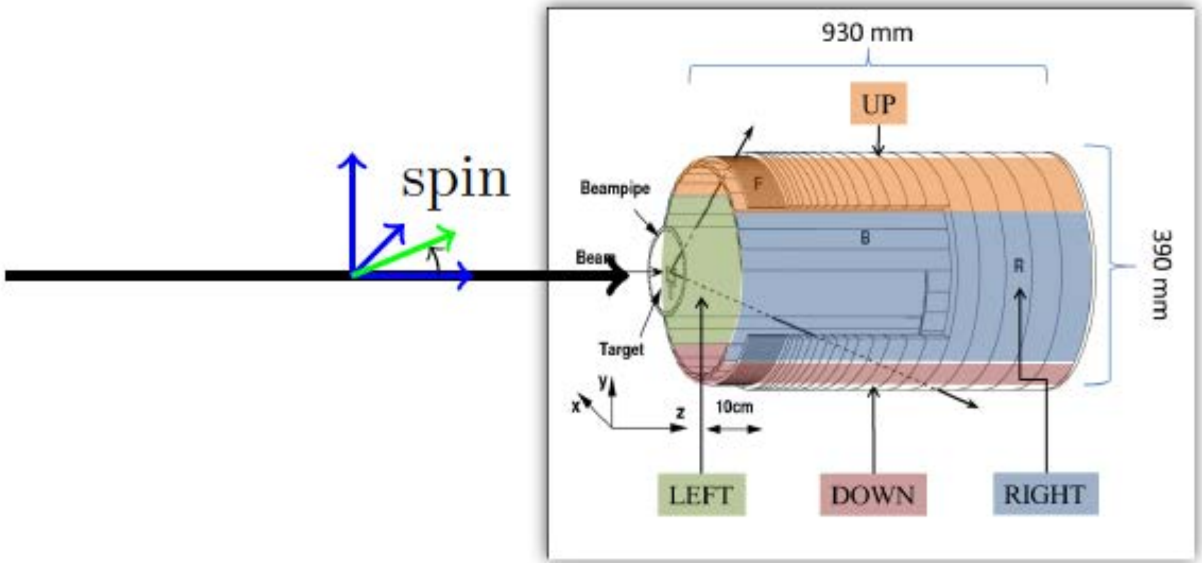


Polarimeter

elastic deuteron-carbon scattering

Up/Down asymmetry $\propto$ horizontal polarization $\rightarrow \nu_s = \gamma G$

Left/Right asymmetry $\propto$ vertical polarization $\rightarrow d$



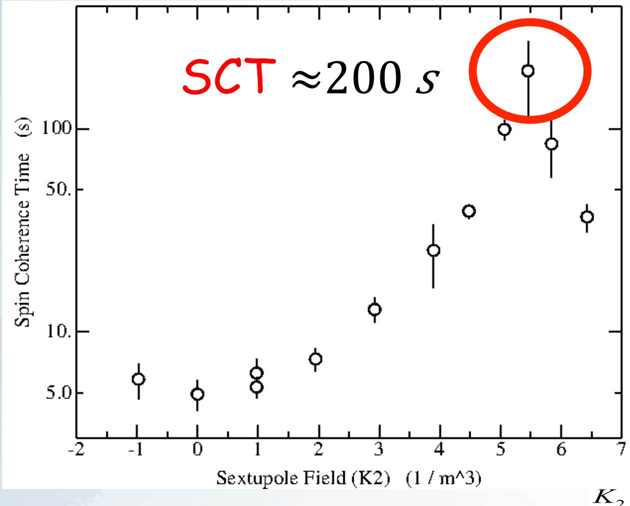
$$N_{up,dn} \propto 1 \pm PA\sin(\nu_s f_{rev} t), \quad \nu_s f_{rev} \approx 125\,\text{kHz}$$

Results: spin-coherence time measurement

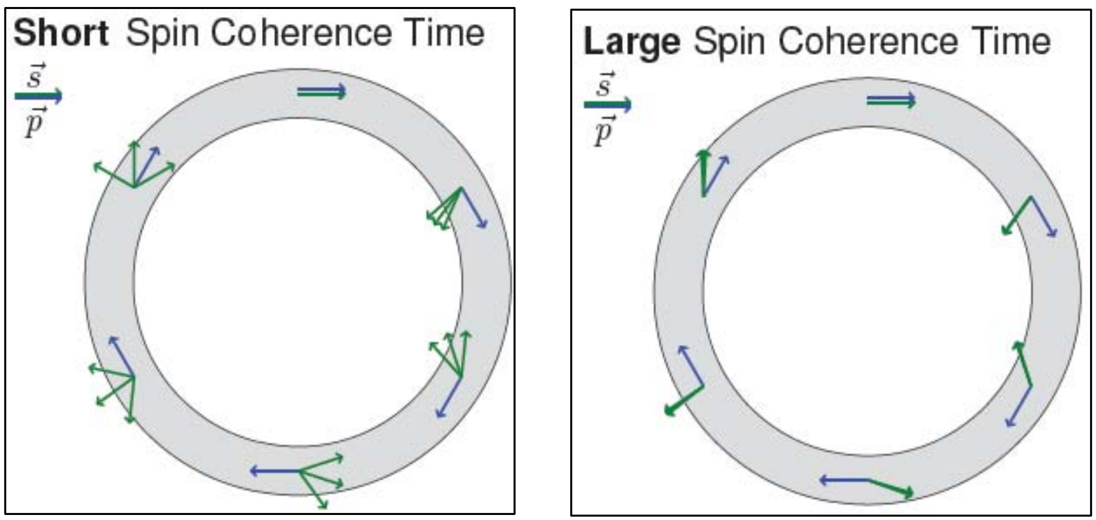
Compensation by means of 6-pole fields (β_x osc.):

$1/\tau_{SCT} = A\langle\theta^2_x\rangle + a\langle\theta^2_x\rangle$ 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 >4×10^8 revolutions!
- Previous best 10^7 @ Novosibirsk

MILESTONE FOR THE FIELD!

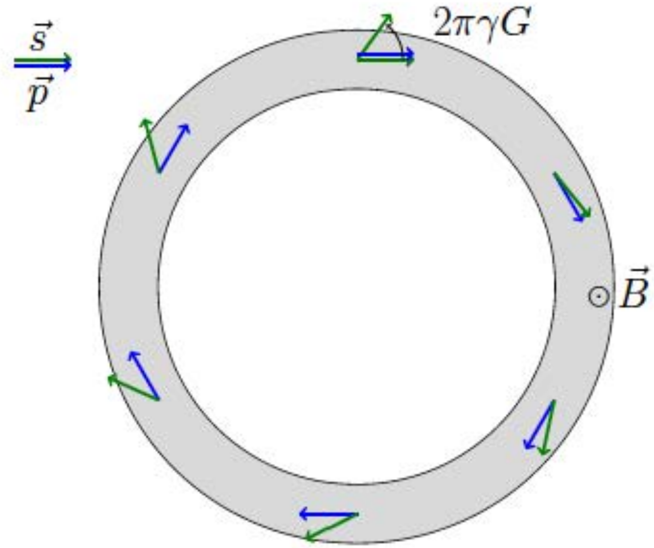
It has been demonstrated that the spin-coherence time may be extended up to 1000 s through:

- Beam bunching
- Electron cooling
- Orbit corrections with 6-poles families

This meets the requirements for a storage ring to search for an EDM!

Spin tune: $\nu_s=\gamma G$

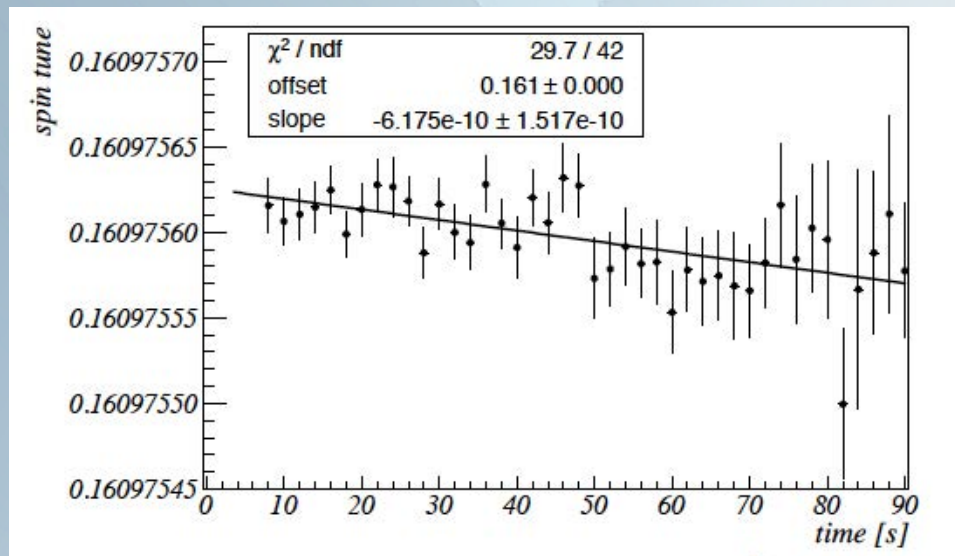
Spin tune: $\nu_s = \gamma G = \dfrac{\text{nb. of spin rotations}}{\text{nb. of particle revolutions}}$



deuterons: $p_d = 1$ GeV/c ($\gamma = 1.13$), $G = -0.14256177(72)$

$\Rightarrow \nu_s = \gamma G \approx -0.161$

Results: spin tune measurement



- Spin tune can be determined to ≈ 10^{-8} in 2s
- Average ν_s in cycle (≈100 s) determined to 10^{-10}
- $\nu_s \approx \gamma G$ varies within one cycle (and from cycle to cycle) ≈ 10^{-8}

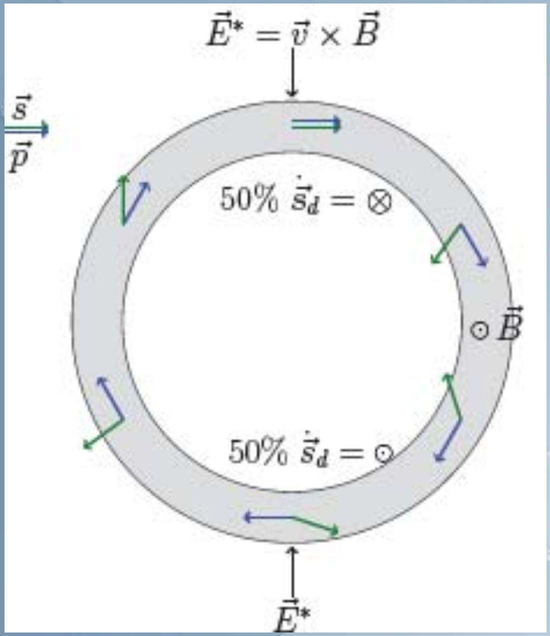
Experiment	Gedankenexperiment
$G \approx -0.14,\ d \approx 0$	$G = 0,\ d = 10^{-24} e\,\mathrm{cm}$
$\nu_s = \gamma G = -0.16$	$\nu_s = \frac{v m \gamma d}{e s} = 5 \cdot 10^{-11}$

Outlook

Precursor experiment with 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-||

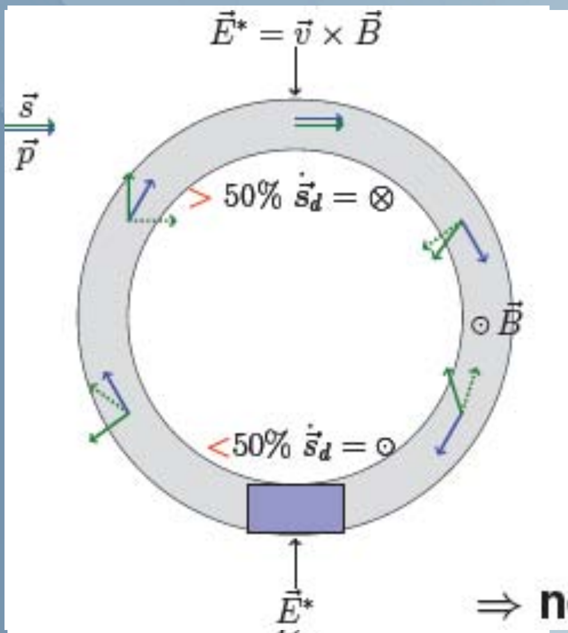
E* in particle rest frame tilts spin (due to EDM) up and down

→ No net EDM effect

OUTLOOK: Precursor experiments with 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)



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

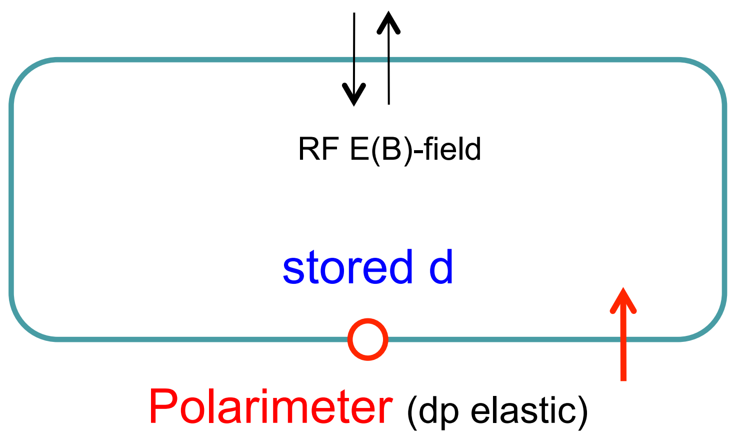
Two ways:

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.

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

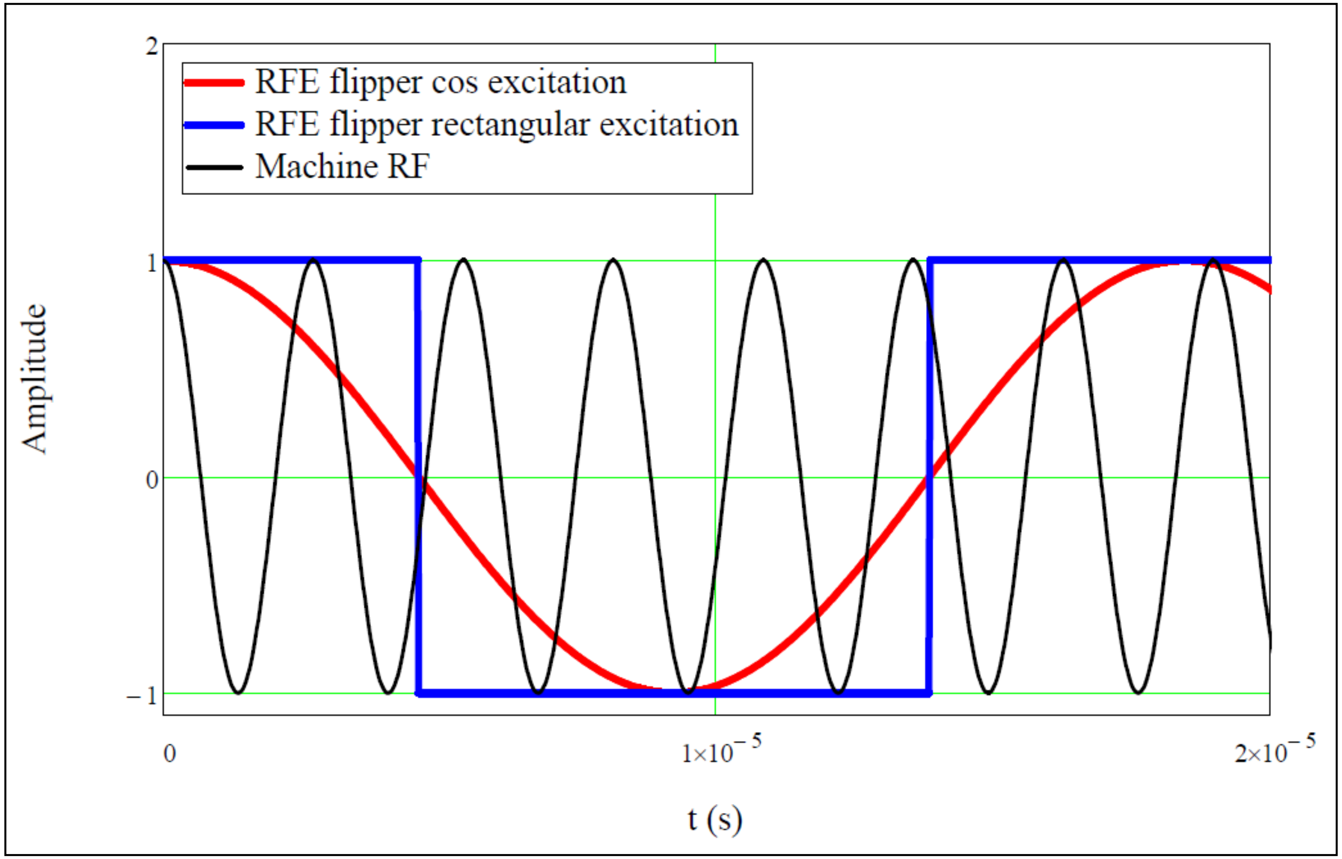


- In plane polarization
- P_y buildup during spin coherence time

Operation of „magic" RF Wien filter

Radial E and vertical B fields oscillate,

beam energy
T_d=50 MeV



Situation

- 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
    - Spin-tune measurements with unprecedented precision

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

Electrostatic electron ring

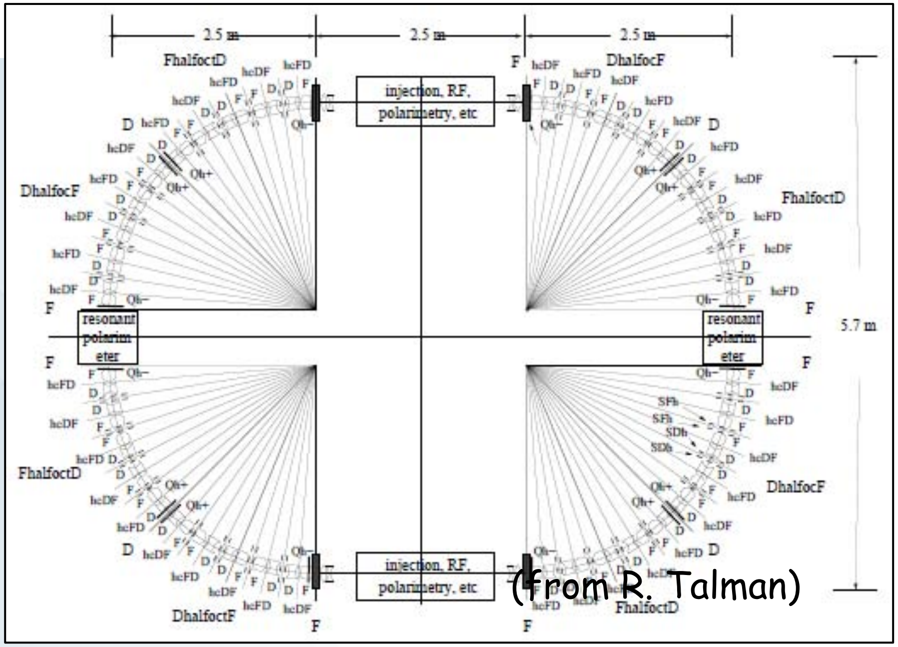
- First ever DIRECT measurement of electron EDM.

- Compact
  - Magic energy for electron: 14.5 MeV (γ=29.4)
  - E = 2-6 MeV/m → $2\pi R$ = 50 - 20 m

- Technical challenge, modest investment.
  - ≈ 15 (± 5) M€
  - ≈ 20 FTE

- Mandatory step for larger machines (proton and deuteron → $2\pi R$ > 250 m).

- Open issue: polarimetry.



(from R. Talman)

Workshop on Electron Storage Ring for EDM studies

Schloss Waldthausen (Mainz), 23-24 February, 2015

- Organizers: K. Aulenbacher (Mainz)
  P. Lenisa (Ferrara)
  F. Rathmann (Jülich)

Spare slides

Costs

Building

7 M€ for a new building.
2 M€ for modification of an existing building.

Polarized pre-accelerator to 15 MeV:

Polarized electron source (0.3 M€) (experienced personnel required)
Standard acc.-section (S-Band, 3 GHz, length ~ 5 m) driven by pulsed Klystron.
Standard pre-injector and spin-rotator;

4.0 M€

Electrostatic ring (*50 m circumference*) with low gradient (<2 MV/m).

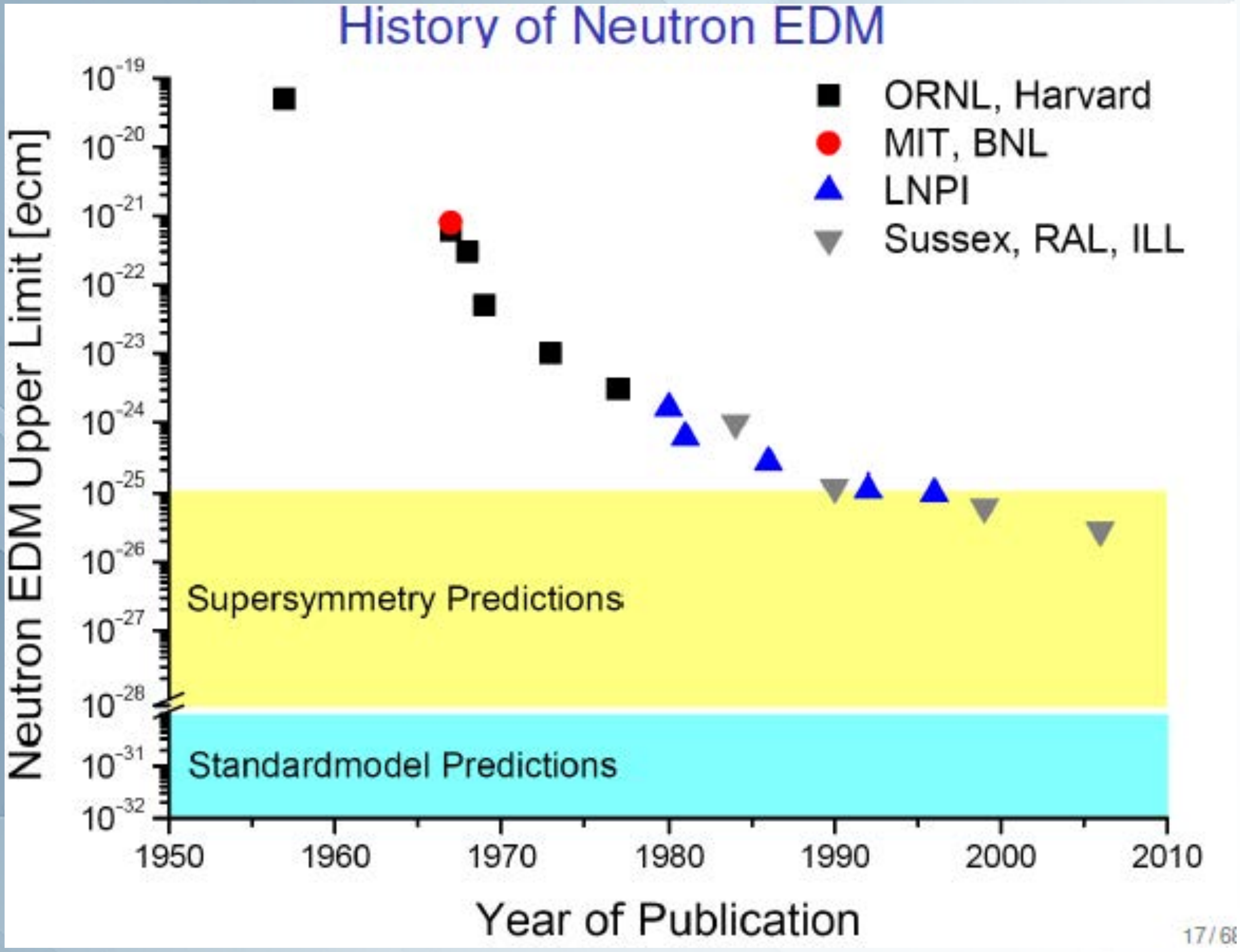
UHV vacuum and deflecting systems: 2 M€ (40 k€/m);
Beam diagnostics, injection kickers, power supplies, polarimetry etc: 3 M€
Magnetic shielding 2 M€

7 M€.

Total Investment: 13-18 M€

Manpower

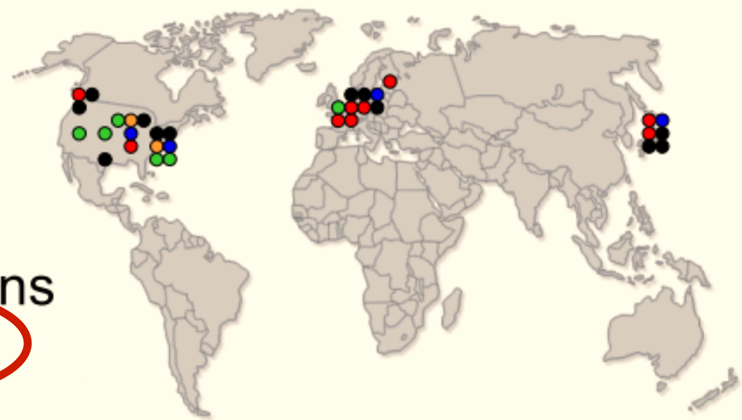
Management:	2
Lattice design:	2
Beam dynamics and spin-tracking simulations:	2
Polarized source:	2
Acceleration system:	2
Electrostatic lattice design:	2
Beam diagnostics (BPM, SQUID) and polarimetry	6
RF system:	2
Magnetic shielding:	2
Total	**22**


History of Neutron EDM
Neutron EDM Upper Limit [ecm]
10-19
10-20
10-21
10-22
10-23
10-24
10-25
10-26
10-27
10-28
10-31
10-32
ORNL, Harvard
MIT, BNL
LNPI
Sussex, RAL, ILL
Supersymmetry Predictions
Standardmodel Predictions
1950
1960
1970
1980
1990
2000
2010
Year of Publication

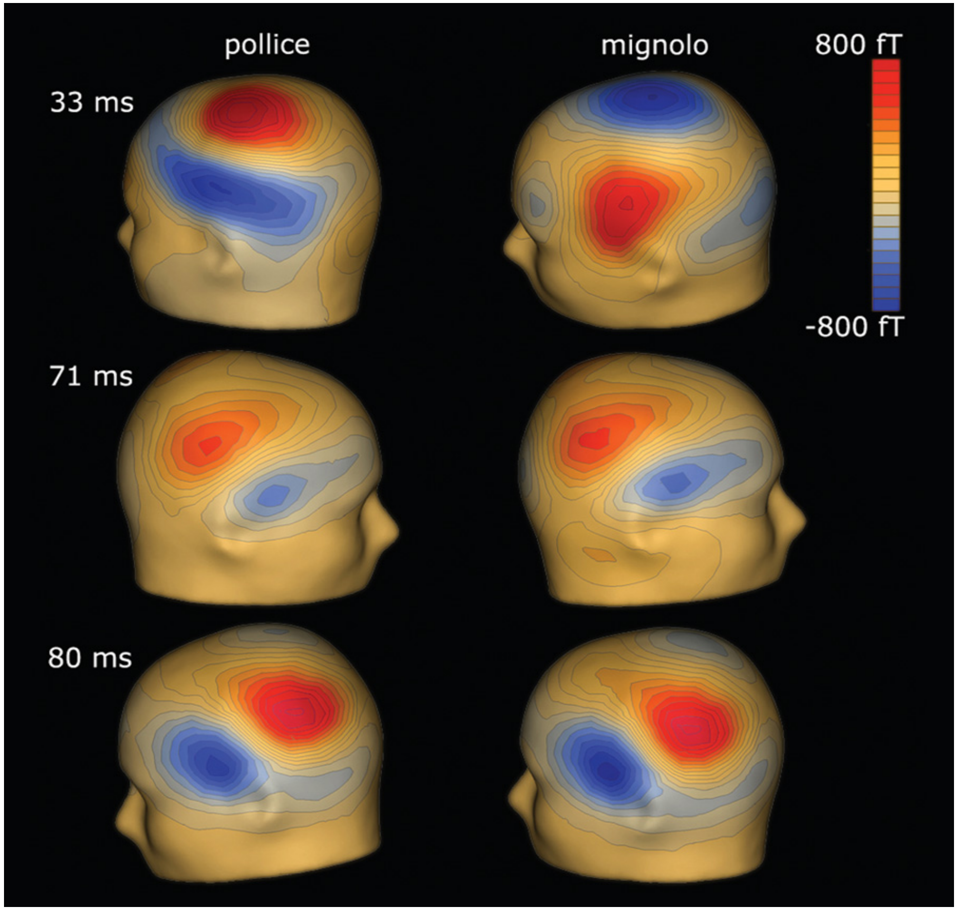
Ongoing/planned Searches

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)
  - @BNL (new)
  - @FZJ
  - @FNAL
  - @JPARC
- Solids (~10)
  - GGG@Indiana
  - ferroelectrics@Yale

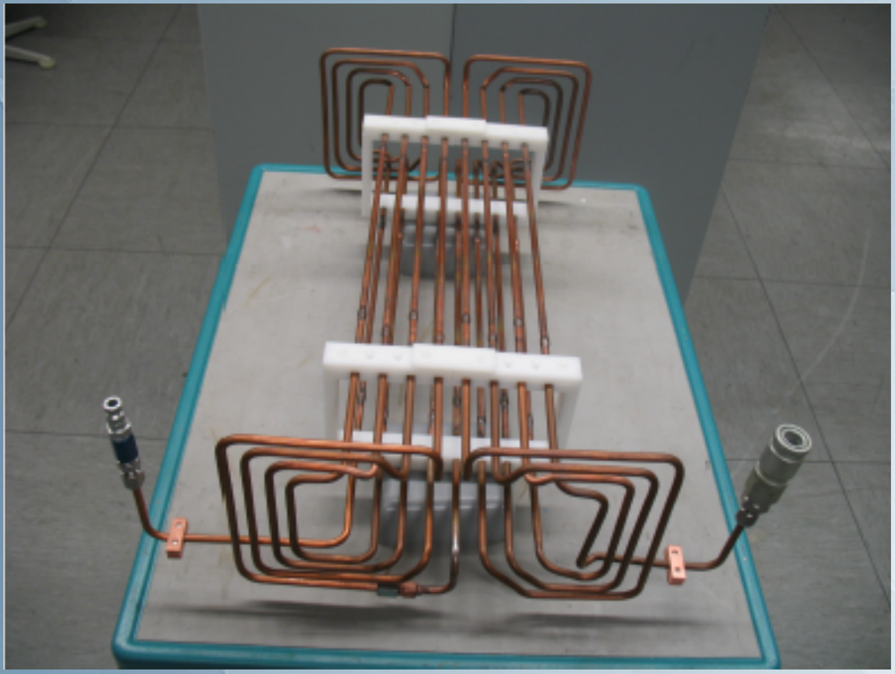


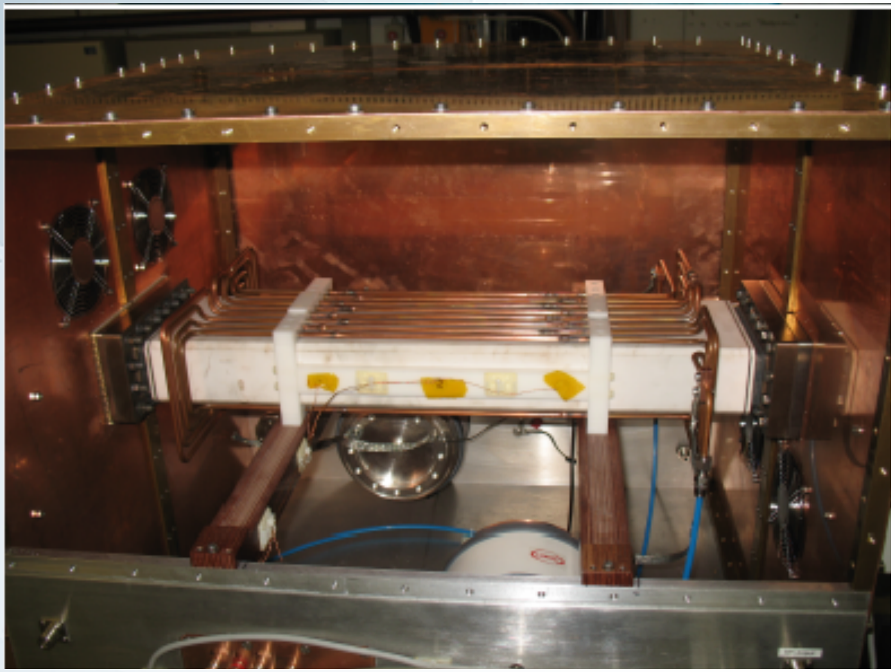
300-Channel SQUID Systems for Magnetoencephalography (MEG)



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

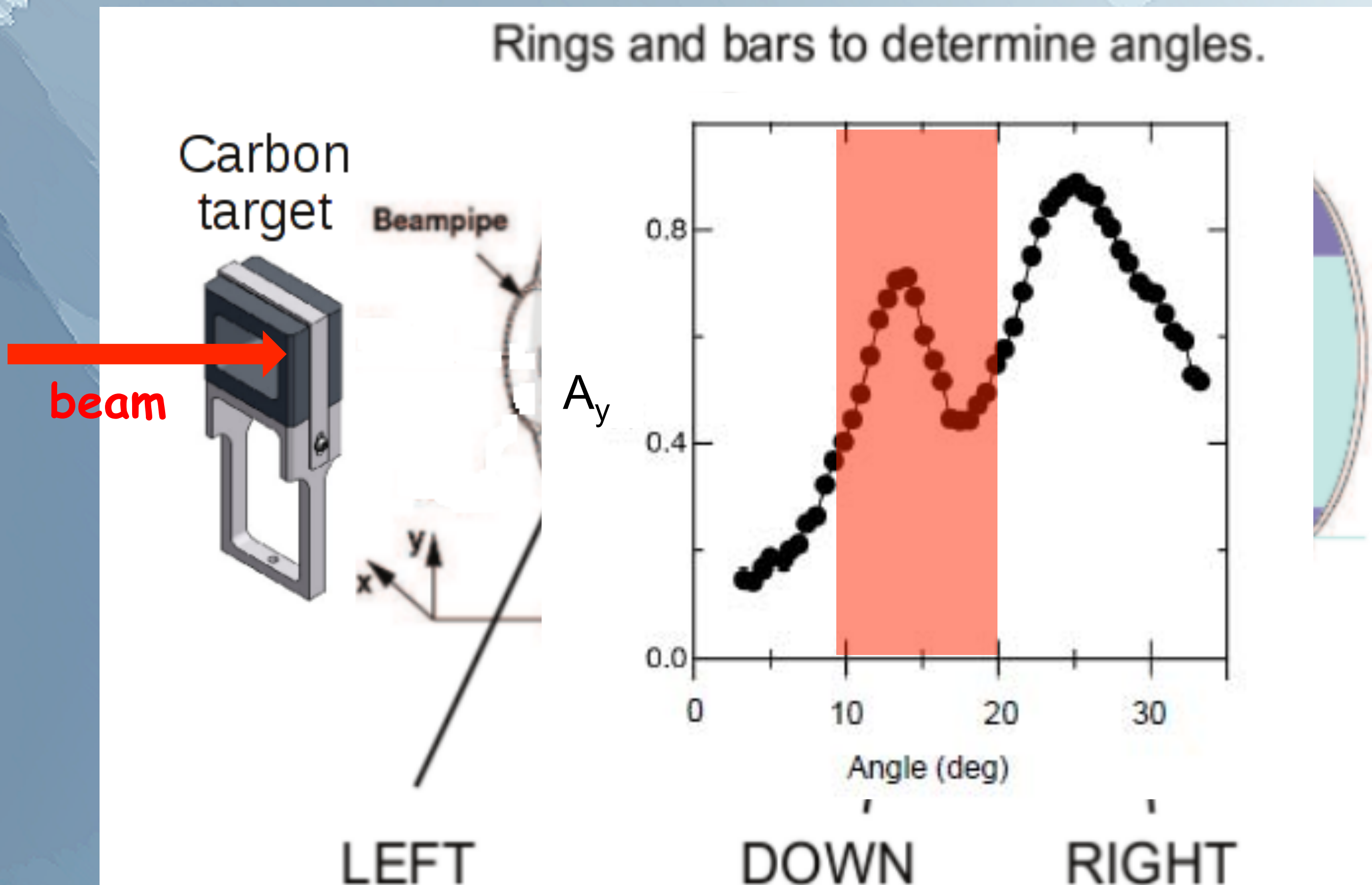
1. Upgrade test flipper with electrostatic field plates (end of year).
2. Build lower power version using a stripline system
3. Build high-power version of stripline system (E>100 kV/m)





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

EDDA beam polarimeter



ASYMMETRIES

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

VERTICAL polarization — **Analyzing power**

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

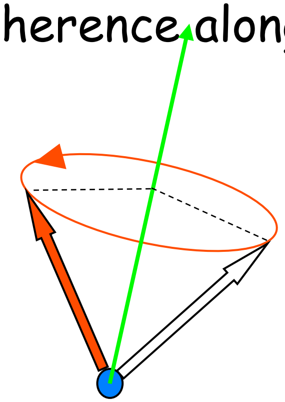
HORIZONTAL polarization — **Analyzing power**

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

Spin coherence time

- Ensemble of particles circulating in the ring

  - Spin coherence along $n \downarrow co$ is not an issue



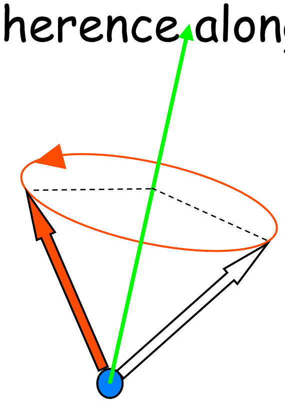
At injection all
spin vectors aligned (coherent)

Spin coherence time

- Ensemble of particles circulating in the ring

- Spin coherence along $n \downarrow co$ is not an issue

Vertical polarization not affected



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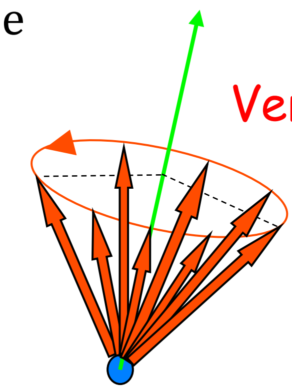
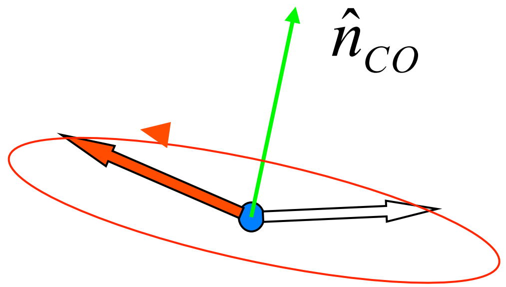


After some time, spin vectors get out of phase and fully populate the cone

- For $S \perp n \downarrow co$ (machines with frozen spin) the situation is different



At injection all spin vectors aligned

In EDM machine observation time is limited by SCT.

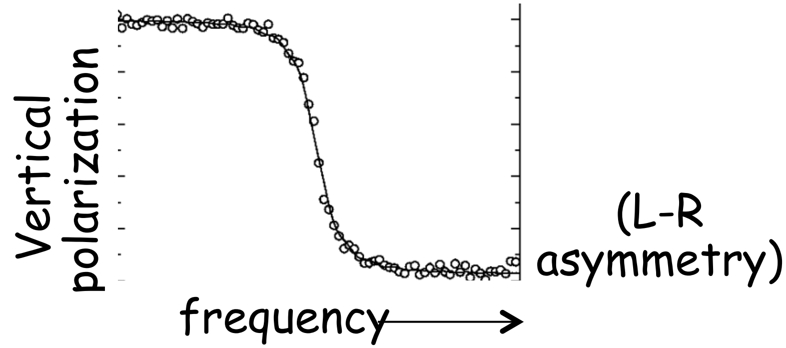
Preparing a longitudinal polarized beam with RF-solenoid

1) Froissart-Stora scan

Identification spin resonance frequency

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

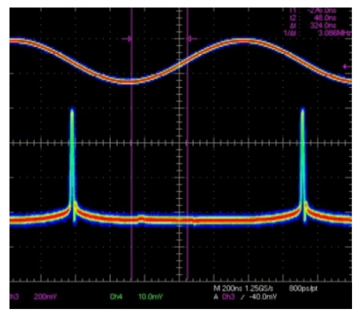
$\Delta f=400$ linear ramping in 40 s

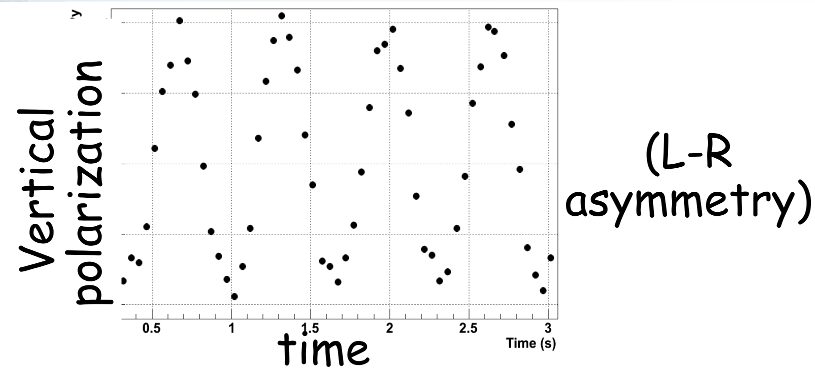


2) Fixed frequency measurements

On resonance

COOLED BEAM

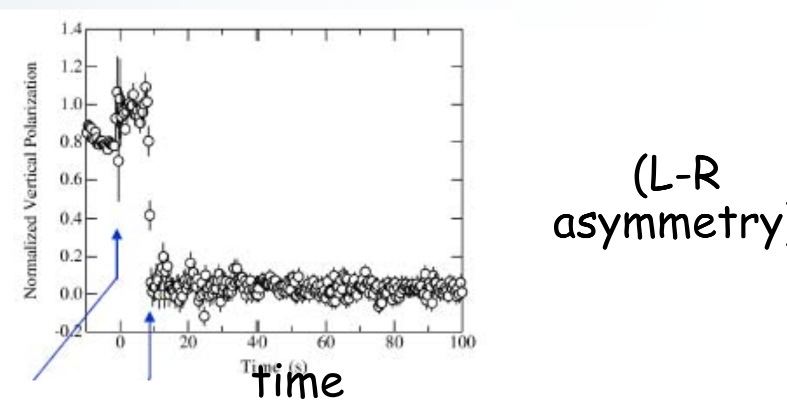




3) Solenoid on for half-cycle

Vertical polarization = 0

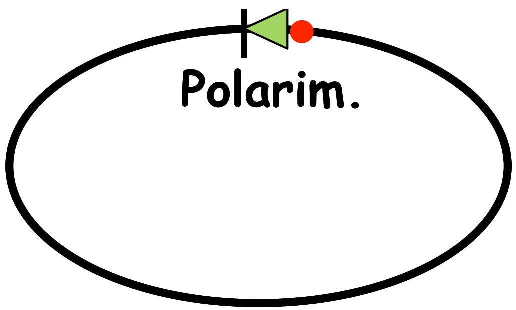
Polarization is horizontal

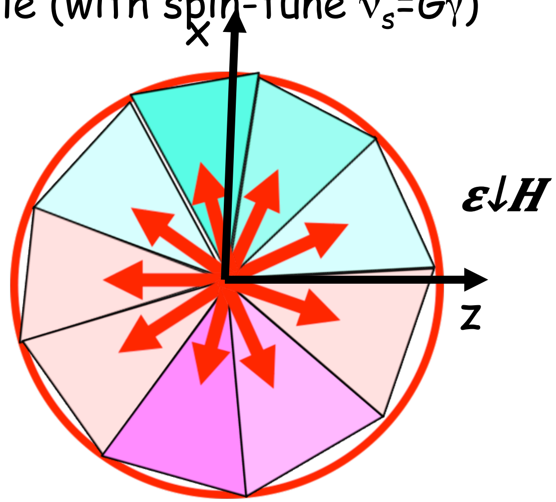


Polarimetry of precessing horizontal polarization

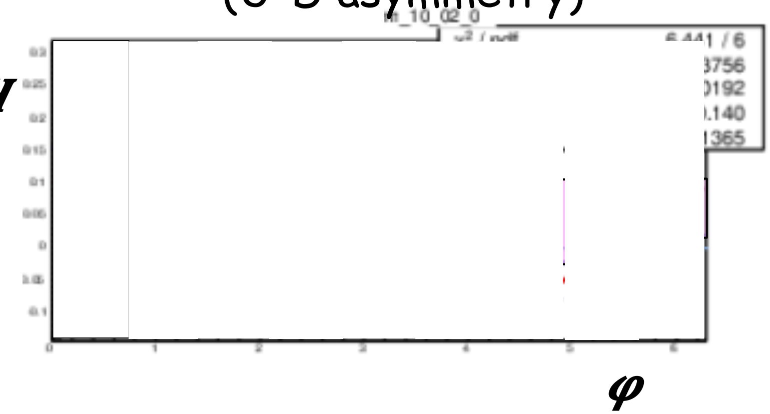
No frozen spin: polarization rotates in the horizonthal plane at 120 kHz

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

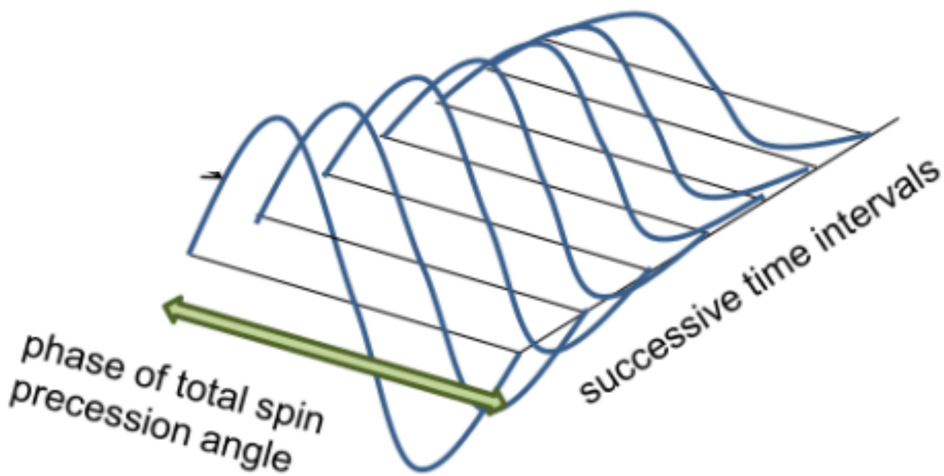




(U-D asymmetry)



- Derivation of horizontal spin coherence time

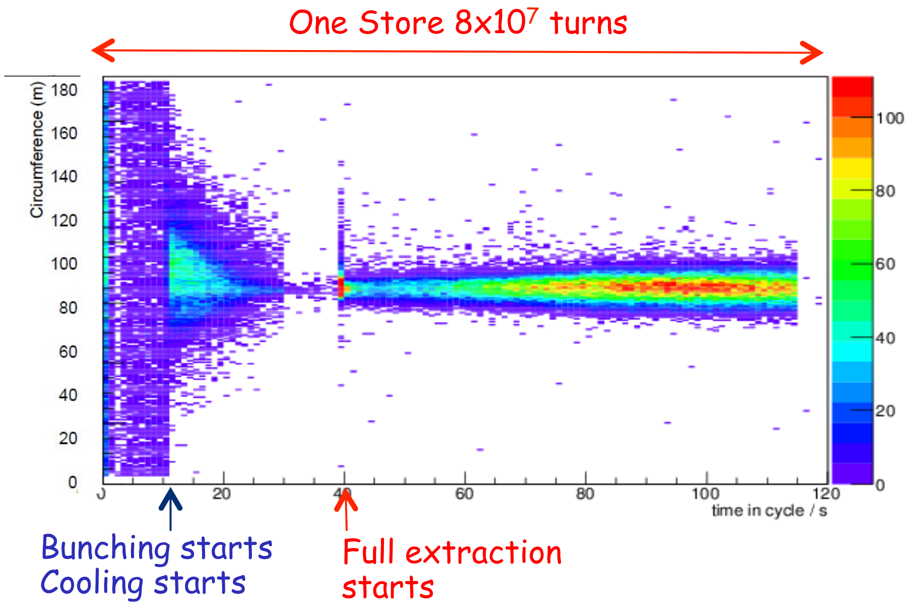


Spin coherence time extracted from numerical fit

Performance

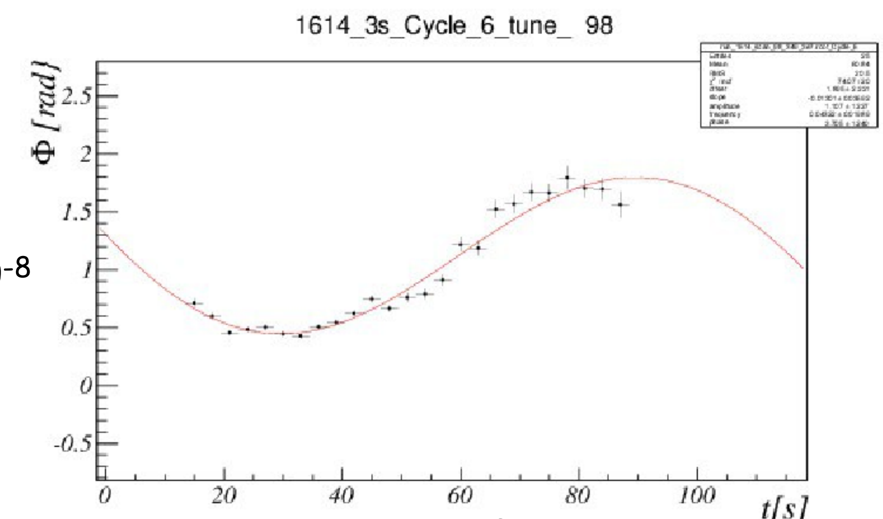
Time stamp system

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}



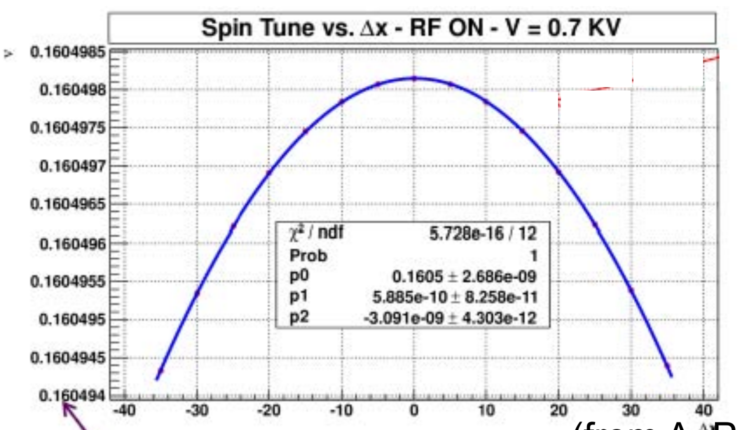
from Dennis Eversmann

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

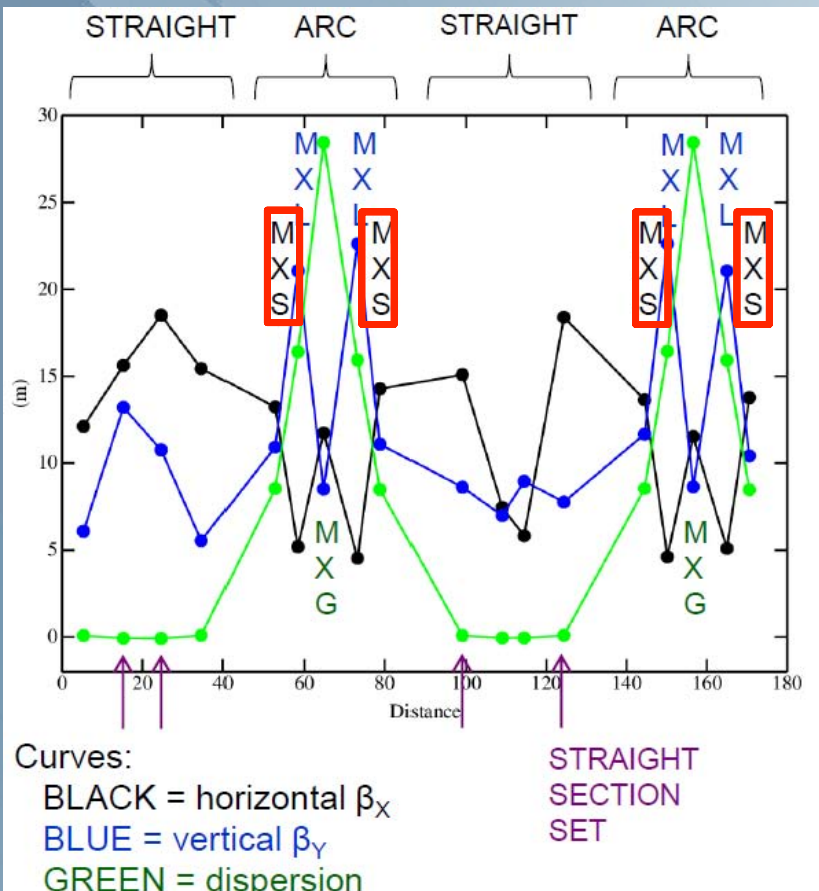
Lengthening the SCT by COSY sextupoles

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

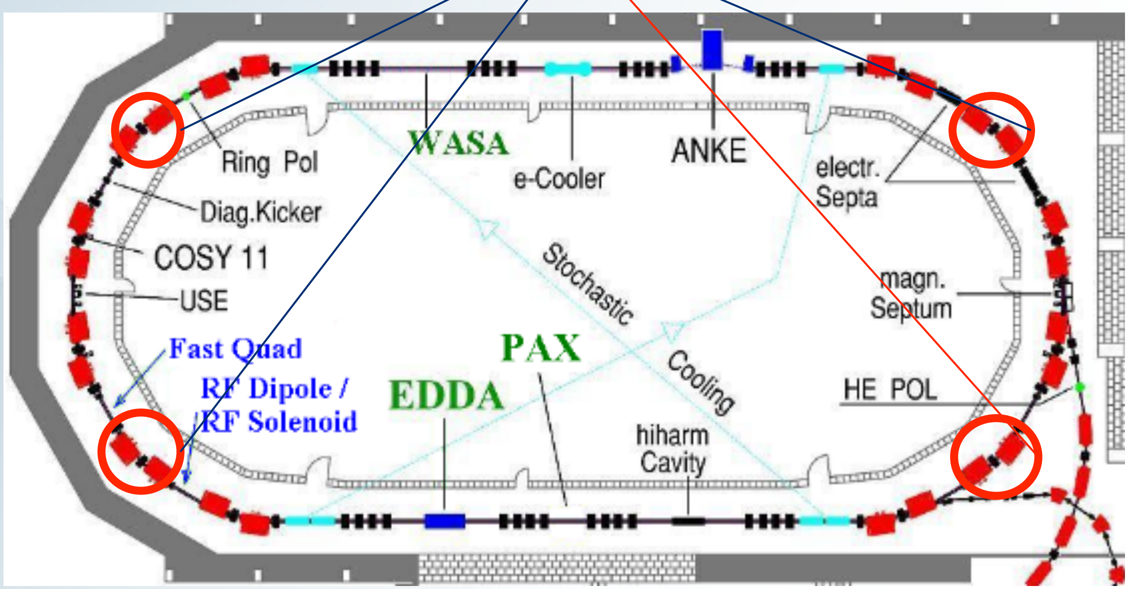
$\Delta L / L_0 = \vartheta_x^2 + \vartheta_y^2 / 4$

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

Use of 6-poles where β_x function is maximal



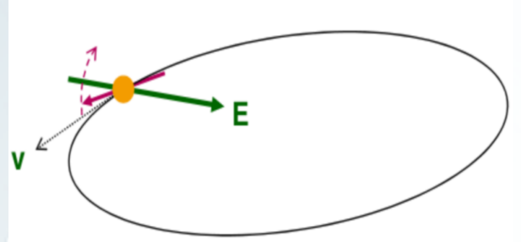
Sextupoles at β_x **max**



EDM buildup time

- Minimal detectable precession

$\theta \approx 10^{-6}$ rad



- Assuming $d \approx 10^{-29}$ e cm
  $E = 17$ MV/m
  1 turn $\approx 10^{-6}$ s

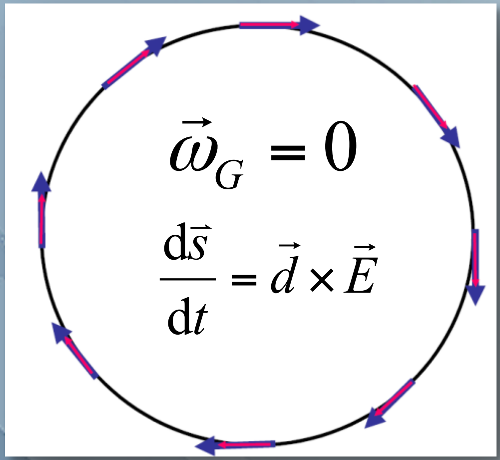
  ➔ $\theta_{EDM} \approx 10^{-15}$ rad/turn

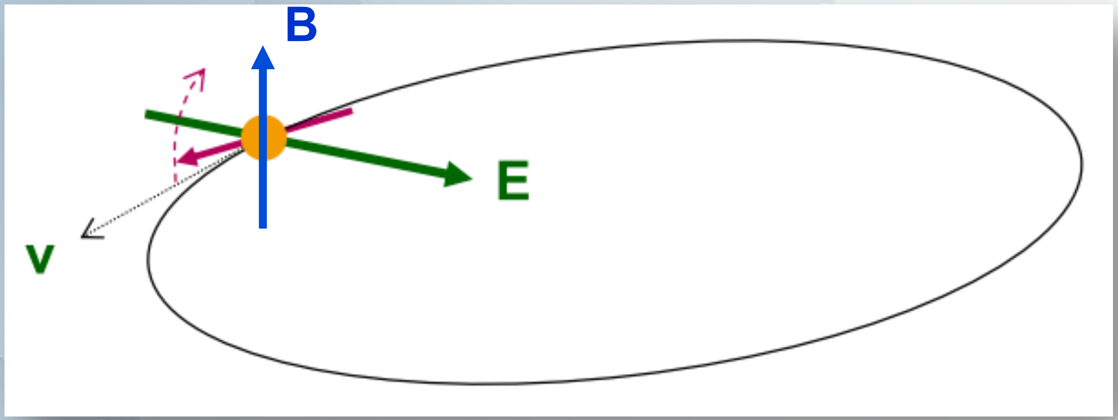
- 10^9 turns needed to detect EDM signal
- Spin aligned with velocity for t>1000 s (→ *Spin Coherence Time*)

Feasibility studies @ COSY

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}He using ONE machine with r ≈ 30 m