Improving Beam-Based Regulation for Continuous-Wave Linear Accelerators with a Disturbance Model-Based Design

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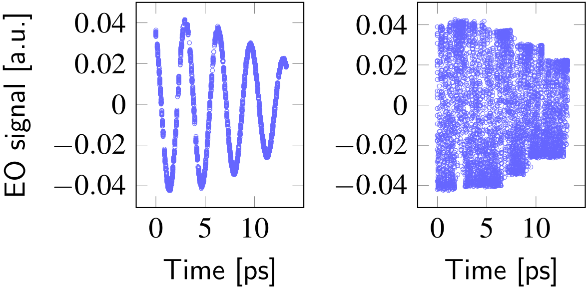
Outline

Outline

Temporal stability of time-resolved experiments

Time-resolved experiments rely on a tight synchronization between a pump source, which is typically an optical laser, and a source that generates the probes, i.e. the accelerator-based light source.

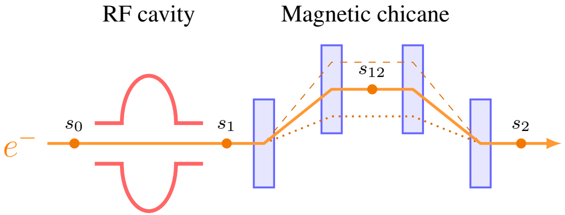


(a) (b)

- **(a)** and **(b)** show TELBE data under different levels of sync
- **(b)** is artificially distorted by a laser system on experimental side

Outline

Bunch compression



- Besides compression, this technology delays or advances an electron bunch w.r.t. some target position in a beamline
- Energy received by the bunch in the cavity defines the subsequent path taken through the chicane
- This side-effect can be used to regulate the bunch arrival time

Required system components

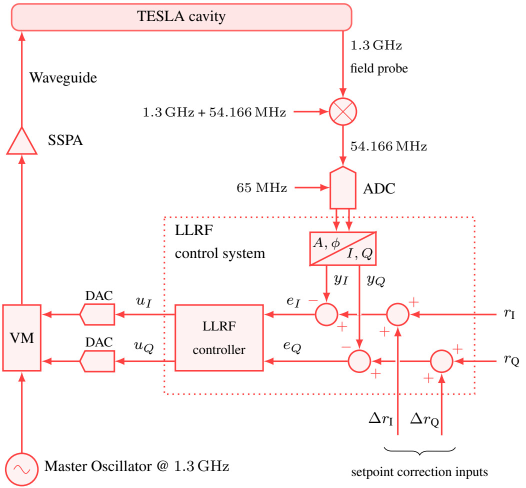
According to the transfer maps of the RF cavity and magnetic chicane

$$\Delta\delta = \frac{eA}{E_0}\cos\phi, \tag{1}$$

$$\Delta\tau = \frac{1}{v}R_{56}\Delta\delta, \tag{2}$$

- Energy change in (1) requires an actuator to modulate the RF field amplitude A and phase ϕ
- Arrival time τ in (2) needs to be diagnosed by a sensor

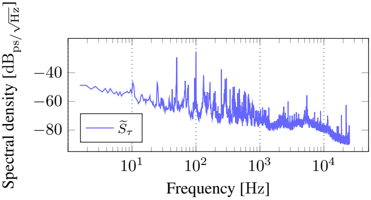
The actuator: low-level RF control system



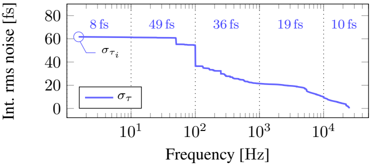
Parameter	Value
SRF cavity bandwidth	100 Hz
LLRF bandwidth	35 kHz
LLRF gain margin	12 dB

The sensor: bunch arrival time monitor (BAM)

Continuous-wave mode enables the analysis of high-resolution frequency spectra



(a)



(b)

- $\widetilde{S}_\tau$ shows the frequency content of τ
- σ_τ is backwards integrated rms noise

$$\sigma_\tau = \sqrt{\int_{f_1}^{f_2} \left[\widetilde{S}(f)\right]^2 \mathrm{df}} \qquad (3)$$

- σ_{τ_i} equals 62 fs rms

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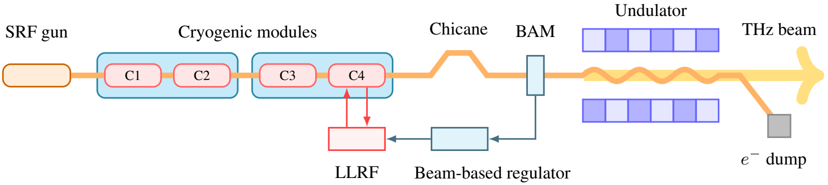
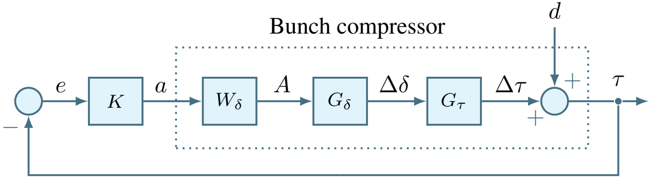
THz beamline of the linear accelerator ELBE



- Electron bunches emitted by SRF gun with 50 kHz repetition rate
- Bunch charge of 225 pC enables BAM resolution of 4 fs rms
- The beamline operates in continuous-wave mode
- A single regulation stage is installed into the THz beamline

Outline

Design of a proportional beam-based regulator



Then let disturbance d be a unit step
and let regulator K be an inverse of the bunch compressor plant, i.e.

$$K = \gamma G_{BC}^{-1}, \quad (4)$$

where

$$G_{BC} = G_\tau G_\delta W_\delta = \frac{1}{v} R_{56} \cdot \frac{eA}{E_0} \cos\phi \cdot \frac{1}{100}, \quad (5)$$

and where γ is an additional gain to adjust the regulator performance.

Means for analytical performance evaluation

The final value theorem shows the final value of $e(t)$, i.e. the error of a closed-loop system, as t approaches infinity.

Final value theorem

Given the assumption that disturbance d is a unit step, the theorem is

$$e(\infty) = \frac{1}{1 + \lim_{s \to 0} L(s)}, \tag{6}$$

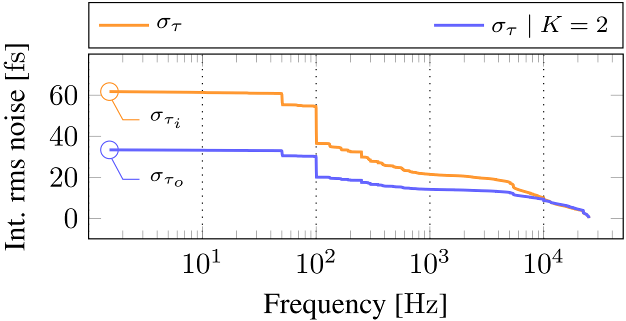
But from (4)

$$\lim_{s \to 0} L(s) = \lim_{s \to 0} G_{BC} K = G_{BC} K = \gamma G_{BC} G_{BC}^{-1} = \gamma, \tag{7}$$

so

$$e(\infty) = \frac{1}{1 + \gamma}. \tag{8}$$

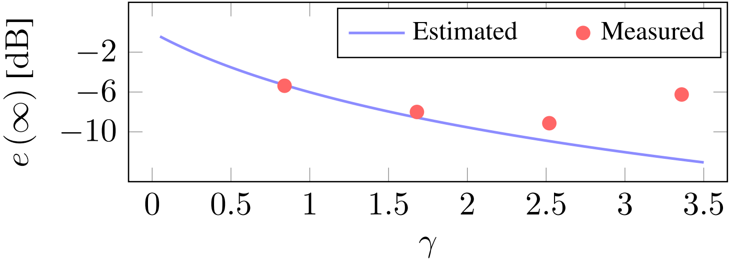
Means for machine performance evaluation



Then, $e(\infty)$ can be redefined as

$$e(\infty) = \frac{\sigma_{\tau_o}}{\sigma_{\tau_i}}. \tag{9}$$

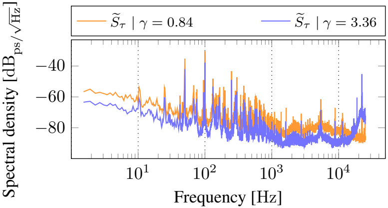
Evaluation of proportional regulator



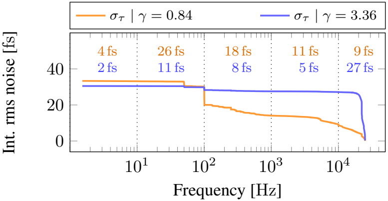
Increasing γ on the real machine, i.e. $K = \begin{bmatrix} 2 & 4 & 6 & 8 \end{bmatrix}^T$,

- Does not reduce $e(\infty)$ according to the analytical estimation in (8)
- Causes (9) to substantially deviate

Worst-case performance: strong oscillations



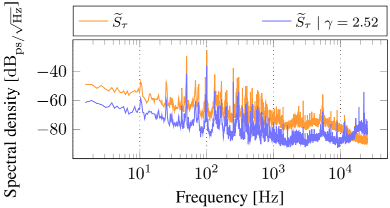
(a)



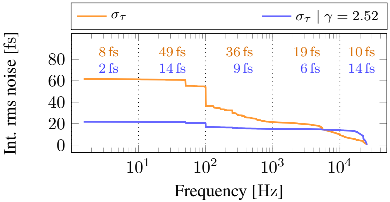
(b)

- **(a)** Proportional regulator affects all frequency range
- **(a)** A pronounced plant oscillation is triggered above 10 kHz
- **(b)** This results in a large integration step above 10 kHz
- **(b)** Compared to a less aggressive regulator, this step almost completely negates the applied regulation effort

Optimal performance: moderate oscillations



(a)



(b)

- **(a)** Setting $\gamma = 2.52$ causes a moderate oscillation above 10 kHz
- **(b)** The set γ allows to suppress the integrated rms noise by a factor of 3, i.e. only 22 fs of rms noise remains out of 62 fs rms

Conclusions on proportional case

Proportional regulator is a constant with no bandwidth defined, so

- It becomes part of LLRF dynamics and shares its stability margins
- Increasing γ consumes the gain margin of LLRF
- This triggers unwanted plant oscillations in high-frequency range

Is it possible to improve this system and decouple from LLRF?

Outline

Disturbance modeling parameters

Bandwidth

- The majority of noise resides below $1\,\mathrm{kHz}$
- Decoupling from LLRF dynamics is important
- Select one order of magnitude less than LLRF, i.e. $< 3.5\,\mathrm{kHz}$

Magnitude

Draw a parallel between the size of signal τ expressed as (3) and the $\mathcal{H}_2$ norm of a system expressed as

$$\|G\|_2 \triangleq \sqrt{\frac{1}{2\pi}\int_{-\infty}^{\infty} |G(j\omega)|^2 \,\mathrm{d}\omega}, \tag{10}$$

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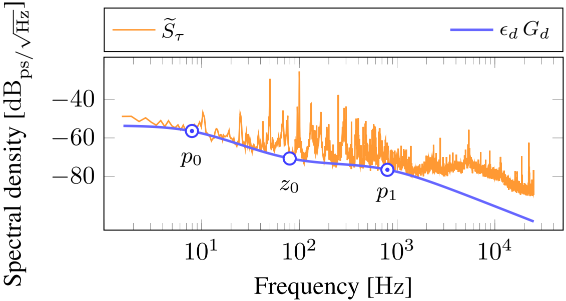
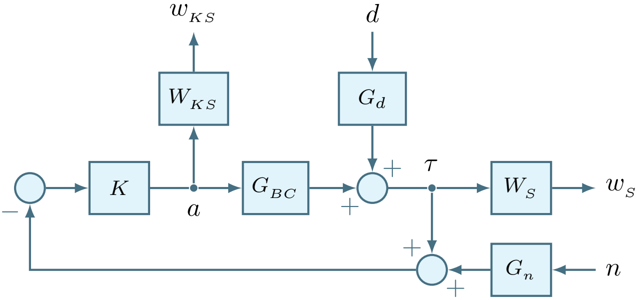
Filtered frequency content



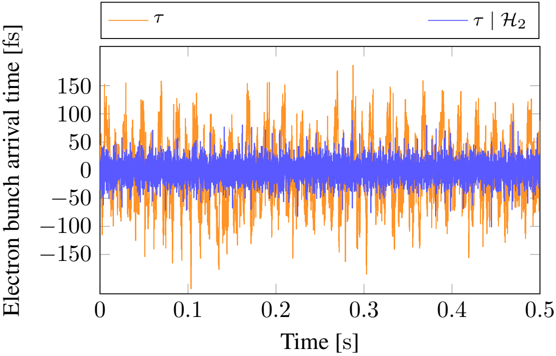
- G_d filters theoretical white noise into the frequency content of $\widetilde{S}_\tau$
- G_d is defined in terms of s-domain poles p and zeros z
- G_d matches the frequency content up to $1.5\,$kHz
- $\mathcal{H}_2$ norm of G_d corresponds to σ_{τ_i}

$\mathcal{H}_2$ regulation method



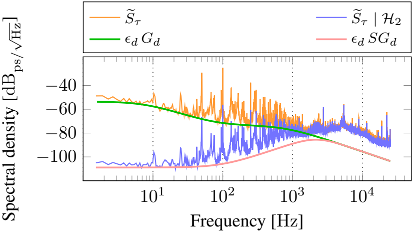
- $\mathcal{H}_2$ method tries to minimize the $\mathcal{H}_2$ norm of a transfer function from d to τ
- K is now a dynamical 4th-order $\mathcal{H}_2$ regulator
- Due to decoupling, the plant G_{BC} is still a constant

$\mathcal{H}_2$ performance: time domain

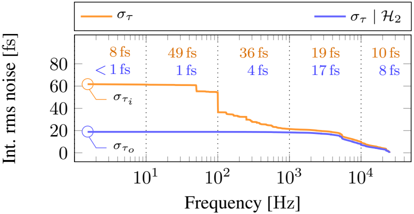


- Large slow fluctuations disappear, whereas small fast ones stay
- Natural outcome for a bandwidth-limited regulator

$\mathcal{H}_2$ performance: frequency domain



(a)



(b)

- **(a)** In frequency domain, machine data shows correspondence with the model
- **(b)** Integrated rms noise data show suppression below 20 fs, i.e. from $\sigma_{\tau_i} = 62$ fs rms down to $\sigma_{\tau_o} = 19$ fs rms
- **(b)** High-frequency range is left intact

Outline

Conclusion and thesis of this work

A single regulation stage, which is installed in a continuous-wave linear accelerator and features a disturbance model-based beam-based regulator, has a potential to outperform a commonly used proportional regulator, without compromising the accelerator stability.

Future work

- Regulation of high-frequency noise, i.e. above $3.5\,$kHz
- Regulation of electron bunch compression
- Elimination of slow drifts

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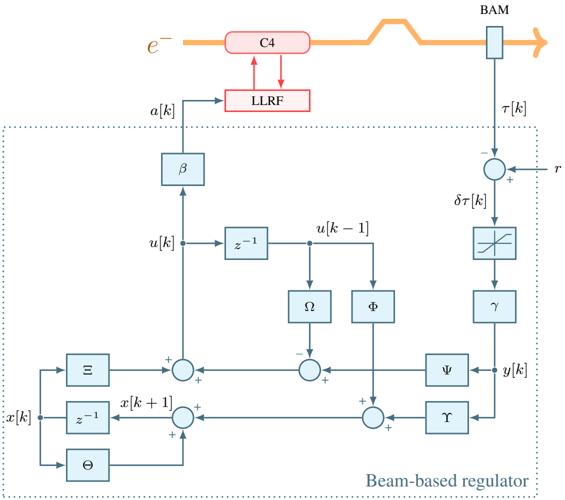
Reference

A. Maalberg, M. Kuntzsch, K. Zenker and E. Petlenkov,
"Regulation of electron bunch arrival time for a continuous-wave linac: Exploring the application of the $\mathcal{H}_2$ mixed-sensitivity problem,"
Phys. Rev. Accel. Beams, accepted for publication.

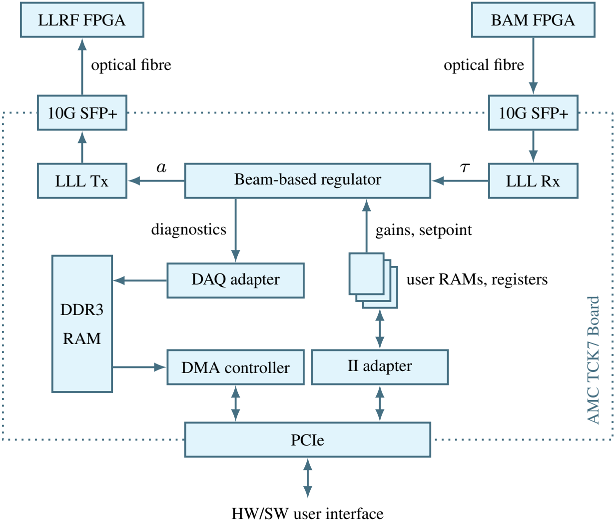
Thank you for your attention!

Backup slides

Cascaded loops with regulator matrices

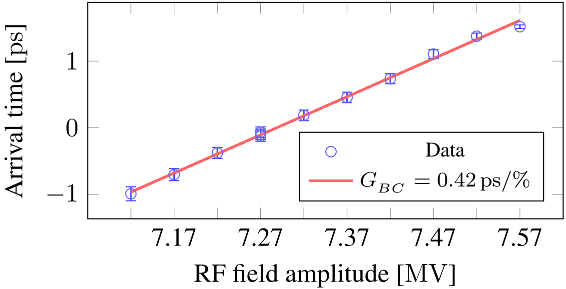


MTCA hardware environment



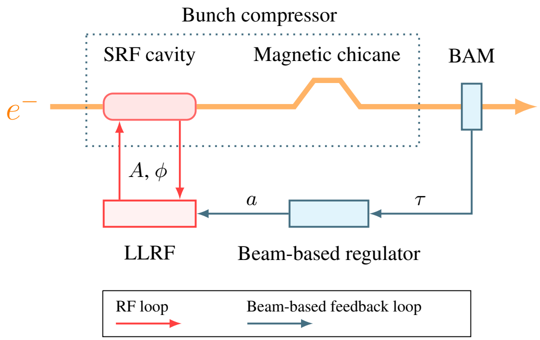
Measuring beam response matrix

- Evaluation of (5) with machine parameters does not match reality
- So measure beam response matrix on the real machine



- RF field amplitude setpoint $A = 7.27\,\text{MV}$ changed by steps of $50\,\text{kV}$

Beam-based feedback and cascaded loops



- Beam-based feedback introduces cascaded loops into the system
- RF becomes the inner loop, beam-based feedback - the outer loop
- Regulator uses the inner loop to regulate τ by manipulating A

Transfer maps of bunch compressor

Transfer map of RF cavity

$$z(s_1) = z(s_0), \tag{11}$$

$$\delta(s_1) = \delta(s_0) + \frac{eA}{E_0}\cos\left(\frac{\omega}{c}z(s_0) + \phi\right), \tag{12}$$

Transfer map of magnetic chicane

$$z(s_2) = z(s_1) + R_{56}\,\delta(s_1), \tag{13}$$

$$\delta(s_2) = \delta(s_1), \tag{14}$$

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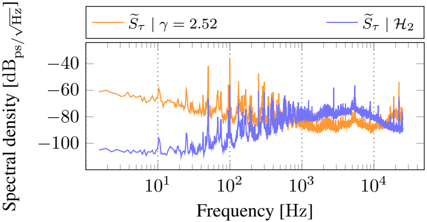
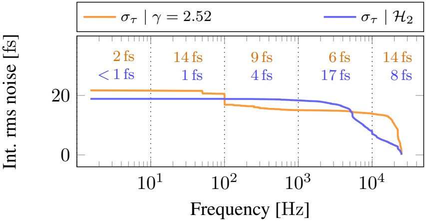
Proportional vs. $\mathcal{H}_2$ in frequency domain



(a)



(b)

- **(a)** shows different behaviors of the two regulators depending on the frequency range
- **(b)** elaborates this difference by displaying band-limited amounts of integrated rms noise