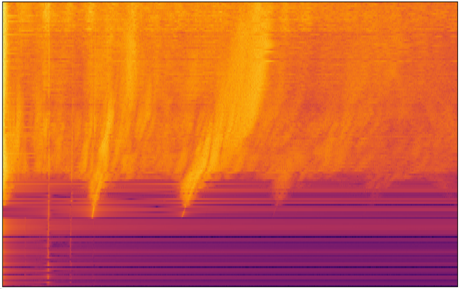
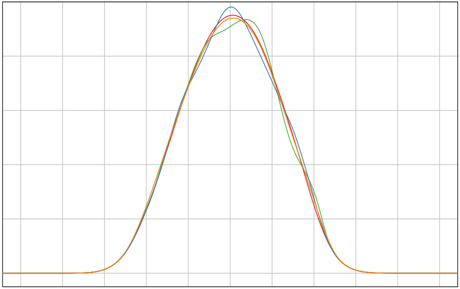
Comprehensive Analysis of Micro-Bunching Instabilities using Machine Learning

Tobias Boltz, Miriam Brosi, Erik Bründermann, Florian Rämisch, Patrik Schönfeldt, Markus Schwarz, Minjie Yan and Anke-Susanne Müller | July 4, 2017

Laboratory for Applications of Synchrotron Radiation (LAS)





Outline

- Motivation
- Introduction of the Clustering Method *k*-means
- Pre-Processing
- Analysis of Micro-Structure Dynamics
- Analysis of Further Characteristics
- Outlook

Motivation

General Approach

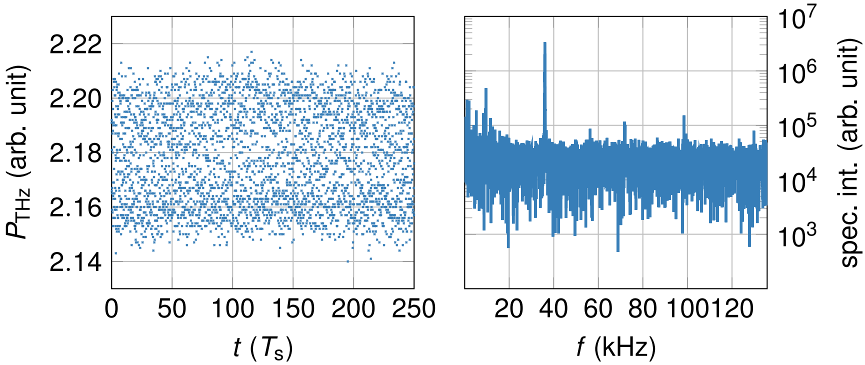
- operation of storage rings with short electron bunches increases coherent synchrotron radiation (CSR) power
- leads to micro-structure dynamics within the bunch
- indirect measurement: resulting fluctuations in the emitted CSR power
- direct measurement: electron distribution, difficult due to the small scale of the micro-structures

$\Rightarrow$ simulation of longitudinal dynamics with the simulation code Inovesa

Schönfeldt, P. *et al.* Parallelized Vlasov-Fokker-Planck solver for desktop personal computers. *Phys. Rev. Accel. Beams* **20** (2017)

Motivation

Measured Fluctuations of the CSR power (Bursting)

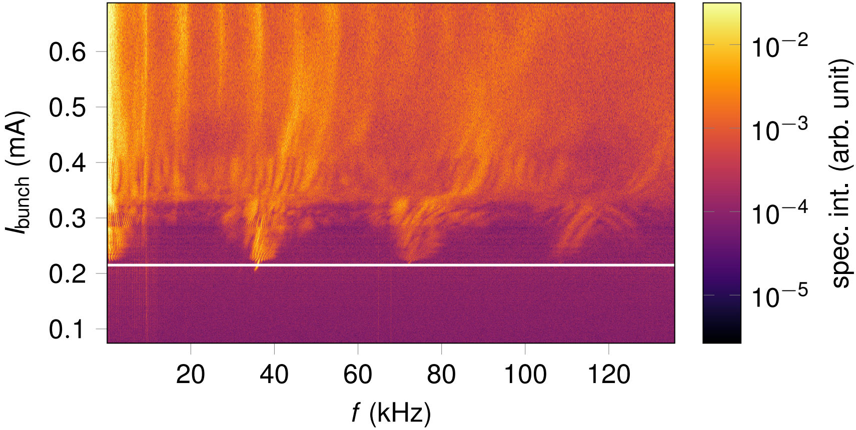


⇒ fluctuations occur with characteristic frequencies

Data taken at ANKA, courtesy of Miriam Brosi

Motivation

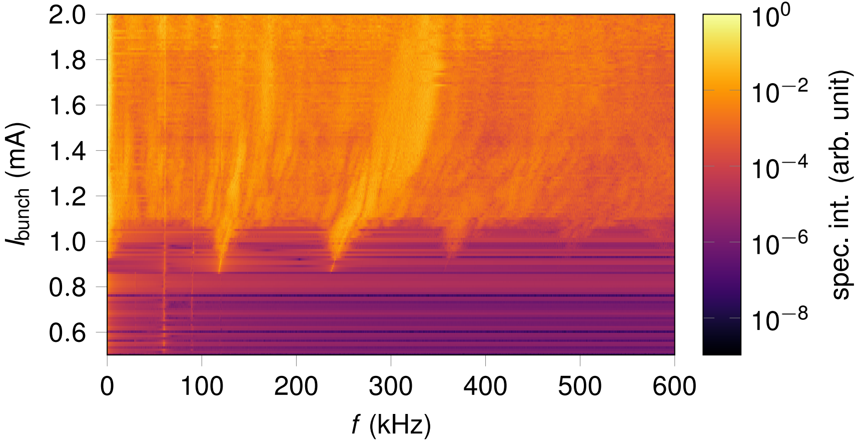
Measured Bursting Spectrogram



Data taken at ANKA, courtesy of Miriam Brosi

Motivation

Simulated Bursting Spectrogram



Motivation

General Approach

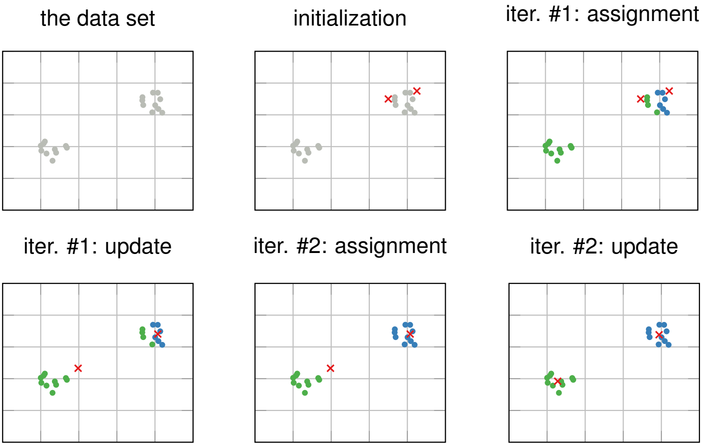
- identify micro-structures on the simulated longitudinal bunch profiles
- correlate findings to the emitted synchrotron radiation, i.e. the CSR power spectrogram

⇒ large amounts of data to analyze!
(151 bunch currents with 10 000 time steps each,
i.e. 1.5 million bunch profiles in the simulation data set)

⇒ application of the machine learning technique *k*-means
to reveal micro-structures within a fixed bunch current

Clustering method *k*-means

Principle of the *k*-means algorithm



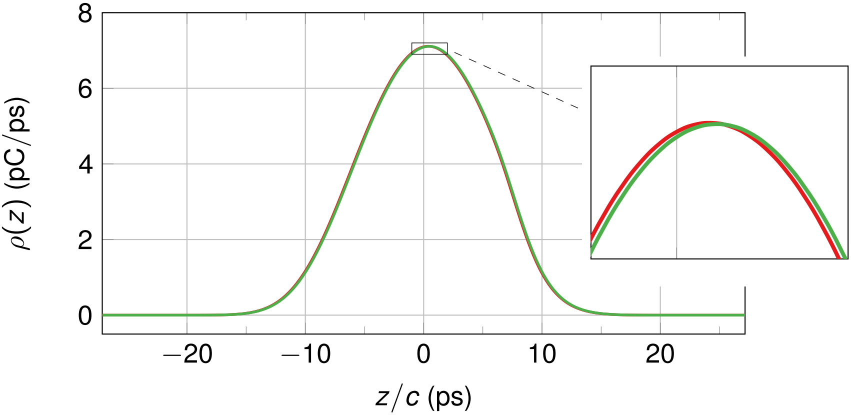
Clustering method *k*-means

Introduction

- clustering is an example of unsupervised learning, a sub field of machine learning
- can be used as an exploratory tool of data analysis to reveal underlying structure
- the *k*-means method is one of many different clustering algorithms
- relatively simple procedure which can be understood intuitively
- aims to achieve an appropriate categorization of the given data set
- number of categories or clusters *k* is a free parameter
- cluster means can be used as reasonable representatives to analyze the found clusters

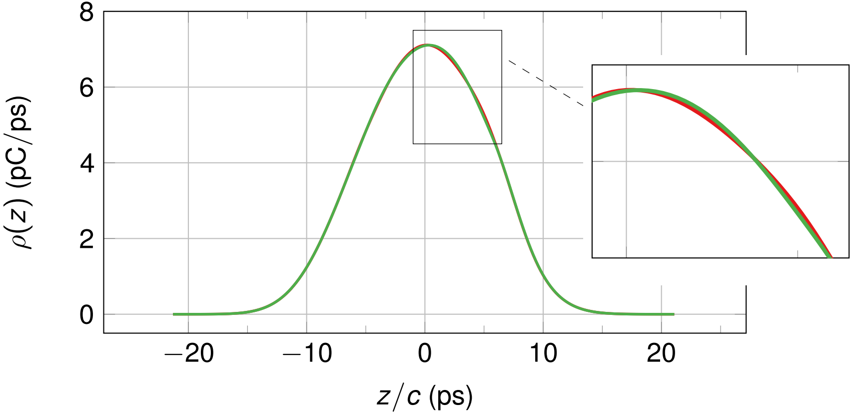
Pre-Processing

Initial Application of *k*-means



Pre-Processing

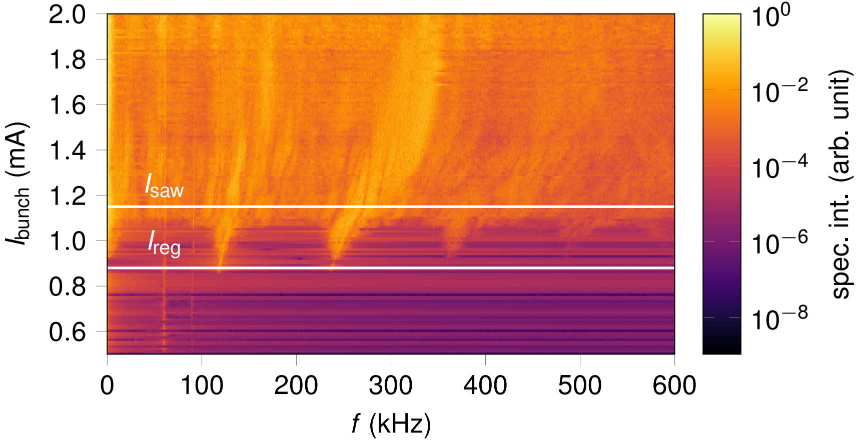
After Re-Centering Procedure



Analysis of Micro-Structure Dynamics

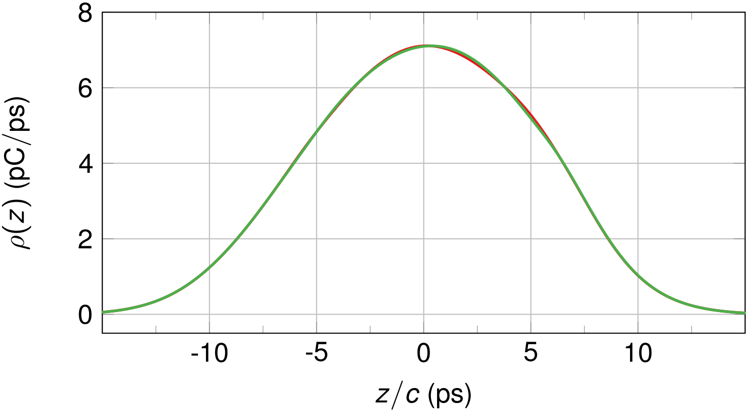
Analysis of Micro-Structure Dynamics

Different Bursting Regimes



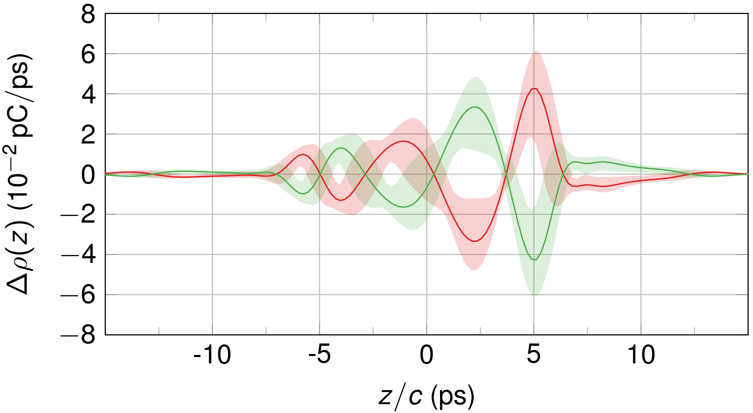
Regular Bursting Regime

Cluster Centers, $I_{\text{reg}} = 0.88\,\text{mA}$, $k = 2$



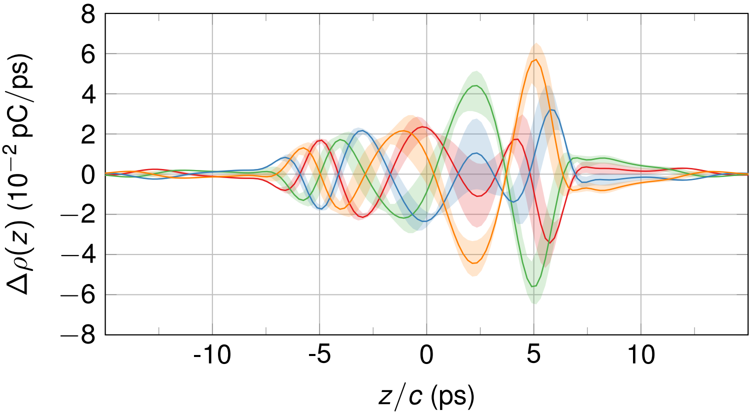
Regular Bursting Regime

Cluster Centers Ref. to Mean, $I_{\text{reg}} = 0.88\,\text{mA}$, $k = 2$



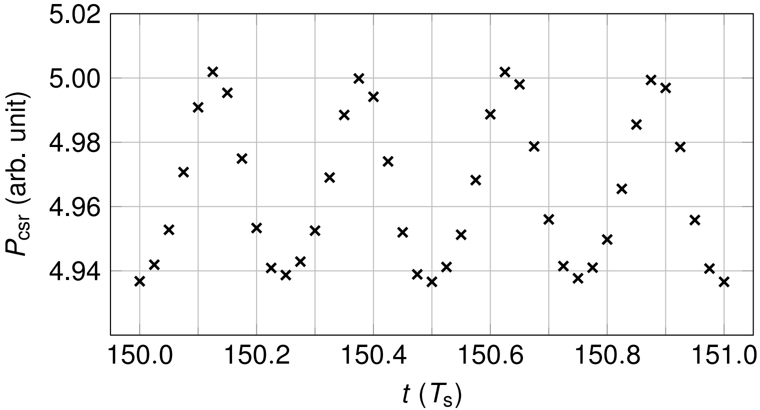
Regular Bursting Regime

Cluster Centers Ref. to Mean, $I_{reg} = 0.88\,\mathrm{mA}$, $k = 4$



Regular Bursting Regime

Correlation to CSR Power, $I_{reg} = 0.88\,\text{mA}$, $k = 2$



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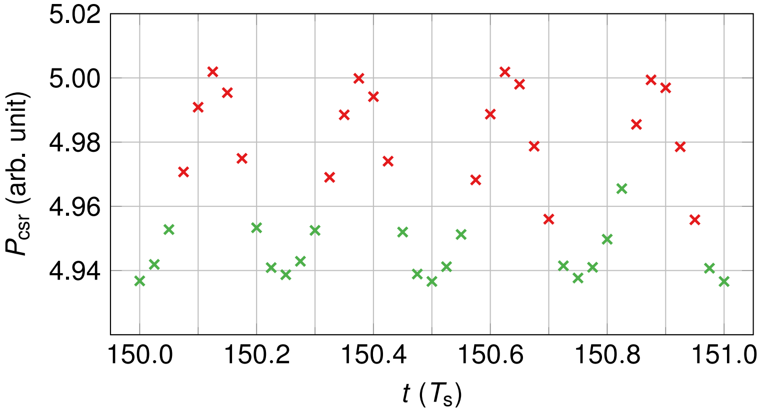
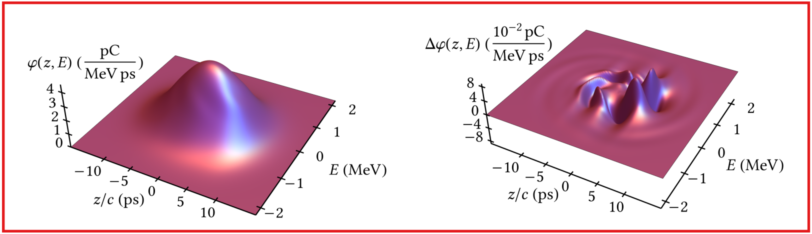
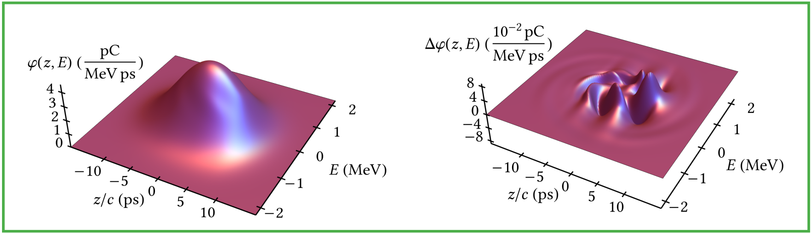


Regular Bursting Regime

Longitudinal Phase Space, $I_{\text{reg}} = 0.88\,\text{mA}$, $k = 2$





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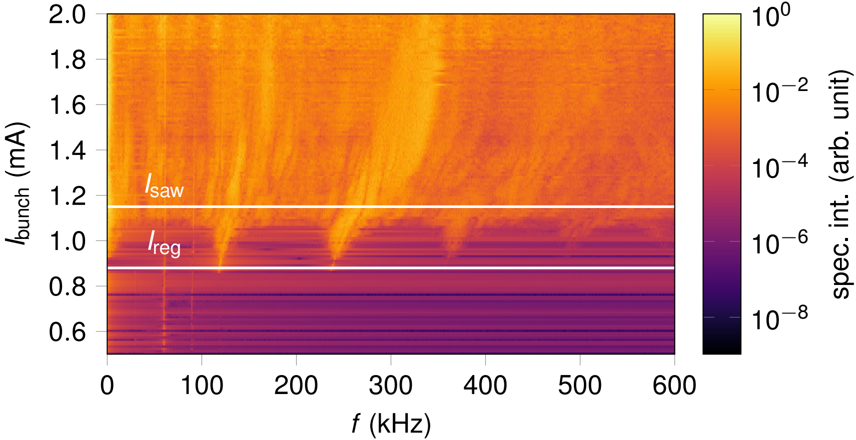
Longitudinal Phase Space, $I_{\mathrm{reg}} = 0.88\,\mathrm{mA}$, $k = 2$

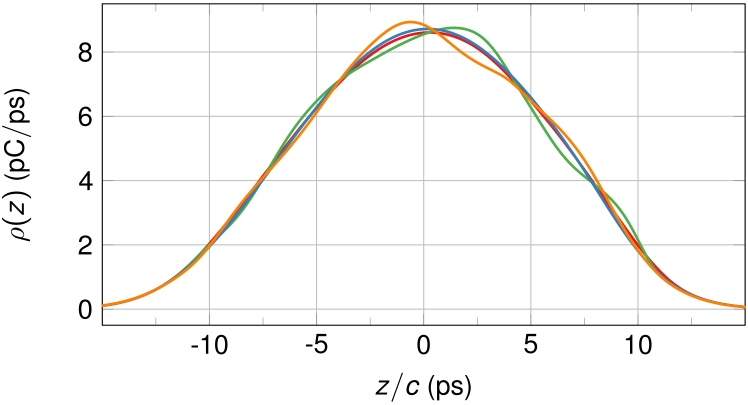
Analysis of Micro-Structure Dynamics

Different Bursting Regimes



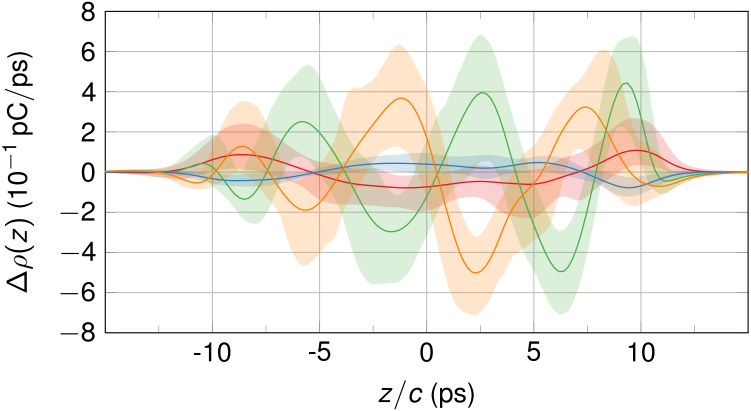
Sawtooth Bursting Regime

Cluster Centers, $I_{\mathrm{saw}} = 1.15\,\mathrm{mA}$, $k = 4$



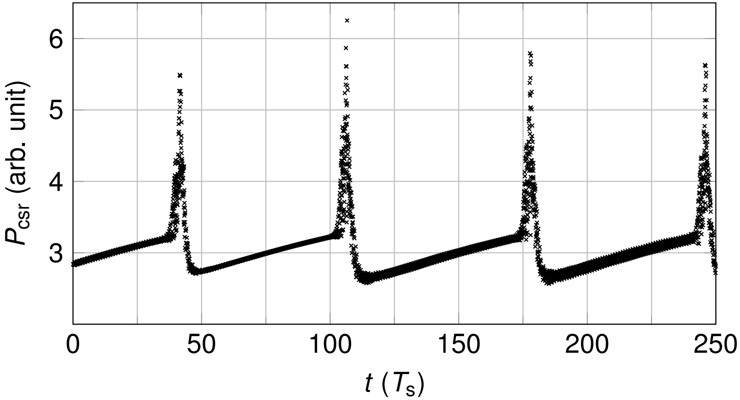
Sawtooth Bursting Regime

Cluster Centers Ref. to Mean, $I_{\mathrm{saw}} = 1.15\,\mathrm{mA}$, $k = 4$



Sawtooth Bursting Regime

Correlation to CSR Power, $I_{saw} = 1.15\,\text{mA}$, $k = 4$



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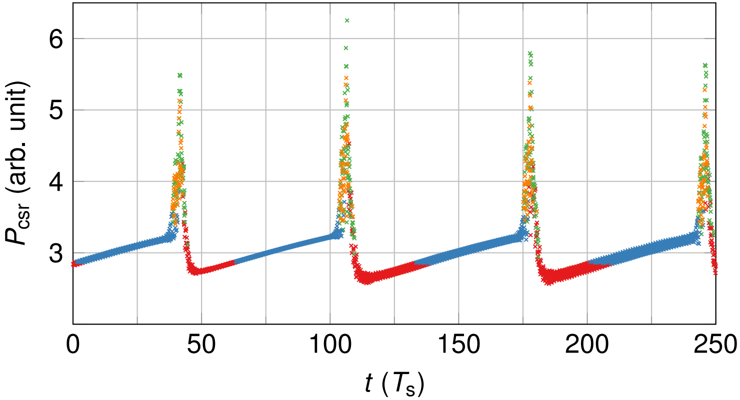

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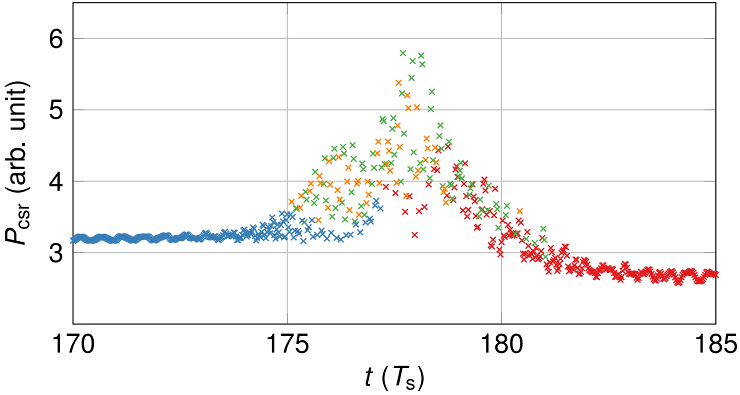

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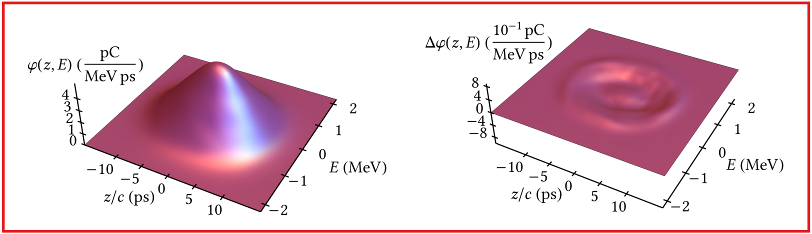

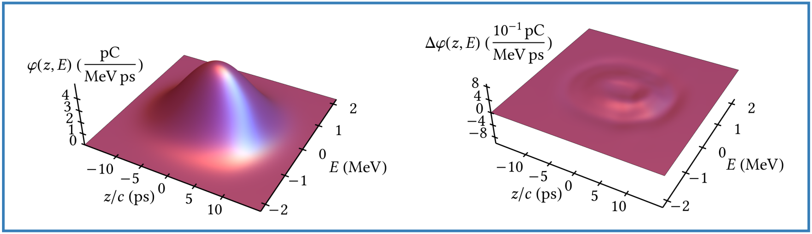

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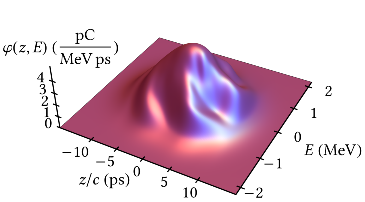
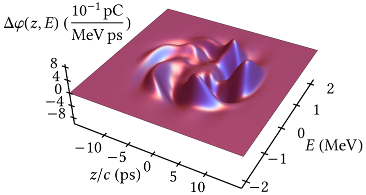
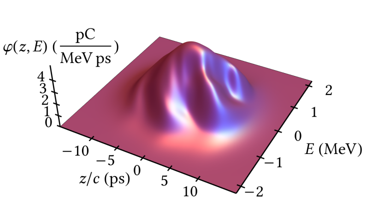
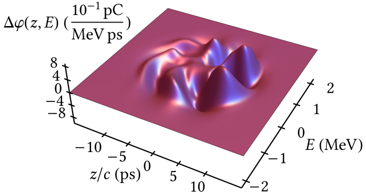






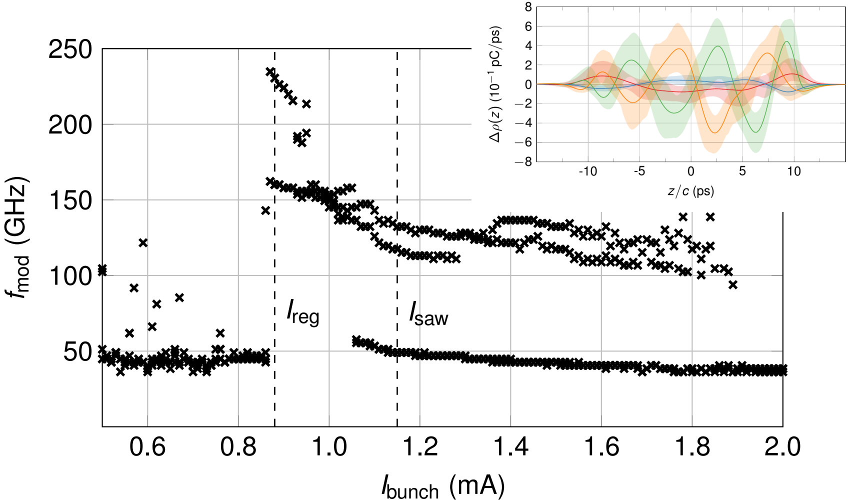


Sawtooth Bursting Regime

Longitudinal Phase Space, $I_{\mathrm{saw}} = 1.15\,\mathrm{mA}$, $k = 4$

Modulation Amplitude and Frequency

Modulation Frequencies for all Bunch Currents



Modulation Amplitude and Frequency

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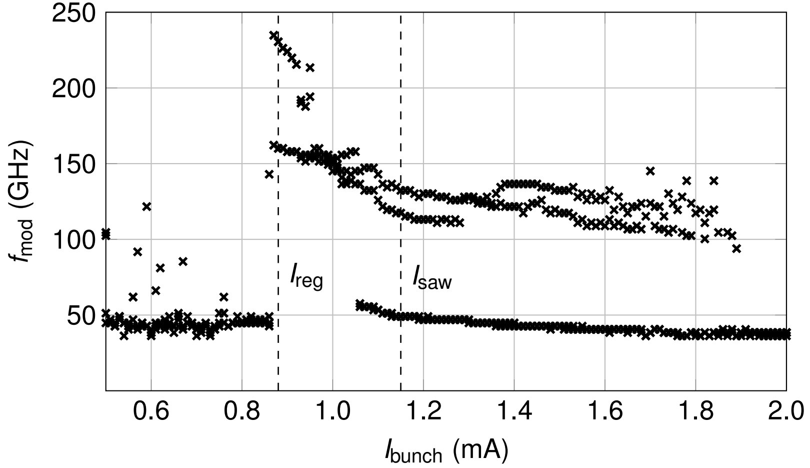

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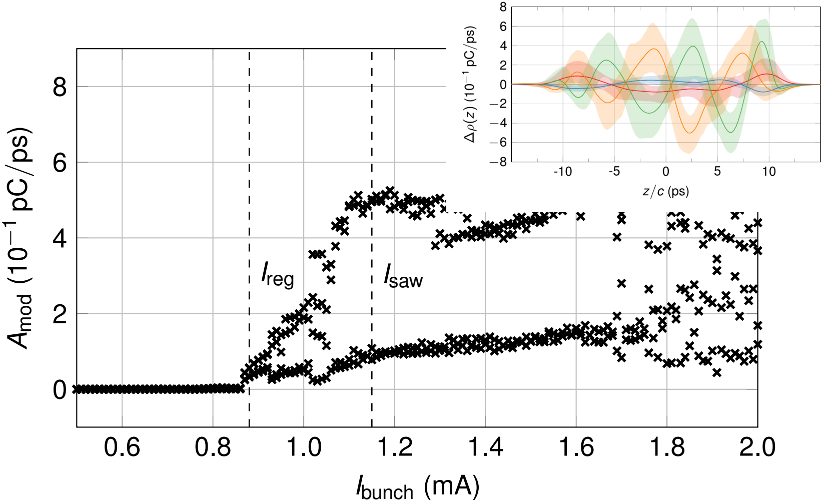

Modulation Amplitude and Frequency

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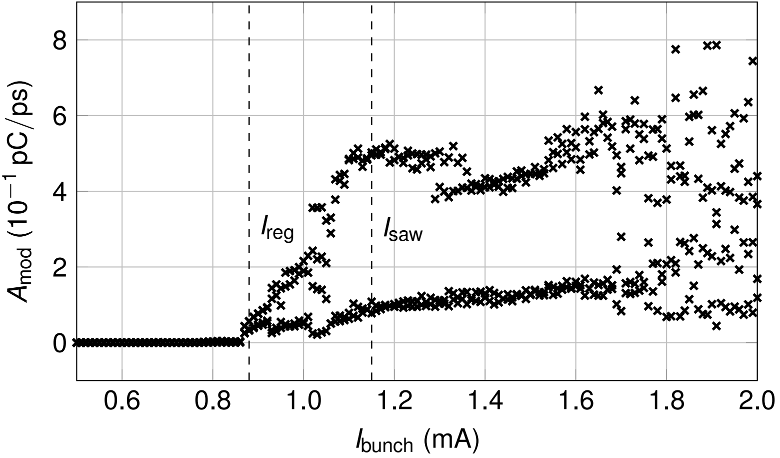
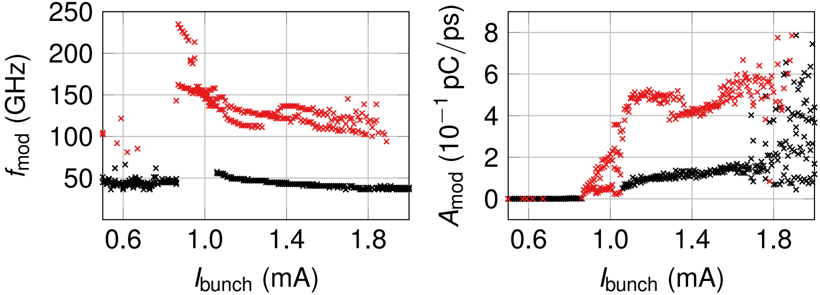


Modulation Amplitude and Frequency

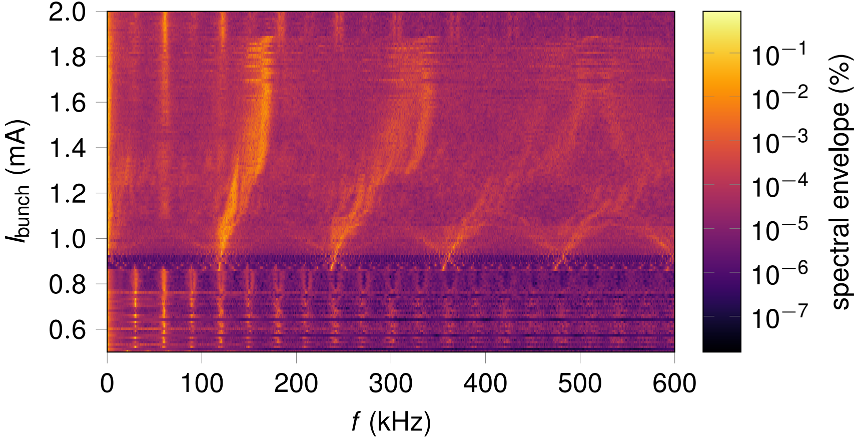
Correlation of Modulation Frequency and Amplitude

- $f_{mod} > 75$ GHz colored red
- same color scheme applied to modulation amplitudes A_{mod}



Cluster Label Spectrogram

Spectral Analysis of Categorical Time Series



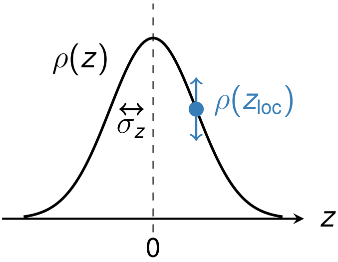
Stoffer, D. S. *et al.* Spectral analysis for categorical time series: Scaling and the spectral envelope. *Biometrika* **80,** 611–622 (1993)

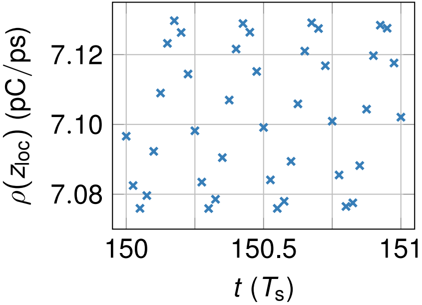
Analysis of Further Characteristics

Dynamics of a Localized Charge Density

Charge Density at CoM Position, $I_{reg} = 0.88\,\mathrm{mA}$

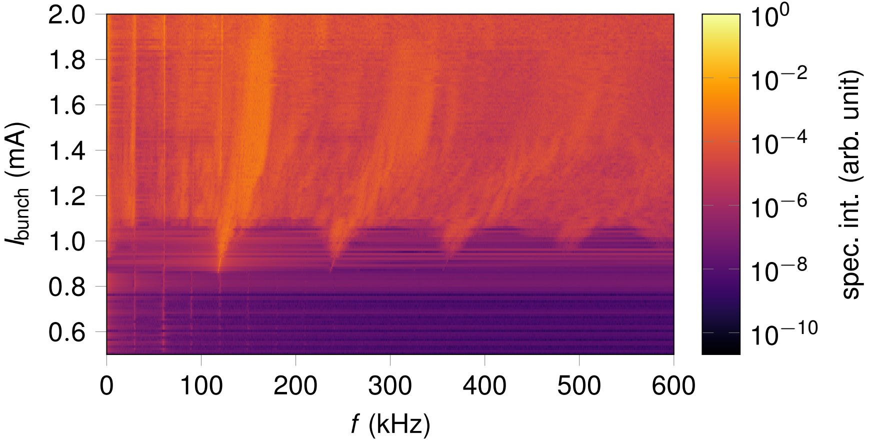
- analysis of temporal changes of the charge density at a fixed position within the electron bunch
- the gained time signal resembles the corresponding CSR power signal





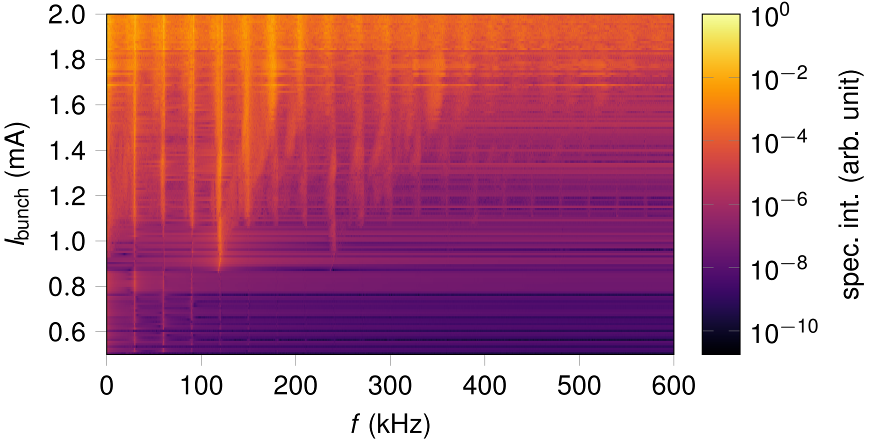
Dynamics of a Localized Charge Density

Spectrogram for CoM Position



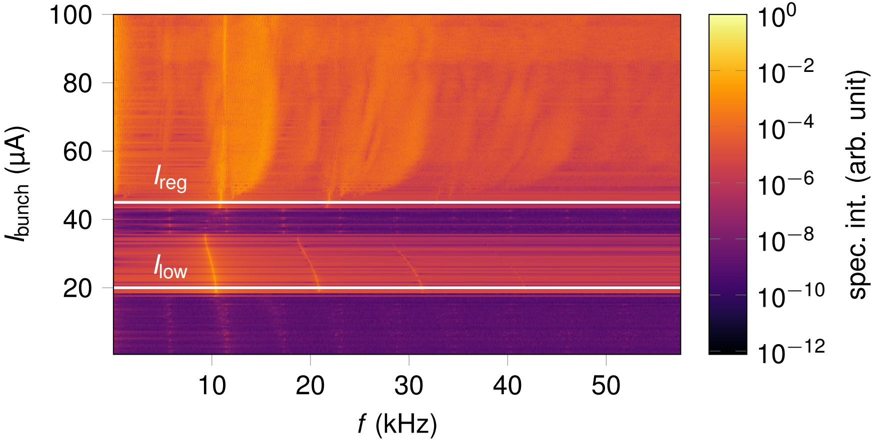
Dynamics of a Localized Charge Density

Spectrogram for a Position far away from CoM



Low Current Bursting

2nd Data Set: CSR Power Spectrogram

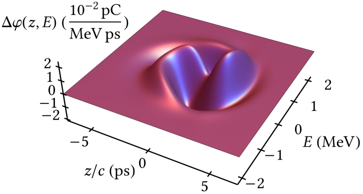


Low Current Bursting

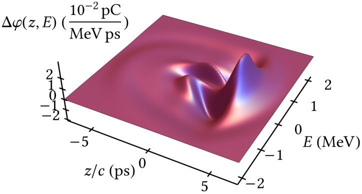
Longitudinal Phase Space, $I_{\text{low}} = 20\,\mu\text{A}$, $k = 2$

- micro-structures in the low current bursting regime look similar as well
- however, there is one structure less than for the regimes above!

$I_{\text{low}} = 20\,\mu\text{A}$

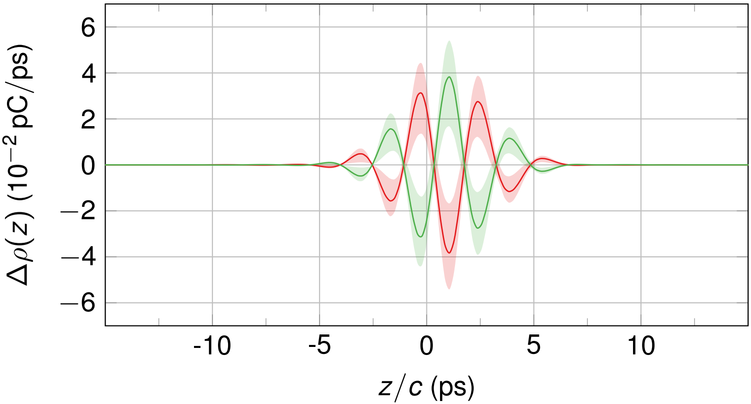


$I_{\text{reg}} = 45\,\mu\text{A}$



Vacuum Chamber Height

Ref. Cluster Centers, $I_{\text{bunch}} = 1.4\,\text{mA}$, $k = 2$, $g' = 0.5\,g$



Vacuum Chamber Height

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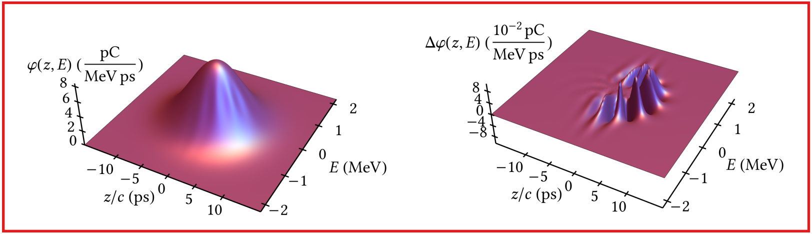

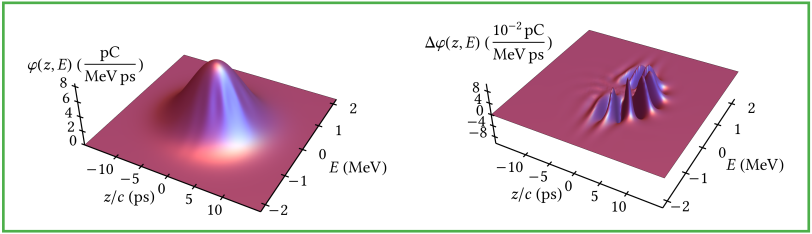

Outlook

Outlook

Ideas and Open Questions

- modulation frequencies are very similar across different bunch currents, but show a slight decay
  $\Rightarrow$ Where does this come from?
  $\Rightarrow$ Does it maybe depend on changes in the bunch length?
- systematic studies of the f_{mod} dependence on different parameters, e.g. the vacuum chamber height or bending radius
- reproduce these results on measured data (EO setup)
- additional ideas/suggestions?

Outlook

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- systematic studies of the f_{mod} dependence on different parameters, e.g. the vacuum chamber height or bending radius
- reproduce these results on measured data (EO setup)
- additional ideas/suggestions?

Thank you for your attention!

Backup

Simulation Parameters
1st Data Set

Physical parameter	Value
RF voltage U_0	1 MV
revolution frequency f_{rev}	9 MHz
synchrotron frequency f_{s}	30 kHz
damping time τ_{d}	5 ms
harmonic number h	50
parallel plates distance g	3.2 cm
initial electron distribution $\varphi(z, E, t_0)$	2-dim. Gaussian
simulation time t	250 T_{s}
bunch current I_{bunch}	0.5 mA to 2.0 mA

Control parameter	Value
grid size n_{grid}	256
time steps n_{steps}	10 000

Simulation Parameters

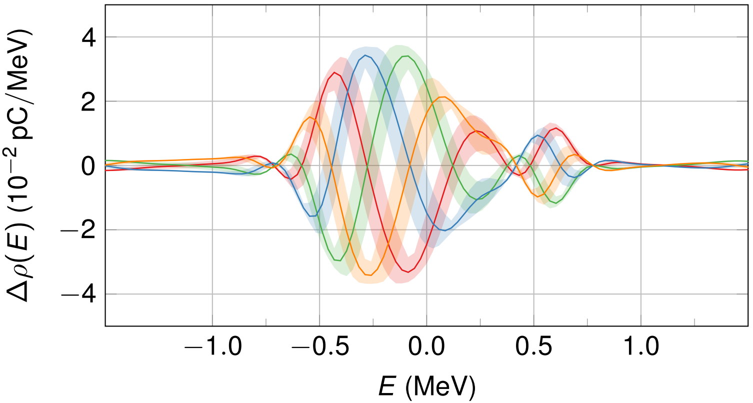
2nd Data Set

Physical parameter	Value
RF voltage U_0	1.3 MV
revolution frequency f_{rev}	2.72 MHz
synchrotron frequency f_s	5.76 kHz
damping time τ_d	2.66 ms
harmonic number h	184
parallel plates distance g	3.2 cm
initial electron distribution $\varphi(z, E, t_0)$	2-dim. Gaussian
simulation time t	500 T_s
bunch current I_{bunch}	0.5 µA to 200 µA

Control parameter	Value
grid size n_{grid}	256
time steps n_{steps}	10 000

Micro-Structures on Energy Profiles

Cluster Centers Ref. to Mean, $I_{\mathrm{reg}} = 0.88\,\mathrm{mA}$, $k = 4$



Online Access

Master's Thesis

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