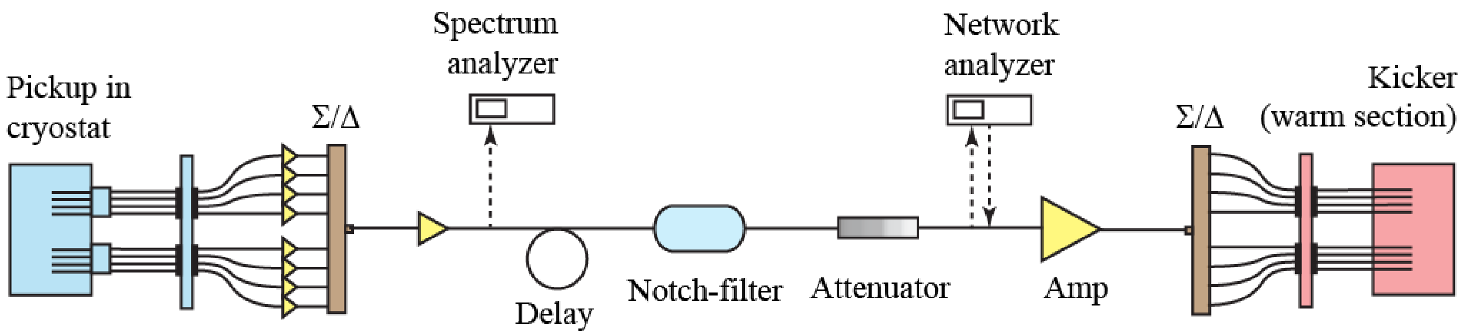
Algorithmic control
of stochastic cooling systems

21 January 2019 | Nikolay Shurkhno, FZ Jülich

Stochastic cooling system as an object



Approaches to cooling system control:

1. Individual control of each device

Devices:
- Amplifiers
- Switches
- Delays
- Attenuators
- Power supplies
- Meas. devices
- …

Interfaces:
- USB
- RS232
- Ethernet
- I2C
- Custom API
- …

2. Control independent of specific hardware

Cooling system
- Gain
- Delay
- Mode
- HTF
- Adjust to energy
- …

Class hierarchy

Base instr. → **Generic instr.**

Base instr.
- self-test
- address
- name
- ..

Generic instr.
- Switch
- VNA
- Power supply
- ..

Interface → **Instrument**

Interface
USB/RS232/TCPIP
- read
- write
- connect
- ..

Instrument
VNA, SA, Switch
- read
- write
- connect
- ..

The only system-dependent part

Complex instrument
- Any device-specific methods
- delay
- adjust_gain
- ..

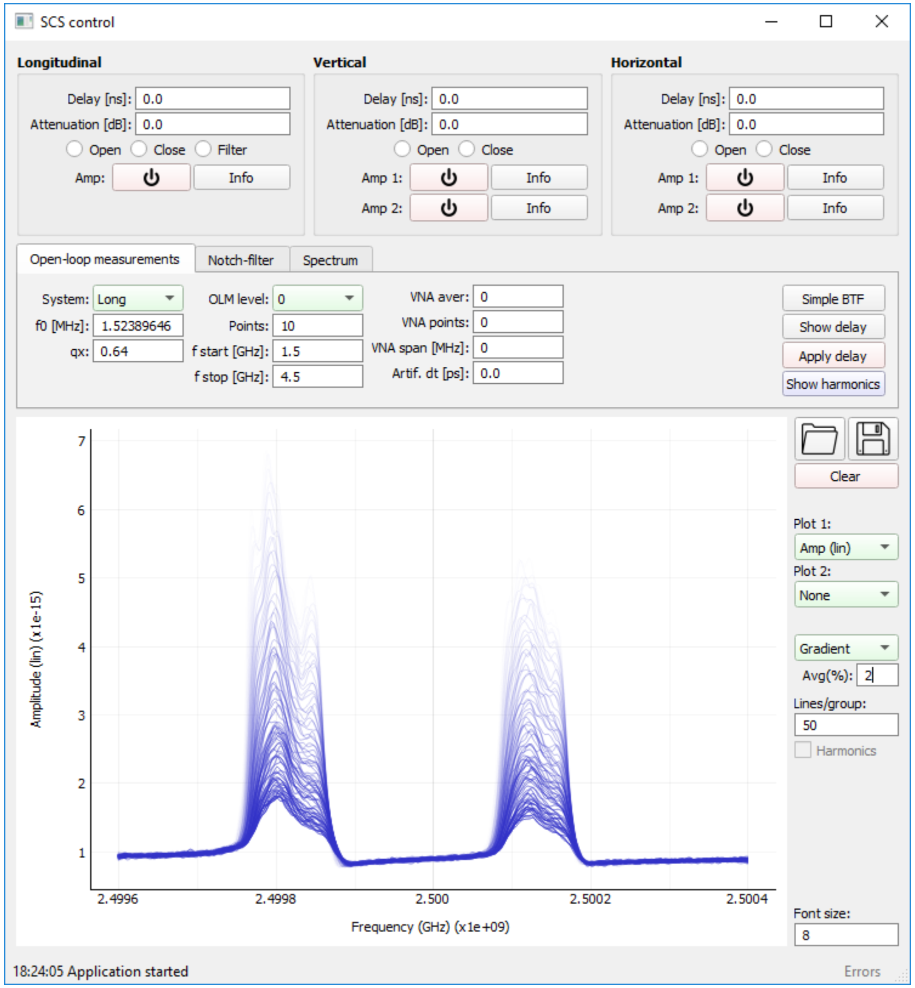
Notch-filters
Complex delays with adjustable attenuation
Complex gains/attenuations
Thin clients
Measurement subsystems
…

Stochastic cooling system
- gain
- delay
- mode
- complex gain
- …

Issues

1. Multi-threading – “per query”
2. Built-in simulation
3. Embedding into accelerator control system (EPICS, FESA, TANGO, etc.) – reimplement classes for specific instruments

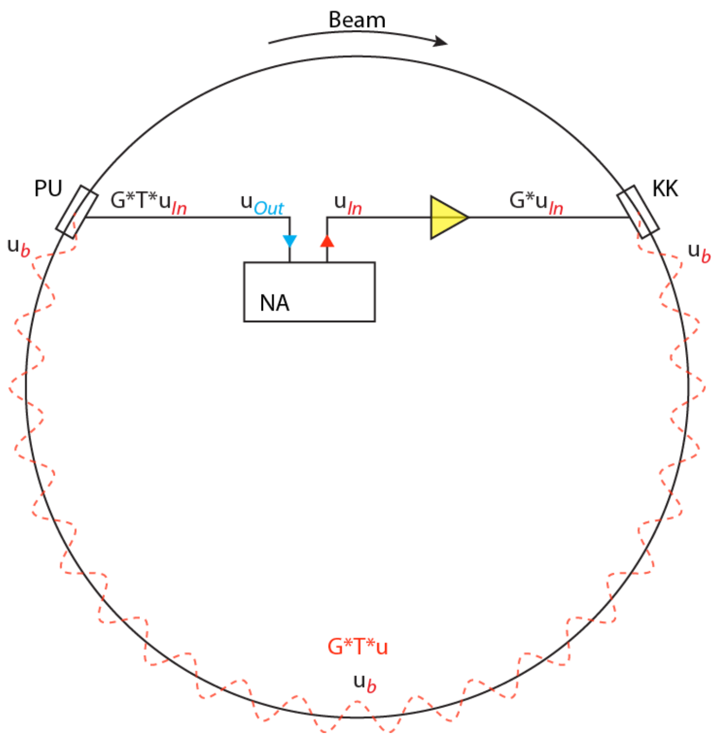
Control software basic draft



Algorithms

1. Vector network analyzer
    1. Single open-loop measurements
    2. Multiple open-loop measurements
2. Notch-filter
    1. Frequency
    2. Depth
3. Spectrum analyzer
    1. Distribution evolution (Psi(t))
    2. PU amplitude measurements
    3. Open/closed loop measurements

Open-loop measurements



$$S_{21} = \frac{u_{out}}{u_{in}} = HTF \cdot BTF$$

(HTF = hardware transfer function
BTF = beam transfer function)

Transverse and longitudinal BTF:

$$\tilde{T}_n^{\perp} = \frac{1}{2\omega_\beta}\int \frac{\Psi(E)}{\omega_n(E) - \omega} dE$$

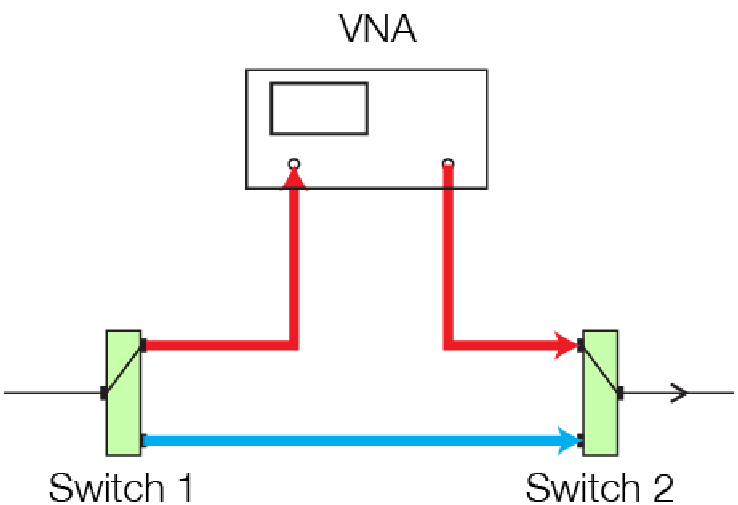
$$\tilde{T}_n^{\Sigma} = i\frac{e^2 f_0^2}{nk}\int \frac{\partial\Psi/\partial E}{E - E} dE$$

BTF theoretically could be de-embedded with PDF measurements, but in any case relative HTF is enough:

$$S_{21} \rightarrow S_{21} * n = HTF * const$$

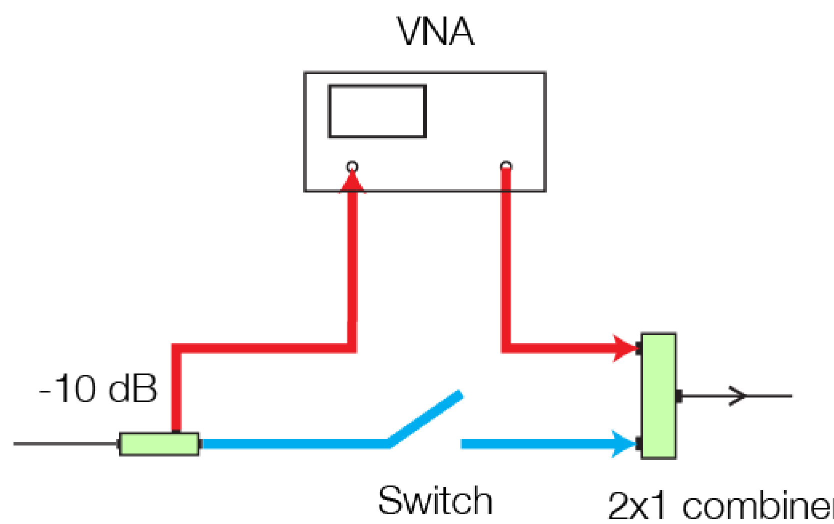
Setup for open-loop measurements

Traditional scheme



Maintenance stops for adjustment

New scheme



Parallel adjustment

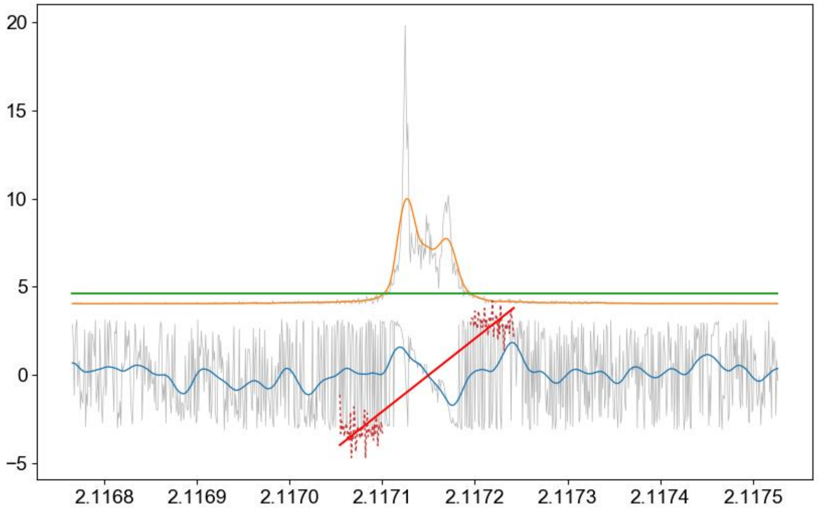
VNA calibration is done manually and data is saved to a PC, so the VNA could be changed if needed

Open-loop measurements techniques

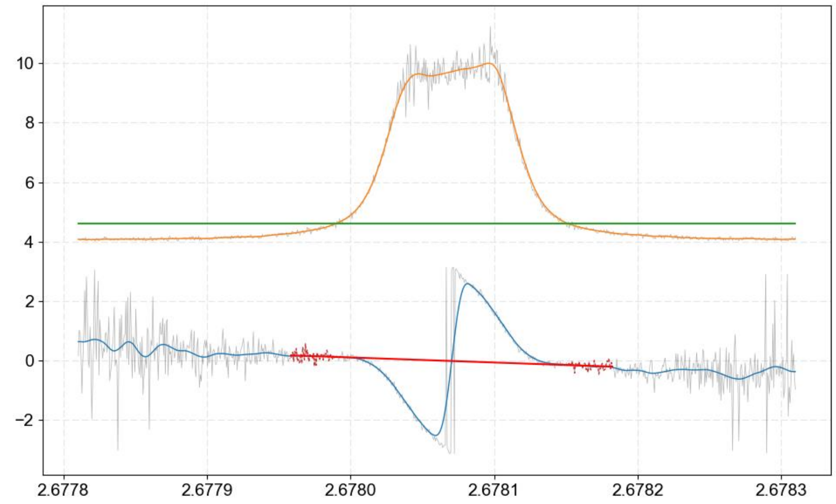
- Single sweep
  - Set VNA f_{Start}, f_{stop} to the n_1, n_2 of the passband, set VNA points to $n_2 - n_1 - 1$
  - Very fast (~s), especially for small number of points

- Multiple sweep
  - Measure harmonics individually and calculate
  - Time-consuming (seconds to minutes, depends on number of points), but clear and precise and doesn’t require manual setting for points of NA (not every device has this option)

Trick for automatic multiple sweep



Measured phase near -180deg



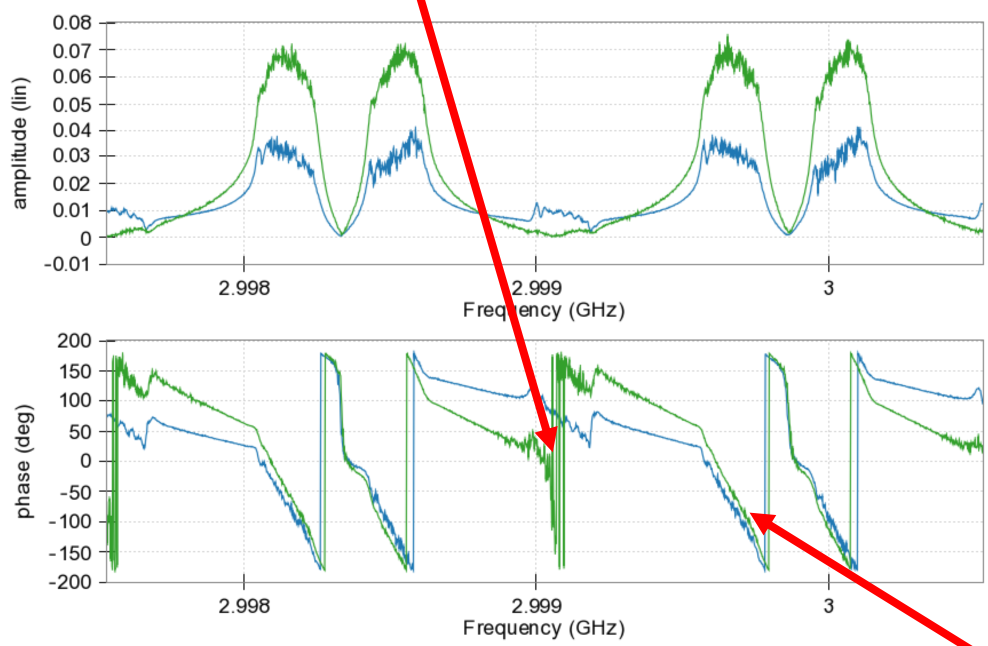
Corrected phase

$$dt_{opt} = min(\arg(S_{21}(dt)))$$

dt – artificial delay

Transverse harmonic sweep

It’s easy to measure center frequency for longitudinal cooling



But for transverse cooling one need to know exact fractional tune, which could be unknown

System adjustment after open-loop measurements

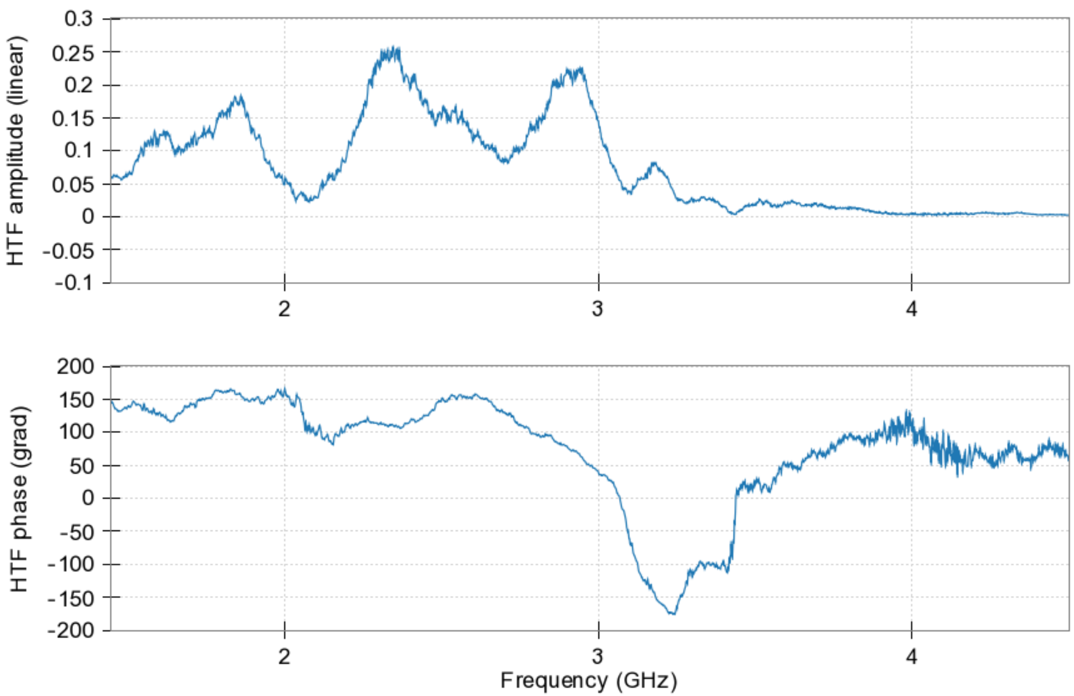
The real HTF is fundamentally non-linear, so things like “lets make the phase flat” don’t fully solve the problem

The adjustment must be done with respect to the task:

$$\tau_0 \quad VS. \quad \sigma_\infty / A_\infty^\beta$$

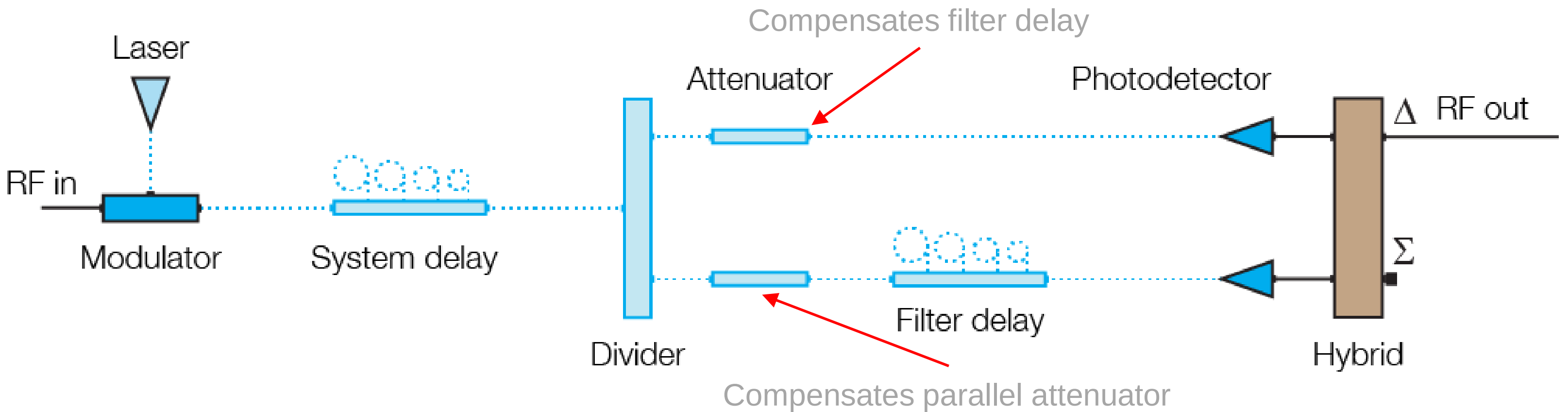
So one can do a lot of measurements studying the behavior of the system wrt to gain and delay or immediately simulate the process

HTF of system with turned-around kicker:

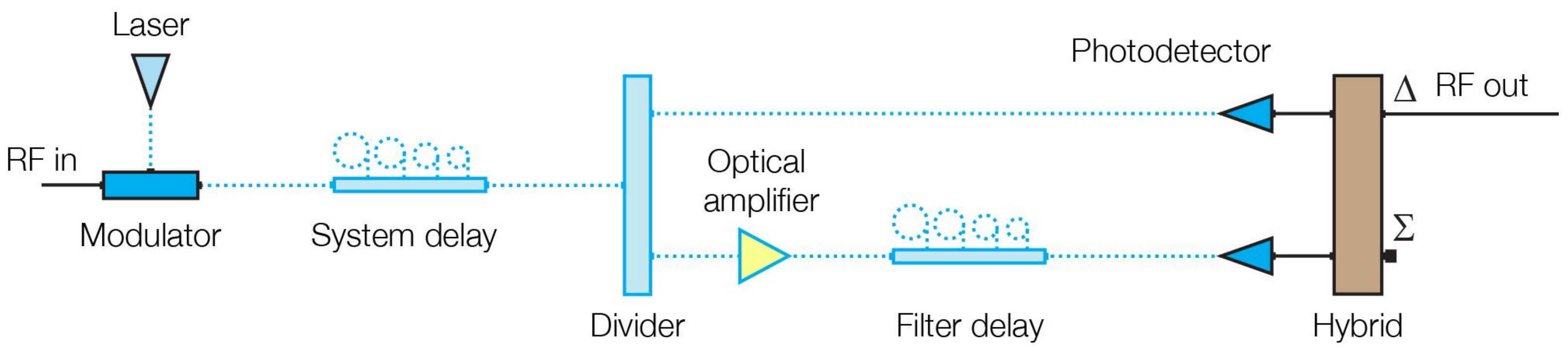


Optical notch-filter

“Traditional” scheme:

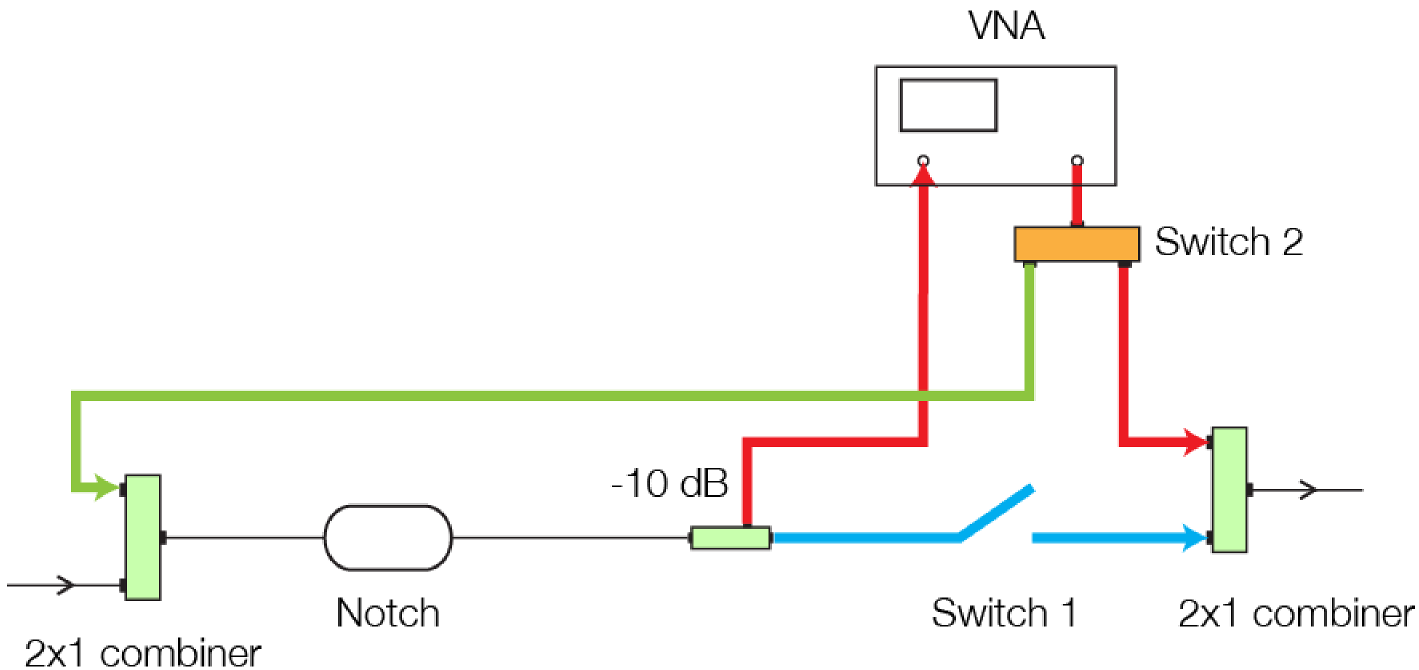


New scheme:



The intrinsic delay of notch-filter was significantly enhanced

Open-loop measurements with notch-filter



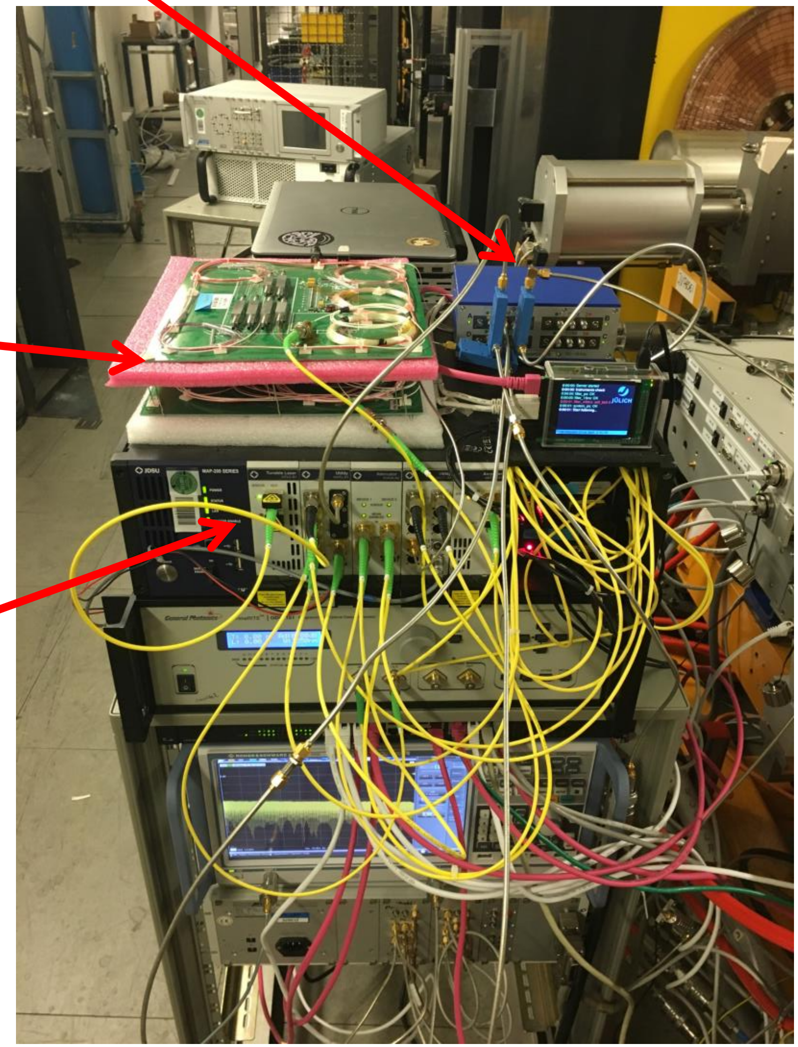
Notch-filter and open-loop measurements can be done independently of system operation

Notch-filter

Switch for OLM/filter measurements

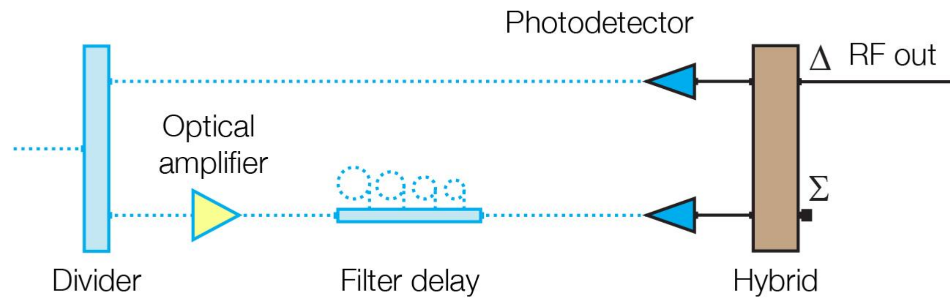
Two step delays
0-15.5ns / dt=0.5ns
0-496ns / dt=16ns

JDSU platform
Laser, modulator, attenuators, amplifier precise delay, etc.



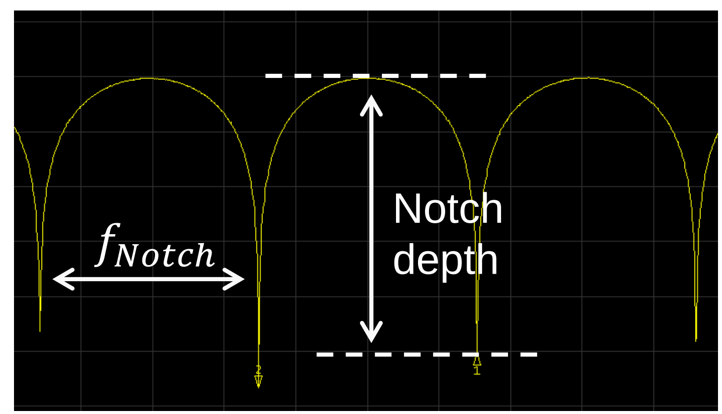
Notch-filter adjustment

Parameters of interest:
- Notch frequency (~Δdelay)
- Notches' depths (~Δattenuation)



The intuitive measurements of *power* and *delay differences* for both legs are fast, but not accurate (and breaks the loop), so

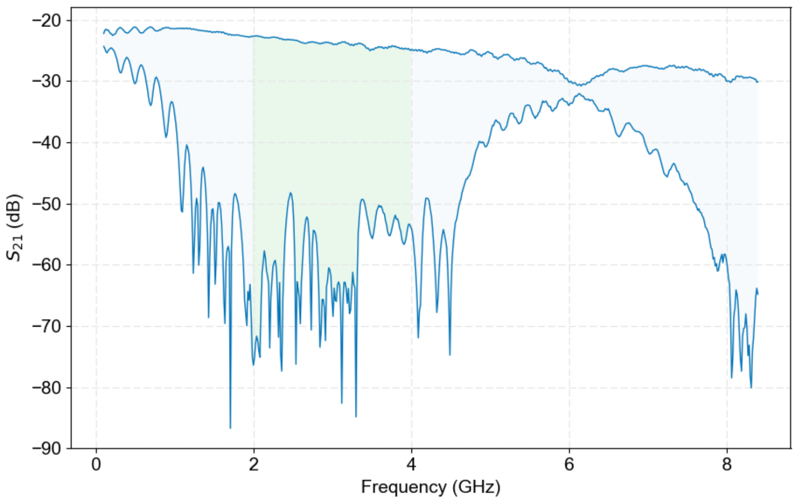
- **Frequency** is adjusted by measuring the average frequency (3 meas. for extending spans) and correction
- **Depths** are adjusted by binary search for the optimum gain value



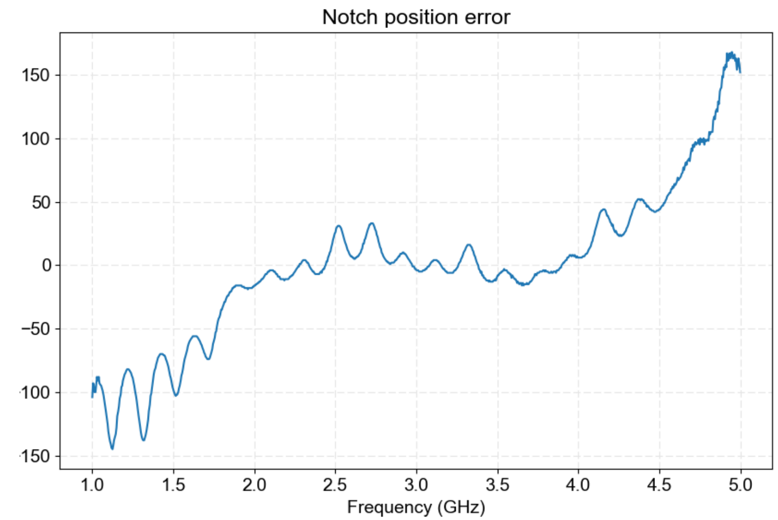
The complete adjustment takes <1 min, but we always missed several ps!

Notch-filter dispersion

Notch frequency and depths fluctuate in passband



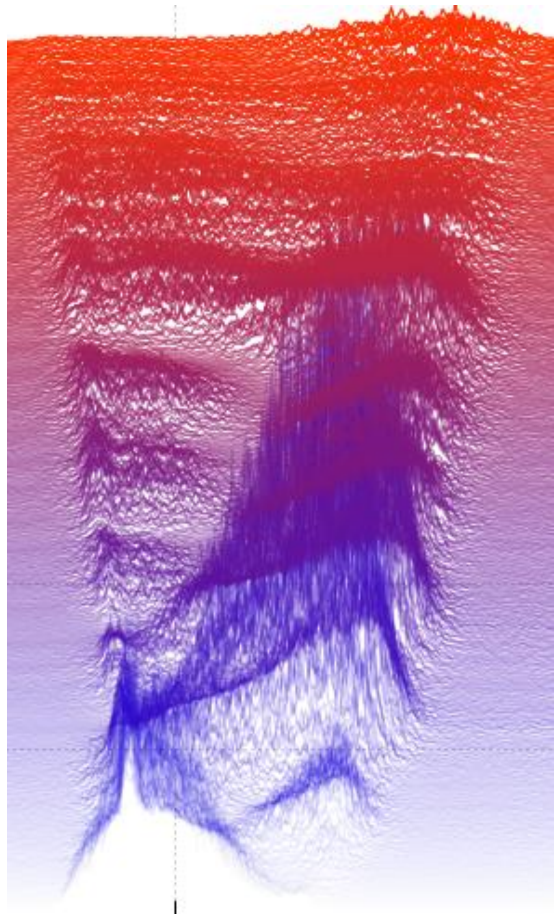
Notch-filter amplitude response



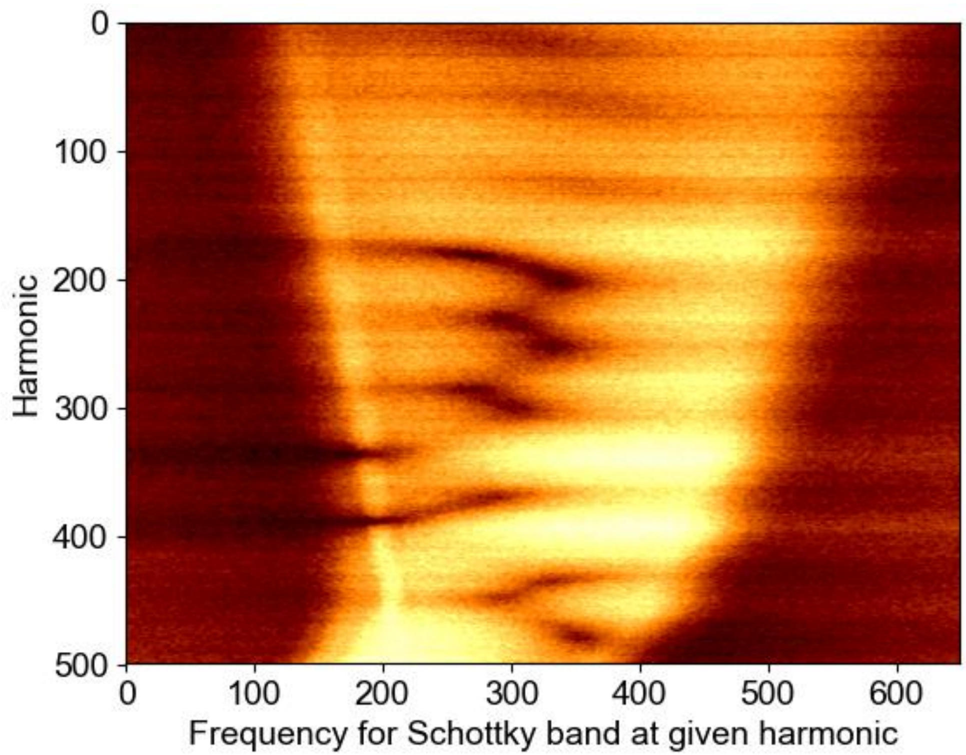
Measured notches' position errors (difference between expected and measured notch)

To make proper adjustment we can use simulation of PDF's center of mass evolution and compensate for lost ps

Spectrum Analyzer
Notch-filter dispersion and the beam



Waterfall plot of filtered longitudinal Schottky noise



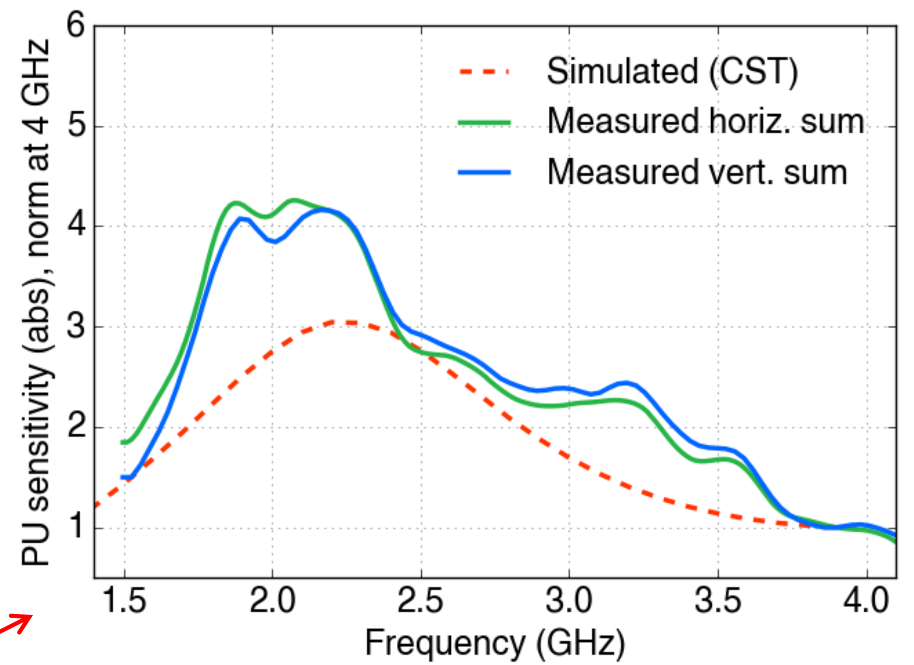
Pick-up amplitude behavior (and sometimes kicker)

Signal from the spectrum analyzer:

$$S(f) \sim \frac{\Psi}{n}$$

So

$$|S_{PU}| \sim S(f) \cdot n$$

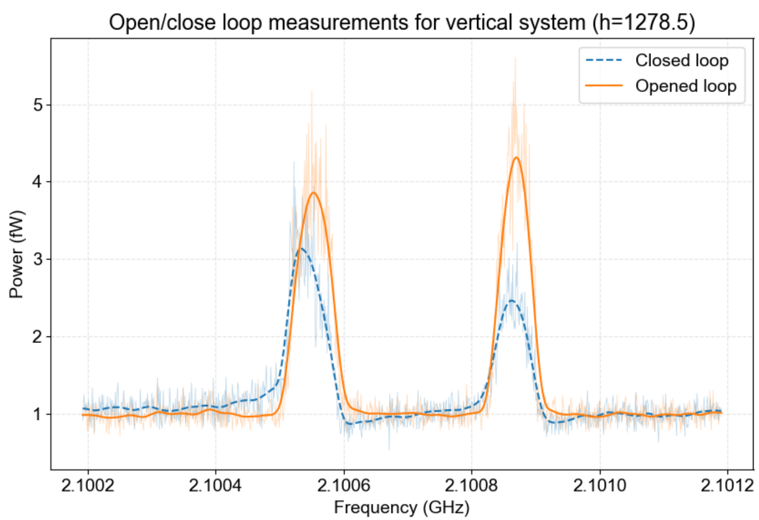


Comparison of measured pick-up amplitude with the results of spectrum measurements, cables and preamplifiers were de-embedded

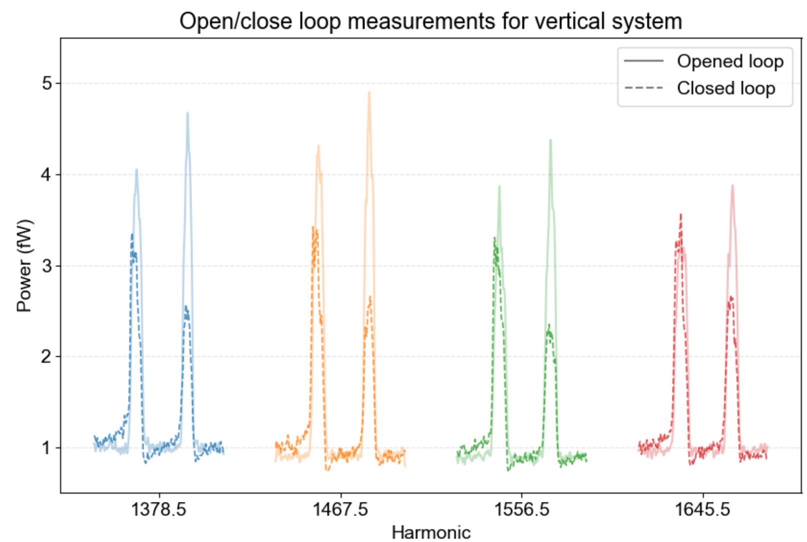
Opened/closed loop measurements

With opened/closed loop measurements system also can be fully adjusted.

Method is straightforward, at all desired harmonics:
open loop, measure, close loop, measure. It is also advantageous to make normal open-loop measurements with VNA for further simulation



OCLM for single harmonic

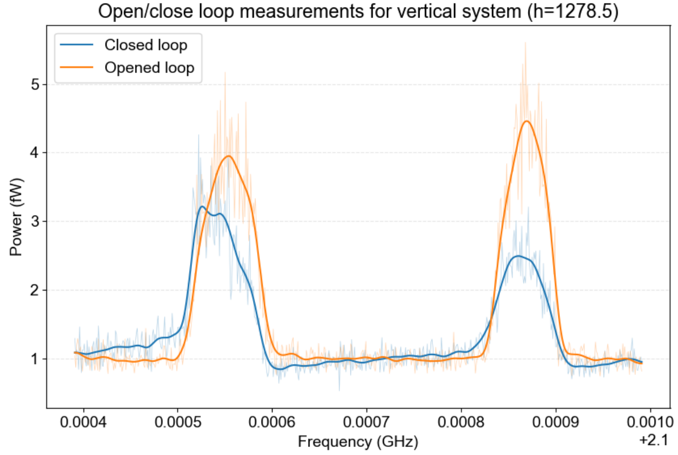


OCLM for several harmonics

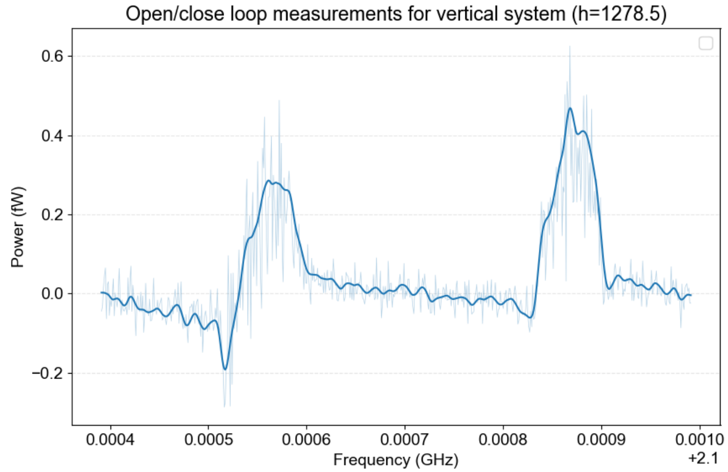
Clean measurements with SA are time-consuming, so every closed loop measurement influence the beam, thus measurements in the beginning and in the end could be inconsistent

Transverse opened/closed loop measurements

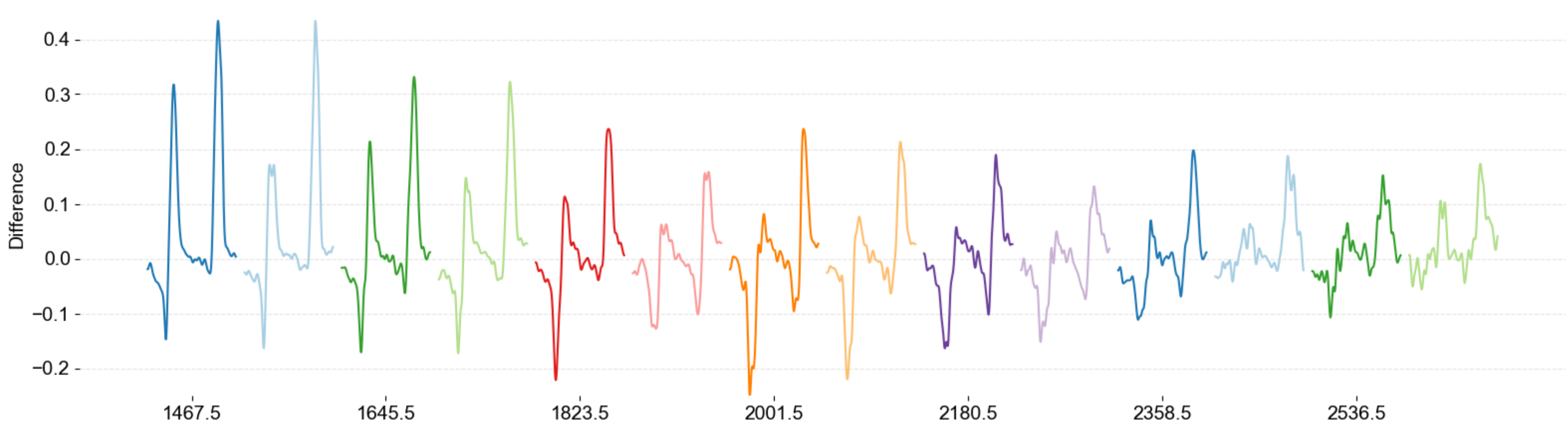
Raw measurements:



$$\left(S_{Open} - S_{Closed}\right)/\max(S_{Open})$$

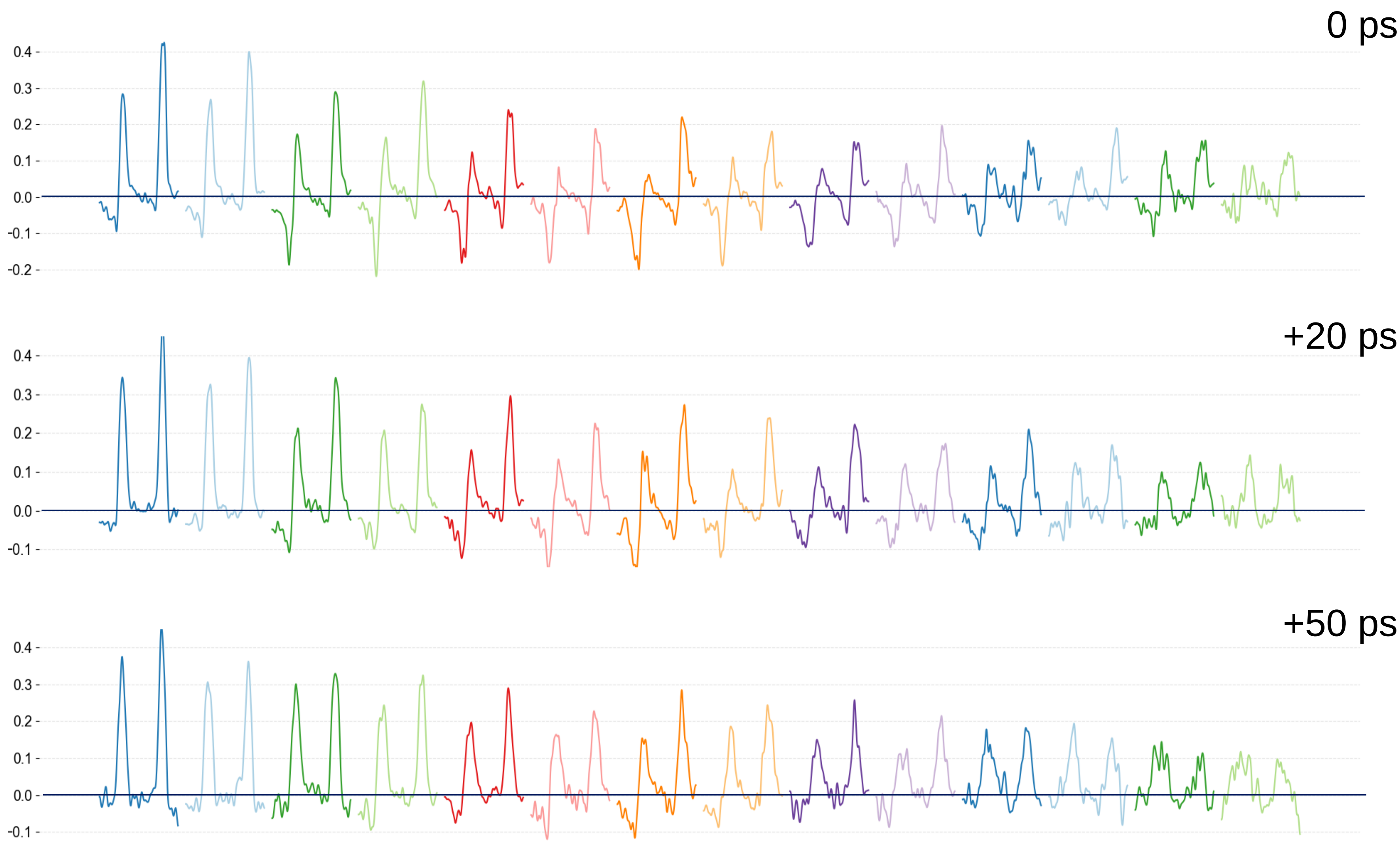


Differences within passband:



Different attenuations

Different system delays



Thank you for your attention!