

GUN DETUNING ESTIMATION.

Performance Comparison of Linear vs. Unscented Kalman Filter-Based
Gun Detuning Estimation with a Focus on Parameter Identification

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LLRF 2026 Workshop, Nova Gorica, Slovenia

Thu OCT 15 2026

HELMHOLTZ



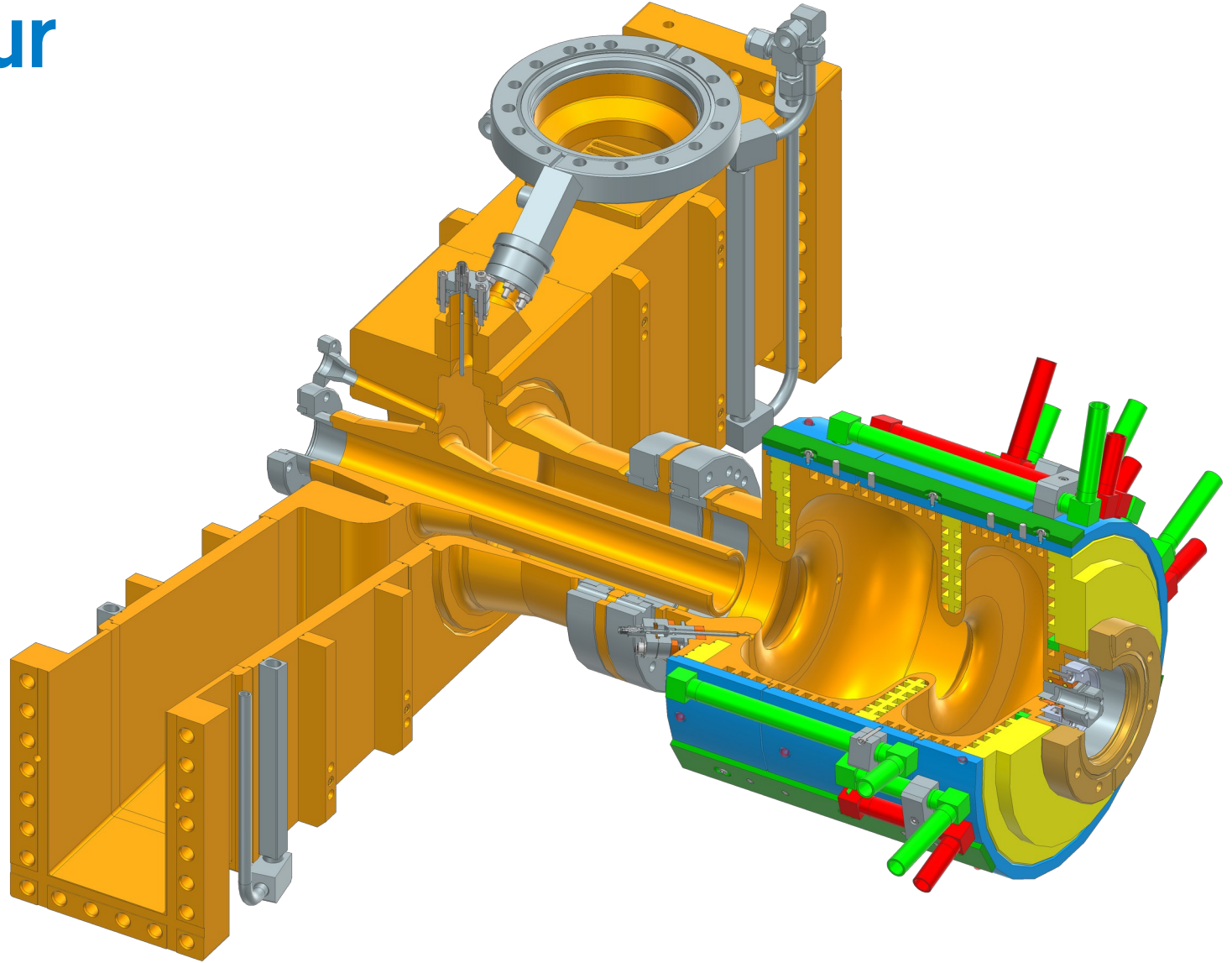
Gun 5.3 at PITZ

Gun 5.3 developed at the Photo Injector Test Facility at DESY (PITZ) in Zeuthen, Germany, is a **normal-conducting photogun**.

Its predecessor, rev. 5.2, is currently operated at EuXFEL.

Version 5.3 served as a study object for validating the estimation algorithm.

A Short Gun 5.3 Tour

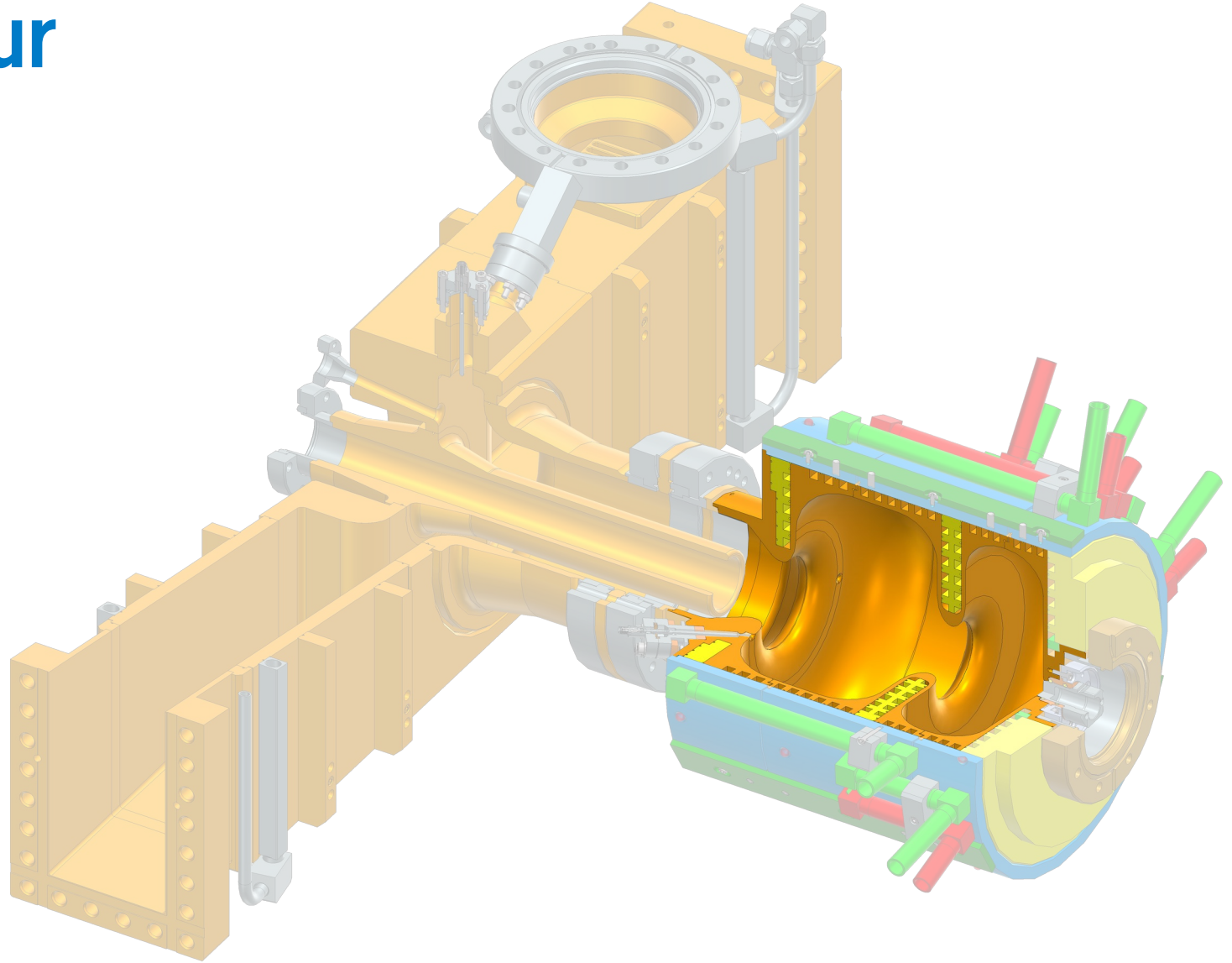


Courtesy of M. Krasilnikov

A Short Gun 5.3 Tour

cavity

1 ½-cell, elliptical

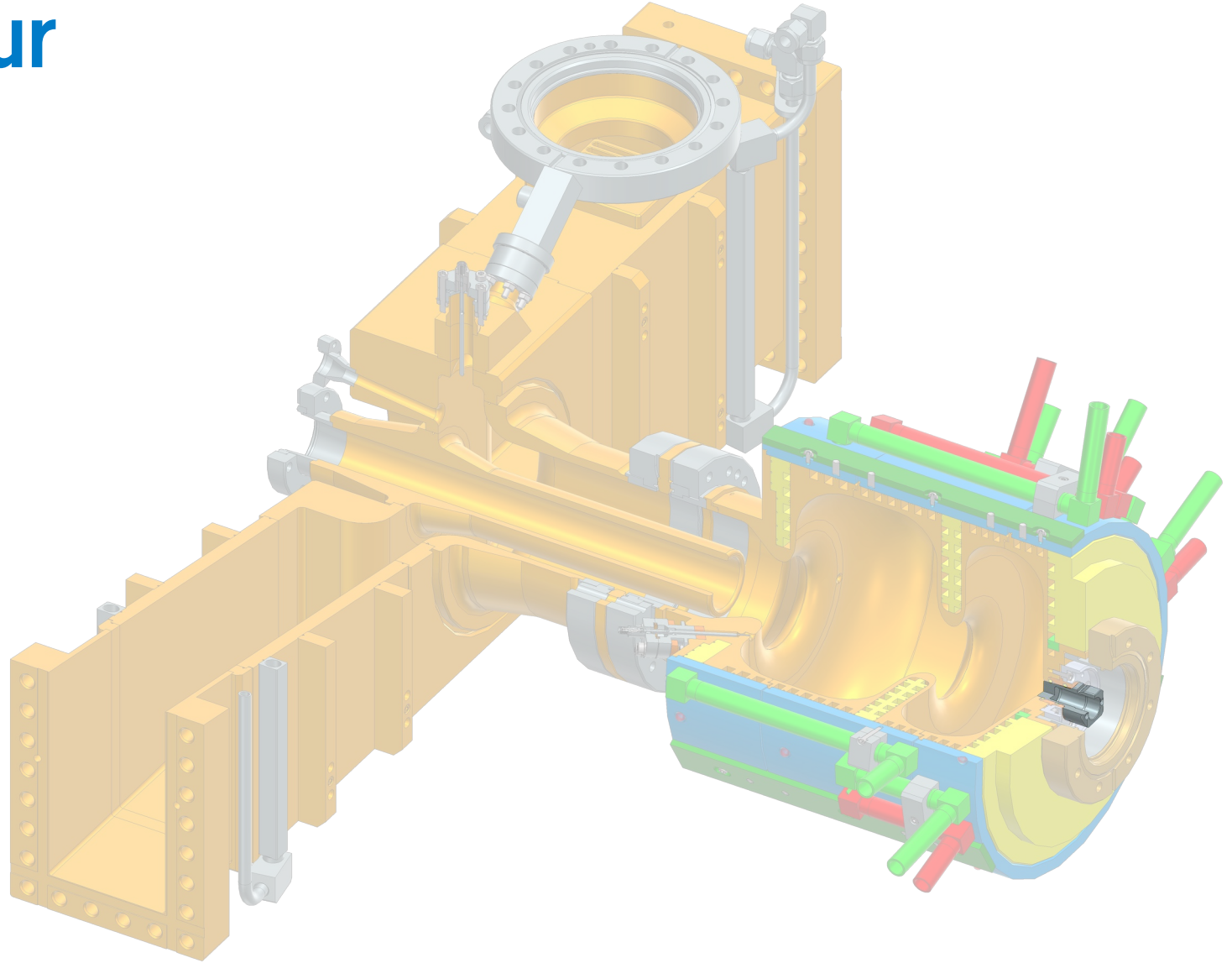


Courtesy of M. Krasilnikov

A Short Gun 5.3 Tour

cathode

Ce₂Te film on Mo substrate

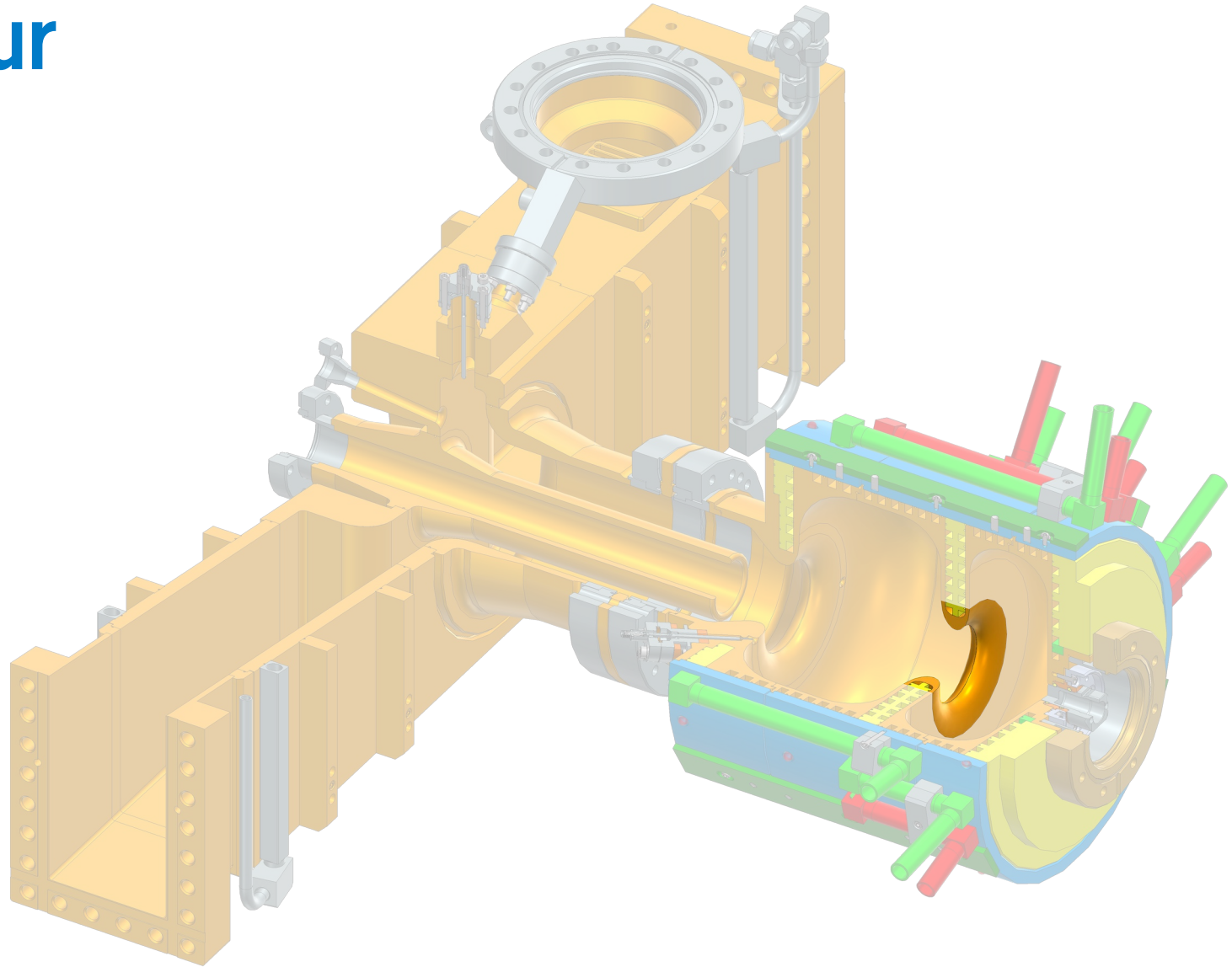


Courtesy of M. Krasilnikov

A Short Gun 5.3 Tour

iris

Equipped with cooling
channels and thermocouple
elements

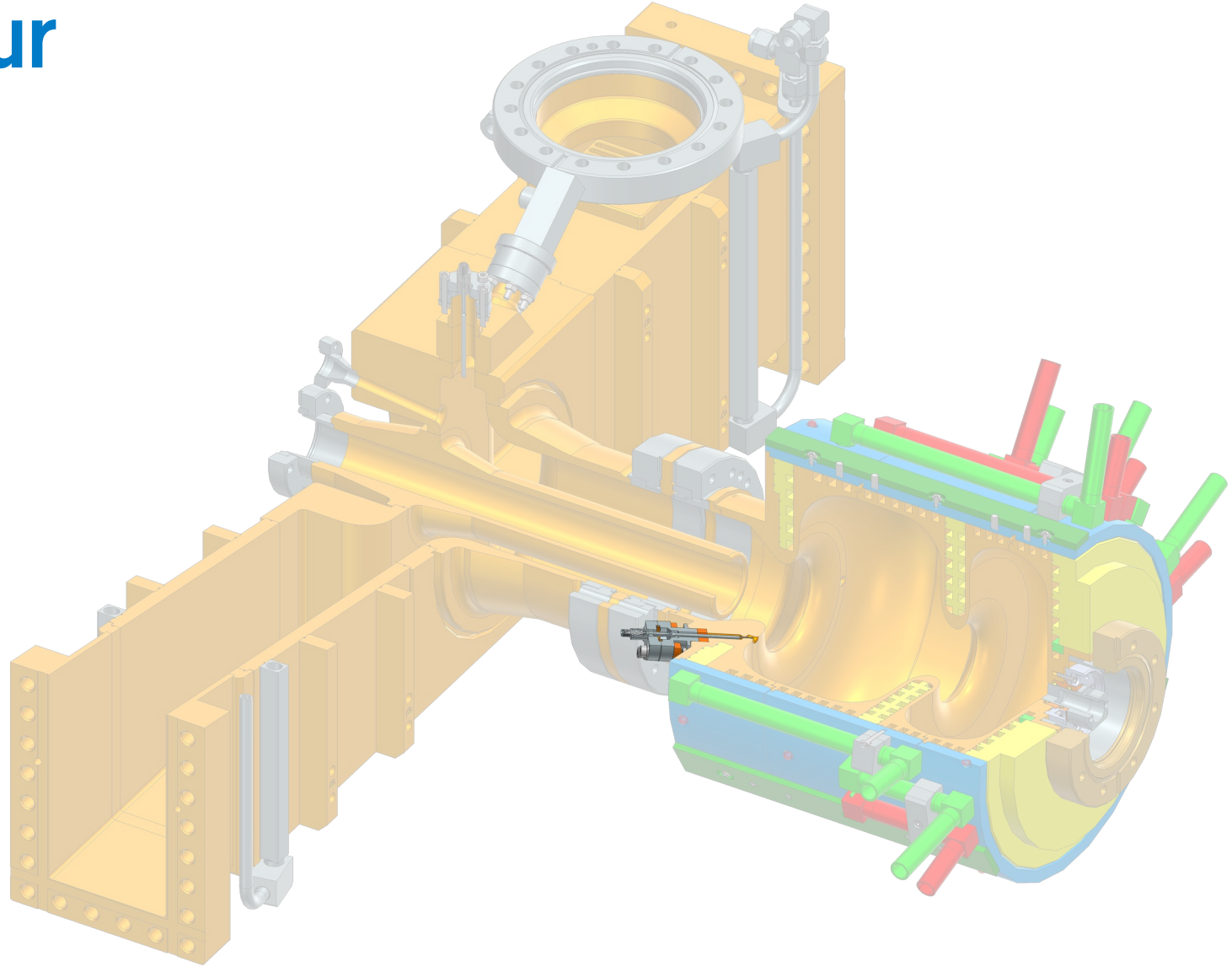


Courtesy of M. Krasilnikov

A Short Gun 5.3 Tour

probe

2 × L-band RF pickup

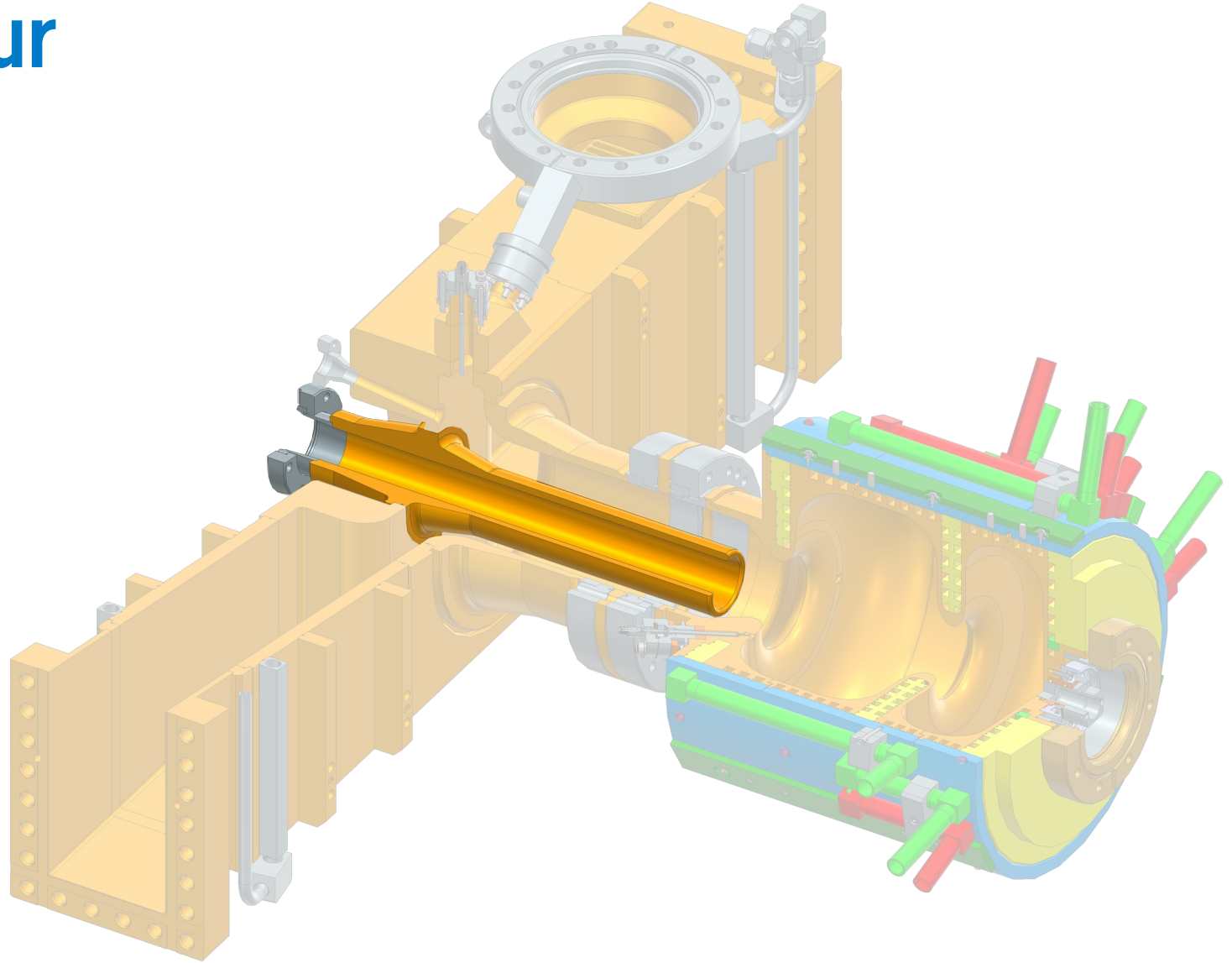


Courtesy of M. Krasilnikov

A Short Gun 5.3 Tour

RF coupler

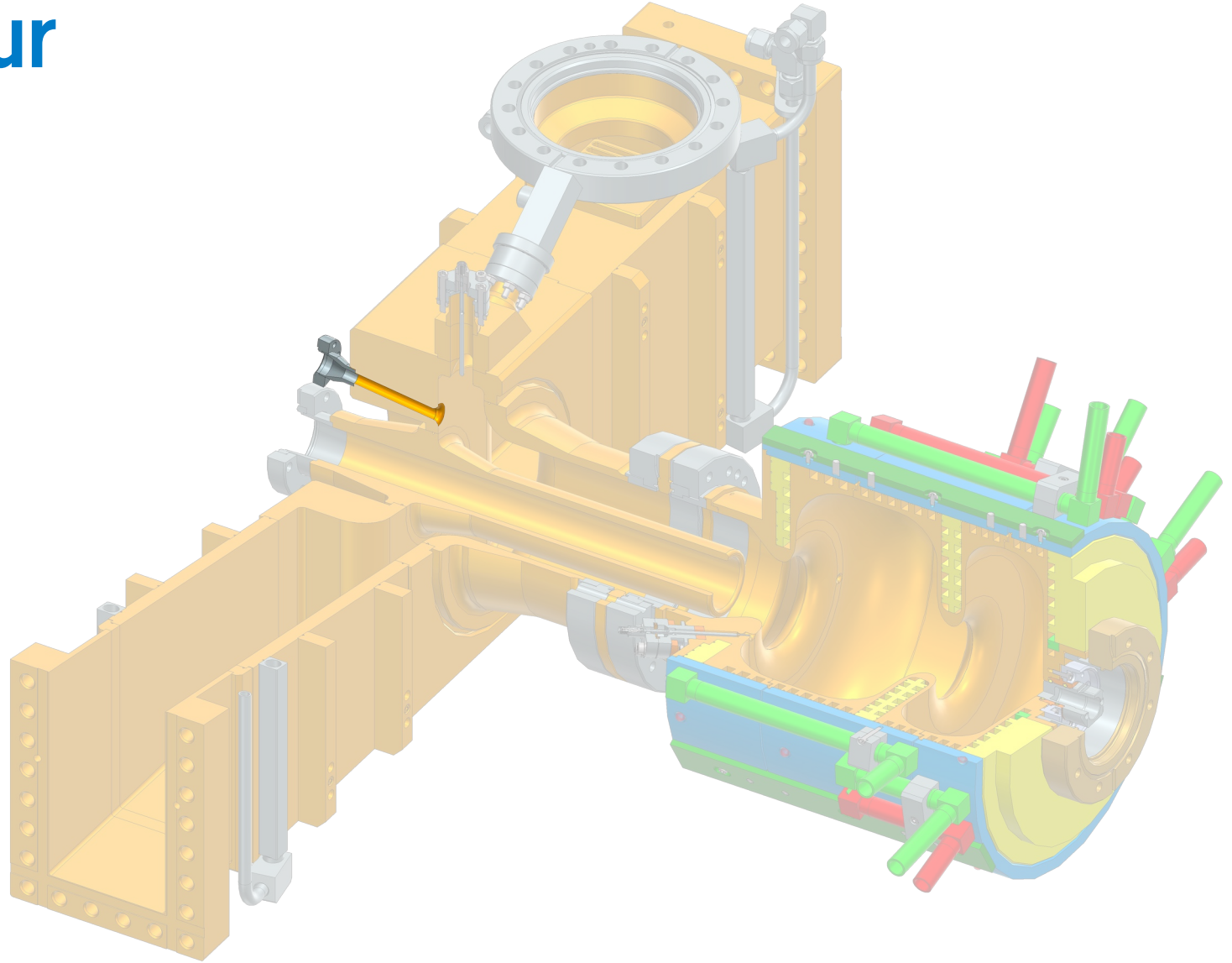
Co-axial, 2-feed



Courtesy of M. Krasilnikov

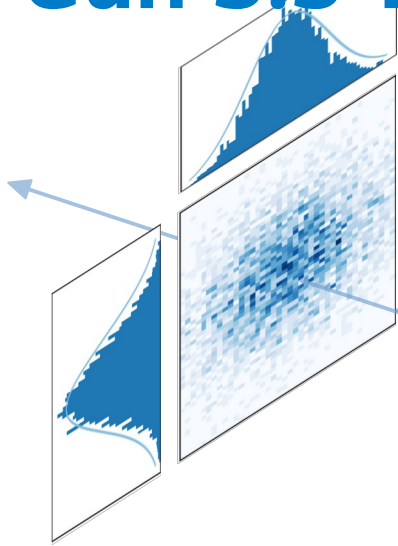
A Short Gun 5.3 Tour

laser coupler



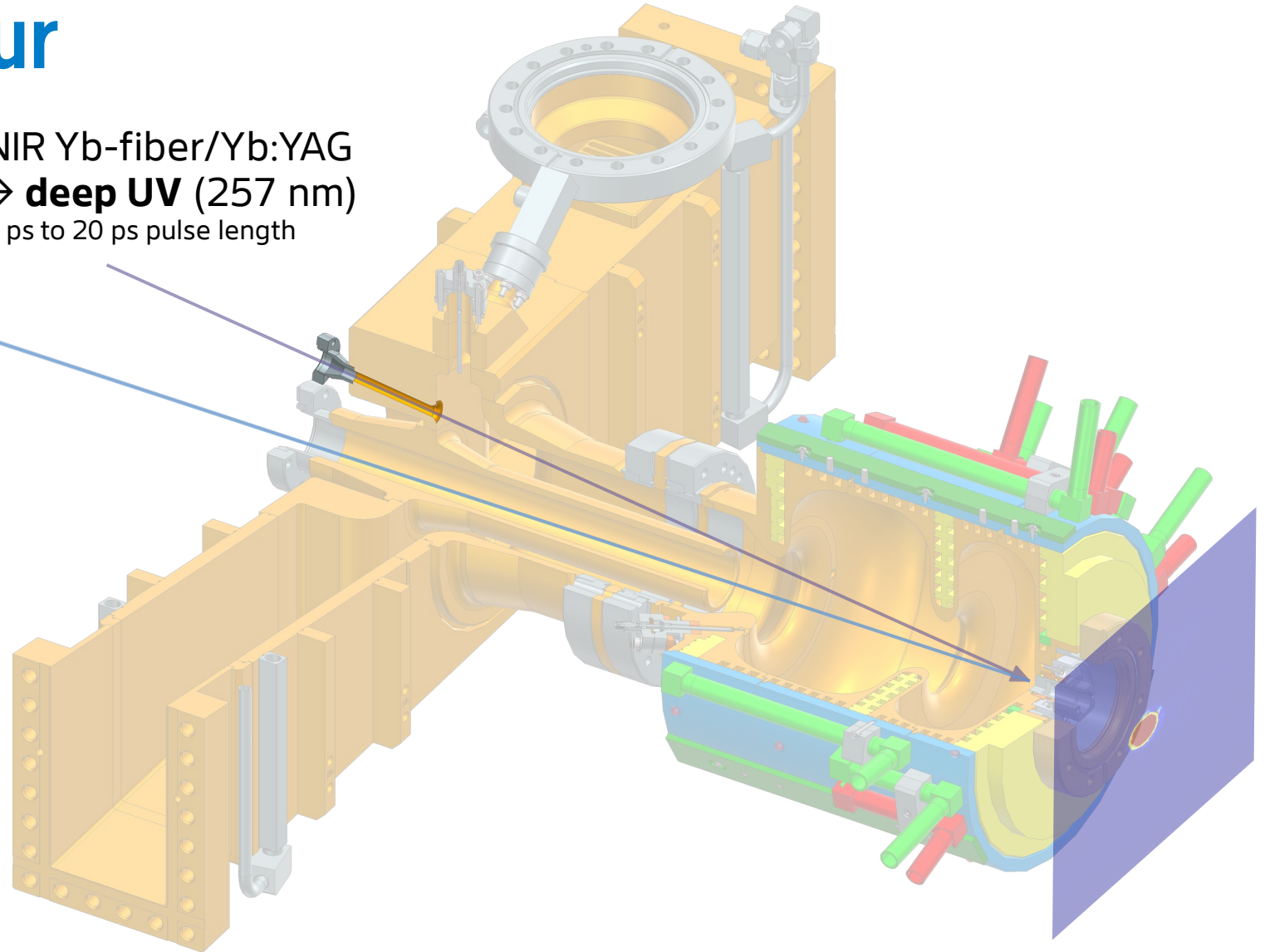
Courtesy of M. Krasilnikov

A Short Gun 5.3 Tour



NIR Yb-fiber/Yb:YAG
→ **deep UV** (257 nm)
1 ps to 20 ps pulse length

250 pC per e^- bunch
150 MeV energy gain
~ **1% duty cycle**
0.375 mm mrad emittance

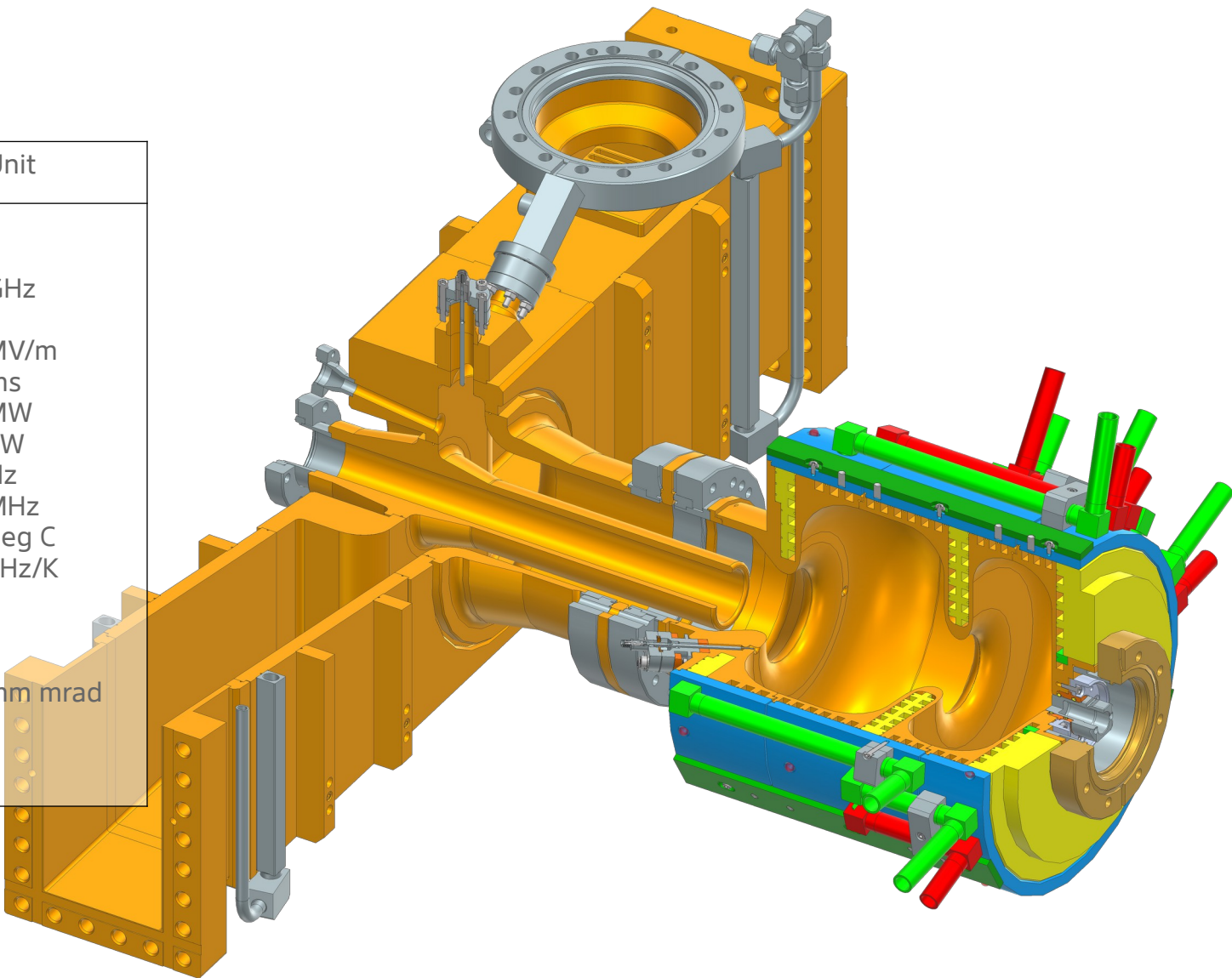


C. Mahnke et al., "Novel Photocathode Lasers for the Hard- and Soft-X-ray Free Electron Lasers EuXFEL and FLASH", 11th EPS-QEOD Europhoton Conference 2024 (EUROPHOTON 2024), Vilnius (Lithuania), August 2024. doi: 10.1051/epjconf/202430704001

Courtesy of M. Krasilnikov

Gun 5.3 Specs

Parameter	Value	Unit
Revision	5.3	-
Resonance Frequency	1.299 997	GHz
Mode of operation	normal-conducting	-
Gradient	60	MV/m
Pulse length (max.)	1	ms
Power (max. @ 600μs)	6.2	MW
Power (avg. @ 810μs)	48.6	kW
Repetition rate	10	Hz
Bunch repetition rate	4.5	MHz
Temperature, operational	50	deg C
Sensitivity	-22	kHz/K
Cavity	elliptical, 1 ½-cell	-
Coupler	coaxial, 2-feed	-
Field balance (Ecath/Ecell)	1.044	-
Emittance (250pC, 18MeV/c)	0.494	mm mrad
Mini-breakdown rate (nbd/ntotal)	4 · 10 ⁻⁴	-



M. Krasilnikov et al., "Gun5: A New Generation of Normal-Conducting RF Photogun for Long-Pulse Operation at the European XFEL", 42nd Free Electron Laser Conference 2026 (FEL2026), Stanford, California (USA), August 2026, contribution TUP20 (to be published).

A. Oppelt et al., "L-Band Development and Operation at DESY", 33rd Linear Accelerator Conference 2026 (LINAC2026), Daejeon (South Korea), August 2026 (to be published).

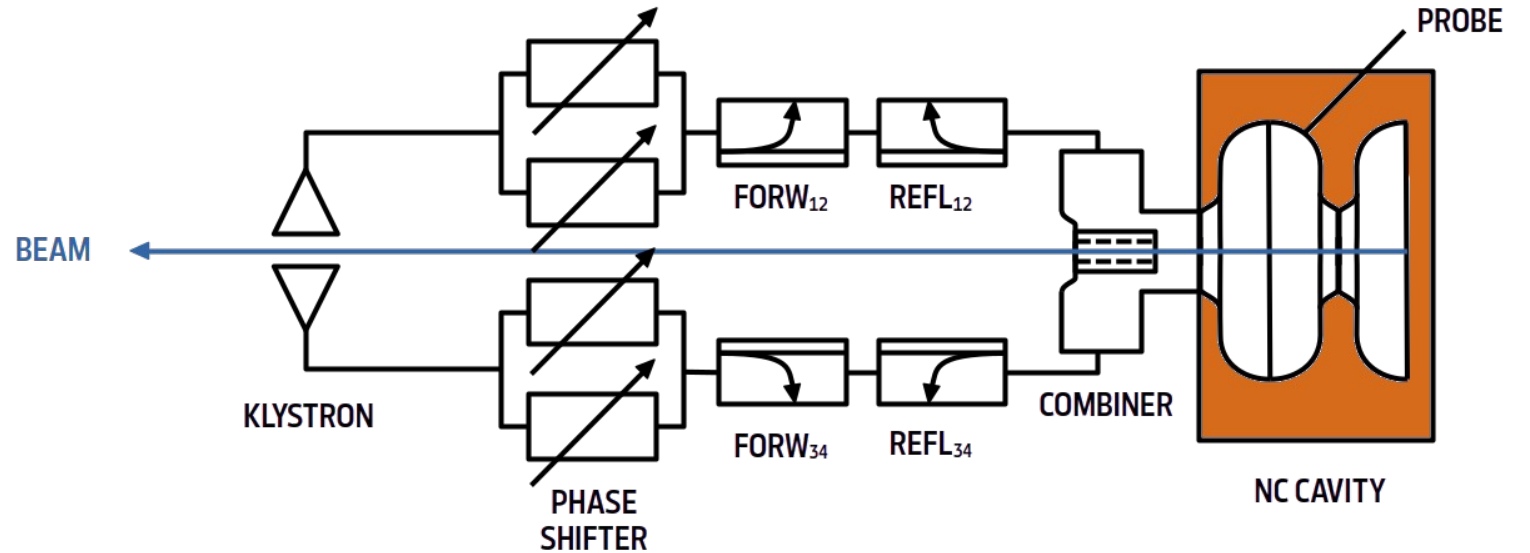
Courtesy of M. Krasilnikov

Gun 5.3 Plant

Modeling the gun.

From a control perspective, the gun is a massive copper body with an RF resonator inside.

It is fed by a combiner which couples klystron power from two independently phase-shifted branches into the cavity. Directional couplers provide for forward and reflected power measurements. Two redundant pick-up antennae yield probe amplitude and phase.



Motivation

The introduced RF energy heats the gun, and thereby increases its volume, effectively shifting the gun out of resonance.

Detuning makes the RF field susceptible to oscillations, causes power losses and phase drifts.

It needs to be mitigated, but can only be measured indirectly.

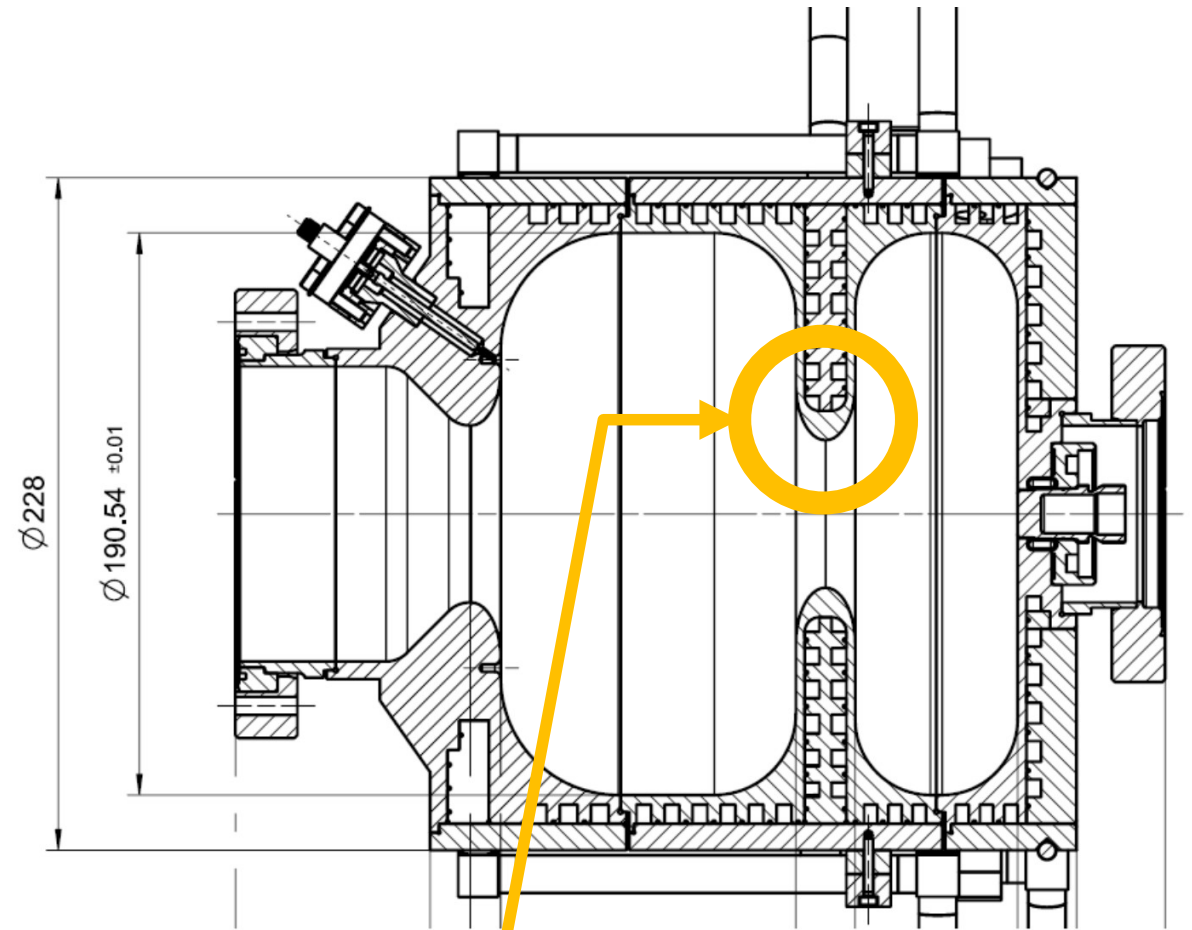
Detuning Is Unmeasurable

Temperature measurements raise timing constraints

Inner surface temperature cannot be measured accurately.

The closest that we can get to inner surface temperature is the sensor placed at the iris.

But even then, the lag of measurements due to the caloric inertia of mass, renders physical sensors unsuitable for an intra-pulse detuning measurement.



iris temperature sensor

Installed Feedbacks

Detuning Computation and Control for Gun Rev. 5.1.

The blueprint for pulsed gun operation.

The 2018 paper details the implementation of the detuning computation, and the **four involved control loops** (in ascending order of cycle time):

- RF PI fast feedback for **AP stabilization**
- RF pulse width modulation for **resonance control**
- RF frequency modulation for **ramp up**
- cooling water **temperature stabilization**

Back then, the gun was **single-feed** and **no cavity pick-ups** were available.

PHYSICAL REVIEW ACCELERATORS AND BEAMS **21**, 092802 (2018)

Precision feedback control of a normal conducting standing wave resonator cavity

S. Pfeiffer,^{*} L. Butkowski, O. Hensler, M. Hoffmann, C. Schmidt, H. Schlarb, and S. Schreiber
Deutsches Elektronen-Synchrotron (DESY), Hamburg, Notkestraße 85, 22607, Germany

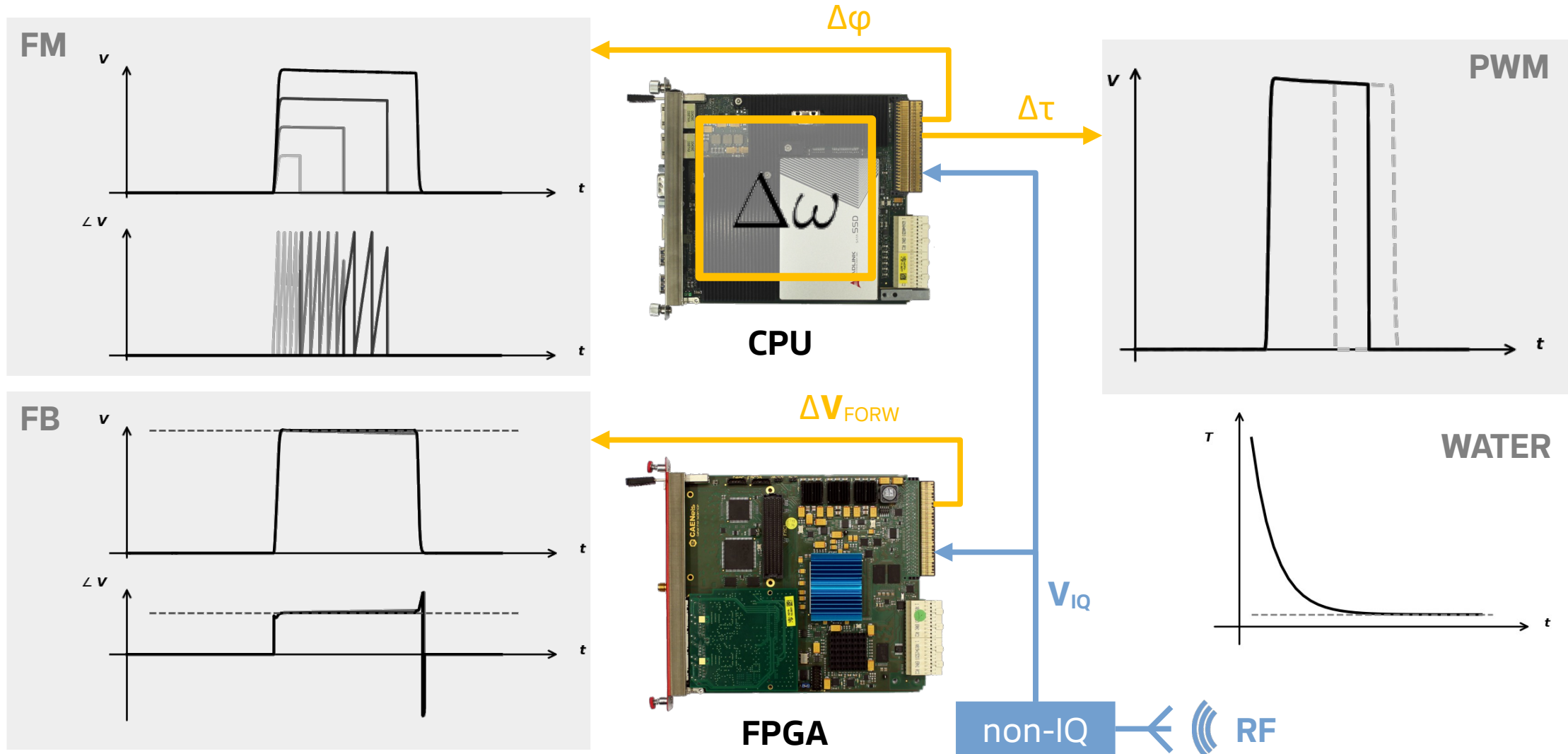
 (Received 25 January 2018; published 10 September 2018)

In this paper, the system identification and feedback controller design for a normal conducting standing wave radio frequency cavity operated in pulsed mode of a free electron laser is presented. The system identification, essential to achieve high performance control, is based on a grey box model, with *a priori* knowledge about the physical behavior. The feedback regulation concept is separated into two basic controller parts. A radio frequency controller design, based on the identified radio frequency model, is followed by a system identification and regulation of the pulse width to overcome the limitation of the underlying temperature regulation. It will be shown by measurements at the free electron laser FLASH at DESY, Germany, that the combination of both cascaded control schemes lead to high radio frequency field performance.

DOI: 10.1103/PhysRevAccelBeams.21.092802

Installed Feedbacks

Detuning Computation and Control for Gun Rev. 5.1.



Installed Feedbacks

Detuning Computation and Control for Gun Rev. 5.1.

Based on linear cavity equation and stationary detuning.

Detuning can be obtained by solving the cavity equation for detuning $\Delta\omega$ and a coupling coefficient term β^* , possibly using a least-squares method if many measurements are available.

This works well if flat top is stationary/actively controlled, and can be easily implemented on a CPU.

$$\mathbf{0} = \begin{pmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{pmatrix} \mathbf{V}_{\text{probe}} + 2 \underbrace{\frac{\beta}{\beta + 1}}_{\beta^*} \omega_{1/2} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \mathbf{V}_{\text{forw}}$$
$$\begin{pmatrix} \Delta\omega \\ \beta^* \end{pmatrix} = (A^T A)^{-1} A \mathbf{b}$$

Phase Roll

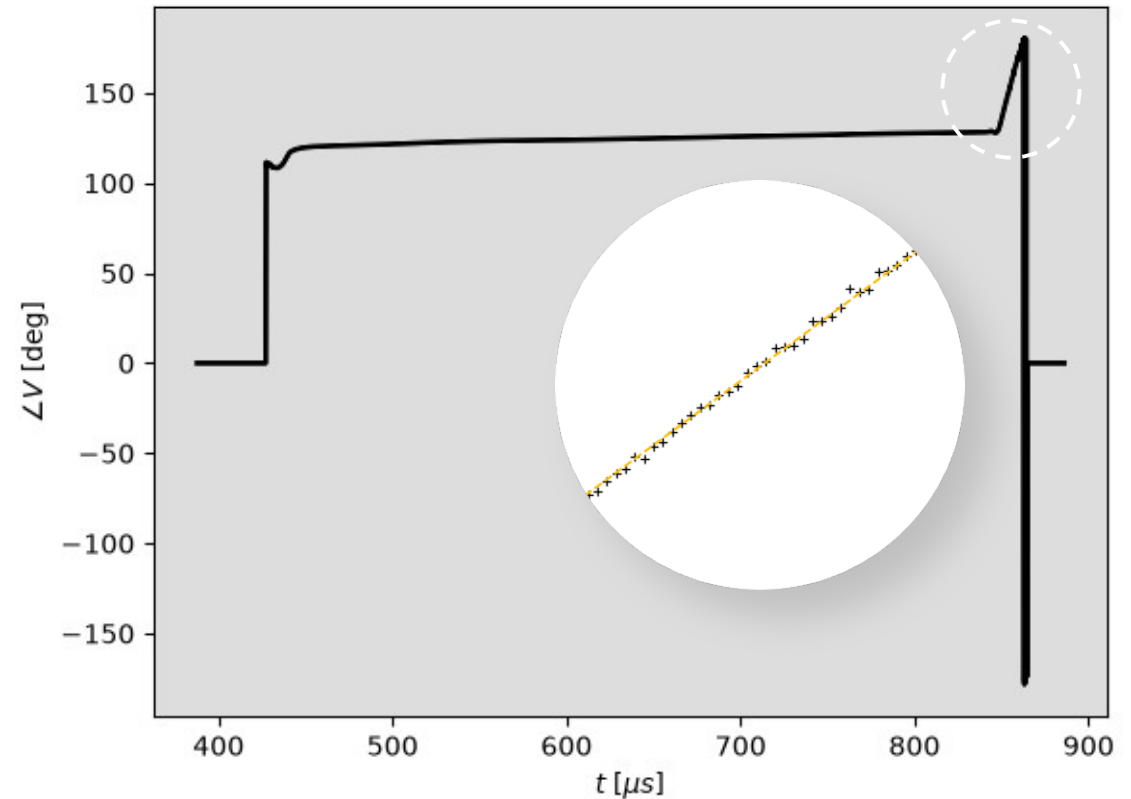
The Direct Observable

Detuning is slope of phase roll.

When turning off forward power, the cavity's eigendynamics show in the probe's RF readings:

- half bandwidth from amplitude decay
- **detuning** from **phase roll**

The problems with deriving detuning from phase measurements are that, due to fast transients and pulse trajectories, there are just a **few samples left**, and that detuning can only be evaluated **at the end of the pulse**.



$$\sin((\omega_0 + \Delta\omega)t) = \sin(\omega_0 t + \int \partial_t \varphi \, dt)$$

The Observer Concept

Observers are filters that act as simulations of the real plant.
When supplied with input and output signals of the process under surveillance, observers may extend the space of observable variables.
Specifically, given cavity voltage and forward power, the observer can deduce detuning.

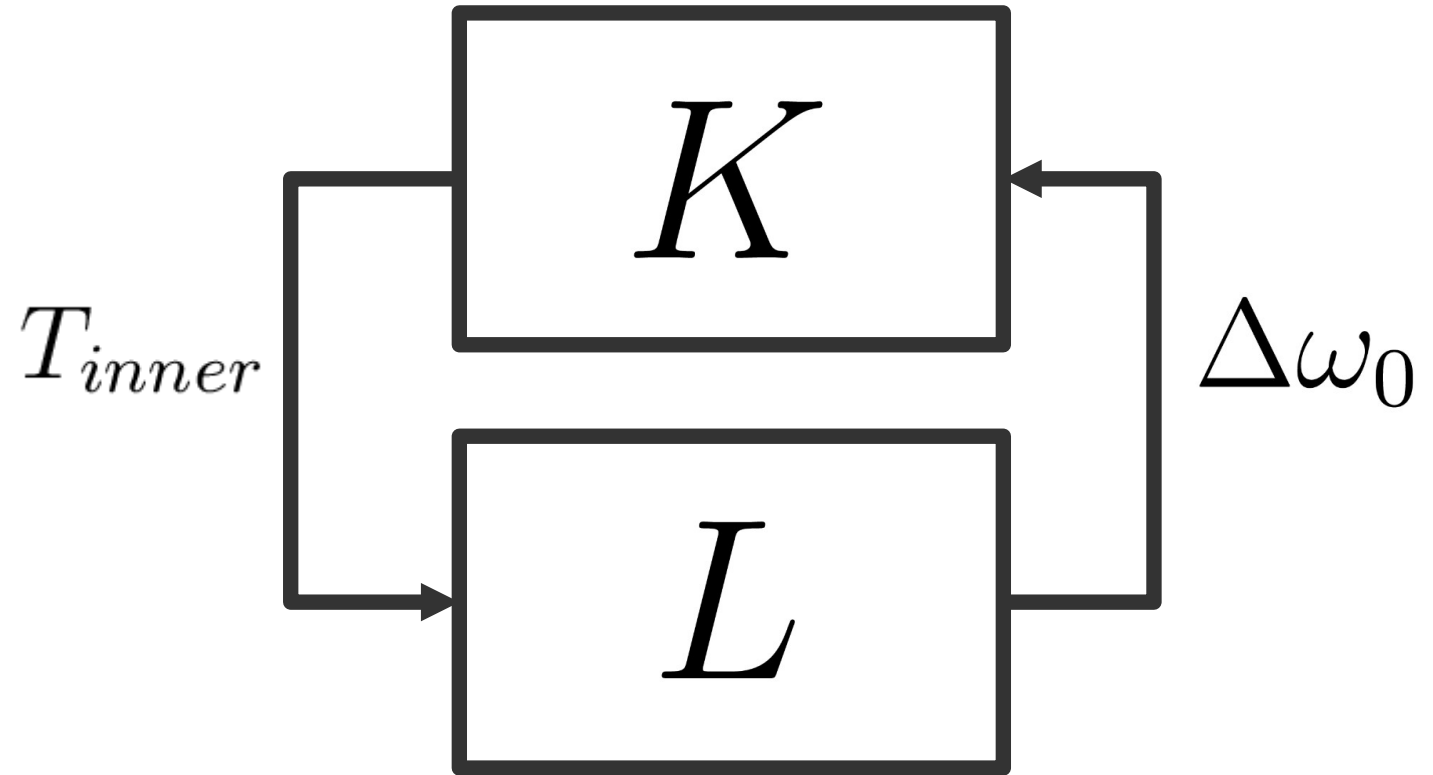
The Conjugated Observer Scheme

Make Kalman and Luenberger talk

Dedicating time frames.

The challenge of employing a model-based estimation scheme in pulsed operation is the different time constants involved: Fast intra-pulse dynamics dominated by RF and slow inter-pulse dynamics dominated by heat transfer.

For each time domain, we propose a dedicated observer: a **slow Luenberger** and a **fast Kalman** filter.

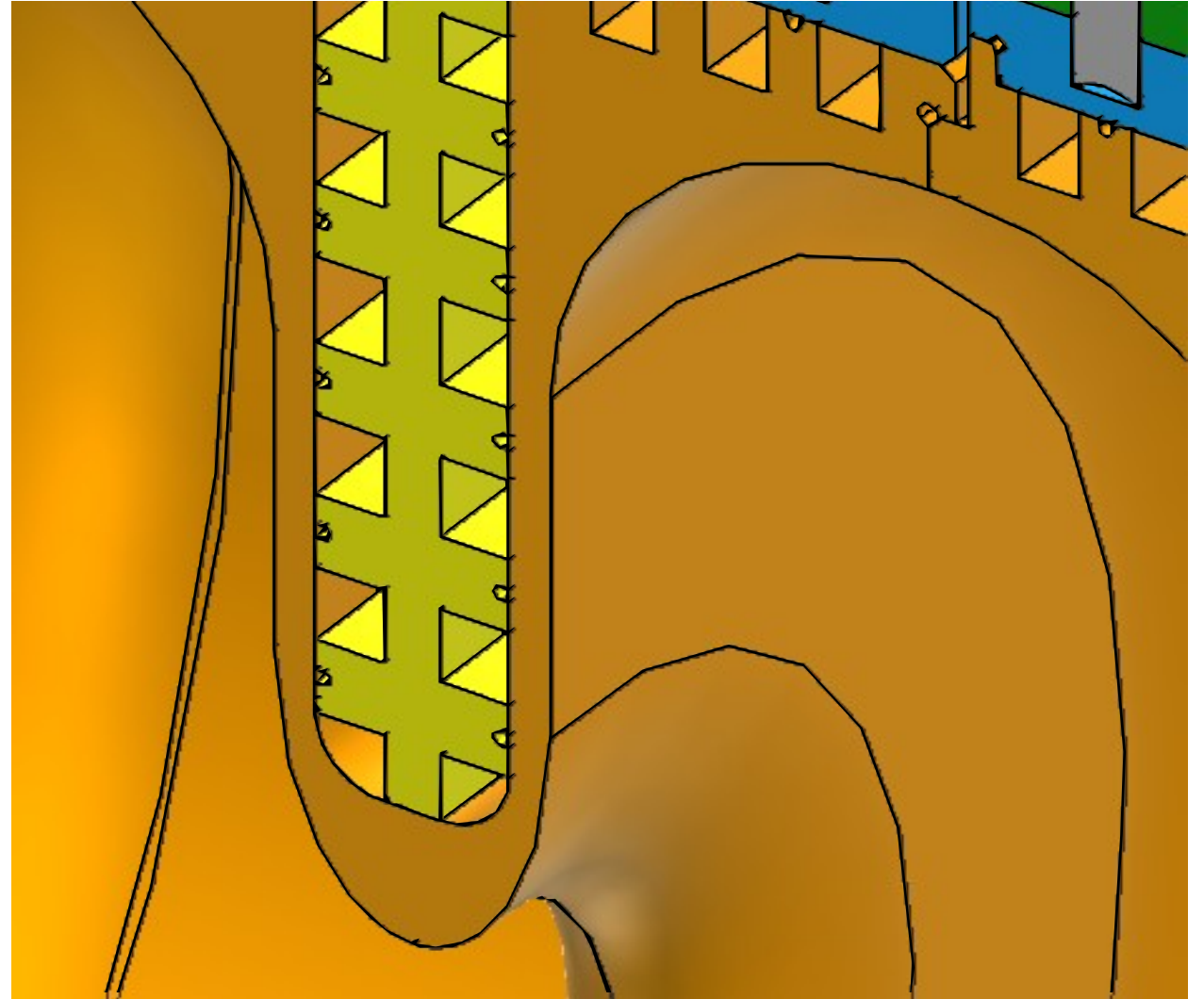


The Initial Detuning Estimation Scheme

Luenberger observer for iris temperature smoothing

Capturing slow transients.

Between pulses, water cooling dominates the dynamics: in absence of RF input, the copper **temperature drops** until the arrival of the next pulse. A linear Luenberger observer serves as an estimation scheme for tracking the iris temperature, and thereby providing the **initial condition** for the conjugated Kalman filter.

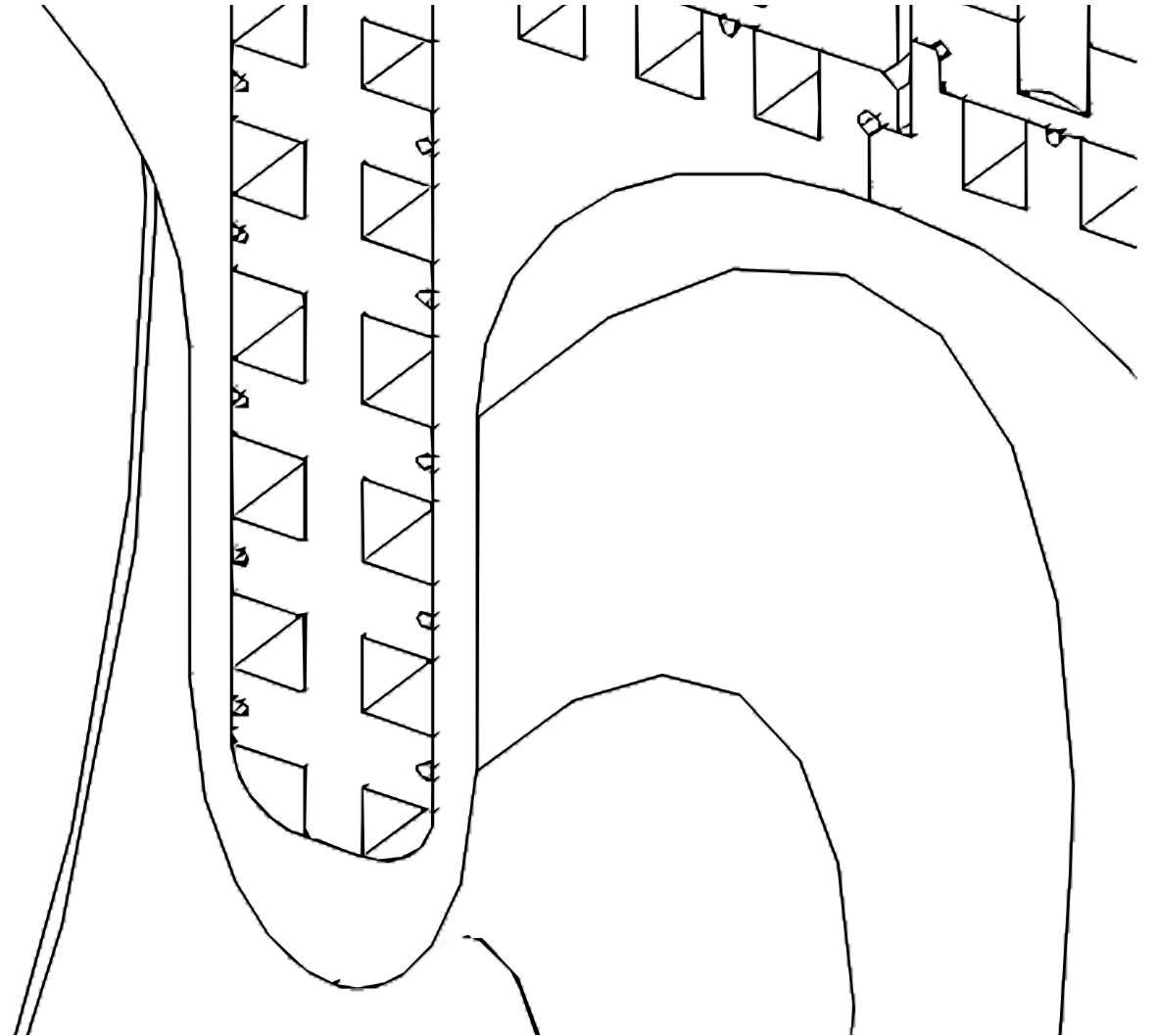


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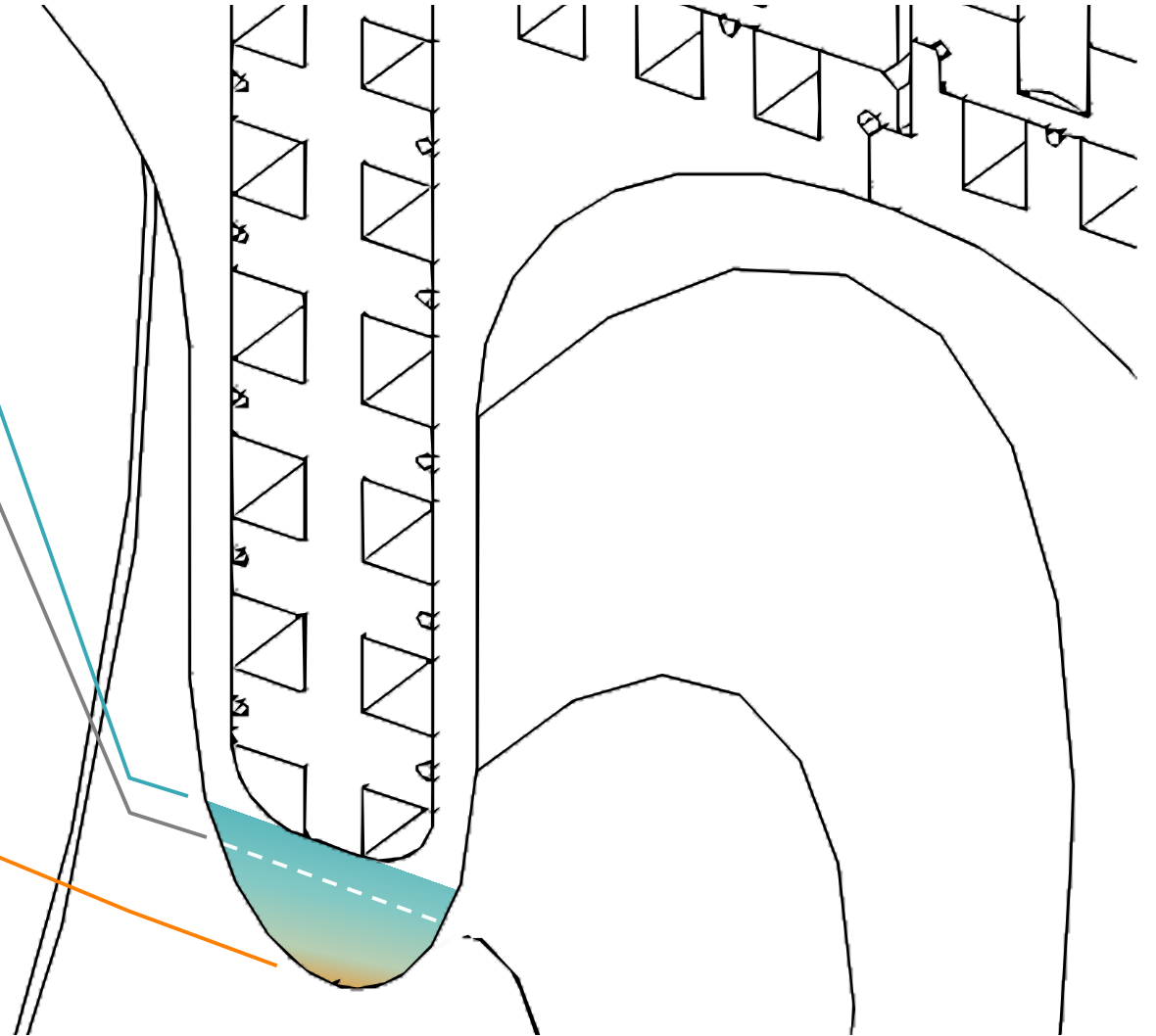
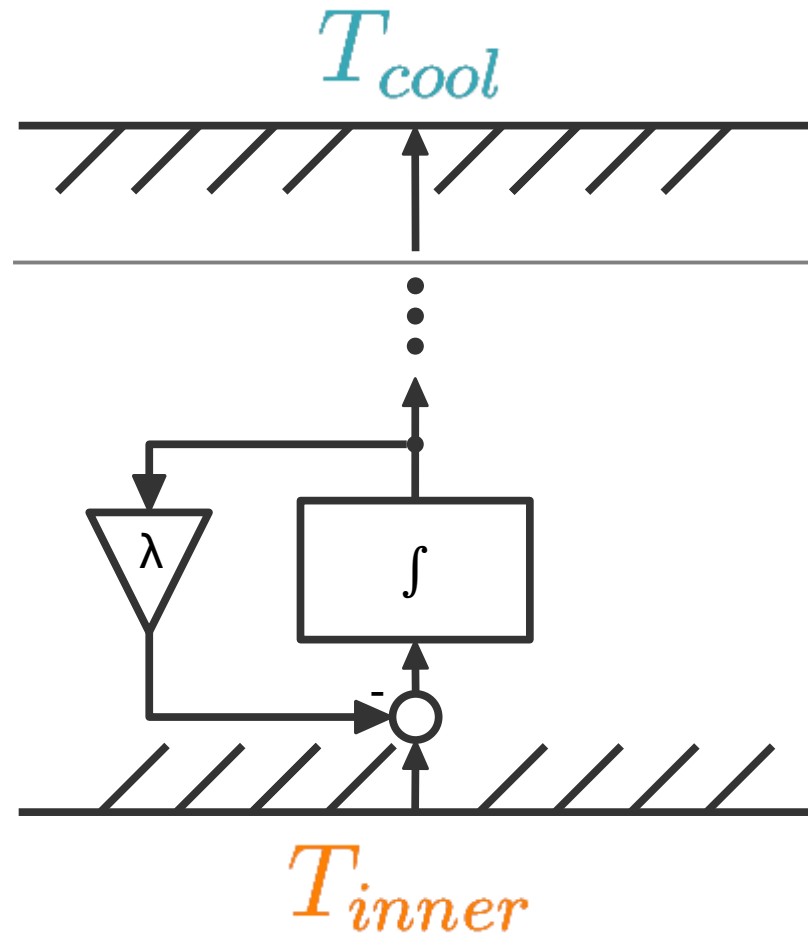
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Luenberger observer for iris temperature smoothing



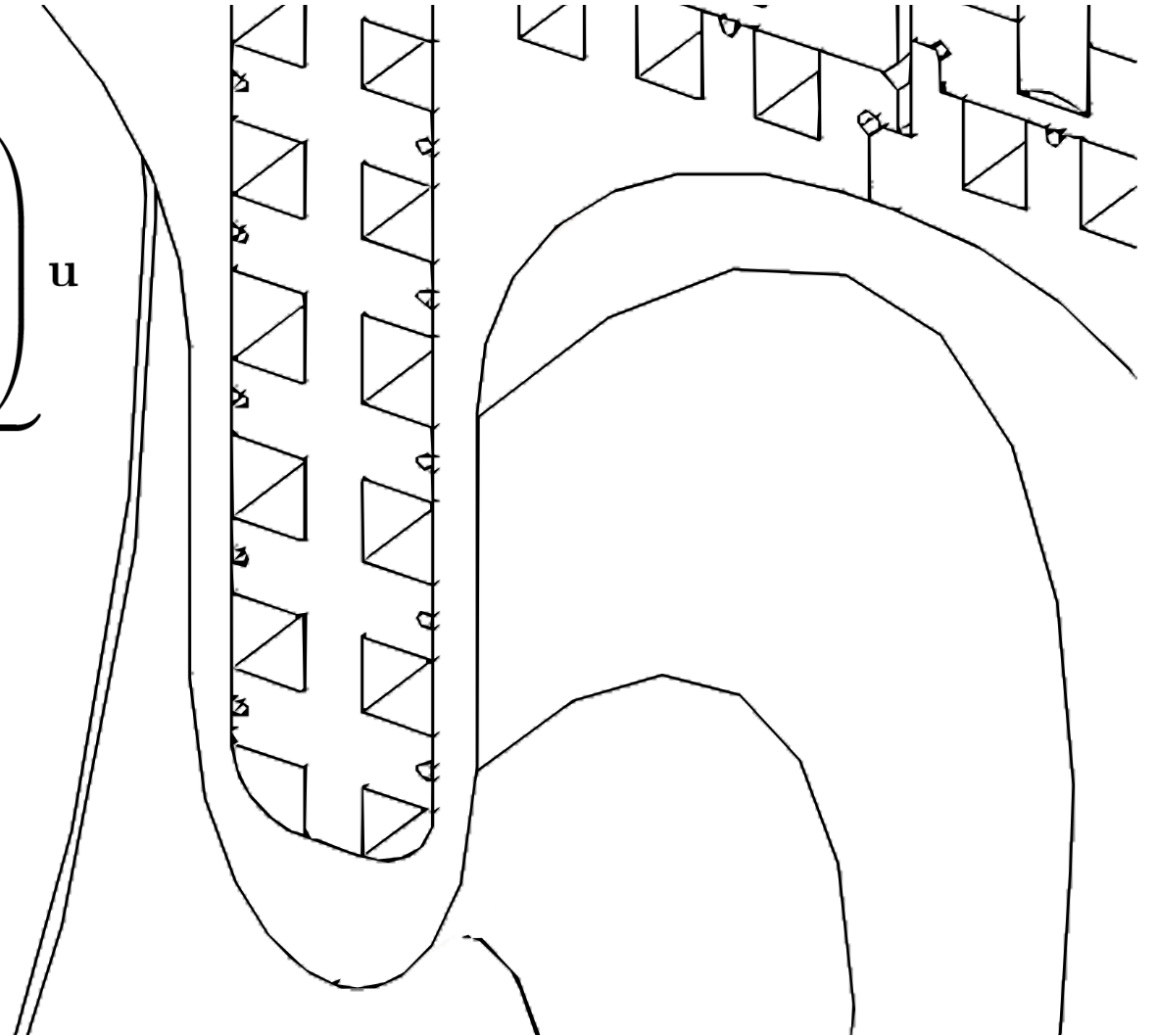
The Initial Detuning Estimation Scheme

Luenberger observer for iris temperature smoothing

$$\dot{\mathbf{x}} = \underbrace{\begin{pmatrix} -2\lambda & \lambda & 0 & \dots & 0 \\ \lambda & -2\lambda & \lambda & \dots & 0 \\ \vdots & & & \ddots & \vdots \\ 0 & \dots & 0 & \lambda & -2\lambda \end{pmatrix}}_A \mathbf{x} + \underbrace{\begin{pmatrix} \lambda & 0 \\ 0 & 0 \\ \vdots & \\ 0 & \lambda \end{pmatrix}}_B \mathbf{u}$$

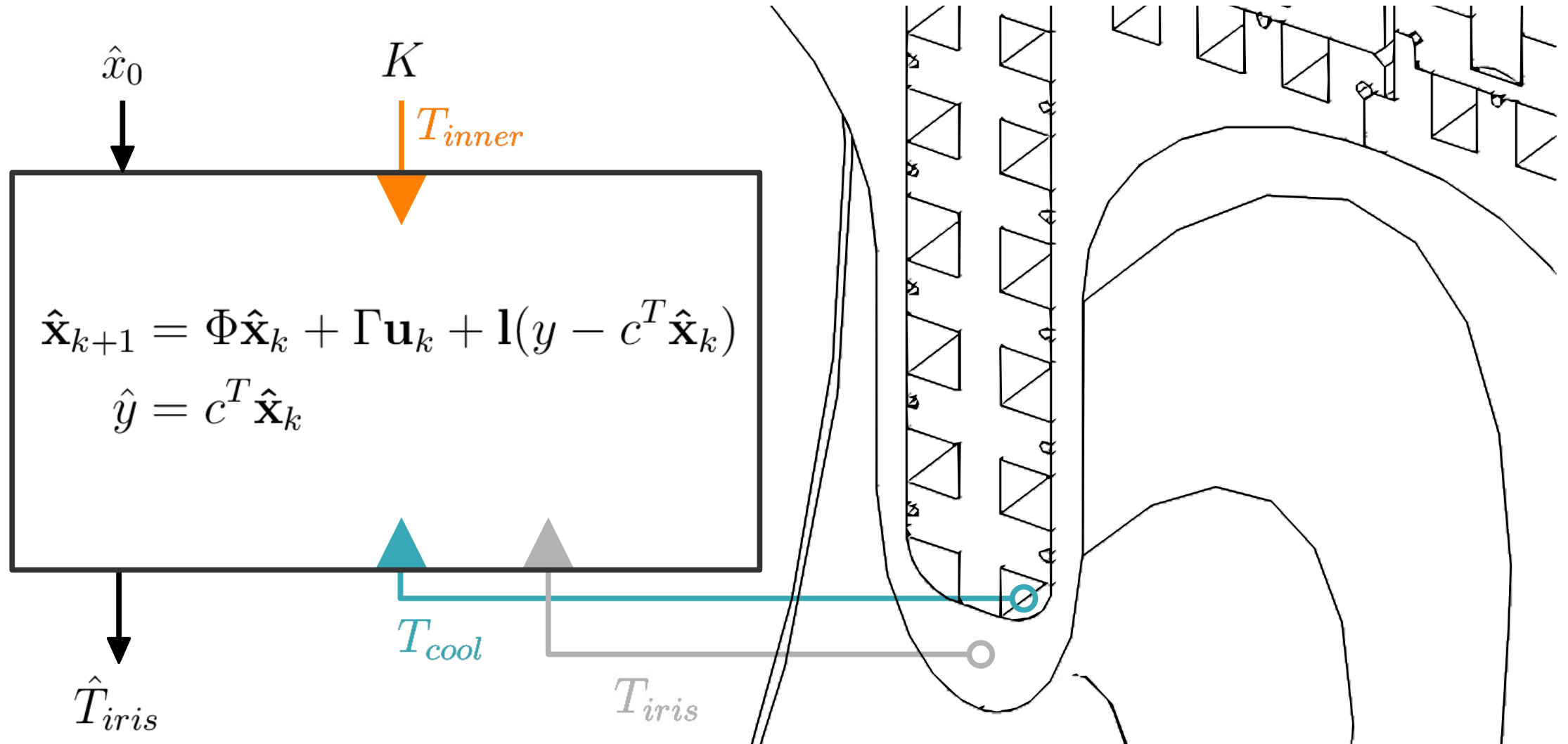
$$\min_{\lambda, T(t_0)} \sum_k (T_{\text{iris}}^{\text{meas}}(t_k) - T_{\text{iris}}(t_k))^2$$

$$T^{(0)}(t_0, z_i) = -A^{-1}(\lambda^{(0)})B(\lambda^{(0)})\mathbf{u}_{ss}$$



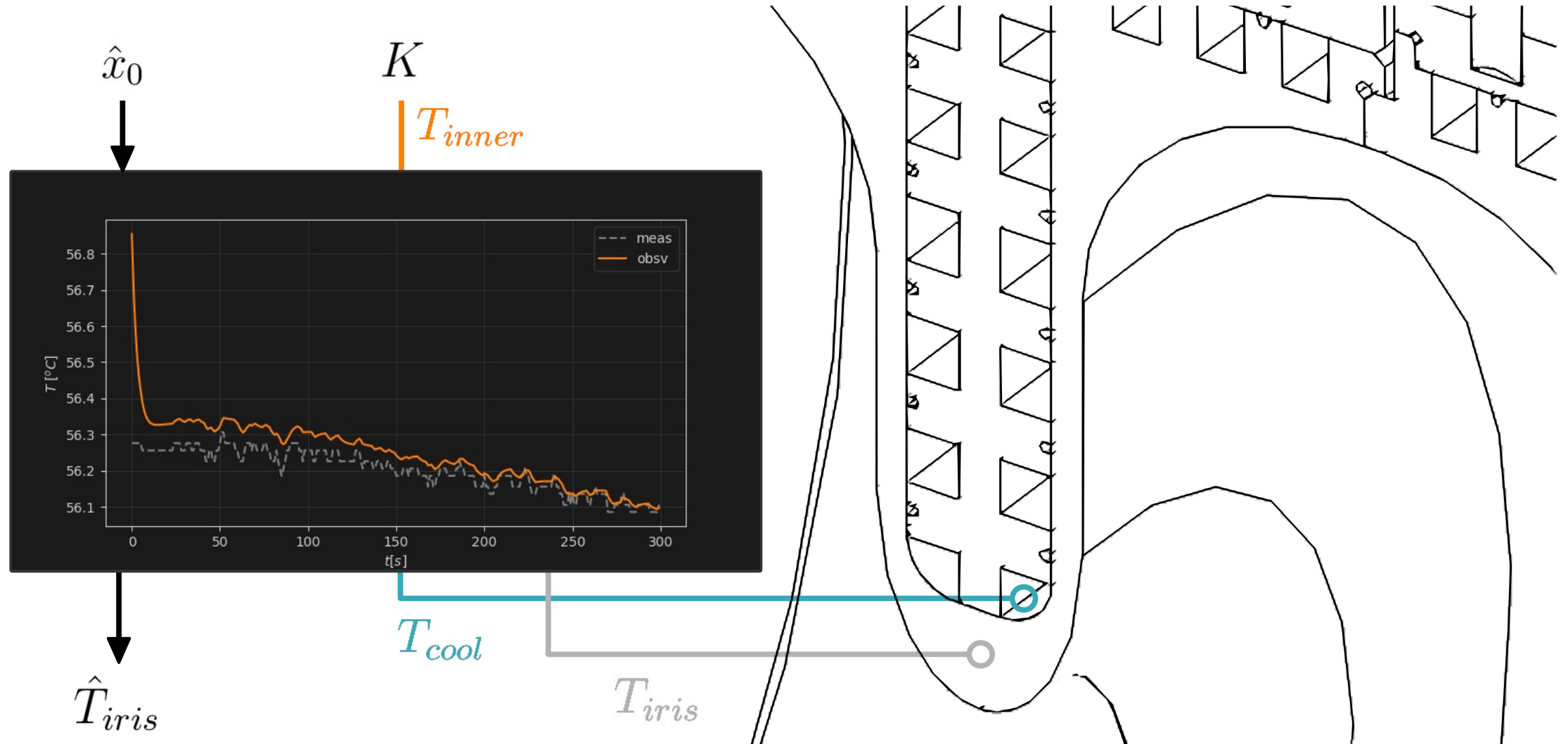
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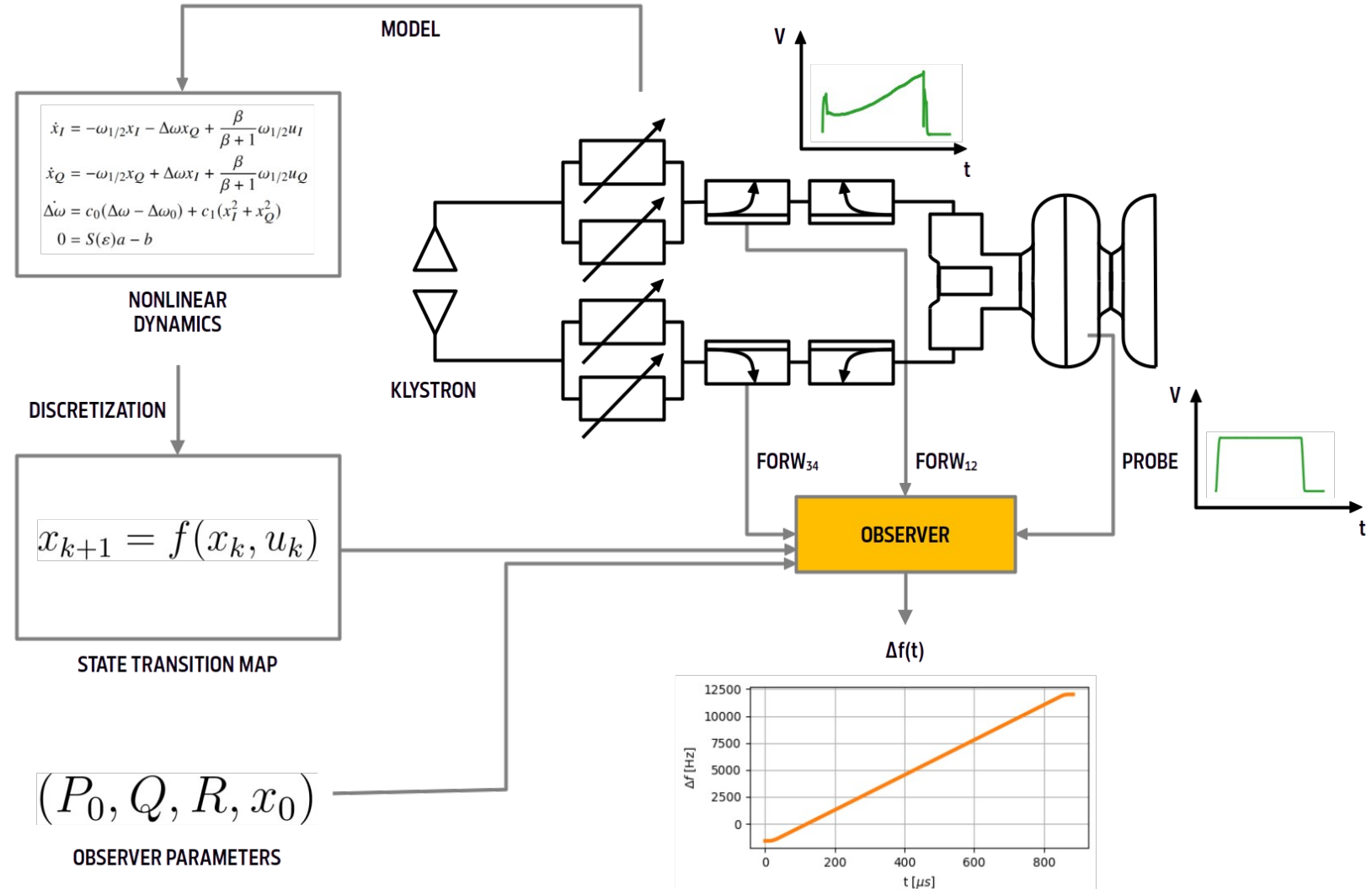
Luenberger observer for iris temperature smoothing



The Unscented Kalman Filter Estimation Scheme

Extending the observable space.

An observer acts as a model-based simulation of the plant under surveillance, and extends the space of observable variables. In case of the gun detuning estimation scheme, forward voltages and probe signal serve as input to the observer which returns detuning over time. Computationally fast state transition maps potentially allow for implementation on FPGA for realtime monitoring.



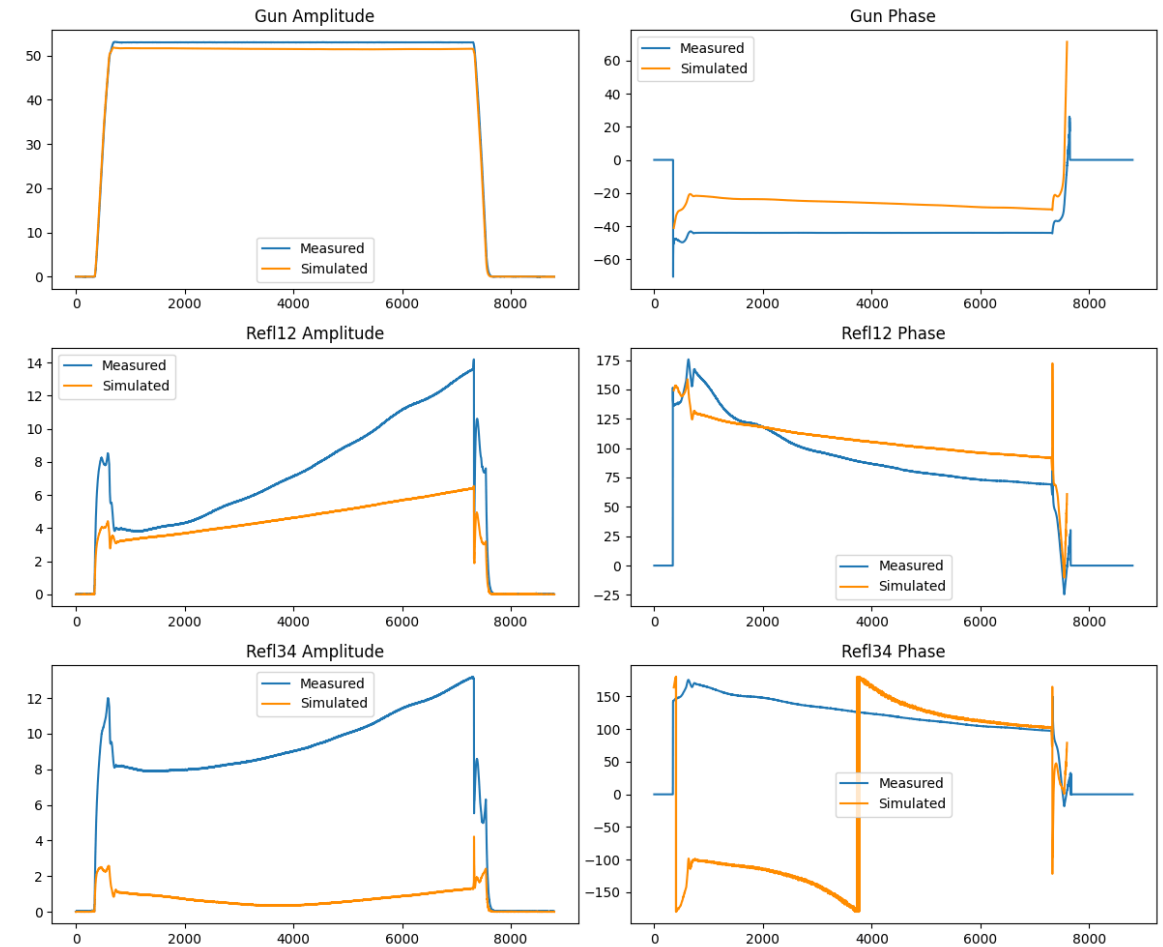
System Parameters Identification

White-Box parameter identification for the nonlinear gun model

White-Box model limits the number of free parameters.

The governing equations, derived from first principles, require an overall of 22 unknown parameters to be identified:

- half bandwidth
- coupling coefficient
- initial detuning
- RF-to-detuning sensitivity
- 9 complex coefficients of the scattering matrix



Courtesy of Philéas Bour

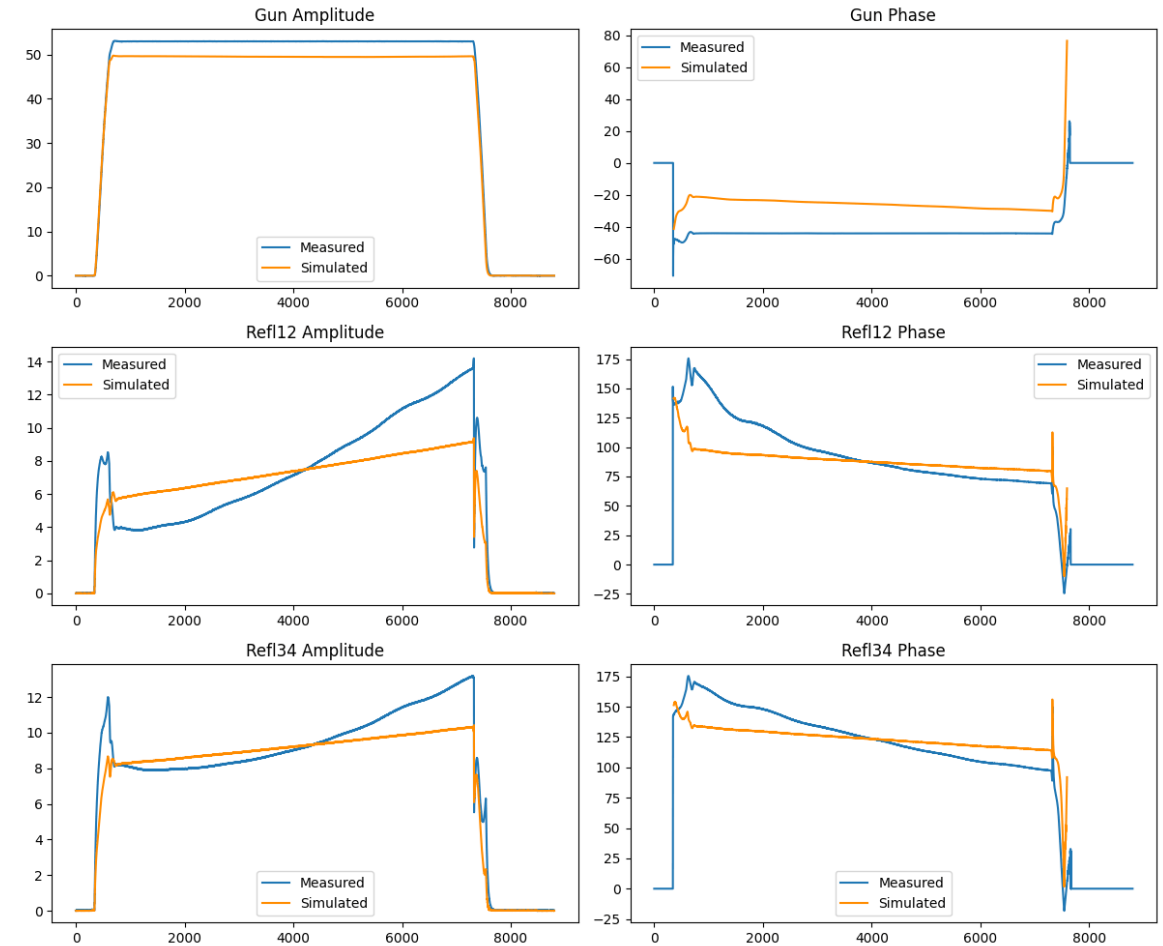
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The parameters are identified by making a set of measurements match the solution of the ordinary differential equations governing the cavity dynamics.

$$\min_p \left(\sum_k (y_{\text{meas},k} - y_{\text{sim},k}(p))^2 \right)$$



Courtesy of Philéas Bour

System Parameters Identification

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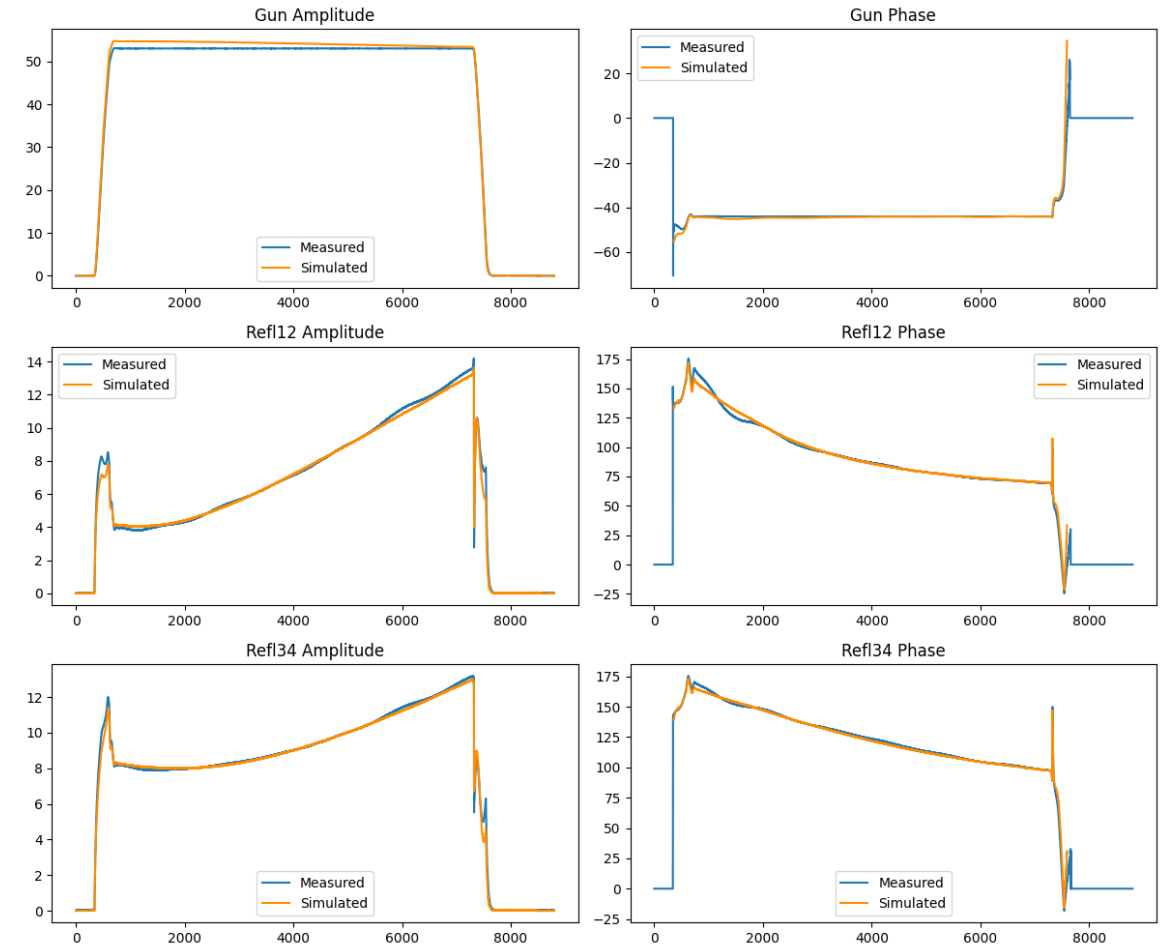
The differential-algebraic system can be partitioned into three constituent parts:

$$\dot{x}_I = -\omega_{1/2}x_I - \Delta\omega x_Q + \frac{\beta}{\beta + 1}\omega_{1/2}u_I$$

$$\dot{x}_Q = -\omega_{1/2}x_Q + \Delta\omega x_I + \frac{\beta}{\beta + 1}\omega_{1/2}u_Q$$

$$\dot{\Delta\omega} = c_0(\Delta\omega - \Delta\omega_0) + c_1(x_I^2 + x_Q^2)$$

$$0 = S(\varepsilon)a - b$$



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$$0 = Sa - b$$

CAVITY VOLTAGE DYNAMICS

Essentially, the fundamental linear **resonator equation** for the enveloping amplitude and phase on the carrier frequency with a driving term and time-dependent detuning which accounts for cross-couplings and oscillations.

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DETUNING DYNAMICS

Covers **convective heat losses**, and **RF energy input**.

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COMBINER CONSTRAINTS

The RF **scattering matrix coefficients** relating forward power, reflective power, and cavity feed.

System Parameters Identification

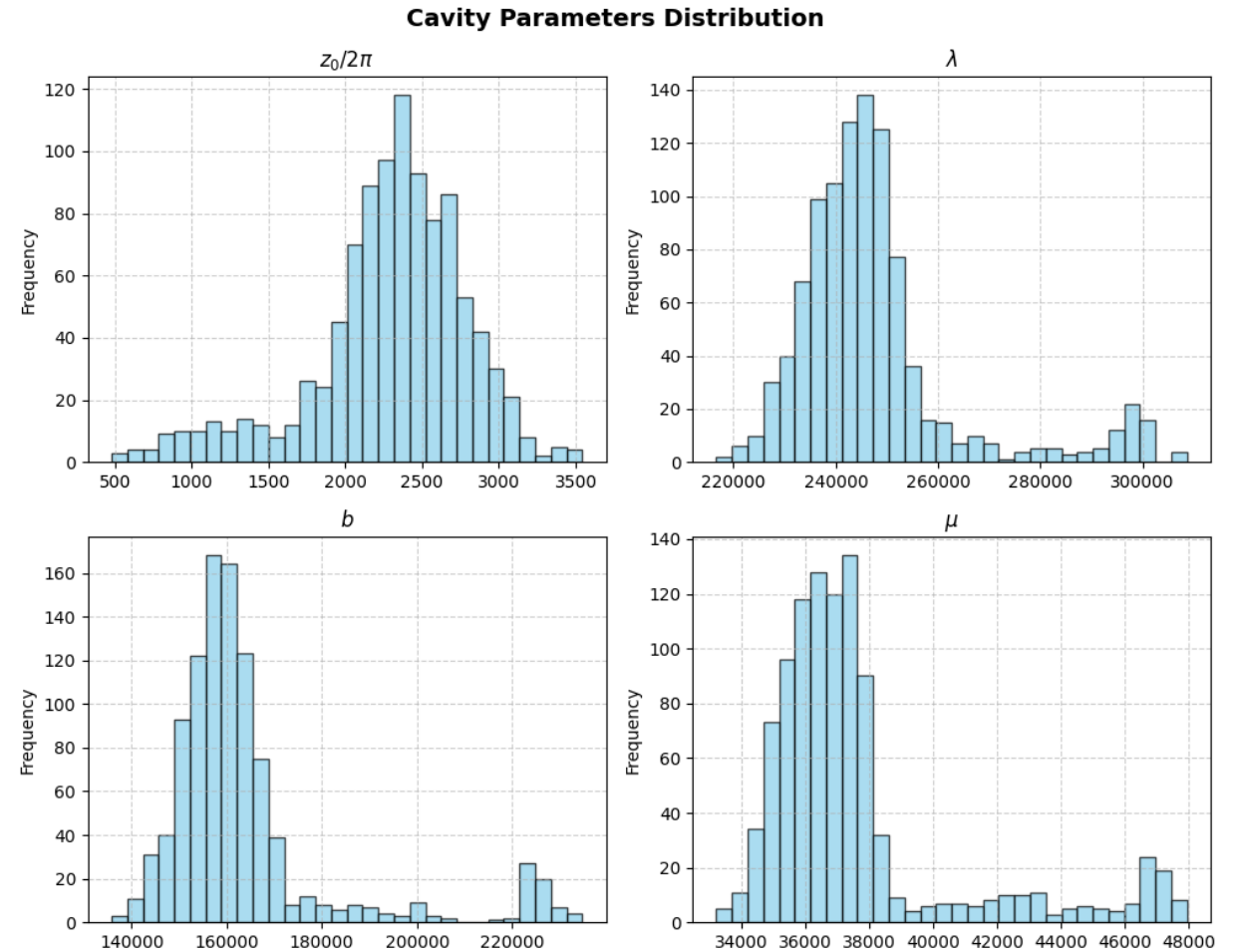
White-Box parameter identification for the nonlinear gun model

Identified parameters.

An overall of 10^3 measurements have been employed to find system parameters that make the measurements match the integrated differential equations.

In the following, histograms of the identified parameters are shown:

- half bandwidth λ
- Input scalar b
- initial detuning z_0
- RF-to-detuning sensitivity μ
- 9 complex coefficients of the scattering matrix S_{ij}

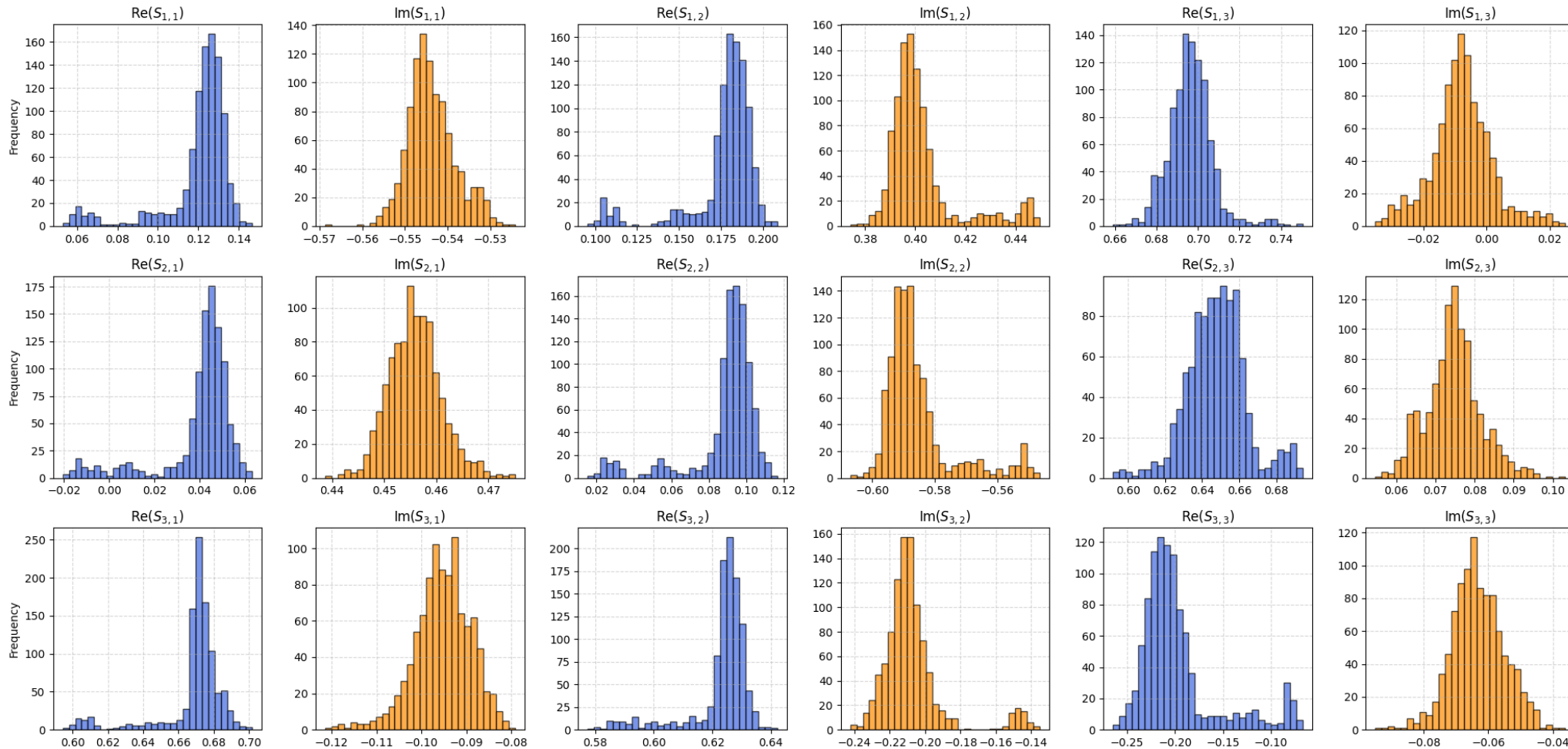


Courtesy of Philéas Bour

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S-Matrix Coefficients Distribution



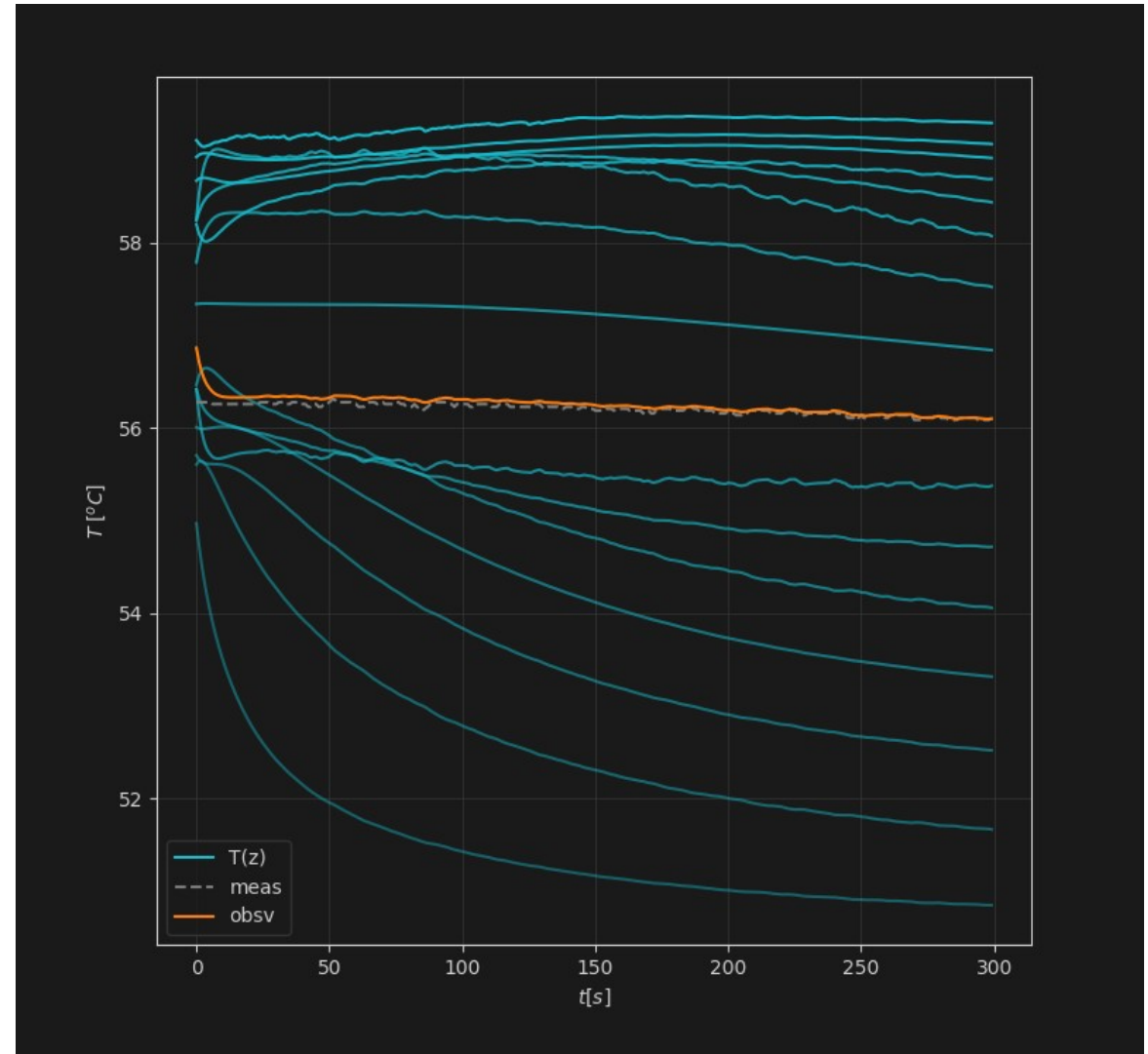
Courtesy of Phil  as Bour

Results

Luenberger temperature tracking

Temperature sweep.

Following an initialization phase of about 20 pulses, the temperature profile converges towards the measured iris temperature. The other spatially distributed states unfold according to the identified thermal conductivity, and the „driving“ temperatures of cooling water and inner surface wall.

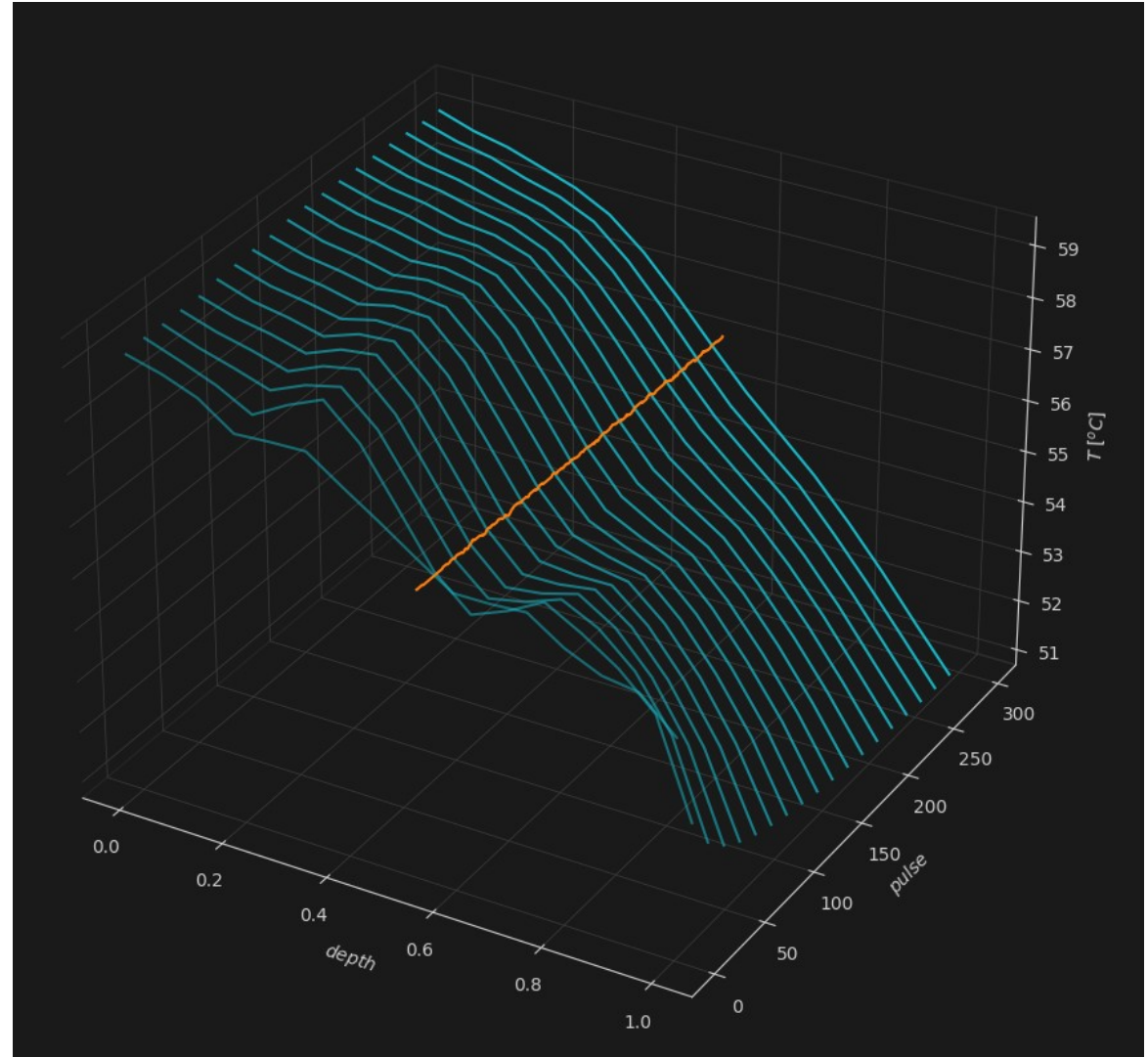


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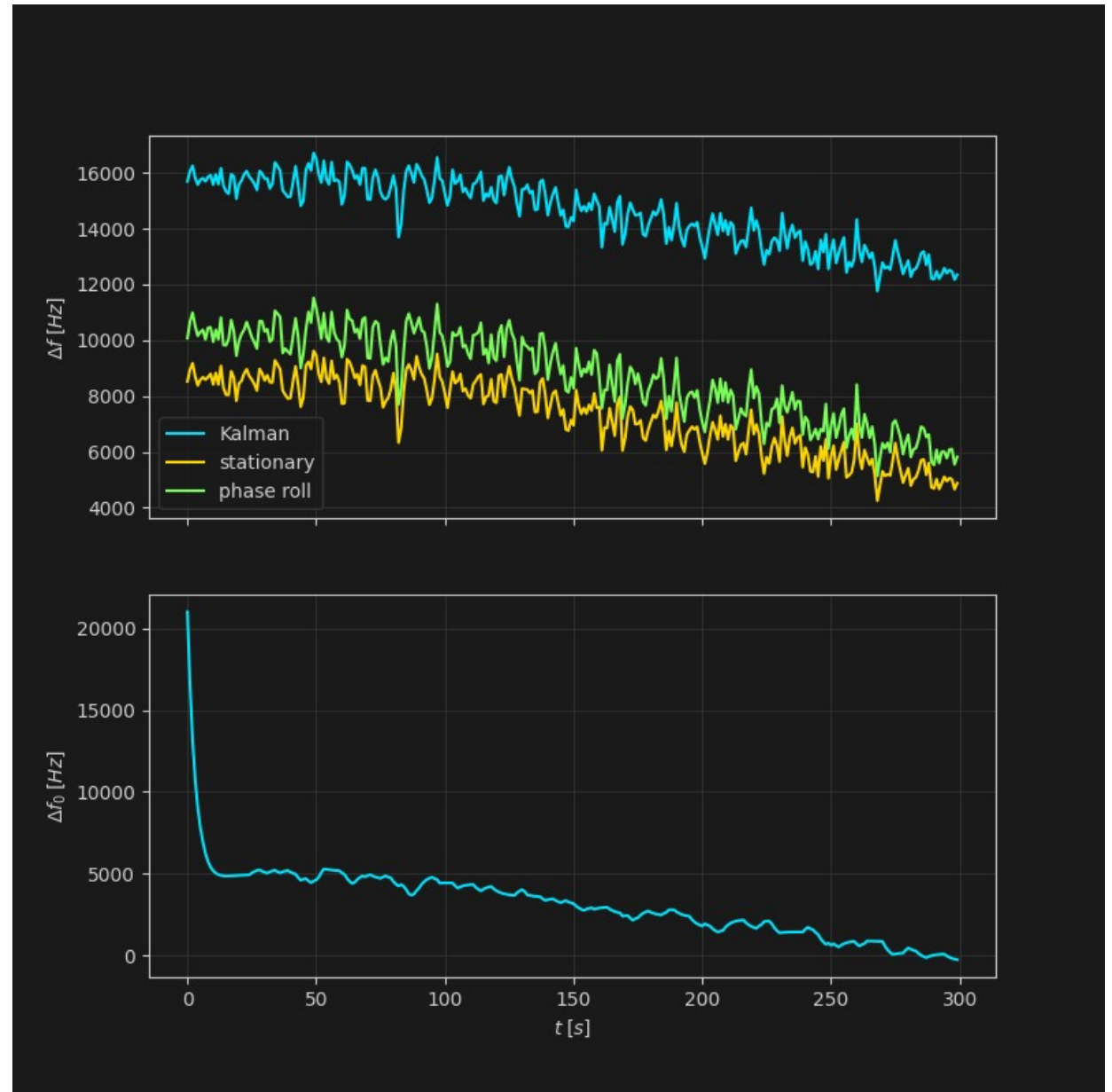
Kalman filter vs stationary approximation

Three methods. Four results.

The plot shows a **comparison** of the estimated detuning at the end of the pulse using the **Kalman** filter vs. detuning computed with the **linear, stationary approach** (yellow). As additional reference, the detuning computed from phase roll is given (green). Provided that phase roll is ground truth, the Kalman filter largely overestimates detuning, and is almost as noisy as the competing methods.

Note

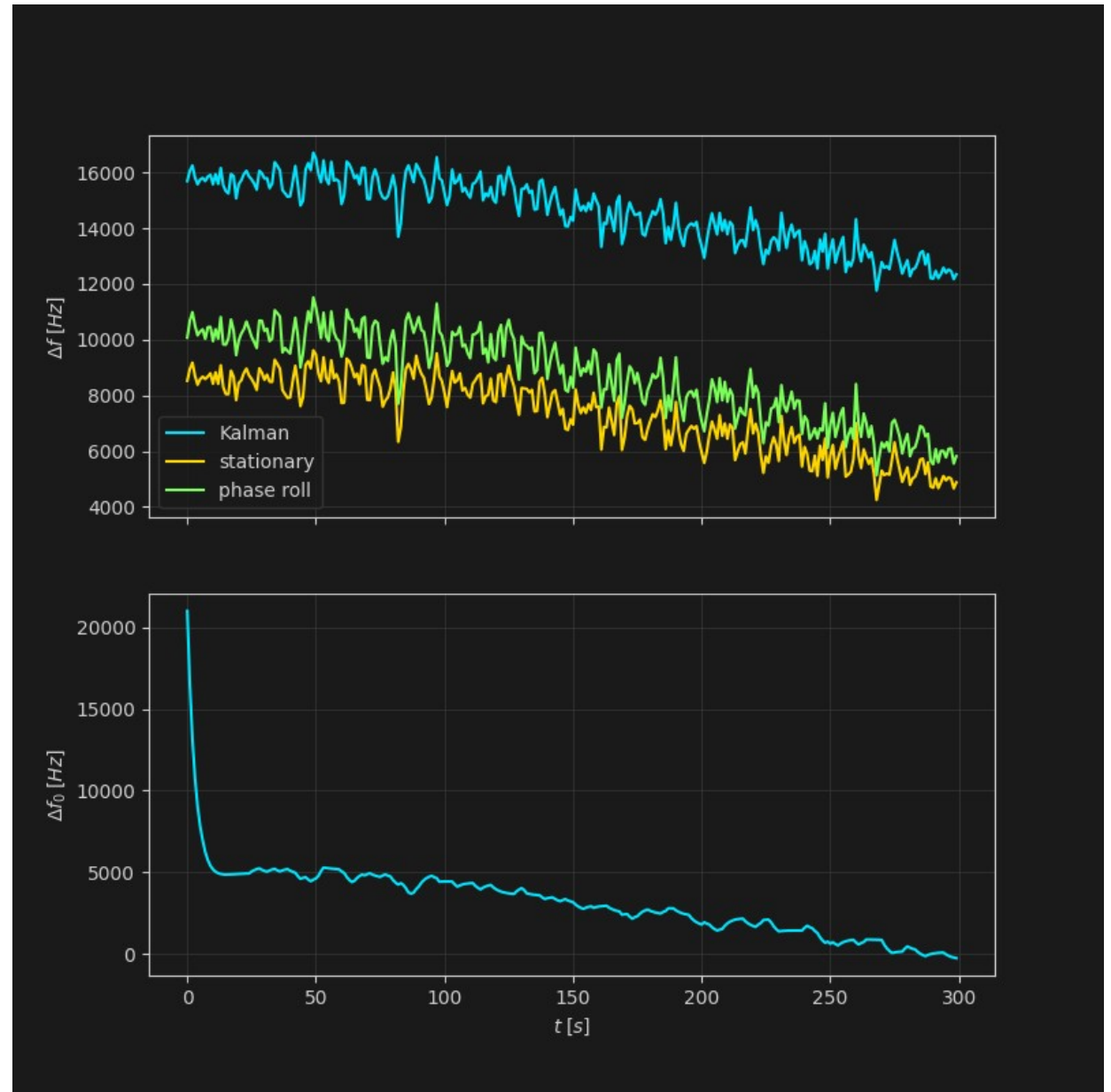
For the linear, stationary approach, the phase of the probe signal needed to be adjusted to make minimum of reflected power match zero-crossing of the phase.



Results

Kalman filter vs stationary approximation

BUT, ...



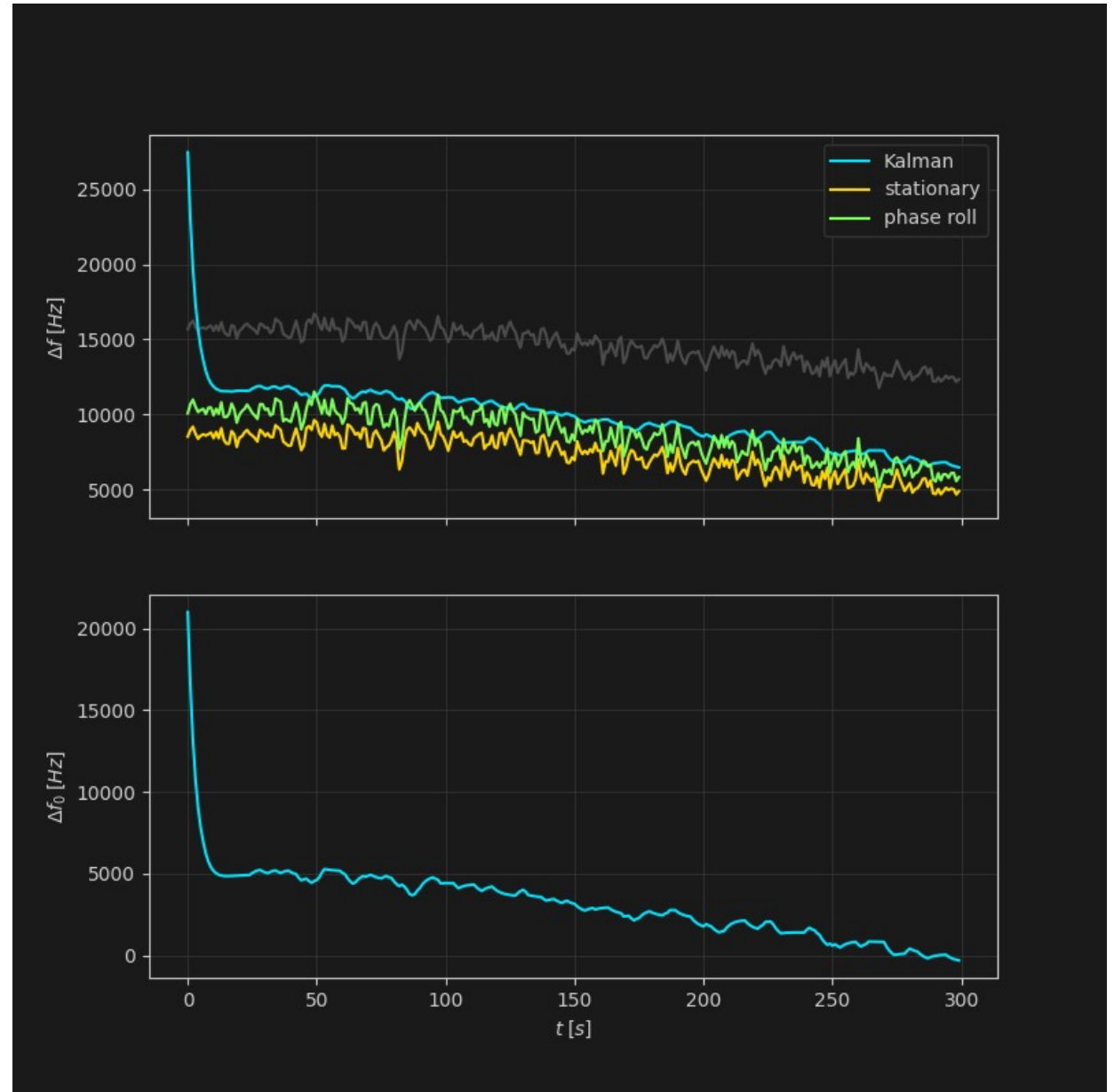
Results

Kalman filter vs stationary approximation

Process noise.

Due to the Bayesian nature of the Kalman filter, there is a **tuning knob** which lets you choose if you rather believe in the model, or in the measurements: **detuning process noise Q** .

If confidence is high that your system parameters are very accurately chosen, you would set Q to be small, otherwise you would need to assume a noise or uncertainty model, e.g. quantization noise of temperature measurements $\times$ sensitivity.

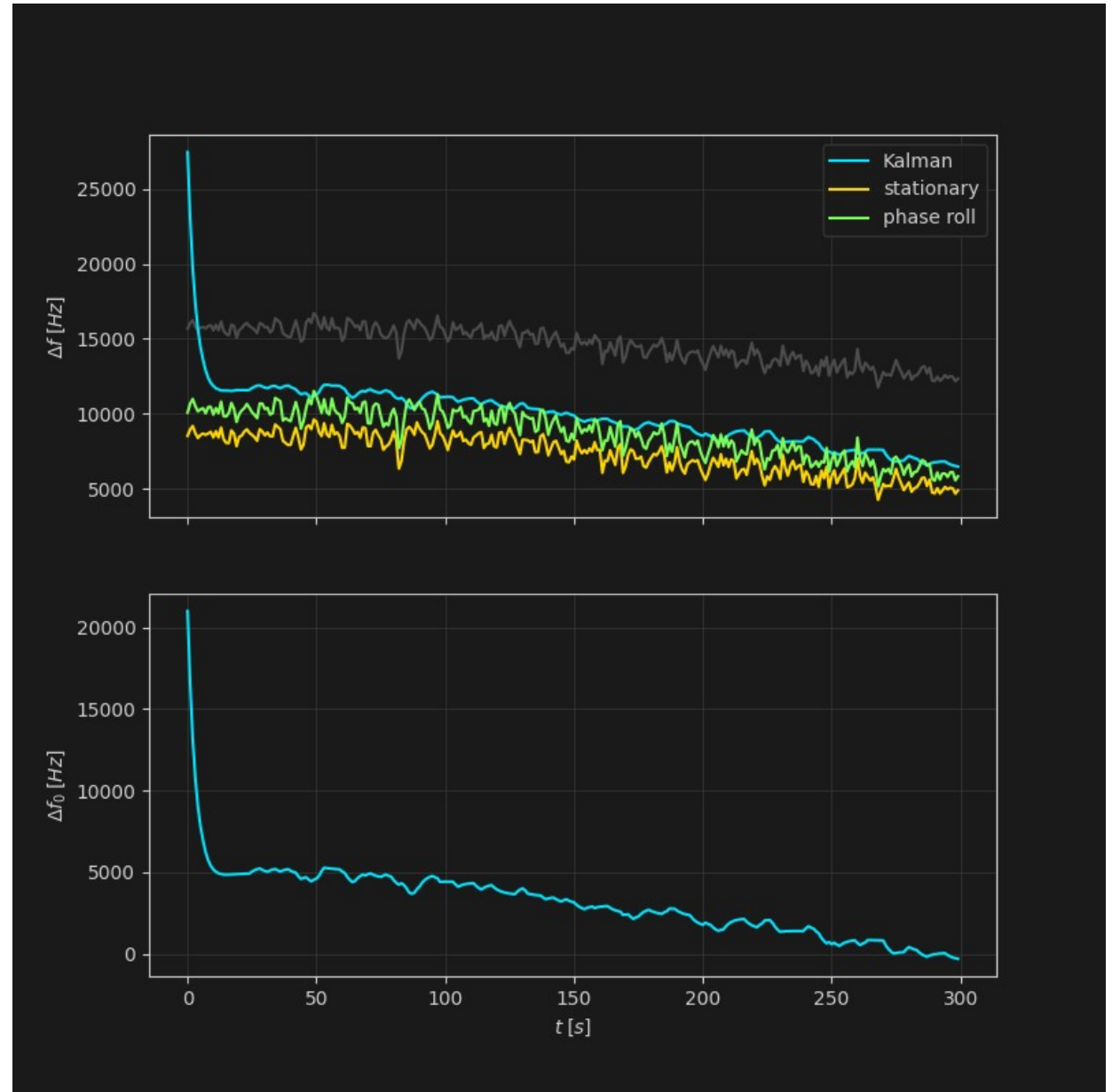
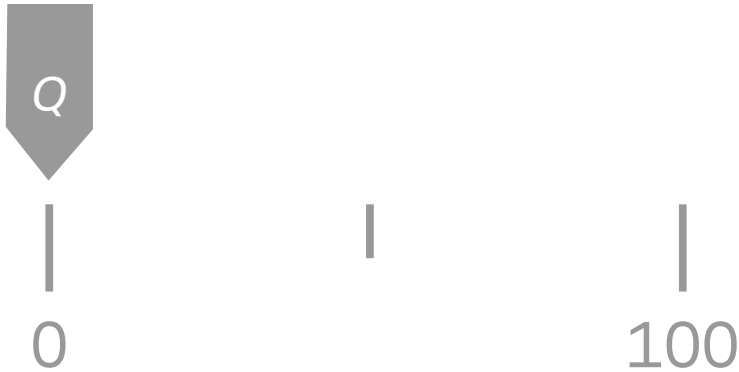


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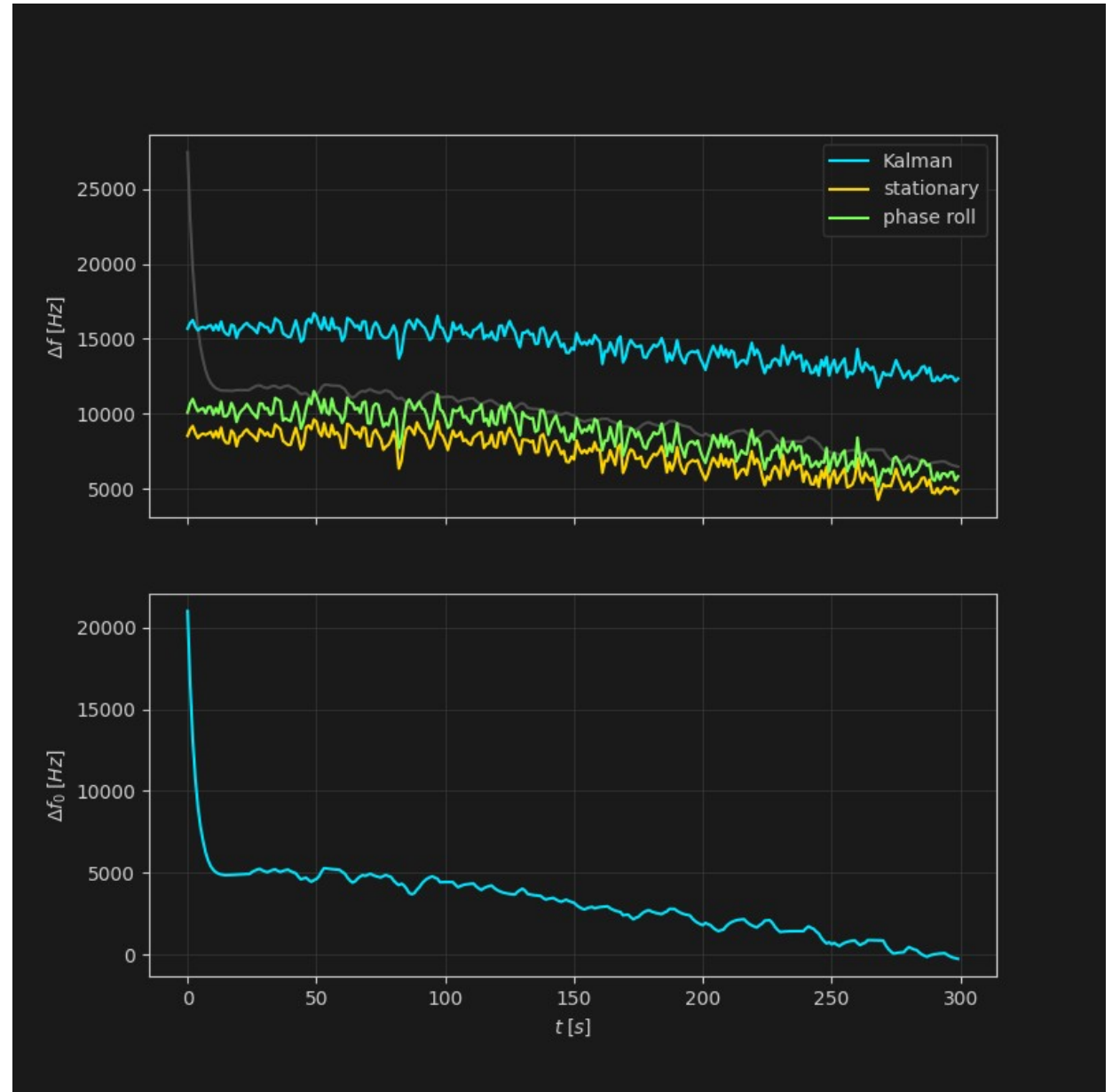


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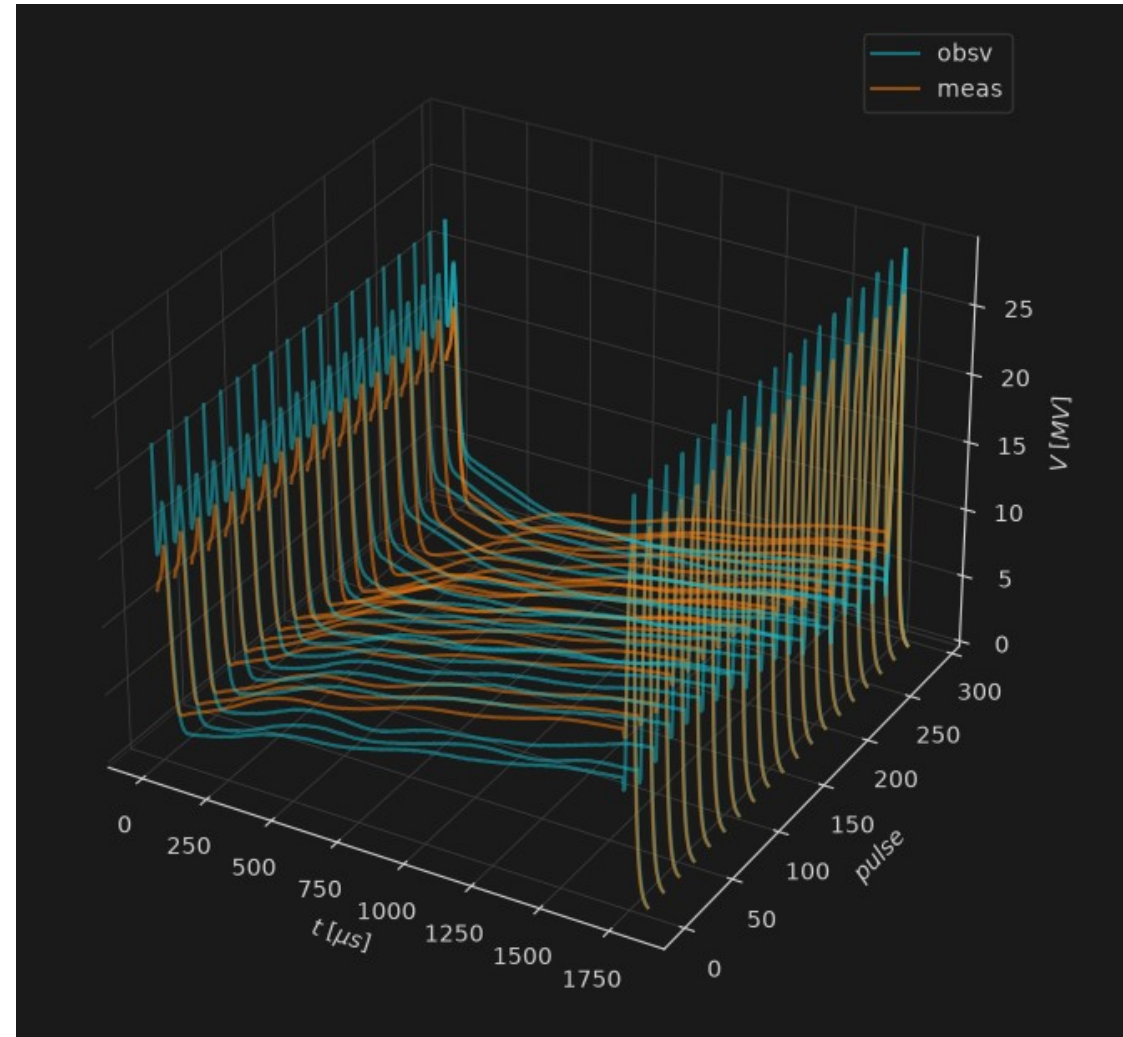
Results

Reflected voltage

Diagnostic and calibration potentials.

Besides detuning traces, the proposed filter also provides timely resolved observables like reflected voltage for both gun and combiner.

The plots to the right show a comparison of reflected voltage in one of the feeding branches to the combiner in amplitude and phase. They clearly show large errors, but also a qualitative agreement which legitimate further refinement of combiner parameters.



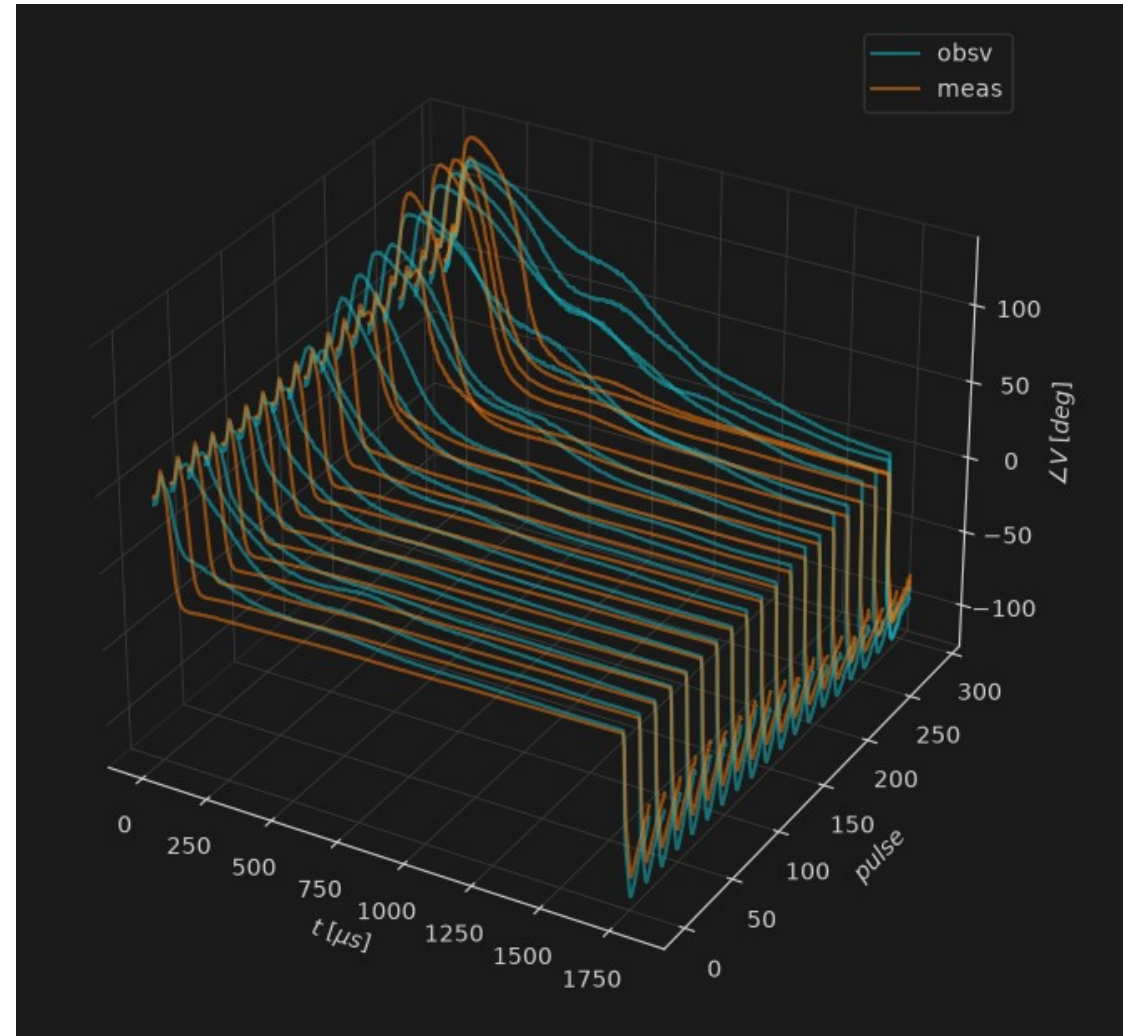
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Conclusion

The bottom line.

For pulsed operation, the currently implemented linear, stationary detuning approximation scheme shows a **similar level of noise and accuracy** compared to the proposed conjugated observer scheme.

In terms of the **number of observed variables**, the full characterization of the **combiner**, and the underlying **timely resolved nonlinear model**, the combined Luenberger/Kalman filter opens up **diagnostics** that have been out of reach before.

Acknowledgements

Funding.

This work was partially funded in the context of the R&D program of the European XFEL. This project has also received funding from the European Unions Horizon Europe research and innovation program under grant agreement N. 101131435.

Thank you

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