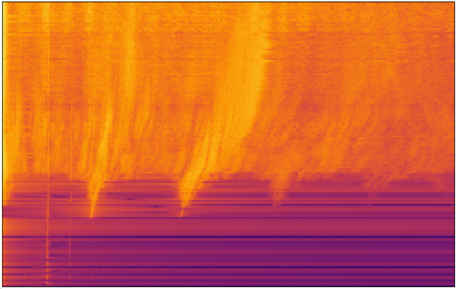
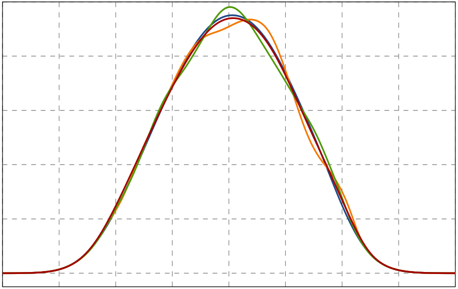
Machine Learning Application on the Investigation of the Micro-Bunching Instability at Storage Rings

Tobias Boltz, Miriam Brosi, Erik Bründermann, Patrik Schönfeldt, Markus Schwarz, Minjie Yan and Anke-Susanne Müller | March 2, 2018

Karlsruhe Institute of Technology

Laboratory for Applications of Synchrotron Radiation (LAS)





Micro-Bunching Instability

Motivation and Introduction

- operation of storage rings with short electron bunches increases coherent synchrotron radiation (CSR) power
- leads to micro-structure dynamics within the bunch

measurements

- indirect: resulting fluctuations in the emitted CSR power
- direct: electron distribution, challenging due to the small scale of the micro-structures

$\Rightarrow$ KIT storage ring KARA (KArlsruhe Reasearch Accelerator) has a dedicated short-bunch mode

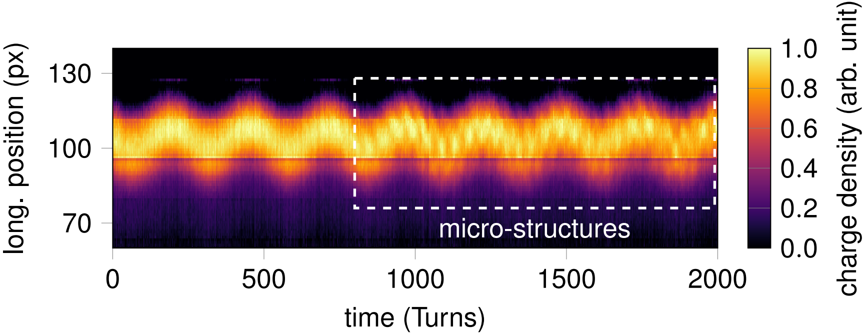
$\Rightarrow$ synchronized sensor network (e.g. KAPTURE[1] and KALYPSO[2]) enables studies of beam dynamics turn-by-turn

(1) Caselle, M. *et al.* JINST **12 C01040** (2017) (2) Rota, L., Caselle, M. *et al.* IBIC **WEPG46** (2016)

Micro-Bunching Instability

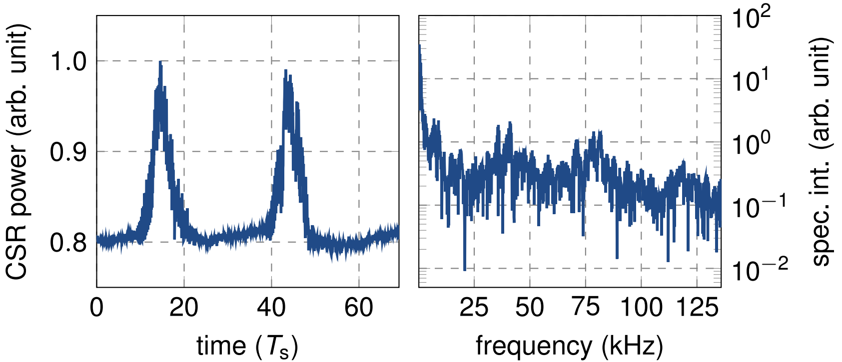
Occurrence of Micro-Structures within the Electron Bunch

- electro-optical near-field setup at KARA enables the measurement of longitudinal bunch profiles
- small micro-structures within the electron bunch can be observed



Micro-Bunching Instability

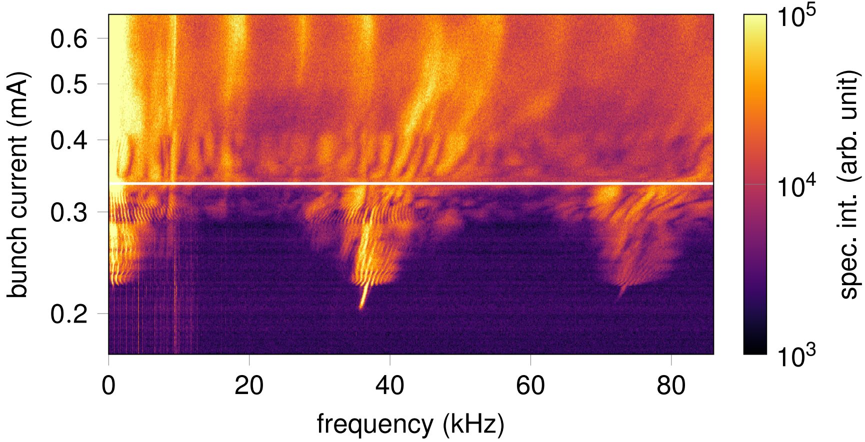
Fluctuations of the emitted CSR Power



$\Rightarrow$ micro-structure dynamics lead to fluctuating CSR emission

Micro-Bunching Instability

Beam Dynamics are changing with Bunch Current



⇒ CSR power spectrogram reveals distinct frequencies

Simulation Code Inovesa

VFP Solver to study the Longitudinal Dynamics

- in-house developed at KIT,
  published as open source project:
  `https://github.com/Inovesa/Inovesa`
- simulates longitudinal phase space density
- parallel plates model yields quite comparable results to measured data

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

$\Rightarrow$ Inovesa enables comprehensive studies of the micro-bunching instability on low-noise data

Machine Learning

Analysis of the Longitudinal Bunch Profiles using *k*-means

Motivation:

- identify the dominant micro-structures and their correlation to the fluctuating CSR emission
- around 1.5 million bunch profiles in the data set corresponding to a simulated CSR power spectrogram

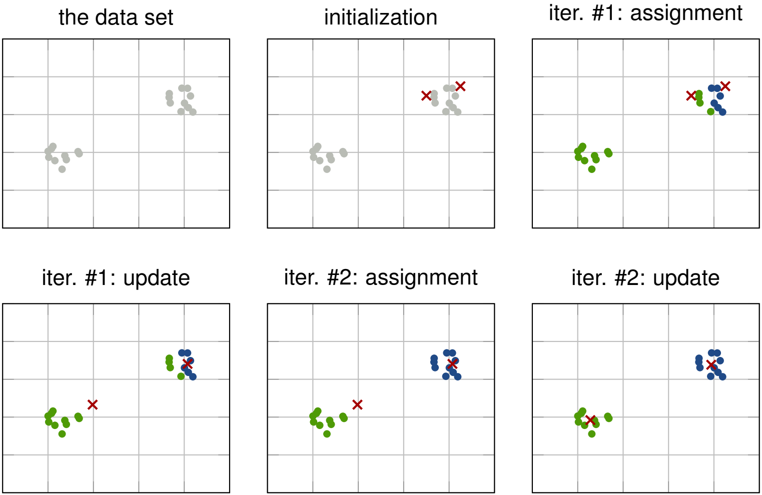
$\Rightarrow$ application of *k*-means to the bunch profiles within a specific bunch current

Investigation:

- Does the shape of these micro-structures follow a pattern or are they rather random fluctuations?
- Is it possible to characterize their nature by only a few different discrete states (clusters)?

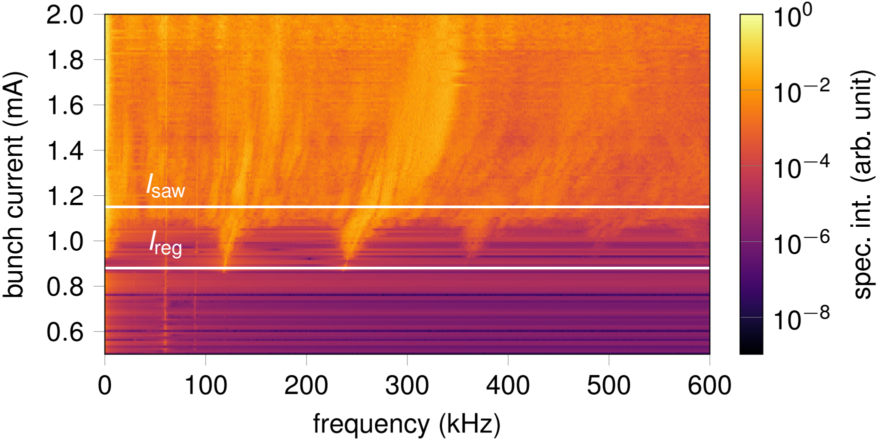
Machine Learning

Unsupervised Learning: Clustering Method *k*-means



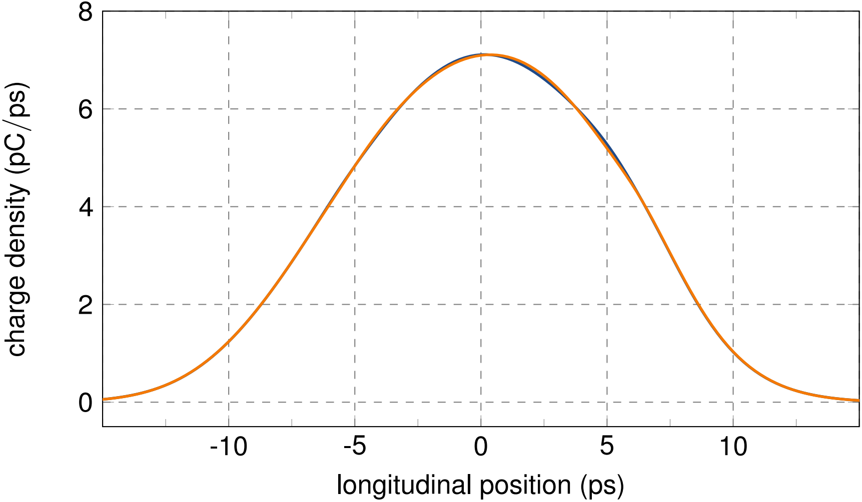
Analysis of Micro-Structure Dynamics

Different Bursting Regimes: Exemplary Bunch Currents



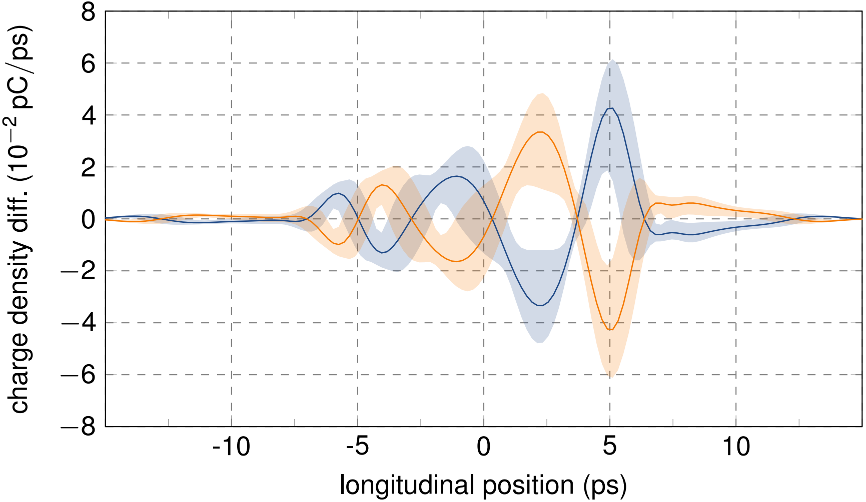
Regular Bursting Regime

Cluster Centers, $I_{\text{reg}} = 0.88\,\text{mA}$, $k = 2$ (10 000 profiles)



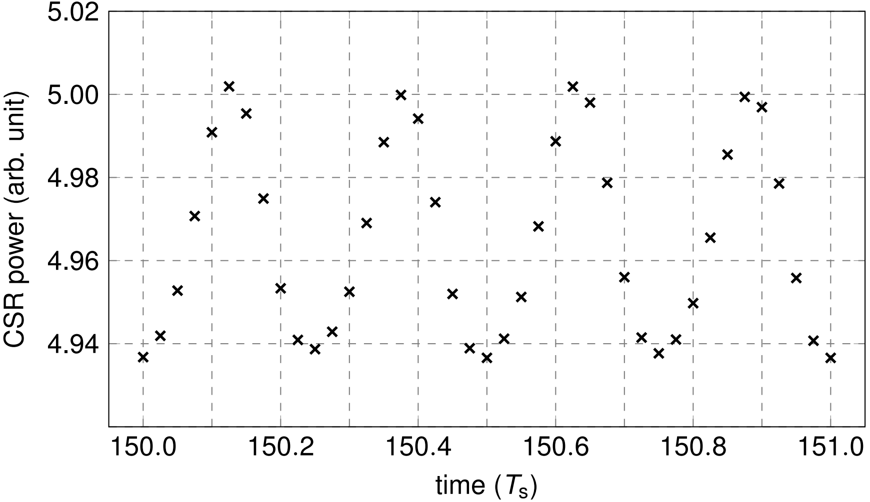
Regular Bursting Regime

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



Regular Bursting Regime

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



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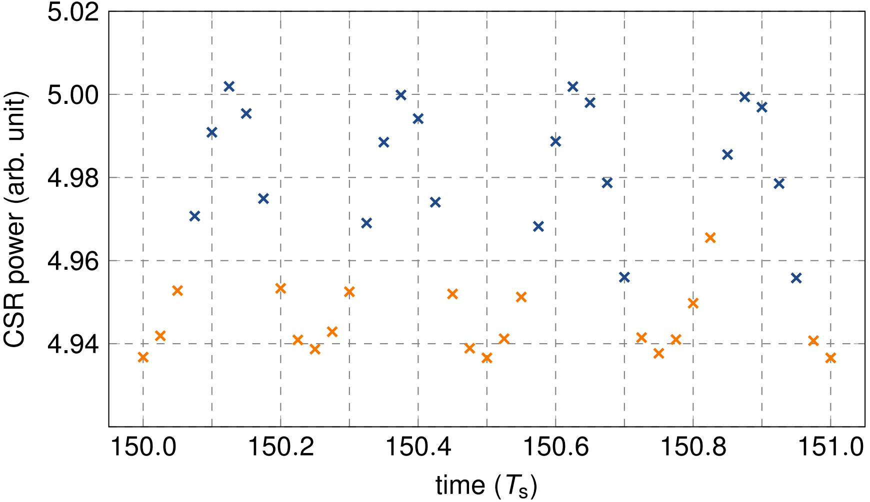
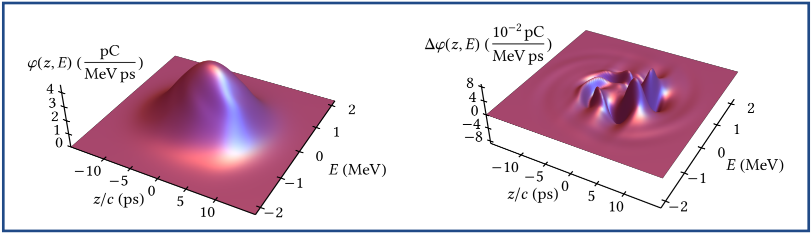
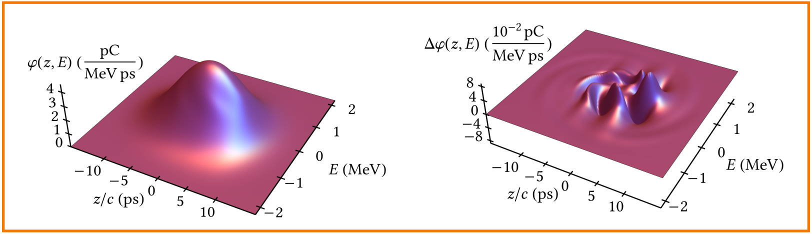


Regular Bursting Regime

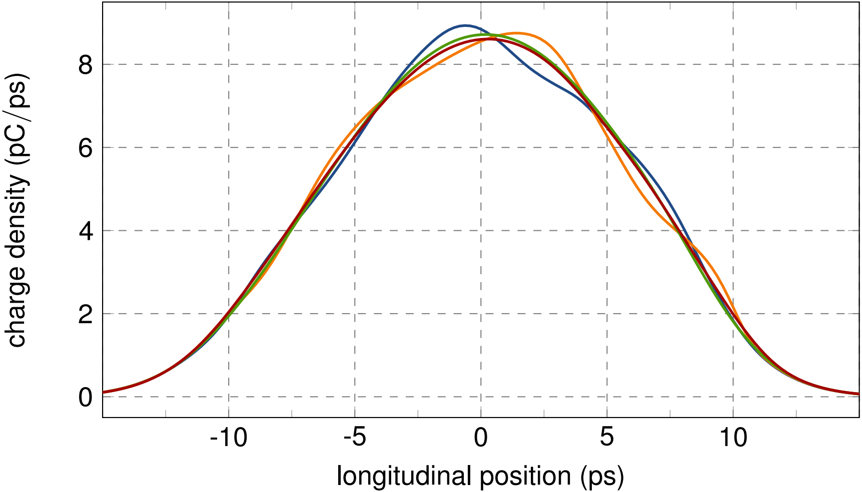
Longitudinal Phase Space Density, $I_{\mathrm{reg}} = 0.88\,\mathrm{mA}$, $k = 2$





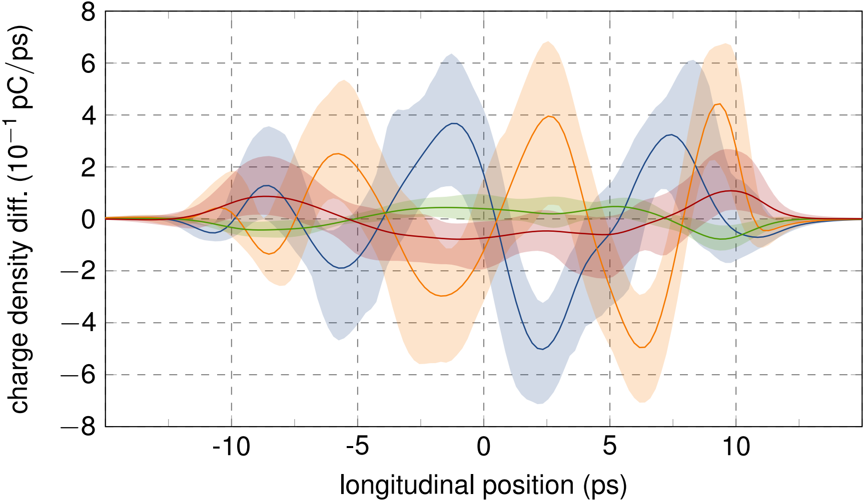
Sawtooth Bursting Regime

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



Sawtooth Bursting Regime

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



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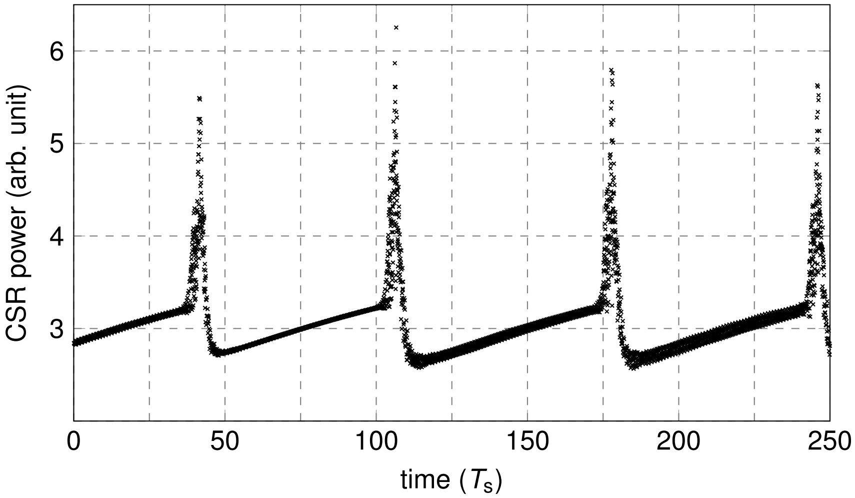

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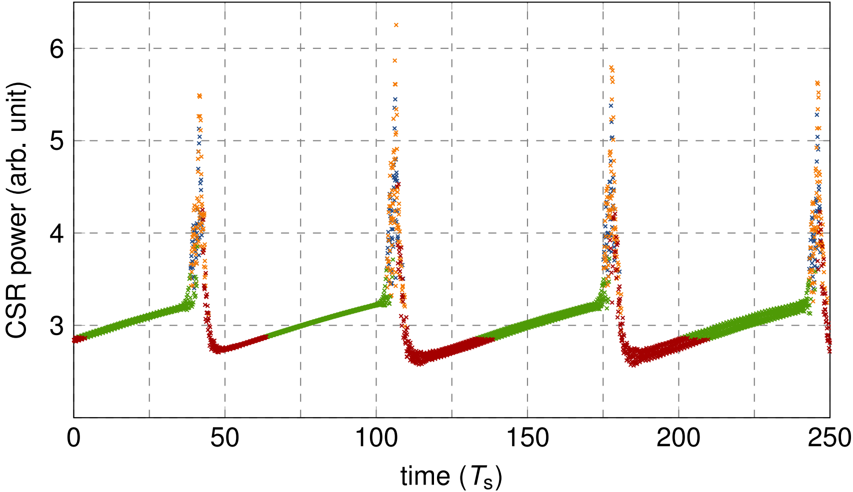

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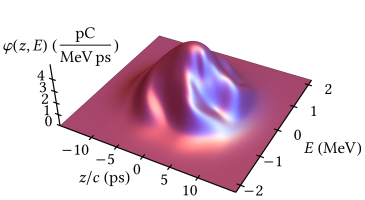
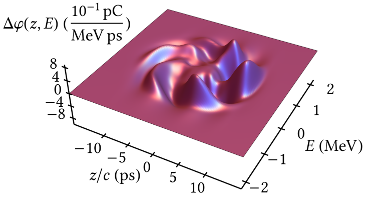
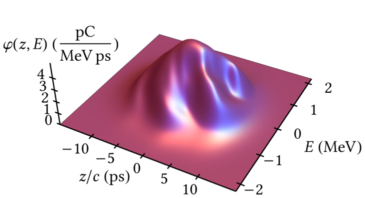
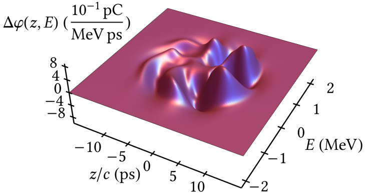


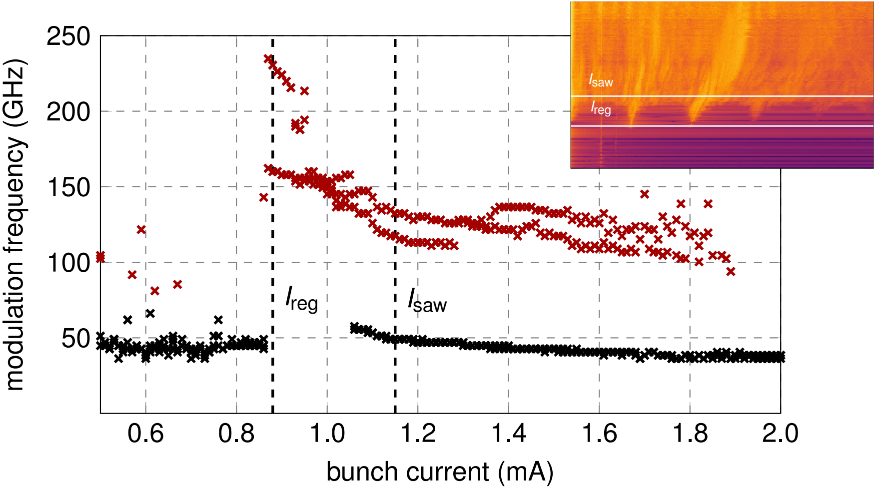






Micro-Structure Characteristics

Modulation Frequencies across different Bunch Currents



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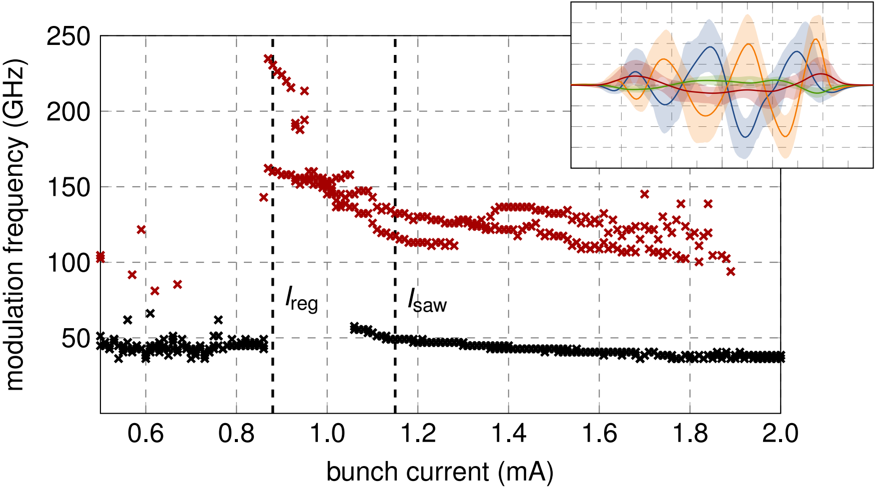
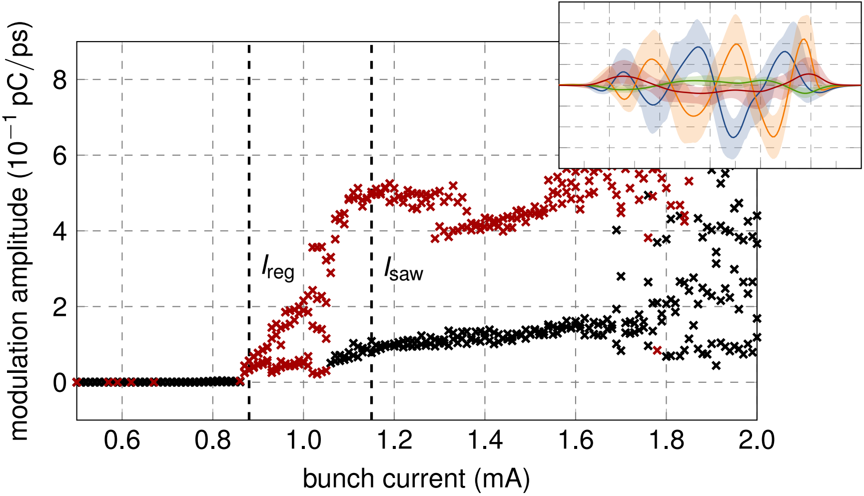


Micro-Structure Characteristics

Modulation Amplitudes across different Bunch Currents



Summary

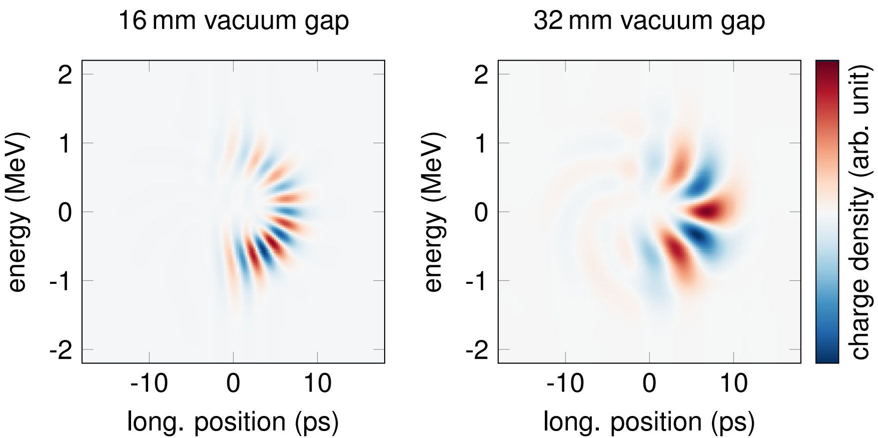
What was gained by using Machine Learning?

- efficient tool for data exploration and knowledge extraction
- distinct micro-structures could be identified
- yields the possibility to correlate the results to the fluctuations of the CSR power
- new insights gained, e.g. number of structures is a constant across different bunch currents

$\Rightarrow$ still useful for further studies of the micro-structure characteristics as it yields very condensed information about the dynamics

Outlook

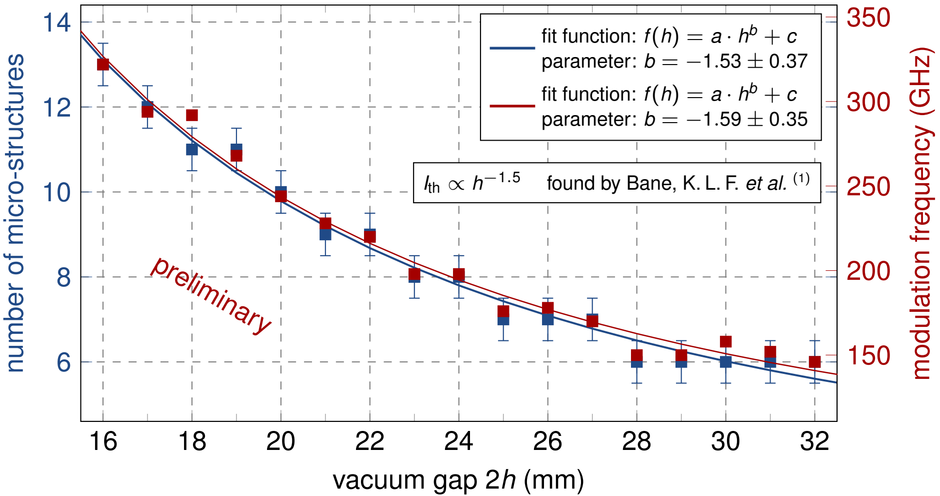
Further Studies using the Application of *k*-means



⇒ number of micro-structures changes with vacuum gap

Outlook

Further Studies using the Application of *k*-means



(1) Bane, K. L. F., Y. Cai, and G. Stupakov Phys. Rev. ST Accel. Beams **13** (2010)

Thank you for your attention!

Backup

Backup

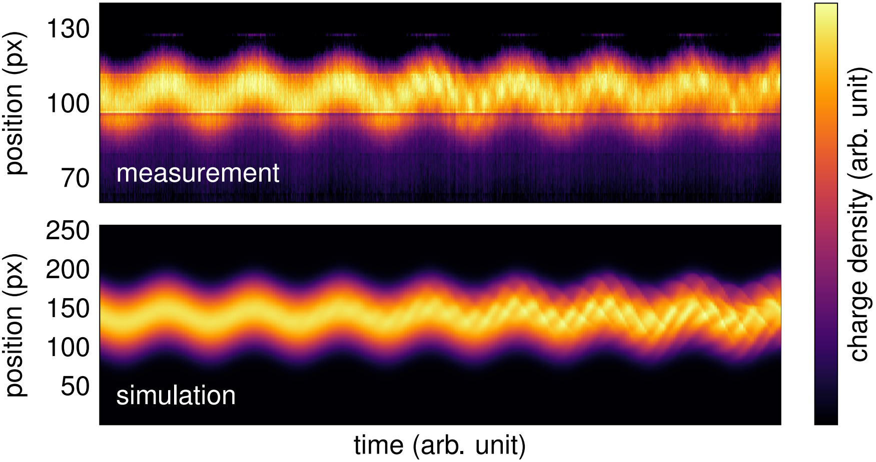
Simulation Parameters

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

Backup

Simulation and Measurement: Longitudinal Bunch Profiles



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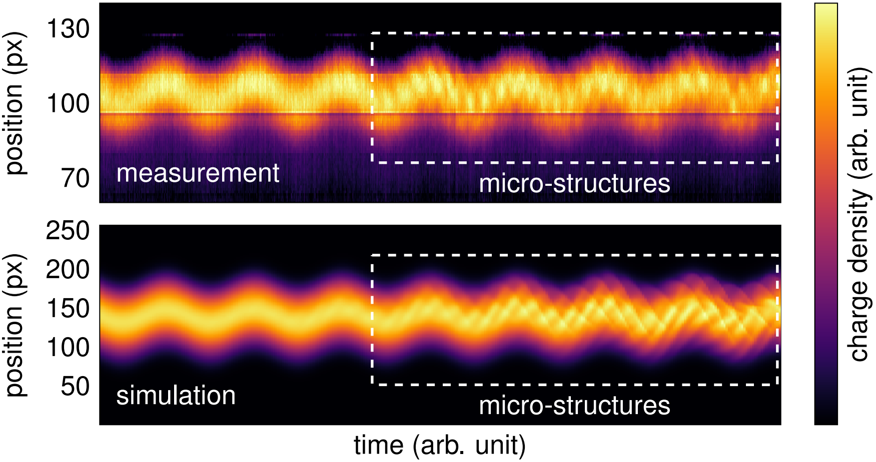
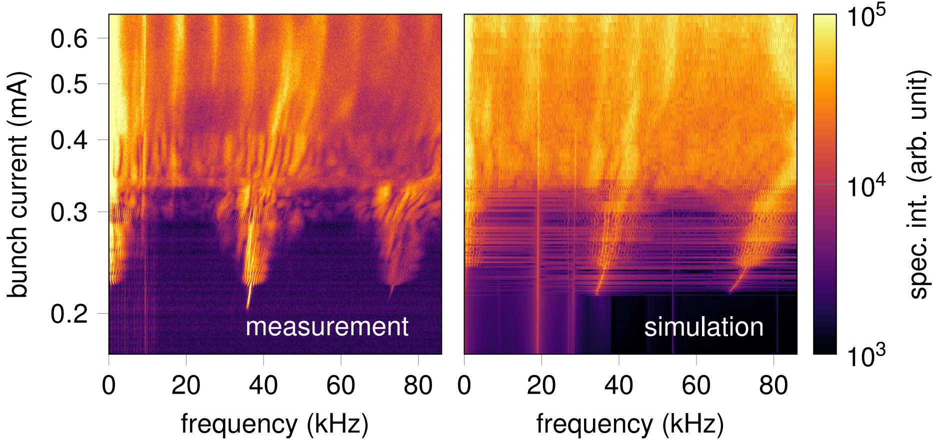


Backup

Simulation and Measurement: CSR Power Spectrogram



⇒ simulation and measurement show qualitative agreement