Parameter estimation of short pulse normal-conducting standing wave cavities.

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Abstract

The linear accelerator ARES (Accelerator Research Experiment at SINBAD) is a new research facility at DESY. Electron bunches with a maximum repetition rate of 50 Hz are accelerated to a target energy of 155 MeV. The facility aims for ultra-stable sub-femtosecond arrival-times and high peak-currents at the experiment, placing high demands on the reference distribution and field regulation of the RF structure. In this contribution, we present the physical parameter estimation of key RF properties such as cavity detuning not directly measurable on the RF field decay. The method can be used as a fast monitor of inner cell temperature. The estimated properties are finally compared with the measured ones.

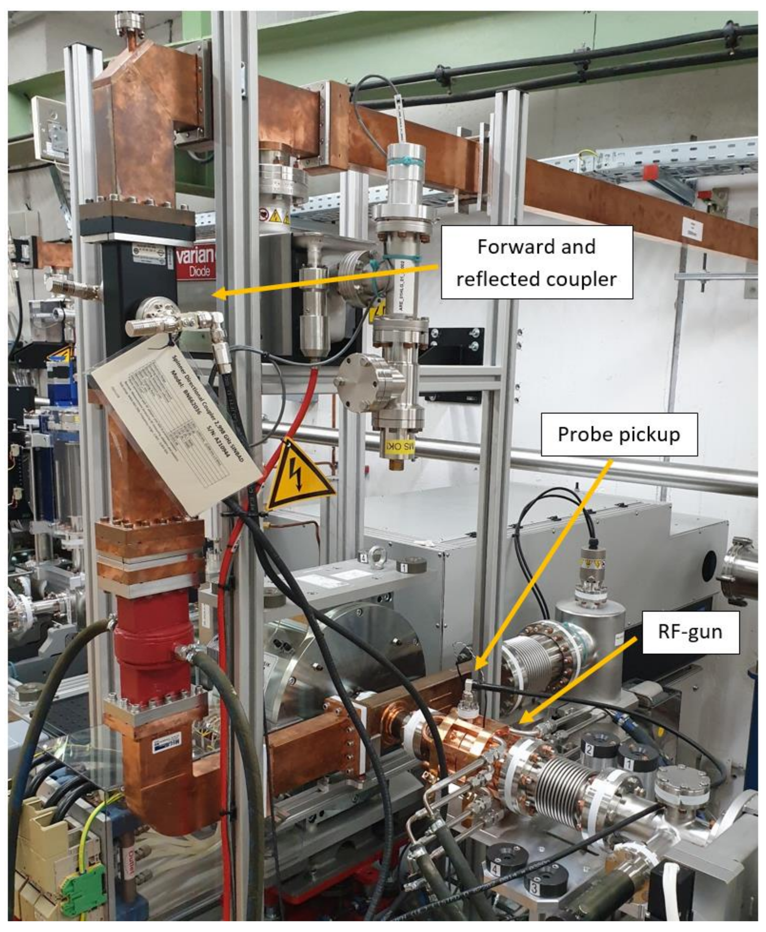
Proposal

> **Estimation of Key Parameters of an RF Structure**

- Essential for proper system setup and operation
- Additional system checks e.g. fault detection and isolation

> **Usage of an Estimation Algorithm based on Cavity White Box Model**

- Depending on coupling factor, the detuning and the half bandwidth
- Increase resolution by using the whole RF pulse
- Decay approach with free response sometimes not applicable due to missing circulator



Assumptions

> Short RF pulse in microsecond range

> No intra-pulse heating/detuning variation of the RF structure nor the input coupling changing the coupling coefficient and half bandwidth

> Delay of the signal detection for the forward, reflected and probe signal are of same size

> Signals used for parameter estimation physically next to each other to avoid additional effects like signal damping etc.

(1) Signal Calibration

> The detected forward, reflected and probe RF signals are expressed in the complex domain

$$\widetilde{V}_{forw,I} + i\widetilde{V}_{forw,Q} = \widetilde{A}_{forw} \cdot e^{i\widetilde{\phi}_{forw}} = \widetilde{\mathbf{V}}_{forw} \in \mathbb{C},$$
$$\widetilde{V}_{refl,I} + i\widetilde{V}_{refl,Q} = \widetilde{A}_{refl} \cdot e^{i\widetilde{\phi}_{refl}} = \widetilde{\mathbf{V}}_{refl} \in \mathbb{C} \text{ and}$$
$$\widetilde{V}_{probe,I} + i\widetilde{V}_{probe,Q} = \widetilde{A}_{probe} \cdot e^{i\widetilde{\phi}_{probe}} = \widetilde{\mathbf{V}}_{probe} \in \mathbb{C}$$

> Calibrate the forward and reflected signal by the complex coefficients **a** and **b** which need to be determined:

$$\mathbf{V}_{probe} = \mathbf{a}\widetilde{\mathbf{V}}_{forw} + \mathbf{b}\widetilde{\mathbf{V}}_{refl} = \mathbf{V}_{forw} + \mathbf{V}_{refl}$$

$$\overbrace{\widetilde{\mathbf{V}}_{probe}}^{B} = \overbrace{\left[\widetilde{\mathbf{V}}_{forw}\,\widetilde{\mathbf{V}}_{refl}\right]}^{A} \overbrace{\begin{bmatrix}\mathbf{a}\\ \mathbf{b}\end{bmatrix}}^{x}$$

$$B = A \cdot x \iff x = (A^T A)^{-1} A^T B$$

> *Otherwise use resonance circle.*

(2) System Model

> Static cavity probe signal for an RF structure operated in standing wave mode with tuning angle, coupling factor and forward signal mapped to cavity side works well for steady state case:

$$\mathbf{V}_{probe} = \frac{\beta}{\beta+1} \cdot \cos(\psi) e^{i\psi} \cdot \left(2 \cdot \mathbf{V}_{forw} + \cancel{\frac{R}{\beta} I_b}^{\,0}\right)$$

> Beam contribution is neglected for pC bunch charge.

> Replaced by dynamic transfer function in s-domain for short RF pulse operation:

$$\frac{\mathbf{V}_{probe}}{\mathbf{V}_{forw}} = G(s) = \frac{\beta}{\beta+1} \cdot \frac{2\omega_{1/2}}{s + \omega_{1/2} - j\Delta\omega} = \frac{\mathbf{K}}{s - \mathbf{p_1}}$$

with static gain $\mathbf{K}$ and complex eigenvalue $\mathbf{p_1}$ as

$$\mathbf{K} = \frac{2\beta\omega_{1/2}}{\beta+1} \quad \text{and} \quad \mathbf{p_1} = -(\omega_{1/2} - j\Delta\omega)$$

(3) Parameter Estimation

> Estimation method for system identification known as the Prediction Error Method (PEM).

> The input and output data, i.e. complex forward and probe signal, is used for an optimization resulting in a system model in Laplace or s-domain.

> System identification algorithm in discrete time estimates the pole and gain as free parameters with complex system model.

> System model is converted into continuous time using 'zoh' method.

$$f_{1/2} = \omega_{1/2}/(2\pi) = -\Re\{\mathbf{p_1}\} \text{ and } \Delta f = \Delta\omega/(2\pi) = \Im\{\mathbf{p_1}\}$$

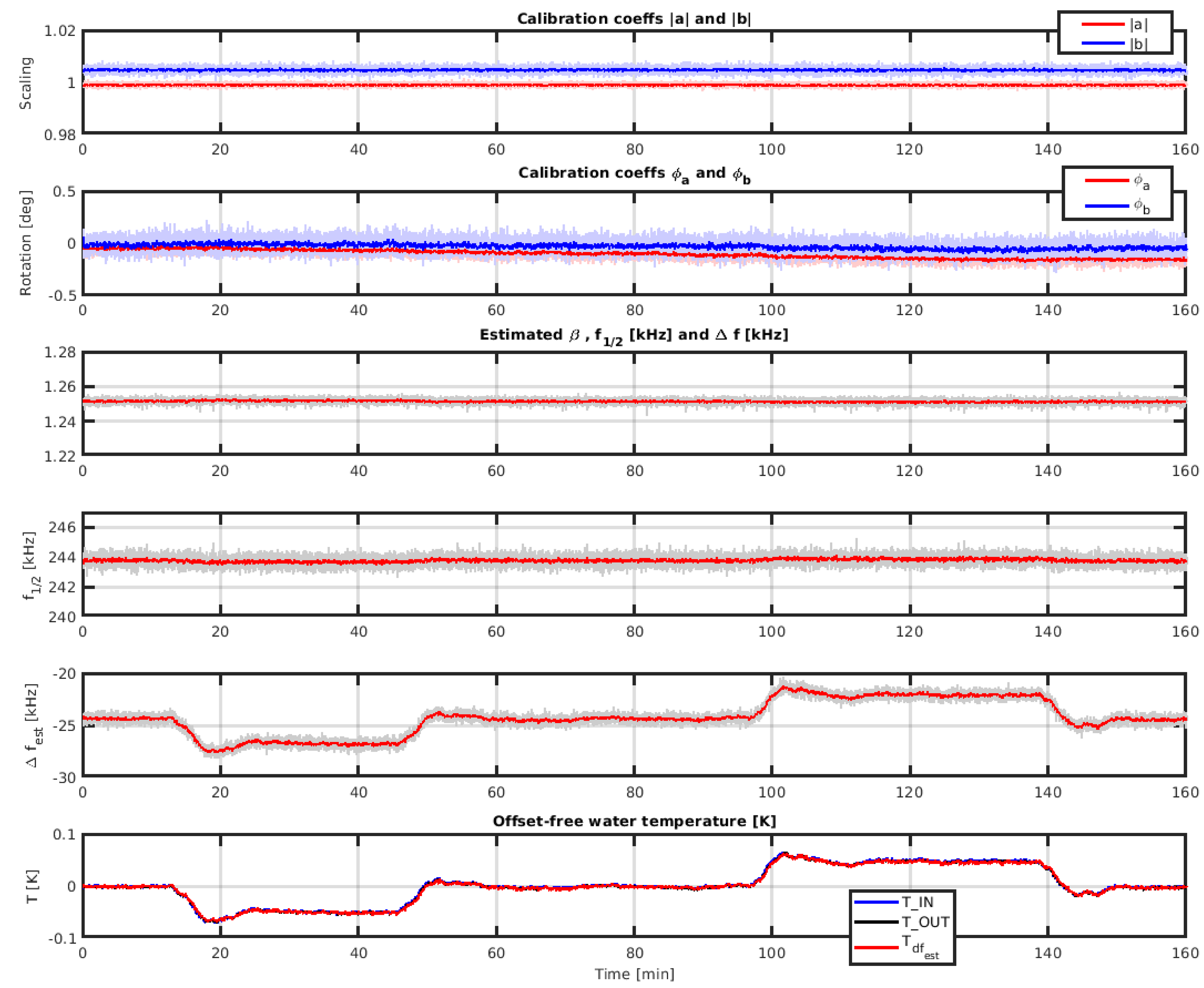
> Gain at low frequencies and gain factor depending on pole

$$G_0 = \sup(G(s))|_{s\to 0} = \frac{\beta}{(\beta+1)} \frac{2\omega_{1/2}}{\omega_{1/2} - j \cdot \Delta\omega}$$

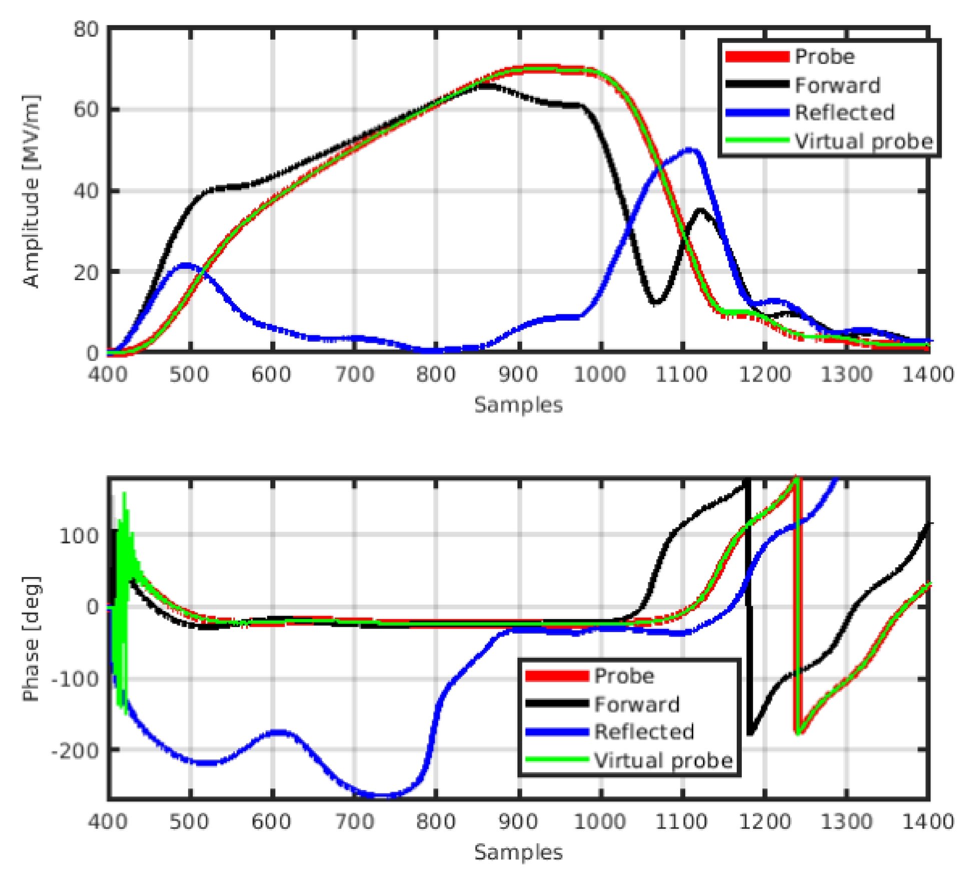
$$\beta_{est} = \frac{G_0}{G_0 - \frac{2\omega_{1/2}}{(\omega_{1/2} - j\cdot\Delta\omega)}}$$

$$\omega_{1/2} = \omega_0/(2 \cdot Q_L); \quad Q_0 = Q_L \cdot (1+\beta)$$

$$\Gamma = \frac{\mathbf{V}_{refl}}{\mathbf{V}_{forw}} = \frac{\mathbf{b}\widetilde{\mathbf{V}}_{refl}}{\mathbf{a}\widetilde{\mathbf{V}}_{forw}}, \; \Gamma_{min} = \frac{\beta-1}{\beta+1}$$



Example



Conclusion & Outlook

> Parameter estimation based on physical model at 3.3 Hz to 5 Hz

> Good agreement between measurement of temperature sensor and the estimated temperature with the detuning

> Detuning to temperature conversion factor of 48.5 kHz/K

> Q_L = 6150 and Q_0 = 13830

> Next focus on calibration coefficients drifts over time

> 10 Hz – 50 Hz solution as server is targeted

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