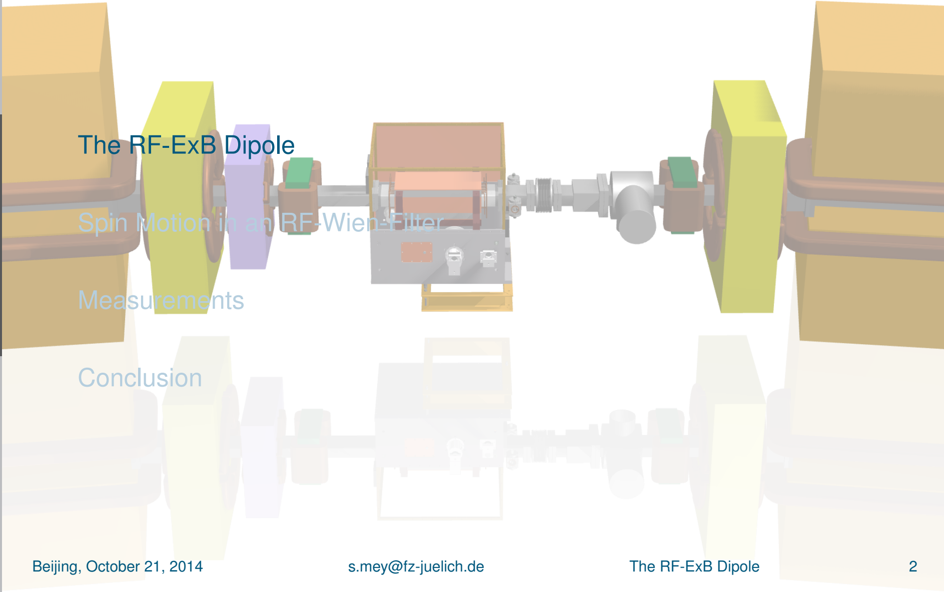
A Novel RF-ExB Spin Manipulator at COSY

Contribution to SPIN2014

Beijing, October 21, 2014 | Sebastian Mey and Ralf Gebel for the JEDI Collaboration |

Forschungszentrum Jülich

Content



- The RF-ExB Dipole
- Spin Motion in an RF-Wien-Filter
- Measurements
- Conclusion

The RF-ExB Dipole

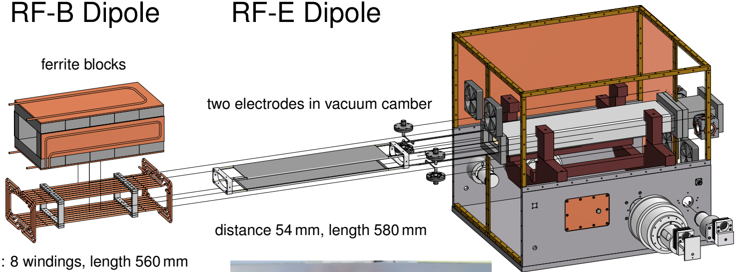
RF-B Dipole

RF-E Dipole

shielding Box

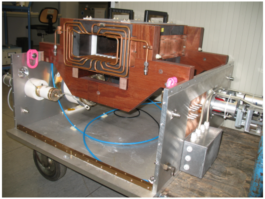
ferrite blocks

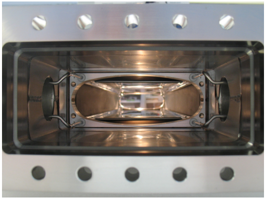
two electrodes in vacuum camber



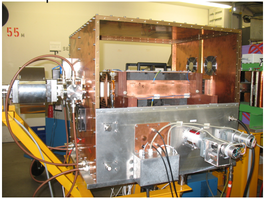
distance 54 mm, length 580 mm

coil: 8 windings, length 560 mm



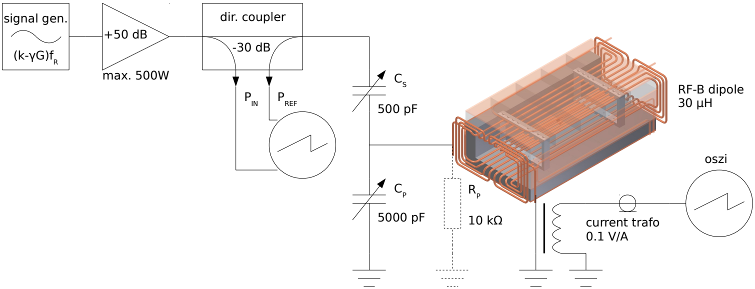


ceramic beam chamber
two separate resonance circuits



Member of the Helmholtz-Association

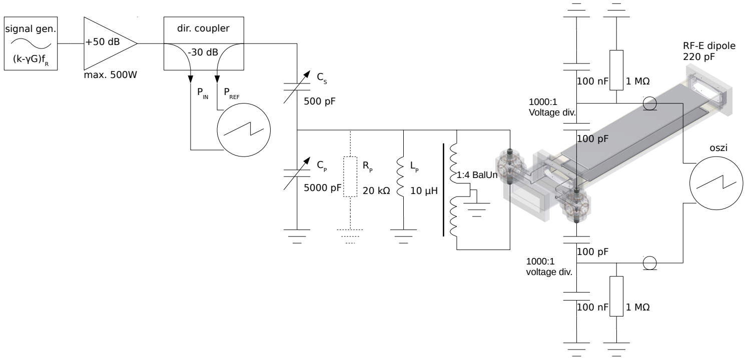
RF-B Circuit *



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

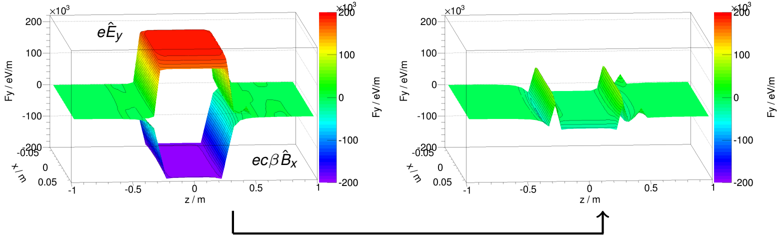
[* A. Schnase, "RF-Dipole System at COSY for spin-flipping experiments", IKP Annual Report 2002]

RF-E Circuit



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

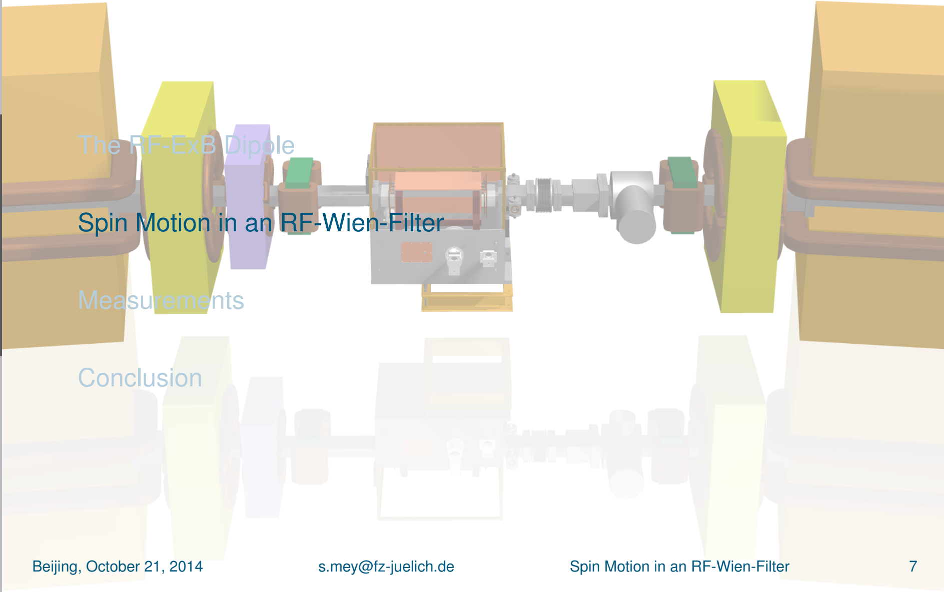
Lorentz Force Compensation



$$F_y = e\left(\hat{E}_y + c\beta\hat{B}_x\right)$$

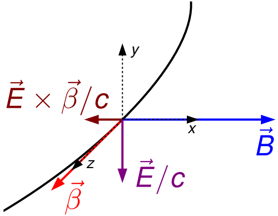
- $\beta \equiv \beta_z = 0.459$; $\hat{I} = 1\,\text{A}$; $\int \hat{B}_x\,\text{d}z \approx -0.035\,\text{T mm}$
- $\hat{U} = 395\,\text{V}$; $\int \hat{E}_y\,\text{d}z = 4818\,\text{V}$
- simulated optimization for integral compensation along beam path $\int \hat{F}_y\,\text{d}z = 0\,\text{eV/m}$

Content



Thomas-BMT Equation in Case of a Wien-Filter

- consider device with pure radial magnetic and vertical electric field
- net Lorentz force can be adjusted to zero $\Rightarrow \quad \frac{\vec{E}}{c} = -\vec{\beta} \times \vec{B}$
- Thomas-BMT Eq.: $\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \frac{e}{\gamma m}\,\vec{S} \times \vec{\Omega}$



$$\vec{\Omega} = (1+\gamma G)\vec{B}_\perp + \cancelto{0}{(1+G)\vec{B}_\parallel} + \left(\frac{\gamma}{\gamma+1} + \gamma G\right)\frac{\vec{E}\times\vec{\beta}}{c}$$

$$\frac{\vec{E}\times\vec{\beta}}{c} = -(\vec{\beta}\times\vec{B})\times\vec{\beta} = \vec{\beta}\cdot\underbrace{(\vec{\beta}\cdot\vec{B})}_{=0} - \vec{B}\cdot(\vec{\beta}\cdot\vec{\beta}) = -\beta^2\vec{B}$$

$$\Rightarrow \vec{\Omega} = \left(1 - \frac{\beta^2\gamma}{\gamma+1} + (1-\beta^2)\gamma G\right)\vec{B} = \frac{1+G}{\gamma}\vec{B}$$

Spin-Resonance Strength of a RF-Wien-Filter *

- $B(t) = \hat{B}\cos(\omega_{\mathrm{RF}} t + \phi)$
- particles sample localized RF field once each turn, define modulation tune $\nu_m = \frac{\omega_{\mathrm{RF}}}{\omega_{\mathrm{rev}}}$

$\Rightarrow$ $b(\theta) = \int \hat{B}\,\mathrm{d}l \cos(\nu_m \theta + \phi) \sum_{n=-\infty}^{\infty} \delta(\theta - 2\pi n)$

$\Rightarrow$ $\int \hat{B}\,\mathrm{d}l \cos(2\pi n \nu_m + \phi)$ is the spin kick in turn n

- intrinsic resonance strength given by amplitude of Fourier integral over driving fields along orbit:

$$\begin{aligned}
\epsilon &= \frac{1+G}{2\pi\gamma} \oint \frac{b(\theta)}{B\rho} e^{ik\theta}\,\mathrm{d}\theta \\
&= \frac{1+G}{2\pi\gamma} \frac{\int \hat{B}\,\mathrm{d}l}{B\rho} \sum_{n=-\infty}^{\infty} \cos(2\pi n \nu_m + \phi) e^{i2\pi kn} \\
&= \frac{1+G}{2\cdot 2\pi\gamma} \frac{\int \hat{B}\,\mathrm{d}l}{B\rho} \left(e^{i\phi} \sum_n e^{i2\pi(k+\nu_m)n} + e^{-i\phi} \sum_n e^{i2\pi(k-\nu_m)n} \right)
\end{aligned}$$

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

Resonance Condition

- spin tune given by γG

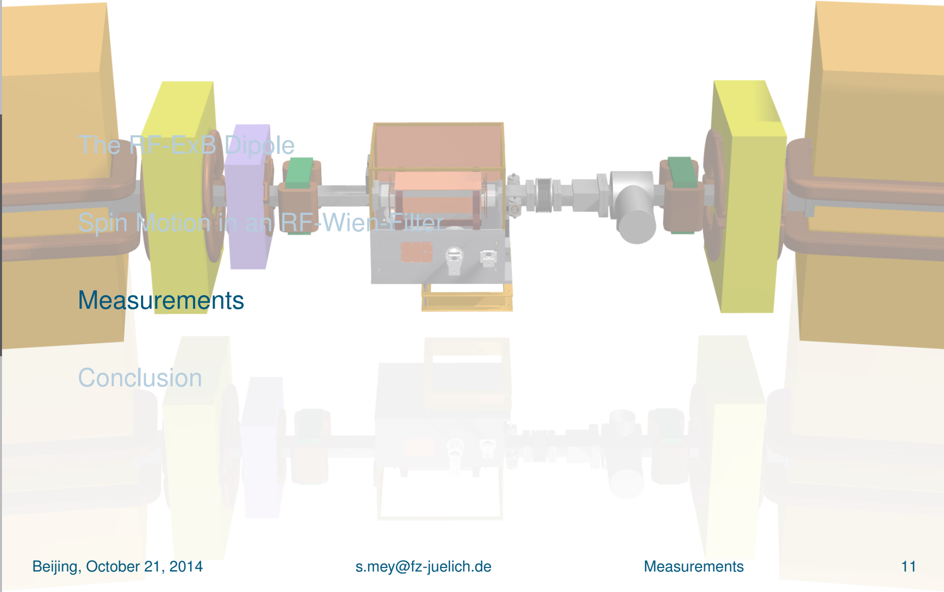
$\Rightarrow$ resonance at $k \stackrel{!}{=} \gamma G = n \pm \nu_m \quad \Leftrightarrow \quad f_{RF} = f_{rev}|n + \gamma G|;\ n \in \mathbb{Z}$

- d at 970 MeV/c: $\beta = 0.459$; $\gamma = 1.126$; $G = -0.142\,987$;

$\Rightarrow$ $f_{rev} = 750$ kHz; $\gamma G = -0.16098$:

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

Content



- The RF-ExB Dipole
- Spin Motion in an RF-Wien-Filter
- Measurements
- Conclusion

Field Compensation

- measurement on betatron frequency for max. sensitivity
- polarimeter target directly above beam-pipe-center *

$\Rightarrow$ exited part of beam is removed

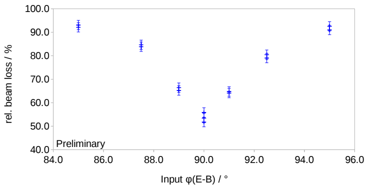
$\Rightarrow$ diagnosis with COSY beam current transformer

- measurement gives minimal beam disturbance at $\frac{\hat{I}}{\hat{U}} = 1.76\,\mathrm{mA/V}$
- $\int B_x dz \approx 0.008\,\mathrm{T\,mm}$

[* $\rightarrow$ E. Stephenson, contribution to SPIN2014]

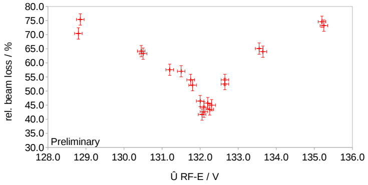
Phase Scan @ 30% Output Amplitude, Natural Beamloss (38.2±1.1)%

fQy = 871.52 kHz, f = 871.4282 kHz, Î RF-B = (232.6±0.6) mA, Û RF-E = (132.0±0.3) V



Amplitude Scan @ 30% Output Amplitude, Natural Beamloss (38.2±1.1)%

fQy = 871.52 kHz, f = 871.4282 kHz, Î RF-B = (232.5±0.6) V, Input φ(E-B) = 90°

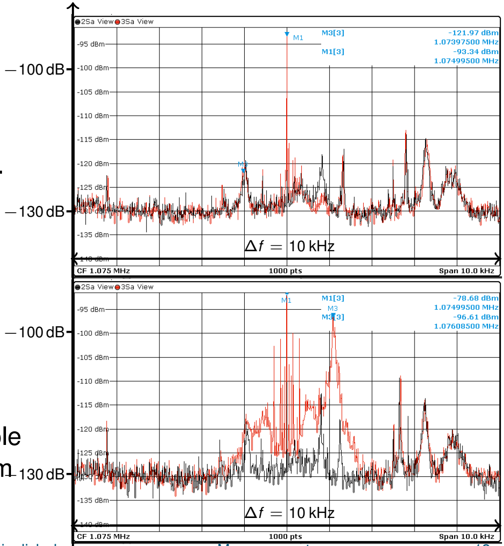


Vertical Beam Spectrum

- analogue signal from one vertical BPM pickup electrode
- spectra taken after beam prep. (black) and after RF-ExB is switched on (red)
- optimum matching results in narrow beam response

⇒ very slight coherent beam oscillation

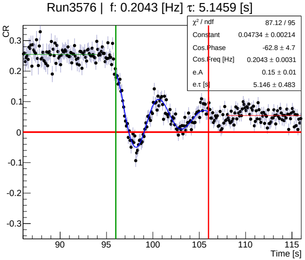
- not fully matched RF-ExB dipole results in more wideband beam response

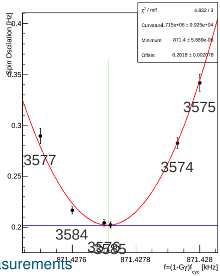


Measurement of Resonance Strength

- continuous polarimertry allows fixed frequency scan for resonance determination
- damping due to time-of-arrival ($\sim \frac{\Delta p}{p}$) and decoherence *
- cross-ratio of UD-asymmetries goes to zero ($\leftrightarrow$ average polarization)
- minimum vertical polarization oscillation frequency gives resonance strength $\varepsilon = \frac{f_{P_y \, \text{min}}}{f_{\text{rev}}}$

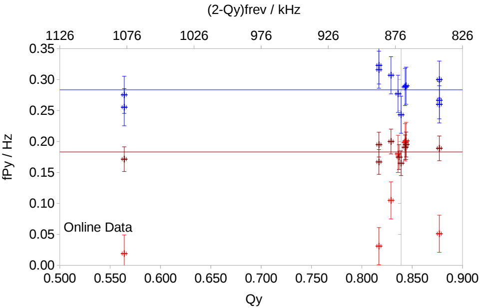
[* $\rightarrow$ E. Stephenson, contribution to SPIN2014]

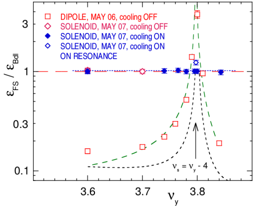




Preliminary result of Fixed Frequency Scans

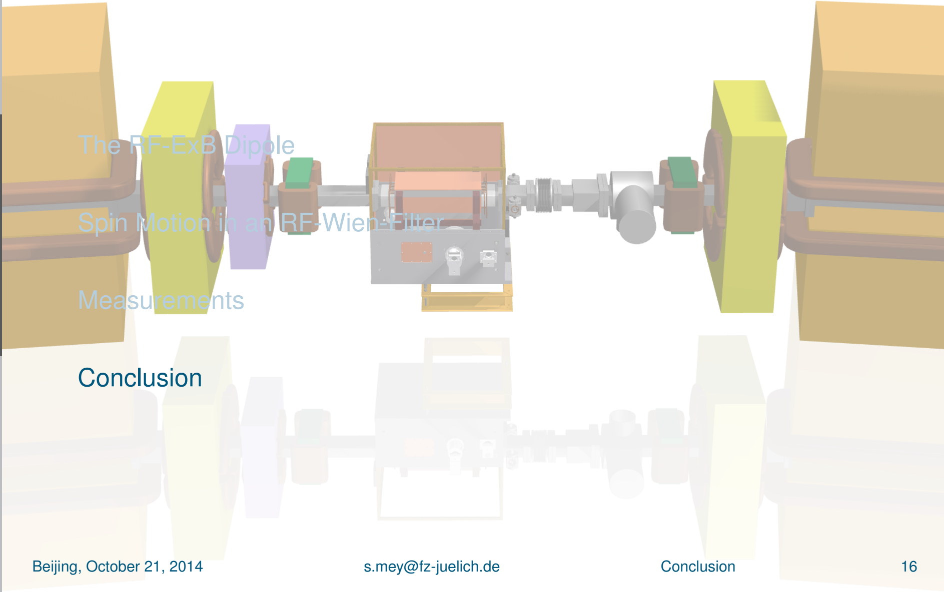
- RF-solenoid: $f_{P_y} \propto \frac{1+G}{4\pi}\frac{\int \hat{B}_{\parallel}\,\mathrm{d}l}{B\rho}$; RF-Wien-Filter: $f_{P_y} \propto \frac{1+G}{4\pi\gamma}\frac{\int \hat{B}_{\perp}\,\mathrm{d}l}{B\rho}$
- RF-dipole w.o. driven beam osc.: $f_{P_y} \propto = \frac{1+\gamma G}{4\pi}\frac{\int \hat{B}_{\perp}\,\mathrm{d}l}{B\rho}$
- $\int \hat{B}\,\mathrm{d}l$ normalization has to be done to compare resonance strengths





[M.A. Leonova et Al., contribution to Spin 2008, Charlottsville, VA)]

Content



Member of the Helmholtz-Association

Conclusion

- RF-ExB dipole acting on MDM with minimal disturbance has been successfully commissioned
  - RF-B amplitude: $\int \hat{B}_x \, \mathrm{d}z \approx 0.18\,\mathrm{T\,mm}$ @ $\hat{I}_{\mathrm{max}} = 5\,\mathrm{A}$
  - RF-E amplitude: $\int \hat{E}_y \, \mathrm{d}z \approx 24\,\mathrm{kV}$ @ $\hat{U}_{\mathrm{max}} = 1975\,\mathrm{V}$
  - ± 1 spin harmonics at 629 kHz and 871 kHz available for studies

$+$ field strengths necessary for spin manipulation ($\approx 0.01\,\mathrm{T\,mm}$) available at very low input powers ($\approx 10\,\mathrm{W}$)

$-$ complicated and time-consuming matching of Wien-Filter condition

$\Rightarrow$ routine operation of the prototype requires sophisticated phase and amplitude control system (feedback?)

ToDo

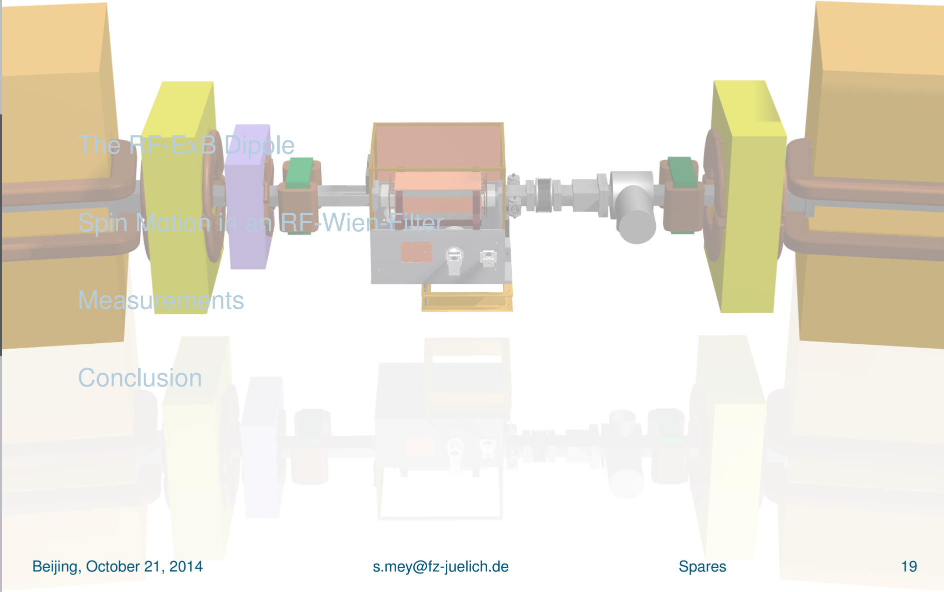
- offline analysis of resonance scans
  - incorporate LR-asymmetries, driven vertical oscillation appears in Fourier spectrum of idle horizontal spin precession

  $\Rightarrow$ statistically independent analysis
- $\int \hat{B}\,\mathrm{d}l$ determination from measurements
  - resonance strength independence of betatron tune

  $\Rightarrow$ field calibration from fit of intrinsic resonance strength formula to scans at different amplitudes
- repeat measurements at +1 spin harmonic (629 kHz)

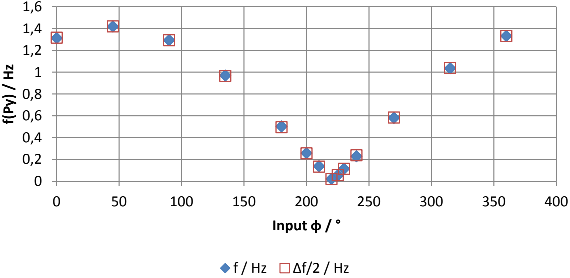
  $\Rightarrow$ less damping of driven oscillation
- finally turn the RF-ExB dipole upright for systematics estimation in "EDM" mode

Content



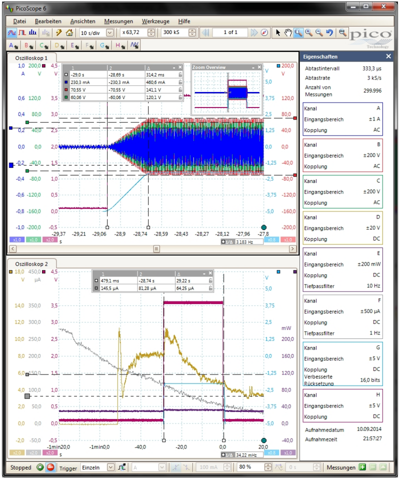
Example measurement to determine B dl

- varying phase between the RF-ExB dipole and the RF-Solenoid to compensate both spin kicks
- at minimum vary RF-Solenoid amplitude to set the sum resonance strength to 0
- both systems have exactly the same resonance strength

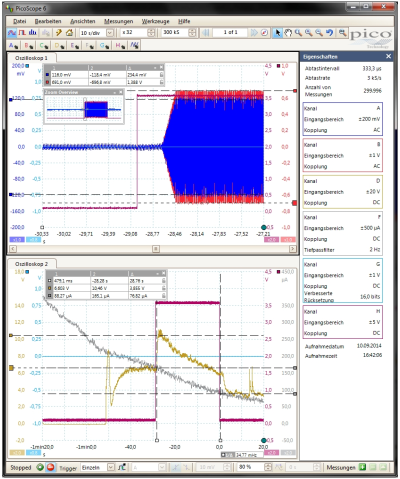


[measurement idea by A. Saleev]

RF-Solenoid and RF-Wien-Filter on Resonance



RF-Wien-Filter at ≈ 0.01 T mm



RF-Solenoid at ≈ 0.015 T mm