Design of the electrical circuit of the new RF Wien Filter at COSY-Jülich

J. Slim[1], R. Gebel[2], D. Heberling[1,3], A. Nass[2], F. Rathmann[2], H. Soltner[4] and R. Stassen[2]
(on behalf of the JEDI collaboration)*

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The JEDI (Jülich Electric Dipole Investigations) Collaboration aims at measuring the electric dipole moments (EDMs) of charged particles (deuterons and protons) at the COoler SYnchrotron (COSY) with Jülich. To make this possible, a high-precision (up to the level of 10^{-5} to 10^{-6}) novel waveguide RF Wien filter will be integrated in COSY to modulate the spin of deuterons and protons. With a Wien filter, the force of the radial electric field is canceled by the vertical magnetic force which permits to directly manipulate the polarization vector of the particles without introducing any beam oscillations. The RF Wien filter is expected to introduce vertical spin polarization (S_y) in a horizontally polarized beam. This RF Wien filter is designed to operate at harmonics of the spin precession frequency ranging from 0.1 to 2 MHz. The working principle is based on the Transverse Electromagnetic (TEM) mode of a parallel-plates waveguide structure that is able to meet the Wien filter condition while being able to generate high-quality electromagnetic fields.

This paper reports on a specific aspect of the RF Wien filter design, *i.e.* the driving circuit. The basic concept of the variable resistor is explained and validated with field simulations.

I. Introduction

The spin $\vec{S}$ dynamics in an electromagnetic ($\vec{E}$ and $\vec{B}$) storage ring with non-vanishing electric dipole moment (EDM) is described by the generalized T-BMT equation [1, 2]. Neglecting the longitudinal field contributions, the T-BMT equation reads:

$$\frac{d\vec{S}}{dt} = \vec{S} \times \left(\Omega_{\text{EDM}} + \Omega_{\text{MDM}}\right), \text{with},$$

$$\Omega_{\text{EDM}} = -\frac{q}{m}\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B}\right)$$

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

Ω is the angular velocity of the spin precession, $\vec{\beta}$ is the Lorentz-β, G describes the anomalous magnetic moment ($G = -0.143$ for deuterons [3]). η is a dimensionless factor that describes the strength of the particles' permanent EDM relative to their magnetic dipole moment (MDM), t is the time in the laboratory system, q is the elementary charge, m is the relativistic mass of the particle and γ is the relativistic Lorentz factor.

In an ideal EDM measurement, an all-electric ring should be used without magnetic components. Nevertheless, before establishing such a dedicated ring the JEDI collaboration aims at using the existing magnetic COSY ring for EDM measurements with the installation of a new device called the RF Wien filter. Unlike the classical DC Wien filter, the designed device operates at RF frequencies ranging from 128 kHz to 1.6 MHz (some harmonics of the spin precession frequencies).

II. Waveguide RF Wien filter

The transverse electromagnetic (TEM) is a special case of the TM (transverse magnetic) mode, that is able to propagate in two-conductors systems such as the parallel-plates waveguide [3]. The generated field configuration is characterized by a radial electric field $\vec{E} = (E_x, 0, 0)$ and a vertical magnetic field (flux density) $\vec{B} = (0, B_y, 0)$ with no field components in the direction of propagation.

An attractive feature of the waveguide RF Wien filter [4] is that the matching between the electric and magnetic fields is fulfilled *by design*. This is in contrast to all the existing (DC) Wien filters and also to the prototype RF Wien filter recently operated in COSY [5]. For a waveguide to operate under the Wien filter conditions, the field pattern must fulfill the TEM field pattern.

An important quantity is the so-called field quotient denoted as Z_q. This concept is similar to the notion of field impedance but with a main difference; the field quotient is defined as the ratio of the total electric fields and the total magnetic fields. The word "total" means that the forward and reverse (the reflected) propagating fields are considered. In order to operate the waveguide as a Wien filter, the field quotient must be set to a particular value; for instance, in the case of deuterons, the field quotient must be 173 Ω (see [4] for more details). To control this value in real-time, the total fields in the device must be managed. The forward propagating field is related to the geometrical properties of the parallel-plates waveguide, whereas, the reflected field can be manipulated by

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* [1] Institute of High-Frequency Technology, Rheinisch-Westfälische Technische Hochschule Aachen, 52074 Aachen, Germany.
[2] Institute of Nuclear Physics (IKP), Forschungs-zentrum Jülich GmbH, 52428 Jülich, Germany.
[3] JARA-FAME (Forces and Matter Experiments), Forschungszentrum Jülich and RWTH Aachen University, 52056 Aachen, Germany.
[4] Central Institute of Engineering and Analytics (ZEA), Forschungszentrum Jülich GmbH, 52428 Jülich, Germany.

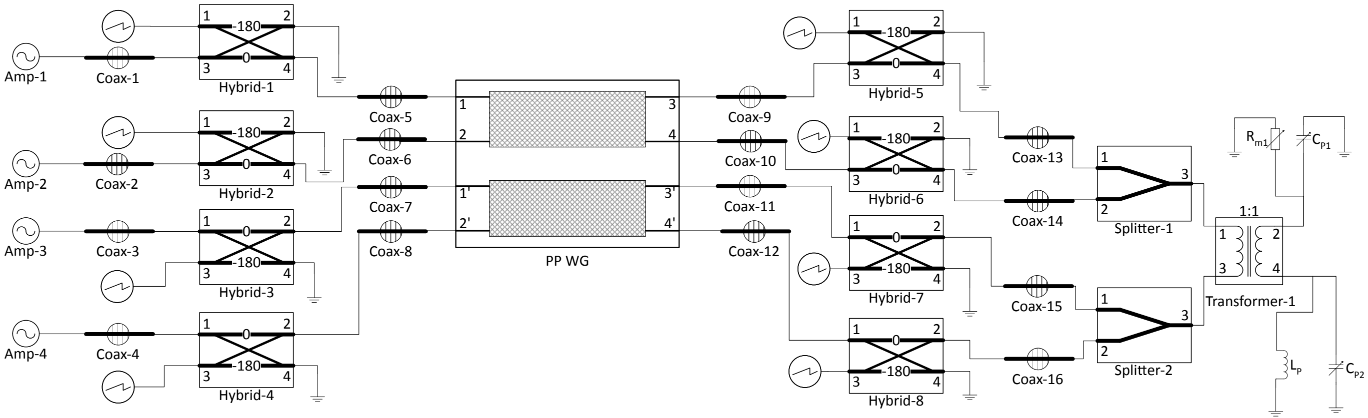

FIG. 1. The schematic of the driving circuit of the novel waveguide RF Wien filter. The high-frequency components including the cables (Coax-1 to Coax-16), the -30 dB couplers (Hybrid-1 to Hybrid-8), power combiners (Splitter-1 and Splitter-2), a transformer and the discrete elements are shown. The rf Wien Filter is denoted PP WG (parallel-plates waveguide).

introducing a mismatch resistor at the load side of the waveguide. Details of the wave mismatch theory for this particular case have been explained before [6].

III. Circuit Design

The scheme of the driving circuit of the RF Wien filter is shown in Fig.1. It has been approved and will be manufactured by an external company[?]. On the source side, four power amplifiers are used. The driving signal generator provides sufficient power in the order of 7 dBm and guarantees a stable frequency. The power amplifiers are operated in push-pull mode. This means the sources feeding the upper electrodes (labels Amp-1 and Amp-2) are in phase and they are 180° out of phase with the ones connected to the lower electrodes (labels Amp-3 and Amp-4). Then 2 m of coaxial cables (type RG213) are used. After that, four -30 dB power hybrids are used and connected to 50 Ω terminations that emulate the current and voltage measurements devices. Dedicated circuits are used to perform these tasks (these signals are used to adapt the operation of the RF Wien filter in real time). Additional cables are used for the direct connection with the electrodes. The electromagnetic design and simulation of the device is explained in [4]. On each side of the electrodes two feedthroughs are used to equaly distribute the RF current, thus providing more homogeneous electromagnetic fields. At the load side of the RF Wien filter another four -30 dB power hybrids are used. Two 3 dB combiners feed a 1:1 transformer to which the load is connected. This forms a three-conductor system, *i.e.* two high potentials and 180° out of phase with a common ground.

Ideally, the load is purely resistive. A resistor does not introduce a phase shift between the voltages and currents flowing on the electrodes and therefore, Z_q is expected to be real. The cables, unfortunately, add capacitive reactance to the load making the field quotient Z_q complex, which corresponds to an undesired phase shift between the electric and the magnetic field. To solve this problem, a fixed inductor with two capacitors C_{p1} and C_{p2} as shown in Fig. 1 are connected to the load.

A. Concept of a high-accuracy high-power variable resistor

In practice dealing with high power (10 kW) within the entire operating frequency range while preserving the same levels of homogeneity is a challenging task. The most critical part is the development of a variable resistor for the required power level because there is no commercial solution. Additionally, classical resistors are very sensitive to the power deposited in them. As a consequence, the large variation of the field quotient may lead to beam loss due to the violation of the Wien filter condition. For this reason, a concept of a less power-dependent variable resistor was investigated.

The concept is based on the matching network principle and is being realized at the moment. It is not important for the operation of the RF Wien filter if the impedance is provided by a resistor or an impedance network, as will be shown later. The impedance may be realized by a simple resistor or a more complex RLC network.

B. Design of the matching network

The basic idea is to use a **fixed** high-power, water-cooled 50 Ω resistor. For a required impedance of, say 165 Ω, a matching T-network can be used to match 165 Ω to the fixed 50 Ω as can be seen in Fig. 2.

The inductor L_{mf} is fixed and is maintained at 30 μH. The realization of such a high inductance for the required

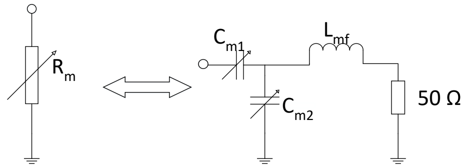

FIG. 2. The variable resistor (left) is replaced by a T-type matching network (right). The inductor L_{mf} is fixed while the two capacitors are variable.

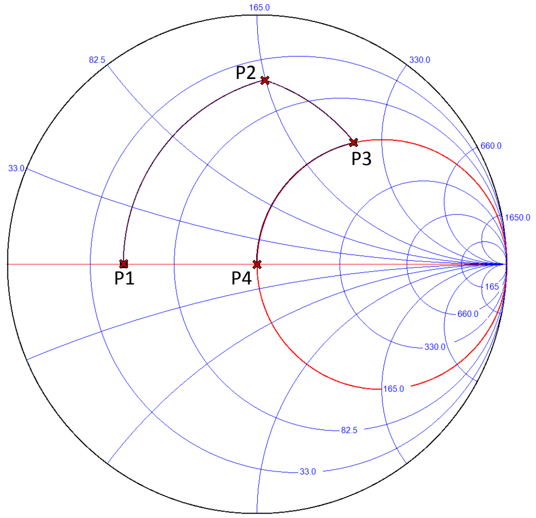

FIG. 3. The impedance points are shown in the Z-Smith chart. This chart permits to find the values of the required inductor and the capacitors in the matching network.

power was challenging. Many solutions including different types of ferrite cores have been calculated but they are all very temperature-dependent and thus call for active cooling. We designed an air core coil to avoid the effort of active cooling. For instance, 30 μH is achieved with an air coil using 29 windings, a length of 113 mm with a separation distance of 3 mm. The main drawback of this design is that the maximum possible inductance reads 33 μH within the allowed space. This means that the frequency bands from 630 kHz to 1600 kHz can be covered but not the lowest operation frequency of 120 kHz which requires the inductance of L_{mf} to be 200 μH.

The vacuum capacitors C_{m1} and C_{m2} are characterized by very low tolerances on the order of 0.01 pF, which means a very stable and accurate system can be expected. They reside within the same rack with the inductor and they are co-connected via a high-current connector without any cables reducing the chances of mismatches and reflections.

The Smith chart in Fig. 3 explains the working principle of the matching network [3]. With a normalization of the chart values to the required impedance value *i.e.* 165 Ω (for an operating frequency of the Wien filter of 871 kHz), the 50 Ω resistor is located at point P1. P4 represents the required 165 Ω impedance (located at the center of the Smith chart). The target is to map P1 to P4 with only reactive elements, i.e. capacitors and inductors. Placing the 30 μH inductor L_{mf} in series with the load brings P1 to P2. Then the two capacitors as shown in Fig. 2 fulfill the goal. This network is flexible in the sense that within a very large range of L_{mf} from 20 to 35 μH the same capacitors can be used to yield exactly the required value of 165 Ω.

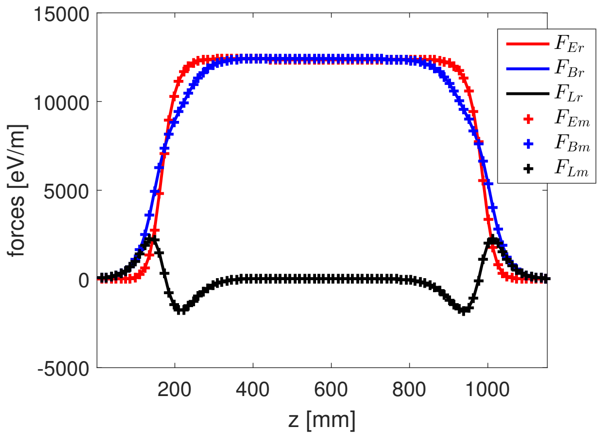

FIG. 4. Forces calculated for the cases of a simple resistor and the matching network cases. The electric, magnetic and Lorentz forces are calculated. z is the coordinate along the beam axis. The solid lines are the forces calculated using the resistor and the lines with the +-sign correspond to the forces computed with the T-matching network.

TABLE I. Different combinations of the reactive elements in the T-matching network lead to the same impedance values, and also large variations of the load impedance are possible with the same elements.

$R_m[\Omega]$	$L_{mf}[\mu H]$	$C_{m1}[pF]$	$C_{m2}[pF]$
165	20	838	1300
165	31	503	659
165	32	486	637
165	35	438	572
150	30	488	712
176	30	543	675

It is also important to note that the path to follow from P1 to P4 is not unique. Many possible combinations yield the same result. Table I shows some of them.

The fields and consequently the forces are recalculated for the cases of a concrete load resistor R_m and for the matching network concept. With the load resistor, the electric, magnetic and Lorentz forces are denoted as F_{Er}, F_{Br} and F_{Lr} respectively. The matching network counterparts are similarly noted as F_{Em}, F_{Bm} and F_{Lm}, respectively. The perfect match between the two cases is clear (Fig. 4).

IV. Summary and outlook

This paper reports on the progress of the construction of a novel waveguide-based RF Wien filter for EDM measurements at COSY/Jülich, in particular the corresponding electrical circuit design. The concept of a high-accuracy, high-power load resistor has been presented including the design steps and the equivalent circuit. Additionally, the electric, magnetic and Lorentz forces along the beam axis have been shown to yield identical behavior between the resistor-based and matching network solution. The crossing at the edges between the forces is independent of the circuit used.

At the moment the electrical components are being manufactured by a company. It is expected to be ready at the end of January 2017. The RF Wien filter will be installed at COSY in April 2017 at the latest.

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