Feedback Design for Control of the Micro-Bunching Instability based on Reinforcement Learning

Tobias Boltz, Miriam Brosi, Erik Bründermann, Bastian Härer, Peter Kaiser, Christoph Pohl, Patrick Schreiber, Minjie Yan, Tamim Asfour and Anke-Susanne Müller | September 26, 2019
Micro-Bunching Instability

Micro-Bunching and CSR Power Fluctuations

Simulation code: Parallelized VFP solver Inovesa (https://github.com/Inovesa/Inovesa)
Micro-Bunching Instability

CSR Power Spectrogram: Dependency on Bunch Current

![Graph showing measurement and simulation of CSR power spectrogram with dependency on bunch current. The x-axis represents frequency in kHz, and the y-axis represents bunch current in mA. The color scale indicates the specific intensity in arbitrary units.]
Micro-Bunching Instability

CSR self-interaction

\[ \sigma_E (\sigma_{z,0}) \]

\[ \rho \left( \frac{pC}{\sigma_{z,0}} \right) \]

\[ \rho_z \left( \frac{pC}{\sigma_{z,0}} \right) \]

\[ F^{-1}(\tilde{\rho}_z Z_{CSR}) \]

\[ \tilde{\rho}_z = F(\rho_z) \]

RF+wake potential (kV)

wake potential (kV)

projection

perturbation

long. position (\sigma_{z,0})

long. position (\sigma_{z,0})
Micro-Bunching Instability

CSR self-interaction

\[ \rho \left( \frac{pC}{\sigma_{z,0}} \right) \]

\[ \text{RF+wake potential (kV)} \]

\[ \rho \left( \frac{pC}{\sigma_{z,0}} \sigma_{E,0} \right) \]

\[ \rho \left( \frac{pC}{\sigma_{z,0} \sigma_{E,0}} \right) \]

\[ \text{long. position (} \sigma_{z,0} \text{)} \]

\[ \text{long. position (} \sigma_{z,0} \text{)} \]

projection

perturbation

\[ F^{-1}(\tilde{\rho}_{z} Z_{\text{CSR}}) \]

\[ \tilde{\rho}_{z} = F(\rho_{z}) \]
Single Particle Synchrotron Motion

Perturbation of the Restoring Force

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Perturbation of the Restoring Force

bunch current (µA)

CSR wake potential (kV)

effective potential (kV)

long. position ($\sigma_{z,0}$)

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Perturbation of the Restoring Force

CSR wake potential (kV)

bunch current (µA)

long. position ($\sigma_{z,0}$)

Effective potential (kV)

bunch current (µA)

long. position ($\sigma_{z,0}$)
Single Particle Synchrotron Motion

Perturbation of the Restoring Force

bunch current (µA)

50 100 150 200 250

CSR wake potential (kV)

50 100 150 200 250

bunch current (µA)

50 100 150 200 250

effective potential (kV)

50 100 150 200 250

long. position ($\sigma_{z,0}$)

-4 -2 0 2 4

-4 -2 0 2 4

-20 -10 0 10 20

-20 -10 0 10 20

$k''$

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Single Particle Synchrotron Motion
1D-Harmonic Oscillator with perturbed Restoring Force

- RF potential acts as a linear restoring force
  \[ \Rightarrow 1D\text{-}\text{harmonic oscillator} \]
  \[ \Rightarrow \text{particle motion in generalized coordinates is perfectly circular} \]

- CSR wake potential introduces position-dependent perturbation that affects the strength of the restoring force \( k' < k \)

- Particle motion in generalized coordinates becomes elliptical
Single Particle Synchrotron Motion
1D-Harmonic Oscillator with perturbed Restoring Force

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  ⇒ 1D-harmonic oscillator
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Single Particle Synchrotron Motion

Elliptical Deformation of Trajectories below Threshold

- visualization of particle trajectories with uniformly distributed energies
- position-dependent elliptical deformation of particle trajectories $\Rightarrow$ local charge densities
- quadrupole-like mode below the instability threshold

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Elliptical Deformation of Trajectories above Threshold

long. position ($\sigma_{z,0}$)

time ($T_s$)

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Elliptical Deformation of Trajectories above Threshold

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- Particle trajectories

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long. position \((\sigma_{z,0})\)

- time \((T_s)\)
Micro-Bunching Control

... via Dynamic RF Amplitude Modulation

![Graph showing the relationship between normalized RF amplitude and CSR power over time](image)
Reinforcement Learning

Developing some Intuition . . .

- goal-directed learning from interaction (trial-and-error search)
- finding a sequence of actions (e.g. moves in a game)
- taken actions affect the following states (e.g. board positions)

cartpole balancing
(a textbook RL problem)
RL based Control of Micro-Bunching

Feedback Scheme

goal: control micro-bunching (longitudinal beam dynamics) to optimize emitted CSR

proof of principle: control in simulation (Inovesa)

implementation: THz diagnostics (KAPTURE) and RF system at KARA
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RL based Control of Micro-Bunching

Observation, Reward and Action

- **observation**: state of electron bunch / micro-bunching dynamics
  1) in theory/simulations: longitudinal charge distribution
  2) measurable: CSR power signal $\Rightarrow$ feature vector encoding the state

- **reward function**: optimization of emitted CSR signal
  $$ R = w_1 \mu_{CSR} - w_2 \sigma_{CSR} \quad \text{with} \quad w_1, w_2 > 0 $$
  $\Rightarrow$ maximize $\mu_{CSR}$, minimize $\sigma_{CSR}$!

- **action**: RF amplitude modulation
  dynamically adjust amplitude & frequency
  $\Rightarrow$ counteract perturbation by CSR
  $\Rightarrow$ include RF phase?

![Graph showing RF and wake potential relationship](image_url)
RL based Control of Micro-Bunching

... behind the curtain: Actor-Critic System using NNs

state $s = (s_1, s_2, s_3, s_4)^T$
action $a = (a_1, a_2, a_3)^T$

chosen action to be evaluated

evaluation and update based on estimation of expected reward $\hat{q}(s, a)$

e.g. DDPG algorithm*
(Deep Deterministic Policy Gradient)

Summary

- goal: control micro-bunching ⇒ optimize CSR emission
- CSR self-interaction: perturbation is dependent on the state of the micro-bunching dynamics
  ⇒ countermeasure should be state-dependent as well!
- CSR wake potential causes perturbation of effective restoring force
  ⇒ compensate via dynamic RF amplitude modulation scheme
- interaction with the bunch changes the micro-bunching dynamics
  ⇒ sequence of actions is required (deal with consequences)

Further Questions

- dependency on machine settings / current ⇒ control in one system?
- general-purpose approach ⇒ transferability to other control tasks?
Thank you for your attention!
mathematical foundation: Markov decision process (MDP)

“The future is independent of the past given the present.”

policy: defines agent’s behavior

goal: maximize cumulative reward

agent

state, reward

environment

start

△t

action

goal
value function $q_\pi$ is the expected cumulative reward following policy $\pi$

general policy iteration (GPI)

- policy evaluation: learning the value function
- policy improvement: exploiting the gained knowledge

Figure: adapted from *Reinforcement Learning*, Sutton, R.S. and Barto, A.G., 2nd edition, MIT Press (November 2018)