Aspects of Hadron Polarimetry & New Spin Physics tools

Experience from the Indiana Cooler and COSY

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(partially on behalf of JEDI)

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Introduction

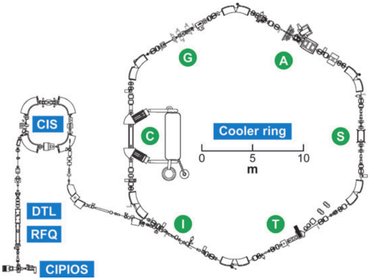
In this talk, various aspects of hadron polarimetry are discussed:

- Polarimetry in unexplored regions where, e.g., no analyzing powers exist.
- New tools for spin physics and precision experiments.
- Toward spin manipulation of *individual* stored beam bunches.
- In-plane spin precession provides access to new observables.

Nucleon-Nucleon scattering at Indiana Cooler[1]

When NN scattering program at IUCF was launched in early 90's:

- **Few NN data with well characterized uncertainties.**
- **Absence of calibration standards.**

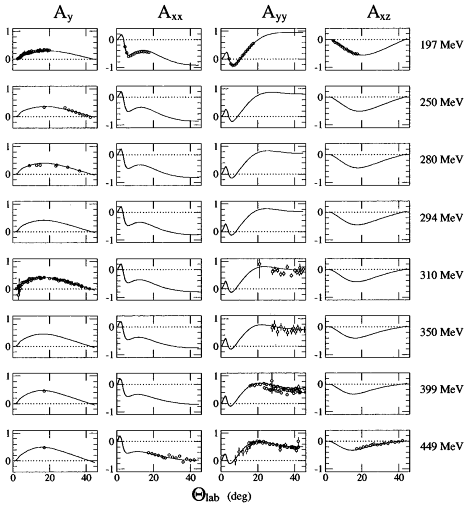


2001:
- cooler injector polarized ion source (CIPIOS),
- rf quadrupole (RFQ),
- drift-tube linac (DTL),
- cooler injector synchrotron (CIS), and storage ring.

[1] For a review of the physics results achieved with the Cooler, see [1].

Improving the NN data base [2, 3]

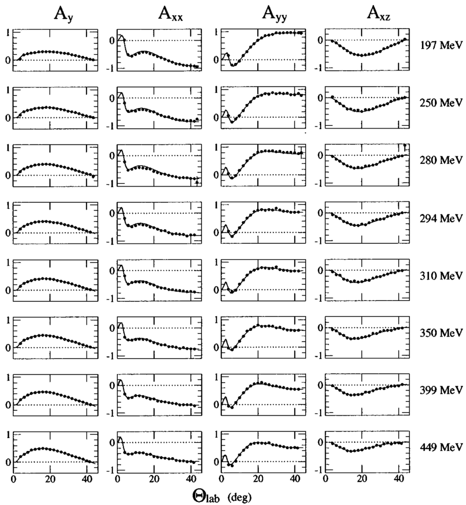
Before NN program at the Cooler



- All previously existing data between 175 MeV and 475 MeV from SAID, for references, see [25] of [2]. Curves are SM97 phase shift analysis.

Improving the NN data base [2, 3]

After NN program at the Cooler



- Analyzing power and spin correlation coefficients as fct of energy and angle.

$p + p$ scattering scattering at Indiana Cooler

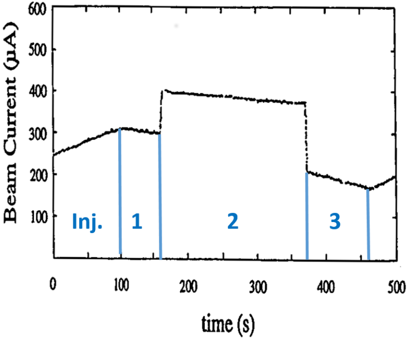
First thing the group did, was to establish a calibration standard: **An absolute measurement of a $p + p$ analyzing power**

- A_y for $p + p$ elastic scattering at $\theta_{\text{lab}} = 8.64^\circ \pm 0.07^\circ$, at beam kinetic energy $183.1 \pm 0.4\,\text{MeV}$ determined to be $\boxed{A_y = 0.2122 \pm 0.0017}$ [4].
- Error includes statistical and systematic uncertainties, and uncertainty in beam energy and angle.
- **Measurement represents calibration standard for polarized beams in this energy range.**
- Absolute scale obtained by comparison with $p + C$ elastic scattering at same energy at angle where A_y very nearly unity.

Polarization export to arbitrary energy [5]

- Calibration standards are few and exist at selected energies only.
- **Of interest to extend their use to arbitrary new energies.**

- Flattops 1 and 3 at same energy, used to determine P_1 and P_3 from known A_y.
- $P_2 \approx (P_1 + P_3)/2$ yields polarization on flatop 2, $\Rightarrow A_y(2)$.
- Knowledge about P from flattops 1 and 3 "exported" to flattop 2.



Relative uncertainty of normalization of A_y [2]

T [MeV]	197	250	280	294	310	350	400	450
$\mathrm{d}k/k$ [%]	0.31	1.08	0.89	1.17	1.01	1.03	0.86	1.0

- At 197 MeV uncertainty arises from comparison to reference data [4].
- At higher energies it includes uncertainty from calibration export.
- Normalization uncertainty of spin correlation coefficients A_{mn} is $2 \times \mathrm{d}k/k$.

Price to pay

- In order to carry out polarization export, considerable fraction ($\approx 1/2$) of data needs to be collected on lower flattops.

Polarized deuterium jet to calibrate *d* beam polarization

- RHIC jet target [6] built to provide an absolute calibration of the RHIC proton beam polarization.
- Jet polarization known from Breit-Rabi polarimeter.
  - Device used by HERMES and PAX [7], but here, however, w/o a cell.
- In *pp* scattering, situation simplified, because beam and target protons are identical.
  - For same reason, polarimeter does not have to be very sophisticated.

Polarized deuterium gas jet to calibrate beam polarization

Scenario to calibrate deuteron beam polarization:

1. Store unpolarized proton beam and bring to interaction with polarized deuterium jet at some cm energy.
   - All deuterium vector and tensor polarizations are known from Breit-Rabi.
   - Characterise simultaneously to 1. in suitable detector the reaction

$$p + \vec{d} \rightarrow ppn \quad \text{(or some other suitable final state)}\,. \tag{1}$$

2. Reverse kinematics and adjust deuteron momentum to cm energy of 1.
   - Bring polarized deuteron beam of unknown polarization to interaction with protons from unpolarized H jet.
   - Using the data from 3., determine deuteron beam polarization from

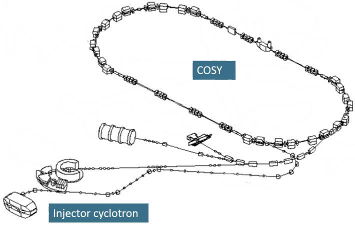
$$\vec{d} + p \rightarrow ppn \quad \text{(or some other suitable final state)}\,. \tag{2}$$

- Of course, the established CNI polarimetry pC and pp scattering may be extended to $\vec{d} + p$, $p + \vec{d}$, and $\vec{d}$C scattering.

Complementing the spin physics 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[2]:

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

[2] For a review of the experimental hadron physics program at COSY, see [8].

Colliding beam source at COSY-Jülich

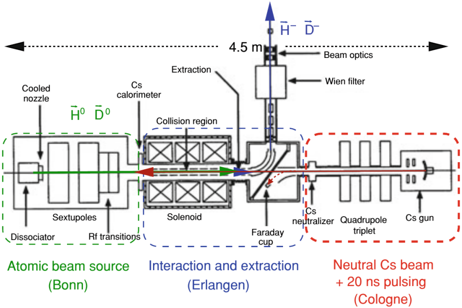
Developed by cooperation of Universities of Erlangen, Bonn and Cologne

Based on charge-exchange reaction [9]:

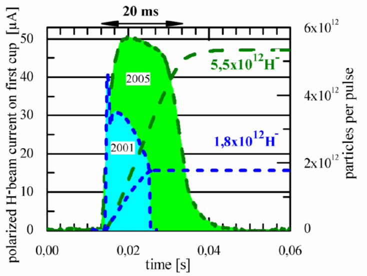
$$\vec{\mathrm{H}}^0 + \mathrm{Cs}^0 \rightarrow \vec{\mathrm{H}}^- + \mathrm{Cs}^+ \quad \text{same for D} \tag{3}$$

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

- High output, high polarization, reliable long-time running capability [10].
- 20 ms pulsing of atomic beam, and gas inputs of H_2 (D_2) (also N_2/O_2).
- Synchronous pulsing of Cs beam [11].



Intensity and polarization of CBS at COSY-Jülich[3]

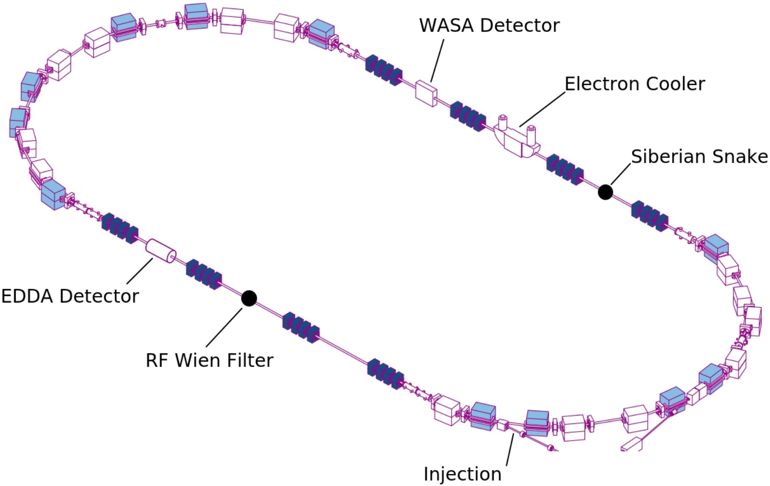


- Typical COSY fill has a few 1×10^{10} protons or deuterons stored.
- Space charge limit is about 1×10^{11} particles.

Mode	$P_z^{\rm Ideal}$	$P_{zz}^{\rm Ideal}$	$I_0^{\rm Ideal}$	$\rm RFT_1$	$\rm RFT_2$	$\rm RFT_3$	$P_z^{\rm LEP}$	$P_z^{\rm LEP}/P_z^{\rm Ideal}$	$P_z^{\rm EDDA}$	$P_{zz}^{\rm EDDA}$
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

[3] For more details on COSY operation with polarized deuterons, see [10].

COSY Landscape for the storage ring EDM program[4]



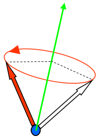
[4]For a progress report on storage ring EDM experiments (srEDM), see [12, 13].

Spin coherence

Most polarization experiments don‘t care about coherence of spins along $\vec{n}_s$

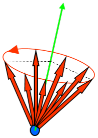
Spins aligned:

Ensemble *coherent*



Spins out of phase:

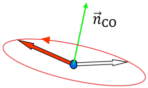
Ensemble *decoherent*



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

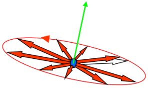
With in-plane spins: $\vec{S} \perp \vec{n}_s$:

Ensemble *coherent*



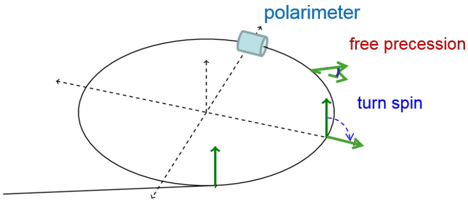
Over time:

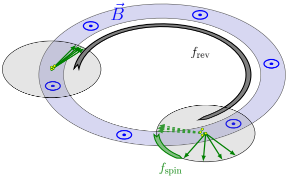
Spins out of phase in horizontal plane



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

Principle of spin-coherence time measurement

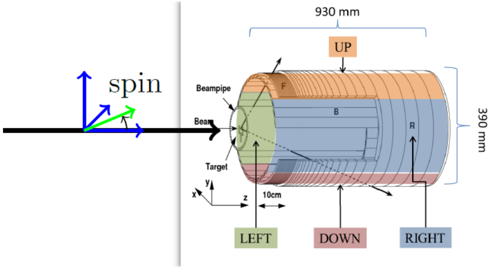


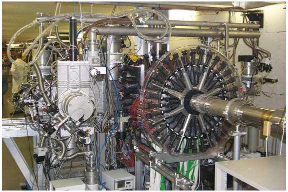


Measurement procedure:

1. Vertically polarized deuterons stored at $p \simeq 1\,\mathrm{GeV\,c^{-1}}$.
2. Polarization flipped into horizontal plane with RF solenoid ($\approx 200\,\mathrm{ms}$).
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 [14] (meanwhile replaced by JEPO)





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

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

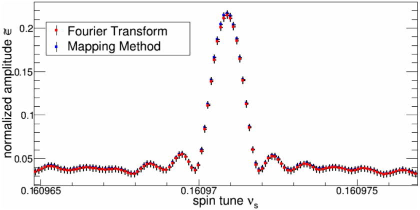
$$N_{\mathrm{U,D}} \propto 1 \pm \frac{3}{2} p_z A_y \sin(\underbrace{\nu_s \cdot f_{\mathrm{rev}}}_{f_s = -120.7\,\mathrm{kHz}} \cdot t), \;\; \text{where } f_{\mathrm{rev}} = 750.0\,\mathrm{kHz}. \qquad (4)$$

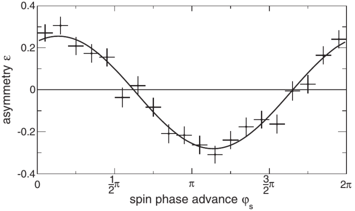
Determination of spin tune [15]

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

$$\varepsilon(\varphi_s) = \tilde{\varepsilon}\sin(\varphi_s + \tilde{\varphi})\,. \tag{5}$$



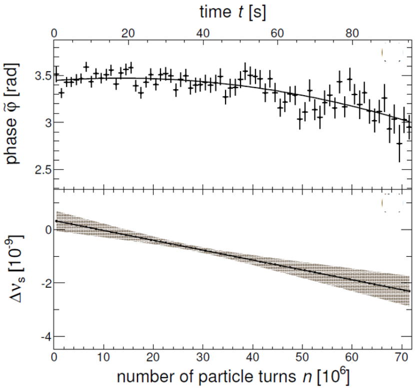


Determination of spin tune [15]

Analyze all time intervals:

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

$$\nu_s(n) = \nu_s^{\text{fix}} + \frac{1}{2\pi}\frac{\mathrm{d}\tilde{\phi}}{\mathrm{d}n} = \nu_s^{\text{fix}} + \Delta\nu_s(n) \qquad (6)$$

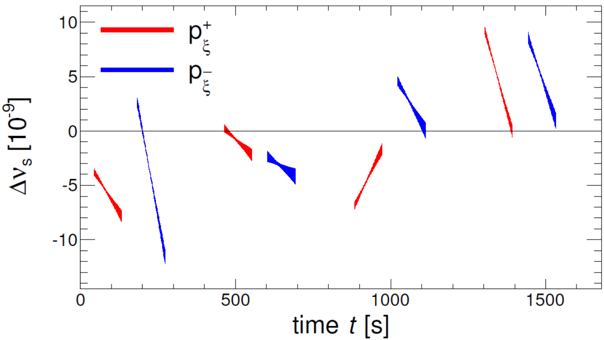


Experimental technique allows for:

- 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

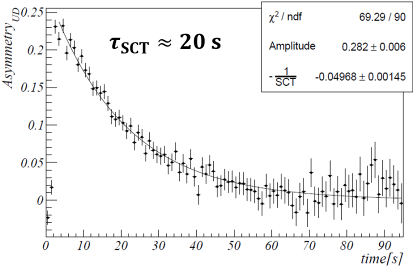


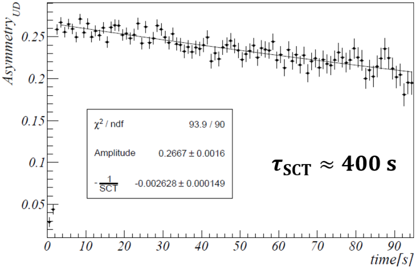
Walk of spin tune ν_s [15].

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



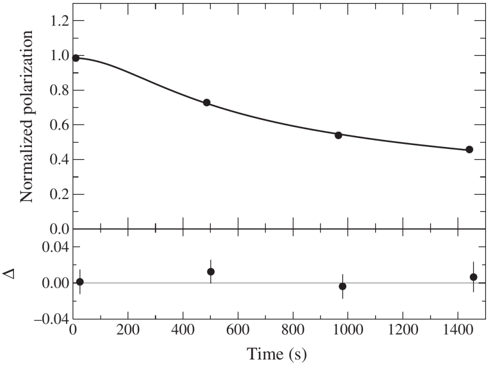


2012: Observed experimental decay of asymmetry

$$\epsilon_{UD}(t) = \frac{N_D(t) - N_U(t)}{N_D(t) + N_U(t)}. \quad (7)$$

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

Optimization of spin-coherence time [17]



JEDI progress on τ_{SCT}:

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

- Previous record: τ_{SCT}(VEPP) $\approx 0.5\,\mathrm{s}$ [16] ($\approx 10^7$ spin revolutions).

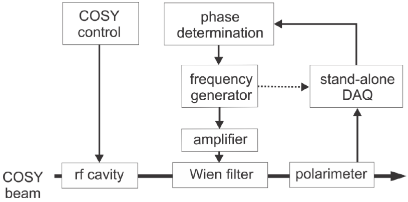
In 2015, way beyond expectation:

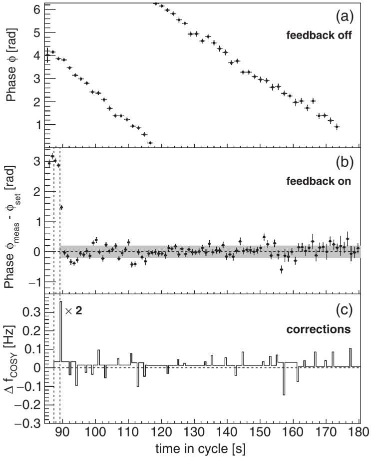
- With about 10^9 stored deuterons.
- Spin decoherence considered one main obstacle of srEDM experiments.

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)

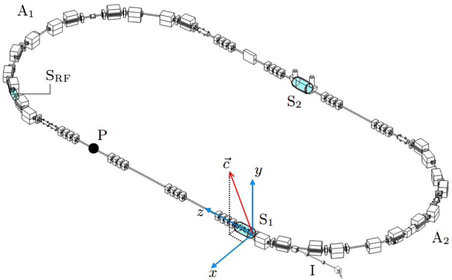




Major achievement : Error of phase-lock $\sigma_\phi = 0.21\,\text{rad}$ [18].

Study of machine imperfections I

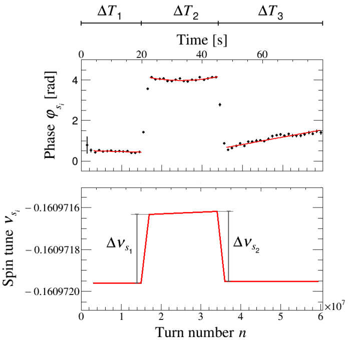
JEDI developed new method to investigate magnetic imperfections based on highly accurate determination of spin-tune [19].



Spin tune mapping:

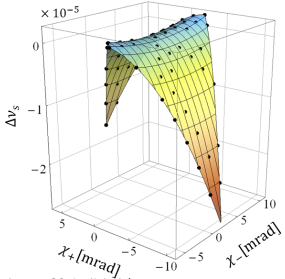
- Two cooler solenoids act as spin rotators
  - ⇒ Generation of artificial imperfection fields.
- Measure spin tune shift vs spin kicks in solenoids.

Study of machine imperfections II [19]



- 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.



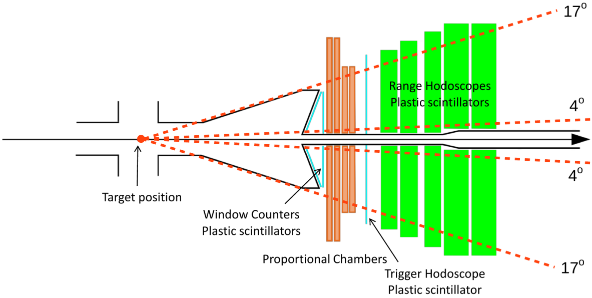
dC polarimetry data base I

Motivation: Optimize polarimetry for future srEDM experiments:

- Determine vector and tensor analyzing powers A_y, A_{yy}, and differential cross sections $d\sigma/d\Omega$ of dC elastic scattering at
  - deuteron kinetic energies $T = 170 - 380\,\text{MeV}$.

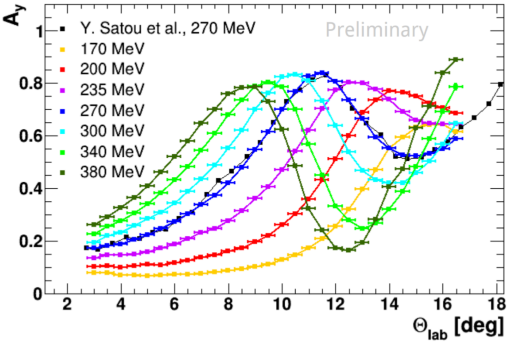
Detector system: former WASA forward detector, modified:

- Targets: C and CH2
- Full azimuthal coverage, scattering angle range $\theta = 4^\circ - 17^\circ$.



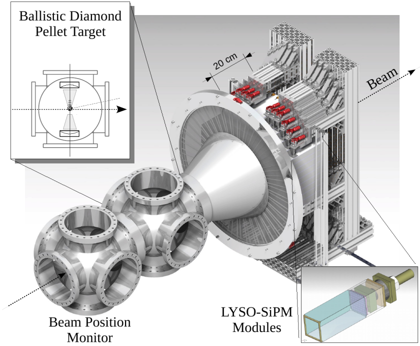
dC polarimetry data base II [20]

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 [22, 23]



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 [21, Appendix K].

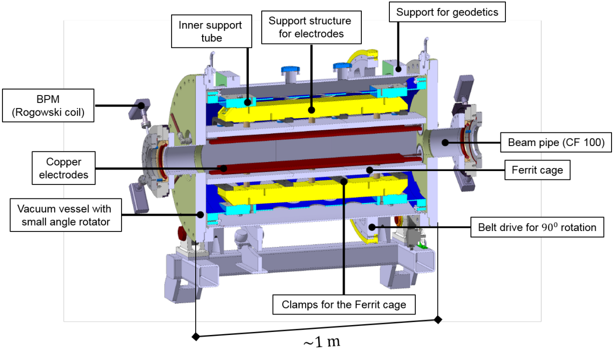
Toward spin manipulation of *individual* beam bunches

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 16.
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.

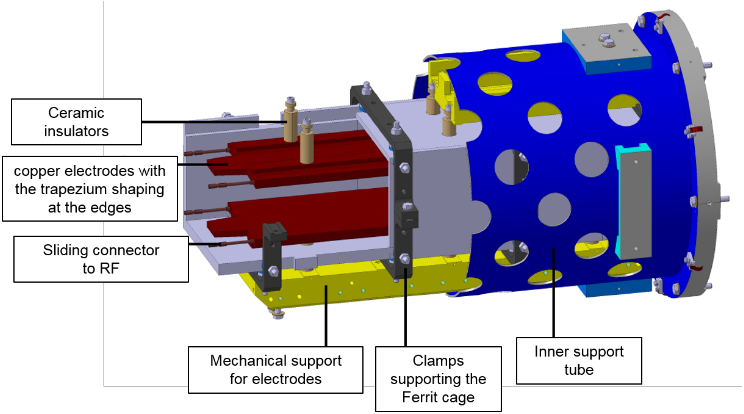
Spin manipulator based on waveguide RF Wien filter [24]

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



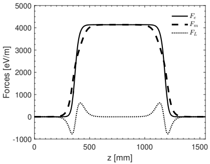
Aim was to build best possible device, with respect to

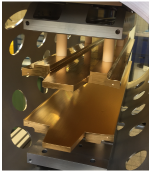
- Electromagnetic performance [24] and mechanical tolerances [25].

Lorentz force compensation [24]

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.





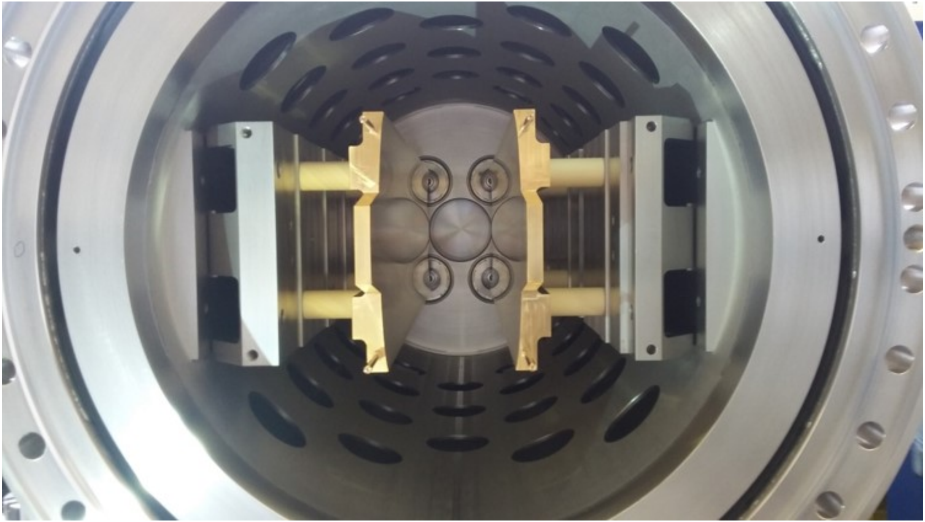
Lorentz force

$$\vec{F}_\mathrm{L} = q\left(\vec{E} + \vec{v} \times \vec{B}\right) , \tag{8}$$

- 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 $\vec{F}_\mathrm{L} = 0$, field quotient Z_q given by

$$E_x = -c \cdot \beta \cdot \mu_0 \cdot H_y \quad \Rightarrow \quad \boxed{Z_q = -\frac{E_x}{H_y} = c \cdot \beta \cdot \mu_0 \approx 173\ \Omega}. \tag{9}$$

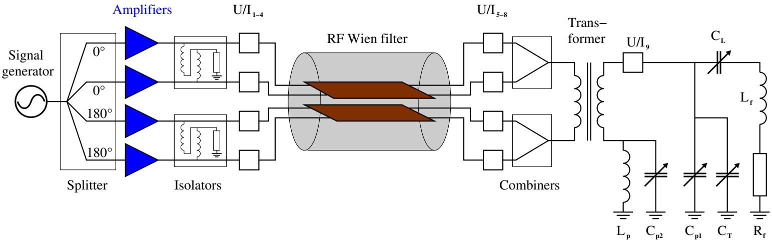
View along beam axis into RF Wien filter



Driving circuit [26]

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

- Design layout using four separate 1 kW power amplifiers.

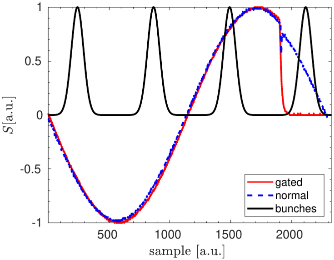


Circuit fully operational and tested.

- Tuneable elements[5] allow [24]:
  - minimization of Lorentz-force, and
  - velocity matching to β of beam.
- With input power of up to 4×2 kW: $\int B_z \mathrm{d}z = 0.218$ 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:

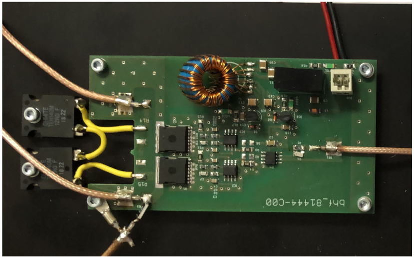
- revolution frequency $f_{rev} = 750\,\text{kHz}$
- RF WF at $K = -1$ with $f_{WF} = 871\,\text{kHz}$

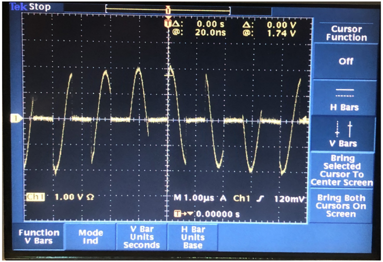
- Fields generated in RF WF visible to only three of the four bunches.
  - (or to a single one)
- Leads to one RF field-free bunch, called "pilot bunch".
- Pilot bunch used only to determine spin tune/precession frequency.
- Feedback maintains phase-lock and $f_{WF} = f_s$ for RF exposed bunches.

Fast switches for RF power input of Wien filter

GaN HEMT-based solution (Gallium Nitride Transistors):

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





- symmetric switch on/off times (≈ 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.

Suggestion for EIC:

- Take fresh look at oscillating in-plane polarization of relativistic deuterons.
- Increase horizontal spin coherence time of $\approx 1400\,$s, achieved at COSY by more than one order of magnitude to match storage time of $10\,$h at EIC [27].

[6] For a preprint, see [28].

Summary I

- To provide absolute calibration standards for vector and tensor polarized deuteron beams at EIC, a polarized atomic deuterium jet very useful:
  - Polarized jet needs a Breit-Rabi polarimeter, capable to determine the populations of all deuterium HFS.
  - Detection system needed to identify suitable reaction channels for $\vec{d}p$ and $p\vec{d}$ kinematics.
- Once calibration standards are established, polarization export to other energies becomes viable option.

- JEDI is making steady progress in spin dynamics of relevance to future searches for EDM.
- Substantial progress producing coherent ensembles of polarized deuteron beams near 1 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:
  - identify unwanted magnetic fields in machine via spin-tune mapping.
- New spin tools will be applied to perform a first direct measurment of dEDM.

Summary II

- Spin manipulation of individual bunches of a stored beam appears feasible in near future:
  - RF Wien filter well-suited as spin manipulator, not-perturbing the beam orbit.
  - Technique requires long spin-coherence time of stored particle ensemble, and
  - phase-lock of in-plane spin precession to device RF.
- Pilot bunch technique based on fast RF switches at input of RF WF shall be applied to selectively spin manipulate individual or groups of bunches.
- Since parity is largely conserved, longitudinal analyzing powers are tiny, and unpolarized targets very inefficient to determine polarization of beam along its direction of flight.
  - However, as soon as particle spins oscillate in machine plane, sideways oscillating polarization components allow one to readily calibrate the unknown longitudinal polarization components.
- In-plane oscillating deuterons provide novel approach to parity-even and parity-odd time-reversal violation beyond Standard Model.
  - Does this present an opportunity for the EIC that should not be missed?

JEDI Collaboration

JEDI = Jülich Electric Dipole Moment Investigations

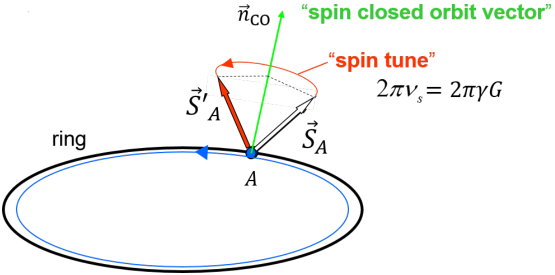
- $\sim$ 140 members (Aachen, Daejeon, Dubna, Ferrara, Indiana, Ithaka, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St Petersburg, Stockholm, Tbilisi, ...
- `http://collaborations.fz-juelich.de/ikp/jedi`

Spare slides

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 closed orbit and spin tune

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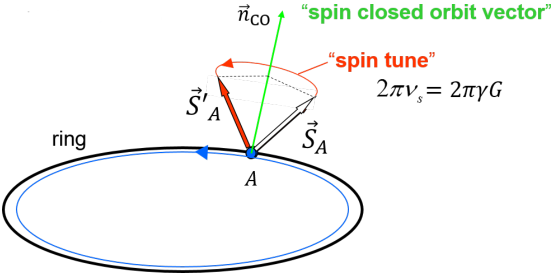
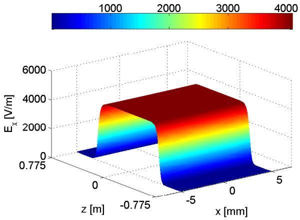


Number of spin precessions per turn is called spin tune ν_s.

Electromagnetic field simulations (incl. ferrites) [29]

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 (**$\ell = 1.550\,\mathrm{m}$**):**

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

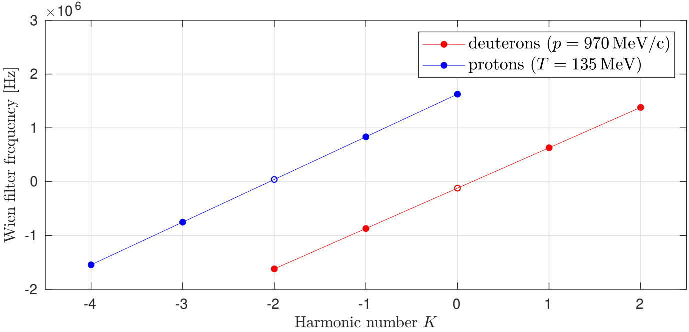
[7] Computer Simulation Technology AG, Darmstadt, Germany, http://www.cst.com

Frequencies of RF Wien filter

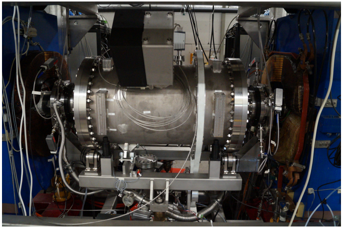
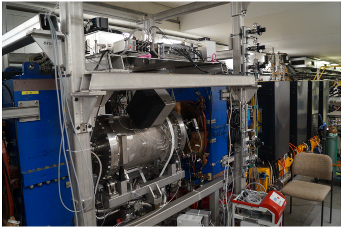
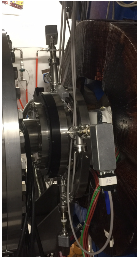
Spin resonance condition:

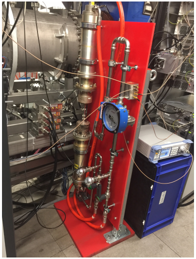
$$f_{\mathrm{WF}} = f_{\mathrm{rev}}\left(\gamma G \pm K\right),\, k \in \mathbb{Z}. \tag{11}$$

- 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 kHz), and
  - protons at $K = -2$ (39.4 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.

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