RF CONTROL OF THE SUPERCONDUCTING LINAC FOR THE BESSY FEL*

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Abstract

For the BESSY-FEL superconducting linac, precise RF control of the cavities' voltage is imperative to maintain a bunch-to-bunch time jitter of less than 50 fs for synchronization in the HGHG section. Noise, in particular microphonic detuning, strongly impact the achievable level of control. Presented here are simulations of the cavity-feedback system, taking into account beam loading and noise sources such as measurement noise, microphonics and injection jitter. These simulations are used to estimate the resultant time and energy jitter of the bunches as they enter the HGHG section of the BESSY-FEL. It will be shown, that under the given assumptions these requirements can be fulfilled.

INTRODUCTION

The superconducting linac for the BESSY-FEL will operate in continuous wave (CW) mode with a high-average-flux operation and flexible bunch pattern. The average beam loading in BESSY-FEL cavites is low. To match the cavity to the klystron, ideally weak input coupling is necessary and thus the cavity bandwidth (FWHM) is small (order 10 Hz). Thus the cavity is very sensitive to microphonic detuning of the resonance and an RF control system has to stabilize the cavity voltage. It is critical to minimize the bunch-to-bunch energy spread for two reasons:

1. The energy jitter should be less than the FEL bandwidth in order to not affect the FEL light output. The relative bunch-to-bunch energy σ_E/E should be less than $1{\cdot}10^{-3}$ [1].
2. Even assuming perfect synchronisation of the injection with the master clock, the bunches will jitter in time when arriving at the FEL stages. The requirements for this time jitter σ_t are less than 50 fs. Theoretically the bunch compressors (BC) will decrease the injection time jitter from the photoinjector by the same factor as for the bunch length, assuming the uncorrelated energy jitter is small. For effective time-jitter compression the field fluctuations have to be kept to a minimum.

To better understand the performance of the linac cavities, a simulation tool based on [2] has been developed. A model for a single cavity with controller was programmed and tested with respect to accuracy and stability. Later this model was expanded to calculate the energy and time jitter in the undulators. The momentum-path length dependency of the BC's and the linearising effect of a 3$^\mathrm{rd}$ harmonic cavity were included.

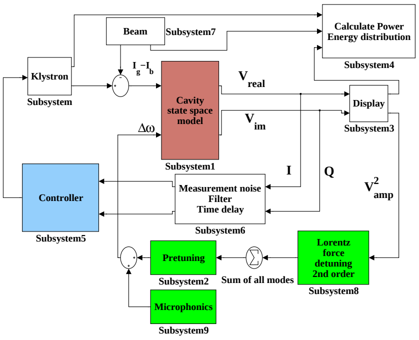

Figure 1: Simulation scheme

THE MATLAB MODEL

Cavity model

With the help of the Simulink Toolbox of the Matlab environment a model for a TESLA-type cavity has been developed. An overview is given in Fig. 1. Based upon the LCR circuit model for superconducting cavities [2] linear 2$^\mathrm{nd}$ order differential equations were solved by separating the slow variations of the field amplitude's envelope from the fast field oscillations. The beam and the RF source are modelled as current sources and, like the accelerating field are represented by phasors. Decoupling and linearizing around the cavity resonant frequency ω_0 allows the conversion to a linear state-space description (Eq. 1).

$$\begin{pmatrix}\dot{V}_\mathrm{r}\\ \dot{V}_\mathrm{i}\end{pmatrix} = \begin{pmatrix}-\omega_{1/2} & \Delta\omega\\ -\Delta\omega & -\omega_{1/2}\end{pmatrix}\cdot\begin{pmatrix}V_\mathrm{r}\\ V_\mathrm{i}\end{pmatrix} + \omega_0\cdot\left(\frac{R}{Q}\right)_\mathrm{L}\cdot\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}\cdot\begin{pmatrix}\frac{1}{m}\cdot I_\mathrm{gr}+I_\mathrm{br}\\ \frac{1}{m}\cdot I_\mathrm{gi}+I_\mathrm{bi}\end{pmatrix} \quad (1)$$

Here V is the cavity voltage, $\omega_{1/2}$ is the cavity bandwidth ($\omega_{1/2}$=$\omega_0/2Q_\mathrm{L}$), $\Delta\omega$ the detuning, m the transformer coupling, $(R/Q)_\mathrm{L}$ the loaded shunt impedance and I_g and I_b the RF generator current and beam current, respectively. The additional subscripts i and r refer to the imaginary and real components of the phasors.

Detuning model

The dominant error source affecting the cavities' field are the mechanisms that shift the cavity resonance (detuning). Two mechanisms are contributing to the total detuning: Lorentz-force (LF) and microphonics (mic.). Lorentz-force detuning is modelled by a 2$^\mathrm{nd}$ order state-space model

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[3], that incorporates mechanical eigenmodes of the cavity as measured at DESY [4]. Adding externally imposed microphonics yields the total detuning component $\Delta\omega$ of the cavities' system matrix at each time step. In CW mode the field causes a constant LF detuning of about 200–400 Hz. This is counteracted by a constant pretuning in the model.

The controller

The controller submodel is based on I-Q control of the cavity field. The control loop is realized as a PID controller with a feedback time delay to represent digital control latencies. So far, only the proportional controller has been examined. Additionally a low pass filter acts on the probe signal. I-Q control is the preferred solution rather than amplitude/phase control as a big phase error could otherwise shift the controller signal into the wrong quadrant.

Error sources

To find a realistic estimate for the bunch-to-bunch energy variation and time jitter several error sources have been included:

- Microphonics, a spectrum of 60 frequencies (0–500 Hz) simulating mechanical oscillations from vacuum pumps etc. with a normalized detuning of 5 Hz rms, this value being of the same order as measured at DESY [2].
- Klystron phase noise and saturation
- Beam loading including charge and injection time-jitter due to gun errors and laser jitter
- Measurement and conversion noise at the antenna and the ADC/DAC of the order of $\leq$0.1% of the measured signal
- Time delay in the control loop producing a phase shift of the controlling signal

Error sources uncorrelated from cavity to cavity are supressed by a factor of $\sqrt{N}$ (N= number of cavities) and are therefore less critical. For the linac calculations correlated errors include beam loading effects and phase noise of the master oscillator. Microphonics may contain both correlated and uncorrelated components, so that simulations were performed for both cases. To improve upon the simulations, more detailed measurements of microphonics are needed. Some of these will be carried out at the HoBiCaT facility [5].

Gain limit

Limiting parameters for the proportional gain K_{P} is the delay time (T_{d}) of the closed loop feedback. Applying standart control theory methods a critical gain of K_{P}=1900 ($\omega_{1/2} = 2\pi \cdot 27$ Hz, T_{d}=2μs) has been determined (compare [2]) and a gain of $\simeq 1/2{\cdot}K_{\mathrm{crit}}$ should guarantee a stable performance.

Table 1: Cavity simulation parameter

Parameter	**Value**
Quality factor (Q_0)	$1.3 \cdot 10^{10}$
External Quality factor (Q_{ext})	$2.4 \cdot 10^{7}$
Shunt impedance	1041 Ω
Klystron power (P_{max})	15 kW
Lorentz-force detuning constant (K_{L})	-1 $\frac{\mathrm{Hz}}{(\mathrm{MV/m})^2}$
Microphonics σ_{mic}	5 Hz RMS
Cavity mechanical modes [Hz]	111, 132, 146, 151, 173, 184, 205, 208, 217, 222
Mech. quality factors (q_{m}) [4]	5, 10, 80, 110, 55, 40, 71, 218, 230, 57
Measurement noise (white) σ_{M}	0.05–0.1 %
Feedback latency	1–2 μs
Injection time jitter (Gun) σ_{t}	250–500 fs
Charge jitter σ_{Q}	5–10 %
Proportional gain K_{P}	100–1000

SIMULATION RESULTS

Single Cavity

The cavity model was tested to determine the amplitude and phase stability under the conditions given in Table 1. Given in Fig. 2 is the calculated amplitude and phase stability of one cavity. The phase follows the dominant fluctuations in the detuning curve, whereas the amplitude is superimposed by the amplified noisy input of the klystron. The relative amplitude jitter is of the order of $\sigma_{\mathrm{A}}/A \approx 1.5 \cdot 10^{-4}$, the achievable phase error is $\sigma_{\Phi} \approx 0.014°$. This leads to an energy deviation of $\sigma_{\mathrm{E}}/E \approx 1.7 \cdot 10^{-4}$. In contrast to pulsed machines like TESLA there is little influence of LF detuning on the achievable stability because it is essentially constant. Rather microphonics are the dominant error source. The variation of LF detuning is about 4 Hz and less.

Given a restricted klystron power LF detuning may cause the cavity field to collaps. Fig. 3 shows amplitude and klystron power with a given detuning of 10 Hz rms, 21 Hz peak and a maximum klystron power of 8 kW. The solid curve represents a stable case, where sufficient klystron power is available to counteract the total detuning. The dashed curve shows the same case with an additional constant detuning (+ 12 Hz). The peak detuning (33 Hz) gives rise to a change in field amplitude, which results in a further change of the LF detuning. Because of insufficient power the loss of amplitude cannot be compensated enough to keep the change of the resulting LF detuning small. Thus the cavity is several bandwidths out of resonance. The field drops to a small amount of the set value.

BESSY-FEL linac simulations

To calculate the bunch-to-bunch deviations at the linac exit the model was expanded to 144 cavities including a 3 rd

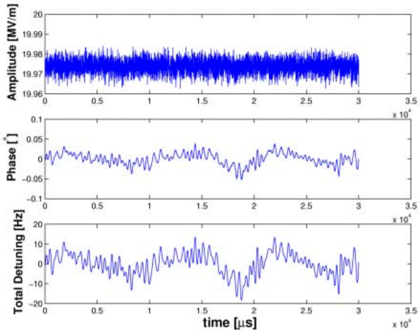

Figure 2: Amplitude-, phase stability and detuning, $K_\mathrm{P} = 800$, setpoints: $\Phi = 0.0°$, $V_\mathrm{set} = 16.0$ MV/m, $\frac{\sigma_\mathrm{A}}{A} = 1.5 \cdot 10^{-4}$, σ_Φ=$1.4 \cdot 10^{-2}$deg.

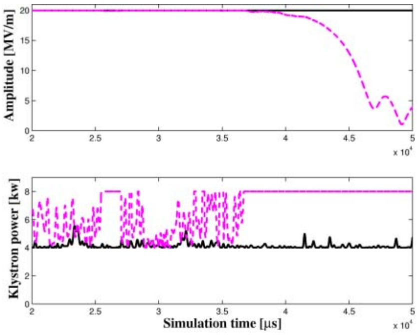

Figure 3: Amplitude and klystron power for $\sigma_\mathrm{mic} = 10$ Hz rms (black) and the same with constant detuning of 12 Hz (magenta, dashed curve), peak detuning 35 Hz. Maximum klystron power: 8 kW

harmonic cavity and the two BC stages.

For bunch compression acceleration is off-crest prior to the BCs. Due to the injection time jitter there is correlation of the energy jitter with the longitudinal position of the bunches. It follows, that the BC compress that jitter by the same factor as the bunch length, provided the uncorrelated energy jitter is small. To ensure this, the gain for the first linac sections should be higher (200–1000) than after the BCs, where acceleration is on crest (100).

Table 2 shows several simulation results where the error sources were varied. Under the conditions assumed so far with a total starting time jitter of 250 fs and uncorrelated mic. of 5 Hz rms the relative energy jitter of $\approx 6 \cdot 10^{-5}$ and the time jitter of 22 fs fulfill the FEL boundary conditions (Case A). Even with an injection jitter of 500 fs these conditions are achievable [1]. These cases incorporate an injector energy jitter of $1 \cdot 10^{-3}$.

The time jitter at the linac exit is mainly affected by the starting conditions, i.e. the injection time -and energy jitter. Assuming an energy jitter of $1 \cdot 10^{-2}$ from the gun and booster section (injection time jitter 250 fs) this leads to a total time jitter of 78 fs (Case B). It is therefore important to minimize the amplitude and phase errors of the injection and booster section.

Table 2: Linac simulation results for energy jitter (σ_E/E) and bunch-to-bunch time jitter (σ_t)

Case	Main Parameter	Result
A	σ_t=250 fs, σ_M=0.05 % σ_Q=5 %, σ_mic=5 Hz	σ_t=22 fs $\frac{\sigma_\mathrm{E}}{E} = 6.1 \cdot 10^{-5}$
B	σ_t=250 fs, σ_M=0.05 % σ_Q=5 %, σ_mic=5 Hz	σ_t=78fs $\frac{\sigma_\mathrm{E}}{E} = 6.0 \cdot 10^{-5}$
C	σ_t=500 fs, σ_M=0.1 % σ_Q=10 %, σ_mic=5 Hz corr.	σ_t=129 fs $\frac{\sigma_\mathrm{E}}{E} = 1.2 \cdot 10^{-4}$

σ_t = injection time jitter, σ_M = measurement noise, σ_Q = charge jitter and σ_mic = rms value of $\Delta\omega$. Case B with starting energy jitter of σ_E=40 keV. A and C include σ_E=4 keV. Case C is calculated with a totally correlated microphonics.

Also of significant influence are microphonics. Assuming an unlikely case of completely correlated microphonics this leads to a final time jitter of 130 fs (Case C).

OUTLOOK

The simulations show so far, that the requirements of the BESSY-FEL are attainable. Still for more realistic results several of the input parameters will be measured in the HoBiCaT cavity test facility [5]:

- Mechanical eigenmodes of the cavities and the spectrum of microphonic detuning, sources of microphonics
- Finding means of passive and active compensation of mechanical detuning with for example piezo actuators (e.g. [6])
- Measure phase noise of the complete feedback system including noise from the RF probe, klystron, mixers, ADC's, oscillators, cables, etc.

Furthermore one has to understand the achievable phase and amplitude control of the gun cavity for the total injection time and energy jitter.

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