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
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 $\vec{S}$

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

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

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

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

- CPT Theorem: permanent EDMs violate $\mathcal{CP}$ 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)
  \[
  \vec{\Omega}_{\text{MDM}} = \frac{q}{m} \left( (1 + \gamma G) \vec{B}_\perp + (1 + G) \vec{B}_\parallel - \left( \frac{\gamma}{\gamma + 1} + \gamma G \right) \vec{\beta} \times \vec{E}/c \right)
  \]
  \[
  \vec{\Omega}_{\text{EDM}} = \frac{a \eta}{m^2} \left( \vec{E}/c + \vec{\beta} \times \vec{B} \right)
  \]
- MDM: \( \vec{\mu} = 2(G + 1) \frac{q\hbar}{2m} \vec{S} \) with anomalous magnetic moment \( G \)
- EDM: \( \vec{d} = \eta \frac{q\hbar}{2mc} \vec{S} \approx 10^{-31} \) ecm \( \Leftrightarrow \eta \approx 10^{-15} \) 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: \( \frac{d\vec{S}}{dt} = \vec{S} \times (\vec{\Omega}_{\text{MDM}} + \vec{\Omega}_{\text{EDM}}) \) (Thomas-BMT Equation)
- stationary ring with vertical guiding field \( \vec{B}_\perp \) and \( \vec{B}_\parallel = \vec{E} = \vec{0} \)

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

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

- MDM: \( \vec{\mu} = 2(G + 1) \frac{q_h}{2m} \vec{S} \) with anomalous magnetic moment \( G \)
- EDM: \( \vec{d} = \eta \frac{q_h}{2mc} \vec{S} \approx 10^{-31} \text{ ecm} \iff \eta \approx 10^{-15} \) for SM light hadrons
Generating an EDM Signal

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

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

- 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, but signal much too small to observe
Generating an EDM Signal

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

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

- 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 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
  \[ \vec{\Omega}_{MDM} = \frac{q}{m} \left( (1 + \gamma G) \vec{B}_{WF} - \left( \frac{\gamma}{\gamma+1} + \gamma G \right) \vec{\beta} \times \vec{E}_{WF}/c \right) \]
  \[ \vec{\Omega}_{EDM} = \frac{q}{m} \frac{n}{2} \left( \vec{E}_{WF}/c + \vec{\beta} \times \vec{B}_{WF} \right) = \vec{0} \]
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
  $$\vec{E}_{WF}/c = -\vec{\beta} \times \vec{B}_{WF} \quad \text{(Wien-Filter condition)}$$
- additional spin rotation in RF Wien-Filter around vertical axis
  $$\vec{\Omega}_{MDM} = \frac{a}{m} \frac{1+G}{\gamma} \vec{B}_{WF}$$

The RF Wien-Fielter 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: \( \vec{\Omega}_{\text{MDM}} = \frac{1+G}{\gamma} \vec{B} \)

- particles sample localized RF field once each turn at orbit angle \( \theta \)

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

- intrinsic resonance strength given by spin rotation per turn, calculate Fourier integral over driving fields along orbit*:
  \[
  \epsilon K = \frac{f_{\text{spin}}}{f_{\text{rev}}} = \frac{1+G}{2\pi\gamma} \oint b(\theta) \frac{B}{B\rho} e^{iK\theta} d\theta
  \]
  \[
  = \frac{1+G}{2\pi\gamma} \int \hat{B} \frac{dz}{B\rho} \sum_{n=-\infty}^{\infty} \cos(2\pi n \frac{f_{\text{RF}}}{f_{\text{rev}}} + \phi) e^{i2\pi Kn}
  \]
  \[
  = \frac{1+G}{2\cdot 2\pi\gamma} \int \hat{B} \frac{dz}{B\rho} \sum_{n} e^{\pm i\phi} \delta(n - K \mp \frac{f_{\text{RF}}}{f_{\text{rev}}})
  \]
- spin tune \( \approx \gamma G \), resonance at every sideband with
  \[
  K \overset{!}{=} \gamma G = n \pm \frac{f_{\text{RF}}}{f_{\text{rev}}} \iff f_{\text{RF}} = f_{\text{rev}} | n - \gamma G |; \ n \in \mathbb{Z}
  \]
- \( d \) at 970 MeV/c: \( f_{\text{rev}} = 750.603 \) kHz; \( \gamma G = -0.16098 \)

<table>
<thead>
<tr>
<th>( n )</th>
<th>( f_{\text{RF}} ) kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>120</td>
</tr>
<tr>
<td>1</td>
<td>629</td>
</tr>
<tr>
<td>-1</td>
<td>871</td>
</tr>
<tr>
<td>2</td>
<td>1380</td>
</tr>
<tr>
<td>-2</td>
<td>1621</td>
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</table>

The Prototype RF ExB Dipole

- Coil: 8 windings
- Length: 560 mm
- Distance: 54 mm
- Length: 580 mm

<table>
<thead>
<tr>
<th>Parameters</th>
<th>RF B dipole</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{RMS} / W$</td>
<td>90</td>
</tr>
<tr>
<td>$\hat{I} / A$</td>
<td>5</td>
</tr>
<tr>
<td>$\int \hat{B}_x , dl / Tmm$</td>
<td>0.175</td>
</tr>
<tr>
<td>$f_{RF}$ range / kHz</td>
<td>629 - 1170</td>
</tr>
</tbody>
</table>
The Prototype RF ExB Dipole

coil: 8 windings
length 580 mm

x / m
-0.05 0 0.05

z / m
-1 -0.5 0 0.5 1

Fy / eV/m
-200 -100 0 100 200

\[ \hat{F}_y = 0 \text{ eV/m} \]

\[ e\hat{E}_y \]

ec\beta\hat{B}_x

\[
\int F_y \, dz
\]

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Measurements
COSY as Spin Physics R&D Facility

RF solenoid

RF ExB dipole

$\varepsilon_{x,y}$ and $\Delta p / p$ control

electron cooling

fast, continuous polarimetry

polarized source
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

position along ring / m

all events

left, right
up, down

sum

time in cycle / s
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
  \[ \Rightarrow \text{exited part of beam is removed} \]
  \[ \Rightarrow \text{diagnosis with COSY beam current transformer over} \]
  \[ \Delta t = 30 \text{ s} \]
- determination of amplitudes and phase corresponding to Lorentz force compensation down to per mille!

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Measurements 13
Analogue signal from one vertical BPM pickup electrode during RF operation exactly on resonance
Center $f_{qy} = f_{rev}(1 + q_y) = 1380$ kHz, Span $\Delta f = 10$ kHz

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

RF Sol.: $\hat{I}_{Sol.} \approx 780$ 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 $f_{RF} = f_{rev}(1 - \gamma G)$

- total spin flip only on resonance $\Rightarrow$ average polarization $\rightarrow 0$

$\Rightarrow$ 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: $f_{Py} = \frac{q}{p} \frac{1+G}{4\pi} \int \hat{B}dl$  
  RF Wien-Filter: $f_{Py} = \frac{q}{p} \frac{1+G}{4\pi \gamma} \int \hat{B}dl$
- RF B-Dipole: $f_{Py} = \frac{q}{p} \frac{1+\gamma G}{4\pi} \int \hat{B}dl + \text{interference due to beam motion}$
- RF E-Dipole: $f_{Py} = \frac{q}{mc^2} \frac{1/\gamma+1+G}{4\pi} \int \hat{E}dl + \text{interference due to beam motion}$
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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”