TOWARDS AN RF WIEN-FILTER FOR EDM EXPERIMENTS AT COSY

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Abstract

The JEDI Collaboration (**J**ülich **E**lectric **D**ipole Moment **I**nvestigations) is developing tools for the measurement of permanent **E**lectric **D**ipole **M**oments (EDMs) of charged, light hadrons in storage rings. The Standard Model predicts unobservably small values for the EDM. In contrast, a non-vanishing EDM could be detected by measuring an induced tiny build-up of vertical polarization in a beforehand horizontally polarized beam. This technique requires a spin tune modulation by an RF Dipole without any excitation the beam itself.

In the course of 2014, a prototype RF ExB-Dipole has been successfully commissioned and tested. The force of a radial magnetic field is canceled out by a vertical electric one. In this configuration, the dipole fields form a *Wien*-Filter that directly rotates the particles' polarization vector. We verified that the device can be used to continuously flip the vertical polarization of a 970 MeV/c deuteron beam without exciting any coherent beam oscillations. For a first EDM Experiment, the RF ExB-Dipole in *Wien*-Filter Mode is going to be rotated by 90° around the beam axis and will be used for systematic investigations of sources for false EDM signals.

MOTIVATION

The motion of a relativistic particle's spin in an electromagnetic storage ring ($\vec{\beta}\cdot\vec{B} = \vec{\beta}\cdot\vec{E} = 0$) with non vanishing EDM contributions is given by the generalized *Thomas-BMT* Equation, $\mathrm{d}\vec{S}/\mathrm{d}t = \vec{S}\times(\vec{\Omega}_{\mathrm{MDM}} + \vec{\Omega}_{\mathrm{EDM}})$ [1, 2], with

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

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

Here, the anomalous magnetic moment G is given by the particle's **M**agnetic **D**ipole **M**oment (MDM), $\vec{\mu} = 2(G+1)\frac{q\hbar}{2m}\vec{S}$. This corresponds to $G = -0.142$ for deuterons. As an analogue, the dimensionless factor η describes the strength of the particle's permanent EDM relative to its MDM. For a Standard Model prediction of $d = \eta\frac{q\hbar}{2mc}\vec{S} \approx 10^{-32}$ ecm its value is $\eta \approx 10^{-16}$.

In a purely magnetic storage ring, all the terms containing electric fields in Eq. 1 vanish and the EDM contribution due to the interaction with the motional electric field ($\vec{\beta}\times\vec{B}$) will lead to a tiny tilt of the spin's precession axis. This leads to a very slow oscillation of the vertical polarization, but for $\eta \approx 10^{-16}$ its contribution is far below measurable. Adding an RF *Wien*-Filter with vertical magnetic field orientation to the ring's lattice yields a modulation of the horizontal spin precession by means of a phase kick without disturbing the beam dynamics. Together with the EDM's interaction with the motional electric field in the rest of the ring, the frequency modulation can lead to a continuous buildup of vertical polarization in a horizontally polarized beam [3].

SETUP OF THE PROTOTYPE

While the above described approach could provide a measurable EDM signal, it doesn't provide an observable to characterize the RF *Wien*-Filter itself. Therefore, a first prototype with a radial magnetic field ($\vec{B} = (B_x, 0, 0)^T$) compensated by a vertical electric field ($\vec{E} = (0, E_y, 0)^T$) has been commissioned. Here, the magnetic field directly manipulates the vertical beam polarization. Expressing the electric field in Eq. 1 in terms of the magnetic field leads to a simple formula for the spin precession in an ideal *Wien*-Filter [4]:

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

The particles sample the localized RF fields once every turn. Their contribution may be approximated by the integrated field along the particles' path assigned to a point-like device at an orbital angle θ:

$$b(\theta) = \int \hat{B}_x\,\mathrm{d}l\,\cos(f_{\mathrm{RF}}/f_{\mathrm{rev}}\,\theta + \phi)\sum_{n=-\infty}^{\infty}\delta(\theta - 2\pi n). \quad (3)$$

The resonance strength $|\varepsilon_K|$ of such a device is given by the amount of spin rotation per turn and can be calculated by the *Fourier* integral over one turn in the accelerator [6, 7]:

$$\begin{aligned}|\varepsilon_K| &= \frac{f_{\mathrm{spin}}}{f_{\mathrm{rev}}} = \frac{1+G}{2\pi\gamma}\oint\frac{b(\theta)}{B\rho}e^{iK\theta}\,\mathrm{d}\theta \\ &= \frac{1+G}{4\pi\gamma}\frac{\int\hat{B}_x\,\mathrm{d}l}{B\rho}\sum_n e^{\pm i\phi}\delta(n - K \mp f_{\mathrm{RF}}/f_{\mathrm{rev}}). \quad (4)\end{aligned}$$

An artificial spin resonance occurs at all side-bands with a frequency corresponding to the spin tune:

$$K \stackrel{!}{=} \gamma G = n \pm f_{\mathrm{RF}}/f_{\mathrm{rev}} \;\Leftrightarrow\; f_{\mathrm{RF}} = f_{\mathrm{rev}}|n - \gamma G|;\; n\in\mathbb{Z}. \quad (5)$$

In the scope of the current JEDI experiments, deuterons with a momentum of 970 MeV/c are stored at COSY [5]. In this case, $\gamma = 1.126$ and the resulting spin tune is $\gamma G = -0.1609$.

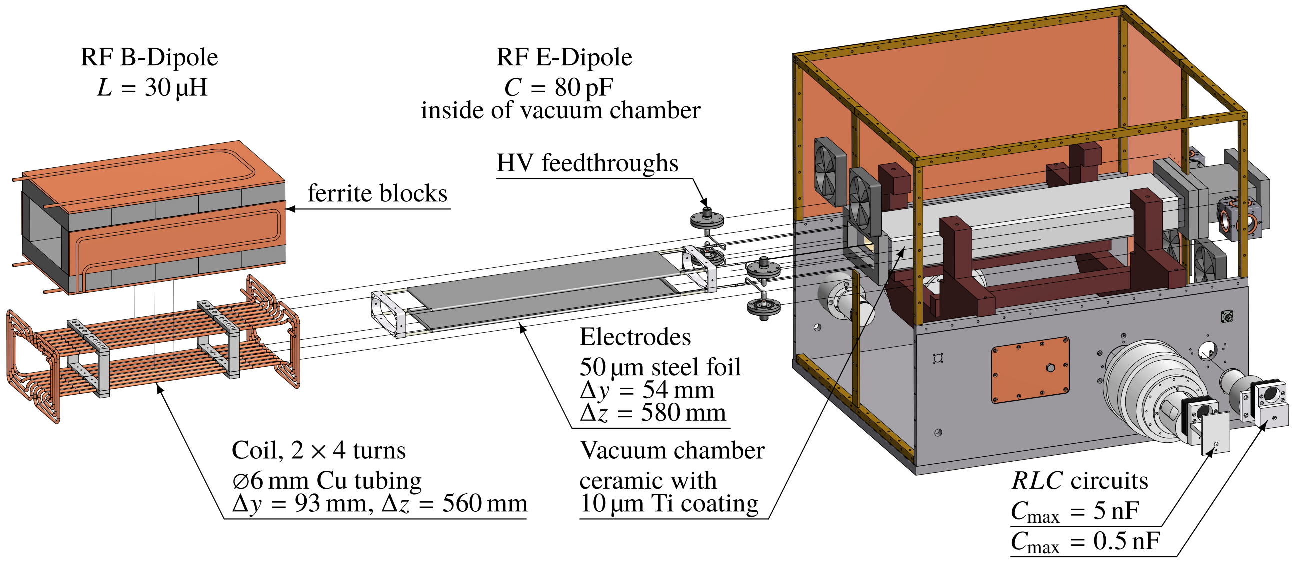

Figure 1: An explosion drawing showing the main components of the RF ExB-Dipole.

The fundamental mode is located at f_{RF} = 121 kHz with $n = \pm 1$ harmonics at 629 kHz and 871 kHz.

The magnetic RF Dipole has been realized in the form of coil wound lengthwise around a ceramic part of the beam-pipe. It is driven by means of a parallel resonance circuit with a quality factor of $Q \approx 20$. A similar but separate resonance circuit drives the electric RF Dipole. The electric field is generated by the potential difference between two stainless steel electrodes inside the vacuum chamber spanned over glass rods held by a frame inside the flanges of the ceramic beam-chamber. For details see Fig.1.

Without any additional control loops and further dedicated cooling systems it is possible to run the system up to 90 W input power in continuous, long term operation. The corresponding operating parameters have been collected in Table 1.

Table 1: The RF ExB-Dipole at 90 W input power.

Parameter	RF B-Dipole	RF E-Dipole
$\hat{U}$		2 kV
$\int \hat{E}_y \, dl$		24.1 kV
$\hat{I}$	5 A	
$\int \hat{B}_x \, dl$	0.175 T mm	
f_{RF} range	630 kHz - 1170 kHz	630 kHz - 1060 kHz

Fig. 2 shows the distribution of the main component of the *Lorentz*-Force. Due to different drop-off rates of the electric and magnetic field, particles will encounter a down-up kick at the entrance and a corresponding up-down kick at the exit of the *Wien*-Filter, but the geometry has been optimized insofar that for particles entering the system on axis, the integrated *Lorentz*-Force along the beam path is set to zero.

MEASUREMENTS

To achieve *Lorentz*-Force cancellation, the phase as well as the amplitudes of the E and B fields have to be adjusted. The accelerator's optics were modified so that a vertical betatron sideband was shifted exactly to the RF ExB-Dipole frequency at 871.5 kHz to achieve maximum sensitivity to induced beam oscillations. Next, the acceptance was limited by installing a massive carbon block directly above the beam as target for the polarimeter. The beam current monitor of COSY could thus be used as a precise tool for the matching of the RF *Wien*-Filter. With a well cooled beam, a sensitivity to amplitude and phase changes in the per mill regime has been achieved.

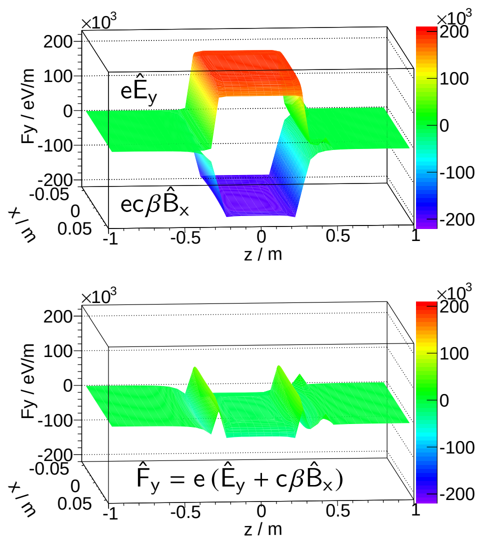

Figure 2: Simulation of the *Lorentz*-Force on a particle entering the RF ExB-Dipole on axis across a horizontal cut through the center of the beam pipe. The results have been normalized to a coil current amplitude of $\hat{I} = 1A$.

For polarimetry runs, the deuteron beam is slowly moved onto the carbon target providing a stable event rate in the four quadrant polarimeter detector [8]. Beam polarization manifests in the angular distribution of $^{12}\mathrm{C}(\vec{\mathrm{d}},\mathrm{d})$ scattering. In case of a vertical polarized beam, it leads to an asymmetry in the event rates of the left and right quadrants of the polarimeter detector.

The RF ExB-Dipole was operated continuously for 40 s per fill. Spin-kicks of the RF system in every turn lead to an adiabatic rotation of the polarization vector, corresponding to an oscillation of its vertical component, in turn represented by the left-right cross-ratio CR_{LR} of the detector asymmetry in Fig. 3.

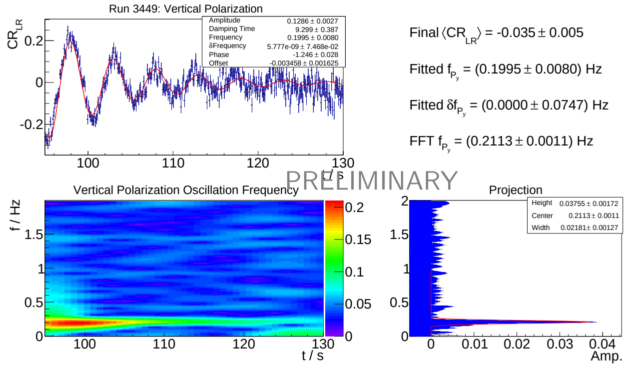

Figure 3: The top panel shows the driven oscillation of the vertical polarization component in case of excitation close to the spin resonance. The bottom panels show the frequency content of the signal determined by FFT analysis, resolved over time to detect fluctuations on the left and integrally over the whole run on the right.

A complete spin flip occurs only if the RF device is operated exactly on the spin resonance frequency, otherwise the excitation will slip beneath the precessing spin, accompanied by an increase in polarization oscillation frequency. This allows the determination of the spin resonance frequency down to ≈ 0.01 Hz with a series of runs like the one depicted in Fig. 3, scanning the tip of the resonance curve. It also constitutes a measurement of the strength of the RF induced resonance, since the frequency of the driven polarization oscillation on resonance is directly proportional to its strength (see Eq. 4).

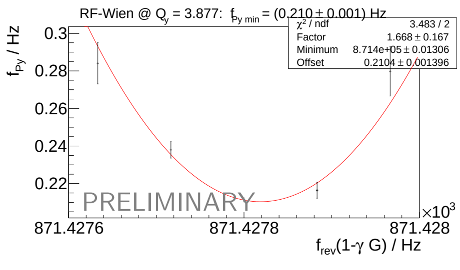

Figure 4: Polarization oscillation frequencies from a series of runs with varying excitation frequencies. The points form the tip of the spin resonance curve.

A series of such resonance scans have been taken during the September 2014 JEDI beam time at COSY. Once the *Wien*-Filter was matched at exactly coinciding betatron and spin resonance side bands, the optics of the accelerator was varied in small steps toward different betatron frequencies. At each tune value similar scans were performed with an already installed RF Solenoid, the RF ExB-Dipole in *Wien*-Filter mode and the RF ExB-Dipole operated without compensating electric field as a pure magnetic RF Dipole.

Fig. 5 shows that the RF Solenoid as well as the matched *Wien*-Filter don't excite any coherent betatron oscillations. As the simple derivation of Eq. 4 suggests, the resonance strength is indeed independent of the vertical betatron tune. In contrast, the resonance strength of the pure magnetic RF dipole is dominated by the interference between the driven spin motion and the one induced by coherent beam oscillations.

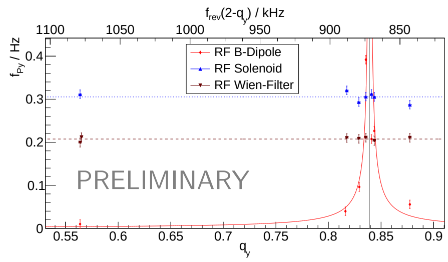

Figure 5: Results of the resonance scans at the nominal tune of COSY at $Q_y = 3.56$ and for a set of vertical betatron tunes with sideband frequencies around the spin resonance, depicted by the vertical line at 871 428.00 Hz.

CONCLUSION

In preparation for future EDM experiments in storage rings, a first prototype of an RF Wien-Filter has been commissioned at COSY. We have shown that this device fulfills the expectation of generating a configuration of RF dipole fields for spin manipulation without any excitation of coherent beam oscillations.

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