CAVITY AND LINAC RF AND DETUNING CONTROL SIMULATIONS[*]

A. Neumann[†], J. Knobloch, BESSY, Berlin, Germany

Abstract

Single pass free electron lasers, such as the planned BESSY-FEL, require a very stable beam with a bunch-to-bunch time jitter of less than 50 fs and a relative energy jitter below $1\cdot 10^{-3}$. Regarding the low beamloading the 144 cavities of the superconducting linac will be operated in CW at a high loaded quality factor of $3\cdot 10^{7}$. To understand the achievable stability of the beam and the budget of the individual error sources for the cavity field stability a single cavity simulation tool has been developed. It includes the cavity field envelope model, an LLRF feedback system model and further on mechanical transfer functions, tuner characteristics, the fast piezo control system, microphonics and other noise sources measured or developed at HoBiCaT. Incorporating realistic beam parameters due the acceleration process in the photoinjector and the first booster cavity allows to model the resultant energy and time jitter of the beam at the end of the linac entering the undulator section of the FEL. Furthermore the model has been used to find optimum operation parameters for the cavity and controller.

INTRODUCTION

The linac of the future BESSY Free Electron Laser (FEL) will be operated in CW mode with a flexible bunch pattern and a low average beam loading. Therefore to optimize the power coupling from the klystron to the cavity only weak input coupling is required. The optimum loaded quality factor Q_L will be around $3\cdot 10^{7}$ for an expected peak detuning of 20 Hertz. This makes the RF field in the cavity very sensitive to any mechanical detuning, which has to be compensated for by additional power provided by the RF control system or to be suppressed by external means.

To allow the seeded high-gain-harmonic generation FEL process the requirements for the electron beam stability are very stringent. The bunch-to-bunch jitter has to be kept below 50-60 fs to allow a synchronization of the external seeding radiation and the beam in the undulator section. Secondly the energy jitter and thus the energy offset error should be low ($<1\cdot 10^{-}$) to preserve the desired intra-bunch correlated energy spread for efficient lasing in the undulators.

The timing jitter will be mainly influenced by correlated acceleration errors along the linac, especially in the first section, where the beam is accelerated off-crest. This correlated bunch-to-bunch energy spread will be partly compressed by the bunch compressors. It is caused by acceleration phase errors in the injector and first booster cavity. The residual time jitter after compression is mainly determined by individual cavity energy deviations from the design value, that are transferred by the bunch compressor in a phase error and arrival time shift of the bunches for the following cavities. Thus it is important to derive an upper limit for the allowable single cavity errors given by the individual cavity detuning. A simulation of the RF control system and of the implemented detuning control by piezo tuners allows to determine the possible field stability for given error sources and optimum control parameters for the parallel acting LLRF control and adaptive feedforward piezo-based tuning control.

Therefore the model presented in [2] has been extended by the CW cavity operation characteristics measured at the HoBiCaT cavity test facility given e.g. in [3] and [4]. It further features the least-mean-square based adaptive feedforward microphonics control by the piezo tuner [5] and measured piezo-to-RF detuning -and dynamic Lorentz force detuning transfer functions.

In total the requirements for the field stability of the cavities in the linac have been derived. Especially the cavities in the first section before the first bunch compression require a phase stability of better than 0.02° in phase, as they imprint the correlated energy spread onto the beam.

MODELING OF MEASURED CAVITY-TUNER PROPERTIES

Cavity model

The cavity field is modeled by the well established LCR circuit model [6] as given by Figure 1. Here the cavity

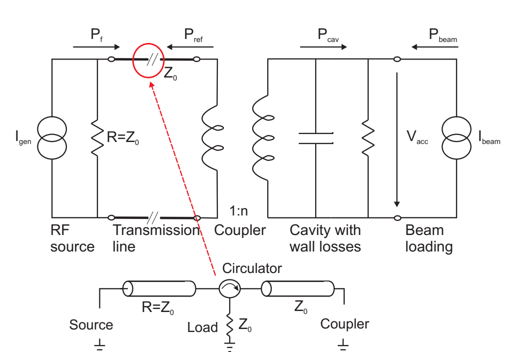

Figure 1: LCR circuit model of a beam-loaded cavity connected to a power source via an input coupler.

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[†] Axel.Neumann@bessy.de

is given by the LCR circuit, the coupling ratio is modeled by an ideal transformer while the currents driving the cavity, the beam and the klystron, are described by current sources. The resulting linear 2nd order equations by Kirchhoff's rule are simplified by separating the fast RF oscillations from the slow field variations as they result from the cavity detuning and beam loading by the beam's RF component. Decoupling the equations for the real and imaginary field components and linearizing around the cavity resonance frequency ω allows the description of the transient field envelope with a linear state-space description in phasor notation as follows:

$$\frac{d}{dt}\begin{pmatrix} V_{re} \\ V_{im} \end{pmatrix} = \begin{pmatrix} -\omega_{1/} & -\Delta\omega \\ \Delta\omega & -\omega_{1/} \end{pmatrix} \cdot \begin{pmatrix} V_{re} \\ V_{im} \end{pmatrix} \qquad (1)$$
$$\begin{pmatrix} R_L\omega_{1/} & 0 \\ 0 & R_L\omega_{1/} \end{pmatrix} \cdot \begin{pmatrix} I_{re} \\ I_{im} \end{pmatrix}$$

Here V is the cavity voltage, $\omega_{1/}$ the half-bandwidth of the RF π-passband mode, $\Delta\omega$ the current detuning at the given time, R_L the loaded shunt impedance representing the residual resistance of the cavity and the power loss due to the external coupling. The current is in total given by the beam current and transformed klystron current $I = I_b \quad 1/nI_{kly}$. The total model is depicted in Figure 2. The

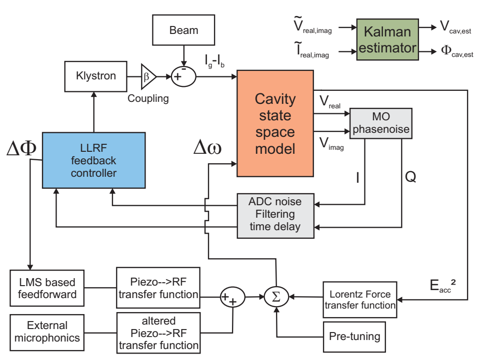

Figure 2: Simulation scheme of the Matlab-based cavity RF control model.

cavity field is regulated by a standard PI-controller detecting and correcting for the I-Q components of the field. It further includes a lowpass filter and the latency given by time delays of the analog and digital components of the RF control system. It features furthermore conversion noise of the ADC/DAC's and phase noise from the local oscillator occurring in the up -and down-conversion process of the RF field for field control. The latter is simulated by creating time domain phase noise measured from a real signal source scaled to the desired corresponding integrated time jitter.

The klystron or IOT model includes a measured saturation curve of the CPI prototype IOT at HoBiCaT. Additionally phase and amplitude jitter of the IOT are included.

The beam current simulation features bunch-to-bunch charge jitter and arrival time jitter. This is a result of the laser pulse amplitude -and time jitter in the photo-injector and following phase errors in the first cavities, where the acceleration process is still affected by non-relativistic effects.

Detuning model

The detuning for each time step t_k of the simulation is given by the sum:

$$\Delta\omega\ t = k{\cdot}T_{sim} \quad = \Delta\omega_{mic} \quad \Delta\omega_{LF} \quad \Delta\omega_{pretune} \quad \Delta\omega_{piezo} \qquad (2)$$

The pre-detuning $\Delta\omega_{pretune}$ is fixed to compensate for the static Lorentz force detuning being -(16 MV/m)^2·1.4 Hz/(MV/m)^2. The external microphonics acting on the cavity structure by helium pressure fluctuations, deterministic oscillations and random noise is given by the detuning measurement as e.g. in Figure 3. To represent the real external detuning it has been deconvolved by the measured piezo-to-RF detuning transfer function (lower plot) and is convolved again with an altered transfer function. This should reflect the fact, that the transfer function of the cavity detuning to external noise is of different nature than the piezo transfer function, but still incorporates the mechanical eigenmode characteristic of the cavity.

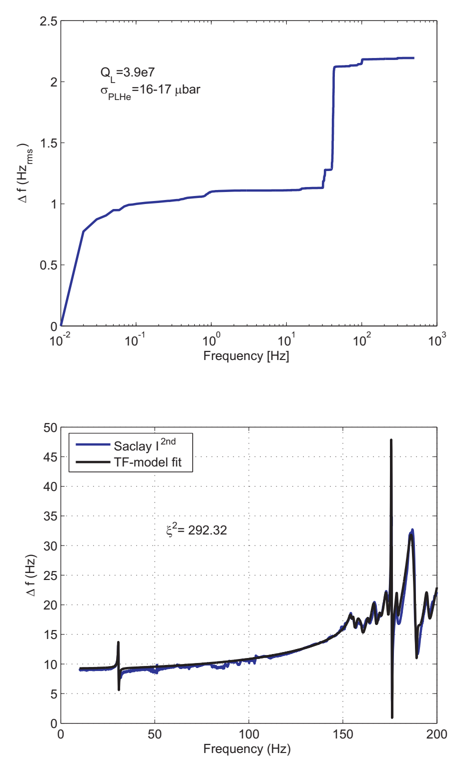

Figure 3: Integrated microphonics detuning spectrum of a TESLA cavity measured at HoBiCaT. The lower plot shows the measured piezo-to-RF detuning transfer function in the range 10-240 Hz of the Saclay I tuner and a fit to that curve. The microphonics signal and the fit served as realistic inputs for the modeling.

The Lorentz force detuning and piezo action on the cavity tuning is modeled by a set of second order systems describing the mechanical eigenmode response of the nine-cell structure to external forces. The time domain detuning models, only differing in the driving terms and the coupling constant of that terms to the detuning, is given by [7]:

$$\begin{aligned} \Delta\ddot{\omega}_i \ t \quad 2\xi\omega_{m,i}\Delta\dot{\omega}_i \ t \quad \omega_{m,i}\Delta\omega_i &= -k_i 2\pi\omega_{m,i} F \ t \\ \Delta\omega \ t &= \sum_i \Delta\omega_i \ t \qquad (3) \end{aligned}$$

Here $\omega_{m,i}$ is the frequency of the i$^{\text{th}}$ mechanical eigenmode , ξ the damping constant, $\Delta\omega_i$ the detuning contribution by this mode, k some coupling constant between the external time varying forces and this mode. The damping time constant of each mode is $\tau_m = 1/\xi\omega_m$. The parameters of these modes have been extracted from the measured piezo-to-RF detuning transfer function (Figure 3) and dynamic Lorentz force transfer function by fitting this model in frequency domain to the data (steady state response).

SINGLE CAVITY PERFORMANCE

To find optimum controller settings for a parallel working LLRF control system and the simulated adaptive feedforward piezo control, which is demonstrated experimentally in [5], first stable settings for both systems have been found by varying the controller parameter sets. Figure 4

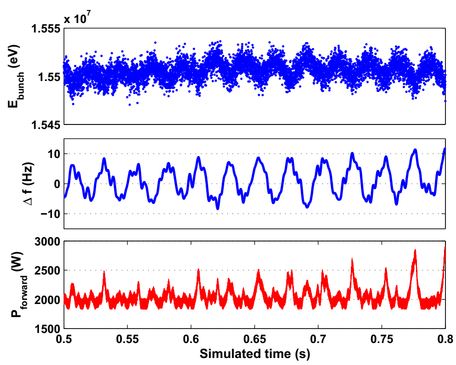

Figure 4: Simulated single cavity stability and beam energy with σ_f=5.4 Hz at Q_L=4.1·10^7. The beam energy is clearly modulated by the RF detuning.

shows an example with Q_L=4·10^7 and σ_f=5.4 Hz rms where the tuning compensation has been switched off and just the LLRF system worked. The needed power is clearly varied with the microphonics detuning and even with the high gain feedback of 100 the beam energy is clearly modulated by the detuning. Figure 5 shows the two situations where the system has been driven with and without the adaptive feedforward piezo control. The detuning has been reduced by a factor of three damping mainly the first eigenmode's detuning contribution. The current detuning information is needed for a reference signal of the feedforward and to adapt the filter coefficients according to the least-mean-square algorithm. This information is extracted from the measured I and Q components of the RF field. Except the existence of various measurement noise sources, the algorithm could extract this information at that LLRF feedback gain ($K_P = 200$).

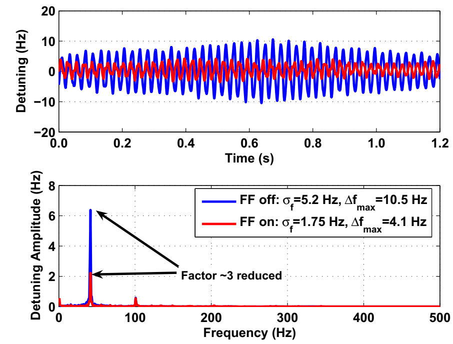

Figure 5: Simulated adaptive least-mean-square based feedforward control of the microphonics detuning by the piezo tuner. A reduction of a factor of three has been achieved.

The LLRF controller damps the residual phase error by $1/\ 1 \quad K_P$, thus for too high feedback gains the measured detuning may be dominated by the phase noise of the reference system, which is also amplified. This can be seen in Figure 6. Here for a gain of 100 the phase error signal is made up of the faster detuning component at 41 Hz and of low frequency phase noise. To study if there

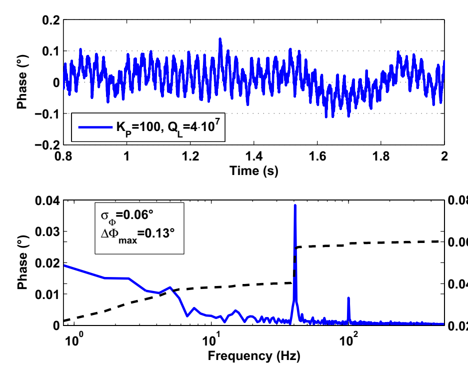

Figure 6: Residual phase error for LLRF feedback gain of 100 and active microphonics feedforward control. The blue line in the lower plot shows the FFT spectrum and the integrated spectrum is given by the black line.

is a optimum combination of mechanical tuning and high gain LLRF control, the system parameters have been varied as given by Table 1. The signal provided to the detuning control by the LLRF control measurement has been scaled

[1] Three modes are provided by the measurements at HoBiCaT, the remaining nine are from measurements at DESY. [8]

Table 1: Parameters for the cavity simulations including a combination of LLRF control and piezo based adaptive feedforward

Parameter	Value
Microphonics σ_f (Hz)	5.2
Feedforward sampling frequency (Hz)	2.0k
Reference samples $\vec{x}$ $n]$	4.0k
Number of filter taps	400
Phase noise $\sigma_{\Phi,noise}$ (°)	0.036≙70 fs
Klystron noise (/)	5.0
Beam current (mA)	2.5
Beam charge jitter (%)	5
Beam time jitter (fs)	250
Amplitude noise (1 σ) (/)	1.9
# Lorentz force modes	12^1
k_{LF} (Hz/(MV/m))	1.4
# Mechanical modes piezo→RF	20 (DC-450 Hz)
Q_L	$4{\cdot}10^7$
$f_{1/}$ (Hz)	16.3
Q	$2{\cdot}10^1$
V_{cav} (MV/m)	16.0
Acceleration phase Φ_b (°)	0.0
Feedback gain K_P	25-2000
IOT avail. power (kW)	17.0
LLRF time delay (μs)	1.0
Simulation time constant T_{sample} (s)	$1{\cdot}10^{-6}$

by the proportional gain to estimate the open loop detuning. Figure 7 shows the achieved residual detuning and phase error for different LLRF feedback gains. It shows a

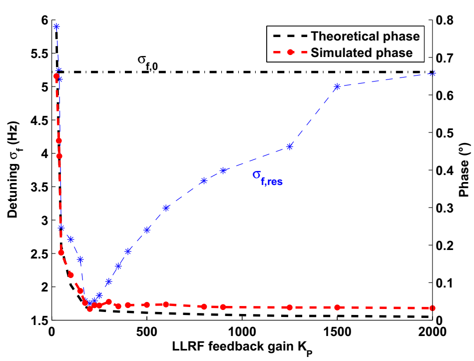

Figure 7: Residual detuning and phase error for parallel working LLRF and adaptive feedforward tuning control. The parameters are given as in Table 1.

minimum for a gain of 200, where both systems together achieved the best residual phase error. There are several reasons for that observation. The tuning algorithm cannot extract the open loop detuning for too high gains, as the signal is dominated by measurement noise. The phase stability is achieved by investing increased forward power. For lower gains there are amplitude variations, which excite dynamic lorentz force detuning increasing the total detuning. As the feedforward reference signal is not updated that often this change in the detuning is not accounted for and the algorithm may even diverge. In total this may even lead to ponderomotive instabilities of the field.

The essence of this simulation is, that a change in the LLRF operation parameters have also to be applied to the detuning control to keep the desired field stability. Finally very high feedback gains result in a saturation of the residual phase error. The measurement noise limits any further increase in the LLRF control performance.

LINAC RF CONTROL SIMULATIONS

Finally the single cavity model has been extended to a complete RF control linac simulation. It calculates the bunch-to-bunch longitudinal phase space by incorporating the acceleration errors of the 144 cavities of the linac and the influence of the starting beam jitter from the gun, the effect of the two bunch compression stages and the third harmonic cavity. For present phase stability of a photoinjector RF cavity of 0.2° the expected time jitter of the beam after the first off-crest acceleration in the booster cavities is between 500-1200 fs depending on the jitter of the injector's laser. This produces an correlated energy spread, which will be compressed by the bunch compressors.

It is important how much this is influenced by the individual cavity field errors mainly induced by microphonics detuning. Two extreme scenarios may be possible concerning the nature of microphonics in a module. It could be correlated between the cavities or totally uncorrelated. The correlated case is more critical as any error is not suppressed statistically by the number of cavities in a module or in total. Thus for different detuning levels assuming both cases the final beam time jitter at the linac exit for different starting time jitters has been simulated. The feedback gain has been chosen as 200 for the first linac section and 100 for the following cavities.

Figure 8 shows the result for the correlated case, Figure 9 for the uncorrelated case, respectively. Depending on the scenario detuning levels below 2 Hz rms or 3 Hz rms are allowable. It has to be stressed, that none of the strong peak events observed at HoBiCaT have been included in the simulations. Moreover the simulation is limited to half a second simulated time as it consumes at lot of computational power. The real detuning at HoBiCaT, which may be similar to a TESLA cryo-module, shows a correlation for the helium pressure driven low frequency microphonics between two cavities. The excited eigenmodes are not correlated at all and cavity-to-cavity coupling may be prevented by sorting the cavities according to their mode's structure in a module. The real upper level for the detuning is therefore more probably the uncorrelated value. But even there higher starting time jitters of more than 1.0 ps are not allowed. This shows the need for a very precise field control of the photo-injector cavity. Maybe it should be equipped

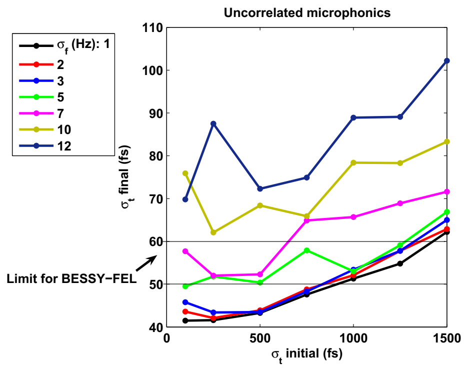

Figure 8: Final time jitter of the electron beam at the linac exit for different detuning level vs. the starting time jitter of the beam due to gun caused jitter.

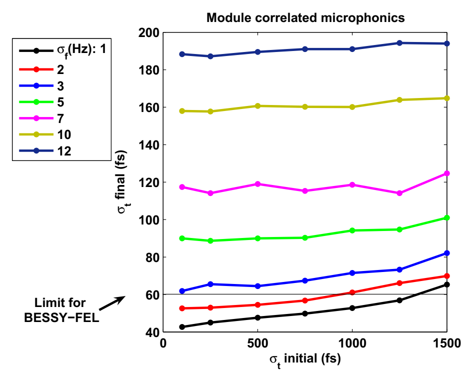

Figure 9: Final time jitter of the electron beam at the linac exit for different module-correlated detuning level vs. the starting time jitter of the beam due to gun caused jitter.

with a similar fast tuning system like a TESLA cavity assuming the superconducting injector solution.

OUTLOOK

A first estimate for the performance of the TESLA cavity at high loaded quality factor including the LLRF control and tuning controller has been shown. It bases on the modeling of the real tuning algorithm, which already showed its possible performance in the experiment. The expected required phase stability of 0.02-0.03° has been shown to be achievable by simulating with real measured error sources. This needed field stability has been the result of RF control linac simulations. To understand if phase noise and other sources for measurement noise are a limiting factor for LLRF controller performance, measurements with a real system have to be performed with different gain settings and even different accurate reference sources.

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