First implementation and tests of a Smith Predictor for the LLRF controller at the RF Guns of FLASH, PITZ and EuXFEL.

2019 LLRF Workshop, Chicago

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Overview.

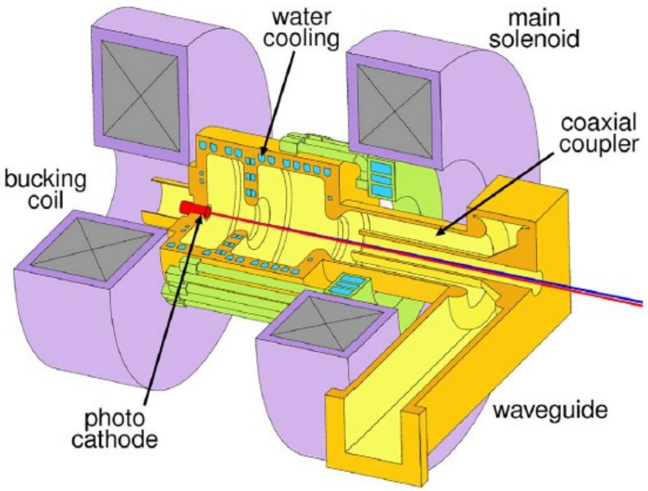
What we expect to see…

Introduction.

The LLRF system for RF guns at FLASH/EuXFEL/PITZ

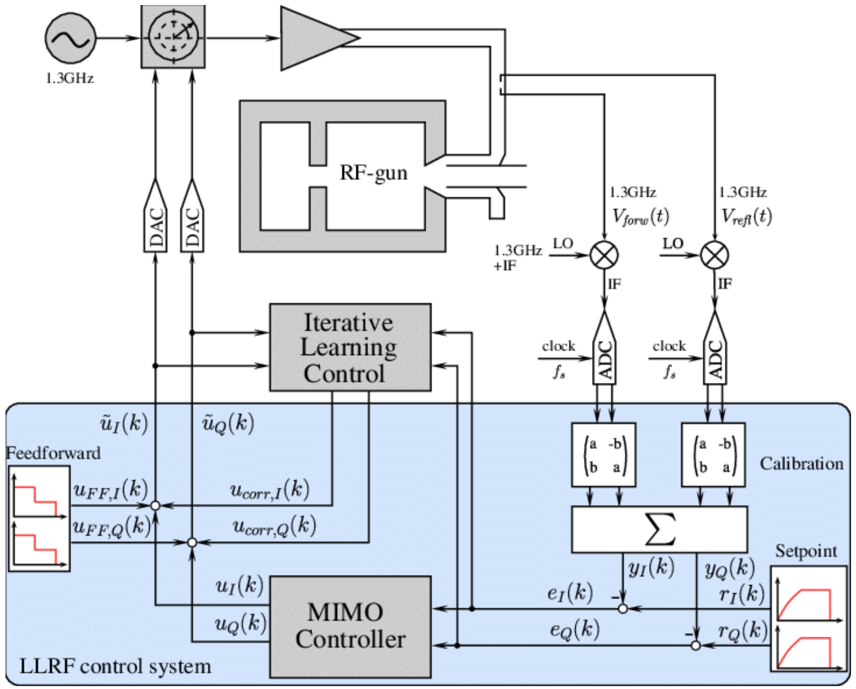
Laser-driven RF gun based photo injector

- Used at FLASH, EuXFEL, PITZ
- L-Band, 1.3 GHz
- 1.5-cell copper cavity



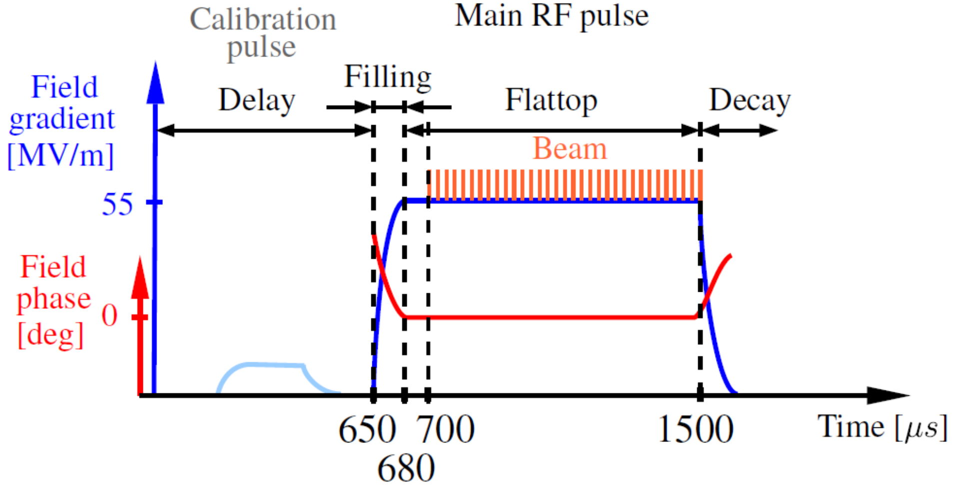
The LLRF system:

- Down conversion to 54 MHz (IF)
- Sampling with 81 MHz (clock)
- Virtual probe (Forward + Reflected)
- MIMO controller (controlling in I and Q)
- Learning Feed-Forward
- DC IQ drive signal (vector modulator)
- Pulse width modulation



RF pulse structure:

- Repetition rate: 10 Hz
- RF pulse length: 650 us



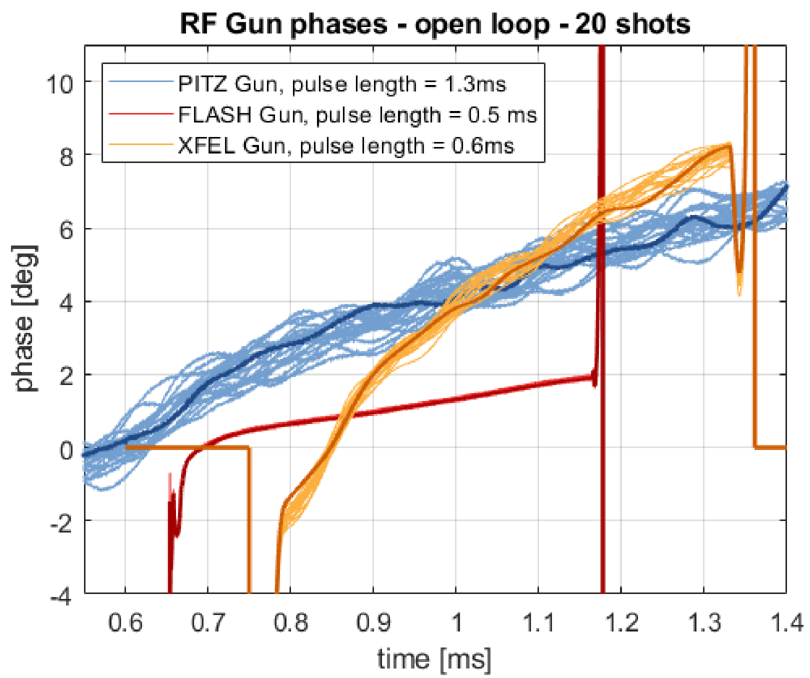
"Precision Feedback Control of Normal Conducting Standing Wave Resonator Cavity"
S. Pfeiffer, et al., PhysRevAccelBeams, 2018

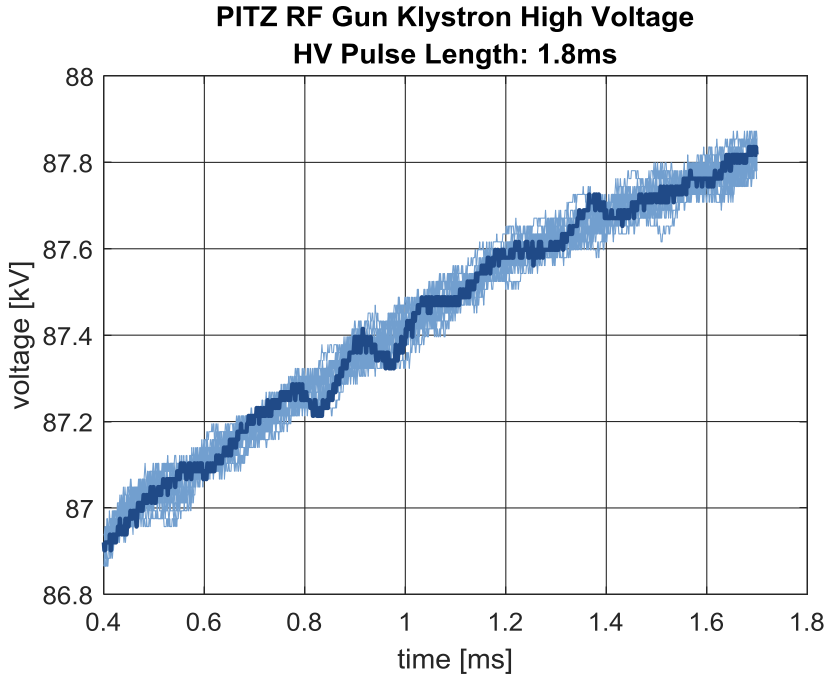
Motivation.

Why do we want to use the Smith Predictor?

RF field stability at FLASH/EuXFEL/PITZ RF gun:

- Large difference in closed-loop performance:
  - PITZ: $\Delta\varphi_{rms} \sim 0.1°$
  - FLASH/XFEL: $\Delta\varphi_{rms} \sim 0.02°$
- Comparison of **open loop** data:
  - PITZ: bad **$\Delta\varphi_{rms} \sim 0.5°$**
  - XFEL: poor **$\Delta\varphi_{rms} \sim 0.3°$**
  - FLASH: acceptable **$\Delta\varphi_{rms} \sim 0.1°$**
- PITZ/EuXFEL gun modulator HV stability issue
  - PITZ/EuXFEL: new solid state type
  - FLASH: older bouncer type
- **Intra pulse disturbance => fast feedback**
- Loop delay ~1.5 us => stability issue at higher gain

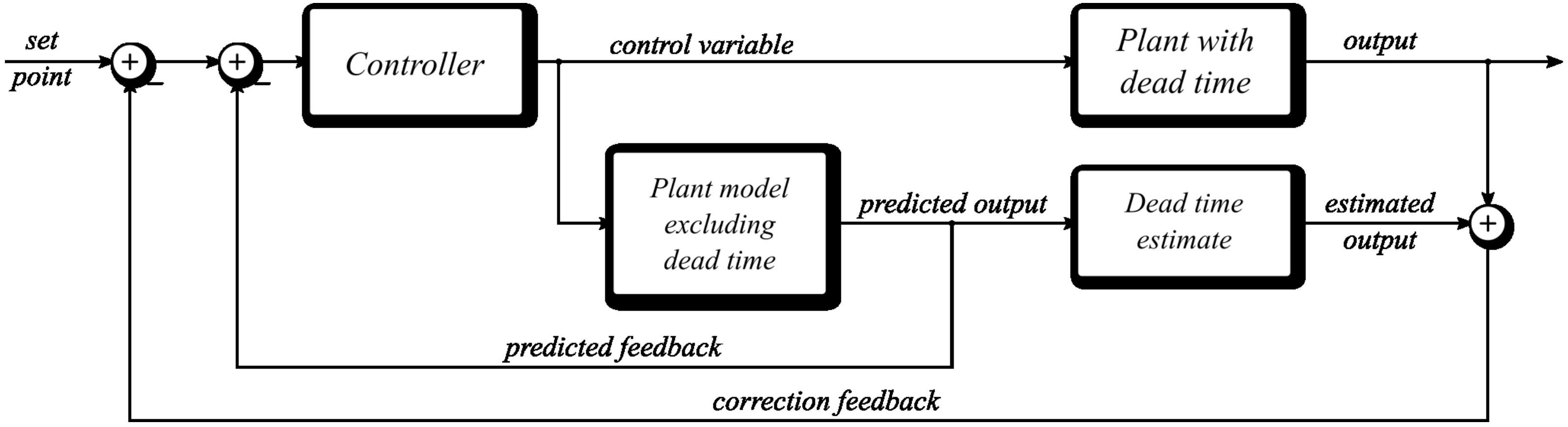




The Smith Predictor.

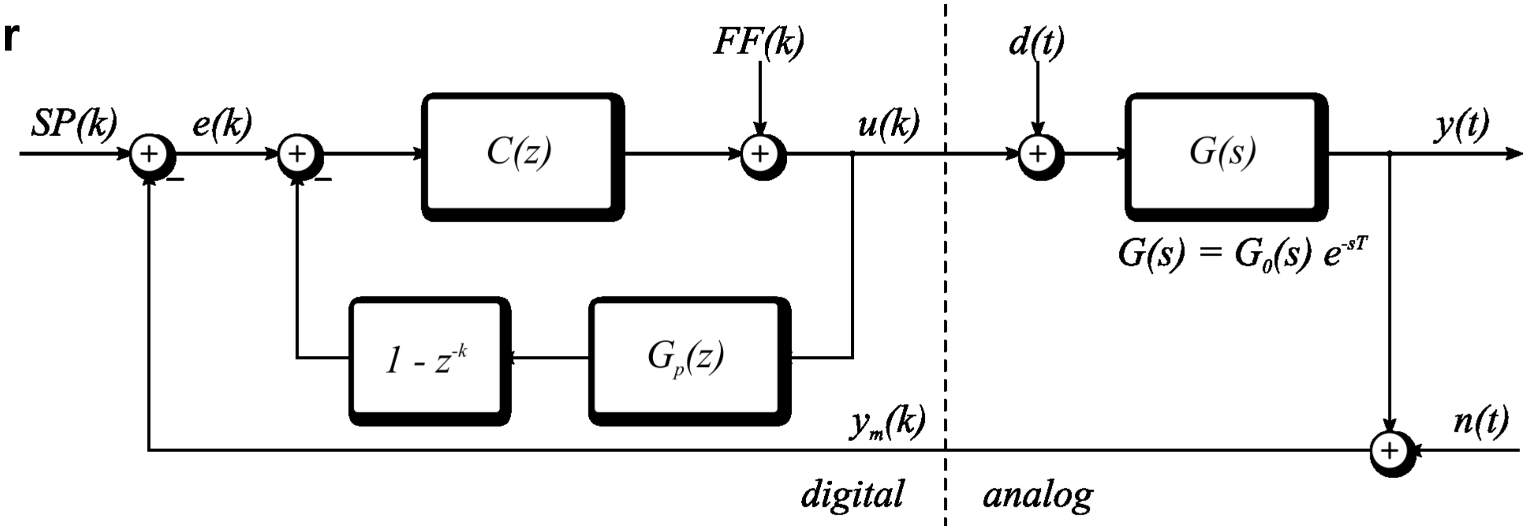
What does it look like?

- Invented 1957 by O.J.M Smith
- Model based/predictive controller
- Dead time compensation
- Two control loops
- Model uncertainty



Implementation in our LLRF controller

- MIMO controller => $C(z)$
- MIMO prediction model => $G_p(z)$
- Feed forward control => $FF(k)$

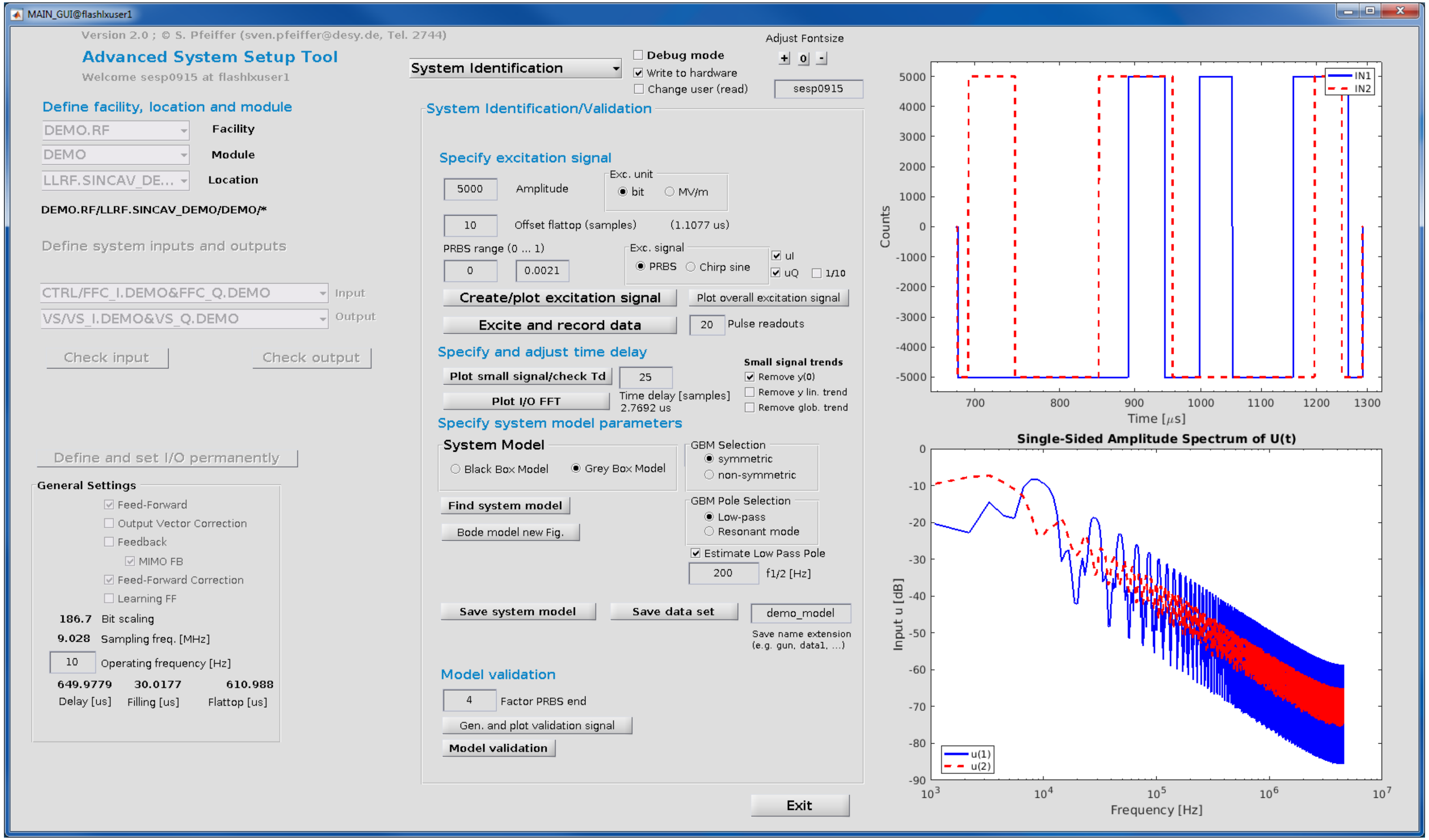


Sven’s Advanced System Setup Tool.

How to find your model?

Features:

- Select facility
- Select subsystem
- System identification
- Controller design
- Learning feed-forward
- Load Smith model



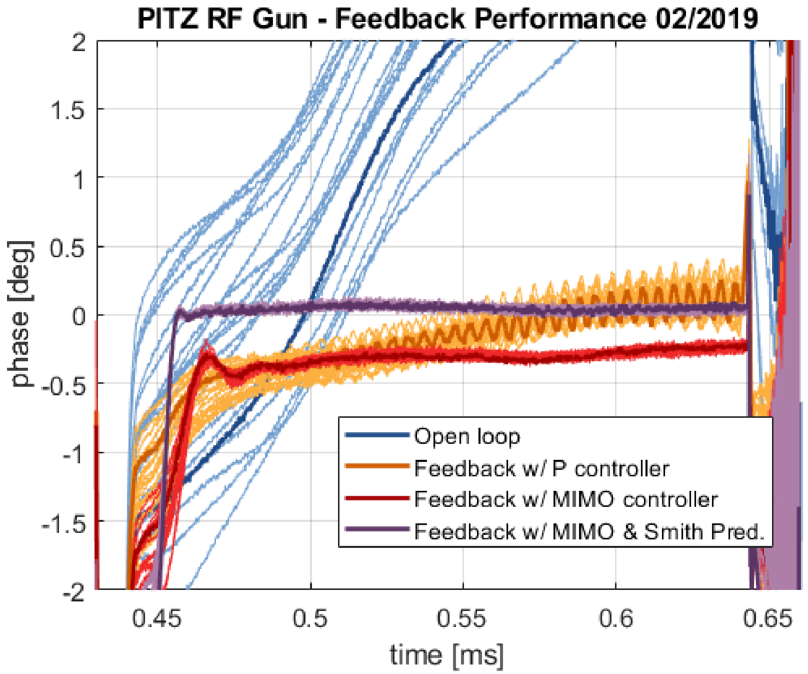
“Advanced LLRF System Setup Tool for RF Field Regulation of SRF Cavities”
S. Pfeiffer, et al., Proceedings of SRF2019, Dresden, Germany

First Tests at PITZ and EuXFEL.

Let's give it a try.

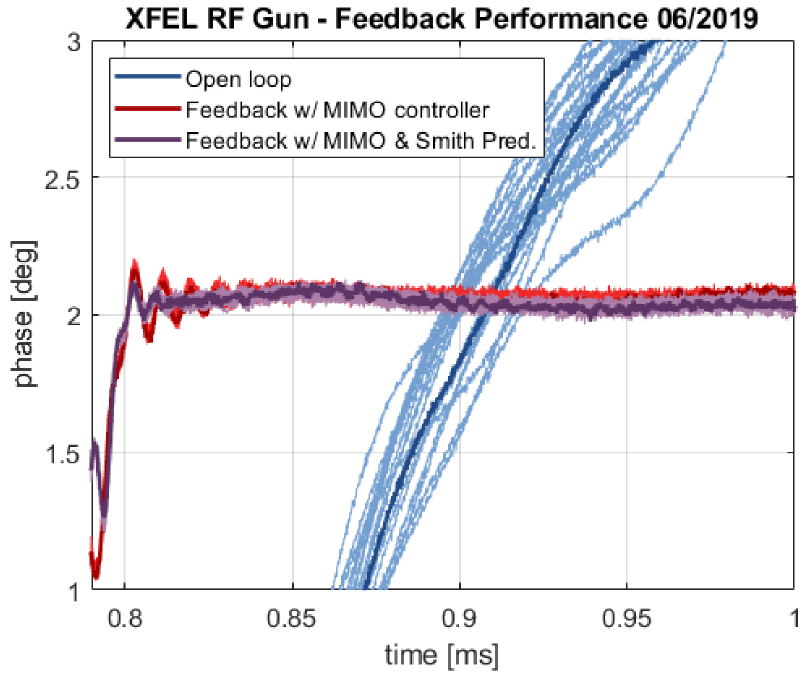
Measurement at the PITZ gun (02/2019):

- Open loop $\Delta\varphi_{rms} \lesssim 0.6°$
- Feedback w/ P controller $\Delta\varphi_{rms} \lesssim 0.12°$
- Feedback w/ MIMO controller $\Delta\varphi_{rms} \lesssim 0.035°$
- Feedback w/ MIMO & Smith Pred. $\Delta\varphi_{rms} \lesssim 0.02°$



Measurement at the EuXFEL gun (06/2019):

- Open loop $\Delta\varphi_{rms} \lesssim 0.3°$
- Feedback w/ MIMO controller $\Delta\varphi_{rms} \lesssim 0.02°$
- Feedback w/ MIMO & Smith Pred. $\Delta\varphi_{rms} \lesssim 0.02°$



Optimizing Controller.

Can we make it better?

- Matlab tutorial about “Smith Predictor”
- Simulation used to tune controller settings
- Comparison: PI controller vs. Smith Predictor
  - Set-point tracking: **15 dB**
  - Disturbance rejection: **3 dB**

Control of Processes with Long Dead Time: The Smith Predictor

R2018b

This example shows the limitations of PI control for processes with long dead time and illustrates the benefits of a control strategy called "Smith Predictor."

Open Script

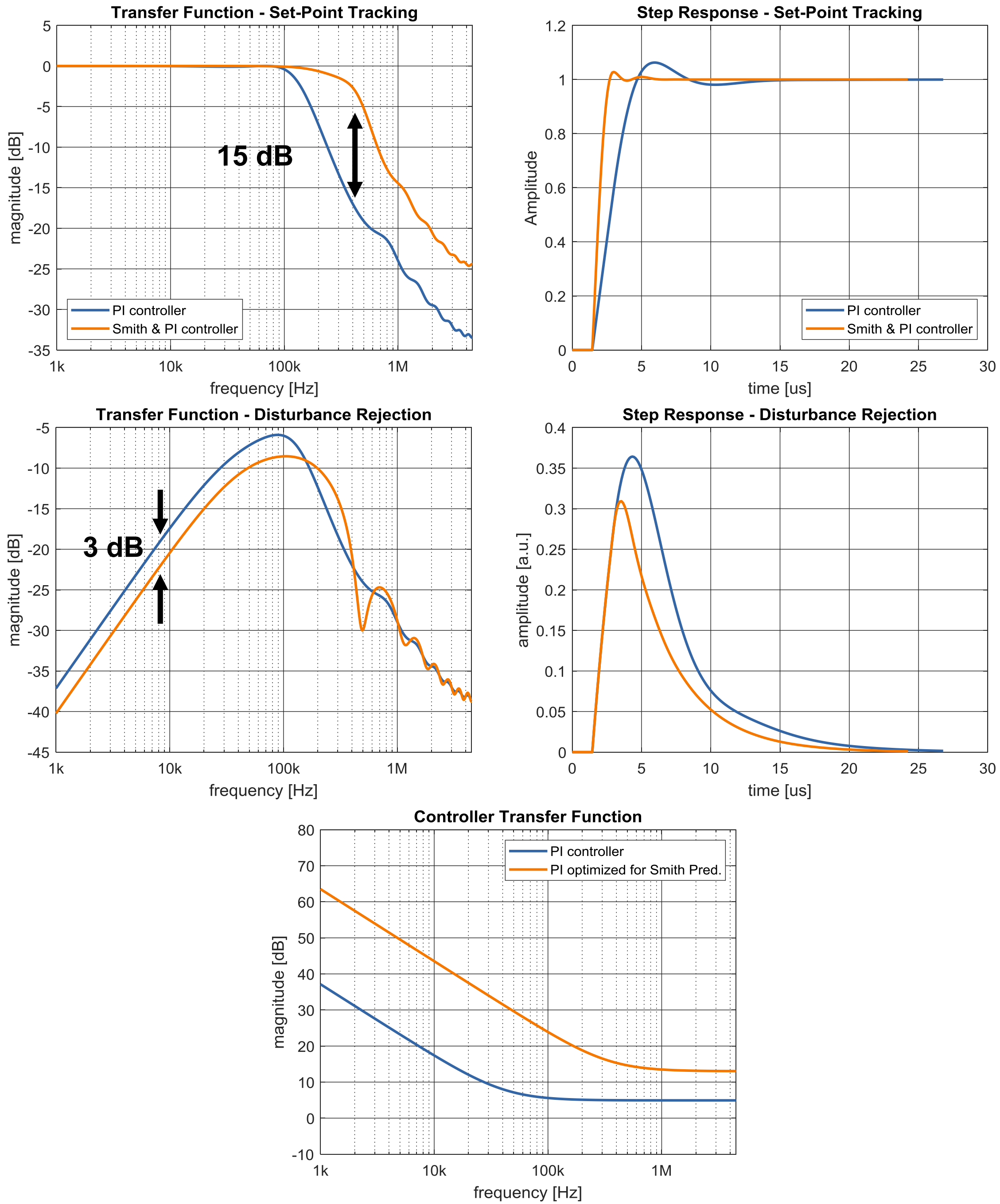
The example is inspired by:

```
A. Ingimundarson and T. Hagglund, "Robust Tuning Procedures of
Dead-Time Compensating Controllers," Control Engineering Practice,
9, 2001, pp. 1195-1208.
```

Process Model

The process open-loop response is modeled as a first-order plus dead time with a 40.2 second time constant and 93.9 second time delay:

```
s = tf('s');
P = exp(-93.9*s) * 5.6/(40.2*s+1);
P.InputName = 'u';
```

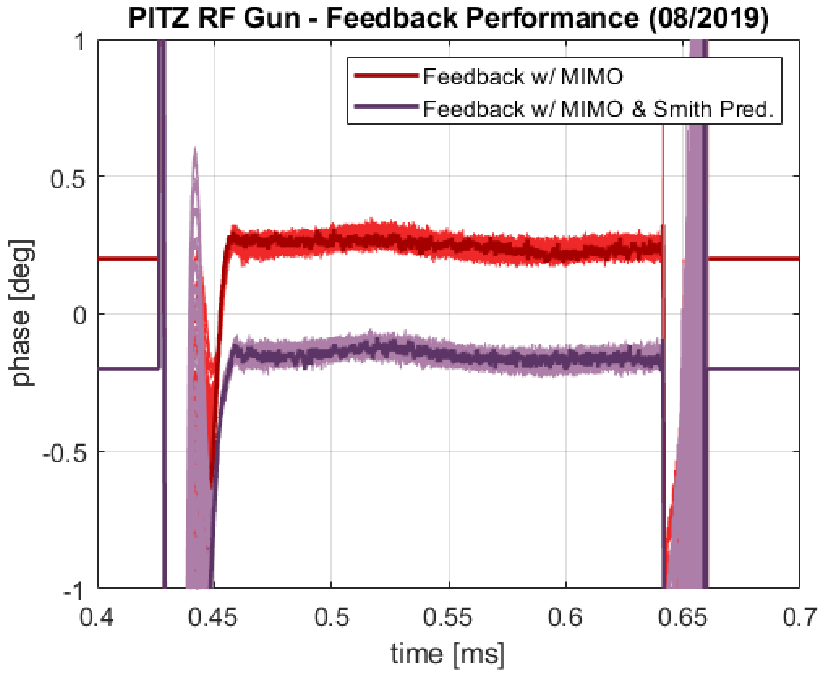


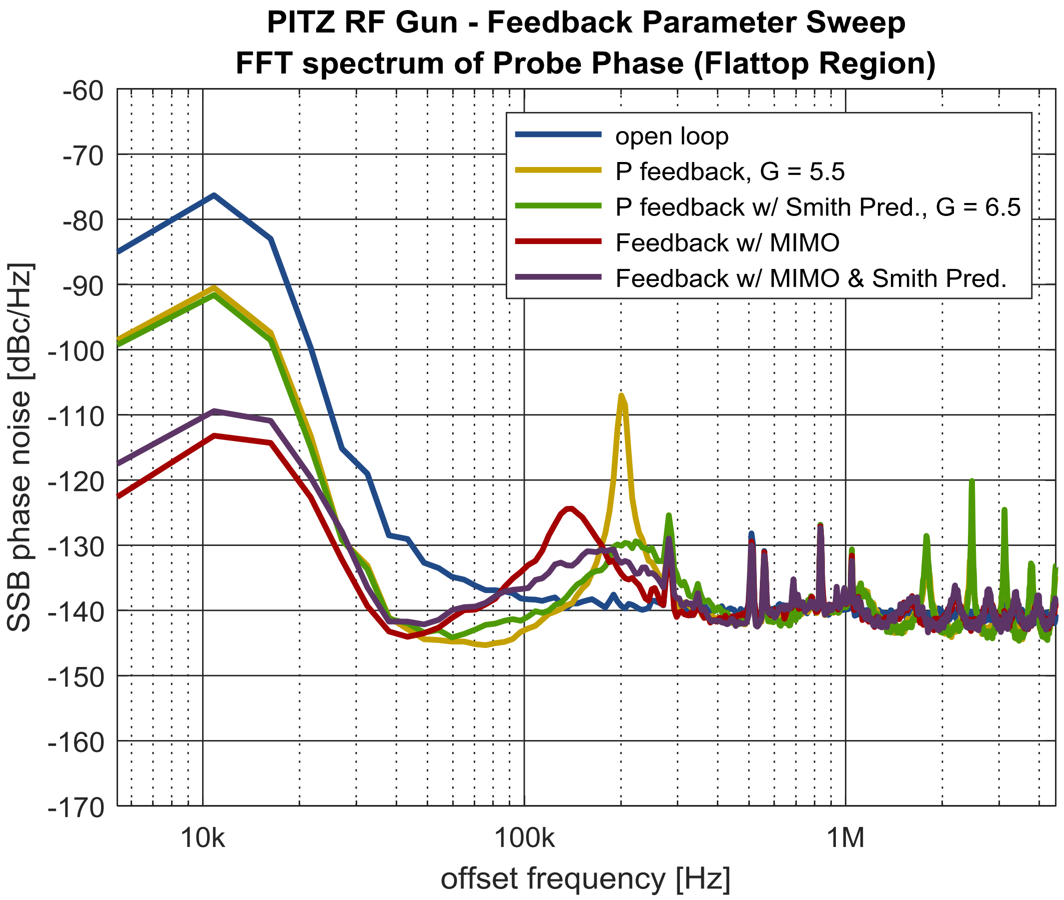
Second Tests at PITZ.

With Optimized Controller

Measurement at the PITZ gun (08/2019):

- Used online tool to tune MIMO controller
- Best Results:
  - Feedback w/ MIMO: $\Delta\varphi_{rms} \lesssim 0.02°$
  - Feedback w/ MIMO & Smith Pred. $\Delta\varphi_{rms} \lesssim 0.02°$





Conclusion.

Lessons learned & open points…

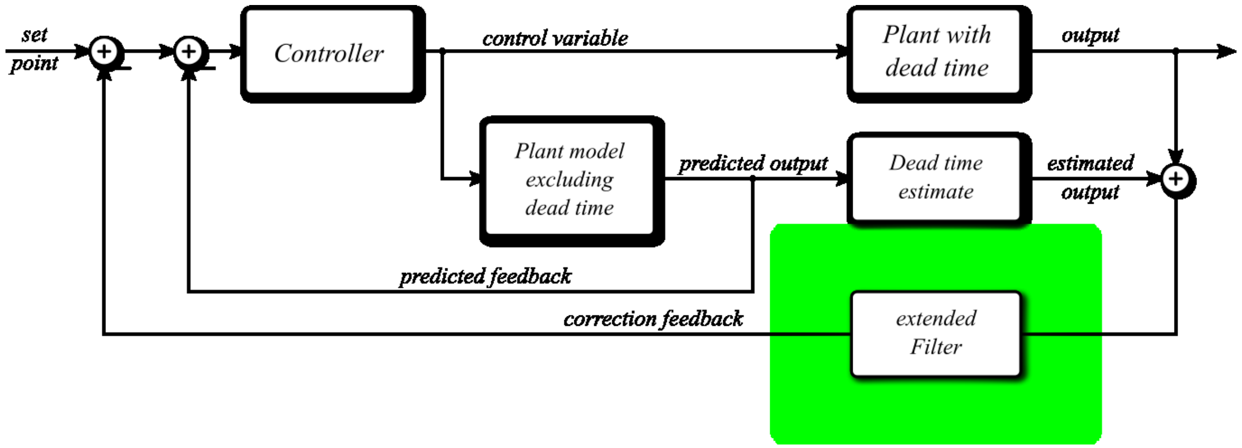
- No real improvement with the Smith Predictor compared to pure MIMO setup.
- Limited in controller gain and bandwidth compared to simulations
  - Caused by model and/or delay mismatch ?
  - Behavior of Feed-forward vs. Smith Predictor ?
  - Try to match simulations and measurements
- To be checked: Limited by detector resolution ?
- From text books and simulation: *Smith Predictor improves mainly set-point tracking!*

Outlook.

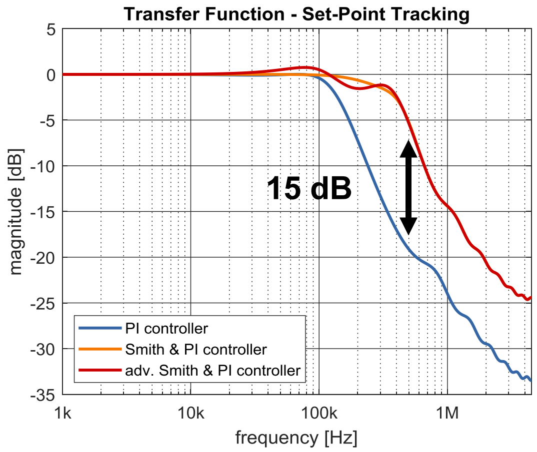
What comes next…

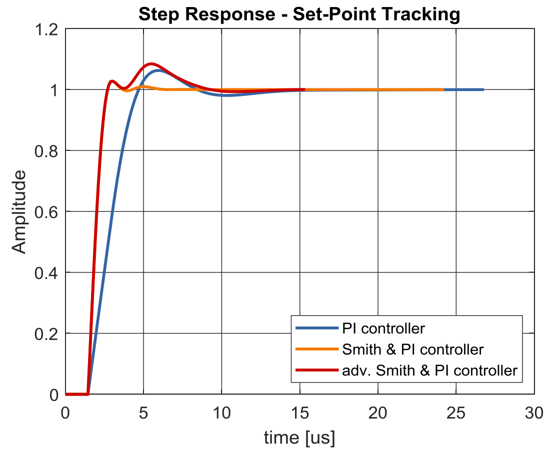
“Advanced Smith Predictor for improved disturbance rejection”

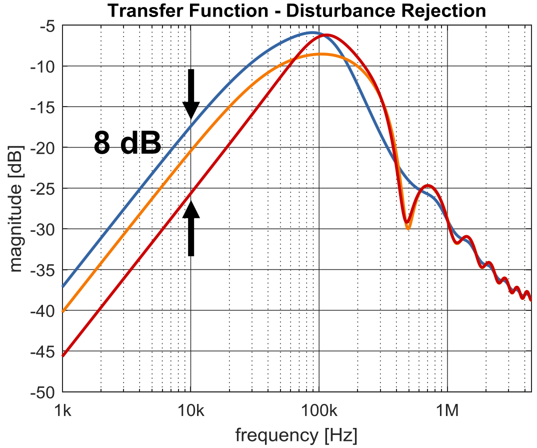
- Additional filter in correction feedback path
- “Approximate inverse of dead time”
- Requires change in controller structure

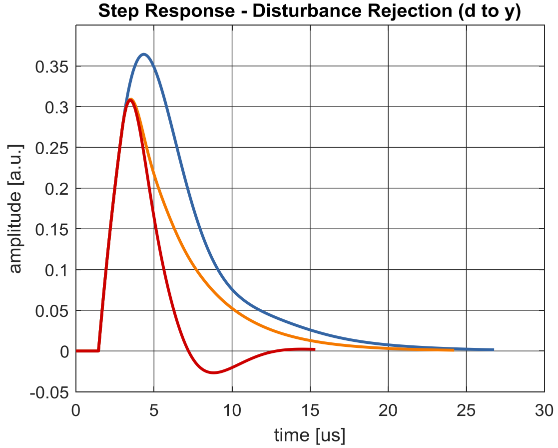


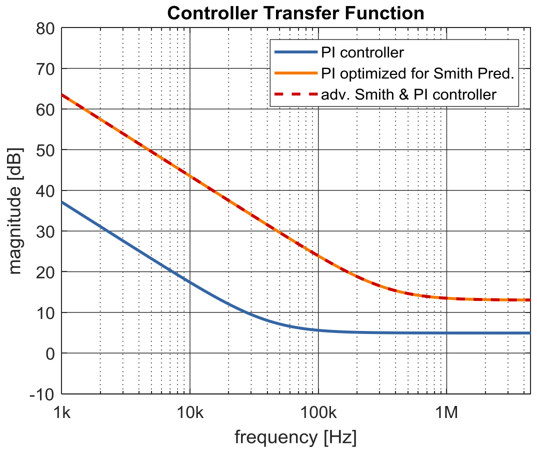
Huanh, H.-P., et al., “A modified Smith predictor with an approximate inverse of dead time”, AiChe Journal, 36 (1990), pp. 1025-1031









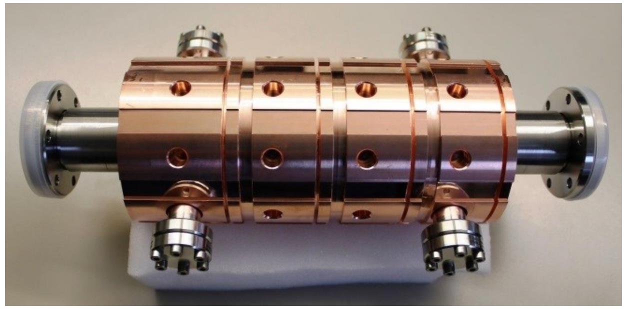


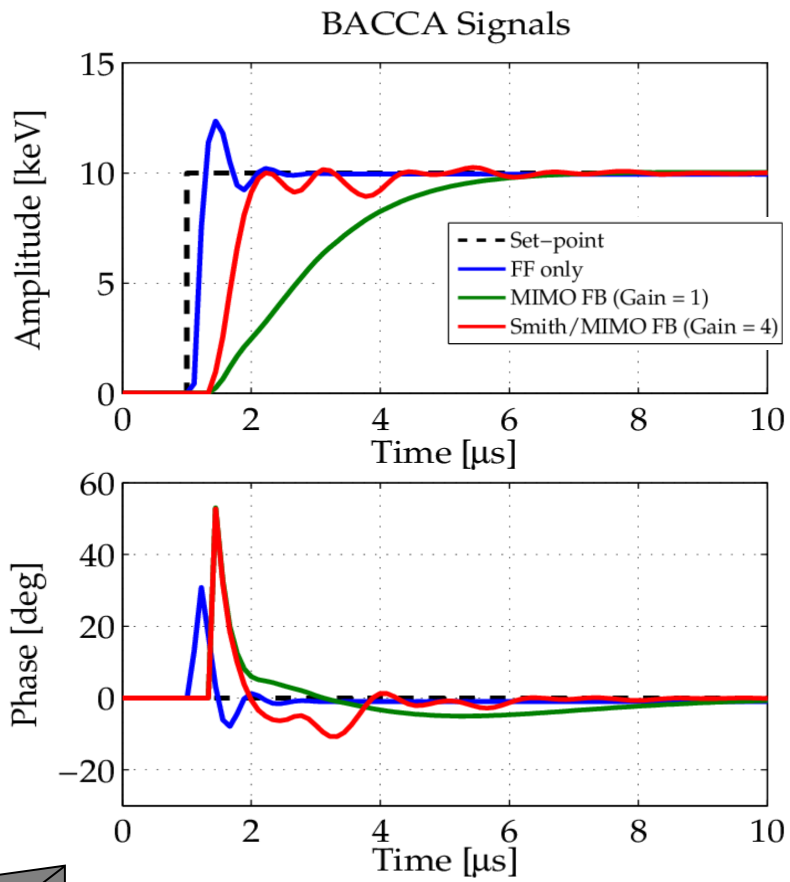
Outlook.

What comes next…

Further application for Smith Predictor

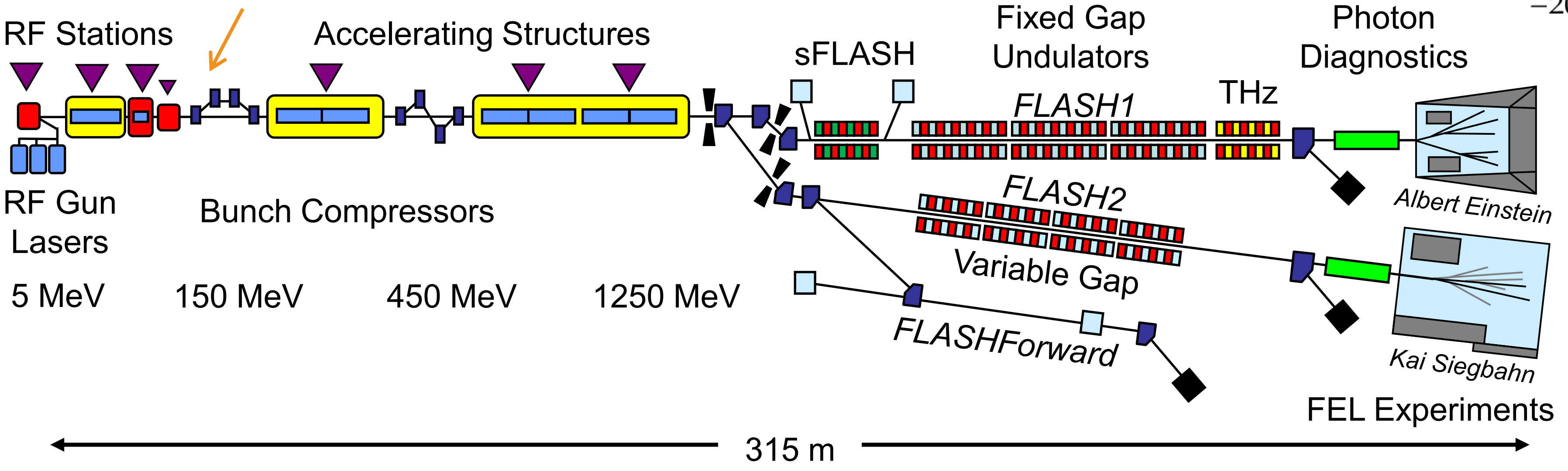
- BACCA (**B**unch **A**rrival **C**orrector **CA**vity) at FLASH
  - NRF feedback cavity
  - For longitudinal beam-based feedback
  - Increase actuator bandwidth (0.5 – 1.0 MHz)
  - Fast set-point changes





"Feedback and Synchronization Upgrades at FLASH", S. Pfeiffer, DESY MAC, 2018

Upgrade with BACCA



Thank you for your attention!

Any Questions?

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