CW and Long Pulse Operation of XFEL-type Modules at DESY

CHIFEL seminar series

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INTRODUCTION: the XFEL CW upgrade

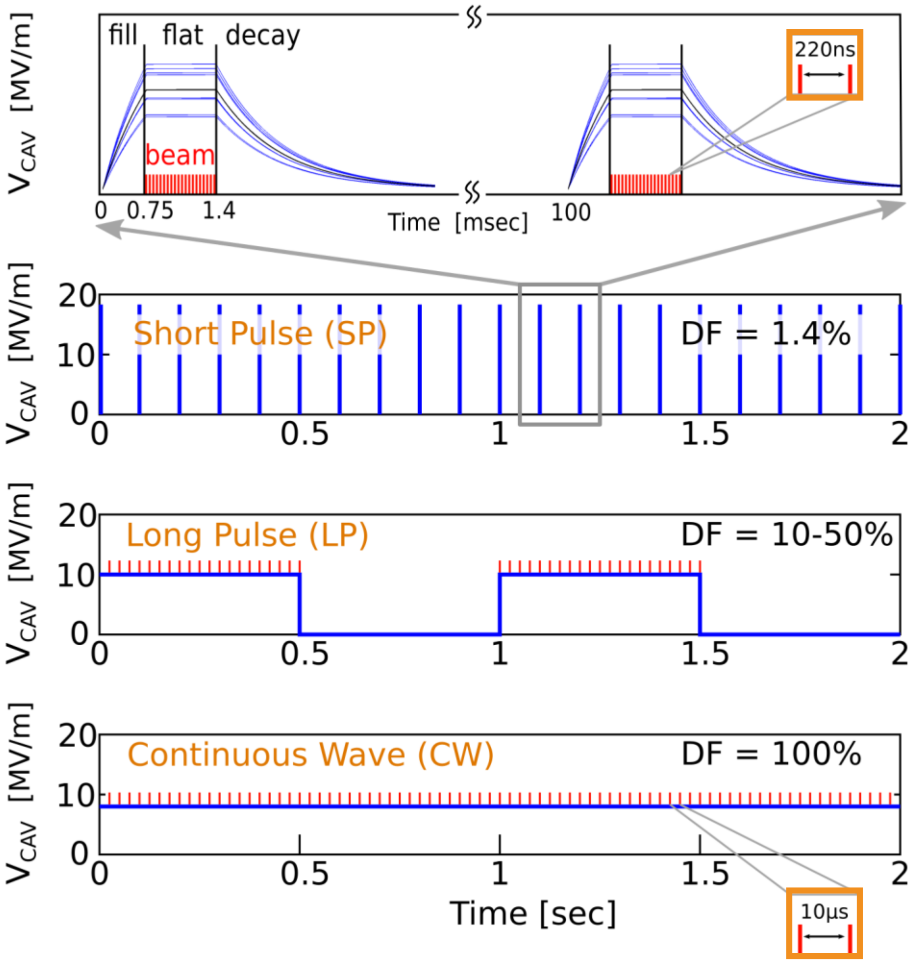
Continuous Wave (CW) Long Pulse (LP) and Short Pulse (SP) operation

Why CW ?

- Users: less complex detectors
- *"Better 100 kHz bunches all the time rather than 4.5 MHz bursts with 100 msec gaps"*

CW operation means CW RF

- Still pulsed beam
- More dissipated heat → more cooling
- CW-capable power sources
- Different control scheme / regime



E = 17.5 GeV
N_{bunch}/s = 27k

E = 10 GeV
N_{bunch}/s = 50k
*up to 500 kHz for 20pC

E = 8 GeV
N_{bunch}/s = 100k
*up to 1 MHz for 20pC

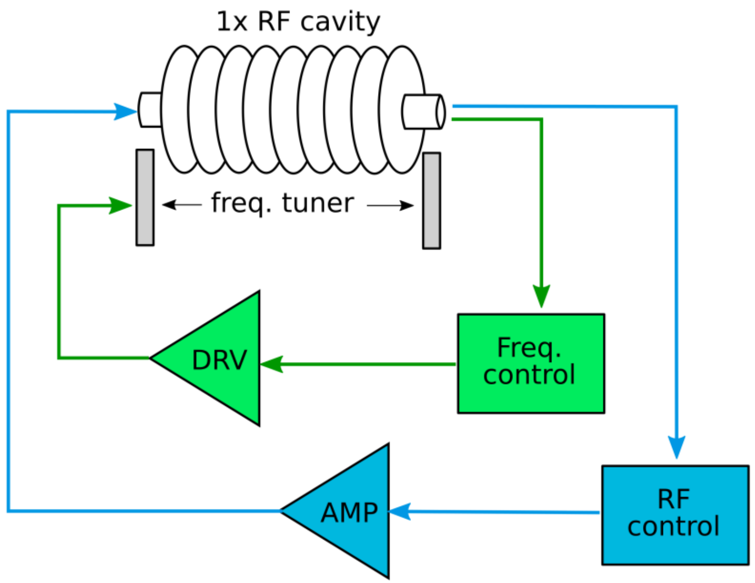
INTRODUCTION: the XFEL CW upgrade

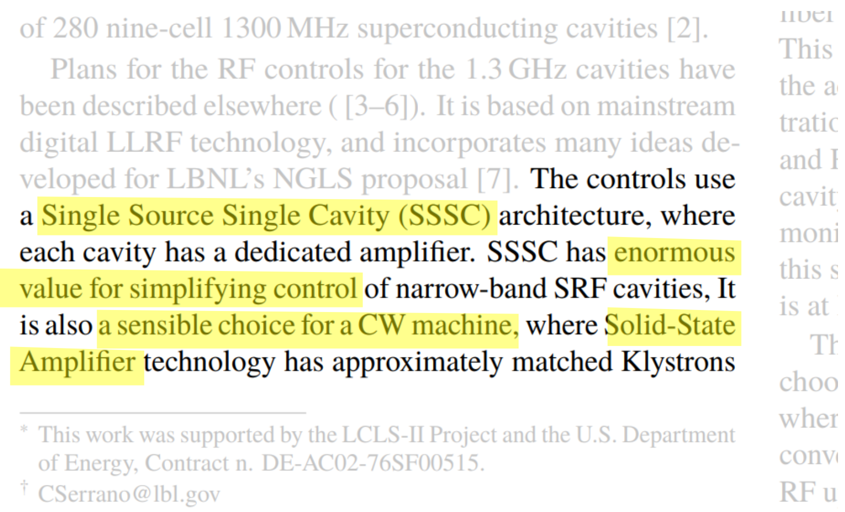
Standard LLRF Control for CW Machines

1. Single Cavity Single Source (SCSS) regulation

Example

- JLAB: CEBAF
- SLAC: LCLS-II




of 280 nine-cell 1300 MHz superconducting cavities [2].

Plans for the RF controls for the 1.3 GHz cavities have been described elsewhere ([3–6]). It is based on mainstream digital LLRF technology, and incorporates many ideas developed for LBNL's NGLS proposal [7]. The controls use a Single Source Single Cavity (SSSC) architecture, where each cavity has a dedicated amplifier. SSSC has enormous value for simplifying control of narrow-band SRF cavities, It is also a sensible choice for a CW machine, where Solid-State Amplifier technology has approximately matched Klystrons

* This work was supported by the LCLS-II Project and the U.S. Department of Energy, Contract n. DE-AC02-76SF00515.

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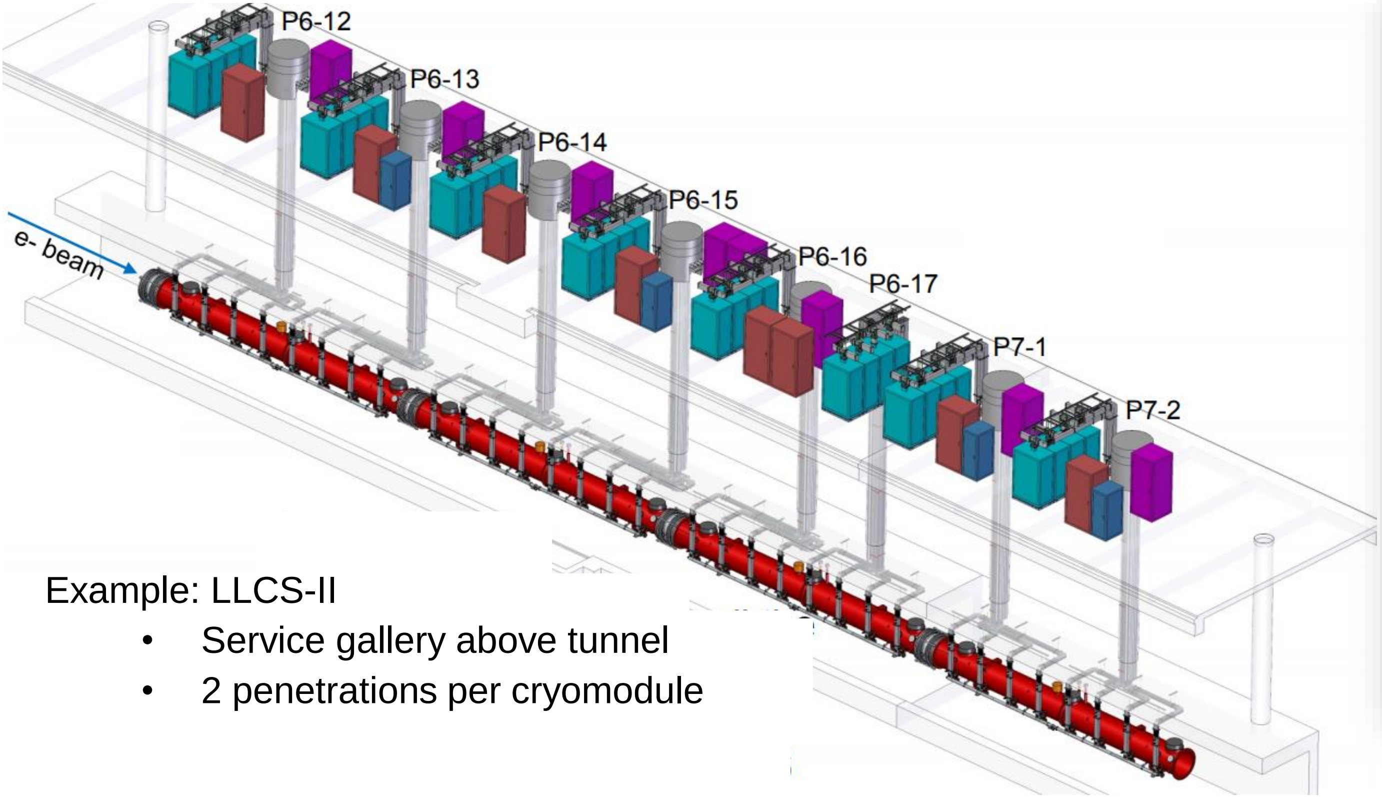
Extract from: "*Design and implementation of the llrf system for lcls-ii*" C. Serano *et al.* Proceedings from ICALEPCS2017, Barcelona, Spain

INTRODUCTION: the XFEL CW upgrade

Standard LLRF Control for CW Machines

2. High Power Solid State Amplifiers (SSA)



Example: LLCS-II

- Service gallery above tunnel
- 2 penetrations per cryomodule

Source: "*High Power RF–Solid State Amplifiers*" A. Dian Yeremian

INTRODUCTION: the XFEL CW upgrade

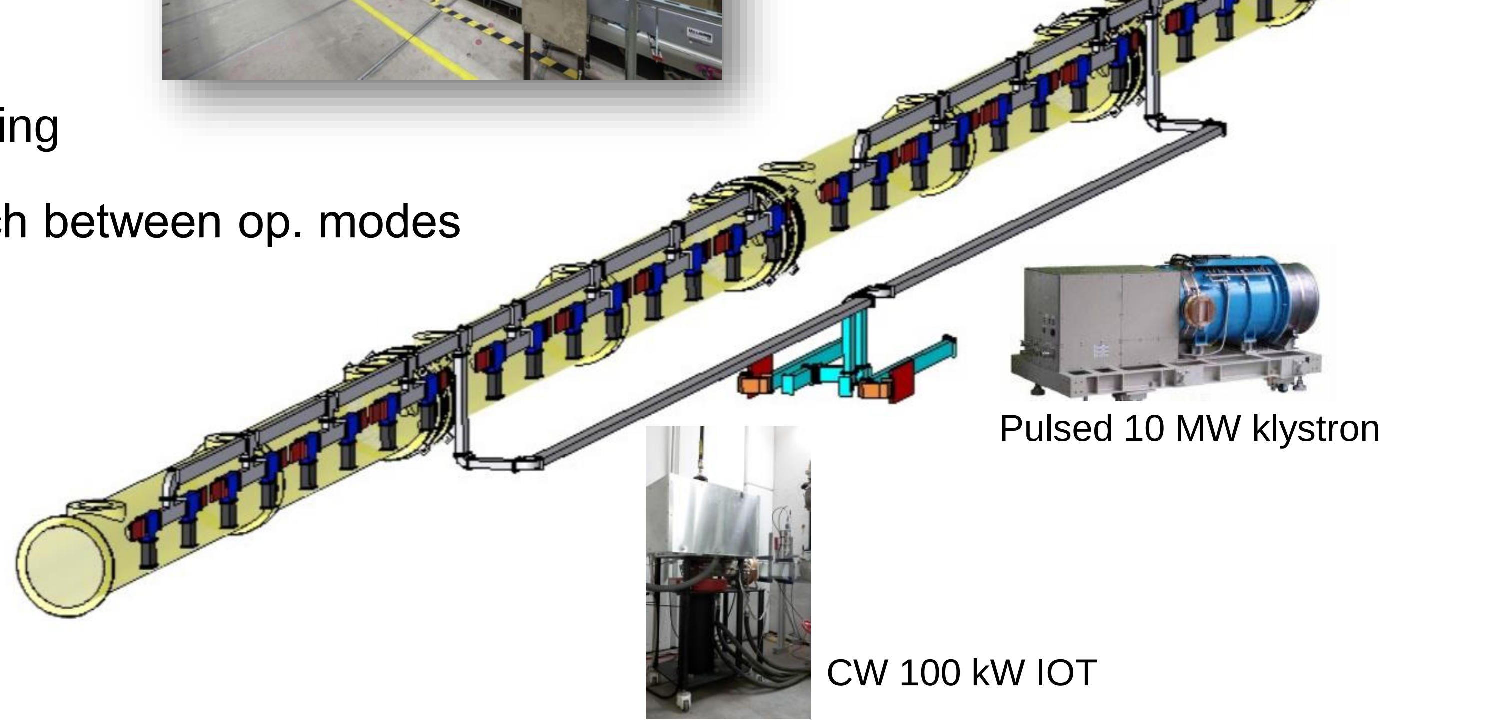
Special case of the Eu-XFEL

No service gallery

- CW RF sources should fit in the tunnel
- Large SSAs not an option, smaller ones?

CW operation ON TOP of pulsed operation

- Maintain the waveguide distribution + cabling
- Only “minor adjustments” required to switch between op. modes



Pulsed 10 MW klystron

1 RF station

- 4 cryomodules = 32 cavities
- 1 power source
  - ➢ **Klystron** for pulsed
  - ➢ **Inductive Output Tube** (IOT) for CW
- 1 RF control system ➔ **Vector Sum control**

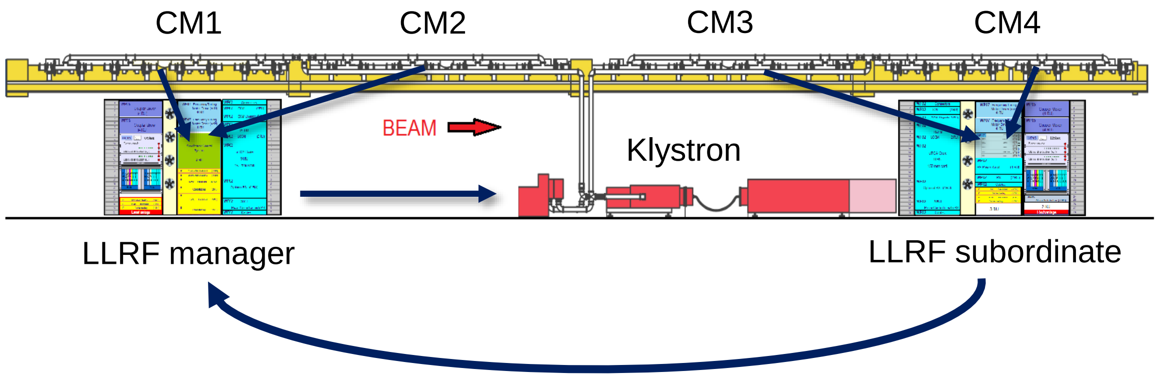
CW 100 kW IOT

INTRODUCTION: the XFEL CW upgrade

(LL)RF drive

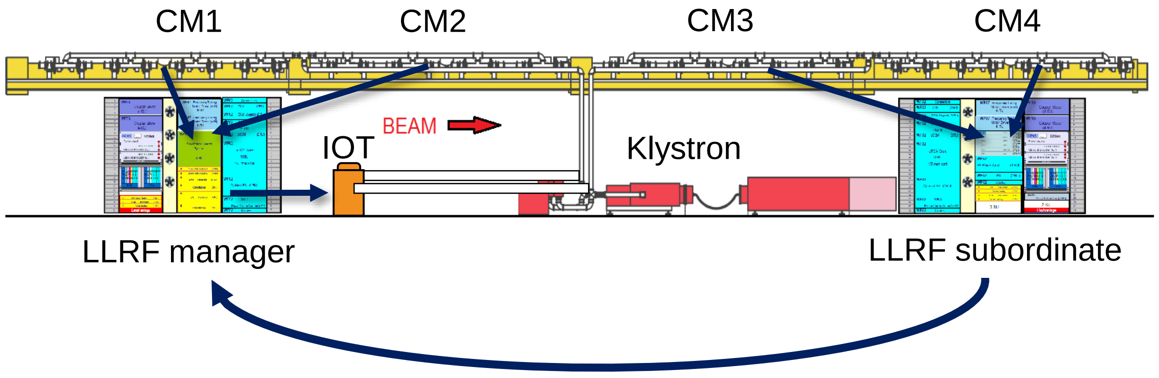
Pulsed operation

- 17.5 GeV max energy
- 1x klystron to drive 1 RF station (32 cavities)
- 1x LLRF system per RF station
- Q_L = 4.6e6 (i.e. ½ bandwidth ~280 Hz)



CW / LP operation

- 8 GeV max energy (CW), 10 GeV (LP)
- 1x IOT to drive 1 RF station
- 1x LLRF system per RF station
- Q_L up to 3e7 (i.e. ½ bandwidth down to 40 Hz)



INTRODUCTION: the XFEL CW upgrade

(LL)RF drive

Pulsed operation

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- 1x klystron to drive 1 RF station (32 cavities)
- 1x LLRF system per RF station
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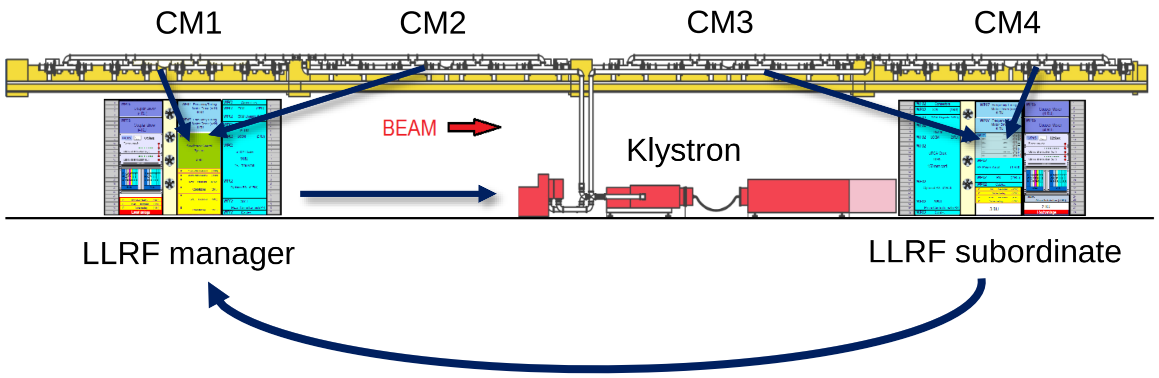
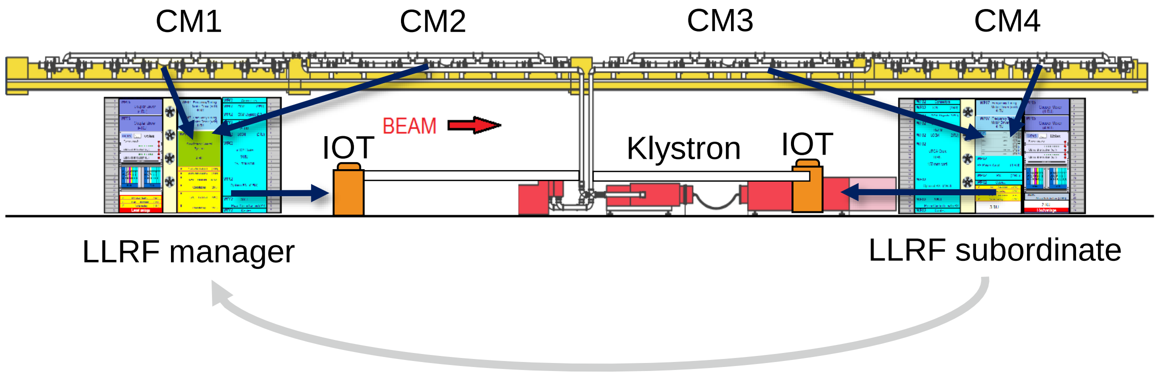
CW / LP operation

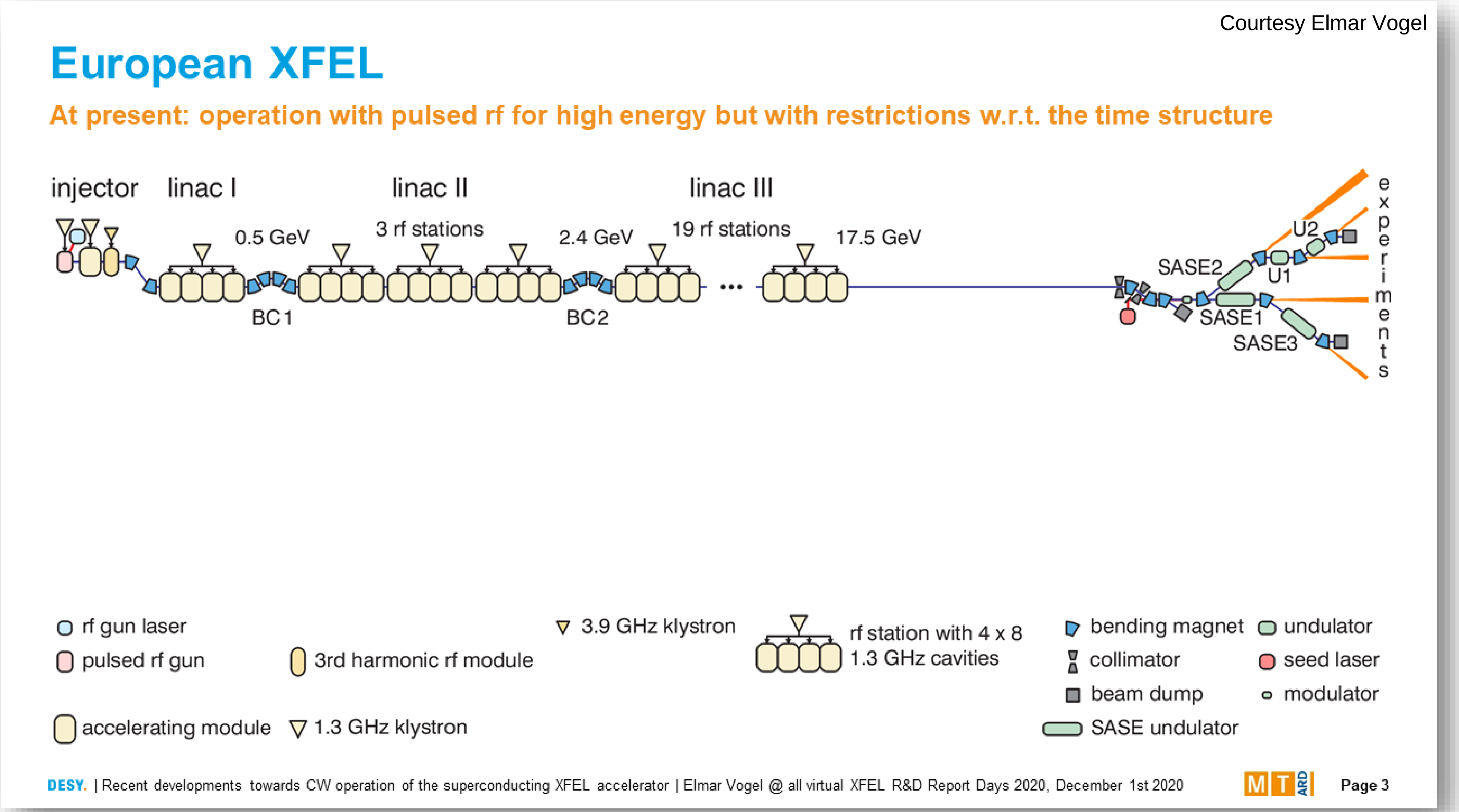
- 8 GeV max energy (CW), 10 GeV (LP)
- **2x** IOTs to drive 1 RF station
- **2x** LLRF systems per RF station
- Q_L up to 3e7 (i.e. ½ bandwidth down to 40 Hz)





INTRODUCTION: the XFEL CW upgrade

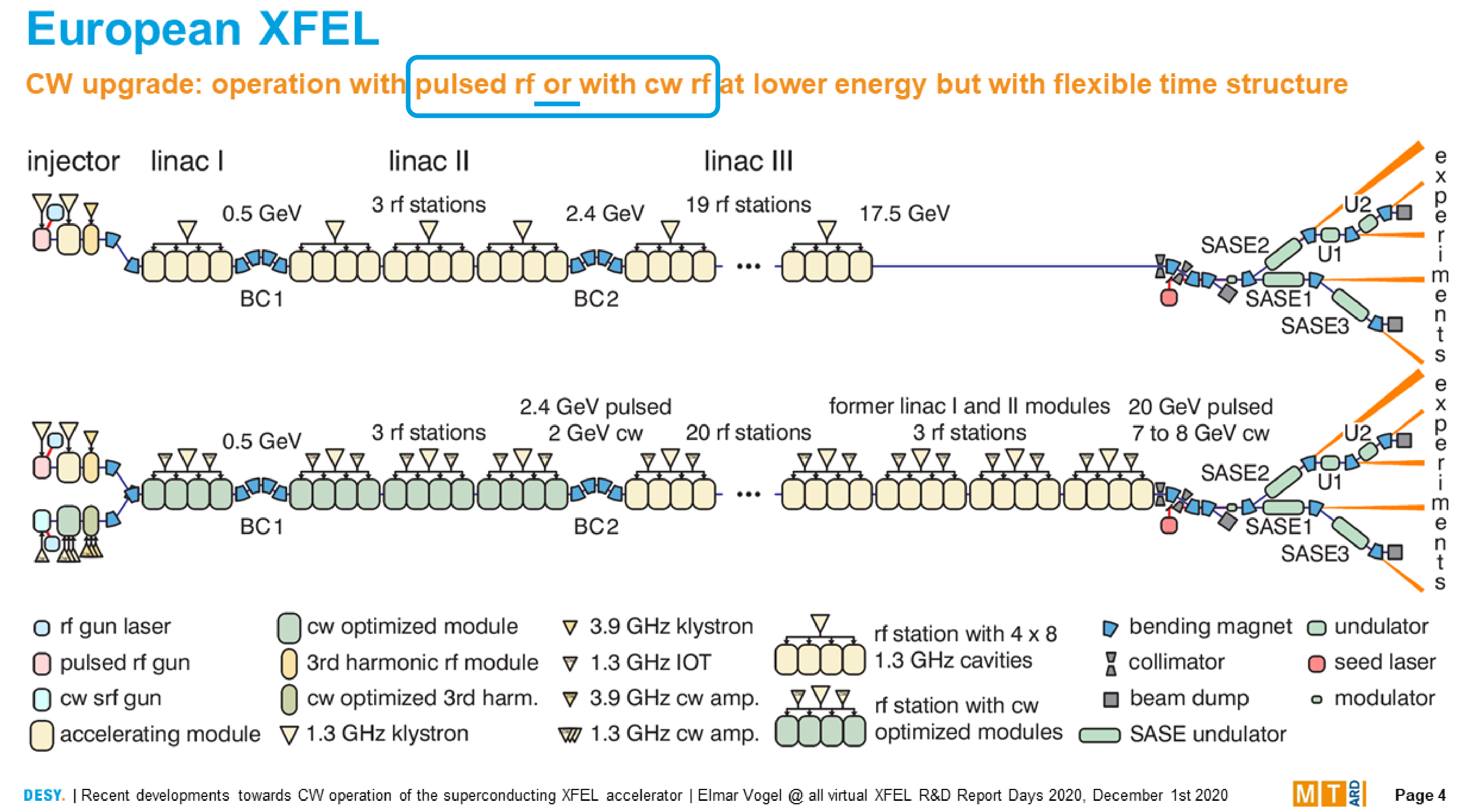
Modifying the linac



INTRODUCTION: the XFEL CW upgrade

Modifying the linac

Courtesy Elmar Vogel



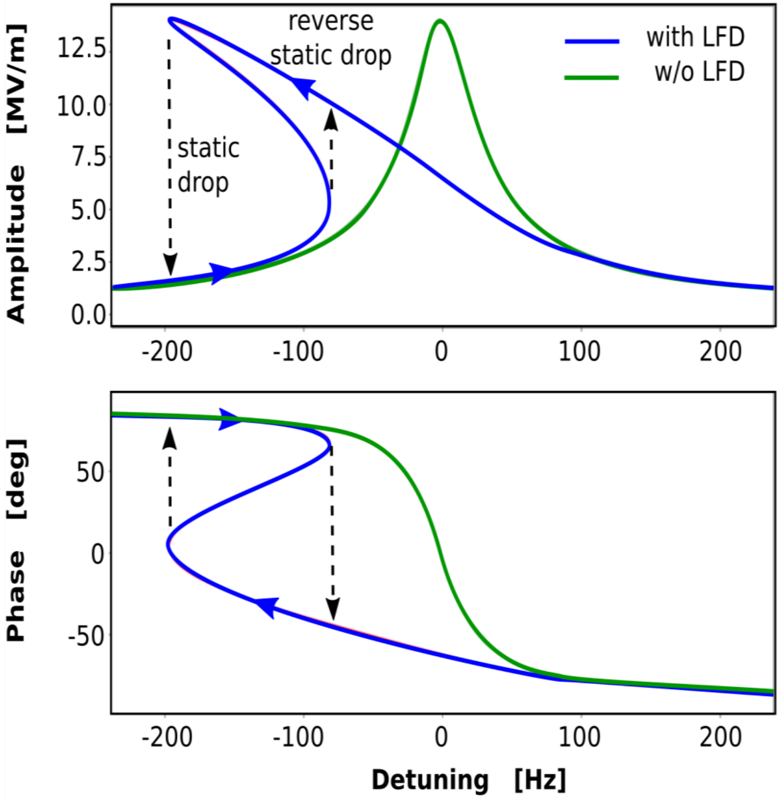
Challenges

CHALLENGES

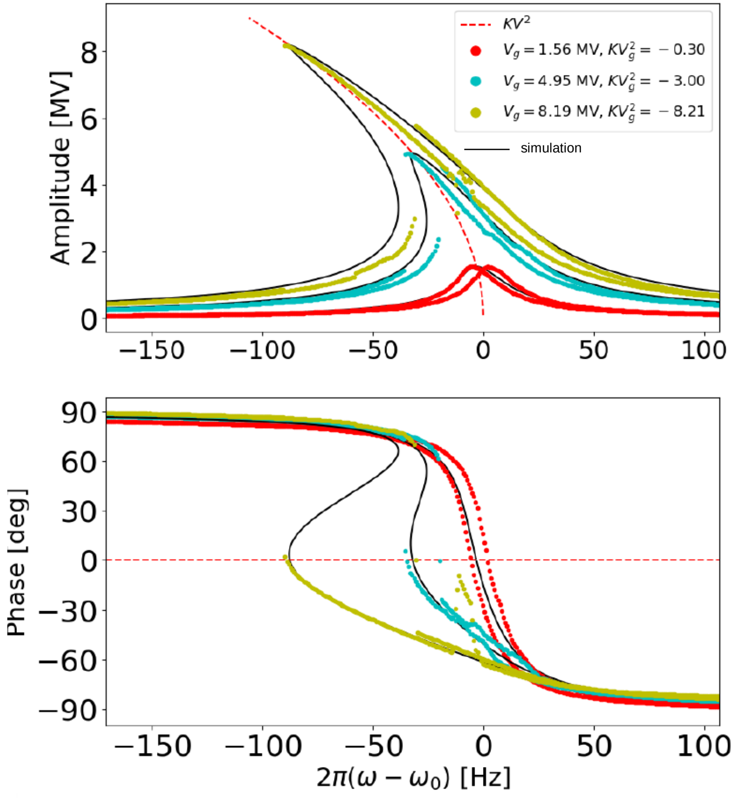
Monotonic Instability

- Lorentz forces induce a detuning as gradient increases
- Microphonics will make the cavity experience a static drop
- Effect is worsened for higher Q_L and higher gradients
- In case of individual cavity control

Lorentz Force Detuning (LFD)



Measured vs simulated data



Reference: Monotonic instabilities in CW cryomodules, A. Bellandi

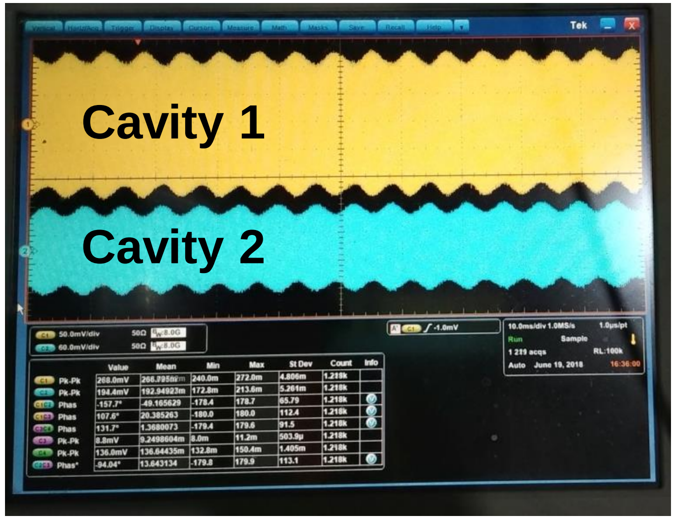
CHALLENGES

Vector Sum (VS) RF control

Example of CW VS operation

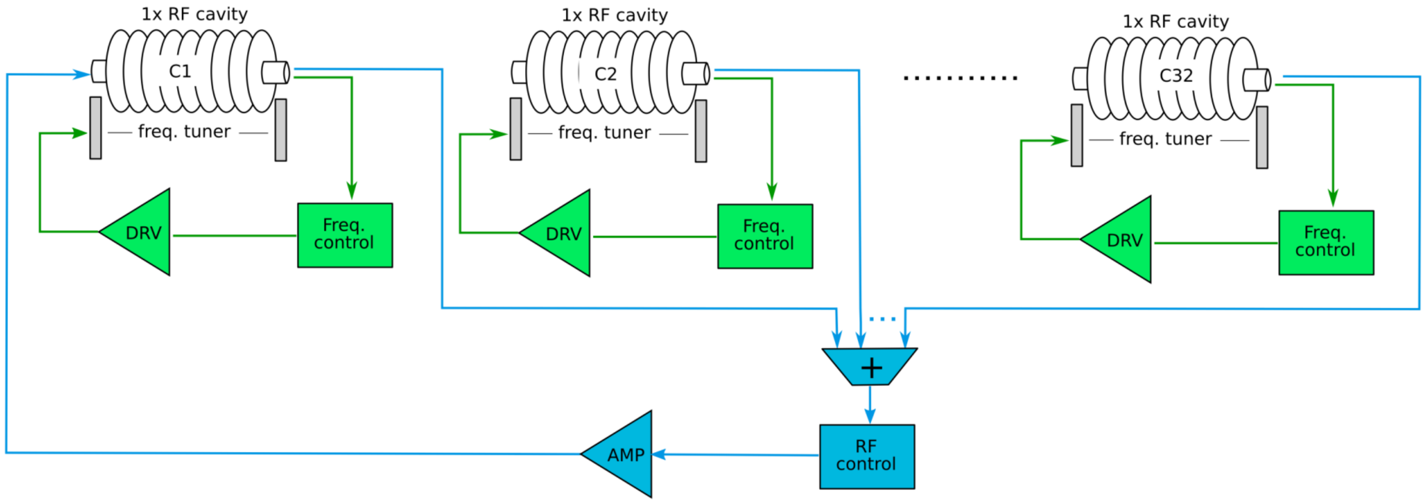
- TRIUMF e- linac
- VS or 2 cavities operated in CW
- No piezo (yet)

Source: "*Lorentz force induced oscillations*", Ramona Leewe, TTC 2019



Eu-XFEL

- 32 cavity VS
- We have **individual piezo ctrl**



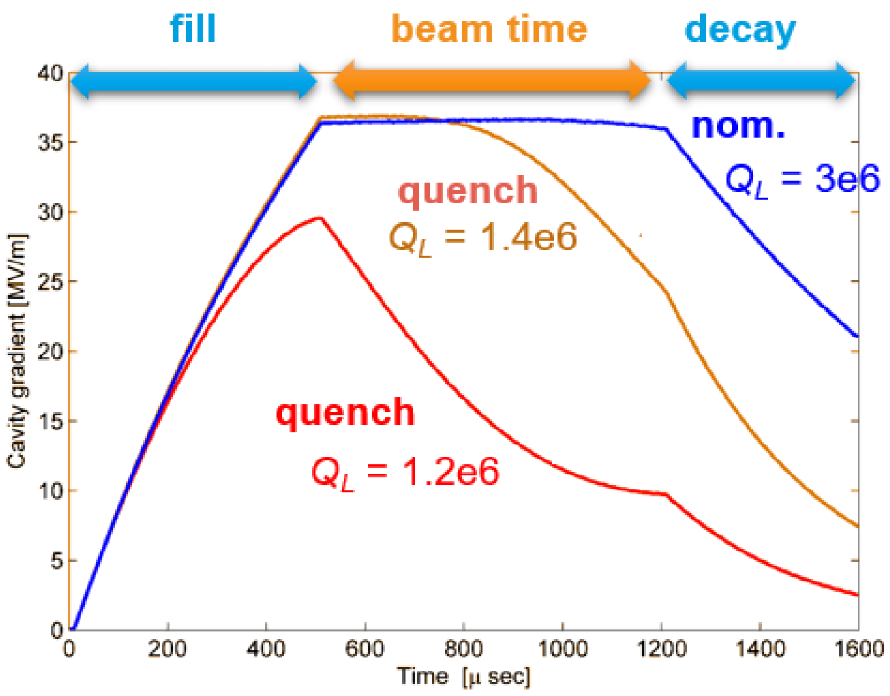
CHALLENGES

CW RF Diagnostics

in pulsed mode

For ex. Q_L and detuning computation

- In pulsed mode: compute Q_L during decay at each pulse and compare
- Easy diagnostic for **quench detection**
- Q_L used to compute **beam loading**
- Decay also used for **detuning** computation



CHALLENGES

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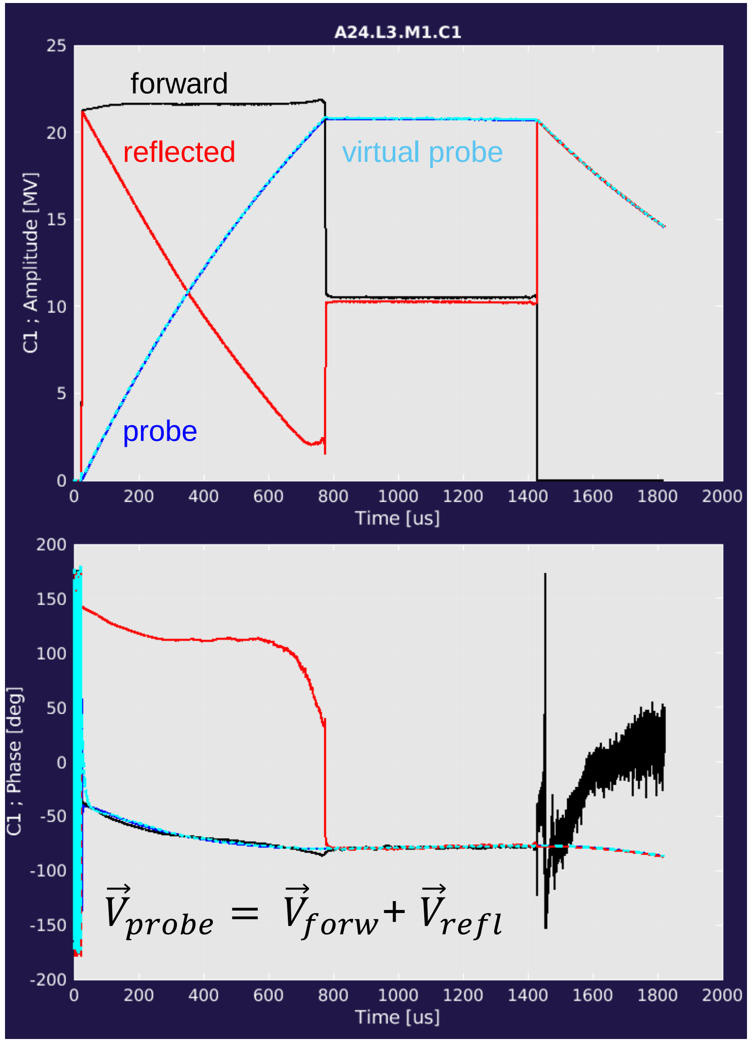
- In CW, no decay, no "easy" way to compute Q_L
- Alternative techniques, **based on virtual probe** (cavity model) are developed and implemented

Example of "virtual" probe computation using a cavity model



Reference: *Online Detuning Computation and Quench Detection for Superconducting Resonators*, A. Bellandi *et al.*, IEEE trans. on nucl. science. vol.68, no.4 Apr. 2021

CHALLENGES

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↓

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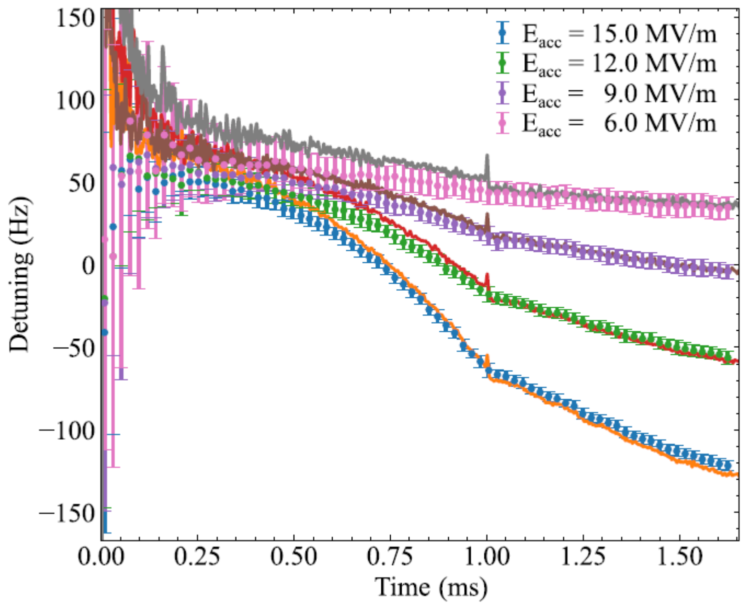
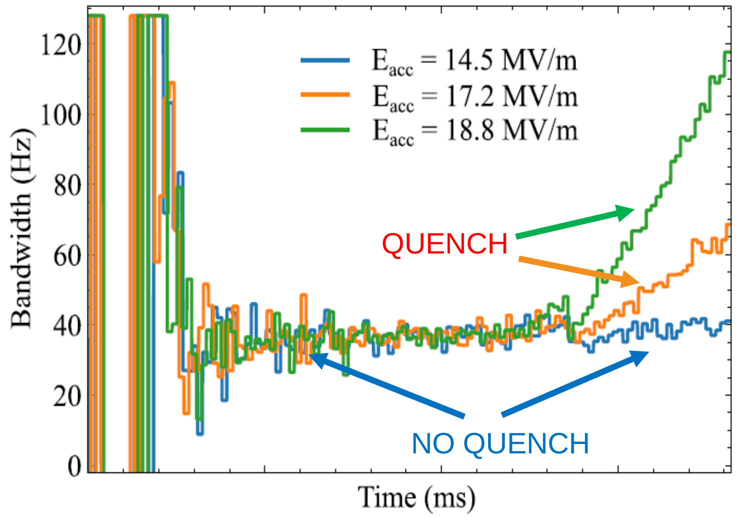


Detuning validation between reference measurement and model-based estimation



The model-based bandwidth computation can be used to detect quenching

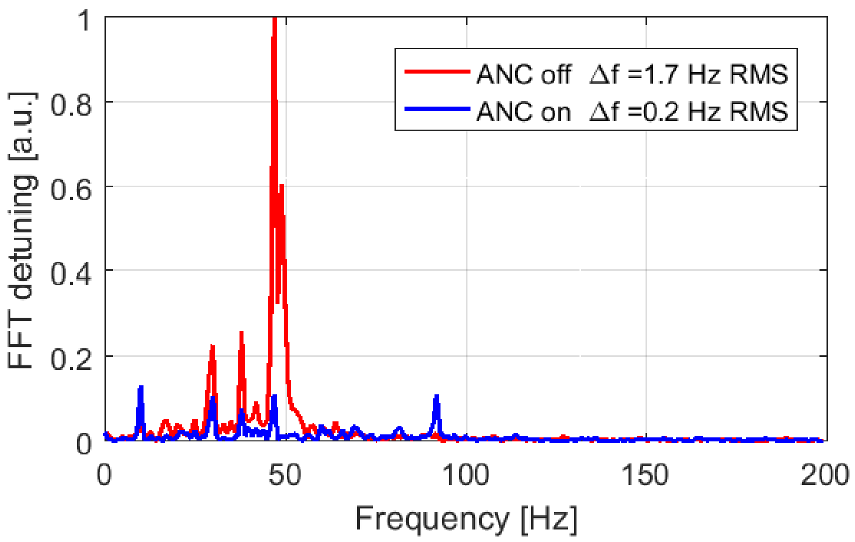
Reference: *Online Detuning Computation and Quench Detection for Superconducting Resonators*, A. Bellandi *et al.*, IEEE trans. on nucl. science. vol.68, no.4 Apr. 2021

CHALLENGES

Microphonics Suppression

Using Active Noise Cancellation (ANC) techniques

- Active Noise Cancellation (**ANC**) techniques applied to notch measured frequencies (adjusted for individual cavities)
- > 20 dB suppression can be achieved



Source: "FPGA-Based RF and Piezo controllers for SRF Cavities in CW Mode",
R. Rybaniec *et al*. IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 64, NO. 6, JUNE 2017

Future improvements

- Current approach requires lot of manual settings
  ➔ unpractical for XFEL
- How to adapt current approach to changing environment
  ➔ detect microphonics and adapt notch settings

CHALLENGES

Other RF Control Challenges

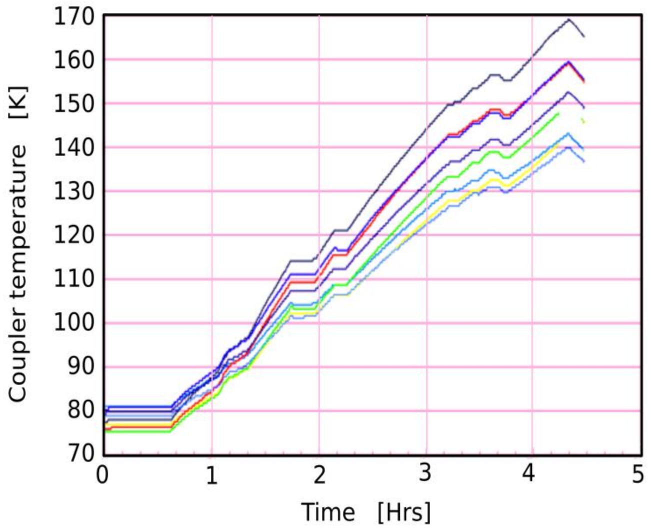
Heating up of high power couplers

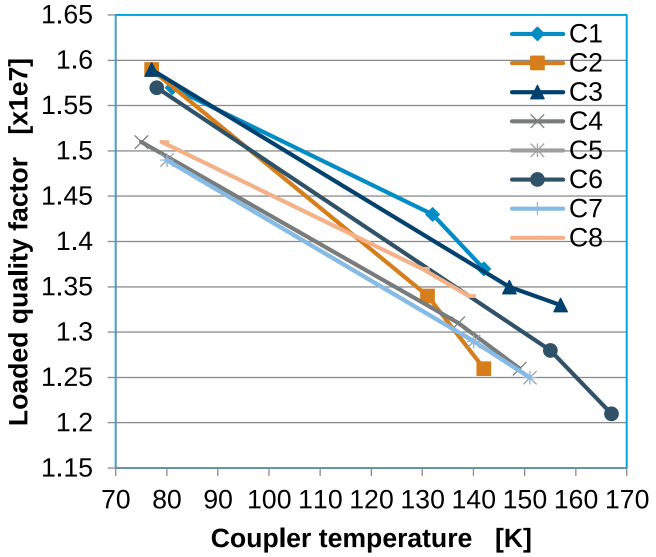
- Can expect up to 25% change in QL
- Lead to positive feedback
- Steady state reached after ~ 12 hours ?
- Note: XFEL has motorized couplers

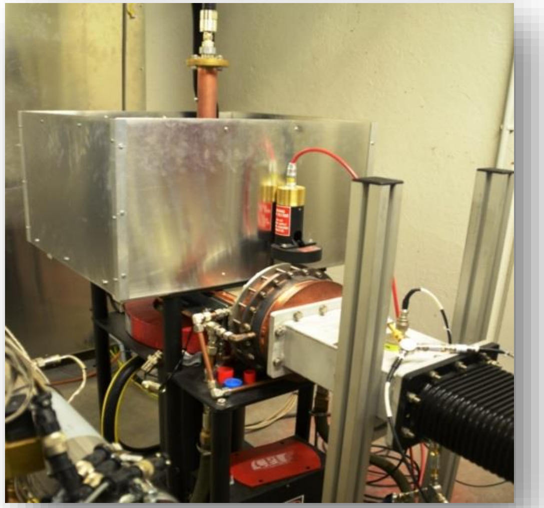
IOT non linearities

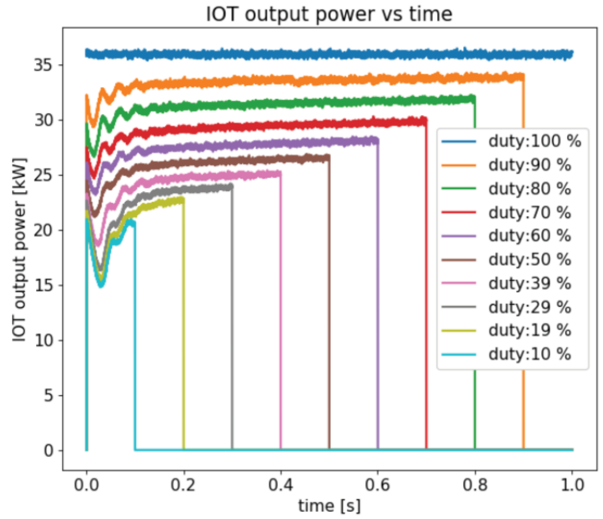
- Especially problematic for long pulse (transients)
- Can be mitigated with linearization look up tables
- Successfully demonstrated at CMTB

courtesy W. Cichalewski









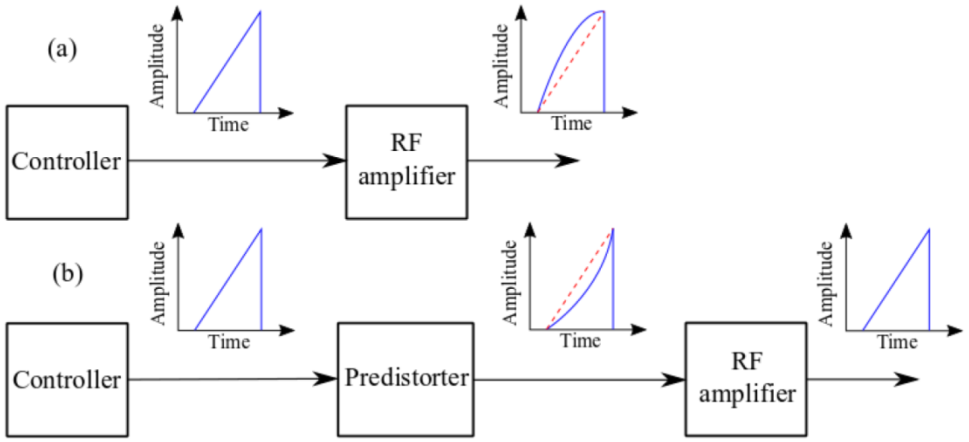
Reference: “Status of Cryomodule Testing at CMTB for CW R&D” J. Branlard, *et al.* SRF2019

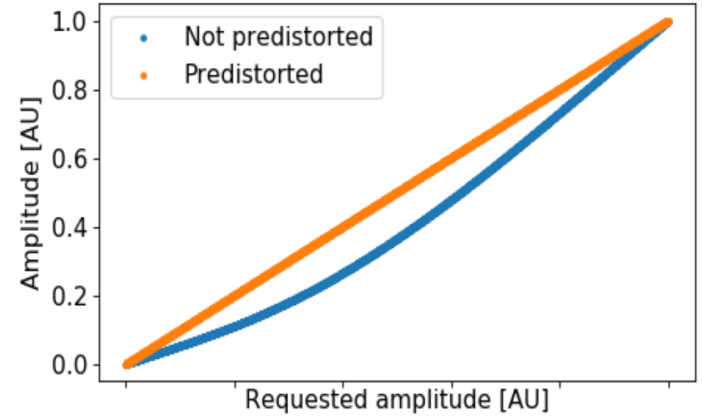
CHALLENGES

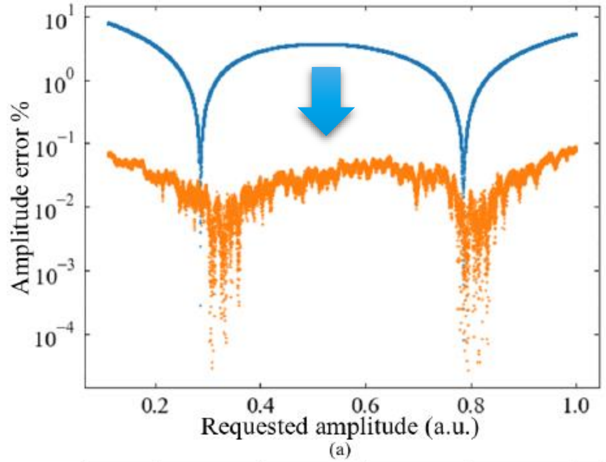
RF power source linearization

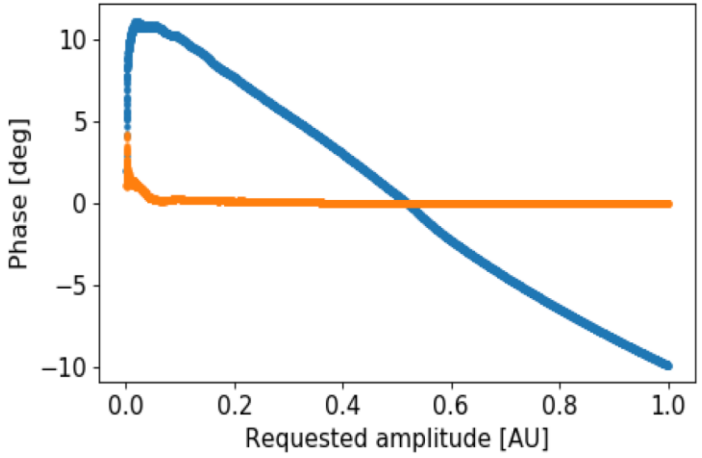
Development of a pre-distorter in the LLRF drive firmware

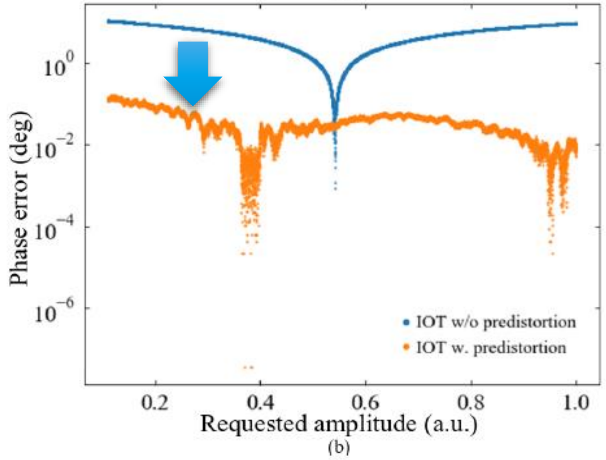
- Tested with IOT and klystron
- Provides 2 orders of magnitude improvement in linearization











Reference : “Results on FPGA-based High Power Tube Amplifier Linearization at DESY“, A. Bellandi et al.
IEEE Transactions on Nuclear Science (Volume: 67, Issue: 5, May 2020)

CMTB test facility

CMTB Test Facility

CryoModule Test Bench

- 5 MW klystron for **pulsed** operation
- 80-100 kW (20-35 kW) IOT for **CW** and **LP** operations
- 2x LLRF systems
  - One for **vector sum** operations (8 cavities)
  - One for **single cavity** control
- Individual **piezo** control
- Helium flow measurement for **heat load** studies

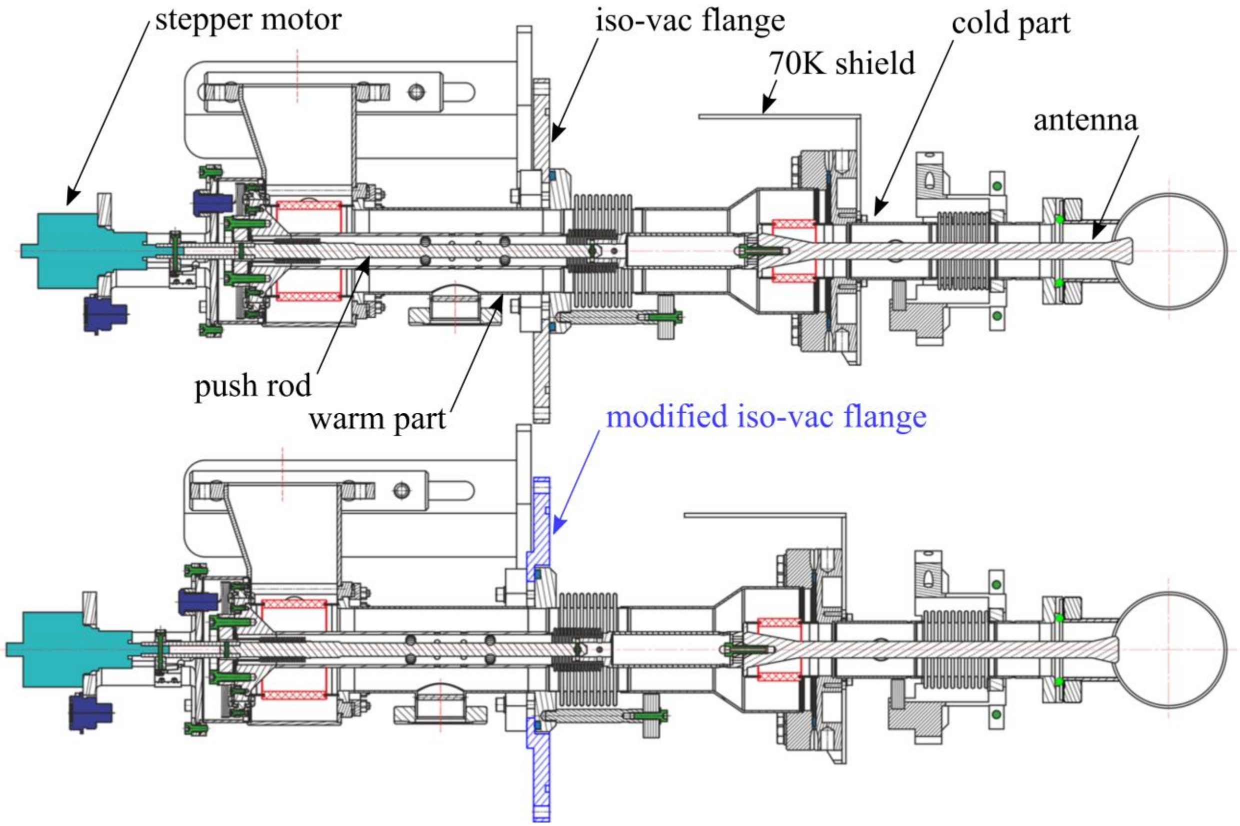
CMTB Test Facility

Cryomodule Tests

- Recently tested CM
  - **XM50.1** (2019 and 2020)
  - **XM46.1** (2021)

- Both modules have **modified couplers**
  - Modified iso-vac flange to **shift Q_L range to higher values** [1e6 – 1e7] → [1e7 – 4e7]
  - Coupler heating effect studied
  - Note: XM46.1 also has **re-plated power coupler**
    → see Elmar Vogel's CHIFEL Seminar presentation 6.5.2021

- Cavity gradients are assessed in **pulsed mode**
- **CW and LP studies** are then carried out

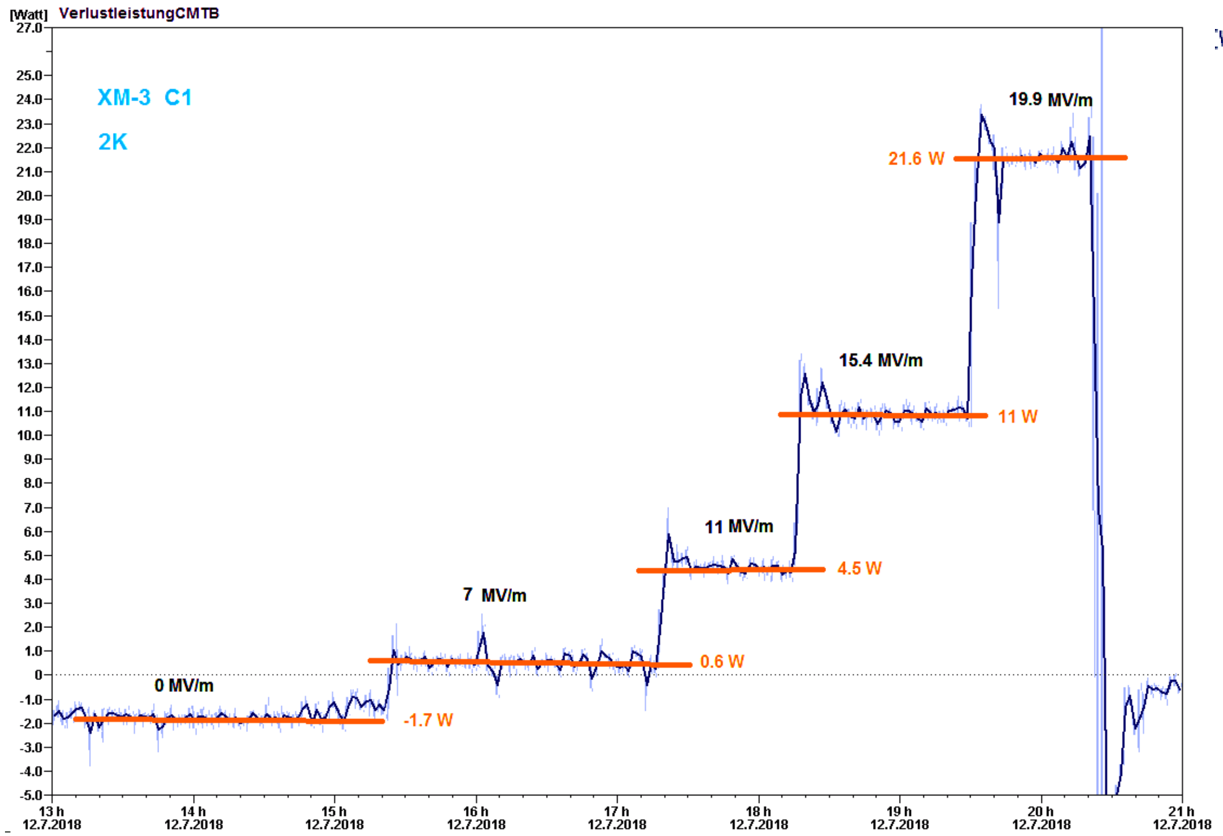


Courtesy D. Kostin

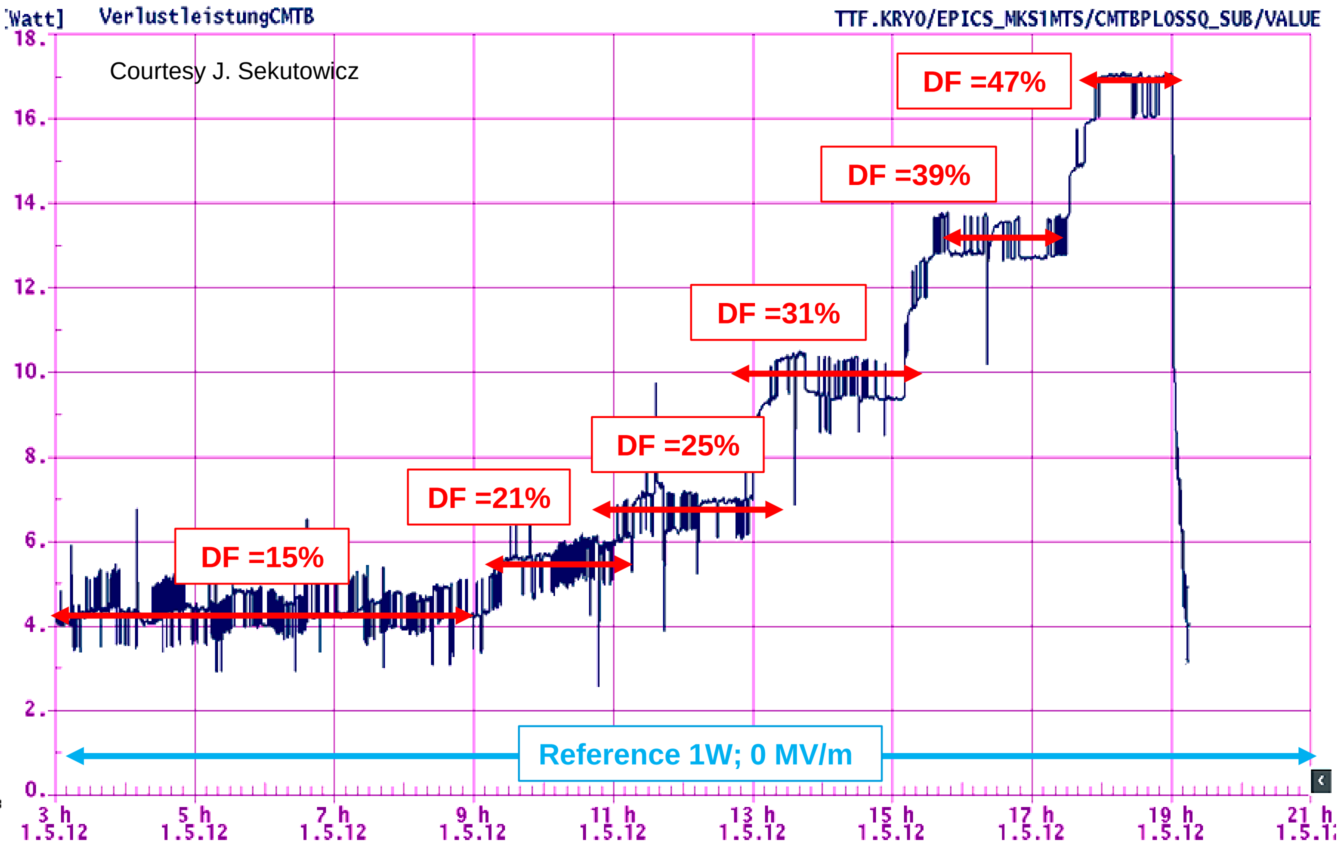
Heat load measurements

Based on Helium flow

- in **CW**, as a function of **gradient**



- In **LP**, as a function of **duty cycle**



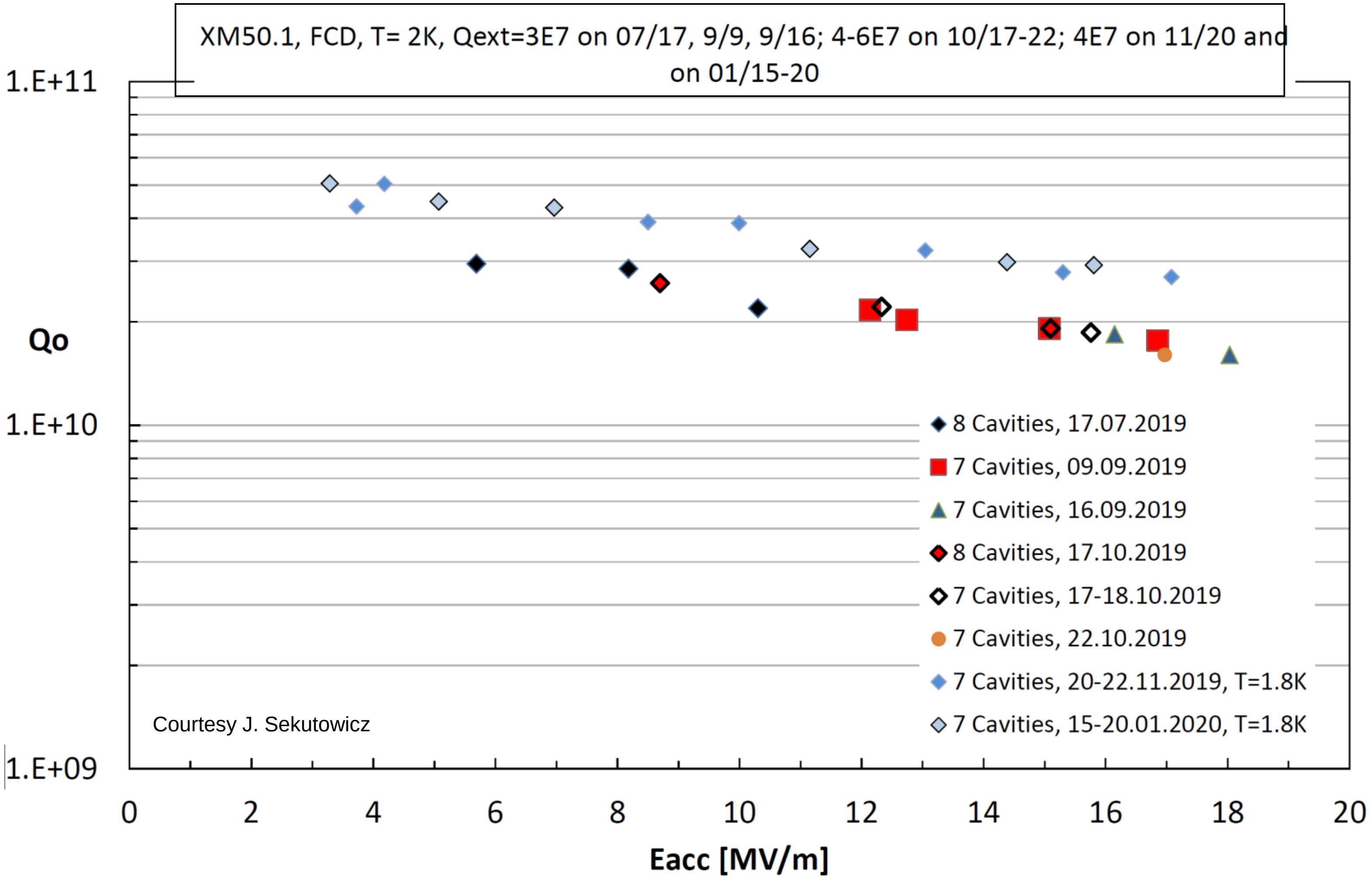
RESULTS

Results

XM50.1 in CW

Conditions (2K)	Results
Q_L = 3e7 for all 8 cavities	Q_0 = 2e10 at 10 MV/m
Q_L = 4-6e7 for 7 cavities	Q_0 = 1.5e10 at 18 MV/m

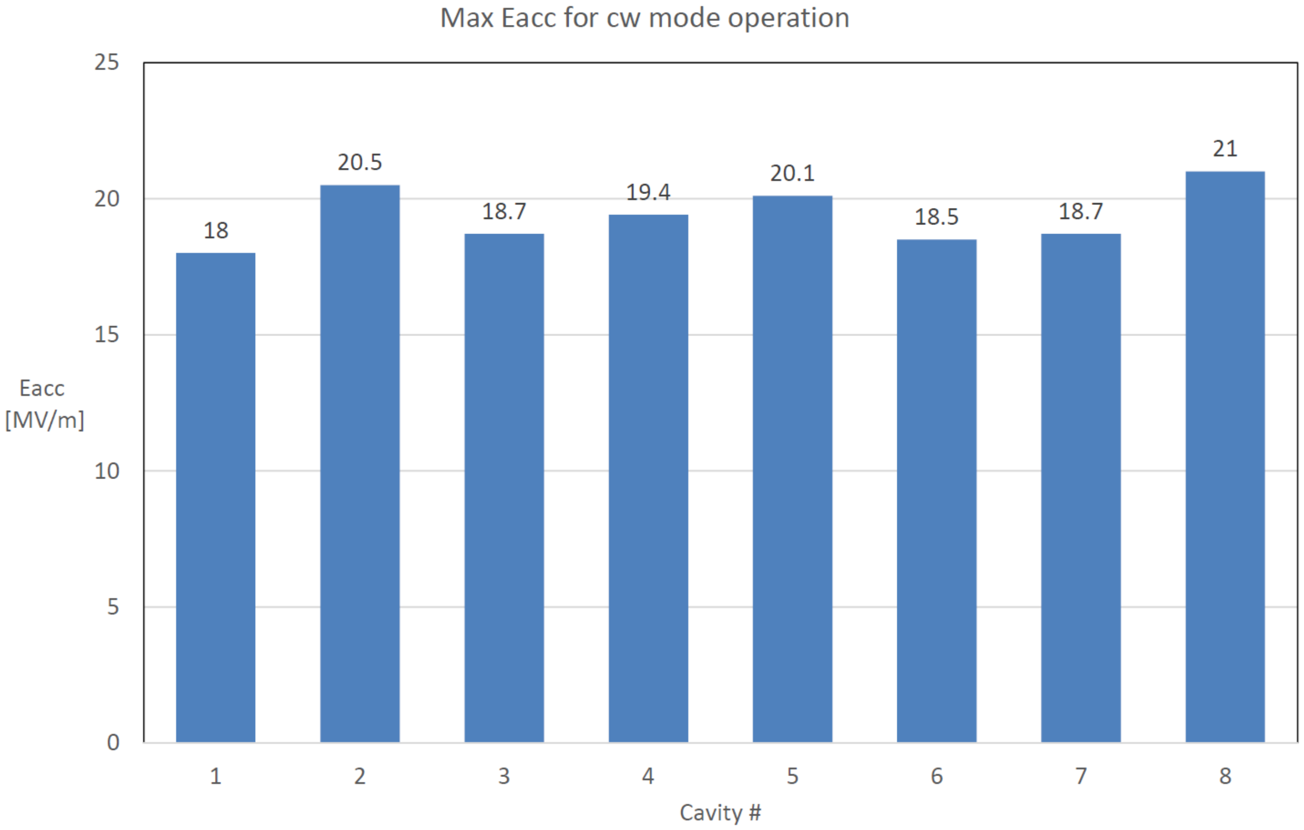
Conditions (1.8K)	Results
Q_L = 4e7 for all 8 cavities	Q_0 = 2.5e10 at 18 MV/m



Results

XM46.1 in CW

- Each cavity tested individually in CW (by detuning all others)
- All gradients above 18 MV/m
- Maximum gradient typically limited by quench

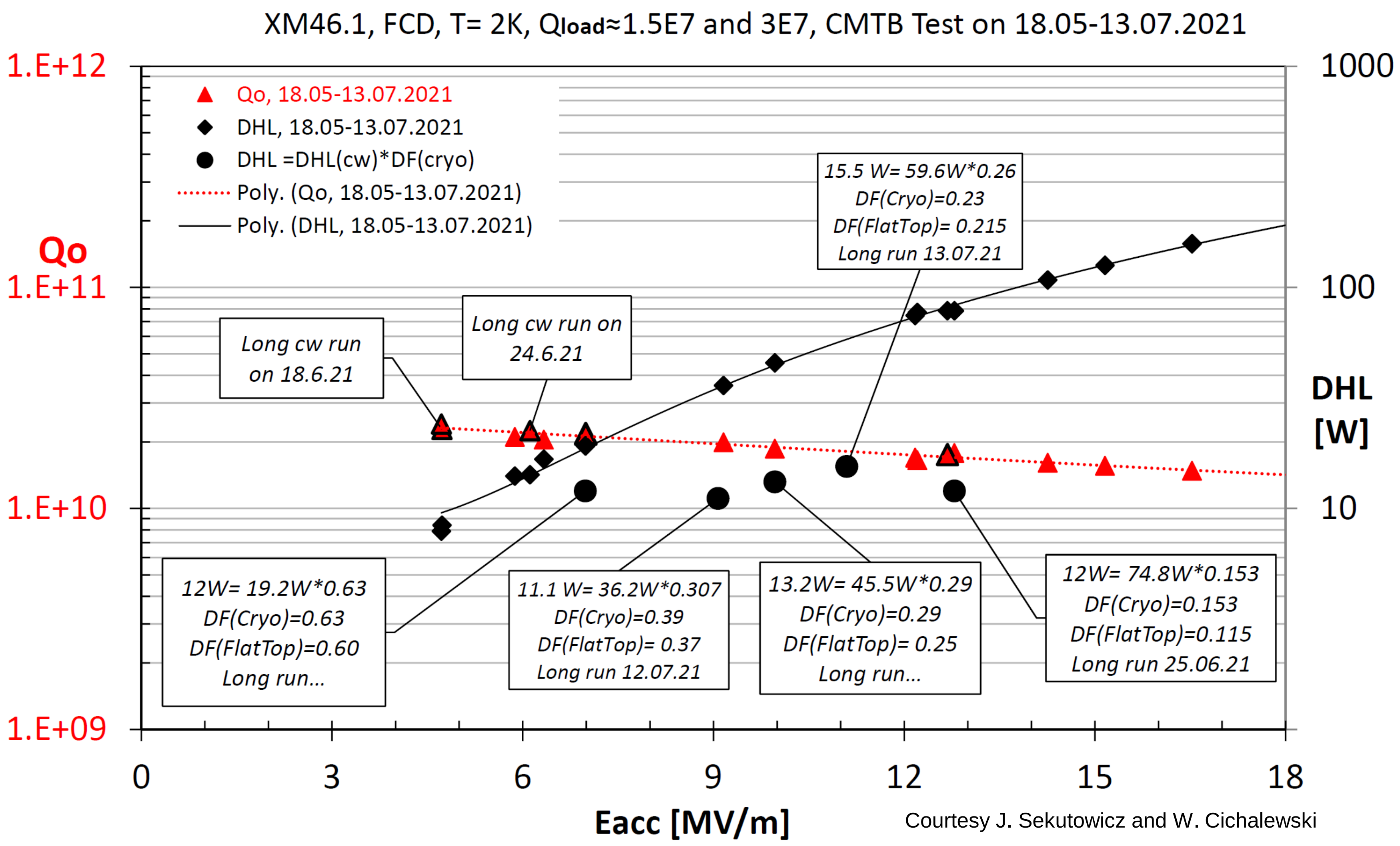


Implications for XFEL

- Such cavities meet the CW gradient requirement for the injector cryomodules (expected gradient is 17 MV/m)
- Q_0 ~ 1-2e10

Results

XM46.1 in CW and LP



Courtesy J. Sekutowicz and W. Cichalewski

Results

XM46.1 in CW and LP

- CW long run tests (5-7 hours)
- LP long run test (7 hours)

} show that there is **no heating of the end groups** of cavities

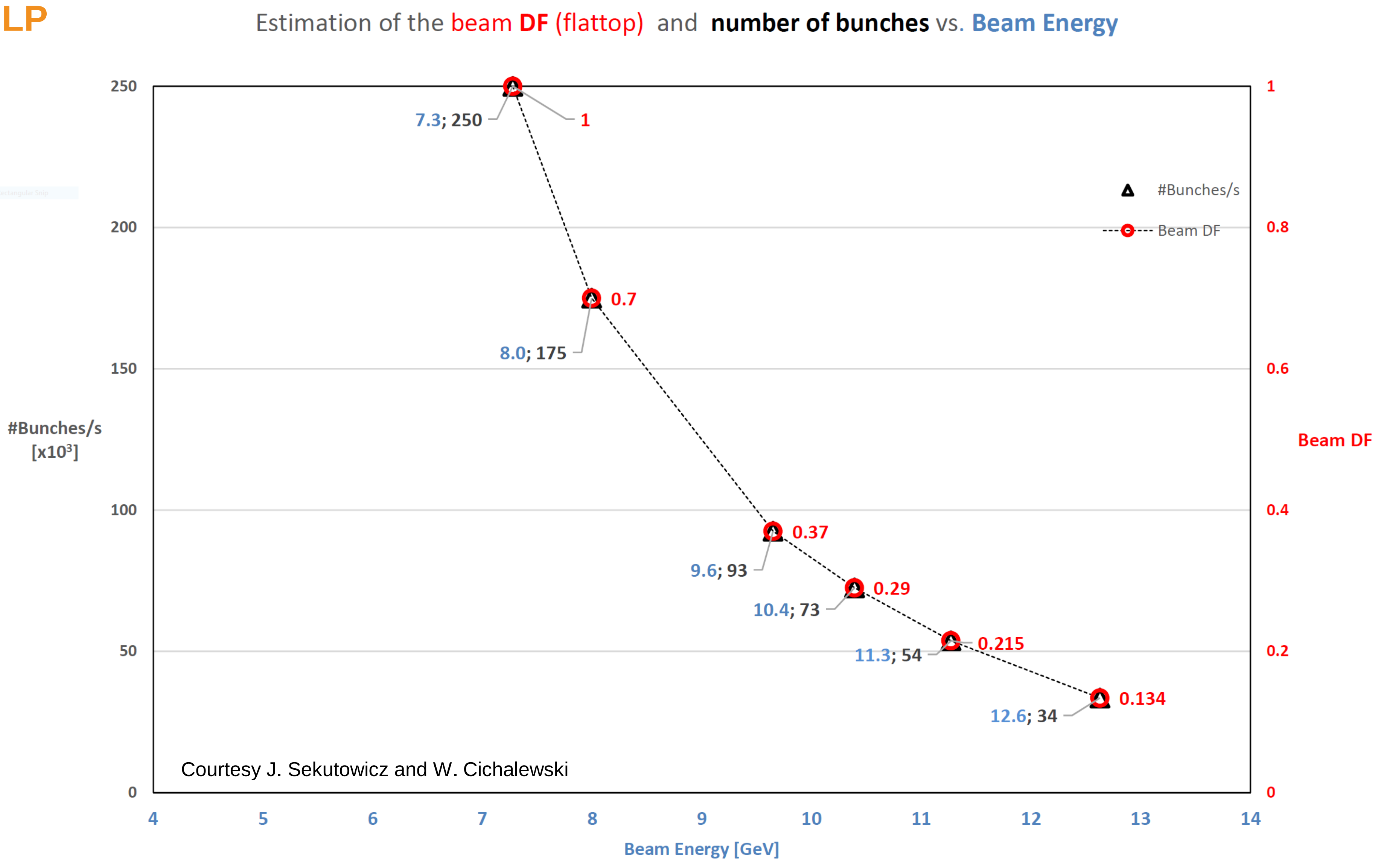
Parameter	Value
Q_L	3.1e7
Eacc	7 MV/m
Pforw / cav	350 W
ANC freq	30 Hz
DHL (CW)	19.2 W
DHL (LP)	12W
Fill time	150 msec
Flat time (“beam”)	600 msec

Implications for XFEL

- L3 can operate at **7 MV/m** with effective beam-on time of **60%**
- Assuming 100 kHz bunch rep. rate (10usec spacing) → **60 000 bunches/s**
- Total cryogenic load / CM = 6W static (assumed) + 12W dynamic = **18W** (budget = 20W)
- Assuming 24 stations in L3 and < Eacc > = 17 MV/m up to BC2 → Final beam energy close **8 GeV**
- If Q_L = 3.1e7 required power < 3.3 kW / CM (i.e. **13 kW / RF station**)
- If max Q_L = 1e7 (default range) power < 10 kW / CM (i.e. **40 kW / RF station**)

Results

XM46.1 in LP



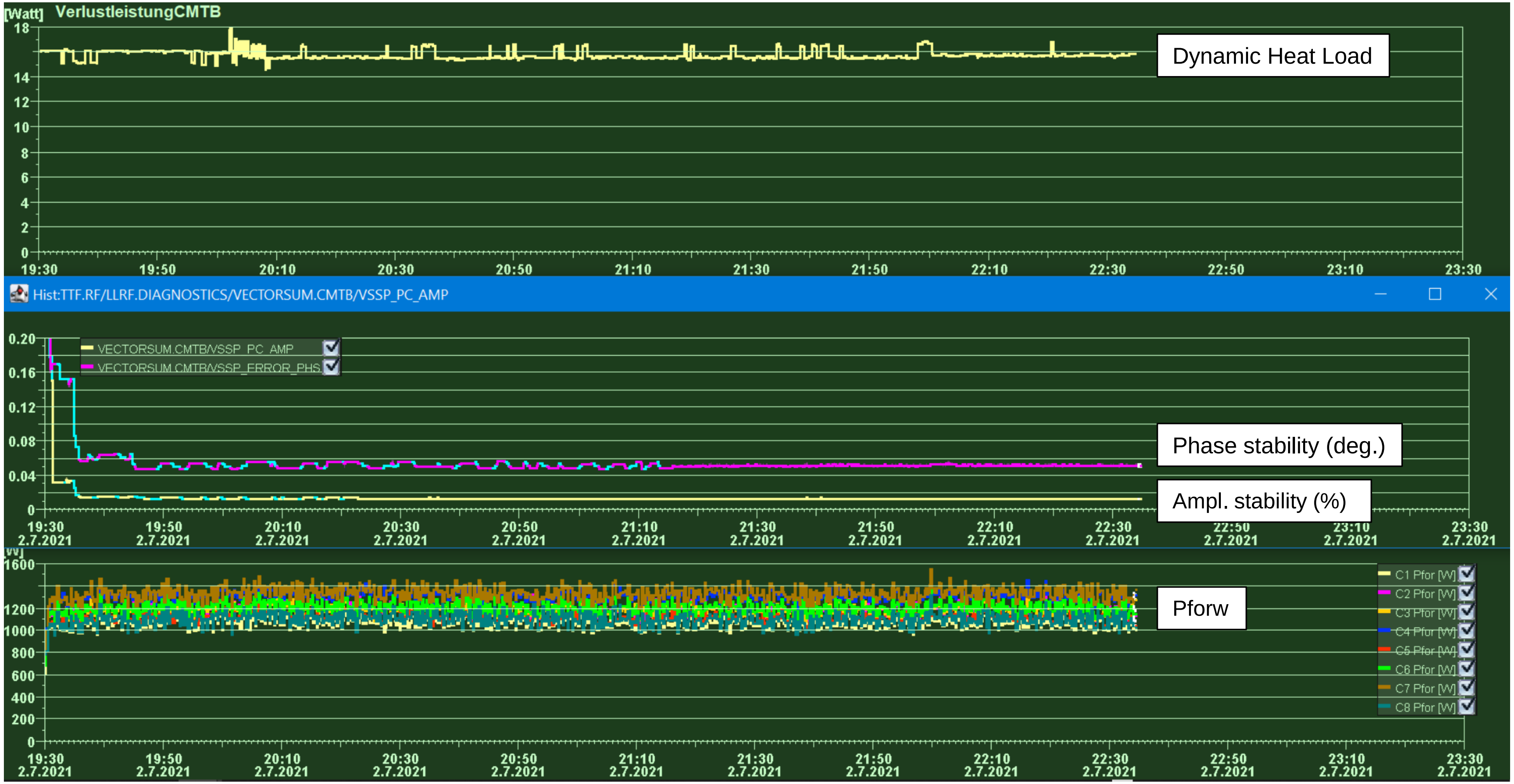
Results

XM46.1 in LP

Courtesy J. Sekutowicz and W. Cichalewski

- Eacc = 10 MV/m
- Pforw < 1.5 kW
- DHL ~ 14W
- dA/A <1e-4
- dP < 60 mdeg

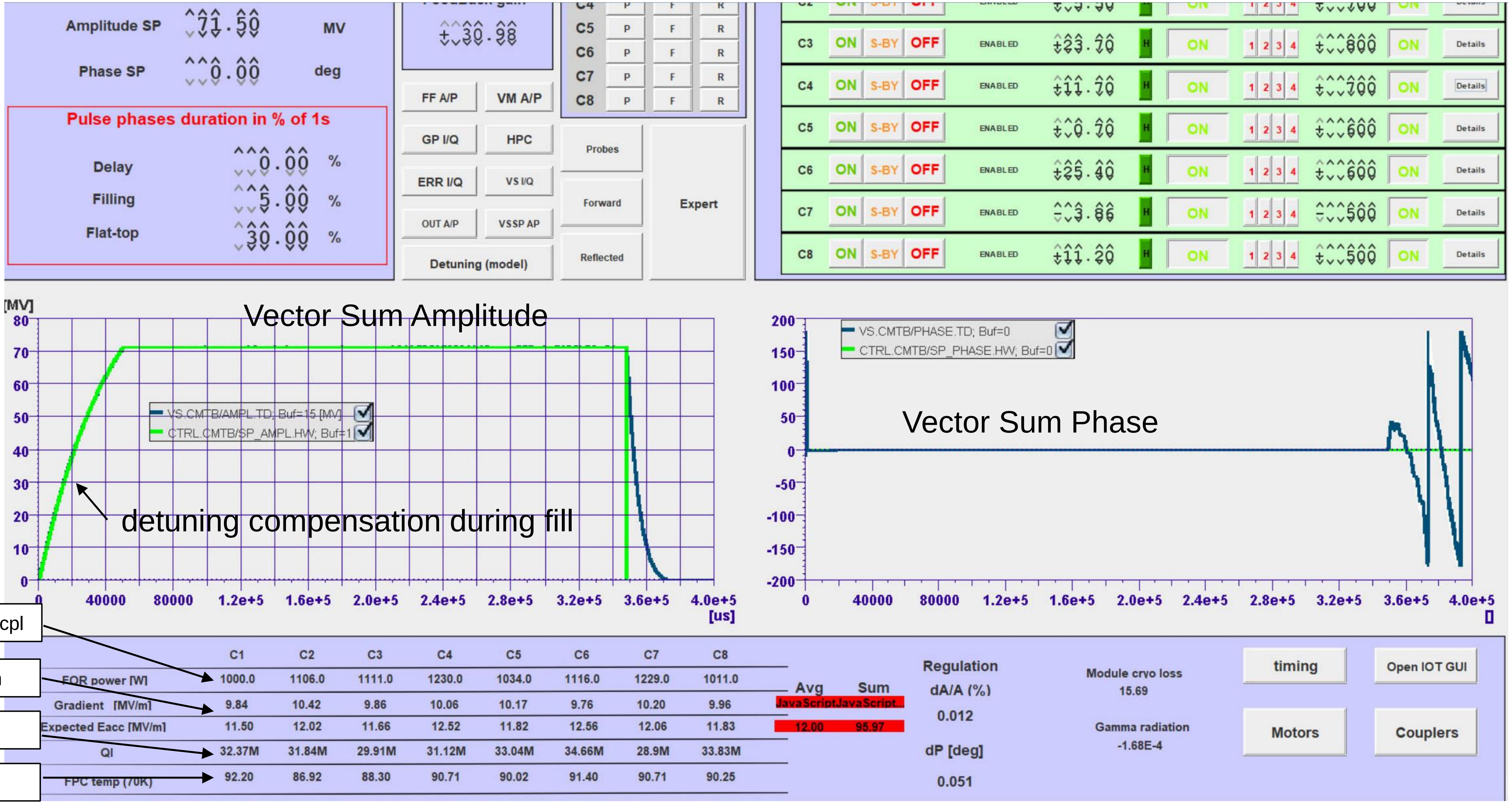
Shortening of rise time 120 msec → 50 msec using feed forward piezo tuning during fill time



Results

XM46.1 in LP

Courtesy J. Sekutowicz and W. Cichalewski



Pforw ~ 1.2 kW/cpl

Eacc ~ 10 MV/m

Q_L ~ 3e7

T_{cpl} ~ 90 K

SUMMARY and OUTLOOK

- Promising results in CW with **standard “XFEL-batch”** cavities / cryomodules
  - In terms of CW gradient
  - In terms of dynamic heat load
- Based on the recent tests, operating L3 in LP at 7 MV with another 3 RF stations
  - could yield **8 GeV** beam energy
  - still complies with the **20W / CM** DHL limitation
  - would provide **60,000 bunches / sec** (assuming 100 kHz rep. rate)
  - for a forward power (**40 kW**) largely within range of IOTs capability
- Coupler modifications were tested and could allow **to further relax the power** requirement
  - default Q_L = 1e7 → 40 kW / RF station
  - improved Q_L = 3e7 → 13 kW / RF station

SUMMARY and OUTLOOK

- The achieved field stability is **close to specifications**
  - dA/A < 1e-4
  - dP < 60 mdeg
  - Note: uncorrelated noise source scale down with $\sqrt{N}$ (N = number of RF stations)

- The Long Pulse option opens a very **large spectrum of operation** modes
  - Keeping the DHL constant, one can increase the gradient while scaling down the duty factor
  - → verified experimentally

- Diverse **R&D activities** in terms of control techniques are being developed and tested
  - Promising results (RF source linearization, microphonics mitigation, advanced RF and detuning controllers)
  - **OUTLOOK : putting it all together !**

Thank you

Many thanks to all colleagues who have contributed to these results and in particular to **Andrea Bellandi**, **Wojtech Cichalewski** and **Jacek Sekutowicz** for the discussions and all the material shown in this presentation.

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