Advanced LLRF system setup tool for RF field regulation of SRF cavities.

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Abstract

Feedback operation at the European XFEL ensures an amplitude and phase stability of 0.01% and 0.01 deg, respectively. To reach such high RF field stability, model-based approaches for RF field system characterization and RF field controller design are in use. High demand on this system modelling is set especially to the characterization of additional passband modes for small bandwidth SRF cavities operated in pulsed mode and vector-sum regulation. This contribution discusses the developed "Advanced system setup tool" using a graphical user implementation in Matlab® for the RF field system characterization and the multiple-input-multiple-output feedback controller setup. Examples and current limitations will be presented.

Problem description

- Well known cavity transfer function in time and frequency

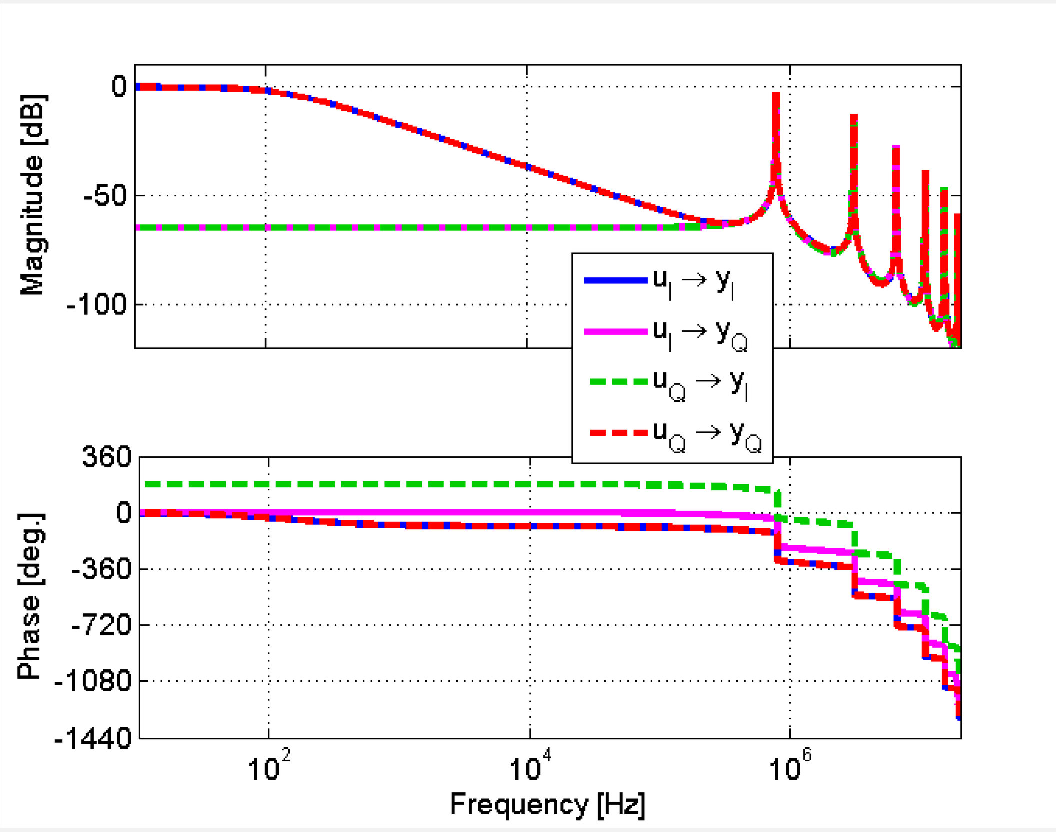
$$\frac{d}{dt}\begin{bmatrix} V_I(t) \\ V_Q(t) \end{bmatrix} = \begin{bmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{bmatrix} \begin{bmatrix} V_I(t) \\ V_Q(t) \end{bmatrix} + R_L\omega_{1/2} \begin{bmatrix} I_I(t) \\ I_Q(t) \end{bmatrix}$$

$$\frac{Y(s)}{U(s)} = G(s) = \frac{(\omega_{1/2})}{(\Delta\omega)^2 + (s+\omega_{1/2})^2} \begin{bmatrix} s+(\omega_{1/2}) & -\Delta\omega \\ \Delta\omega & s+(\omega_{1/2}) \end{bmatrix}$$

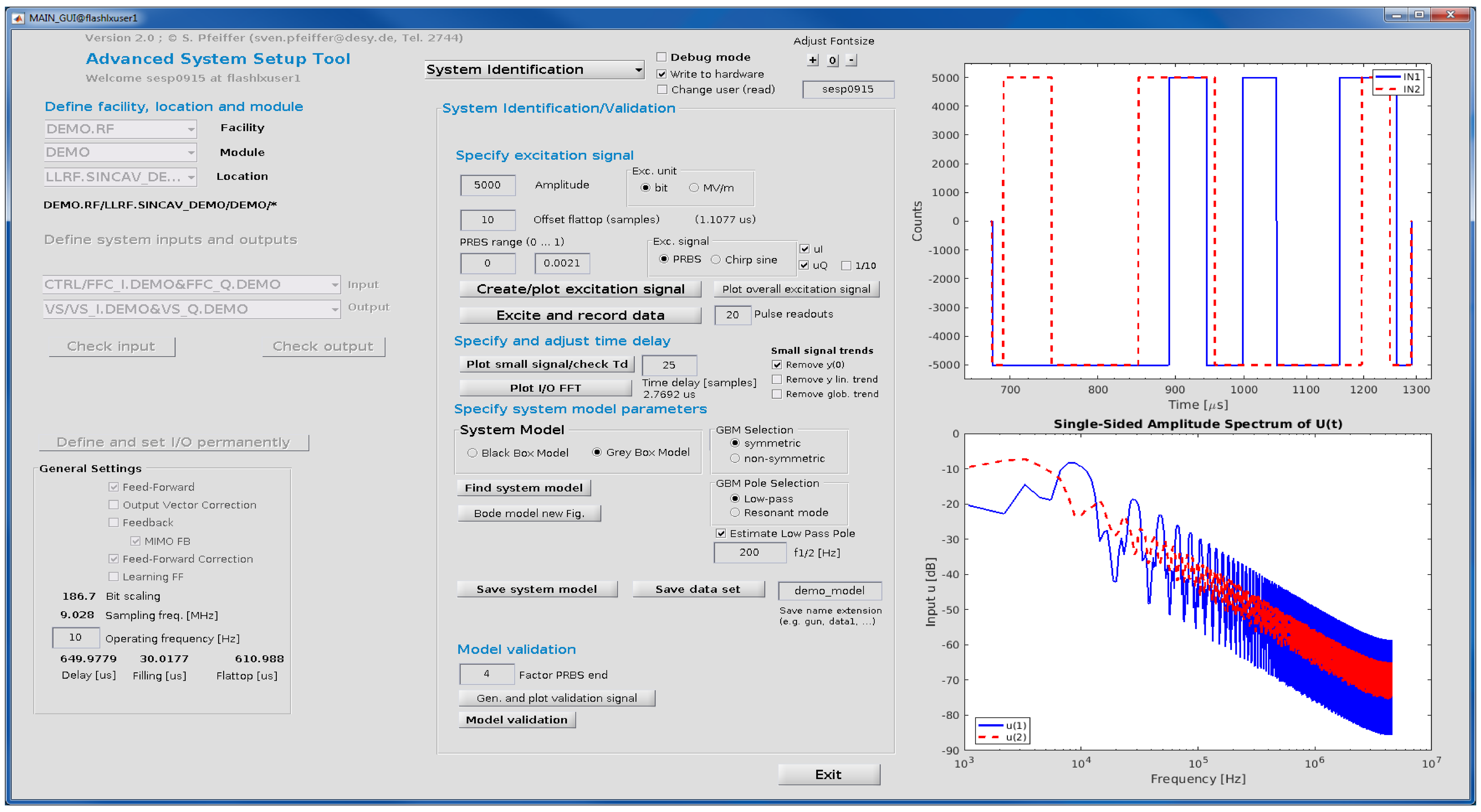
- 9 fundamental modes for 9-cell TESLA type SRF cavity

Mode m	$8\pi/9$	$7\pi/9$	$6\pi/9$	$5\pi/9$	$4\pi/9$	$3\pi/9$
f_m [kHz]	785	3053	6501	10694	15122	19237
$Q_{L,m}/Q_{L,\pi}$	0.516	0.566	0.667	0.852	1.21	2.0

- Overall cavity model is superposition of 9 modes
- Half-bandwidth $\omega_{1/2} = \omega_0/(2 \cdot Q_L)$ of the additional passband modes is in the order of the fundamental π-mode
- Excitation time for all modes is similar



Advanced system setup tool



Implemented methods

System identification
- Selection of excitation signals
  - Pseudo random binary and chirp sine signals
- Time delay estimation
- Black box modelling
- Grey box modelling
  - Symmetric
  - Non-symmetric
  - Low-pass
  - Complex-conjugated pole pair
- Model validation

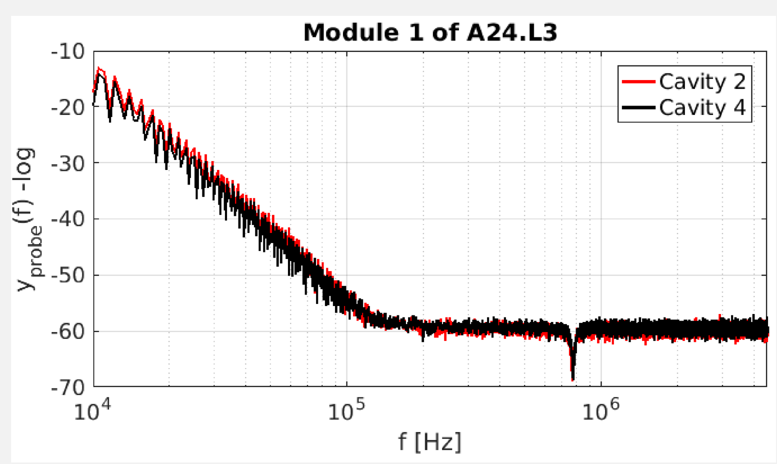
MIMO feedback controller design
- SRF notch design
- Lead-lag design } e.g. SRF CW-operation
- PID design

Learning feedforward design
- Model-based norm-optimal iterative learning control

Smith predictor design
- Setup to cope with latencies

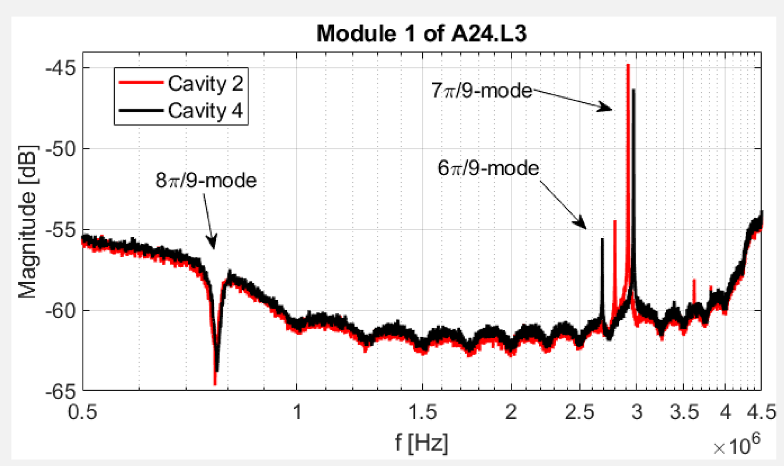
System modelling

FFT of cavity signal
- Open loop with nominal drive signal



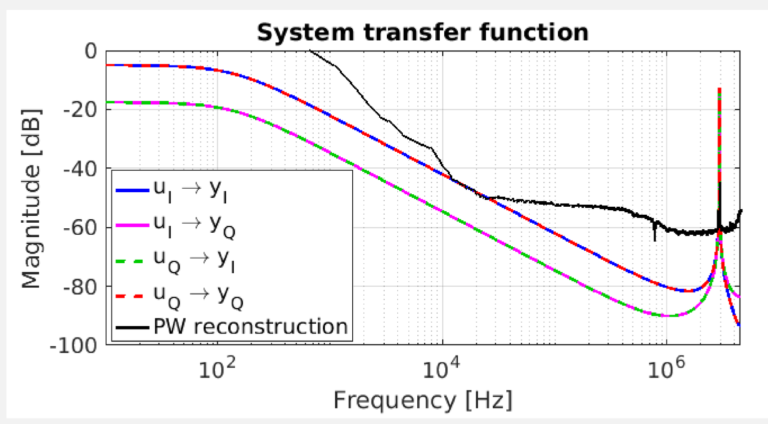
→ Digitally implemented notch filter in ADC detection chain

Piecewise reconstruction of transfer function
- System excitation with chirp sine signal
- I/O difference in logarithmic scale gives magnitude

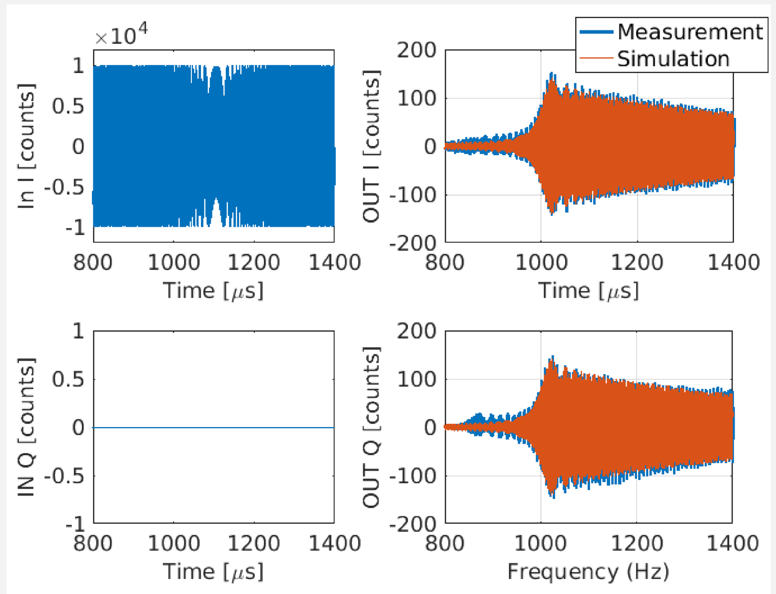


→ Digitally implemented notch filter at ADC
→ 2 additional modes per cavity
→ 7π/9 and 6π/9-mode

System identification
- Open loop with special excitation signals
  - 2 step approach
  - Low-pass characteristic
  - High frequency modes



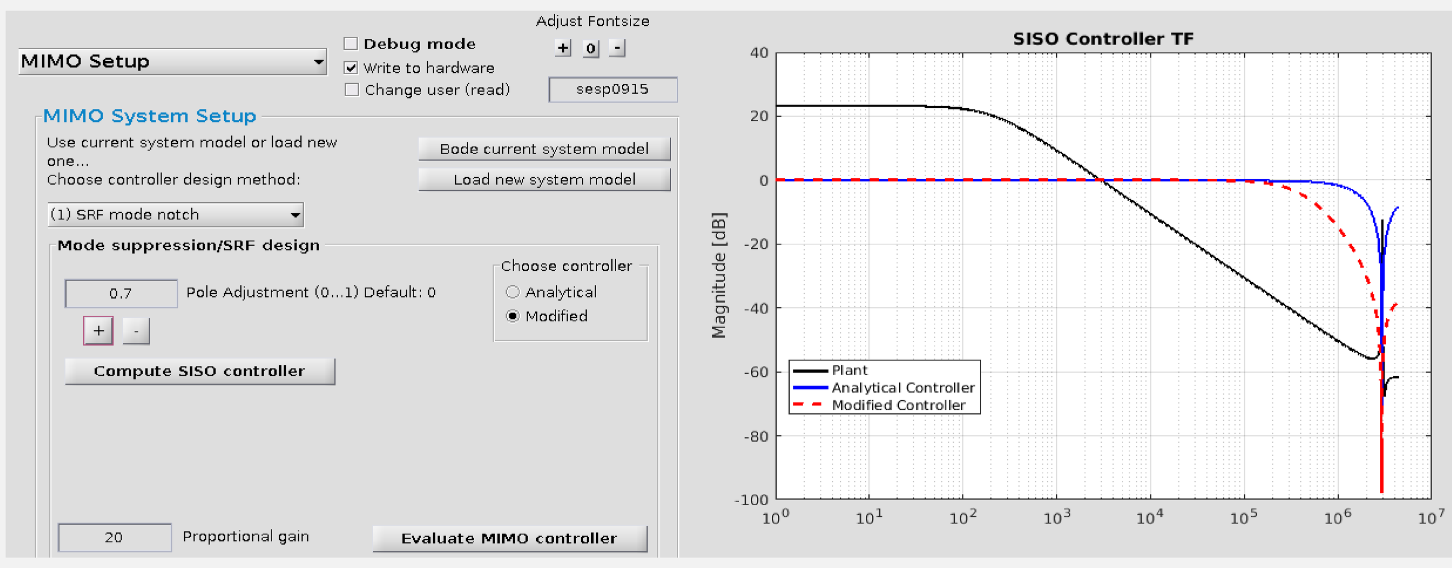
Model validation for 7π/9-mode



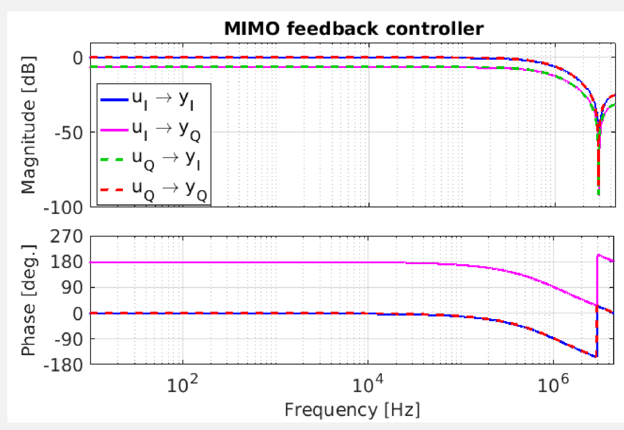
→ Simulation matches measurement
→ Same magnitude for I and Q

Advanced system setup

MIMO feedback controller

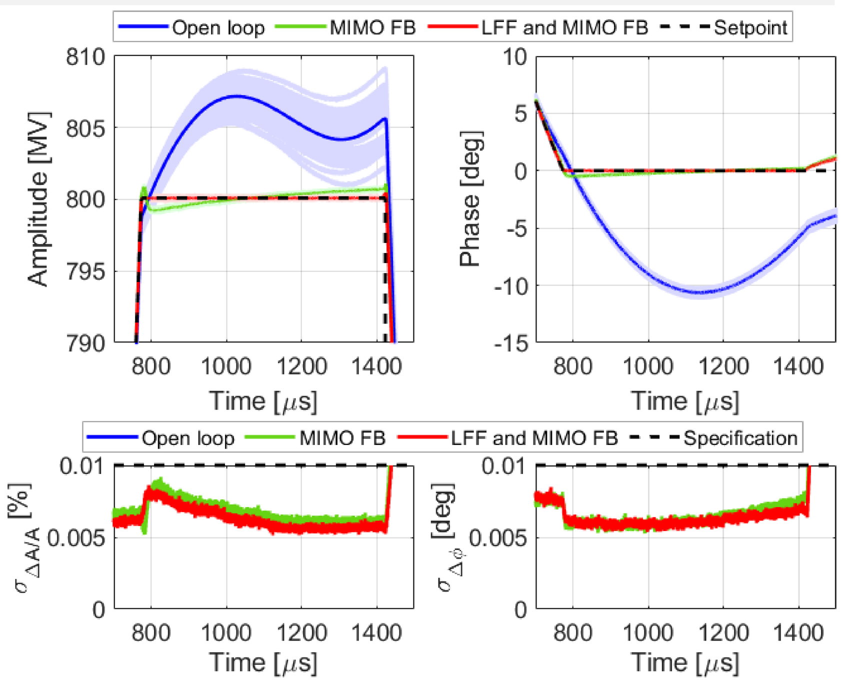


- MIMO on FPGA as transfer matrix; each 2[nd] order IIR filter
- Proportional controller in series to it
- MIMO setup ensures
  - Plant decoupling
  - Suppression of one passband mode



Result & Conclusion

- Model-based system setup to reach RF field regulation within the XFEL/FLASH specs of 0.01% and 0.01 deg.
- Remaining error compensated by pulse to pulse feedforward adaptation
- CW system identification optimization with variation in detuning currently under development



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