Spin physics using storage rings

Spin-physics tools, instruments, opportunities and perspectives

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(partially on behalf of PAX and JEDI)

17th SPARC WORKSHOP (collaboration meeting)
September 14-16, 2020
Zoom meeting: `https://gsi-fair.zoom.us/j/94810461910`

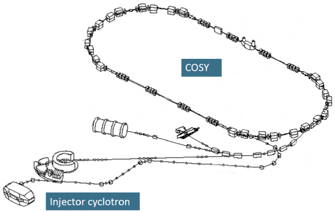
Contents

Tools for spin physics in storage rings

Perfecting the tool box

COoler SYnchrotron COSY

- Cooler and storage ring for (polarized) protons and deuterons.
- Momenta $p = 0.3 - 3.7\,\mathrm{GeV}/c$.
- Phase-space cooled internal and extracted beams.



COSY formerly used as spin-physics machine for hadron physics[1]:

- Provides ideal starting point for srEDM related R&D.
- Will be used for first direct measurement of deuteron EDM.

[1] For a review of the experimental hadron physics program at COSY, see [1].

Colliding beam source at COSY-Jülich

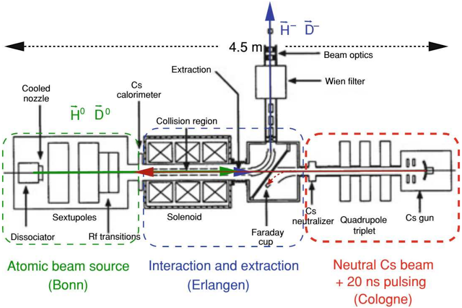
Developed by cooperation of Universities of Erlangen, Bonn and Cologne

Based on charge-exchange reaction [2]:

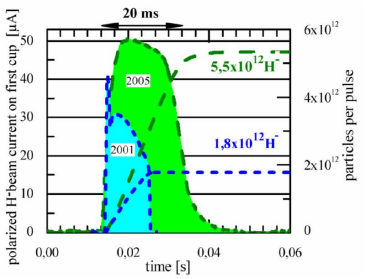
$$\vec{\mathrm{H}}^0 + \mathrm{Cs}^0 \rightarrow \vec{\mathrm{H}}^- + \mathrm{Cs}^+ \quad \text{same for D} \tag{1}$$

Similar sources built previously at Madison, Brookhaven, and Seattle:

- High output, high polarization, reliable long-time running capability [3].
- 20 ms pulsing of atomic beam, and gas inputs of H_2 (D_2) (also N_2/O_2).
- Synchronous pulsing of Cs beam [4].



Intensity and polarization of CBS at COSY-Jülich[2]



- Typical COSY fill has a few 1×10^{10} protons or deuterons stored.
- Space charge limit $\approx 1 \times 10^{11}$ particles.

Mode	$P_z^{\rm Ideal}$	$P_{zz}^{\rm Ideal}$	$I_0^{\rm Ideal}$	RFT$_1$	RFT$_2$	RFT$_3$	$P_z^{\rm LEP}$	$P_z^{\rm LEP}/P_z^{\rm Ideal}$	$P_z^{\rm EDDA}$	$P_{zz}^{\rm EDDA}$
0	0	0	1	Off	Off	Off	0.000 ± 0.010	—	0	0
1	$-2/3$	0	1	Off	Off	On	-0.516 ± 0.010	0.774 ± 0.015	-0.499 ± 0.021	0.057 ± 0.051
2	$+1/3$	$+1$	1	Off	On	Off	0.257 ± 0.010	0.771 ± 0.030	0.290 ± 0.023	0.594 ± 0.050
3	$-1/3$	-1	1	Off	On	On	-0.272 ± 0.010	0.817 ± 0.030	-0.248 ± 0.021	-0.634 ± 0.051
4	$+1/2$	$-1/2$	2/3	On	On	Off	0.356 ± 0.013	0.712 ± 0.025	0.381 ± 0.027	-0.282 ± 0.064
5	-1	$+1$	2/3	On	On	On	-0.683 ± 0.013	0.683 ± 0.013	-0.682 ± 0.027	0.537 ± 0.064
6	$+1$	$+1$	2/3	On	Off	Off	0.659 ± 0.013	0.659 ± 0.013	0.764 ± 0.027	0.545 ± 0.061
7	$-1/2$	$-1/2$	2/3	On	Off	On	-0.376 ± 0.013	0.752 ± 0.027	-0.349 ± 0.027	-0.404 ± 0.065

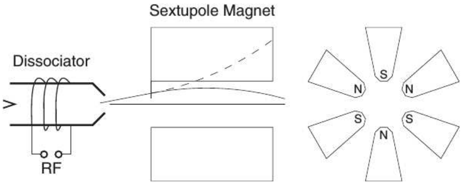
[2] For more details on COSY operation with polarized deuterons, see [3].

Polarized targets

Physics and techniques of atomic beam sources (ABS)

Overview

- Production of H and D ground-state atomic beams,
- Dissociators, beam formation and accomodation,
  - RF discharge dissociators [5]
  - Microwave Dissociators [6]
- State-separation magnets [7]



- RF transitions
- Ionizers
- Gain of target density using storage cells [8]

A state-of-the-art ABS used at ANKE at COSY [5]

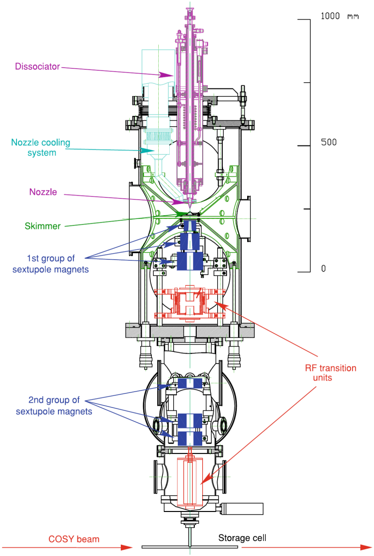
Saturation of source intensity:

- Behind last magnet, polarized atomic beam sources reach

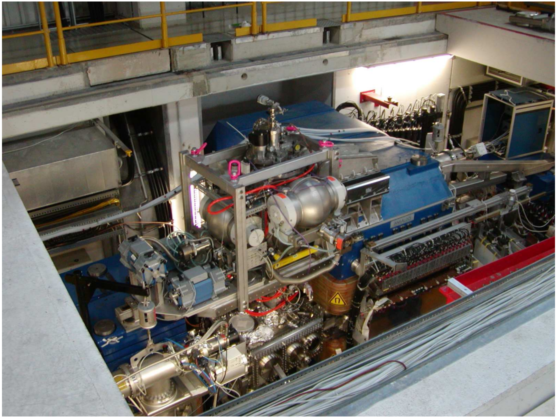
$$I \simeq 10^{17}\ \text{atoms}/\text{s}. \qquad (2)$$

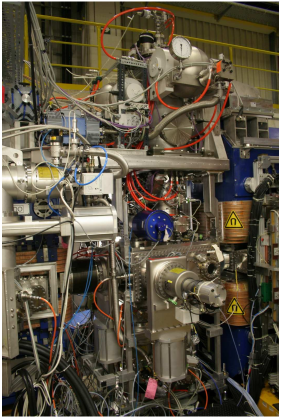
- Comparison of source intensities (two hyperfine states):

Source	Intensity $[10^{16}$ at/s$]$	Year	Reference
Madison/IUCF	6.7	1993	[9]
FILTEX	8.2	1994	[10]
Munich	6.4	1998	[11]
Novosibirsk	7.9	2002	[12]
HERMES/FILTEX	6.4	2003	[13]
ANKE	7.5	2002	[5]
RHIC H-jet	12.4	2005	[14, 15]



ABS installed at the ANKE spectrometer magnet

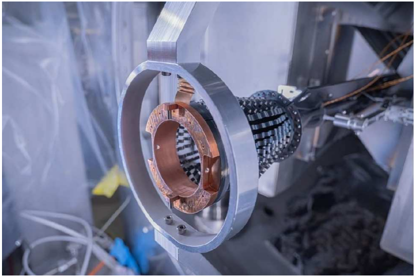




Storage cells for polarized targets

Advantages of the injection of *precious* target particles into a cell

- Target thickness scales approximately with number of wall collisions in cell.
- Gain of 100 units in target thickness, but residual gas in ring loaded only by equivalent of one unit.
- A storage cell will soon be used at LHC.



Openable storage cell at the SMOG internal gas target of the LHCb detector [16].

Polarized antipotons (for FAIR)

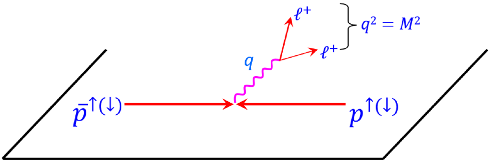
Since about 2004, renewed interest in experiments with polarized $\bar{p}$:

- In 2005, PAX TP for FAIR suggested to upgrade HESR to a double-polarized $\bar{p}p$ collider to measure proton transversity distribution [17, 18].

Polarized $\bar{p}p$ interactions at HESR of FAIR:

- provide unique access to a number of new fundamental physics observables that can be studied neither at other facilities nor at HESR without transverse polarization of protons and antiprotons.

Drell-Yan process in $\bar{p}p$ collisions [17]



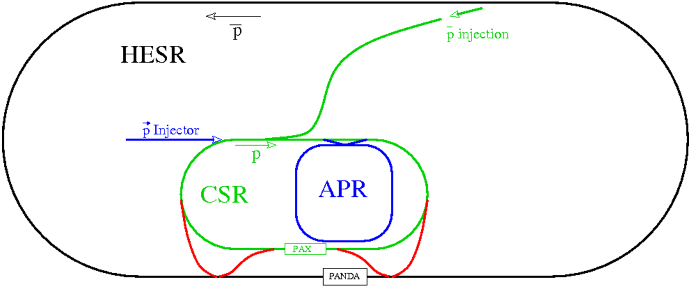
$\bar{p}^{\uparrow} + p^{\uparrow}$ (transversely polarized) impinging head on in a collider:

- First ever direct measurement of quark transversity distribution h_1, by measuring double transverse spin asymmetry A_{TT} in Drell-Yan processes $p^{\uparrow}\bar{p}^{\uparrow} \to e^+e^-X$ as function of Bjorken x and Q^2 $(= M^2)$ [19, 20].

$$A_{TT} \equiv \frac{\mathrm{d}\sigma^{\uparrow\uparrow} - \mathrm{d}\sigma^{\uparrow\downarrow}}{\mathrm{d}\sigma^{\uparrow\uparrow} + \mathrm{d}\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 h_1^q(x_1, M^2) h_1^{\bar{q}}(x_2, M^2)}{\sum_q e_q^2 q(x_1, M^2)\bar{q}(x_2, M^2)}\,, \quad \text{where} \tag{3}$$

  - $q = u, \bar{u}, d, \bar{d}, \ldots,$ runs over all quark flavours.
  - M is invariant mass of lepton pair, and
  - $\hat{a}_{TT}$ (of order 1) calculable double-spin asymmetry of elementary QED process $q\bar{q} \to e^+e^-$.

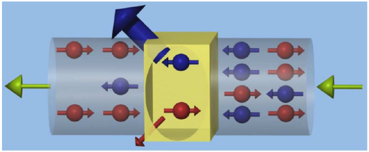
Convert HESR into double-polarized $\bar{p}p$ collider



Asymmetric $\bar{p}p$ collider (for details, see [17])

- Asymmetric collider using HESR storing p at 15 GeV/c, plus
- a COSY-like ring to store $\bar{p}$ at 3.5 GeV/c.
- Antiproton Polarizer Ring (APR) to produce polarized $\bar{p}$'s by spin filtering.

How to polarize antiprotons?

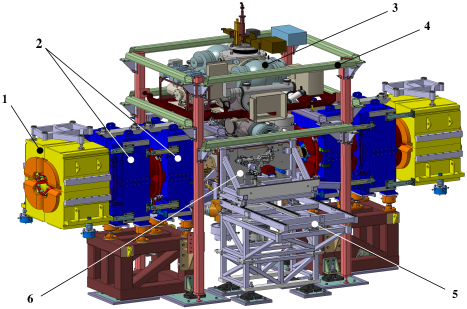


- Polarizing antiprotons by spin filtering using the spin-dependent part of NN interaction [21] remains *the only viable method*:

$$\sigma_{\text{tot}} = \sigma_0 + \sigma_1 \vec{P}_1 \cdot \vec{P}_2 + \sigma_2 (\vec{P}_1 \cdot \vec{k})(\vec{P}_2 \cdot \vec{k}) \,, \tag{4}$$

  - $P_{1,2}$: vector polarizations of protons 1 and 2,
  - σ_0: total spin-independent cs,
  - σ_1: spin-dependent total cs with transverse polarizations, and
  - σ_2: spin-dependent total cs with longitudinal polarization ($\vec{k} \parallel$ beam).
- Method experimentally confirmed to work for protons [22].
- Repetition of spin-filtering experiment with p in 2011 at COSY [23, 24] confirmed that only pp scattering contributes to polarization build-up.
- Theoretical work on $\bar{p}p$ interactions [25, 26] extended to $\bar{p}d$ [27] and $\bar{p}^3$He [28].

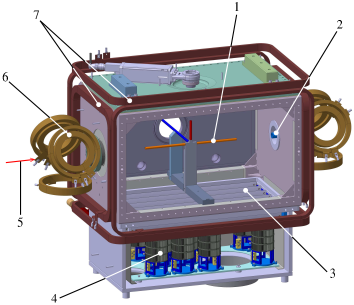
Experimental setup for spin-filtering at COSY [24]



Target installation (beam from the left):

1. COSY quadrupole magnet of triplet,
2. four quadrupoles (formerly used at CELSIUS [29]) forming low-β insertion by doublet focusing (DF-FD),
3. Atomic beam source,
4. Flange supporting rail system,
5. Target chamber housing storage cell,
6. Breit-Rabi polarimeter (BRP) and Target-Gas Analyzer (TGA), mounted outside of ring.

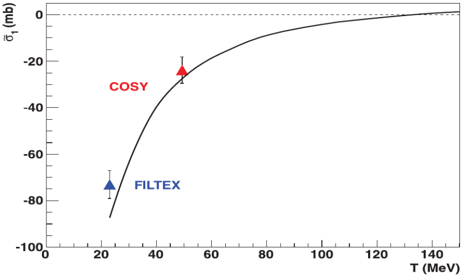
Target chamber [24]



Section view of target chamber:

1. Storage cell with feeding tube to ABS (vertical), and extraction tube to BRP,
2. Flow limiters of 19 mm diameter and 80 mm length,
3. Jalousie to protect cell from heat radiation during activation of
4. NEG pumps,
5. COSY beam,
6. guide field compensation coils, and
7. magnetic guide field coils.

Results for σ_1 and theoretical predictions



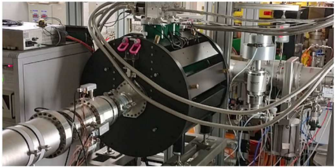
Comments

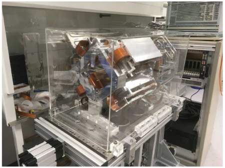
- Measured spin-dependent polarizing cross section (statistics only) [22, 23].
- Solid line represents predictions from SAID NN database.
- Prediction basically independent of ring acceptance in interval of values covered by TSR and COSY spin-filtering experiments.

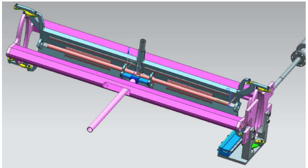
Future perspectives for PAX

Next Steps for PAX

- Complete spin-filtering *pp* studies by measurement of σ_2 [see Eq. (4)].
  - Requires longitudinal polarization in COSY.
  - Siberian snake is installed and first commissioning took place [30]
  - PAX multipurpose SI detector to measure beam and target polarizatons with openable storage cell ready







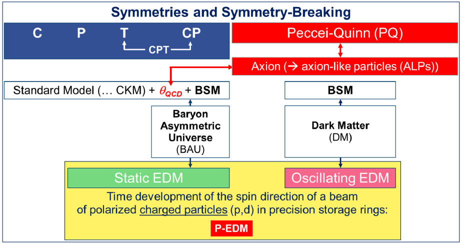
- Once $\bar{p}$'s are available at FAIR, spin-filtering studies at ESR could be envisioned to determine σ_1 and σ_2 as fct of energy in the $\bar{p}p$ system.
- Once spin-dependent $\sigma_{1,2}(\bar{p}p)$ are known, APR ring can be designed [31].

Search for electric dipole moments in storage rings (JEDI)

Most intriguing puzzles of contemporary physics

Open issues

- Predominance of matter over antimatter in the Universe
- Nature of Dark Matter



Approach

- Measurements of static EDMs of fundamental particles.
- Searches for axions and axion-like particles (ALPs) as Dark Matter candidates through oscillating EDMs

Electric dipole moments (EDMs)

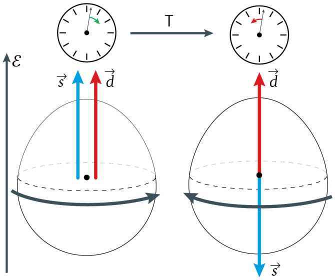


Figure taken from [32].

- Permanent separation of centers of $+$ and $-$ charges.
- Fundamental property of particles (like magnetic moment, mass, and charge).
- Possible only via violation of time-reversal: $T \stackrel{CPT}{=} CP$ and parity P.
- EDMs provide connection to matter-antimatter asymmetry of the Universe

EDM measurements test the violation of P and T symmetries

Baryon asymmetry in the Universe

CP-violation & Matter-Antimatter Asymmetry

Carina Nebula: Largest-seen star-birth regions in the galaxy

Observation and expectation Standard Cosmological Model (SCM):

	$\eta = (n_b - n_{\bar{b}})/n_\gamma$	
Observation	$(6.11^{+0.3}_{-0.2}) \times 10^{-10}$	Best Fit Cosmological Model [33]
	$(5.53 - 6.76) \times 10^{-10}$	WMAP [34]
Expectation from SCM	$\sim 10^{-18}$	Bernreuther (2002) [35]

SCM has it wrong by about 9 orders of magnitude

- New *CP* violating sources beyond SM needed
  - *CP*-V required for baryogenesis already predicted by Sakharov in 1967 [36]
- Could show via EDMs of elementary particles

Current upper limits of EDMs

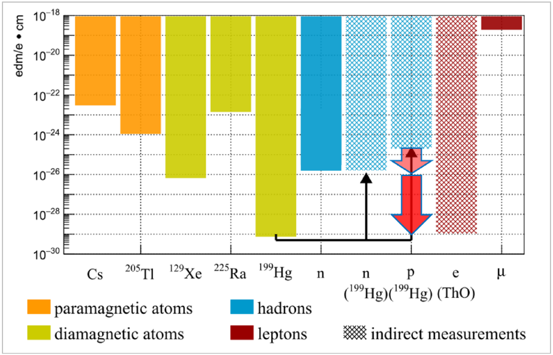


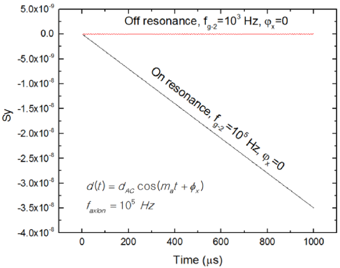
Figure taken from [37].

- Full colored boxes: results from direct measurements
- Hatched boxes: deduced limits from indirect measurements.
- Wide red arrows: sensitivity limits for EDM prototype ring and final ring.

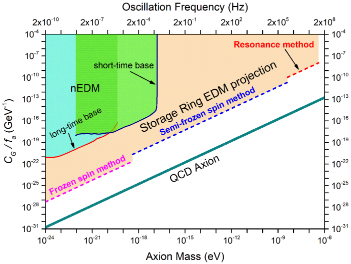
Oscillating Axion-EDM search using a storage ring

Measurement principle:

- Oscillating axion field couples to gluons and induces oscillating EDM in hadronic particles [38, 2011].
- Oscillating EDM resonates with particle $g-2$ spin-precession in storage ring $\rightarrow$ EDM precession can be accumulated.
- Strong effective electric field (from $\vec{v} \times \vec{B}$) improves sensitivity significantly.



Courtesy of Seongtae Park (IBS, Daejeon)



Limits for axion-gluon coupled to oscillating EDM [39].

Possible in magnetic ring with polarized beam

- First test experiment carried out at COSY in 2019.

Experimental method for static EDMs

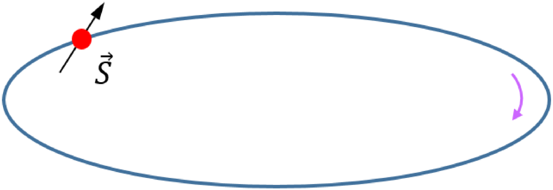
Spin precession of particles with MDM ($\vec{\mu}$) and EDM ($\vec{d}$)

In rest frame of particle

- equation of motion for spin vector $\vec{S}$:

$$\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \vec{\Omega} \times \vec{S} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}. \tag{5}$$

Put protons in a ring



$\rightarrow$ Spin-precession with MDMs and EDMs governed by Thomas-BMT eq. [40].

Frozen-spin

Spin precession frequency of particle *relative* to direction of flight:

$$\begin{aligned}\vec{\Omega} &= \vec{\Omega}_{\text{MDM}} - \vec{\Omega}_{\text{cyc}} \\ &= -\frac{q}{\gamma m}\left[G\gamma\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel} - \left(G\gamma - \frac{\gamma}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right].\end{aligned} \tag{6}$$

$\Rightarrow$ $\vec{\Omega} = 0$ **called frozen spin, because all spins point in same direction.**

- In the absence of magnetic fields ($B_{\perp} = \vec{B}_{\parallel} = 0$),

$$\vec{\Omega} = 0, \text{ if } \left(G\gamma - \frac{\gamma}{\gamma^2-1}\right) = 0. \tag{7}$$

  - Possible only for particles with $G > 0$, such as proton ($G = 1.793$) or electron ($G = 0.001$).

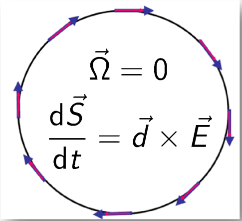
For protons, (7) leads to *magic momentum*:

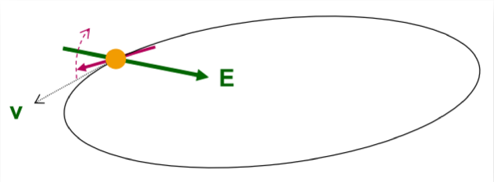
$$G - \frac{1}{\gamma^2-1} = 0 \Leftrightarrow G = \frac{m^2}{p^2} \quad \Rightarrow \quad \boxed{p = \frac{m}{\sqrt{G}} = 700.740\,\text{MeV}\,\text{c}^{-1}} \tag{8}$$

Protons at magic momentum in pure electric ring:

Recipe to measure EDM of proton:

1. Place polarized particles in a storage ring.
2. Align spin along direction of flight at magic momentum.
   $\Rightarrow$ *freeze* spin precession.
3. Search for time development of vertical polarization.

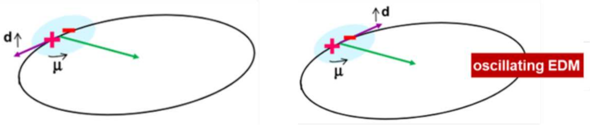




New method to measure EDMs of charged particles:

- **Magic rings with spin frozen** along momentum of particle.
- Polarization buildup $P_y(t) \propto d$.

Experimental method to detect oscillating (Axion) EDMs



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

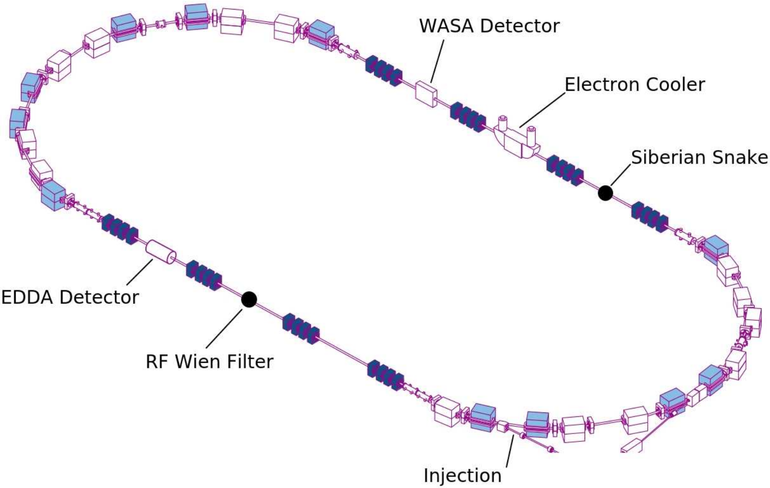
$$\eta = \eta_0 + \eta_1 \sin(\omega_{\text{axion}} t + \phi_a)$$

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

Combined E/B ring

- Particle spin precesses in horizontal plane due to magnetic field and its effect on MDM.
- Oscillating EDM (oEDM) at right frequency creates a resonant situation in which not only the torque changes sign, but also the EDM vector changes direction $\Rightarrow$ constructive out-of-plane spin rotation.
- Changing the beam momentum in ring, the precession frequency, the oEDM frequency, and thus the Compton frequency, proportional to the axion/ALP mass, can be probed.

COSY Landscape for the storage ring EDM program[3]

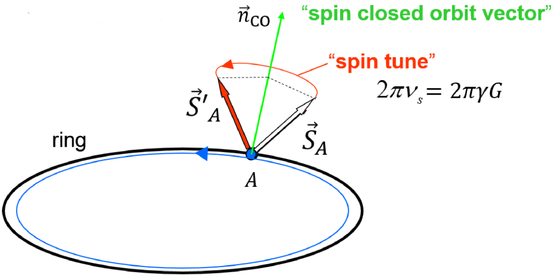


[3]For a progress report on storage ring EDM experiments (srEDM), see [41, 37].

Spin closed orbit and spin tune

One particle with magnetic moment makes one turn in machine ($A - A$):

- Stable direction of polarization in ring, if $\vec{S} \parallel \vec{n}_s$.
- Vector $\vec{n}_s$ around which spins precess called spin-closed orbit:
  - stable spin direction $\vec{n}_s \equiv \vec{n}_s(s)$, is a fct of position along orbit.

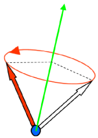


Number of spin precessions per turn is called spin tune ν_s.

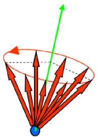
Spin coherence

Most polarization experiments don't care about coherence of spins along $\vec{n}_s$

Spins aligned:
Ensemble *coherent*

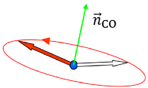


Spins out of phase:
Ensemble *decoherent*

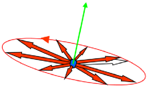


$\Rightarrow$ **Polarization components along $\vec{n}_s$ not affected**

With in-plane spins: $\vec{S} \perp \vec{n}_s$:
Ensemble *coherent*

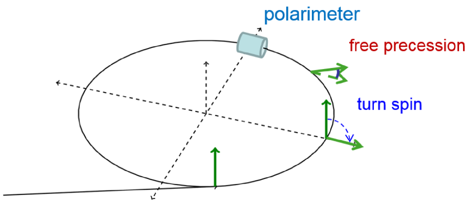


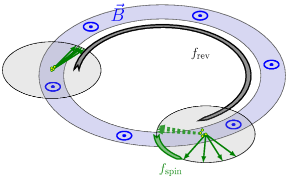
Over time:
Spins out of phase in horizontal plane



$\Rightarrow$ **In-plane polarization vanishes**

Principle of spin-coherence time measurement

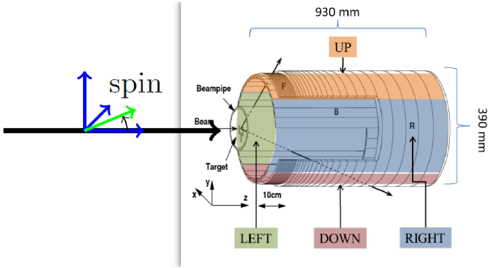


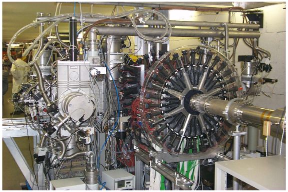


Measurement procedure:

1. Vertically polarized deuterons stored at $p \simeq 1\,\text{GeV}\,\text{c}^{-1}$.
2. Polarization flipped into horizontal plane with RF solenoid ($\approx 200\,\text{ms}$).
3. Beam extracted on Carbon target with ramped bump or by heating.
4. Horizontal (in-plane) polarization determined from $U - D$ asymmetry.

Detector system EDDA [42, EDDA EPJA] (meanwhile replaced by JEPO)





EDDA was used to determine $\vec{p}\vec{p}$ elastic polarization observables:

- Deuterons at $p = 1\,\text{GeV}\,\text{c}^{-1}$, $\gamma = 1.13$, and $\nu_s = \gamma G \simeq -0.161$
- Spin-dependent differential dC cross section (unpolarized target):

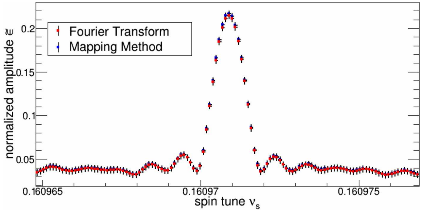
$$N_{\text{U,D}} \propto 1 \pm \frac{3}{2} p_z A_y \sin(\underbrace{\nu_s \cdot f_{\text{rev}}}_{f_s = -120.7\,\text{kHz}} \cdot t), \text{ where } f_{\text{rev}} = 750.0\,\text{kHz}. \tag{9}$$

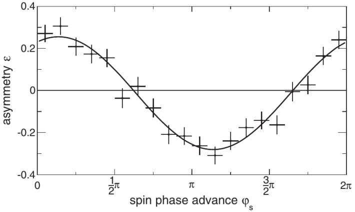
Determination of spin tune [43, JEDI PRL]

Time-stamping events in each detector quadrant accurately:

1. Based on turn number n, 100 s measurement interval split into turn intervals of $\Delta n = 10^6$ turns, each interval lasting ≈ 1.3 s.
2. For all events, spin phase advance $\varphi_s = 2\pi|\nu_s^{\text{fix}}|n$ calculated assuming certain fixed spin tune ν_s^{fix}.
3. Either map events into one full polarization oscillation in range $\varphi_s \in [0, 2\pi)$, or perform Fourier analysis of rates in detector $\Rightarrow$ determine $\tilde{\varepsilon}$ and $\tilde{\phi}$ in

$$\varepsilon(\varphi_s) = \tilde{\varepsilon}\sin(\varphi_s + \tilde{\varphi})\,. \tag{10}$$



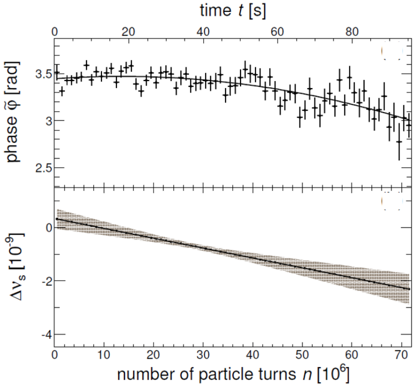


Determination of spin tune [43, JEDI PRL]

Analyze all time intervals:

- Monitor phase of measured asymmetry with assumed fixed spin tune ν_s^{fix} in a 100 s cycle:

$$\begin{aligned}\nu_s(n) &= \nu_s^{\text{fix}} + \frac{1}{2\pi}\frac{\mathrm{d}\tilde{\phi}}{\mathrm{d}n} \\ &= \nu_s^{\text{fix}} + \Delta\nu_s(n)\end{aligned} \qquad (11)$$

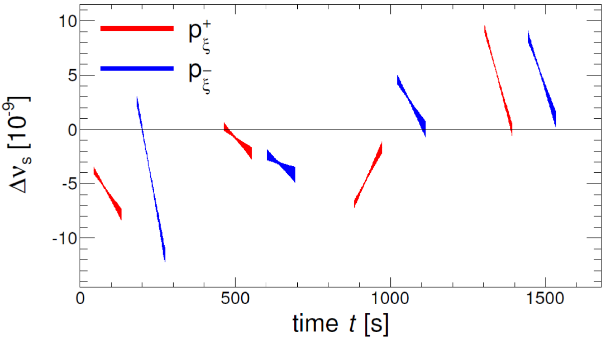


Experimental technique allows for:

- Spin tune ν_s determined to $\approx 10^{-8}$ in 2 s time interval.
- In a 100 s cycle at $t \approx 38$ s, interpolated spin tune amounts to $|\nu_s| = (16097540628.3 \pm 9.7) \times 10^{-11}$, *i.e.*, $\Delta\nu_s/\nu_s \approx 10^{-10}$.

$\Rightarrow$ **New precision tool to study systematic effects in a storage ring.**

Spin tune as a precision tool for accelerator physics

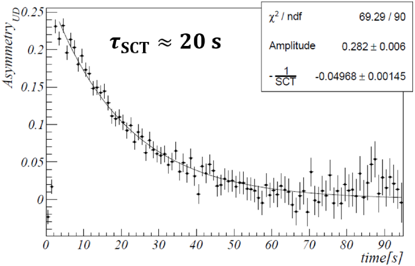


Walk of spin tune ν_s [43].

Applications of new technique:

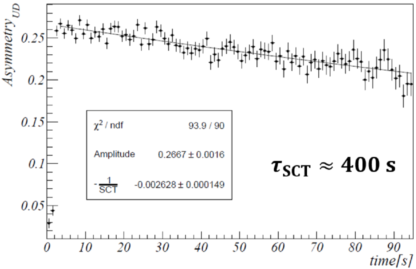
- Study long term stability of an accelerator.
- Feedback system to stabilize phase of spin precession relative to phase of RF devices (so-called **phase-lock**).
- Studies of machine imperfections.

Spin coherence time



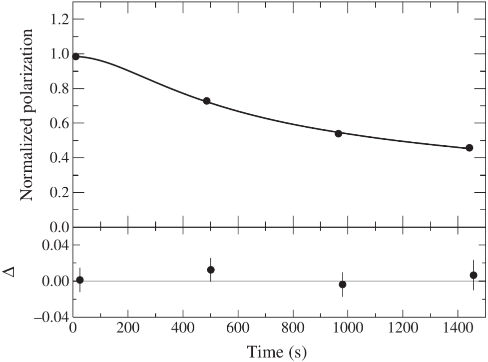
2012: Observed experimental decay of asymmetry

$$\epsilon_{\mathrm{UD}}(t) = \frac{N_D(t) - N_U(t)}{N_D(t) + N_U(t)}. \qquad (12)$$



2013: Using various sextupole magnet families in the machine, higher order effects are corrected, and spin coherence substantially increased.

Optimization of spin-coherence time [45, JEDI PRL]



JEDI progress on τ_{SCT}:

$$\tau_{\mathrm{SCT}} = (\mathbf{782} \pm \mathbf{117})\,\mathrm{s}$$

- Previous record: $\tau_{\mathrm{SCT}}(\mathrm{VEPP}) \approx 0.5\,\mathrm{s}$ [44] ($\approx 10^7$ spin revolutions).

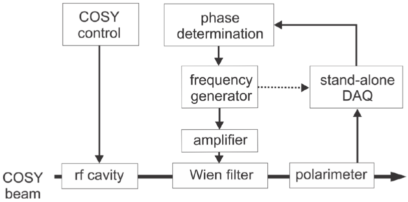
In 2015, way beyond expectation:

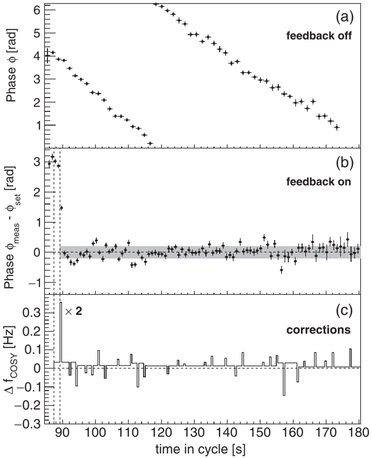
- With about 10^9 stored deuterons.
- Spin decoherence considered one main obstacle of srEDM experiments.

Phase locking spin precession in machine to device RF

Feedback system maintains

1. resonance frequency, and
2. phase between spin precession and device RF (solenoid or Wien filter)

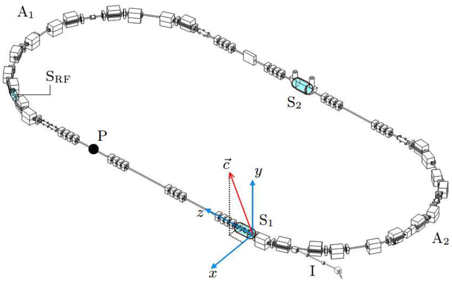




Major achievement : Error of phase-lock $\sigma_\phi = 0.21\,\text{rad}$ [46, JEDI PRL].

Study of machine imperfections I

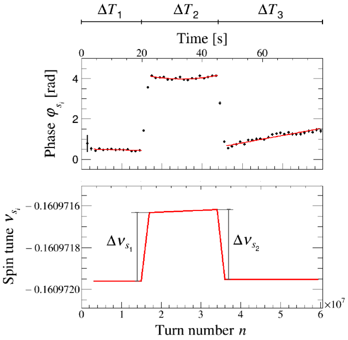
JEDI developed new method to investigate magnetic imperfections based on highly accurate determination of spin-tune [47, JEDI PRAB].



Spin tune mapping:

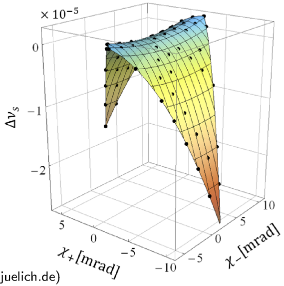
- Two cooler solenoids act as spin rotators
  - ⇒ Generation of artificial imperfection fields.
- Measure spin tune shift vs spin kicks in solenoids.

Study of machine imperfections II [47, JEDI PRAB]



- Spin phase φ_{s_i} as fct of n for time intervals $i = 1, 2, 3$.
- Spin tunes ν_{s_i} and spin tune jumps $\Delta\nu_{s_{1,2}}$.

- Position of saddle point determines tilt of stable spin axis by magnetic imperfections.
- Control of background from MDM at level $\Delta c = 2.8 \times 10^{-6}$ rad.
- Systematics-limited sensitivity for deuteron EDM at COSY $\sigma_d \approx 10^{-20}$ e cm.



Strategy toward a dedicated EDM ring

Charged Particle Electric Dipole Moment Collaboration[4]

Project stages and time frame toward a dedicated EDM ring: [48, CPEDM→ CYR]

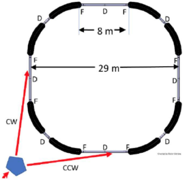
Stage 1

- precursor experiment

- magnetic storage ring
- Now

Stage 2

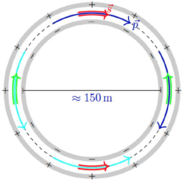
- prototype ring



- electric/magnetic bends
- simultaneous ↺ and ↻ beams
- 5 years

Stage 3

- dedicated storage ring



- at magic p momentum
- 10 years

$\sigma_{EDM}/(e\cdot\mathrm{cm})$

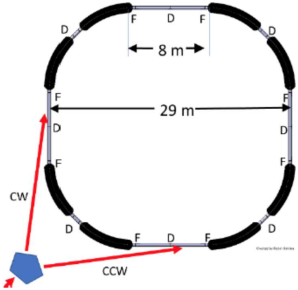
10^{-17} 10^{-18} 10^{-19} 10^{-20} 10^{-21} 10^{-22} 10^{-23} 10^{-24} 10^{-25} 10^{-26} 10^{-27} 10^{-28} 10^{-29}

[4] http://pbc.web.cern.ch/edm/edm-default.htm

Stage 2: prototype EDM storage ring (PTR)

100 m circumference

- p at 30 MeV all-electric CW-CCW beams operation
- p at 45 MeV frozen spin including additional vertical magnetic fields



Challenges – open issues

- All electric & E/B combined deflection
- Storage time
- CW-CCW operation
- Spin-coherence time
- Polarimetry
- Optimum orbit control
- Magnetic moment effects
- Stochastic cooling

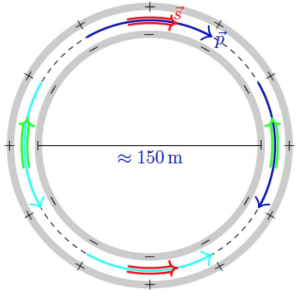
Primary purpose of PTR

- study remaining open issues.

Stage 3: Precision EDM ring

500 m circumference

- All-electric deflection
- Magic momentum for protons ($p = 701\,\mathrm{MeV/c}$)



Challenges

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

"Holy Grail" EDM storage ring

- largest purely electrostatic machine ever conceived

Grants and evaluations

PAX

- ERC Advanced Grant **POLPBAR** (Hans Ströher, Grant Agreement 246980)
- STRONG-2020: WP30 **SpinForFAIR** Horizon 2020 (P. Lenisa, Grant No 824093).

JEDI

- ERC Advanced Grant srEDM (Hans Ströher, Proposal No. 694340)
- HGF Evaluation Report, Topic 2, Cosmic Matter in Laboratory, 01/2020:
  - **Goals** in the PoF IV period
    - Initiation of the proton Electric Dipole Moment (EDM) project at COSY-ring to open an opportunity to explore physics beyond the standard model.
  - **Work program:**
    - Use COSY, the world's only storage ring for polarized proton and deuterium beams at the IKP facility at FZJ. This will explore the scientific potential for proton/deuteron EDM experiments in the COSY-ring.
    - Perform within PoF IV an Axion search via oscillating EDMs at COSY, which may open the way to new concepts that may extend the reach in precision down to 1×10^{-29} e cm.
- Deliberation Document on 2020 Update of European Strategy for Particle Physics:
  - [...] the COSY facility could be used as a demonstrator for measuring the electric dipole moment of the proton at Jülich. These initiatives should be strongly encouraged and supported. [...]

Conclusion I

Polarized sources and targets:

- routinely operated at many facilities around the world.
- employed as a target inside a storage ring, or after ionization, as used a beam that is fed into a ring, mostly comprise H (protons) and D (deuterons).
- Polarized sources generate a flux of about 1×10^{17} atoms/s, which translates into a target thickness of 1×10^{12} atoms/cm^2. Employing a suitable cell, target densities of 1×10^{14} atoms/cm^2 can be achieved.
- Nuclear (or electron) polarizations of neutral H^0 (D^0) atomic beams, typically exceeds $P = 0.9$.

Conclusion II

Polarized antipotons for FAIR:

- Polarized $\bar{p}p$ interactions at FAIR provide unique access to new fundamental physics observables:
  - First ever direct measurement of quark transversity distribution h_1 from double transverse spin asymmetry A_{TT} in Drell-Yan processes $p^{\uparrow}\bar{p}^{\uparrow} \rightarrow e^{+}e^{-}X$.
- Spin filtering using the spin-dependent attenuation in a polarized hydrogen target remains *the only viable method* to polarize antiprotons.
- Next steps for PAX:
  1. pp spin-filtering with longitudinal polarization and a Siberian snake at COSY.
  2. Medium term aim is to extend studies to $\bar{p}p$ system and to determine spin-dependent total cross sections σ_1 and σ_2 via spin filtering over range of energies in suitable ring (AD-CERN, ESR-GSI, ...).
  3. Once $\sigma_{1,2}$ known for $\bar{p}p$ system between about 200 and 500 MeV kinetic beam energy, design of dedicated Antiproton Polarizer Ring for FAIR can be targeted.

Conclusion III

Search for charged hadron particle EDMs (p, d, light ions):

- New window to disentangle sources of CP violation, and to possibly explain matter-antimatter asymmetry of the Universe.

EDM precursor experiment at COSY

- Progress by JEDI in spin dynamics in rings for EDM searches [49].
- Substantial progress producing coherent ensembles of polarized deuteron beams near $1\,\mathrm{GeV}/c$ with typical $\tau_{\mathrm{SCT}} \approx 1500\,\mathrm{s}$.
- Determination of spin tune to better than 1 part in 10^{10} provides new precision diagnostic tool for accelerator physics:
- First direct JEDI deuteron EDM measurement at COSY underway.
  - New spin tools crucial to perform a first direct measurement of deuteron EDM.
  - Making use of a wave-guide RF Wien filter [50–52].
  - Sensitivity goal 10^{-18} to $10^{-20}\,\mathrm{e\,cm}$.

Conclusion IV

Strong interest of high-energy community in srEDM searches

- Protons and light nuclei as part of physics program of the post-LHC era to search for BSM physics:
  - Physics Beyond Collider process (CERN) and European Strategy for Particle Physics Update.
  - As part of this process, staged approach with prototype EDM storage ring (**PTR**) prepared by CPEDM ([48] → CERN Yellow Report)
    - host sites considered for the PTR: CERN or COSY.

EDM searches in storage rings

- Excellent synergic perspectives between nuclear/hadron, astroparticle physics and accelerator technology.
- Search for static charged particle EDMs (p, d, ^{3}He)
  - EDMs → probes of CP-violating interactions
  - Matter-antimatter asymmetry
- Search for oscillating EDMs
  - Axion gluon coupling
  - Dark matter search

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Spare slides

JEDI Collaboration

JEDI = **J**ülich **E**lectric **D**ipole Moment **I**nvestigations

- $\sim$ 140 members (Aachen, Daejeon, Dubna, Ferrara, Indiana, Ithaka, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St Petersburg, Stockholm, Tbilisi, . . .
- `http://collaborations.fz-juelich.de/ikp/jedi`

Physics case

Transversity distribution:

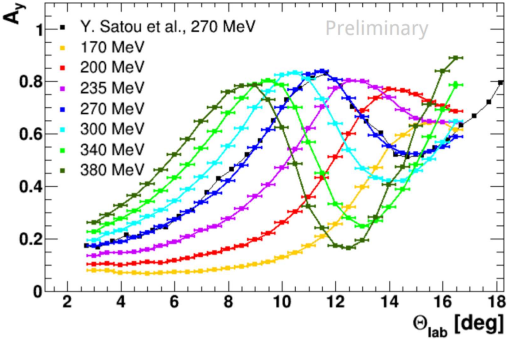
- Transversity distribution constitutes last leading–twist missing piece of QCD description of the partonic structure of nucleon.
- Describes quark transverse polarization inside transversely polarized proton [53].
- Unlike more conventional unpolarized quark distribution $q(x, Q^2)$ and helicity distribution $\Delta q(x, Q^2)$, transversity $h_1^q(x, Q^2)$ can neither be accessed in inclusive deep-inelastic scattering of leptons off nucleons nor can it be reconstructed from knowledge of $q(x, Q^2)$ and $\Delta q(x, Q^2)$.
- It may contribute to some single-spin observables, but always coupled to other unknown functions.

Transversity distribution:

- directly accessible uniquely via **double transverse spin asymmetry $\mathbf{A_{TT}}$** in Drell-Yan production of lepton pairs.
- Theoretical expectations for A_{TT} in Drell-Yan with transversely polarized antiprotons interacting with transversely polarized protons target at HESR in range $0.3 - 0.4$ [19, 20].

dC polarimetry data base II [54]

Results of elastic dC analyzing powers

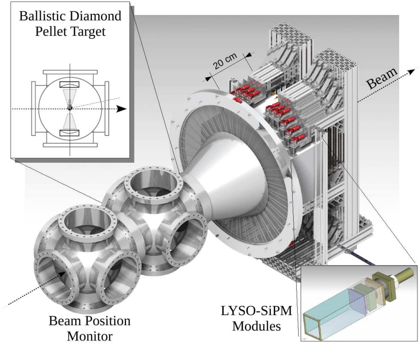


- Analysis of differential *dC* cross sections in progress.
- Similar data base measurements carried out to provide *pC* data base.

High-precision polarimeter with internal C target [55, 56]

Based on LYSO Scintillation Material

- Saint-Gobain Ceramics & Plastics: $Lu_{1.8}Y_{.2}SiO_5$:Ce
- Compared to NaI, LYSO provides
  - high density (7.1 vs 3.67 g/cm^3),
  - very fast decay time (45 vs 250 ns).



After runs with external beam:

- System installed at COSY in 2019.
- New developments:
  - Ballistic diamond pellet target for homogeneous beam sampling
  - For details, see [48, Appendix K].

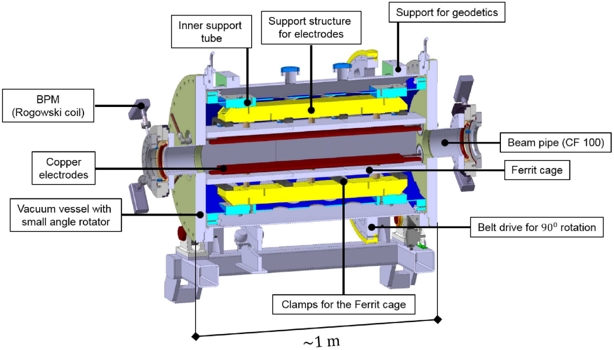
Toward spin manipulation of *individual* beam bunches

1. Particles are usually injected into a ring using beam bunches that are prepared and spin-manipulated inside a suitable beam injection system.
2. Once the bunches are then stored in the machine, spin manipulations are confined to those ones that affect all bunches simultaneously.
   - see, *e.g.*, the procedure shown on slide 30.
3. There are two main obstacles to overcome these limitations:
   - RF spin manipulators, like solenoids, dipoles or Wien filters usually employ resonant circuits.
     - The devices take typically hundreds of ms to power up and down, so that during that time interval, thousands of orbit revolutions take place.
   - Furthermore, even if one could realize a fast spin manipulator, the issue of keeping the RF of the manipulator in phase with the spin precession remains.

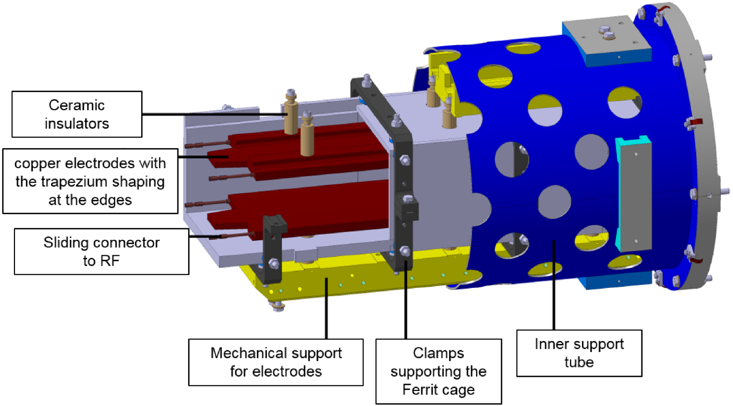
Spin manipulator based on waveguide RF Wien filter [51]

RF Wien filter avoids coherent betatron oscillations of beam:

- Joint Jülich – Aachen development (IKP – IHF RWTH Aachen).
- Waveguide provides $\vec{E} \times \vec{B}$:
  - Minimization of $\vec{F}_\mathrm{L} = q(\vec{E} + \vec{v} \times \vec{B})$ by careful design of all components.
- Spin-tune feedback system ensures:
  - operation of Wien filter on spin resonance,
  - while RF phase is fixed (phase-lock).



Internal structure



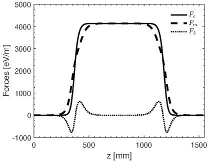
Aim was to build best possible device, with respect to

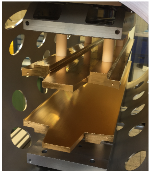
- Electromagnetic performance [51] and mechanical tolerances [57].

Lorentz force compensation [51]

Lorentz force along the RF Wien filter:

- Electric force F_e, magnetic force F_m, and Lorentz force F_L.
- Trapezoid-shaped electrodes determine crossing of F_e and F_m.





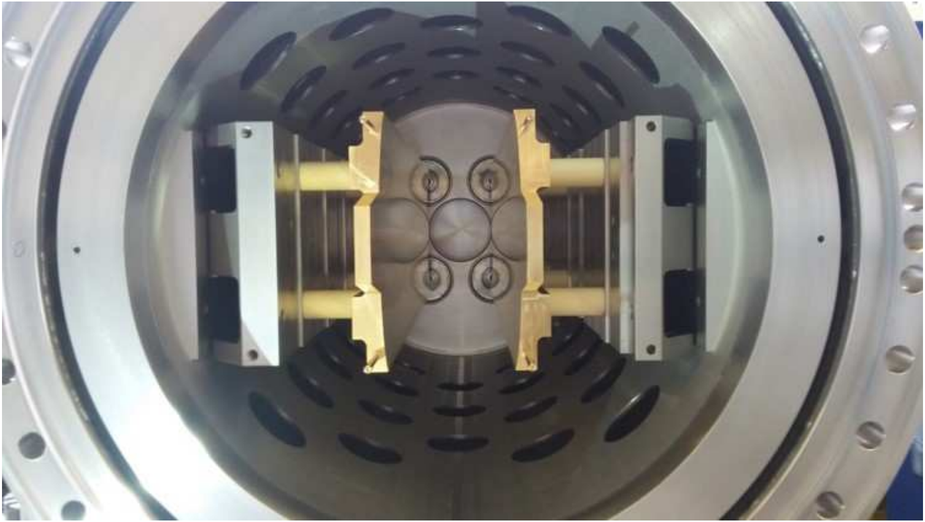
Lorentz force

$$\vec{F}_L = q\left(\vec{E} + \vec{v} \times \vec{B}\right) , \tag{13}$$

- particle charge q, velocity vector $\vec{v} = c(0, 0, \beta)$, fields $\vec{E} = (E_x, E_y, E_z)$ and $\vec{B} = \mu_0(H_x, H_y, H_z)$, μ_0 vacuum permeability.
- For vanishing Lorentz force $\vec{F}_L = 0$, field quotient Z_q given by

$$E_x = -c \cdot \beta \cdot \mu_0 \cdot H_y \quad \Rightarrow \quad \boxed{Z_q = -\frac{E_x}{H_y} = c \cdot \beta \cdot \mu_0 \approx 173\ \Omega}. \tag{14}$$

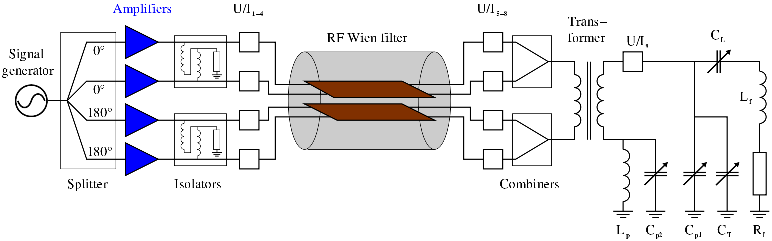
View along beam axis into RF Wien filter



Driving circuit [52]

Realization with load resistor and tunable elements (L's and C's):

- Design layout using four separate 1 kW power amplifiers.

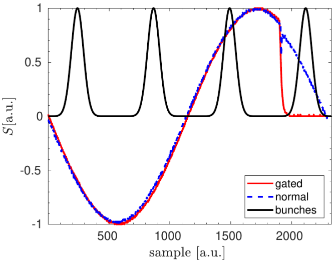


Circuit fully operational and tested.

- Tuneable elements[5] allow [51]:
  - minimization of Lorentz-force, and
  - velocity matching to β of beam.
- With input power of up to $4 \times 2\,$kW: $\int B_z \mathrm{d}z = 0.218\,\mathrm{T\,mm}$ possible.

[5] built by Fa. Barthel, `http://www.barthel-hf.de`.

Pilot bunch concept with RF Wien filter

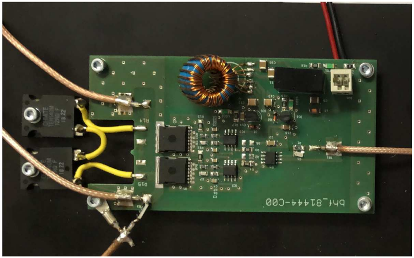


Example for stored beam with 4 bunches:

- revolution frequency $f_{\text{rev}} = 750\,\text{kHz}$
- RF WF at $K = -1$ with $f_{\text{WF}} = 871\,\text{kHz}$

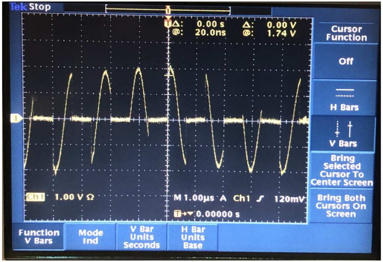
- Fields generated in RF WF visible to only three of the four bunches.
  - (or to a single one)
- Leads to one RF field-free bunch, called "pilot bunch".
- Pilot bunch used only to determine spin tune/precession frequency.
- Feedback maintains phase-lock and $f_{\text{WF}} = f_s$ for RF exposed bunches.

Fast switches for RF power input of Wien filter



GaN HEMT-based solution (Gallium Nitride Transistors):

- Short switch on/off times ($\approx$ few ns).
- High power capabilities ($\approx$ few kV).
- On board power damping.



- symmetric switch on/off times ($\approx$ few ns).
- $-30\,$dB power damping.
- promising results.

Test with polarized deuterons at COSY take place in October 2020.

In-plane oscillating deuterons

Parity-even and parity-odd time-reversal violation beyond Standard Model[6]

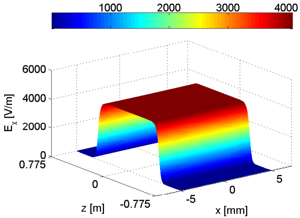
- Time-reversal breaking and parity-conserving millistrong interactions remain viable mechanisms of CP-violation beyond the Standard Model.
- **Possible manifestation:** T-odd asymmetry in transmission of tensor-polarized deuterons through a vector-polarized hydrogen gas target.
- With deuteron polarizations oscillating in ring plane, T-odd asymmetries, oscillate continuously with first or second harmonic of f_s.
- Fourier analysis of oscillating T-odd asymmetries allows separation from background,
  - prevailing in experiments employing static vector and tensor polarizations.

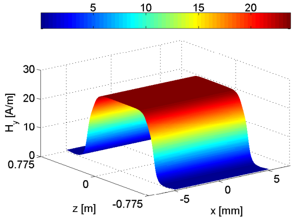
[6] For a preprint, see [58].

Electromagnetic field simulations (incl. ferrites) [50]

Full-wave simulations:

- using CST Microwave Studio[7].
- Each simulation required up to 12 h of computing time on a 4-T C2075 GPU cluster, with 2 six-core Xeon E5 processors and a RAM capacity of 94 GB.





At input power of 1 kW**, magnetic and electric field integrals (**$\ell = 1.550\,\mathrm{m}$**):**

$$\int_{-\ell/2}^{\ell/2} \vec{B} dz = \begin{pmatrix} 2.73 \times 10^{-9} \\ \mathbf{2.72 \times 10^{-2}} \\ 6.96 \times 10^{-7} \end{pmatrix} \mathrm{T\,mm}\,, \quad \int_{-\ell/2}^{\ell/2} \vec{E} dz = \begin{pmatrix} \mathbf{3324.577} \\ 0.018 \\ 0.006 \end{pmatrix} \mathrm{V} \qquad (15)$$

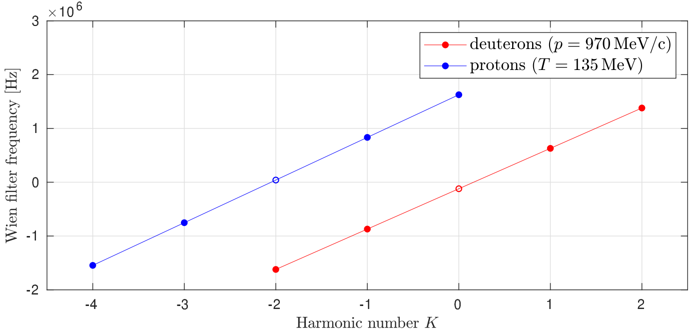
[7] Computer Simulation Technology AG, Darmstadt, Germany, `http://www.cst.com`

Frequencies of RF Wien filter

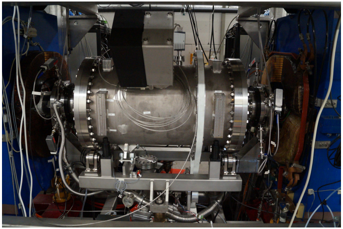
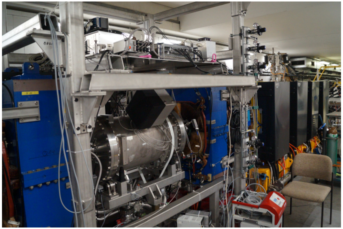
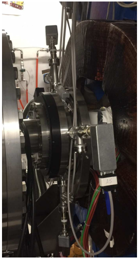
Spin resonance condition:

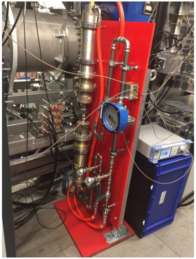
$$f_{\mathrm{WF}} = f_{\mathrm{rev}} \left(\gamma G \pm K\right) , k \in \mathbb{Z}. \tag{16}$$

- RF Wien filter operates at frequencies between 0 to 2 MHz,
- Open symbols not reachable with present setup of driving circuit, *i.e.*,
  - deuterons at $K = 0$ ($-120.8\,\mathrm{kHz}$), and
  - protons at $K = -2$ ($39.4\,\mathrm{kHz}$).



RF Wien filter installation at COSY



- Upstream Rogowski coil; racks with power amplifiers, each unit delivers up to 500 W; water-cooled 25 Ω resistor.

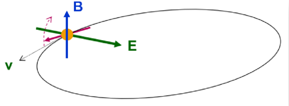
Search for charged particle EDMs with frozen spins

Magic storage rings

For any sign of G, in *combined* electric and magnetic machine:

- Generalized solution for magic momentum

$$\frac{E_x}{B_y} = \frac{Gc\beta\gamma^2}{1 - G\beta^2\gamma^2}, \qquad (17)$$



where E_x is radial, and B_y vertical field.

- Some configurations for circular machine with fixed radius $r = 25\,\mathrm{m}$:

particle	G	$p\,[\mathrm{MeV\,c^{-1}}]$	$T\,[\mathrm{MeV}]$	$E_x\,[\mathrm{MV\,m^{-1}}]$	$B_y\,[\mathrm{T}]$
proton	1.793	700.740	232.792	16.772	0.000
deuteron	−0.143	1000.000	249.928	−4.032	0.162
helion	−4.184	1200.000	245.633	14.654	−0.044

Offers possibility to determine EDMs of

protons, deuterons, and helions in one and the same machine.