Beam-based feedbacks for CW machines

A. Maalberg[1,2] M. Kuntzsch[1] K. Zenker[1] E. Petlenkov[2]

[1]Helmholtz-Zentrum Dresden-Rossendorf
Department Radiation Source ELBE

[2]Tallinn University of Technology
Department of Computer Systems

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Outline

1 Introduction
- Context and scope

2 Beam-based feedbacks
- State of the art
- Continuous wave-enabled control design

3 Summary
- Conclusions

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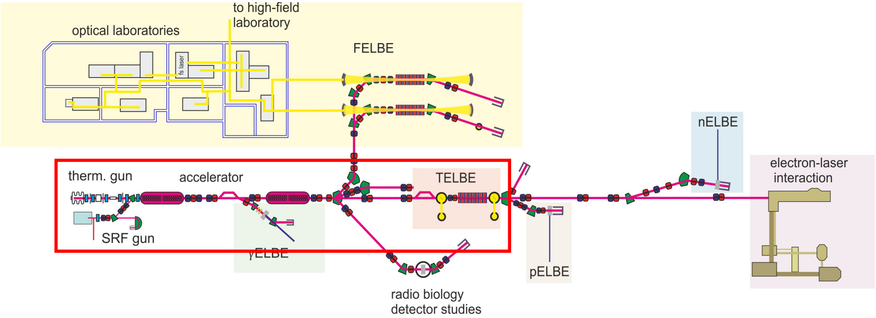
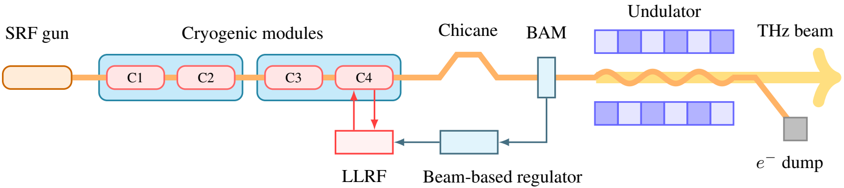
ELBE - a versatile source of secondary radiation



- User facility with secondary radiation sources
- Operation in pulsed and continuous-wave mode
- Up to 40 MeV of beam energy and 1.6 mA of avg. beam current

Beam-based feedback upgrade of TELBE



- Digital LLRF enabled beam-based feedback
- Bunch arrival time monitor has a resolution of 4 fs rms at 200 pC of bunch charge

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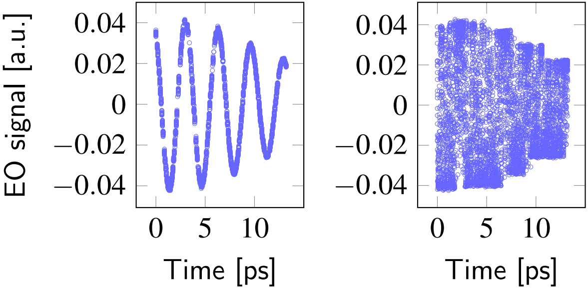
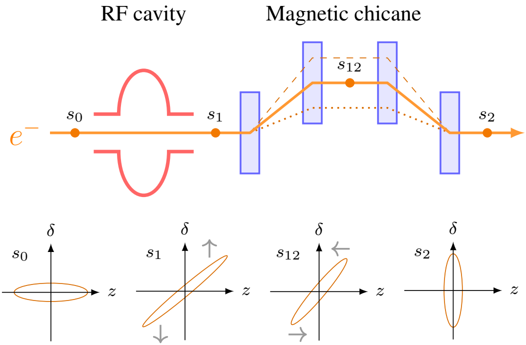
Improving temporal stability for TELBE



- Time-resolved user experiments are sensitive to timing fluctuations
- Stability of bunch arrival time becomes crucial

Bunch compressor as a plant



- Besides compression, the technology can delay or advance an electron bunch w.r.t. a target position
- Use RF field amplitude to change bunch arrival time

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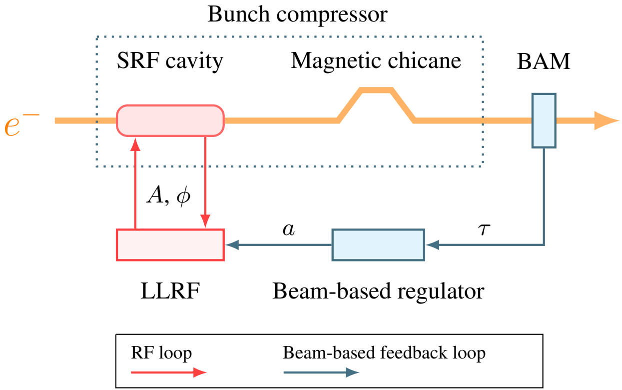
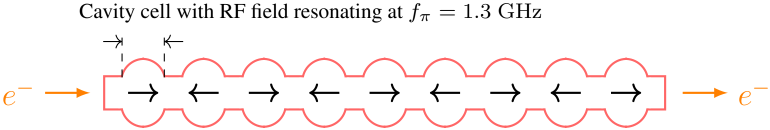
Bunch compressor with a beam-based feedback



- Cascaded loops are introduced into the control system, where
  - RF is the inner loop
  - Beam-based feedback is the outer loop

TESLA cavity



- Band-pass filter with a rather narrow half-bandwidth of $100\,$Hz
- Closing the loop with LLRF controller extends the closed-loop bandwidth as $100\,$Hz $\rightarrow 35\,$kHz
- LLRF introduces a gain margin

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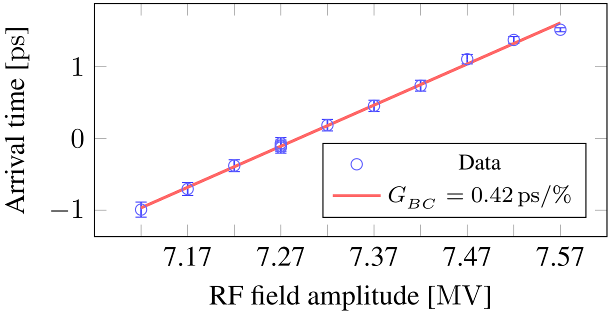
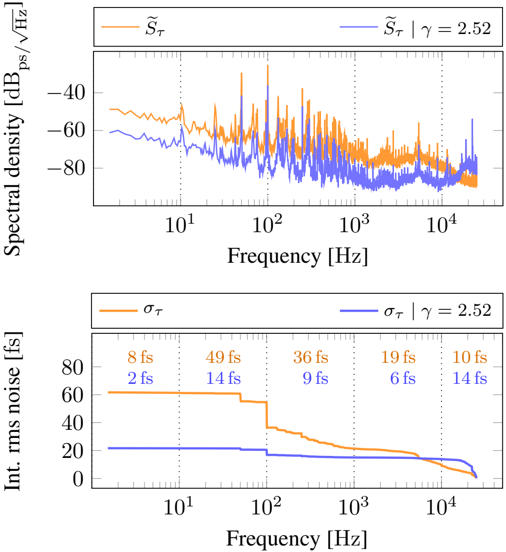
State-of-the-art beam-based regulator

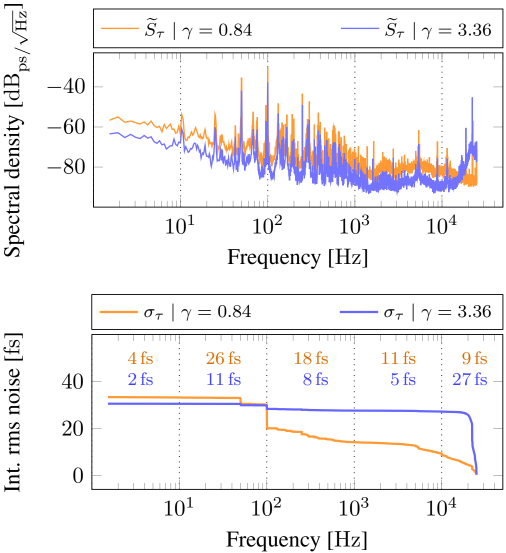


- Machine measurement of beam response to RF field changes
- RF field amplitude setpoint $A = 7.27\,\mathrm{MV}$ changed by steps of $50\,\mathrm{kV}$
- Inverse of plant G_{BC} becomes a beam-based regulator

Performance of a state-of-the-art regulator



When gain is further increased ...



Takeaways from state-of-the-art control

- State-of-the-art regulator has no bandwidth definition
- Beam-based feedback becomes coupled with RF loop dynamics
- Regulator has to rely on inner loop parameters, e.g. gain margin
- Noise suppression of 62 fs rms $\rightarrow$ 22 fs rms

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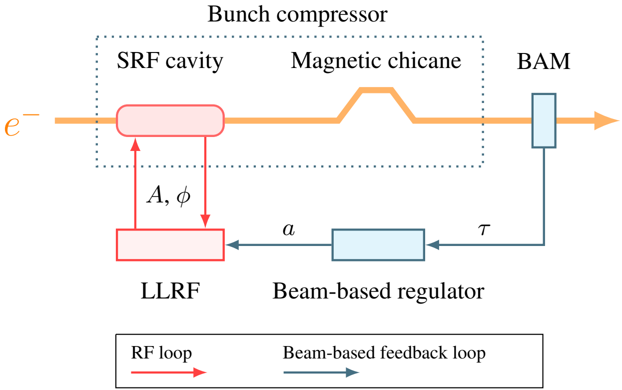
Bunch compressor with beam-based feedback



- Cascaded loops are introduced into the control system, where
  - RF is the inner loop
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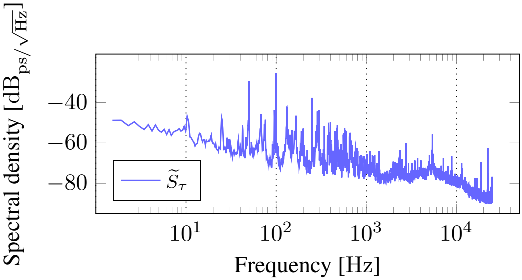
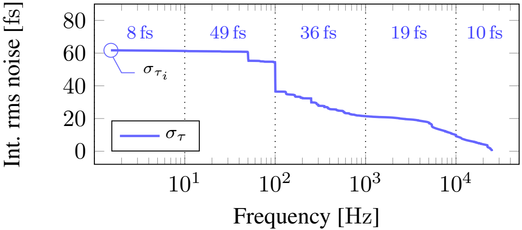
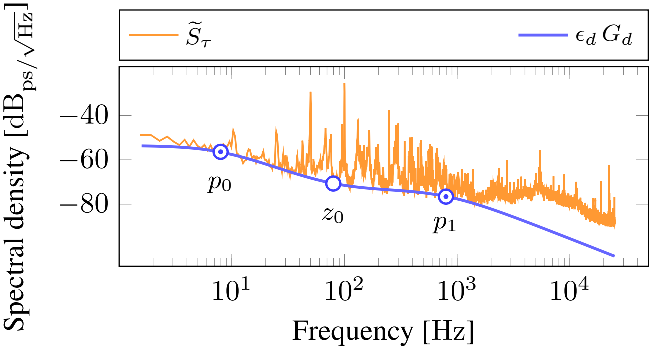
Bunch arrival time signal



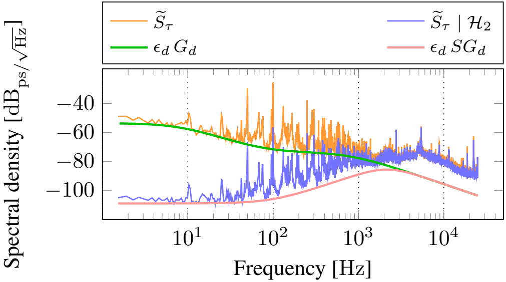


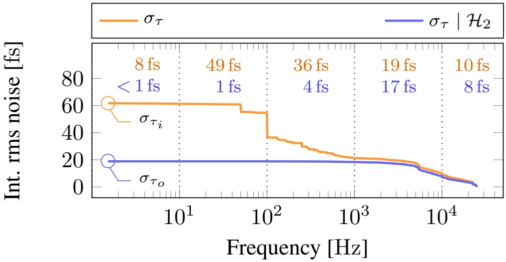
Disturbance model



- Model matches the frequency content up to 1.5 kHz
- $\mathcal{H}_2$ norm of the model corresponds to the size of rms fluctuations

Performance of a CW-enabled regulator





Takeaways from CW-enabled control design

- CW allows to create high-resolution frequency spectra from data
- Modeling of dynamical disturbance becomes feasible
- CW-enabled regulator becomes decoupled from RF loop dynamics
- High-frequency range is left intact by the new regulator
- Noise suppression of $62\,\text{fs}$ rms $\rightarrow 19\,\text{fs}$ rms

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Limitations of established technologies

- Beam-based feedback can become coupled with RF dynamics
  - CW allows dynamical modeling of noise
- Superconducting RF cavity is a slow actuator
  - Normal conducting cavity can be used for fine tuning of noise
- BAM has a resolution of 4 fs rms
  - Remains an open question??

Member of the Helmholtz Association
Andrei Maalberg | Helmholtz-Zentrum Dresden-Rossendorf | http://www.hzdr.de

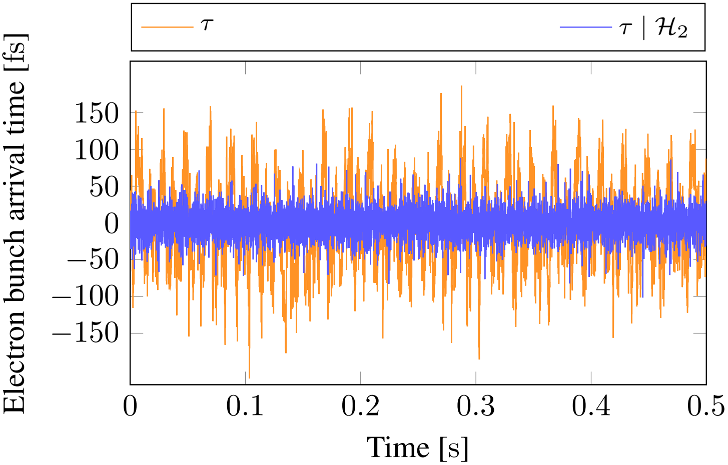
More on the topic of CW-enabled control design

Maalberg, A.; Kuntzsch, M.; Zenker, K.; Petlenkov, E. 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* **26**, 072801 (2023), doi: 10.1103/PhysRevAccelBeams.26.072801

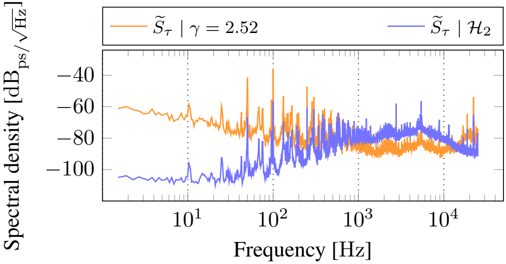
Thank you for your attention!

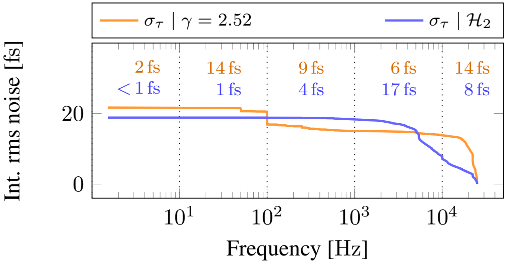
Backup slides

Performance in time domain ...

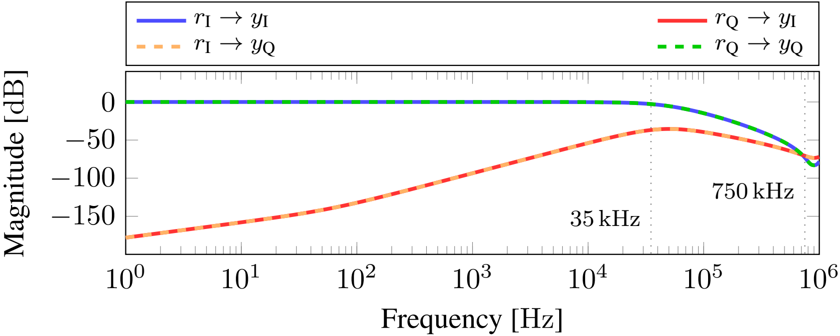


State-of-the-art vs. CW-enabled regulation



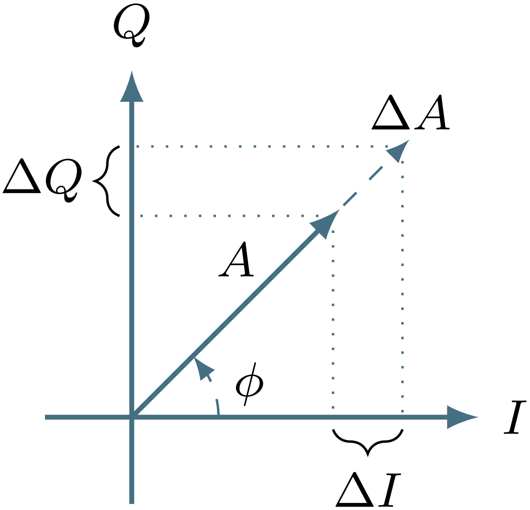


Closed-loop LLRF control system

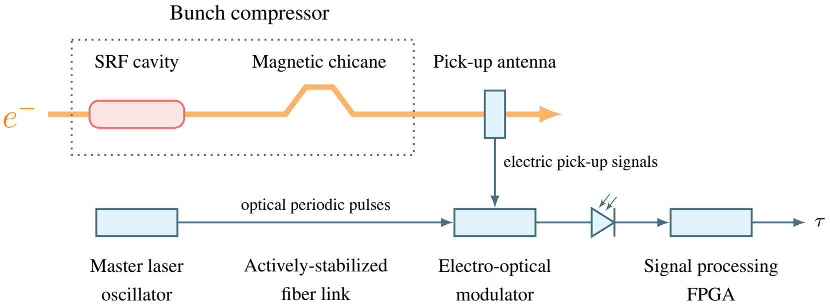


- Closed-loop bandwidth is 35 kHz
- Suppression of the parasitic $\frac{8}{9}\pi$ mode is observed at 750 kHz

Modulation of I and Q with amplitude A

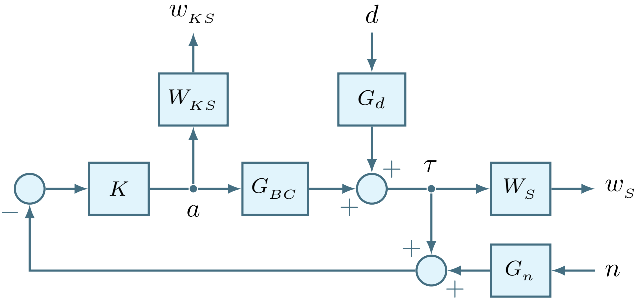


Bunch arrival time monitor (BAM)



- Bunch arrival time is measured relative to an actively-stabilized timing reference
- BAM has a resolution of 4 fs rms

$\mathcal{H}_2$ mixed-sensitivity problem



- Synthesize K that makes output τ less sensitive to disturbance d

Integration with MicroTCA digital platform