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STATUS OF BEAM-BASED FEEDBACK RESEARCH AND DEVELOPMENT FOR CONTINUOUS WAVE SRF LINAC ELBE

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Abstract

The superconducting electron linear accelerator ELBE at Helmholtz-Zentrum Dresden-Rossendorf is a versatile light source operated in continuous wave mode. As the demand on the beam stability increases, the improvement of the beam control schemes currently installed at ELBE becomes highly relevant. This improvement can be achieved by an upgrade of the existing digital MicroTCA.4 based LLRF control scheme by a beam-based feedback. By presenting both the design and implementation details of the new control scheme this contribution reports the status of the work in progress.

INTRODUCTION

The Electron Linear accelerator for beams with high Brilliance and low Emittance (ELBE) is a versatile light source located at Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Germany. ELBE is one of the few electron linear accelerators routinely operated in a continuous wave (CW) mode, i.e. a mode in which a RF electromagnetic field that resonates inside a RF cavity is driven continuously. Compared to the much more common pulsed mode, the CW allows flexible electron bunch repetition rates, thus enabling experiments that would otherwise be impossible to perform, hence the versatility. Still, in order to achieve high quality of experimental results the properties of the accelerated electron beam, such as the energy E, arrival time ϕ_e and electron bunch length σ_z, must fulfill certain stability requirements. The resulting need for electron beam stabilization is highlighted in Fig. 1 that illustrates a general beamline layout affected by potential sources of instabilities, including the RF amplitude and phase noise δA_{RF} and $\delta\phi_{RF}$ together with the initial electron beam arrival time jitter $\delta\phi_e$.

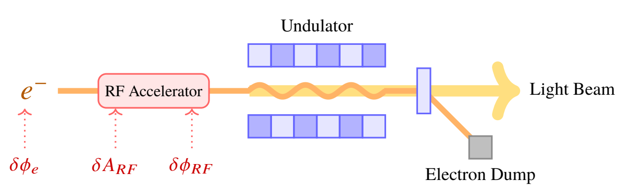

Figure 1: Beamline with potential sources of instabilities.

Usually the process of stabilization is carried out by a low level RF (LLRF) controller that tracks RF field amplitude and phase inside a RF cavity. However, a typical LLRF controller operates only in terms of the RF field and thus lacks any feedback from the beam. To overcome this limitation the control system of ELBE is planned to be upgraded by a beam-based feedback (BBF). The BBF controller will sense the beam properties and based on this feedback will instruct the existing LLRF controller to make corrections to the RF field of the accelerating cavity in order to improve the quality of the passing electron beam. Figure 2 presents a general concept of such control system upgrade when applied to a bunch compressor section of a beamline.

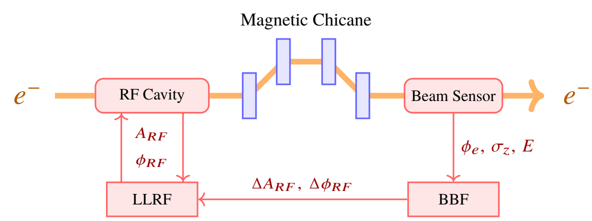

Figure 2: Conceptual scheme of a beam-based feedback.

Even though there exists a number of beam-based feedback designs applied to linear accelerators, including [1] and [2], these examples target pulsed machines. Yet ELBE is operated in CW mode. From a control perspective such operation mode could allow us to see much more of the noise spectrum when compared to the pulsed mode where one sees only snapshots. Therefore, there exists a research and development gap in the field of beam-based feedback regulation applied to CW machines, and in this paper we aim to bridge this gap by presenting the essential points of our system analysis followed by the corresponding conclusions.

SYSTEM IDENTIFICATION

In this work the interaction between an electron beam and a linear accelerator is modelled in terms of a bunch compressor, i.e. an interconnection of a chirping RF cavity and a magnetic chicane. This allows to elaborate the commonly known mathematical definition of a bunch compression [3] in such a way that exposes the propagation of various noise sources to electron beam properties, namely

$$\Delta\phi_{e_f} = R_{56}\cdot\frac{\Delta E}{E_0}, \tag{1}$$

$$\Uparrow$$

$$E_f = E_i + e\underset{\substack{\Uparrow\\ \delta A_{RF}}}{A_{RF}}\cdot\cos\left(\underset{\substack{\Uparrow\\ \delta\phi_{RF}}}{\phi_{RF}} + \underset{\substack{\Uparrow\\ \delta\phi_{e_i}}}{\phi_{e_i}}\right), \tag{2}$$

where E_i and E_f are the initial and final electron bunch energy respectively, while E_0 is the nominal energy expected at the magnetic chicane, R_{56} is a magnetic chicane design parameter that translates energy deviation into longitudinal position deviation, e is an electron charge, and finally $\Delta\phi_{e_f}$

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is the final arrival time change. Above all, (1) and (2) reveal that from a control point of view a bunch compressor represents a static system [4], and thus a sensitivity scan suffices to build an electron beam model. In this work we consider a static matrix $G_e = \begin{bmatrix} m_{11} & m_{12} \end{bmatrix}$ that represents the sensitivity between changes in RF amplitude and phase and a response in beam arrival time. Figure 3 demonstrates the result of such a scan performed at ELBE.

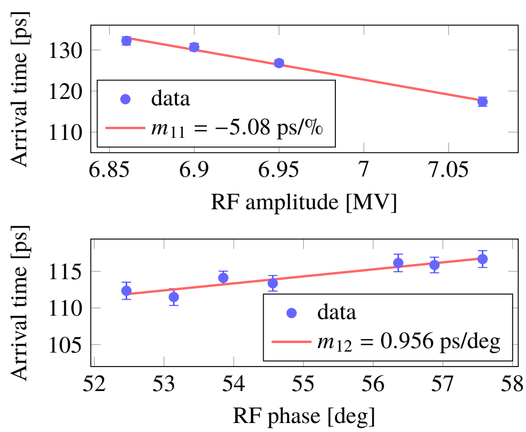

Figure 3: RF to beam arrival time sensitivity scan.

Furthermore, a static model of a bunch compressor implies that any dynamic behavior observed at the output of the bunch compressor is determined by 1) RF noise sources δA_{RF} and $\delta\phi_{RF}$ and 2) initial electron beam arrival time fluctuations $\delta\phi_{e_i}$. Since the latter come from the up-stream region of the beamline where beside noise contribution originating from the electron gun other RF noise sources may reside as well, in this work we turn special attention to RF noise modelling.

Radio Frequency Noise

An ideal radio frequency signal does not exist in the real world, because typically amplitude and phase fluctuations contaminate the signal. As illustrated in Fig. 4 these unwanted fluctuations cause the spectral representation of the signal to contain a spread of spectral lines both below and above the carrier frequency.

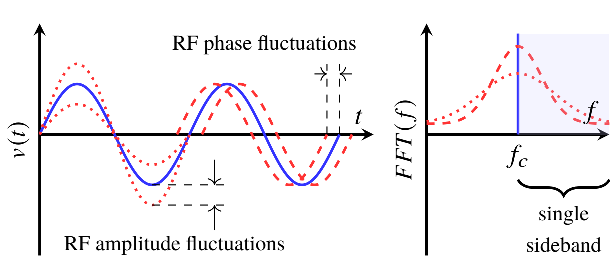

Figure 4: RF noise in time and frequency domain.

According to the standard [5] the spectral components, or sidebands, produced by RF amplitude and phase fluctuations can be represented as one-sided spectral densities S_a and S_ϕ respectively. Figure 5 presents such spectral densities that were first measured at a TESLA cavity installed at ELBE and then approximated by corresponding shaping filters G_a and G_ϕ. These infinite impulse response (IIR) filters approximate the RF noise shapes up to 1 kHz only, because we consider the major RF noise contributors to reside below this particular frequency [6].

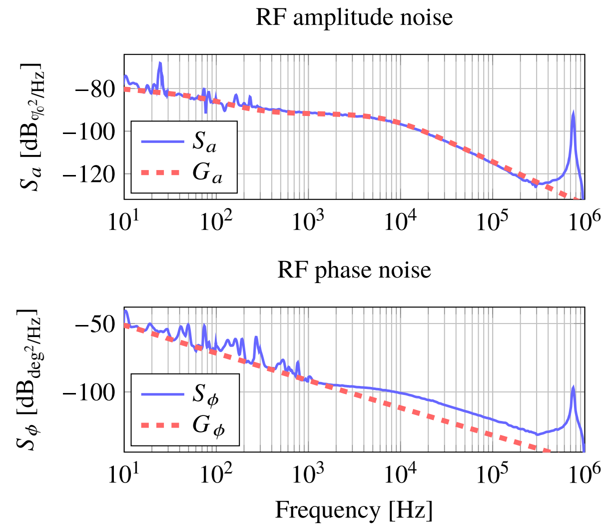

Figure 5: RF amplitude and phase noise frequency spectra approximated by shaping filters.

As the resulting shaping filters describe the noise dynamics that acts on the beam, these filters can now be used as noise models to build a controller for electron beam regulation.

ELECTRON BEAM REGULATION

By taking into account the stochastic nature of RF noise together with the steady state operation of a CW machine we could reinterpret our control objective as a regulation goal where we would like to minimize the response of our system to white noise excitation. Obviously, this minimization should be carried out in terms of the corresponding rms value. But rms response of a system H driven by white nose excitation is given by its $\mathcal{H}_2$ norm [7]

$$\|H\|_2 \triangleq \left(\frac{1}{2\pi}\int_{-\infty}^{\infty}\left|H(j\omega)^2\right|d\omega\right)^{1/2}, \tag{3}$$

where $|H(j\omega)|$ designates the magnitude frequency response of H evaluated at frequency ω. Indeed, the presence of RF noise makes the assumption of white noise disturbances totally relevant in our case [8], thus allowing us to meaningfully apply $\mathcal{H}_2$ control method [9] to stabilize the electron beam with respect to RF noise.

Following this, a disturbance rejecting controller was designed, and the corresponding simulation result is demonstrated in Fig. 6. In this simulation a noise model was applied that caused beam arrival time fluctuations y_{arr} with a rms value of ca. 200 fs. After that, starting at second 1, feedback

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was turned on to counteract the fluctuations and produce a compensated output $y_{\tilde{arr}}$ with a rms value of ca. 20 fs.

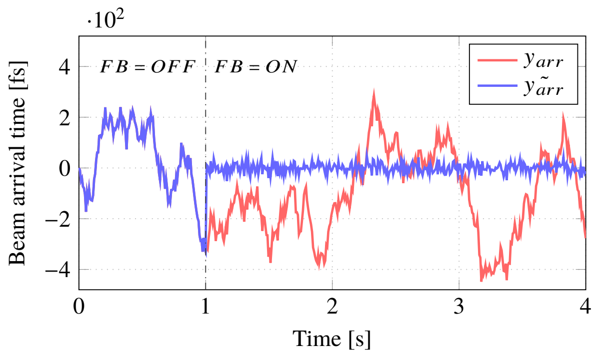

Figure 6: $\mathcal{H}_2$ controller performance in simulation.

CONCLUSIONS

Beam-based feedback can be used as an effective control method to enhance the properties of a particle beam. While solutions exist for electron linear accelerators operated in pulsed mode, the continuous wave mode enables additional interpretations of the given control problem. In particular, the inherent steady state operation of a continuously driven accelerating RF cavity allows focusing the control objective exclusively on disturbance rejection.

Therefore, in this paper we used the RF noise shaping filters obtained from a measurement at ELBE to reinterpret the beam-based feedback control objective as a disturbance rejection goal. By considering the stochastic nature of the disturbance we were able to build a $\mathcal{H}_2$ controller to compensate the beam arrival time fluctuations with respect to RF noise.

OUTLOOK

The next step would be to express the designed control algorithm using a hardware description language VHDL in order to implement the controller on a FPGA. This will allow to integrate the new controller into the existing digital MicroTCA.4 based hardware platform, thus bringing us one step closer to realizing beam-based feedback control at the linear accelerator ELBE.

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