Spin Manipulation with an RF Wien-Filter at COSY
PSTP Workshop 2015

Bochum, September 15, 2015 | Sebastian Mey and Ralf Gebel for the JEDI Collaboration | Forschungszentrum Jülich
Content

EDM Measurements in Magnetic Storage Rings
The Prototype RF ExB-Dipole Measurements
Summary and Conclusion

Bochum, September 15, 2015  s.mey@fz-juelich.de  EDM Measurements in Magnetic Storage Rings
Motivation

JEDI Collaboration: First direct measurement of charged light hadrons’ permanent Electric Dipole Moment in storage rings

- simple system with EDM $\vec{d}$ and MDM $\vec{\mu}$ aligned with spin $\vec{S}$

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

$$\mathcal{P}(\mathcal{H}) = -\mu \frac{\vec{S}}{S} \cdot \vec{B} + d \frac{\vec{S}}{S} \cdot \vec{E}$$

$$\mathcal{T}(\mathcal{H}) = -\mu \frac{\vec{S}}{S} \cdot \vec{B} + d \frac{\vec{S}}{S} \cdot \vec{E}$$

$\Rightarrow$ EDMs violate tests both parity $\mathcal{P}$ and time reversal $\mathcal{T}$ symmetry

- CPT Theorem: permanent EDMs violate $CP$ symmetry
Spin Motion in a Magnetic Storage Ring

JEDI Collaboration: First direct measurement of charged light hadrons’ permanent EDM in storage rings

- spin motion: \( \frac{d\vec{S}}{dt} = \vec{S} \times (\vec{\Omega}_{\text{MDM}} + \vec{\Omega}_{\text{EDM}}) \) (Thomas-BMT Equation)

\[
\vec{\Omega}_{\text{MDM}} = \frac{q}{m} \left( (1 + \gamma G)\vec{B}_\perp + (1 + G)\vec{B}_\parallel - \left( \frac{\gamma}{\gamma + 1} + \gamma G \right) \vec{\beta} \times \vec{E}/c \right)
\]

\[
\vec{\Omega}_{\text{EDM}} = \frac{a n}{m^2} \left( \vec{E}/c + \vec{\beta} \times \vec{B} \right)
\]

- MDM: \( \vec{\mu} = 2(G + 1) \frac{q\hbar}{2m} \vec{S} \) with anomalous magnetic moment \( G \)

- EDM: \( \vec{d} = \eta \frac{q\hbar}{2mc} \vec{S} \approx 10^{-31} \text{ ecm} \iff \eta \approx 10^{-15} \) for SM light hadrons
Spin Motion in a Magnetic Storage Ring

JEDI Collaboration: First direct measurement of charged light hadrons’ permanent EDM in storage rings

- spin motion: \( \frac{d\vec{S}}{dt} = \vec{S} \times (\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}) \) (Thomas-BMT Equation)

- stationary ring with vertical guiding field \( \vec{B}_\perp \) and \( \vec{B}_\parallel = \vec{E} = \vec{0} \)

\[
\vec{\Omega}_{MDM} = \frac{q}{m} \left( (1 + \gamma G)\vec{B}_\perp + (1 + G)\vec{B}_\parallel - \left( \frac{\gamma}{\gamma+1} + \gamma G \right) \vec{\beta} \times \vec{E} / c \right)
\]

\[
\vec{\Omega}_{EDM} = \frac{q}{m} \frac{\eta}{2} \left( \vec{E} / c + \vec{\beta} \times \vec{B}_\perp \right)
\]

- MDM: \( \vec{\mu} = 2(G + 1)\frac{q\hbar}{2m} \vec{S} \) with anomalous magnetic moment \( G \)

- EDM: \( \vec{d} = \eta \frac{q\hbar}{2mc} \vec{S} \approx 10^{-31} \text{ ecm} \iff \eta \approx 10^{-15} \) for SM light hadrons
Generating an EDM Signal

stationary ring with vertical guiding field $\vec{B}$ and $\vec{B}_{||} = \vec{E} = \vec{0}$

$$\vec{\Omega}_{\text{ring}} = \frac{a}{m} \left( (1 + \gamma G) \vec{B} + \frac{n}{2} \vec{\beta} \times \vec{B} \right)$$

- spin precession around vertical axis with tune $\gamma G$
- tiny EDM tilt of precession axis
- prepare beam with purely horizontal spins

⇒ oscillating vertical spin component, but signal much too small to observe
Generating an EDM Signal

stationary ring with vertical guiding field $\vec{B}$ and $\vec{B}_{\parallel} = \vec{E} = \vec{0}$

$$\vec{\Omega}_{\text{ring}} = \frac{q}{m} \left( (1 + \gamma G) \vec{B} + \frac{n}{2} \vec{\beta} \times \vec{B} \right)$$

- spin precession around vertical axis with tune $\gamma G$
- tiny EDM tilt of precession axis
- prepare beam with purely horizontal spins

$\Rightarrow$ oscillating vertical spin component

- introduce additional in-plane spin kick in phase with precession

$\Rightarrow$ oscillating spins point forward most of the time

$\Rightarrow$ continuous build-up of vertical spin component $\Rightarrow$ EDM Signal
Generating an EDM Signal, cont.

- supplement lattice with \textbf{local} vertical magnetic field $\vec{B}_{WF}$ oscillating with spin precession

- minimize beam perturbation by adjusting net Lorentz Force to zero

\[ \frac{\vec{E}_{WF}}{c} = -\vec{\beta} \times \vec{B}_{WF} \] (Wien-Filter condition)

- additional spin rotation in RF Wien-Filter around vertical axis

\begin{align*}
\vec{\Omega}_{MDM} &= \frac{q}{m} \left( (1 + \gamma G) \vec{B}_{WF} - \left( \frac{\gamma}{\gamma+1} + \gamma G \right) \vec{\beta} \times \frac{\vec{E}_{WF}}{c} \right) \\
\vec{\Omega}_{EDM} &= \frac{q}{m} \frac{\eta}{2} \left( \frac{\vec{E}_{WF}}{c} + \vec{\beta} \times \vec{B}_{WF} \right) = \vec{0}
\end{align*}
Generating an EDM Signal, cont.

- supplement lattice with local vertical magnetic field $\vec{B}_{WF}$ oscillating with spin precession
- minimize beam perturbation by adjusting net Lorentz Force to zero

$$\vec{E}_{WF}/c = -\vec{\beta} \times \vec{B}_{WF}$$ (Wien-Filter condition)

- additional spin rotation in RF Wien-Filter around vertical axis

$$\vec{\Omega}_{MDM} = \frac{q}{m} \frac{1+G}{\gamma} \vec{B}_{WF}$$

The RF Wien-Filter itself is EDM transparent, but is capable of generating an EDM signal due to modulation of the spin precession.*

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Prototype RF Wien-Filter with Radial Magnetic Field

- investigate action of RF Wien-Filter fields by direct observation of resulting MDM motion
- use radial magnetic field with vertically prepared spins
- continuous rotation of spin vector during operation

- Lorentz force compensation: \( \vec{E}/c = -\vec{\beta} \times \vec{B} \)
- spin precession: \( \vec{\Omega}_{MDM} = \frac{1+G}{\gamma} \vec{B} \)
- particles sample localized RF field once each turn at orbit angle \( \theta \)

\[ b(\theta) = \int \hat{B} \, dz \cos \left( \frac{f_{RF}}{f_{rev}} \theta + \phi \right) \sum_{n=-\infty}^{\infty} \delta(\theta - 2\pi n) \]
Resonance Strength of an RF Wien-Filter

- Intrinsic resonance strength given by spin rotation per turn, calculate Fourier integral over driving fields along orbit*:

\[
\epsilon_K = \frac{f_{\text{spin}}}{f_{\text{rev}}} = \frac{1+G}{2\pi \gamma} \oint \frac{b(\theta)}{B\rho} e^{iK\theta} \, d\theta
\]

\[
= \frac{1+G}{2\pi \gamma} \oint \hat{B} \, dz \sum_{n=-\infty}^{\infty} \cos(2\pi n \frac{f_{\text{RF}}}{f_{\text{rev}}} + \phi) e^{i2\pi K n}
\]

\[
= \frac{1+G}{2 \cdot 2\pi \gamma} \oint \hat{B} \, dz \sum_n e^{\pm i\phi} \delta(n - K \mp \frac{f_{\text{RF}}}{f_{\text{rev}}})
\]

- Spin tune \( \approx \gamma G \), resonance at every sideband with

\[
K \equiv \gamma G = n \pm \frac{f_{\text{RF}}}{f_{\text{rev}}} \iff f_{\text{RF}} = f_{\text{rev}} |n - \gamma G|; \ n \in \mathbb{Z}
\]

- \( d \) at 970 MeV/c: \( f_{\text{rev}} = 750.603 \text{ kHz}; \ \gamma G = -0.16098 \)

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<th>1</th>
<th>-1</th>
<th>2</th>
<th>-2</th>
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<td>120</td>
<td>629</td>
<td>871</td>
<td>1380</td>
<td>1621</td>
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The Prototype RF ExB Dipole

RF B dipole
- ferrite blocks
- coil: 8 windings
- length 560 mm

RF E dipole
- foil electrodes
- 50 µm stainless steel
- distance 54 mm
- length 580 mm
- ceramic beam chamber

**Parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>RF B dipole</th>
<th>RF E dipole</th>
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<tbody>
<tr>
<td>$P_{\text{RMS}}$ / W</td>
<td>90</td>
<td>90</td>
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<td>$\hat{I}$ / A</td>
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<td>2</td>
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<td>$\int \hat{B}_x , dl$ / Tmm</td>
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<td>$f_{\text{RF}}$ range / kHz</td>
<td>629 - 1170</td>
<td>629 - 1060</td>
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<tr>
<td>$\Delta \hat{U}$ / kV</td>
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<td>2</td>
</tr>
<tr>
<td>$\int \hat{E}_y , dl$ / kV</td>
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<td></td>
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\[ \int \hat{F_y} \, dz = 0 \text{ eV/m} \]
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COSY as Spin Physics R&D Facility

RF solenoid

RF ExB dipole

\( \varepsilon_{x,y} \) and \( \frac{\Delta p}{p} \) control
electron cooling

fast, continuous polarimetry

polarized source

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Measurement
COSY as Spin Physics R&D Facility

RF solenoid

RF ExB dipole

$\varepsilon_{x,y}$ and $\frac{\Delta p}{p}$ control
electron cooling

fast, continuous polarimetry

polarized source

bunch-shape evolution per fill

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Measurements
RF ExB Setup for Field Compensation

- move betatron sideband onto RF freq. for max. sensitivity
  \[ q_y \cdot f_{\text{rev}} = (1 + \gamma G) f_{\text{rev}} = 629 \text{ kHz} \]
- polarimeter target directly above beam limits acceptance
  ⇒ exited part of beam is removed
  ⇒ diagnosis with COSY beam current transformer over \( \Delta t = 30 \text{ s} \)
- determination of amplitudes and phase corresponding to Lorentz force compensation down to per mille!

Amplitude Scan RF-E at \( \hat{i}_{\text{RF-B}} = 2 \text{ A} \)

Phase Scan

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Beam Response

Analogue signal from one vertical BPM pickup electrode during RF operation exactly on resonance
Center $f_{qy} = f_{\text{rev}}(1 + q_y) = 1380 \text{ kHz}$, Span $\Delta f = 10 \text{ kHz}$

RF Wien-Filter: $\hat{I}_{\text{RF-B}} \approx 740 \text{ mA}; \hat{U}_{\text{RF-E}} \approx 108 \text{ V}$

RF Sol.: $\hat{I}_{\text{Sol.}} \approx 780 \text{ mApp}$
Polarization Measurements

- beam polarization $\Leftrightarrow$ average over all particles’ spins
- massive carbon target with slow extraction $\Rightarrow$ long observation time
- polarization signal $\Rightarrow$ rate asymmetries in $^{12}\text{C}(\vec{d}, d) : P_y \propto \frac{N_{\text{left}} - N_{\text{right}}}{N_{\text{left}} + N_{\text{right}}}$
- continuous rotation of $\vec{P} \Rightarrow$ oscillation of $P_y$
Measurement Resonance Strength

- RF Wien-Filter and RF Solenoid both drive continuous rotation of $\vec{P}$
- Find resonance by scan of driving frequency $f_{RF} \equiv f_{rev}(1 - \gamma G)$
- Total spin flip only on resonance $\Rightarrow$ average polarization $\rightarrow 0$
- Minimum of oscillation frequency $f_{Py}$
- Measurement of resonance strength $\varepsilon = \frac{f_{Py_{\text{min}}}}{f_{rev}}$

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Preliminary result of Fixed Frequency Scans

- resonance strength measurements to determine level of field compensation
- RF Solenoid: $f_{Py} = \frac{q}{p} \frac{1+G}{4\pi} \int \hat{B} dI$
- RF Wien-Filter: $f_{Py} = \frac{q}{p} \frac{1+G}{4\pi} \int \hat{B} dI$
- RF B-Dipole: $f_{Py} = \frac{q}{p} \frac{1+\gamma G}{4\pi} \int \hat{B} dI + \text{interference due to beam motion}$
- RF E-Dipole: $f_{Py} = \frac{q}{mc^2} \frac{1/\gamma + 1+G}{4\pi} \int \hat{E} dI + \text{interference due to beam motion}$

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Summary

- versatile prototype RF ExB dipole with minimal excitation of coherent beam oscillations has been successfully commissioned
- \( P_{\text{RMS}} = 90 \text{ W} \Rightarrow \int \hat{B}_x \, dl = 0.175 \text{ T mm}; \int \hat{E}_y \, dl = 24.1 \text{ kV} \)
- Frequency Range 630 kHz - 1060 kHz
- entirely beam-based method for field matching has been worked out and verified
- spin manipulation performance on the same level as with the “proven” RF-Solenoid” system
Outlook

- first attempt of a direct measurement of the deuteron EDM requires a upright, high precision version of an RF Wien-Filter
- rotatable stripline solution scheduled for commissioning at COSY in summer 2016

⇒ introduction of the concept and field simulations → J. Slim, “Towards a High-Accuracy RF Wien Filter for Spin Manipulation at COSY Jülich”
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Spares