Towards an RF Wien-Filter for EDM Searches in Storage Rings

DPG Annual Spring Meeting 2015

Wuppertal, March 10, 2015 | Sebastian Mey and Ralf Gebel for the JEDI Collaboration | Forschungszentrum Jülich
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EDM Measurements in Magnetic Storage Rings
The RF ExB Dipole
Measurements
Conclusion

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EDM Measurements in Magnetic Storage Rings
Spin Motion in a Magnetic Storage Ring

- Thomas-BMT Equation: \( \frac{d\vec{S}}{dt} = \vec{S} \times (\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}) \)
  
  \[ \vec{\Omega}_{MDM} = \frac{q}{m} \left( (1 + \gamma G)\vec{B}_\perp + (1 + G)\vec{B}_\parallel - \left( \frac{\gamma}{\gamma + 1} + \gamma G \right) \vec{\beta} \times \vec{E}/c \right) \]

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

- Standard Model: \( \vec{d} = \eta \frac{q \hbar}{2mc} \vec{S} \approx 10^{-32} \text{ ecm} \iff \eta \approx 10^{-16} \)
Spin Motion in a Magnetic Storage Ring

- Thomas-BMT Equation: \[ \frac{d\vec{S}}{dt} = \vec{S} \times (\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}) \]
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- spin precession around main dipole’s guiding field
- spin tune \( \nu_S = \gamma G \)
- vertical polarization component \( S_y \) is constant
Spin Motion in a Magnetic Storage Ring

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

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  \]

  \[
  \vec{\Omega}_{\text{EDM}} = \frac{aqm}{2mc} \vec{\beta} \times \vec{B}
  \]

- **Standard Model:** \( \vec{d} = \eta \frac{q}{2mc} \vec{S} \approx 10^{-32} \text{ ecm} \leftrightarrow \eta \approx 10^{-16} \)

- motional electric field pointing to the ring’s center

  \( \Rightarrow \) tilts precession axis in case of non-vanishing EDM contribution

  \( \Rightarrow \) oscillation of vertical spin component \( S_y \)
Generating an EDM Signal

- utilize beam with spins oriented in the horizontal plane
- modulate spin precession with vertical magnetic RF field in phase with the spin precession
  \[ \Rightarrow \text{additional precession every turn} \]
- frequency spectrum of spin precession picks up a zero component
- together with tilted precession axis this will cause a continuous build-up of vertical spin component
  \[ ! \text{minimize beam disturbances by RF field} \]
- utilize Wien-Filter configuration\[\ast\]

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The RF ExB Dipole Measurements

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The RF ExB Dipole in Wien-Filter Configuration

RF B dipole
- ferrite blocks
- coil: 8 windings
- length 560 mm
- distance 54 mm
- length 580 mm

RF E dipole
- foil electrodes
- 50 µm stainless steel
- ceramic beam chamber

Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>RF B dipole</th>
<th>RF E dipole</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{RMS}}$ / W</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>$\hat{I}$ / A</td>
<td>5</td>
<td>2</td>
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<tr>
<td>$\int \hat{B}_x , dl$ / Tmm</td>
<td>0.175</td>
<td>24.1</td>
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<tr>
<td>$f_{\text{RF}}$ range / kHz</td>
<td>629 - 1170</td>
<td>629 - 1060</td>
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</tbody>
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The RF ExB Dipole in Wien-Filter Configuration

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RF E dipole
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\[ \int \hat{F}_y \, dz = 0 \text{ eV/m} \]
COSY as Spin Physics R&D Facility

RF solenoid

RF ExB dipole

fast, continuous polarimetry

polarized source

experiments with $\vec{d}$ @ 970 MeV/c

$G = -0.142 \Rightarrow \gamma G = -0.161$

$f_{\text{rev}} = 750 \text{ kHz} \Rightarrow f_S = 120 \text{ kHz}$

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

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$f_{\text{RF}} = f_{\text{rev}}|n - \gamma G|; \ n \in \mathbb{Z}$

<table>
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<tr>
<th>$n$</th>
<th>$f_{\text{RF}}/ \text{kHz}$</th>
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<tr>
<td>0</td>
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<tr>
<td>1</td>
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<tr>
<td>-1</td>
<td>871</td>
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Vertical Polarization Measurements

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

RF ExB dipole: localized radial magnetic field $\Rightarrow$ tilt of $\vec{\Omega}$
RF field in phase with spin precession $\Rightarrow$ accumulation of spin kicks
Continuous rotation of $\vec{P}$ $\Rightarrow$ oscillation of $P_y$
Vertical Polarization Measurements

- beam polarization $\iff$ average over all particles’ spins
- massive carbon target with slow extraction $\Rightarrow$ long observation time
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Measurement Resonance Strength

- total spin flip only on resonance $\Rightarrow$ average polarization $\rightarrow 0$
- minimum of vertical polarization oscillation frequency

$!$ measurement of resonance strength $\varepsilon = \frac{f_{Py\min}}{f_{rev}}$

$
\begin{align*}
\text{f}_{Py\min} &= 0.2012 \text{ Hz at f}_{RF} = 871.427713 \text{ kHz} \\
\chi^2 / \text{ndf} &= 4.811 / 3 \\
\text{Curvature} &= 1.73e+06 \pm 9.91e+04 \\
\text{Minimum at} &= 871.4 \pm 5.632e-06 \\
\text{Offset} &= 0.2012 \pm 0.002057
\end{align*}$

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Measurements
Determination of Lorentz Force Compensation

- RF Wien-Filter at $f_{RF} = (-1 + \nu_s)f_{rev} = 871\,427.74\,Hz$
- RF Wien-Filter: $f_{Py} \propto \frac{1+G}{4\pi\gamma} \int \frac{\hat{B}_\perp}{B\rho} \, dl$; RF-solenoid: $f_{Py} \propto \frac{1+G}{4\pi} \int \frac{\hat{B}_\parallel}{B\rho} \, dl$
- RF-dipole: $f_{Py} \propto \frac{1+G}{4\pi} \int \frac{\hat{B}_\perp}{B\rho} \, dl + \text{interference from beam oscillations}^*$

\[\begin{array}{cccccccc}
\text{0.00} & \text{0.05} & \text{0.10} & \text{0.15} & \text{0.20} & \text{0.25} & \text{0.30} & \text{0.35} \\
\text{qy} & \text{f}_{Py}/\text{Hz} & (2-qy)f_{rev}/\text{kHz} & \text{preliminary data} \\
\end{array}\]
Conclusion

- versatile RF ExB dipole prototype minimal excitation of coherent beam oscillations has been successfully commissioned

- rotated version with vertical magnetic field scheduled for commissioning at the end of 2015

⇒ systematic studies for disentangling possible EDM signals from imperfection background

- Tuesday, March 10, 18:00 (HS1) Artem Saleev: Systematic studies of spin dynamics in preparation for the EDM searches
- Thursday, March 12, 14:30 (HS 1) Fabian Hinder: Development of new Beam Position Monitors at COSY
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RF ExB Setup for Field Compensation

- move betatron sideband onto RF frequency for max. sensitivity
- polarimeter target directly above beam limits acceptance
  ⇒ exited part of beam is removed
  ⇒ diagnosis with COSY beam current transformer
- determination of amplitudes and phase corresponding to Lorentz force compensation down to permille!

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Spares 15
Thomas-BMT Equation in Case of an RF Wien-Filter

- consider device with pure radial magnetic and vertical electric field
- adjust net Lorentz force to zero
  \[ \mathbf{E}/c = -\beta \times \mathbf{B} \]
- from Thomas-BMT Equation:
  \[ \vec{\Omega} = (1 + \gamma G)\vec{B} + (1 + G)\vec{B}_\parallel - \left( \frac{\gamma}{\gamma + 1} + \gamma G \right) \vec{B} = \left( 1 - \frac{\beta^2 \gamma}{\gamma + 1} + (1 - \beta^2)\gamma G \right) \vec{B} = \frac{1+G}{\gamma} \vec{B} \]
- 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 by turn, calculate Fourier integral over driving fields along orbit*:
  \[
  \epsilon_K = \frac{f_{\text{spin}}}{f_{\text{rev}}} = \frac{1+G}{2\pi\gamma} \oint b(\theta) \frac{e^{iK\theta}}{B\rho} d\theta
  \]
  \[
  = \frac{1+G}{2\pi\gamma} \int \frac{\hat{B} \, dz}{B\rho} \sum_{n=-\infty}^{\infty} \cos(2\pi n \frac{f_{\text{RF}}}{f_{\text{rev}}} + \phi) e^{i2\pi Kn}
  \]
  \[
  = \frac{1+G}{2\cdot2\pi\gamma} \int \frac{\hat{B} \, dz}{B\rho} \sum_{n} e^{\pm i\phi} \delta(n - K \mp \frac{f_{\text{RF}}}{f_{\text{rev}}})
  \]

- spin tune \( \approx \gamma G \), resonance at every sideband with
  \[
  K = \gamma G = n \pm \frac{f_{\text{RF}}}{f_{\text{rev}}} \iff f_{\text{RF}} = f_{\text{rev}}|n - \gamma G|; \ n \in \mathbb{Z}
  \]

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

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