First electric dipole moment measurement of the deuteron with a waveguide RF Wien Filter

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Contents

Proof of principle experiment using COSY
("Precursor experiment")

Highest EDM sensitivity shall 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 behind 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 ($\sim 1000\,\mathrm{s}$).

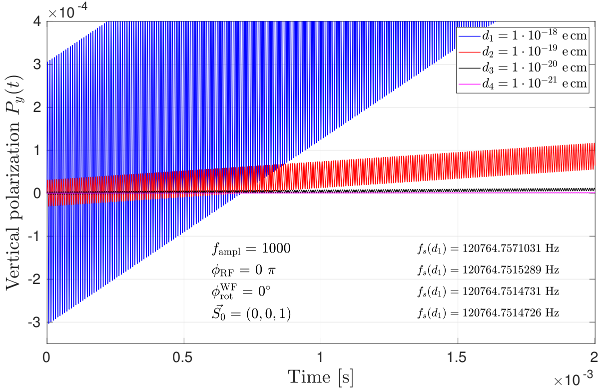
Goal of proof-of-principle experiment:

Show that conventional storage ring useable for first direct EDM measurement

Model calculation of EDM buildup with RF Wien filter

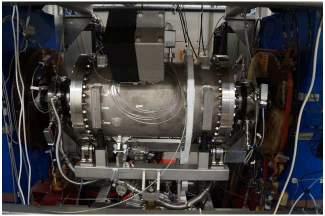
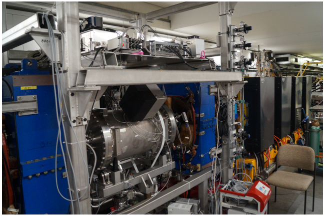
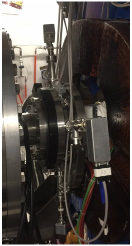
Ideal ring with deuterons at $p_d = 970\,\mathrm{MeV/c}$:

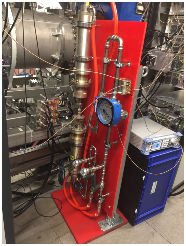
- $G = -0.143$, $\gamma = 1.126$, $f_s = |f_{\mathrm{rev}}(\gamma G + K_{(=0)})| \approx 120.765\,\mathrm{kHz}$
- Electric RF field integral assumed $1000 \times \int E_{\mathrm{WF}} \cdot d\ell \approx 2200\,\mathrm{kV}$ (w/o ferrites) [1].



EDM accumulates in $P_y(t) \propto d_{\mathrm{EDM}}$ [2, 3, 4].

RF Wien filter
Overview

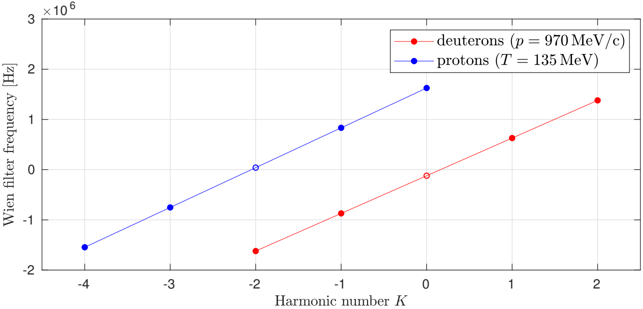


- RF Wien filter between PAX magnets. Upstream Rogowski coil; racks with power amplifiers, each unit delivers up to 500 W; water-cooled 25 Ω resistor.

Operational frequencies of RF Wien filter

Resonance condition:

$$f_{\mathrm{WF}} = f_{\mathrm{rev}} \left(\gamma G \pm K \right) , k \in \mathbb{Z}. \tag{1}$$

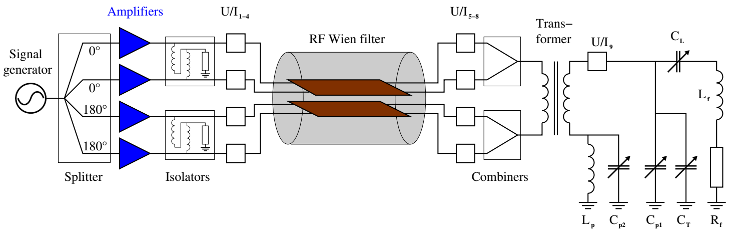


- RF Wien filter operational at frequencies between 0 to 2 MHz.
- Open symbols not reachable with present setup of driving circuit:
  - deuterons at $K = 0$ (-120.8 kHz), and
  - protons at $K = -2$ (39.4 kHz)

Driving circuit

Realization with load resistor and tunable elements (L's and C's):

- Design layout using four separate 1 kW power amplifiers.



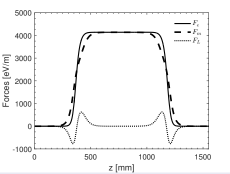
Circuit tested and ready

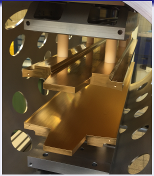
- Elements built by Fa. Barthel, `http://www.barthel-hf.de`.
- Tuneable elements allow [1]:
  - minimization of Lorentz-force, and
  - velocity matching to β of the beam.
- Power upgrade to 4×2 kW: $\int B_z dz = 0.218$ T mm possible later.

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}.
- Trapezoidal electrodes determine where F_{e} and F_{m} cross.





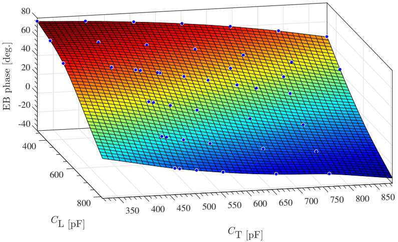
Lorentz force

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

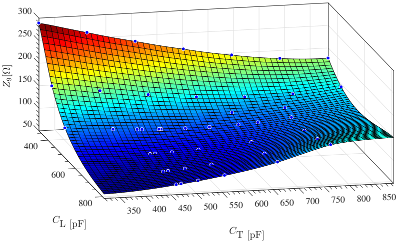
- q particle charge, velocity vector $\vec{v} = c(0, 0, \beta)$, fields $\vec{E} = (E_x, E_y, E_z)$ and $\vec{B} = \mu_0(H_x, H_y, H_z)$, where μ_0 is vacuum permeability.
- Vanishing Lorentz force $\vec{F}_{\mathrm{L}} = 0 \Rightarrow$ field quotient Z_q

$$E_x = -c \cdot \beta \cdot \mu_0 \cdot H_y \quad \Rightarrow \quad \boxed{Z_q = -\frac{E_x}{H_y} = c \cdot \beta \cdot \mu_0 \approx 173\ \Omega}. \tag{3}$$

Measured phase and impedance mismatch $f_{\mathrm{WF}} = 871\,\mathrm{kHz}$



E/B phase as function of C_{L} and C_{T}.



Impedance Z_9 as function of C_{L} and C_{T}.

β matching:

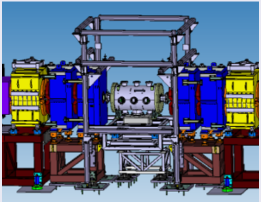
$Z_9 = 79\,\Omega$ when matched to deuteron momentum of $970\,\mathrm{MeV}/c$

Variation of β-functions using PAX section

Device installed in PAX low-β section at COSY:

$\Rightarrow$ Allows for systematic studies with respect to divergence of beam.

- β-functions at RF Wien filter [5] (rel. uncertainty $\approx 10\%$):



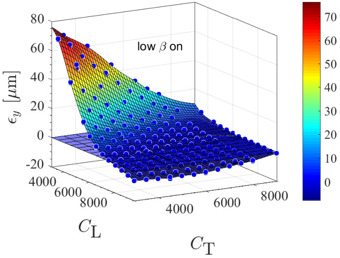
	Low-β Off	Low-β On
β_x	4 m	1.0 m
β_y	3 m	1.2 m

Table: from Bernd Lorentz using MAD.

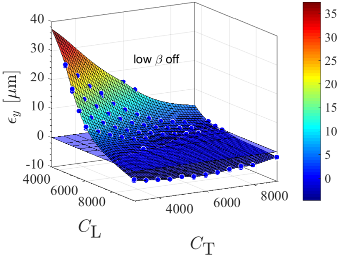
- Measurements of Lorentz force $\vec{F}_{\mathrm{L}}$ with low-β section ON/OFF were carried out at the $K = -1$ harmonic at $f_{\mathrm{WF}} = 871\,\mathrm{kHz}$.

Beam oscillations at $f_{\mathrm{WF}} = 871\,\mathrm{kHz}$ for low-β ON/OFF

Vertical



Low-β section ON.



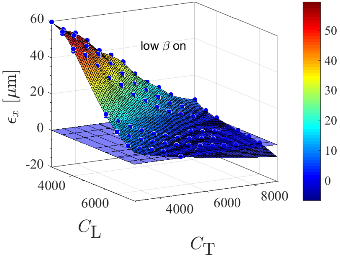
Low-β section OFF.

RF power $P = 1\,\mathrm{kW}$, driving circuit uses fixed $L_{\mathrm{f}} = 28\,\mu\mathrm{H}$:

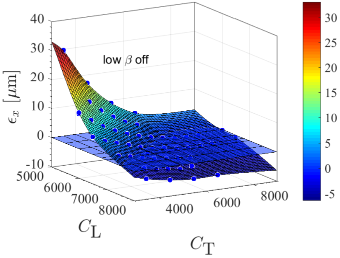
- Beam oscillation amplitudes measured using BPM #17.
- Matching point (MP):
    - located at $C_{\mathrm{L}} = 6800$ and $C_{\mathrm{T}} = 4950$.
    - Location, where E and B in phase and Lorentz force $\vec{F}_{\mathrm{L}} = 0$,
    - C_{L} and C_{T} in steps from 0 to 10000, C's here range from 50 to 950 pF.

Beam oscillations at $f_{\mathrm{WF}} = 871\,\mathrm{kHz}$ for low-β ON/OFF

Horizontal



Low-β section ON.



Low-β section OFF.

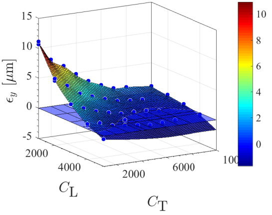
RF power $P = 1\,\mathrm{kW}$, driving circuit uses fixed $L_\mathrm{f} = 28\,\mu\mathrm{H}$:

- Beam oscillation amplitudes measured using BPM #17.
- Matching point (MP):
  - located at $C_\mathrm{L} = 6800$ and $C_\mathrm{T} = 4950$.
  - Location, where E and B in phase and Lorentz force $\vec{F}_\mathrm{L} = 0$,
  - C_L and C_T in steps from 0 to 10000, C's here range from 50 to 950 pF.

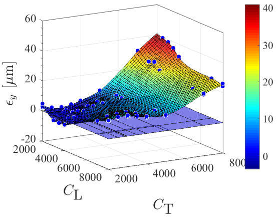
Beam oscillations at 630 kHz, 1380 kHz, and 1621 kHz
Vertical

All measurements with low-β section OFF and RF power $P = 1\,\mathrm{kW}$:

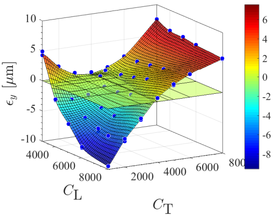
- Beam oscillation amplitudes measured using BPM #17.



630 kHz: Fixed $L_\mathrm{f} = 30\,\mu\mathrm{H}$. C's: 500 pF to 1.5 nF. MP: $C_\mathrm{L} = 4400$ and $C_\mathrm{T} = 3700$.



1380 kHz: Fixed $L_\mathrm{f} = 25\,\mu\mathrm{H}$. C's: 50 pF to 950 pF. MP: $C_\mathrm{L} = 2450$ and $C_\mathrm{T} = 2980$.



1621 kHz: Fixed $L_\mathrm{f} = 20\,\mu\mathrm{H}$. C's: 50 pF to 950 pF. MP: $C_\mathrm{L} = 3200$ and $C_\mathrm{T} = 4700$.

Interpretation

Observation

- Typical horizontal and vertical COSY working points at $\nu_{x,y} \approx 3.6$

$$\Rightarrow \quad \Omega^{\text{betatron}} \approx 0.6 \cdot f_{\text{rev}} = 450\,\text{kHz}$$
$$\text{calculate ratio} \quad R = \frac{f_{\text{WF}}}{\Omega^{\text{betatron}}} \tag{4}$$

- From inspection of previous graphs, it appears that the closer R is to an integer, the larger the observed oscillation amplitude ε_y:

f_{WF}	R	ε_y
630 kHz	1.40	small
871 kHz	1.94	large
1380 kHz	3.07	large
1621 kHz	3.60	small

Conclusion

- Each harmonic induces different oscillation amplitudes, which generate different contributions to the systematic error of the experiment.

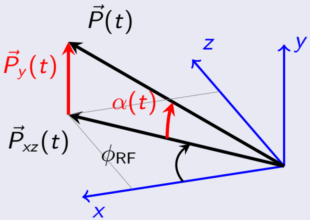
Strength of EDM resonance

EDM induced vertical polarization oscillations,

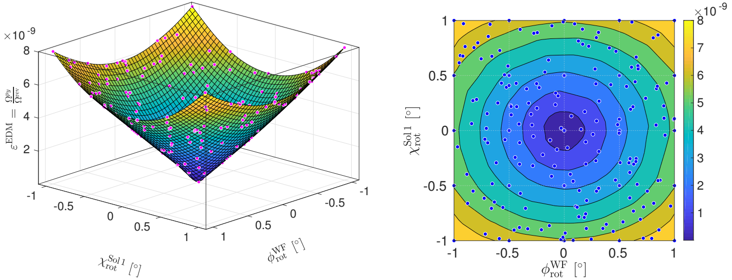
- can be described by
$$p_y(t) = a \sin(\Omega^{p_y}\, t + \phi_{\mathrm{RF}})\,. \tag{5}$$
- Define EDM resonance strength $\varepsilon^{\mathrm{EDM}}$ as ratio of angular frequency Ω^{p_y} relative to orbital angular frequency Ω^{rev},
$$\varepsilon^{\mathrm{EDM}} = \frac{\Omega^{p_y}}{\Omega^{\mathrm{rev}}}\,, \tag{6}$$

Alternatively, $\varepsilon^{\mathrm{EDM}}$ can be determined from the measured slopes $\dot{p}_y(t)$

- through variation of ϕ_{RF}
$$\varepsilon^{\mathrm{EDM}} = \frac{\dot{p}_y(t)\big|_{t=0}}{a \cos\phi_{\mathrm{RF}}} \cdot \frac{1}{\Omega^{\mathrm{rev}}}\,. \tag{7}$$
- If $|\vec{P}| = 1 \quad \Rightarrow \quad \dot{p}_y(t) = \dot{\alpha}(t)$



Expectation for $d = 10^{-20}\,\mathrm{e\,cm}$ in ideal COSY ring

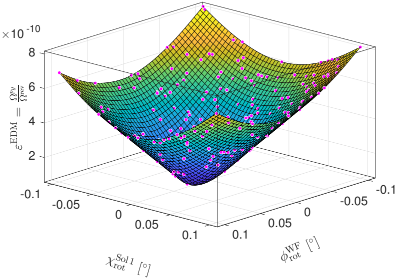


(a) $\varepsilon^{\mathrm{EDM}}$ for $d = 10^{-20}\,\mathrm{e\,cm}$. (b) Contour plot of (a).

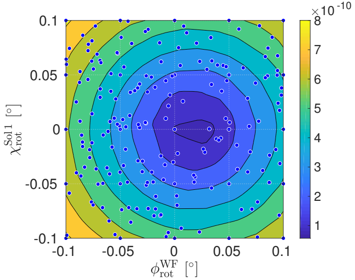
Resonance strengths $\varepsilon^{\mathrm{EDM}}$ from Eq. (6) (≈ 175 random-points)

- $\phi^{\mathrm{WF}}_{\mathrm{rot}} = [-1\,°, \ldots, +1\,°]$,
- $\chi^{\mathrm{Sol\,1}}_{\mathrm{rot}} = [-1\,°, \ldots, +1\,°]$ (100 keV cooler), and
- $\chi^{\mathrm{Sol\,2}}_{\mathrm{rot}} = 0$ (2 MeV cooler).
- Each point from calculation with $n_{\mathrm{turns}} = 50\,000$ and $n_{\mathrm{points}} = 200$.

Expectation for $d = 10^{-18}\,\mathrm{e\,cm}$ in ideal COSY ring



(c) $\varepsilon^{\mathrm{EDM}}$ for $d = 10^{-18}\,\mathrm{e\,cm}$.



(d) Contour plot of (c).

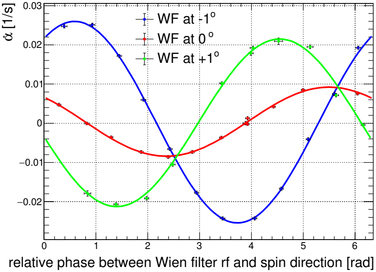
Resonance strengths $\varepsilon^{\mathrm{EDM}}$ from Eq. (6) (≈ 175 random-points)

- $\phi_{\mathrm{rot}}^{\mathrm{WF}} = [-0.1\,°, \ldots, +0.1\,°]$,
- $\chi_{\mathrm{rot}}^{\mathrm{Sol\,1}} = [-0.1\,°, \ldots, +0.1\,°]$ (100 keV cooler), and
- $\chi_{\mathrm{rot}}^{\mathrm{Sol\,2}} = 0$ (2 MeV cooler).
- Each point from calculation with $n_{\mathrm{turns}} = 200\,000$ and $n_{\mathrm{points}} = 100$.

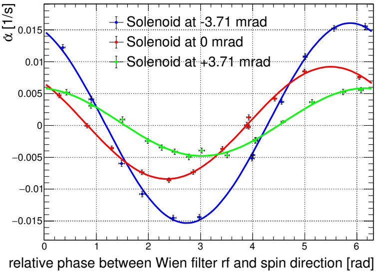
First measurement of EDM-like buildup signals

Rate of out-of-plane rotation angle $\dot{\alpha}$ as function of Wien filter RF phase ϕ_{RF}

- B field of RF Wien filter normal to the ring plane.
- Wien filter operated at $f_{\mathrm{WF}} = 871\,\mathrm{kHz}$.
- Variations of $\phi^{\mathrm{WF}}_{\mathrm{rot}}$ and $\chi^{\mathrm{Sol\,1}}_{\mathrm{rot}}$ affect the pattern of observed $\dot{\alpha}$ (see also Figs. on slides 16 and 17).



$\dot{\alpha}$ for $\phi^{\mathrm{WF}}_{\mathrm{rot}} = -1^\circ,\ 0^\circ,\ +1^\circ$ and $\chi^{\mathrm{Sol\,1}}_{\mathrm{rot}} = 0$.



$\dot{\alpha}$ for $\chi^{\mathrm{Sol\,1}}_{\mathrm{rot}} = -1,\ 0,\ +1^\circ$ and $\phi^{\mathrm{WF}}_{\mathrm{rot}} = 0$.

Improvements I

Machine setup

- Reliable automatic COSY orbit control with Schneider box feedback to stabilize detector rate in horizontal and vertical ring planes toward end **E005.4** run.
- Progress with beam-based alignment at COSY.
  - Purpose: better characterize real position offsets of BPMs at COSY.
  - Based on first recent test using quadrupole QT12, dedicated JEDI proposal (**A015** T. Wagner & B. Lorentz) submitted for present CBAC [6].
- During **E005.4**, new mode of operation established at COSY:
  - Switch off electron beam on flattop, and magnetic elements of 100 keV cooler.
  - Magnitude of strong steerer fields in cooler section reduced to $\approx 5\%$ of nominal value.
  - New operation mode simplifies COSY lattice $\Rightarrow$ spin-tracking simulations shall become simpler.

Improvements II

WASA Polarimeter

1. Commissioning times were successfully used to make WASA available as on-line polarimeter for polarization monitoring, spin tune measurement and phase-locking.
2. Carbon block target at WASA routinely operated. Orbit control in conjunction with extraction process optimized.
3. During commissioning runs in Nov. '17 (**E005.2**) and May '18 (**E005.4**), improved versions of phase-lock feedback tested with polarized beam.

Improvements III

Further items addressed during commissioning runs

1. Read-back of dipole, steerer, quadrupole, sextupole, and solenoid currents implemented at COSY.
   - Data stored in EPICS database, including settings of Schneider box, and active spin bits from polarized ion source.
2. Two more Zurich lock-in amplifiers[a] implemented for $\vec{F}_\mathrm{L}$ measurement, making use of BPM #17.
   - Signals from four BPM quadrants now acquired individually.
3. 10 MHz frequency reference signal prepared and distributed to COSY RF, solenoid RF, and Wien filter RF.
   - Makes sure that all frequency generators agree frequency-wise.

[a] Zurich Instruments, model HF2LI, `https://www.zhinst.com/products/hf2li`.

Improvements IV

Further items addressed during commissioning runs.

4. Wien filter aligned with respect to the COSY ring plane,
    - determined during recent COSY magnet survey & alignment campaign[a].
    - New electronic levels[b] implemented to set WF rotation angle with accuracy of at least 170 µrad[c]:

$$\begin{aligned} \#3483\text{Z:} \quad & \theta(\vec{B} \parallel \vec{e}_y) = (+0.74 \pm 0.17)\,\text{mrad at } T = 21.006\,^\circ\text{C} \\ \#3486\text{Z:} \quad & \theta(\vec{B} \parallel \vec{e}_x) = (+0.57 \pm 0.17)\,\text{mrad at } T = 20.865\,^\circ\text{C} \end{aligned} \tag{8}$$

        - $\vec{e}_y$ denotes true normal to ring plane, and
        - $\vec{e}_x$ is radially-outward pointing vector in ring plane.
5. Improved calibration of new pair of Rogowski coil BPMs presently established using upgraded laboratory test setup.
    - Calibrated coils will be installed at entrance and exit of RF Wien filter during summer shutdown.

[a] Vermessungsbüro Stollenwerk & Burghof, Bergheim, Germany
[b] ZEROTRONIC inclination sensor, WylerAG, https://www.wylerag.com.
[c] Corresponds to ½ year drift, weekly recalibration shall give acurracy < 50 µrad.

Planned sequence of beam times (as of CBAC # 7)

2017				
Q2			**E005.1**	WF + unpolarized beam
Q3				
Q4		**E005.2**		WF + WASA + polarized beam

2018				
Q1		**E005.3**		WF + WASA + unpol. beam (cont'd)
Q2			**E005.4**	1^{st} EDM measurement w/o ferrites
Q3	**Shutdown**			Installation of ferrites
Q4			**E005.5**	2^{nd} EDM measurement with ferrites

2019				
Q1	**E005.5**			2^{nd} EDM measurement with ferrites

Difficulties with polarized beam operation during previous runs:

- ⇒ Only few days of polarized beam during **E005.2** and **E005.4**, no polarized beam in **E005.3**.
- ⇒ Modified strategy for 1^{st} EDM measurement w/o ferrites.
  - JEDI decision: Ferrites will be installed only *after* 1^{st} EDM measurement.

Actual sequence of used beam times

2017				
Q2			**E005.1**	WF + unpolarized beam
Q3				
Q4		**E005.2**		WF + WASA + polarized beam

2018				
Q1		**E005.3**		• $\vec{F}_{\mathrm{L}}$ measurements at 4 WF frequencies, $f_{\mathrm{WF}} = 630$, 871, 1380, and 1621 kHz.
Q2			**E005.4**	• Set up with 100 keV e-cooler magnets and steerers switched off on flattop. • Operation of Siberian snake as small angle spin rotator. • Few ϕ_{RF} scans of EDM-like polarization buildup during last weekend.
Q3	**Shutdown**			**No installation of ferrites**
Q4		**E005.5**		**1st EDM measurement w/o ferrites**

Beam Request **E005.5**

Production run to perform a first EDM measurement without ferrites:

- In view of past experience with machine development for JEDI, we would kindly like to **request 2 MD weeks** to set up machine.
- Essentially all subsystems of experimental setup have been tested successfully.
  - Recalibrated and improved Rogowski-BPM system at RF Wien filter shall be installed in next shutdown.
- We would like to **request 4 weeks for the EDM measurement**.

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] A. Saleev et al., Phys. Rev. Accel. Beams **20**, 072801 (2017).

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

[4] Y. F. Orlov, W. M. Morse, and Y. K. Semertzidis, Phys. Rev. Lett. **96**, 214802 (2006).

[5] C. Weidemann et al., Phys. Rev. ST Accel. Beams **18**, 020101 (2015).

[6] T. Wagner and B. Lorentz, Beam-based alignment, 2018, available from `http://collaborations.fz-juelich.de/ikp/jedi/public_files/proposals/Proposal_Beam_Based_Alignment_short.pdf`.

[7] J. Slim et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **859**, 52 (2017).

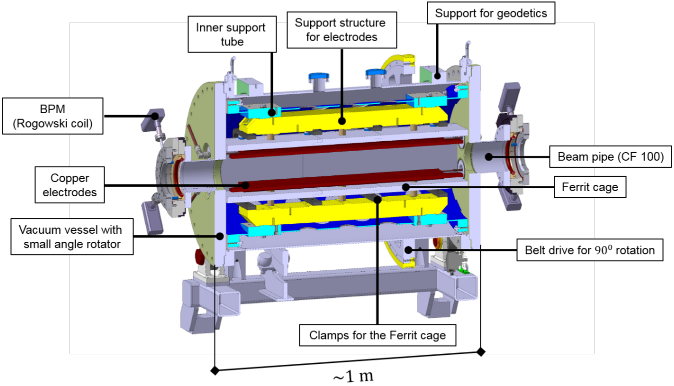
Spare transparencies

Sequence of JEDI related beam times at COSY

Priority list for JEDI:

Priority	Experiment	number	starting in
0	EDM proton database	E004	already scheduled
1	Precursor experiment	E005.5	2018
1b	COSY beam studies	A005.4	2018
2	Beam-based alignment	A015	2019
3a	Spin dynamics issues	E007.1	2019
3b	Axion-EDM	E008	2019
4	Polarimetry	E002.6	2019

Features of the waveguide RF Wien filter



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

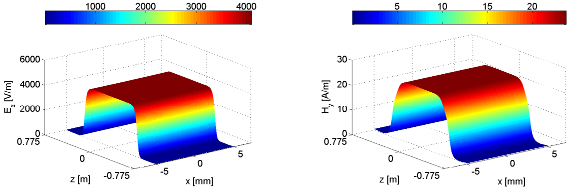
- Electromagnetic performance [1] and mechanical tolerances [7].
- Excellent cooperation with RWTH Aachen University and ZEA-Jülich.

Electromagnetic field simulations (incl. ferrites) [1]

Full-wave simulations

- using CST Microwave Studio[a].

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



At an input power of 1 kW, magnetic and electric field integrals are ($\ell = 1.550\,\mathrm{m}$):

$$\int_{-\ell/2}^{\ell/2} \vec{B} dz = \begin{pmatrix} 2.73 \times 10^{-9} \\ \mathbf{2.72 \times 10^{-2}} \\ 6.96 \times 10^{-7} \end{pmatrix} \mathrm{T\,mm}\,, \quad \int_{-\ell/2}^{\ell/2} \vec{E} dz = \begin{pmatrix} \mathbf{3324.577} \\ 0.018 \\ 0.006 \end{pmatrix} \mathrm{V} \quad (9)$$