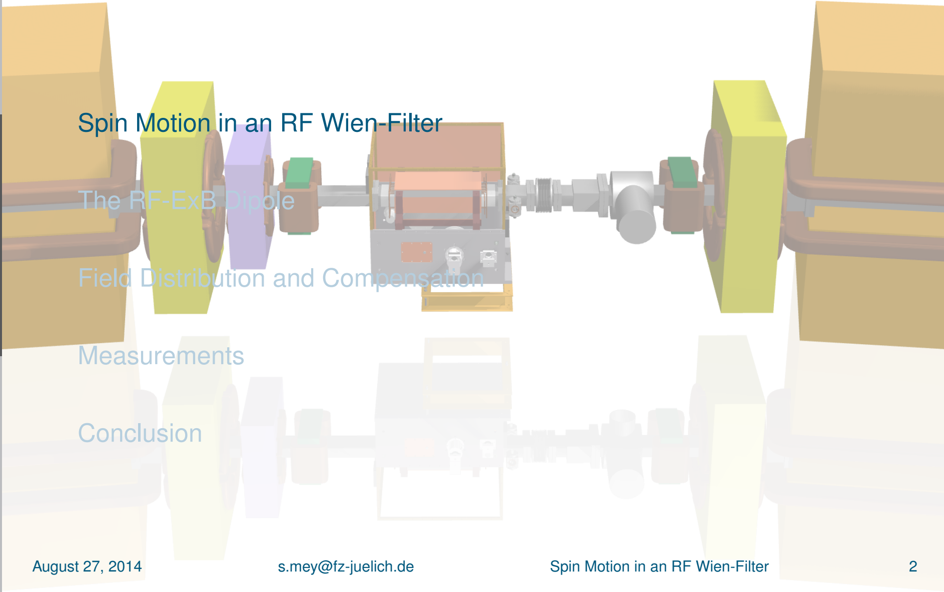
A Novel RF-ExB Spin Manipulator at COSY

August 27, 2014 | Sebastian Mey for the JEDI Collaboration | Forschungszentrum Jülich

Content

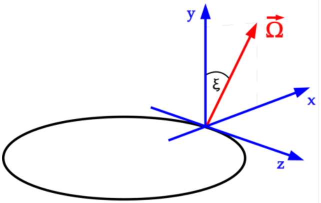


The Thomas-BMT Equation

$$\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \frac{e}{\gamma m}\,\vec{S} \times \vec{\Omega}$$

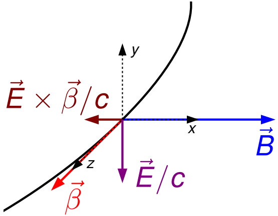
$$\vec{\Omega} = (1 + \gamma G)\vec{B}_{\perp} + (1 + G)\vec{B}_{\parallel} + \left(\frac{\gamma}{\gamma + 1} + \gamma G\right)\frac{\vec{E} \times \vec{\beta}}{c}$$

- spin precession of revolving, relativistic particles in the main dipoles' guiding field
- manipulation of the precession axis $\vec{\Omega}$ with RF fields oscillating resonantly on the spins' precession frequency



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: $\vec{F} = e\,(\vec{E} + c\vec{\beta} \times \vec{B}) \stackrel{!}{=} \vec{0}$



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

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

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

Spin-Resonance Strength of a RF Wien-Filter *

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

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

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

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

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

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

Resonance Condition

- spin tune given by γG

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

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

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

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

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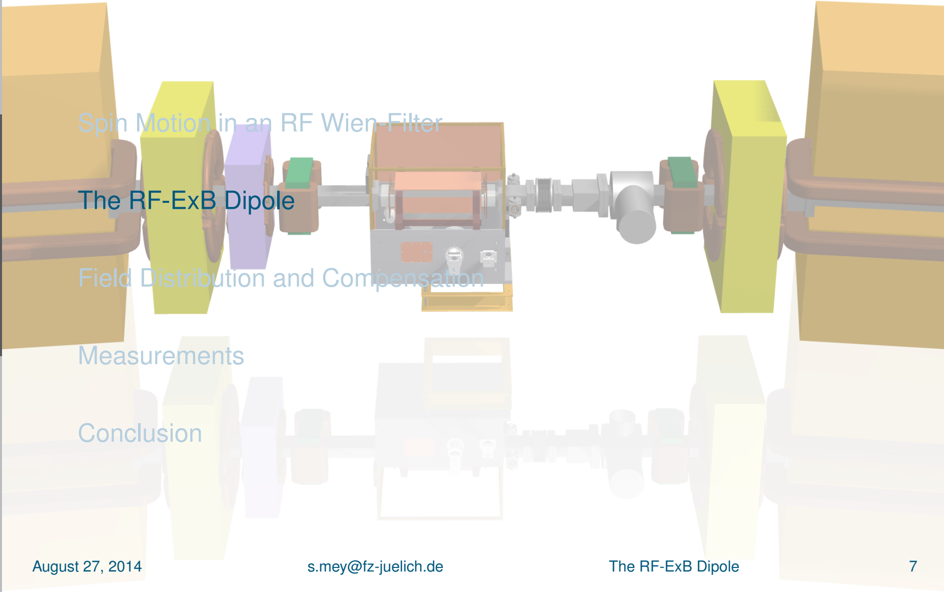

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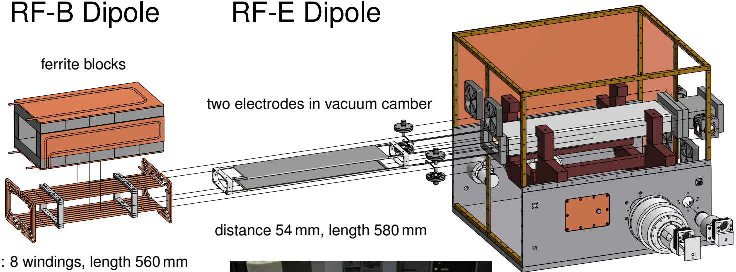
The RF-ExB Dipole

RF-B Dipole

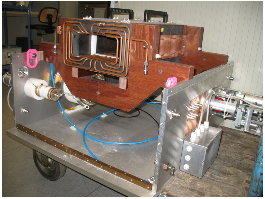
RF-E Dipole

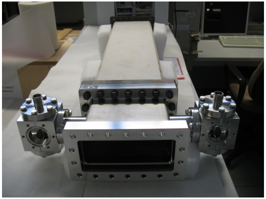
shielding Box



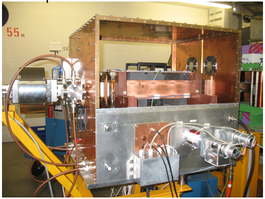
distance 54 mm, length 580 mm

coil: 8 windings, length 560 mm

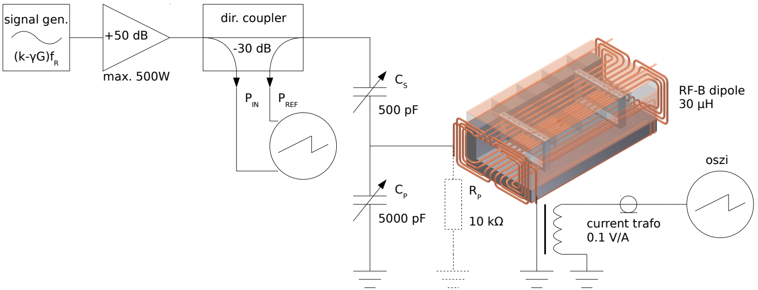




ceramic beam chamber
two separate resonance circuits

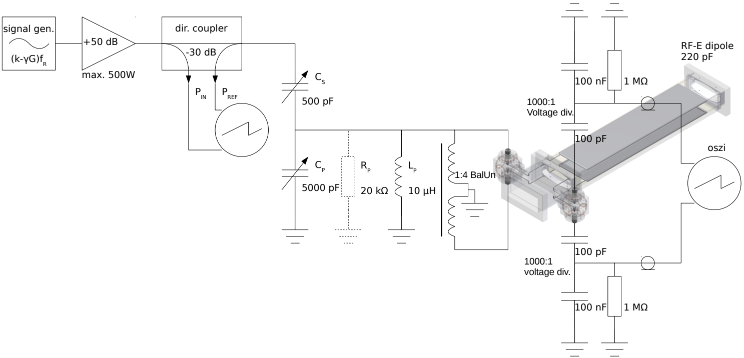


RF-B Circuit



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

RF-E Circuit



- $\hat{U}_{max} \approx 5\,kV$ limited by high-voltage feedthroughs
- frequency range 630 kHz - 1060 kHz
- electrode voltage directly available via capacitive voltage divider

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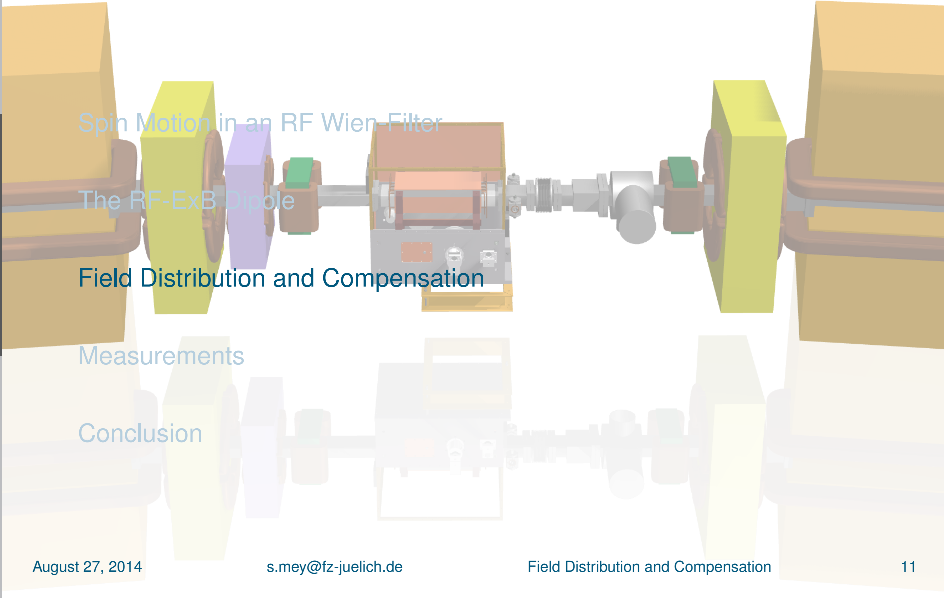


Spin Motion in an RF Wien-Filter

The RF-ExB Dipole

Field Distribution and Compensation

Measurements

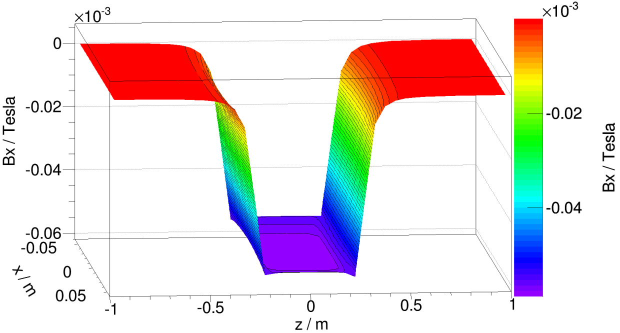
Conclusion

Magnetic Flux Density

$$\hat{I} = 1\,\mathrm{A}$$

$$\hat{B}_x = 0.058\,\mathrm{mT}$$

$$\int \hat{B}_x\,\mathrm{d}z = -0.035\,\mathrm{T\,mm}$$



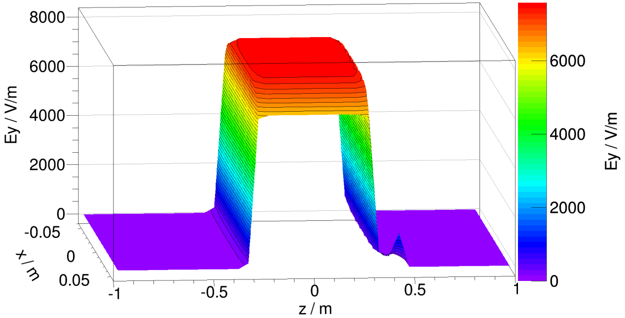
- distribution of radial component of magnetic flux density
- fields shown in central beam plane at $y = 0$

Electric Field

$$\hat{U} = 395\,\text{V}$$

$$\hat{E}_y = 7594\,\text{V/m}$$

$$\int \hat{E}_y\,\text{d}z = 4818\,\text{V}$$



- distribution of vertical component of electric field

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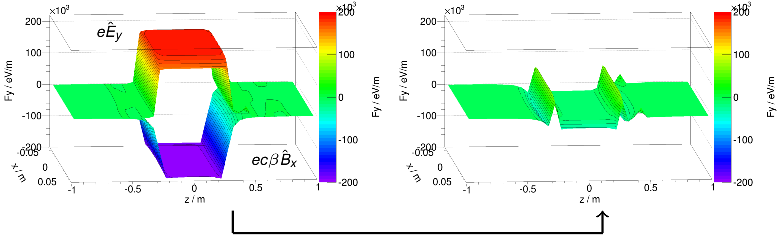
Lorentz Force

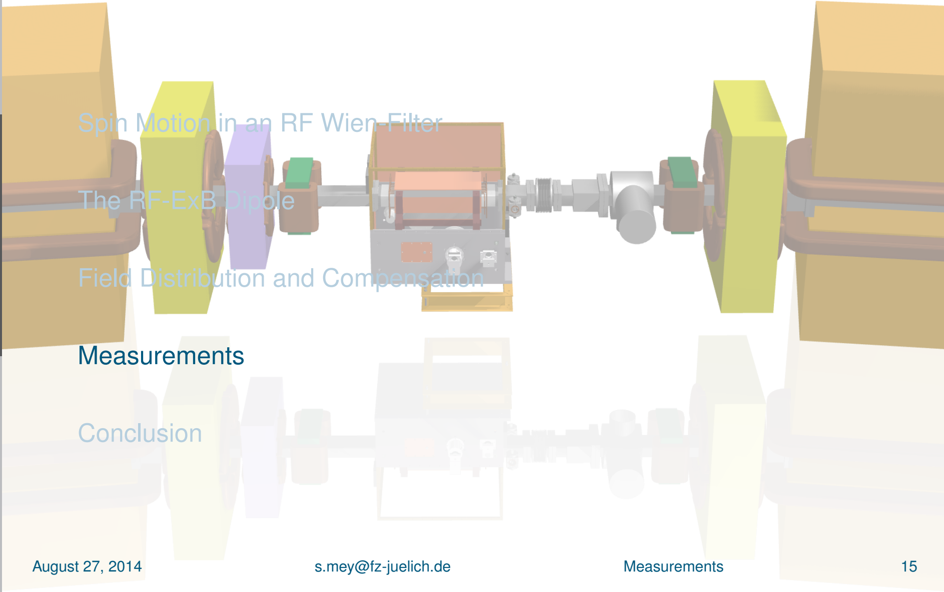


$$F_y = e\left(\hat{E}_y + c\beta\hat{B}_x\right)$$

- $\beta \equiv \beta_z = 0.459; \quad \hat{I} = 1\,\text{A}; \quad \hat{U} = 395\,\text{V}$
- optimization for integral compensation along beam path

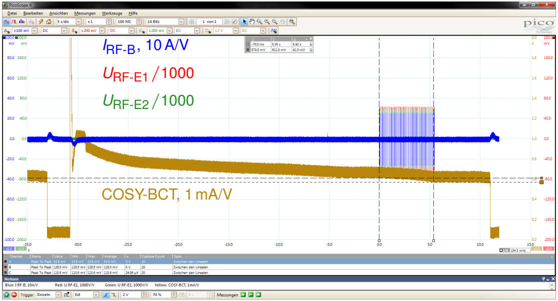
$$\int \hat{F}_y \, \mathrm{d}z = 0\,\text{eV/m}$$

Content



First Measurement of Field Compensation

$$f_{\text{RF-ExB}} = f_{\beta Y} = 1186\,\text{kHz}$$
$$\hat{I} = 0.27\,\text{A}$$
$$\hat{U}_1 = 129\,\text{V}$$
$$\hat{U}_2 = 116\,\text{V}$$



- measurement exactly on betatron frequency for max. sensitivity
- diagnosis with COSY beam current transformer
- pulsed mode of operation, 38 pulses, each 10 ms long
- compensation observed, minimum of 7 % beam-loss achieved
- fringe fields and transient time behaviour have to be further studied

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Measurement Proposal

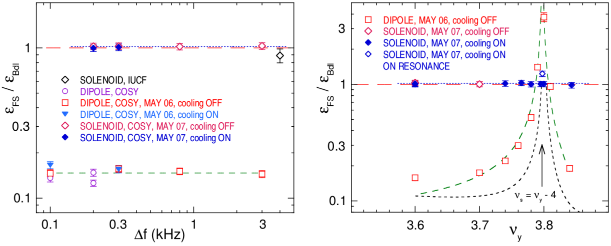
- resonance Strength of Wien-Filter:

$$\left|\epsilon_{B_\perp \mathrm{d}l}\right| = \frac{1+G}{4\pi\gamma}\frac{\int \hat{B}_x \,\mathrm{d}l}{B\rho}$$

- compare with measured one from Foissart-Stora scan:
  - vector polarization of spin-1 particle: $P_V = \frac{N_1 - N_{-1}}{N_1 + N_0 + N_{-1}}$
  - crossing resonance rotates spin axis, resulting polarization: $P_V^f = P_V^i \cos\vartheta$
  - $\frac{P_V^f}{P_V^i} = 2\exp\left(-\frac{(\pi\epsilon_{FS} f_c)^2}{\frac{\Delta f}{\Delta t}}\right) - 1$
- measurements of ratio $\frac{\epsilon_{FS}}{\epsilon_{B\mathrm{d}L}}$ should yield 1 if the RF Wien-Filter is perfectly matched since it doesn't introduce coherent beam oscillations

Measurement Proposal (cont.)

- measurements by Spin@COSY collaboration:
  - RF-solenoid: $\left|\epsilon_{B_{\|}\mathrm{d}l}\right| = \frac{1+G}{4\pi}\frac{\int \hat{B}_{\|}\,\mathrm{d}l}{B\rho}$
  - RF-dipole: $\left|\epsilon_{B_{\perp}\mathrm{d}l}\right| = \frac{1+\gamma G}{4\pi}\frac{\int \hat{B}_{\perp}\,\mathrm{d}l}{B\rho}$
    (doesn't take into account induced coherent betatron oscillations)



[M.A. Leonova et Al., arXiv:0901.2564 (2009)]

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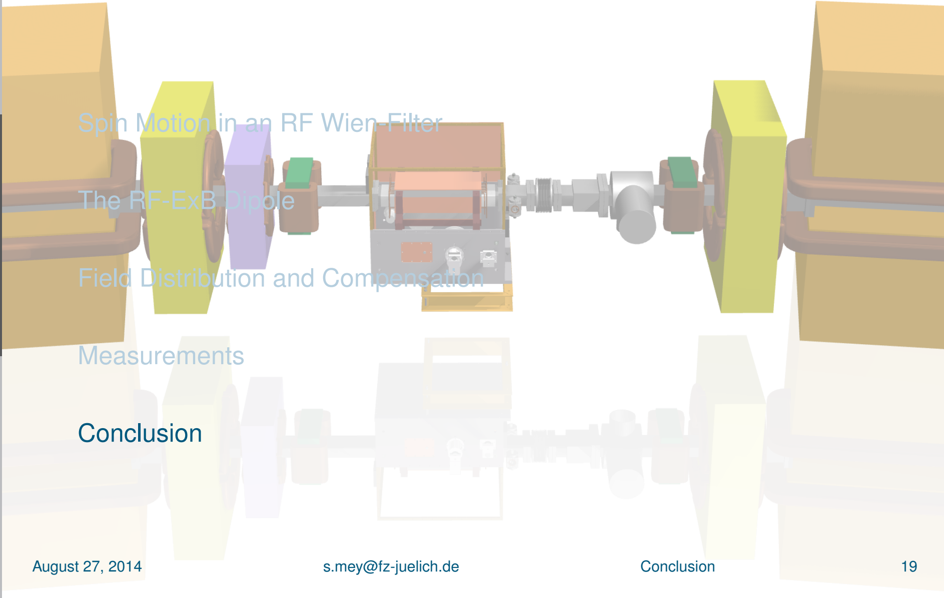


Conclusion

Hardware development

- RF dipole for spin manipulation with minimal beam disturbance has been successfully commissioned
- RF-B amplitude: $\int \hat{B}_x \, ds = 0.175\,\mathrm{T\,mm}$ @ $\hat{I}_{max} = 5\,\mathrm{A}$
- RF-E amplitude: $\int \hat{E}_y \, ds = 24\,\mathrm{kV}$ @ $\hat{U}_{max} = 1975\,\mathrm{V}$
- ± 1 spin harmonics at 629 kHz and 871 kHz available for studies

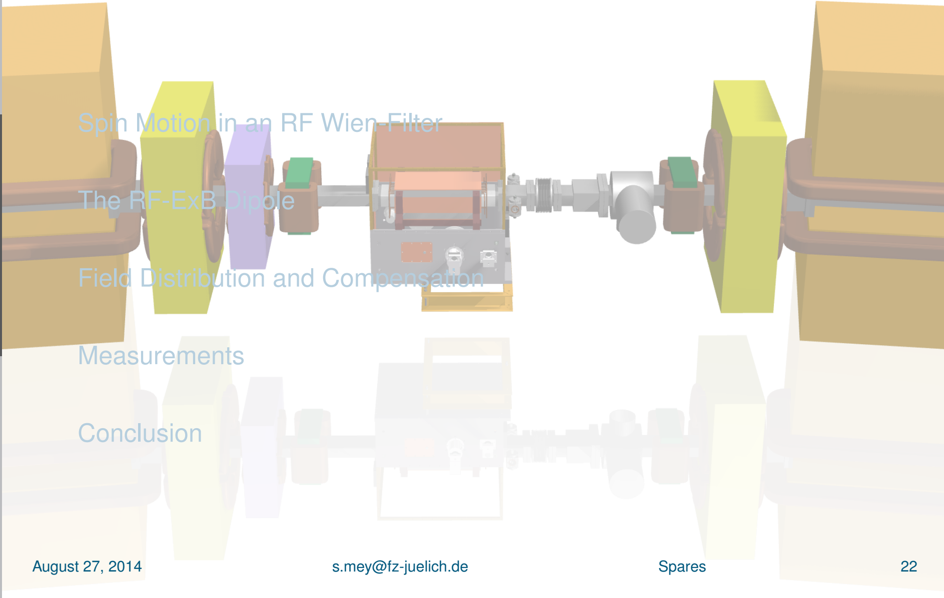
Measurements

- resonance strength measurements planned for August/ September 2014 in JEDI-beam-time with polarized d-beam

Thanks for Your Kind Attention!

In case of additional questions contact s.mey@fz-juelich.de

Content

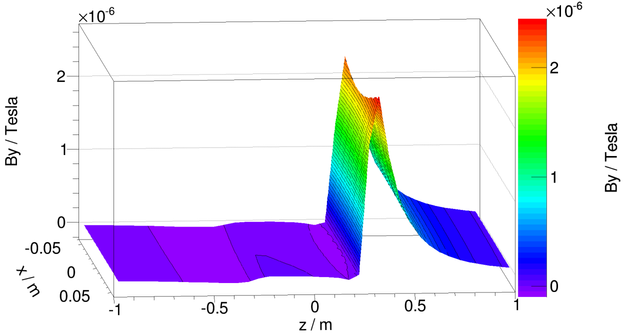


B_y

$$\hat{I} = 1\,\text{A}$$

$$\hat{B}_y \approx 10^{-3}\,\hat{B}_x$$

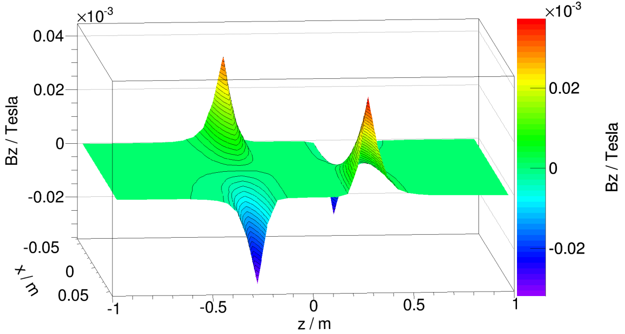
in central field region



- vertical component dominated by fields from leads to the coil

B_z

$\hat{I} = 1$ A



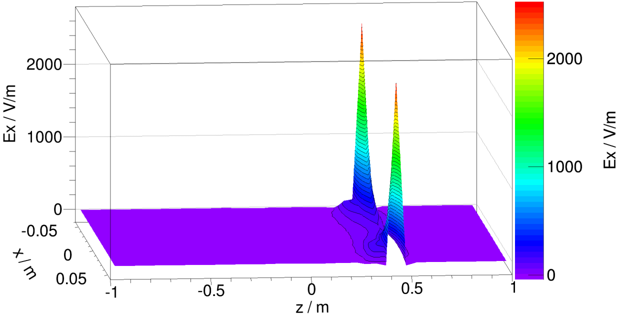
- longitudinal component dominated by fields from the coil going around the beam chamber

E_x

$\hat{U} = 395\,\text{V}$

$\hat{E}_x \approx 10^{-3}\,\hat{E}_Y$

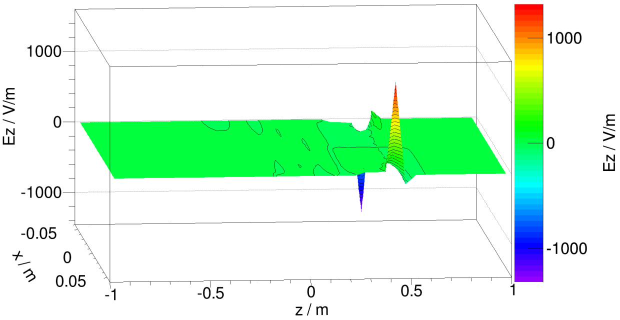
in central field region



- distribution of radial component of electric field dominated by fields from leads to the electrodes

E_z

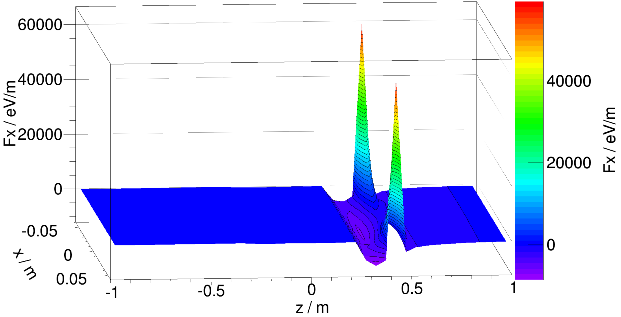
$\hat{U} = 395\,\mathrm{V}$



- distribution of longitudinal component of electric field dominated by fields from leads to the coil

F_x

$$\beta \equiv \beta_z = 0.459$$
$$\hat{I} = 1\,\text{A}$$
$$\hat{U} = 395\,\text{V}$$

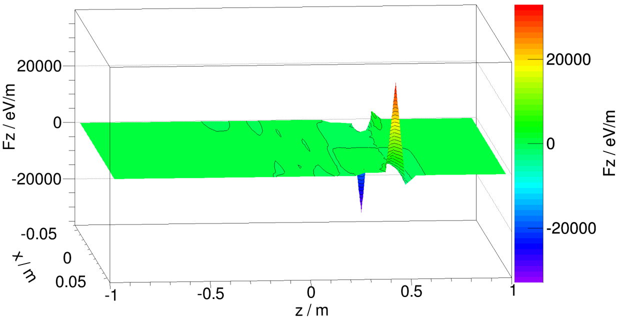


- $F_x = e\left(\hat{E}_x + c\beta\hat{B}_y\right)$

F_z

$\hat{I} = 1\,\text{A}$

$\hat{U} = 395\,\text{V}$

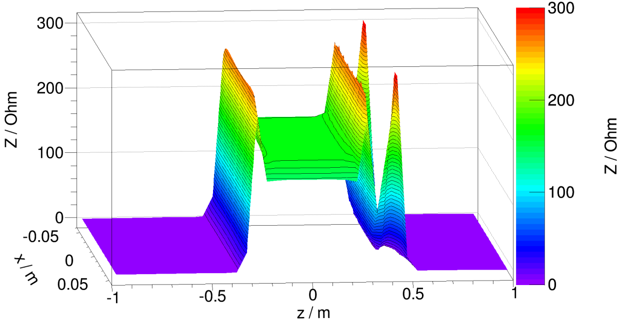


Wave Impedance

$$\hat{I} = 1\,\text{A}$$

$$\hat{U} = 395\,\text{V}$$

$$Z_{\text{theory}} = 173\,\Omega$$



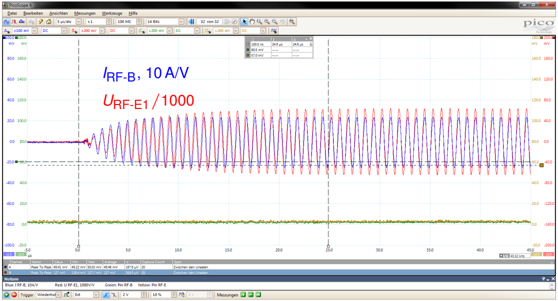
- $Z = \frac{\hat{E}_x}{\hat{H}_y} = -\frac{\hat{E}_y}{\hat{H}_x} = \beta_z Z_0$

Transient Time Behaviour

$\Delta t = 45\,\mu s$

$\hat{I} = 0.27\,A$

$\hat{U}_1 = 129\,V$



- Wien-Filter condition not fulfilled during first $\approx 15\,\mu s$ of each pulse
- complete transient time lasts $\approx 100\,ms$

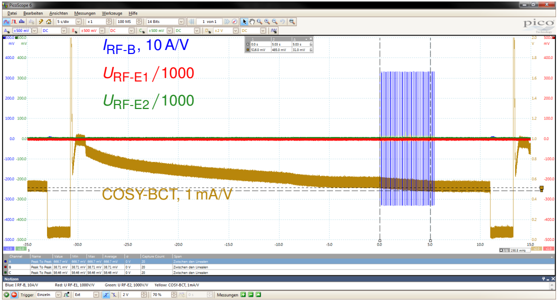
$\Rightarrow$ rework of resonance circuit required

$\Rightarrow$ ultimate precision needs feed forward control during activation cycle

Measurement at Spin Resonance Frequency

$f_{\text{RF-ExB}} = 871\,\text{kHz}$

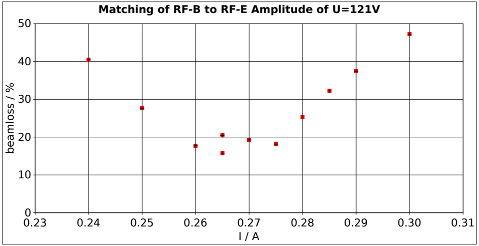
$\hat{I} = 3.38\,\text{A}$

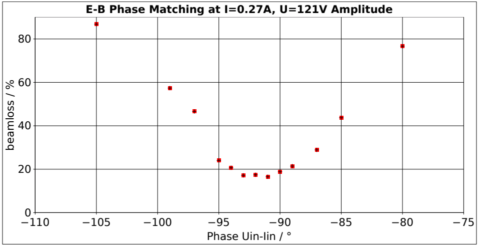


- $f_{-1} = f_{\text{rev}} |-1 + \gamma G|$
- relatively low current in RF-B-part already induces beamloss
- fields at $\hat{I} = 3.38\,\text{A}$: $\hat{B}_x = 0.2\,\text{mT}$; $\int \hat{B}_x\,dz = 0.12\,\text{T mm}$
- required power $\approx 120\,\text{W}$

First Systematic Measurements

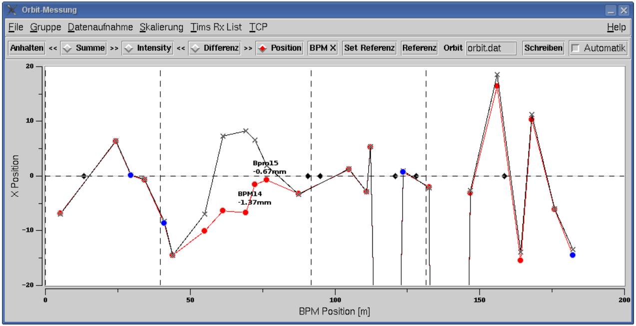
- set up well cooled beam
- orbit correction in the RF-dipole
- tune measurement
- fix one setting for the amplitude of RF-E-part
- vary amplitude and phase offset of RF-B-part to reach minimum beam loss





Orbit Corrections

$$\Delta x = 0.7\,\text{mm}$$
$$\Delta x' = 0.06\,\text{mrad}$$

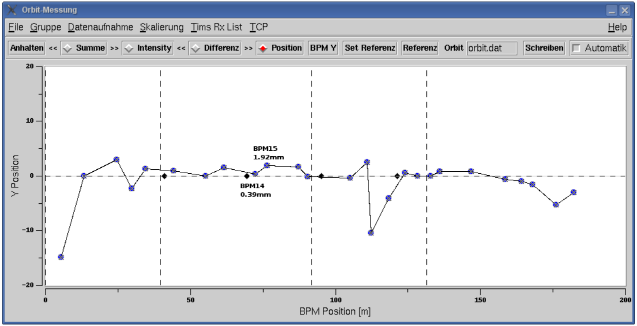


- corrected orbit with closed bump at RF-Dipole
- BPM 14 and 15 at Dipole before and after RF-ExB
- distance $\Delta z = 4.2\,\text{m}$

Orbit Corrections

$\Delta y = 1.53\,\text{mm}$

$\Delta y' = 0.13\,\text{mrad}$



- corrected orbit with closed bump at RF-Dipole
- BPM 14 and 15 at Dipole before and after RF-ExB
- distance $\Delta z = 4.2\,\text{m}$