JÜLICH
FORSCHUNGSZENTRUM

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

Content

Spin Motion in a Magnetic Storage Ring

- Thomas-BMT Equation: $\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \vec{S} \times (\vec{\Omega}_{\mathrm{MDM}} + \vec{\Omega}_{\mathrm{EDM}})$

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

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

- Standard Model: $\vec{d} = \eta \frac{q\hbar}{2mc}\vec{S} \approx 10^{-32}\,\mathrm{ecm} \;\Leftrightarrow\; \eta \approx 10^{-16}$

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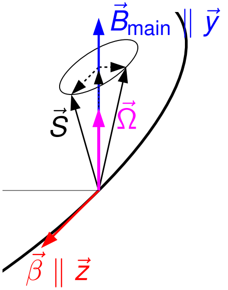
- spin precession around main dipole's guiding field
- spin tune $\nu_S = \gamma G$

! vertical polarization component S_y is constant



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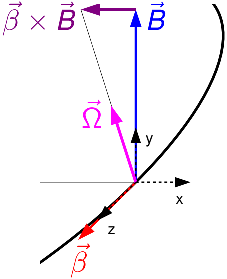
- motional electric field pointing to the ring's center

$\Rightarrow$ 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

$\Rightarrow$ 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

! minimize beam disturbances by RF field

$\Rightarrow$ utilize Wien-Filter configuration*

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

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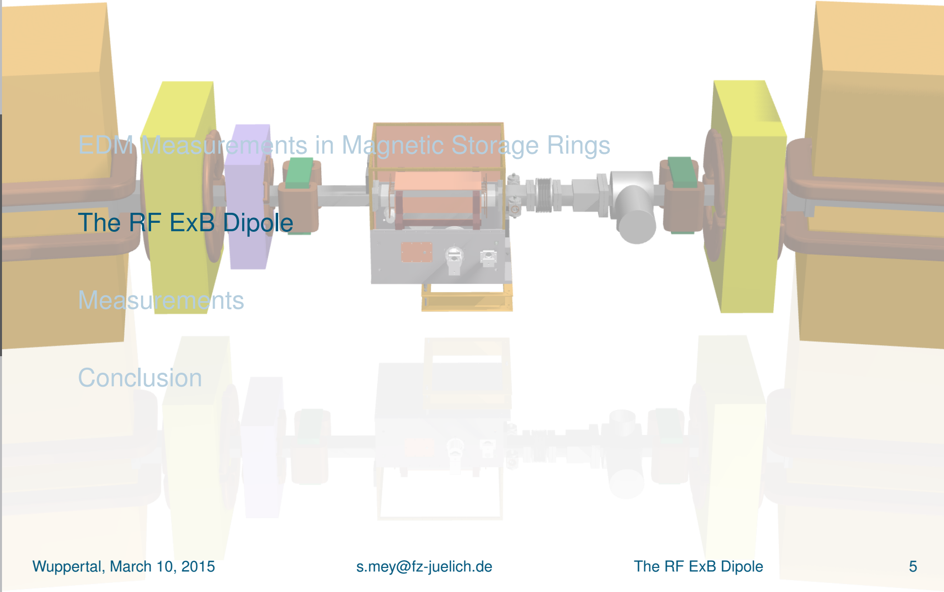


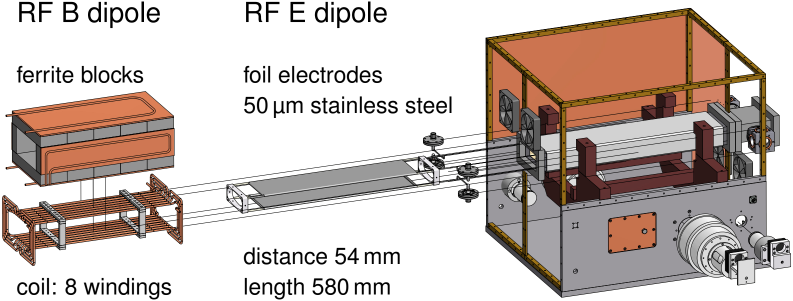
EDM Measurements in Magnetic Storage Rings

The RF ExB Dipole

Measurements

Conclusion

The RF ExB Dipole in Wien-Filter Configuration



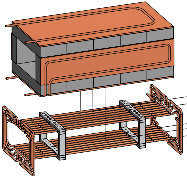
Parameters	**RF B dipole**
P_{RMS} / W	90
$\hat{I}$ / A	5
$\int \hat{B}_x \, \mathrm{d}l$ / Tmm	0.175
f_{RF} range / kHz	629 - 1170

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

The RF ExB Dipole in Wien-Filter Configuration

RF B dipole

ferrite blocks

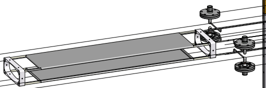


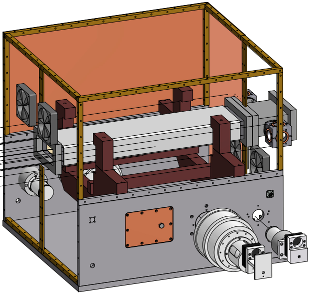
coil: 8 windings

RF E dipole

foil electrodes

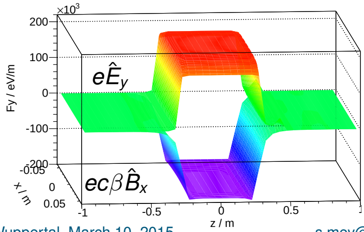
50 µm stainless steel



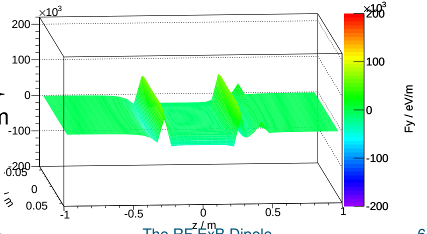


distance 54 mm

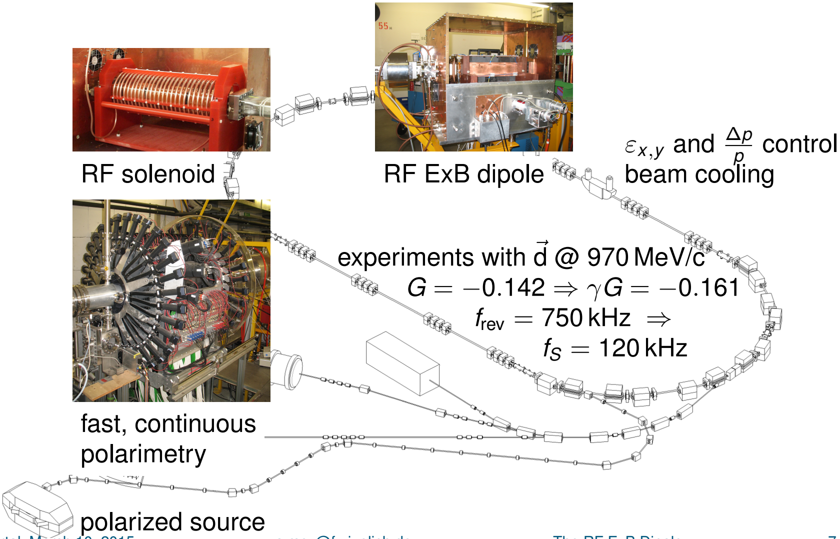
length 580 mm



$$\int \hat{F}_y \, dz \xrightarrow{} \stackrel{!}{=} 0\,\mathrm{eV/m}$$



COSY as Spin Physics R&D Facility



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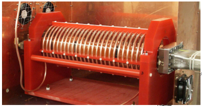
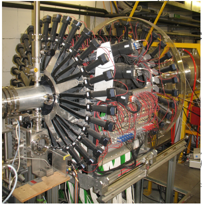


RF solenoid

RF ExB dipole

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



fast, continuous
polarimetry

polarized source

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

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

$f_{\text{rev}} = 750\,\text{kHz} \Rightarrow$

$f_S = 120\,\text{kHz}$

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

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

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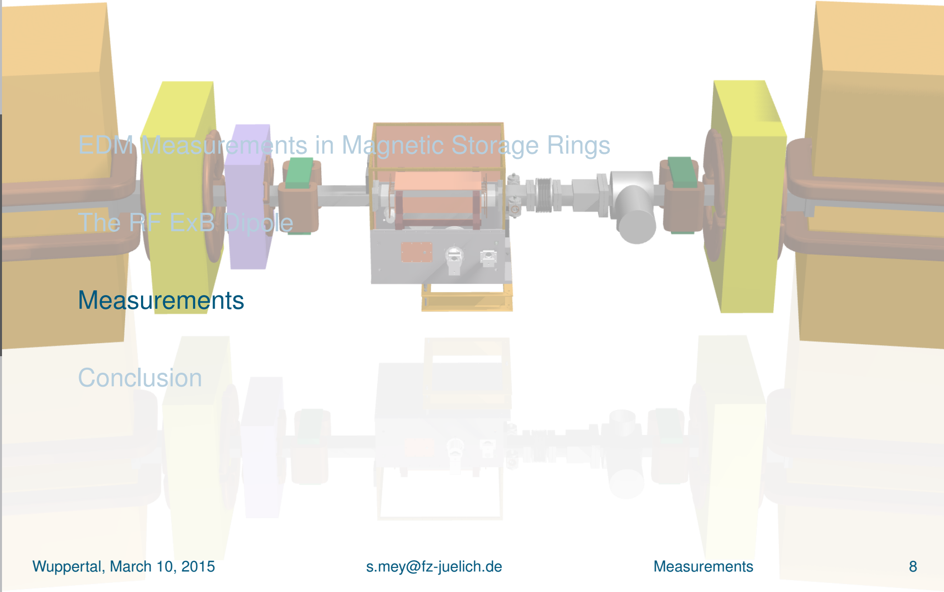
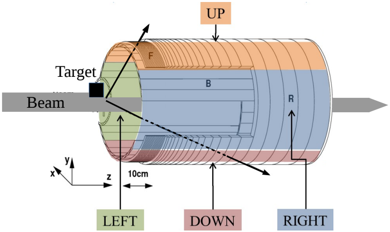


Vertical Polarization Measurements

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



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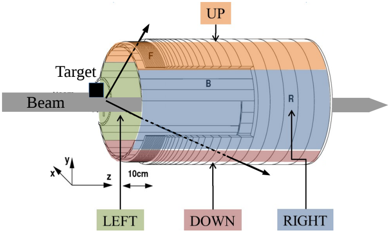
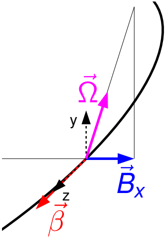
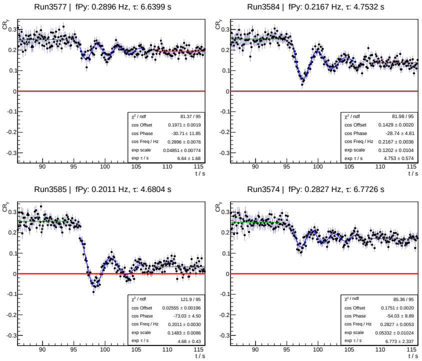
- RF ExB dipole: localized radial magnetic field $\Rightarrow$ tilt of $\vec{\Omega}$
- RF field in phase with spin precession $\Rightarrow$ accumulation of spin kicks
- continuous rotation of $\vec{P}$ $\Rightarrow$ oscillation of P_y

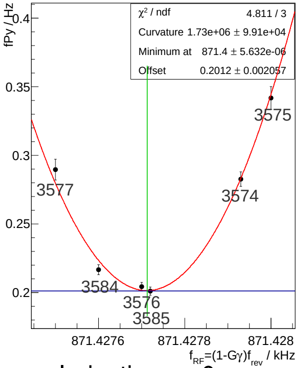




Measurement Resonance Strength



$fPy_{min} = 0.2012$ Hz at $f_{RF} = 871.427713$ kHz

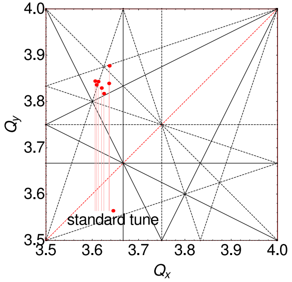


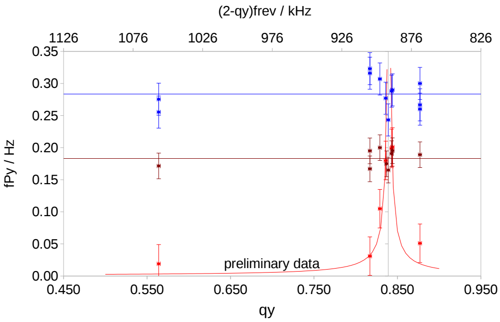
- total spin flip only on resonance $\Rightarrow$ average polarization $\rightarrow$ 0
- minimum of vertical polarization oscillation frequency

! measurement of resonance strength $\varepsilon = \frac{f_{P_{y\,min}}}{f_{rev}}$

Determination of Lorentz Force Compensation

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





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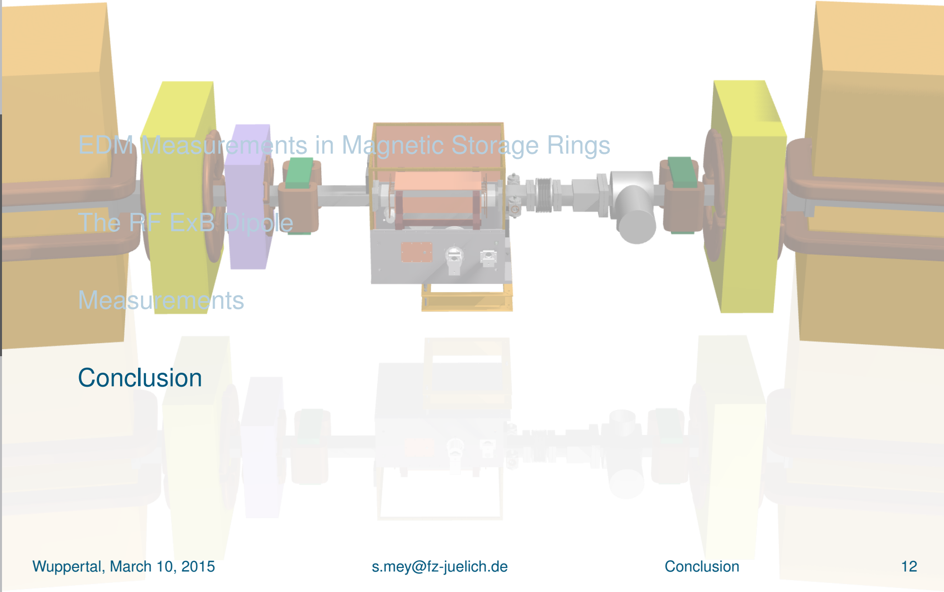

Conclusion

- 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

$\Rightarrow$ systematic studies for disentangeling 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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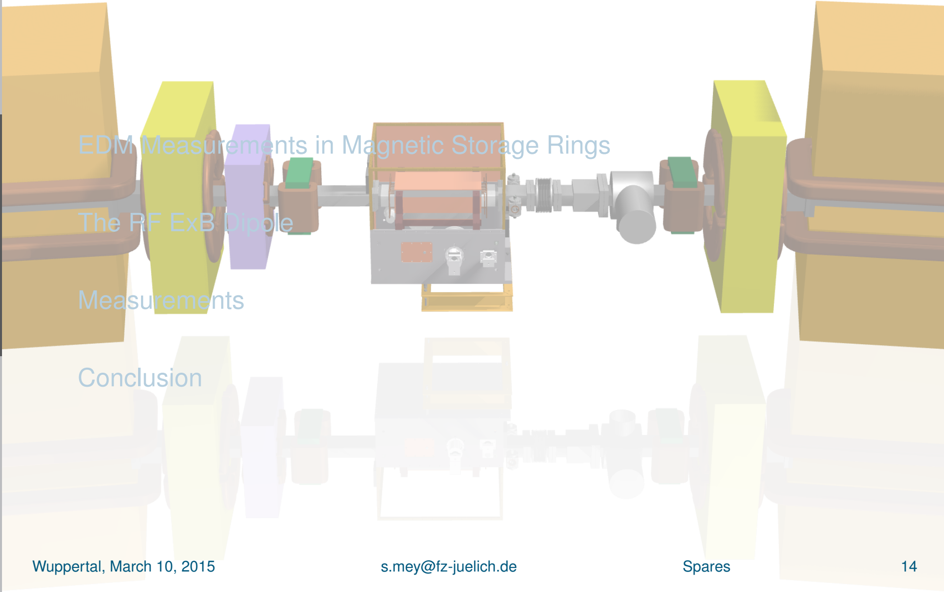


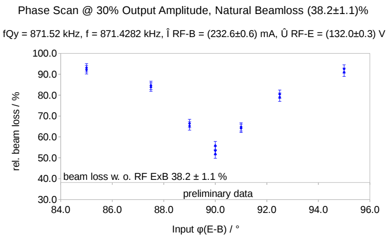
RF ExB Setup for Field Compensation

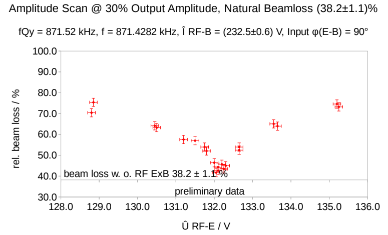
- move betatron sideband onto RF frequency for max. sensitivity
- polarimeter target directly above beam limits acceptance

⇒ exited part of beam is removed

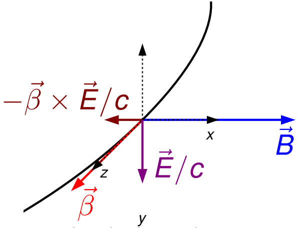
⇒ diagnosis with COSY beam current transformer

- determination of amplitudes and phase corresponding to Lorentz force compensation down to per mille!





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

  $\Rightarrow \; \vec{E}/c = -\vec{\beta} \times \vec{B}$
- from Thomas-BMT Equation:
  - $$\vec{\Omega} = (1+\gamma G)\vec{B} + \cancelto{0}{(1+G)\vec{B}_{\parallel}} - \left(\frac{\gamma}{\gamma+1} + \gamma G\right) \overbrace{\vec{\beta} \times \vec{E}/c}^{=\vec{\beta}\times(\vec{\beta}\times\vec{B})=\beta^2\vec{B}}$$

    $$= \left(1 - \frac{\beta^2\gamma}{\gamma+1} + (1-\beta^2)\gamma G\right)\vec{B} = \frac{1+G}{\gamma}\vec{B}$$
  - particles sample localized RF field once each turn at orbit angle θ

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

Resonance Strength of an RF Wien-Filter

- intrinsic resonance strength given by spin rotation by turn, calculate Fourier integral over driving fields along orbit*:

$$\begin{aligned}\epsilon_K = \frac{f_{\mathrm{spin}}}{f_{\mathrm{rev}}} &= \frac{1+G}{2\pi\gamma}\oint \frac{b(\theta)}{B\rho} e^{iK\theta}\,\mathrm{d}\theta \\ &= \frac{1+G}{2\pi\gamma}\frac{\int \hat{B}\,\mathrm{d}z}{B\rho}\sum_{n=-\infty}^{\infty}\cos\left(2\pi n\frac{f_{\mathrm{RF}}}{f_{\mathrm{rev}}}+\phi\right)e^{i2\pi Kn} \\ &= \frac{1+G}{2\cdot 2\pi\gamma}\frac{\int \hat{B}\,\mathrm{d}z}{B\rho}\sum_n e^{\pm i\phi}\delta\left(n-K\mp\frac{f_{\mathrm{RF}}}{f_{\mathrm{rev}}}\right)\end{aligned}$$

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

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