Estimating key operation parameters for SRF cavities in CW.

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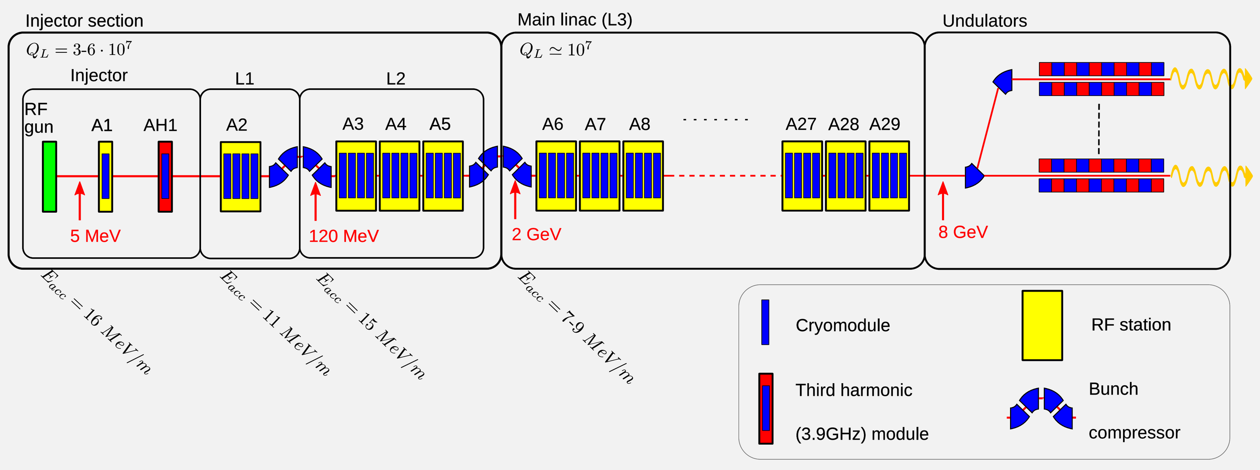
Abstract

Future superconducting continuous wave (CW) linear accelerators for hard X-ray free electron lasers will need tight control on cavity parameters such as the detuning and RF bandwidth to achieve a cavity accelerating field regulation within the specifications. It is further requiread to minimize the RF power in order to reduce construction costs. For European XFEL a proposal to add a CW mode of operation requires to lower the cavity bandwidth to some tens of hertz, one order of magnitude smaller than the one currently used in pulsed operation with a required input RF power of some kilowatts per cavity. Therefore a high sensitivity of cavity detuning to external microphonic excitations is expected as well as coupler heating related to drifts of the cavity bandwidth. In such a case the LLRF control system has to detect these disturbances and react accordingly by either automatically bringing the cavity parameters back to their nominal values or informing the operators about the system status. This paper proposes a way to continuously measure the detuning and RF bandwidth using a real time evaluation of inverted cavity equations. Preliminary test results of the implemented algorithms at the Cryo Module Test Bench (CMTB) and the European XFEL are presented.

European XFEL CW/LP upgrade

Layout

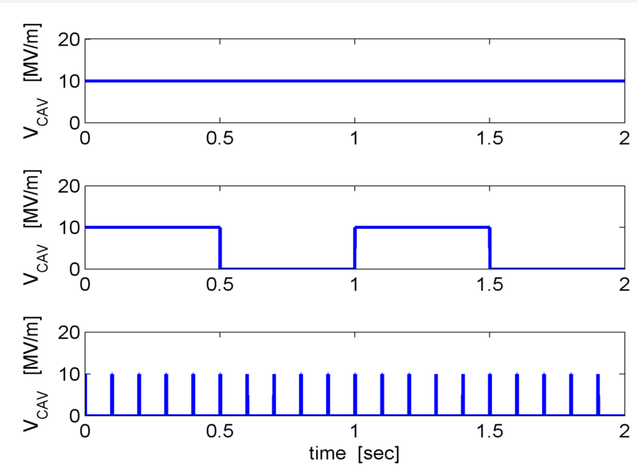


Modes of operation (at 0.1nC)

Continuous wave (CW)
E = 8.6 GeV
$N_{bunches}$/s = 100k

Long Pulse (LP)
E = 12.6 GeV
$N_{bunches}$/s = 50k

Short Pulse (SP) (actual)
E = 17.5 GeV
$N_{bunches}$/s = 27k



Mode	Bunch number	Bunch spacing	Energy
CW	↑	↑	↓
LP	–	↑	–
SP	↓	↓	↑

Benefits

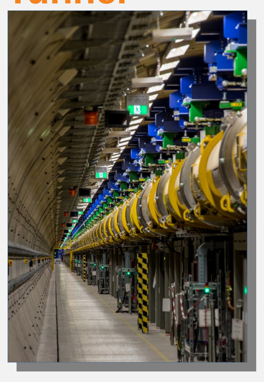
- Higher bunch repetition rate and current up to 0.025 mA
- Higher bunch spacing is beneficial for many FEL experiments
- Bunch repetition rate and spacing can be traded for beam energy for more flexible operations

After the upgrade European XFEL will be able to switch between SP and CW/LP mode of operation!

To do

- Double the cryogenic plant capacity to 5kW
- Replace injector cryomodules with higher Q_0 ones (> 2.8 10^{10}). These cryomodules will be able to operate in the range of Q_L ~ 10^6 - 10^8
- Install Induction Output Tubes (IOT) with pulsed multi beam klystrons
- Modify the RF distribution system to allow selectable SP or CW/LP operations
- Add 12 modules to the main linac

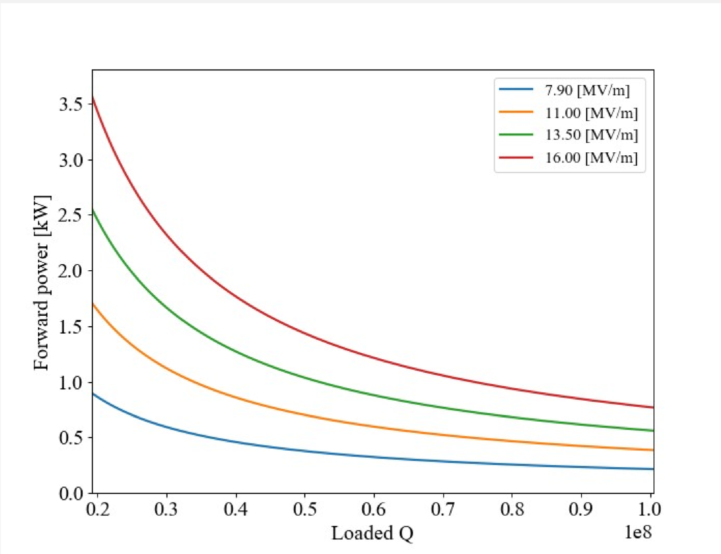
Tunnel



- European XFEL has a single, 5.2 m diameter, 1.5 km long tunnel for the accelerating section
- For the upgrade the size of every component has to be optimized
- Because of RF costs, size and the need to keep SP mode of operation, the Vector Sum drive scheme will be used for CW/LP and SP mode

Coupler Heating

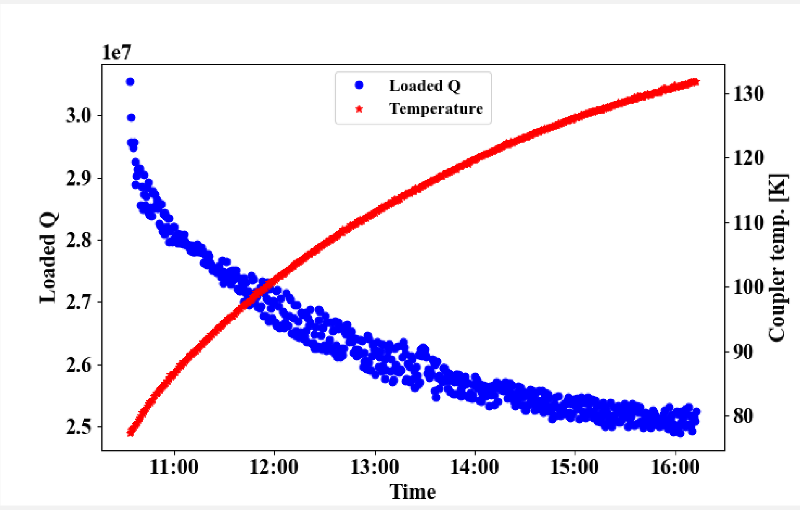
Power in function of loaded Q



Beam current of 0.025 mA

- Because of the expected loaded quality factor during CW operations, between 10^7 and 10^8 every cavity is expected to need some kilowatts of RF power to reach the desired gradient of 16MV/m in the injector
- This produces a noticeable coupler heating. The Q_L is changed due to the mechanical variation of the coupler

Variation of loaded Q due to coupler heating



P_{for} = 4 kW Q_L = 3x10^7 measured at CMTB

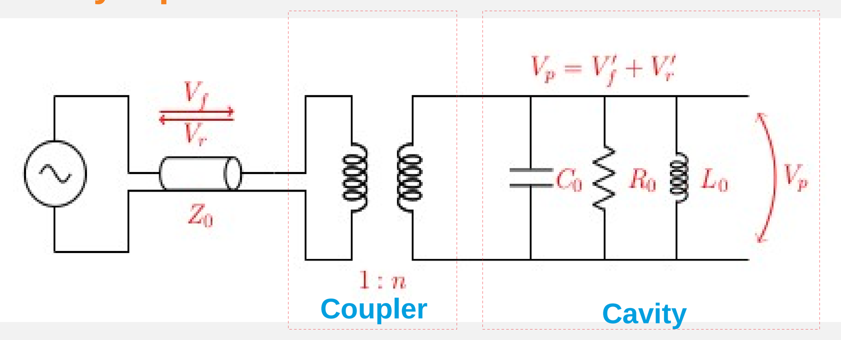
Unwanted coupler heating loop

Average RF power of kW → Heat loading on the couplers → The feedback increases the RF power → Q_L decreases → Average RF power of kW

- Due to such effect the coupling has to be preemptively readjusted to avoid an excessive RF power consumption
- In CW the decay measurement method cannot be used

Proposed Q_{ext} measurement method in CW

Cavity equivalent circuit



Coupler Cavity

Equations

$\frac{r}{Q} Q_0 = R_0$	Shunt impedance
$\omega_0 = \frac{1}{\sqrt{C_0 L_0}}$	Resonance frequency
V_p	Probe signal
V_f	Forward signal
V_r	Reflected signal
$(V_p)_{virt} = V_f + V_r$	Virtual probe

using:

$$\beta = \frac{\frac{r}{Q} Q_0}{n^2 Z_0} \qquad V_p = n (V_p)_{virt}$$

It is possible to demonstrate that

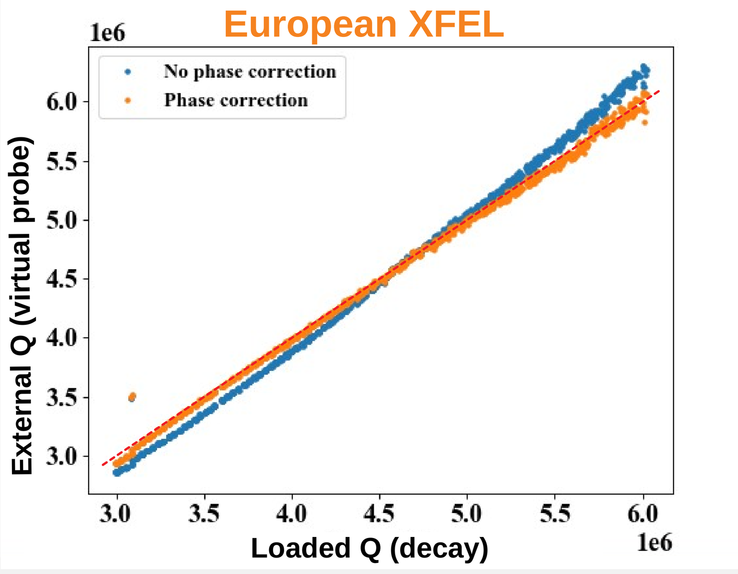
$$Q_{ext} = Q^* \frac{V_p^2}{(V_p)_{virt}^2}$$ with Q^* a calibration factor

- The method is insensitive to detuning
- It allows to maximize the beam delivery time
- Can be used to decide whether to change the coupling
- Because the changes in coupling might change the phase relationship between the RF signals, the reflected one has to be corrected applying a rotation $V_r \rightarrow V_r e^{i\theta}$

Measurements done changing the coupler insertion

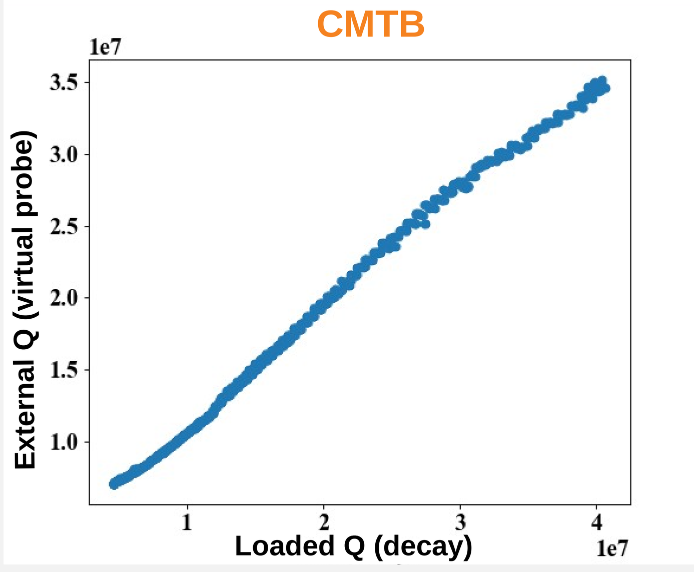
Q_{ext}-virtual probe vs Q_L-decay comparison

European XFEL



- Measured in SP mode
- Significant deviations if not corrected
- Correcting the reflected phase produces a good agreement between the two methods

CMTB



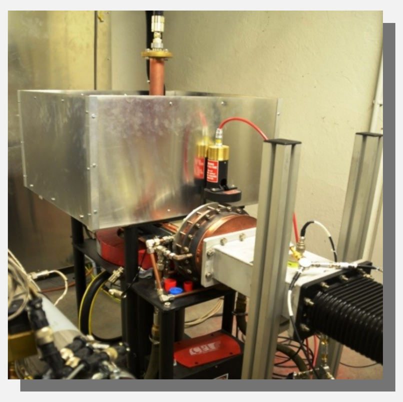
- Measured in LP mode (duty 50%)
- Significant deviations at higher Q_L
- Correcting the reflected signal didn't produce improvements
- The measurement has to be redone with pure thermal Q_L changes

Cryo Module Test Bench (CMTB)

Module XM50.1

- European XFEL production module
- Equipped with eight TESLA cavities
- Q_0 at 2 K and 15 MV/m ~ 1.8x10^{10}
- The couplers were modified to operate in a range of Q_L between 10^6 - 10^8
- At CMTB since the beginning of this year

IOT



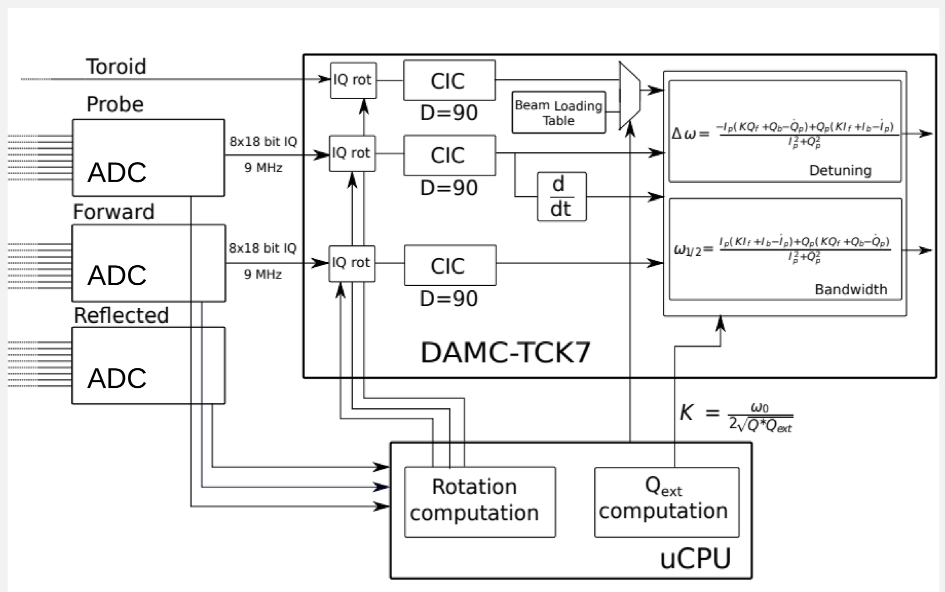
- 120 kW output
- 22.3 dB gain
- 54 % efficiency

LLRF crate

- Based on MicroTCA.4
- 12 slot crate 9U
- NAT MCH
- Concurrent CPU
- Wiener 1kW uPM
- 3x Struck SIS8300 ADC + DWC
- Vadatech DAMC-TCK7 + DESY VM2
- 19" XFEL 16 ch piezo driver (external)

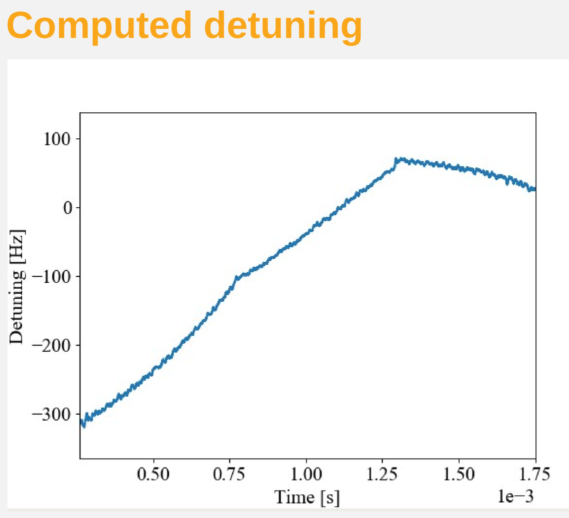
Detuning and quench detection

Proposed LLRF extension

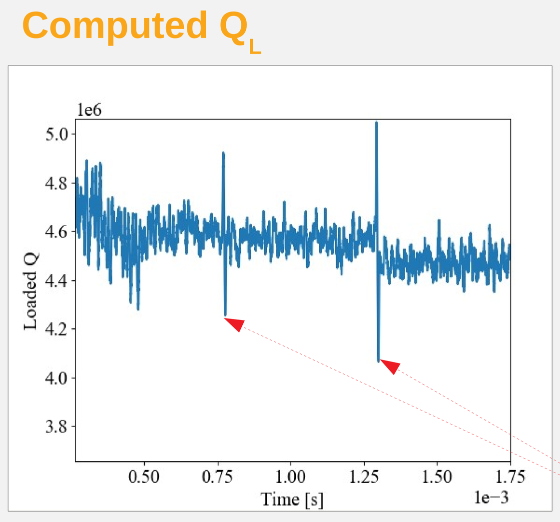


- IxQ cavity signals sampled by SIS 8300L2 ADCs are sent at 9 MHz rate to a DAMC-TCK7 card
- The signals are rotated to match the coupler produced rotation.
- The signals are downconverted by a factor 90 by a Cascaded Integrator–Comb decimator filter. In such a process the high frequency noise is removed
- The derivative of the probe is computed
- Cavity equations are used to compute the detuning and the bandwidth of the cavity

Computed detuning



Computed Q_L



- Simulated performance of this scheme
- European XFEL data was used
- Further studies will be done at CMTB

Produced by filling-flattop-decay pulse transients

Conclusion

- A blueprint of the parameter estimation scheme was done
- For Q_{ext} estimation the measurements are promising. Further tests are required for CW operations
- For the detuning and quench detection some preliminary simulations on European XFEL data were done. The component has to be implemented in our LLRF controller and tested at CMTB.
- The parameters for the CIC decimator have to optimized. A possible droop compensator after the interpolator is under evaluation.
- The detuning estimation will be used in the piezo-based active noise cancellation of the microphonics

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LLRF2019

September 29, 2019 - October 3, 2019
Swissotel Chicago, Illinois, USA

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European XFEL