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

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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

⇒ KIT storage ring KARA (KArlsruhe Reasearch Accelerator) has a dedicated short-bunch mode
⇒ synchronized sensor network (e.g. KAPTURE\(^{(1)}\) and KALYPSO\(^{(2)}\)) enables studies of beam dynamics turn-by-turn

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

⇒ 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


⇒ 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
  ⇒ 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)?
Unsupervised Learning: Clustering Method $k$-means

- The data set
- Initialization
- Iter. #1: assignment
- Iter. #1: update
- Iter. #2: assignment
- Iter. #2: update
Analysis of Micro-Structure Dynamics

Different Bursting Regimes: Exemplary Bunch Currents

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Regular Bursting Regime

Cluster Centers, $I_{\text{reg}} = 0.88\ mA$, $k = 2$ (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, \( I_{\text{reg}} = 0.88 \text{ mA}, \ k = 2 \)
Regular Bursting Regime

Correlation to CSR Power, $l_{\text{reg}} = 0.88 \text{ mA, } k = 2$
Regular Bursting Regime
Longitudinal Phase Space Density, $I_{\text{reg}} = 0.88\ mA$, $k = 2$
Sawtooth Bursting Regime
Cluster Centers, $I_{\text{saw}} = 1.15 \text{ mA}$, $k = 4$

![Graph showing charge density vs. longitudinal position](image-url)
Sawtooth Bursting Regime
Referenced Cluster Centers, $l_{\text{saw}} = 1.15 \text{ mA}, k = 4$
Sawtooth Bursting Regime

Correlation to CSR Power, $I_{\text{reg}} = 1.15$ mA, $k = 4$
Sawtooth Bursting Regime
Correlation to CSR Power, $I_{\text{reg}} = 1.15 \text{ mA}, k = 4$
Sawtooth Bursting Regime

Longitudinal Phase Space Density, $I_{\text{saw}} = 1.15 \text{ mA}$, $k = 4$
Micro-Structure Characteristics
Modulation Frequencies across different Bunch Currents

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Micro-Structure Characteristics
Modulation Frequencies across different Bunch Currents

![Graph showing modulation frequencies across different bunch currents. The graph has a y-axis labeled 'modulation frequency (GHz)' and an x-axis labeled 'bunch current (mA)'. The graph includes data points and curves depicting the relationship between modulation frequency and bunch current.]
Micro-Structure Characteristics
Modulation Amplitudes across different Bunch Currents

![Graph showing modulation amplitudes vs. bunch current.](image)

- Modulation amplitude (10^{-1} pC/ps)
- Bunch current (mA)

- $I_{reg}$
- $I_{saw}$
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

⇒ 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

fit function: $f(h) = a \cdot h^b + c$
parameter: $b = -1.53 \pm 0.37$

fit function: $f(h) = a \cdot h^b + c$
parameter: $b = -1.59 \pm 0.35$

$I_{th} \propto h^{-1.5}$ found by Bane, K. L. F. et al. (1)

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Thank you for your attention!
## Simulation Parameters

<table>
<thead>
<tr>
<th>Physical parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>RF voltage $U_0$</td>
<td>1 MV</td>
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<tr>
<td>revolution frequency $f_{\text{rev}}$</td>
<td>9 MHz</td>
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<td>synchrotron frequency $f_s$</td>
<td>30 kHz</td>
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<td>damping time $\tau_d$</td>
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<td>harmonic number $h$</td>
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<td>parallel plates distance $g$</td>
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<td>initial electron distribution $\varphi(z, E, t_0)$</td>
<td>2-dim. Gaussian</td>
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<td>simulation time $t$</td>
<td>250 $T_s$</td>
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<td>bunch current $I_{\text{bunch}}$</td>
<td>0.5 mA to 2.0 mA</td>
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<td>time steps $n_{\text{steps}}$</td>
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</table>
Backup

Simulation and Measurement: Longitudinal Bunch Profiles

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Simulation and Measurement: Longitudinal Bunch Profiles

- ** measurment vs. simulation 
- ** micro-structures vs. charge density (arb. unit)

Backup

Simulation and Measurement: CSR Power Spectrogram

⇒ simulation and measurement show qualitative agreement