Online detuning computation and quench detection for SRF Resonators

An FPGA based implementation

Andrea Bellandi
7th MT meeting, 3/2/2020

European XFEL CW/LP upgrade

From pulsed to continuous 1/2

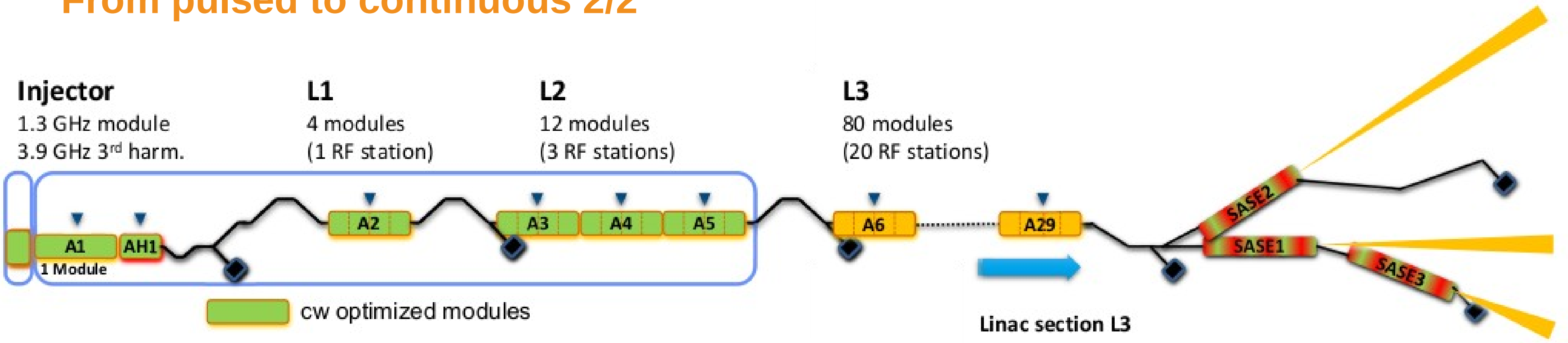
Upgrade objectives

- Current Short Pulse (SP) mode has a duty factor of 0.6 % and produces up to 27000 bunches per second @ 17.5 GeV
- Add the possibility to drive European XFEL at 8 GeV in CW or ~12 GeV at reduced duty factor (Long Pulse or LP)
- Beam energy is traded with an increased bunch spacing

  (8 GeV @ 100 kHz vs 17.5 GeV @ 4.5 MHz)
  → advantageous for experiments
- Operation at 1 MHz also possible

European XFEL CW/LP upgrade

From pulsed to continuous 2/2



Upgrade requirements

Courtesy: J.Branlard

- Double the available cryogenic power at 2 K

  2.5 kW → 5 kW
- Add a CW-optimized Gun →
- Substitute the accelerating modules in the Injector/L1/L2 with higher quality factor ones. Main coupler modifications necessary
- Add 120 kW Inductive Output Tube (IOT) as CW RF power source.

Talk from Dmitry Bazyl :
SRF photo injector development
for the European XFEL
Today 10:30

European XFEL CW/LP upgrade

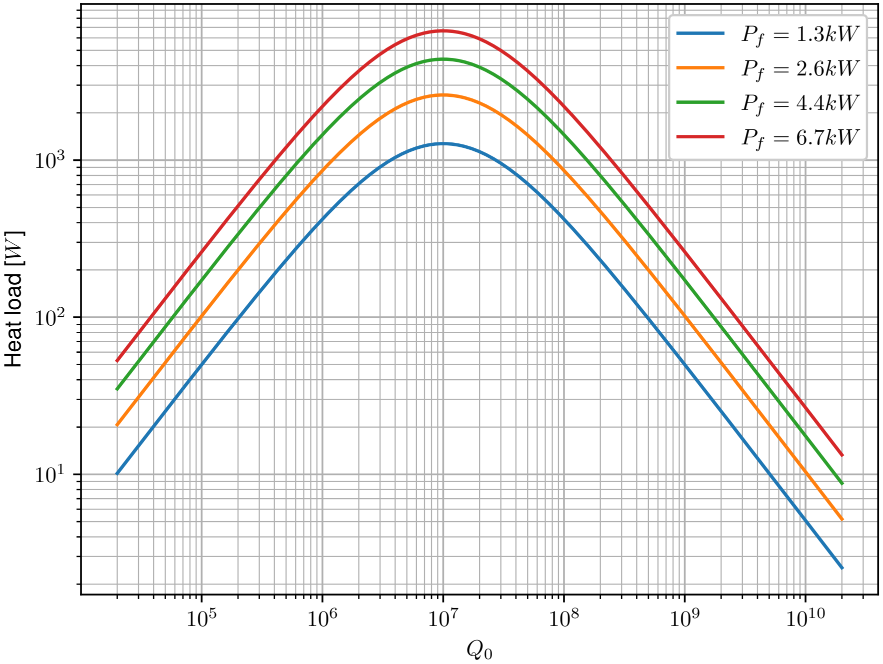
From pulsed to continuous: an LLRF perspective

Additional LLRF requirements

- Capability to operate the machine either in CW, LP or SP mode
- Operate superconducting cavities at very narrow bandwidths (65 Hz – 10.8 Hz)

  Few nanometer deformations can modify the RF power requirements significantly.
- An active way to compensate for tuning errors is required
- Quenches have to be detected in few hundreds microseconds to limit excessive cavity heat load

Heat load at different Q_0 values



European XFEL CW/LP upgrade

Quench detection: pulsed vs continuous wave

Pulsed mode

- Uses probe decay to compute the cavity Q_L

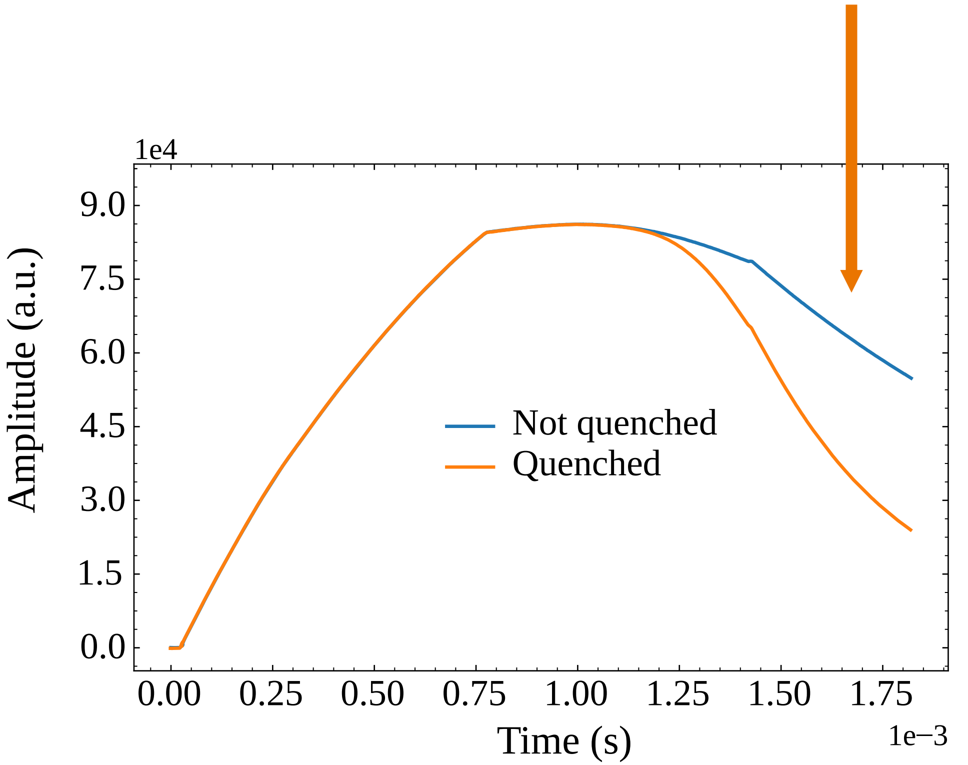
$$\frac{1}{Q_L} = \frac{1}{Q_{ext}} + \frac{1}{Q_0} \qquad Q_L = \tau \pi f_0$$

- If the cavity Q_L is smaller than a certain threshold, a quench is detected
- Detuning-resistant algorithm

CW mode

- No decay!
- A quench detector has to discriminate between real quenches and detuning generated gradient drops.

Field decay



European XFEL CW/LP upgrade

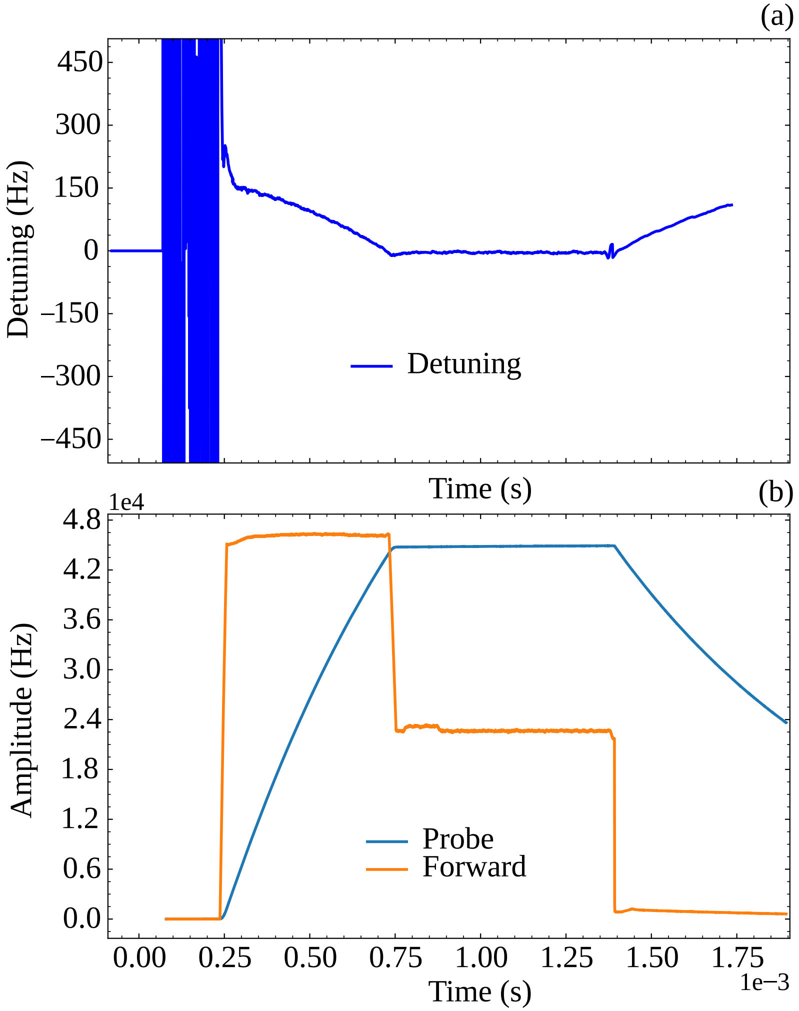
Detuning estimation and control: pulsed vs continuous wave

Pulsed mode

- Detuning is driven by the periodic RF pulse radiation pressure
- Detuning estimation and resonance control can be performed between two RF pulses
- Due to the repetitive nature of the resonance disturbance, iterative algorithms can be used

CW mode

- Disturbances are uncorrelated from machine timing
- An effective resonance controller has to perform an online correction



Quench detection and detuning estimation

Inverse model based approach

How it works

- Some studies were already done in the past[1,2]
- It uses an inverse cavity model[3] to compute simultaneously cavity bandwidth (which is inversely proportional to Q_L) and detuning

$$\begin{bmatrix}\dot{I}_p\\ \dot{Q}_p\end{bmatrix} = 2\pi\begin{bmatrix}-f_{(1/2)} & -\Delta f\\ \Delta f & -f_{(1/2)}\end{bmatrix}\begin{bmatrix}I_p\\ Q_p\end{bmatrix} + 2\pi B\begin{bmatrix}I_b\\ Q_b\end{bmatrix} + 2\pi K\begin{bmatrix}I_f\\ Q_f\end{bmatrix},$$

$$K = \frac{f_0}{Q_{ext}}, \quad B = \frac{f_0}{2}\frac{r}{Q}, \quad f_{(1/2)} = \frac{f_0}{2Q_L},$$

$$\longrightarrow$$

$$\begin{aligned} f_{(1/2)} &= \frac{I_p(KI_f - \dot{I}_p/2\pi + BI_b)}{I_p^2 + Q_p^2} \\ &+ \frac{Q_p(KQ_f - \dot{Q}_p/2\pi + BQ_b)}{I_p^2 + Q_p^2}, \\ \Delta f &= \frac{Q_p(KI_f - \dot{I}_p/2\pi + BI_b)}{I_p^2 + Q_p^2} \\ &- \frac{I_p(KQ_f - \dot{Q}_p/2\pi + BQ_b)}{I_p^2 + Q_p^2}. \end{aligned}$$

[1] (Rybaniec, Radoslaw, et al. "Real-time estimation of superconducting cavities parameters." Proc. 5th Int. Particle Accelerator Conf.(IPAC'14). 2014.)

[2] (Echevarria, P, et al. "Simulation of quench detection algorithms for Helmholtz Zentrum Berlin SRF cavities." Journal of Physics: Conference Series. Vol. 1350. No. 1. IOP Publishing, 2019.)

[3] (Schilcher, T. Vector sum control of pulsed accelerating fields in Lorentz force detuned superconducting cavities. No. TESLA-98-20. DESY, 1998.)

Quench detection and detuning estimation

Requirements and hardware

Requirements

- Few hundreds µs to detect a quench
  → realtime FPGA computations
- Hertz detuning resolution
- Target clock frequency 125 MHz

Boards

- MTCA.4 based
- SIS8300L2 - SIS8300-KU

  → single cavity regulation
- DAMC-TCK7 – DAMC-FMC2ZUP

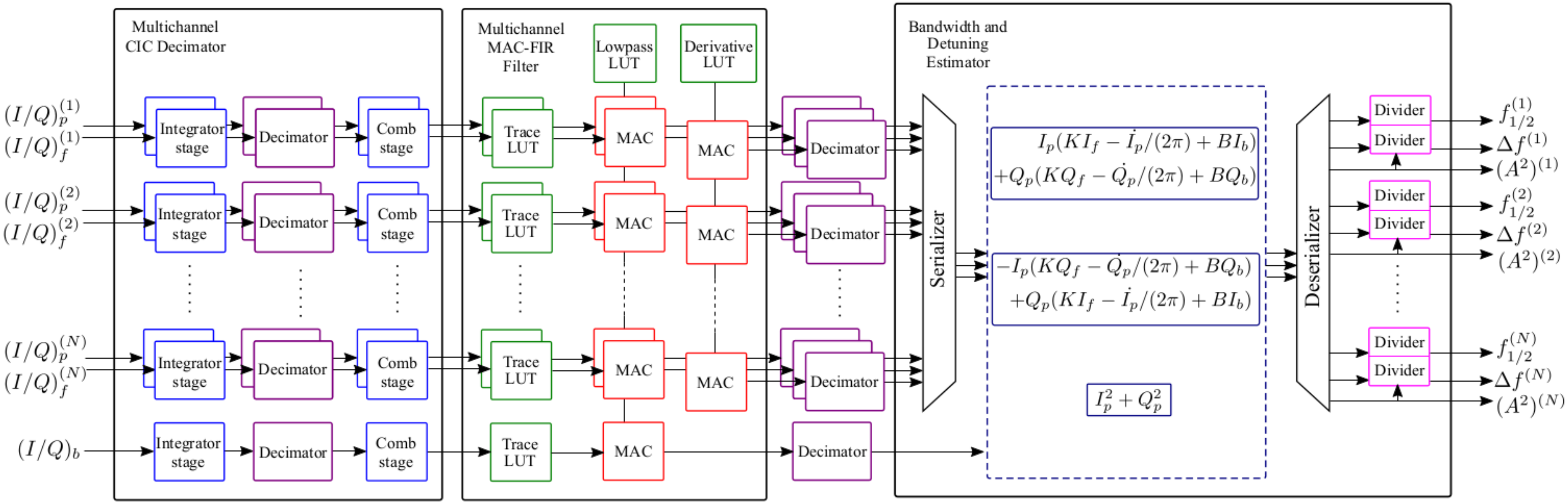
  → VS of 16 cavities

DAMC-FMC2ZUP

https://techlab.desy.de

Quench detection and detuning estimation

Model scheme

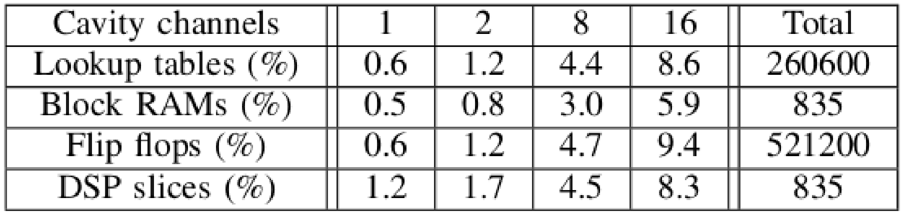


Structure

- A chain of Cascaded Integrator-Comb (CIC) and and Multiply-Accumulate FIR, filters and decimates the sample rate from 9.027 MHz → 72.2 kHz

- A serial structure is used to compute the cavities bandwidth and detuning

COMPONENT RESOURCE UTILIZATION ON XC7K420T.



Cavity channels	1	2	8	16	Total
Lookup tables (%)	0.6	1.2	4.4	8.6	260600
Block RAMs (%)	0.5	0.8	3.0	5.9	835
Flip flops (%)	0.6	1.2	4.7	9.4	521200
DSP slices (%)	1.2	1.7	4.5	8.3	835

Experimental tests

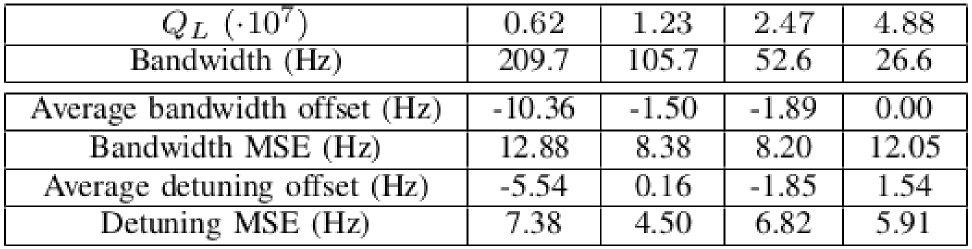
Pulsed tests: CMTB

Results

- Able to detect loss of Q_0 in realtime

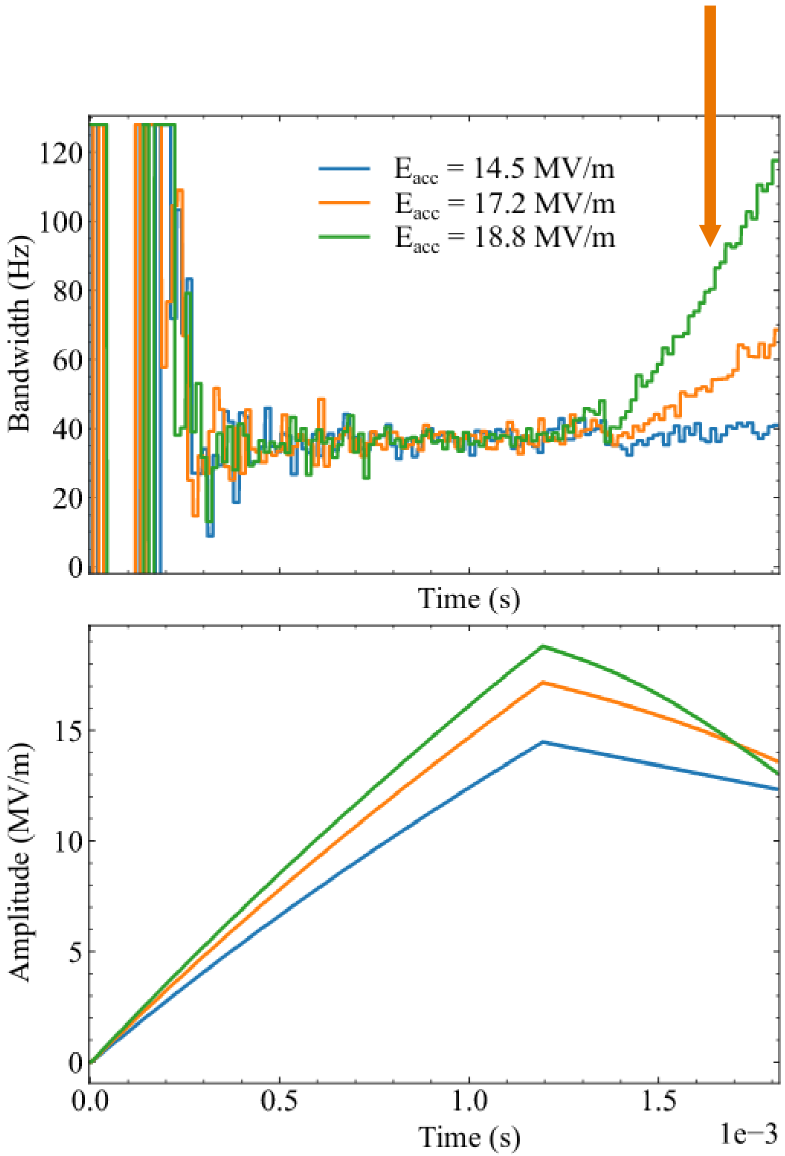
  Detection happens when $Q_0 \sim 10^8$
- Latency of 170 µs (optimizable)
- MSE errors on detuning of few Hertz

Estimation errors for pulsed mode of operation.



Q_L $(\cdot 10^7)$	0.62	1.23	2.47	4.88
Bandwidth (Hz)	209.7	105.7	52.6	26.6
Average bandwidth offset (Hz)	-10.36	-1.50	-1.89	0.00
Bandwidth MSE (Hz)	12.88	8.38	8.20	12.05
Average detuning offset (Hz)	-5.54	0.16	-1.85	1.54
Detuning MSE (Hz)	7.38	4.50	6.82	5.91

Bandwidth increases due to multipacting



Experimental tests

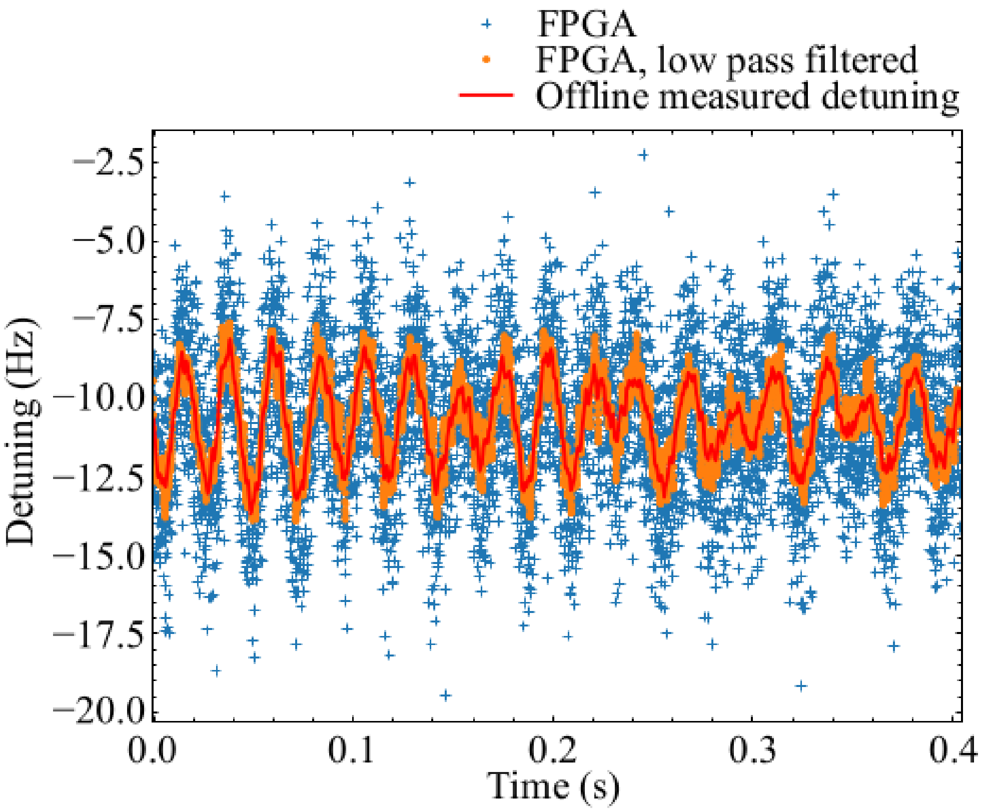
CW tests: CMTB

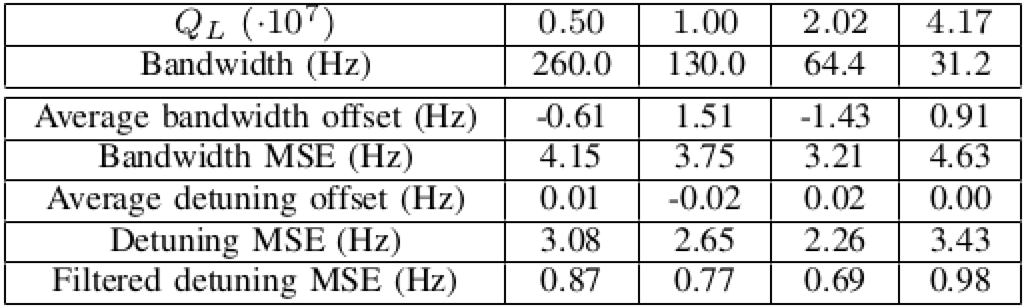
Results

- Sub-Hertz average detuning offset
- Sub-Hertz MSE detuning error

  (after 1kHz filtering)
- Few Hertz MSE bandwidth error

It was not possible to test quench detection due to radiation interlock!





ESTIMATION ERRORS FOR CW MODE OF OPERATION.

Q_L $(\cdot 10^7)$	0.50	1.00	2.02	4.17
Bandwidth (Hz)	260.0	130.0	64.4	31.2
Average bandwidth offset (Hz)	-0.61	1.51	-1.43	0.91
Bandwidth MSE (Hz)	4.15	3.75	3.21	4.63
Average detuning offset (Hz)	0.01	-0.02	0.02	0.00
Detuning MSE (Hz)	3.08	2.65	2.26	3.43
Filtered detuning MSE (Hz)	0.87	0.77	0.69	0.98

Experimental tests

CW tests with beam: ELBE

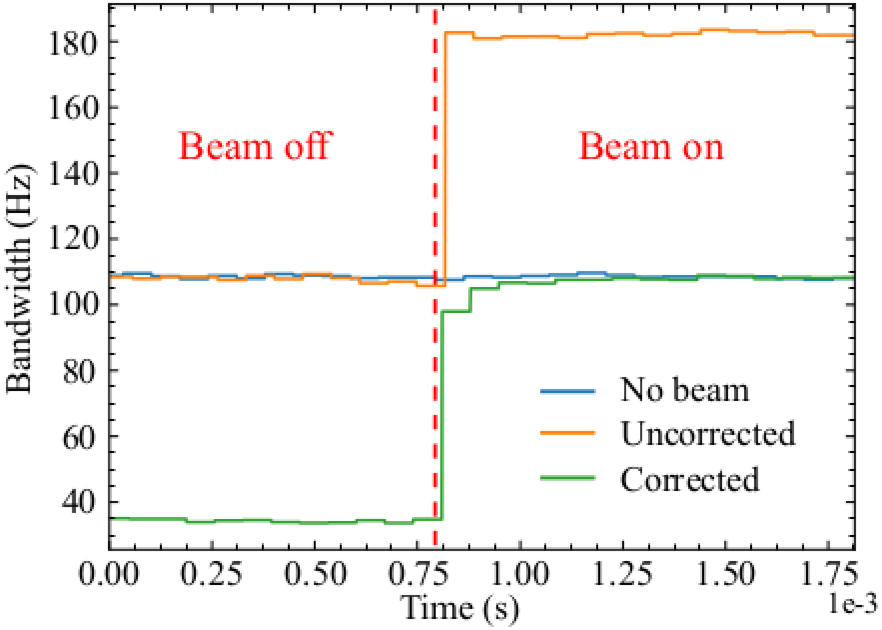
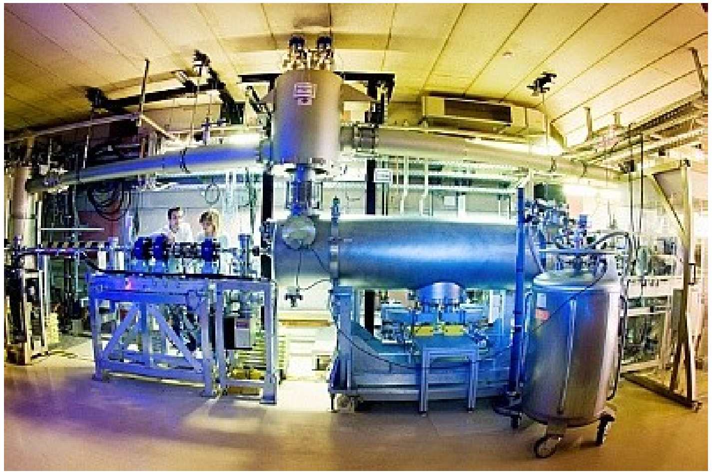


TABLE IV
BANDWIDTH ERRORS IN PRESENCE OF BEAM LOADING.

Gun current (µA)	600	450	300	150
Average bandwidth offset (Hz)	-0.88	0.62	-0.39	-0.19

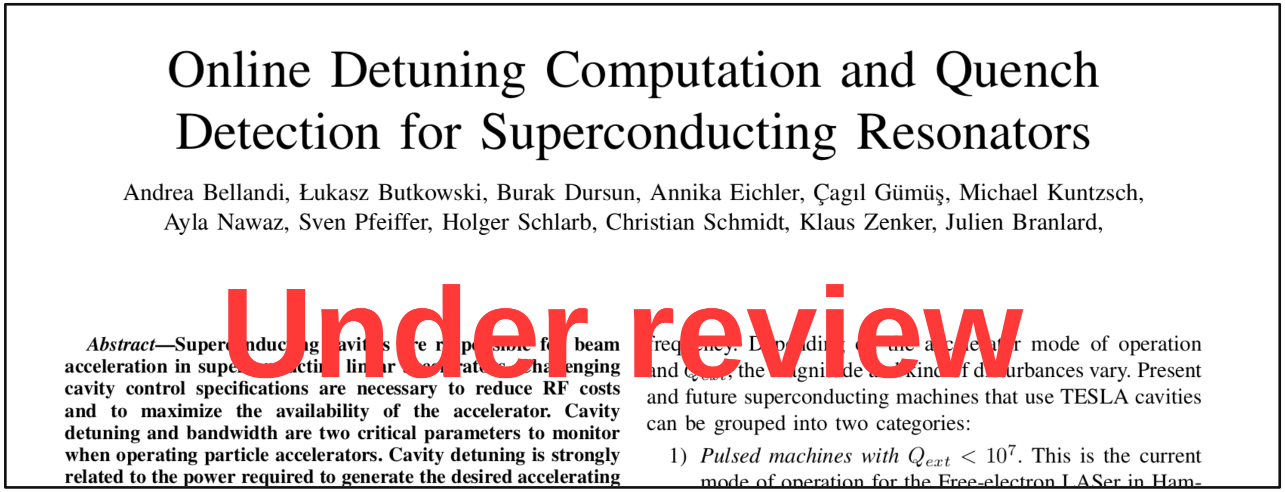
Results

- ✓ Beam loading correction works!
- ✓ The component will help HZDR operators in optimizing the detuning
- ✓ HZDR wrote a support package for the estimator



Final remarks

- A Vector-Sum ready FPGA-based component was tested
- The estimator fullfills delay (170 µs) and precision (~Hz) requirements for both detuning and bandwidth
- It was not possible to perform a quench detection in CW due to limitations of the facility. However pulsed tests and simulations suggest that the component is capable of such a task
- Next step: program a resonance controller that uses estimated detuning for LFD/microphonics compensation



Online Detuning Computation and Quench Detection for Superconducting Resonators

Andrea Bellandi, Łukasz Butkowski, Burak Dursun, Annika Eichler, Çagıl Gümüş, Michael Kuntzsch,
Ayla Nawaz, Sven Pfeiffer, Holger Schlarb, Christian Schmidt, Klaus Zenker, Julien Branlard,

Under review

***Abstract*—Superconducting cavities are responsible for beam acceleration in superconducting linear accelerators. Challenging cavity control specifications are necessary to reduce RF costs and to maximize the availability of the accelerator. Cavity detuning and bandwidth are two critical parameters to monitor when operating particle accelerators. Cavity detuning is strongly related to the power required to generate the desired accelerating**

frequency. Depending on the accelerator mode of operation and Q_{ext}, the magnitude and kind of disturbances vary. Present and future superconducting machines that use TESLA cavities can be grouped into two categories:

1) *Pulsed machines with* $Q_{ext} < 10^7$. This is the current mode of operation for the Free-electron LASer in Ham-

Thanks to

L. Butkowski, B. Dursun, A. Eichler, Ç. Gumus, A. Nawaz,
S. Pfeiffer, H. Schlarb, C. Schmidt and J. Branlard
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Helmholtz-Zentrum Dresden-Rossendorf, Dresden 01328, Germany.

Special thanks to

C. Papon, author of SpinalHDL

(See https://spinalhdl.github.io/SpinalDoc-RTD/)

Contact

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Experimental tests

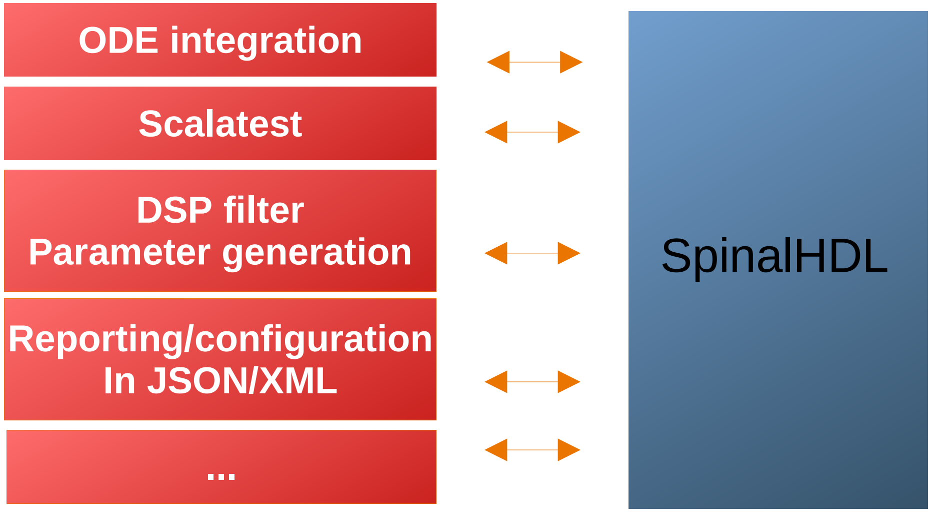
Technical details

The component was programmed in SpinalHDL

- It is an Hardware Description Language (HDL) just like VHDL and Verilog <u>not HLS</u>
- Provide abstracted functionalities through an object-oriented interface
- SpinalHDL components are converted in VHDL or Verilog
- SpinalHDL can use the Java libraries for metaprogramming / generation / testing and cosimulation tasks

SpinalHDL

An alternative hardware description language



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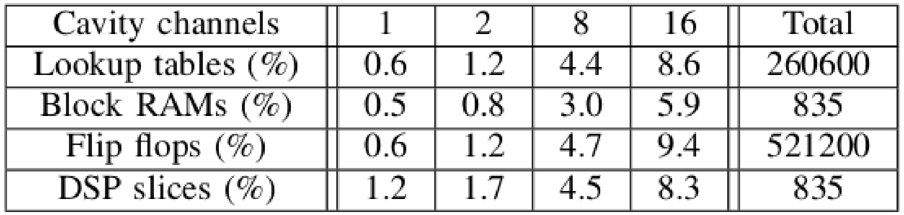

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See https://spinalhdl.github.io/SpinalDoc-RTD/