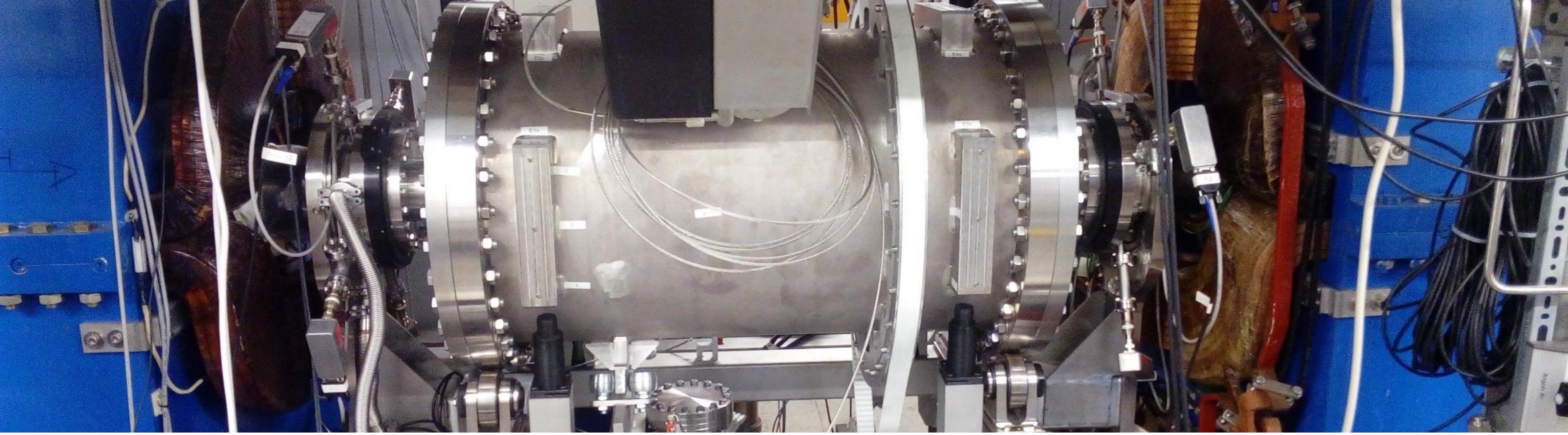


Lorentz-Force Free RF Spin Manipulator

Meeting on Polarized Ion Sources and Beams at EIC

Jamal Slim
11.03.2025

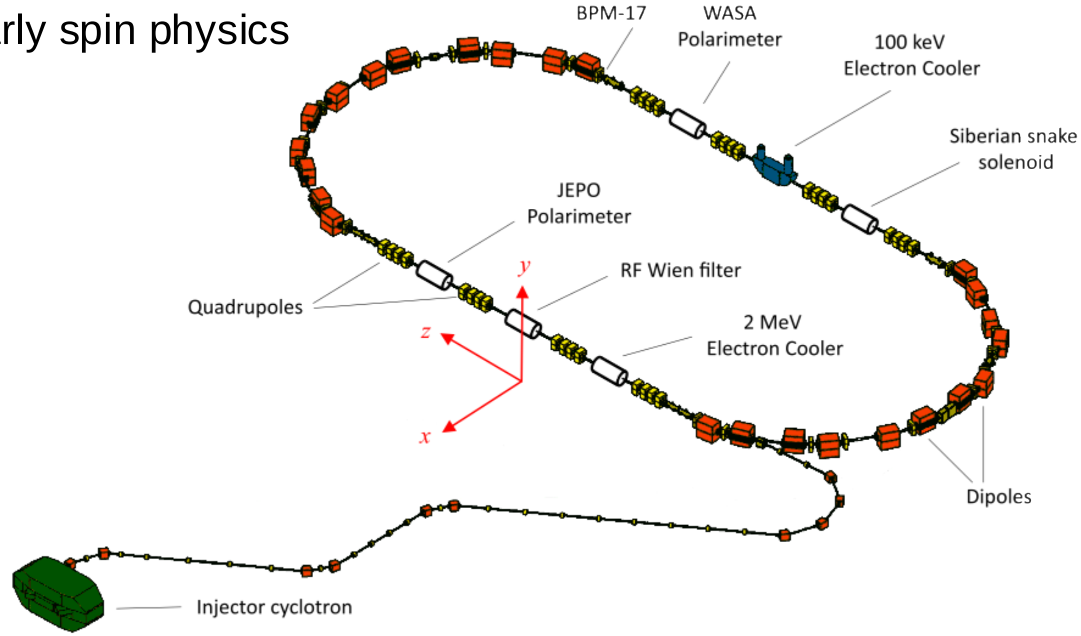
Content

- Design concept
- Electromagnetic simulations
- RF driving circuit
- Uncertainties
- Lorentz-Force measurements
- Spin Manipulation
- Potential use at EIC

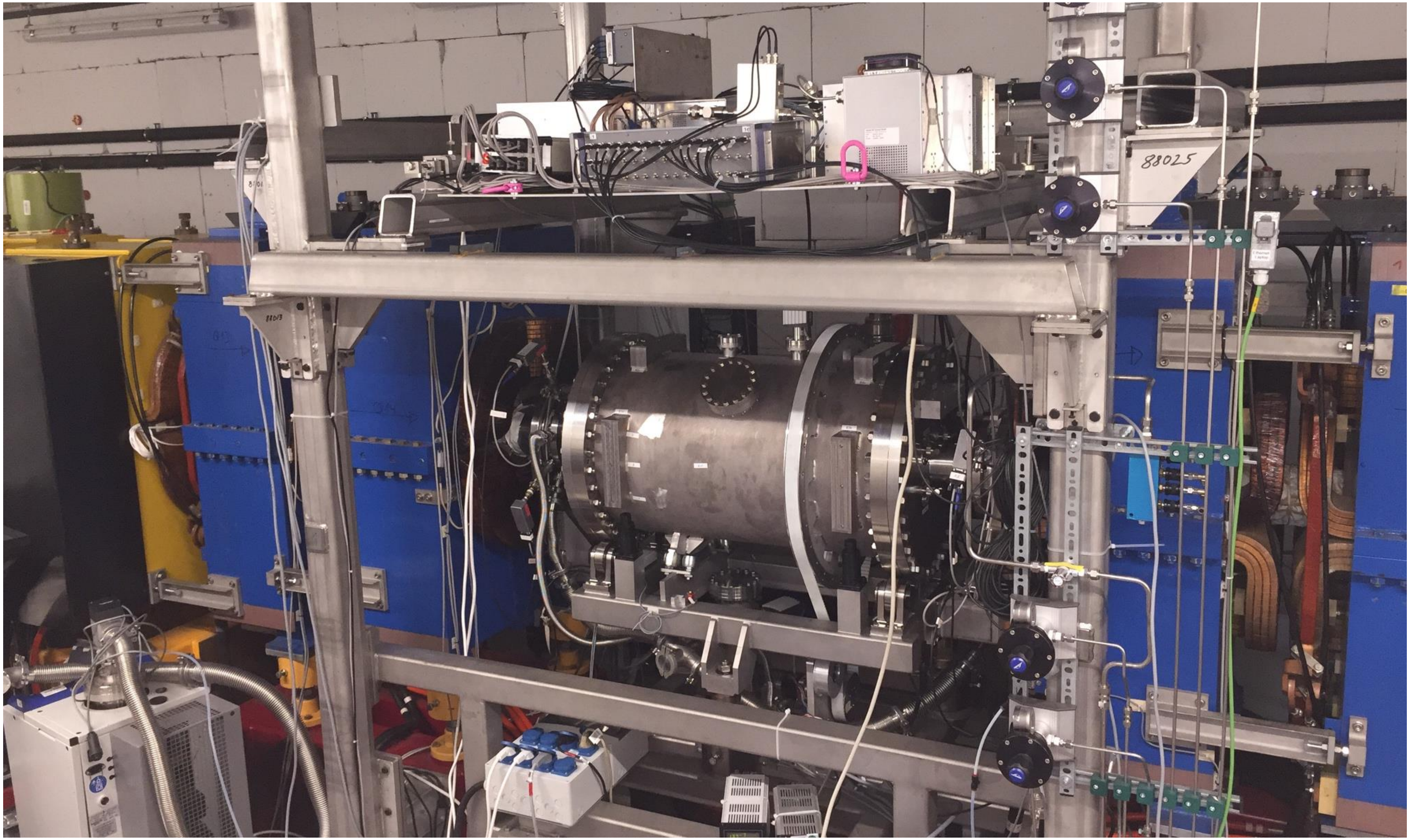
Experimenl Environpnment

COSY: COoler SYnchrotron

- **Polarized** and unpolarized protons and deuterons synchrotron and storage ring
- Nuclear and particle physics, particularly spin physics
- Two 180 deg. ~ 52 m each
- Two straight sections ~ 40m each
- Max momentum 3.7 GeV/c
- Electron and stochastic cooling
- Polarimeter (JePo,)
- Spin Manipulators
  - **The waveguide RF Wien Filter**



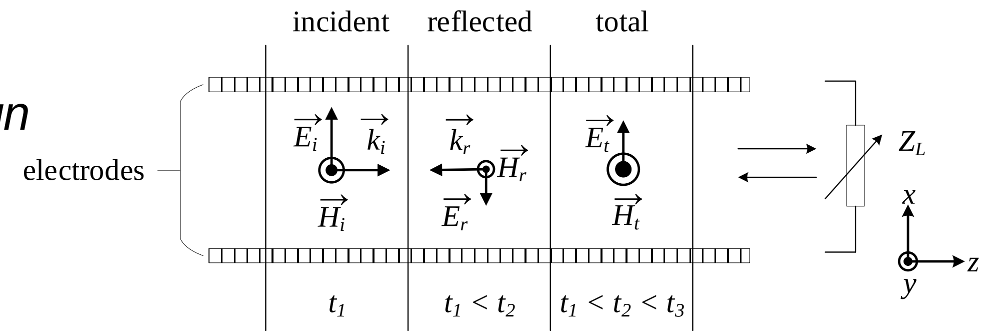
The RF Wien Filter



Electromagnetic Concept

Waveguide RF Wien filter

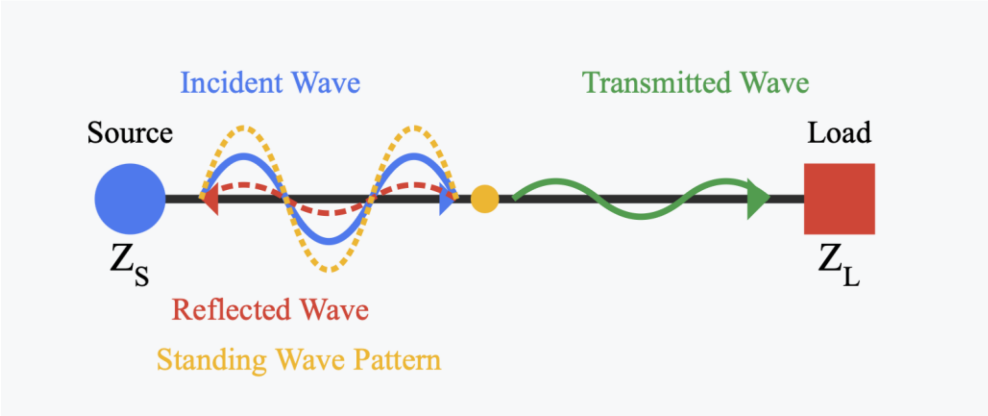
- Transverse electromagnetic mode
- Orthogonality is fulfilled *by-design*



Field quotient is controlled by the complex load impedance: wave mismatch

$$\vec{\underline{E}}(\vec{r}) = \left(E_0\, e^{-jk_z z} - \Gamma\, E_0\, e^{jk_z z}\right)\, \vec{e}_x$$

$$\vec{\underline{H}}(\vec{r}) = \left(H_0\, e^{-jk_z z} + \Gamma\, H_0\, e^{jk_z z}\right)\, \vec{e}_y$$



$$E_x = c \cdot \beta \cdot \mu_0 \cdot H_y$$

$$Z_q = \frac{E_x}{H_y} = c \cdot \beta \cdot \mu_0 \approx 173\ \Omega$$

This is designed for a *970 MeV/c* deuteron beam with a revolution frequency ~ 750 kHz, β~0.459

Basic Requirements

Wien filter condition

- Orthogonal electric and magnetic fields
- The quotient of the total electric and magnetic fields corresponds to the Lorentz β-factor

$$E_x = c \cdot \beta \cdot \mu_0 \cdot H_y$$

$$Z_q = \frac{E_x}{H_y} = c \cdot \beta \cdot \mu_0 \approx 173\ \Omega$$

Homogeneous electric and magnetic fields

$$\vec{E}_D = \begin{pmatrix} E_x \\ 0 \\ 0 \end{pmatrix} \quad \vec{H}_D = \begin{pmatrix} 0 \\ H_y \\ 0 \end{pmatrix}$$

$$\vec{E}_\perp = \begin{pmatrix} 0 \\ E_y \\ E_z \end{pmatrix} \quad \vec{H}_\perp = \begin{pmatrix} H_x \\ 0 \\ H_z \end{pmatrix}$$

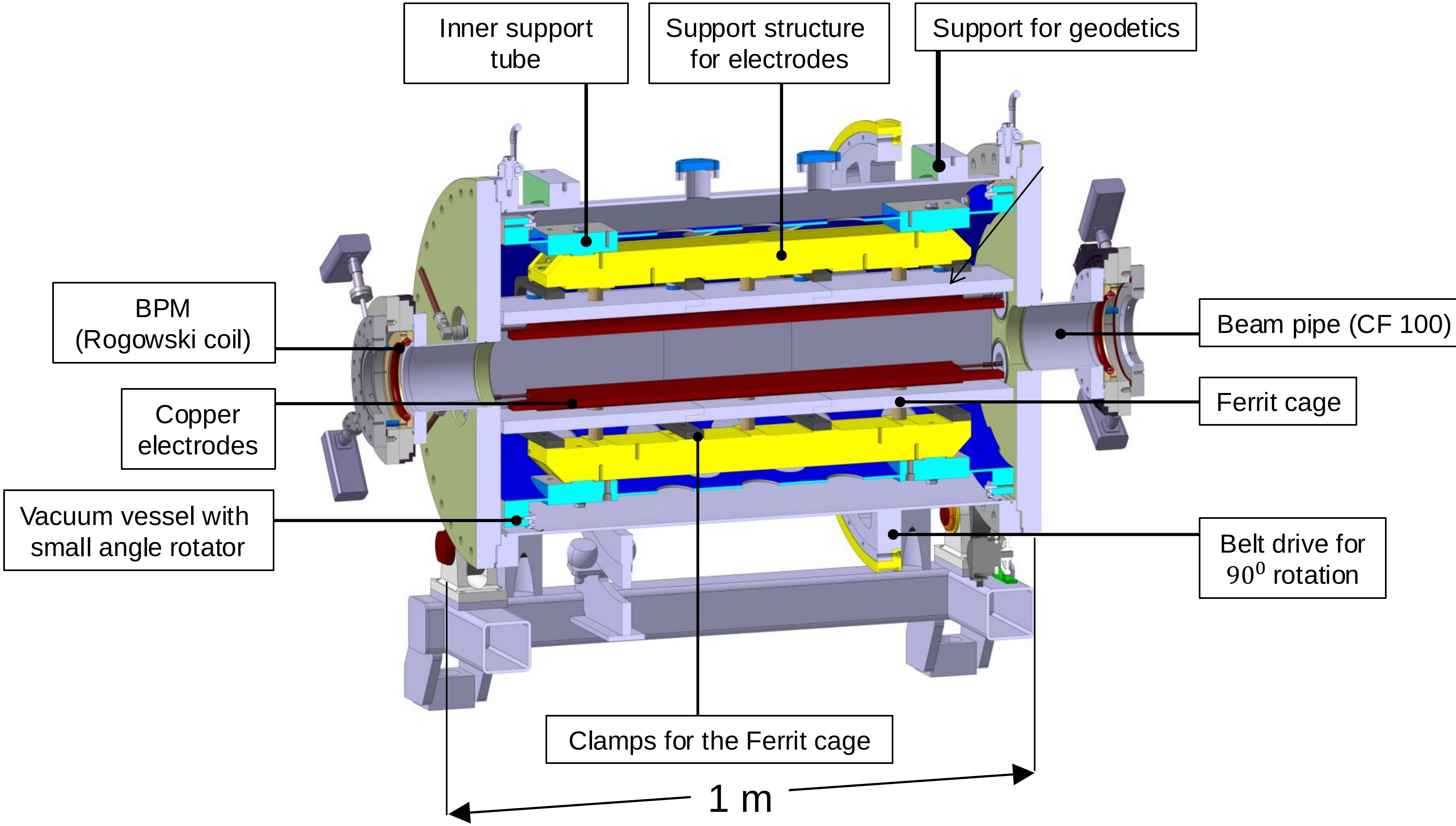
$$f_{E_\perp}^{\text{int}} = \frac{\int |\vec{E}_\perp| d\ell'}{\int |\vec{E}| d\ell'} \quad f_{H_\perp}^{\text{int}} = \frac{\int |\vec{H}_\perp| d\ell'}{\int |\vec{H}| d\ell'}$$

Resonance frequencies for protons and deuterons:

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

	f_{RF} [kHz]						
	$k=-4$	$k=-3$	$k=-2$	$k=-1$	$k=0$	$k=+1$	$k=+2$
d	3121.6	2371.4	**1621.2**	**871.0**	**120.8**	**629.4**	**1379.6**
p	**1543.9**	**752.2**	39.4	**831.0**	**1622.7**	2414.3	3206.0

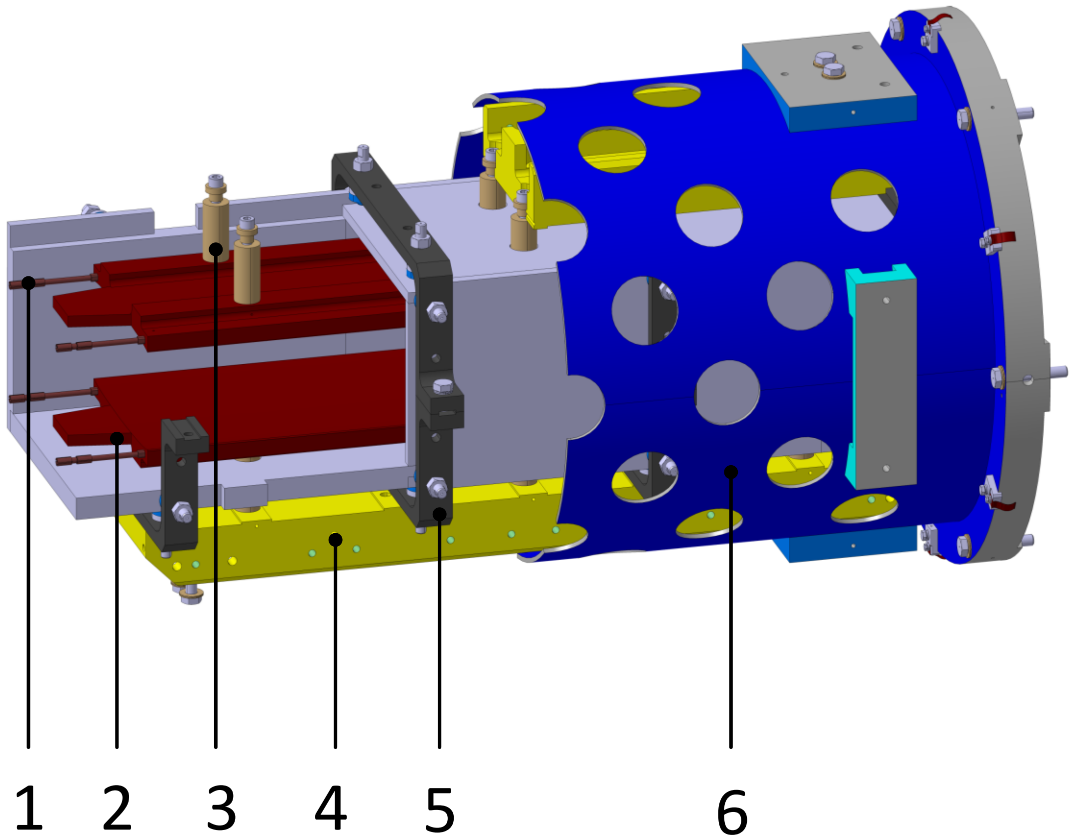
Electromagnetic Design



Mechanical Support

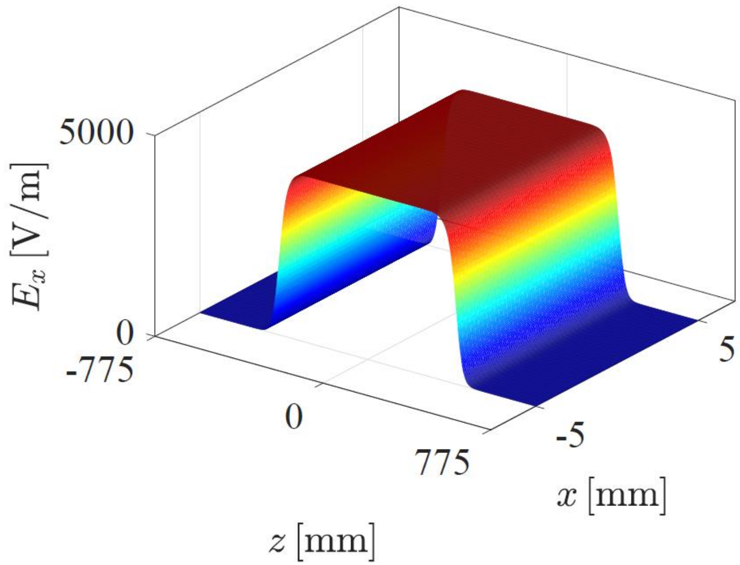
Mechanical structure

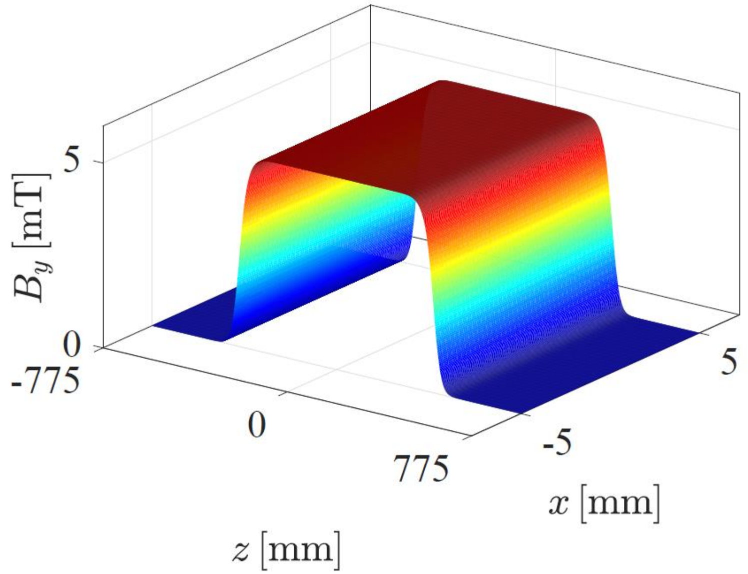
1. Sliding RF connectors
2. copper electrodes with the trapezium shaping at the edges
3. Ceramic insulators
4. Mechanical support for electrodes
5. Clamps supporting the ferrite cage
6. Inner support tube



Fields Profile

Uniform fields

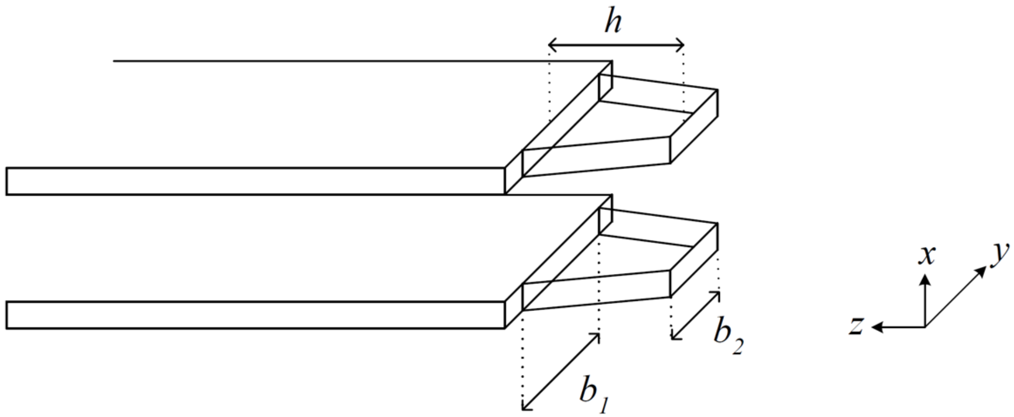


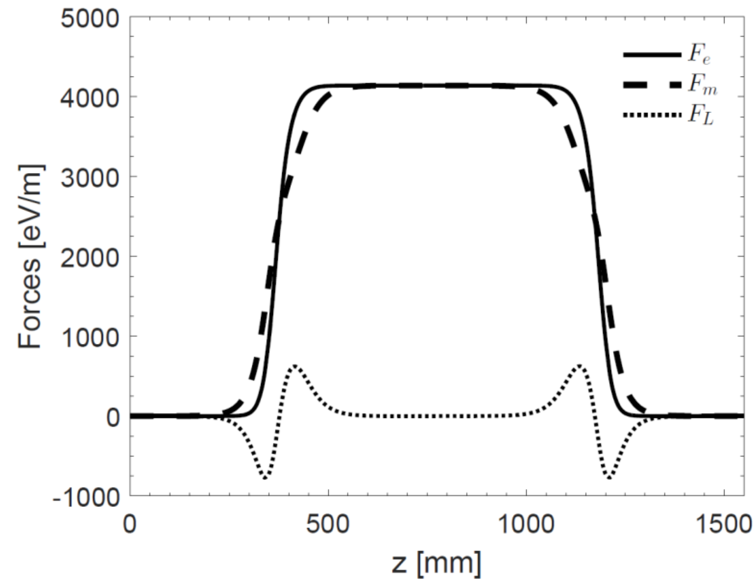


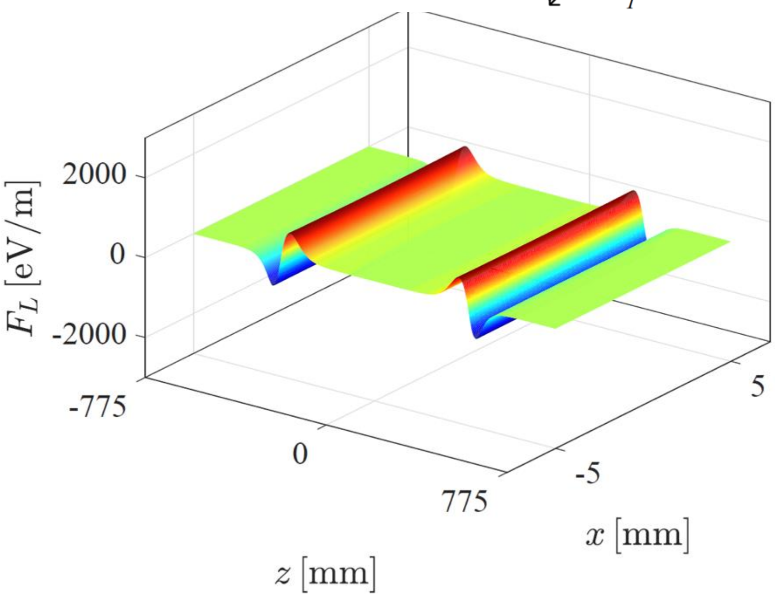
Total field integrals at 1kW of input power

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

Lorentz Force



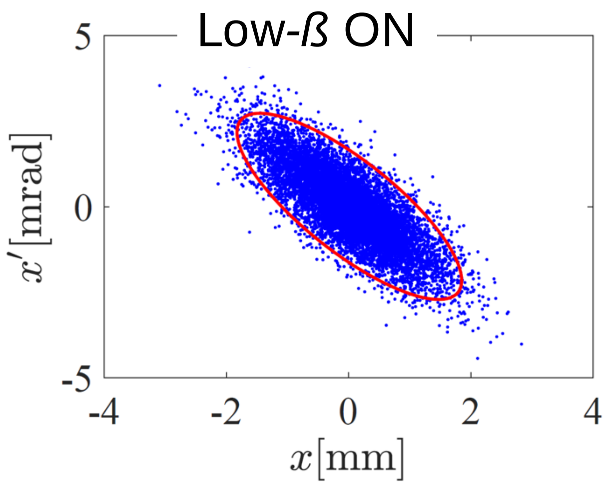


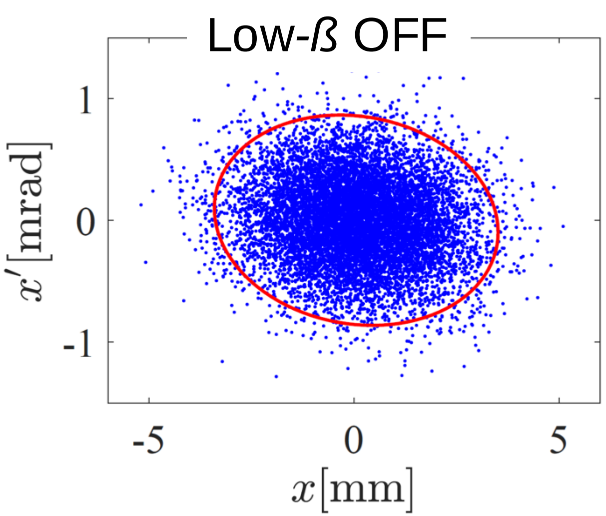


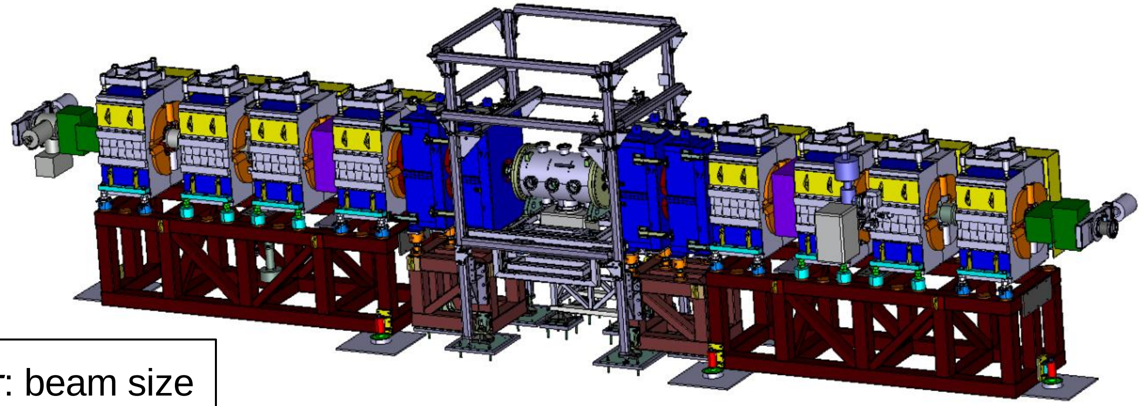
$$\frac{q}{\ell}\int_{-\ell/2}^{\ell/2}\begin{pmatrix} E_x - c\beta B_y \\ E_y + c\beta B_x \\ E_z \end{pmatrix} dz = \begin{pmatrix} 5.97\times 10^{-3} \\ 7.97\times 10^{-3} \\ 1.27\times 10^{-21} \end{pmatrix} \mathrm{eV/m}$$

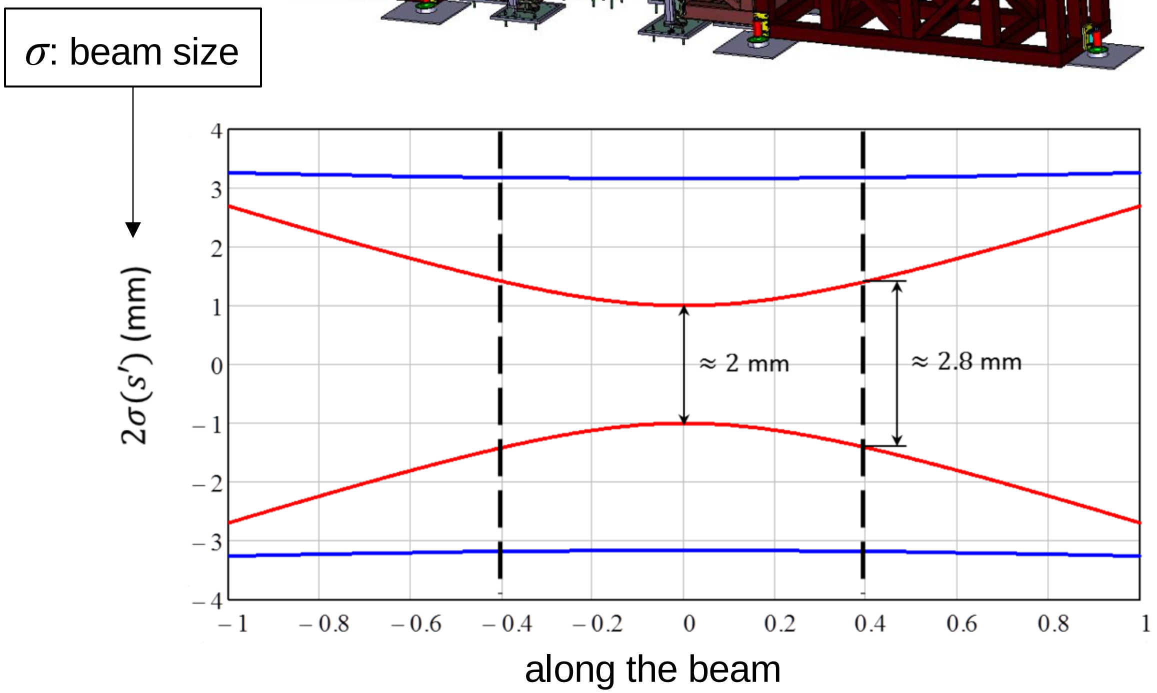
$$\frac{1}{b_x b_y \ell}\int_{-b_x/2}^{b_x/2}\int_{-b_y/2}^{b_y/2}\int_{-\ell/2}^{\ell/2}\vec{F}_\mathrm{L}\,dx\,dy\,dz = \begin{pmatrix} 0.6238 \\ 0.0214 \\ 1.61\times 10^{-20} \end{pmatrix} \mathrm{eV/m}$$

Field Homogeneity









Field Homogeneity

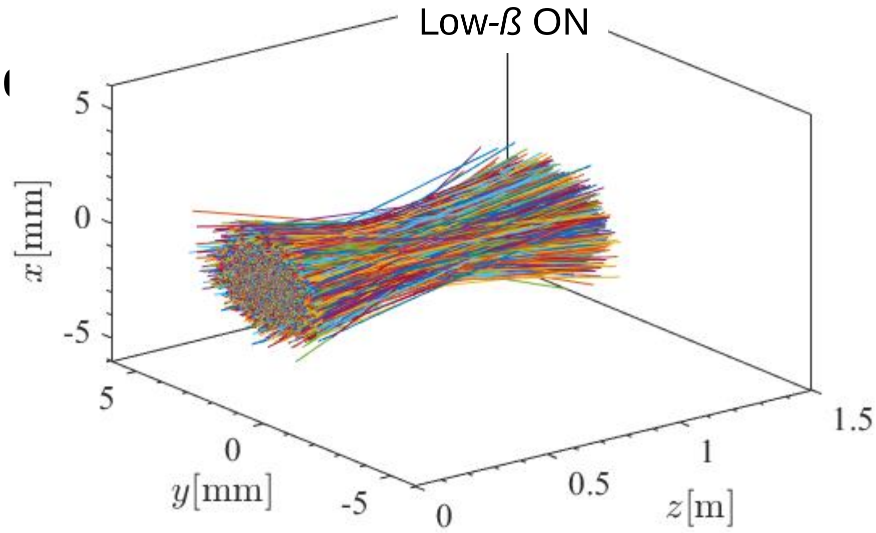
Evaluating the field homogeneity based on beam tracking/simulation

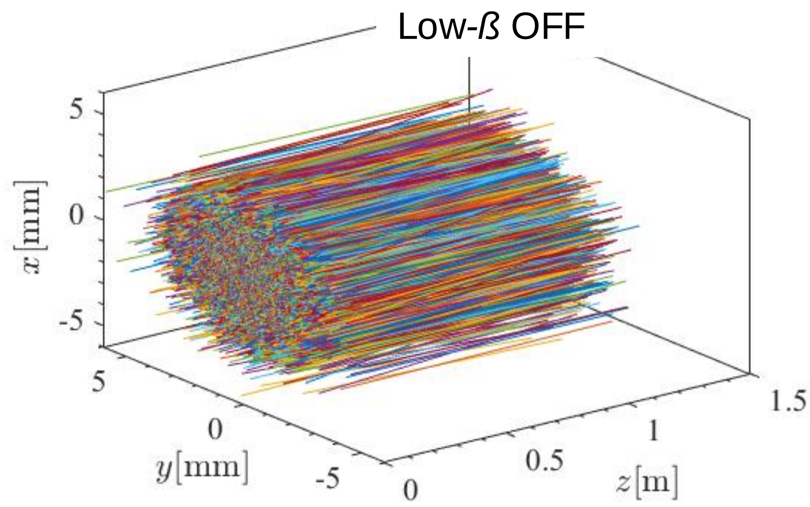
$$\frac{d\vec{v}}{dt} = \frac{q}{m\gamma}\left[\vec{E}(\vec{r},t) + \vec{v}\times\vec{B}(\vec{r},t)\right] - \frac{q}{m\gamma c^2}\vec{v}\left[\vec{v}\cdot\vec{E}(\vec{r},t)\right]$$

$$\frac{d\vec{r}}{dt} = \vec{v}$$

$$\vec{E}_\perp = \begin{pmatrix} 0 \\ E_y \\ E_z \end{pmatrix} \quad \vec{H}_\perp = \begin{pmatrix} H_x \\ 0 \\ H_z \end{pmatrix}$$

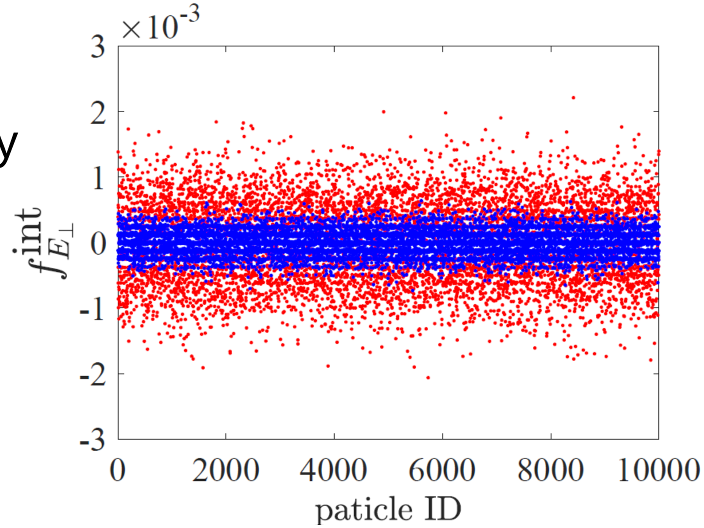
$$f_{E_\perp}^{\text{int}} = \frac{\int |\vec{E}_\perp| d\ell'}{\int |\vec{E}| d\ell'} \quad f_{H_\perp}^{\text{int}} = \frac{\int |\vec{H}_\perp| d\ell'}{\int |\vec{H}| d\ell'}$$

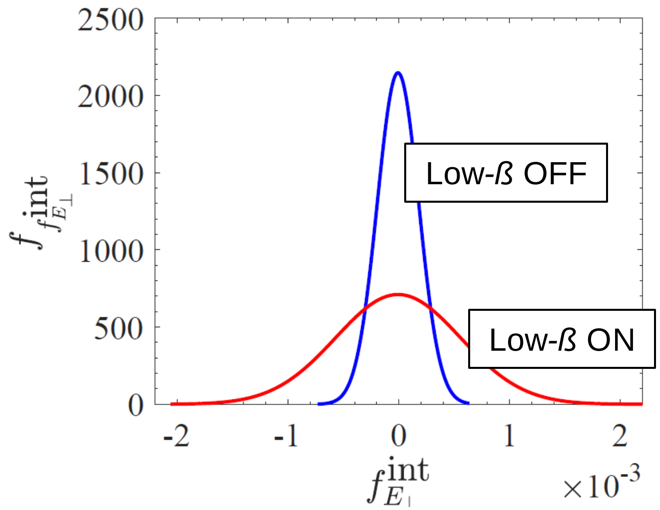




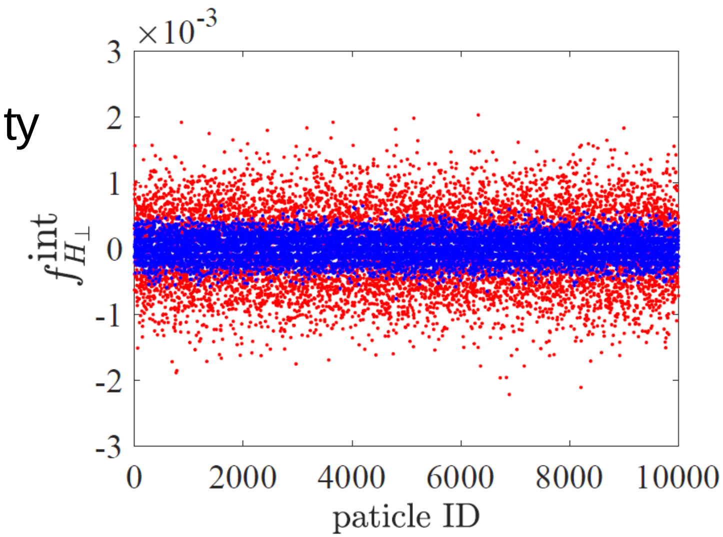
Electromagnetic Fields Homogeneity

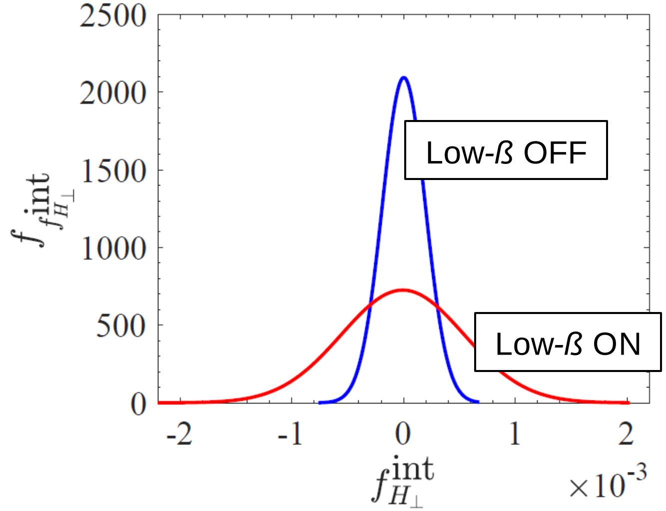
- E-field homogeneity
  - Low-beta ON
    5.7×10^{-4}
  - Low-beta OFF
    1.8×10^{-4}





- H-field homogeneity
  - Low-beta ON
    5.5×10^{-4}
  - Low-beta OFF
    1.8×10^{-4}



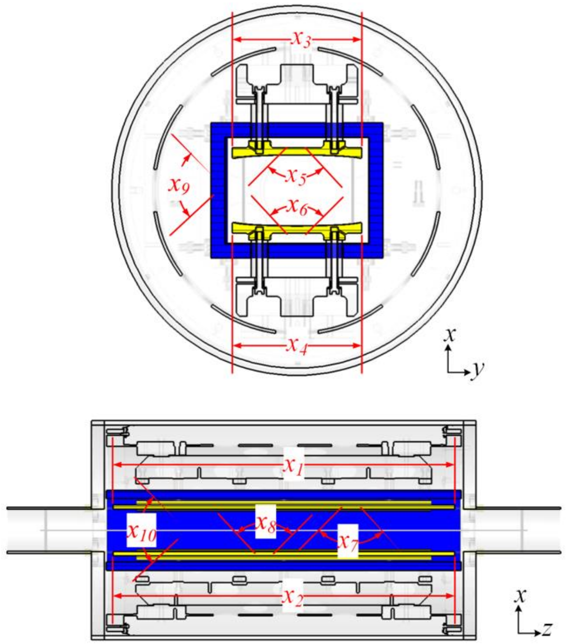


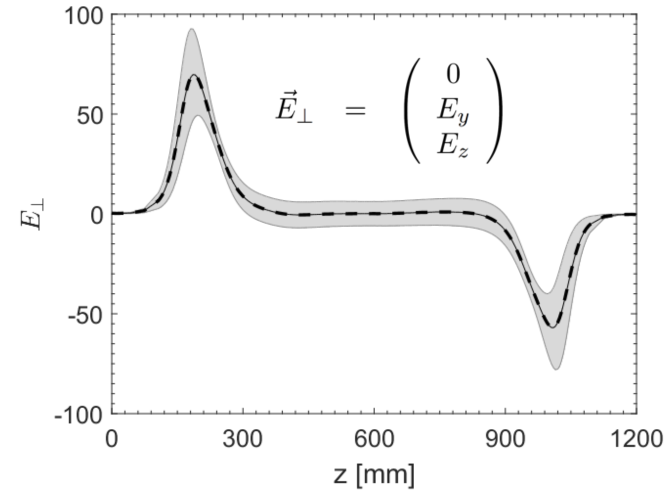
Tolerance Analysis

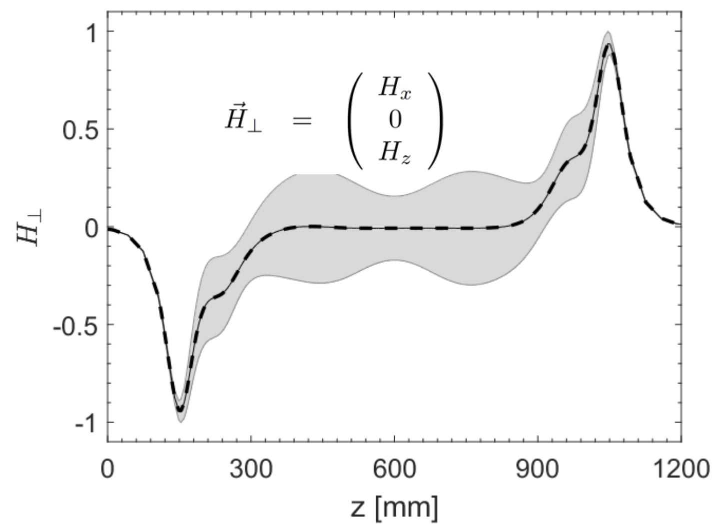
variable	distribution
x_1	$G\,(808.8, 0.1)$ mm
x_2	$G\,(808.8, 0.1)$ mm
x_3	$G\,(182, 0.1)$ mm
x_4	$G\,(182, 0.1)$ mm
x_5	$G\,(0, 1)$ mrad
x_6	$G\,(0, 1)$ mrad
x_7	$G\,(0, 1)$ mrad
x_8	$G\,(0, 1)$ mrad
x_9	$G\,(0, 1)$ mrad
x_{10}	$G\,(0, 1)$ mrad

$$f^{\mathrm{int}}_{E_\perp} = \frac{\int_{-\ell/2}^{\ell/2} |\vec{E}_\perp| d\ell}{\int_{-\ell/2}^{\ell/2} |\vec{E}| d\ell} = \mathcal{Y}_E$$

$$f^{\mathrm{int}}_{H_\perp} = \frac{\int_{-\ell/2}^{\ell/2} |\vec{H}_\perp| d\ell}{\int_{-\ell/2}^{\ell/2} |\vec{H}| d\ell} = \mathcal{Y}_H$$







Performance Analysis

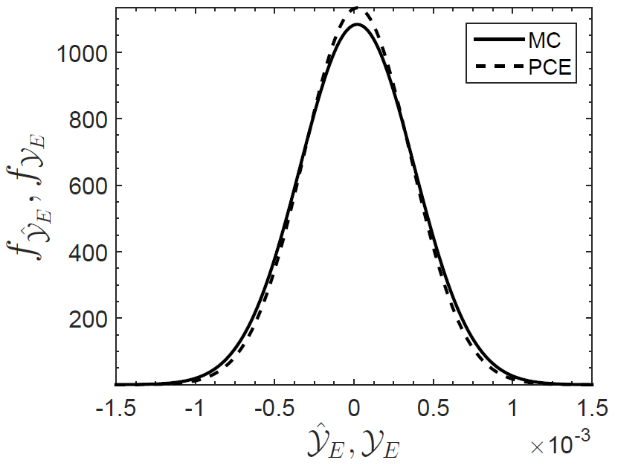
With mechanical uncertainties

E-field homogeneity

$\boxed{4.8\times10^{-4}}$

H-field homogeneity

$\boxed{3.1\times10^{-4}}$



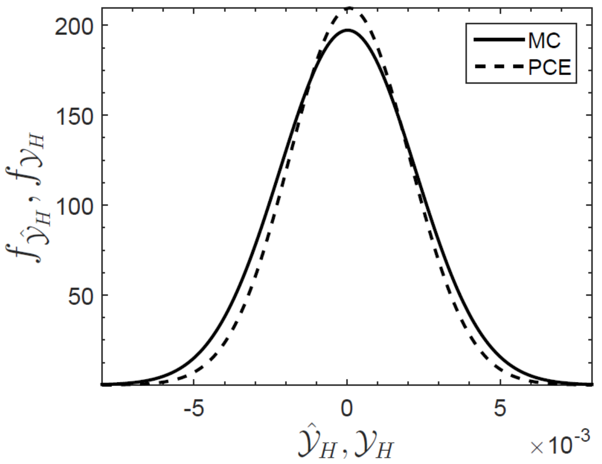
Without mechanical uncertainties

E-field homogeneity

$\boxed{1.8\times10^{-4}}$

H-field homogeneity

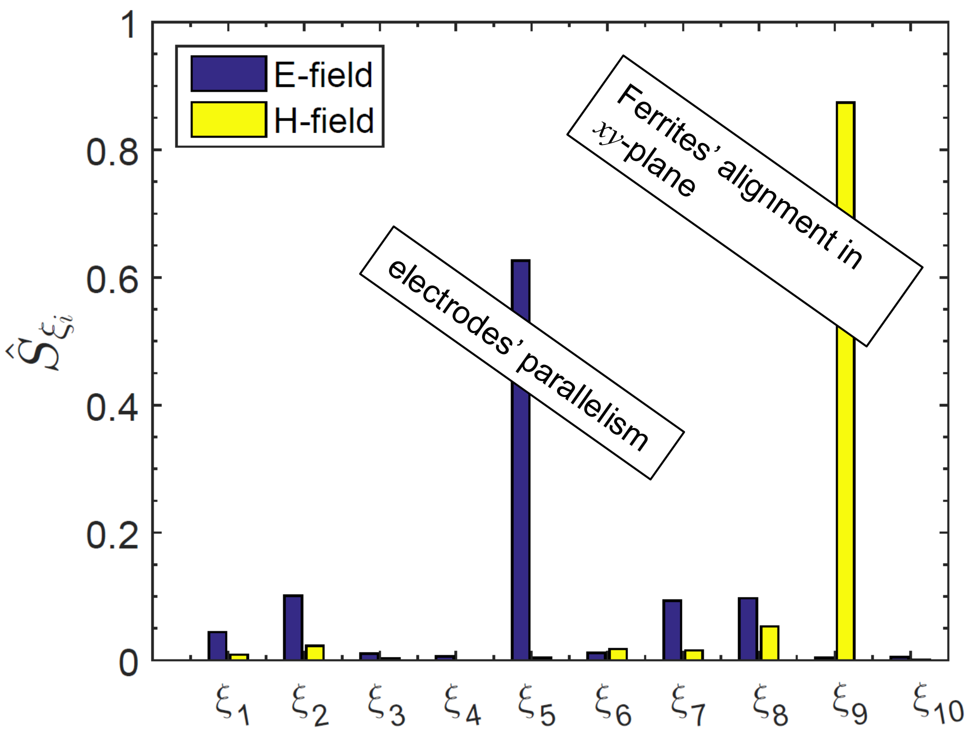
$\boxed{1.8\times10^{-4}}$



Sensitivity Analysis

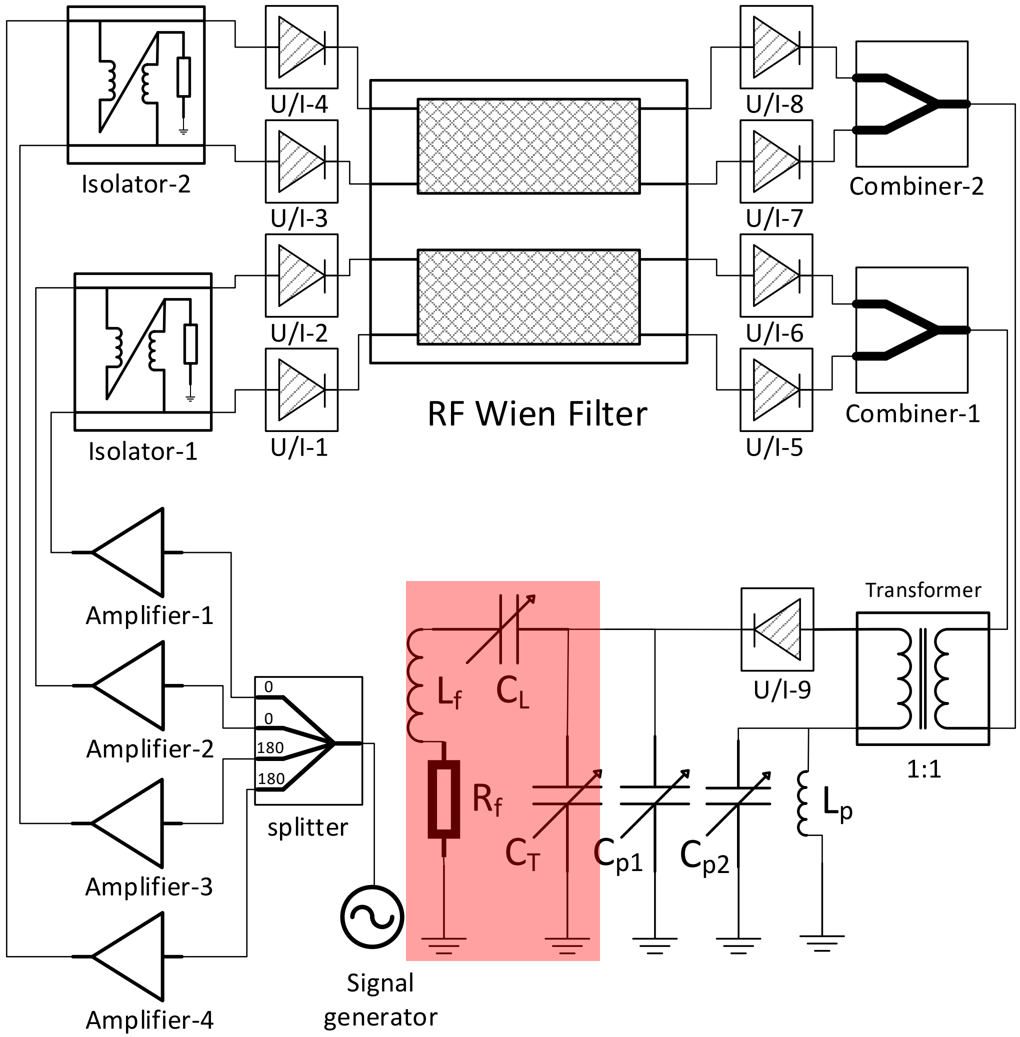
- Sobol sensitivity analysis
- Indices are calculated using the PCE method
- Each index value denotes the sensitivity of the variance of the output to the corresponding input variable

- E-field homogeneity
  - Electrodes rotation (62%)
    - Parallelism
- H-field homogeneity
  - Ferrites alignment in *xy*-plane (85%)



Driving Circuit

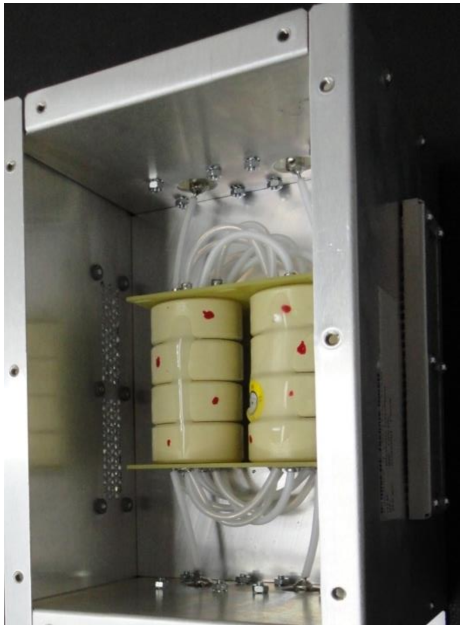
1 signal generator
1 signal splitter
4 power amplifiers
2 isolators
9 voltage/current detectors
2 power combiners
1 1:1 transformer
4 vacuum high precision capacitors
2 air coils
1 water cooled fixed-resistor

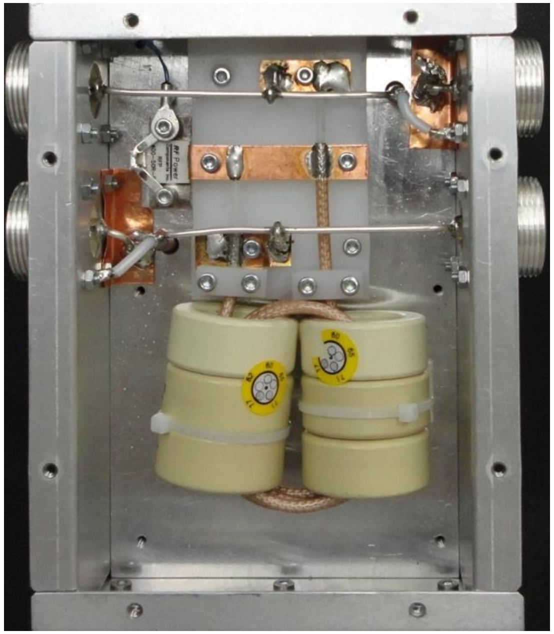


High-Power Analog Electronics

- High-power RF electronics (10 kW up to 10 MHz)
- Active cooled
- High-precision
- Custom designed

Vacuum capacitors
50 pF...1 nF





Air coil: 28.7 µH
@ 871 kHz

Sensitivity Analysis

E-field homogeneity

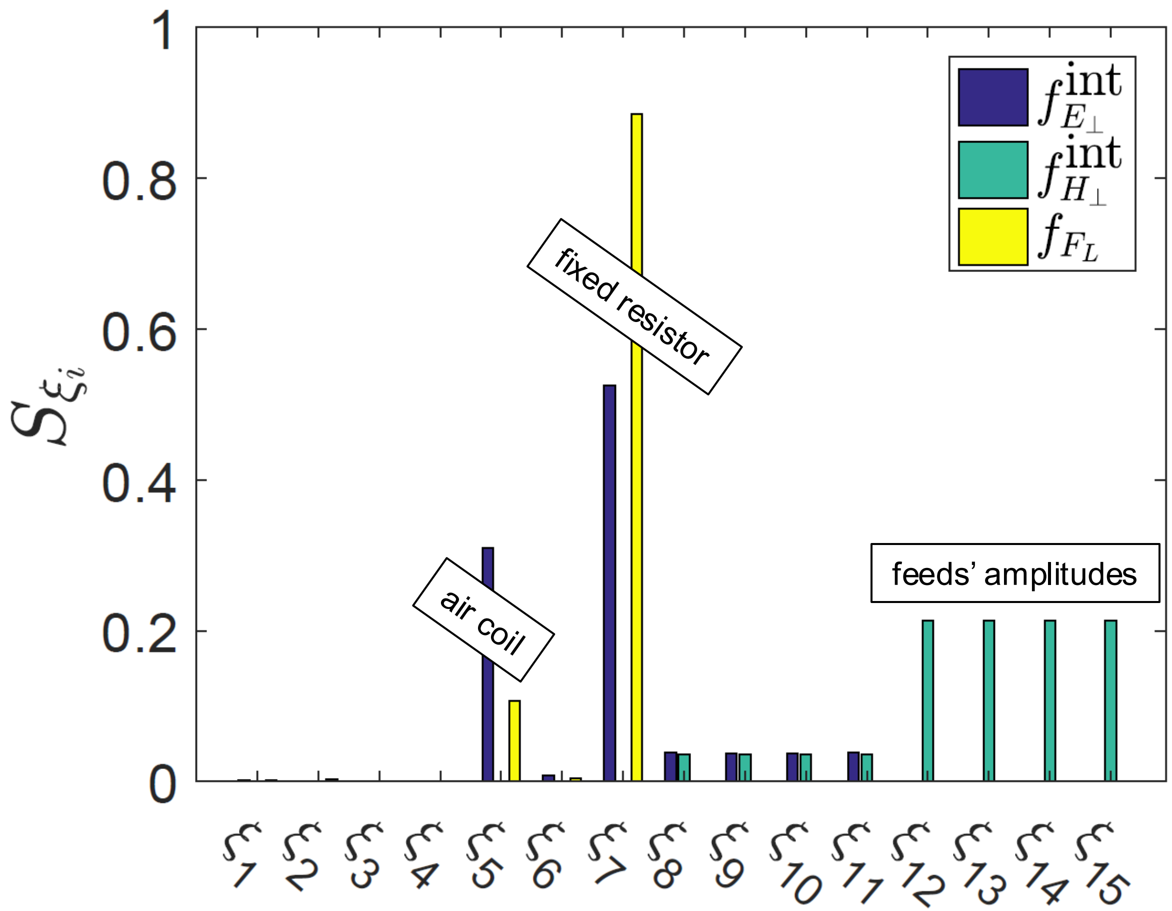
50% fixed resistor
30% air-coil of the impedance

H-field homogeneity

85% amplitude of the feed signals

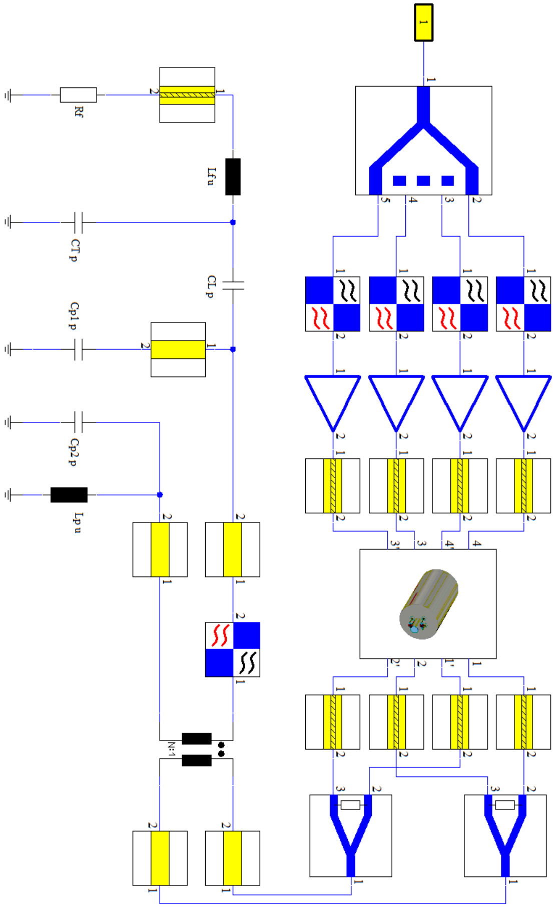
Lorentz force

76% fixed resistor
21% air coil

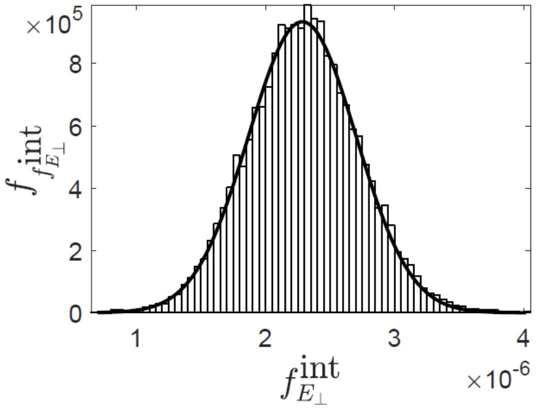


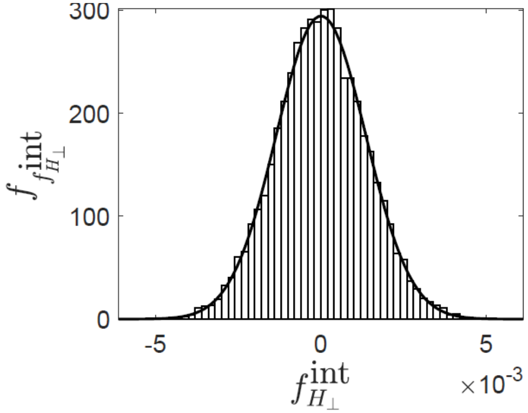
Probabilistic Model of the Electrical Uncertainties

variable	standardized	description	distribution	Unit
x_1	ξ_1	Capacitance C_L	$G\,(725{,}1)$	pF
x_2	ξ_2	Capacitance C_T	$G\,(503{,}1)$	pF
x_3	ξ_3	Capacitance C_{P1}	$G\,(148{,}1)$	pF
x_4	ξ_4	Capacitance C_{P2}	$G\,(334{,}1)$	pF
x_5	ξ_5	fixed inductance L_f	$G\,(27.5, 0.5)$	μH
x_6	ξ_6	fixed inductance L_p	$G\,(5.07{,}0.1)$	μH
x_7	ξ_7	fixed resistance R_f	$G\,(25{,}2)$	Ω
x_8	ξ_8	phase variation on electrode 1 (feed 1)	$G\,(0{,}0.05)$	deg
x_9	ξ_9	phase variation on electrode 1 (feed 2)	$G\,(1.7{,}0.05)$	deg
x_{10}	ξ_{10}	phase variation on electrode 2 (feed 3)	$G\,(178.4{,}0.05)$	deg
x_{11}	ξ_{11}	phase variation on electrode 2 (feed 4)	$G\,(179.2{,}0.05{,})$	deg
x_{12}	ξ_{12}	attenuation on the electrode 1 (feed 1)	$G\,(0{,}0.12)$	dB
x_{13}	ξ_{13}	attenuation on the electrode 1 (feed 2)	$G\,(0.1{,}0.12)$	dB
x_{14}	ξ_{14}	attenuation on the electrode 2 (feed 3)	$G\,(0.3{,}0.12)$	dB
x_{15}	ξ_{15}	attenuation on the electrode 2 (feed 4)	$G\,(0.2{,}0.12)$	dB



Performance Analysis





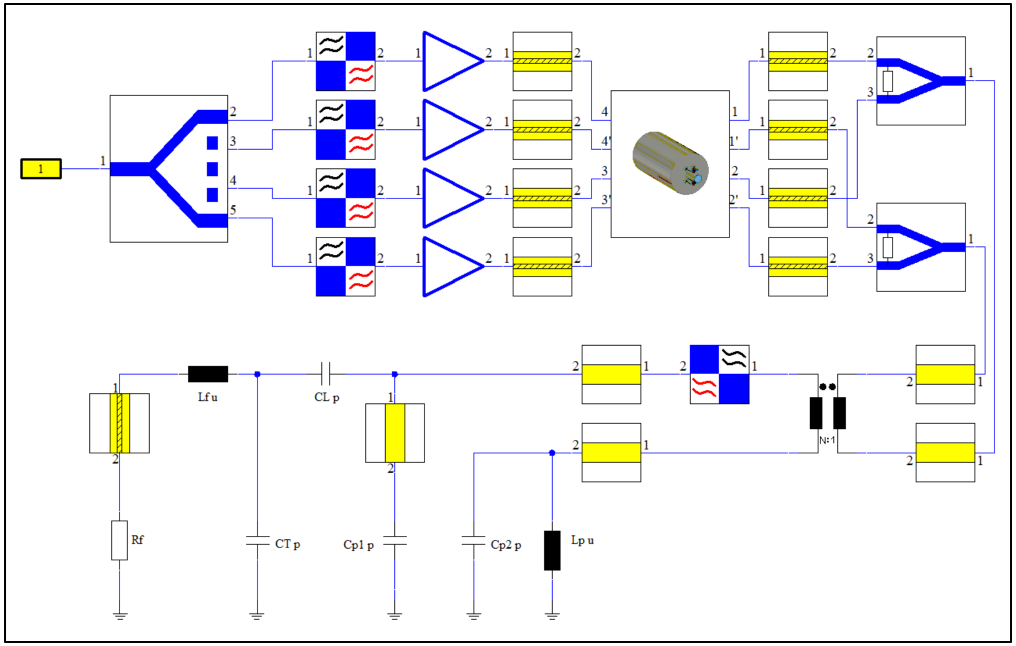
Performance analysis under electrical uncertainties

E-field homogeneity

4.33×10^{-7}

H-field homogeneity

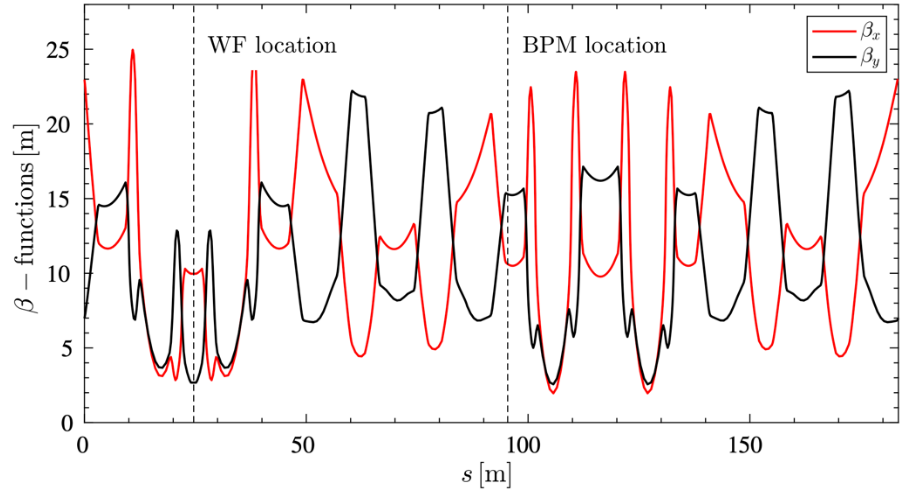
1.36×10^{-4}



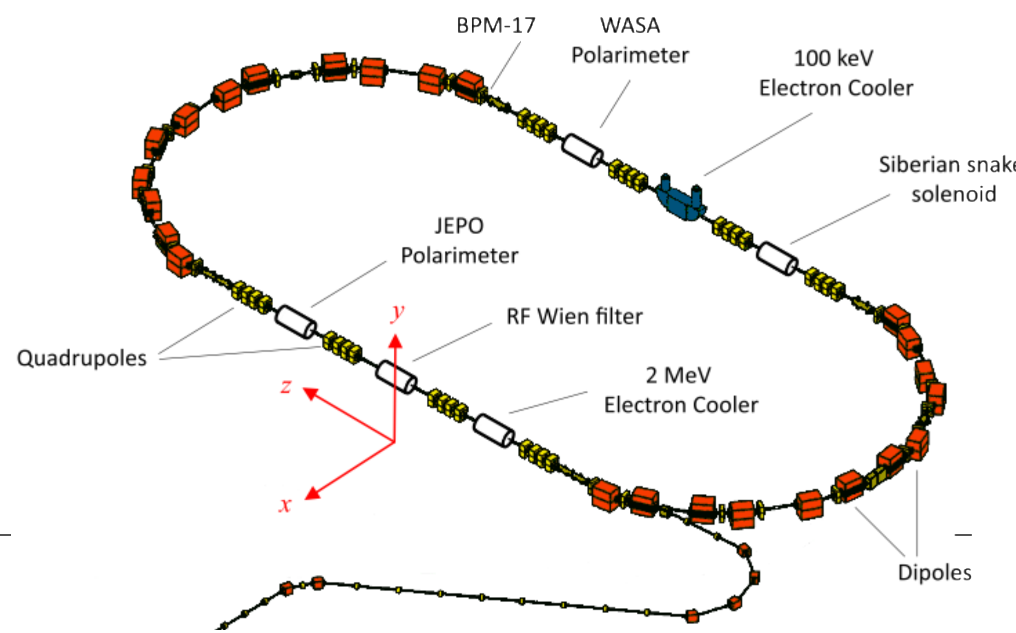
Measurement of Induced Beam oscillation

Commissioning the RF WF

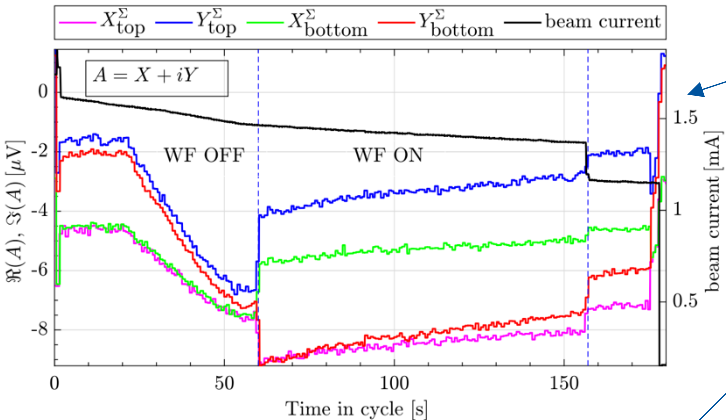
- Experimental setup
  - Mismatch the field quotient (induce coherent beam oscillation)
  - Measure the beam oscillation at the most sensitive location of COSY



Quantity	Symbol	Value
Deuteron beam momentum	p	970.0000 MeV/c
Deuteron mass	m	1875.6128 MeV/c^2
Deuteron G factor	G	−0.1430
Lorentz factor	β	0.4594
Lorentz factor	γ	1.1258
COSY circumference	L_{COSY}	183.4728 m
Revolution frequency	f_{rev}	750603.7600 Hz
Vertical machine tune	ν_y	3.6040
Vertical β function at BPM 17	β_y^{BPM}	15.3049 m
Vertical β function at WF	β_y^{WF}	2.6784 m
Effective length WF	ℓ	1.1600 m
Frequency WF	f_{WF}	871000.0000 Hz
Tune WF	ν_{WF}	1.1604



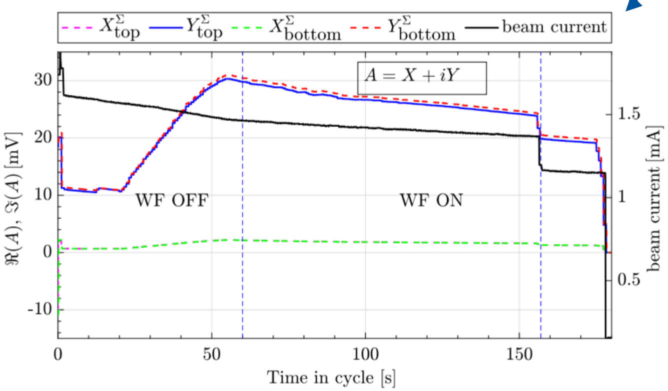
Measurement Setup

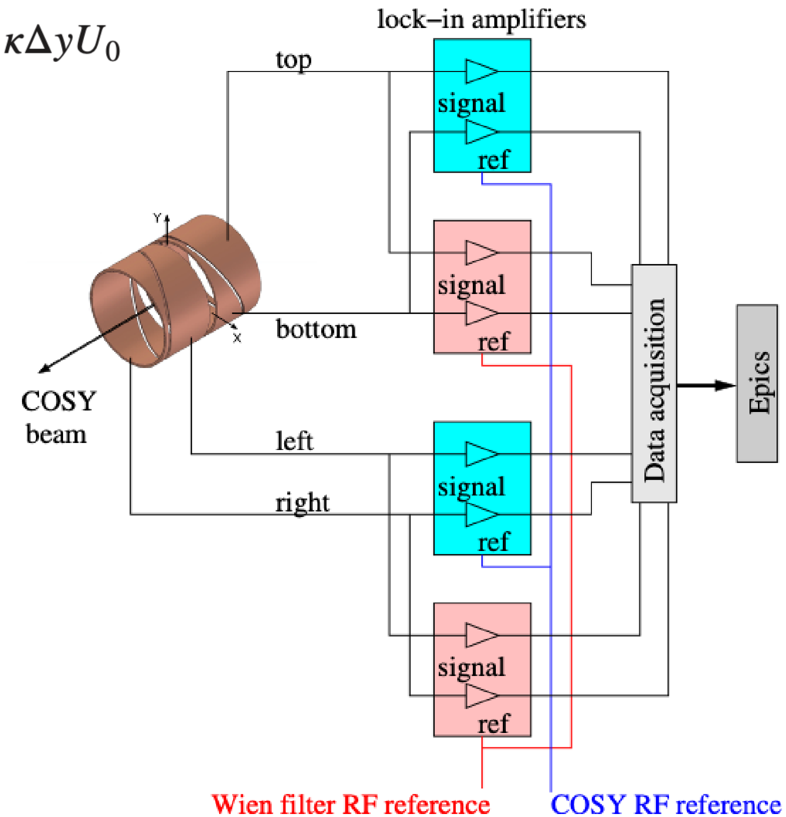


$$A^{\Sigma}_{\rm t,b} = \mp \frac{1}{2} \kappa \xi_y U_0$$

$$\frac{A^{\Sigma}_{\rm t} - A^{\Sigma}_{\rm b}}{A^{\rm rev}_{\rm t} + A^{\rm rev}_{\rm b}} = \hat{\xi}_y = \kappa \frac{U_0}{2U_0} \xi_y = \frac{1}{2} \kappa \xi_y$$

$$A^{\rm rev}_{\rm t,b} = U_0 \pm \kappa \Delta y U_0$$





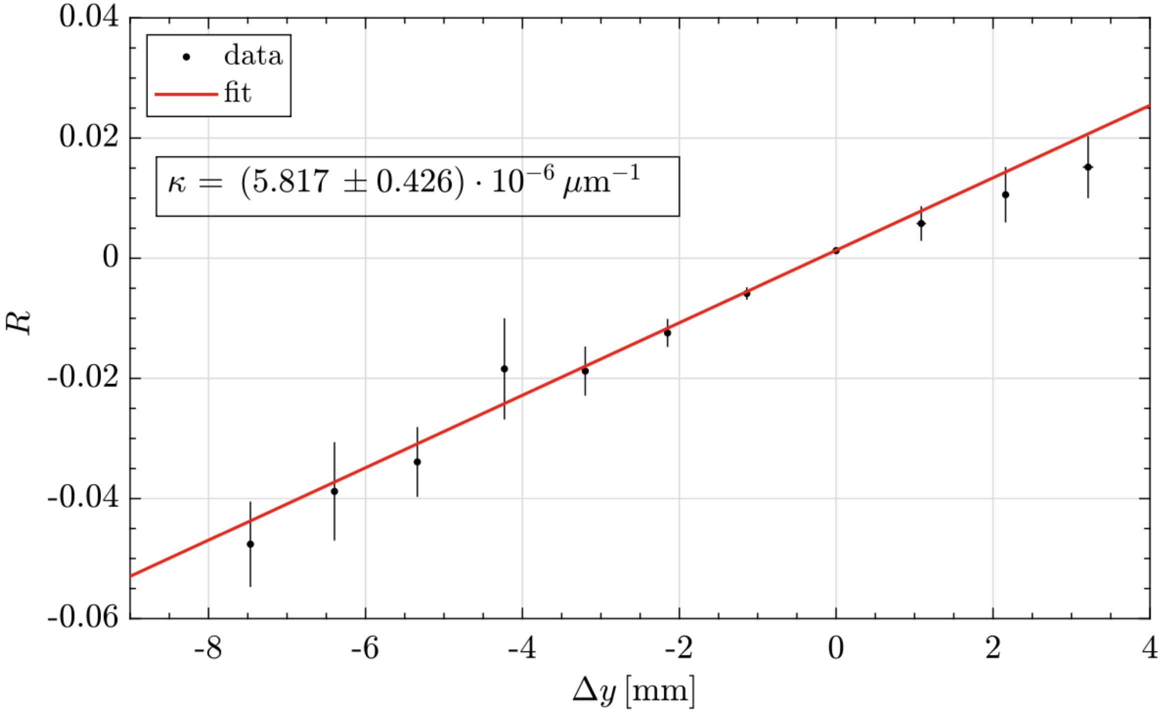
$$\begin{aligned} U_{\rm t,b}(t) &= [U_0 \pm \Delta U(\Delta y) \pm \Delta U(y(t))] \cos(\omega_{\rm rev} t) \\ &= [U_0 \pm \Delta U(\Delta y) \pm \kappa \xi_y U_0 \cos(\omega_s t)] \cos(\omega_{\rm rev} t) \\ &= [U_0 \pm \kappa \Delta y U_0] \cos(\omega_{\rm rev} t) \pm \frac{1}{2} \kappa \xi_y U_0 \cos(\omega_\Delta t) \pm \frac{1}{2} \kappa \xi_y U_0 \cos(\omega_\Sigma t) \end{aligned}$$

Calibration of the pickup

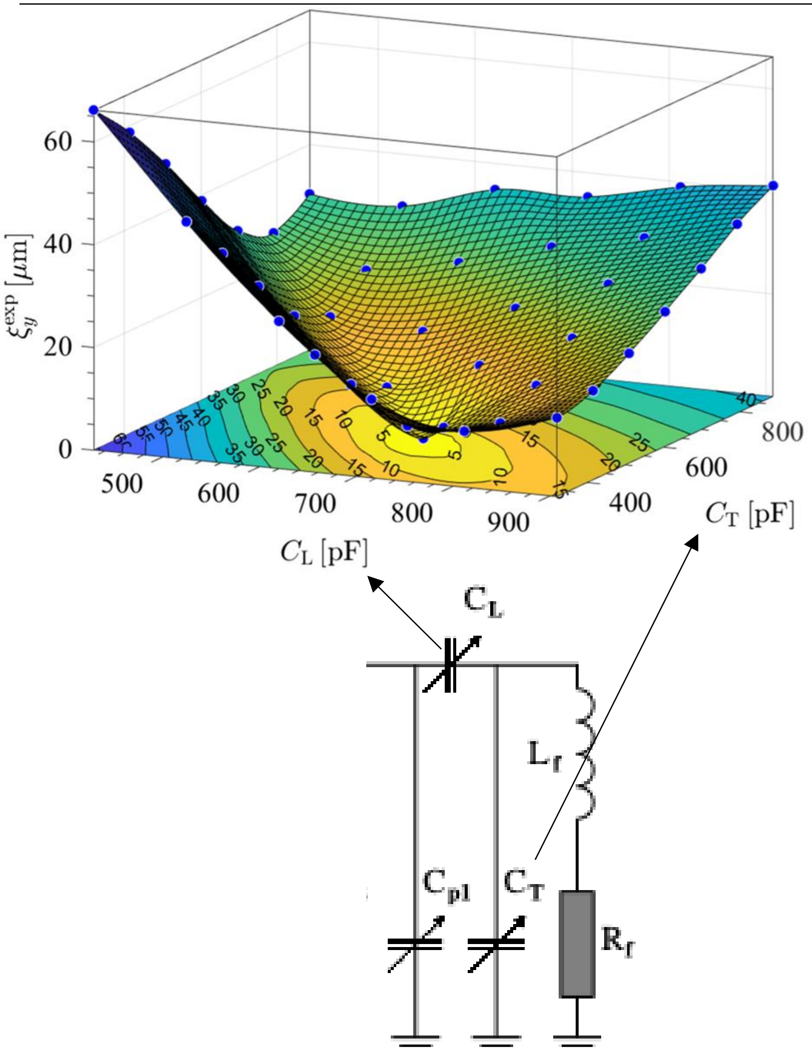
Ratio to displacement

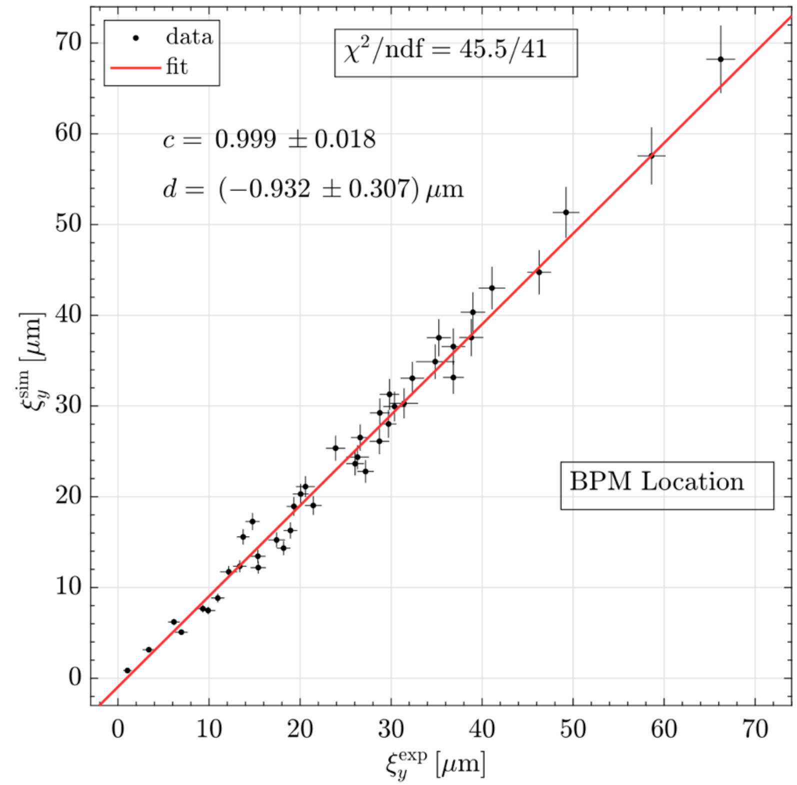
I (steerer) [%]	y [mm]	Δy [mm]
−5	−7.756 ± 0.030	−7.466 ± 0.030
−4	−6.684 ± 0.038	−6.395 ± 0.038
−3	−5.629 ± 0.016	−5.339 ± 0.016
−2	−4.518 ± 0.020	−4.229 ± 0.020
−1	−3.489 ± 0.018	−3.119 ± 0.018
0	−2.439 ± 0.029	−2.150 ± 0.029
+1	−1.429 ± 0.020	−1.140 ± 0.020
+2	−0.288 ± 0.028	0.000 ± 0.000
+3	+0.798 ± 0.044	+1.085 ± 0.044
+4	+1.872 ± 0.014	+2.160 ± 0.014
+5	+2.928 ± 0.069	+3.211 ± 0.069

$$R = \frac{A_t^{rev} - A_b^{rev}}{A_t^{rev} + A_b^{rev}} = \kappa \frac{2U_0 \Delta y}{2U_0} = \kappa \Delta y$$



Impedance Scan





$$\xi_y^{\mathrm{BPM}} = (1.086 \pm 0.082)\ \mu\mathrm{m}$$

$$\xi_y^{\mathrm{WF}} = (0.435 \pm 0.031)\ \mu\mathrm{m}$$

$$\xi_y^{\mathrm{max}}\big|_{\mathrm{BPM}} = (66.2 \pm 3.1)\ \mu\mathrm{m}$$

Quantum Limit

- When the electric and magnetic fields in the WF are mismatched, i.e., when the electric and magnetic forces no longer cancel each other, the rf fields excite collective beam oscillations at the frequency at which the WF is operated
- In the present experimental setup, a mismatch between electric and magnetic fields provides a vertically mismatched Lorentz force
- With a vanishing Lorentz force, the beam performs idle vertical (and horizontal) betatron oscillations

$$y(t) = y(0)\sqrt{\frac{\beta_y(t)}{\beta_y(0)}}\cos\left[\psi_y(t)\right]$$

- $\beta_y(t)$ is the betatron amplitude function
- $\psi_y(t)$ is the betatron phase advance satisfying

$$\psi_y(t+T) - \psi_y(t) = \omega_y T = 2\pi\nu_y$$

- ν_y is the vertical betatron tune given by

$$\nu_y = \omega_y/\omega_{\mathrm{rev}}$$

Quantum Limit

- The change of the vertical velocity of the stored particle, accumulated during the time interval Δt the particle spends per, turn n inside the WF, is given by

$$\Delta v_y(nT) = \frac{F_y(n)\Delta t}{\gamma m} = -\zeta\omega_y \cos(n\,\omega_{\mathrm{WF}} T)$$

- A lock-in amplifier may be used to selectively measure the corresponding Fourier component of the beam oscillation

$$\xi_y = \frac{\zeta}{2} \cdot \frac{\sin(2\pi\nu_y)}{\cos(2\pi\nu_{\mathrm{WF}}) - \cos(2\pi\nu_y)}$$

- This equation describes Hooke's constant $F_y = k_{\mathrm{H}}\epsilon_y$ with

$$k_{\mathrm{H}} = \left| \frac{2\gamma m\omega_y}{\Delta t} \cdot \frac{\cos(2\pi\nu_{\mathrm{WF}}) - \cos(2\pi\nu_y)}{\sin(2\pi\nu_y)} \right|$$

- An approximate description of the betatron motion by a harmonic oscillator with constant betatron function and evaluate the Heisenberg uncertainty limit Q for the betatron oscillation amplitude in terms of the zero-point oscillator energy $\frac{1}{2}\hbar\omega_y$ leading to

$$Q^2 = \frac{\hbar}{m\gamma\omega_y} \approx 41\ \mathrm{nm}$$

RF Wien Filter as a Resonant Spin Manipulator

- The RF Wien filter has been used at COSY as a Lorentz-force free resonant spin manipulators in 2 modes of operation
  - Radial B-field
  - Vertical B-field

- The spin rotation angle induced by the WF

$$\Omega_{\mathrm{WF}} \cdot \Delta t = \psi_{\mathrm{WF}} = -\frac{q}{m} \cdot \frac{(1+G)}{\gamma^2} \cdot B^{\mathrm{WF}} \cdot \frac{\ell_{\mathrm{WF}}}{\beta c}$$

- Usages
  - EDM experiments
  - Axion search
  - Search for proton spin coherence time
- Operated in CW and gated mode

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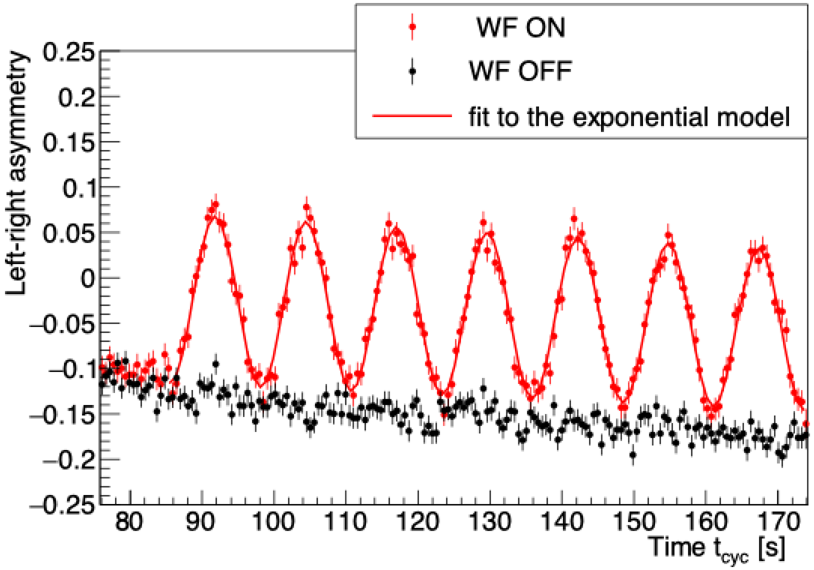
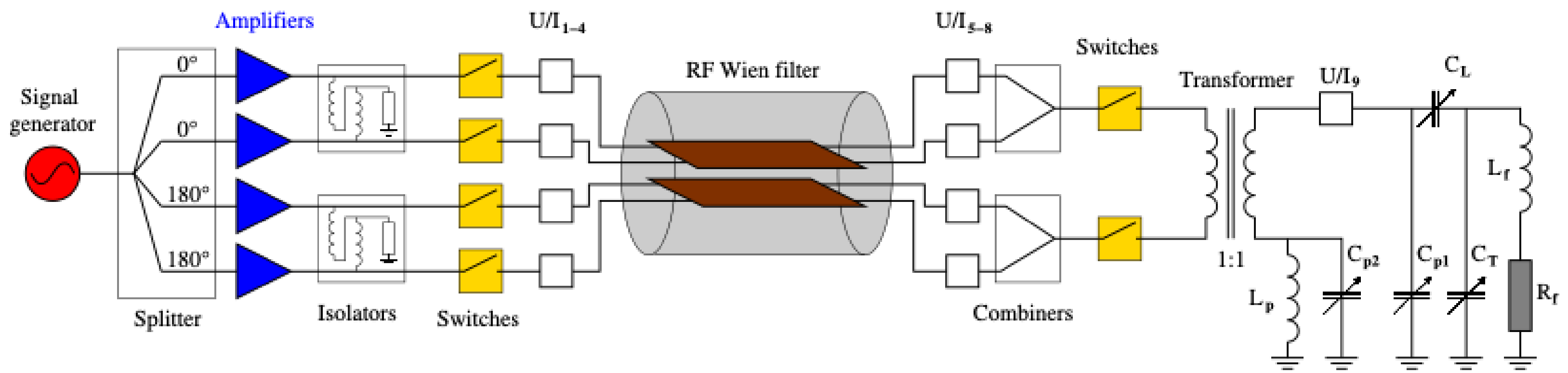
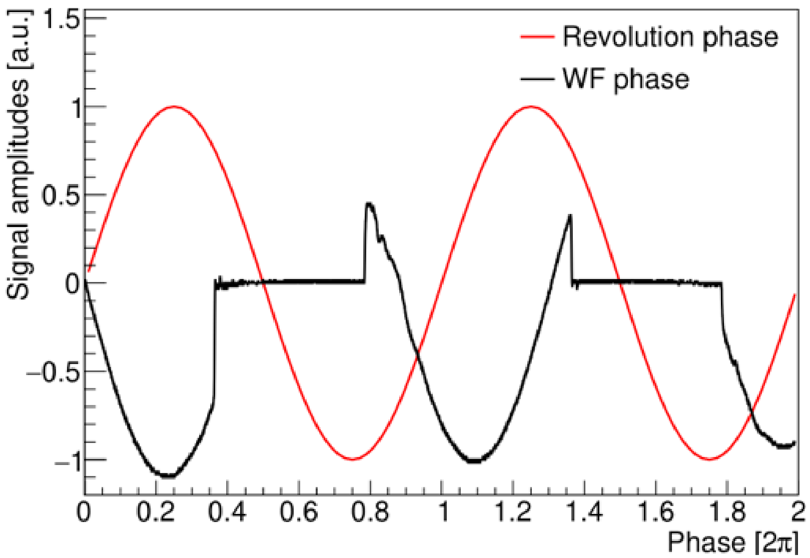


Bunch Selective Operation of the RF Wien Filter



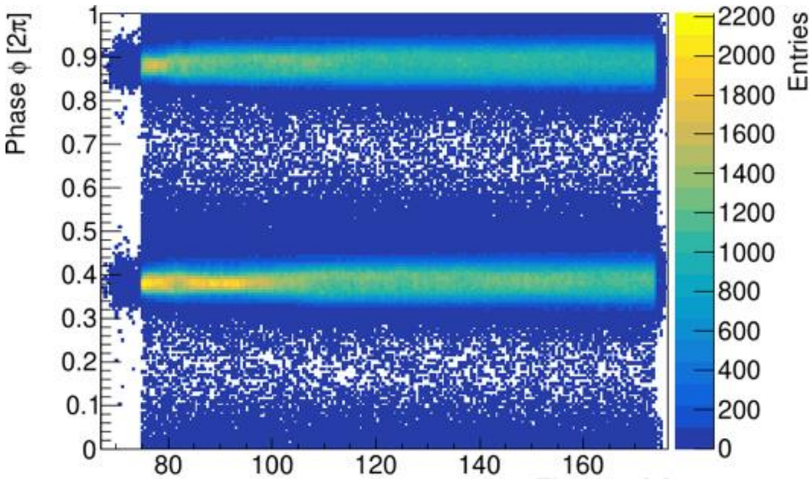
- Spin tune is ill-defined in the presence of RF fields – running spin tune

- Co-magnetometer for precise determination of the resonance frequency
- Multi-bunch operation
- Gated mode

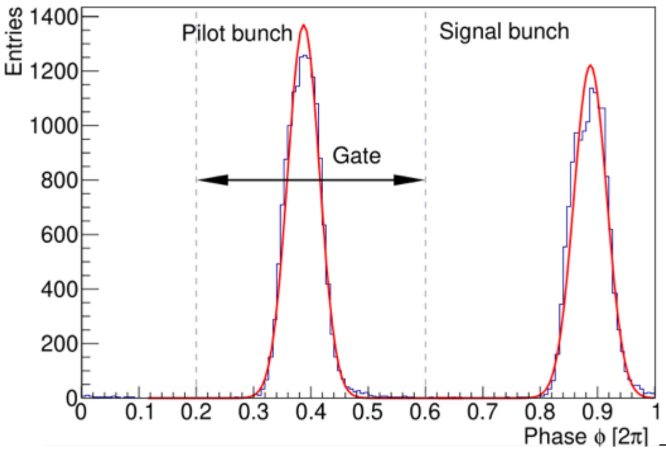


Bunch Selective Operation of the RF Wien Filter

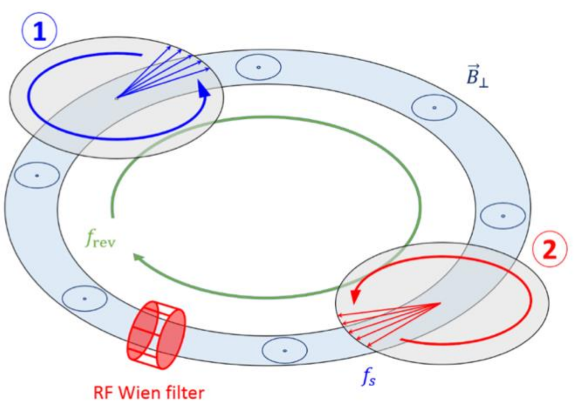
Parameter	Symbol [Unit]	Value
Deuteron momentum (lab)	P [MeV/c]	970.663 702
Deuteron kinetic energy (lab)	T [MeV]	236.284 783
Lorentz factor	γ [1]	1.125 977
Beam velocity	β [c]	0.459 617
Nominal COSY orbit circumference	ℓ_{COSY} [m]	183.572
Revolution frequency	f_{rev} [Hz]	750 602.6
Spin precession frequency $f_s = G\gamma f_{\mathrm{rev}}$	f_s [Hz]	−120 847.303 520
Deuteron mass	m [MeV]	1875.612 793
Deuteron g factor	g [1]	1.714 025
Deuteron $G = (g-2)/2$	G [1]	−0.142 987
Slip factor	η [1]	0.6545
Momentum spread in middle of cycle	$\Delta p/p$ [1]	$7.397 \cdot 10^{-5}$
Synchrotron oscillation frequency	f_{sync} [Hz]	205 ± 21
RF Wien filter electric field integral	$\int E_x^{\mathrm{WF}} \mathrm{d}s$ [V]	763.295 09
RF Wien filter magnetic field integral	$\int B_y^{\mathrm{WF}} \mathrm{d}s$ [µT m]	5.655 677 04
RF Wien filter active length	ℓ_{WF} [m]	1.550



$$\phi = 2\pi \left[f_{\mathrm{rev}} t_{\mathrm{cyc}} - \mathrm{int}(f_{\mathrm{rev}} t_{\mathrm{cyc}}) \right] \in [0, 2\pi]$$



$$\frac{\mathrm{d}N_{\mathrm{p,s}}}{\mathrm{d}\phi} \propto \exp\left(-\frac{(\phi - \phi_{\mathrm{p,s}})^2}{2\sigma_{\mathrm{p,s}}^2} \right)$$



Bunch Selective Operation of the RF Wien Filter

- Exponential damping model

$$A_s(t) = a_s(t - t_0) + b_s + d_s \exp\left(-\Gamma_s(t - t_0)\right) \cos\left[2\pi f_{SF}(t - t_0)\right]$$

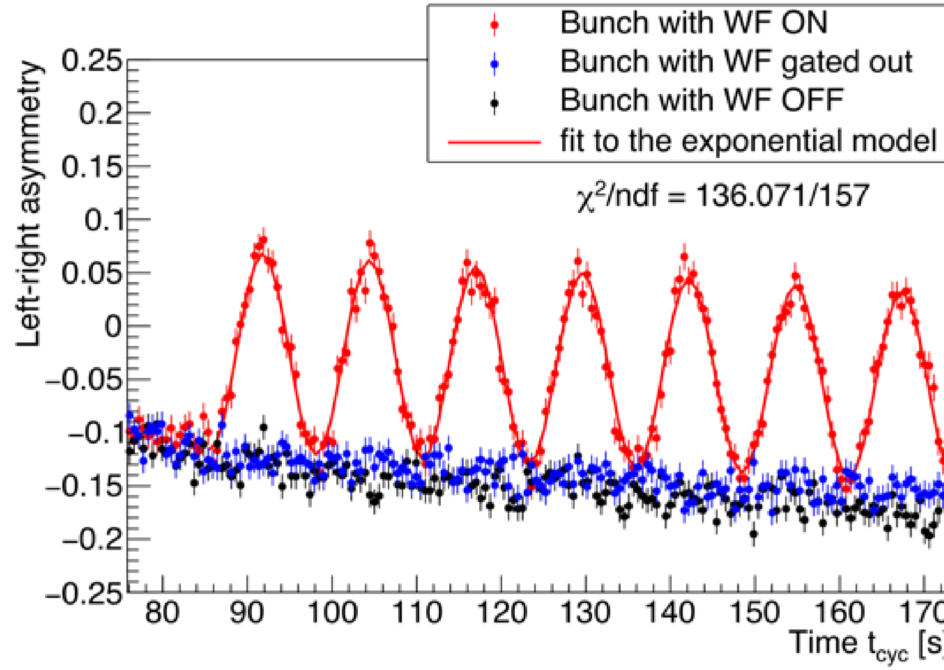
  - Caused by the spin decoherence in terms of the time constant
  - d_s is the spin-flip amplitude
  - f_{SF} is the spin-flip frequency
- Efficiency ϵ_{SF}, ratio of polarizations after and before a single spin flip

$$\epsilon_{SF} = 1 - \frac{\Gamma_s}{2f_{SF}} = 0.9954 \pm 0.0037$$

- The total polarization loss after the 14 spin flips $\frac{\Delta P}{P} = 0.062 \pm 0.050$

- Efficiency of the gate

$$\epsilon_{gate} = 1 - \frac{d_p}{d_s} = 0.9921 \pm 0.0136$$



Parameter	Value	Error	Unit
a_s	-4.04	0.38	10^{-4}/s
t_0	85.548	0.060	s
b_s	-0.0228	0.0019	1
d_s	-0.0936	0.0027	1
Γ_s	7.30	5.86	10^{-4}/s
f_{SF}	0.079 44	0.000 10	Hz

RF Wien Filter at EIC

- Using a Lorentz force-free RF WF operating at a fixed frequency as a spin manipulator has the potential to open new possibilities for spin physics experiments at future accelerators such as the EIC and NICA.
- In terms of continuous spin flips, such a device does not suffer from the limitations of the Froissart-Stora scanning technique employed at the RHIC spin flipper using RF dipoles

- The RF WF can be tuned to minimize adverse effects on the beam orbit produced by RF dipoles and RF solenoids.

- Instead of injecting polarized bunches with a predefined alternating polarization pattern into the collider, one can inject one polarization state and invert the vertical polarization by selective gating on individual bunches or on trains of bunches on flattop.

RF Wien Filter at EIC

- As the rate of spin flip of an RF WF scales with the inverse energy squared

- To obtain similar spin flip rates as in our experiment, such a device for EIC
  - *275 GeV*
  - γ ~ 295
  - f_{rev} ~ 78 kHz
  - require RF fields increased by a factor of γ^2 ~ 10^4
    - 10 m long RF WF at sideband K = 15000, frequency f_{WF} ~1.1 GH driven by a 1 MW amplifier (Amateur Radio PA would also be an option at 78 kHz)
  - spin flip periods of one minute appear feasible for protons
- Regarding the prospects for gating out an individual bunch with an RF WF at EIC, we note that the RF switches used in the present experiment already provide switching times of 2 ns while at EIC with 1180 bunches, the bunch period will be 11 ns
- Thus, the achieved switching time is already in the ballpark of the EIC requirements, but handling the considerably higher power will require a dedicated development effort.