An RF Wien-Filter as Spin Manipulator in Storage Rings

Freitags Seminar, III. Physikalisches Institut B, RWTH Aachen

Aachen, November 13, 2015 | Sebastian Mey and Ralf Gebel for the JEDI Collaboration |

Content

Motivation

JEDI Collaboration: First direct measurement of charged light hadrons' permanent **E**lectric **D**ipole **M**oment in storage rings

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

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

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

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

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

- assuming $\mathcal{CPT}$ symmetry $\wedge$ $\mathcal{T}$ violation $\Rightarrow$ **permanent EDMs also violate $\mathcal{CP}$ symmetry**

Spin Motion in a Magnetic Storage Ring

- assume stationary ring with vertical guiding field $\vec{B}_\perp$, $\vec{B}_\parallel = \vec{E} = \vec{0}$
- relativistic particles' spin in EM-fields: Thomas-BMT Equation

$$\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \vec{S} \times (\vec{\Omega}_{\mathrm{MDM}} + \vec{\Omega}_{\mathrm{EDM}})$$

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

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

- MDM: $\vec{\mu} = 2(G+1)\frac{q}{2m}\vec{S}$, G anomalous magnetic moment
- EDM: $\vec{d} = \eta\frac{q}{2mc}\vec{S} \approx 10^{-31}$ ecm $\Leftrightarrow$ $\eta \approx 10^{-15}$ for SM light hadrons

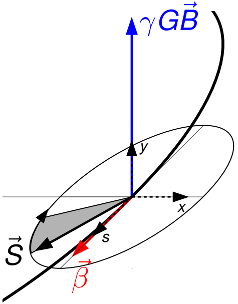
Generating an EDM Signal

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

$$\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \vec{S} \times \vec{\Omega} = \frac{q}{\gamma m}\vec{S} \times \left((1 + \gamma G)\vec{B} + \frac{\eta}{2}\gamma\vec{\beta} \times \vec{B} \right)$$

$\Rightarrow$ spin precession around y-axis with **spin tune**

$$q_s = \frac{\Omega_{\text{spin}}}{\Omega_{\text{rev}}} = \frac{\frac{q}{\gamma m}\gamma G B}{\frac{q}{\gamma m} B} = \gamma G$$



Generating an EDM Signal

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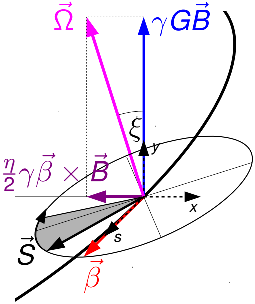
⇒ spin precession around y-axis with **spin tune**
$q_s = \frac{\Omega_{\text{spin}}}{\Omega_{\text{rev}}} = \; = \gamma G$

- EDM introduces tiny tilt of precession axis
  $\tan\xi = \frac{\beta\eta}{2G}$
- prepare beam with spins oriented in accelerator plane (pure S_{xz} polarization)

⇒ **vertical spin component S_y appears**

- oscillation of S_y, but for $\eta \approx 10^{-15}$ one needs **accumulation** of vertical component to generate measurable result



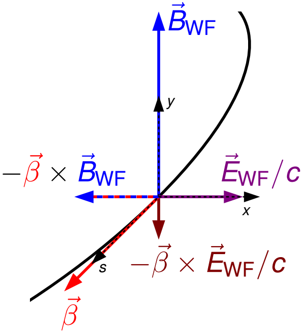
Generating an EDM Signal, cont.

- cancel the $\gamma G B$ contribution to the spin precession with a **localized R**adio-**F**requency field **oscillating in phase with the spin precession**
- beam perturbation has to be minimized by adjusting net Lorentz Force to zero:

  $\vec{E}_{\text{WF}}/c = -\vec{\beta} \times \vec{B}_{\text{WF}}$ (Wien-Filter condition)
- spin motion in Wien-Filter: additional precession around vertical axis, **no EDM interaction!**

$$\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \vec{S} \times \vec{\Omega}_{\text{WF, MDM}} = \frac{q}{\gamma m} \vec{S} \times \left(\frac{1+G}{\gamma} \vec{B}_{\text{WF}} \right)$$

$$\vec{\Omega}_{\text{WF, EDM}} = \frac{q}{m} \frac{\eta}{2} \left(\vec{E}_{\text{WF}}/c + \vec{\beta} \times \vec{B}_{\text{WF}} \right) = \vec{0}$$



Generating an EDM Signal, Summary:

- non-vanishing EDMs introduce vertical spin components in a beforehand horizontally polarized beam
- introduce cancellation of the free MDM precession with a localized RF field, cancel beam perturbation by utilizing Wien-Filter configuration

$\Rightarrow$ spin tune is modulated so that $\langle S_{xz} \rangle_T$ is aligned with the particles' velocity $\vec{\beta}$

- EDM interaction with the motional electric field in the rest of the ring will yield a **continuous** buildup of S_y*

[* W. M. Morse, Y. F. Orlov and Y. K. Semertzidis, Phys. Rev. ST Accel. Beams 16, 114001 (2013)]

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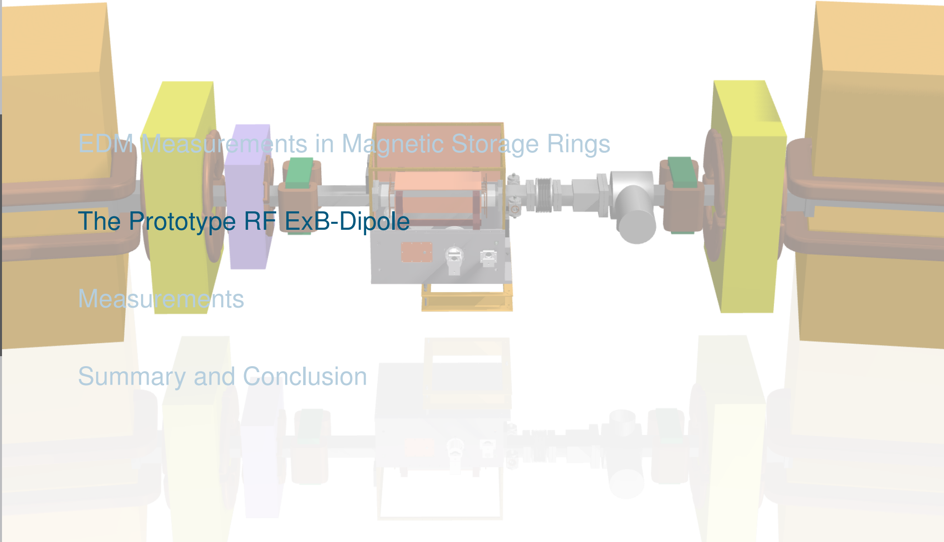
- EDM interaction with the motional electric field in the rest of the ring will yield a **continuous** buildup of S_y*
- many challenges involved, today: **Generating RF fields in Wien-Filter configuration for spin manipulation**

[* W. M. Morse, Y. F. Orlov and Y. K. Semertzidis, Phys. Rev. ST Accel. Beams 16, 114001 (2013)]

Content



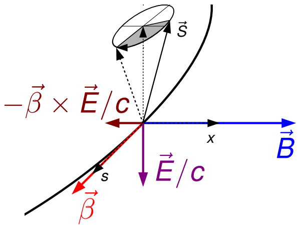
Prototype RF Wien-Filter with Radial Magnetic Field

Goal: characterize RF Wien-Filter fields by **direct observation of spin manipulation**

- use radial magnetic field with vertically prepared spins $\Rightarrow S_y = \text{const.}$
- Lorentz force compensation: $\vec{E}/c = -\vec{\beta} \times \vec{B}$

$\Rightarrow$ spin precession:

$$\frac{d\vec{S}}{dt} = \vec{S} \times \vec{\Omega}_{\text{WF}} = \frac{q}{\gamma m} \vec{S} \times \left(\frac{1+G}{\gamma} \vec{B} \right)$$



- fields oscillate in phase with spin precession

$\Rightarrow$ spin kicks accumulate turn by turn

$\Rightarrow$ continuous rotation of spin vector around $\vec{e}_s$

Resonance Strength of an RF Wien-Filter

- particles sample localized RF field once each turn at orbit angle θ

$$b(\theta) = \int \hat{B}\,\mathrm{d}s \cos\left(\frac{f_{\mathrm{RF}}}{f_{\mathrm{rev}}}\theta + \phi\right) \sum_{n=-\infty}^{\infty} \delta(\theta - 2\pi n)$$

- resonance strength given by spin rotation per turn:

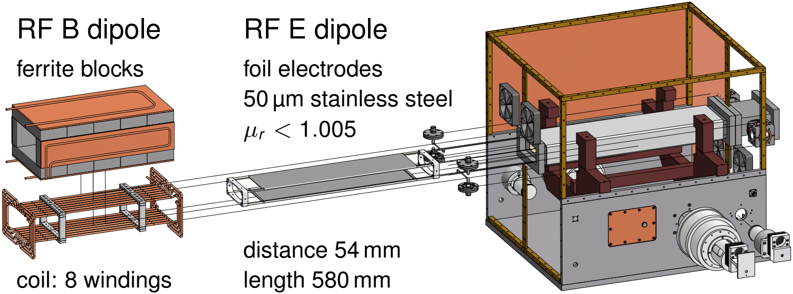
$$\epsilon_K = \frac{f_{\mathrm{spin}}}{f_{\mathrm{rev}}} = \frac{1+G}{2 \cdot 2\pi\gamma} \frac{\int \hat{B}\,\mathrm{d}s}{B\rho} \sum_n e^{\pm i\phi} \delta\left(n - K \mp \frac{f_{\mathrm{RF}}}{f_{\mathrm{rev}}}\right)$$

- spin tune $\approx \gamma G \Rightarrow$ **resonance at every sideband with**
  $K \overset{!}{=} \gamma G = n \pm \frac{f_{\mathrm{RF}}}{f_{\mathrm{rev}}} \Leftrightarrow f_{\mathrm{RF}} = f_{\mathrm{rev}} |n - \gamma G|;\ n \in \mathbb{Z}$
- d at 970 MeV/c: $f_{\mathrm{rev}} = 750.603\,\mathrm{kHz}; \gamma G = -0.16098$

n	0	1	-1	2	-2
f_{RF}/ kHz	120	629	871	1380	1621

[* S. Y. Lee, 10.1103/PhysRevSTAB.9.074001 (2006)]

The Prototype RF ExB Dipole



RF B dipole

ferrite blocks

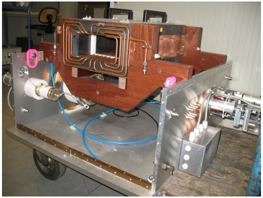
coil: 8 windings
length 560 mm

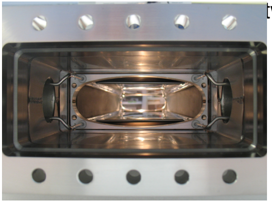
RF E dipole

foil electrodes
50 µm stainless steel
$\mu_r < 1.005$

distance 54 mm
length 580 mm

ceramic beam chamber
two separate *LC* circuits





The Prototype RF ExB Dipole

RF B dipole

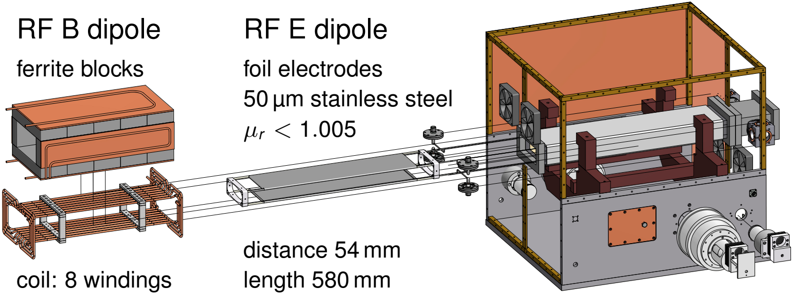
ferrite blocks

coil: 8 windings
length 560 mm

RF E dipole

foil electrodes
50 µm stainless steel
$\mu_r < 1.005$

distance 54 mm
length 580 mm



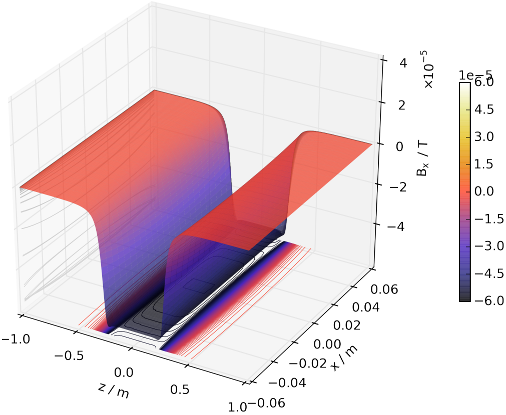
ceramic beam chamber
two separate *LC* circuits

Parameters	**RF B dipole**
P_{RMS} / W	90
$\hat{I}$ / A	5
$\int \hat{B}_x \, \mathrm{d}l$ / Tmm	0.175
f_{RF} range / kHz	629 - 1170

Parameters	**RF E dipole**
P_{RMS} / W	90
$\Delta\hat{U}$ / kV	2
$\int \hat{E}_y \, \mathrm{d}l$ / kV	24.1
f_{RF} range / kHz	629 - 1060

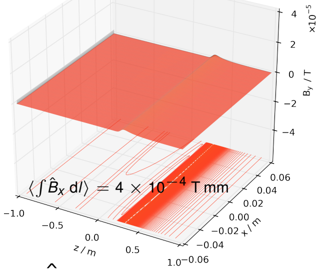
Magnetic Field Distribution

$\hat{B}_x$ at $y = 0.0\,\mathrm{m}$ normalized to $\hat{I} = 1\,\mathrm{A}$

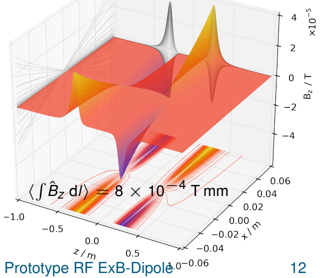


- $\langle \int \hat{B}_x \,\mathrm{d}l \rangle = -0.035\,\mathrm{T\,mm}$ at $\hat{I} = 1\,\mathrm{A}$
- $\langle \int \hat{B}_y \,\mathrm{d}l \rangle / \langle \int \hat{B} \,\mathrm{d}l \rangle \approx \langle \int \hat{B}_z \,\mathrm{d}l \rangle / \langle \int \hat{B} \,\mathrm{d}l \rangle < 10^{-2}$

$\hat{B}_y$ at $y = 0.0\,\mathrm{m}$

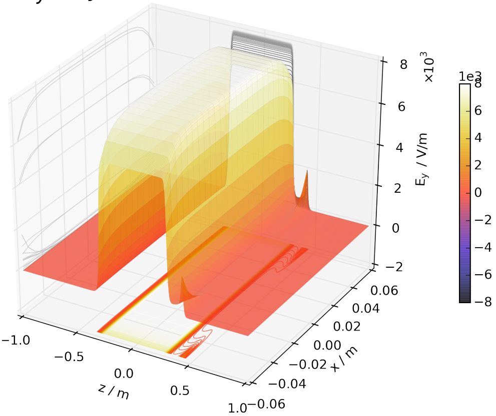


$\hat{B}_z$ at $y = 0.0\,\mathrm{m}$

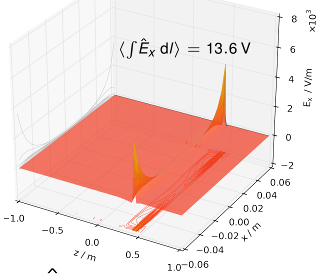


Electric Field Distribution

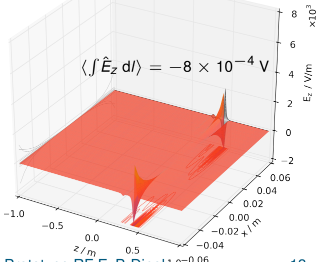
$\hat{E}_y$ at $y = 0.0\,\mathrm{m}$ normalized to $\hat{U} = 146\,\mathrm{V}$



$\hat{E}_x$ at $y = 0.0\,\mathrm{m}$



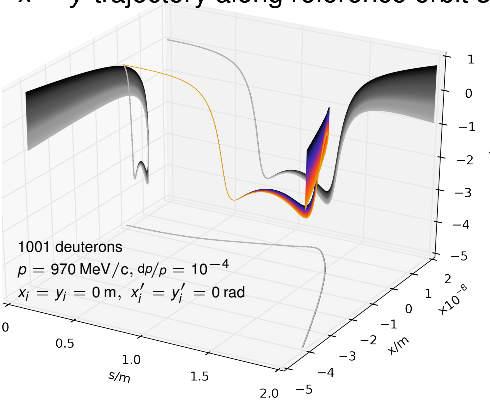
$\hat{E}_z$ at $y = 0.0\,\mathrm{m}$



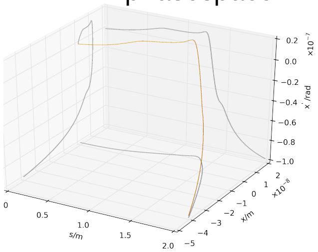
- $\langle \int \hat{E}_y \, \mathrm{d}l \rangle = 4796\,\mathrm{V}$ at $\hat{U} = 146\,\mathrm{V}$
- $\langle \int \hat{E}_x \, \mathrm{d}l \rangle / \langle \int \hat{E} \, \mathrm{d}l \rangle \approx \langle \int \hat{E}_z \, \mathrm{d}l \rangle / \langle \int \hat{E} \, \mathrm{d}l \rangle < 10^{-3}$

Particle Traces

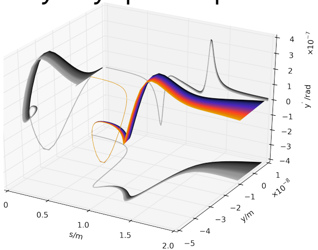
$x - y$ trajectory along reference orbit s



$x - x'$ phasespace



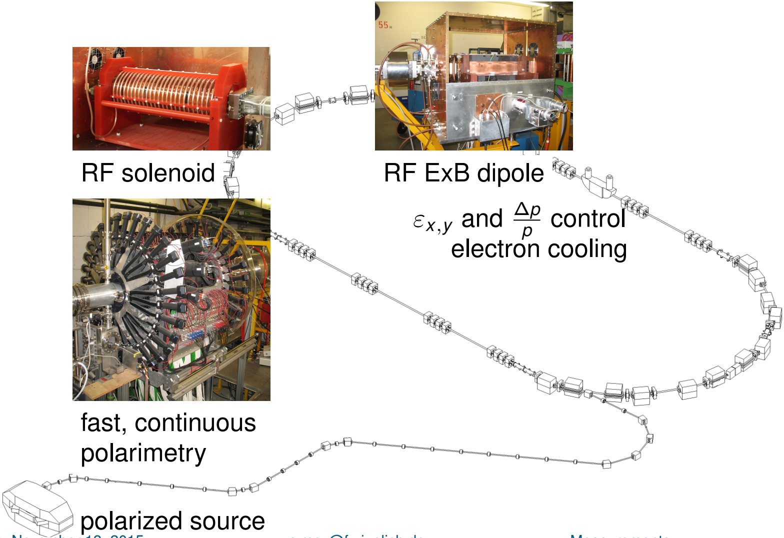
$y - y'$ phasespace



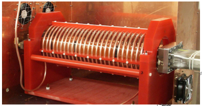
- optimization for $\langle y_f \rangle \approx 0$ m, $\langle y'_f \rangle \approx 0$ rad
- small spread in vertical plane $\sigma_{y_f} < 4$ nm
- small shift in horizontal plane, $\langle x_f \rangle \approx 40$ nm, $\langle x'_f \rangle \approx -0.1$ µrad

Content

COSY as Spin Physics R&D Facility

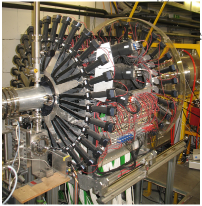


COSY as Spin Physics R&D Facility



RF solenoid

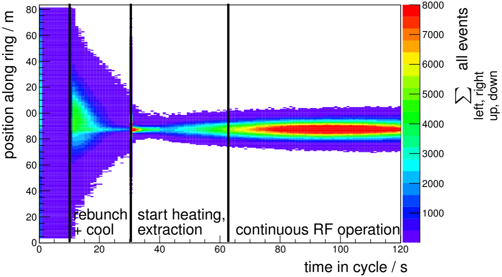
RF ExB dipole



fast, continuous polarimetry

polarized source

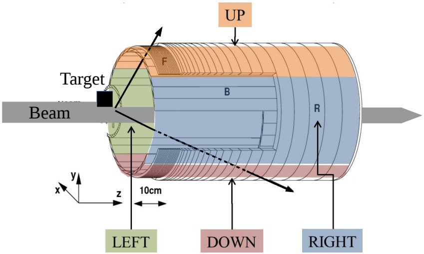
particles on internal polarimeter target:

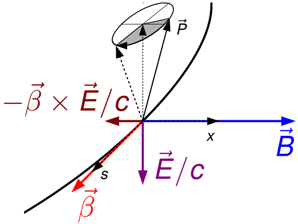


Polarization Measurements

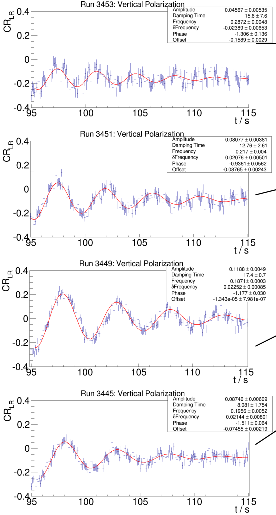
- beam polarization ⇔ average over all particles' spins
- massive carbon target with slow extraction ⇒ long observation time
- polarization signal ⇒ rate asymmetries in $^{12}\mathrm{C}(\vec{\mathrm{d}},\mathrm{d})$: $P_y \propto \frac{N_\mathrm{left} - N_\mathrm{right}}{N_\mathrm{left} + N_\mathrm{right}}$
- $\frac{\mathrm{d}\vec{P}}{\mathrm{d}t} = \vec{P} \times \vec{\Omega}_\mathrm{WF} = \frac{q}{\gamma m}\vec{P} \times \left(\frac{1+G}{\gamma}\vec{B}\right)$
- fields oscillating in phase with spin ⇒ accumulation of spin kicks

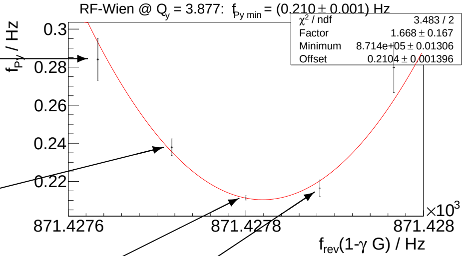
⇒ continuous rotation of $\vec{P}$ ⇒ oscillation of P_y





Measurement of Resonance Strength





- total spin flip only on resonance

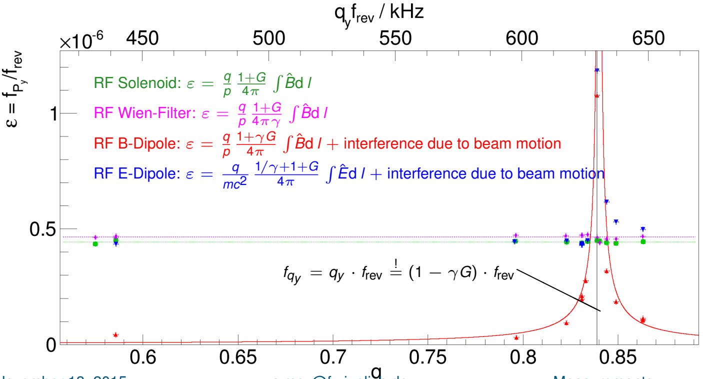
⇔ minimum of oscillation frequency f_{Py}

- find resonance by scan of driving frequency $f_{\mathrm{RF}} \overset{!}{=} f_{\mathrm{rev}}(1-\gamma G)$
- **directly yields resonance strength:**

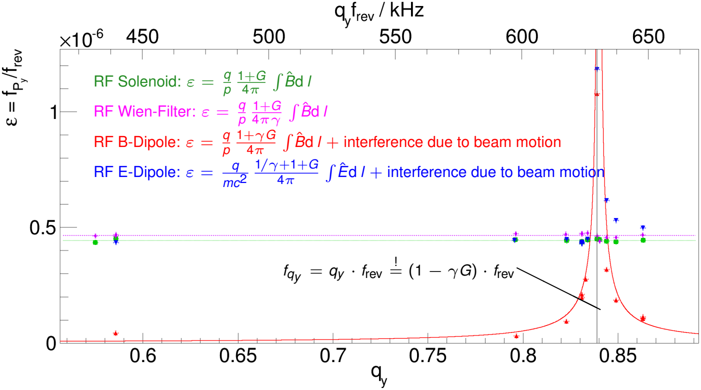
$$\varepsilon = \frac{f_{P_{y\,\mathbf{min}}}}{f_{\mathbf{rev}}}$$

Verification of Field Compensation

- modify vertical beam oscillation frequency by changing the overall focusing of the accelerator lattice
- scan betatron tune across coinciding beam and spin resonance:
  $f_{q_y} = q_y \cdot f_{\text{rev}} \stackrel{!}{=} (1 - \gamma G) \cdot f_{\text{rev}} = f_{\text{RF}}$ with q_y betatron tune



Verification of Field Compensation



- **RF Wien-Filter doesn't excite any beam oscillations!**
- spin resonance strength comparable to the proven RF Solenoid
- extreme cases of RF B-Dipole and and RF E-Dipole both show clear influnce of beam motion in the resonane strength

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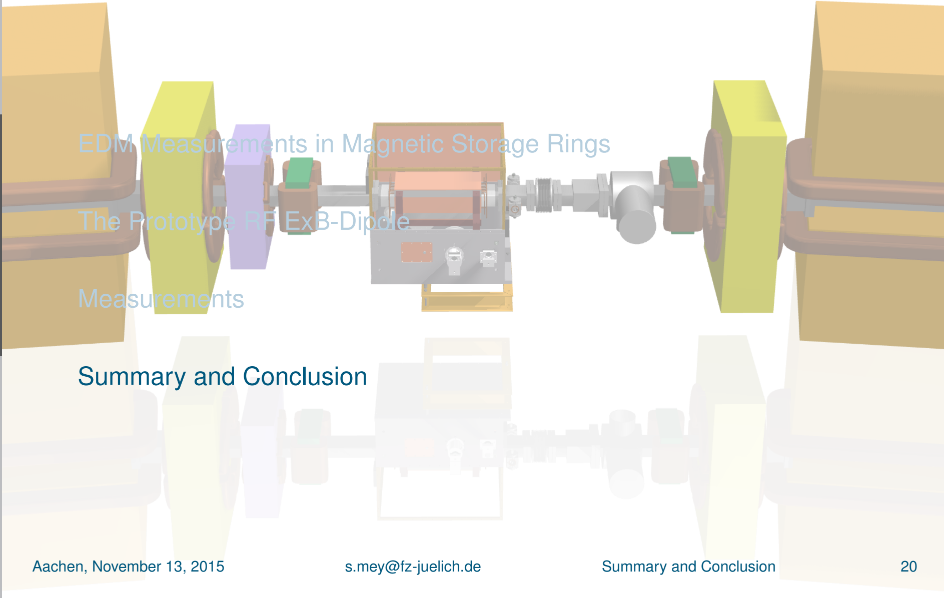

Summary

- versatile prototype RF ExB dipole has been successfully commissioned
- $P_{\mathrm{RMS}} = 90\,\mathrm{W} \Rightarrow \int \hat{B}_x\,\mathrm{d}l = 0.175\,\mathrm{T\,mm};\ \int \hat{E}_y\,\mathrm{d}l = 23.98\,\mathrm{kV}$

  Frequency Range 630 kHz - 1060 kHz
- Wien-Filter capability has been verified, even when operating the RF Wien-Filter excactly on resonance no beam excitation has been observed

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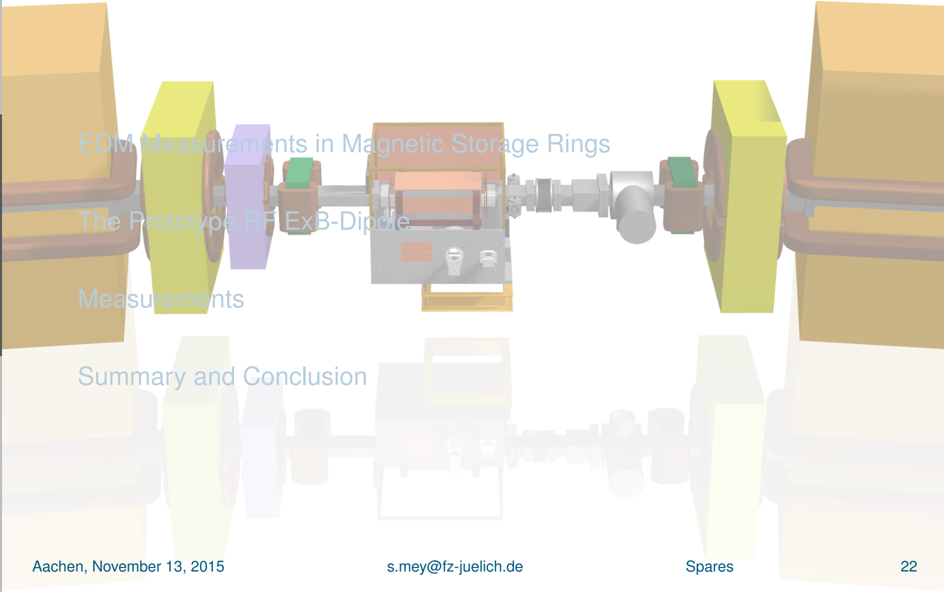
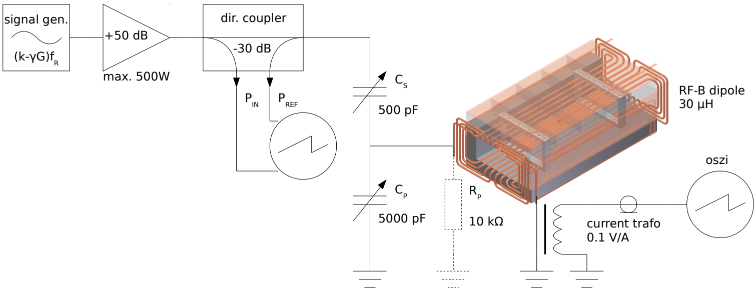


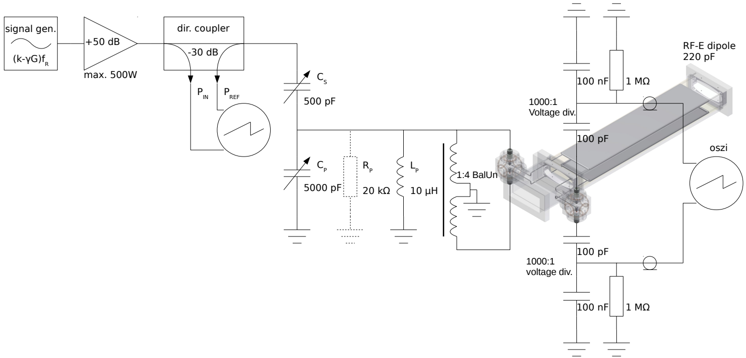
RF-B Circuit *



- amplitude limited by losses $\Rightarrow \hat{I}_{max} \approx 5\,\text{A}$ @ $P_{in} \approx 90\,\text{W}$
- matching to 50 Ω with bidirectional coupler
- frequency range 630 kHz - 1170 kHz
- current in coil directly available via current transformer

[* A. Schnase, “RF-Dipole System at COSY for spin-flipping experiments”, IKP Annual Report 2002]

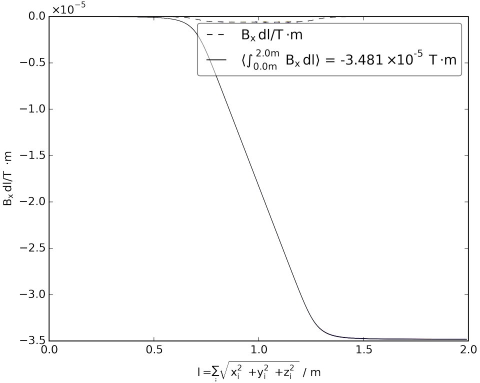
RF-E Circuit



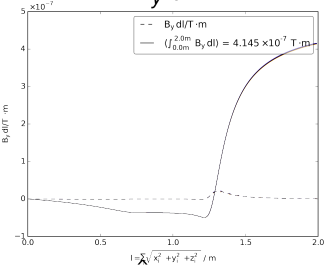
- $\hat{U}_{max} \approx 2\,\text{kV}$ @ $P_{in} \approx 90\,\text{W}$
- frequency range 630 kHz - 1060 kHz
- electrode voltage directly available via capacitive voltage divider

Field Integrals

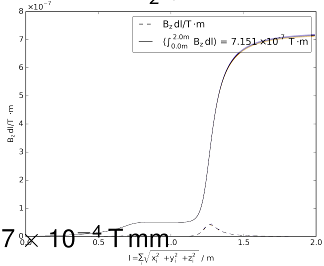
$\hat{B}_x \, \mathrm{d}l$ along $x - y$ trajectory



$\hat{B}_y \, \mathrm{d}l$



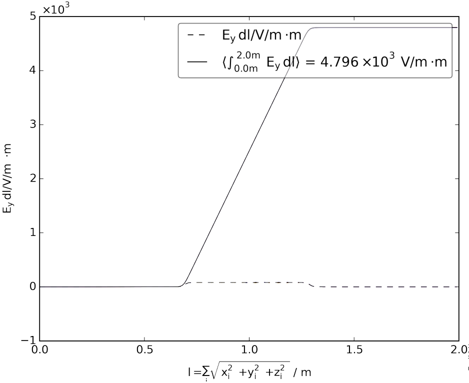
$\hat{B}_z \, \mathrm{d}l$



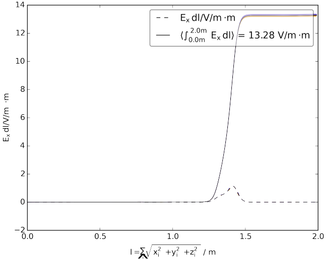
- $\langle \int \hat{B}_x \, \mathrm{d}l \rangle = -0.035 \, \mathrm{T\,mm}$ at $\hat{I} = 1 \, \mathrm{A}$
- $\langle \int \hat{B}_y \, \mathrm{d}l \rangle = 4 \times 10^{-4} \, \mathrm{T\,mm}$, $\langle \int \hat{B}_z \, \mathrm{d}l \rangle = 7 \times 10^{-4} \, \mathrm{T\,mm}$

Field Integrals

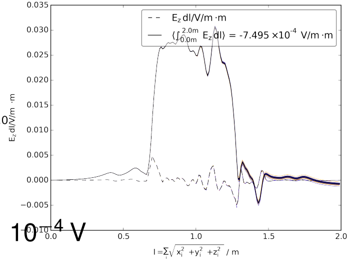
$\hat{E}_y\,\mathrm{d}l$ along $x - y$ trajectory



$\hat{E}_x\,\mathrm{d}l$



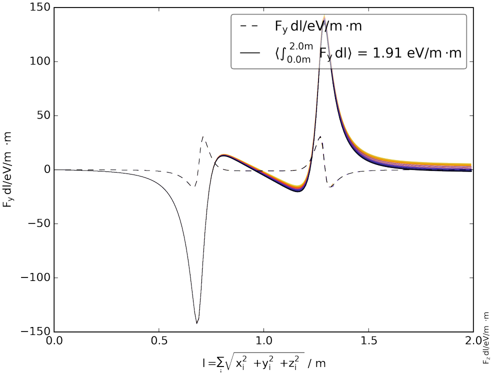
$\hat{E}_z\,\mathrm{d}l$



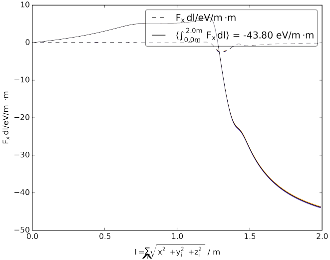
- $\langle \int \hat{E}_y\,\mathrm{d}l \rangle = 4796\,\mathrm{V}$ at $\hat{U} = 146\,\mathrm{V}$
- $\langle \int \hat{E}_x\,\mathrm{d}l \rangle = 13.28\,\mathrm{V}$, $\langle \int \hat{E}_z\,\mathrm{d}l \rangle = -8 \times 10^{-4}\,\mathrm{V}$

Lorentz Force Compensation

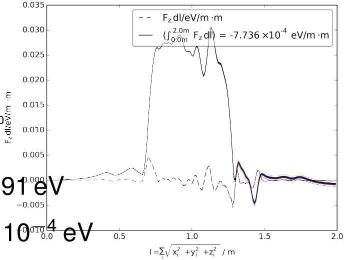
$\hat{F}_y\,\mathrm{d}l$ along $x - y$ trajectory



$\hat{F}_x\,\mathrm{d}l$



$\hat{F}_z\,\mathrm{d}l$



- $\langle \int \hat{F}_y\,\mathrm{d}l \rangle = \langle e \int (\hat{E}_y + c\beta_z \hat{B}_x)\,\mathrm{d}l \rangle = 1.91\,\mathrm{eV}$
- $\langle \int \hat{F}_x\,\mathrm{d}l \rangle = -43.8\,\mathrm{eV}$, $\langle \int \hat{F}_z\,\mathrm{d}l \rangle = 8 \times 10^{-4}\,\mathrm{eV}$

RF ExB Setup for Field Compensation

- move betatron sideband onto RF freq. for max. sensitivity

$$q_y \cdot f_{\text{rev}} \stackrel{!}{=} (1+\gamma G) f_{\text{rev}} = 629\,\text{kHz}$$

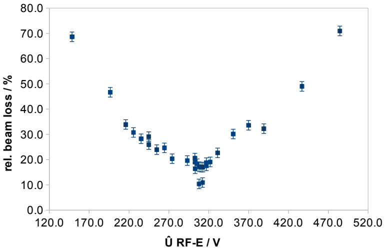
- polarimeter target directly above beam limits acceptance

$\Rightarrow$ exited part of beam is removed

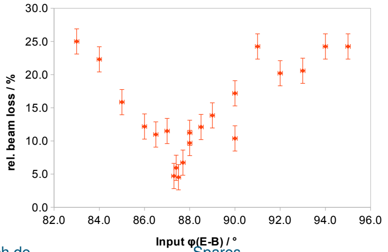
$\Rightarrow$ diagnosis with COSY beam current transformer over $\Delta t = 30\,\text{s}$

- determination of amplitudes and phase for Lorentz force compensation down to per mille!
- minimal beam disturbance at $\hat{U}/\hat{I} = 1/155\,\text{A/V}$

Amplitude Scan RF-E at $\hat{I}_{\text{RF-B}} = 2\,\text{A}$



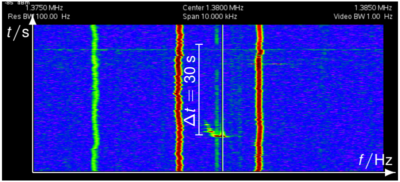
Phase Scan



Beam Response

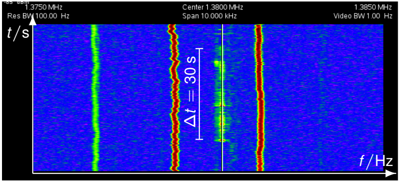
Analogue signal from one vertical BPM pickup electrode during RF operation exactly **on resonance**

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.:

$\hat{I}_{\text{Sol.}} \approx 780\,\text{mApp}$