# Search for Static and Oscillating EDMs in Storage Rings

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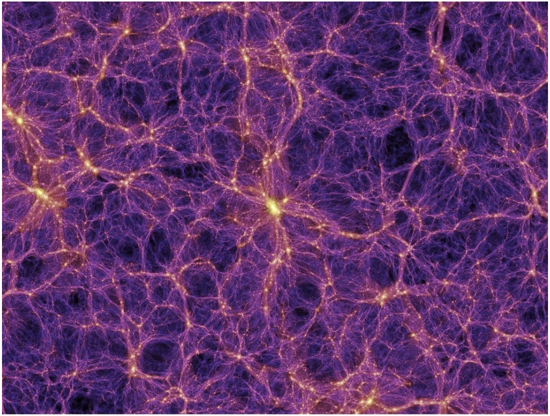
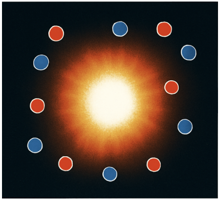
on behalf of the JEDI Collaboration

SPIN2025
$26^{th}$ *International Symposium on Spin Physics*
Qingdao (China), September $26^{th}$, 2025

# Motivation

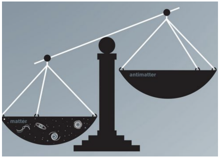


# Question 1: Why is our Universe Made of Matter?



## Big-bang

- Equal amounts of matter and antimatter




## Now

- Universe dominated by matter: $\eta = \frac{n_B - n_{\overline{B}}}{n_\gamma}$
  - Measured: $\eta \approx 10^{-10}$
    Bennet et al., Astrophys. J. Suppl. 148 (2003); Barger et al., PLB 566 (2003)
  - SM prediction: $\eta \approx 10^{-18}$
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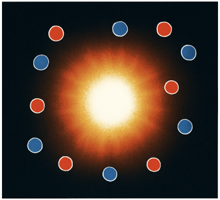

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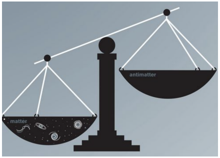


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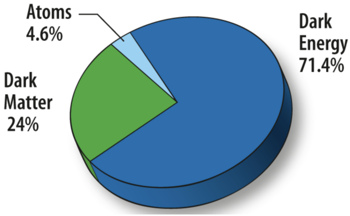
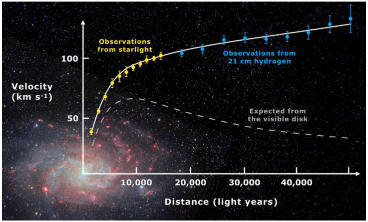
### Beyond the Standard Model

- Additional sources of CP violation beyond CKM mechanism required to explain the matter-antimatter asymmetry. Sakharov, Soviet Physics Uspekhi 5 (1991)

# Question 2: What is the Nature of Dark Matter?




## Experimental evidence

- Rotation curves of galaxies
  Vera Rubin & Kent Ford, The Astrophysical Journal, 159 (1970)
- Gravitational lensing
  Douglas Clowe et al, Astroph. Journal Letters, 648 (2006)
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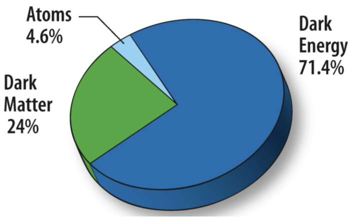


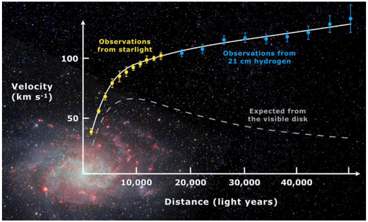


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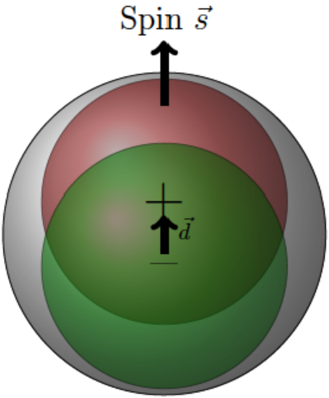
## What is Dark Matter made of?

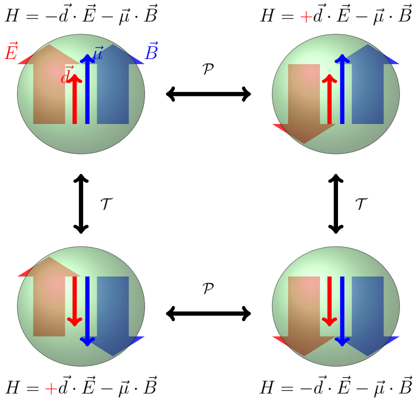
- WIMPs, Sterile neutrino, Axions? Axion like particles?
- Implies new physics beyond the Standard Model

# Electric Dipole Moment (EDM)




- Permanent separation of positive and negative charge in the particle volume
- Fundamental particles property (like mag. moment, mass, charge)
- *Axion field → oscillating EDM:*
  $d = d_{DC} + d_{AC}\cos(\omega_a t + \phi_a)$; $m_a c^2 = \hbar\omega_a$

# $\mathcal{T}$ and $\mathcal{P}$ Violations in EDMs



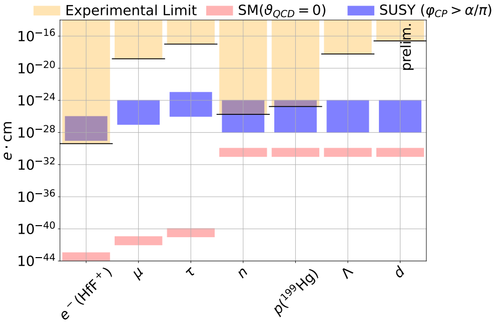

$$H = -\mu\frac{\vec{s}}{s}\cdot\vec{B} - d\frac{\vec{s}}{s}\cdot\vec{E}$$

- $\mathcal{T}$: $H = -\mu\frac{\vec{s}}{s}\cdot\vec{B} + d\frac{\vec{s}}{s}\cdot\vec{E}$
- $\mathcal{P}$: $H = -\mu\frac{\vec{s}}{s}\cdot\vec{B} + d\frac{\vec{s}}{s}\cdot\vec{E}$

## Implications of CP violation

- EDMs violate both $\mathcal{T}$ and $\mathcal{P}$ symmetries ($\stackrel{CPT}{=}\mathcal{CP}$)
- Nonzero EDM would indicate new CP-violating sources beyond SM
- Essential to explain matter-antimatter asymmetry

# Static EDM Upper Limits




## Current status

- No nonzero EDM has been measured so far

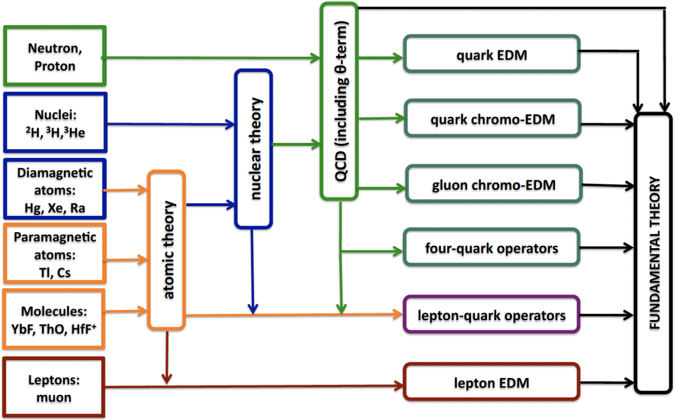
## Direct measurements

- Electron: no direct measurement; strongest limit from $HfF^+$ molecule.
- Proton no direct measurement; strongest limit from $^{199}_{80}Hg$.

## Theoretical considerations

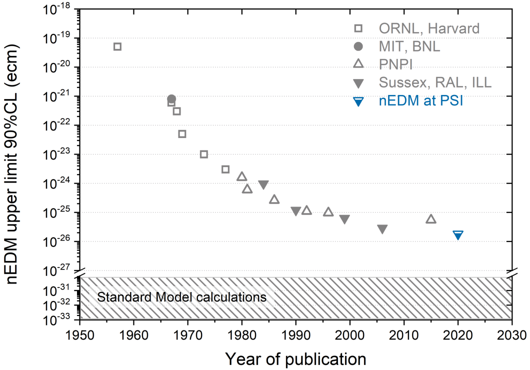
- EDM of single particle not sufflcient to pinpoint the source of CP violation

# Complementarity of EDM Measurements




J. de Vries

# Precision Takes Time: the Neutron EDM Limit



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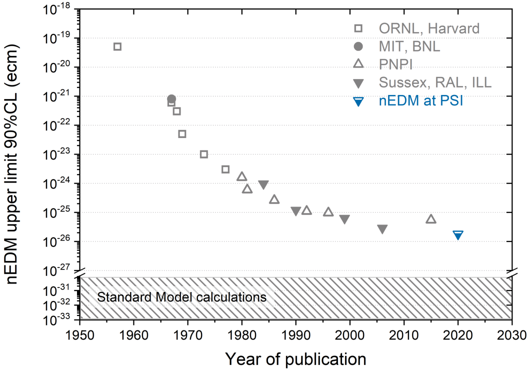


## Historical note

- Purcell and Ramsey (1950): *"The question of the possible existence of an electric dipole moment of a nucleus or of an elementary particle ... becomes a purely experimental matter"*
- First measurement of neutron EDM carried out in the early 1950s
- Published only in 1957, after Wu's discovery of PV in weak interaction

H.J. Smith, E.M. Purcell and N.F. Ramsey, Phys. Rev. 108, 1957

# Axions and Axion-Like Particles (ALPs)

## The Strong CP Problem

- QCD allows a CP-violating term: $\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$
- This would induce a large neutron EDM, but experiments find it $\simeq 0$.
- $\Rightarrow$ Implies an extremely small $\theta$: the strong CP problem.

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## Peccei-Quinn Mechanism and Axions

- Peccei-Quinn dynamically drives $\theta \to 0$ Peccei, Quinn, PRL 38 (1977);
- Predicts a new pseudoscalar particle: the axion Wilczek, PRL 40 (1978)
- Generalizations $\Rightarrow$ Axion-Like Particles (ALPs) Kim, PRL 43 (1979); Dine et al, PLB 104 (1981)

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## Connection to Dark Matter

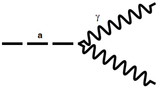
- Axion/ALPs are excellent dark-matter candidates:
  - Very light, very stable; extremely weakly interacting

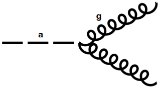
## Experimental Searches

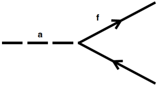
- Large effort to detect axion/APLs
  - Haloscopes (galactic DM axions); P. Sikivie (1983); CAST-CAPP, CAST-RADES, ...
  - Helioscopes (solar axions); P. Sikivie, CAST; IAXO ...
  - Light-shining-trough wall experiments (photon coupling); P. Sikivie; ALPS; CROWS..

# Axion Coupling - Axion Induced Oscillations

$\mathcal{L}: -\frac{\alpha}{8\pi}\frac{C_\gamma}{f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu}$ $\quad -\frac{\alpha_s}{8\pi}\frac{C_G}{f_a} a G^b_{\mu\nu}\tilde{G}^{b,\mu\nu}$ $\quad -\frac{1}{2}\frac{C_N}{f_a}\partial_\mu a \bar{\Psi}_f\gamma^\mu\gamma^5\Psi_f$




oscillating Electric Dipole Moment (oEDM)

axion wind term

## Axion-field description

- For low axion masses, if axions saturate dark matter they can be described as: $a(t) = a_0 cos(\omega_a(t) + \phi_a)$; $m_a c^2 = \hbar\omega_a$ ; coupling scales as $\propto \frac{1}{f_a} \propto m_a$

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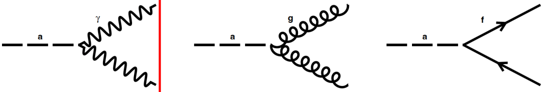


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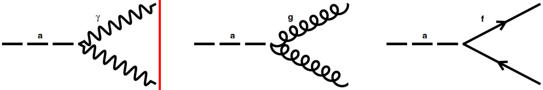


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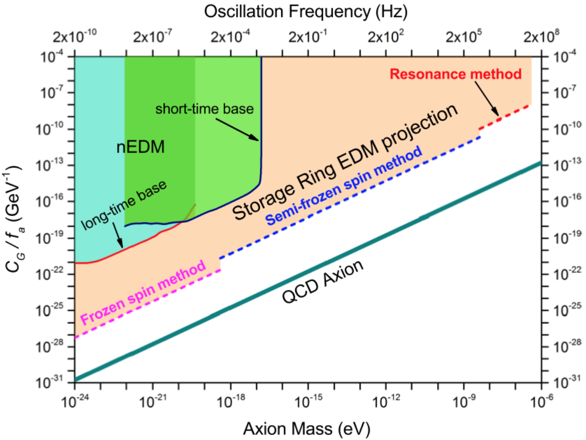
## ALP-induced spin-interaction

- Gluon fields $\Rightarrow$ *oscillating EDMs*; Graham et al., PRD 84 (2011)
- Fermion coupling with axion field gradient (pseudomagnetic field) $\Rightarrow$ *axion wind* effect; Graham et al., PRD 88 (2013)

## Measurement concept in a storage ring

- Use spin procession of polarized beam in a storage ring
- Look for resonance signatures

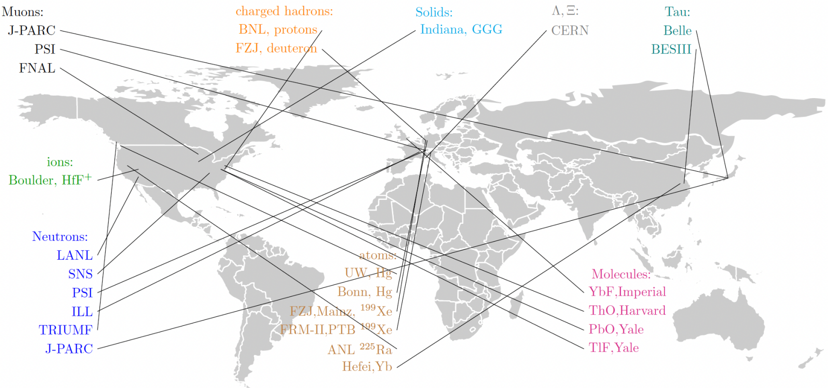
# Axion Search with Storage Ring EDM Method



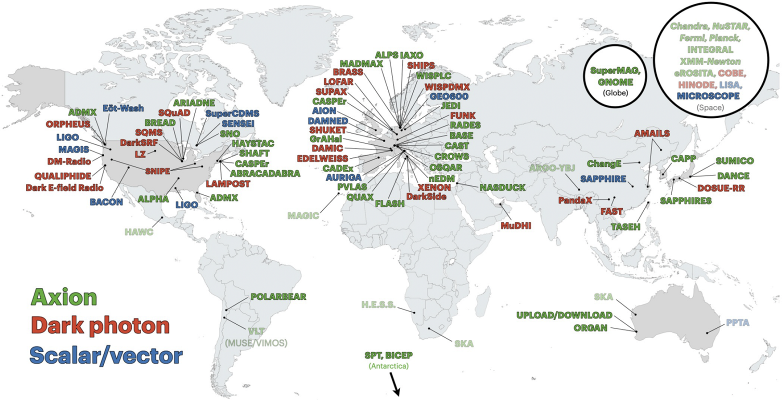

S. P. Chang et al. Phys. Rev. D 99, 083002

- Experimental limits on axion-gluon coupling from oscillating EDM searches.

# EDM Experiments/Activities around the World

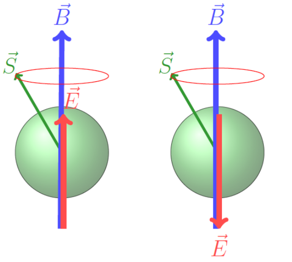


# World Map of Current Experiments on Wavy Dark Matter

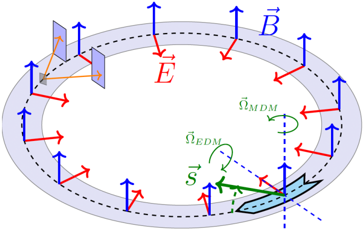



C. O'Hare, doi:10.5281/zenodo.3932430, https://github.com(cajohare/AxionLimits

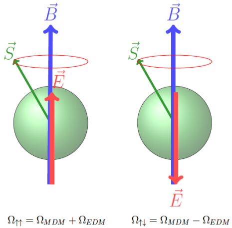
# Experimental methods




$\Omega_{\uparrow\uparrow} = \Omega_{MDM} + \Omega_{EDM}$ $\Omega_{\uparrow\downarrow} = \Omega_{MDM} - \Omega_{EDM}$



# Measuring the EDM of Neutral Particles




## Spin Precession in E and B Fields

$$\vec{\Omega} = \Omega_{\mathrm{MDM}} \pm \Omega_{\mathrm{EDM}} = \frac{\mu B \pm d E}{|\vec{S}|}$$

## Orders of Magnitude for $d_n = 1 \times 10^{-26}\, e \cdot \mathrm{cm}$

- In $B_{\mathrm{earth}}$: $\Omega \approx 9{,}000\,\mathrm{s}^{-1}$
- In $E = 10^7\,\mathrm{V/m}$: $\Omega_{\mathrm{EDM}} \approx 3 \times 10^{-6}\,\mathrm{s}^{-1}$

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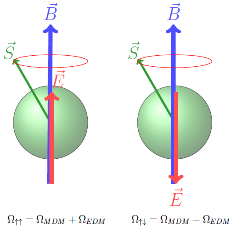


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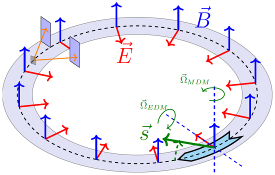
## Measuring the EDM of Charged Particles

More challenging $\Rightarrow$ requires dedicated storage rings.

# Spin-Precession of Charged Particles in Storage Rings




- Equation of motion for spin vector $\vec{S}$ in the rest frame of the particle:

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

- Spin-precession relative to the direction of motion:

$$[(\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}) - \vec{\Omega}_{cycl}] = \frac{-q}{m}\left[\underbrace{G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E}}_{=\Omega_{MDM} - \Omega_{cycl}} + \underbrace{\frac{\eta}{2}\left(\vec{E} + \vec{v} \times \vec{B}\right)}_{=\Omega_{EDM}}\right]$$

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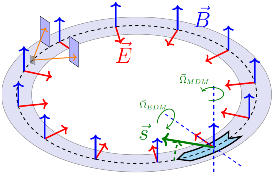


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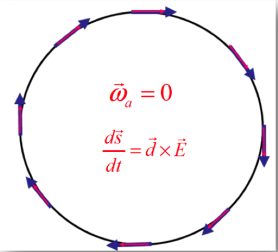
## Frozen spin

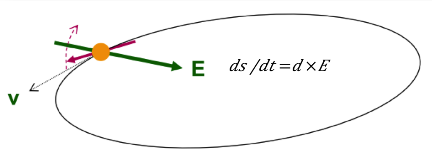
- $\vec{\Omega}_{MDM} - \vec{\Omega}_{cycl} = 0 \Rightarrow$ frozen spin (momentum and spin stay aligned)
  - Achievable with pure electric field for proton (G > 0): $G = \frac{1}{\gamma^2 - 1}$

# Search for Static EDM in Storage Rings

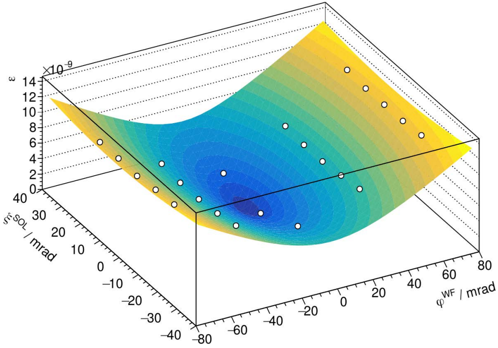
**Storage ring method to measure EDM of charged particle**

1. Inject beam of polarized particles in storage ring
2. Align spin along momentum ($\rightarrow$ freeze horiz. spin-precession)
3. Search for time development of vertical polarization



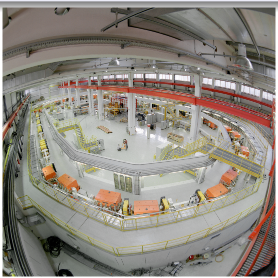
# Achievements at COSY Storage Ring

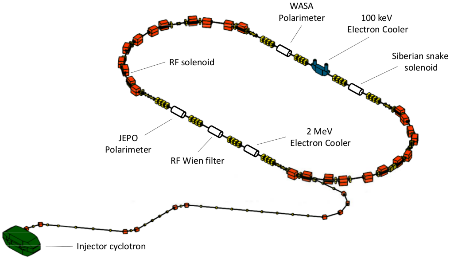


# The COSY Storage Ring at FZ-Jülich (Germany)

## COoler SYnchrotron COSY

- Cooler and storage ring for (pol.) protons and deuterons.
- Momenta p= 0.3-3.7 GeV/c
- Phase-space cooled internal and extracted beams



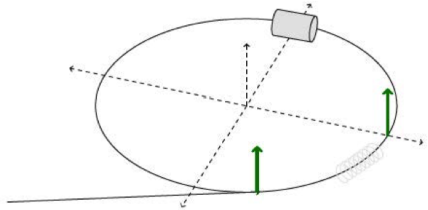



## Previously used as spin-physics machine for hadron physics:

- Ideal starting point for Storage Ring EDM related R&D
- Dedicated and unique experimental effort worldwide
- Closed end 2023: essential R&D expts. with MAGNETIC ring successfully done.

# Experiment Preparation

1. Inject and accelerate vertically pol. deut. to p $\approx$ 1 GeV/c



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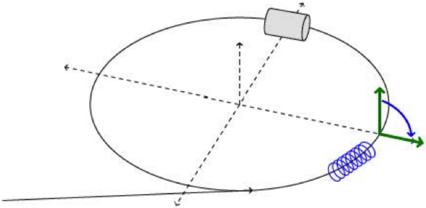
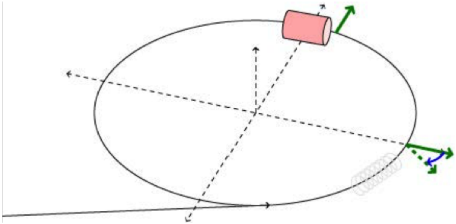


# Experiment Preparation

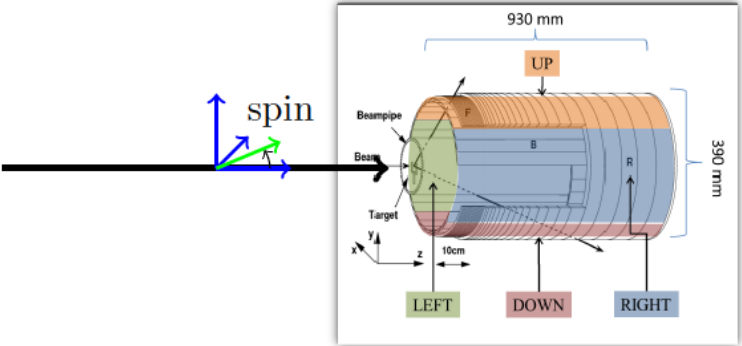
1. Inject and accelerate vertically pol. deut. to p $\approx$ 1 GeV/c
2. Flip spin with solenoid into horizontal plane
3. Extract beam slowly (100 s) on Carbon target
4. Measure asymmetry and determine spin precession



# Prerequisite: Polarimetry

## Spin-dependent elastic deuteron-carbon scattering

- Up/Down asymmetry $\propto$ *horizontal polarization*
  - $N_{up,down} \propto 1 \pm \frac{3}{2} p_z A_y sin(\nu_s \omega_{rev} t)$;
    $\nu_s = \gamma G \simeq$ - 0.161 (spin-tune); $f_{rev}$ = 781 kHz; $f_s$ = 126 kHz.
- Left/Right asymmetry $\propto$ *vertical polarization* $\rightarrow$ d



# Time-Stamp System

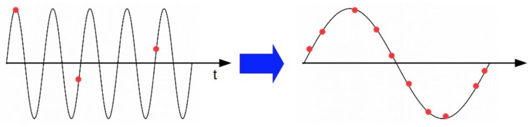
$$\text{Asymmetry: } \epsilon = \frac{N_{up} - N_{down}}{N_{up} + N_{down}} = p_z A_y \sin\left(2\pi \cdot \nu_s \cdot n_{turns}\right)$$

**Challenge**

- Spin precession frequency: 126 kHz
- event rate: 5000 $s^{-1}$ $\rightarrow$ 1 hit / 25 precessions $\rightarrow$ no direct fit of rates

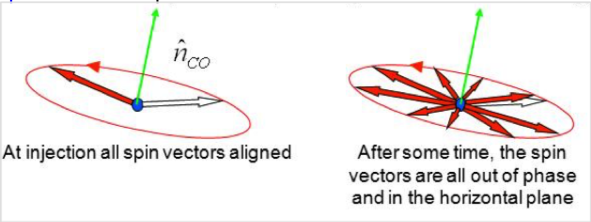
**Solution: map many event to one cycle**

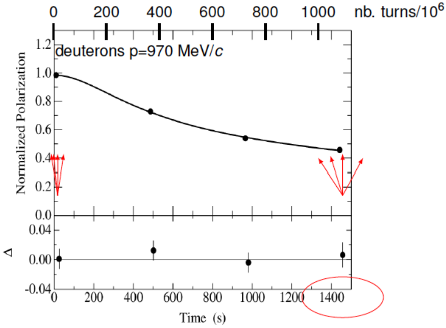
- Counting turn number n $\rightarrow$ phase advance $\phi_s = 2\pi\nu_s n$
- For intervals of $\Delta n = 10^6$ turns: $\phi_s \rightarrow \phi_s \bmod 2\pi$



# Prerequisite: Long Spin-Coherence Time

- Invariant spin axis and spin-coherence time

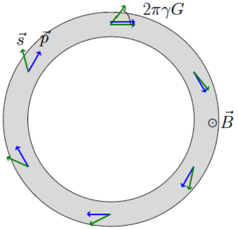


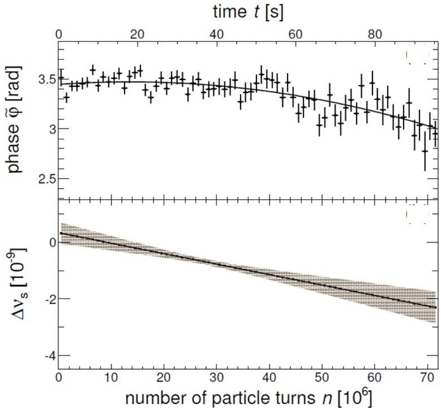




**1st Major Achievement**
*[Phys. Rev. Lett. 117 (2016) 054801]*

- $\tau_{SCT} = (1173 \pm 172)\,\mathrm{s}$
- Previously: $\tau_{SCT}(\text{VEPP}) \approx 0.5\,\mathrm{s}$
- SCT is of crucial importance, since $\sigma_{STAT} \propto \frac{1}{\tau_{SCT}}$

# Precise Determination of the Spin-Tune




**Spin-tune $\nu_s$**

$$\nu_s = \gamma G = \frac{nb.spin-rotations}{nb.particle-revolutions}$$

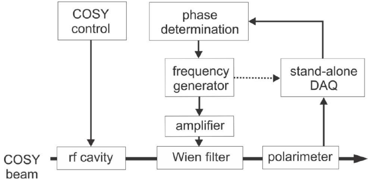
2nd **major achievement** *[Phys. Rev. Lett. 115 (2015) 094801]*

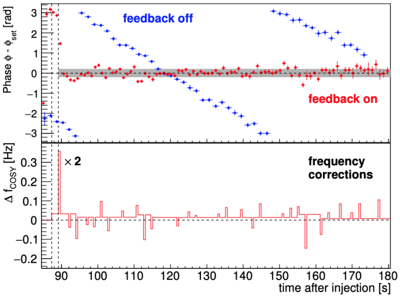
- Interpolated spin tune in 100 s:
- $|\nu_s| = (16097540628.3 \pm 9.7) \times 10^{-11}$ ($\Delta\nu_s/\nu_s \approx 10^{-10}$)
- $\rightarrow$ new tool to study systematic effects in storage rings

# Phase-Locked Spin Precession

**Spin-feedback system maintains:**

- resonance frequency
- phase between spin-precession and device RF




3rd **major achievement** *[Phys. Rev. Lett. 119 (2017) 014801]*:

Error of phase-lock $\sigma_\phi$ = 0.21 rad

# Phase-Locked Spin Precession

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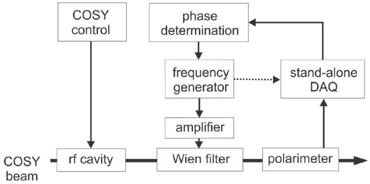


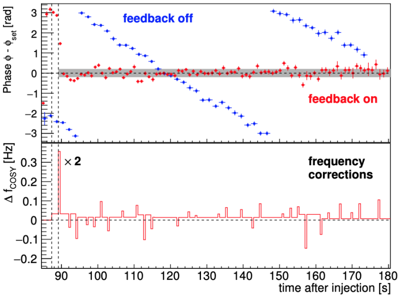


**$3^{rd}$ major achievement** *[Phys. Rev. Lett. 119 (2017) 014801]*:

Error of phase-lock $\sigma_\phi$ = 0.21 rad

At COSY freezing of spin precession not possible
$\rightarrow$ phase-locking required to achieve precision for EDM

# Measurement of EDM in a magnetic ring

## First-ever direct EDM measurement using this method

### Concept

- Radial field $\vec{E} = c\vec{\beta} \times \vec{B}$ from relativistic motion in vertical $\vec{B}$
- Spin precession: $\frac{d\vec{S}}{dt} \propto \vec{d} \times \vec{E}$

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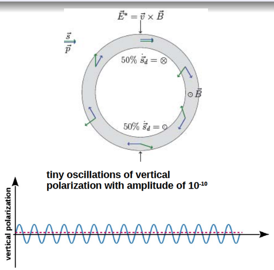
### Problem: ⇒ only small oscillation of vertical polarization $p_y$ due to EDM.

- Momentum ↑, spin ↑ ⇒ spin kicked up
- Momentum ↑, spin ↓ ⇒ spin kicked down
- ⇒ no accumulation of vert. asymmetry



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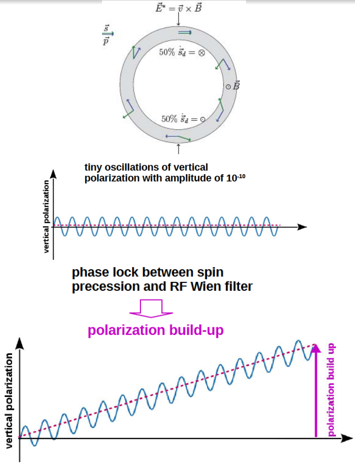
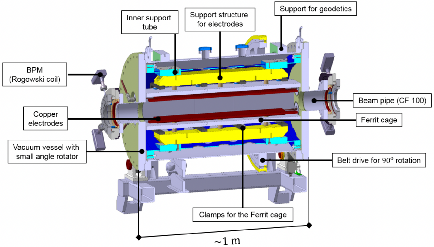
### Solution: RF-Wien filter

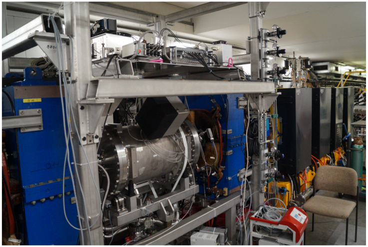
- Lorentz force: $\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) = 0$
  → particle trajectory not affected
- $\vec{B} = (0, B_y, 0)$ and $\vec{E} = (E_x, 0, 0)$
  → mag. moment influenced



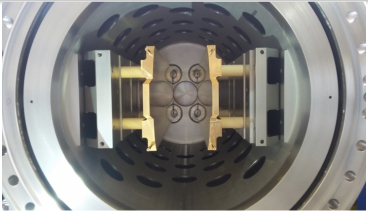
# Measurement of EDM in a magnetic ring

## RF-Wien filter[1]



- Waveguide provides $\vec{E} \times \vec{B}$ by design.
- Minimal $\vec{F_L}$ by careful electromagnetic design of all components.



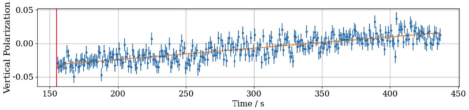
[1] Joint development with RWTH Aachen

# Pilot Bunch Comagnetometer

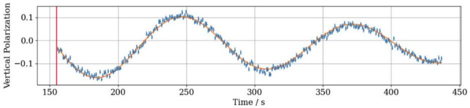
$4^{th}$ **major achievement** *[Phys. Rev. Research 7, 023257]*

- Observation of $p_y$ (t) with two stored bunches: pilot bunch and signal bunch
  - Pilot bunch shielded from Wien-fillter RF by fast RF switches

- Pilot bunch

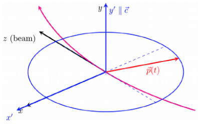



- Signal bunch

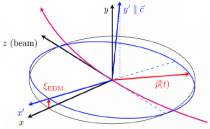



- No oscillations in pilot bunch.
- Decoherence visible in signal bunch.

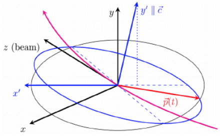
# Tilting of the Invariant Spin Axis




EDM absence




EDM effect




Magnetic misalignm.

$$\phi_{EDM} = \arctan\left(\frac{\eta_{EDM}\beta}{2G}\right)$$

$$\vec{n}_{ISA} \approx \begin{pmatrix} \phi_{EDM} + \phi_{Ring} \\ 1 \\ \xi_{Ring} \end{pmatrix}$$

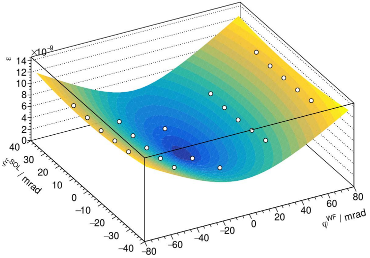
## EDM + magnetic misalignments tilt the invariant spin axis

- Presence of EDM $\rightarrow \phi_{EDM} > 0$
- Presence of magnetic misaligments $\rightarrow \phi_{EDM}$ & $\xi_{ring} > 0$
  - $\rightarrow$ spin precess around the $\vec{n}_{ISA}$ axis
  - $\rightarrow$ oscill. vert. polarization $p_y(t)$

# Results of dEDM Precursor Experiment

## EDM resonance strength map for $\epsilon^{EDM}$

- Includes tilts of invariant spin axis due to EDM and magnetic ring imperfections.




## Preliminary result on static EDM - $1^{st}$ ever measurement of deuteron's EDM

- Determination of minimum via fit with theoretical surface function yields:
  - $n_x^{WF}$ (mrad) = - 2.1(12)
  - $n_z^{WF}$ (mrad) = 3.9(6)

$$\Rightarrow d_{EDM} < 3 \cdot 10^{-17} e \cdot cm \text{ (95 \% CL)}$$

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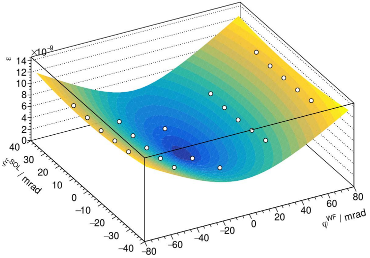


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$$\Rightarrow d_{EDM} < 3 \cdot 10^{-17} e \cdot cm \text{ (95 \% CL)}$$

- Only other direct measurement: $\mu_{EDM} < 1.9 \cdot 10^{-19} e \cdot cm$ (95 % CL)

→ see talk of A. Andres on 23.09 for details

# Search for Axion-Like Particles in a Storage Ring

## First-ever search using this method

### Axions and oscillating EDM

- Axion interaction with ordinary matter: $\frac{a}{f_0} F_{\mu\nu} \tilde{F}_{\mu\nu}$, $\frac{a}{f_0} G_{\mu\nu} \tilde{G}_{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \bar{\Psi} \gamma^\mu \gamma_5 \Psi$
- $\frac{a}{f_0} G_{\mu\nu} \tilde{G}_{\mu\nu} \rightarrow$ coupling to gluons with same structure as QCD-$\theta$ term
- Generation of an oscillating EDM with freq. related to mass: $\hbar\omega_a = m_a c^2$

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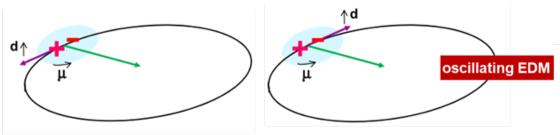
- Generation of an oscillating EDM with freq. related to mass: $\hbar\omega_a = m_a c^2$

### Experimental approach

- Mag. dipole moment (MDM) $\rightarrow$ spin prec. in B field $\rightarrow$ nullifies static EDM effect
- Osc. EDM resonant condition ($\omega_a = \omega_s$) $\rightarrow$ buildup of out-of-plane spin rotation



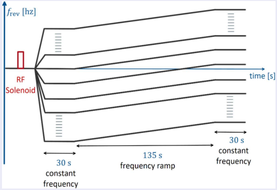

$$\vec{d} = \eta \frac{q\hbar}{2mc}\vec{S}$$

$$\eta = \eta_0 + \eta_1 \sin(\omega_{\text{axion}} t + \varphi_a)$$

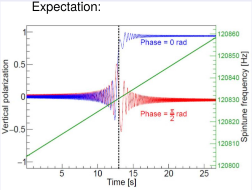
$$\omega_{\text{axion}} = \frac{m_a c^2}{\hbar}$$

# Experiment at COSY

## Momentum ramps ($f_{rev}$) searching for polarization changes

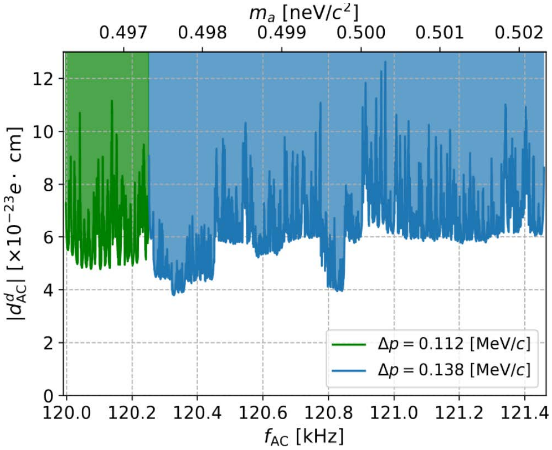



- Organization of frequency ramps.




- Jump of vertical polarization when resonance is crossed, for $\omega_a = \omega_s$

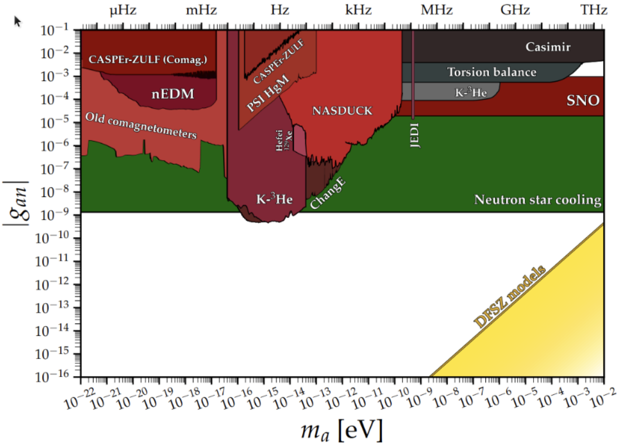
# Bound on the Oscillating EDM of the Deuteron




### Observed oscillation amplitudes from 4 bunches

- 90 % CL upper limit on the ALPs induced oscillating EDM
- Average of individual measured points $d_{AC} < 6.4 \times 10^{-23}$ e cm

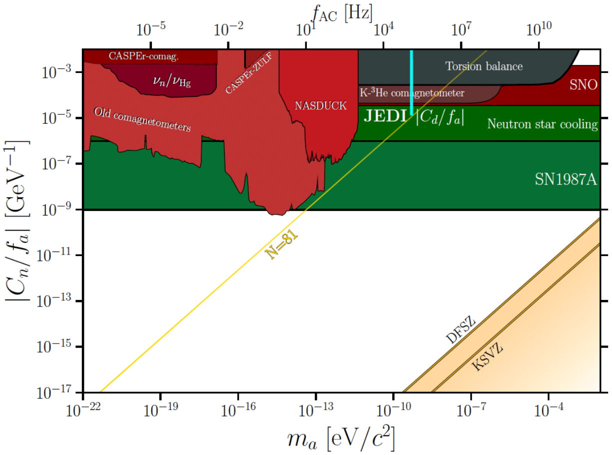
# Axion Coupling to EDM Operator $g_{ad\gamma}$ (e.g. Axion/Gluon Coupling)




**Limits on axion/ALP neutron coupling from the Particle Data Group**

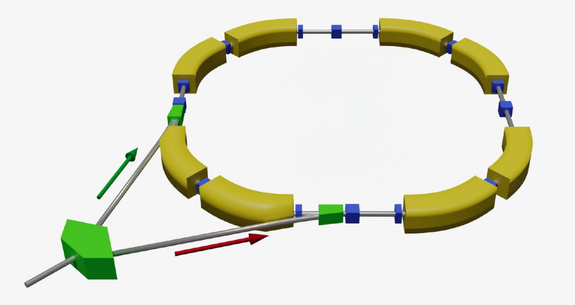
- $g_{ad\gamma} = d_{AC} = \frac{d_A C}{a_0}$; $a_0 = 0.55\ \frac{GeV}{cm^3}$ (Dark Matter saturated by ALPs)
- It includes JEDI result: S. Karanth et al., Phys. Rev. X 13 (2023) 031004

# Axion Wind Effect: Coupling to Nucleons $\frac{C_N}{f_a}$




- Storage ring experiments particularly sensitive to axion wind effect

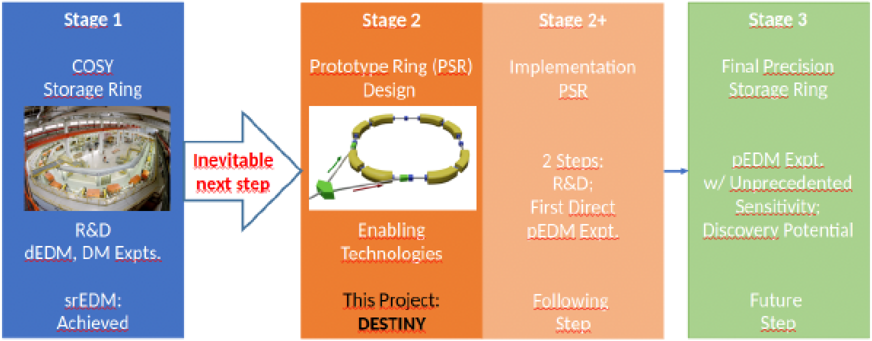
# Next steps



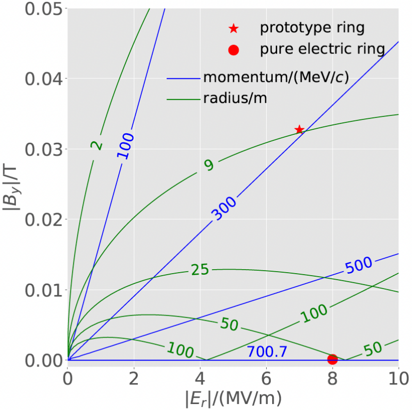
# Objective: Construction of a Dedicated SR for EDM Studies

**Possible approaches**

- One step approach: immediate construction of final ring
- Staged approach: intermediate prototype ring



# Design Options for Frozen-Spin Proton Rings



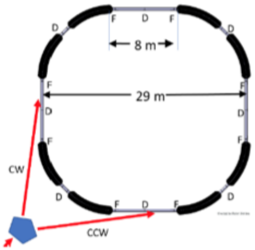

**Two-options:**

- Hybrid - 100 m ring:
  p = 300 MeV/c
  bending radius ≈ 9 m at E=7 MeV/m
- Pure electric - 800 m ring:;
  p = 707 MeV/c;
  bending radius ≈ 50 m at E = 8 MeV/m

# Stage 2: Prototype EDM Storage Ring

## 100 m circumference

- p at 30 MeV all-electric CW-CCW beams operation
- Frozen spin including additional vertical magnetic fields




## Challenges

- All electric & E-B combined deflection
- Storage time
- CW-CCW operation $\rightarrow$ next slide
  - Orbit control
  - Control of orbit difference
- Polarimetry
- Spin-coherence time
- Magnetic moment effects
- Stochastic cooling

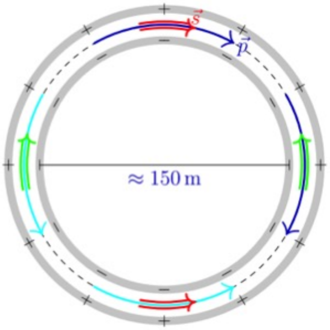
## Objectives of PSR

- Study open issues.
- First direct proton EDM measurement.

# Stage 3: Precision EDM Ring

**500 m circumference (with E = 8 MV/m)**

- All-electric deflection
- Magic momentum for protons (p = 707 MeV/c)




**Challenges**

- All-electric deflection
- Simultaneous CW/CCW beams
- Phase-space cooled beams
- Long spin coherence time ($>$ 1000 s)
- Non-destructive precision polarimetry
- Optimum orbit control
- Optimum shielding of external fields
- Control of residual $B_r$ fields

*"Holy Grail"* storage ring (largest electrostatic ever conceived)

# Developm.: Extending the Spin-Coherence Time in Storage Rings

## Spin-Coherence Time (SCT)

- Polarization vector: $\vec{P}(t) = \frac{1}{n}\sum_{i=1}^{n} \vec{s}_i(t)$
- Definition: $P(\tau) = P_0/e$

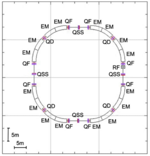
## Analytical Model

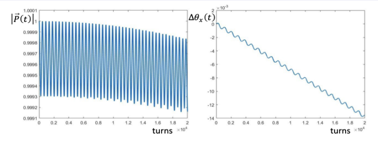
- $\tau \propto 1/\Delta\nu_s$ (spin-tune spread)
- $\Delta\nu_s \propto \Delta L/L$ (path lengthening)

$$\frac{\Delta L}{L} = -\frac{\pi}{L}(\epsilon_x\xi_x + \epsilon_y\xi_y) + \alpha_0\delta + \alpha_1\delta^2 = \alpha_1\delta^2 - \frac{\pi}{L}\epsilon_x\xi_x - \frac{\pi}{L}\epsilon_y\xi_y$$

- $\Rightarrow$ Optimization via sextupole families

## Validation through Bmad Simulations




$\Rightarrow$ see talk of R. Shankar on 23.09 for details

# Statistical Reach of the EDM Ring

## High precision, primarily electric storage ring

- Beam intensity: $N=4 \cdot 10^{10}$ per fill
- Polarization: P=0.8
- Spin coherence time: $\tau$ = 1000 s
- Electric fields: E = 8 MV/m
- Polarimeter analyzing power: A = 0.6
- Polarimeter efficiency: f = 0.005

## Expected statistical sensitivity in 1 year of DT:

- $\sigma_{stat} = \frac{2\hbar}{\sqrt{Nf\tau}PAE} \Rightarrow \sigma_{stat} = 2.4 \cdot 10^{-29} e \cdot cm$
- $\Rightarrow$ Challenge: get $\sigma_{syst}$ to the same level.

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## B. Marciano (Snowmass Workshop, Sept. 2020) about $d_p \sim 10^{-29}$:

- $d_p \sim \frac{e \cdot m}{\Lambda_{NP^2}} sin\phi^{NP}$ ($\Lambda_{NP} \equiv$ scale of NP; $\phi^{NP} \equiv$ complex CP violation phase of NP)
- If $\phi^{NP}$ is of O(1) $\Rightarrow \Lambda_{NP} \sim$ 3000 TeV probed
- If $\Lambda_{NP} \sim$ O(1 TeV) $\Rightarrow \phi^{NP} \sim 10^{-6}$ probed

# Systematic Limits and Mitigation

- Signal: $\Omega_{EDM} = \frac{dE}{s\hbar} = 2.4 \cdot 10^{-9} s^{-1}$ for $d = 10^{-29} e \cdot cm$

## Possible systematic contributions

- Radial B-field: $B_r = 10^{-17}$ T: $\Omega_{B_r} = 1.7 \cdot 10^{-9} s^{-1}$
- Geometric phase: $B_{long} = B_{vert} = 10^{-9}$ T: $\Omega_{B_r} = \frac{eGB_r}{16m} \frac{1}{f_{rev}} = 3.7 \cdot 10^{-9} s^{-1}$
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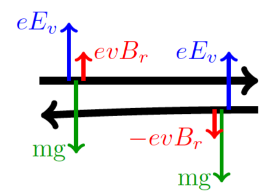
- General relativity: $\Omega_{GR} = - \frac{\gamma}{\gamma^2+1} \frac{\beta g}{c} = - 4.4 \cdot 10^{-8} s^{-1}$

## Control strategy

- Use of two beams running clockwise (CW) and counterclockwise (CCW):
  $\Omega_{CW} = \Omega_{EDM} + \Omega_{GP} + \Omega_{GR} + \Omega_{B_r}$; $\Omega_{CCW} = \Omega_{EDM} - \Omega_{GP} - \Omega_{GR} + \Omega_{B_r}$
  $\Rightarrow$ In the sum, $\Omega_{GP} + \Omega_{GR}$ cancel out.
  $\Rightarrow$ Effect of $B_r$ removed by observing relative displacement of the two beams.




J. Pretz

# Conclusions

## EDM searches in Storage Rings

- EDM searches probe new CP violation $\Rightarrow$ key to matter-antimatter asymmetry
- Key developments in accelerator technology

## Fundamental achievements at COSY

- Spin-control tools
- First measurement of (static and oscillating) deuteron EDM

## Next step

- Design and construction of a *pure electrostatic* EDM proton ring
- Possible approaches
  - Direct approach
  - Staged approach

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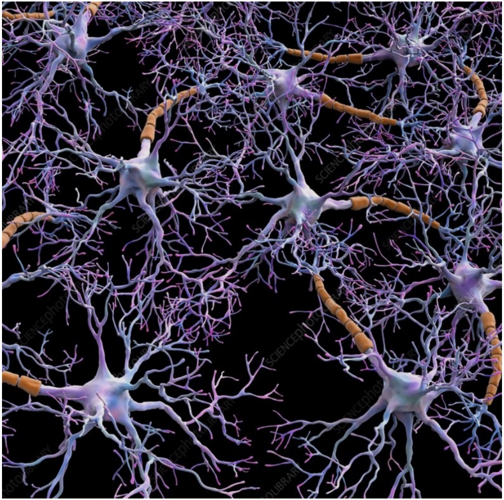
Outstanding discovery potential!



# Thank you!

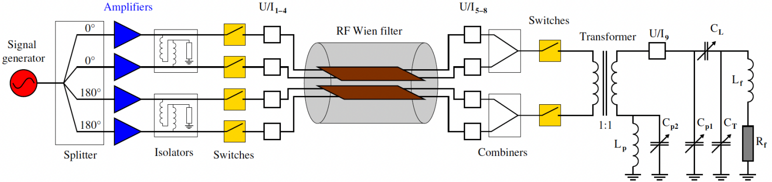
# JEDI Collaboration: selected publications

- D. Eversmann et al (JEDI Collaboration): New method for a continuous determination of the spin tune in storage rings and implications for precision experiments - Phys. Rev. Lett. 115, 094801 (2015)
- J. Slim, et al.:Electromagnetic simulation and design of a novel waveguide rf-Wien filter for electric dipole moment measurements of protons and deuterons - Nucl. Instr. and Meth. A: 828, 116 (2016), ISSN 0168-9002
- G. Guidoboni et al. (JEDI Collaboration): How to reach a thousand-second in-plane polarization lifetime with 0:97 Gev/c deuterons in a storage ring - Phys. Rev. Lett. 117, 054801 (2016)
- N. Hempelmann et al. (JEDI Collaboration): Phase locking the spin precession in a storage ring - Phys. Rev. Lett. 119, 014801 (2017)
- F. Abusaif (CPEDM Collaboration): Storage Ring to Search for Electric Dipole Moments of Charged Particles - Feasibility Study - (CERN, Geneva, 2021)
- S. Karanth et al. (JEDI Collaboration): First Search for Axion-Like Particles in a Storage Ring Using a Polarized Deuteron Beam - S. Karanth et al., Phys. Rev. X 13 (2023) 031004.
- J. Slim, et al. (JEDI Collaboration): Proof-of-principle demonstration of a pilot bunch comagnetometer in a stored beam - J. Slim et al., Phys. Rev. Research 7, 023257

# Spare slides

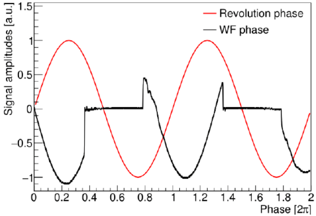
# Implementation of fast switches[2] at RF Wien filter

## Modification of driving circuit




### GaN HEM FET-based solution:

- Short switch on/off times (≈ few ns).
- High power capabilities (≈ few kV).
- On board power damping (- 30 dB )
- Symmetric switch on/off times (≈ ns).




### Switches

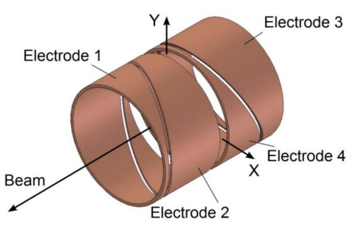
- Capable to handle up to 200 W each
- Permits system to run near a total power of 0.8 kW in pulsed mode

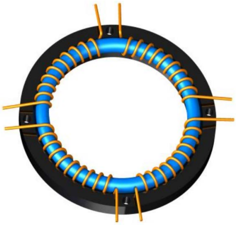
[1] Developed together with Fa. barthel HF-Technik GmbH, Aachen

# Measurement of EDM in a magnetic ring

## Beam position monitors for srEDM experiments

- Main adv.: short install. length (≈ 1 cm in beam direction)



**Conventional BPM**

- Easy to manifacture
- Length = 20 cm
- Resolution ≈ 10 $\mu$m

**Rogowski BPM (warm)**

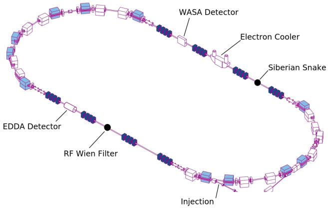
- Excellent RF-signal response
- Length = 1 cm
- Resolution ≈ 1.25 $\mu$m

- 2 coils installed at entrance and exit of RF Wien filter

# Strength of EDM resonance

## EDM induced polarization oscillation

- Described by: $p_y(t) = a\ sin(\Omega^{p_y} t + \phi_{RF})$
- EDM resonance strength: ratio of $\Omega^{p_y}$ to orbital ang. frequency $\Omega^{rev}$: $\epsilon^{EDM} = \frac{\Omega^{p_y}}{\Omega^{rev}}$




## Methodology of EDM measurement

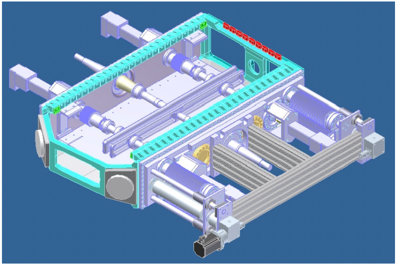
Two features simultaneously applied in the ring:

1. RF Wien-filter rotated by a small angle → generates small radial magnetic RF-field → affects the spin evolution.
2. In addition: longitudinal magnetic field in ring opposite to Wien-flter, about which spins rotate as well

## Concept of EDM measurement

- Determination of the invariant spin axis
- Deduce upper limit for deuteron EDM

# E/B deflector development using real-scale lab setup

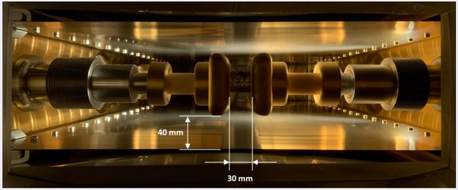
**Equipment:**

- Dipole magnet $B_{max}$ = 1.6 T
- Mass = 64 t
- Gap height = 200 mm
- Protection foil between chamber wall and detector

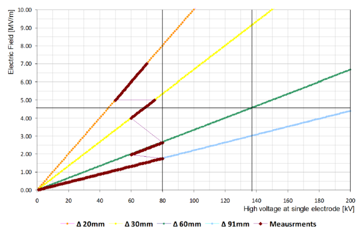
**Parameters:**

- Electrode length = 1020 mm
- Electrode height = 90 mm
- Electrode spacing = 20 to 80 mm
- Max. applied voltage = $\pm$ 200 kV
- Material: Aluminum coated by TiN

# Results




- Electrodes at the distance of 30 mm inside the vacuum chamber




- Electric field between the electrodes vs displacement.

- Measurement procedure shortened due to time constraints.
- Max. electric field strength: 7 MV/m with 60 mm spacing between electrodes
- $\rightarrow$ Next step: setup moved to BNL?