COSY Beam Time Request

For Lab. use

Exp. No.:	Session No.
E 005.1	**4**

Collaboration: JEDI

Commissioning of the waveguide RF Wien Filter at COSY

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Total number of particles and type of beam (p,d,polarization)	Kinetic energy (MeV)	Intensity or internal reaction rate (particles per second)	
		minimum needed	maximum useful
polarized deuterons	**~970 MeV/c**	**stored ~10^9**	**stored ~10^{10}**
Experimental area	Safety aspects (if any)	Earliest date of installation	Total beam time (No.of shifts)
EDDA detector and electron cooler	**none**	**January 1, 2017**	**2 weeks + 1 MD**

Commissioning of the waveguide RF Wien Filter

The JEDI collaboration

May 17, 2016

Abstract

In this proposal, we outline the plans for the first use of a waveguide RF Wien filter that was designed to perform a first direct measurement of the Electric Dipole Moment (EDM) of the deuteron at COSY. The RF Wien filter is based on a parallel plane waveguide, *i.e.*, a pair of conductors oriented parallel to the beam direction produces electric and magnetic fields. Thereby, the orthogonality condition $\vec{E} \times \vec{B}$ for a Wien filter can be fulfilled very accurately.

The device shall become available for first tests at COSY in the early spring of 2017. We would like to perform a first commissioning with a vector polarized deuteron beam at 970 MeV/c, and this requires **two weeks of beam time preceded by one machine development (MD) week.** The commissioning phase will be used to make sure that the wave guide RF Wien filter is properly performing before we approach further investigations.

1 Design of the waveguide RF Wien filter

The transverse electromagnetic (TEM) mode of a waveguide comes closest to the requirement of orthogonal electric and magnetic fields. Therefore, for the use of the RF Wien filter at frequencies of about 100 kHz to 1 MHz, a parallel-plate waveguide was chosen as the basic geometry. The axis of the waveguide points along the beam direction (z). The plates are separated along the x-direction by 10 cm, and the width of the plates extends along the y-direction, parallel to the magnetic field. This setup ensures that the main component of the electric field is in the x-direction, while the main component of the magnetic field points along the y-direction. Figure 1 shows a model of the RF Wien filter[1] [1].

We intend to start the commissioning effort of the new waveguide RF Wien filter with deuteron EDM measurements at $T = 235\,\text{MeV}$ for which $\beta = 0.459$. The operational frequencies of the RF Wien filter are given by the spin precession frequencies of the particles at COSY of about 100 kHz to 1 MHz. The working frequencies of the RF Wien filter are given by

$$f_{\text{RF}} = f_{\text{rev}}|k + \gamma G|, k \in \mathbb{Z} \tag{1}$$

where k is the harmonic number, G the gyromagnetic anomaly, γG the spin tune, and f_{rev} the revolution frequency. With deuterons at 970 MeV/c, $\beta = 0.459$, $\gamma = 1.126$ and $G = -0.143$, $f_{\text{rev}} = 750\,\text{kHz}$, $\gamma G = -0.161$. Table 1 summarizes the resonance frequencies under these conditions for the different harmonics in the range $k = -2, -1, \ldots, +2$.

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[1] The design of the RF Wien filter has been worked out by a PhD student, Jamal Slim, from the Institute of High Frequency Technology, led by Prof. Dr.-Ing. Dirk Heberling, RWTH Aachen University.

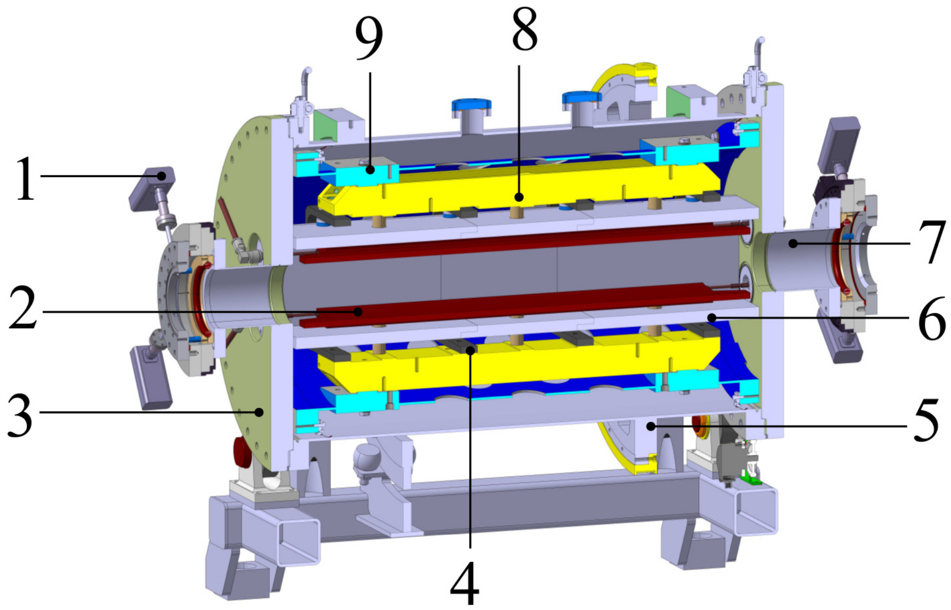

Figure 1: Design model of the RF Wien filter showing the parallel-plates waveguide and the support structure. 1: Rogowski-coil beam position monitor (BPM); 2: copper electrodes; 3: vacuum vessel; 4: clamps to hold the ferrite cage; 5: belt drive for 90° rotation (precision 0.01° (0.17 mrad)); 6: ferrite cage; 7: CF100 beam pipe; 8: support structure of the electrodes; 9: inner support tube. (Figure taken from Ref. [1].)

Harmonic k	-2	-1	0	1	2
—f_{RF}— [kHz]	1621.2	871.0	120.8	629.4	1379.6

Table 1: Harmonic number and operating frequencies of the RF Wien filter for deuterons orbiting at 970 MeV/c in COSY under the conditions given by Eq. (1).

The electromagnetic full-wave simulations using CST Microwave Studio[2] were capable to model the field with an accuracy of 10^{-6}. In order to provide a zero net Lorentz force, the electric and magnetic forces must be matched at the center and the edges of the RF Wien filter. At the edges however, a special solution is required, because the rise and drop of the electric and magnetic forces are not the same, resulting in kicks on the particles passing through the device. The chosen solution aims to decompose the kicks at each side into two kicks of opposite directions in a way that they average out. To do so, the fields at the edges were decoupled, keeping the electric field unchanged while manipulating the magnetic field so that the rise and drops cross each other, as shown in Fig. 2.

The Lorentz force is given by

$$\vec{F}_{\mathrm{L}} = q\left(\vec{E} + \vec{v} \times \vec{B}\right) , \tag{2}$$

where q is the charge of the particle, $\vec{v} = c(0,0,\beta)$ is the velocity vector, $\vec{E} = (E_x, E_y, E_z)$ and $\vec{B} = \mu_0(H_x, H_y, H_z)$ denote the components of the electric and magnetic fields, and μ_0 the vacuum permeability.

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[2] CST - Computer Simulation Technology AG, Darmstadt, Germany, `http://www.cst.com`

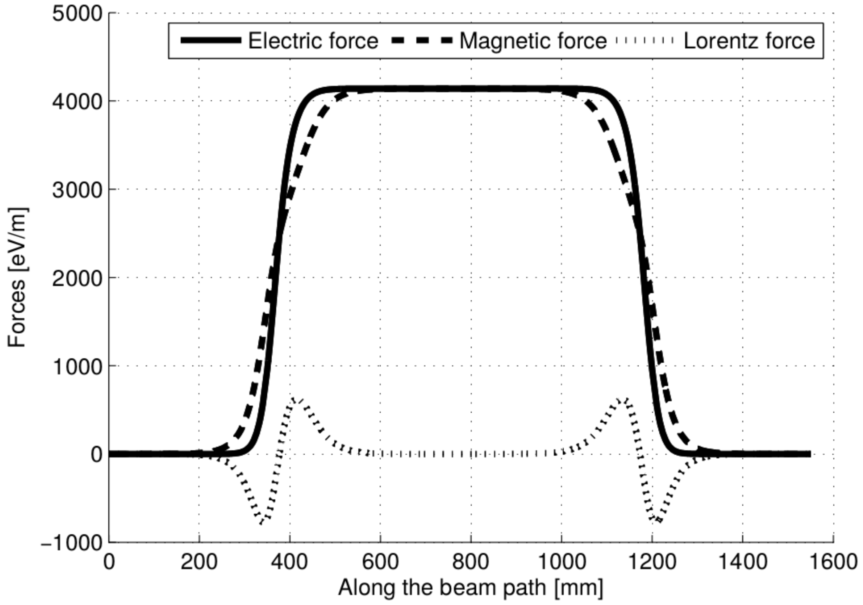

Figure 2: Electric, magnetic, and Lorentz force F_L as function of position along the beam direction (z coordinate). (Figure taken from Ref. [1].)

Integrating and averaging the Lorentz force $\vec{F}_\mathrm{L}$, given in Eq. (2), along the axis of the RF Wien filter for the geometry shown in Fig. 1 at an input power of 1 kW, yields

$$\frac{q}{\ell}\int_{-\ell/2}^{\ell/2}\begin{pmatrix} E_x - c\beta B_y \\ E_y + c\beta B_x \\ E_z \end{pmatrix} dz = \begin{pmatrix} 5.97\times 10^{-3} \\ 7.97\times 10^{-3} \\ 1.27\times 10^{-21} \end{pmatrix} \mathrm{eV/m}\,, \tag{3}$$

where $\ell = 1550\,\mathrm{mm}$ denotes the active length of the RF Wien filter, defined as the region where the fields are non-zero.

The waveguide RF Wien filter can be rated according to its ability to manipulate the spins of the stored particles, and as a figure of merit, the field integral of $\vec{B}$ along the beam axis is evaluated, yielding for an input power of 1 kW,

$$\int_{-\ell/2}^{\ell/2}\vec{B}dz = \begin{pmatrix} 2.73\times 10^{-9} \\ 2.72\times 10^{-2} \\ 6.96\times 10^{-7} \end{pmatrix} \mathrm{T\,mm}\,. \tag{4}$$

Under these conditions, the corresponding integrated electric field components are given by

$$\int_{-\ell/2}^{\ell/2}\vec{E}dz = \begin{pmatrix} 3324.577 \\ 0.018 \\ 0.006 \end{pmatrix} \mathrm{V}\,. \tag{5}$$

2 Technical realization

All parts of the waveguide RF Wien filter shall be available by the end of June 2016, and we will begin to assemble the device soon after at ZEA in Jülich.

The layout of the driving circuit (see Fig. 3 of Ref. [1]) for the waveguide RF Wien filter is presently being worked out, and we anticipate the driving circuit to be available for tests in the laboratory in October 2016.

3 Commissioning of the waveguide RF Wien filter

3.1 Protoype RF Wien filter

In 2014, a prototype RF E×B Wien filter using separate systems for the generation of electric and magnetic fields has been successfully commissioned and utilized during two weeks of beam time. As a result of these investigations, it was shown that the prototype can be operated in a Wien-Filter configuration at harmonic $k = -1$ (at a frequency of 871.0 kHz, see Table 1) to flip the vertical polarization of a 970 MeV/c deuteron beam without exciting coherent beam oscillations. Tuning of the device to minimize the transverse Lorentz force was accomplished by operating the machine near a betatron resonance. It was possible to show that the device effectively operates like an RF-solenoid. Further details about these investigations can be found in Ref. [2]. During 2015, measurements with the prototype RF Wien filter at harmonic $k = +1$ (at a frequency of 629.4 kHz) were carried out equally successful, and with these measurements, the frequency range of the prototype RF Wien filter was exhausted.

3.2 First tests with the waveguide RF Wien filter

The waveguide RF Wien filter will be installed at the PAX interaction point at COSY. Proper alignment of the beam position in the device will be accomplished by a pair of Rogowski coils at the entrance and exit of the vessel that serve as BPMs [3] (see label 1 in Fig. 1). The β-functions at the PAX interaction point can be adjusted in the range between about $\beta = 0.4$ to 4 m, whereby the beam size can be changed accordingly. With respect to the commissioning of the waveguide RF Wien filter, we would like to repeat the procedures during the commissioning of the prototype using the different harmonics available, in order to show that the device is functioning as expected.

The waveguide RF Wien filter can be rotated in short time in-situ by more than 90° about the beam axis without breaking the vacuum with an angular precision of 0.01° (0.175 mrad) using a belt drive (see label 5 in Fig. 1). Once the spin manipulation behavior of the system is determined, the waveguide RF Wien filter can be rotated by 90° around the beam axis. In this configuration, the RF E×B dipole in Wien filter mode will no longer directly act on the particles' MDM, but still modulate their spin tune γG. In conjunction with the imperfection fields distributed along the accelerator ring, an RF Wien filter with radial electric fields can lead to an EDM induced build-up of a vertical polarization component. It is foreseen to use the new waveguide RF Wien filter for systematic investigations of sources for false EDM signals. To this end, extensive studies about the polarization buildup using an RF Wien filter to detect the EDM signal were carried out by JEDI. These are described in Ref. [4], where it is shown that in particular quadrupole misalignments mimic the buildup of polarization due to an EDM (see Figs. 4 and 5 of Ref. [4].

As explained above, the commissioning of the prototype RF Wien filter took about one week for each of the employed harmonics ($k = -1$ and $+1$, see Table 1). It proved time comsuming to set up the machine near a betatron resonance, because in order to gain a high sensitivity to the induced beam oscillations, the accelerators optics needed to be modified so that a vertical betatron sideband was shifted exactly to the RF E×B frequency at 871.5 kHz (see Fig. 5 of Ref [2]). In this reference, details about the measurement procedure are described as well. Once the machine is setup near the betatron resonance, testing the performance of the waveguide RF Wien filter at the different harmonics should be achievable within the proposed two weeks of beam time. Further details about the various steps for the commissioning of the waveguide RF Wien filter will be presented in the oral presentation at the CBAC meeting in June 2016.

4 Request for beam time for the first half of 2017

We request **two weeks of beam time, plus one MD week** preceding the activities in early 2017.

Once the commisioning experiment with the waveguide RF Wien filter with beam at COSY has been carried out, the JEDI collaboration would like to carry out a first EDM run with the new device as soon as possible, i.e., in the time period May – July 2017. A detailed proposal about these measurements will be presented to the CBAC in December 2016, where also the results of the laboratory tests will be presented.

References

[1] J. Slim *et al.*, *Electromagnetic Simulation and Design of a Novel Waveguide RF Wien Filter for Electric Dipole Moment Measurements of Protons and Deuterons*, accepted for publication in Nucl. Instr. Meth. Phys. Res., available from `http://dx.doi.org/10.1016/j.nima.2016.05.012`. (2016).

[2] S. Mey *et al.*, *Towards an RF Wien filter for EDM Experiments at COSY*, Proceedings of the International Beam Instrumentation Conference, IBIC2015, Melbourne, Australia, available from `http://collaborations.fz-juelich.de/ikp/jedi/public_files/proceedings/THPF031.pdf`.

[3] F. Hinder *et al.*, *Development of new beam position monitors at COSY*, Proceedings of the International Beam Instrumentation Conference, IBIC2015, Melbourne, Australia – Pre-Release, available from `http://ibic.synchrotron.org.au/papers/tupb015.pdf`.

[4] M. Rosenthal *et al.*, *Spin tracking simulations towards electric dipole measurements at COSY*, Proceedings of the International Beam Instrumentation Conference, IBIC2015, Melbourne, Australia, available from `http://collaborations.fz-juelich.de/ikp/jedi/public_files/proceedings/THPF032.pdf`.