Innovate for Sustainable Accelerating Systems
WP2: Low Level RF Controls

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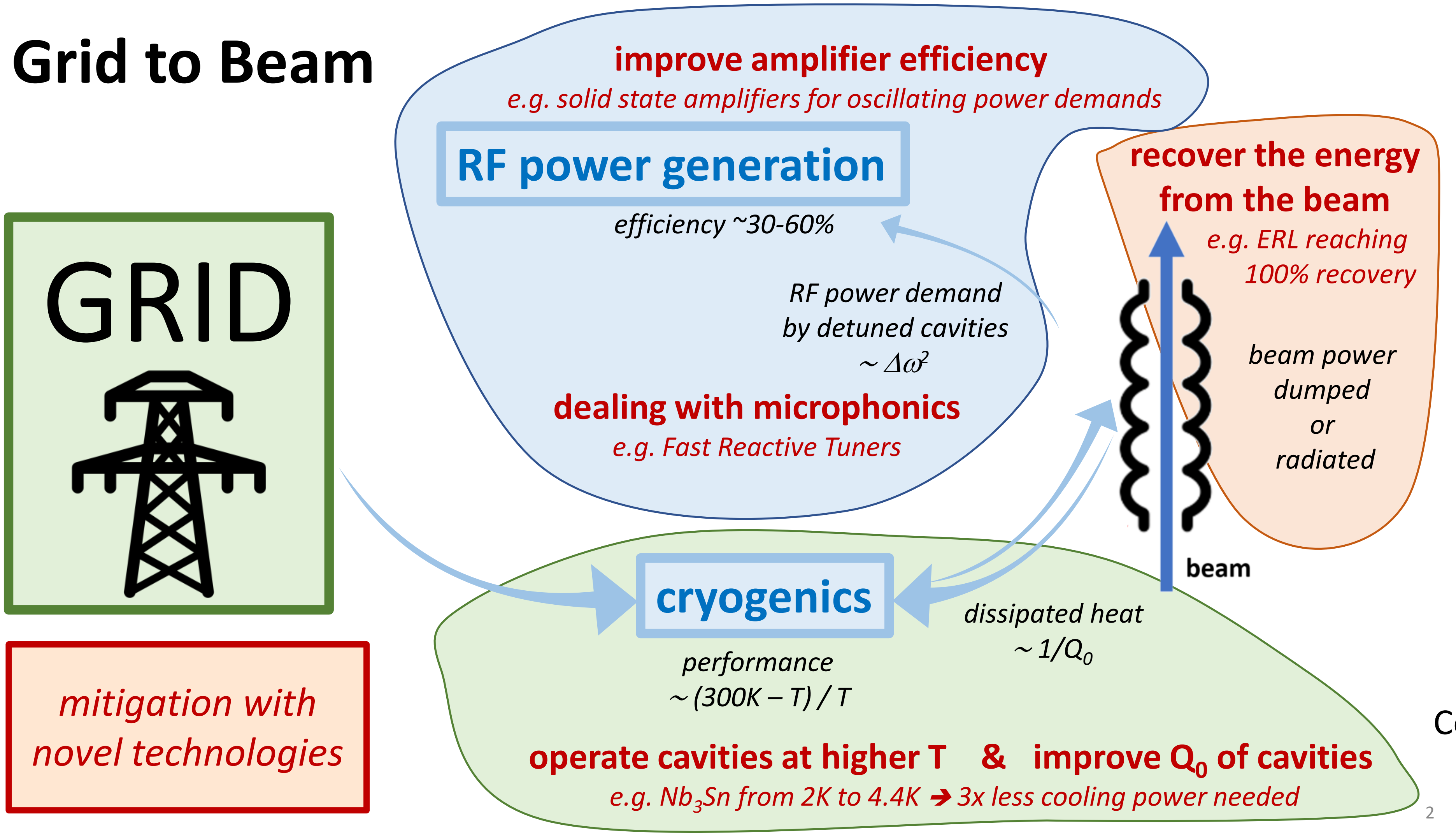
15. April 2024

WP2: Low Level RF controls
Introduction

From Grid to Beam

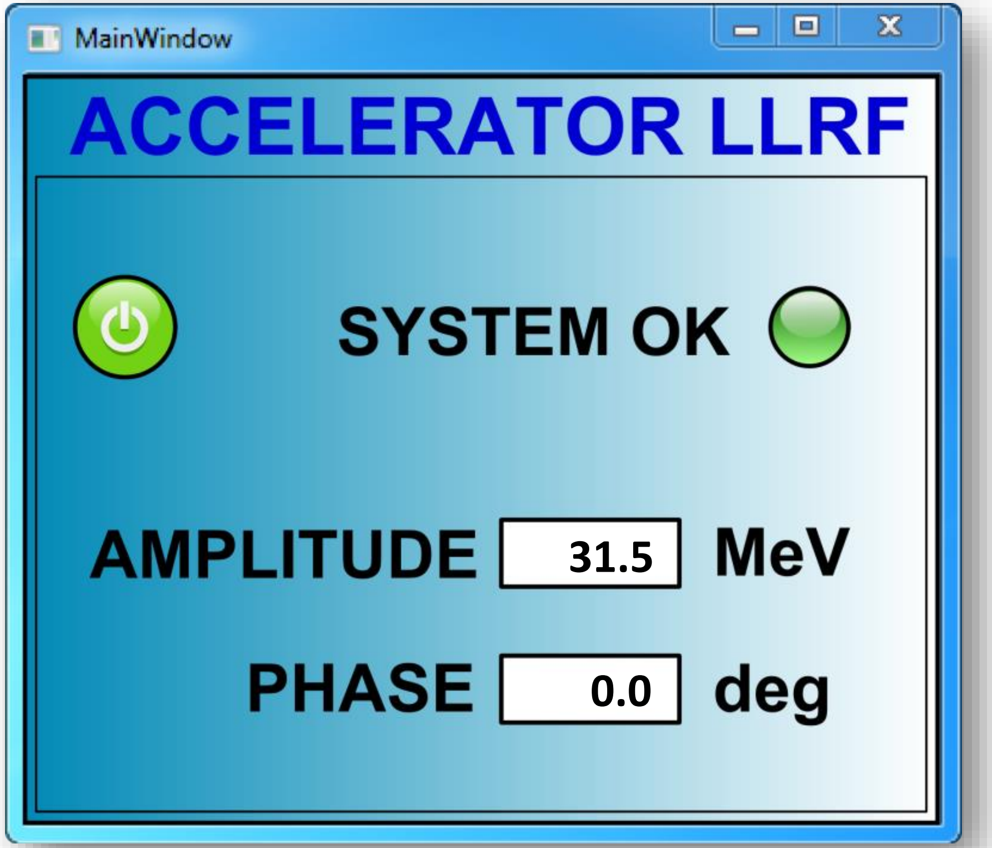


Courtesy: J. D'Hondt

WP2: Low Level RF controls

Introduction

Ideally what we would like to have:



Advanced automation

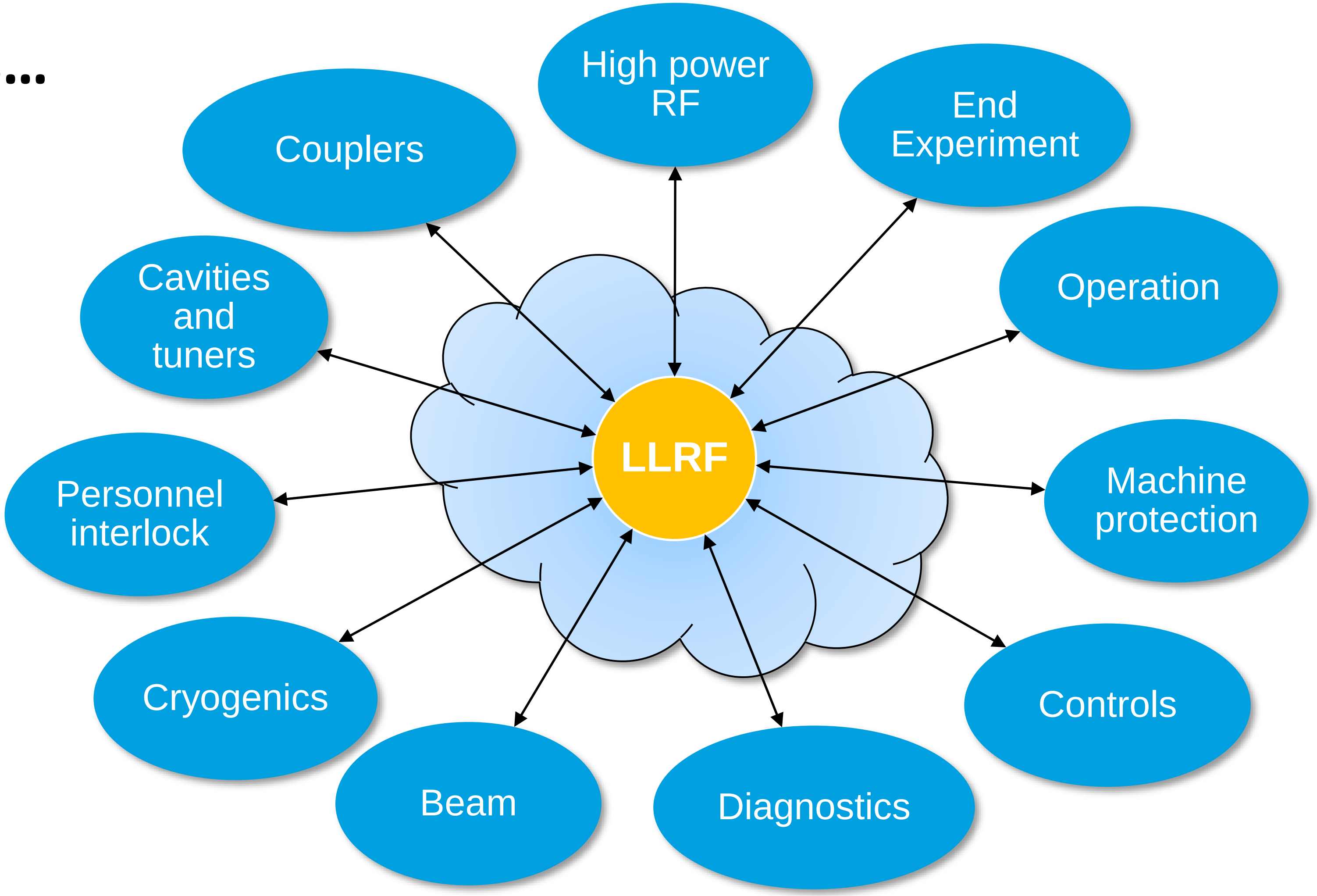
And meets:

- Ampl. & Phase stability
- Operates reliably
- Is maintainable & upgradable
- Adopts parameter changes e.g. $I_b(t)$
- Compensates environmental changes
- Identifies faults in the system
- **Minimizes DC power consumption!**

WP2: Low Level RF controls

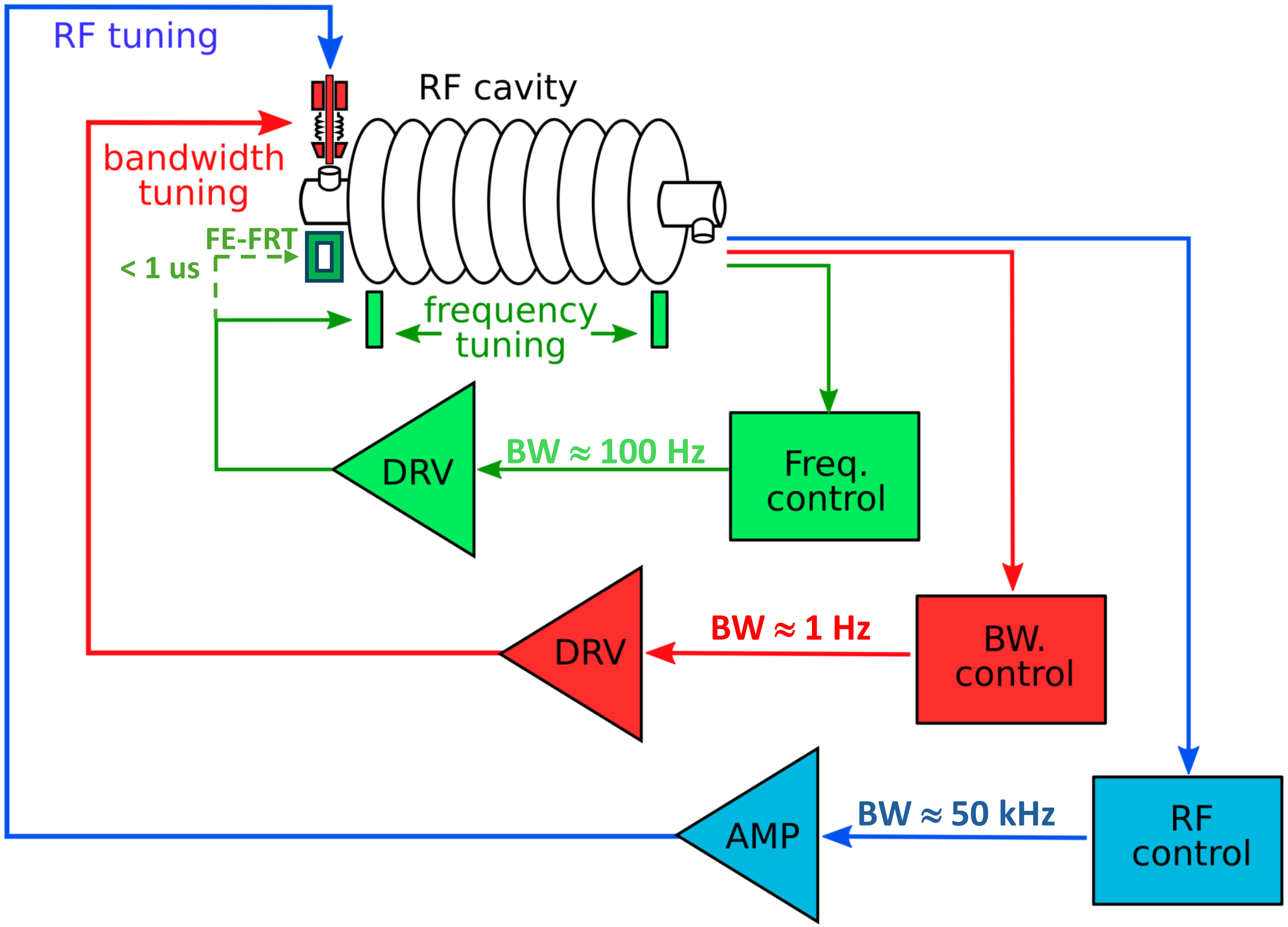
Introduction

Many interfaces…



WP2: Low Level RF controls
Introduction

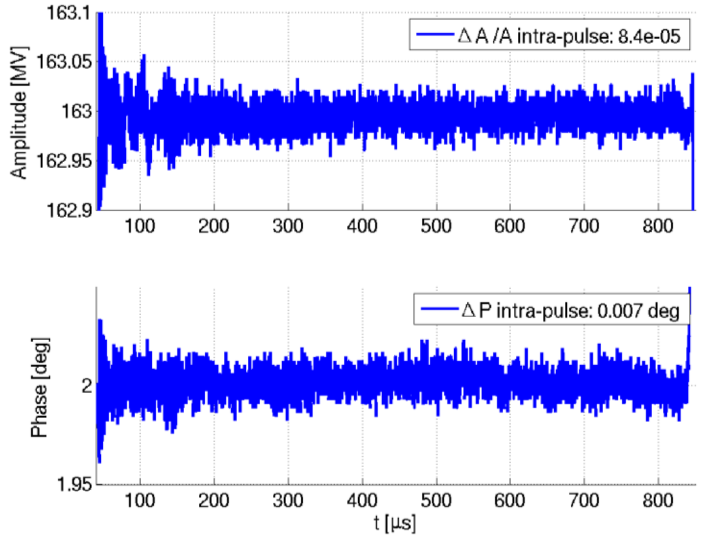
LLRF control tasks:



WP2: Low Level RF controls

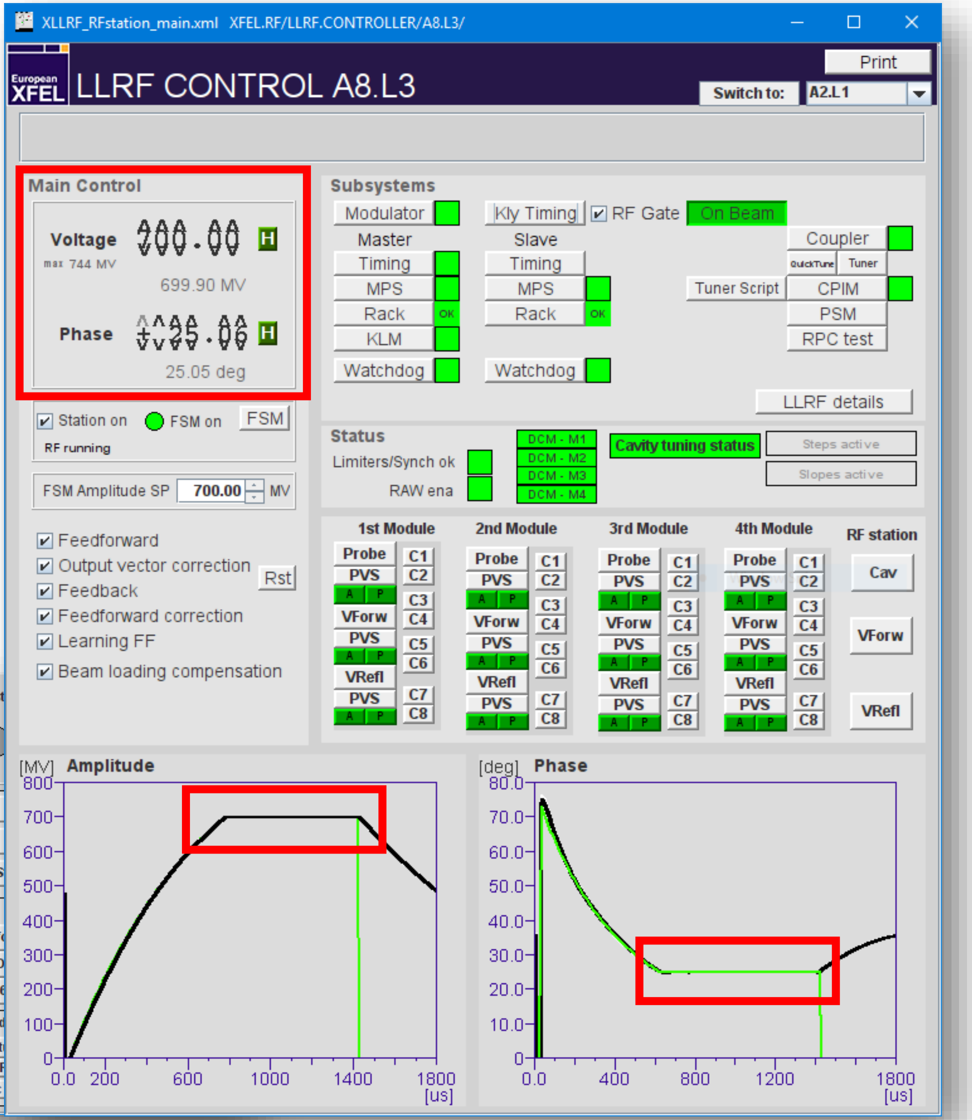
Introduction

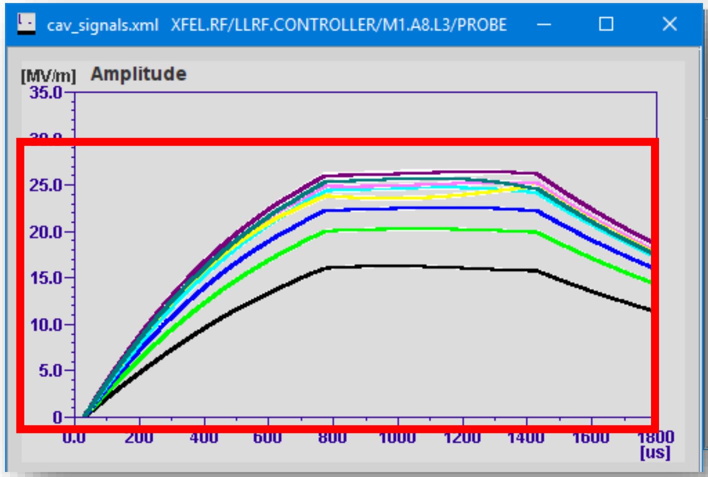
High stability!

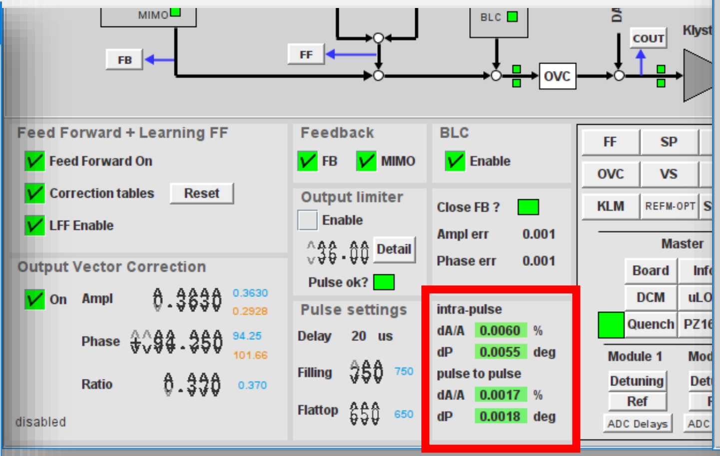


Amplitude
$< 10^{-4}$

Phase
$< 0.01°$



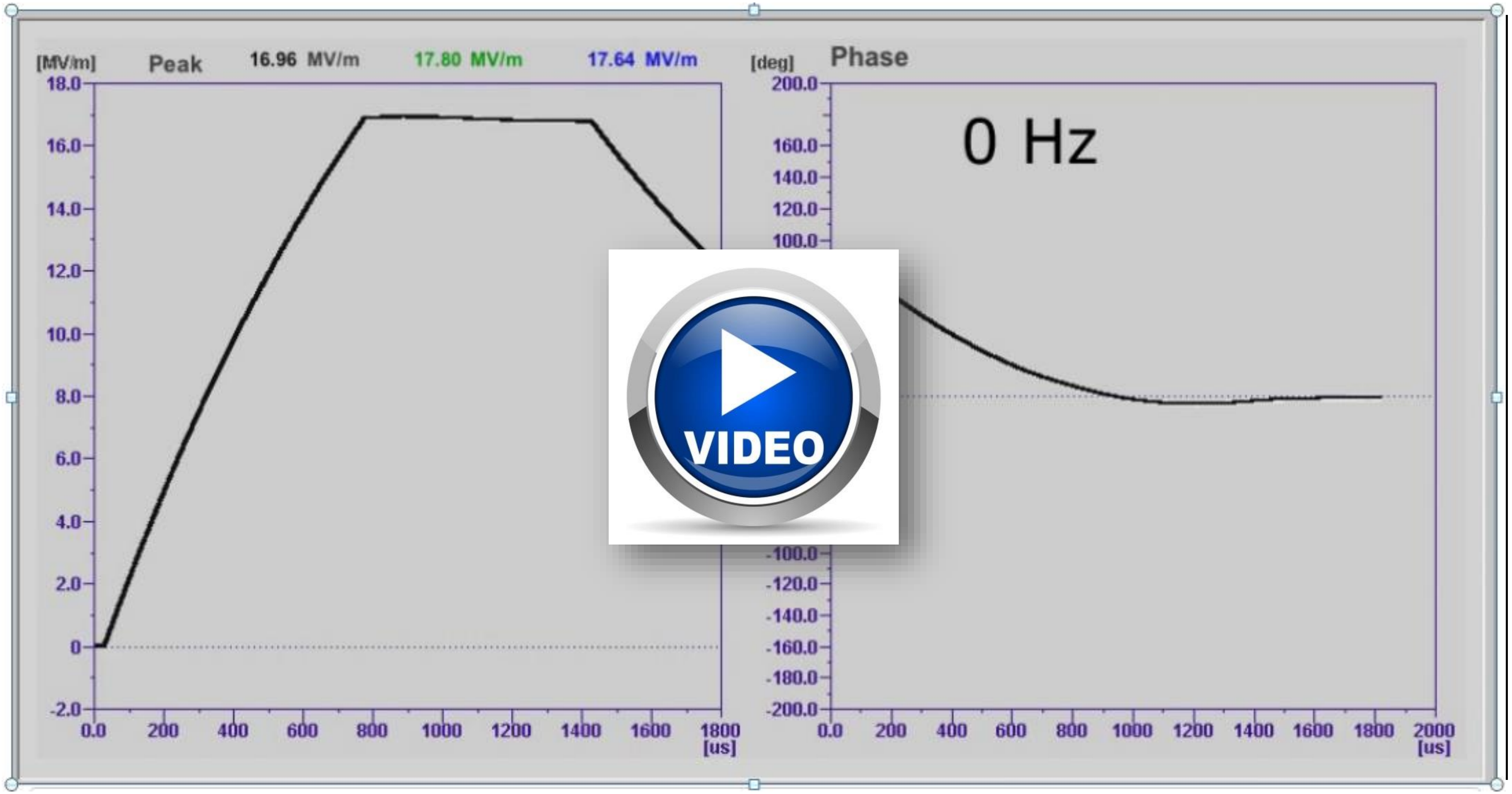




Courtesy: J. Branlard

Introduction

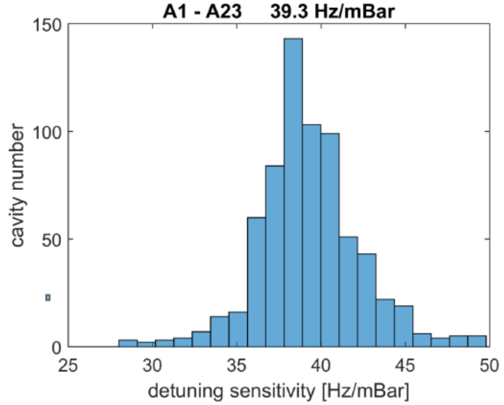
Impact of cavity tuning…



Courtesy: J. Branlard

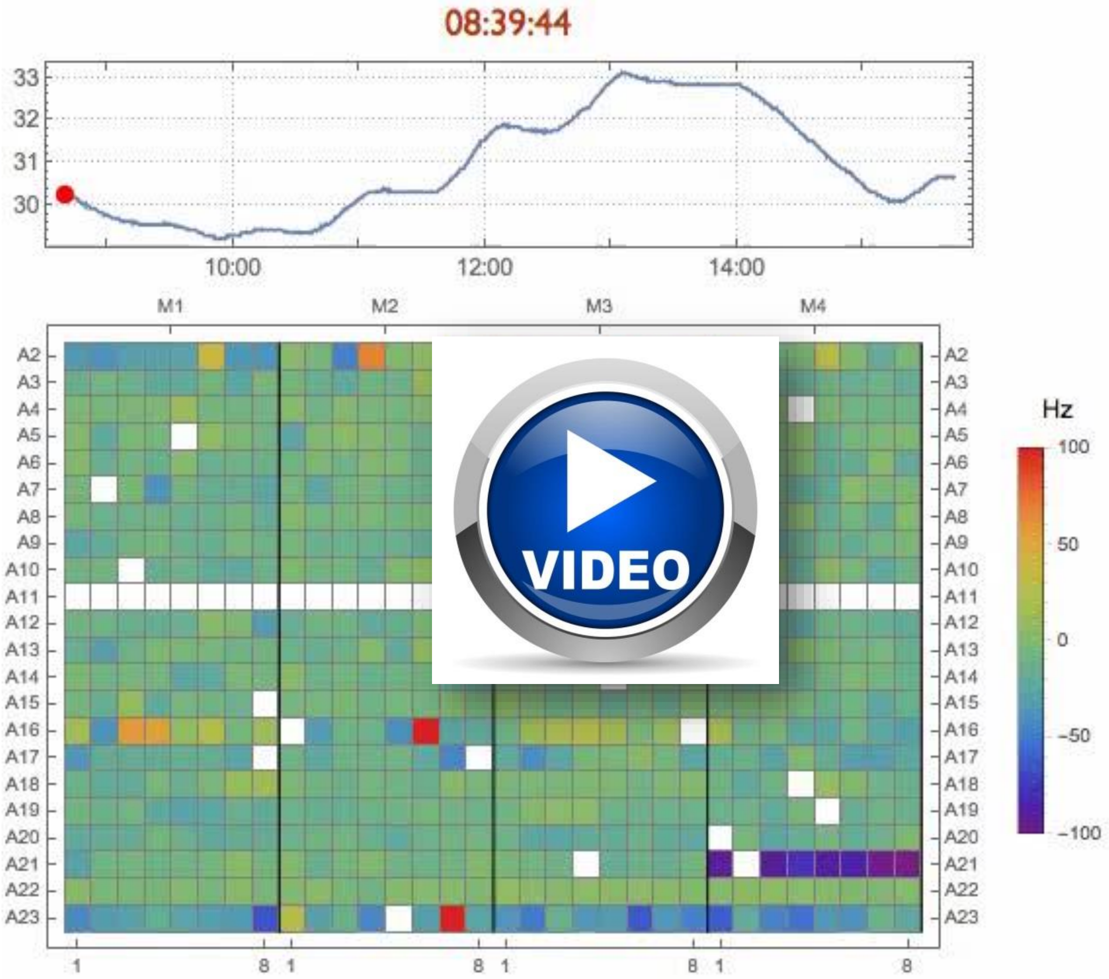
Introduction

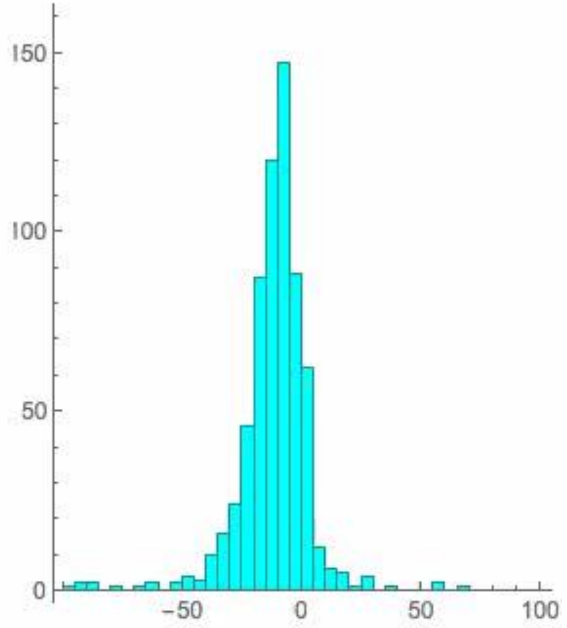
Impact of cryogenic …



40 Hz/mBar for
1.3 GHz cavities

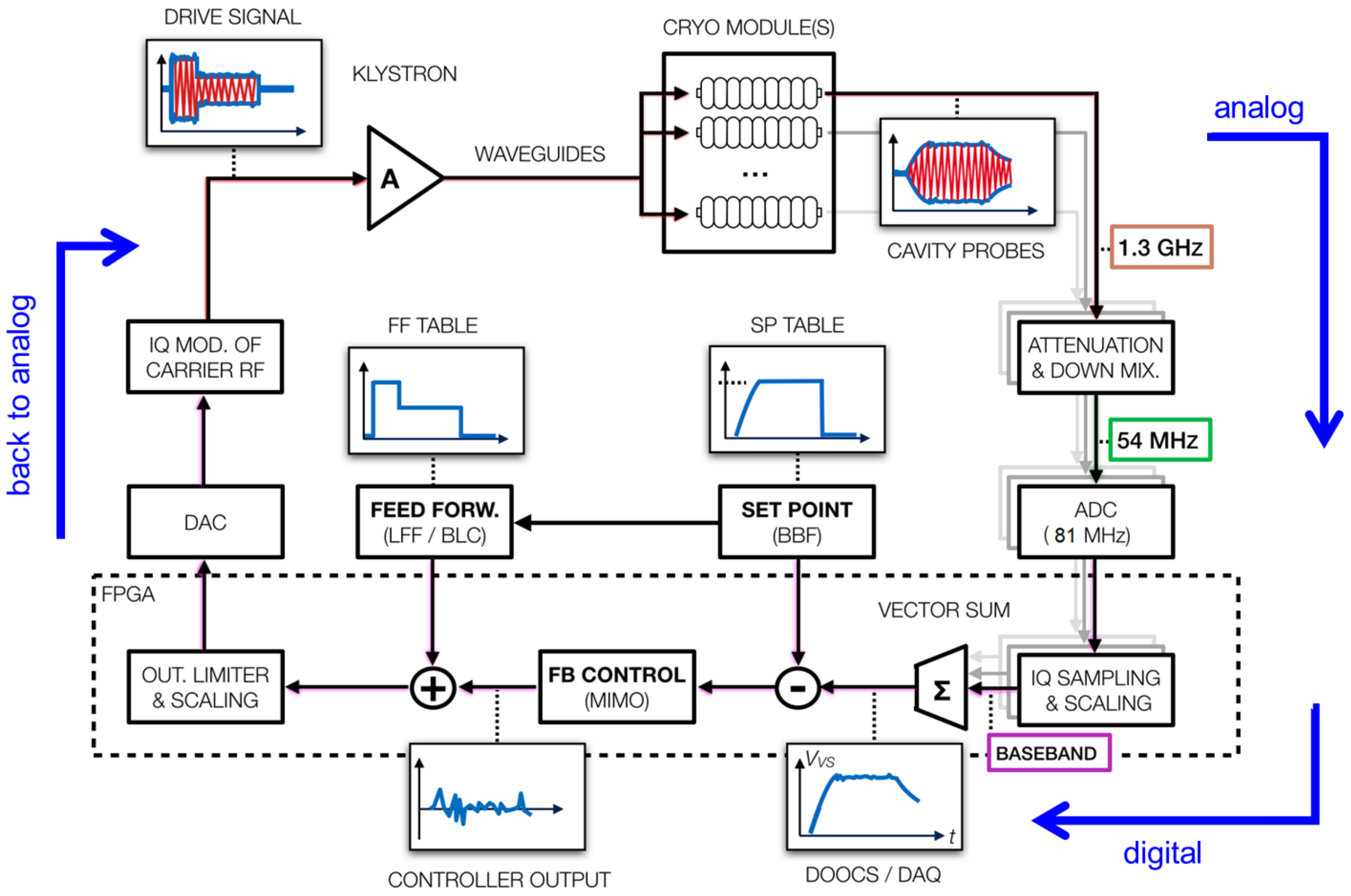
62 Hz/mBar for
3.9 GHz cavities





WP2: Low Level RF controls
Introduction

Regulation loop EuXFEL

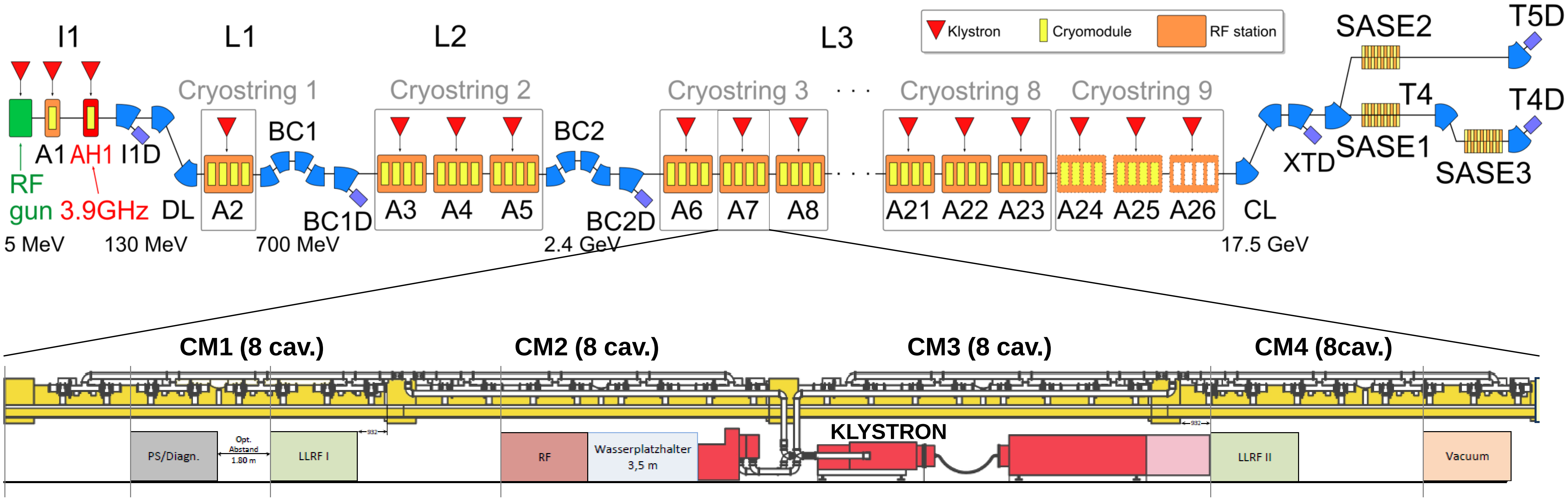


Courtesy. T. Hellert

WP2: Low Level RF controls

Introduction

The European XFEL Accelerator : one RF station



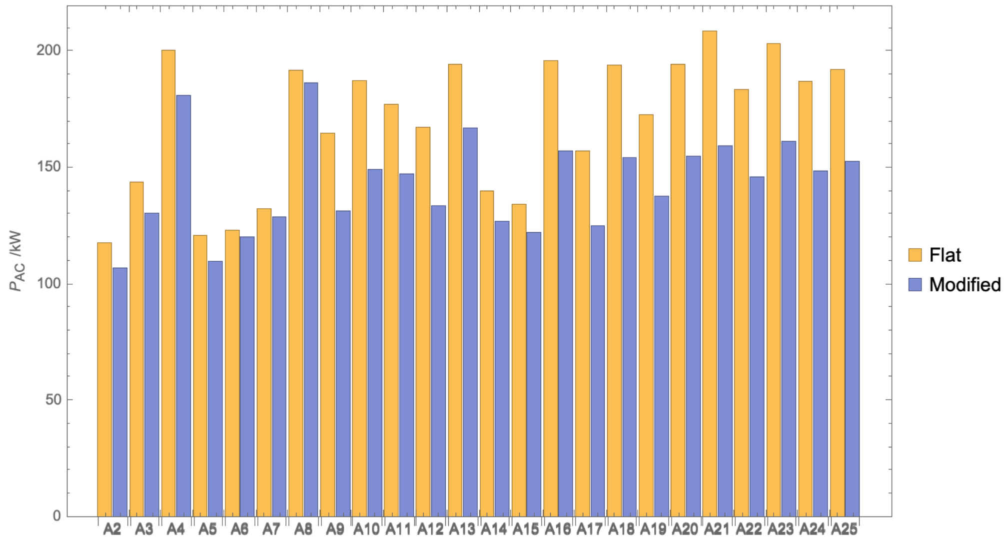
- 10 MW klystron to power 32 cavities
- one accelerating field RF control FB loop
- remote frequency tuning (motor / piezo) / cavity
- remote phase and external coupling tuning / cavity

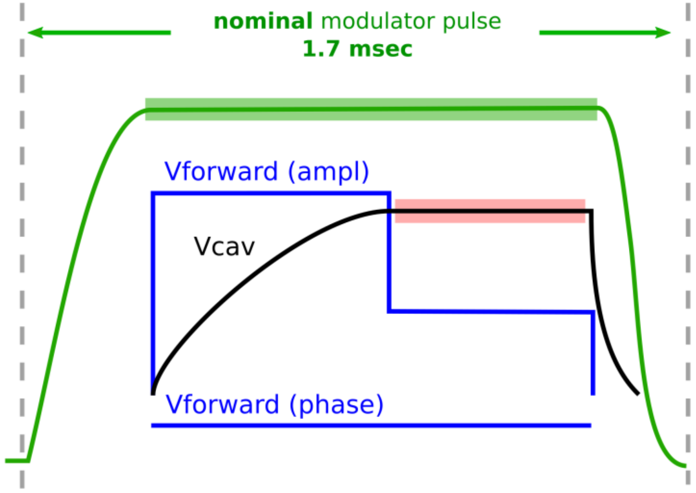
- average coupler peak power 102 kW (140 kW) for low (high) runs
- average gradient 18.5 MV/m (22.5 MV/m) for low (high) runs
- average detuning +/- 10 Hz
- average Q_{ext} = 4.6e6 average Q_0 = 1e10

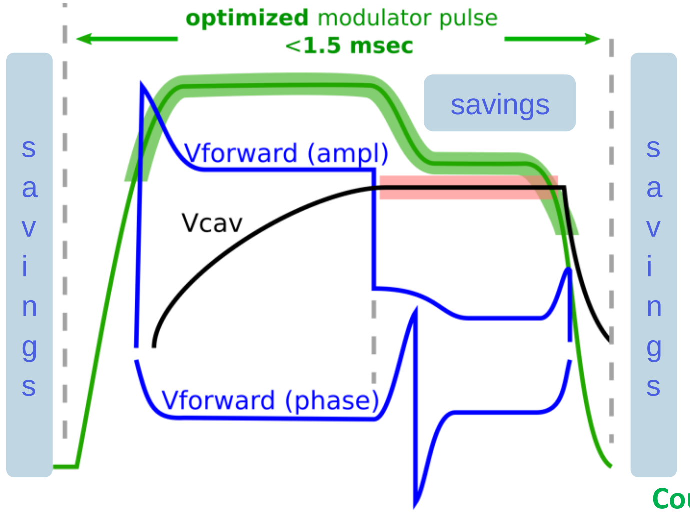
WP2: Low Level RF controls
Reduce energy consumption @ EuXFEL

Successive iterations, implemented over the last 2+ years

- **Shorten** modulator pulse : 1700 msec → 1500 msec
- **Step down** 15-20% over 100 usec
- Implemented on **17/20** stations in L3
- Estimated additional power savings **~ 650 kW** (out of 5 MW total power)







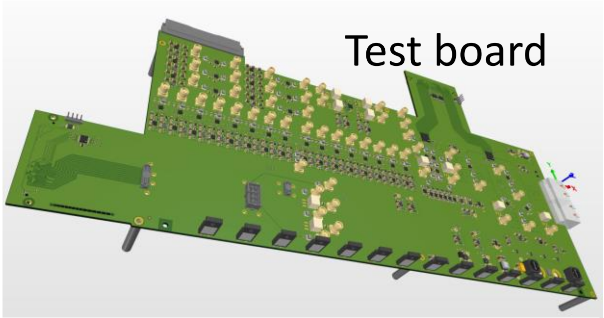
Courtesy: J. Branlard

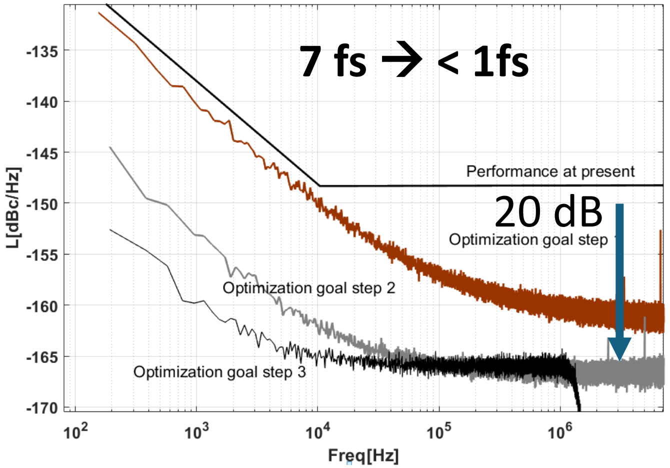
WP2: Low Level RF controls
Introduction

Field detector development …

- ➔ Higher performance
- ➔ Better diagnostics
- ➔ Lower latency

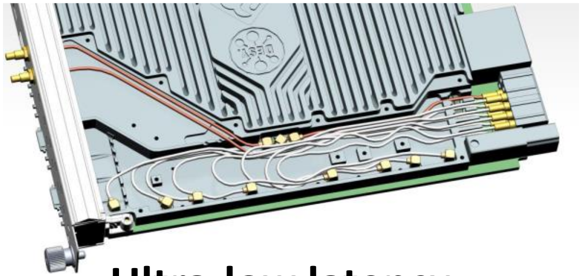
1) LN-ADC (~ 2025 as AMC)





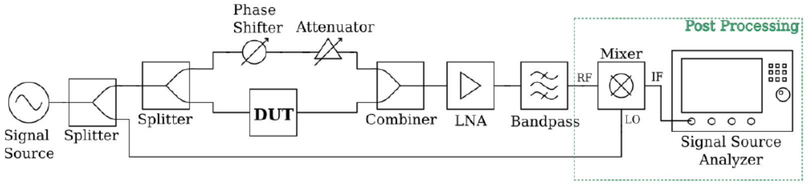
2) RFSoC (~ 2026 as AMC)

Gen3
5 GSPS

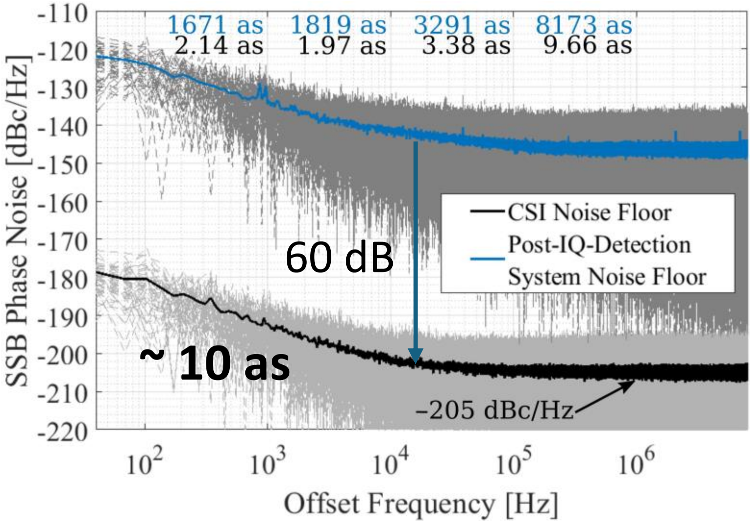


Ultra-low latency
Rapid prototyping

3) Carrier Suppression Interferometer



Ultra LN-noise RF-MO essential



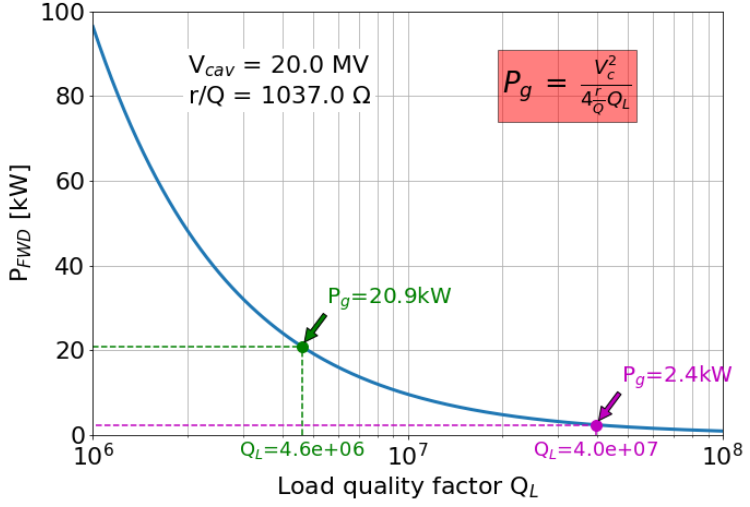
Ref.: S. Springer *et al.*, doi: 10.1109/TIM.2022.3170975

iSAS motivation & challenges
WP2

WP2: Low Level RF controls

Introduction

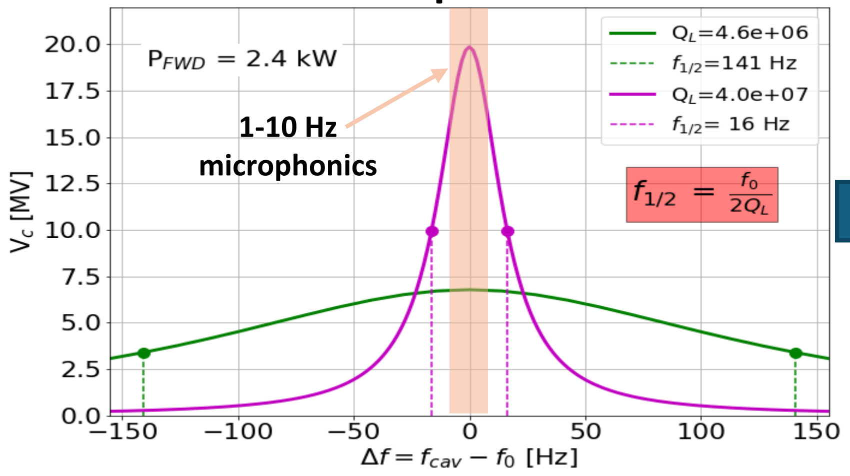
Impact of Q_L



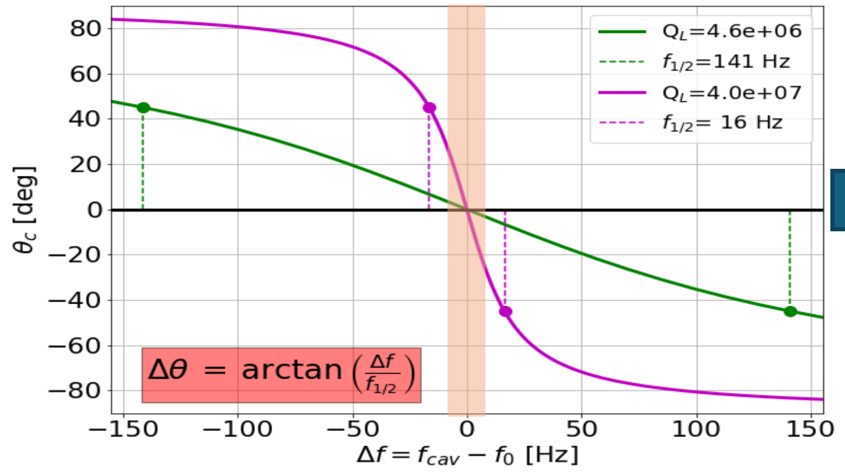
WP2.2:
Optimizing & tuning Q_L

WP2.3:
Microphonics control

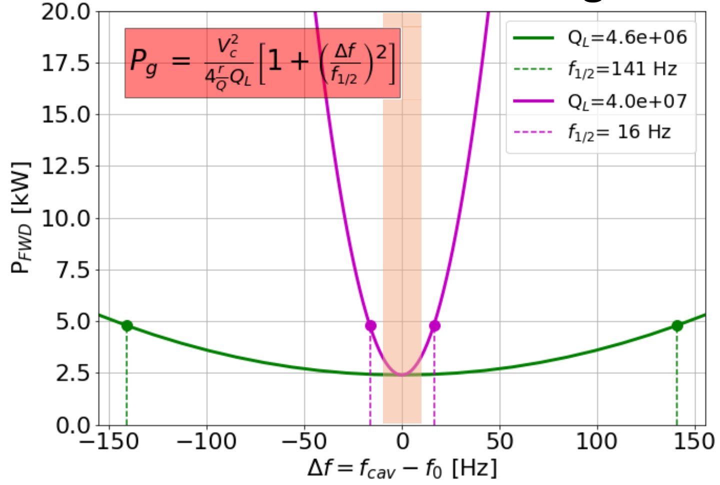
Amplitude



Phase



Power vs detuning



Cav. Tuner ~ 300 kHz/mm

1 nm ➔ 1 deg phase change

Excellent strain meters!

EuXFEL $\delta\theta_p < 0.01$ deg

➔ Equivalent to 10 pm

➔ RF feedback overhead

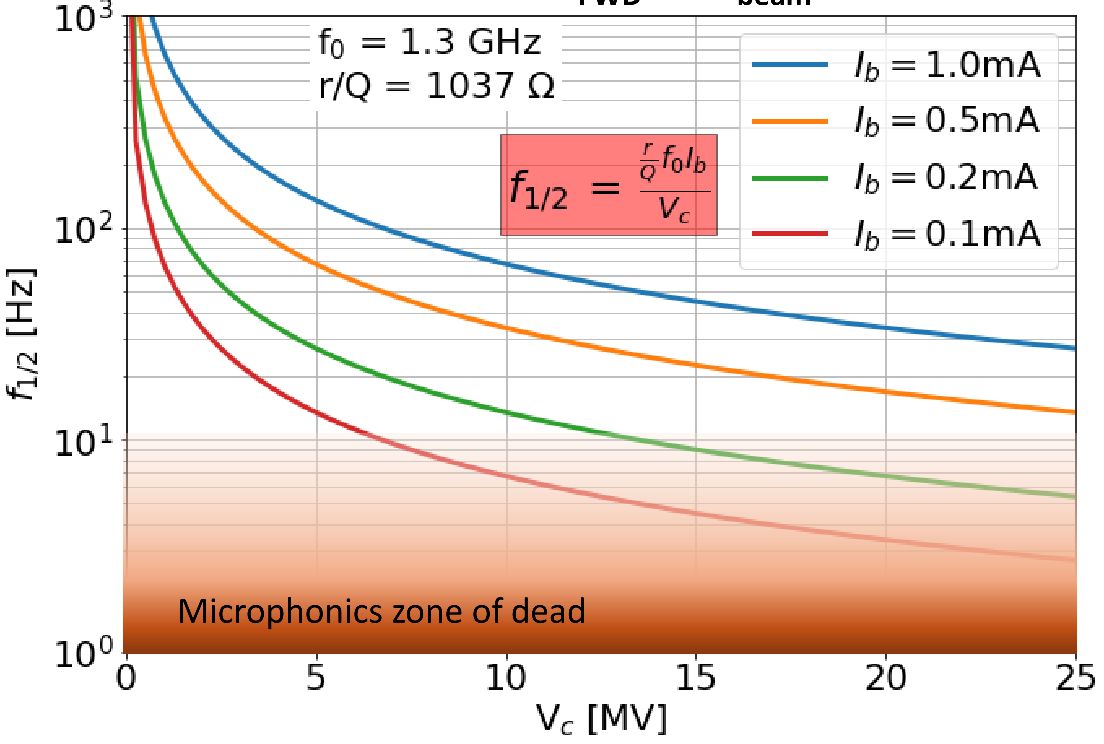
WP2: Low Level RF controls

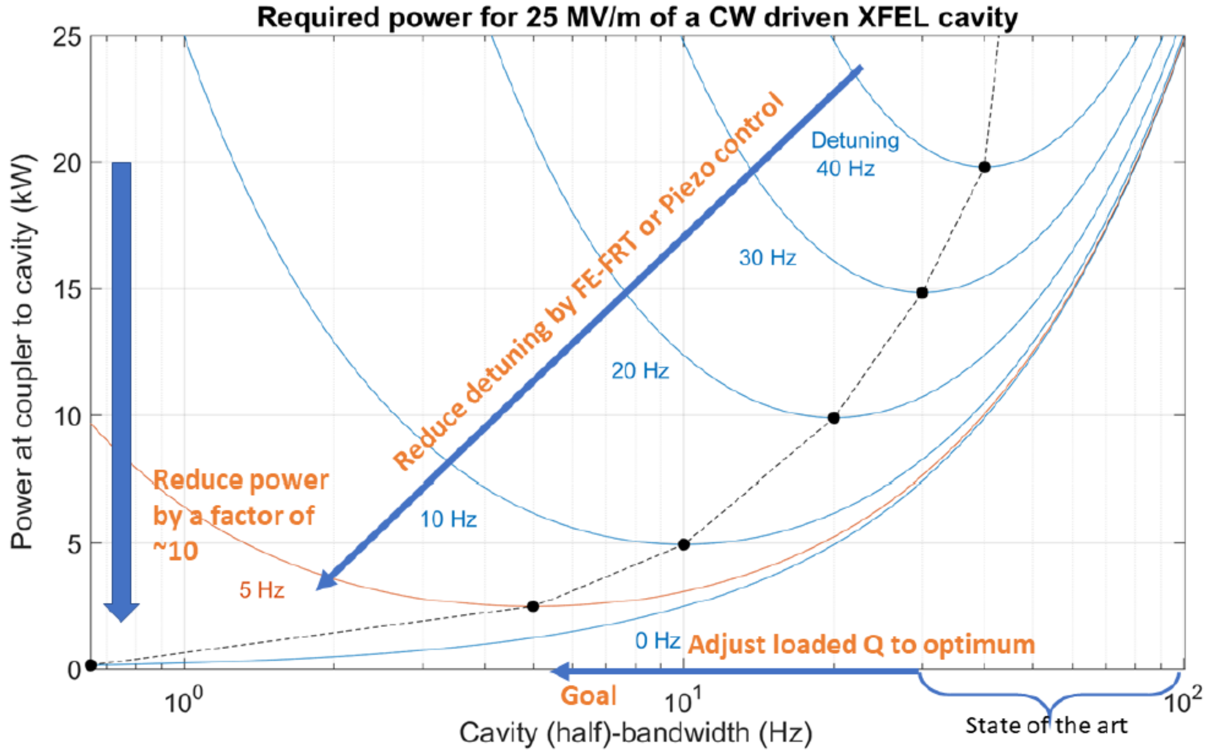
Introduction

Q_L range of interests:

$$P_g = \frac{V_c^2}{4\frac{r}{Q}Q_L}\left[\left(1+\frac{\frac{r}{Q}Q_L I_b}{V_c}\right)^2 + \left(\frac{\Delta f}{f_{1/2}}\right)^2\right] \Rightarrow Q_{L,opt} = \frac{V_c}{\frac{r}{Q}I_b}$$

100% Eff. P_{FWD} → P_{beam}





WP2: Low Level RF controls

Introduction

Q_L low

Lorentz force detuning…

Cavity equation:

$$\dot{V}_I = \omega_{1/2}\left[-V_I + yV_Q + V_{g,I}\right]$$
$$\dot{V}_Q = \omega_{1/2}\left[-V_Q - yV_I + V_{g,Q}\right]$$

Detuning:

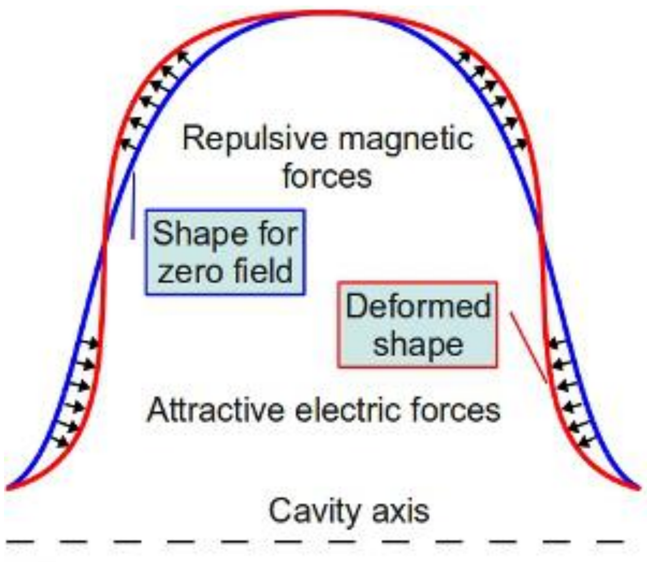
$$\Delta\omega = \omega_{1/2}y$$

Non-linear coupling:

$$y = y_\star + K_{lfd}V_{acc}^2$$

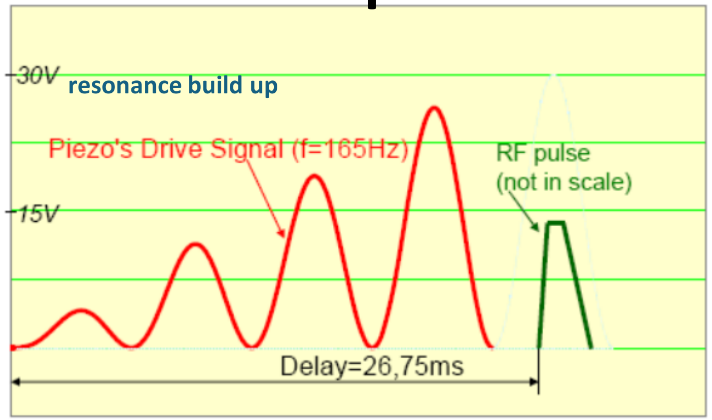
$k_{lfd} \approx -1\ Hz/(MV/m)^2$

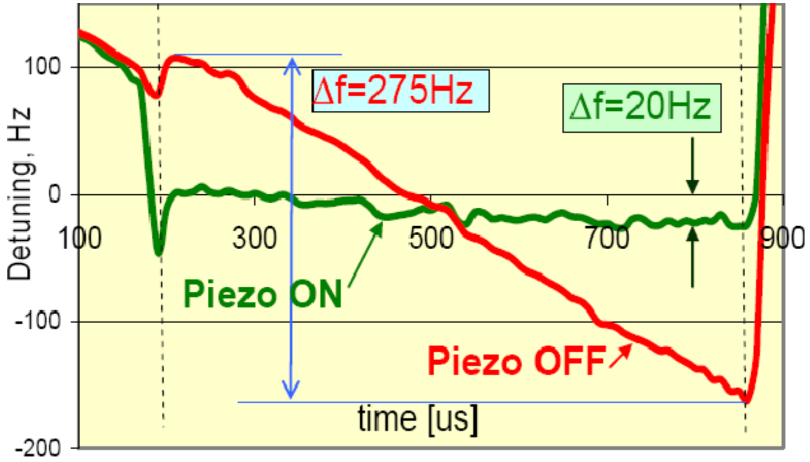
20 MV/m ➔ 400 Hz huge!!!



$$P_s = \frac{1}{4}\left(\mu|\vec{H}|^2 - \varepsilon_0|\vec{E}|^2\right)$$
$$\Delta f_0 = (f_0)_2 - (f_0)_1 = -K\,E_{acc}^2$$

Pulsed Operation





Example from FNAL 2007
R. Carcagno *et al. SRF 2007*

WP2: Low Level RF controls

Introduction

Lorentz force detuning…

Cavity equation:

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Detuning:

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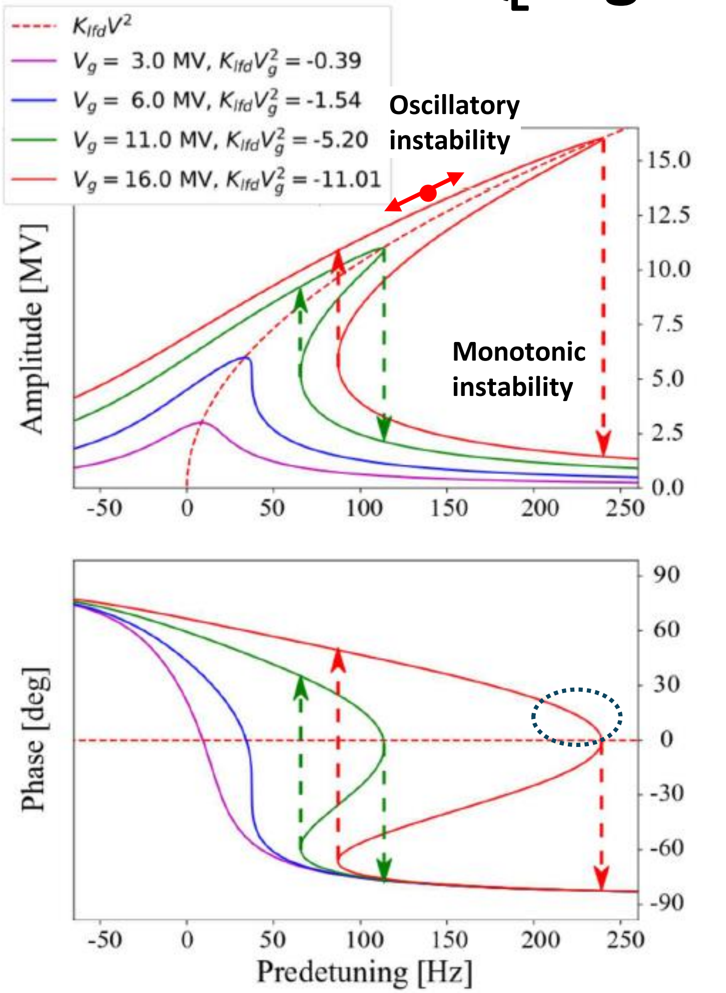
Non-linear coupling:

$$y = y_\star + K_{lfd} V_{acc}^2$$

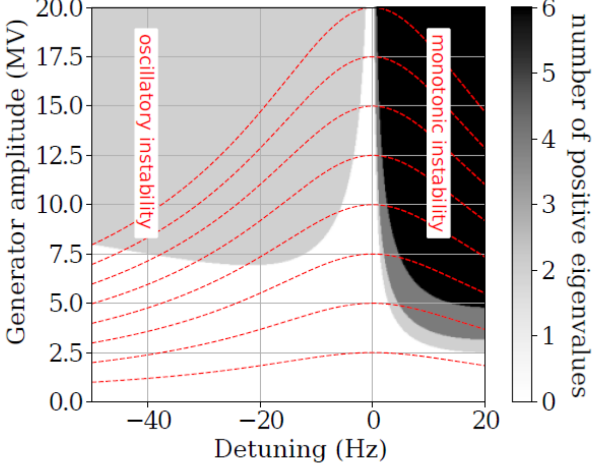
$k_{lfd} \approx -1$ Hz/(MV/m)^2

20 MV/m ➔ 400 Hz huge!!!

Q_L high & CW



Ponderomotive inst. map



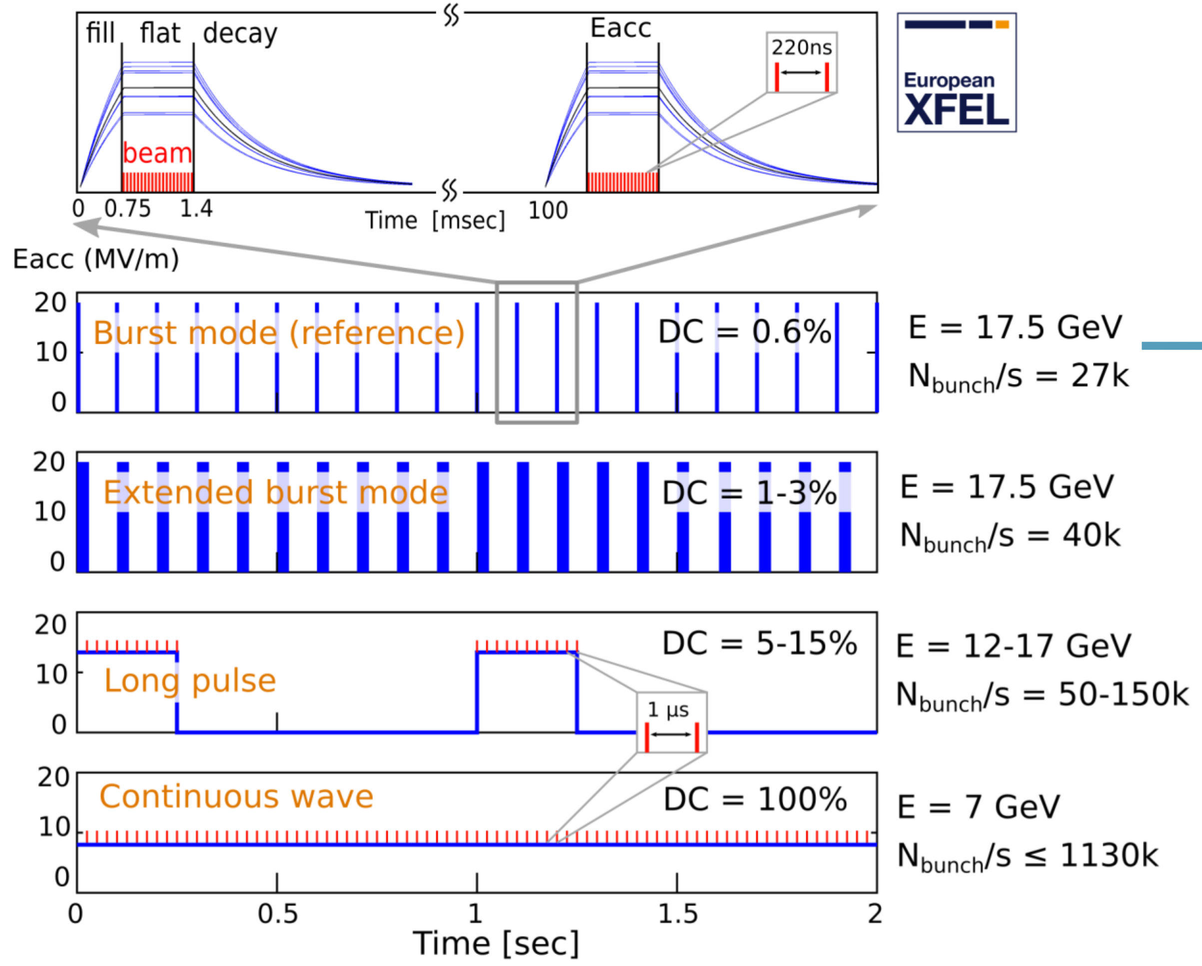
Tricky to operated at high gradient:

- Often SEL → GDR for ramping up used
- Non-linear phase change w.r.t detuning
- Operation only with RF-FB on
- LP … careful piezo FF needed
- Mechanical osc. → interrupts operation
- May exhibit cav – cav. cross-talk

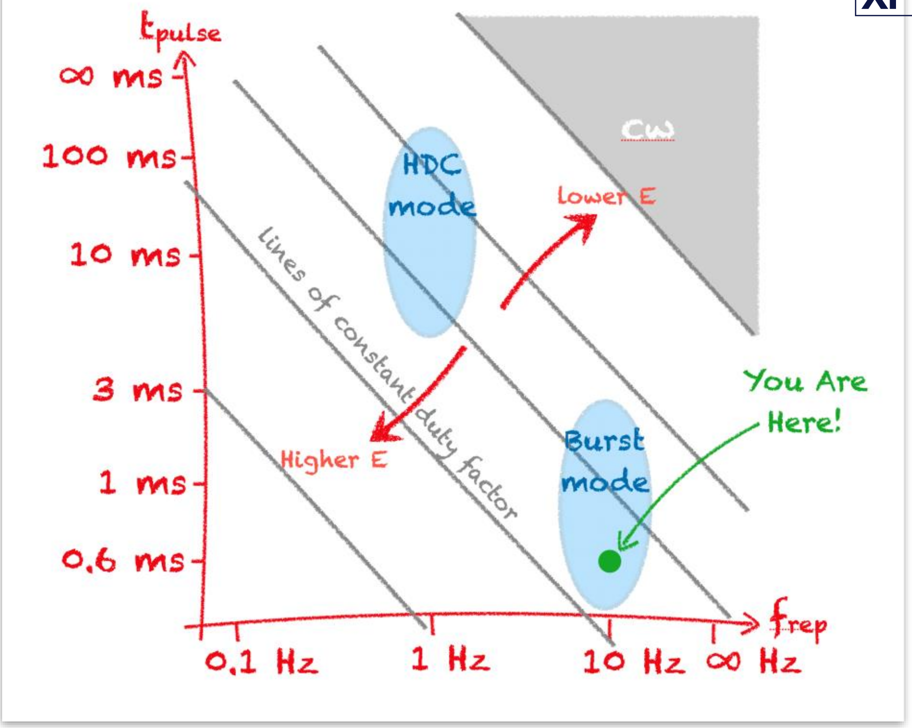
High Duty-Cycle Program @EuXFEL

WP2: Low Level RF controls

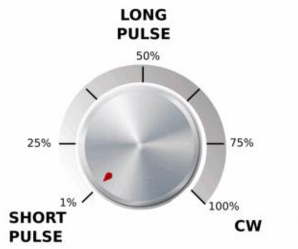
EuXFEL High Duty-Cycle program

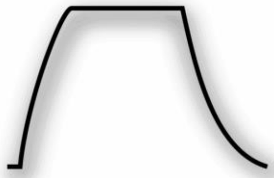


TODAY



High Duty Cycle (HDC)





Courtesy: J. Branlard

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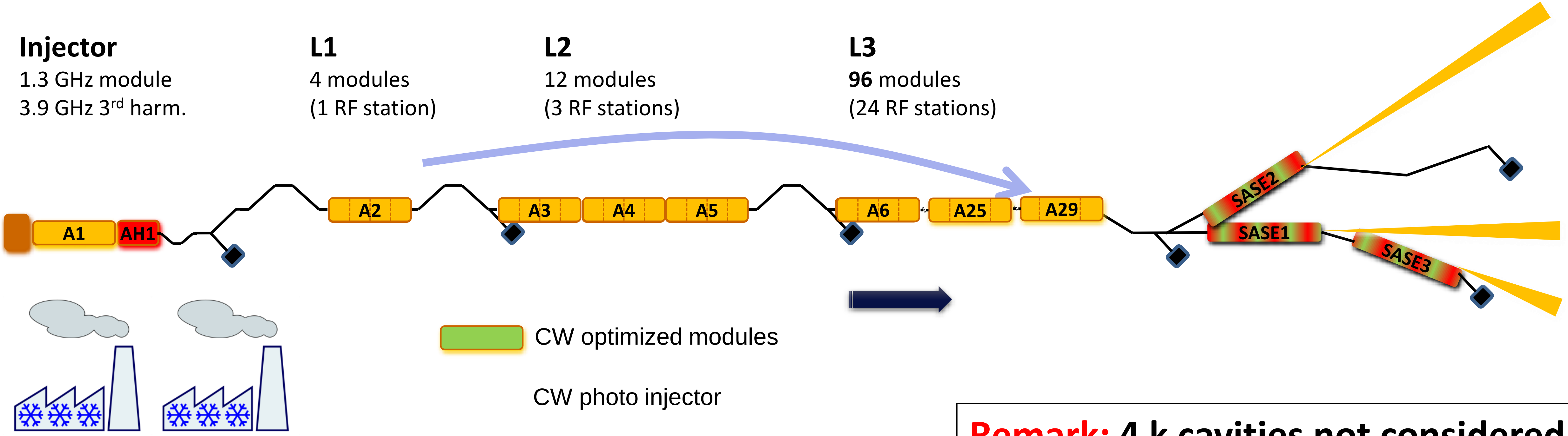
EuXFEL High Duty-Cycle program

Original CW upgrade proposal (canonical upgrade)



CW optimized modules

CW photo injector

CW 3.9-GHz system

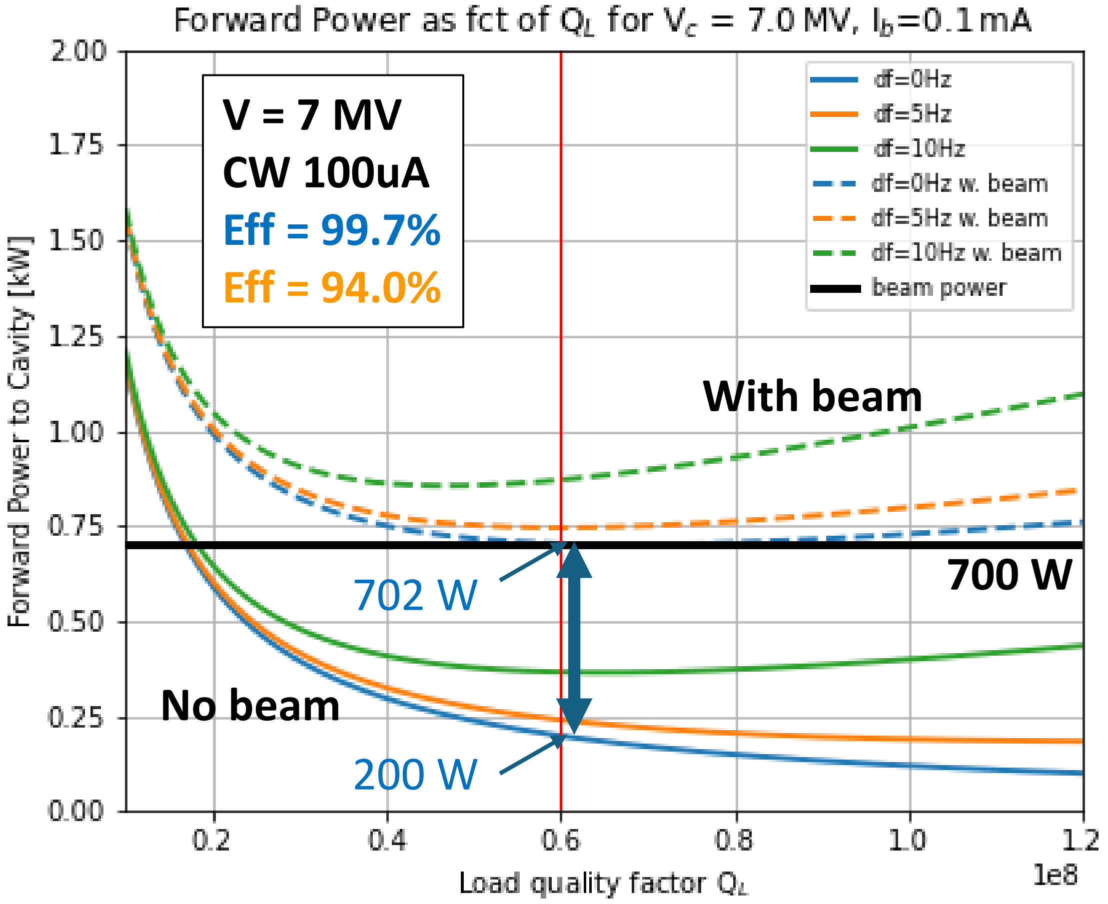
2nd cryo plant (2.5 kW ➔ 5 kW)

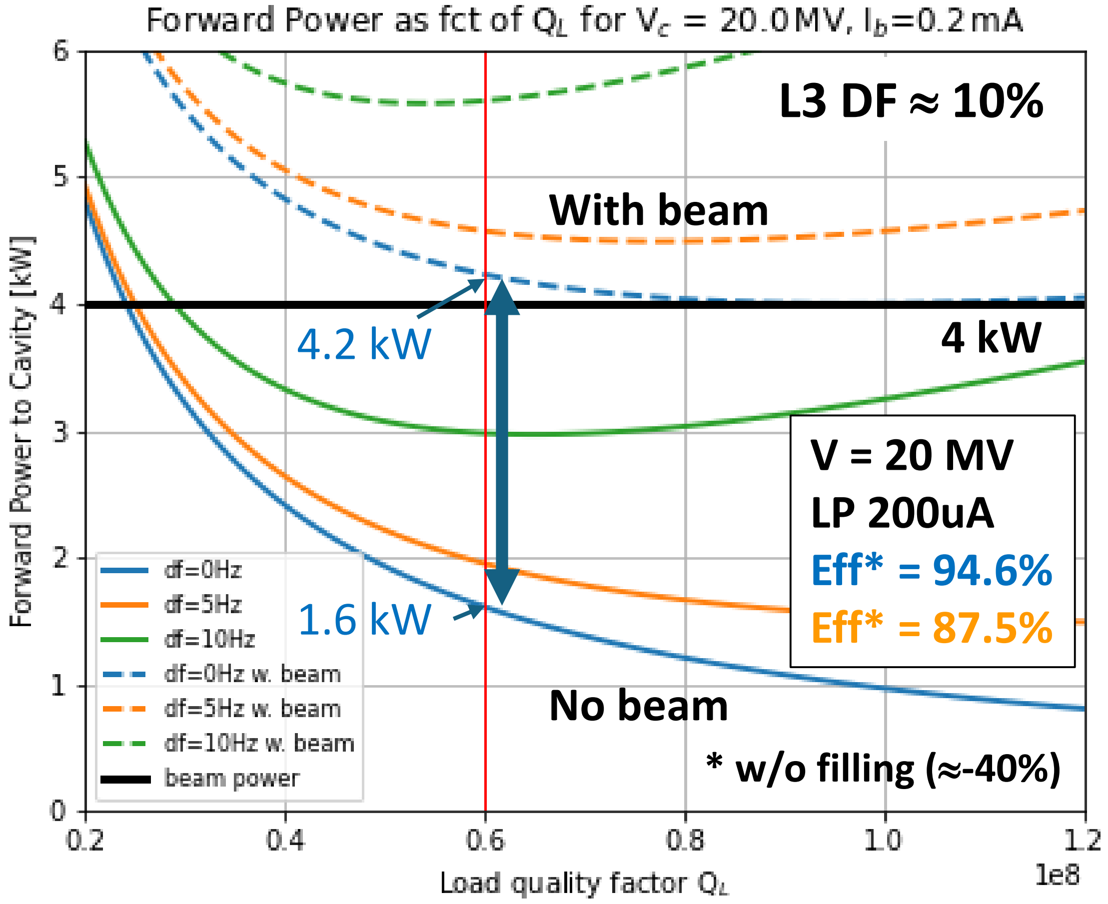
Remark: 4 k cavities not considered

Courtesy: J. Branlard

WP2: Low Level RF controls
Example: EuXFEL L3, CW / LP operation

Transfer efficiency RF → Beam





Remark: EuFEL I_{beam} often changes [0..100%] → P varies ≈ x 3 → adopt SSAM drain voltage

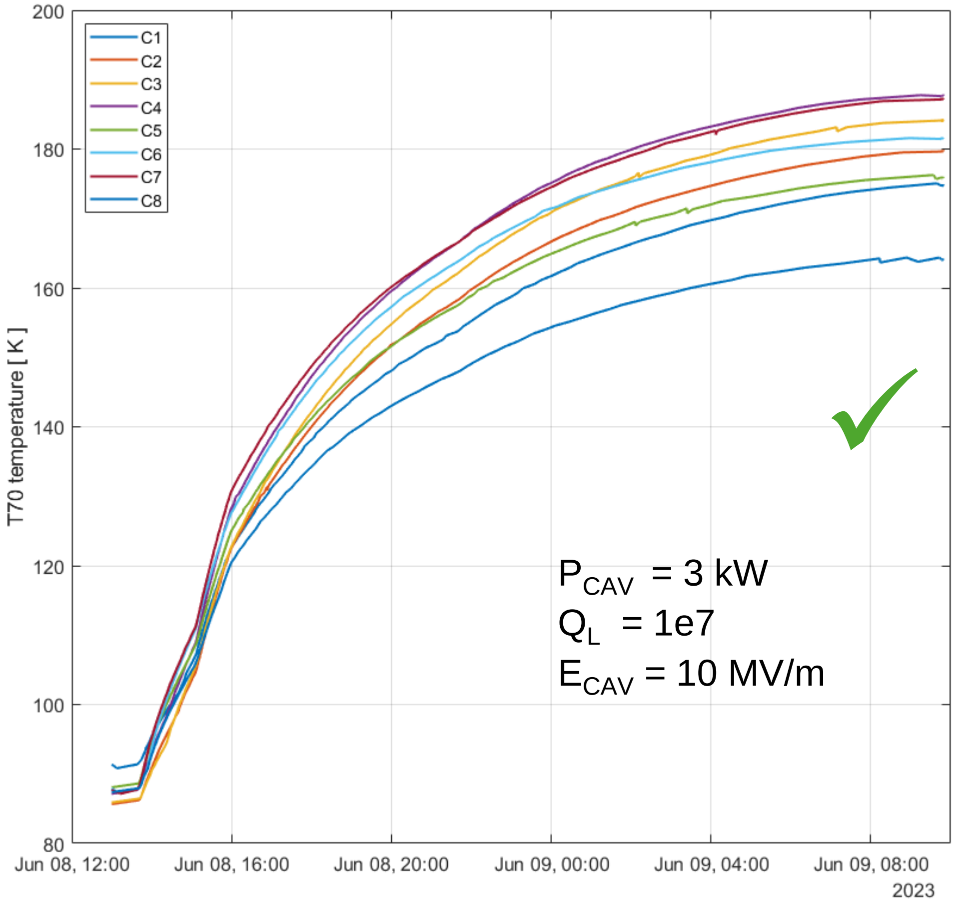
WP2: Low Level RF controls

EuXFEL HDC: Coupler heating & Quench limit

Tests at CMTB to investigate the suitability of series cryomodules for CW/LP operation

- Checking **heating** (and thermal equilibrium) of fundamental input power couplers

- Checking **quench limit** as a function of duty factor



Courtesy: J. Branlard

WP2: Low Level RF controls

EuXFEL HDC: Coupler heating & Quench limit

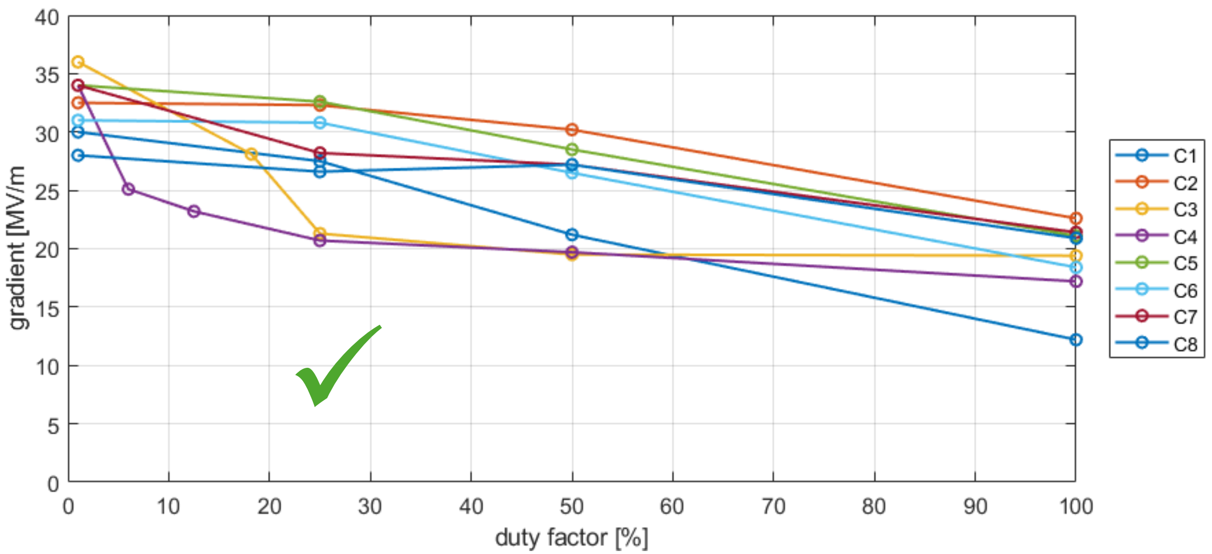
European XFEL

Tests at CMTB to investigate the suitability of series cryomodules for CW/LP operation

- Checking **heating** (and thermal equilibrium) of fundamental input power couplers

- Checking **quench limit** as a function of duty factor

On average, for DF of up **25%**, cavities can reach **> 85%** of the pulsed quench limit



	C1	C2	C3	C4	C5	C6	C7	C8	
DF [%]	Emax [MV/m]	Emax [MV/m]	Emax [MV/m]	Emax [MV/m]	Emax [MV/m]	Emax [MV/m]	Emax [MV/m]	Emax [MV/m]	**<Emax > [MV/m]**
1.3	30	32.5	36	34	34	31	34	28	**32.5**
6				25.1					
12.5 18.2			28.1	23.2					
25	27.5	32.3	21.3	20.7	32.6	30.8	28.2	26.6	**27.5**
50	21.2	30.2	19.5	19.7	28.5	26.5	27.2	27.2	**25**
100	12.2	22.6	19.4	17.2	21.1	18.4	21.4	20.9	**19.2**

Courtesy: J. Branlard

WP2 Program

WP2: Low Level RF controls

DESY, HZB, CNRS

Convener: Holger Schlarb (DESY)/ Julien Branlard (DESY)

Main contacts with other partners: Axel Neumann (HZB), Christophe Joly (CNRS)

Task 2.1: **Coordination of R&D on LLRF – *M1-M48***

Task 2.2: **Efficient field control for high loaded-quality factor cavities – *M1-M48***

Task 2.3: **Vibration analysis and detuning control of cavities – *M1-M36***

Task 2.4: **Integrated LLRF control using Ferro-Electric Fast Reactive Tuners– *M13-M48***

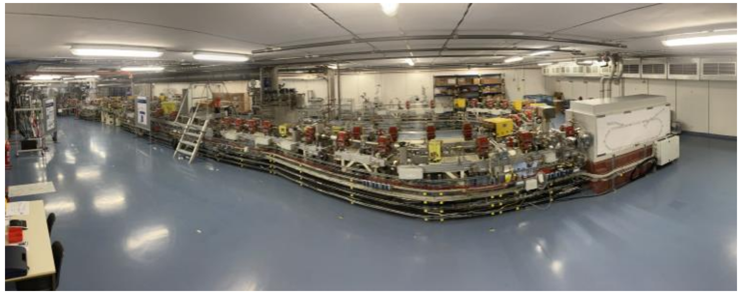
Task 2.5: **Energy efficient supervisory control and fault diagnosis– *M1-M48***

WP2 – LLRF: General Remark

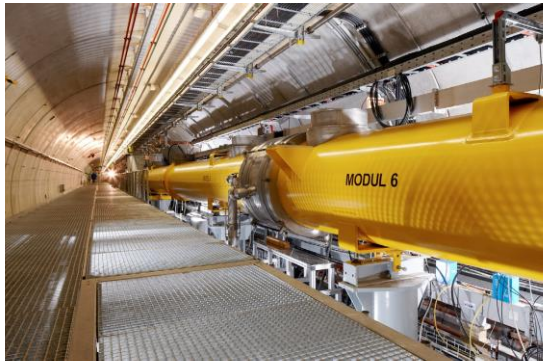
- SRF test stands & access to SRF accelerators is essential!
- 3 new hires @ DESY / + 2 openings @HZB/@DESY

HoBiCaT@HZB

bERLinPro



FLASH



CMTB@DESY

EuXFEL

AMTF@DESY

…

SRF Photoinjector Test Stand (Ts4i)

Task 2.2: **Efficient field control for high loaded-quality factor cavities – *M1-M48***

- *Identify **optimal loaded-quality factor (QL)** to achieve efficient field control for various operation scenarios.*

- *Evaluate **methods for changing QL** (at the cavity coupler and waveguide level).*

- *Investigate benefits of advanced ML-based **combined RF and mechanical feedback controllers.***

- *Demonstrate **RF-efficient control** in continuous wave (CW) and long pulse (LP) operation.*

Task 2.2: Efficient field control for high loaded-quality factor cavities – *M1-M48*

- *Evaluate **methods for changing QL** (at the cavity coupler and waveguide level).*

3-stub tuner at **HoBiCaT@HZB**

+ simulation have been performed

Introduce an additional waveguide Q tuner :
extend tuning range x10

Existing motorized coupler tuner :
usual tuning range Q_L = [1e6 – 1e7]

Q tuner at the AMTF

Task 2.3: **Vibration analysis and detuning control of cavities –** ***M1-M36***

- ***Characterize microphonics*** *and detuning during cavity operation.*
- *Characterize* ***environmental disturbances*** *and transfer to the cavity perturbation.*
- *Investigate and* ***develop detuning counter measures*** *based on advanced feedforward, feedback and active noise cancellation including AI methods.*

Task 2.3: Vibration analysis and detuning control of cavities – *M1-M36*

- ***Characterize microphonics** and detuning during cavity operation.*

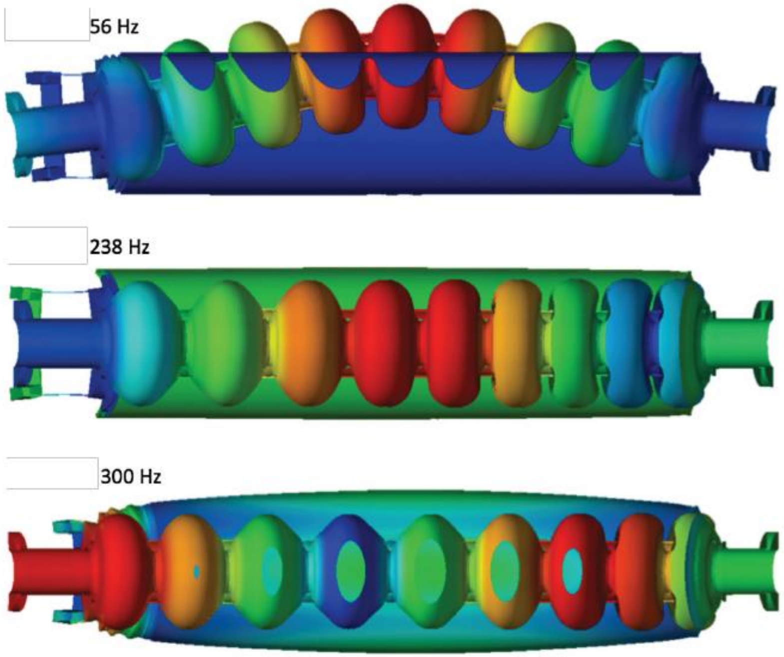
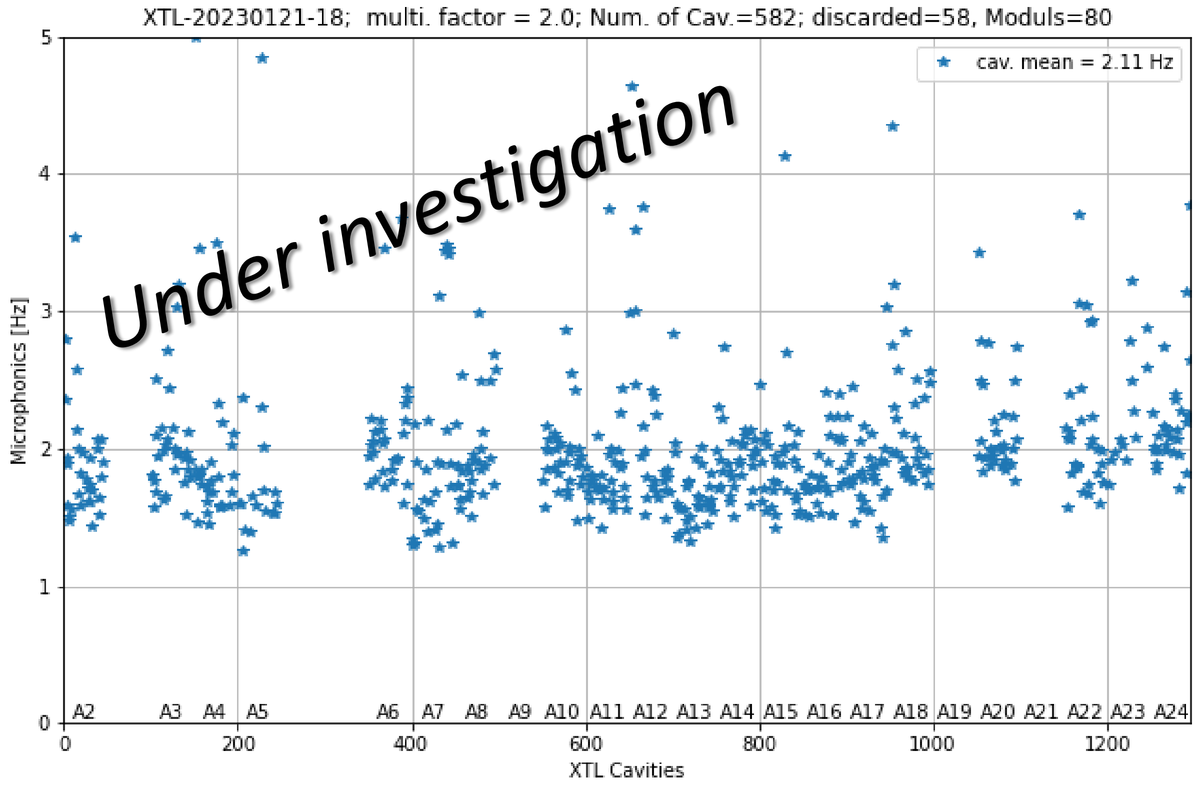


Figure (5.1) Illustrations of the structural displacements for three selected modes. The magnitudes of the displacements (a.u.) are color coded with a linear scale [93].



Mostly < 2.5 Hz rms

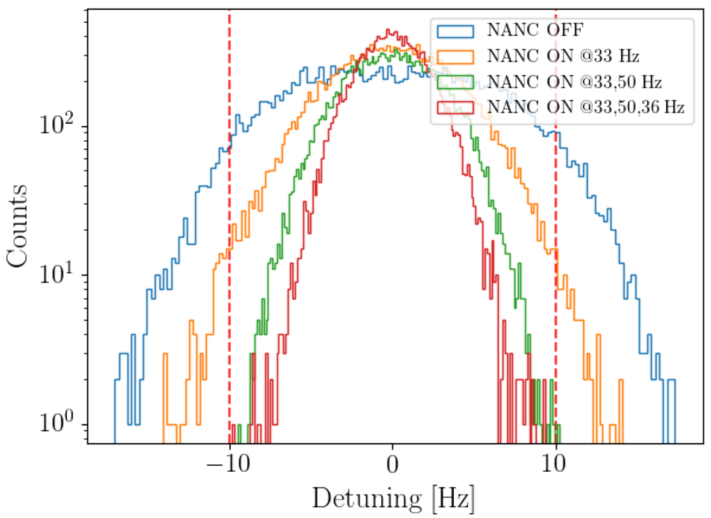
Very promising

WP2 – LLRF: status/evolution of Task 2.3

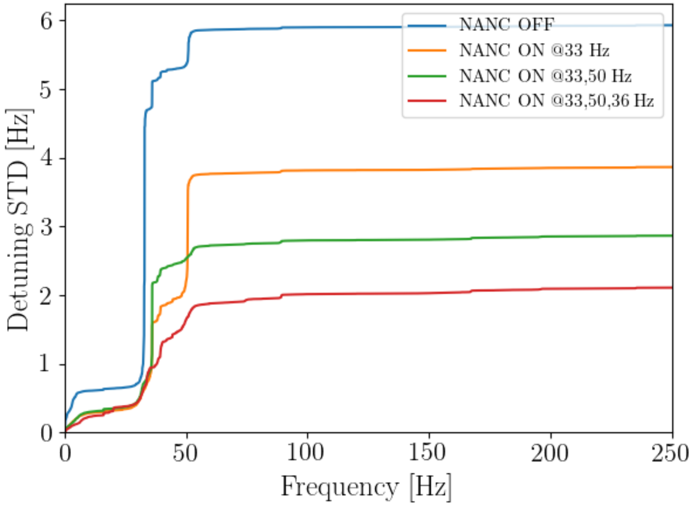
Task 2.3: Vibration analysis and detuning control of cavities – *M1-M36*

• *Investigate and* ***develop detuning counter measures*** *based on advanced feedforward, feedback and active noise cancellation including AI methods.*

Detuning distribution

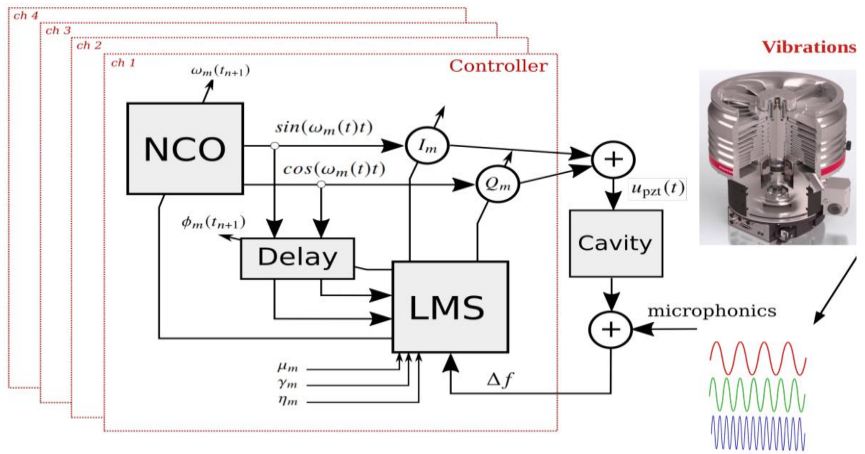


Detuning integrated STD



➔ **typically x 3-6 suppression**
+ broadband FB desired

Active Noise Cancellation (ANC)@FPGA



New: tracks frequency $\omega_m(t_{n+1}) = \omega_m(t_n) + \gamma_m \frac{I_m(t_n)Q_m(t_{n+1}) - Q_m(t_n)I_m(t_{n+1})}{I_m(t_n)^2 + Q_m(t_n)^2}$

Ref.: R. Rybaniec *et al.*, doi:10.1109/RTC.2016.7543112
Ref.: A. Bellandi *et al.*, doi:10.18429/JACoW-LINAC2022-THPOPA21

Task 2.5: Energy efficient supervisory control and fault diagnosis– M1-M48

- *Develop schemes to **adjust SSA parameters** for efficient RF generation.*
- *Investigate RF control parameters for **energy-efficiency optimization using ML***
- *Develop **fault diagnosis** and **anomaly detection** using ML approaches*
- *Develop **fault counter measures** for sustainable cavity operation*
- *Develop a **digital twin and surrogate models** to improve energy efficiency.*

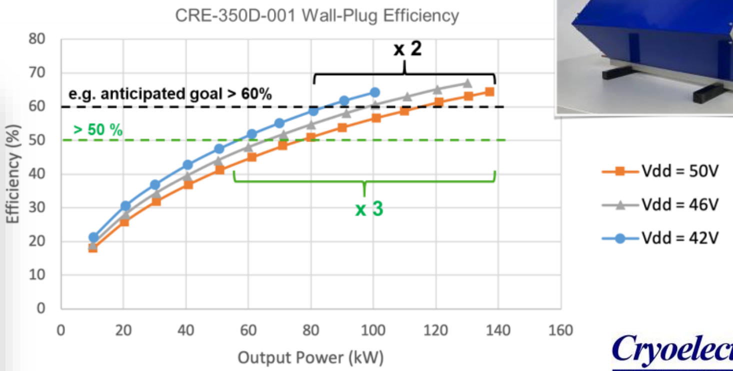
WP2 – LLRF: status/evolution of Task 2.5

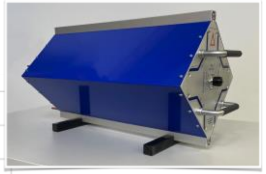
Task 2.5: Energy efficient supervisory control and fault diagnosis– M1-M48

4kW SSA at the AMTF

Courtesy: MHF group@DESY

SSA interface & tuning rate

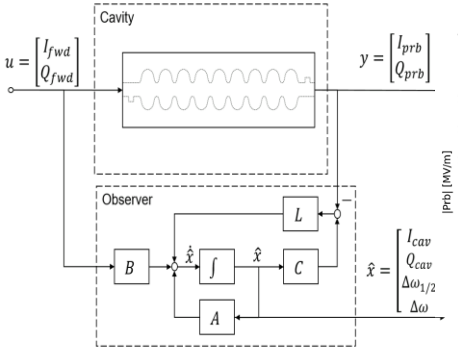




Cryoelectra
RF Technology for Particle Accelerators

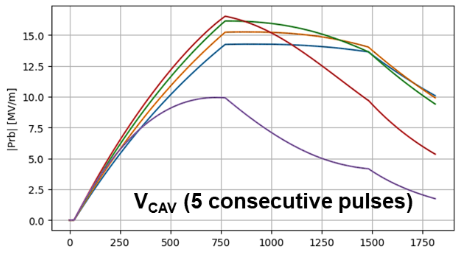
Courtesy: N. Pupeter/B. Nordmann

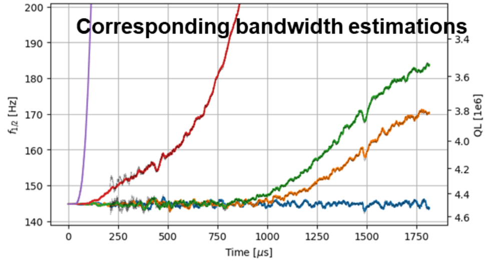
Luenberger observer estimates cavity **bandwidth** and **detuning**



Courtesy: B. Richter (PhD)

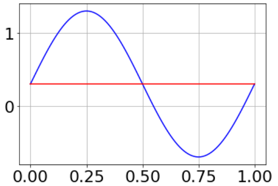
Validation of quench detection in pulsed mode

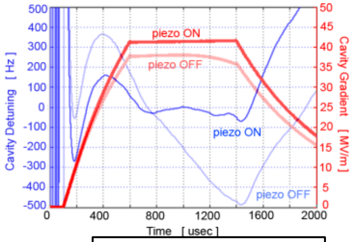




Global optimizer

Piezo pulse





(DC, A, ω, t)

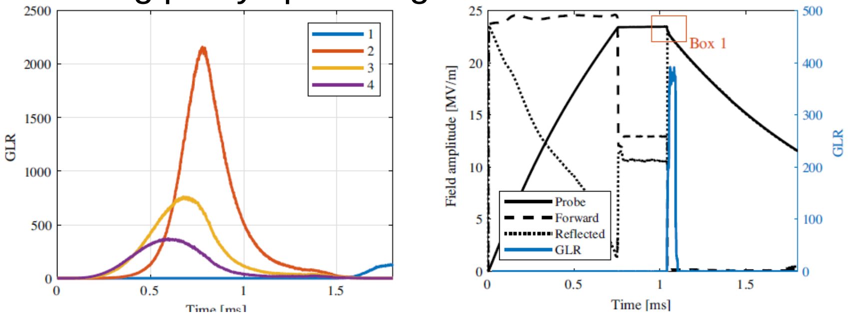
Detuning error

Bayesian process

Courtesy:
J. Lubke (PhD)

Anomaly detection (e.g. quenches)

using parity space & general likelihood ratio



A. Eichler et al. DOI: 10.1103/PhysRevAccelBeams.26.012801

Thanks for attention

...

Looking forward to a fruitful collaboration

WP2: Low Level RF controls

DESY, HZB, CNRS

Convener: Holger Schlarb (DESY)/ Julien Branlard (DESY)

Main contacts with other partners: Axel Neumann (HZB), Christophe Joly (CNRS)

Task 2.1: **Coordination of R&D on LLRF – *M1-M48***

Task 2.2: **Efficient field control for high loaded-quality factor cavities – *M1-M48***

Task 2.3: **Vibration analysis and detuning control of cavities – *M1-M36***

Task 2.4: **Integrated LLRF control using Ferro-Electric Fast Reactive Tuners– *M13-M48***

Task 2.5: **Energy efficient supervisory control and fault diagnosis– *M1-M48***

Task 2.2: Efficient field control for high loaded-quality factor cavities – *M1-M48*

• *Identify optimal loaded-quality factor (QL) to achieve efficient field control for various operation scenarios.*
→ *Can be carried out using numerical simulation (achievable stability vs. power)*
→ *Test at CMTB/AMTF/HoBiCaT (without beam)*
→ *Test at SRF guns, Ts4i & BerLinPro (with beam), other options?*

• *Evaluate methods for changing QL (at the cavity coupler and waveguide level).*
→ *Test and simulations are ongoing at HoBiCaT & AMTF / (3-stub tuner or phase shifter design)*

• *Investigate benefits of advanced ML-based combined RF and mechanical feedback controllers.*
→ *Started investigation to model transfer function PZT→ RF (M. Herrmann @ DESY)*
→ *New position will be open at HZB.*

• *Demonstrate RF-efficient control in continuous wave (CW) and long pulse (LP) operation.*
→ *depends on results 2.2.1-3, but is already regularly investigated e.g. at CMTB*

Task 2.3: Vibration analysis and detuning control of cavities – *M1-M36*

• *Characterize microphonics and detuning during cavity operation.*
→ *Measurements and characterization at several facilities feasible*
→ *Strongly depending on the facility, vary over time and operation setups*
→ *Long term microphonics at XFEL/FLASH (Y. Sun & A. Bellandi & H.S.@DESY)*
→ *Evaluation at HoBiCaT & future SRF gun test stands*

• *Characterize environmental disturbances and transfer to the cavity perturbation.*
→ *First test using ext. geophones at CMTB (PhD thesis Uni. Lodz)*
→ *More sophisticated sensor techniques envisioned (Distributed Fiber Optic Sensing)*

• *Investigate and develop detuning counter measures based on advanced feedforward, feedback and active noise cancellation including AI methods.*
→ *Improve LLRF diagnostics on detuning (e.g. Luenberger Observer, PhD, B. Richter)*
→ *Advanced feedforward technique is worked on (A. Bellandi)*
→ *Surrogated models will be tested*

Task 2.4: Integrated LLRF control using Ferro-Electric Fast Reactive Tuners– M13-M48

- *Integrate a ferro-electric fast reactive tuner (FE-FRT) with a digital LLRF system*

→ *Hardware development 2026/27 within WP1*
→ *Simulation on effect and operation range can be carried out*
→ *When type and actuation is defined, digital interface can be defined*

- *Demonstrate microphonics compensation using a FE-FRT at a horizontal test stand*

→ *Depends on WP1 outcome*
→ *Develop smart tuning algorithm to combine FE-FRT and mechanical tuner*

Task 2.5: Energy efficient supervisory control and fault diagnosis– M1-M48

- *Develop schemes to adjust solid state amplifier (SSA) parameters for efficient RF generation.*

→ *Cryoelectra GmbH presentation last year at DESY/ Continue discussion on digital interface*
→ *Achievable drain voltage slew rate to be determined/update rates … level of few tens of ms*

- *Investigate RF control parameters for energy-efficiency optimization using ML methods*

→ *Started… e.g. Bayesian optimization of LFD compensation in LP operation (PhD student)*

- *Develop fault diagnosis and anomaly detection of LLRF systems using ML approaches*

→ *Started… e.g. Quench Detection, Microphonics Detuning Anomalies, …*
→ *Started …Fault diagnostics on digital HW e.g. PCIe failure & restarts, SEU on FPGAs…*
→ *Implementation of real-time anomaly detection on FPGA (N. Omidsajedi)*

- *Develop fault counter measures (i.e., fast detection and reaction) for sustainable cavity operation*

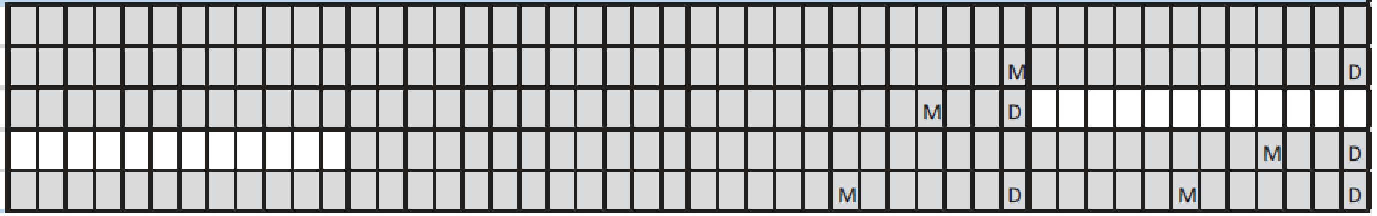
→ *On HW level some are implements/ wait for fast algorithm to be developed*

- *Develop a digital twin and surrogate models of LLRF systems to improve energy efficiency.*

→ *Modelling of entire system/software, combine achievements from other sub-WP2 packages*
→ *hardware in the loop first test ongoing (B. Dursum)*

WP2 – LLRF: plans to achieve milestones & deliverables

WP2	Low Level RF Controls
2.1	Coordination of R&D on LLRF
2.2	Efficient field control for high loaded-quality factor cavities
2.3	Vibration analysis and detuning control of cavities
2.4	Integrated LLRF control using Ferro-Electric Fast Reactive Tuners
2.5	Energy efficient supervisory control and fault diagnosis



D2.1	ML based MC	Report on microphonics study & ML-based mitigation	2	DESY	R	PU	36
D2.2	SSA	Report on interface study of LLRF with SSA	2	DESY	R	PU	36
D2.3	LLRF control	Report on LLRF RF control studies	2	DESY	R	PU	48
D2.4	FRT based MC	Report on integration of FE-FRT in LLRF	2	HZB	R	PU	48
D2.5	Anomaly det.	Report on anomaly detection & LLRF optimization	2	DESY	R	PU	48

M2.1	Demonstration of energy-efficient SSA operation	WP2	30	Test report/publication
M2.2	Demonstration of detuning control techniques	WP2	33	Test report/publication
M2.3	Demonstration of RF control for CW/LP ops	WP2	36	Test report/publication
M2.4	Demonstration of ML and anomaly detection	WP2	42	Test report/publication
M2.5	Demonstration of FE-FRT Microphonics compensation	WP2	45	Test report/publication

→ Deliverables and Milestones are still fine and in reach

→ To support the WP2 program additional position will be open: 1) at DESY ~Q4/24 2) HZB soon

WP2 – LLRF: points of attention

- **Changes in laboratory**
  - Delay: SRF photoinjector test stand Ts4i likely not be available before 2026 (DESY)
  - Risk: CMTB may not be operable during FLASH2020+ shutdown – 14 month (DESY)
    - ➔ LLRF tests for LP and CP operation delayed
    - ➔ Mitigation: prepare AMTF test stands with SSA operation
  - Additional loads: FALCO, NRF gun test stand pulls resources (DESY)

- **Risks:**
  - Finding qualified personnel HZB (1 open position) / DESY (1 open position)
  - Other projects may pulls resources, QL test slowed down (DESY)
  - Heavy load on SW and FW developers may delay development

- **New opportunities:**
  - New LLRF field detection hardware improves detection possibilities and regulation capabilities

WP2 – LLRF: budget plans

WP	WP Subject	CNRS	CERN	ESS	DESY	VUB	CEA	HZB	INFN	UKRI	UL	*EPFL*	EU-budget kEUR	Matching personnel kEUR	Matching materials kEUR	Total budget kEUR
	Technology Areas															
WP.1	Ferro-Electric Fast Reactive Tuners							LEAD					989,3	784,0	277,8	2051,1
WP.2	Low-Level RF Controls				LEAD								498,9	612,0	204,0	1314,9
WP.3	Nb3Sn-on-Cu films for 4.2-K cavity operation								LEAD				871,4	616,0	232,0	1719,4
WP.4	HOM Dampers & Fundamental Power Couplers	LEAD											572,2	620,0	296,0	1488,2
	TOTAL FOR iSAS Technology R&D												2931,8	2632	1009,8	6573,6

→ No deviations