First exploratory deuteron EDM experiments with the waveguide RF Wien Filter

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Contents

Proof of principle experiment using COSY
(“Precursor experiment”)

Highest sensitivity will be achieved with a new type of machine:

- An **electrostatic circular storage** ring, where
  - centripetal force produced primarily by electric fields.
  - E field couples to EDM and provides required sensitivity ($< 10^{-28}\,\mathrm{e\,cm}$).
  - In this environment, magnetic fields mean evil (since μ is large).

Idea for proof-of-principle experiment with novel RF Wien filter ($\vec{E} \times \vec{B}$):

- In magnetic machine, particle spins (deuterons, protons) precess about stable spin axis ($\simeq$ direction of magnetic fields in dipole magnets).
- Use RF device operating on some harmonic of the spin-precession frequency:

  $\Rightarrow$ *Phase lock* between spin precession and device RF.

  $\Rightarrow$ Allows one to accumulate EDM effect as function of time in cycle ($\sim 1000\,\mathrm{s}$).

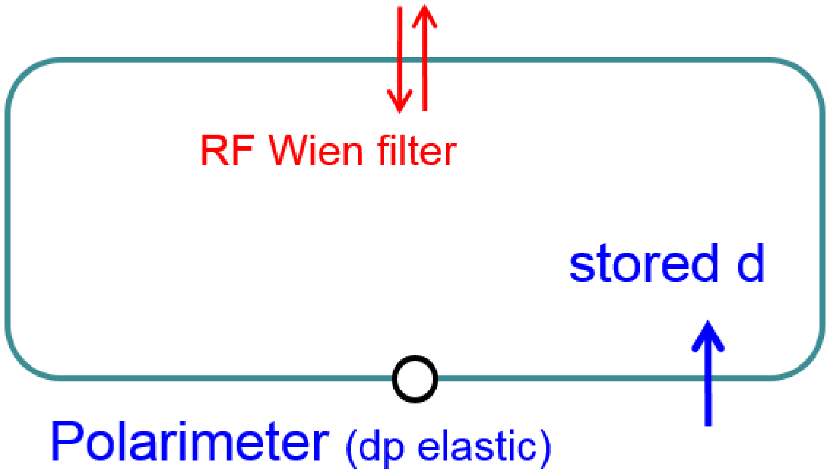
Goal of proof-of-principle experiment:

Show that storage ring (COSY) can be used for a first direct EDM measurement.

RF Wien filter

A couple more aspects about the technique:

- RF Wien filter ($\vec{E} \times \vec{B}$) avoids coherent betatron oscillations in the beam:
  - Lorentz force $\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) \simeq 0$.
  - EDM measurement mode: $\vec{B} = (0, B_y, 0)$ and $\vec{E} = (E_x, 0, 0)$.



- Deuteron spins lie in machine plane.
- If $d \neq 0 \Rightarrow$ *accumulation* of vertical polarization P_y, during spin coherence time $\tau_{\mathrm{SCT}} \sim 1000\,\mathrm{s}$.

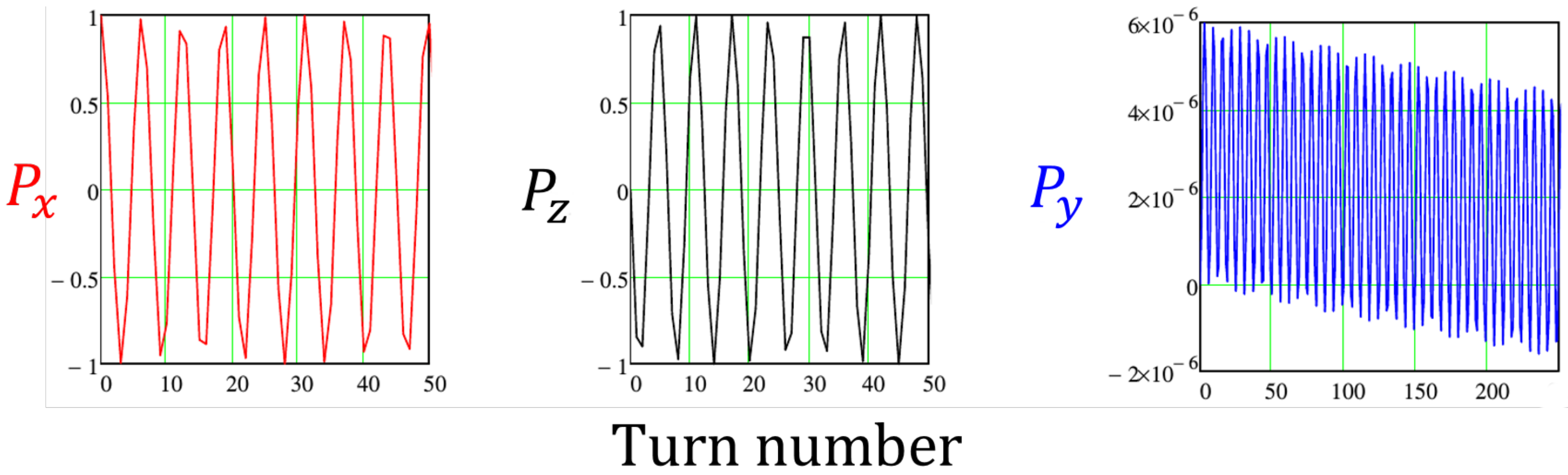
Statistical sensitivity:

- in the range 10^{-23} to $10^{-24}\,\mathrm{e\,cm}$ for $d(\textit{deuteron})$ possible.
- Systematic effects: Alignment of magnetic elements, magnet imperfections, imperfections of RF-Wien filter, etc.

Buildup of $P_y(t)$ using RF Wien filter for deuterons

Model calculation at beam momentum $p_d = 970\,\mathrm{MeV/c}$:

- $G = -0.143$, $\gamma = 1.126$, $f_s = |f_{\mathrm{rev}}(\gamma G + K_{(=0)})| = 120.765\,\mathrm{kHz}$
- Length of device: $L_{\mathrm{WF}} = 1.55\,\mathrm{m}$ [1].
- Assumed deuteron EDM: $d = 10^{-20}\,\mathrm{e\,cm}$.
- Electric RF field: $1000 \times E_{\mathrm{WF}} = 2.145 \times 10^6\,\mathrm{MV/m}$ [1].

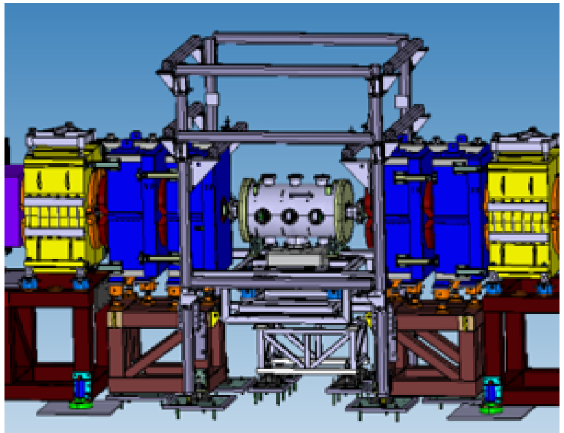


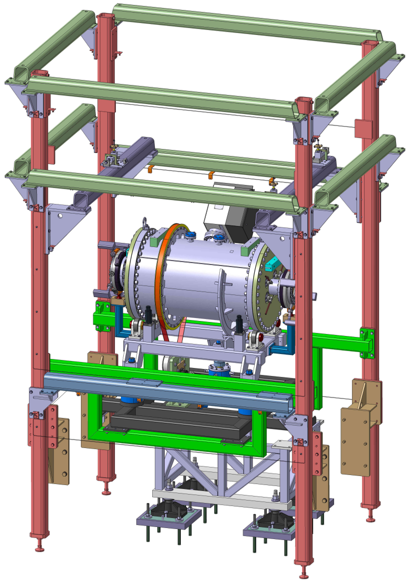
EDM effect accumulates in $P_y \propto d$ [2, 3].

Waveguide RF Wien filter

Device developed at IKP in cooperation between:

- **RWTH Aachen, Institute of High Frequency Technology:** Dirk Heberling, Dominik Hölscher, and PhD Student Jamal Slim
- **ZEA-1 of Jülich:** Helmut Soltner, Lars Reifferscheidt, Heidi Straatmann

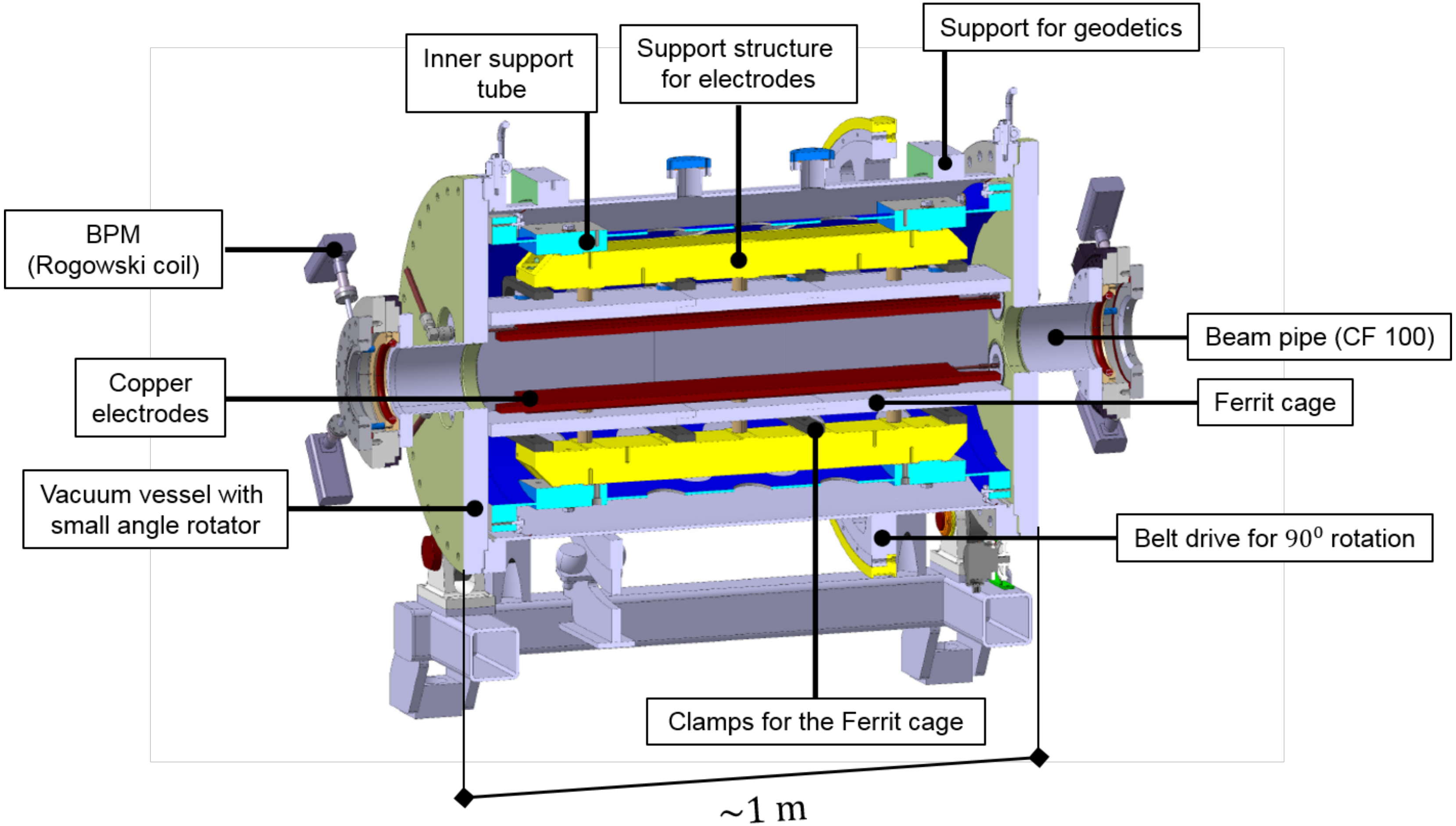




Device has been installed in PAX low-β section at COSY.

$\Rightarrow$ PAX section allows for systematic studies with respect to divergence of beam.

Features of the waveguide RF Wien filter



Aim was to build the best possible device, with respect to

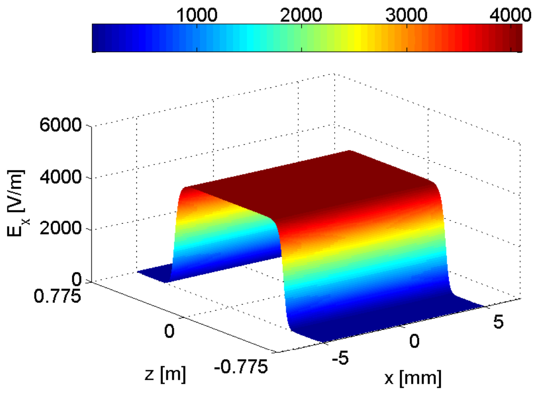
- electromagnetic performance [1] and mechanical tolerances [4].
- Excellent cooperation with RWTH Aachen University and ZEA-Jülich

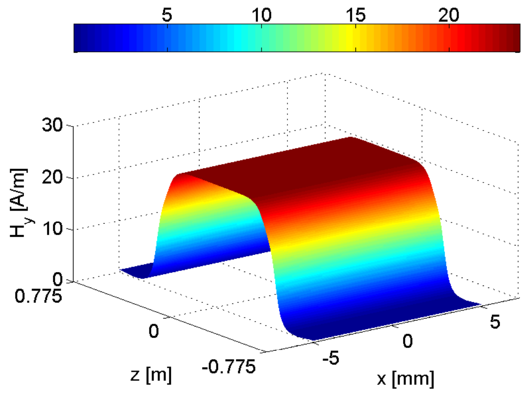
Electromagnetic field simulations [1]

Full-wave simulations

- using CST Microwave Studio[a].

[a] Computer Simulation Technology AG, Darmstadt, Germany, http://www.cst.com





At input power of 3.2 kW, magnetic and electric field integrals are ($\ell = 1.550\,\mathrm{m}$):

$$\int_{-\ell/2}^{\ell/2} \vec{B} dz = \begin{pmatrix} 4.88 \times 10^{-9} \\ \mathbf{4.87 \times 10^{-2}} \\ 6.96 \times 10^{-6} \end{pmatrix} \mathrm{T\,mm}\,, \qquad \int_{-\ell/2}^{\ell/2} \vec{E} dz = \begin{pmatrix} \mathbf{5947.18} \\ 0.03 \\ 0.01 \end{pmatrix} \mathrm{V} \qquad (1)$$

Required frequencies of RF Wien filter

Resonance condition:

$$f_{\mathrm{WF}} = f_{\mathrm{rev}}\left(\gamma G \pm K\right)\,, k \in \mathbb{Z}. \tag{2}$$

Wien filter frequencies f_{WF}

- **Deuterons** at $T_d = 236.0\,\mathrm{MeV}$ $(970.0\,\mathrm{MeV/c})$:

			harmonic K [kHz]				
β	G	γ	**−2**	**−1**	0	**1**	**2**
0.459	−0.143	1.126	−**1621.2**	−**871.0**	−120.8	**629.4**	**1379.6**

- **Protons** at $T_p = 134.5\,\mathrm{MeV}$ $(520\,\mathrm{MeV/c})$:

			harmonic K [kHz]				
β	G	γ	**−4**	**−3**	−2	**−1**	**0**
0.485	1.793	1.143	−**1543.9**	−**752.2**	39.4	**831.0**	**1622.7**

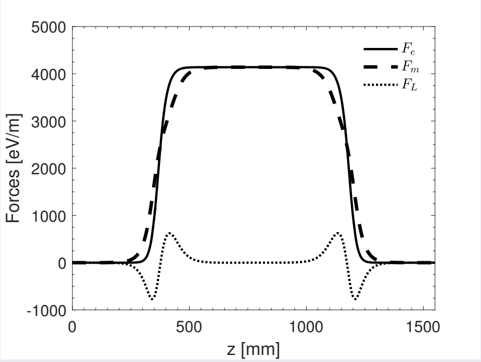
Accomplished design goal of wave guide RF Wien filter and driving circuit [1]:

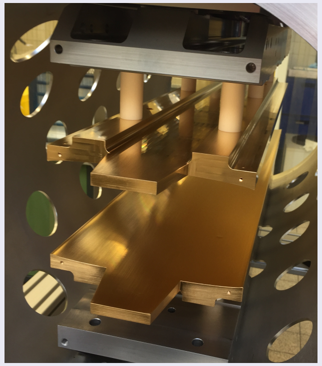
Provide a number of operational frequencies for p and d between 0 to 2 MHz.

Lorentz force compensation [1]

Integral Lorentz force is of order of $-3\,\mathrm{eV/m}$:

- Electric force F_e, magnetic force F_m, and Lorentz force F_L inside RF Wien filter.
- Trapezoid-shaped electrodes determine crossing of electric and magnetic forces.





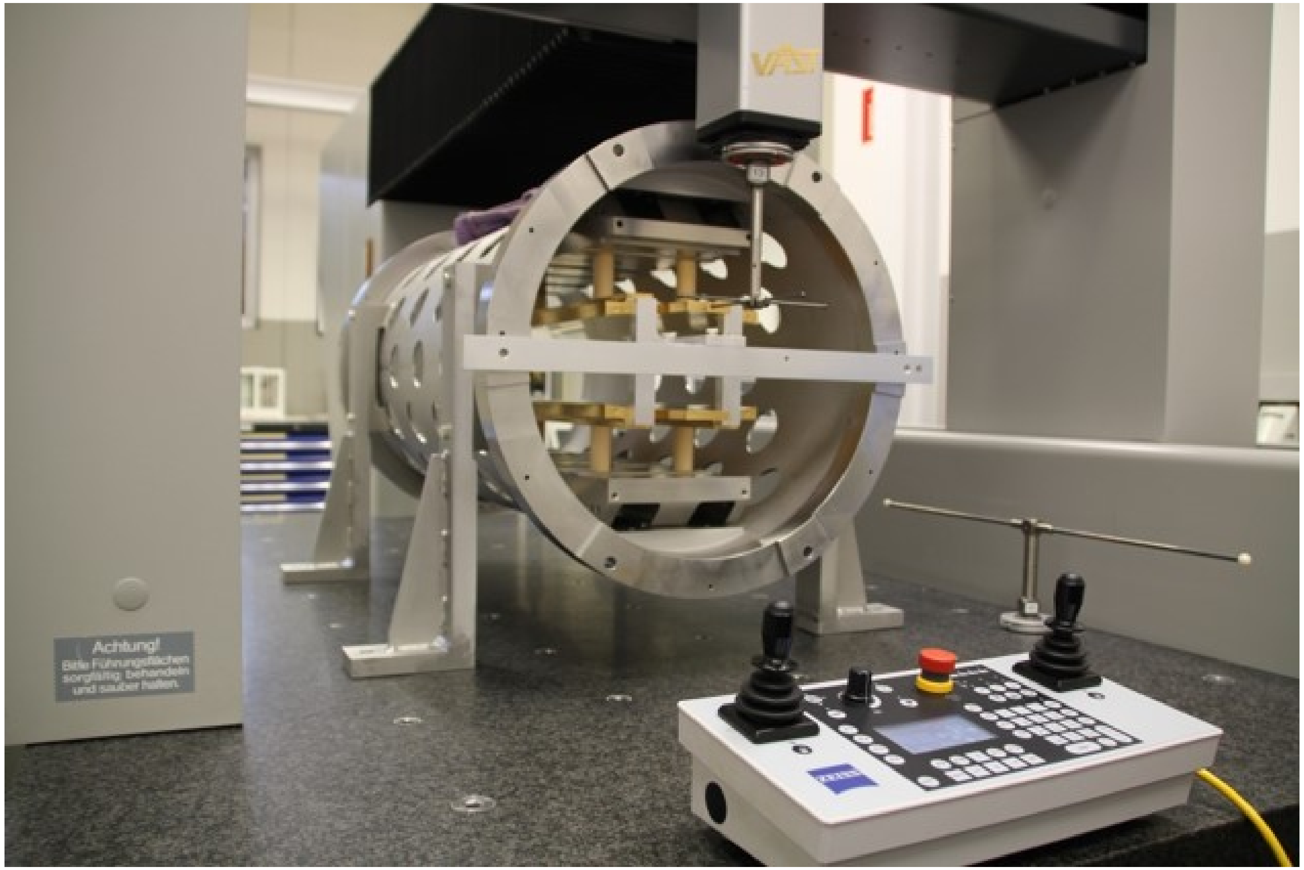
Lorentz force

$$\vec{F}_\mathrm{L} = q\left(\vec{E} + \vec{v} \times \vec{B}\right) , \tag{3}$$

- particle charge q, velocity vector $\vec{v} = c(0, 0, \beta)$, fields $\vec{E} = (E_x, E_y, E_z)$ and $\vec{B} = \mu_0(H_x, H_y, H_z)$, μ_0 vacuum permeability.
- For vanishing Lorentz force $\vec{F}_\mathrm{L} = 0$, field quotient Z_q given by

$$E_x = -c \cdot \beta \cdot \mu_0 \cdot H_y \quad \Rightarrow \quad \boxed{Z_q = -\frac{E_x}{H_y} = c \cdot \beta \cdot \mu_0 \approx 173\ \Omega} . \tag{4}$$

Assembly of RF Wien filter

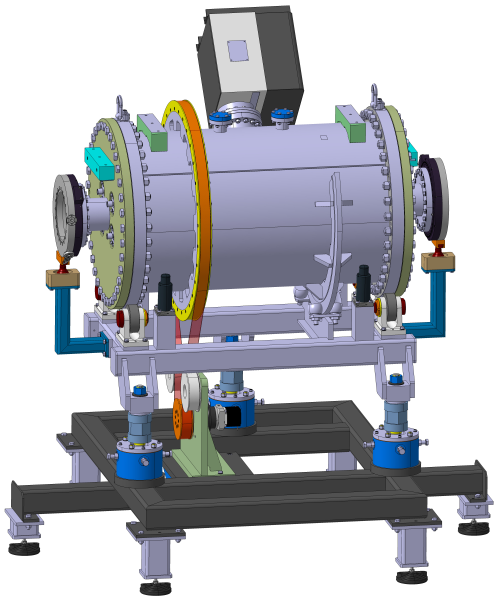


Device moved from ZEA to COSY hall for tests with driving circuit.

Clean room at COSY hall

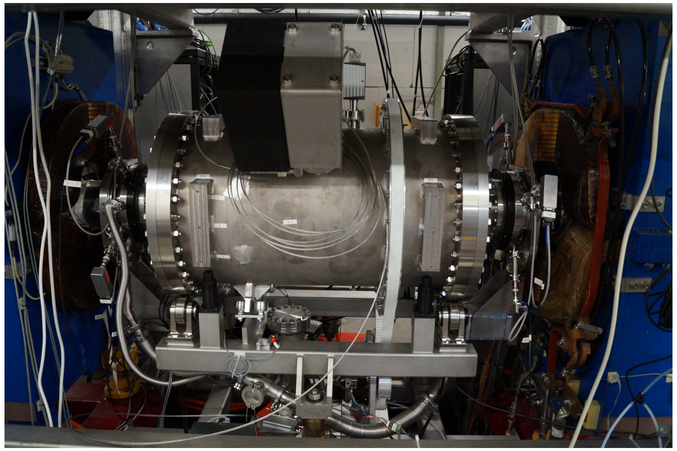
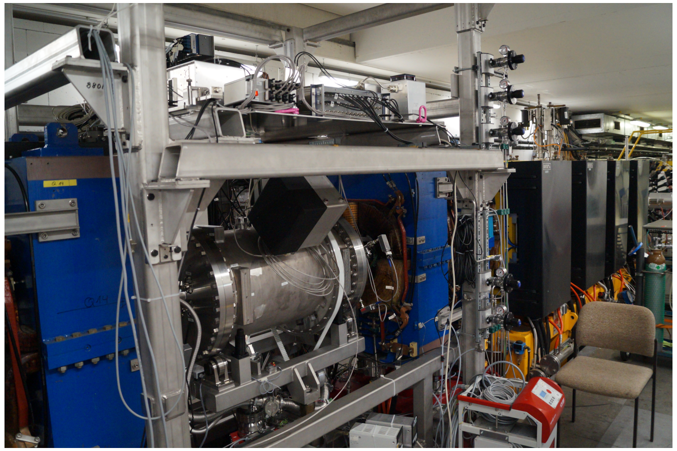
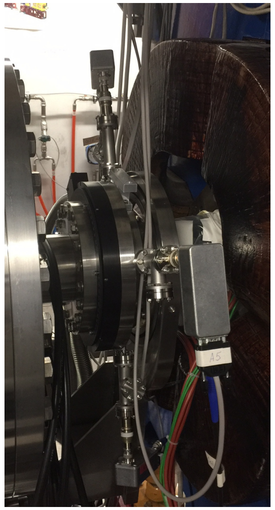
Commissioning of experimental setup:

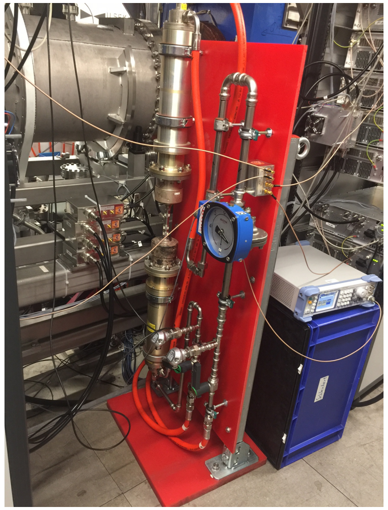
- Test of vessel rotation under vacuum.
- RF tests with driving circuit.
- Control system.



RF Wien filter installation at COSY took place in April 2017.

Setup at COSY

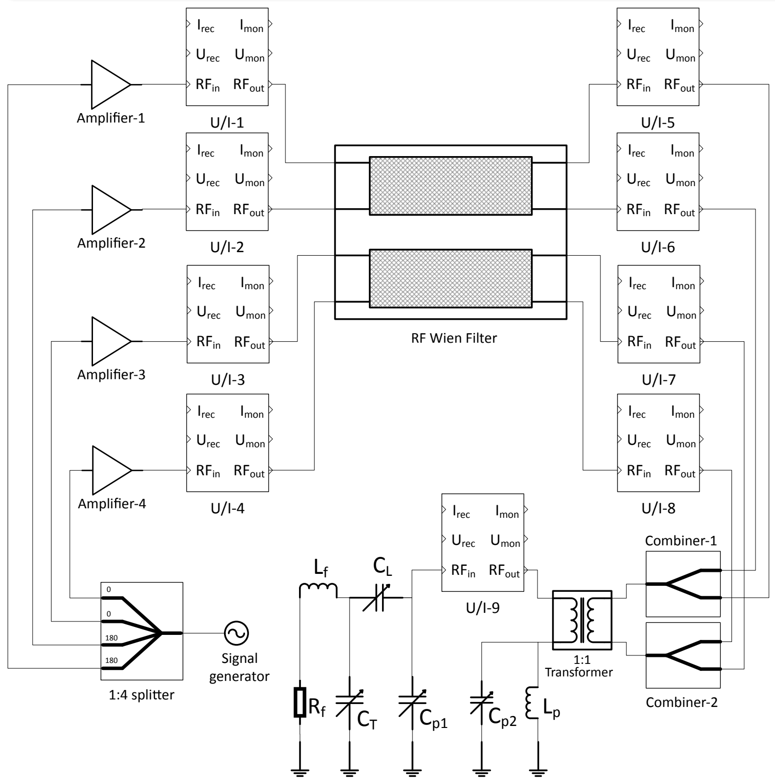


- RF Wien filter between PAX magnets. Upstream Rogowski coil; racks with power amplifiers, each unit delivers up to 500 W; water-cooled 25 Ω resistor.

Driving circuit

Uses four separate 1 kW power amplifiers.

- Fixed load resistor $R_f = 25\,\Omega$, fixed inductances $L_f = 28.8\,\mu\text{H}$ and $L_p = 5.07\,\mu\text{H}$, and four tunable elements capacities C_T, C_L, C_{p1}, and C_{p2}.



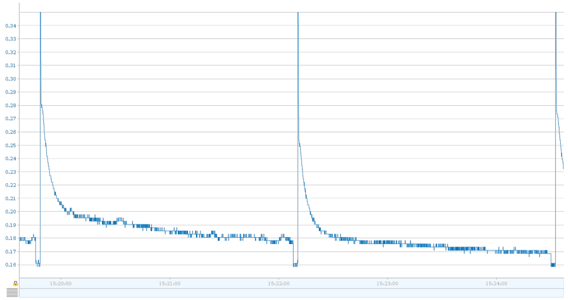
Components built by Fa. Barthel, `http://www.barthel-hf.de`:

- Input power $4 \times 0.8\,\text{kW}$:
  $$\boxed{\int B_z dz = 0.049\,\text{T mm}}$$ [see Eq. (1)].
- Upgrade later to $4 \times 1.6\,\text{kW}$: $\int B_z dz = 0.069\,\text{T mm}$.

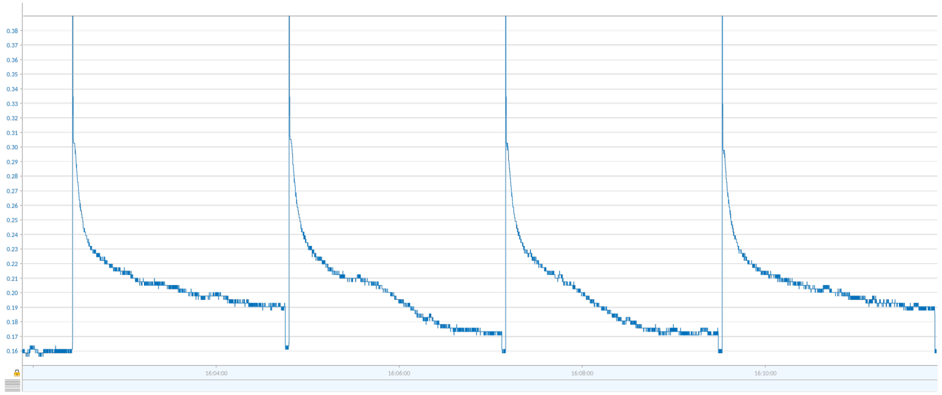
First results from ongoing RF Wien filter run

Operation at 2.2 kW

- 3×10^8 protons in fill after acceleration and beam cooling.
- With E and B fields in phase, and Z_q matched to β, no beam loss observed.



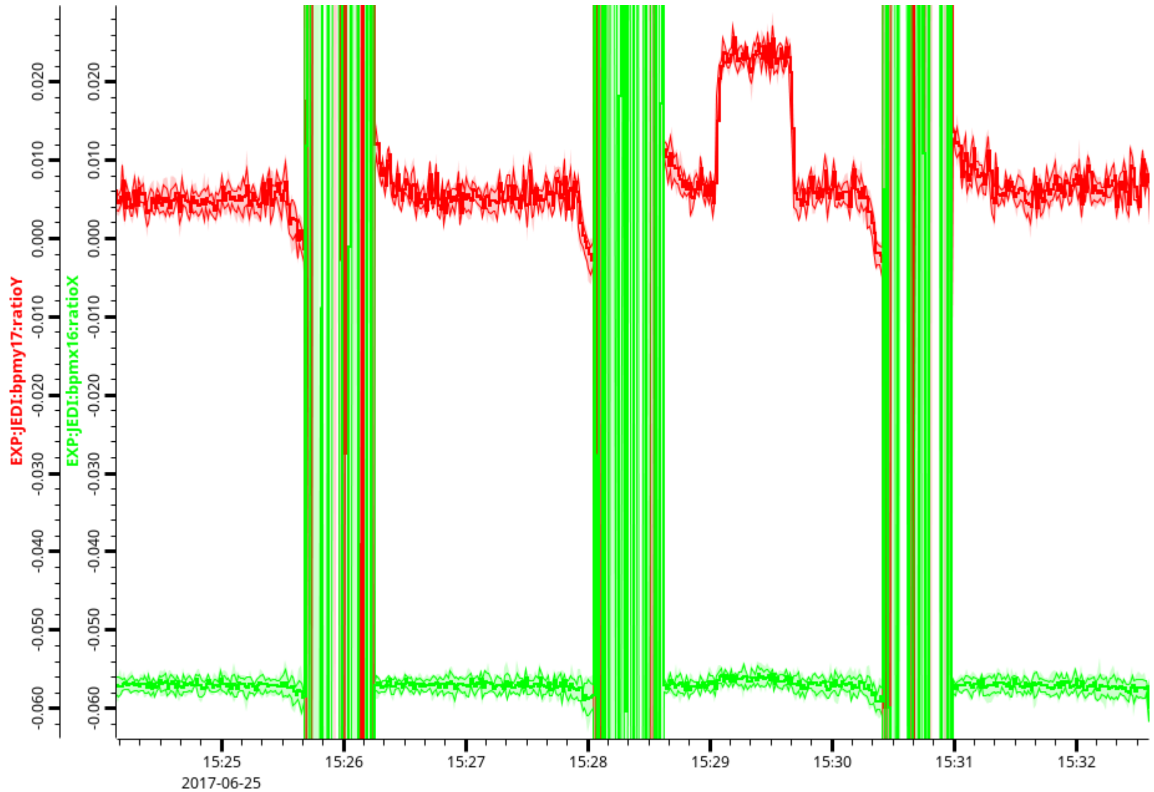
- Detuning of Z_q away from ideal $Z_q = 173\,\Omega$ [see Eq. (4)] to $Z_q = 403\,\Omega$ in cycles 2 and 3 leads to noticable beam losses.



First results from ongoing RF Wien filter run

First measurement of F_L at 400 W

- At present, RF Wien filter provides vertical E-field.
- Detuning Z_q away from the ideal value leads to *vertical* beam oscillations which are detected in BPM 17.
- As expected, BPM 16 shows very small horizontal signal.



Toolbox for precursor experiment

Elements available to study systematics in precursor RF Wien filter experiment:

- Two harmonics $K = \pm 1$, at 630 and 871 kHz available from beginning.
  - End of 2017 also harmonics at $K = \pm 2$ at 1380 and 1621 kHz available.
- All input signals for feedback loops of RF Wien filter tested and available:
  1. Internal loop in RF circuit keeps E and B in phase.
  2. Beam on axis in RF Wien filter (steerer loop with COSYLAB system).
  3. Minimized Lorentz force, thus β matched to $Z_q = -\frac{E_x}{H_y}$ [see Eq. (4)].
  4. Phase-lock of RF Wien filter phase to COSY RF (see [5]).
- Detune RF Wien filter frequency by δ_{WF} and observe response (see [6]).
- Phase variation Δ_{WF} of RF Wien filter (see [6]).
- RF Wien filter can be rotated around z-axis:
  - **Nominal mode:** B_y and E_x, **Rotated mode:** B_x and E_y.
  - Small angle rotations of few degree in situ, large angles without breaking vacuum, needs recabling.

Beam request

RF Wien filter has been installed at COSY together with driving circuit

- Device is fully operational, provides an RF input power of about 3.2 kW.
- Rogowski coils up- and downstream of the RF Wien filter operational as well.
- First results show that Lorentz force induced by RF Wien filter can be measured.

Beam time to commission the RF Wien filter was already granted by CBAC

- One run (MD + 2 weeks) in June 2017 (ongoing) and one in September (MD + 2 weeks).
- **We ask for one additional week to be appended to the second JEDI run in September of 2017, which shall be used to implement the spin tune feedback from the WASA detector with vector polarized deuteron beam at 970 MeV/c.**
- For the first exploratory EDM experiments with the complete system (but without ferrites) **we ask for three weeks of beam time, preceded by one machine development (MD) week in the 4$^{\text{th}}$ quarter of 2017.**

References

[1] J. Slim et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **828**, 116 (2016).

[2] F. Rathmann, A. Saleev, and N. N. Nikolaev, J. Phys. Conf. Ser. **447**, 012011 (2013).

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

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[5] N. Hempelmann et al., Phase locking the spin precession in a storage ring, 2017, accepted for publication in Phys. Rev. Lett.

[6] A. Saleev et al., Spin tune mapping as a novel tool to probe the spin dynamics in storage rings, 2017, accepted for publication in Phys. Rev. Accel. Beams.