Control of the Microbunching Instability and Stabilization of the THz Coherent Radiation

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10th International Beam Instrumentation Conference

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Outline

1. Introduction : microbunching instability in storage rings
2. Control of the microbunching instability - numerical approach
3. Control of the microbunching instability - experimental studies
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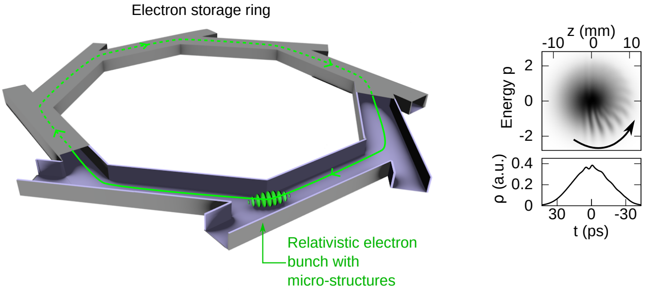
Microbunching instability

- Electron bunch dynamics :
  if charge density $>$ density threshold, interaction between the electrons and their radiation $\Rightarrow$ formation of microstructures (at mm scale) with irregular evolution in space and time : microbunching instability



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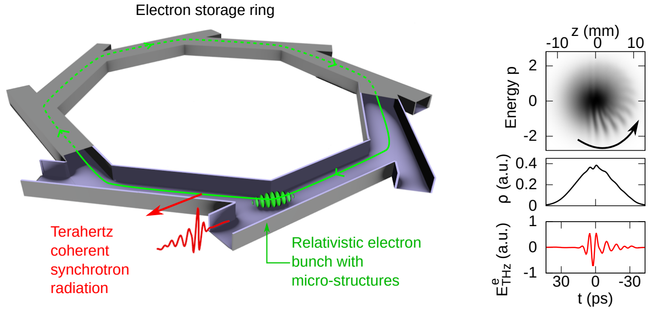
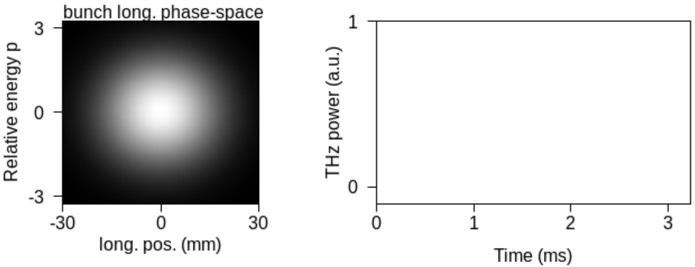


- Effect of the microstructures ⇒ emission of intense coherent THz pulses (typ. >10000 times stronger than normal incoherent synchrotron radiation)
- Observation in a large number of storage rings
  (NLSL, SURF III, BESSY II, ALS, SLAC, UVSOR II, ELETTRA, ANKA/KARA, CNL, DIAMOND, SOLEIL, etc.)

Simulations of the electron bunch dynamics

- **Natural existing solution**
  irregular evolution by burst
  (not usable as THz source)



Bursting behavior due to fluctuations of the bunch length (due to the apparition of the microstructures)

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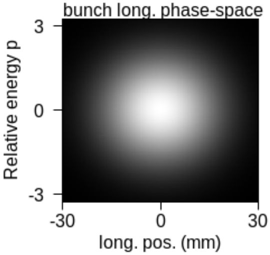
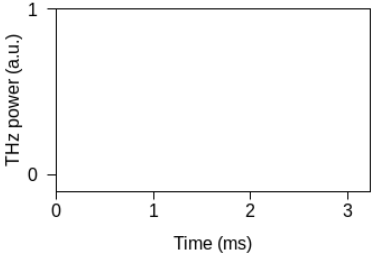
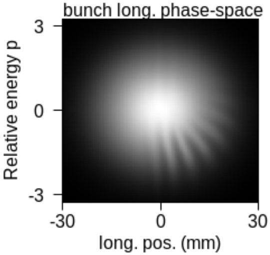
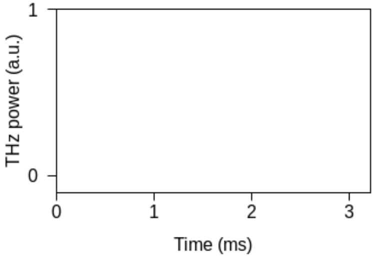




Bursting behavior due to fluctuations of the bunch length (due to the apparition of the microstructures)

- **An other co-existing mathematical solution**
  regular dynamics
  but with unstable properties
  (not observable directly)





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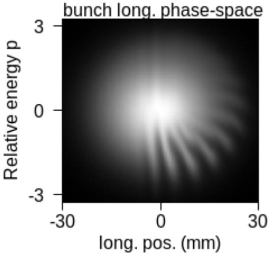

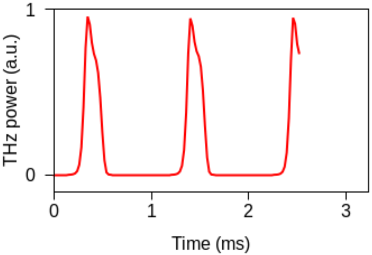

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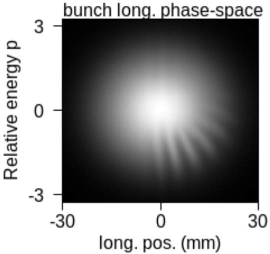

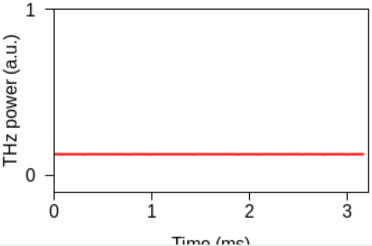

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Implementation of the feedback loop

- Objective : Use of a Feedback loop to stabilize the regular solution [cf. methods of control of chaos for ex.]

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$$\frac{\partial f(q,p,\theta)}{\partial \theta} - p\frac{\partial f}{\partial q} + \frac{\partial f}{\partial p}\left[\overbrace{\left(q\left[1+\underbrace{\Delta q(\theta)}_{\text{feedback}}\right]\right)}^{\text{RF slope}} - I_c E_{wf}\right] = 2\varepsilon\frac{\partial}{\partial p}\left(pf + \frac{\partial f}{\partial p}\right)$$

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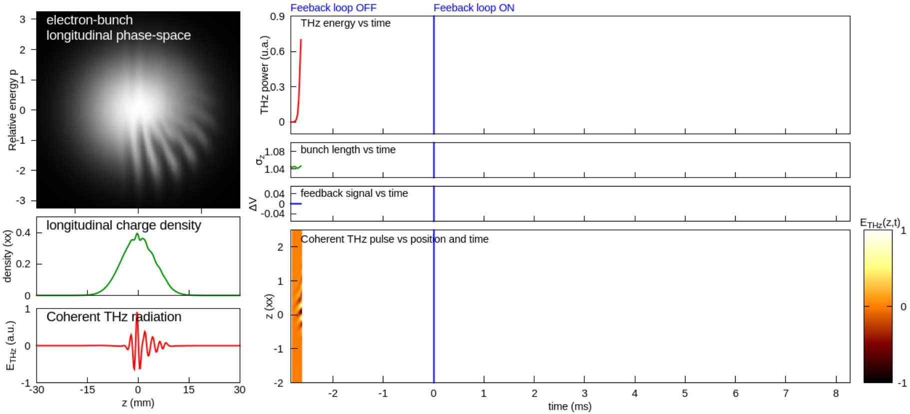
- **Feedback signal**
  - ▷ **Delay feedback** (Pyragas method) [K. Pyragas, Phys. Lett. A, **170**, 421- 428 (1992)]
    - No need to know a priori the unstable solution
    - Feedback signal is practically zero as the system evolves close to the desired stationnary solution
  - ▷ $\Delta q(\theta) = G \times [P_{THz}(\theta) - P_{THz}(\theta - \tau)]$

Control of the microbunching instability : numerical results

- Electron bunch dynamics with feedback

(SOLEIL parameters, normal alpha, above threshold)



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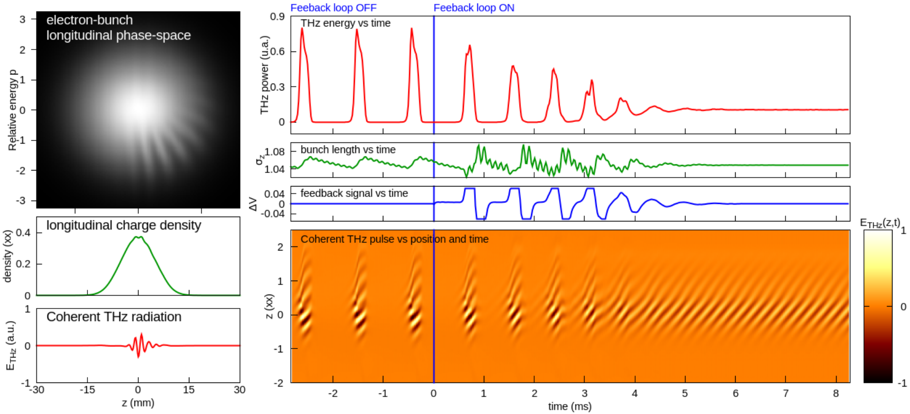

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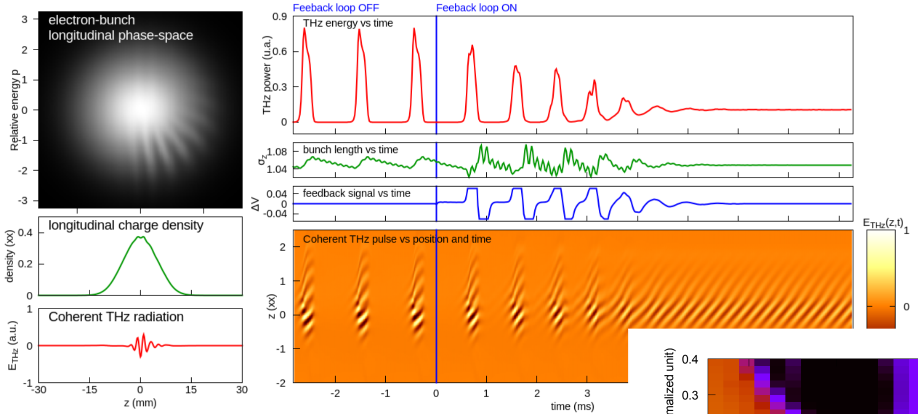
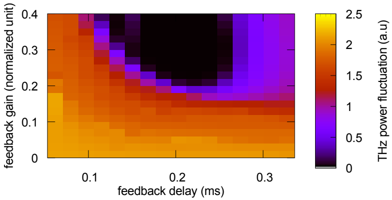


- THz fluctuations vs. feedback parameters $(\tau, G) \rightarrow\rightarrow\rightarrow$



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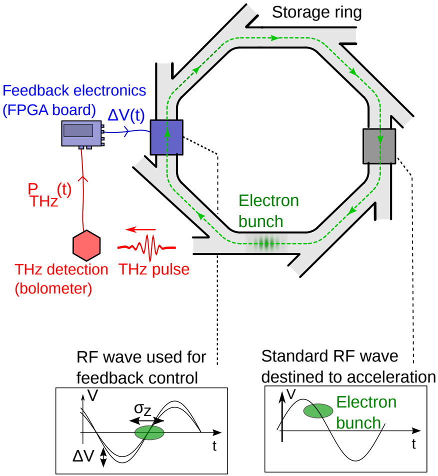
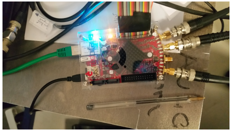
Experimental setup @Synchrotron SOLEIL



- Synchrotron SOLEIL (circumference : 354 m)

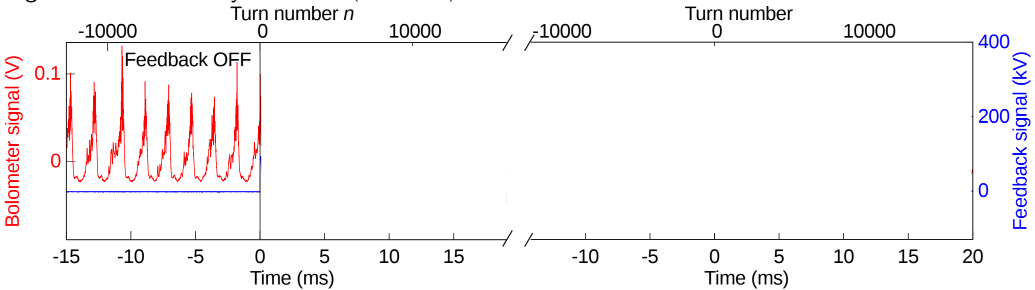
- THz detection @AILES beamline using a InSb bolometer (1-μs response time)
- Feedback loop using an FPGA board (Red Pitaya)



- 1 RF cavity @zero-crossing

Application of the feedback

- THz signal above instability threshold (I = 9.15 mA)



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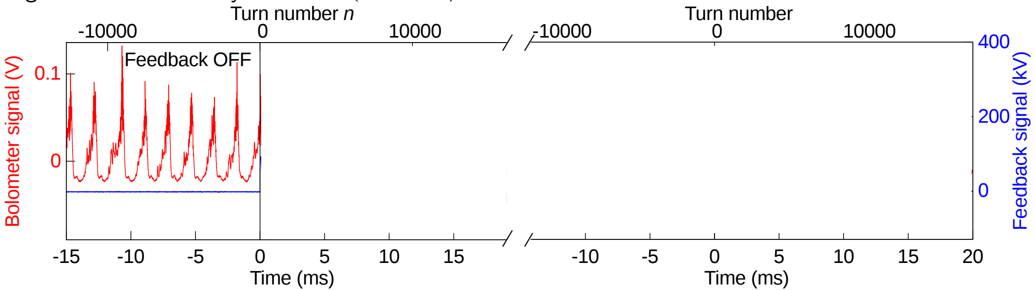
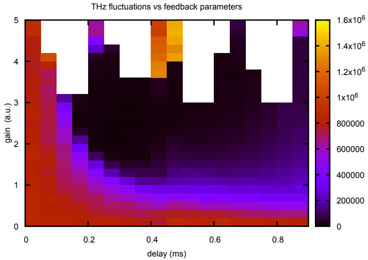


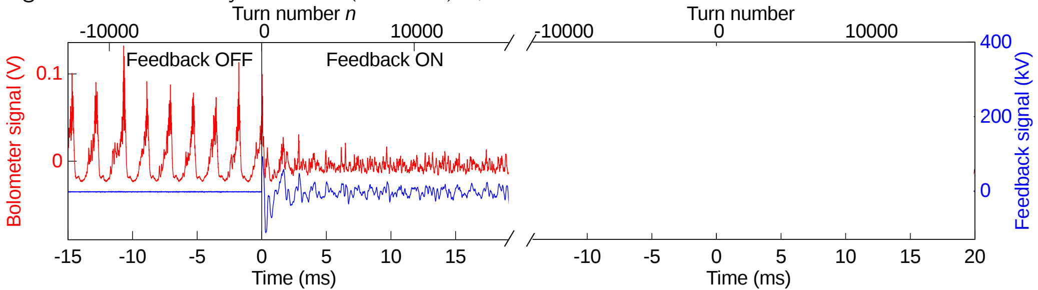
- THz fluctuations vs. feedback parameters (τ, G)

  (10 minutes for 40 × 40 parameters scan)



Application of the feedback

- THz signal above instability threshold (I = 9.15 mA) + **feedback**



- Some frequency components decreased by more than 40 dB
- THz fluctuations vs. feedback parameters (τ, G)

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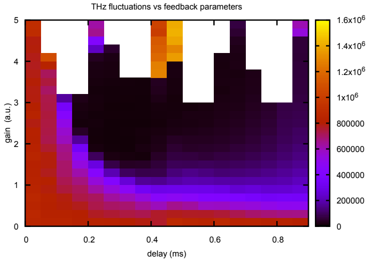

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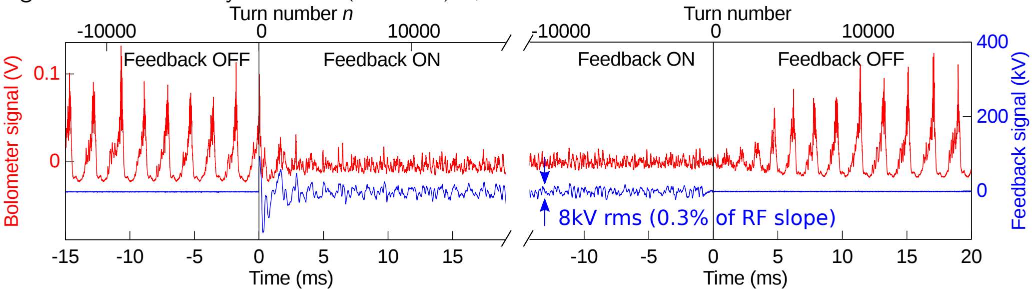

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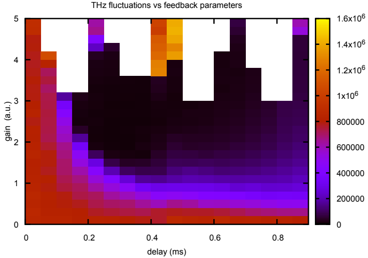

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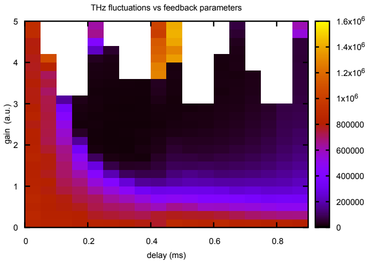
Additional feedback

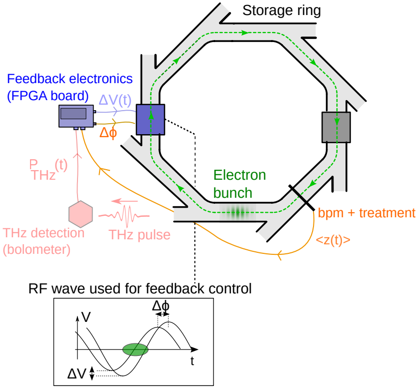
- In the color map, white area associated to a stop of the feedback - not to loose the beam - due to a beam transverse displacement higher than a chosen threshold ($\pm 50\mu$m)



- $\Rightarrow$ Use another feedback loop, to stabilize the beam

Additional feedback principle

- Additional feedback between :
  - a measure of the bunch center $< z(t) >$ (from BPM measurement)
  - the phase of the RF signal

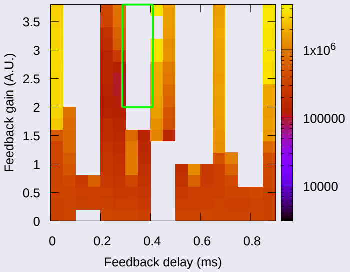


Effect of the additional feedback on the instability control - THz fluctuation map

- Bunch current $I \simeq 9.7$ mA

WITHOUT FB on the RF phase

THz fluct. vs FB par. (on RF amplitude)



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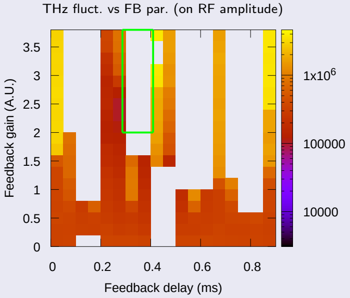

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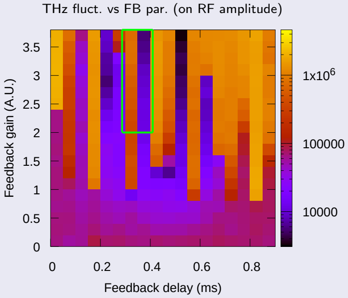
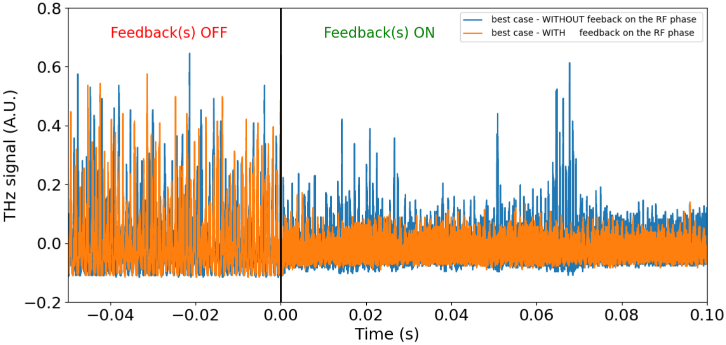


- Feedback on the RF phase permits "to access" new area of feedback parameters (on the RF amplitude)
- The new area are interesting in term of THz stabilization (since there are area with less fluctuations)

Effect of the additional feedback on the instability control - THz power vs time

THz power with and without feedback on the phase (best case of the zoom map)



Conclusion & perspectives

- Microbunching instability in storage rings :
  - irregular evolution (bursting) of microstructures in the bunch
  - **powerfull source of THz** but with **strong fluctuations**

- Control :
  - existence of an **unstable** state where microstructures appear very **regularly**
  - control the instability using a strategy inspired by the **control of chaos**
  - application of the feedback loop at **Synchrotron SOLEIL**
  - [Evain et al., Nature Physics 1745-2481 (2019)]
  - Not shown : possible to observe the spatio-temp. dyn. of the micro-structures [Roussel et al., SciRep. **5**, 10330 (2015)], [Szwaj et. al., RSI **87**, 103111 (2016)], [Evain et al., PRL **118**, 054801 (2017)]
  - Additional feedback on the RF phase permits to access new feedback parameters, with some of them efficient to decrease THz fluct.

- **Other strategies to increase the control efficiency at high current** :
  - more feedback loops using one or several observables
  - other types of feedback
  - machine learning strategy or multi-objective optimization (MOGA)
  - ...